Intermediate Charge-Breaking Phases in the 2-Higgs-Doublet Model

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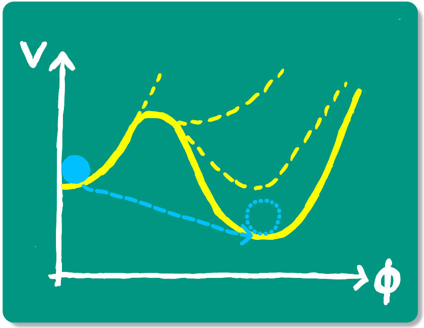
based on JHEP02(2024)232 (arXiv:2308.04141)
with Mayumi Aoki, Lisa Biermann, Igor P. Ivanov, Margarete Mühlleitner, Hiroto Shibuya

LHC Higgs WG3 – Extended Higgs Sector Subgroup Meeting – 19/11/2024

Evolution of the Universe around the electroweak epoch

How did the hot early Universe evolve around the electroweak epoch?



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- Exotic intermediate phases such as charge-breaking ones (massive photons, ...)?
- First-order and multi-step phase transitions?

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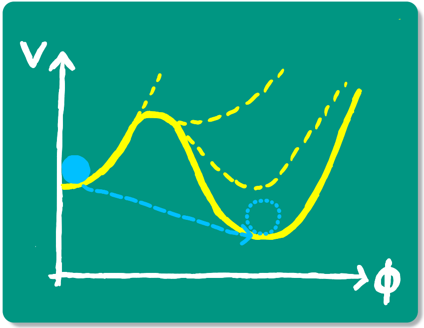
  $\longrightarrow$ charge-breaking $\longrightarrow$ neutral ($T = 0$)

- Compatibility with collider constraints?



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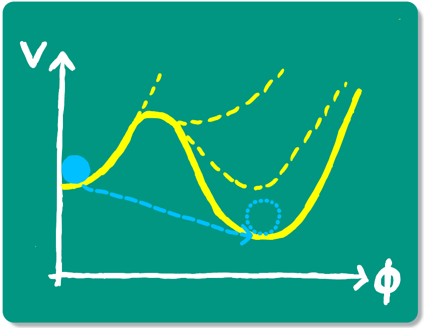

Excellent testbed for BSM physics with extended scalar sectors

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The CP-conserving 2HDM (type I) with softly broken $\mathbb{Z}_2$ symmetry

Tree-level scalar potential of the real 2HDM:

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

with

$$\Phi_1 = \frac{1}{\sqrt{2}}\begin{pmatrix} \rho_1 + i\eta_1 \\ \zeta_1 + \bar{\omega}_1 + i\psi_1 \end{pmatrix}, \qquad \Phi_2 = \frac{1}{\sqrt{2}}\begin{pmatrix} \rho_2 + \bar{\omega}_{\text{CB}} + i\eta_2 \\ \zeta_2 + \bar{\omega}_2 + i\left(\psi_2 + \bar{\omega}_{\text{CP}}\right) \end{pmatrix}$$

and real fields ρ_i, η_i, ζ_i, ψ_i $(i = 1, 2)$, and VEVs $\bar{\omega}_j$ $(j = 1, 2, \text{CP}, \text{CB})$

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

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

Phases in the 2HDM

Type of vacuum	$\sqrt{2}\,\langle\Phi_1\rangle$	$\sqrt{2}\,\langle\Phi_2\rangle$
Neutral EW-symmetric	$\begin{pmatrix}0\\0\end{pmatrix}$	$\begin{pmatrix}0\\0\end{pmatrix}$
Neutral EW-breaking	$\begin{pmatrix}0\\\bar{\omega}_1\end{pmatrix}$	$\begin{pmatrix}0\\\bar{\omega}_2\end{pmatrix}$
CP-breaking	$\begin{pmatrix}0\\\bar{\omega}_1\end{pmatrix}$	$\begin{pmatrix}0\\\bar{\omega}_2+i\bar{\omega}_{\text{CP}}\end{pmatrix}$
Charge-breaking (CB)	$\begin{pmatrix}0\\\bar{\omega}_1\end{pmatrix}$	$\begin{pmatrix}\bar{\omega}_{\text{CB}}\\\bar{\omega}_2\end{pmatrix}$

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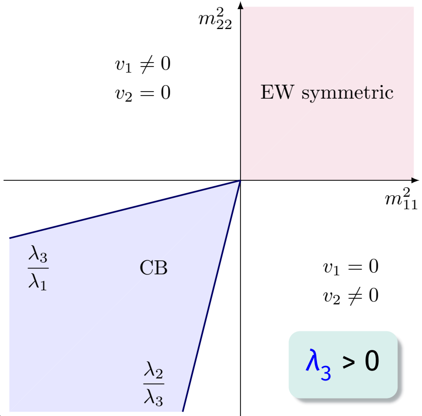
Toy model with $m_{12}^2 = 0$:



$\lambda_3 > 0$

(derive e.g. with geometric methods *[Ivanov '08]*)

Phases in the 2HDM

- **Bounded-from-below conditions:**

$$\lambda_{1,2} > 0\,, \quad \sqrt{\lambda_1\lambda_2} + \lambda_3 > 0\,,$$

$$\sqrt{\lambda_1\lambda_2} + \lambda_3 + \lambda_4 - \lambda_5 > 0$$

- **Conditions for a CB vacuum:**

$$\sqrt{\lambda_1\lambda_2} - \lambda_3 > 0\,, \quad \lambda_4 > |\lambda_5|$$

and

$$m_{11}^2\sqrt{\lambda_2} + m_{22}^2\sqrt{\lambda_1} < 0\,,$$

$$m_{11}^2 < m_{22}^2\frac{\lambda_3}{\lambda_2}\,, \quad m_{22}^2 < m_{11}^2\frac{\lambda_3}{\lambda_1}$$

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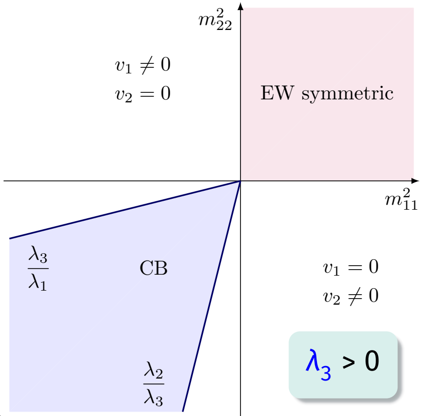

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Effective potential at finite temperatures T

Full one-loop effective potential including thermal corrections:

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

with

- V_{CW}: T-independent one-loop Coleman-Weinberg potential
- V_{CT}: T-independent counterterm potential
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$$\underset{\sim}{T\to\infty} -\frac{\pi^2}{90}T^4 + \frac{1}{24}m_k^2 T^2 - \frac{1}{12\pi}m_k^3 T + \ldots$$

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Perturbative expansion becomes unreliable at high T

- Resum ‘daisy‘ diagrams (‘Arnold-Espinosa‘ method) to recover perturbativity

⇒ Mass eigenvalues obtain T-dependent contributions

Thermal evolution

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

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

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

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

including gauge and Yukawa couplings

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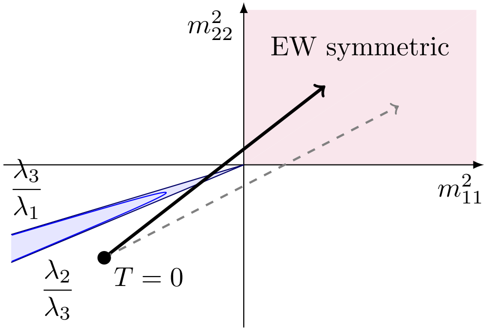

(blue hyperbola: $m_{12}^2 \neq 0$)

Thermal evolution

Full one-loop effective potential including thermal corrections:

$V_{\text{eff}}(T) = V$ ...

Follow-up questions

So far already known [Ivanov '08; Ginzburg, Ivanov, Kanishev '09], but:

- Existence of CB phases in the 2HDM using full one-loop-corrected effective potential including thermal corrections beyond high-T limit?
- Sequences of phase transitions? EW-symmetry restoration at high T?
- Intermediate CB phases vs. collider constraints?

$\frac{\lambda_2}{\lambda_3}$ $T = 0$

including gauge and Yukawa couplings

(blue hyperbola: $m_{12}^2 \neq 0$)

Scan of the 2HDM parameter space

(1) Generate *seed points* at $T = 0$ and scan over parameter space around them

- = Points with a suitable trajectory for an intermediate CB phase in high-T limit
- SM VEV and Higgs mass $v = 246.22$ GeV and $m_h = 125.09$ GeV fixed at $T = 0$

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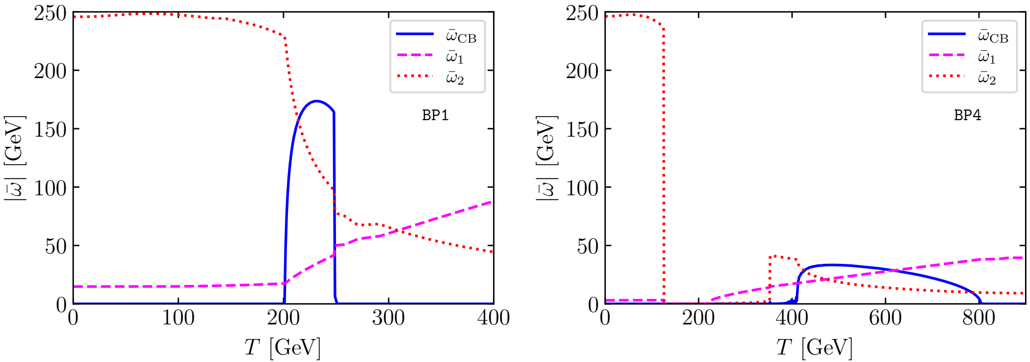
(3) Use ScannerS *[Coimbra et al. '13–'20]* to apply constraints to selected points:

Theoretical constraints:
bounded-from-below, perturbativity, perturbative unitarity *[Akeroyd, Arhrib, Naimi '00]*, absolute stability *[Barroso, Ferreira, Ivanov, Santos '13]*

Experimental constraints:
flavour physics, Higgs searches at colliders (Higgs{Signals/Bounds} *[Bechtle et al. '08-'21]*), *STU*-parameters *[Peskin, Takeuchi '92]*

Results of scan: benchmark points



	m_H (GeV)	m_A (GeV)	$m_{H^\pm}$ (GeV)	$\tan\beta$	$\cos(\beta-\alpha)$	m_{12}^2 (GeV^2)
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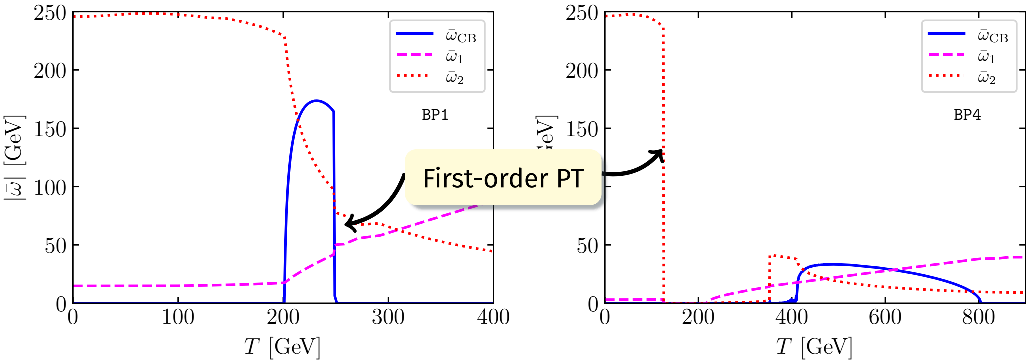

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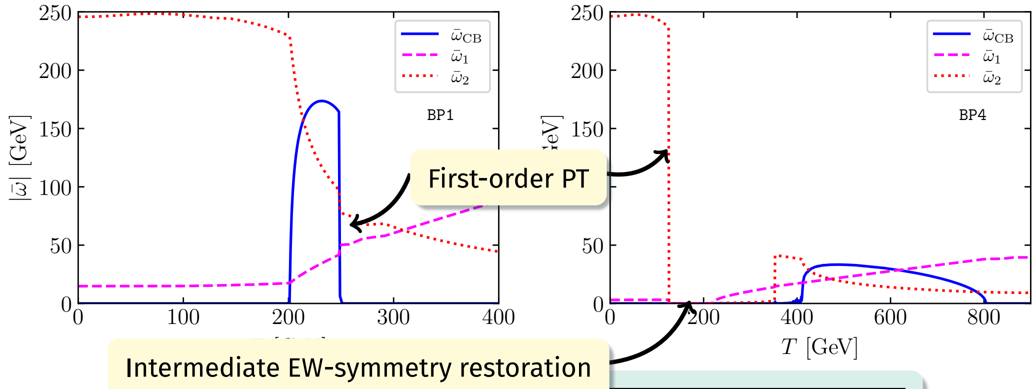

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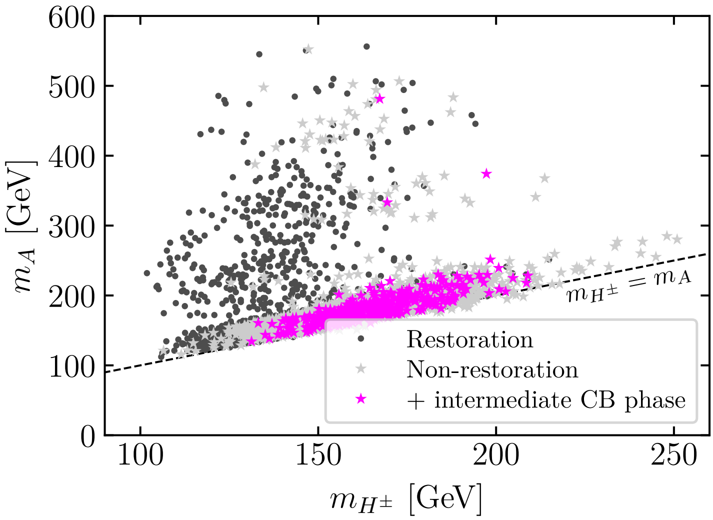

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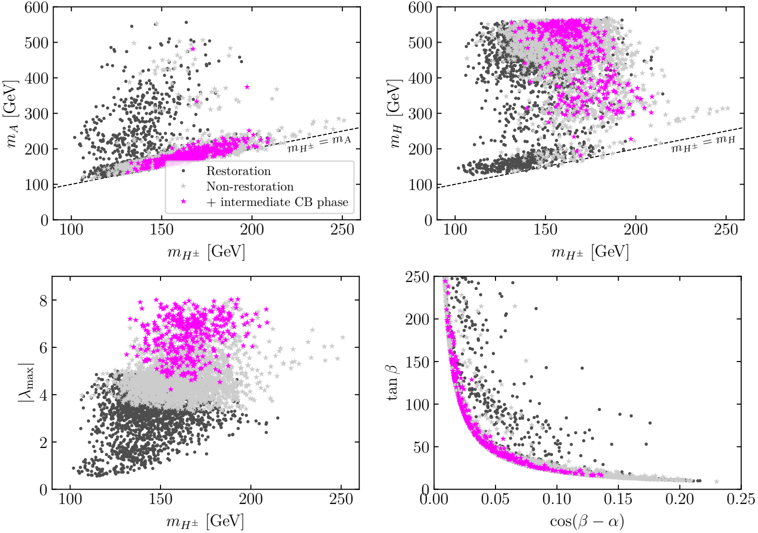

Intermediate CB phase:

- $100 \lesssim m_{H^\pm}/\text{GeV} \lesssim 210$
- $m_{H^\pm} \approx m_A$ or $m_{H^\pm} \approx m_H$
- $|\lambda_{\text{max}}| \gtrsim 4$

EW symmetry restoration (EWSR) at high T: $|\lambda_{\text{max}}| \lesssim 5$

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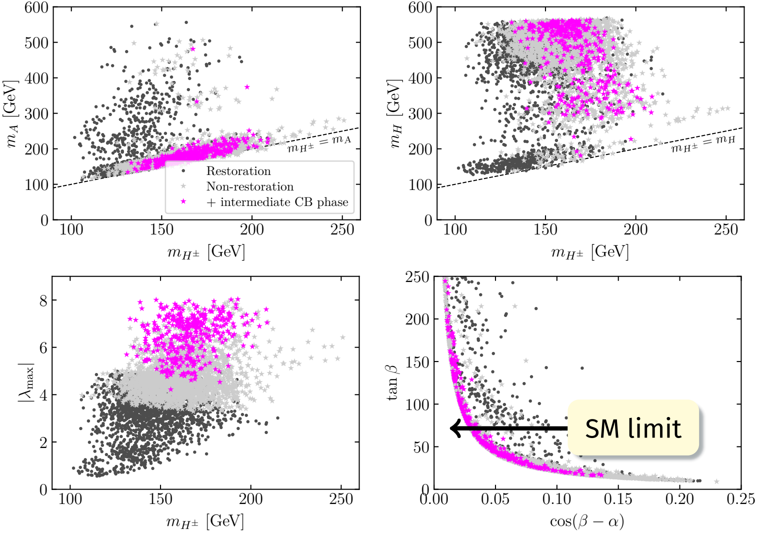

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⇒ Possibility for $H \to AZ$ and $H \to H^\pm W^\mp$ decays

↯ CB phase + EWSR + constraints

↯ All points excluded by latest `HiggsTools` data *[Bahl et al. '22]*

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Summary and conclusions

Phase transitions including intermediate charge-breaking phases in the 2HDM

- Intermediate CB phases can occur in the CP-conserving 2HDM **with full one-loop thermal corrections**
- Difficult to satisfy all experimental constraints
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THANK YOU FOR YOUR ATTENTION! ☺

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