Probing the nature of Higgs boson by colliders in synergy with gravitational waves

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Outline

➢ Research Motivation

➢ Electroweak (EW) baryogenesis and Phase transition gravitational wave (GW) in a nutshell

➢ Explore Higgs potential and EW phase transition by CEPC & LISA

➢ Explore Higgs properties in EW baryogenesis with dynamical CP-violation by CEPC & LISA

➢ Explore Higgs properties in dark matter (DM) by GW & CEPC

➢ Summary and outlook
Motivation from particle

Higgs Independence Day: 4 July 2012@LHC
After the discovery of 125 GeV scalar at the LHC, it becomes an urgent issue to explore the nature of Higgs boson: the Higgs potential and its possible roles in particle cosmology, such as neutrino mass (leptogenesis), Higgs (portal) inflation, cosmological relaxion, EW phase transition/baryogenesis, Higgs portal dark matter…

**Relaxion** \( \mathcal{O} = M^2 - g\phi \)  
*FPH, et. al. arXiv:1605.03120*

**Higgs (bouncing) inflation**,  

**Higgs portal dark matter**  
*FPH, et. al. arXiv:1704.04201*

**Neutrino mass and leptogenesis**  
\( \mathcal{O} = ll \)

**EW phase transition/baryogenesis**  
\( \mathcal{O} = \phi S, \phi\phi \)  
Motivation from wave
Post-GW Era

➢ The observation of GW by aLIGO has initiated a new era of exploring the nature of gravity, cosmology and the fundamental particle physics by GW.

➢ Obvious shortcomings in our understanding of particle cosmology (such as the DM and the baryon asymmetry of the universe), and no evidence of new physics at LHC may just point us GW approach.

➢ GW may be used to hear the echoes of EW symmetry breaking patterns, DM, baryogenesis…
Motivation from cosmology

EW phase transition

QCD phase transition
The nature of Higgs potential and the type of EW phase transition

- The true shape of Higgs potential (Exp: CEPC)
- Baryon asymmetry of the universe (baryogenesis)
- Gravitational wave (Exp: LISA 2034)
- Dark Matter blind spots, Asymmetry dark matter

Study of EW phase physics at CEPC and LISA helps to explore the evolution history of the universe at hundred GeV temperature.
Case I

Why my mass is so light compared to Planck mass??
Cosmological relaxation??

What is my potential??

Hi, I am Higgs boson! I have many questions?

Case II

Hi, Higgs! Let us help you to explore your confusion!

What is the my role in Baryon asymmetry of the universe??
Electroweak baryogenesis??

What is the my role in dark matter models??

Future lepton colliders (ILC,CEPC,FCC-ee)

Future Gravitational wave experiments (LISA)

Case III
EW phase transition GW becomes more interesting and realistic after the discovery of Higgs by LHC and GW by LIGO.

SFOPT can drive the plasma of the early universe out of thermal equilibrium, and bubbles nucleate during it, which will produce GW.

C. J. Hogan, Phys. Lett. B 133, 172 (1983);
Mechanisms of phase transition GW

For simplified cases, the GW spectrum depends on four parameters: $\alpha$, $\beta$, bubble wall velocity $v_b$ and the efficiency factor $\lambda$. (Explicitly, they depend on numerical simulations.)

Bubble collisions:

$$\Omega_{co}(f) h^2 \simeq 1.67 \times 10^{-5} \left( \frac{H_*}{\beta} \right)^2 \left( \frac{\lambda_{co} \alpha}{1 + \alpha} \right)^2 \left( \frac{100}{g^t_*} \right)^{1/3}$$

$$\times \left( \frac{0.11 v^3_b}{0.42 + v^3_b} \right) \left[ \frac{3.8(f/f_{co})^{2.8}}{1 + 2.8(f/f_{co})^{3.8}} \right].$$

Turbulence:

$$\Omega_{tu}(f) h^2 \simeq 3.35 \times 10^{-4} \left( \frac{H_*}{\beta} \right) \left( \frac{\lambda_{tu} \alpha}{1 + \alpha} \right)^{3/2} \left( \frac{100}{g^t_*} \right)^{1/3} v_b$$

$$\times \frac{(f/f_{tu})^3}{(1 + f/f_{tu})^{11/3} (1 + 8\pi f a_0/(a_* H_*))}.$$ 

Sound wave:

$$\Omega_{sw}(f) h^2 \simeq 2.65 \times 10^{-6} \left( \frac{H_*}{\beta} \right) \left( \frac{\lambda_{sw} \alpha}{1 + \alpha} \right)^2 \left( \frac{100}{g^t_*} \right)^{1/3} v_b$$

$$\times \left[ \frac{7(f/f_{sw})^{6/7}}{4 + 3(f/f_{sw})^2} \right]^{7/2},$$
EW baryogenesis in a nutshell

A long standing problem in particle cosmology is the origin of baryon asymmetry of the universe (BAU).

After the discovery of the Higgs boson by LHC and gravitational waves (GW) by aLIGO, electroweak (EW) baryogenesis becomes a timely and testable scenario for explaining the BAU.

\[ \eta_B = \frac{n_B}{n_\gamma} = 5.8 - 6.6 \times 10^{-10} \quad \text{(CMB, BBN)} \]
EW baryogenesis:
SM technically has all the three elements for baryogenesis, (Baryon violation, C and CP violation, Departure from thermal equilibrium or CPT violation) but not enough.

➢ B violation from anomaly in B+L current.
➢ CKM matrix, but too weak.
➢ strong first-order phase transition (SFOPT) with expanding Higgs Bubble wall.

SFOPT in extended Higgs sector motivated by baryogenesis or other new physics

From lattice simulation

SFOPT for $m_H < 75$ GeV

Cross over for $m_H > 75$ GeV

Extension of the Higgs sector can easily produce SFOPT even for 125 GeV Higgs boson.
I. Explore the Higgs potential by CEPC and LISA

From the current data, for the Higgs potential, we know nothing but the quadratic oscillation around the vev 246 GeV with the mass 125 GeV.

$$V(h) = \frac{1}{2} \mu^2 h^2 + \frac{\lambda}{4} h^4$$

or

$$V(h) = \frac{1}{2} \mu^2 h^2 - \frac{\lambda}{4} h^4 + \frac{1}{\Lambda^2} h^6$$

Leads to SFOPT


The Higgs sextic term can be induced from many renormalizable extension of the SM.

Current LHC has no ability to unravel the true potential of the Higgs boson, we need new experiments.

**Particle approach**
we can build more powerful colliders, such as planned CEPC/SppC, etc.

**Wave approach**
GW detectors can test Higgs potential as complementary approach. (LISA launch 2034)

Relate by EW phase transition

Double test on the Higgs potential
New Higgs potential and EW phase transition

For simplicity to investigate the signals from particle colliders to GW detector, we firstly use the effective Lagrangian (discuss renormalizable models later)

\[ V_{\text{tree}}(h) = \frac{1}{2} \mu^2 h^2 + \frac{\lambda}{4} h^4 + \frac{\kappa}{8 \Lambda^2} h^6 \]

To study the EW phase transition, we need to calculate the one-loop finite temperature effective potential using the finite temperature field theory:

\[ V_{\text{eff}}(h, T) = V_{\text{tree}}(h) + V_{1}^{T=0}(h) + \Delta V_{1}^{T \neq 0}(h, T) + V_{\text{daisy}} \]

C. Grojean, G. Servant, J. Well PRD71(2005)036001

Lots of discussions, sorry that I can’t cover all
SFOPT leads to obvious deviation of the tri-linear Higgs coupling

\[ \mathcal{L}_{hhh} = -\frac{1}{3!} (1 + \delta_h) A_h h^3 \]

At one-loop level, deviation of the tri-linear Higgs coupling

\[ \delta_h \in (0.6, 1.5) \]

The Circular Electron Positron Collider (CEPC), ILC, FCC-ee can precisely test this scenario by precise measurements of the hZ cross section \( (e^- e^+ \rightarrow hZ) \).


\[ \delta_\sigma = \frac{\sigma_{hZ}, \delta_h \neq 0}{\sigma_{hZ, SM}} - 1 \]
Correlate particle collider and GW signals: Double test on Higgs nature and baryogenesis from particle to wave

- For CEPC with $10ab^{-1}$ at $\sqrt{s} = 240$ GeV, precision of $\sigma_{zh}$ may be about 0.4% and can test the scenario.

- LISA, BBO, U-DECIGO are capable of detection.

- The study on EW phase transition naturally bridges the particle physics at collider with GW survey and baryogenesis.

**References:**
- FPH, et.al, Phys.Rev.D94(2016)no.4,041702
- Phys.Rev.D93 (2016) no.10,103515
Systematic study on this type of EW phase transition in general dimension-six effective operators from EW observables to future lepton collider

Testing electroweak phase transition in the scalar extension models at lepton colliders
Qing-Hong Cao, FPH, Ke-Pan Xie, Xinmin Zhang arXiv:1708.0473

In general, many other dim-6 operators would occur simultaneously which will make contributions to the EW precise observables. Through the following discussions, we can see that the Higgs sextic scenario still works well after considering all the dim-6 operators.

\[
\mathcal{L} \supset -\mu^2 |H|^2 - \lambda |H|^4 + c_6 |H|^6 + c_T \mathcal{O}_T + c_{WW} \mathcal{O}_{WW} + \text{other dimension-six operators}
\]

\[
\delta_{\sigma(hZ)} \approx (0.26 c_{WW} + 0.01 c_{BB} + 0.04 c_{WB} - 0.06 c_H - 0.04 c_T + 0.74 c^{(3)\ell}_L
\]

\[
+0.28 c^{(3)\ell}_{LL} + 1.03 c^\ell_L - 0.76 c^e_R) \times 1 \text{ TeV}^2 + 0.016 \delta_h.
\]

SFOPT produce large modification of tri-linear Higgs coupling \( \delta_h \) Thus, \( c_6 \) dominate the hZ cross section deviation.
Renormalizable realization from triplet model

The model with an $SU(2)_{L}$ triplet scalar without hypercharge $\Sigma(1,3,0)$

$$\delta \mathcal{L} = \text{Tr}[(D^\mu \Sigma)^\dagger D_\mu \Sigma] - M_\Sigma^2 \text{Tr}(\Sigma^2) - \zeta_\Sigma [\text{Tr}(\Sigma^2)]^2 + 2\xi_\Sigma H^\dagger \Sigma H - 2\kappa_\Sigma |H|^2 \text{Tr}(\Sigma^2)$$

Using the covariant derivative expansion (CDE) method, the matched dim-6 operators and their coefficients at one-loop level in triplet scalar models can be systematically obtained:

<table>
<thead>
<tr>
<th>Dimension-six operator</th>
<th>Wilson coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>$O_{WW} = g^2</td>
<td>H</td>
</tr>
<tr>
<td>$O_{2W} = -\frac{1}{2} (D^\mu W_{\mu \nu}^a)^2$</td>
<td>$c_{2W} = \frac{1}{(4\pi)^2} \frac{g^2}{30M_\Sigma^2}$</td>
</tr>
<tr>
<td>$O_{3W} = \frac{1}{3!} g \varepsilon^{abc} W_{\rho}^{a \mu} W_{\mu}^{b \nu} W_{\nu}^{c \rho}$</td>
<td>$c_{3W} = \frac{1}{(4\pi)^2} \frac{g^2}{30M_\Sigma^2}$</td>
</tr>
<tr>
<td>$O_H = \frac{1}{2} (\partial_\mu</td>
<td>H</td>
</tr>
<tr>
<td>$O_T = \frac{1}{2} (H^\dagger \bar{D}_\mu H)^2$</td>
<td>$c_T = \frac{\xi_\Sigma^2}{M_\Sigma^4} + \frac{1}{(4\pi)^2} \frac{10\xi_\Sigma \xi_\Sigma^2}{M_\Sigma^4}$</td>
</tr>
<tr>
<td>$O_r =</td>
<td>H</td>
</tr>
<tr>
<td>$O_6 =</td>
<td>H</td>
</tr>
</tbody>
</table>
The parameter space of triplet model (without hypercharge) that compatible with strong FOPT and current experiments including the future CEPC's prediction. Qing-Hong Cao, FPH, Ke-Pan Xie, Xinmin Zhang arXiv:1708.0473
Renormalizable realization of the from doublet model

\[ \delta \mathcal{L} = \mathcal{D}_\mu \Phi^\dagger \mathcal{D}^\mu \Phi - M^2_\Phi \Phi^\dagger \Phi - \frac{\lambda_\Phi}{4} (\Phi^\dagger \Phi)^2 - \lambda_1 \Phi^\dagger \Phi H^\dagger H - \lambda_2 |\Phi \cdot H|^2 \\
- \lambda_3 [(\Phi \cdot H)^2 + h.c.] + (\eta_H |H|^2 + \eta_\Phi |\Phi|^2)(\Phi \cdot H + h.c.) , \]

Using **CDE**, the matched dim-6 operators and their coefficients in the doublet scalar models are obtained:

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</tr>
</thead>
<tbody>
<tr>
<td>( \mathcal{O}_{WW} = g^2</td>
<td>H</td>
</tr>
<tr>
<td>( \mathcal{O}<em>{2W} = -\frac{1}{2} (\mathcal{D}^\mu W^a</em>{\mu \nu})^2 )</td>
<td>( c_{2W} = \frac{1}{(4\pi)^2} \frac{g^2}{60} \frac{1}{M^2_\Phi} )</td>
</tr>
<tr>
<td>( \mathcal{O}<em>{3W} = \frac{1}{3!} g</em>\varepsilon^{abc} W^a_{\rho \mu} W^b_{\nu \mu} W^c_{\nu \rho} )</td>
<td>( c_{3W} = \frac{1}{(4\pi)^2} \frac{g^2}{60} \frac{1}{M^2_\Phi} )</td>
</tr>
<tr>
<td>( \mathcal{O}_{BB} = g^2</td>
<td>H</td>
</tr>
<tr>
<td>( \mathcal{O}<em>{WB} = g g^\dagger H^\dagger \sigma^a H W^a</em>{\mu \nu} B^{\mu \nu} )</td>
<td>( c_{WB} = \frac{1}{(4\pi)^2} \frac{\lambda_1}{24} \frac{1}{M^2_\Phi} )</td>
</tr>
<tr>
<td>( \mathcal{O}_{2B} = -\frac{1}{2} (\partial^\mu B^{\mu \nu})^2 )</td>
<td>( c_{2B} = \frac{1}{(4\pi)^2} \frac{g^2}{60} \frac{1}{M^2_\Phi} )</td>
</tr>
<tr>
<td>( \mathcal{O}<em>H = \frac{1}{2} (\partial</em>\mu</td>
<td>H</td>
</tr>
<tr>
<td>( \mathcal{O}<em>T = \frac{1}{2} (H^\dagger \mathcal{D}</em>\mu H)^2 )</td>
<td>( c_T = \frac{1}{(4\pi)^2} \frac{1}{12} (\lambda^2_2 - 4\lambda^2_3) \frac{1}{M^2_\Phi} )</td>
</tr>
<tr>
<td>( \mathcal{O}_r =</td>
<td>H</td>
</tr>
<tr>
<td>( \mathcal{O}_6 =</td>
<td>H</td>
</tr>
</tbody>
</table>
The parameter space of doublet model that compatible with FOPT and current experiments including the future CEPC’s prediction with fixed $M_\Phi = 1$ TeV
Singlet model

\[ \delta \mathcal{L} = \frac{1}{2} \partial_\mu S \partial^\mu S - \frac{M_S^2}{2} S^2 - \frac{\mu_S}{3!} S^3 - \frac{\lambda_S}{4!} S^4 - \frac{\kappa_S}{2} S^2 |H|^2 - a_S S |H|^2 \]

\[ \mathcal{L}_{\text{eff}} \supset \left( - \frac{\kappa_S a_S^2}{2 M_S^4} - \frac{1}{(4\pi)^2} \frac{\kappa_S^3}{12 M_S^2} + \frac{\mu_S a_S^3}{3! M_S^6} \right) \mathcal{O}_6 + \left( \frac{a_S^2}{M_S^4} + \frac{1}{(4\pi)^2} \frac{\kappa_S^2}{12 M_S^2} \right) \mathcal{O}_H \]

(a) \( M_S = 1 \) TeV
II. Explore the Higgs nature in EW baryogenesis with dynamical CP violation by CEPC and LISA

Current electric dipole moment (EDM) experiments put severe constraints on many baryogenesis models. For example, the ACME Collaboration’s new result, i.e. $|d_e| < 1.1 \times 10^{-29}$ cm·e at 90% C.L. (Nature vol.562,357,18th Oct.2018), has ruled out a large portion of the CP violation parameter space for many baryogenesis models.

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

$$|d_e| \sim < 1 \times 10^{-29} \text{ (ACME 2018)}$$

Large enough CP-violating source for successful EW baryogenesis

Strong tension in most cases

How to alleviate this tension for successful baryogenesis?
**Question:** How to *alleviate* the tension between sufficient CP violation for successful electroweak baryogenesis and strong constraints from current EDM data?

**Answer:** Assume the CP violating coupling evolves with the universe. In the early universe, CP violation is large enough for successful baryogenesis. When the universe evolves to today, the CP violation becomes negligible!

Large enough CP-violating source in the early universe for successful EW baryogenesis

*alleviate* by assuming the CP-violating source is time dependent

Dynamical/cosmological evolve

Negligible CP-violating source at current time to avoid strong EDM constraints

• I. Baldes, T. Konstandin and G. Servant, arXiv:1604.04526,
• I. Baldes, T. Konstandin and G. Servant, JHEP 1612, 073 (2016)
• S. Bruggisser, T. Konstandin and G. Servant, JCAP 1711, no. 11, 034 (2017)
First, we study the following case as a representative example:

\[
\mathcal{L}_{\text{SM}} - y_t \frac{\eta}{\Lambda} S \bar{Q}_L \tilde{\Phi} t_R + \text{H.c.} + \frac{1}{2} \partial_\mu S \partial^\mu S + \frac{1}{2} \mu^2 S^2 - \frac{1}{4} \lambda S^4 - \frac{1}{2} \kappa S^2 (\tilde{\Phi}^+ \tilde{\Phi})
\]


Firstly, a second-order phase transition happens, the scalar field $S$ acquire a vacuum expectation value (VEV) and the dim-5 operator generates a sizable CP-violating top-Yukawa coupling for successful baryogenesis.

Secondly, SFOPT occurs when vacuum transits from $(0, \langle S \rangle)$ to $(\langle \Phi \rangle, 0)$.

1. During the SFOPT, detectable GW can be produced.
2. After the SFOPT, the VEV of $S$ vanishes at tree-level which avoids the strong EDM constraints, and produces abundant collider phenomenology at the LHC and future lepton colliders, such as CEPC, ILC, FCC-ee.

J. M. Cline and K. Kainulainen, JCAP 1301, 012 (2013)
- I. Baldes, T. Konstandin and G. Servant, arXiv:1604.04526,
- S. Bruggisser, T. Konstandin and G. Servant, JCAP 1711, no. 11, 034 (2017)

Second, we study a renormalizable model to achieve dynamical CP violation for the successful EW baryogenesis and $\mu$ discrepancy originating from the same coupling. work in progress with Eibun Senaha
Phase transition history in the early universe

To study the phase transition dynamics, we write the effective potential as a function of spatially homogeneous background scalar fields

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

\[ \Gamma / H^4 \big|_{T = T_N} \approx 1 \]

\[ \frac{S_3(T_N)}{T_N} = 4 \ln(T_N/100\,\text{GeV}) + 137 \]

\[ S_3 = \int d^3 r \left\{ \frac{1}{2} \left( \frac{dH}{dr} \right)^2 + \frac{1}{2} \left( \frac{d\sigma}{dr} \right)^2 + V_{\text{eff}}(H, \sigma, T) \right\} \]

\[ \bar{\varphi}(t) = (H(t), \sigma(t)) \]

\[ \frac{d^2 \varphi_b}{dr^2} + \frac{2}{r} \frac{d\varphi_b}{dr} = \frac{\partial V_{\text{eff}}}{\partial \varphi_b}, \quad \lim_{r \to \infty} \varphi_b = 0, \quad \left. \frac{d\varphi_b}{dr} \right|_{r=0} = 0. \]

\[ \tilde{\beta} = T_N \frac{d}{dT} \left( \frac{S_3(T)}{T} \right) \bigg|_{T = T_N} \quad \alpha = \frac{\varepsilon(T_N)}{\rho_{\text{rad}}(T_N)} \]

\[ \varepsilon(T) = -V_{\text{eff}}(\varphi_B(T), T) + T \frac{\partial V_{\text{eff}}(\varphi_B(T), T)}{\partial T} \]

\[ \rho_{\text{rad}}(T) = (\pi^2/30)g_*(T)T^4 \]
Benchmark points, which can give SFOPT and produce phase transition GWs

<table>
<thead>
<tr>
<th>Benchmark set</th>
<th>κ</th>
<th>$m_S$ [GeV]</th>
<th>$T_N$ [GeV]</th>
<th>$\alpha$</th>
<th>$\tilde{\beta}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>2.00</td>
<td>115</td>
<td>106.6</td>
<td>0.035</td>
<td>107</td>
</tr>
<tr>
<td>II</td>
<td>2.00</td>
<td>135</td>
<td>113.6</td>
<td>0.04</td>
<td>120</td>
</tr>
</tbody>
</table>

After the first step of phase transition, $S$ field obtains a VEV, and then the CP violating top quark Yukawa coupling is obtained. Thus, during the SFOPT, the top quark has a spatially varying complex mass

$$m_t(z) = \frac{y_t}{\sqrt{2}} H(z) \left( 1 + (1 + i) \frac{S(z)}{\Lambda} \right) \equiv |m_t(z)|e^{i\Theta(z)}$$

$$\eta_B = \frac{405 \Gamma_{sph}}{4\pi^2 \tilde{\nu}_b g_* T} \int d\zeta \mu_{B_L} f_{sph} e^{-45 \Gamma_{sph}|\zeta|/(4\tilde{\nu}_b)}$$
We choose reasonably small relative velocity $\tilde{v}_b \sim 0.2$, which is favored by the EW baryogenesis to guarantee a sufficient diffusion process in front of the bubble wall, and large enough bubble wall velocity $v_b \sim 0.5$ to produce stronger phase transition GW (Roughly speaking, for deflagration case, a larger bubble wall velocity gives stronger GW)

$$\tilde{v}_b(0.2) < v_b(0.5) < c_s(\sqrt{3}/3)$$


From the roughly numerical estimation, we see that the observed BAU can be obtained as long as $\Delta\sigma/\Lambda \sim 0.1 - 0.3$, where $\Delta\sigma$ is the change of $\sigma$ during the phase transition
Particle phenomenology induced by CP-violating top loop

After the SM Higgs obtains a VEV $v$ at the end of the phase transition, we have

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

The one-loop effective operators can be induced by covariant derivative expansion method

$$\mathcal{L}'_{SVV} = \frac{a \alpha_s}{12 \pi \Lambda} S G^a_{\mu \nu} G^{a \mu \nu} - \frac{b \alpha_s}{8 \pi \Lambda} S G^a_{\mu \nu} \tilde{G}^{a \mu \nu}$$

$$+ \frac{2a \alpha_{EW}}{9 \pi \Lambda} S F_{\mu \nu} F^{\mu \nu} - \frac{b \alpha_{EW}}{3 \pi \Lambda} S F_{\mu \nu} \tilde{F}^{\mu \nu}$$

Mixing for H and S from one-loop contribution
Abundant collider signals

Hadron collider:

\[ pp \rightarrow HS \]

Lepton collider (CEPC for example):

1. Direct search: ZS production recoiled muon pair mass distribution:

\[
\sigma(e^+e^- \rightarrow ZS) = \frac{G_F^2 m_Z^4}{96\pi s} (v_e^2 + a_e^2) |\mathcal{O}_{12}|^2 \sqrt{\frac{\lambda}{\lambda + 12m_Z^2/s}} \frac{1}{(1 - m_Z^2/s)^2}
\]

2. Indirect search: ZH cross section deviation from mixing and field strength renormalization:

\[
\mathcal{Z} = 1 + \frac{\kappa^2 v^2}{32\pi^2 m_H^2} \left( 1 - \frac{4m_S^2}{m_H^2} \right) \frac{1}{\sqrt{\frac{4m_S^2}{m_H^2} - 1}} \arctan \left( \sqrt{\frac{4m_S^2}{m_H^2} - 1} \right)
\]

So \( \sigma(e^+e^- \rightarrow HZ) \) will be rescaled by a factor \( |\mathcal{O}_{22}|^2 \mathcal{Z} \)
Current exclusion limit and future search sensitivity projected on \( \Lambda \) versus \( m_S \) plane. The regions below dotted blue lines have been excluded by EDM measurement; regions below dashed red lines have been excluded by collider scalar searches and Higgs data. In the left plot, regions below dash dotted olive lines can be observed from ZS production at 5 ab\(^{-1}\) CEPC with a C.L. higher than 5\(\sigma\). In the right plot, we show the ratio of ZH cross section with purple dash dotted contour lines.

N.B. Limit from EDM is much weaker than Higgs data, due to the fact the contributions to EDM in this scenario come from three-loop contributions.
The correlation between the future GW and collider signals

For example taking benchmark set I, the GW spectrum is represented by the black line, which can be detected by LISA and U-DECIGO. The black line also corresponds to $0.9339 \sigma_{SM}(HZ)$ of the HZ cross section for $e^+e^- \rightarrow HZ$ process and 115 GeV recoil mass with 13.6 fb cross section for the $e^+e^- \rightarrow SZ$ process, which has a 5σ discovery potential with 5 ab$^{-1}$ luminosity at CEPC.
Motivated by the absence of DM signal in DM direct detection (such as the LUX, PandaX-II, XENON1T), a generic classes of scalar DM models have been pushed to the blind spots where dark matter-Higgs coupling is very small. We use the complementary searches via phase transition GW and the future lepton collider signatures to un-blind the blind DM spots.

### Inert Doublet Models

$$V_0 = M_D^2 D^\dagger D + \lambda_D (D^\dagger D)^2 + \lambda_3 \Phi^\dagger \Phi D^\dagger D$$

$$+ \quad \lambda_4 |\Phi^\dagger D|^2 + (\lambda_5/2)[(\Phi^\dagger D)^2 + h.c.]$$

provide natural DM candidate

provide SFOPT and phase transition GW


FPH, Jiang-hao Yu, arXiv: 1704.04201
One-loop finite temperature effective potential

\[ V_{\text{eff}}(h, T) \approx \frac{1}{2} \left( - \mu^2 + c T^2 \right) h^2 + \frac{\lambda}{4} h^4 \]

- \[ \frac{T}{12\pi} \sum n_b (m_b^2(h, T))^{3/2} \]
- \[ \sum n_b \frac{m_b^4(h, T)}{64 \pi^2} \left[ \log \frac{m_b^2(h, T)}{T^2} - 5.408 \right] \]
- \[ n_t \frac{m_f^4(h)}{64 \pi^2} \left[ \log \frac{m_f^2(h)}{T^2} - 2.635 \right] \]

I. Thermally (BEC) Driven

**EW phase transition type in inert doublet model**

The two-loop finite temperature effective potential slightly weaken the strength of the phase transition. 

DM and FOPT favor Higgs funnel region

\[ \sigma_{\text{SI}} \approx f_N^2 \frac{\lambda_{hXX}^2}{\pi} \left( \frac{m_N^2}{m_\chi m_h^2} \right)^2 \]

Higgs funnel region: the DM mass is about half of the Higgs mass

Considering the above discussion, we take one set of benchmark points \( \lambda_3 = 2.84726 \), \( \lambda_4 = \lambda_5 = -1.41463 \) and \( M_D = 59.6 \text{ GeV} \). Then, the corresponding DM mass is 64 GeV, the pseudo scalar mass and the charged scalar mass are both 299.6 GeV, \( \lambda_{h\chi\chi} = \lambda_{345}/2 = 0.009 \).

\[ \lambda_{h\chi\chi} = \left( \lambda_3 + \lambda_4 + \lambda_5 \right)/2 = \lambda_{345}/2 \]

N.B.: Even though the Higgs-DM coupling are pretty small constrained from DM direct detection, the SFOPT can still be induced.
Correlate DM, particle collider and GW signals

- GW and CEPC detectors can explore the blind spots of DM
- The study naturally bridges the particle physics at collider with GW and DM.

We also study the mixed inert singlet-doublet and mixed inert singlet-triplet model in arXiv: 1704.04201 FPH, Jiang-hao Yu
Summary

➢ We studied three types of EW phase transition by extending the Higgs sector motivated from the Higgs potential, EW baryogenesis and DM, respectively. The Collider and GW signals and their correlation are investigated.

➢ Especially, the correlation between GW signal at LISA and collider signals at CEPC can make a double test on the Higgs nature including its true potential, and its roles in DM and EW baryogenesis.

Truth is always one

Thanks for your attention!