Electroweak phase transition in the 2HDM: collider and Gravitational Wave Complementarity

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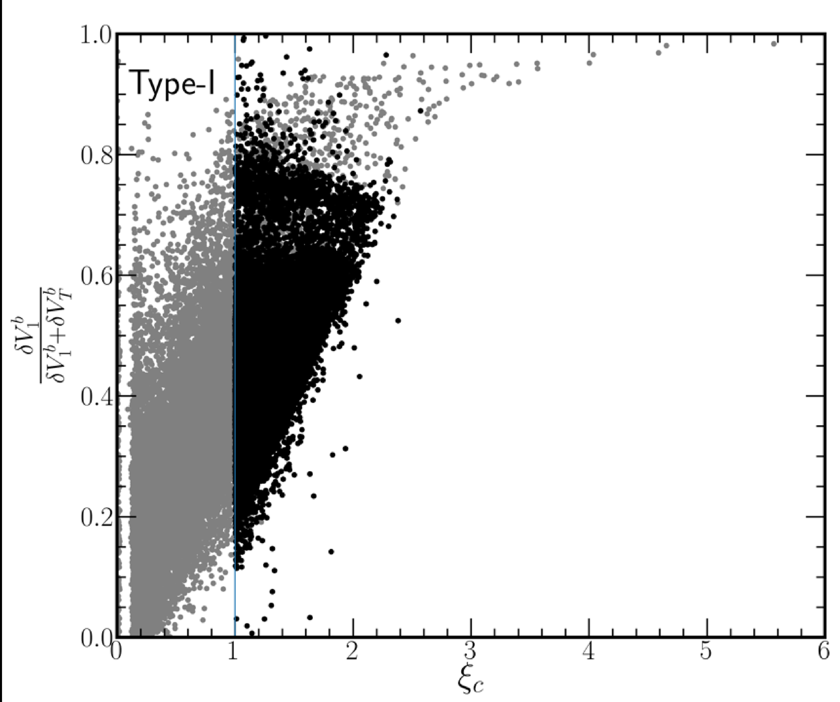
Overview

- We study how collider measurements and observations of stochastic GW signals can complement each other to explore scalar potential in the CP-conserving 2HDM.

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

- We analyze the key ingredients in the shape of the Higgs potential triggering strong first-order phase transition, focusing on the barrier formation and the upliftment of the true vacuum.
- The ξ_c>1 regime is favored for lower scalar masses.
- The HL-LHC will be able to cover a vast range of the ξ_c >1 parameter space, with scalar decays to heavy fermions $H^\pm, H, A \to$ tt, bb being the most promising smoking gun signature of strong first-order EWPT in the 2HDM.

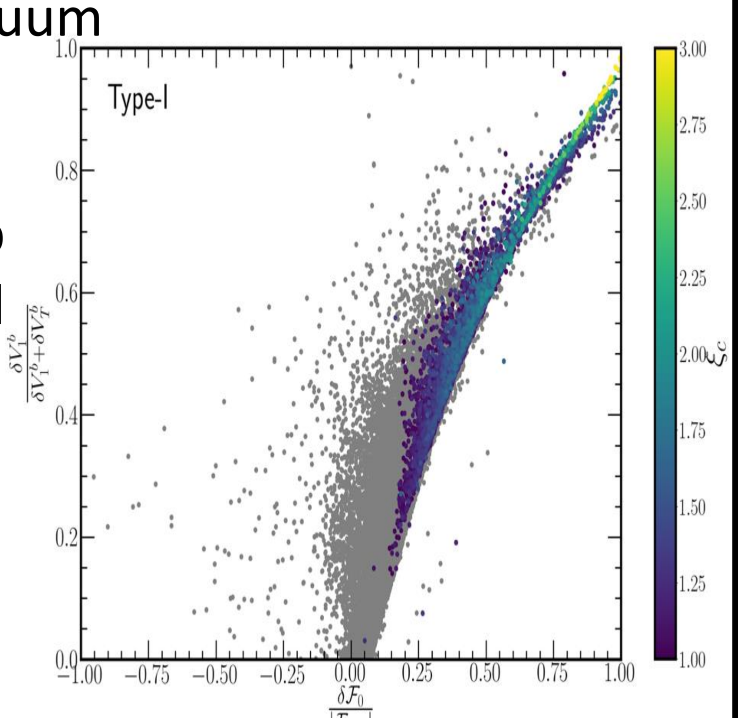
Shape of the potential



In the SFEWPT regime, ξ_c>1 , the phase transition is mostly one-loop driven, i.e., the effective potential barrier is dominantly generated by the one-loop term.

If the fraction of the barrier height provided by the one-loop contribution is close to 100%, the tunnelling from the false vacuum to the true vacuum is more challenging. For this reason, the universe with ξ_c>2.5 is trapped in the false vacuum

The barrier height provided by the one-loop contribution is correlated to $\frac{\Delta F_0}{|F_0^{SM}|}$, which measures the vacuum upliftment at zero temperature.



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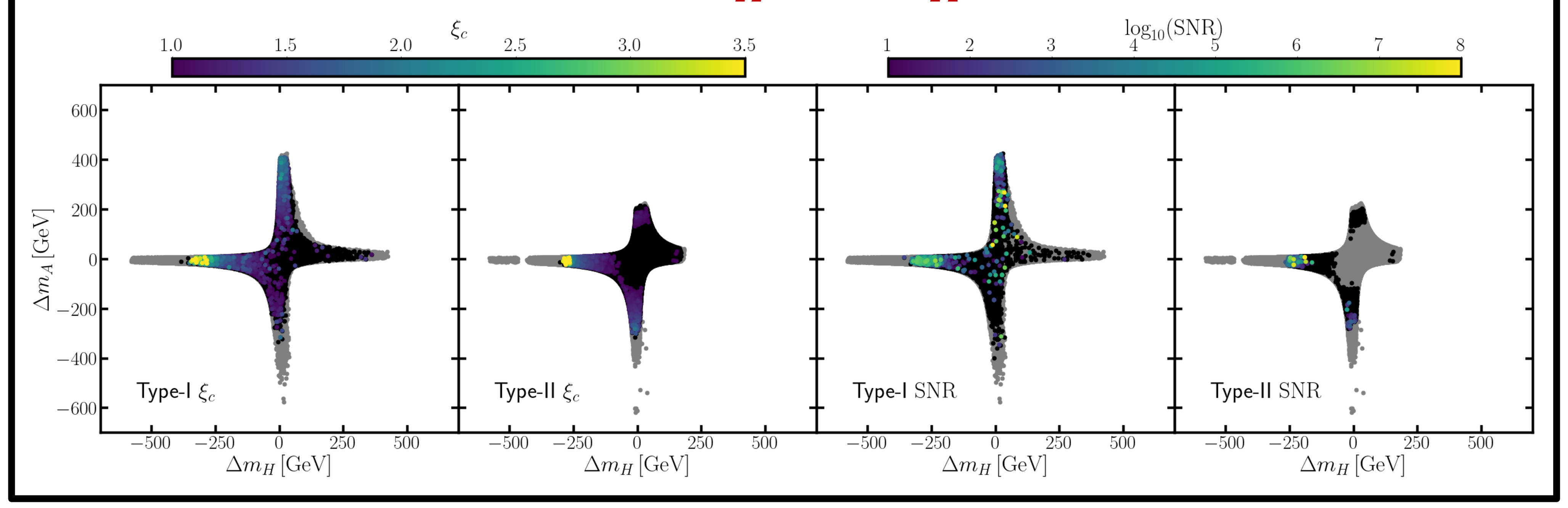
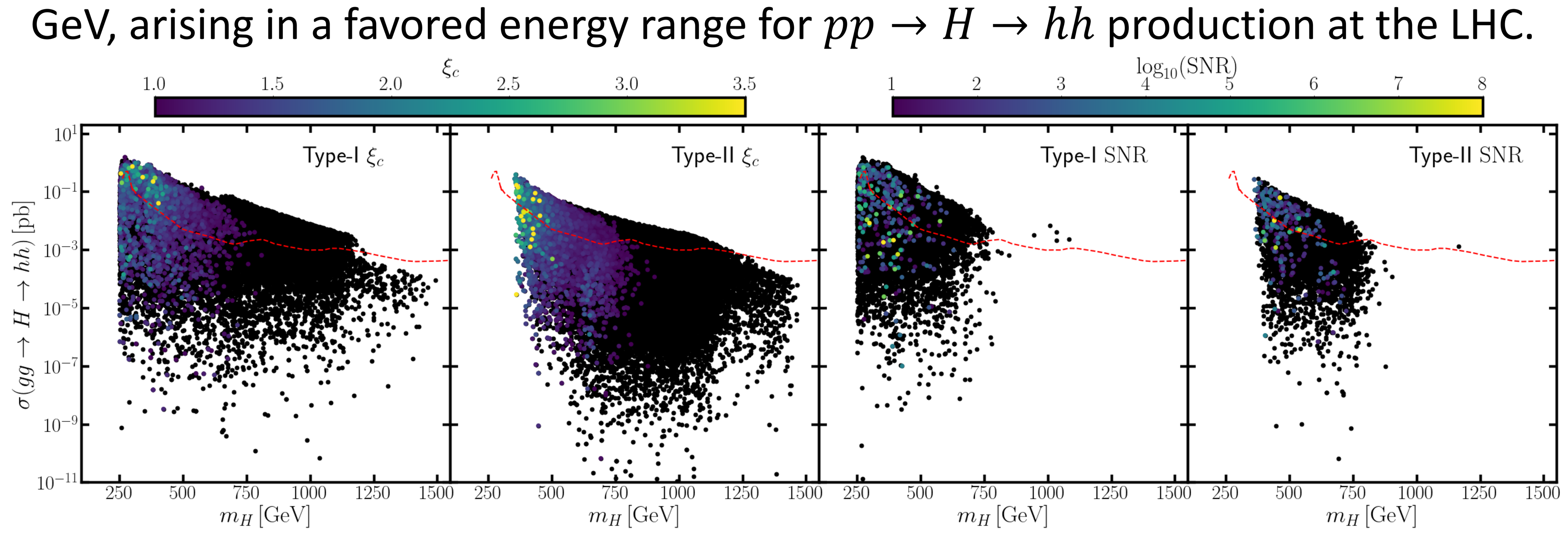
$\Delta m_H - \Delta m_A$

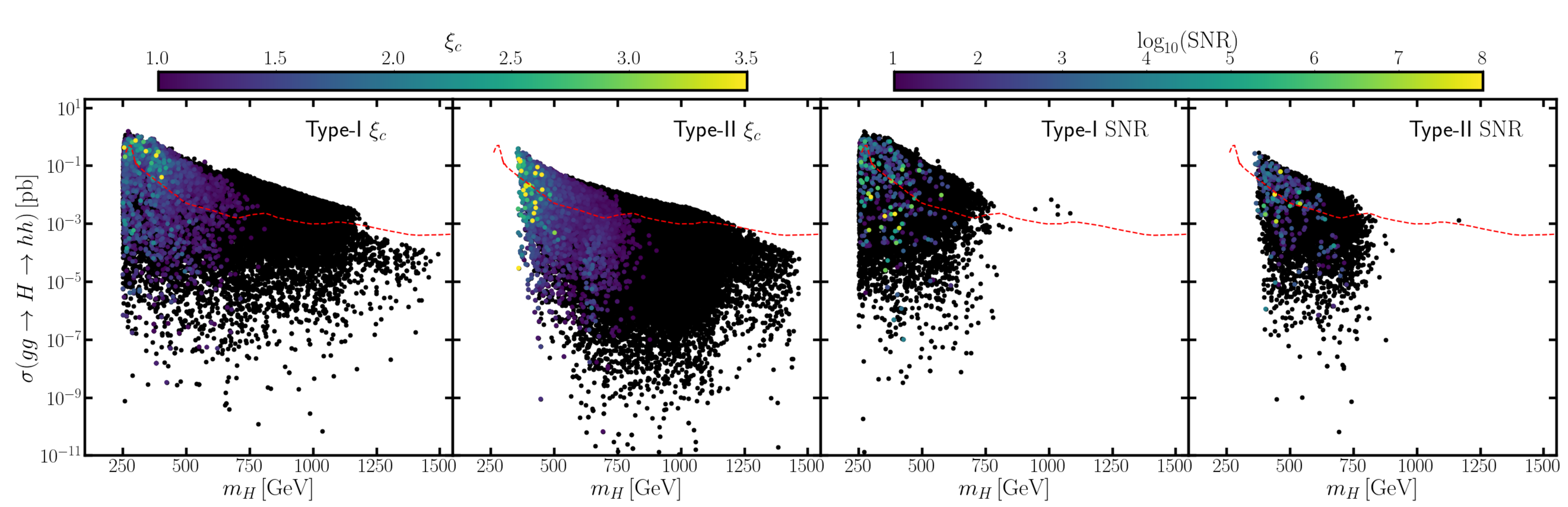


Collider and Gravitational Wave Signals

Resonant di-Higgs searches is a prominent probe for the phase transition pattern in the early universe. SFOEWPT is associated with light extra scalars, $m_H \leq 750$ GeV, arising in a favored energy range for $pp \to H \to hh$ production at the LHC.

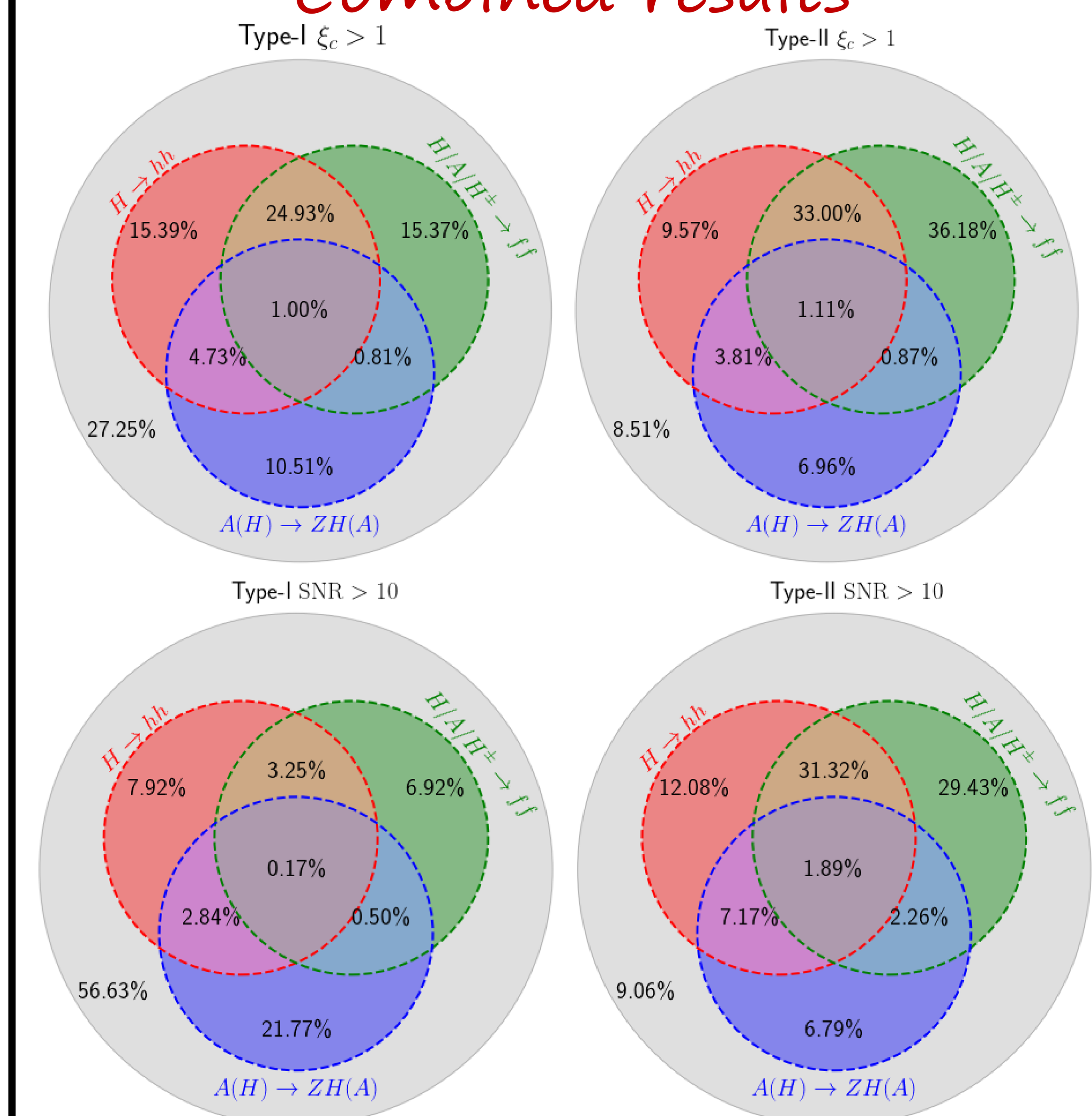


The widely discussed $A(H) \to ZH(A)$ channel in the context of EWPT in 2HDM is still relevant but for a smaller fraction of points compared to other searches. Whereas the $H \to bb$ channel generally provides the strongest limits for this channel, it quickly becomes subdominant once the scalar mass is beyond top-pair threshold. The $H \to WW$ channel shows smaller sensitivity as it is suppressed by $c_{\beta-\alpha}$.



The resonant searches with heavy fermionic final states is crucial for SFOPEWPT sensitivity at the HL-LHC. Type-II 2HDM is more constrained at the HL-LHC for ξ_c >1 points as the type-II have a stronger lower bound on scalar masses favoring the $H/A \to t\bar{t}$ search.

Combined results



Conclusions

- When comparing the parameter space points that survive the theoretical and experimental constraints for type-I and II 2HDM, these scenarios result in an akin phase transition pattern.
- The barrier formation in the Higgs potential of the 2HDM is driven by the one-loop and thermal corrections, with the dominance of the one-loop terms for large order parameter ξ_c >1.
- Scalar decays to heavy fermions $H^\pm, H, A \to$ tb, tt is the most promising smoking gun signature for SFOEWPT at the HL-LHC, followed by the di-Higgs searches.
- In contrast to the HL-LHC, LISA is going to be sensitive to a significantly smaller parameter space region, whereas it renders to complementary sensitivities where the correspondent LHC cross-section is suppressed.

References

Dorival Gonçalves, Ajay Kaladharan, and Yongcheng Wu "Collider and Gravitational Wave Complementarity in the 2HDM": arXiv:2108:05356