Electroweak phase transition (EWPT) enhanced by a CP-violating dark sector

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The model

We study a Z_2-symmetric 3-Higgs doublet model (3HDM) generated by

$$g_{Z_2} = \mathrm{diag}\,(-1,-1,+1)\,,$$

acting on the three doublets. The Standard Model (SM) is trivially charged under the Z_2-symmetry. The potential is

$$\begin{aligned} V = &-\mu_1^2(\Phi_1^\dagger\Phi_1) - \mu_2^2(\Phi_2^\dagger\Phi_2) - \mu_3^2(\Phi_3^\dagger\Phi_3) \\ &+ \lambda_{11}(\Phi_1^\dagger\Phi_1)^2 + \lambda_{22}(\Phi_2^\dagger\Phi_2)^2 + \lambda_{33}(\Phi_3^\dagger\Phi_3)^2 \\ &+ \lambda_{12}(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_{23}(\Phi_2^\dagger\Phi_2)(\Phi_3^\dagger\Phi_3) \\ &+ \lambda_{31}(\Phi_3^\dagger\Phi_3)(\Phi_1^\dagger\Phi_1) + \lambda'_{12}(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\ &+ \lambda'_{23}(\Phi_2^\dagger\Phi_3)(\Phi_3^\dagger\Phi_2) + \lambda'_{31}(\Phi_3^\dagger\Phi_1)(\Phi_1^\dagger\Phi_3) \\ &- \boldsymbol{\mu_{12}^2}(\Phi_1^\dagger\Phi_2) + \boldsymbol{\lambda_1}(\Phi_1^\dagger\Phi_2)^2 + \boldsymbol{\lambda_2}(\Phi_2^\dagger\Phi_3)^2 \\ &+ \boldsymbol{\lambda_3}(\Phi_3^\dagger\Phi_1)^2 + h.c. \end{aligned}$$

Complex couplings source CP-violation without contributing to electric dipole moments [1].

Effective potential

We use DRalgo [2] to compute the 2-loop effective potential at the ultra-soft scale. We numerically minimise the potential and calculate the EWPT strength using **our own python code**.

★ To be released publicly soon ★

Numerical simulations

We generate one million benchmark points which satisfy all experimental and theoretical constraints. We minimise the potential with respect to three CP-invariant background fields,

$$\langle\Phi_i\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ \\ v_i \end{pmatrix}.$$

Conclusion

To accurately determine the EWPT strength, 1-loop calculations are insufficient [3]. The 2-loop analysis closely reproduces non-perturbative lattice simulations' results [4]. Our results clearly show **the importance of 2-loop calculations** in identifying the viable region of the parameter space for a 1st-order EWPT.

References

1. Keus. *Phys. Rev. D* **101,** 073007 (2020).
2. Ekstedt *et al. Computer Physics Communications* **288,** 108725 (2023).
3. Kajantie *et al. Phys. Rev. Lett.* **77,** 2887–2890 (1996).
4. Niemi *et al. Phys. Rev. D* **110,** 115016 (2024).

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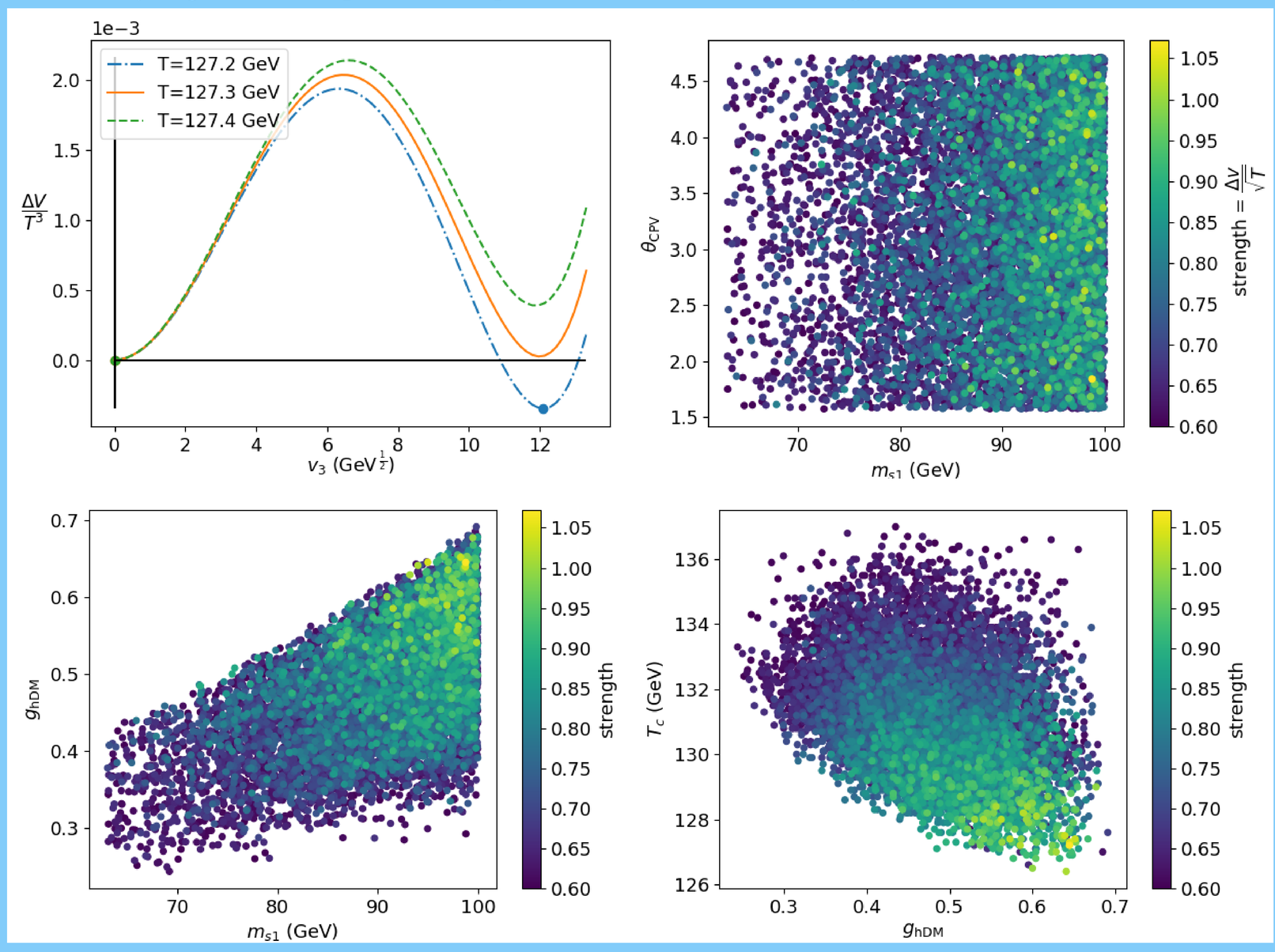
The 1-loop analysis

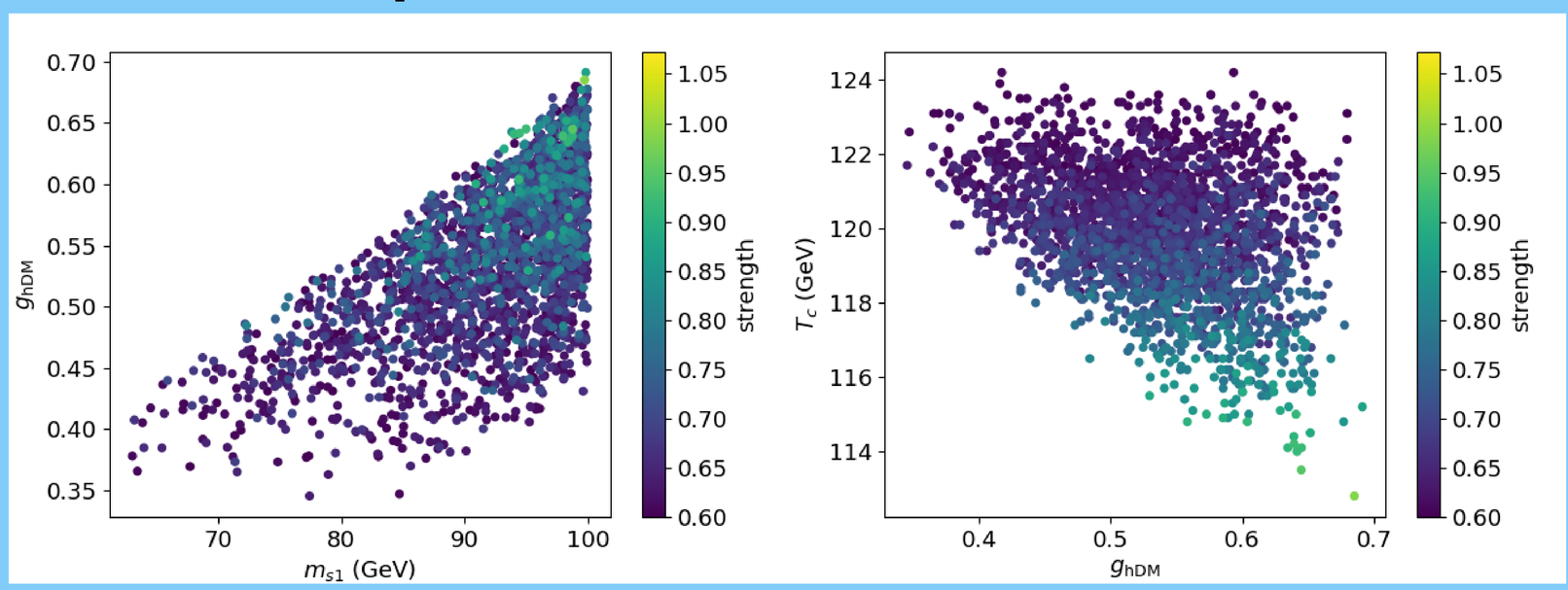
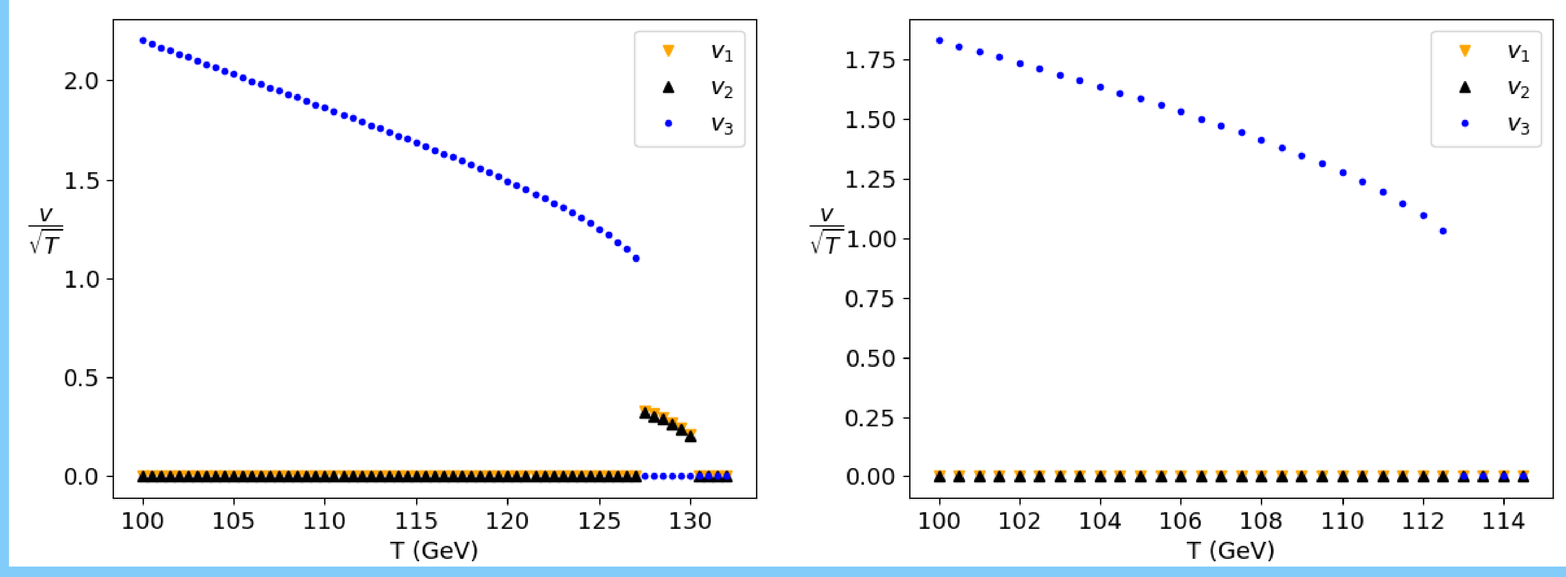
We identify regions of the parameter space which result in a strong 1st-order EWPT.



We see minimal dependence on θ_{CPV} (the cumulative phase of the complex couplings). The parameters m_{S_1} (where S_1 is the lightest CP-mixed scalar, hence the Dark Matter (DM) candidate) and g_{hDM} (equivalent to $g_{hS_1S_1}$ which is the Higgs-DM coupling) need to be sufficiently large, generally leading to an under-production of DM.

The 2-loop analysis

The 2-loop analysis shows a **27% reduction in the mean EWPT strength, and 7% drop in the mean critical temperature.**



What naively appears to be a two-step EWPT at 1-loop, might in fact be a one-step EWPT as the 2-loop analysis shows.