Phase transition, Gravitational waves and baryon asymmetry in the 2HDM

based on arXiv:2108.05356, arXiv:2206.08381, arXiv:2307.03224

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November 19, 2024
LHC Higgs Working Group WG3 (BSM)
Extended Higgs Sector subgroup

OKLAHOMA STATE UNIVERSITY

1. Motivation

2. Electroweak phase transition in the 2HDM

3. Electroweak baryogenesis

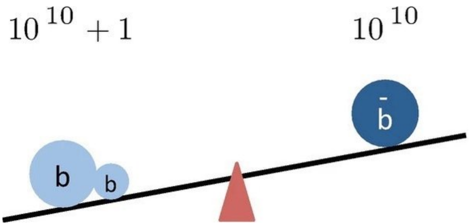
4. Summary

Outline

Matter-antimatter Asymmetry puzzle

- Baryon to photon ratio: $\eta = \frac{n_B - n_{\bar{B}}}{\gamma} = 6 \times 10^{-10} \, \frac{\text{excess baryons}}{\text{photon}}$

(WMAP data)

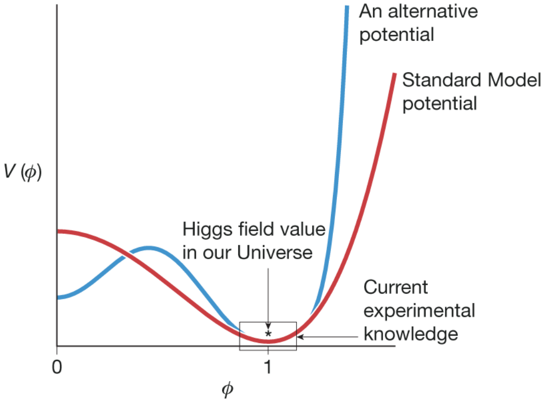


Need physics beyond the standard model!

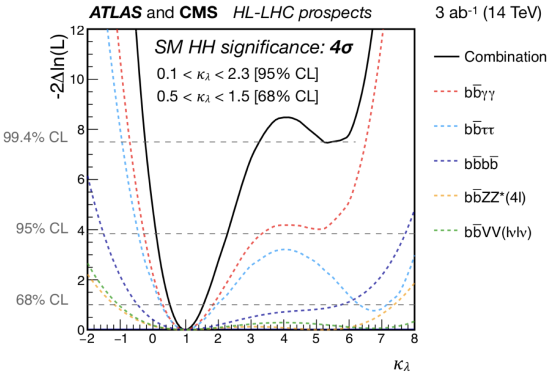
- The three necessary conditions to dynamically generate baryon asymmetry from none previously existed,
  1. Baryon number violation
  2. C and CP violation
  3. Departure from thermal equilibrium

(A Sakharov 1967)

Shape of the Higgs Potential



$$V(h) = \frac{m_h^2}{2}h^2 + \lambda_3 h^3 + \lambda_4 h^4 + \ldots$$



Requires new particles near the electroweak scale with sizable Higgs boson interactions.

GW detector a new window.

For $T \sim 100\,\mathrm{GeV}$, GW frequency (redshifted to today) $\sim mHz$. **LISA**

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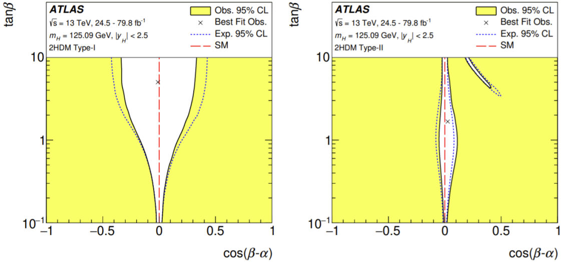
CP-conserving 2HDM

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 $\Phi_2 \rightarrow -\Phi_2$

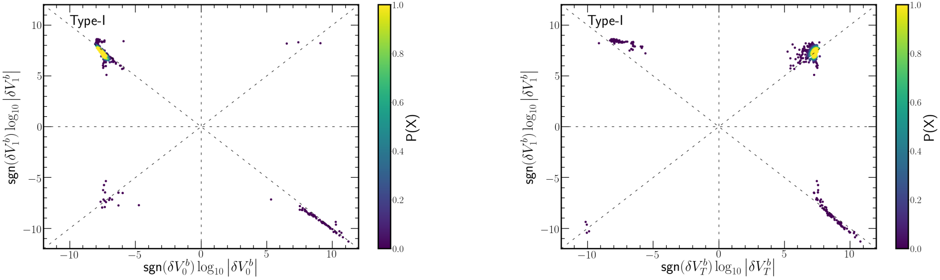


t_β-$C_{\beta-\alpha}$ plot, left side corresponds to type I right side corresponds to type II

Shape of the Higgs Potential

$$V_{\text{eff}}(\omega_1,\omega_2,T) = V_0(\omega_1,\omega_2) + V_{CW}(\omega_1,\omega_2) + V_{CT}(\omega_1,\omega_2,T) + V_T(\omega_1,\omega_2)$$
$$= V_0(\omega_1,\omega_2) + V_1(\omega_1,\omega_2) + V_T(\omega_1,\omega_2).$$

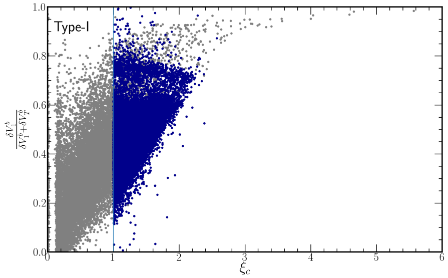
(P.B Arnold, O.Espinosa, 1993)

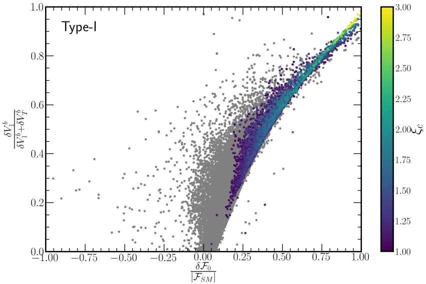


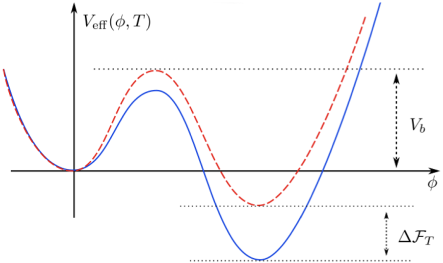
In the $\xi_c > 1$ regime, the phase transition is mostly one-loop driven.

(Gonçalves, **AK**, WU PRD 2022)

Vacuum upliftment $\Delta\mathcal{F}_0/|\mathcal{F}_0^{\rm SM}|$







$\mathcal{F}_0$ is the vacuum energy density of the 2HDM at $T=0$ defined as

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

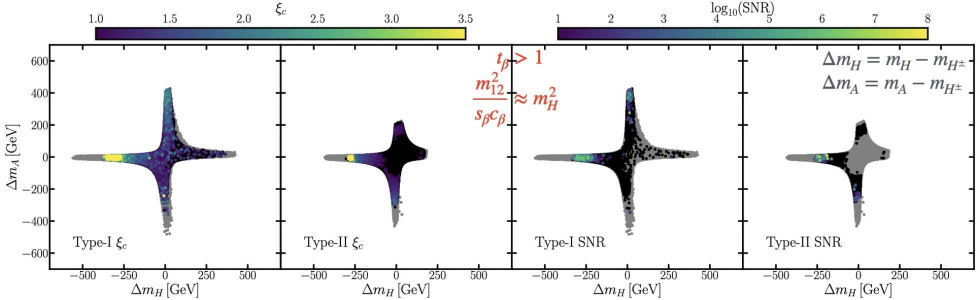
and $\mathcal{F}_0^{\rm SM} = -1.25\times10^8$ GeV^4.

(Gonçalves, **AK**, WU PRD 2022)

Δm_H-Δm_A

The individual contributions from H, A, and $H^{\pm}$ to $\mathcal{F}_0$ are of the same form.

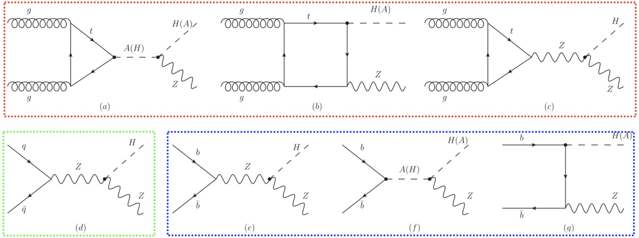
$$\mathcal{F}_0^{1,A}(c_{\beta-\alpha}=0) = \frac{1}{512\pi^2}\left[\left(3m_h^2 + 2m_A^2 - 6\frac{m_{12}^2}{s_\beta c_\beta}\right)\left(m_h^2 + \boxed{2m_A^2 - 2\frac{m_{12}^2}{s_\beta c_\beta}}\right) + \left(m_h^2 - 2\frac{m_{12}^2}{s_\beta c_\beta}\right)^2 \log\left(\frac{4m_A^4}{(m_h^2 - 2m_{12}^2/(s_\beta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

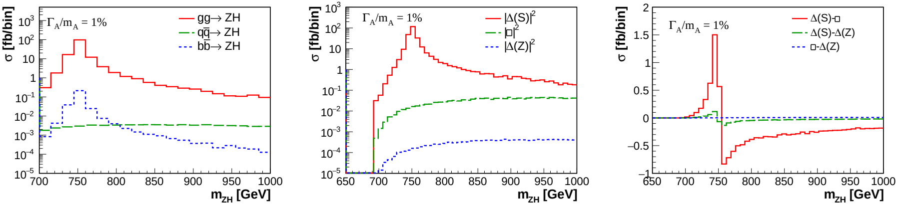


$m_H < m_{H^\pm} \approx m_A$: most favourable for SFOEWPT. Favours $A \to ZH$ channel

Higgstrahlung production $pp \to ZH/A$

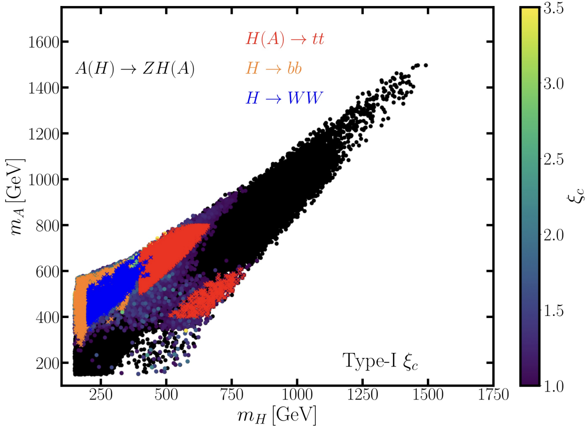
$pp \to ZH/A$ searches mainly accounts for $H/A \to bb$ and $H \to WW$.
(Sensitivity $m_{H/A} \leqslant 350\text{GeV}$)

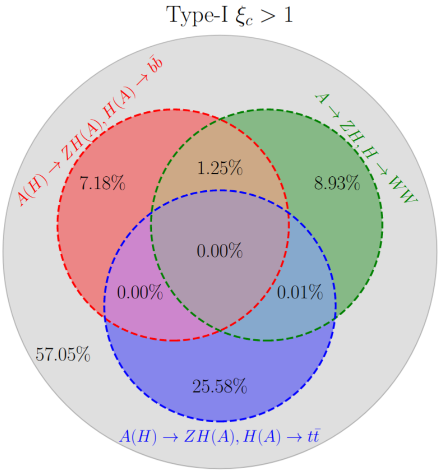




We assume $c_{\beta-\alpha} \approx 0.3$, $m_H = 600$ GeV, $m_A = 750$ GeV, and $t_\beta = 1$ in the type-I.
(Gonçalves, **AK**, WU PRD 2023)

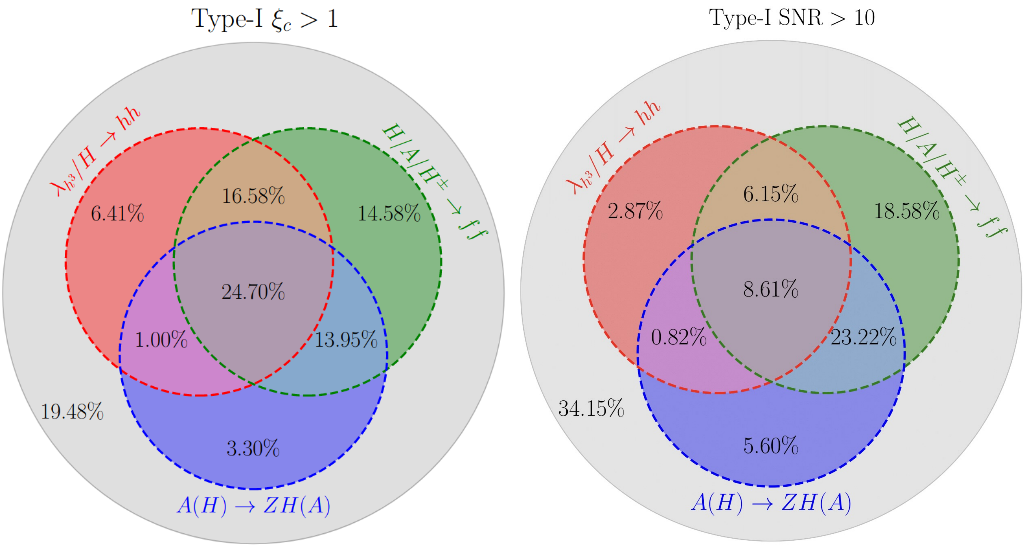
Top Pair Resonant Searches via $pp \to ZH/A$





(Gonçalves, **AK**, WU PRD 2023)

Collider and GW complementarity



(Gonçalves, **AK**, WU PRD 2023)

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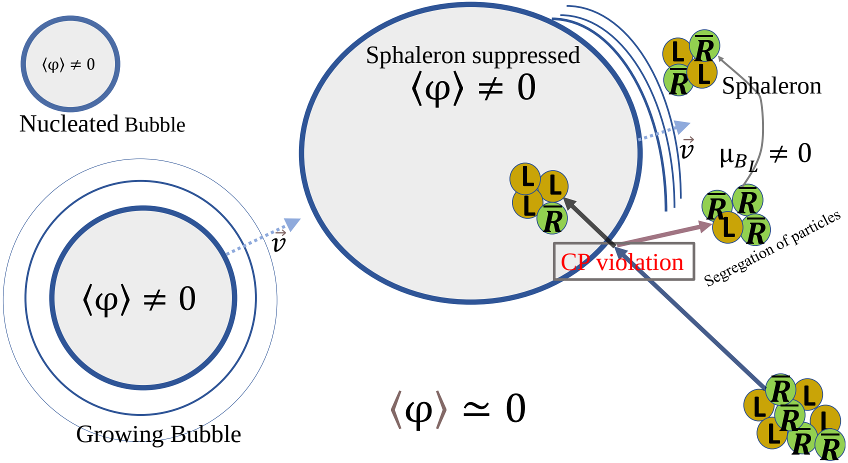
Electroweak baryogenesis



- Sphaleron to be suppressed inside the bubble, we need a strong first-order phase transition $\xi \equiv \frac{\langle\varphi\rangle}{T} \gtrsim 1$

Bubble profile

- Key ingredient in estimation of baryon asymmetry during EWBG is bubble profile

$$\frac{d^2\phi}{dr^2} + \frac{2}{r}\frac{d\phi}{dr} = \frac{dV(\phi,T)}{d\phi}, \quad \text{with} \quad \lim_{r\to\infty}\phi(r) = 0 \quad \text{and} \quad \lim_{r\to 0}\frac{d\phi(r)}{dr} = 0.$$

(A D Linde 1980)

- In the literature, it is a customary practice to parameterize tunneling profile $\theta^i(z)$ by kink profile using $\tanh$ function

$$\theta^i(z) = \left(\frac{\theta^i_{\rm brk} + \theta^i_{\rm sym}}{2} - \frac{\theta^i_{\rm brk} - \theta^i_{\rm sym}}{2}\left(\tanh\left(\frac{z}{L_W}\right)\right)\right).$$

(D Bodeker, L Fromme, S J. Huber, M Seniuch 2004)

$$\theta^i(z \to -\infty) = \theta^i_{\rm brk}$$
$$\theta^i(z \to \infty) = \theta^i_{\rm sym}$$

Semi-classical force method

- Particle interaction with bubble wall can be formalized using the WKB approximation. Force acting on the particle is given by (+particle/-antiparticle)

$$F_z = -\frac{(m^2)'}{2E_0} \pm s\frac{(m^2\theta')'}{2E_0E_{0z}} \mp \frac{\theta' m^2 (m^2)'}{4E_0^3 E_{0z}}.$$

(L Fromme, S J. Huber, 2006)

- Source term of the top quark S_t

$$S_t = -v_W K_{8,t}\partial_z(m_t^2\partial_z\theta) + v_W K_{9,t}(\partial_z\theta)m_t^2(\partial_z m_t^2).$$

In front of the bubble wall, the negative value of $\partial_z\theta$ leads to a positive S_t and, thereby, in most cases, positive asymmetry.

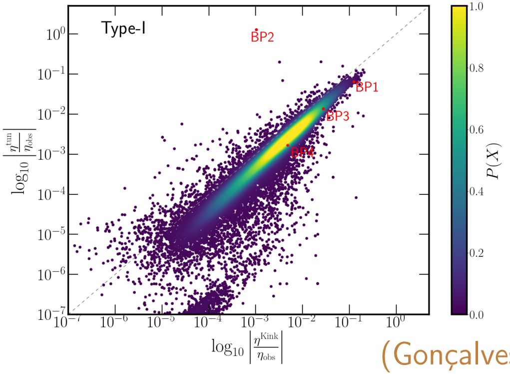
- Chemical potential for left-handed quarks $\mu_{B_L} = \mu_{q_1,2} + \mu_{q_2,2} + \frac{1}{2}(\mu_{t,2} + \mu_{b,2})$.
- LH quark asymmetry is converted into baryon asymmetry by weak sphalerons,

$$\eta_\beta = \frac{n_B}{s} = \frac{405\Gamma_{ws}}{4\pi^2 v_w g_\star T}\int_0^\infty dz\mu_{B_L}\exp\left(-\frac{45\Gamma_{ws}z}{4v_w}\right).$$

Complex 2HDM

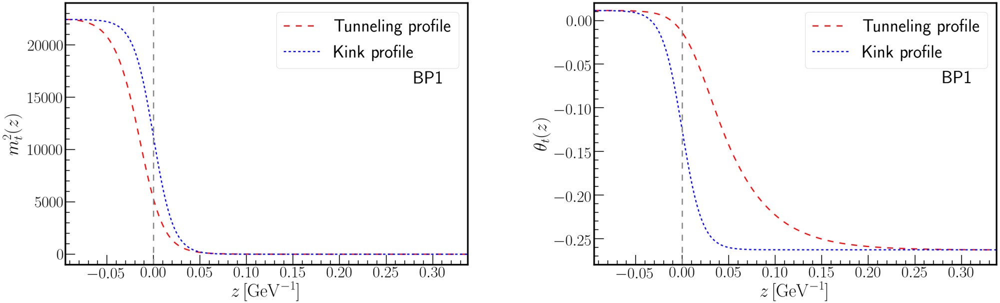
Complex 2HDM with a softly broken $\mathbb{Z}_2$ symmetry.

$$V_0(\Phi_1,\Phi_2) = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - (m_{12}^2\Phi_1^\dagger\Phi_2 + h.c.) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2$$
$$+ \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \left(\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + h.c.\right).$$



(Gonçalves, **AK**, WU PRD 2023)

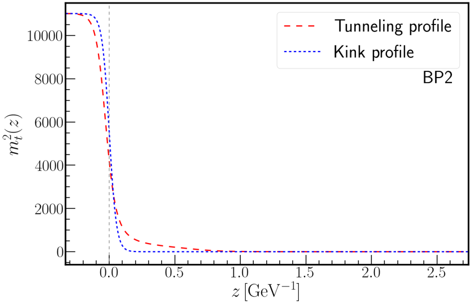
BP1

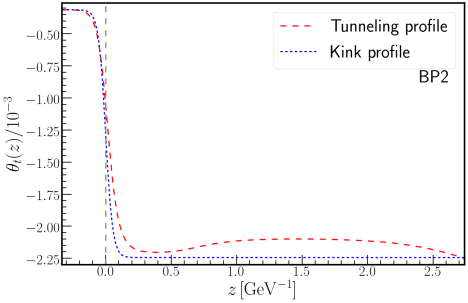


$$\eta_B^{\text{tun}} = 5.51061 \times 10^{-12} \qquad \eta_B^{\text{kink}} = 1.05886 \times 10^{-11}$$

(Gonçalves, **AK**, WU PRD 2023)

BP2

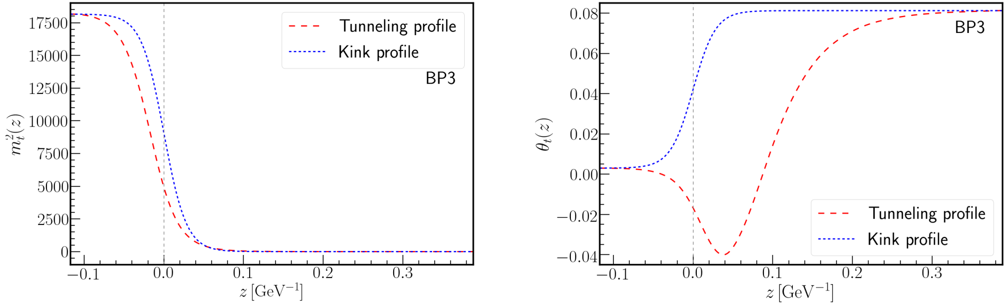




$$\eta_B^{\mathrm{tun}} = 1.08663 \times 10^{-10} \qquad \eta_B^{\mathrm{kink}} = 8.79358 \times 10^{-14}$$

(Gonçalves, **AK**, WU PRD 2023)

BP3



$$\eta_B^{\text{tun}} = 1.16237 \times 10^{-10} \qquad \eta_B^{\text{kink}} = -2.33474 \times 10^{-12}$$

(Gonçalves, **AK**, WU PRD 2023)

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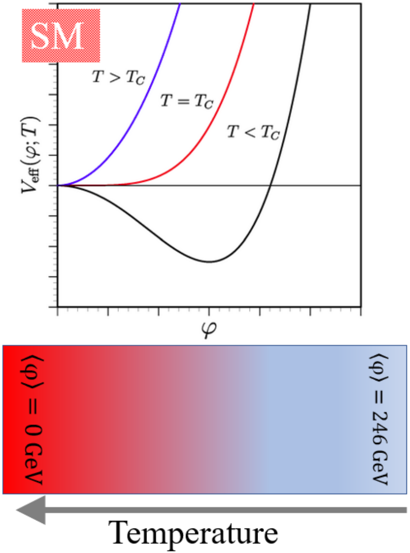
Summary

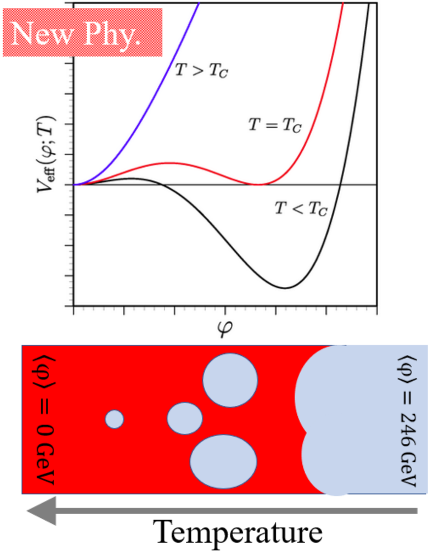
- The barrier formation in the Higgs potential of the 2HDM is mostly driven by the one-loop corrections, for large order parameter $\xi_c > 1$
- Top-quark pair final state, will be a promising signature for $\xi_c \geqslant 1$ at HL-LHC.
- For most parameter points, the kink profile approximation can predict baryon asymmetry to the correct order of magnitude. However, there is a fraction of parameter points where the predicted asymmetry significantly deviates.
- In some cases, source term can be active in larger regime for the tunnelling profile and could yield two or more orders large asymmetry compared to kink profile.

Thank You

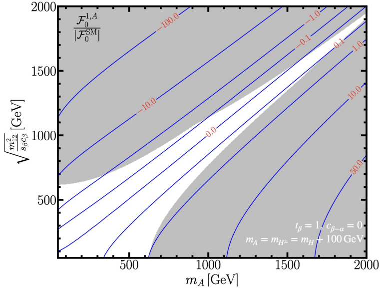
Backup slides

Electroweak phase transition

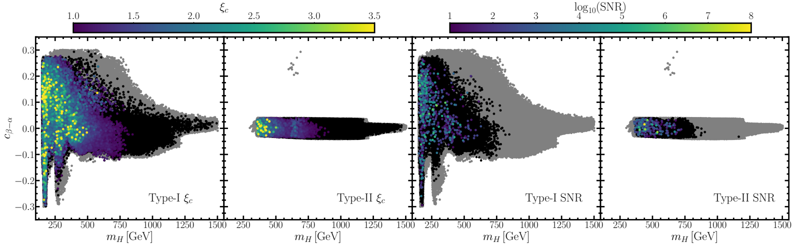




Strong first-order phase transition in the 2HDM



The individual contribution $\mathcal{F}_0^{1,A}/|\mathcal{F}_0^{\rm SM}|$ from A.



Strong first order phase transition prefer $m_H \leqslant 750\text{GeV}$

(Gonçalves, **AK**, WU PRD 2022)

Semi-classical force method

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$$F_z = -\frac{(m^2)'}{2E_0} \pm s\frac{(m^2\theta')'}{2E_0E_{0z}} \mp \frac{\theta' m^2 (m^2)'}{4E_0^3 E_{0z}}.$$

(L Fromme, S J. Huber, 2006)

- Perturbation from equilibrium density of species i due to bubble wall movement

$$f_i = \frac{1}{e^{\beta[\gamma_W(E_0+v_w p_z)-\mu_i]} \pm 1} + \delta f_i$$

- The evolution of f_i is described by the Boltzmann equation

$$\mathbf{L}[f_i] \equiv \left(v_g \partial_z + \dot{p}_z \partial_{p_z}\right) f_i = C[f_i], \qquad v_g = \frac{P_z}{E_0}\left(1 \pm \frac{\theta' m^2}{2E_0^2 E_{0z}}\right).$$

$$\text{Plasma velocity } u_i \equiv \left\langle \frac{p_z}{E_0}\delta f_i \right\rangle.$$

Semi-classical force method

- We can separate CP odd and even parts

$$\mu_i \equiv \mu_{i,1e} + \mu_{i,2o} + \mu_{i,2e}, \qquad \delta f_i \equiv \delta f_{i,1e} + \delta f_{i,2o} + \delta f_{i,2e}.$$

- Second-order CP odd chemical potential and plasma velocities

$$\mu_{i,2} \equiv \mu_{i,2o} - \bar{\mu}_{i,2o}, \qquad u_{i,2} \equiv u_{i,2o} - \bar{u}_{i,2o}.$$

- Source term of the top quark S_t

$$S_t = -v_W K_{8,t} \partial_z (m_t^2 \partial_z \theta) + v_W K_{9,t} (\partial_z \theta) m_t^2 (\partial_z m_t^2).$$

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