



Collider and Gravitational Wave Complementarity in the 2HDM

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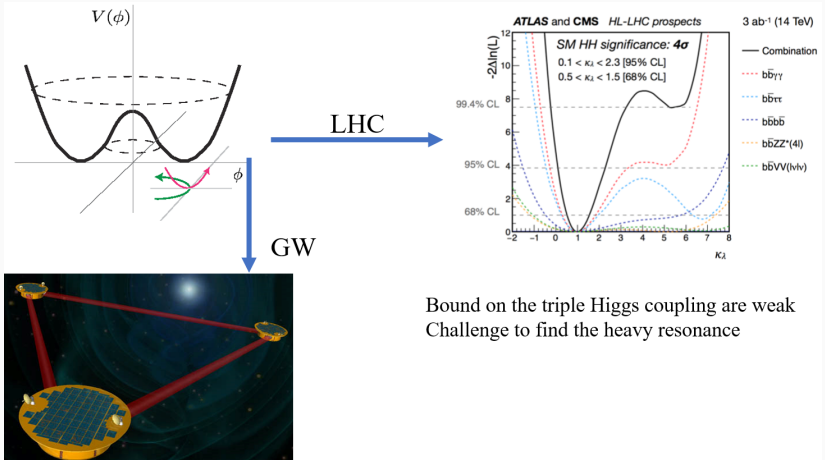
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Collider and GW Complementarity



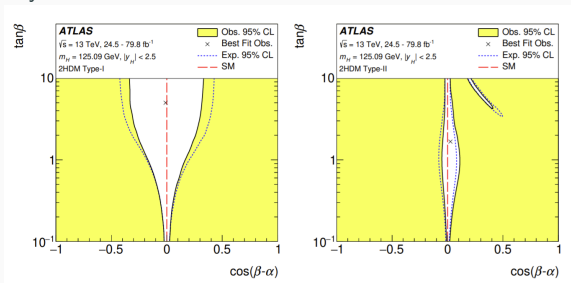
Bound on the triple Higgs coupling are weak
 Challenge to find the heavy resonance

CP-conserving THDM

- CP-conserving 2HDM with a softly broken \mathbb{Z}_2 symmetry.

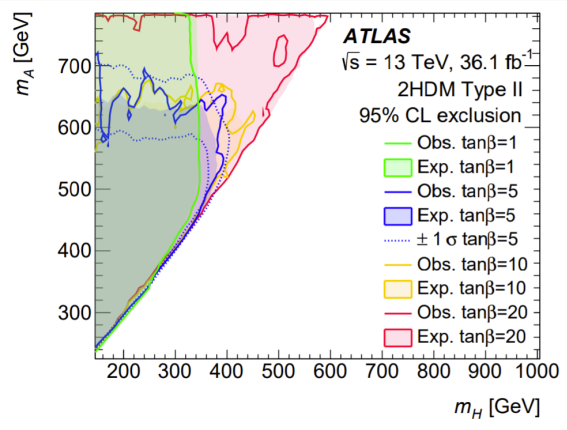
$$V(\Phi_1, \Phi_2) = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + h.c.) + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1) (\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger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

- \mathbb{Z}_2 symmetry transformations $\Phi_1 \rightarrow \Phi_1$ and $\Phi_2 \rightarrow -\Phi_2$



t_β - $C_{\beta-\alpha}$ plot, left side corresponds to type I and right side corresponds to type II

$$\tan\beta = \frac{v_2}{v_1}$$



$m_A - m_H$ for type II

$A \rightarrow ZH \rightarrow llbb$

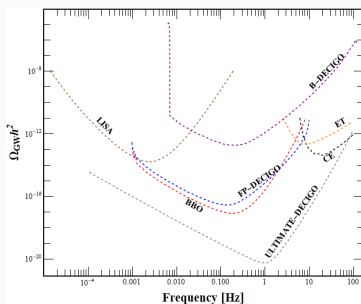
Electroweak phase transition

- To study the thermal evolution of the universe.
- Electroweak baryogenesis provides a mechanism to explain the baryon asymmetry in the universe. Baryon asymmetry can be generated at the bubble walls during first-order phase transition. The condition for strong first-order transition is given by,

(M. Shaposhnikov, 1992)

$$\xi_c \equiv \frac{v_c}{T_c} \geq 1.$$

- First-order phase transition in the early show detectable GW signals today.



$$V_{\text{eff}}(\omega_1, \omega_2, T) = V_0(\omega_1, \omega_2) + V_{CW}(\omega_1, \omega_2) + V_{CT}(\omega_1, \omega_2, T) + V_T(\omega_1, \omega_2).$$

(Philipp Basler, Margarete Muhlleitner, Jonas Muller, 2019)

- Using the $\overline{\text{MS}}$ renormalization scheme, Coleman-Weinberg potential V_{CW} can be written in the Landau gauge as

(Coleman and Weinberg, 1973)

$$V_{CW}(\omega_1, \omega_2) = \sum_i \frac{(-1)^{2s_i} n_i}{64\pi^2} m_i^4(\omega_1, \omega_2) \left[\log \left(\frac{m_i^2(\omega_1, \omega_2)}{\mu^2} \right) - c_i \right],$$

- We add the following counterterms to have correct consistent scalar masses and VEV,

$$V_{CT} = \frac{\omega_1^2}{2} \delta m_{11}^2 + \frac{\omega_2^2}{2} \delta m_{22}^2 - \omega_1 \omega_2 \delta m_{12}^2 + \frac{\omega_1^4}{8} \delta \lambda_1 + \frac{\omega_2^4}{8} \delta \lambda_2 \\ + \frac{\omega_1^2 \omega_2^2}{4} (\delta \lambda_3 + \delta \lambda_4 + \delta \lambda_5),$$

Coefficients of counterterms can be determined using on-shell renormalization procedure

$$\begin{aligned}\partial_{\phi_i}(V_{CW} + V_{CT})|_{\Phi_{1tree}, \Phi_{2tree}} &= 0, \\ \partial_{\phi_i} \partial_{\phi_j}(V_{CW} + V_{CT})|_{\Phi_{1tree}, \Phi_{2tree}} &= 0.\end{aligned}$$

- The one-loop thermal corrections V_T , include the daisy resummation and can be expressed as

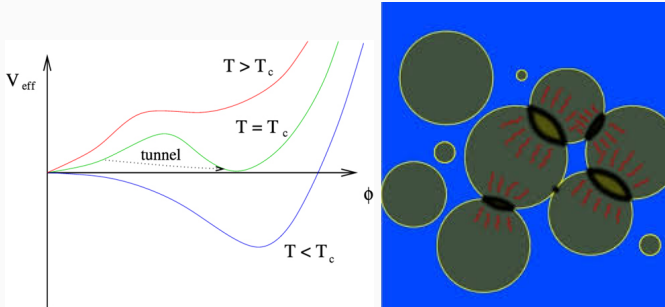
$$V_T = \frac{T^4}{2\pi^2} \left[\sum_f n_f J_+ \left(\frac{m_f^2}{T^2} \right) + \sum_i n_i J_- \left(\frac{m_i^2}{T^2} \right) \right] - \frac{T^4}{2\pi^2} \sum_j \frac{\pi}{6} \left(\frac{\bar{m}_j^3}{T^3} - \frac{m_j^3}{T^3} \right),$$

- The thermal functions J_+ for fermions and J_- for bosons read

$$J_{\pm}(x) = \mp \int_0^{\infty} dy y^2 \log \left(1 \pm e^{-\sqrt{y^2+x^2}} \right). \quad (1)$$

First order phase transition

At the critical temperature, T_C symmetry broken and unbroken vacuum are degenerate.



$$\frac{S_3(T_n)}{T_n} \approx 140.$$

(R. Apreda, M. Maggiore, A. Nicolis, and A. Riotto, 2002)

$$\alpha = \frac{\rho_{vac}}{\rho_{rad}} = \frac{1}{\rho_{rad}} \left[T \frac{d\Delta V}{dT} - \Delta V \right]_{T_n}, \quad \beta = \left(HT \frac{d(s_3/T)}{dT} \right)_{T_n}.$$

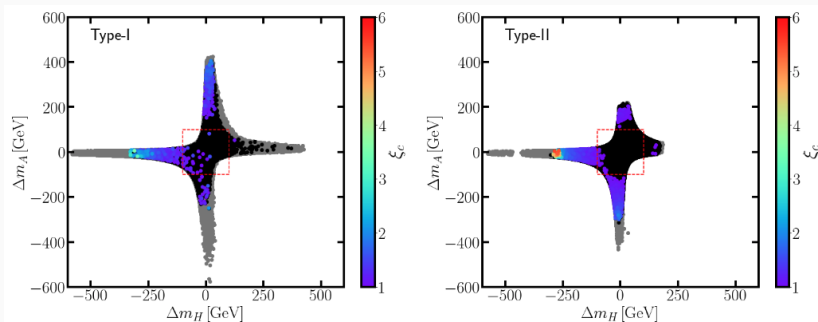
- During the first-order phase transition, GW waves are produced from three sources bubble wall collision, sound waves and magnetohydrodynamics (MHD) solutions.

(P. Binetruy, A. Bohe, C. Caprini, and J.F. Dufaux, 2012)

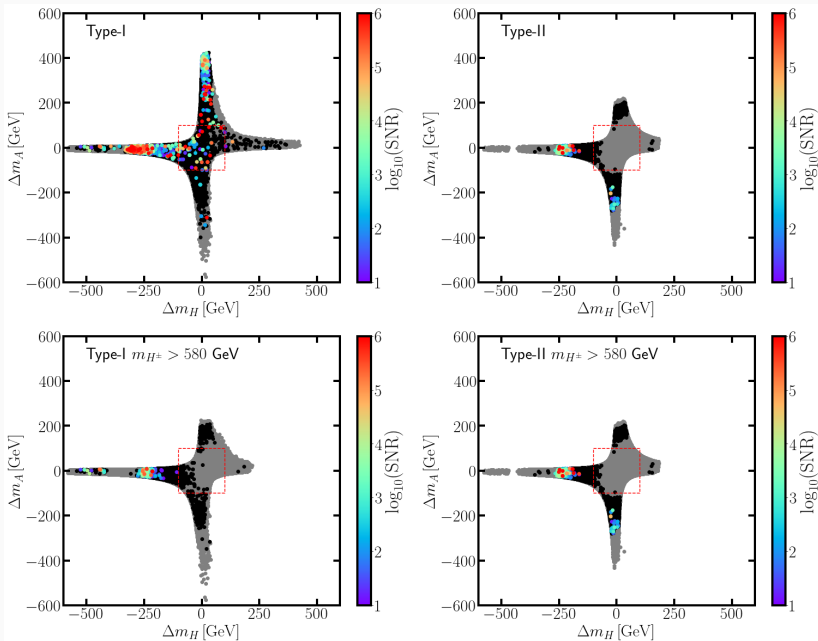
$$\Omega_{GW} h^2 = \Omega_{sw} h^2 + \Omega_{turb} h^2 + \Omega_{coll} h^2.$$

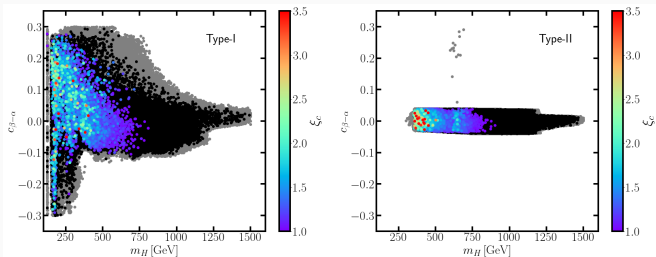
- GW signal is detectable in detector if $SNR > 10$.

$$SNR = \sqrt{\tau \int_{f_{min}}^{f_{max}} df \left[\frac{\Omega_{GW}(f) h^2}{\Omega_{sens}(f) h^2} \right]^2}.$$

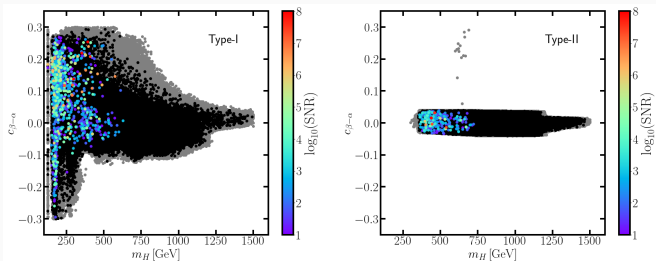


- $\Delta m_H = m_H - m_{H^\pm}$ and $\Delta m_A = m_A - m_{H^\pm}$.
- For type II, $m_{H^\pm} < 580$ GeV has been excluded by the measurements of $\text{BR}(B \rightarrow X_s \gamma)$.

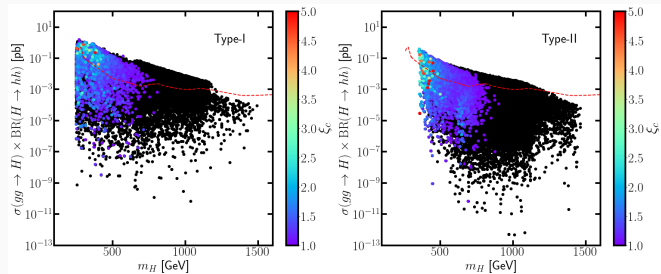




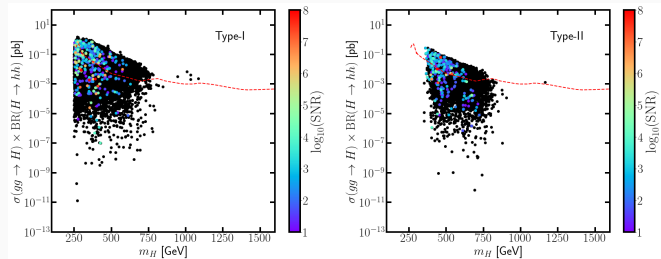
Grey: all points passing HiggsBounds and HiggsSignal. Black: all points with first order phase transition. The heat map tracks ξ_c (top) and SNR (bottom).



$\sigma(gg \rightarrow H) \times \text{BR}(H \rightarrow hh)$ vs. m_H



The cross section $\sigma(gg \rightarrow H) \times \text{BR}(H \rightarrow hh)$ vs. m_H . The red dashed line indicates the projected limits from ATLAS with 3000 fb^{-1} by scaling current limits.



- Collider and GW experiment can offer complementarity to probe the shape of Higgs potential.
- Type I and Type II have similar phase transition behaviour and GW signals.
- Strongly first order electroweak phase transition prefers lower value of m_H .
- GW experiments can probe parameter space which is very challenging for collider experiments.

Thank you!