Phase Transitions in 2HDMS

Juhi Dutta

based on

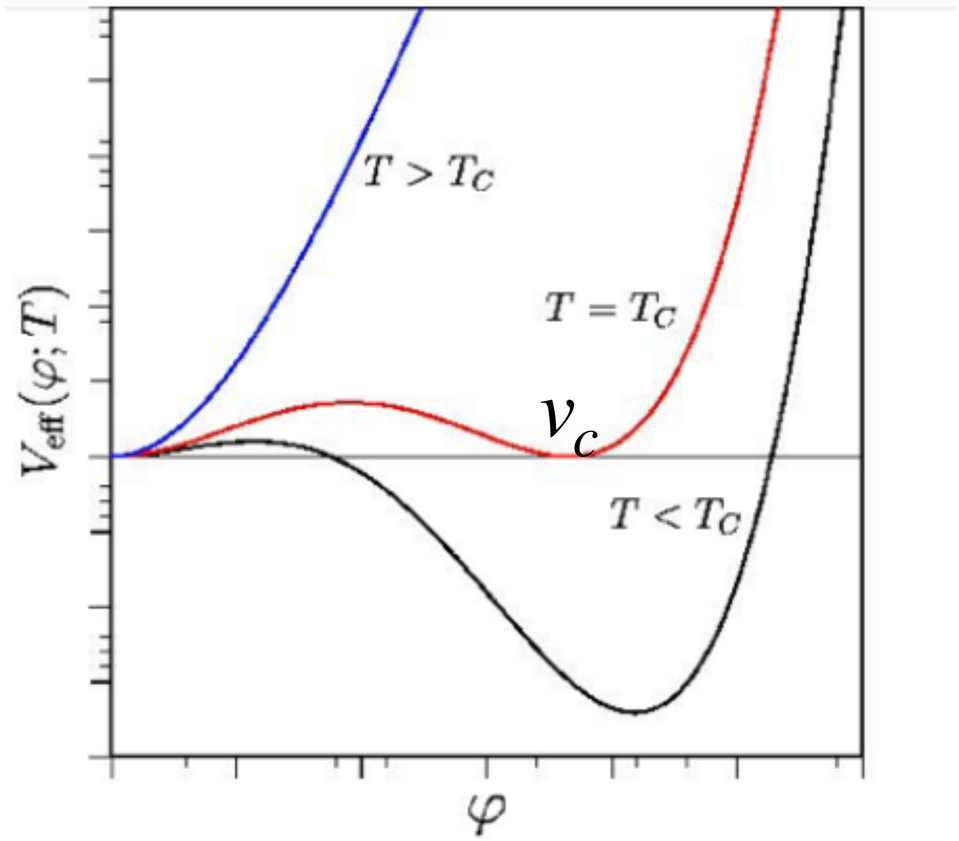
ongoing work with J. Lahiri, C. Li, G. Moortgat-Pick, J.A. Ziegler

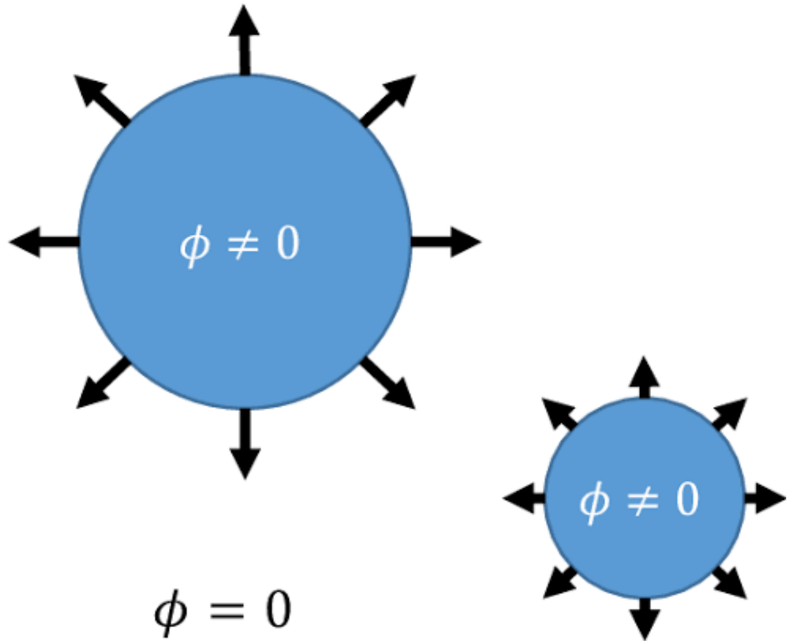
The International Workshop on Future Linear Colliders 2026 (LCWS2026), KEK, Japan

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Motivation

- Electroweak Phase Transition (EWPT) describes the change in the electroweak vacuum structure of the early Universe as it cools, associated with the breaking of electroweak symmetry and the development of a non-zero Higgs vacuum expectation value.





Bubble nucleation.

- In the Standard Model, the electroweak phase transition is a **crossover** for the observed Higgs boson mass, insufficient to support electroweak baryogenesis.

- A strong first-order electroweak phase transition provides the necessary departure from thermal equilibrium for generating the observed matter–antimatter asymmetry.

- A standard criterion for SFOPT is $v_c/T_c > 1$ to avoid washout due to sphaleron processes.

- **Additional scalar degrees of freedom in extended Higgs sectors can significantly modify the finite-temperature effective potential.**

Can an extended Higgs sector modify the electroweak phase transition and accommodate dark matter?

Extended Higgs Portal Models:
2HDM + complex singlet scalar (2HDMS)

- Consider a softly broken Z_2 (to avoid FCNC) symmetric Type II 2HDM augmented with a complex scalar singlet S, with the imaginary component stabilized under Z_2'.

- Depending on the singlet vev v_S, the model can accommodate single or multicomponent dark matter candidates.

- The scalar potential $V_{2HDMS} = V_{2HDM} + V_S$,

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

$$V_S = m_S^2(S^\dagger S) + \frac{m_S^{2'}}{2}(S^2 + h.c) + \frac{\lambda_1''}{24}(S^4 + h.c) + \frac{\lambda_2''}{6}(S^2(S^\dagger S) + h.c) + \frac{\lambda_3''}{4}(S^\dagger S)^4 +$$

$$\lambda_1' S^\dagger S\Phi_1^\dagger\Phi_1 + \lambda_2' S^\dagger S\Phi_2^\dagger\Phi_2 + S^2(\lambda_4'\Phi_1^\dagger\Phi_1 + \lambda_5'\Phi_2^\dagger\Phi_2) + h.c$$

$$\Phi_i = \begin{pmatrix} \phi_i^\pm \\ \frac{1}{\sqrt{2}}(v_i + h_i + ia_i) \end{pmatrix}, \quad i = 1, 2, \quad S = \frac{1}{\sqrt{2}}(v_S + h_S + ia_S)$$

Baum, et.al, *JHEP*12(2018)044

Key Points

Particle content:

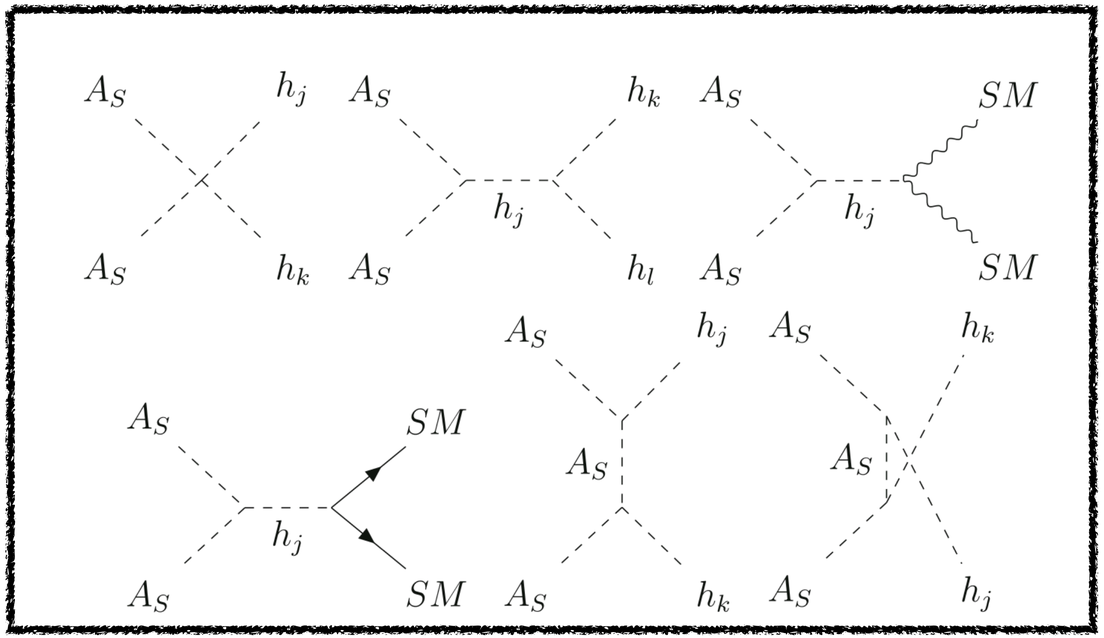
$$h_1, h_2, h_3, A, H^{\pm}, A_S$$

Scalar Mediators **DM**

Dark Matter mass:

$$m^2_{A_S} = \frac{\partial^2 V}{\partial A_S^\dagger \partial A_S}\Big|_{\substack{\Phi_1=\langle\Phi_1\rangle \\ \Phi_2=\langle\Phi_2\rangle \\ S=\langle S\rangle}}$$

$$= -(2m'^2_S + v_S^2(\frac{\lambda''_1}{3} + \frac{\lambda''_2}{3}) + 2(\lambda'_4 v_1^2 + \lambda'_5 v_2^2))$$



Free parameters:

$$m_{h_1}, m_{h_2}, m_{h_3}, m_A, m_{H^\pm}, m_{A_S}, , \tan\beta, v_S, \tilde{\mu}^2, \alpha_1, \alpha_2, \alpha_3$$

$$\lambda'_{14} = \lambda'_1 - 2\lambda'_4, \lambda'_{25} = \lambda'_2 - 2\lambda'_5, \lambda''_{13} = \lambda''_1 - \lambda''_3,$$

Portal Couplings to Higgs sector

Trilinear and Quartic Couplings of DM to Higgs Bosons:

$$\frac{\lambda_{h_j A_S A_S}}{v} = -i[\lambda'_{14} c_\beta R_{j1} + \lambda'_{25} s_\beta R_{j2} - \frac{v_S}{2v}\lambda''_{13} R_{j3}]$$

$$\lambda_{h_j h_k A_S A_S} = -i[\lambda'_{14} R_{j1} R_{k1} + \lambda'_{25} R_{j2} R_{k2} - \frac{1}{2}\lambda''_{13} R_{j3} R_{k3}],$$

Connection to colliders via invisible decays of SM and BSM Higgs bosons.

Dutta, et.al, 2504.14529

Finite Temperature Effects

- The **finite temperature effective potential** is given by:

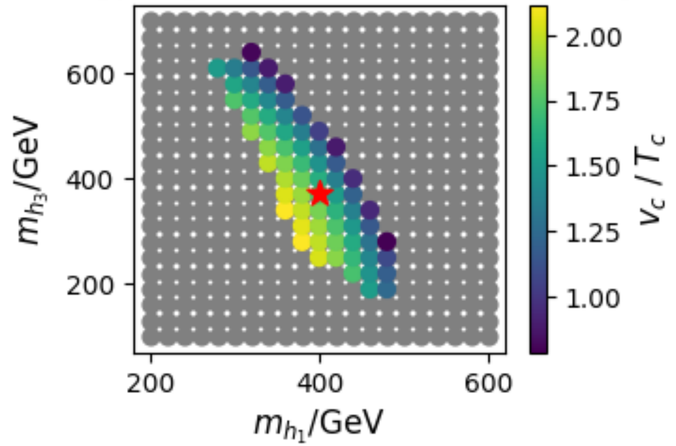
$$V_{EW}(\phi_i, T) = V^0_{Tree}(\phi_i, 0) + V^0_{CW}(\phi_i, 0) + V_{CT} + V^T(\phi_i, T) + V^T_{daisy}(\phi_i, T)$$

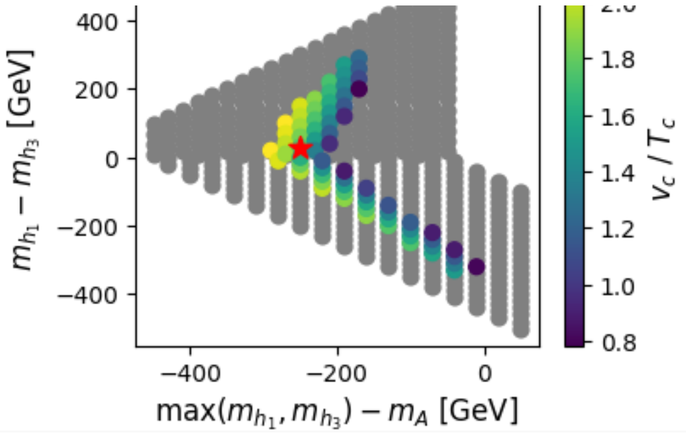
- **Coleman Weinberg Potential:** Incorporates quantum corrections from scalar, gauge boson and fermion loops.
- **Counterterm potential:** Ensures that the chosen renormalisation conditions are satisfied, preserving the desired physical parameters at zero temperature.
- **Finite Temperature potentia**l: Account for finite-temperature contributions from particles in the thermal bath and modify the temperature-dependent scalar potential.
- **Daisy contribution:** Accounts for important higher-order thermal corrections, particularly from bosonic zero modes, improving the perturbative description at finite temperature.

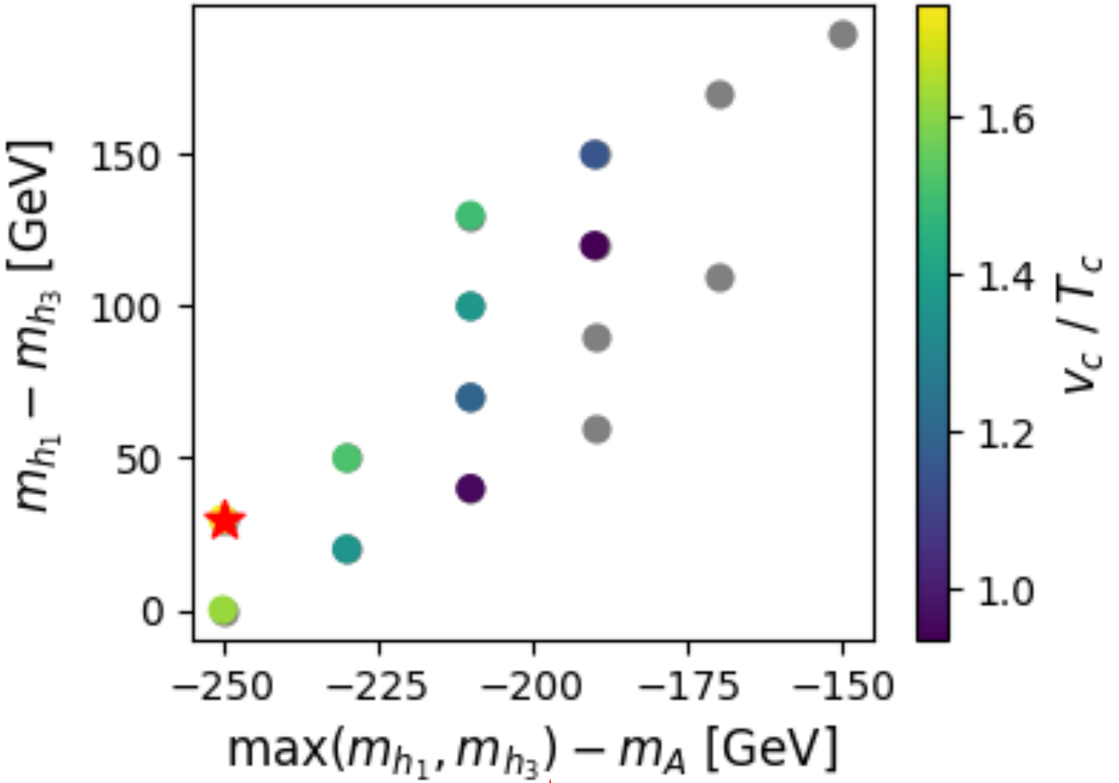
The temperature-dependent effective potential determines the evolution of the vacuum structure and allows us to investigate the nature of the electroweak phase transition.

Impact on mass splitting between Higgses

m_{h_1}/GeV = [200, 600], m_{h_3}/GeV = [100, 700], m_A/GeV = 650, m_{A_S}/GeV = 1000,
$m_{H^\pm}$/GeV = 650, v_S/GeV = 103.2, tanβ = 2, α_1 = -0.393,
α_2 = -0.484, $\tilde{\mu}^2$/GeV^2 = 162500, $\lambda''_{13} = \lambda''_1 - \lambda''_3$ = -0.0819,
α_3 = 0.0469, $\lambda'_{14} = \lambda'_1 - 2\lambda'_4$ = 0.95, $\lambda'_{25} = \lambda'_2 - 2\lambda'_5$ = 0.384







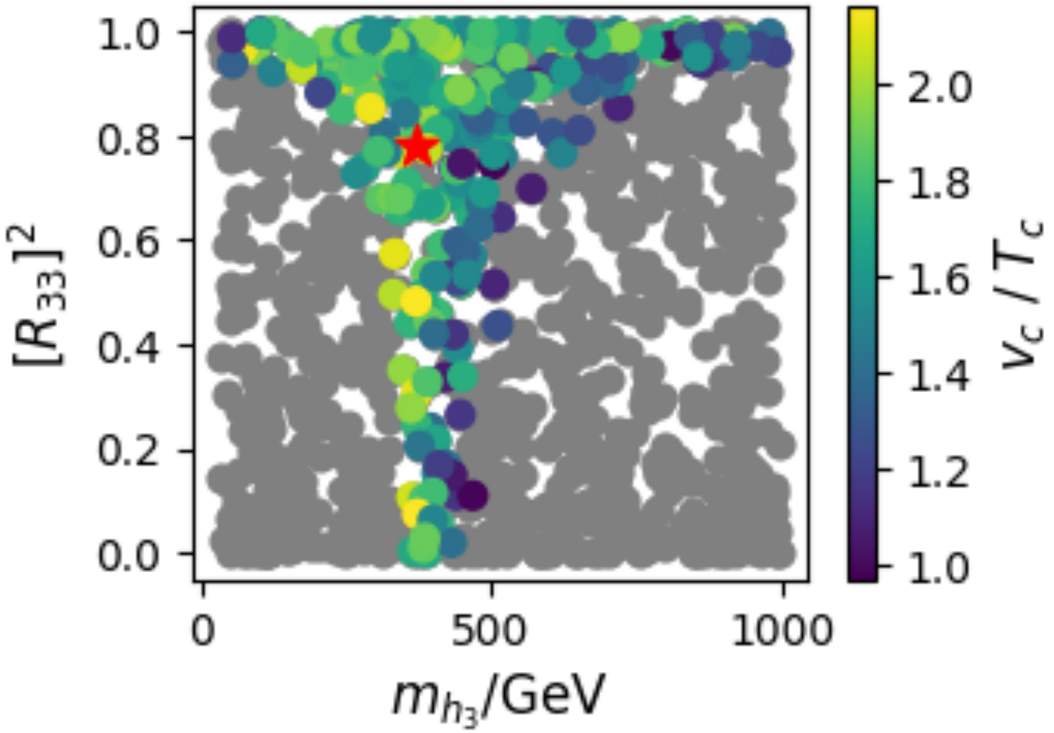
m_{h_1}	m_{h_2}	m_{h_3}	m_A	$m_{H^\pm}$
400 GeV	125.09 GeV	370.6 GeV	650 GeV	650 GeV
m_{A_S}	$\lambda'_1 - 2\lambda'_4$	$\lambda'_2 - 2\lambda'_5$	$\lambda''_1 - \lambda''_3$	tan β
1000 GeV	0.95	0.384	−0.0819	2
v_S	$\tilde{\mu}$	α_1	α_2	α_3
103.2 GeV	403.1 GeV	−0.393	−0.484	−0.0469

$v_c/T_c = 1.74$

The phase transition strength indicator(v_c/T_c) varies across the scalar mass spectrum, suggesting a non-trivial interplay between the scalar mass hierarchy and the electroweak thermal potential.

Singlet content of h_3 versus its mass

m_{h_1}/GeV = 400, m_{h_3}/GeV = [32.43, 998.1], m_A/GeV = 650, m_{A_S}/GeV = 1000,
$m_{H^\pm}$/GeV = 650, v_S/GeV = [2.749, 1000], tanβ = 2, α_1 = -0.464,
α_2 = [-1.57, 1.571], $\tilde{\mu}^2$/GeV^2 = 162500, $\lambda''_{13} = \lambda''_1 - \lambda''_3$ = [-9.989, 9.988],
α_3 = 0.0, $\lambda'_{14} = \lambda'_1 - 2\lambda'_4$ = [-9.989, 9.93], $\lambda'_{25} = \lambda'_2 - 2\lambda'_5$ = [-9.996, 9.988]

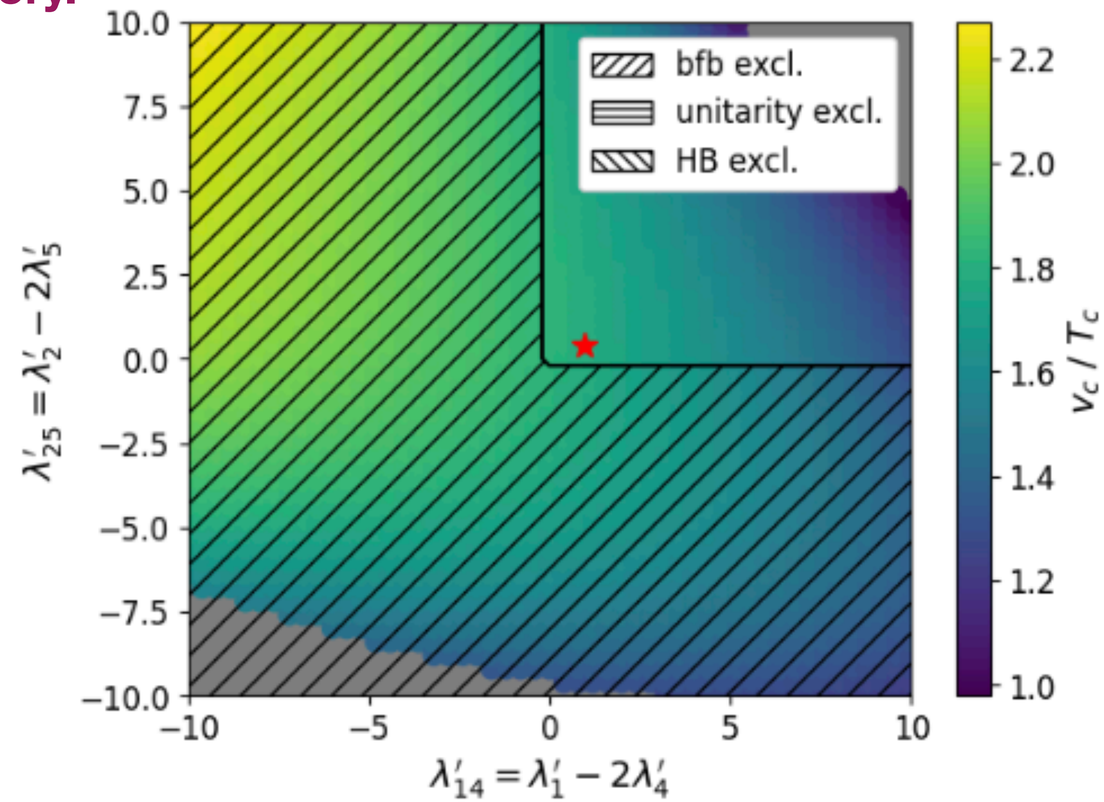


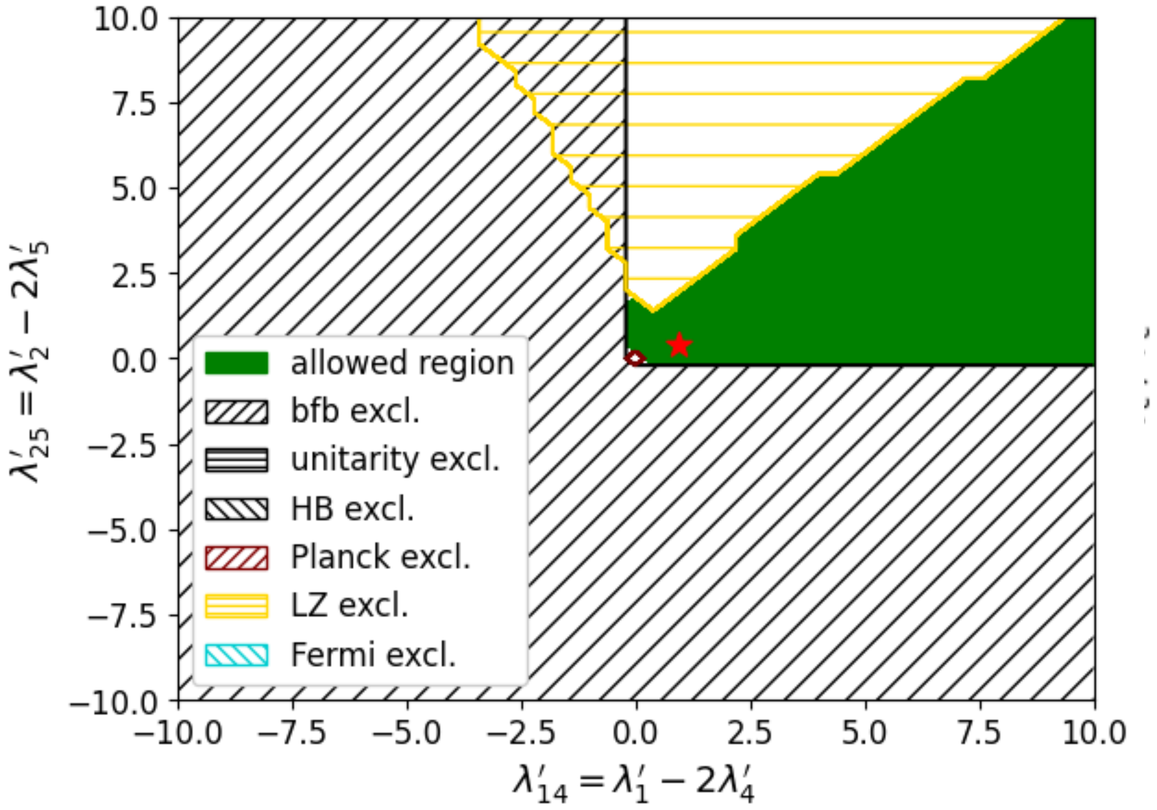
m_{h_1}	m_{h_2}	m_{h_3}	m_A	$m_{H^\pm}$
400 GeV	125.09 GeV	370.6 GeV	650 GeV	650 GeV
m_{A_S}	$\lambda'_1 - 2\lambda'_4$	$\lambda'_2 - 2\lambda'_5$	$\lambda''_1 - \lambda''_3$	$\tan\beta$
1000 GeV	0.95	0.384	−0.0819	2
v_S	$\tilde{\mu}$	α_1	α_2	α_3
103.2 GeV	403.1 GeV	−0.393	−0.484	−0.0469

$v_c/T_c = 1.74$

Impact on portal couplings

The portal interactions connect the dark matter sector to the electroweak scalar sector. Consequently, the same interactions that govern DM phenomenology also enter the scalar potential relevant for the electroweak thermal history.

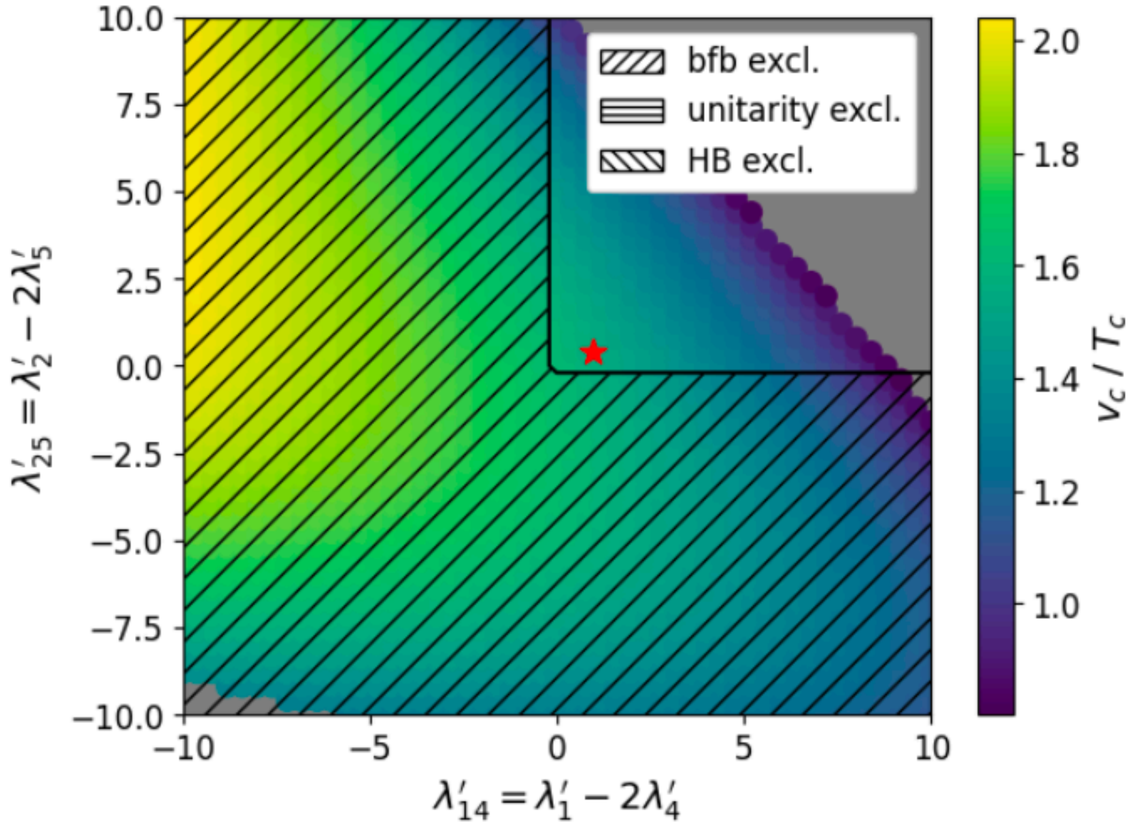


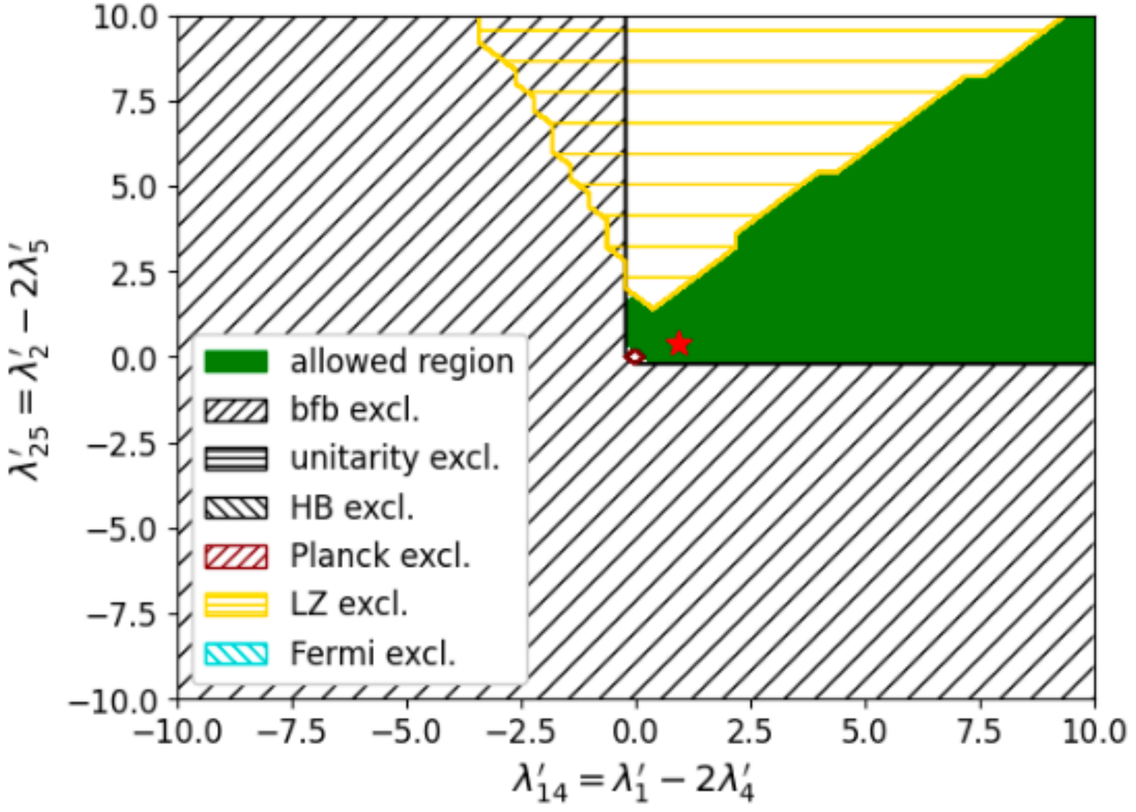


For $|R_{33}|^2$ = 99.3%

★ $m_{h3} = m_{H_b} = 102.75\,\text{GeV}$ and $\alpha_2 = -0.07$ $v_c/T_c = 1.57288$

Allowed region from all constraints in green.





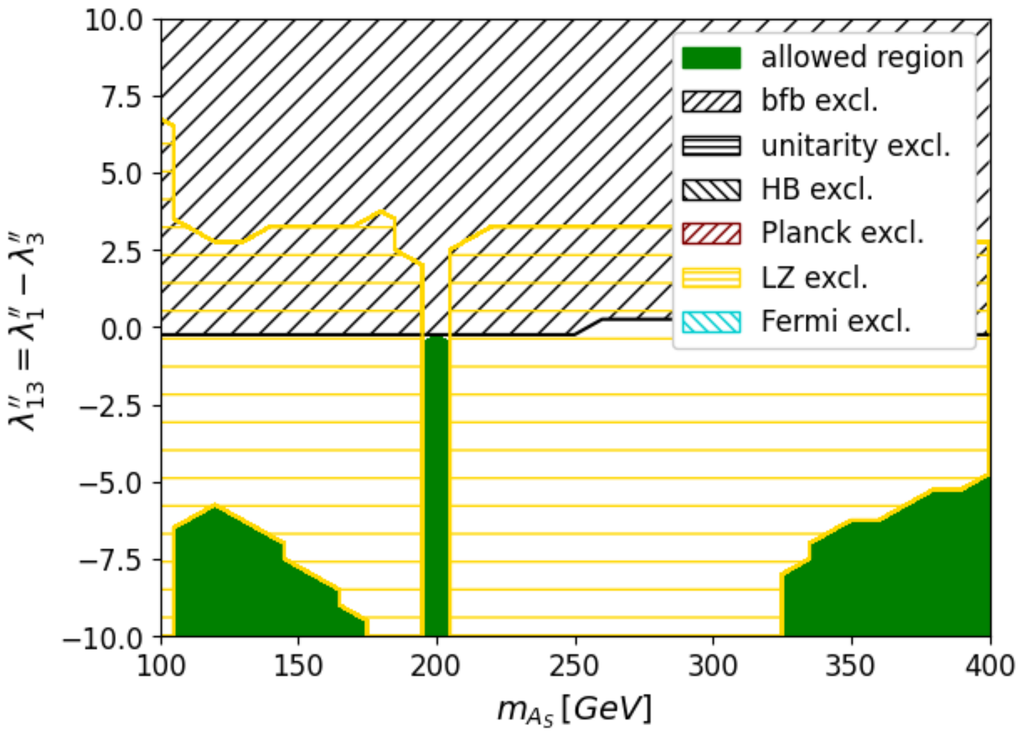
For $|R_{33}|^2$ = 5%

★ $m_{h3} = m_{H_b} = 393.75\,\text{GeV}$ and $\alpha_2 = -1.345$

$v_c/T_c = 1.79228$

Allowed region from all constraints in green.

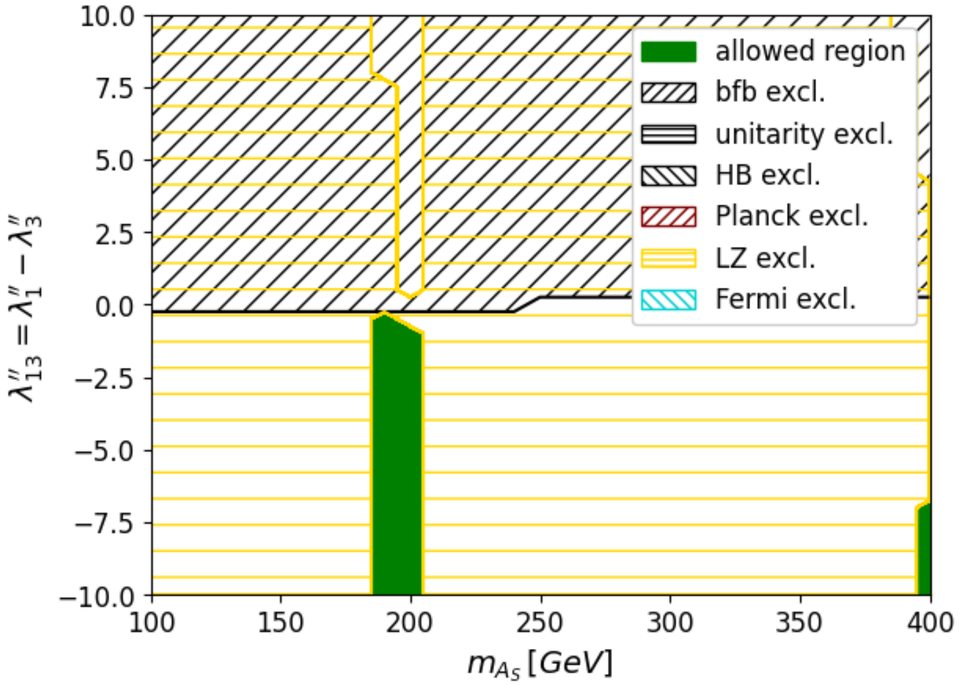
Impact on dark matter mass and self couplings



For $|R_{33}|^2$ = 99.3%

$m_{h3} = m_{H_b} = 102.75\,\text{GeV}$ and $\alpha_2 = -0.07$

$v_c/T_c = 1.57288$



For $|R_{33}|^2$ = 5%

$m_{h3} = m_{H_b} = 393.75\,\text{GeV}$ and $\alpha_2 = -1.345$

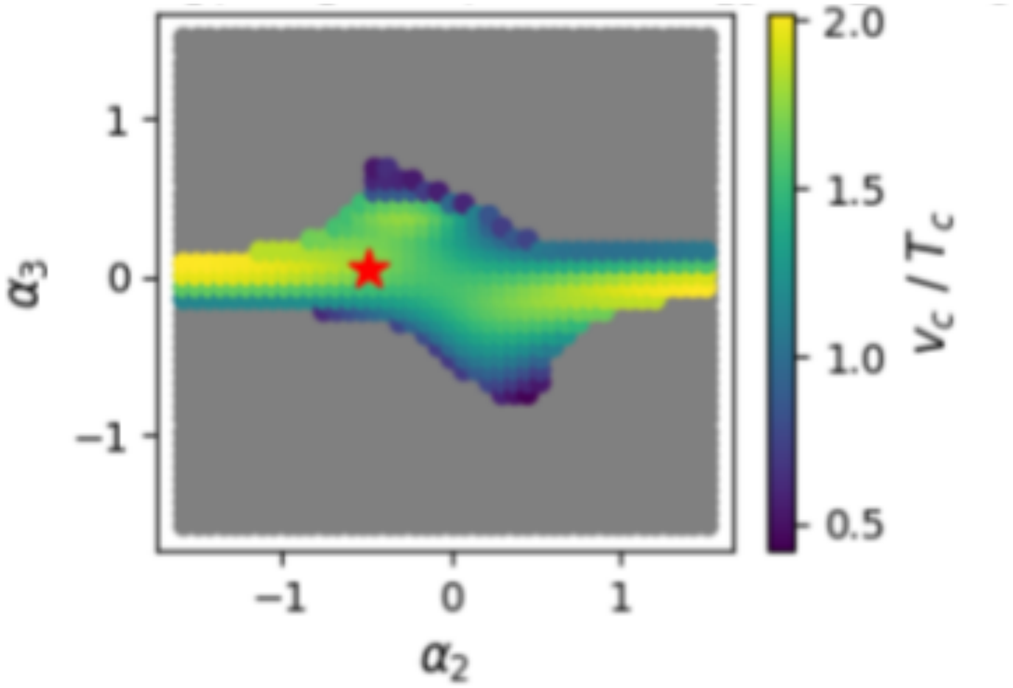
$v_c/T_c = 1.79228$

Summary

- We investigate the electroweak phase-transition properties of the 2HDMS, incorporating an extended scalar sector with a complex singlet accommodating dark matter candidate.
- The **phase-transition strength exhibits a non-trivial dependence on the scalar mass spectrum, mixing angles and singlet composition.**
- **Portal interactions provide an important connection between dark matter phenomenology and the electroweak thermal potential.**
- We identify parameter-space regions satisfying the considered theoretical, collider and dark matter constraints, with values of the phase-transition strength compatible with a strong first-order transition.
- Ongoing work on connecting to gravitational wave signals generated from bubble collisions.

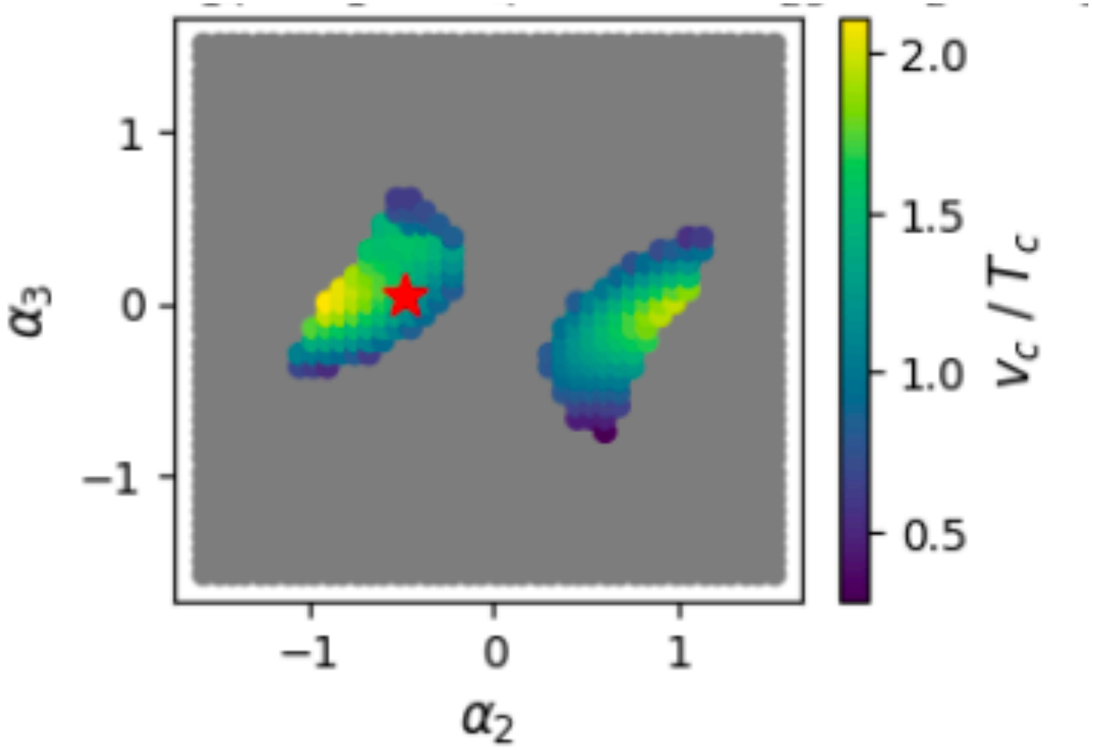
Thank You

Impact on mixing angles



Compressed $h_1 - h_3$ spectrum

$m_{h_1} = 400,\ m_{h_3} = 370.6$ **GeV**



Uncompressed $h_1 - h_3$ spectrum

$m_{h_1} = 440,\ m_{h_3} = 310$ **GeV**