

Exploring dynamical CP violation induced baryogenesis by gravitational waves and colliders

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1804.06813 Phys. Rev. D 98, 015014 (Based on work in Collaboration with Fa Peng Huang, Mengchao Zhang) The observed universe seems to be dominated by matter over anti-matter. Or, baryon asymmetry of the universe (BAU):



Does the SM work?

- baryon number violation possible through non-perturbative sphaleron process
- C and CP symmetry violation
 CKM in weak interaction, but insufficient
- Departure from thermal equilibrium
 Crossover (smooth) EW phase transition
- * Stringent constraints from electric dipole moment (EDM) measurement limits new physics source of CP violation

the source of CP violation evolves to zero at tree level. In this work, we

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- [14] S. Bruggisser, B. Von Harling, O. Matsedonskyi and G. Servant, arXiv:1803.08546 [hep-ph].
 - [15] J. R. Espinosa, B. Gripaios, T. Konstandin and F. Riva, JCAP **1201**, 012 (2012)

doi:10.1088/1475-7516/2012/01/012 [arXiv:1110.2876 [hep-ph]]. J. M. Cline and K. Kainulainen, JCAP **1301**, 012 (2013) doi:10.1088/14

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$$\begin{split} V_{\text{tree}}(H,\sigma) &= -\frac{1}{2}\mu_{SM}^2 H^2 - \frac{1}{2}\mu^2 \sigma^2 + \frac{1}{4}\lambda_{SM} H^4 + \frac{1}{4}\lambda\sigma^4 + \frac{1}{4}\kappa H^2 \sigma^2 \\ V(H,\sigma,T) &= (D_H T^2 - \frac{\mu_{SM}^2}{2})H^2 + (D_\sigma T^2 - \frac{\mu^2}{2})\sigma^2 + \frac{1}{4}(\lambda_{SM} H^4 + \kappa H^2 \sigma^2 + \lambda\sigma^4) \\ D_H &= \frac{1}{32}(8\lambda_{SM} + g'^2 + 3g^2 + 4y_t^2 + 2\kappa/3), \quad D_\sigma &= \frac{1}{24}(2\kappa + 3\lambda) , \\ \blacksquare &= \frac{v(T_c)}{T_c} \sim \frac{2v}{m_H}\sqrt{\frac{D_H - D_\sigma}{\delta_\lambda - 2\delta_{\mu^2}}} \end{split}$$





$$\lambda = \left(\frac{\kappa}{2\lambda_{SM}}\right)^2 \lambda_{SM} (1+\delta_{\lambda})$$
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SFOPT favored region:



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SFOPT favored region:



Numerical results with Finite temperature effective 1-loop potential:

 $V_{\text{eff}}(H,\sigma,T) = V_{\text{tree}}(H,\sigma) + \Delta V_1^{T\neq 0}(H,\sigma,T) + V_1^{T=0}(H,\sigma)$

(setting $\eta = 1 + i$)

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(setting $\eta = 1 + i$)

BAU estimation:

$$\eta_B = \frac{405\Gamma_{\text{sph}}}{4\pi^2 \tilde{v}_b g_* T} \int dz \,\mu_{B_L} f_{\text{sph}} \,e^{-45\,\Gamma_{\text{sph}}|z|/(4\tilde{v}_b)}$$
Observed BAU:
$$\Delta \sigma / \Lambda \sim 0.1 - 0.3$$

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Benchmark points, which can give a SFOPT and produce phase transition GWs.

Benchmark set	κ	$m_S \; [\text{GeV}]$	$T_N \; [\text{GeV}]$	α	\tilde{eta}
Ι	2.00	115	106.6	0.035	107
II	2.00	135	113.6	0.04	120

$$\mathcal{L}_{Stt} = -\left(\frac{m_t}{\Lambda} + \frac{m_t H}{\Lambda v}\right) S\left(a\bar{t}t + ib\bar{t}\gamma_5 t\right) \qquad >> \text{Rich Collider signature}$$

$$\mathcal{L}_{SVV}' = \frac{a\alpha_S}{12\pi\Lambda} SG^a_{\mu\nu} G^{a\mu\nu} - \frac{b\alpha_S}{8\pi\Lambda} SG^a_{\mu\nu} \tilde{G}^{a\mu\nu} + \frac{2a\alpha_{EW}}{9\pi\Lambda} SF_{\mu\nu} F^{\mu\nu} - \frac{b\alpha_{EW}}{3\pi\Lambda} SF_{\mu\nu} \tilde{F}^{\mu\nu}$$



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loop induced effective couplings
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 loop induced effective couplings
$$\mathcal{L}_{mass} = -\frac{1}{2}\left(S \ H\right)\left(\begin{array}{c}m_{S,\text{tree}}^{2} + \Delta m_{S}^{2} & \Delta m_{HS}^{2} \\ \Delta m_{HS}^{2} & m_{H,\text{tree}}^{2} + \Delta m_{H}^{2}\end{array}\right)\left(\begin{array}{c}S \\ H\end{array}\right)$$

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$$\mathcal{L}_{Stt} = -\left(\frac{m_t}{\Lambda} + \frac{m_t H}{\Lambda v}\right) S\left(a\bar{t}t + ib\bar{t}\gamma_5 t\right) \qquad >> \text{Rich Collider signature}$$

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Property of S from loop-induced mixing with H



0.5 1 1.5 2 2.5 3
$$v_c/T_c$$

contribution to electron EDM

 $|d_e| < 8.7 \times 10^{-29} \text{ cm} \cdot \text{e}$ (ACME 2014) $|d_e| \sim < 1 \times 10^{-29}$ (ACME 2018)



J. Brod, U. Haisch and J. Zupan, JHEP **1311**, 180 (2013) doi:10.1 [arXiv:1310.1385 [hep-ph]].

R. Harnik, J. Kopp and J. Zupan, JHEP **1303**, 026 (2013) doi:10.1[arXiv:1209.1397 [hep-ph]].

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2-loop Barr-Zee contribution to EDM



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2-loop Barr-Zee contribution to EDM

$$d_e^{2\text{-loop}} = \frac{e}{3\pi^2} \left(\frac{\alpha_{EW} G_F v}{\sqrt{2\pi}m_t} \right) m_e \left(\frac{vb}{2\Lambda} \right) \mathcal{O}_{11} \mathcal{O}_{12} \Big[-g(z_{ts}) + g(z_{th}) \Big]$$

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R. Harnik, J. Kopp and J. Zupan, JHEP **1303**, 026 (2013) doi:10.1[arXiv:1209.1397 [hep-ph]].

0.5 1 1.5 2 2.5 5
$$v_c/T_c$$

contribution to electron EDM

$$|d_e| < 8.7 imes 10^{-29} ext{ cm} \cdot ext{e}$$
 (ACME 2014)
 $|d_e| \sim < 1 imes 10^{-29}$ (ACME 2018)

e e e e e

2-loop Barr-Zee contribution to EDM

$$d_e^{2\text{-loop}} = \frac{e}{3\pi^2} \left(\frac{\alpha_{EW} G_F v}{\sqrt{2\pi}m_t} \right) m_e \left(\frac{vb}{2\Lambda} \right) \mathcal{O}_{11} \mathcal{O}_{12} \left[-g(z_{ts}) + g(z_{th}) \right]$$

$$z_{ts} = \frac{m_t^2}{m_S^2} , \ z_{th} = \frac{m_t^2}{m_H^2} , \ g(z) = \frac{1}{2}z \int_0^1 dx \frac{1}{x(1-x)-z} \log\left(\frac{x(1-x)}{z}\right)$$

J. Brod, U. Haisch and J. Zupan, JHEP **1311**, 180 (2013) doi:10.1 [arXiv:1310.1385 [hep-ph]].

R. Harnik, J. Kopp and J. Zupan, JHEP **1303**, 026 (2013) doi:10.1[arXiv:1209.1397 [hep-ph]].

• LHC Direct Search through: di-photon, 4-leptons

Production cross sections of S times branching ratios at 14 TeV LHC

$m_S[\text{GeV}]$	$\sigma(pp \to S) \times BR(S \to \gamma\gamma)$	$\sigma(pp \to S) \times BR(S \to ZZ^*)$
115	37.73 fb	54.69 fb
135	18.38 fb	520.60 fb

• LHC Direct Search: pp-> SH



• LHC Direct Search: pp-> SH



LHC Direct Search: pp-> SH



LHC Direct Search: pp-> SH



LHC Direct Search: pp-> SH



• Lepton Collider: CEPC@240, 5 ab⁻¹: Direct Resonance Search

★ Recoiled mass distribution:



• Recoil mass distribution of channel: $ZH, \ Z \rightarrow \mu^{-}\mu^{+}$

- Fit with crystal ball function and polynomial function as CEPC report
- S-peak is fitted by re-scaling and shifting from the Higgs signal

(stats: 2 GeV mass window; syst: $\epsilon_{
m sys}=1\%$)

* arXiv: 1601.05352

* CEPC-SPPC Study Group IHEP-CEPC-DR-2015-01, IHEP-TH-2015-01, IHEP-EP-2015-01

★ ZH Inclusive total Cross section deviation:

 $\sigma(e^+e^- \to HZ)$ rescaled by a factor $|\mathcal{O}_{22}|^2 \mathcal{Z}$

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 $\sigma(e^+e^- \to HZ)$ rescaled by a factor $|\mathcal{O}_{22}|^2 \mathcal{Z}$ wave-function renormalization from $\kappa S^2 H^2$

★ ZH Inclusive total Cross section deviation:

 $\sigma(e^+e^- \to HZ) \text{ rescaled by a factor } |\mathcal{O}_{22}|^2 \mathcal{Z}$ Loop induced SH-mixing wave-function renormalization from $\kappa S^2 H^2$



★ ZH Inclusive total Cross section deviation:

 $\sigma(e^+e^- \to HZ) \text{ rescaled by a factor } |\mathcal{O}_{22}|^2 \mathcal{Z}$ $\textbf{Loop induced SH-mixing} \qquad \textbf{wave-function renormalization from } \kappa S^2 H^2$ $\mathcal{Z} = 1 + \frac{\kappa^2 v^2}{32\pi^2 m_H^2} \left(1 - \frac{4m_S^2}{m_H^2} \frac{1}{\sqrt{\frac{4m_S^2}{m_H^2} - 1}} \arctan \frac{1}{\sqrt{\frac{4m_S^2}{m_H^2} - 1}}\right)$



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 $\sigma(e^+e^- \to HZ) \text{ rescaled by a factor } |\mathcal{O}_{22}|^2 \mathcal{Z}$ $\textbf{Loop induced SH-mixing} \qquad \textbf{wave-function renormalization from } \kappa S^2 H^2$ $\textbf{"Sensitive to m_{S\approx}m_H"} \qquad \mathcal{Z} = 1 + \frac{\kappa^2 v^2}{32\pi^2 m_H^2} \left(1 - \frac{4m_S^2}{m_H^2} \frac{1}{\sqrt{\frac{4m_S^2}{m_H^2} - 1}} \arctan \frac{1}{\sqrt{\frac{4m_S^2}{m_H^2} - 1}}\right)$

"Sensitive to light ms"





Constraints from Resonance search, Higgs signal data



Constraints from Resonance search, Higgs signal data

• Reach from CEPC indirect Zh inclusive measure



Constraints from Resonance search, Higgs signal data

Reach from CEPC direct search

Reach from CEPC indirect Zh
 inclusive measure



Constraints from Resonance search, Higgs signal data

Reach from CEPC direct search

- Reach from CEPC indirect Zh inclusive measure
- Constraints from updated EDM (Comparable and Complementary to collider search)



We evaluate the experimental observables including, Current and future collider search, EDM and gravitational wave signals for a simple and viable EW-baryogenesis scenario, that is soon to be probed/ruled out by EDM result and future lepton collider.