Electroweak Phase Transition in 2HDM

Collider and GW Complementarity

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Introduction

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

Two Higgs Doublet Model (2HDM)

- Two Doublet

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

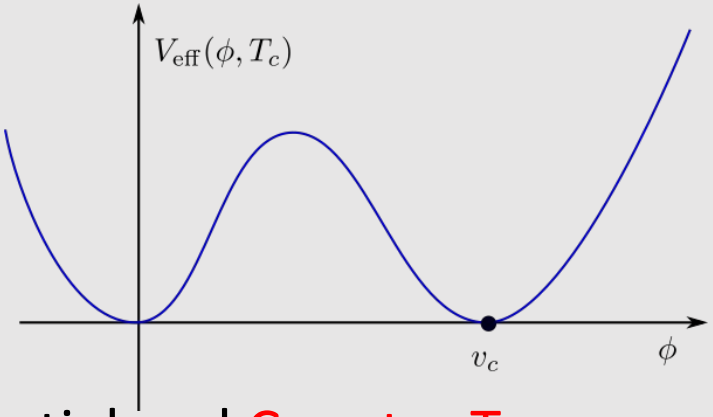
  - Five Mass Eigenstates
    - $h, H, A, H^{\pm}$
- CP Conserving, soft Z2 breaking

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

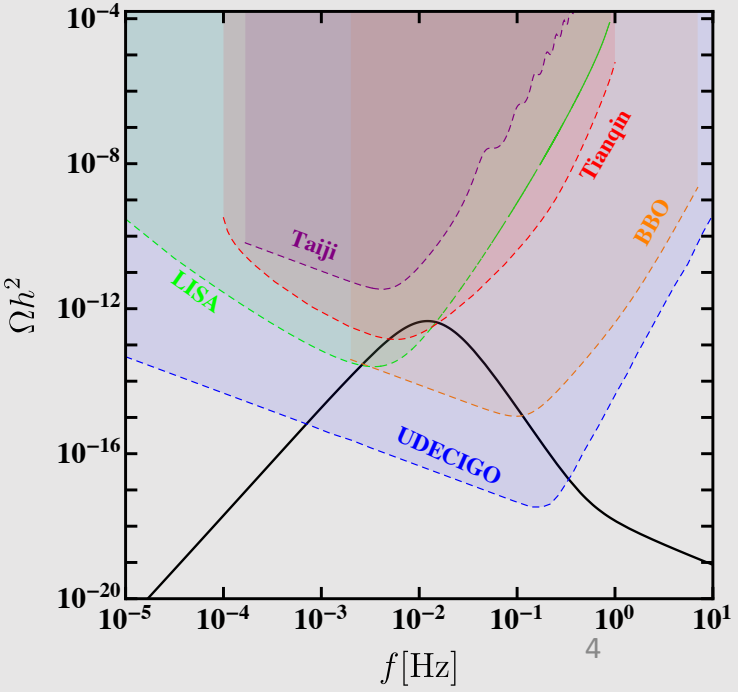
- Type-I/Type-II Yukawa Couplings

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



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

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

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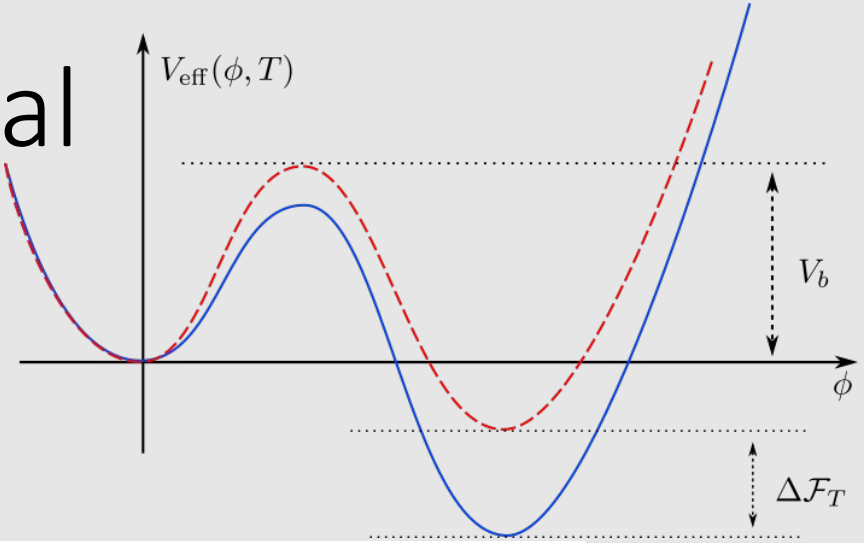
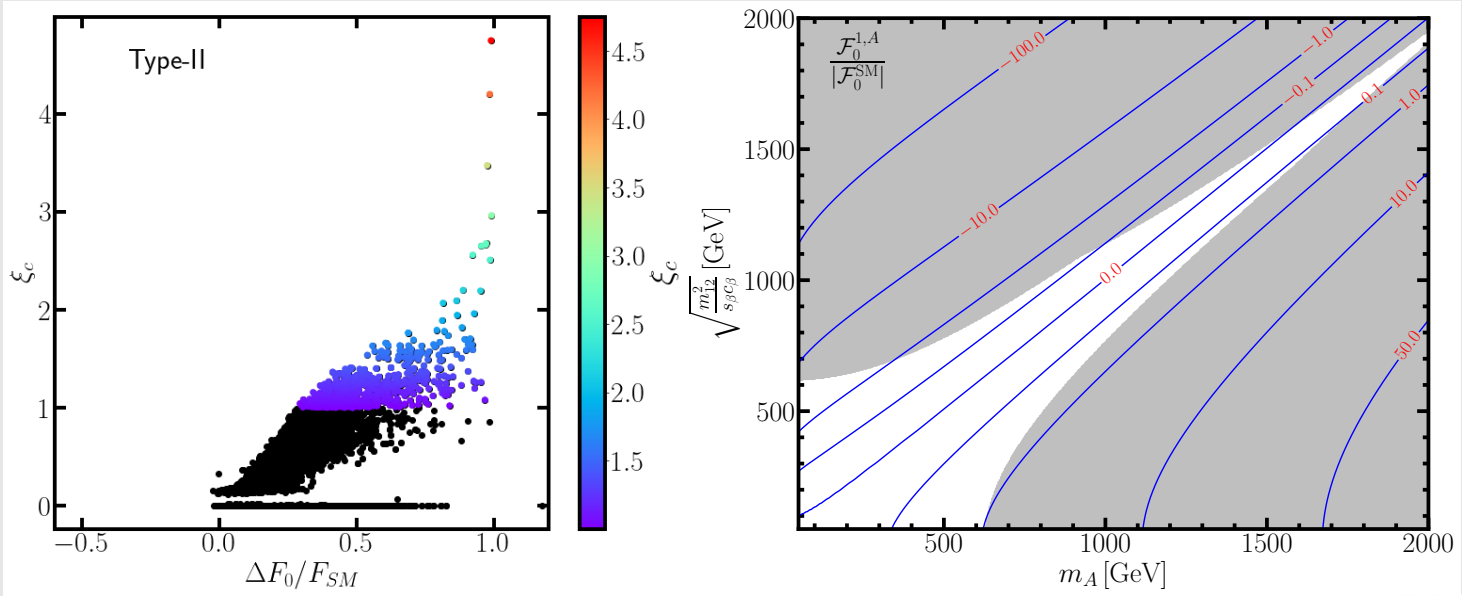
$$\mathcal{F}_0 \equiv V_{\rm eff}(v_1, v_2, T=0) - V_{\rm eff}(0,0,T=0),$$





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

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

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

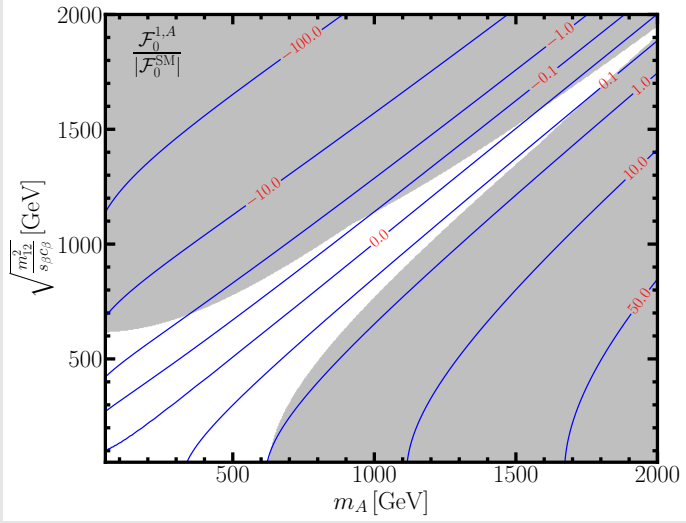
$$\lambda_{1,2} > 0$$

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

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: $m_H \approx m_{H^\pm} < m_A$

$$A \to ZH$$
$$A/H \to t\,t$$

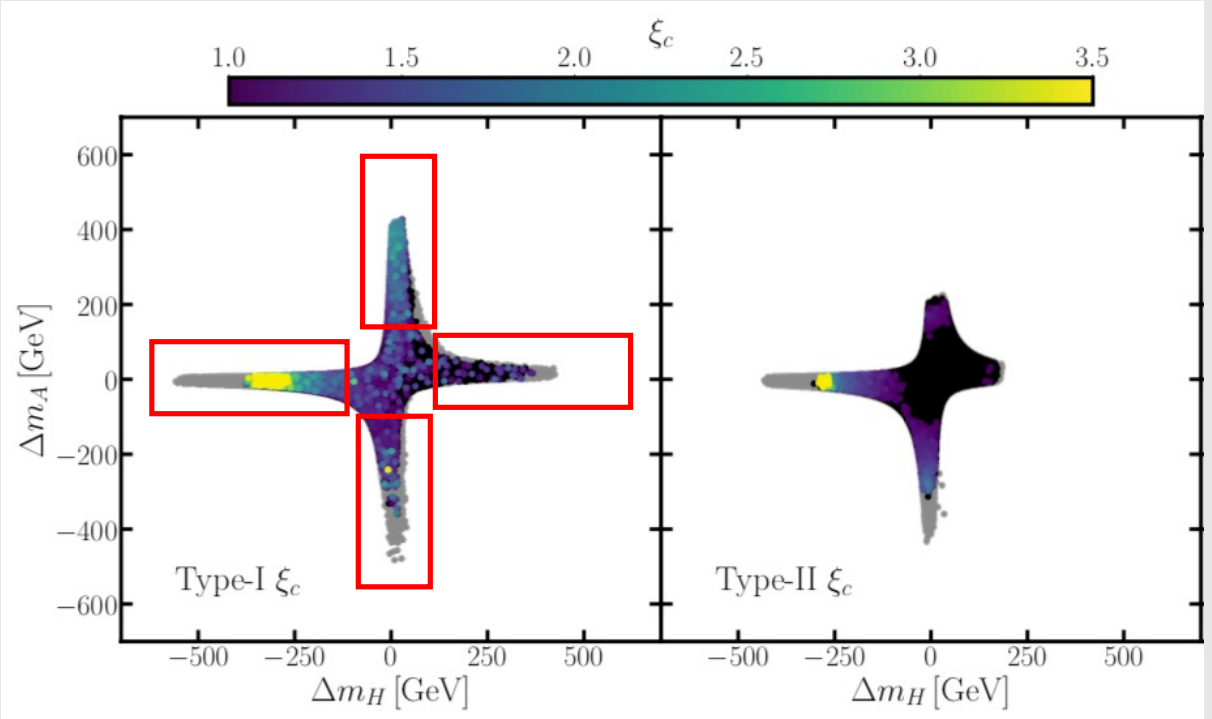
- Left: $m_H < m_{H^\pm} \approx m_A$

$$A \to ZH$$
$$A/H \to t\,t$$
$$H^\pm \to t\,b$$

- Bottom: $m_H \approx m_{H^\pm} > m_A$

$$H \to ZA$$
$$A/H \to t\,t$$
$$H^\pm \to t\,b$$

- Right: $m_H > m_{H^\pm} \approx m_A$



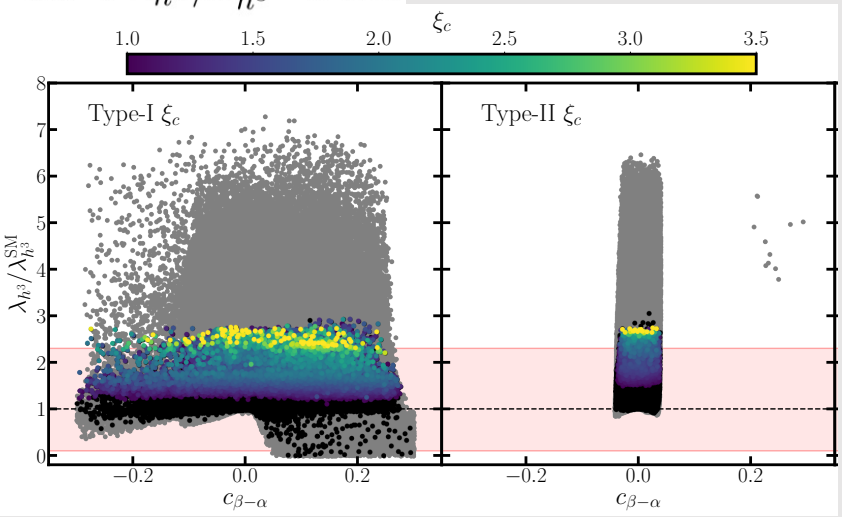
Prospects at the HL-LHC

- Spectrums
  - $A \to ZH,\ H \to ZA$
  - Fermionic Channels:
    - $H/A \to t\,t$
    - $H^{\pm} \to t\,b$

- Triple Scalar Couplings
  - Resonant/non-resonant hh

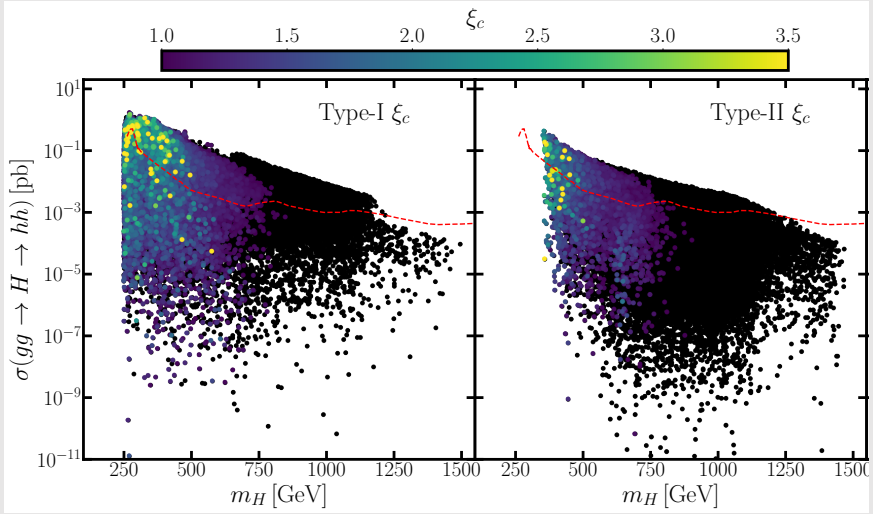
Prospects at the HL-LHC

$0.1 < \lambda_{h^3}/\lambda_{h^3}^{\rm SM} < 2.3$ **1902.00134**



Non-Resonance

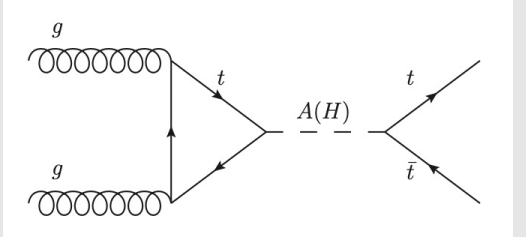
Scaling from 1804.06174

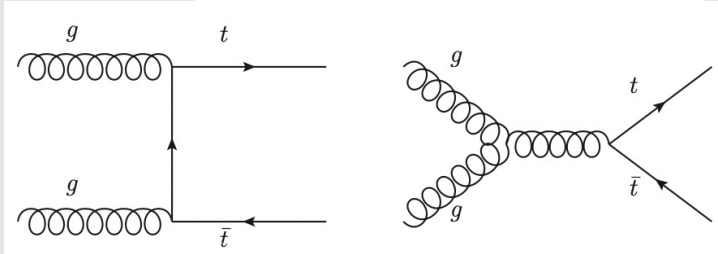


Resonance

- Triple Scalar Couplings
  - Resonance/non-resonance hh

Prospects at the HL-LHC





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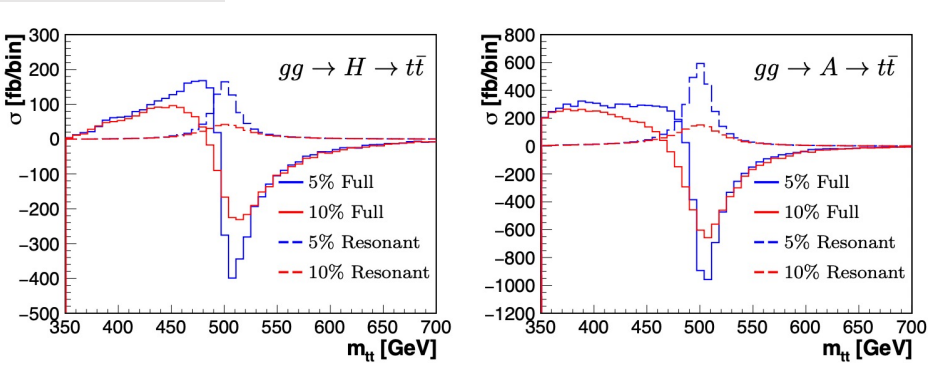

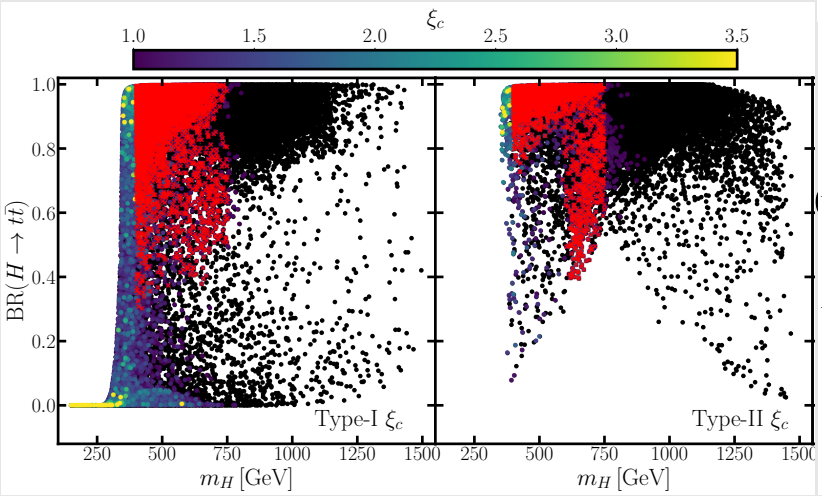

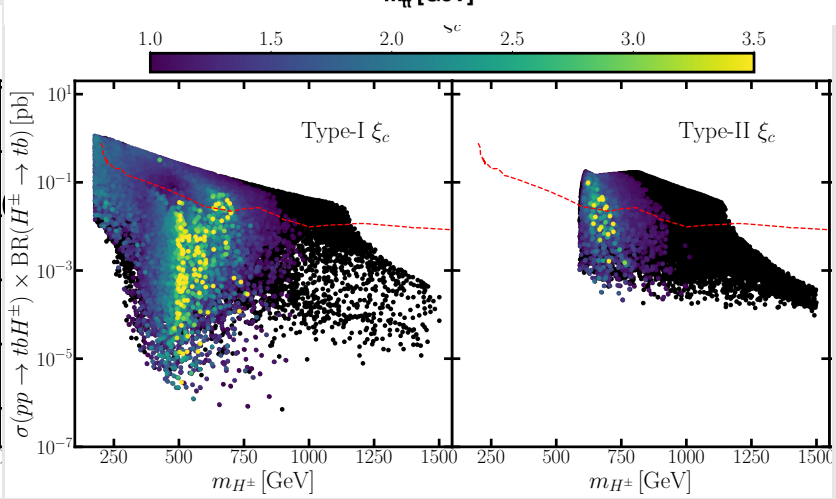

Scaling from 1908.01115

Scaling from 2102.10076

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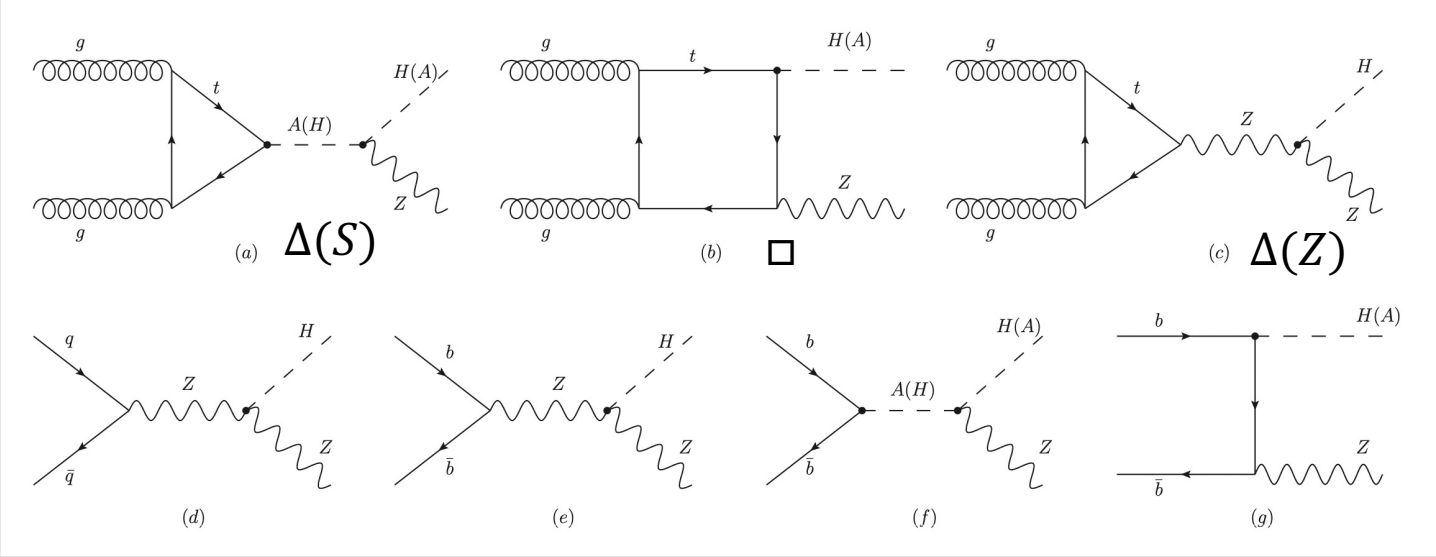
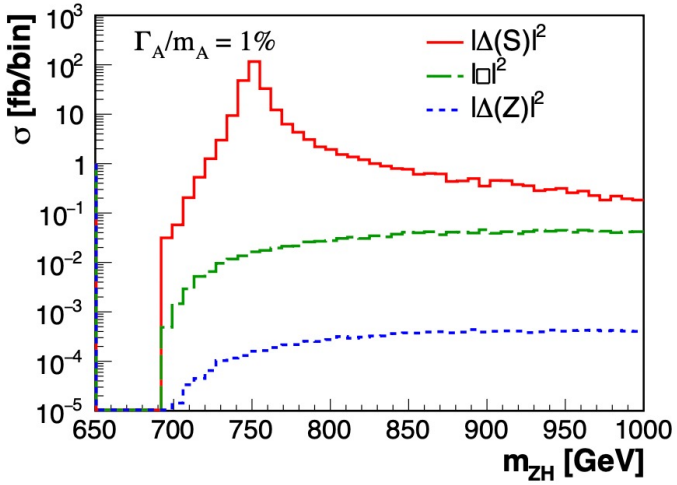
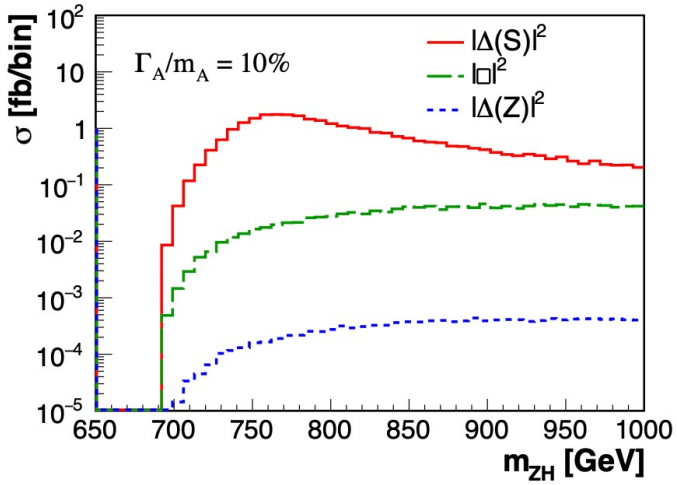
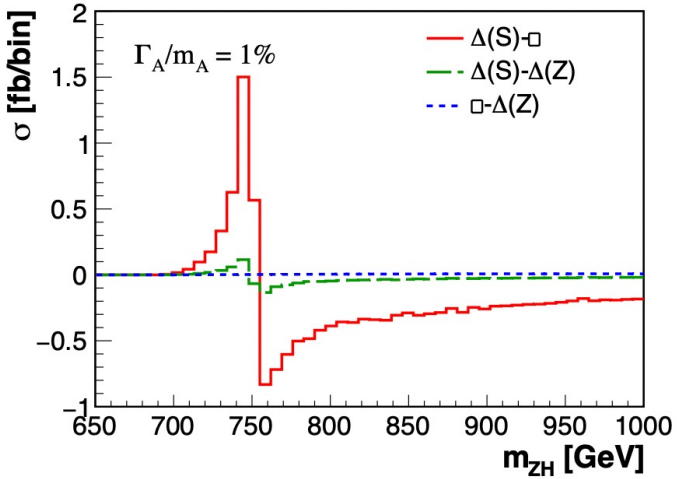


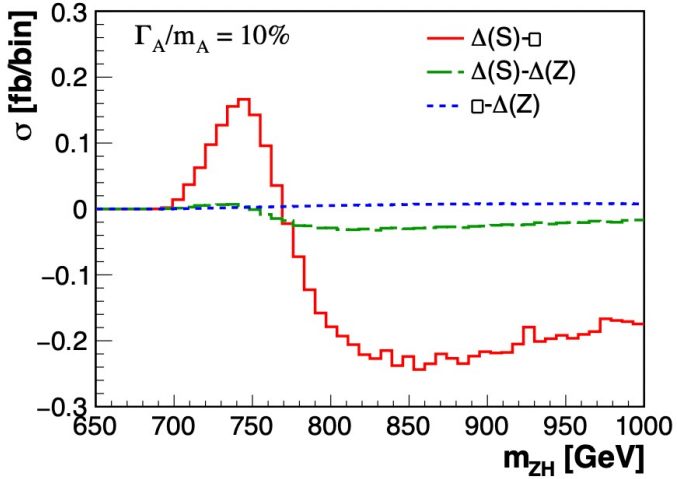
Prospects at the HL-LHC

$gg \to A \to ZH$









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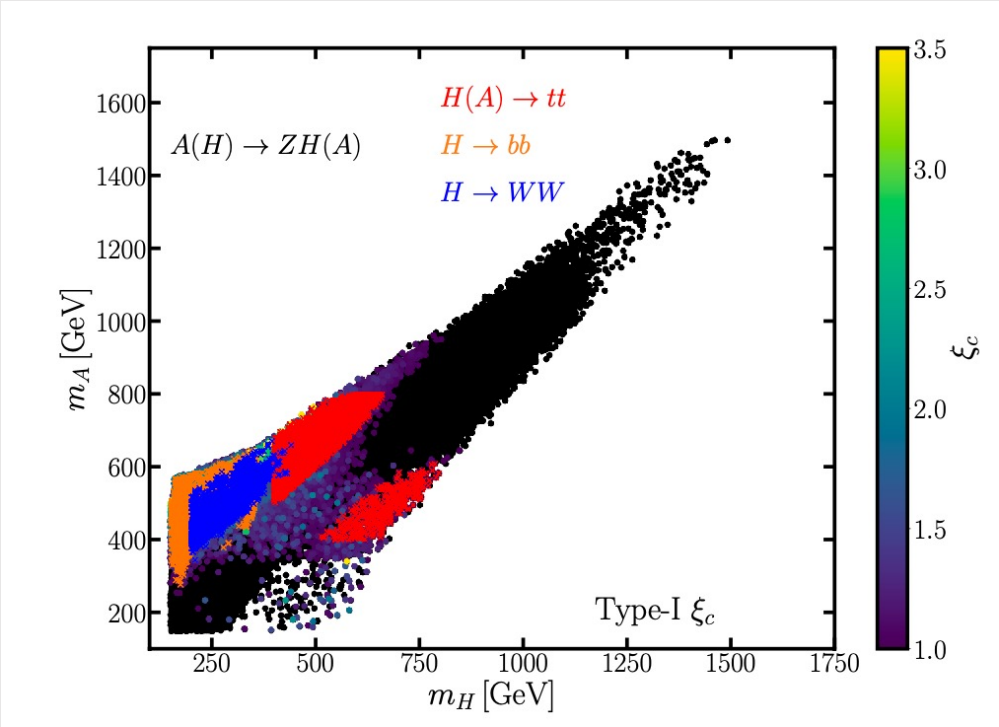
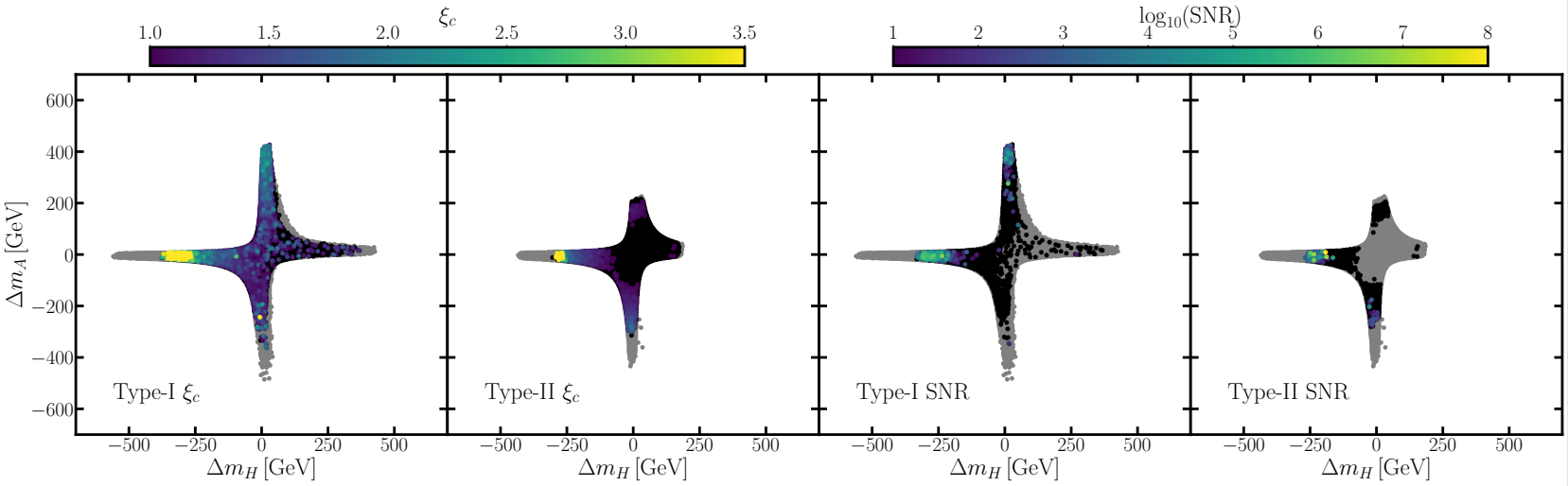


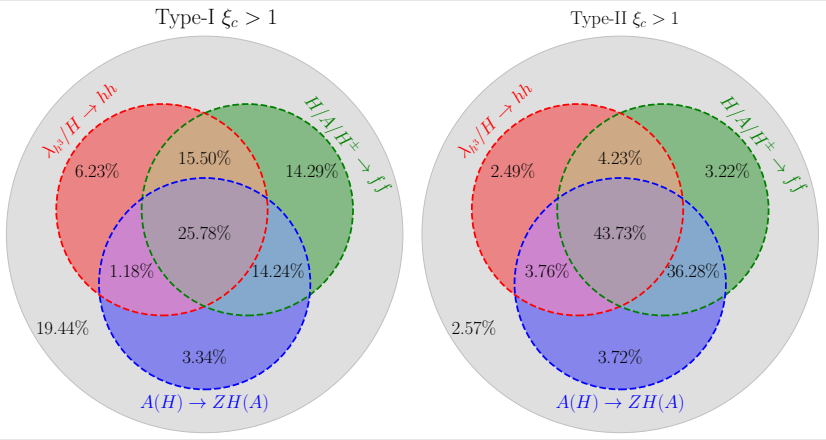
bb/WW Scaling from LHC 2011.05639, 1911.03781

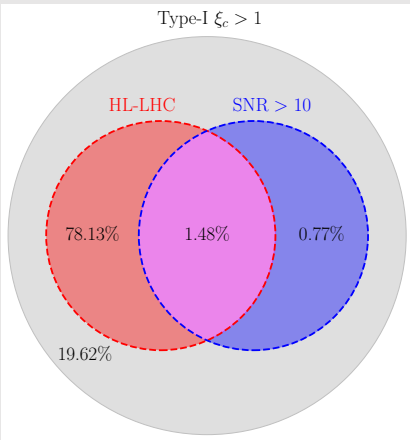
Summary

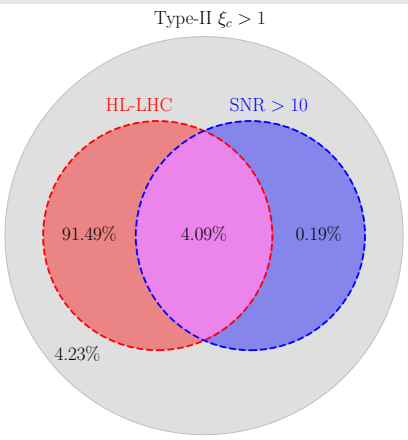
- EWPT prefer particular parameter space



- Collider Searches

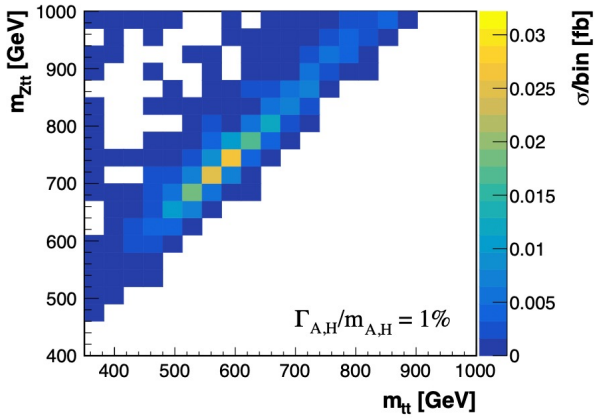


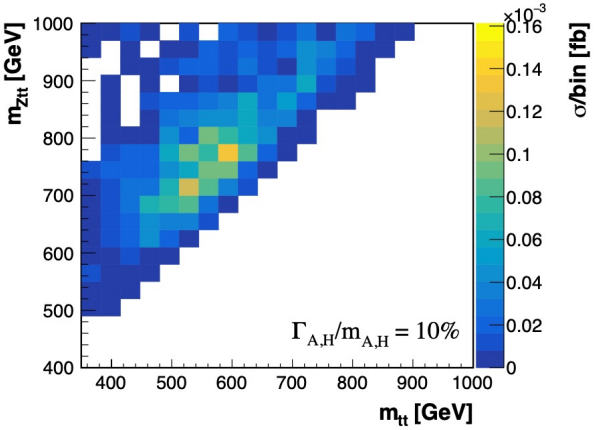


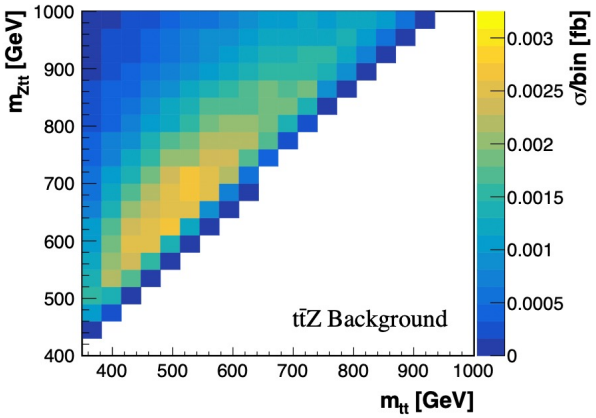


Thanks!

2D Distributions







Upper limits on the Cross section