Collider and Gravitational Wave Complementarity in the 2HDM

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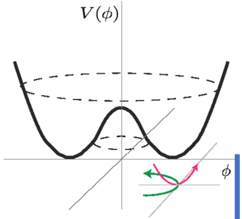
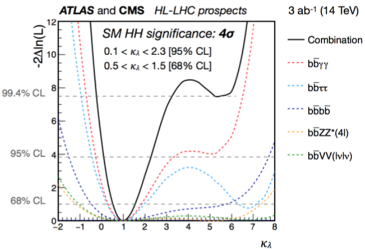
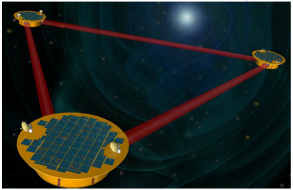
Collider and GW Complementarity



LHC



GW



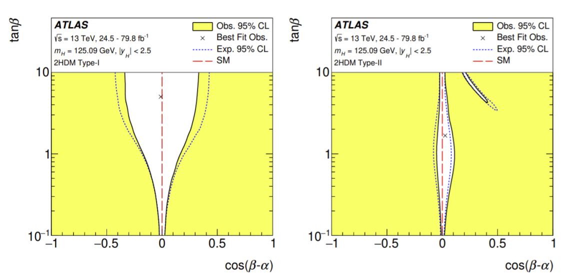
Bound on the triple Higgs coupling are weak
Challenge to find the heavy resonance

CP-conserving THDM

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

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

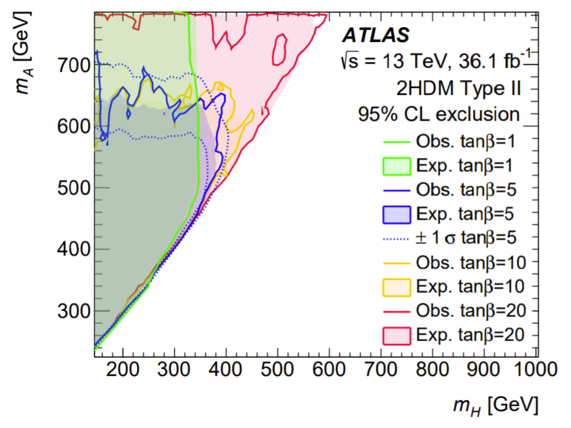
- $\mathbb{Z}_2$ symmetry transformations $\Phi_1 \to \Phi_1$ and $\Phi_2 \to -\Phi_2$



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

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

CP-conserving THDM



m_A-m_H for type II

$$A \to ZH \to \ell\ell bb$$

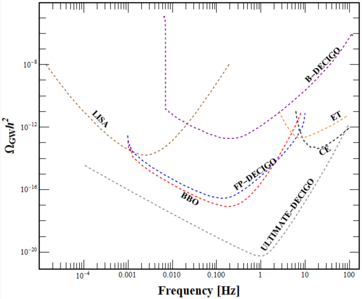
Electroweak phase transition

- 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.



Effective potential

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

(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,

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

Effective potential

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

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

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

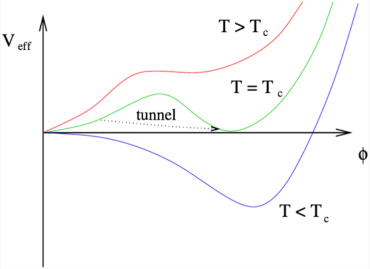
$$V_T = \frac{T^4}{2\pi^2}\left[\sum_f n_f J_+\left(\frac{m_f^2}{T^2}\right) + \sum_i n_i J_-\left(\frac{m_i^2}{T^2}\right)\right] - \frac{T^4}{2\pi^2}\sum_j \frac{\pi}{6}\left(\frac{\overline{m}_j^3}{T^3} - \frac{m_j^3}{T^3}\right)\,,$$

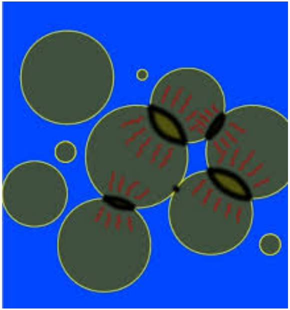
- The thermal functions J_+ for fermions and J_- for bosons read

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

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)

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

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

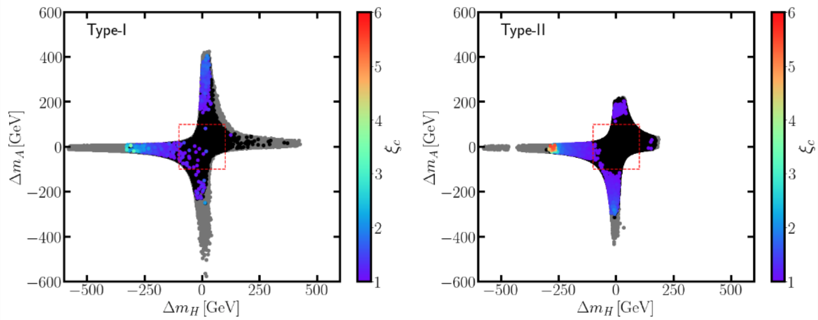
(P. Binetruy, A. Bohe, C. Caprini, and J.F. Dufaux, 2012)

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

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

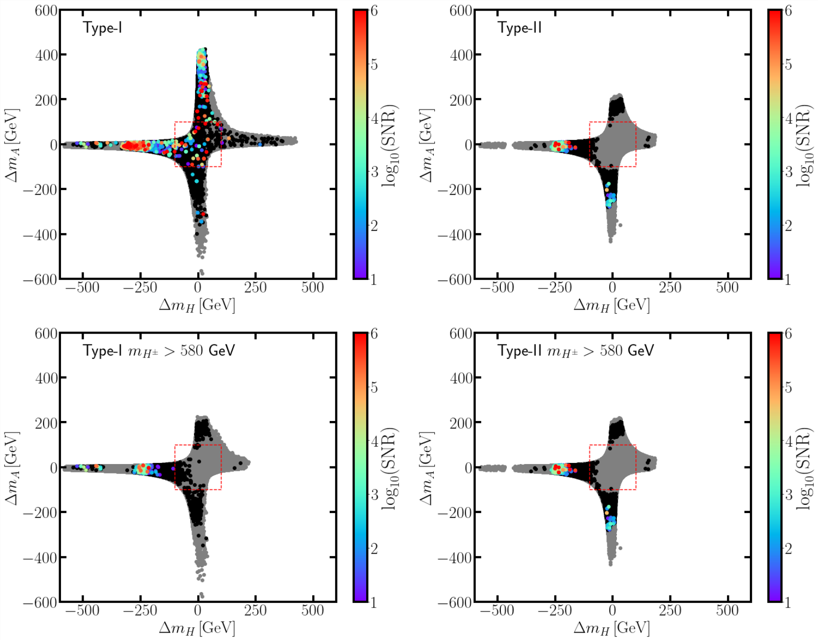
$$SNR = \sqrt{\tau \int_{f_{min}}^{f_{max}} df \left[\frac{\Omega_{GW}(f) h^2}{\Omega_{sens}(f) h^2}\right]^2}.$$

Δm_H-Δm_A

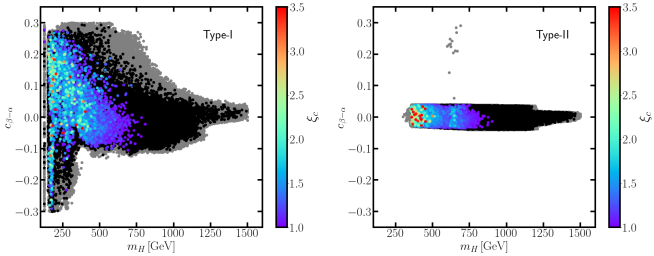


- $\Delta m_H = m_H - m_{H^\pm}$ and $\Delta m_A = m_A - m_{H^\pm}$.
- For type II, $m_{H^\pm} < 580$ GeV has been excluded by the measurements of BR($B \to X_s \gamma$).

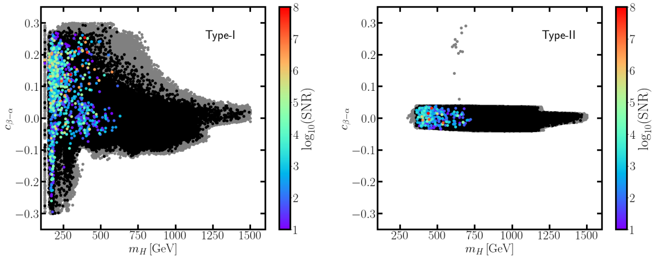
Δm_H-Δm_A



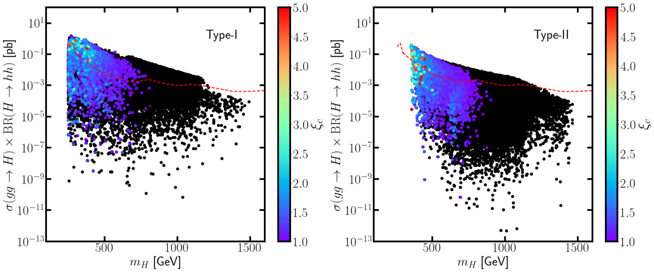
m_H-$c_{\beta-\alpha}$



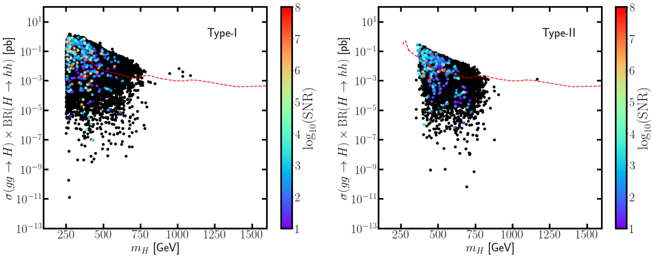
Grey: all points passing HiggsBounds and HiggsSignal. Black: all points with first order phase transition. The heat map tracks ξ_c (top) and SNR (bottom).



$\sigma(gg \to H) \times \mathrm{BR}(H \to hh)$ vs. m_H



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



Summary

- 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!