

Electroweak Phase Transition in 2HDM

Collider and GW Complementarity

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D. Goncalves, A. Kaladharan, Y. Wu: [2108.05356](https://arxiv.org/abs/2108.05356), 21xx.xxxxx

Introduction

- Electroweak Phase Transition
 - Electroweak Symmetry Breaking
 - Electroweak Baryogenesis
 - Possible GW sources
- Preferred Parameter Space in BSM
 - Prospects from Collider Experiments
 - Possible GW detections

Two Higgs Doublet Model (2HDM)

- Two Doublet

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{v_1 + \phi_1^0 + i\eta_1}{\sqrt{2}} \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{v_2 + \phi_2^0 + i\eta_2}{\sqrt{2}} \end{pmatrix}$$

- Five Mass Eigenstates
 - h, H, A, H^\pm
- CP Conserving, soft Z2 breaking
 - $\tan \beta, \cos(\beta - \alpha), m_{12}^2, v, m_h, m_H, m_A, m_{H^\pm}$
- Type-I/Type-II Yukawa Couplings

Yukawa Coupling	Type-I	Type-II
Top quark	Φ_2	Φ_2
Bottom quark	Φ_2	Φ_1

Effective Potential at Finite T

- Effective Potential

- $V_{eff} = V_0 + V_{CW} + V_{CT} + V_T$
- V_0 : Tree level potential
- V_{CW}/V_{CT} : Coleman-Weinberg potential and Counter Terms
- V_T : Thermal corrections

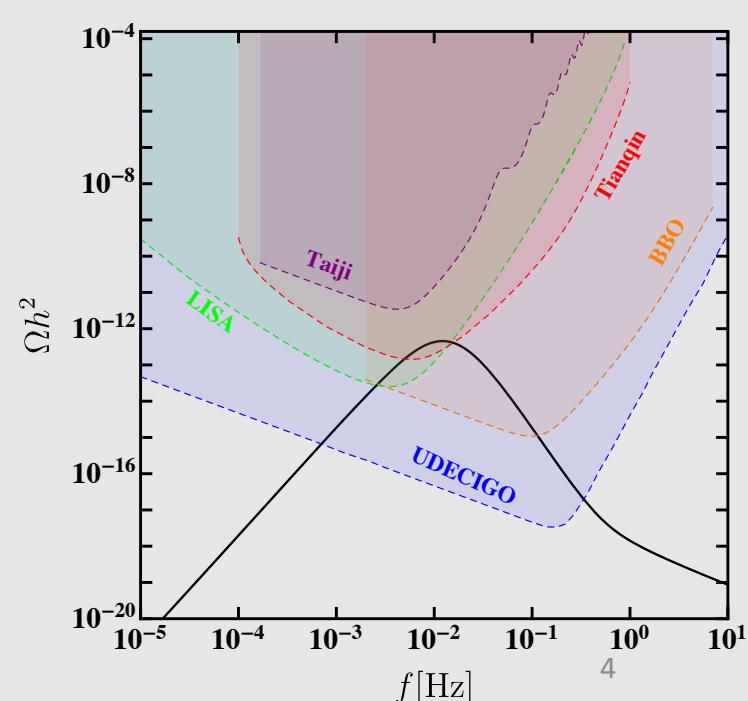
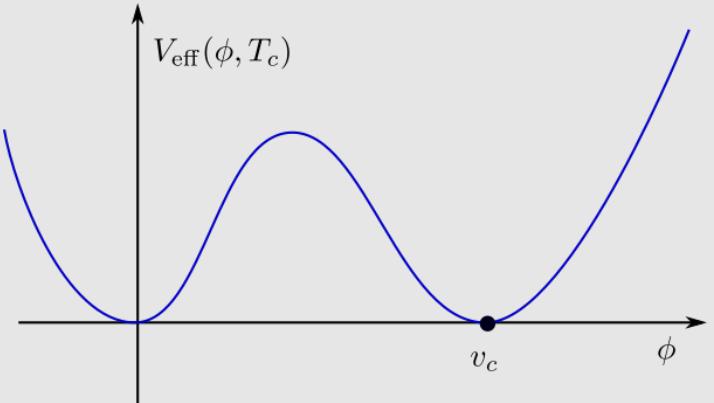
- Parameter relevant for EWPT:

- Strength:

- $\xi_c \equiv \frac{v_c}{T_c}$

- Signal to Noise Ratio

- $$\text{SNR} = \sqrt{\mathcal{T} \int_{f_{\min}}^{f_{\max}} df \left[\frac{h^2 \Omega_{\text{GW}}(f)}{h^2 \Omega_{\text{Sens}}(f)} \right]^2},$$



Scan Setup

- Ranges for Parameters
 - $t_\beta \in (0.8, 25)$, $\cos(\beta - \alpha) \in (-0.3, 0.3)$
 - $m_{H,A,H^\pm} \in (150, 1500)$ GeV
 - $m_{12}^2 \in (10^{-3}, 10^5)$ GeV²
- Constraints Considered
 - Theoretical Constraints:
 - Perturbative unitarity
 - Boundness from below
 - Stability
 - Electroweak Precision (S/T/U)
 - Flavor Constraints
 - Higgs signal strength, Heavy scalar searches

ScannerS

HiggsBounds/HiggsSignals

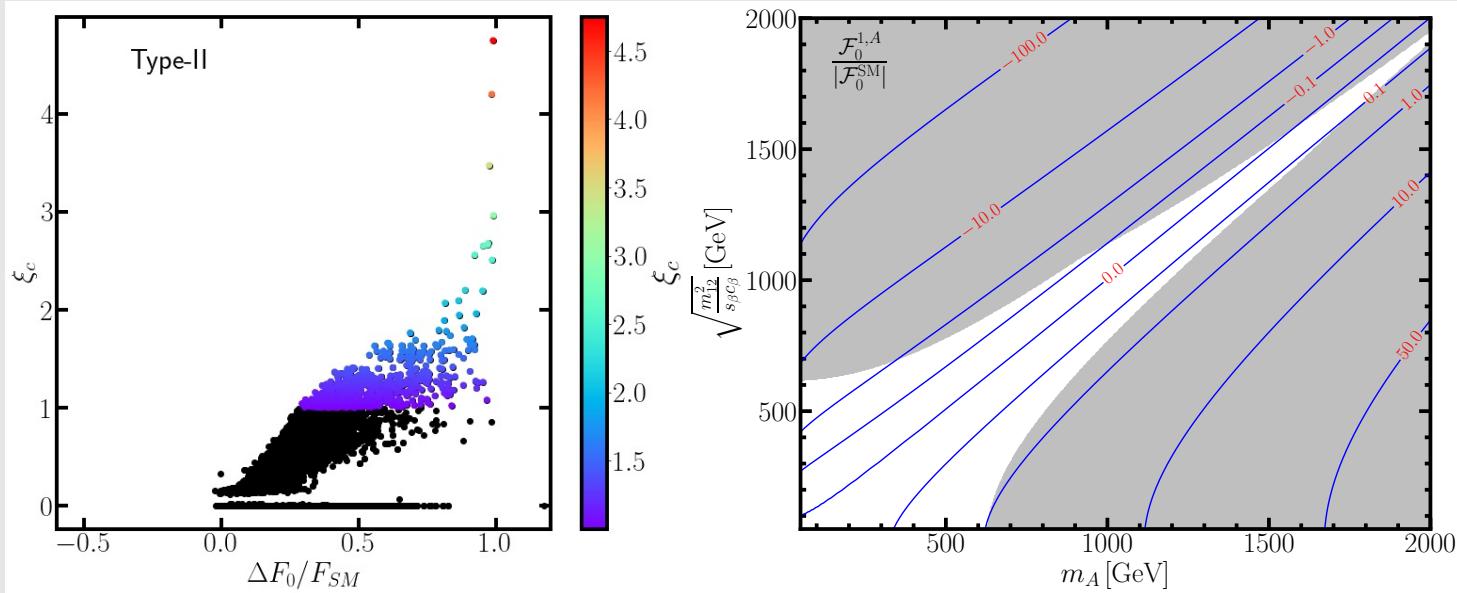
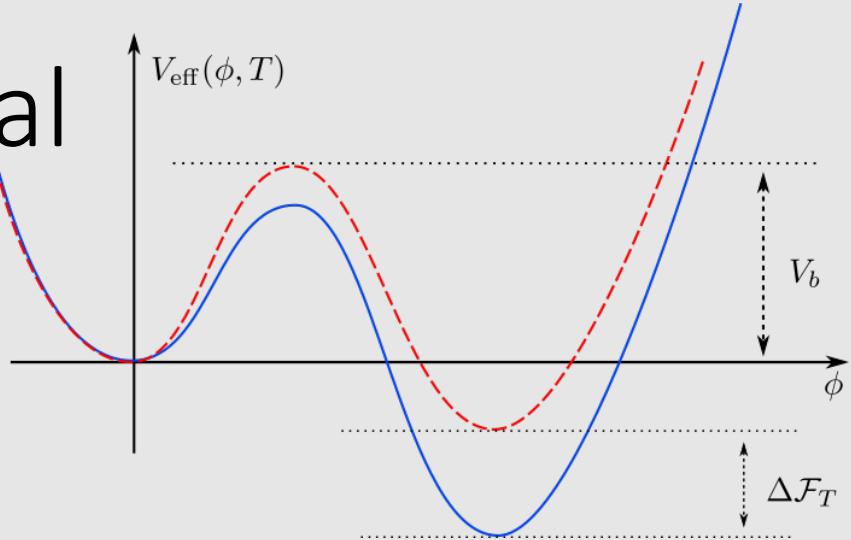
Shape of the Potential

- Vacuum Upliftment

$$\frac{\Delta \mathcal{F}_0}{|\mathcal{F}_0^{\text{SM}}|} \equiv \frac{\mathcal{F}_0 - \mathcal{F}_0^{\text{SM}}}{|\mathcal{F}_0^{\text{SM}}|},$$

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$$\mathcal{F}_0 \equiv V_{\text{eff}}(v_1, v_2, T = 0) - V_{\text{eff}}(0, 0, T = 0),$$



$$\mathcal{F}_0^{1,A}(c_{\beta-\alpha} = 0) = \frac{1}{512\pi^2} \left[\left(3m_h^2 + 2m_A^2 - 6\frac{m_{12}^2}{s_\beta c_\beta} \right) \left(m_h^2 + 2m_A^2 - 2\frac{m_{12}^2}{s_\beta c_\beta} \right) + \left(m_h^2 - 2\frac{m_{12}^2}{s_\beta c_\beta} \right)^2 \log \left(\frac{4m_A^4}{(m_h^2 - 2m_{12}^2/(s_\beta c_\beta))^2} \right) \right]$$

$$\lambda_1 v^2 \approx m_h^2 + t_\beta^2 \left(m_H^2 - \frac{m_{12}^2}{s_\beta c_\beta} \right)$$

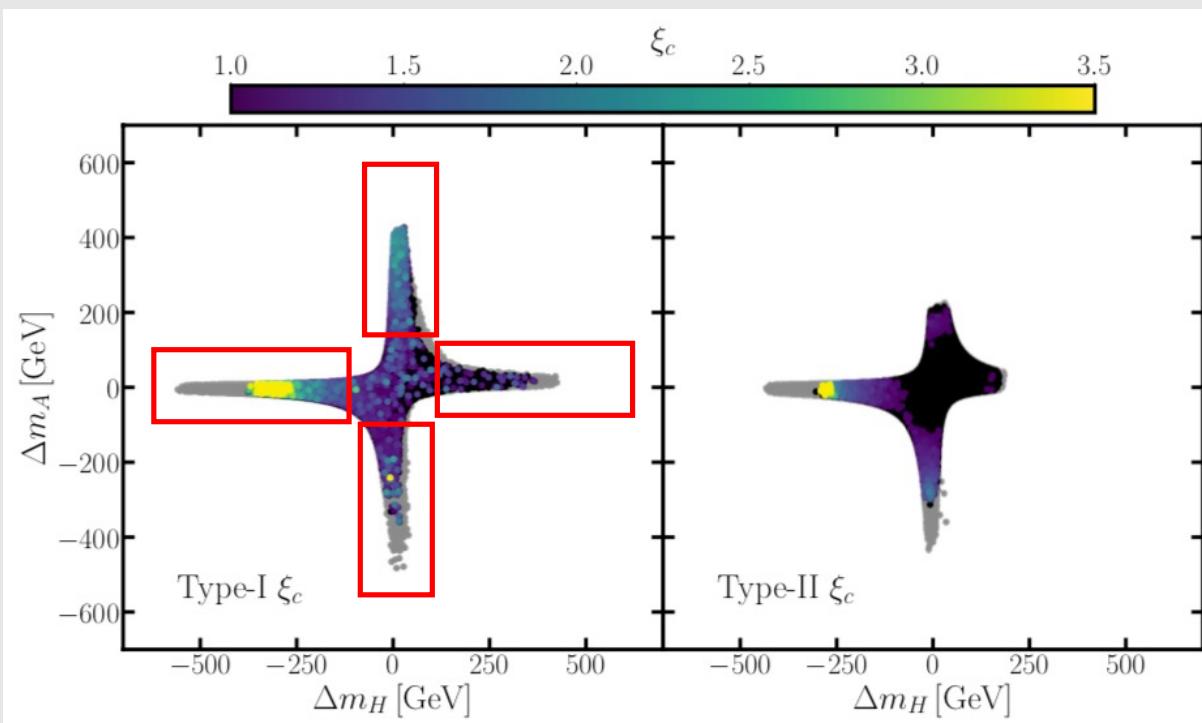
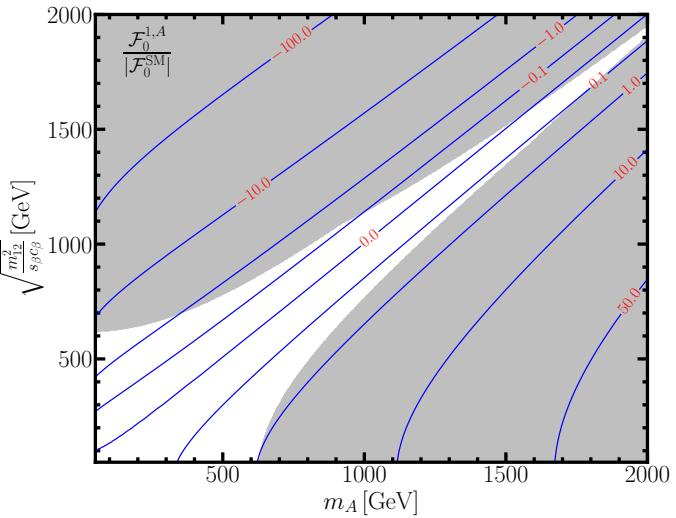
$$\lambda_2 v^2 \approx m_h^2 + \frac{1}{t_\beta^2} \left(m_H^2 - \frac{m_{12}^2}{s_\beta c_\beta} \right)$$

$$\lambda_{1,2} > 0$$

$$m_H^2 \gtrsim \frac{m_{12}^2}{s_\beta c_\beta}$$

Shape of the Potential

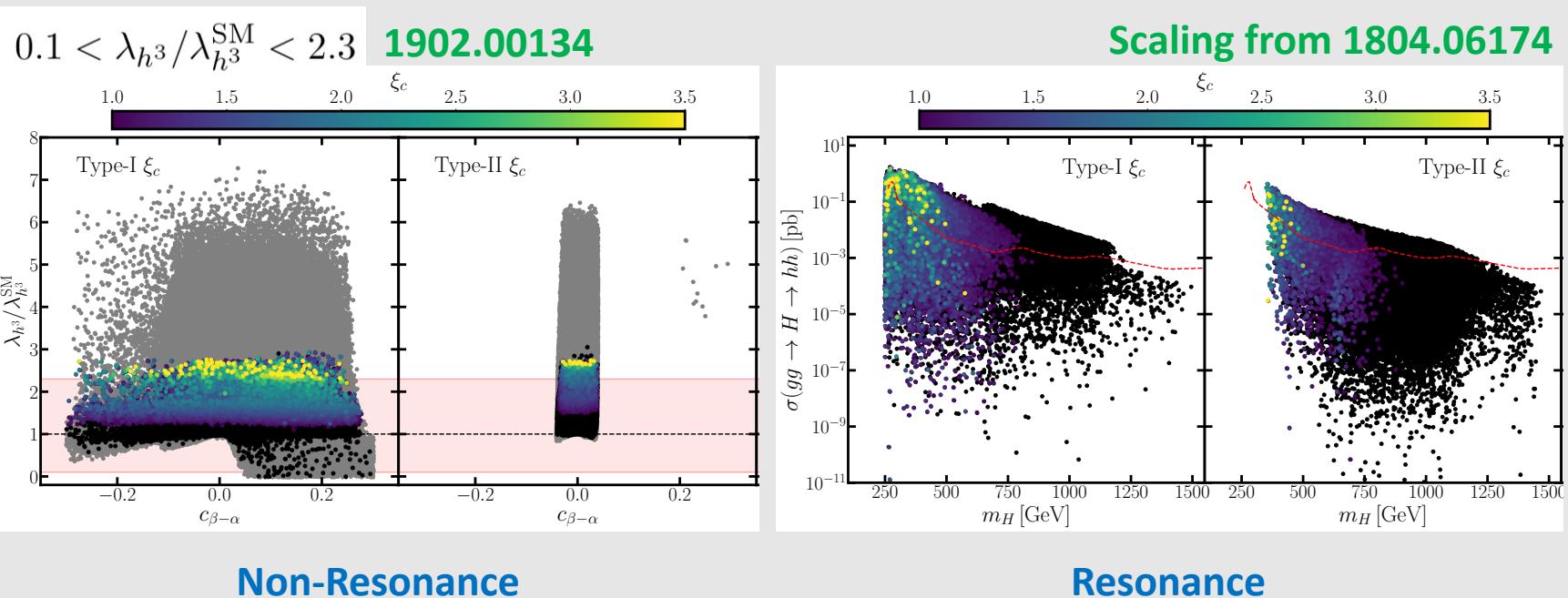
- Four Branches
 - Electroweak Precision Measurement
 - $\Delta m_H = m_H - m_{H^\pm}$, $\Delta m_A = m_A - m_{H^\pm}$
 - $m_H^2 \gtrsim \frac{m_{12}^2}{s_\beta c_\beta}$
- Top: $m_H \approx m_{H^\pm} < m_A$
 - $A \rightarrow ZH$
 - $A \rightarrow t\bar{t}$
- Left: $m_H < m_{H^\pm} \approx m_A$
 - $A \rightarrow ZH$
 - $A \rightarrow t\bar{t}$
 - $H^\pm \rightarrow t\bar{b}$
- Bottom: $m_H \approx m_{H^\pm} > m_A$
 - $H \rightarrow ZA$
 - $H \rightarrow t\bar{t}$
 - $H^\pm \rightarrow t\bar{b}$
- Right: $m_H > m_{H^\pm} \approx m_A$



Prospects at the HL-LHC

- Spectrums
 - $A \rightarrow ZH, H \rightarrow ZA$
 - Fermionic Channels:
 - $H/A \rightarrow t\bar{t}$
 - $H^\pm \rightarrow t b$
- Triple Scalar Couplings
 - Resonance/non-resonance hh

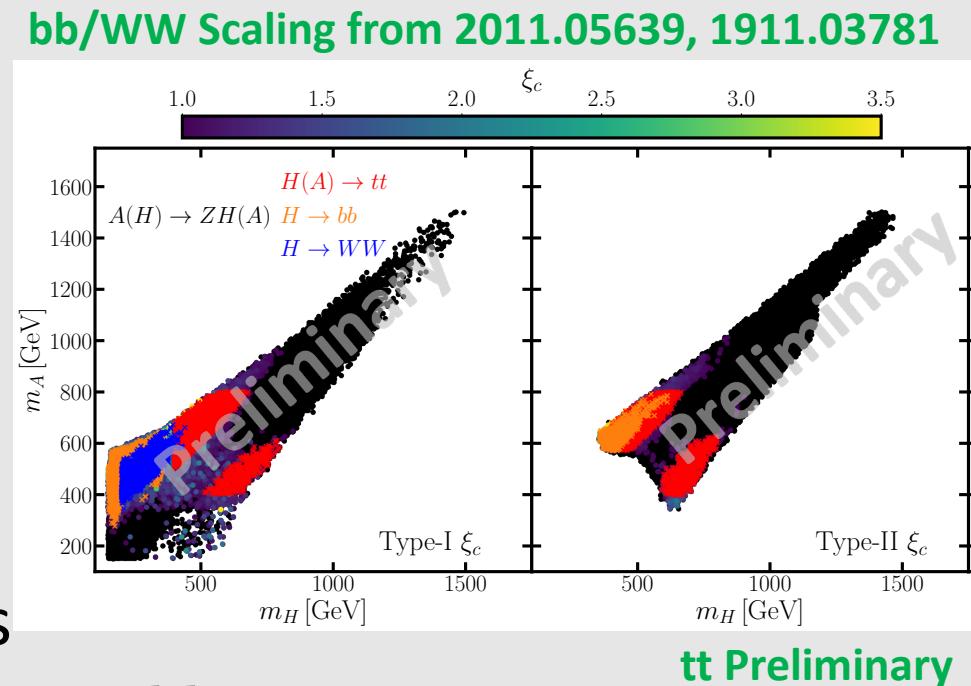
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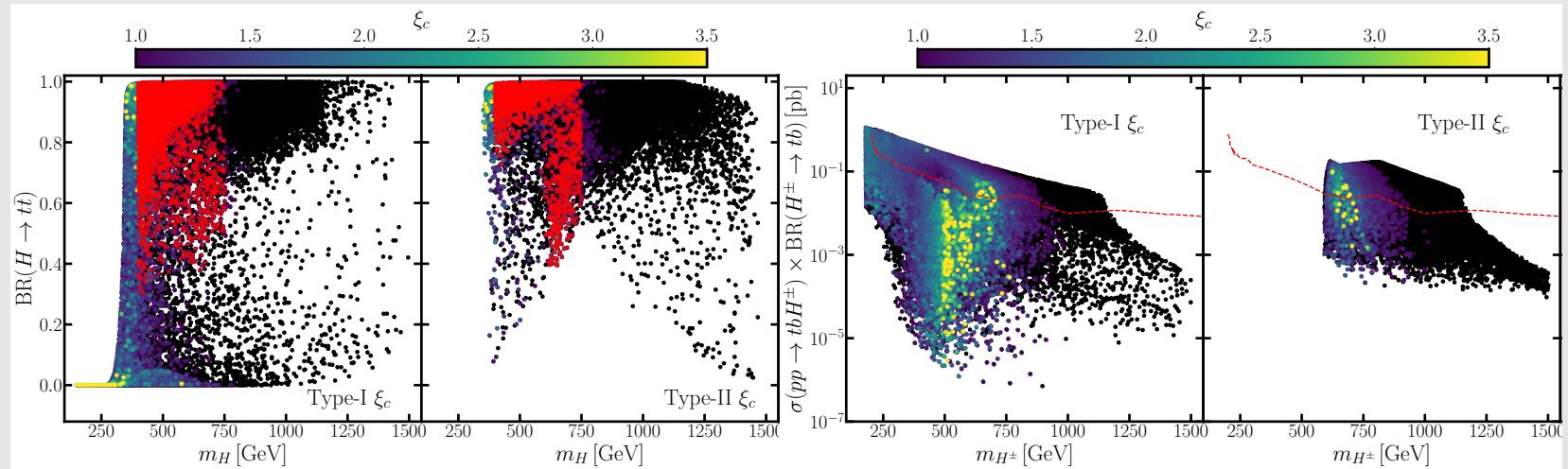
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Scaling from 1908.01115

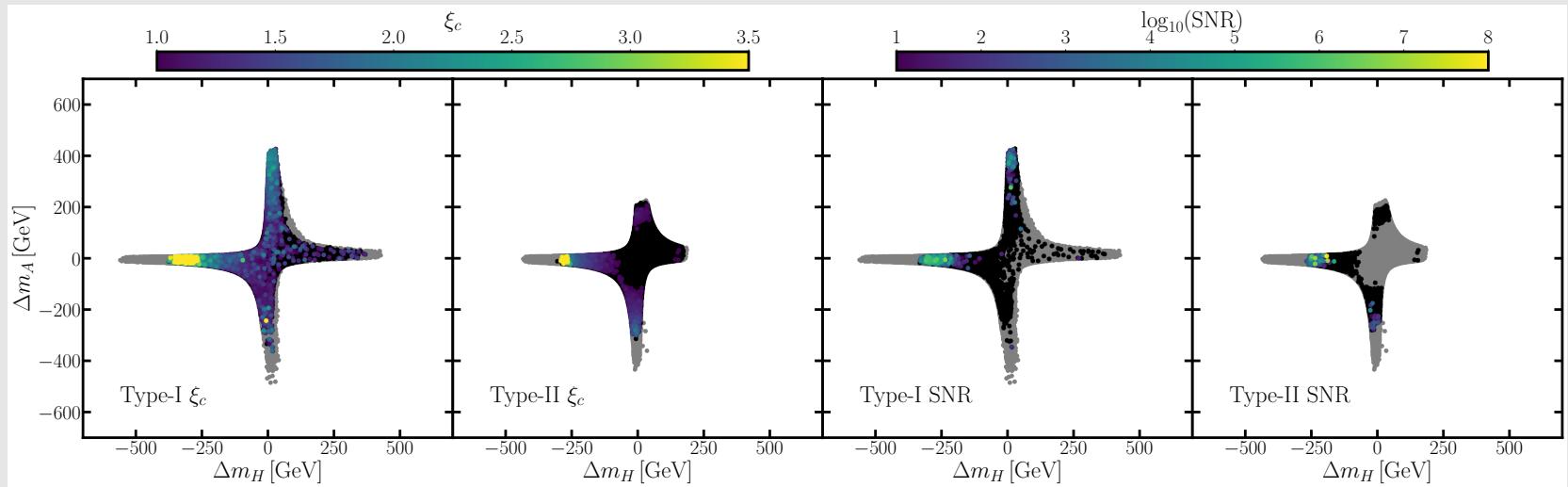
Scaling from 2102.10076

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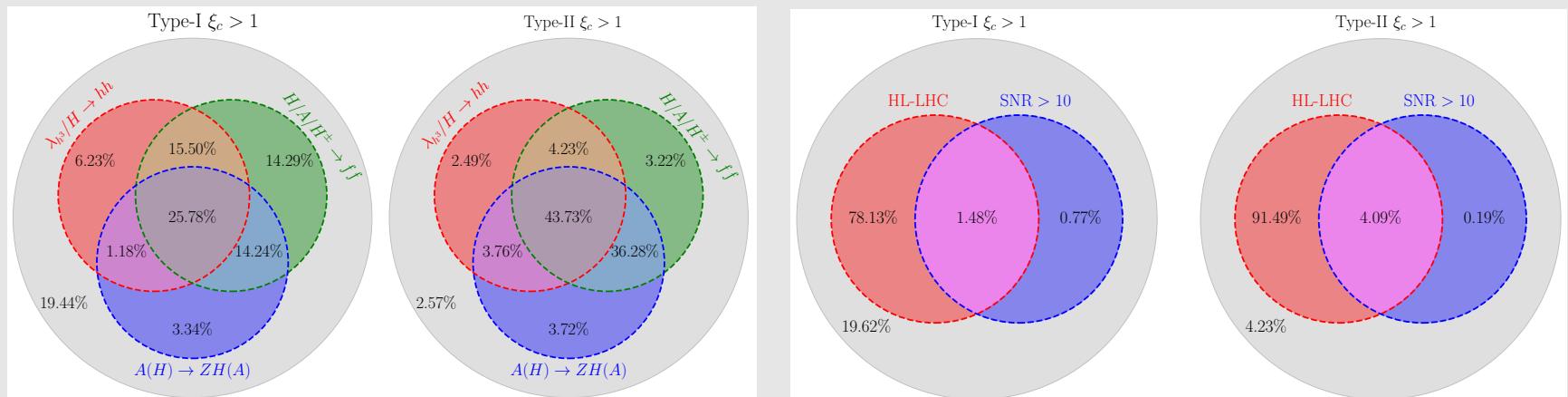
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Summary

- EWPT prefer particular parameter space



- Collider Searches



Thanks!