DESY THEORY WORKSHOP 2025

Synergies Towards The Future Standard Model

2HDM: Alignment limit and strong first-order electroweak phase transition

Name: Debankana Nath
DESY, Hamburg and Universität Hamburg

In Collaboration with:
Francisco Arco, Georg Weiglein, Kateryna Radchenko, Maria Olalla Olea Romacho, Sven Heinemeyer, Thomas Biekötter

SM explains mass generation : EWPT

- A single scalar SU(2) doublet $\Phi = \begin{pmatrix} \phi^+ \\ \phi^o \end{pmatrix}$,
- With $\mu^2 < 0, \lambda > 0$,

$$V(\Phi) = -\mu^2\,(\Phi^\dagger\Phi) + \frac{\lambda}{4}(\Phi^\dagger\Phi)^2$$

EW symmetry spontaneously broken to $SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM}$

➢ Mass to particles (Fermions and Gauge Bosons) and scalar Higgs boson

BEH mechanism

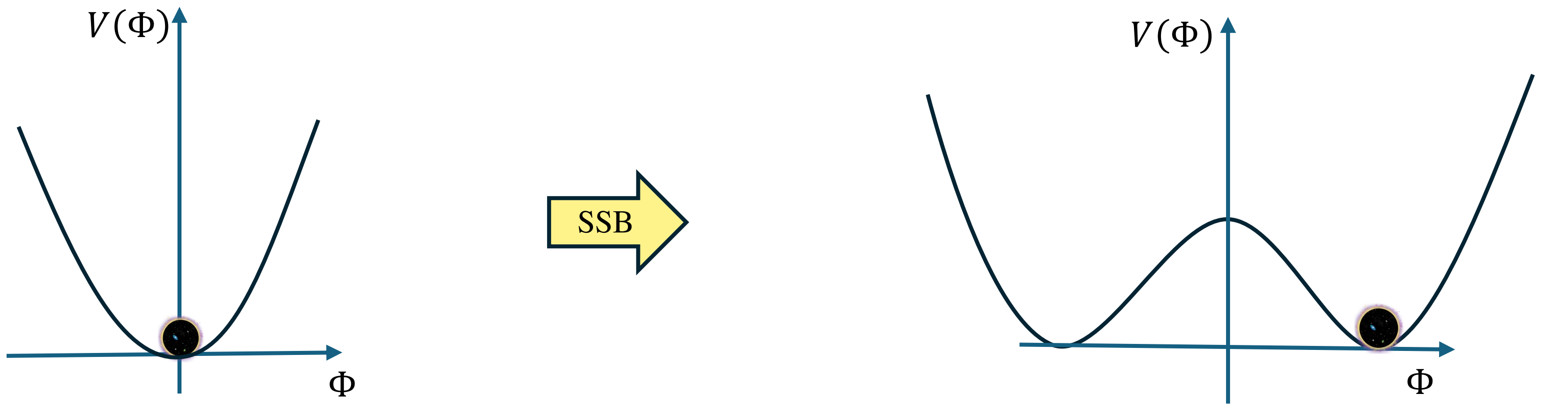


Fig 1. Smooth transition to the EW minimum

Thermal Evolution of the Universe

At finite-temperature:

$$V_{eff} = \underbrace{V_{tree} + V_{CW} + V_{CT}}_{\text{T-independent}} + \underbrace{V_T + V_{daisy}}_{\text{thermal corrections}}$$

V_{tree} : Tree-level scalar potential
V_{CW} : One-loop Coleman Weinberg potential (Ref.2)
V_{CT} : UV-finite counter-term potential
V_T : One-loop thermal corrections
V_{daisy} : Resummation of the daisy diagrams

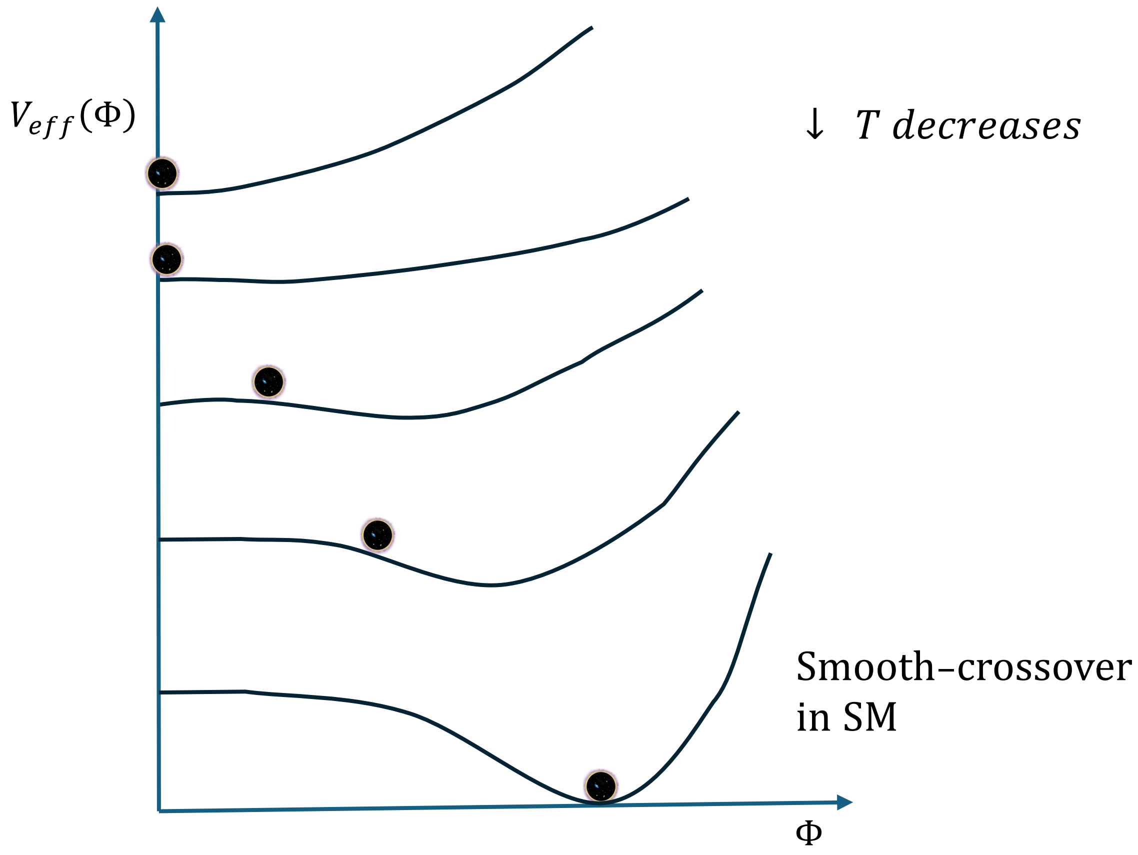


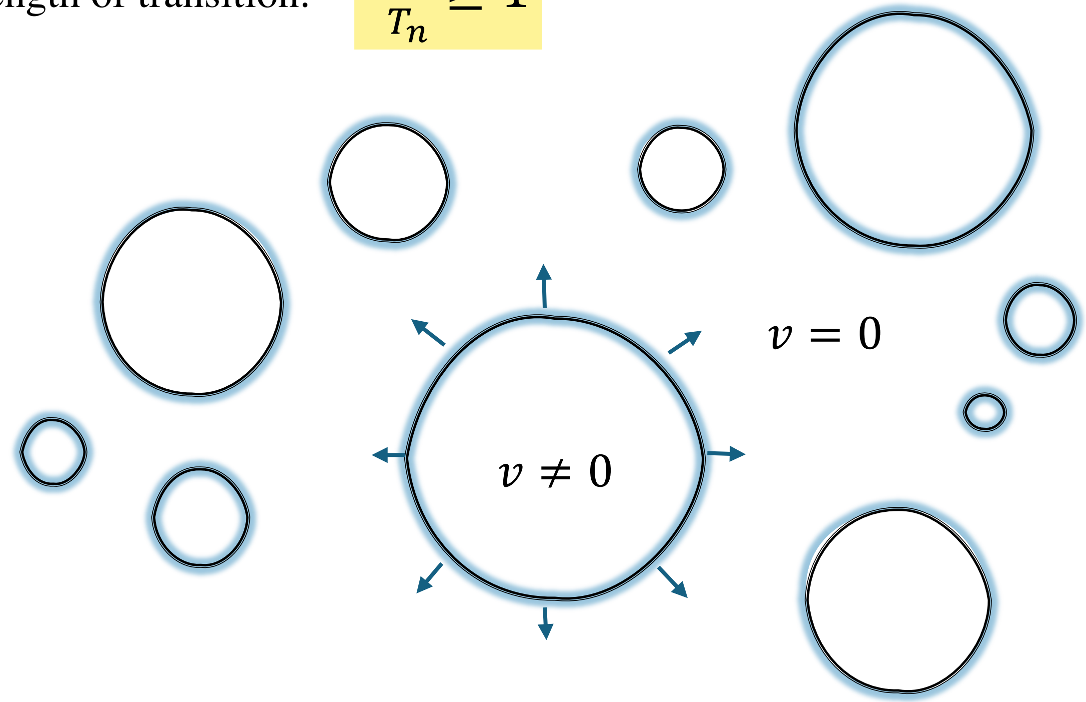
Fig 2.1: Finite-temperature potential: thermal evolution of vacuum as a smooth cross-over

First-order Phase Transition

- At very high temperatures:
  EW symmetry preserved at v = 0

- Temperature decreased :
  -> Universe cooled -> develops non-zero vev
  -> EW symmetry breaks at T_n -> sudden change of vev
  -> Nucleation of vacuum bubbles

Strength of transition: $\frac{v_n}{T_n} \geq 1$



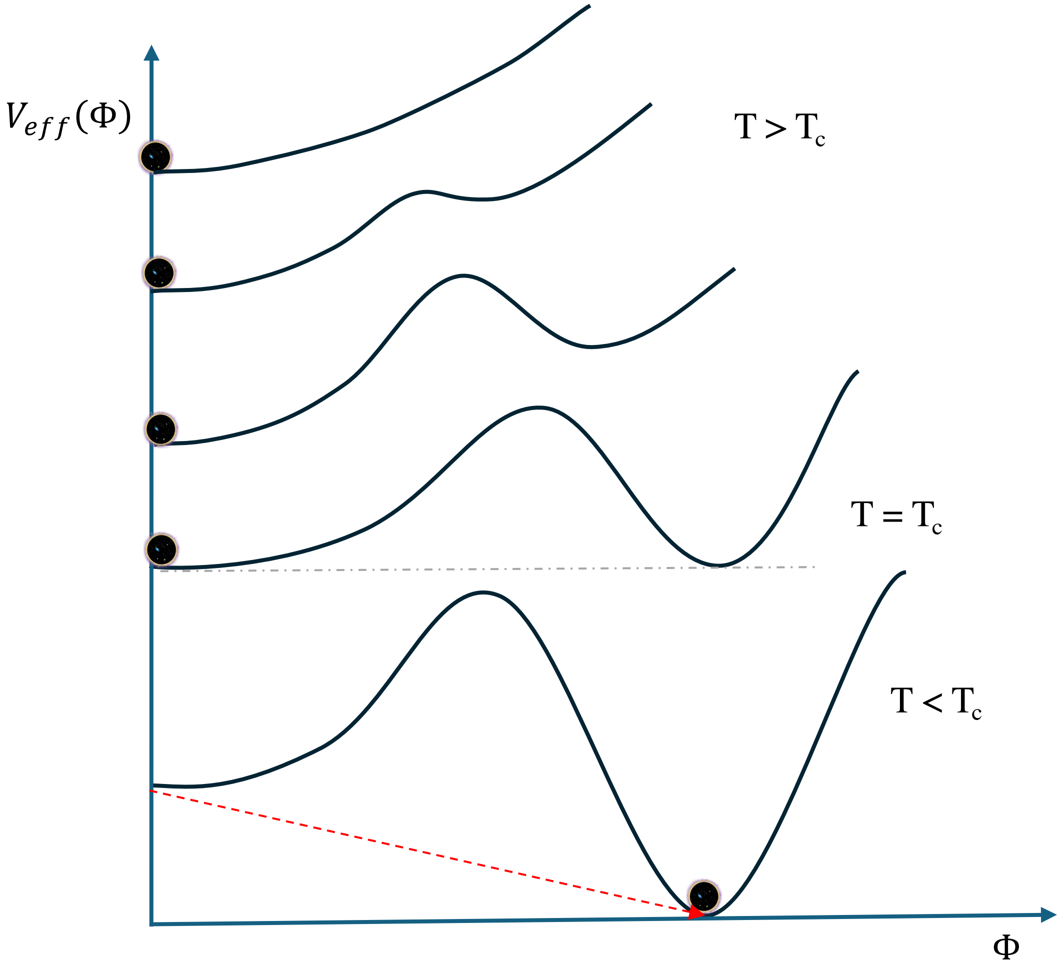


Fig 2.2: First-order phase transition of the universe

What are we looking for?

- EW baryogenesis -> Strong first-order phase transition
- Matter-Antimatter asymmetry

  -> *SM prediction*: $6 \cdot 10^{-19}$; Obser*ved*: $6 \cdot 10^{-10}$

  -> Sakharov conditions

  (B, C and CP violation + Out-of-Thermal-Equilibrium Process)

✓ *BSM (extended) Higgs sector required!*

Two-Higgs-Doublet Model (2HDM)

Z_2 symmetry :
$\Phi_1 \to \Phi_1$
$\Phi_2 \to -\Phi_2$

I, II, III, IV

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

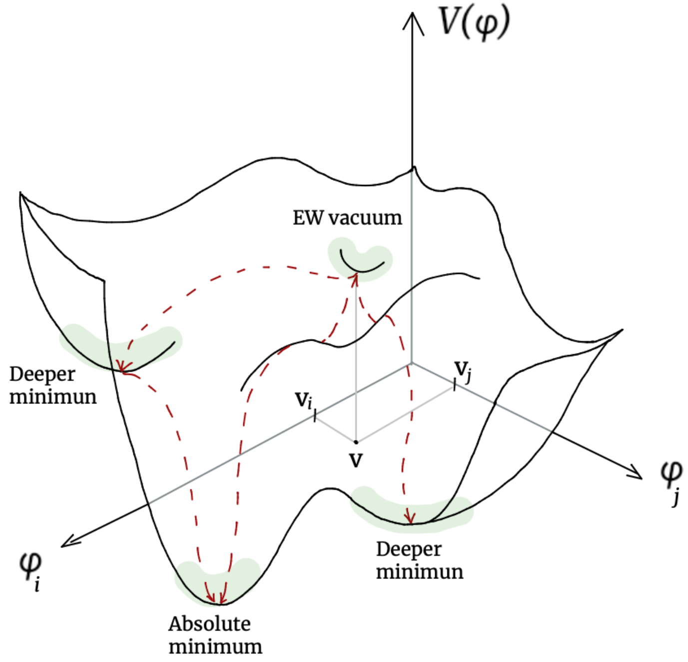


Fig 3: Representation of minima structure of 2HDM (or BSM) scalar potential

SSB

$$\langle\Phi_1\rangle = \begin{pmatrix} 0 \\ \frac{v_1}{\sqrt{2}} \end{pmatrix}$$

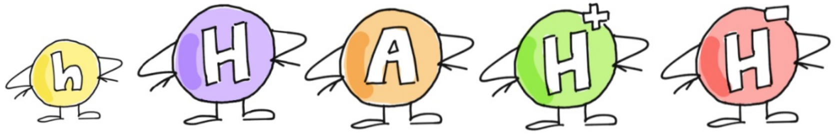
$$\langle\Phi_2\rangle = \begin{pmatrix} 0 \\ \frac{v_2}{\sqrt{2}} \end{pmatrix}$$

In mass basis:

→ 5 physical scalar fields ($h, H, A, H^\pm$) diagonalised by α and β,

→ 3 would-be-Goldstone bosons ($G^0, G^\pm$)

- Non-trivial structure of the scalar potential



Art credit: Kateryna Radchenko

Constraints on 2HDM Parameter Space

Free parameters:

tan β, cos (β - α), v, m_h , m_H, $m_{H^\pm}$, m_A, m_{12}^2

Enters in self-couplings -> barrier shape

Alignment limit:

- cos (β - α) → 0
- Light CP-even Higgs *h* has SM-like couplings of h_{125} at the lowest order
- Possible in both decoupling and non-decoupling regime

Theoretical constraints:

- Vacuum stability and boundedness-from-below
- Perturbative unitarity

Experimental constraints:

- Electroweak precision observables
- Constraints are from the limits from searches for additional Higgs bosons
- Measurements of the properties of h_{125}
- Flavour Constraints

Mass splittings

Key Regions:

1. $m_A = m_{H^\pm}$
2. $m_H = m_{H^\pm}$

- Larger mass splittings $m_A - m_H$ driven by the quartic couplings in the scalar potential correlate to stronger first-order phase transitions.

- For region 1: mass splitting range: 100 – 200 GeV
- For region 2: mass splitting range: 150 – 400 GeV

- This dependence is constrained by perturbative unitarity.

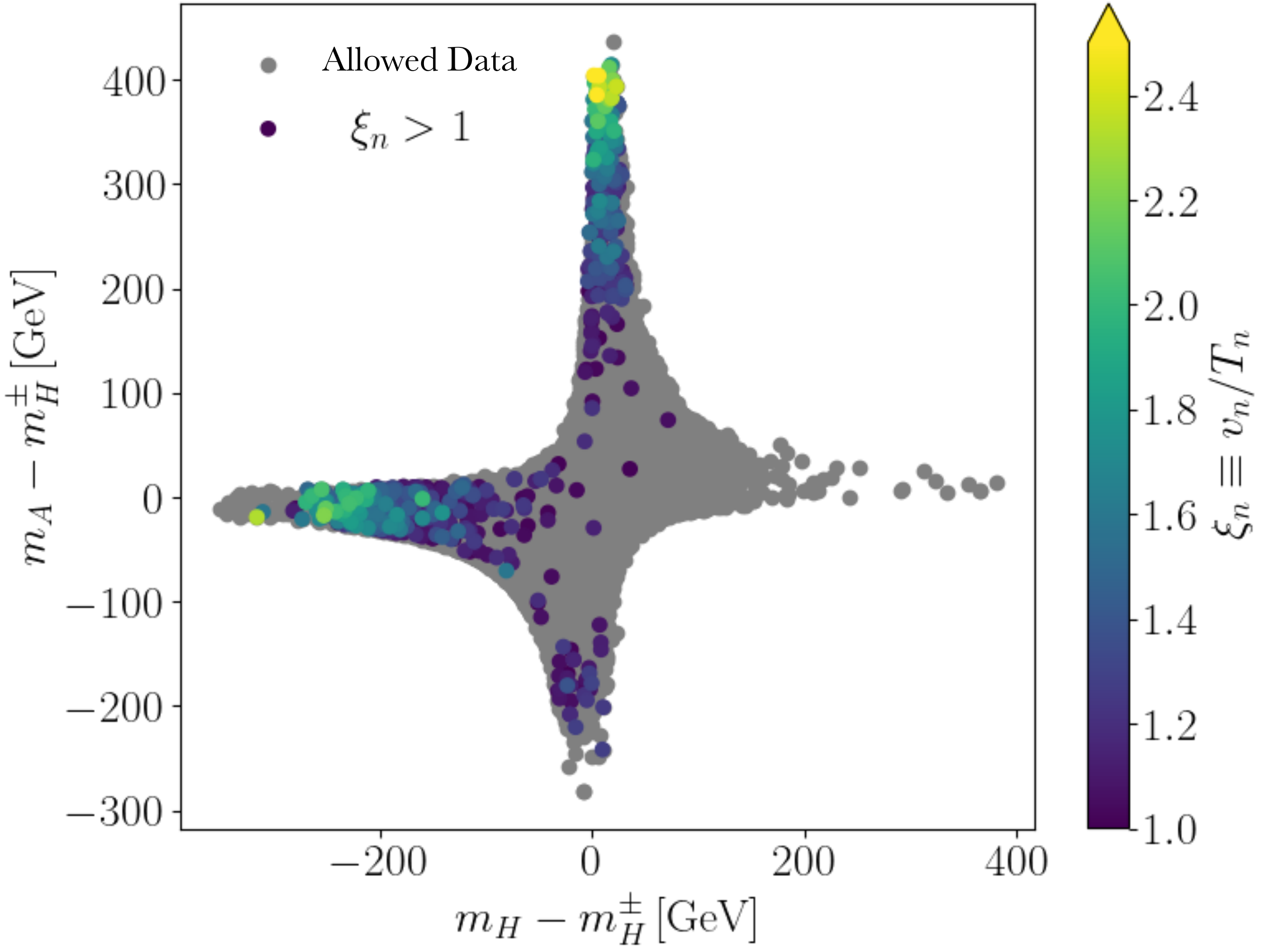


Fig 4: SFOEWPT strength depends on the mass splittings, here the free parameters vary as $1 \leq \tan\beta \leq 50$ and $150 \leq m_H \leq 1400$ GeV.

SFOEWPT in (m_H, cos(β-α)) plane

For low mass values m_H around 200 Gev:

- SFOEWPT occurs for wide range of cos(β-α) values
- Both CP-even neutral Higgs bosons *h* and *H* take part in the EW phase transition → enhanced thermal corrections → relatively higher strengths

For higher mass values m_H (upper bound of 800 GeV):

- SFOEWPT occurs for cos(β-α) → 0
- *H* tends to decouple: only *h* drives the EW phase transition

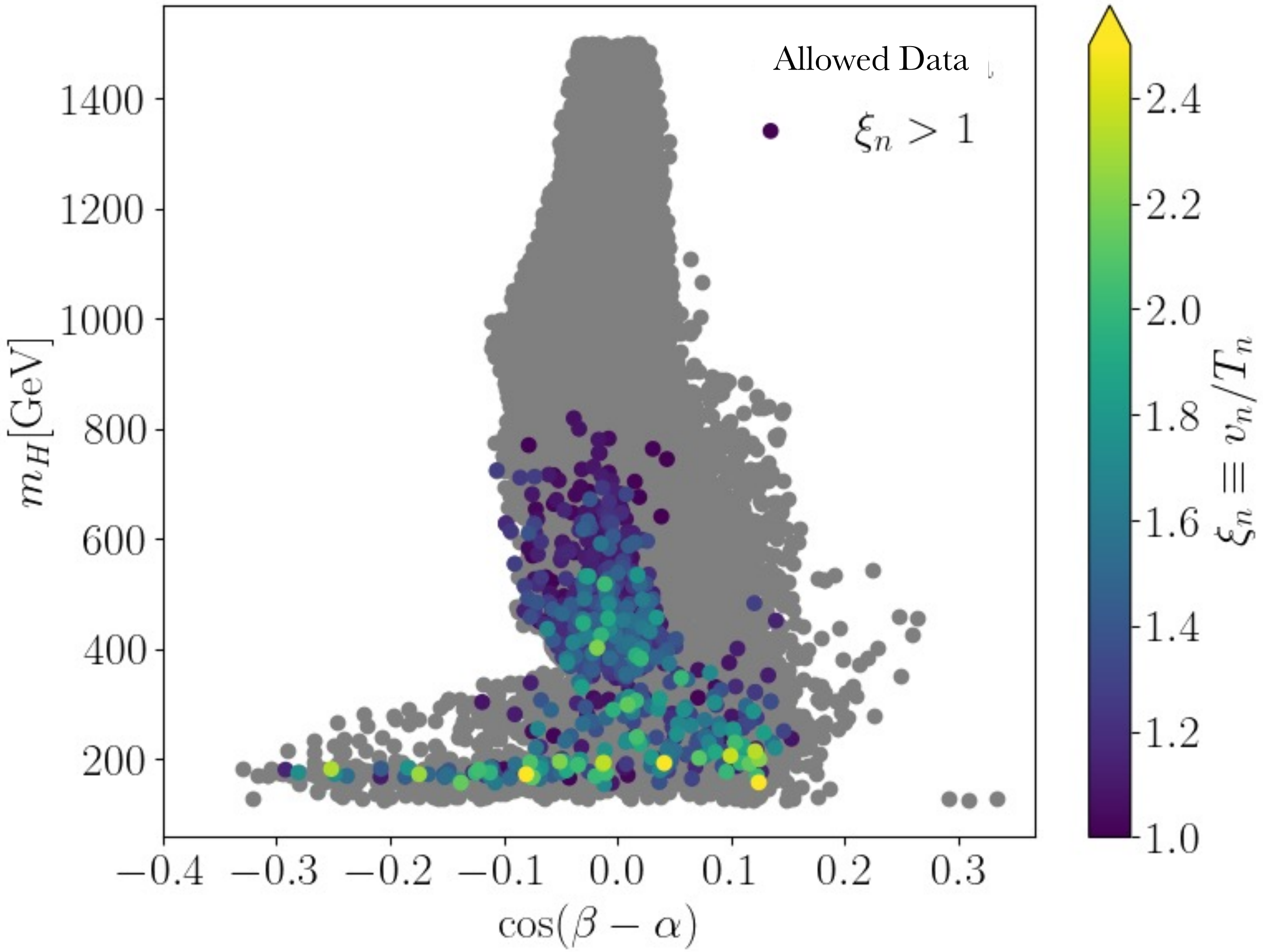
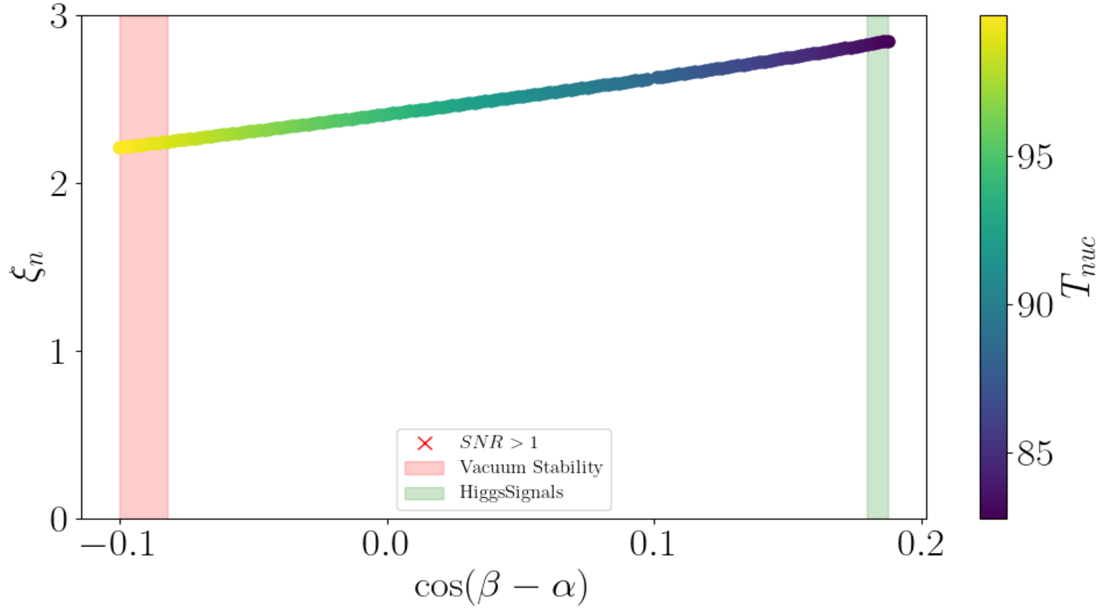


Fig 5: SFOEWPT for CP-even heavy Higgs mass values, here the free parameters vary as $1 \leq \tan\beta \leq 50$

SFOEWPT vs cos (β-α)
for lower m_H

- **SFOEWPT occurs for wide range of cos (β-α), strength increasing as we go away from the alignment limit**

Type I: m_H= 177.3 GeV , $m_{H^\pm}$= 155.7 GeV, m_A = 564 GeV, tan β = 8.46, M = 176 GeV



Type I: m_H= 157.3 GeV ~ $m_{H^\pm}$= 151 GeV, m_A = 500 GeV, tan β = 19.2, M = 156.2 GeV

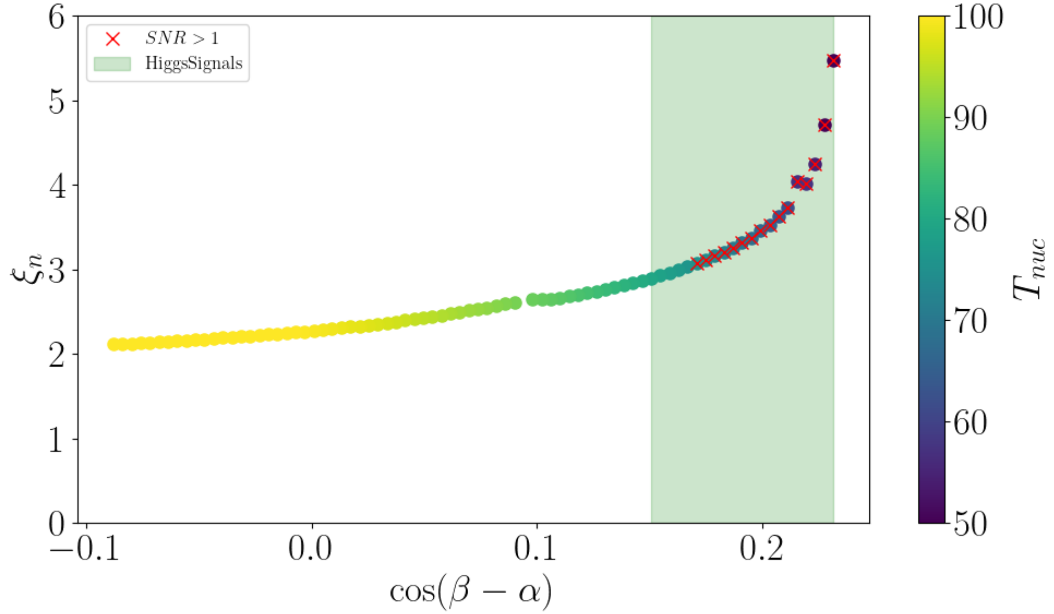


Fig 6a and b: Variation of strength with cos(β-α) for lower CP-even Higgs masses to correlate the SFOEWPT parameter space close to as well as away from alignment limit

SFOEWPT vs cos (β-α) for higher m_H

- **SFOEWPT occurs strongest for cos (β-α) → 0, i.e. strength highest at the alignment limit**

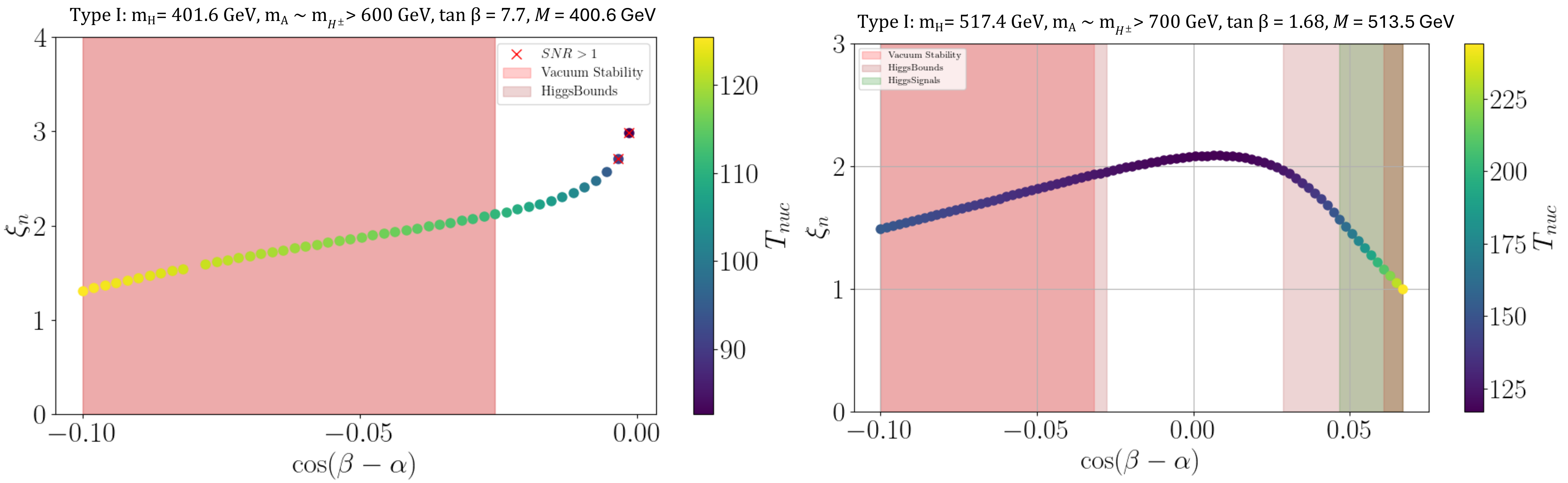


Fig 7a and b: Variation of strength with cos(β-α) for higher CP-even Higgs masses to correlate the SFOEWPT parameter space close to alignment limit

Conclusions

- Extended Higgs sectors can feature a SFOEWT, necessary for EW baryogenesis, can potentially lead to detectable GW signals

- The parameter region giving rise to a SFOEWPT in the 2HDM has a mass splitting between m_A and m_H of about 200 GeV

- For high values of m_H (up to 800 GeV): SFOEWPT occurs close to the alignment limit
- For low values of m_H (~ 200 GeV): SFOEWPT possible for larger deviations from the alignment limit

- Qualitatively, for SFOEWPT parameter points with higher m_H, the strength of phase transition increases with cos $(\beta\text{-}\alpha)$, and is highest near the alignment limit, whereas for the case of lower m_H, the strength is higher as we go away from the alignment limit.

Next Steps:

- Extend the current results for the types II, III and IV of 2HDM
- Check for κ_λ variation for the above parameter regions showing SFOEWPT in correlation to the alignment limit
- Investigate the prospects for possible GW signals

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Thank you