Strong first-order electroweak phase transition in selected extended scalar sector models

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Electroweak Baryogenesis

Observation of a **non-zero baryon asymmetry** of the universe **(BAU)**

$$\boxed{\eta \equiv \frac{n_b - \bar{n}_b}{n_\gamma} \simeq \frac{n_b}{n_\gamma} \simeq 6.1 \times 10^{-10}}$$ [Planck, 2018]

What happened to the antimatter in our universe?
How can we generate a non-zero baryon asymmetry of the universe?

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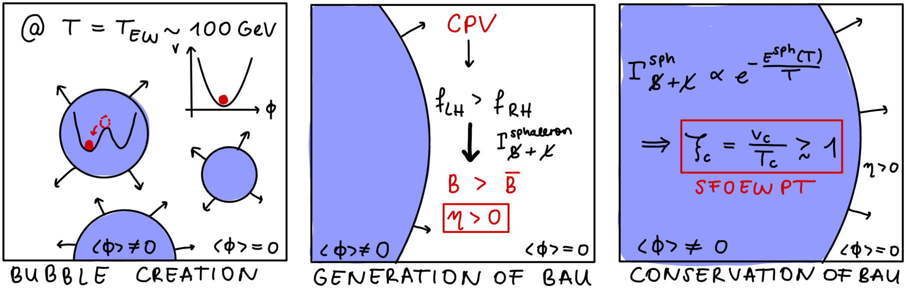

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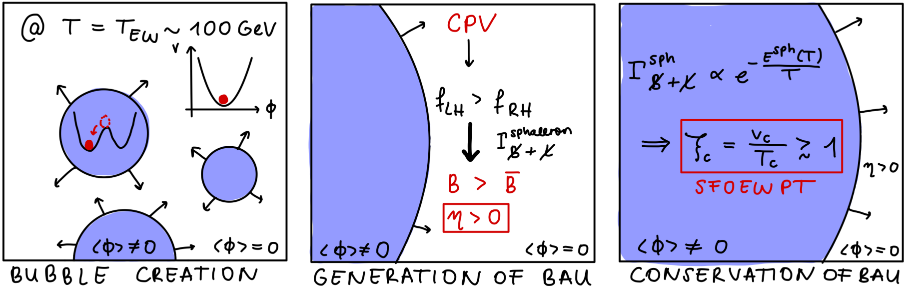

$\Rightarrow$ **BSM physics** required for additional CP violation and *strong first-order electroweak phase transition* (SFOEWPT)

$\rightarrow$ **Extended Higgs sector models** as promising road to BSM

Investigating SFOEWPTs with BSMPT

How do we look for *strong first-order electroweak phase transitions* (SFOEWPTs)?

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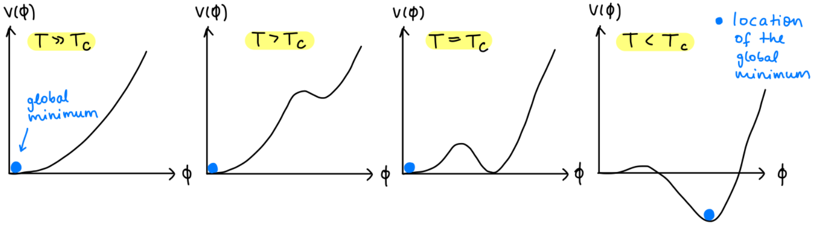

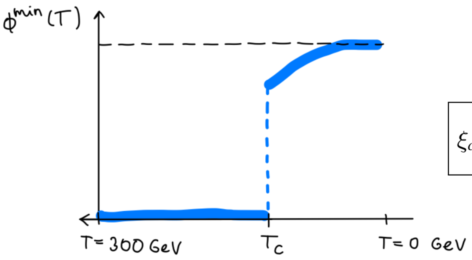

$$\xi_c \equiv \frac{\phi^{\min}(T = T_c)}{T_c} \gtrsim 1$$

SFOEWPT

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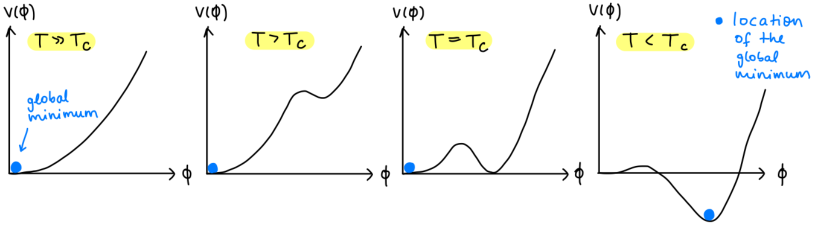

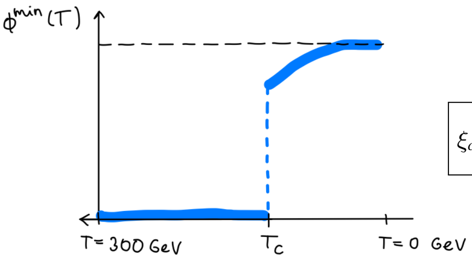

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SFOEWPT

⇒ global minimization of the one-loop corrected effective potential @ $T \neq 0$ with **BSMPT**

[P. Basler, M. Mühlleitner, J. Müller, 2018/20] https://github.com/phbasler/BSMPT

Searching for an SFOEWPT in extended scalar sector models

$\Rightarrow$ **Extended Higgs sector models** as promising road to BSM:

Searching for an SFOEWPT in extended scalar sector models

⇒ **Extended Higgs sector models** as promising road to BSM:

- **2HDM-type II EFT**(*): $\Phi_1, \Phi_2 + \frac{O_6}{\Lambda^2}$

→ struggle to reach SFOEWPT (compared to type I-2HDMs) [P. Basler et al., 2017]

→ look@2HDM-type II parameter points with $\xi_c < 1$:

What extra dynamics are required to achieve an **SFOEWPT**?

⇒ *bottom-up* extension of the 2HDM scalar potential by purely scalar dim-6 operators in an EFT approach

What are the phenomenological implications on **Higgs-Pair production**?

(*) *Two Higgs doublets, Effective Interactions and a Strong First-Order Electroweak Phase Transition*
by Anisha, LB, Christoph Englert and Margarete Mühlleitner

[JHEP 08 (2022) 091]

Searching for an SFOEWPT in extended scalar sector models

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What are the phenomenological implications on **Higgs-Pair production**?

- **CP in the Dark** (2HDM + real singlet)(∗∗): Φ_1, Φ_2, Φ_S

→ provides *viable* particle **DM** candidate and **explicit** CP violation *solely* in the dark sector @ $T = 0$

⇒ Can we generate an **SFOEWPT** within 'CP in the Dark'?

⇒ Can the 'hidden' **CP violation** be translated to the visible sector?

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(∗∗) *Electroweak Phase Transition in a Dark Sector with CP Violation*
by LB, Margarete Mühlleitner and Jonas Müller

[2204.13425]

R2HDM-Type-II EFT in Detail

[Anisha, LB, C. Englert, M. Mühlleitner, 2022]

- CP-conserving 2HDM, softly broken discrete $\mathbb{Z}_2$ symmetry: $\Phi_1 \to -\Phi_1$, $\Phi_2 \to \Phi_2$
  [T. D. Lee, 1973], [G. C. Branco et al., 2012]

$$V_{\text{tree}}(\Phi_1,\Phi_2) = m_{11}^2(\Phi_1^\dagger\Phi_1) + m_{22}^2(\Phi_2^\dagger\Phi_2) - m_{12}^2(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1) + \lambda_1(\Phi_1^\dagger\Phi_1)^2 + \lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}\lambda_5[(\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2]$$

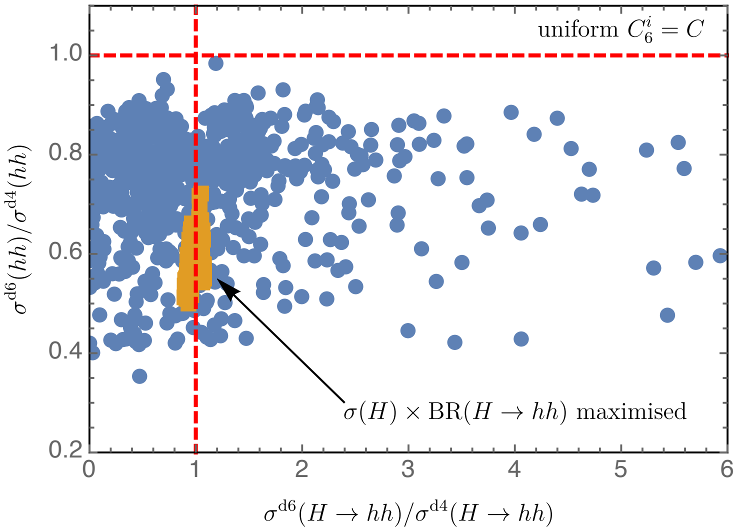
- inclusion of (purely scalar) dim-6 EFT contributions to the Higgs potential [Anisha et al., 2019]

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{2HDM}} + \sum_i \frac{C_6^i}{\Lambda^2} O_6^i \quad \Rightarrow \quad V_{\text{dim-6}} = -\sum_i \frac{C_6^i}{\Lambda^2} O_6^i$$

O_6^{111111}	$(\Phi_1^\dagger\Phi_1)^3$	O_6^{222222}	$(\Phi_2^\dagger\Phi_2)^3$
O_6^{111122}	$(\Phi_1^\dagger\Phi_1)^2(\Phi_2^\dagger\Phi_2)$	O_6^{112222}	$(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2)^2$
O_6^{122111}	$(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)(\Phi_1^\dagger\Phi_1)$	O_6^{122122}	$(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2)$
O_6^{121211}	$(\Phi_1^\dagger\Phi_2)^2(\Phi_1^\dagger\Phi_1)$ + h.c.	O_6^{121222}	$(\Phi_1^\dagger\Phi_2)^2(\Phi_2^\dagger\Phi_2)$ + h.c.

- absorb dim-6 contributions (to scalar masses) in shifts $\lambda_i \to \lambda_i + \delta\lambda_i$, $m_{12}^2 \to m_{12}^2 + \delta m_{12}^2$

$\Rightarrow$ scalar mass spectrum same as for dim-4 @ LO
$\Rightarrow$ shift EFT effects into **Higgs self-couplings** & **multi-Higgs final states**



↓ Higgs-pair **continuum** $gg \to hh$ is decreased

⟶ (exotic) Higgs **resonance** increased (within (future) LHC-sensitivity!)

‘CP in the Dark’ in Detail

[D. Azevedo, P. Ferreira, M. Mühleitner, S. Patel, R. Santos, J. Wittbrodt, 2018]

- N2HDM-like extended scalar sector, *one* discrete $\mathbb{Z}_2$ symmetry

$$\Phi_1 \to +\Phi_1\,, \quad \Phi_2 \to -\Phi_2\,, \quad \Phi_S \to -\Phi_S$$

- $SU(2)_L \times U(1)_Y$ and $\mathbb{Z}_2$-invariant tree-level potential:

$$V^{(0)} = m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 + \frac{m_S^2}{2}\Phi_S^2 + \left(A\Phi_1^\dagger\Phi_2\Phi_S + h.c.\right) + \frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4$$
$$+ \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger\Phi_2\right)^2 + h.c.\right] + \frac{\lambda_6}{4}\Phi_S^4 + \frac{\lambda_7}{2}|\Phi_1|^2\Phi_S^2 + \frac{\lambda_8}{2}|\Phi_2|^2\Phi_S^2$$

- general vacuum structure @ $T \neq 0$:

↲ charge-breaking VEV, $\omega_{CB} = 0$

$$\Phi_1 = \frac{1}{\sqrt{2}}\begin{pmatrix} \rho_1 + i\eta_1 \\ \zeta_1 + \boldsymbol{\omega_1} + i\Psi_1 \end{pmatrix}, \quad \Phi_2 = \frac{1}{\sqrt{2}}\begin{pmatrix} \rho_2 + \boldsymbol{\omega_{CB}} + i\eta_2 \\ \zeta_2 + \boldsymbol{\omega_2} + i(\Psi_2 + \boldsymbol{\omega_{CP}}) \end{pmatrix}, \quad \Phi_S = \zeta_S + \boldsymbol{\omega_S}$$

↳ CP-violating VEV

'CP in the Dark' in Detail

- general vacuum structure @ $T = 0$:

$$\Phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \rho_1 + i\eta_1 \\ \zeta_1 + v_1 + i\Psi_1 \end{pmatrix}, \ \Phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \rho_2 + i\eta_2 \\ \zeta_2 + i\Psi_2 \end{pmatrix}, \ \Phi_S = \zeta_S$$

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

→ $\boldsymbol{\omega_1}\big|_{T=0\,\text{GeV}} = v_1 \equiv v = 246.22\,\text{GeV}$, SM-Yukawa sector and tree-level FCNCs prohibited

→ $\mathbb{Z}_2$ symmetry *unbroken* ⇒ conserved quantum number: *dark charge*

- Φ_1 (*SM-like particles* with $+1$): $G^{\pm}, G^0, h$
- Φ_2, Φ_S (*dark particles* with -1) : $H^{\pm}, h_1, h_2, h_3$ ($m_{h_1} < m_{h_2} < m_{h_3}$)

⇒ **DM**: *stable* particle dark matter candidate h_1

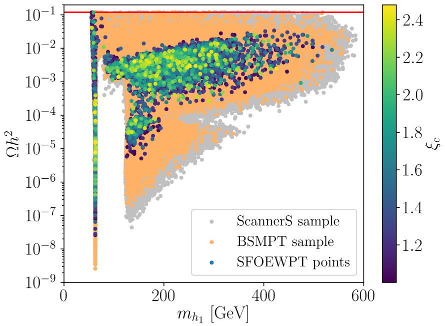
⇒ **explicit CPV**: introduced through $\text{Im}\,(A) \neq 0$

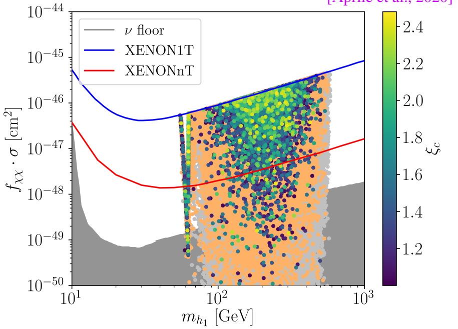
→ CPV after SSB, but vacuum is CP-symmetric ⇒ CPV is ***explicit***

→ solely in the dark sector - h_1, h_2, h_3: states with mixed CP quantum number

⇒ *not* constrained by EDM constraints

SFOEWPT points and DM Observables [LB, M. Mühlleitner, J. Müller, 2022]





$$f_{\chi\chi} \cdot \sigma_{\text{SI, DM-nucl.}} \equiv \frac{\Omega_{\text{prod}}h^2}{\Omega_{\text{obs}}h^2} \cdot \sigma_{\text{SI, DM-nucl.}}$$

Viable SFOEWPT parameter points

⇒ compatible with *relic density* ($< \Omega h^2$)

⇒ above neutrino floor

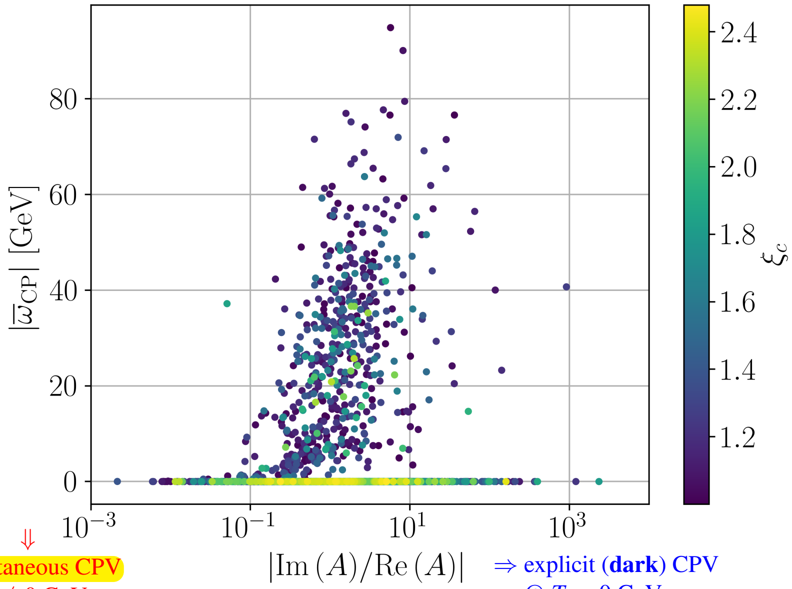
⇒ testable at future *direct detection* experiments

viable parameter points:

- pass constraints imposed by: **ScannerS** [R. Coimbra et al., 2013] [M. Mühlleitner et al., 2020], **BSMPT** [P. Basler, M. Mühlleitner, J. Müller, 2018/20]
- $\text{BR}(h \to \text{inv.}) < 0.11$ [M. Aaboud et al., 2019]
- $\mu_{h\to\gamma\gamma} = 1.12 \pm 0.09$ [A. Sirunyan et al., 2021]

Spontaneous CPV at Finite Temperature

[LB, M. Mühlleitner, J. Müller, 2022]



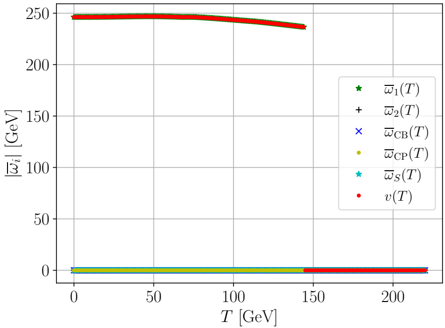
⇓
spontaneous CPV
@ $T \neq 0$ GeV

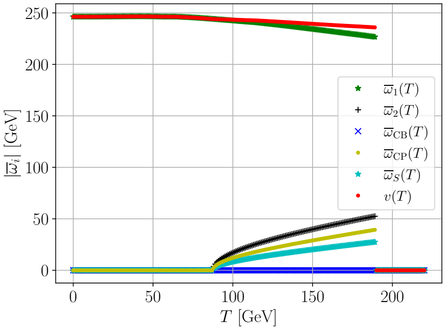
⇒ explicit (**dark**) CPV
@ $T = 0$ GeV

Spontaneous CPV at Finite Temperature

[LB, M. Mühlleitner, J. Müller, 2022]

- Two different VEV patterns in detail:





$\Downarrow$

only ω_1 develops non-zero values

$\Downarrow$

dark VEVs (except $\omega_{\rm CB}$) participate in EWPT

spontaneous CPV!

$\rightarrow$ @ $T \neq 0$: $\mathbb{Z}_2$ symmetry is broken $\rightarrow$ dark charge no longer conserved $\rightarrow$ dark sector **mixes** with SM-like particles

$\Rightarrow$ additional non-standard CPV transferred to the SM-like couplings to fermions @ $T \neq 0$!

Conclusion

- Dynamical generation of the baryon asymmetry of the universe (BAU) possible if *Sakharov conditions* fulfilled
- *Electroweak Baryogenesis*: fulfill Sakharov conditions with
  - **BSM models**
  - Non-standard *CP-violation* (CPV)
  - *Strong first-order electroweak phase transition* (SFOEWPT)
- **Extended Higgs sector models** as promising framework for EWBG:
  - **CP in the Dark**: viable SFOEWPT points that additionally show *spontaneous* CPV at finite temperature

  → *Can these points successfully generate the BAU?*
  - **Type-II R2HDM-EFT**: $|1 - \xi_c^{\mathrm{d4}}|$ **minimised** by scalar dim-6 contributions

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Thanks for Your attention!

Baryon Asymmetry of the Universe and Sakharov Conditions

initial: *Big Bang* (symmetric universe) $\Leftrightarrow$ today: **BAU** (asymmetric universe)

$$\eta \equiv \frac{n_b - \bar{n}_b}{n_\gamma} \simeq \frac{n_b}{n_\gamma} \simeq 6.1 \times 10^{-10}$$ [Planck, 2018]

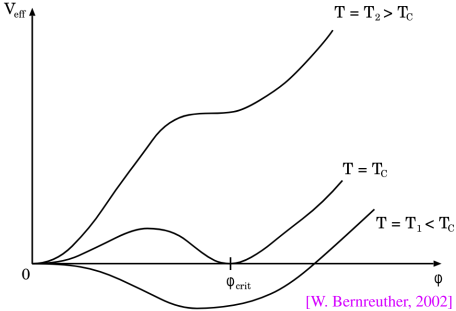
How can we generate a non-zero *baryon asymmetry of the universe*?

[Sakharov, 1967]: Dynamical generation of a BAU with an initially symmetric state possible if

Condition		
Existence of B violating processes	$\Rightarrow$	Sphaleron-mediated @ $T > T_{\text{EW}} = 100\,\text{GeV}$ [N. Manton, 1983], [F. Klinkhammer, N. Manton, 1984]
$\mathcal{C}$ and $\mathcal{CP}$ violation (CPV)	$\Rightarrow$	*Cabibbo-Kobayashi-Maskawa* mechanism [N. Cabibbo, 1963], [M. Kobayashi, T. Maskawa, 1973]
Departure from thermal equilibrium	$\Rightarrow$	Electroweak phase transition (EWPT) [D. Kirznits, 1972], [L. Dolan, R. Jackiw, 1974]

EWBG and an SFOEWPT

[D. Morrissey, M. Ramsey-Musolf, 2012]



[W. Bernreuther, 2002]

- EWBG takes place around $T \sim T_{\text{EW}}$
- EWPT happens and bubbles with non-zero vacuum expectation value (VEV) are created and expand
- Necessary departure from thermal equilibrium achieved through ***strong*** *first-order* EWPT (SFOEWPT)

→ '*first-order*': discontinuity in VEV v at T_c:

$$V(v = 0, T_c) = V(v \neq 0, T_c)$$

- How do we see this in the potential?
  → global minimum jumps from symmetric to broken minimum @ T_c

→ '**strong**': *conservation* of BAU through sufficient suppression of the sphaleron rate inside the bubbles

$$\Gamma^{\text{sph}}_{\not{B}+\not{L}} \propto \exp -\frac{E_{\text{sph}}(T)}{T} \quad \Rightarrow \quad \xi_c \equiv \frac{v_c}{T_c} \gtrsim 1$$

*baryon-wash-out condition** [M. Quiros, 1994]

⇒ EWPT in SM only *smooth cross-over* [K. Kajantie et al., 1996]

⇒ Need BSM models that enable an SFOEWPT* + *non-standard CPV*

Minimizing the One-Loop Corrected Effective Potential @ $T \neq 0$

- true vacuum state @ finite temperature (FT) including radiative corrections = global minimum of the **effective potential** @ $T \neq 0$

- general one-loop effective potential @ $T \neq 0$ splits into temperature-dependent and independent part [L. Dolan, R. Jackiw, 1974]

↵ optional finite shift

$$V^{(1)}(\omega, T) = \underbrace{V^{(0)}(\omega)}_{\text{tree-level}} + \underbrace{V^{\text{CW}}(\omega)}_{T\text{-indep. Coleman-Weinberg potential}} + \underbrace{V^{T}(\omega, T)}_{T\text{-dep.}} + \underbrace{V^{\text{CT}}(\omega)}_{\text{finite shift of scalar masses and mixing angles}}$$

T-indep. *Coleman-Weinberg* potential: renormalized in $\overline{MS}$-scheme [S. Coleman, E. Weinberg, 1973]

T-dep.: UV finite, IR finite after resummation $m^2 \to m^2 + \Pi^{(1)}(0)$ [M. Carrington, 1992], [R. Parwani, 1992], [P. Arnold, O. Espinosa, 1993]

finite shift of scalar masses and mixing angles [P. Basler et al., 2017]

- V^{CT} absorbs NLO scalar mass and angle shift [P. Basler et al., 2017]

$$0 = \partial_{\phi_i}(V^{\text{CW}} + V^{\text{CT}}|_{\vec{\omega}=\vec{\omega}_{\text{tree}}})$$
$$0 = \partial_{\phi_i}\partial_{\phi_j}(V^{\text{CW}} + V^{\text{CT}}|_{\vec{\omega}=\vec{\omega}_{\text{tree}}})$$