RGE effects on new physics search via gravitational waves

Katsuya Hashino (KOSEN/Fukushima Coll.)

Collaborators: Daiki Ueda (Technion)

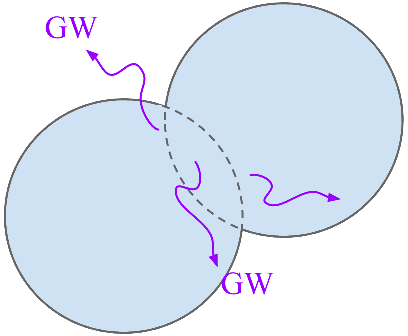
[K. H., Daiki Ueda, Phys.Rev.D 107 (2023) 9, 095022]

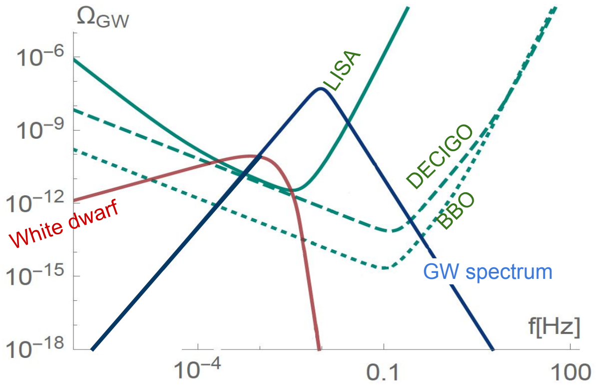
[K. H., Daiki Ueda, arXiv: 2505.13074, JHEP09(2025)094]

Introduction

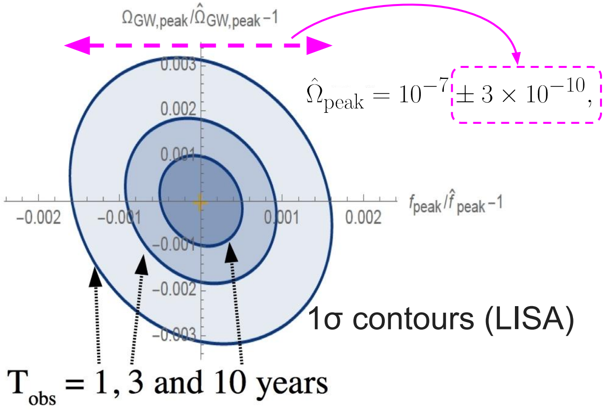
★ The gravitational waves (GWs) are produced by the first-order phase transition (FOPT).

GW observations can be used to explore the new physics (NP) effects for the first-order phase transition.





$\hat{\Omega}_{\rm peak} = 10^{-7}, \hat{f}_{\rm peak} = 10^{-2} Hz$



We can quantitatively discuss how precisely obtain the NP parameter at the GW observation by the Fisher matrix analysis.

Introduction

GW spectra depends on the new physics effects.

Expected uncertainties for GW spectra

$$\hat{\Omega}_{\rm peak} = 10^{-7} \pm 3 \times 10^{-10},$$

$$\hat{f}_{\rm peak} = 10^{-2} \pm 1.5 \times 10^{-5} Hz$$

Error propagation

Expected uncertainties for NP effects

$$\lambda_{\rm new} = 0.5 \pm 0.05$$

$$M_{\rm new} = 300 \pm 3 \text{ GeV}$$

＊Example

We can evaluate the width of confidence interval of the NP effects by GW observation.

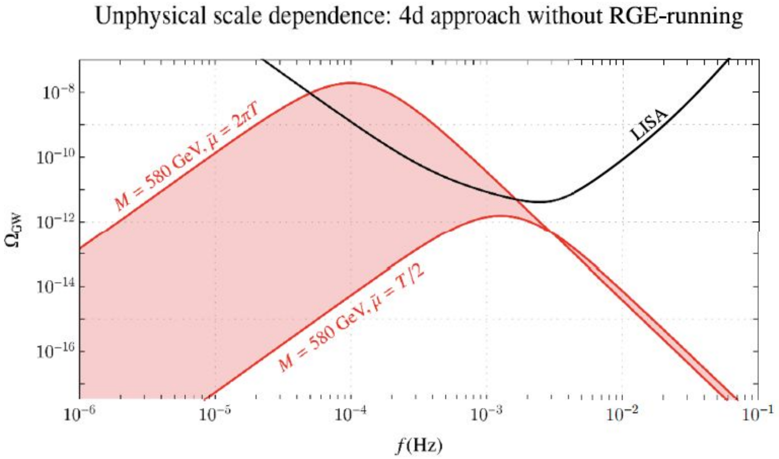
K. H., R. Jinno, M. Kakizaki, S. Kanemura, T. Takahashi and M. Takimoto, PRD 99 (2019) no.7, 075011,
K. H., Daiki Ueda, Phys.Rev.D 107 (2023) 9, 095022

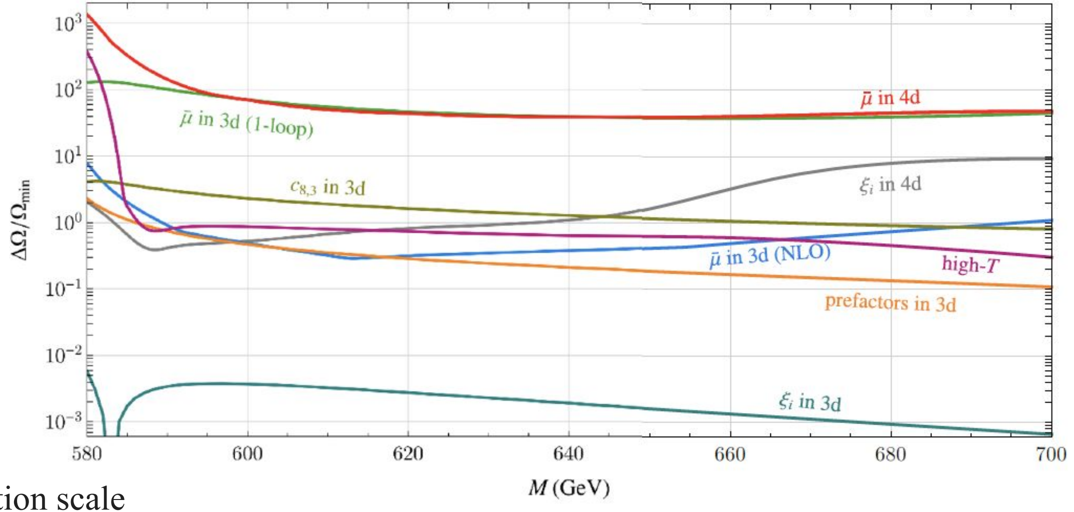
Theoretical uncertainties

★ However, the GW spectra have some theoretical uncertainties...

[D. Croon, O. Gould, P. Schicho, T. V. I. Tenkanen and G. White, JHEP 04 (2021), 055]

$\Delta\Omega_{\rm GW}/\Omega_{\rm GW}$	4d approach	3d approach
RG scale dependence	$\mathcal{O}(10^2 - 10^3)$	$\mathcal{O}(10^0 - 10^1)$
Gauge dependence	$\mathcal{O}(10^1)$	$\mathcal{O}(10^{-3})$
High-T approximation	$\mathcal{O}(10^{-1} - 10^0)$	$\mathcal{O}(10^0 - 10^2)$
Higher loop orders	unknown	$\mathcal{O}(10^0 - 10^1)$
Nucleation corrections	unknown	$\mathcal{O}(10^{-1} - 10^0)$
Nonperturbative corrections	unknown	unknown





$$V_{\rm tree}(\phi) = \mu_h^2\,\phi^\dagger\phi + \lambda\,(\phi^\dagger\phi)^2 + \frac{1}{M^2}(\phi^\dagger\phi)^3$$

$\bar{\mu}$: Renormalization scale

The uncertainties have been highlighted using the Standard Model Effective Field Theory (SMEFT) as a benchmark.

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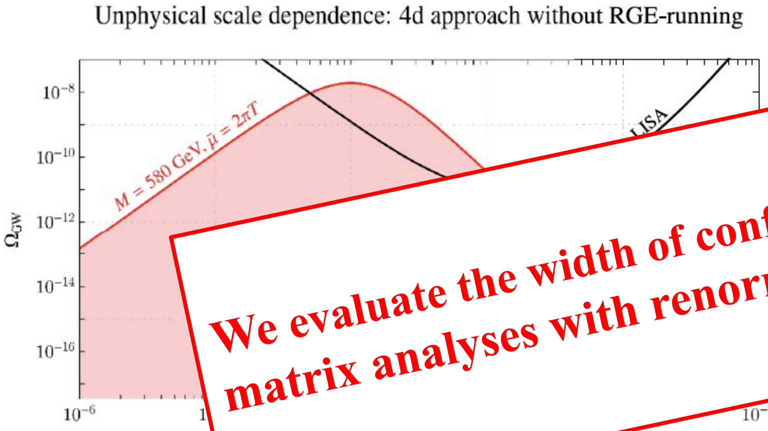
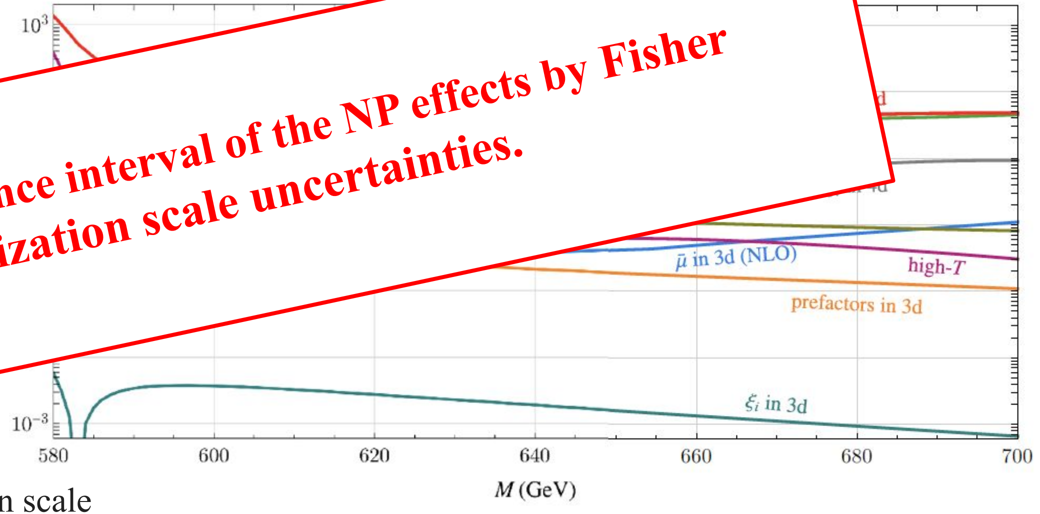
Nucleation corrections	[illegible]	$\mathcal{O}(10^{-1} - 10^0)$
Nonperturbati[illegible]	[illegible]	unknown





We evaluate the width of confidence interval of the NP effects by Fisher matrix analyses with renormalization scale uncertainties.

$$V_{\rm tree}(\phi) = \mu_h^2\, \phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2 + \frac{1}{M^2}(\phi^\dagger\phi)^3$$

$\bar{\mu}$: Renormalization scale

The uncertainties have been highlighted using the Standard Model Effective Field Theory (SMEFT) as a benchmark.

Benchmark model (SMEFT)

SMEFT
- The first-order phase transition
- Theoretical uncertainties

We adopt the SMEFT as a benchmark.

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i C_i \mathcal{O}_i$$

These operators can describe various NP effects in a model-independent manner.

X^3	
$\mathcal{O}_W$	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

H^6 and H^4D^2	
$\mathcal{O}_H$	$(H^\dagger H)^3$
$\mathcal{O}_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
$\mathcal{O}_{HD}$	$(H^\dagger D_\mu H)^* (H^\dagger D_\mu H)$

$\psi^2 H^3 + \text{h.c.}$	
$\mathcal{O}_{uH}$	$(H^\dagger H)(\bar q_p u_r \widetilde H)$

X^2H^2	
$\mathcal{O}_{HG}$	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$
$\mathcal{O}_{H\widetilde G}$	$H^\dagger H\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$
$\mathcal{O}_{HW}$	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$
$\mathcal{O}_{H\widetilde W}$	$H^\dagger H\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$
$\mathcal{O}_{HB}$	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$\mathcal{O}_{H\widetilde B}$	$H^\dagger H\, \widetilde B_{\mu\nu} B^{\mu\nu}$
$\mathcal{O}_{HWB}$	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$
$\mathcal{O}_{H\widetilde W B}$	$H^\dagger \tau^I H\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$

$\psi^2 X H + \text{h.c.}$	
$\mathcal{O}_{uG}$	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde H\, G^A_{\mu\nu}$
$\mathcal{O}_{uW}$	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde H\, W^I_{\mu\nu}$
$\mathcal{O}_{uB}$	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde H\, B_{\mu\nu}$

$\psi^2 H^2 D$	
$\mathcal{O}^{(3)}_{Hl}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar l_p \tau^I \gamma^\mu l_r)$
$\mathcal{O}^{(1)}_{Hq}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar q_p \gamma^\mu q_r)$
$\mathcal{O}^{(3)}_{Hq}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar q_p \tau^I \gamma^\mu q_r)$
$\mathcal{O}_{Hu}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar u_p \gamma^\mu u_r)$

$(\bar L L)(\bar L L)$	
$\mathcal{O}_{ll}$	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$

$(\bar L L)(\bar R R)$	
$\mathcal{O}^{(1)}_{qu}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
$\mathcal{O}^{(8)}_{qu}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$

Benchmark model (SMEFT)

★ The GW spectra is evaluated by the effective potential at typical scales of the FOPT.

The vast number of SMEFT operators affect the potential.

X^3	
$\mathcal{O}_W$	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

H^6 and $H^4 D^2$	
$\mathcal{O}_H$	$(H^\dagger H)^3$
$\mathcal{O}_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
$\mathcal{O}_{HD}$	$(H^\dagger D_\mu H)^* (H^\dagger D_\mu H)$

$\psi^2 H^3$ + h.c.	
$\mathcal{O}_{uH}$	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$

$X^2 H^2$	
$\mathcal{O}_{HG}$	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$
$\mathcal{O}_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}^A_{\mu\nu} G^{A\mu\nu}$
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$\mathcal{O}_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
$\mathcal{O}_{HWB}$	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$
$\mathcal{O}_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}^I_{\mu\nu} B^{\mu\nu}$

$\psi^2 X H$ + h.c.	
$\mathcal{O}_{uG}$	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{H}\, G^A_{\mu\nu}$
$\mathcal{O}_{uW}$	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{H}\, W^I_{\mu\nu}$
$\mathcal{O}_{uB}$	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{H}\, B_{\mu\nu}$

$\psi^2 H^2 D$	
$\mathcal{O}^{(3)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
$\mathcal{O}^{(1)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
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$(\bar{L}L)(\bar{L}L)$	
$\mathcal{O}_{ll}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$

$(\bar{L}L)(\bar{R}R)$	
$\mathcal{O}^{(1)}_{qu}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
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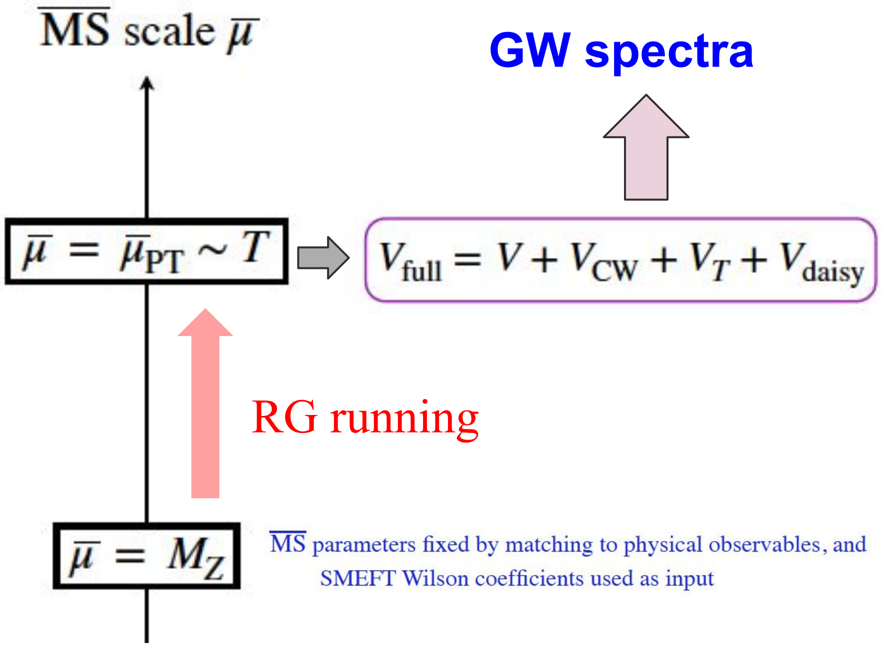
over 20 operators



★ In this work, we compare the GW spectra predicted by the effective potential at two different renormalization scales: $\bar{\mu}_{PT} = 2\pi T_n$ and $T_n/2$

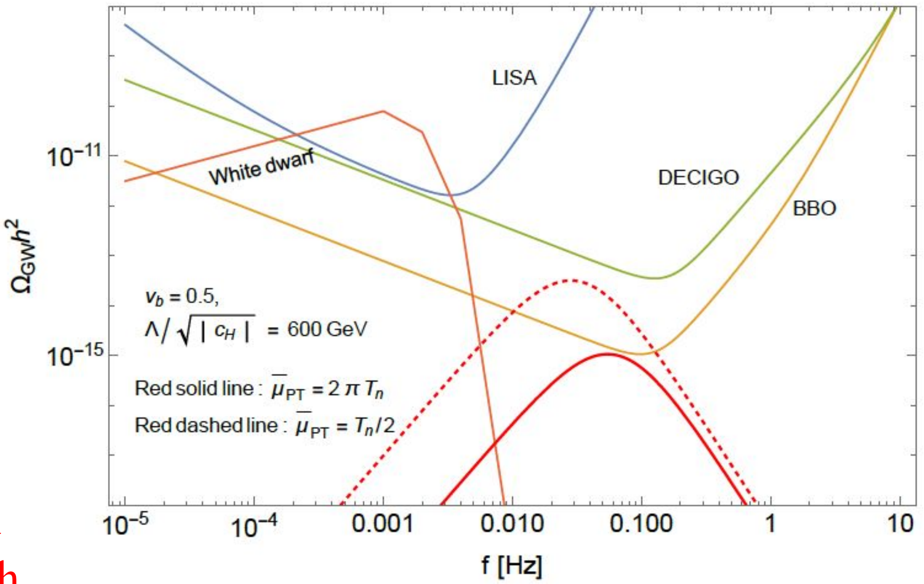
It is the source of first-order PT

The GW spctra

This Λ value is defined at Z boson mass scale.

★ If the value of $|C_H|$ is $1/\Lambda^2 = 1/(600\ \text{GeV})^2$, the GW spectra are given by right figure.

(All others are set to zero)



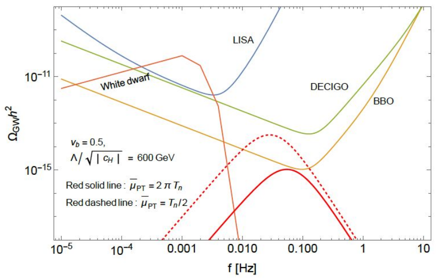
It is difficult to determine the value of C_H by only an observation of GW spectrum.

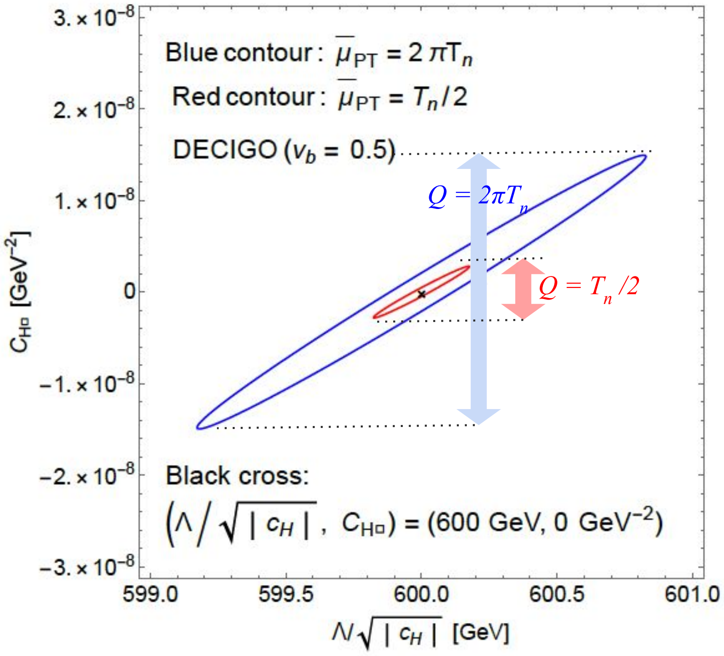
⬇

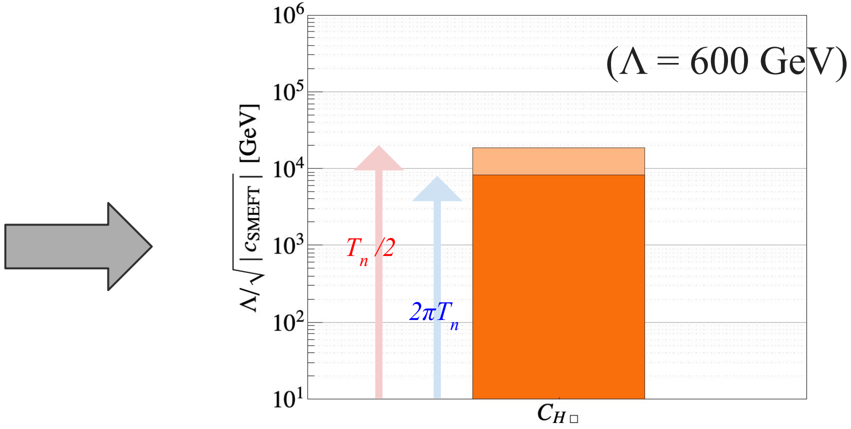
We assume that the value of C_H is provided by future collider experiments, e.g., FCC-hh.

The results

★ $1/\Lambda^2 = 1/(600\ \mathrm{GeV})^2$, $C_{H\Box}$, v_b= 0.5, and DECIGO experiment case







[K. H., Daiki Ueda, arXiv: 2505.13074, JHEP09(2025)094]

We also performed the analysis for different values of Λ, operators, velocities, and experiments.

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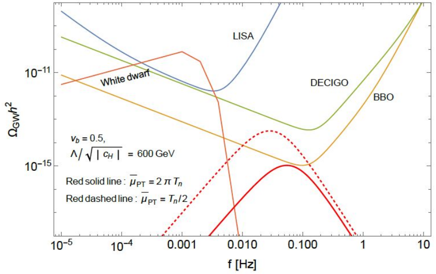
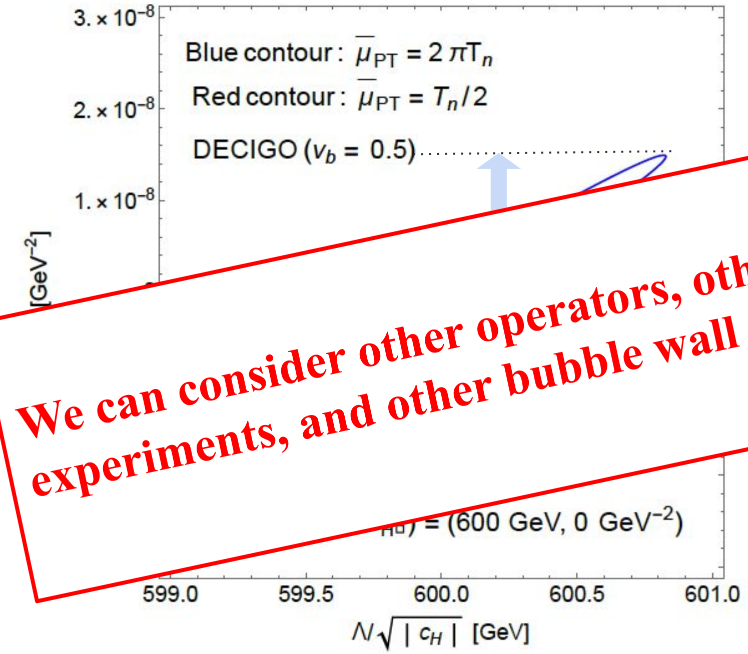
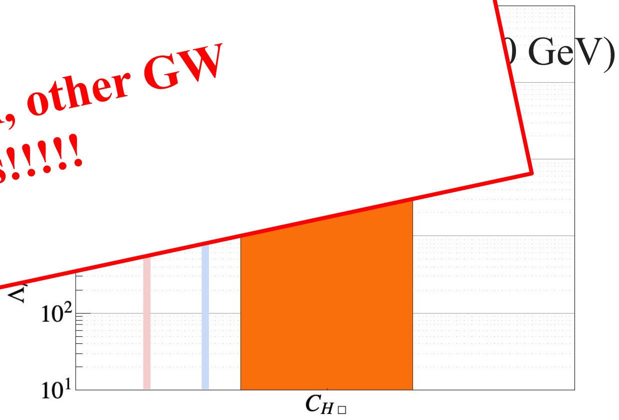




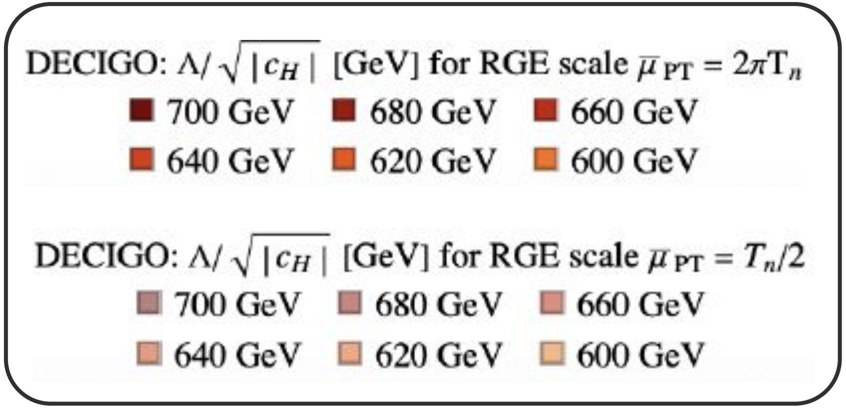


We can consider other operators, other value of Λ, other GW experiments, and other bubble wall velocity cases!!!!!

[K. H., Daiki Ueda, arXiv: 2505.13074, JHEP09(2025)094]

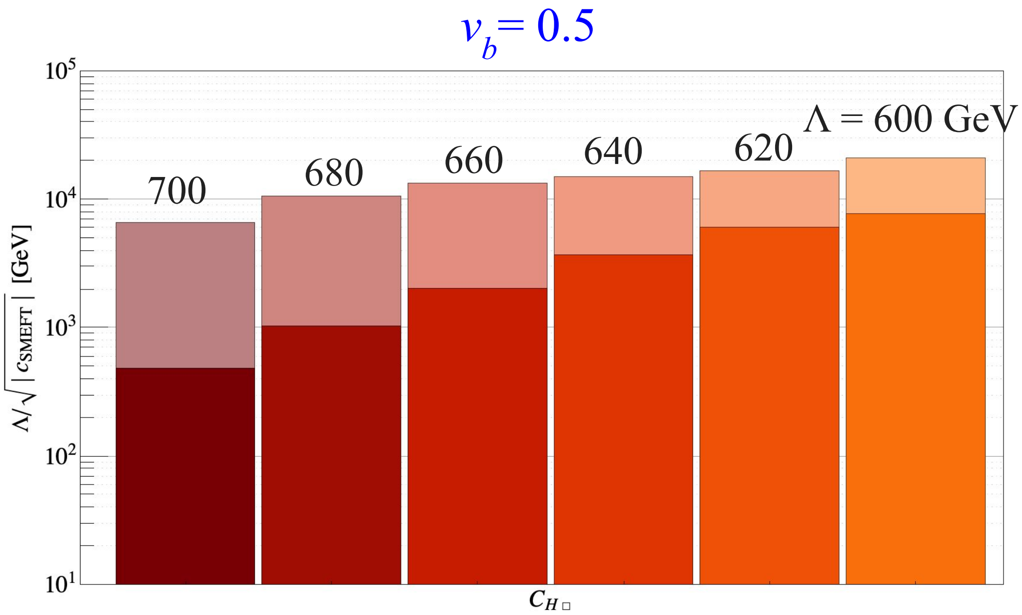
We also performed the analysis for different values of Λ, operators, velocities, and experiments.

Results(DECIGO)



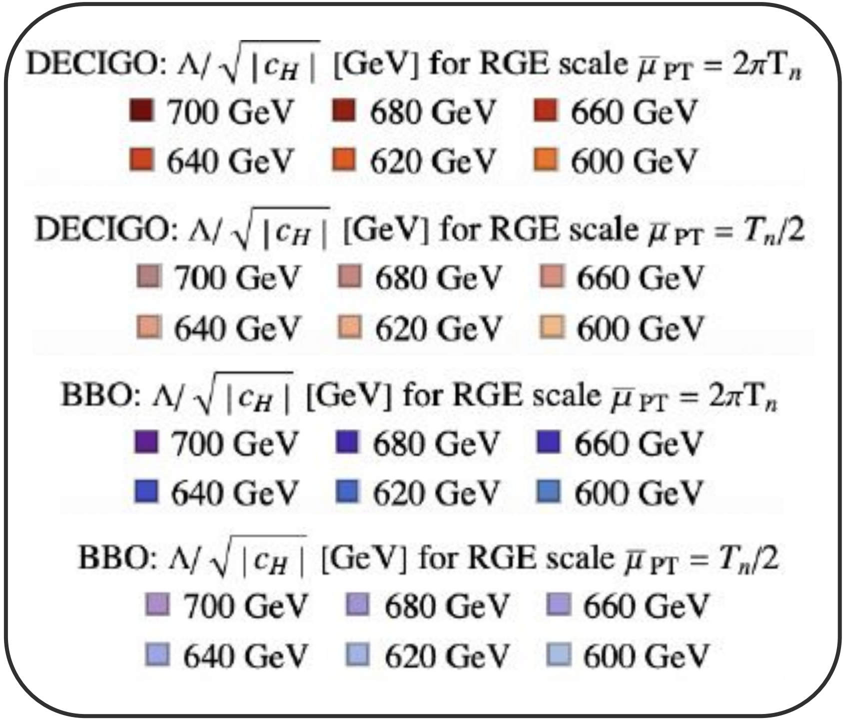
The dark- and light-colored bands represent the choices μPT = 2πTn and Tn/2, respectively,

Within each shade, different colors indicate different central values of |CH|.

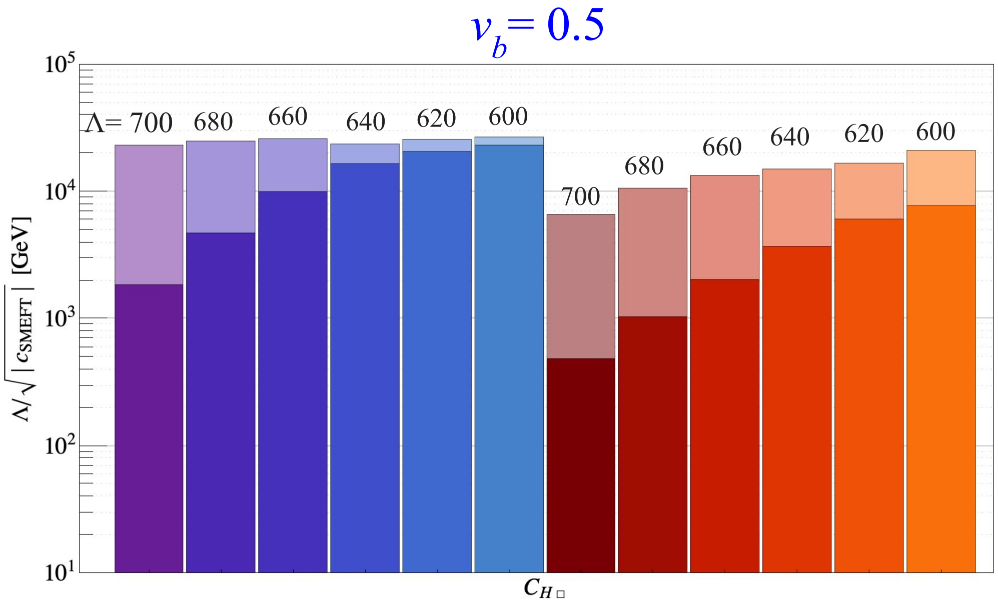


[K. H., Daiki Ueda, arXiv: 2505.13074, JHEP09(2025)094]

Results(DECIGO and BBO)



BBO (bluish bands) and DECIGO (reddish bands)



[K. H., Daiki Ueda, arXiv: 2505.13074, JHEP09(2025)094]

[K. H., Daiki Ueda, arXiv: 2505.13074, JHEP09(2025)094]

Other operators

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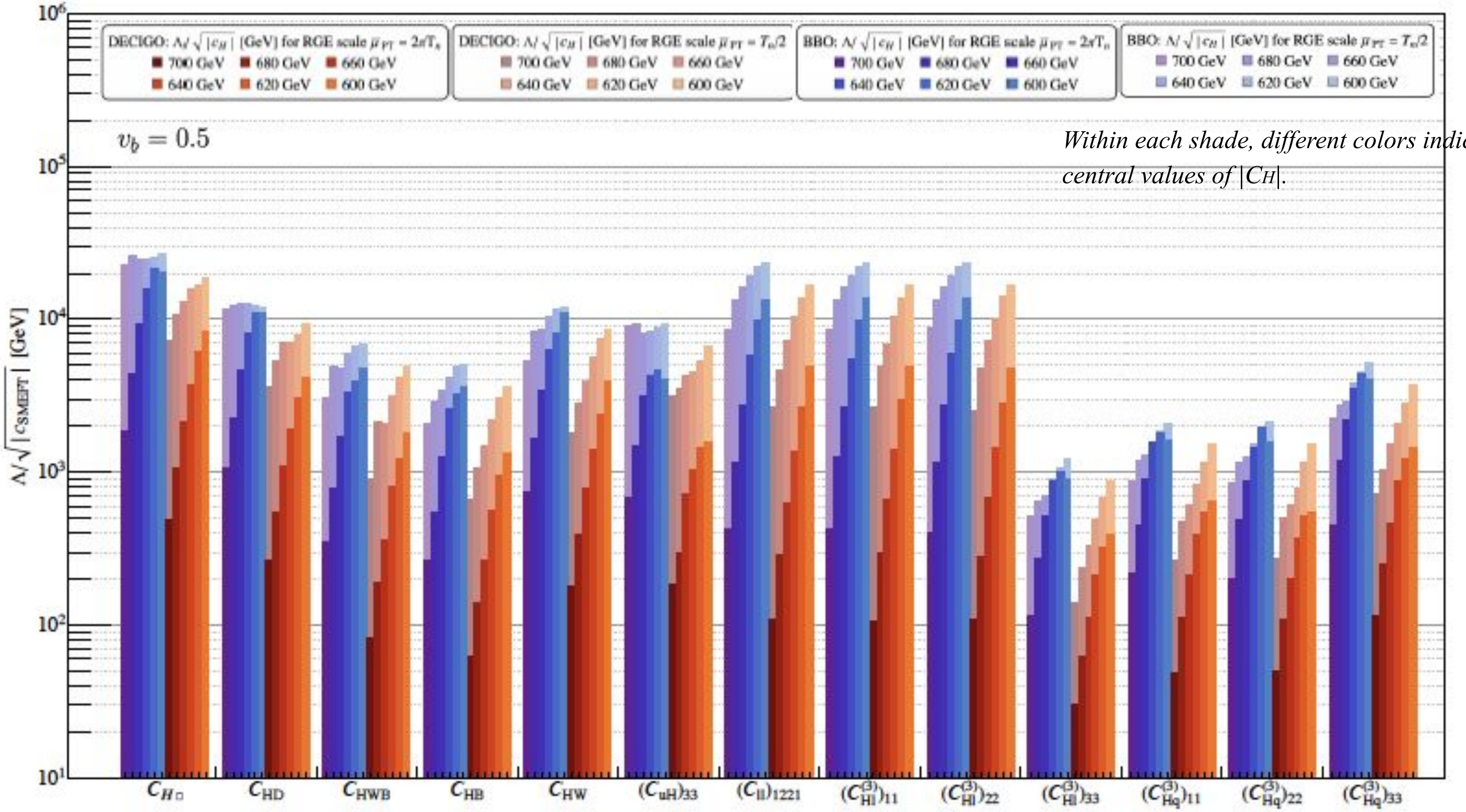
BBO (bluish bands) and DECIGO (reddish bands)

Within each shade, different colors indicate different central values of |CH|.



[K. H., Daiki Ueda, arXiv: 2505.13074, JHEP09(2025)094]

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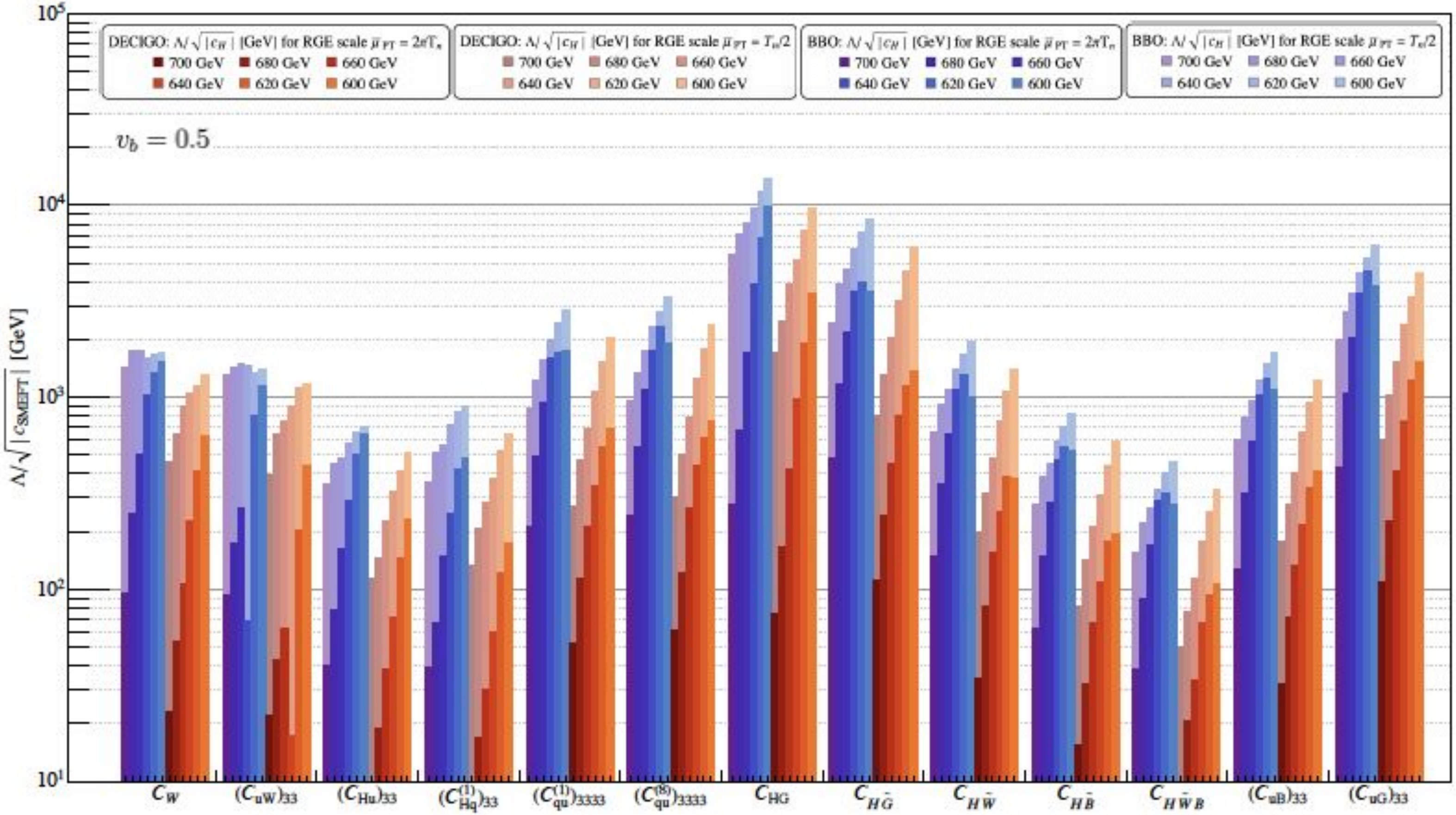
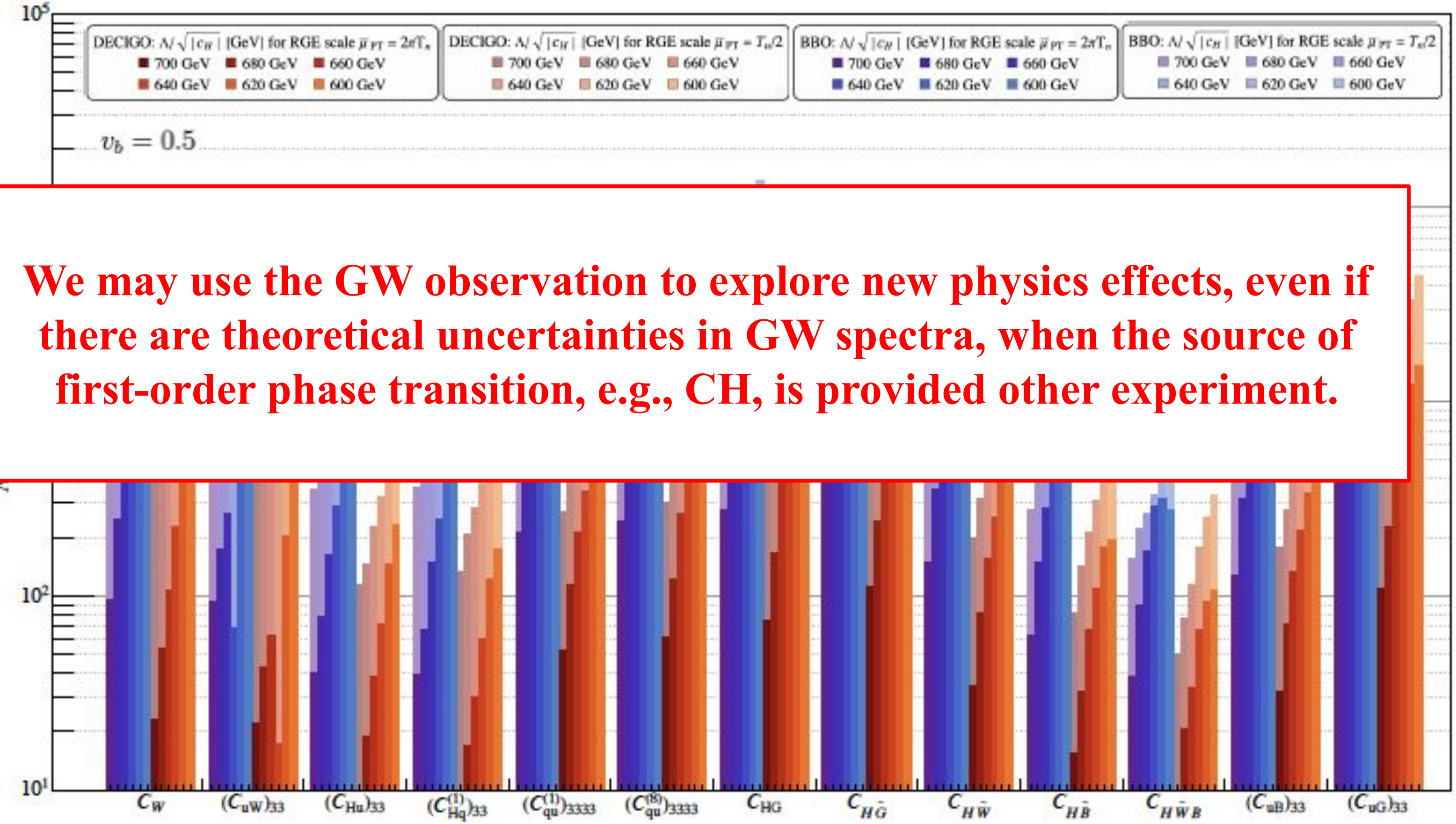


[K. H., Daiki Ueda, arXiv: 2505.13074, JHEP09(2025)094]

Other operators



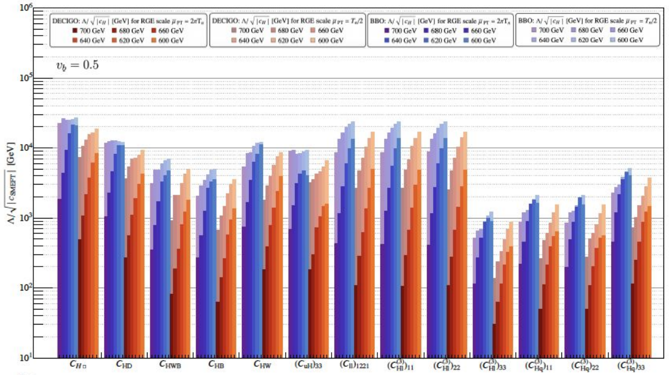
We may use the GW observation to explore new physics effects, even if there are theoretical uncertainties in GW spectra, when the source of first-order phase transition, e.g., CH, is provided other experiment.

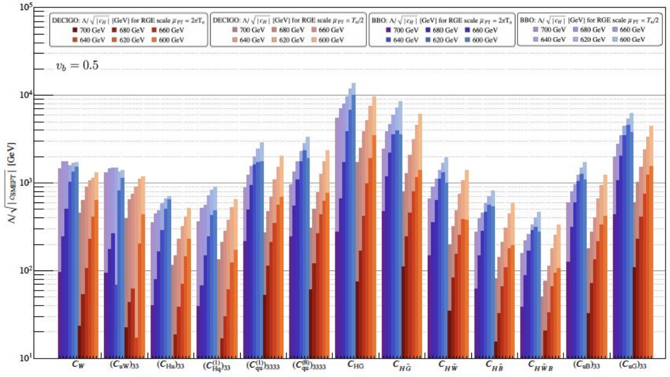
Summary

★ The spectra of GW from first-order phase transition depends on the NP effects.

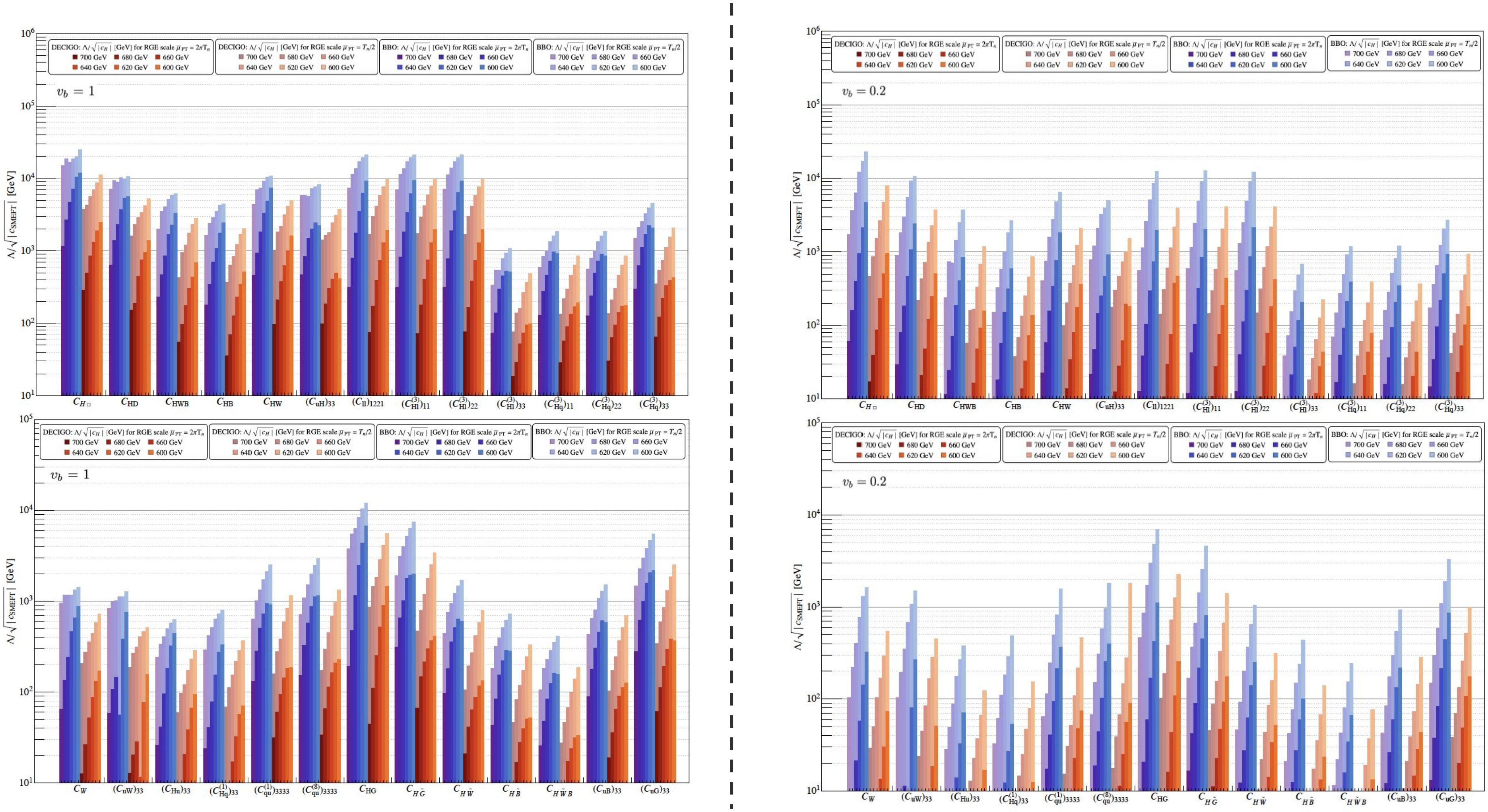
→ We can use the GW observation experiments to explore the NP effects.

★ The GW observations can remain sensitive to various new physics effects, even in the presence of renormalization scale uncertainties, provided that the source of first-order phase transition is precisely measured, e. g., by future collider experiments.



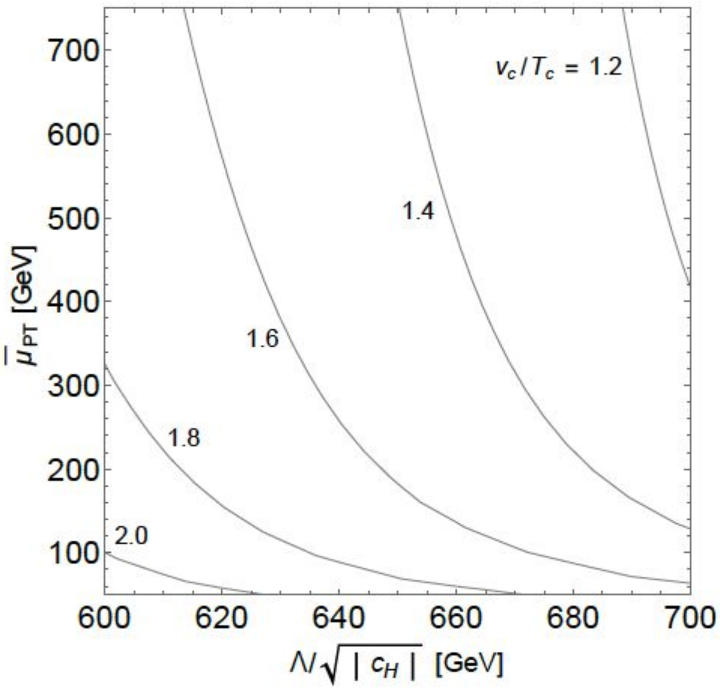


Backup

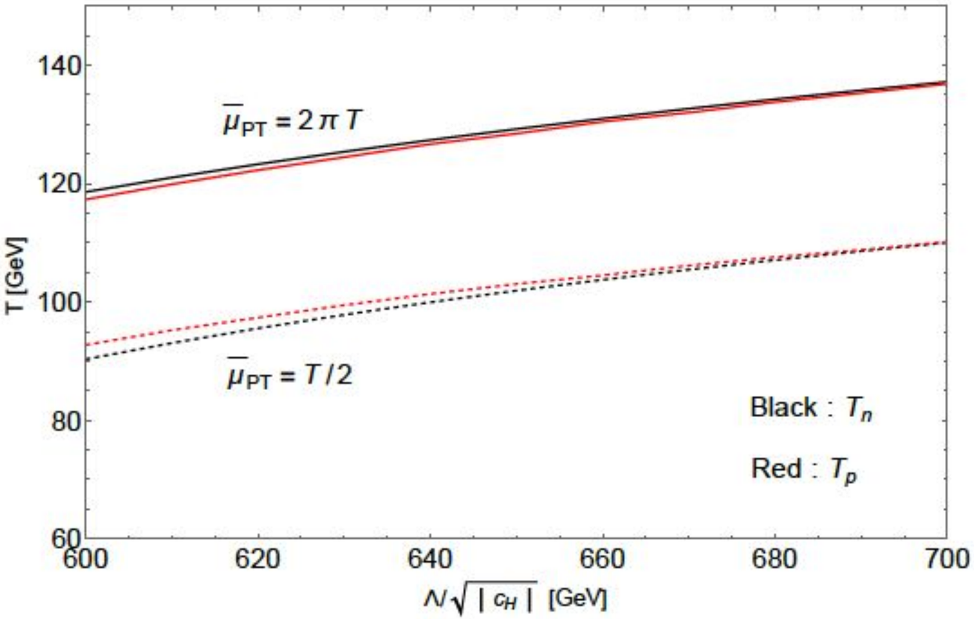


DECIGO: $\Lambda/\sqrt{|c_H|}$ [GeV] for RGE scale $\bar{\mu}_{PT} = 2\pi T_n$
DECIGO: $\Lambda/\sqrt{|c_H|}$ [GeV] for RGE scale $\bar{\mu}_{PT} = T_n/2$
BBO: $\Lambda/\sqrt{|c_H|}$ [GeV] for RGE scale $\bar{\mu}_{PT} = 2\pi T_n$
BBO: $\Lambda/\sqrt{|c_H|}$ [GeV] for RGE scale $\bar{\mu}_{PT} = T_n/2$
700 GeV 680 GeV 660 GeV 640 GeV 620 GeV 600 GeV
$v_b = 1$
$v_b = 0.2$
$\Lambda/\sqrt{|c_{SMEFT}|}$ [GeV]
$C_{H\Box}$ C_{HD} C_{HWB} C_{HB} C_{HW} $(C_{uH})_{33}$ $(C_{ll})_{1221}$ $(C^{(3)}_{Hl})_{11}$ $(C^{(3)}_{Hl})_{22}$ $(C^{(3)}_{Hl})_{33}$ $(C^{(3)}_{Hq})_{11}$ $(C^{(3)}_{Hq})_{22}$ $(C^{(3)}_{Hq})_{33}$
C_W $(C_{uW})_{33}$ $(C_{Hu})_{33}$ $(C^{(1)}_{Hq})_{33}$ $(C^{(1)}_{qu})_{3333}$ $(C^{(8)}_{qu})_{3333}$ C_{HG} $C_{H\tilde{G}}$ $C_{H\tilde{W}}$ $C_{H\tilde{B}}$ $C_{H\tilde{W}B}$ $(C_{uB})_{33}$ $(C_{uG})_{33}$

The results

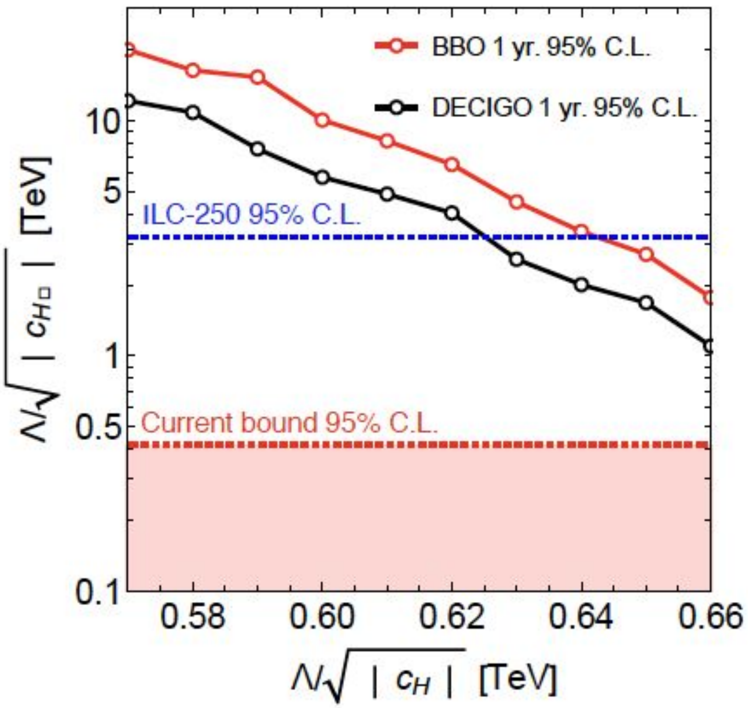


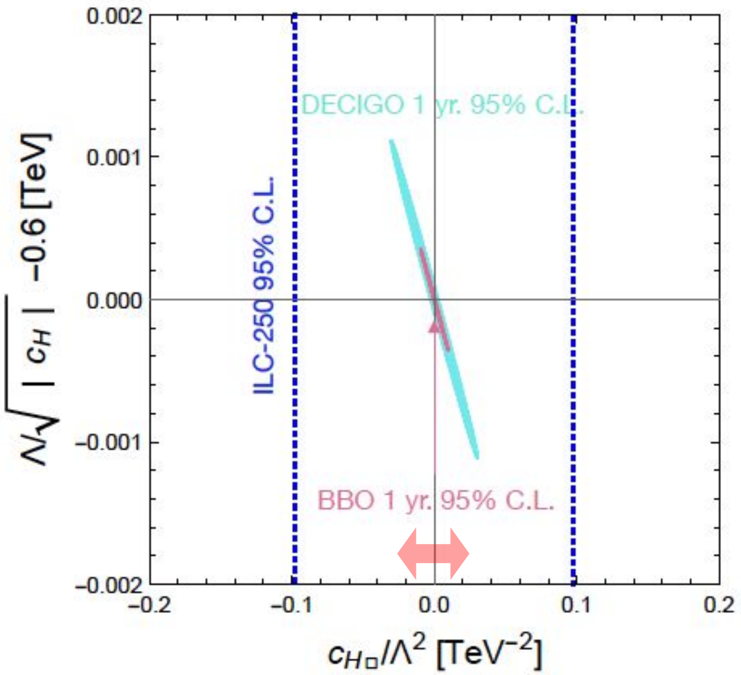
$v_c / T_c = 1.2$
1.4
1.6
1.8
2.0
$\overline{\mu}_{PT}$ [GeV]
$\Lambda/\sqrt{|c_H|}$ [GeV]



$\overline{\mu}_{PT} = 2\pi T$
$\overline{\mu}_{PT} = T/2$
Black : T_n
Red : T_p
T [GeV]
$\Lambda/\sqrt{|c_H|}$ [GeV]

The results



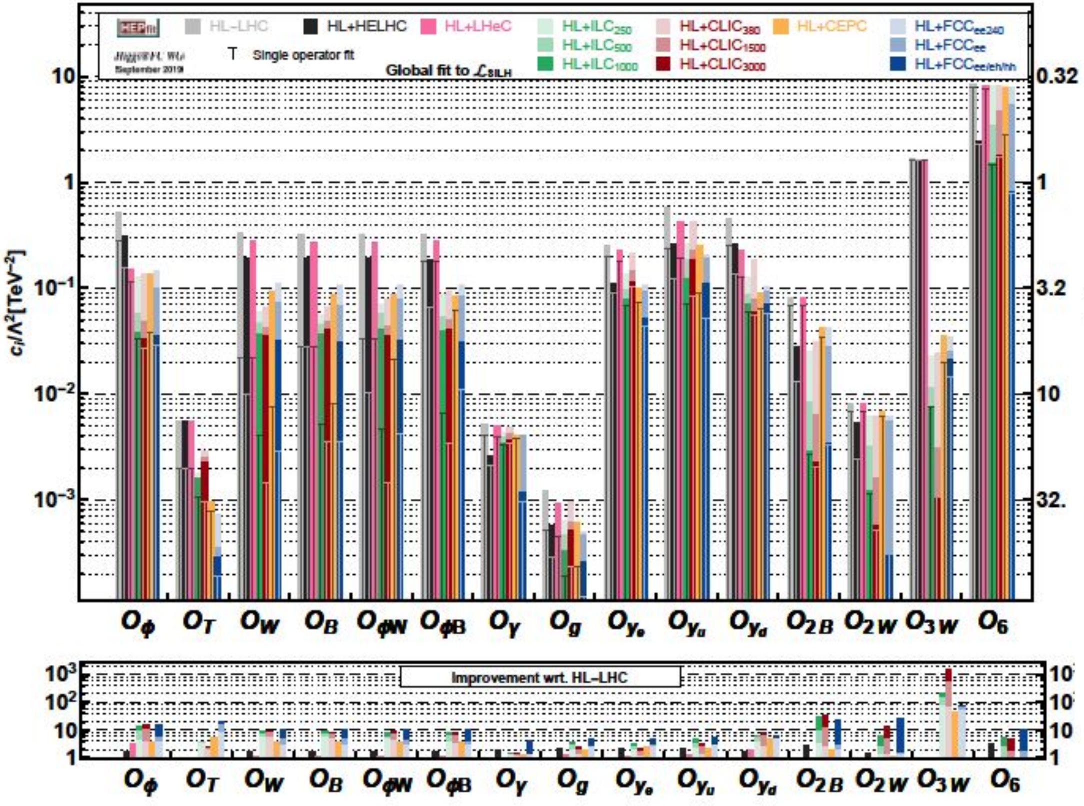


[K. H., Daiki Ueda, Phys.Rev.D 107 (2023) 9, 095022]

EFT (dim. 6)

J. de Blas, M. Cepeda, J. D'Hondt, R. K. Ellis, C. Grojean, B. Heinemann, F. Maltoni, A. Nisati, E. Petit and R. Rattazzi, et al., JHEP 01 (2020), 139 [arXiv:1905.03764 [hep-ph]].

1σ



$$\mathscr{L}_{\rm SILH} = \frac{c_\phi}{\Lambda^2}\frac{1}{2}\partial_\mu(\phi^\dagger\phi)\partial^\mu(\phi^\dagger\phi) + \frac{c_T}{\Lambda^2}\frac{1}{2}(\phi^\dagger \overleftrightarrow{D}_\mu\phi)(\phi^\dagger\overleftrightarrow{D}^\mu\phi) - \frac{c_6}{\Lambda^2}\lambda(\phi^\dagger\phi)^3 + \Big(\frac{c_{y_f}}{\Lambda^2}y^f_{ij}\phi^\dagger\phi\bar\psi_{Li}\phi\psi_{Rj}$$
$$+ \frac{c_W}{\Lambda^2}\frac{ig}{2}\left(\phi^\dagger\overleftrightarrow{D}^a_\mu\phi\right)D_\nu W^{a\,\mu\nu} + \frac{c_B}{\Lambda^2}\frac{ig'}{2}\left(\phi^\dagger\overleftrightarrow{D}_\mu\phi\right)\partial_\nu B^{\mu\nu} + \frac{c_{\phi W}}{\Lambda^2} ig D_\mu\phi^\dagger\sigma_a D_\nu\phi W^{a\,\mu\nu} +$$
$$+ \frac{c_\gamma}{\Lambda^2}g'^2\phi^\dagger\phi B^{\mu\nu}B_{\mu\nu} + \frac{c_g}{\Lambda^2}g_s^2\phi^\dagger\phi G^{A\,\mu\nu}G^A_{\mu\nu}$$
$$- \frac{c_{2W}}{\Lambda^2}\frac{g^2}{2}(D^\mu W^a_{\mu\nu})(D_\rho W^{a\,\rho\nu}) - \frac{c_{2B}}{\Lambda^2}\frac{g'^2}{2}(\partial^\mu B_{\mu\nu})(\partial_\rho B^{\rho\nu}) - \frac{c_{2G}}{\Lambda^2}\frac{g_S^2}{2}(D^\mu G^A_{\mu\nu})(D_\rho G^{A\,\rho\nu})$$
$$+ \frac{c_{3W}}{\Lambda^2}g^3\epsilon_{abc}W^{a\,\nu}_\mu W^{b\,\rho}_\nu W^{c\,\mu}_\rho + \frac{c_{3G}}{\Lambda^2}g_S^3 f_{ABC}G^{A\,\nu}_\mu G^{B\,\rho}_\nu G^{C\,\mu}_\rho,$$