Electroweak phase transition in the nearly aligned Higgs EFT

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Introduction

- Baryon asymmetry of the Universe $\frac{n_b - n_{\bar{b}}}{n_\gamma} = 5.8 - 6.5 \times 10^{-10}$ [PDG 2021]

[Sakharov, Pisma Zh.Eksp.Teor.Fiz. 5 (1967)]

Sakharov's condition

①Baryon # violation

②C and CP violation

③Departure from equilibrium

[Kuzmin, et al. : PLB155 (1985)]

- Electroweak baryogenesis (EWBG)

① Sphaleron process

② new CP phase in extended Higgs sectors

③ 1st order phase transition (1st OPT)

- EW phase transition in the SM is crossover

[Kajantie et al, Nucl. Phys. B493 (1997); Laine and Rummukainen, Nucl. Phys. B73 (1999)]

- CKM phase is not sufficient to explain the observed baryon asymmetry

[Gavela et al., Nucl. Phys. B430 (1994); Huet and Sather, PRD 51 (1995)]

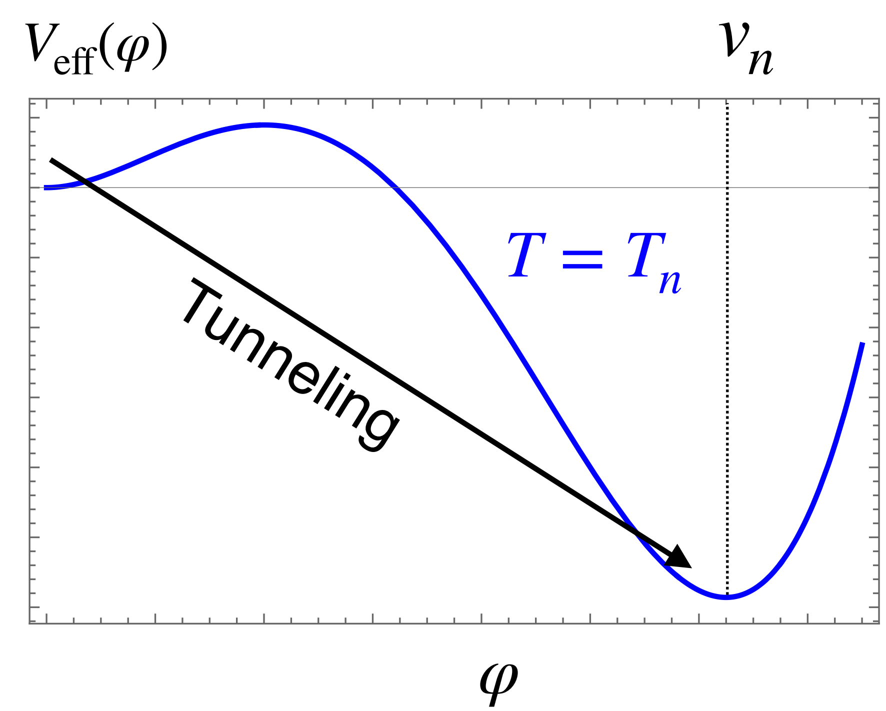
Extension of the Higgs sector is needed

Strongly 1st order phase transition

- Effective potential (High temperature expansion) [Anderson and Hall, PRD 45 (1992)]

$$V_{\rm eff}(\varphi, T) \simeq D(T^2 - T_0^2)\varphi^2 - ET\varphi^3 + \frac{\lambda(T)}{4}\varphi^4$$

Only boson loop contributions



- Strength of the 1st OPT:

$$\frac{v_n}{T_n} \sim \frac{v_c}{T_c} \sim \frac{2E}{\lambda(T_c)}$$

- Large E: extended Higgs models with non-decoupling quantum effects

[Kanemura, Okada and Senaha, PLB606 (2005)]

- Small λ: Standard model effective field theory (SMEFT)

[Grojean, Servant and Wells, PRD 71 (2005)]

- Sphaleron decoupling condition

$$\Gamma^{(b)}_{\rm sph}(T_n) < H_{\rm Hubble}(T_n) \quad \Rightarrow \quad \boxed{\frac{v_n}{T_n} > \zeta_{\rm sph}(T_n) \simeq 1}$$

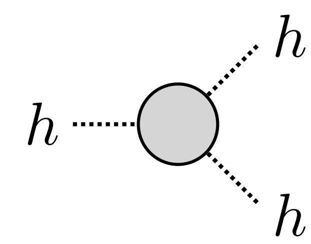
[Bochkarev et al., PRD 43 (1991)]

[Funakubo and Senaha, PRD 79 (2009)]

Non-decoupling effects in hhh coupling

- hhh coupling (effective potential approximation)

$$\left.\frac{\partial^3 V_{\rm eff}(\varphi)}{\partial \varphi^3}\right|_{\varphi=v} = \lambda_{hhh}^{\rm SM}\left(1+\frac{\Delta\lambda_{hhh}^{\rm new}}{\lambda_{hhh}^{\rm SM}}\right), \quad \Delta\lambda_{hhh}^{\rm new} = \lambda_{hhh}^{\rm new} - \lambda_{hhh}^{\rm SM}$$



Eg) Two Higgs doublet model (2HDM) [Kanemura et al.: PRD 70 (2004)] $m_\Phi^2 \simeq M^2 + \lambda_\Phi v^2$

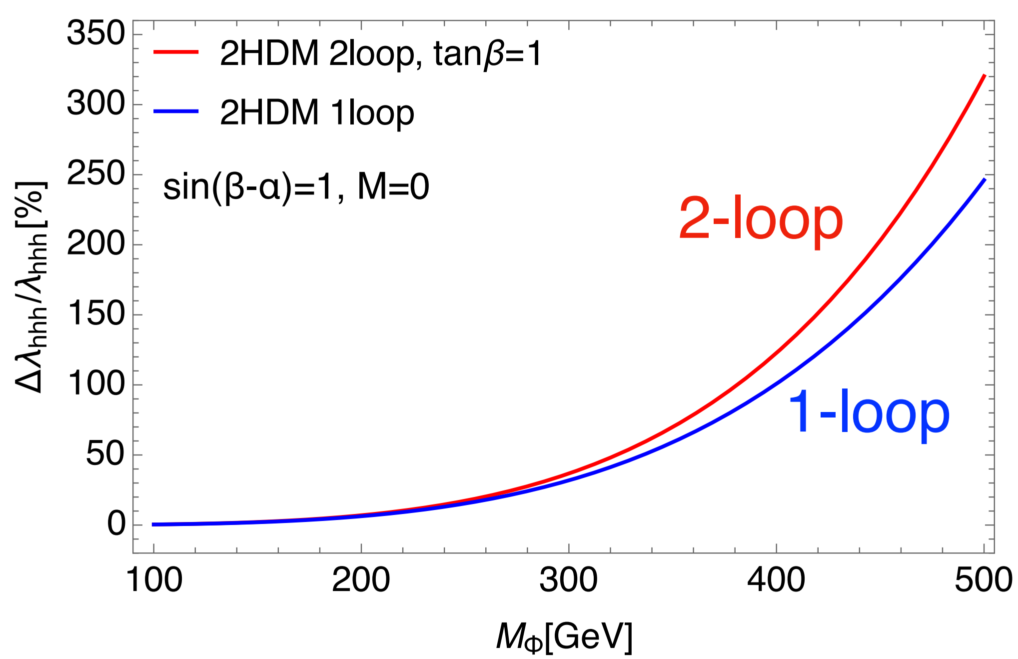
$$\frac{\Delta\lambda_{hhh}^{\rm 2HDM}}{\lambda_{hhh}^{\rm SM}} \simeq \sum_{\Phi=H,A,H^\pm} \frac{n_\Phi m_\Phi^4}{12\pi^2 m_h^2 v^2}\left(1-\frac{M^2}{m_\Phi^2}\right)^3 \simeq \begin{cases} \displaystyle\sum_\Phi \frac{n_\Phi \lambda_\Phi^3 v^4}{12\pi^2 m_h^2 m_\Phi^2} & (\lambda_\Phi v^2 \ll M^2) \\ \displaystyle\sum_\Phi \frac{n_\Phi m_\Phi^4}{12\pi^2 m_h^2 v^2} & (\lambda_\Phi v^2 \gtrsim M^2) \end{cases}$$

Non-decoupling

Two-loop correction is also calculated

[Braathen and Kanemura, PLB796 (2019)]

Large deviation in the hhh coupling appears via the non-decoupling effects

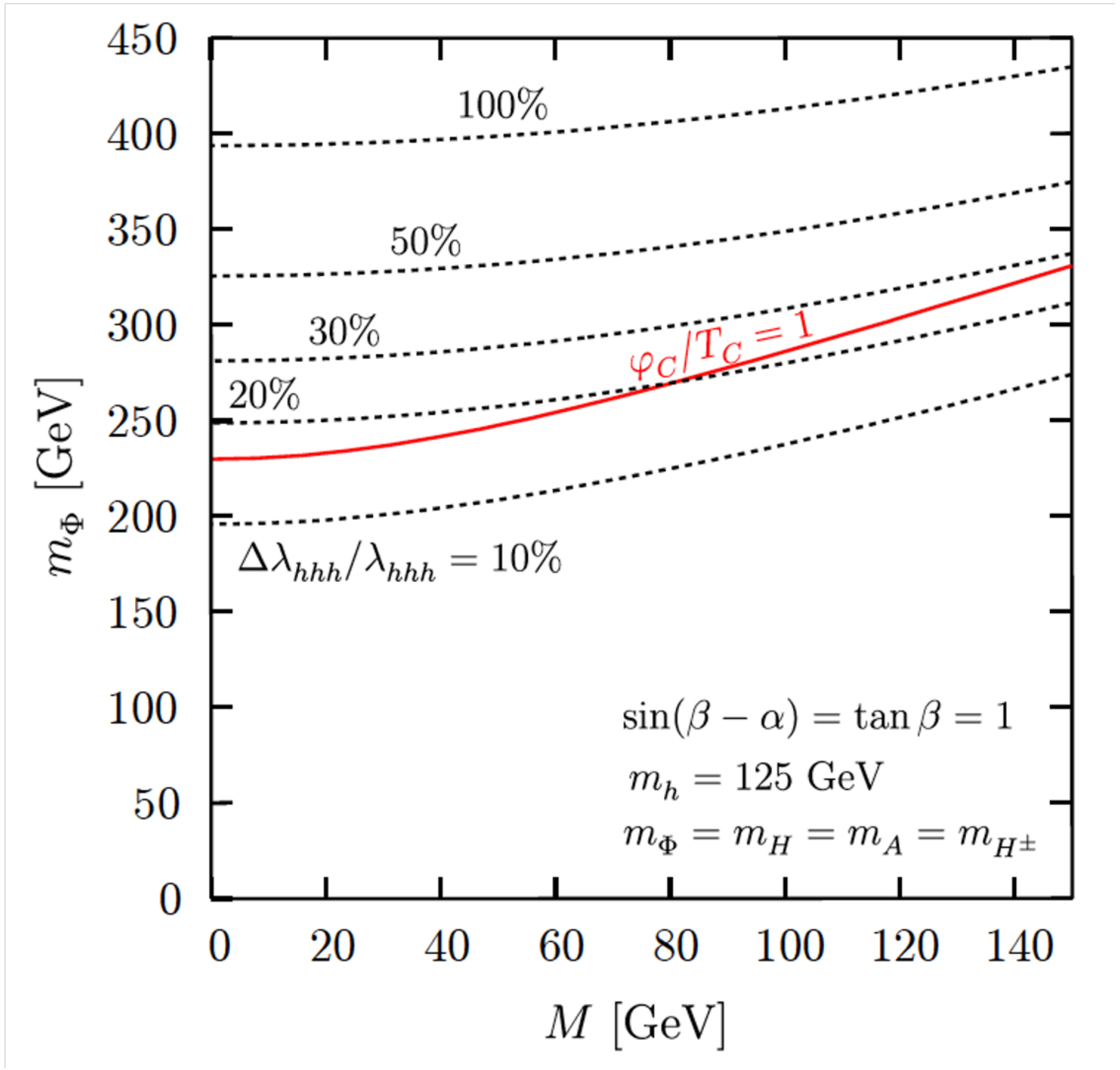


The strongly 1st OPT and hhh coupling

Large deviation in the hhh coupling is important to realize the strongly 1st OPT

[Grojean, Servant and Wells, PRD 71 (2005)], [Kanemura, Okada and Senaha, PLB606 (2005)]

Eg) Two Higgs doublet model (2HDM) [Kanemura, Okada and Senaha, PLB606 (2005)]



$$m_\Phi^2 \simeq M^2 + \lambda_\Phi v^2$$

Non-decoupling effects and new EFT

- Loop corrections to the effective potential [Coleman and Weinberg: PRD 7 (1973)]

$$V_{\mathrm{CW}}(\varphi) = \frac{[M^2(\varphi)]^2}{64\pi^2} \ln \frac{M^2(\varphi)}{Q^2}$$

Important to describe the non-decoupling effects

$$= \ln \frac{M^2}{Q^2} + \ln\left(1 + \frac{\lambda_\Phi \varphi^2}{M^2}\right)$$

- Assuming $M^2(\varphi) = M^2 + \lambda_\Phi \varphi^2$ with $M^2 \gg \lambda_\Phi v^2$

$$V_{\mathrm{CW}}(\varphi) \ni \frac{\lambda_\Phi^3}{64\pi^2 M^2}\varphi^6$$ $\Rightarrow$ SMEFT is good approximation

- In the case with $M^2 \lesssim \lambda_\Phi v^2$, we cannot expand V_{CW} in terms of φ

$\Rightarrow$ SMEFT is not appropriate to describe the non-decoupling effects

[Falkowski, Rattazzi, JHEP 10 (2019), Cohen et. al, JHEP 03 (2021)]

We need a new EFT framework → Nearly aligned Higgs EFT (naHEFT)

Nearly aligned Higgs EFT (naHEFT)

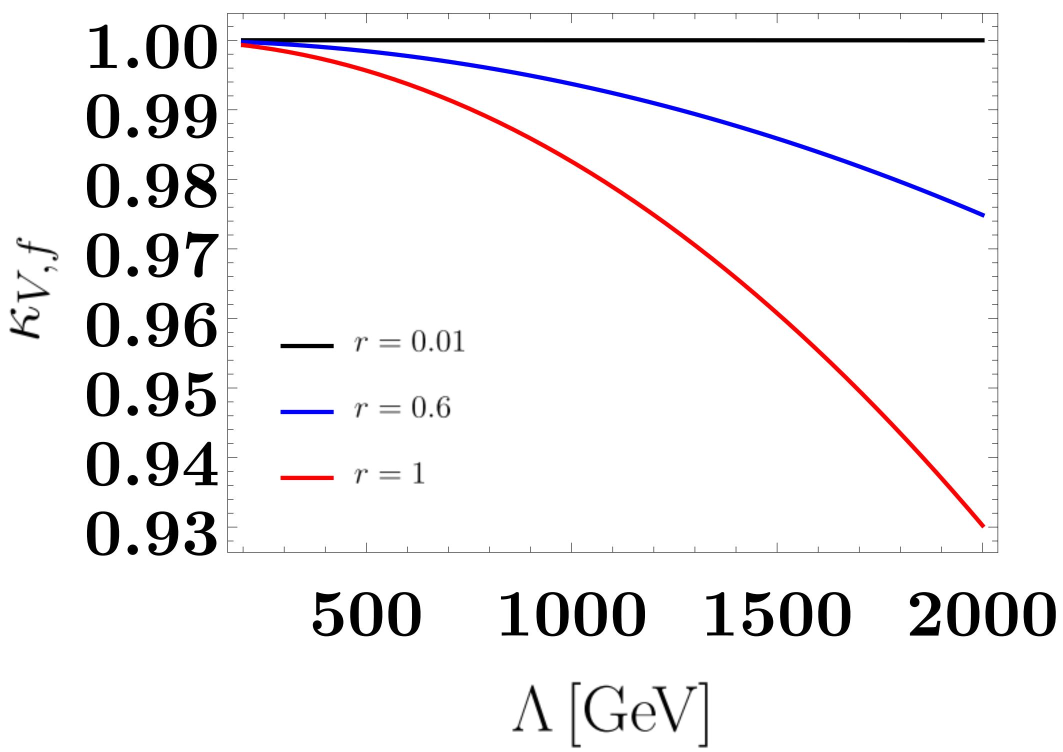
The naHEFT can describe the non-decoupling effects independent of models

[Kanemura and Nagai, JHEP 03 (2022)]

$$\mathcal{L}_{\rm BSM} = \frac{1}{(4\pi)^2}\Bigg[-\frac{\kappa_0}{4}\left[\mathcal{M}^2(h)\right]^2 \ln\frac{\mathcal{M}^2(h)}{\mu^2} + \frac{v^2}{2}\mathcal{F}(h)\,{\rm Tr}\left[D_\mu U^\dagger D^\mu U\right] + \frac{1}{2}\mathcal{K}(h)\left(\partial_\mu h\right)\left(\partial^\mu h\right) - v\left(\bar{q}^i_L U\left[\mathcal{Y}^{ij}_q(h) + \hat{\mathcal{Y}}^{ij}_q(h)\tau^3\right]q^j_R + h.c.\right) - v\left(\bar{l}^i_L U\left[\mathcal{Y}^{ij}_l(h) + \hat{\mathcal{Y}}^{ij}_l(h)\tau^3\right]l^j_R + h.c.\right)\Bigg]$$

$$U = \exp\left(\frac{i}{v}\pi^a\tau^a\right)$$

[Kanemura and Nagai, JHEP 03 (2022)]



$$\mathcal{M}^2(h),\ \mathcal{F}(h),\ \mathcal{K}(h),\ \mathcal{Y}^{ij}_\psi(h),\ \hat{\mathcal{Y}}^{ij}_\psi(h)$$

polynomial in terms of h

What is the meaning of “nearly aligned”?

The naHEFT can describe extended Higgs models without alignment ($\kappa_{V,f} \neq 1$)

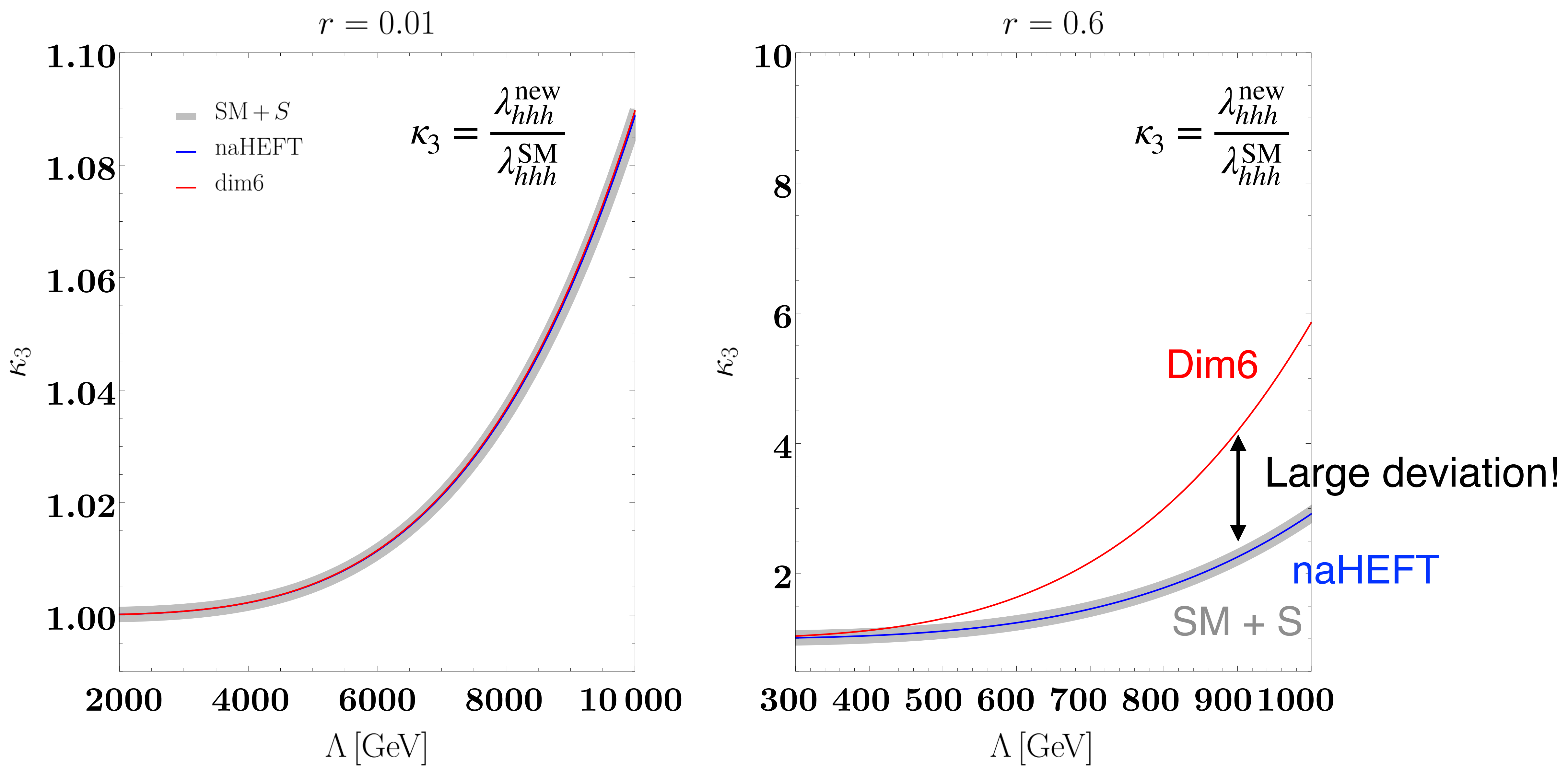
$$\kappa_V = \frac{g^{\rm new}_{hVV}}{g^{\rm SM}_{hVV}},\ \kappa_f = \frac{g^{\rm new}_{hff}}{g^{\rm SM}_{hff}}$$

naHEFT vs. SMEFT: hhh coupling

[Kanemura and Nagai, JHEP 03 (2022)]

Decoupling

Non-decoupling



$$\Lambda^2 = \mathcal{M}^2(h=0) = M^2 + \frac{\kappa_p}{2}v^2, \quad r = \frac{\kappa_p v^2}{2}/\Lambda^2$$

naHEFT at the finite temperature

- To discuss the phase transition, we extend the naHEFT

[Kanemura, Nagai and Tanaka, arXiv: 2202.12774]

$$V_{\mathrm{EFT}} = V_{\mathrm{SM}} + \frac{\kappa_0}{64\pi^2}\left[\mathcal{M}^2(\phi)\right]^2 \ln\frac{\mathcal{M}^2(\phi)}{\mu^2} + \underline{\frac{\kappa_0}{2\pi^2}T^4 J_{\mathrm{BSM}}\left(\frac{\mathcal{M}^2(\phi)}{T^2}\right)}$$

$$J_{\mathrm{BSM}}(a^2) = \int_0^\infty dk^2 k^2 \ln\left[1 - \mathrm{sign}\left(\kappa_0\right) e^{-\sqrt{k^2+a^2}}\right]$$

[Dolan and Jackiw, PRD9 (1974)]

For simplicity, we take $\mathcal{M}^2(\phi) = M^2 + \frac{\kappa_p}{2}\phi^2$

- Daisy resummation (We assume Parwani scheme)

[Carrington, PRD45 (1992)]

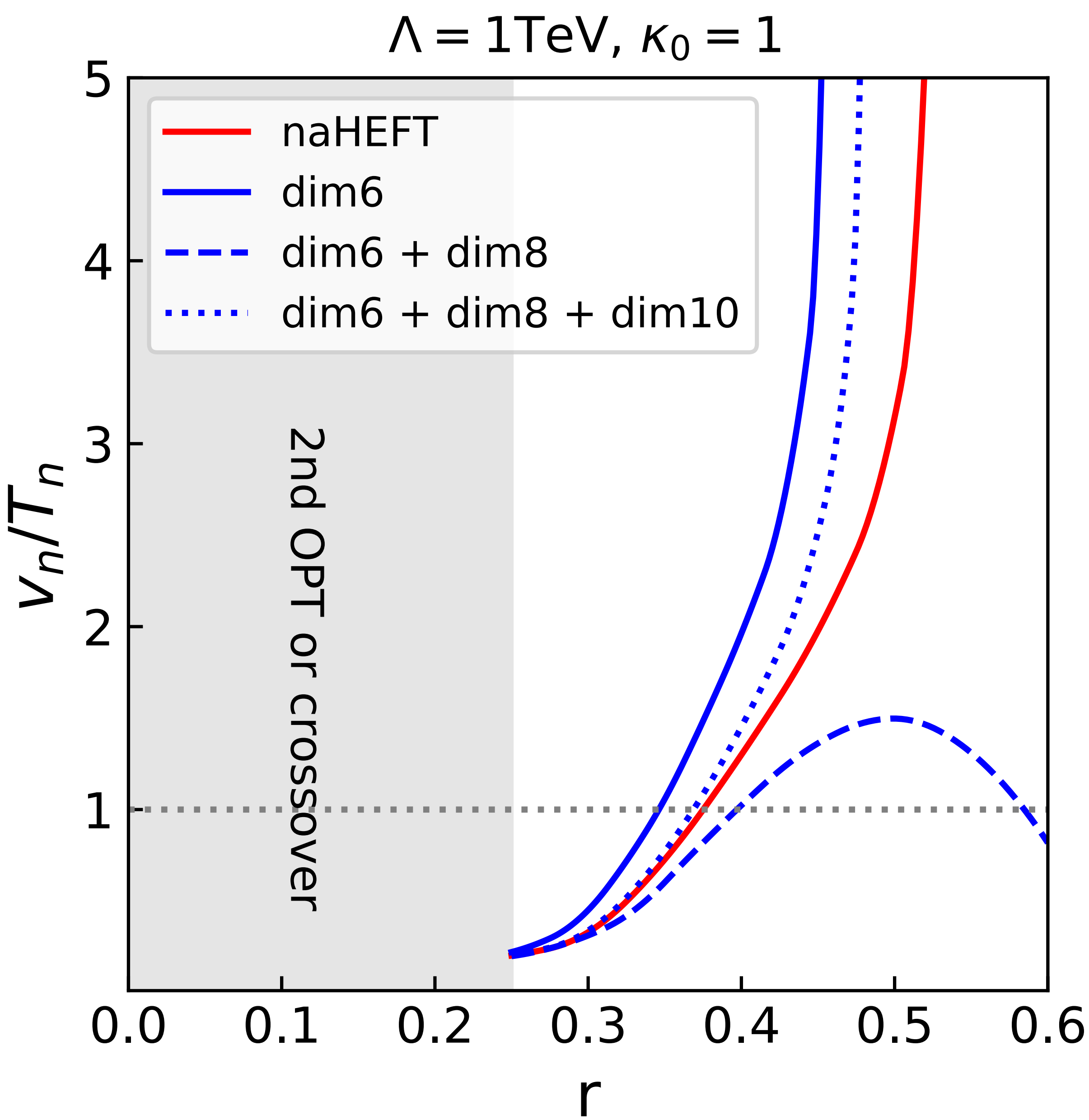
[Parwani, PRD45 (1992)]

$$\mathcal{M}^2(\phi) \to \mathcal{M}^2(\phi, T) = \mathcal{M}^2(\phi) + \Pi_{\mathrm{BSM}}(T), \quad \Pi_{\mathrm{BSM}} = \frac{c}{6}T^2$$

In this talk, we take $c = \kappa_p$

naHEFT vs. SMEFT at the finite temperature

[Kanemura, Nagai and Tanaka, arXiv: 2202.12774]



- Predictions on v_n/T_n are significantly different between SMEFT and naHEFT

- When we add higher dim. operators, the predictions on v_n/T_n is similar

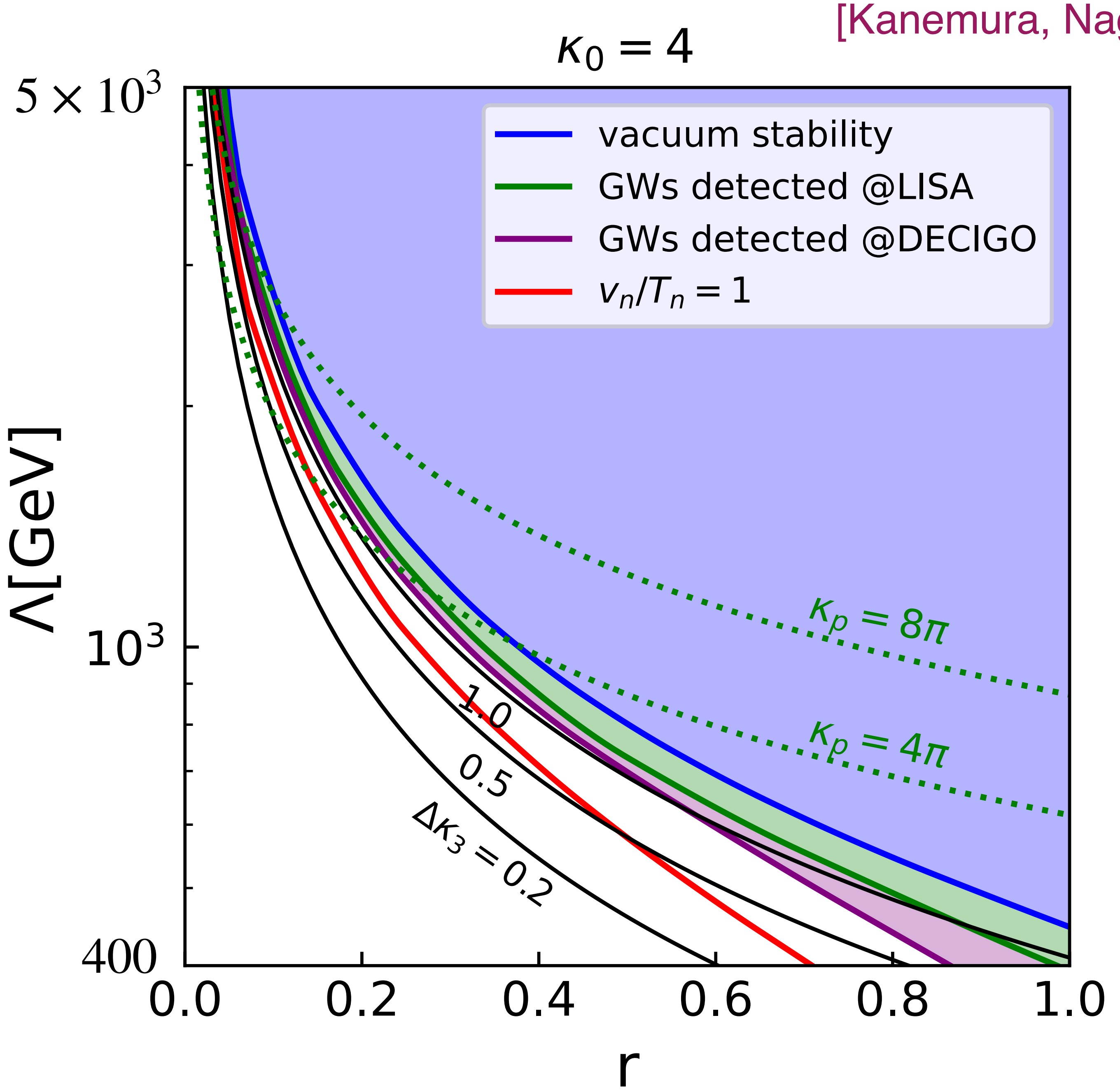
SMEFT is not appropriate when we discuss phenomena w/ the non-decoupling effects (Eg: large hhh coupling, 1st OPT etc…)

$$\Lambda^2 = \mathcal{M}^2(h=0) = M^2 + \frac{\kappa_p}{2}v^2, \quad r = \frac{\kappa_p v^2}{2}/\Lambda^2$$

Gravitational waves from 1st OPT

In addition, we analyzed the gravitational wave spectrum in the naHEFT

[Kanemura, Nagai and Tanaka, arXiv: 2202.12774]



$$\Delta\kappa_3 = \frac{\Delta\lambda_{hhh}^{\rm new} - \lambda_{hhh}^{\rm SM}}{\lambda_{hhh}^{\rm SM}}$$

Measurement of hhh @ILC & HL-LHC
GW observation @LISA & DECIGO

⇩

We may be able to test the models with the non-decoupling effects

$$\Lambda^2 = \mathcal{M}^2(h=0) = M^2 + \frac{\kappa_p}{2}v^2, \quad r = \frac{\kappa_p v^2}{2}/\Lambda^2$$

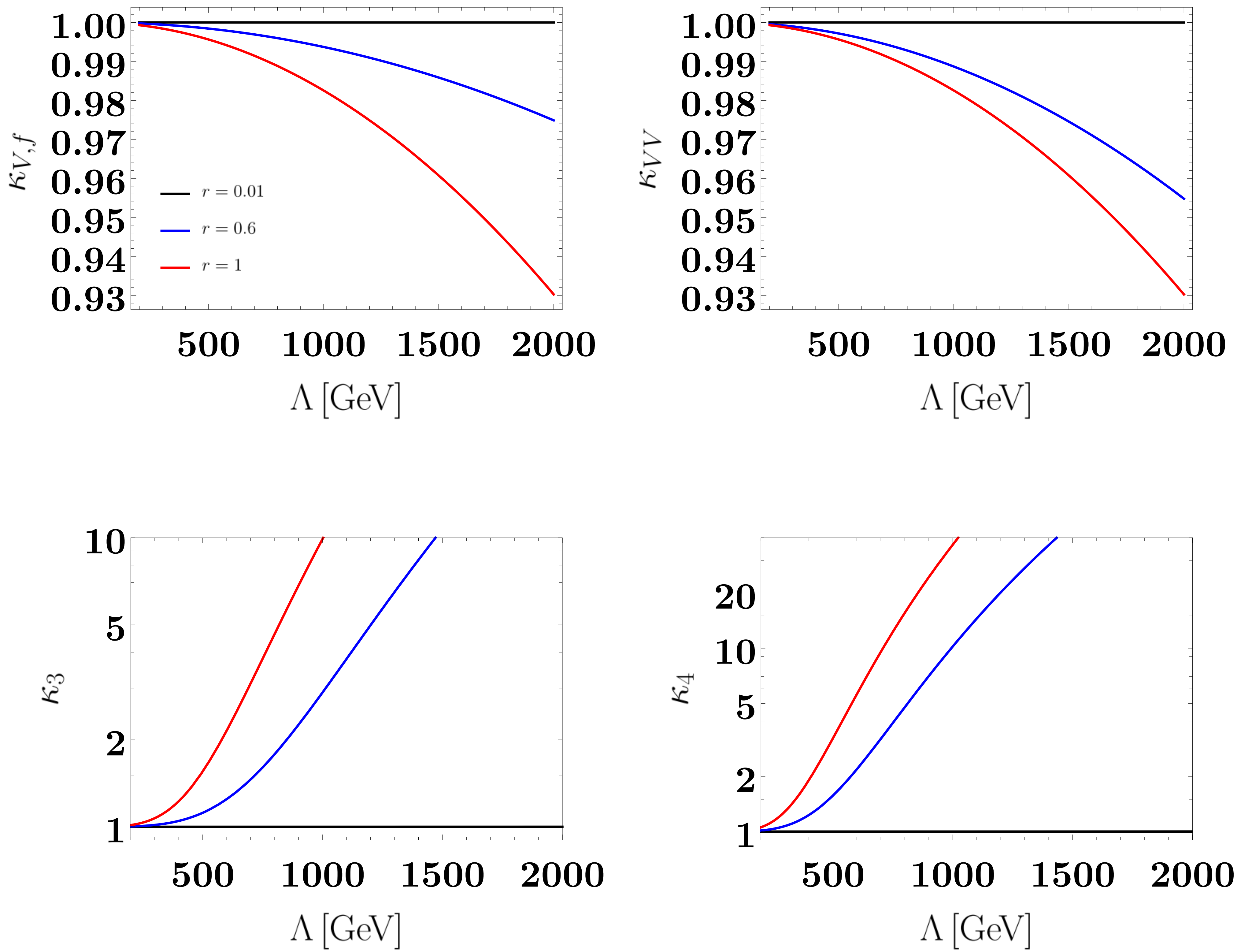
Summary

- To realize the strongly 1st OPT, the non-decoupling quantum effect is important
- We proposed a new EFT framework, which can describe the non-decoupling effects independent of the model details
- By using the new EFT, we discussed the deviation in the hhh coupling and the gravitational waves coming from the strongly 1st OPT
- SMEFT is not appropriate when we discuss phenomena related to the non-decoupling effects such as the strongly 1st OPT.
- We can test extended models with the non-decoupling effects via the measurement of the hhh coupling and the GW observation at future experiments

Backup

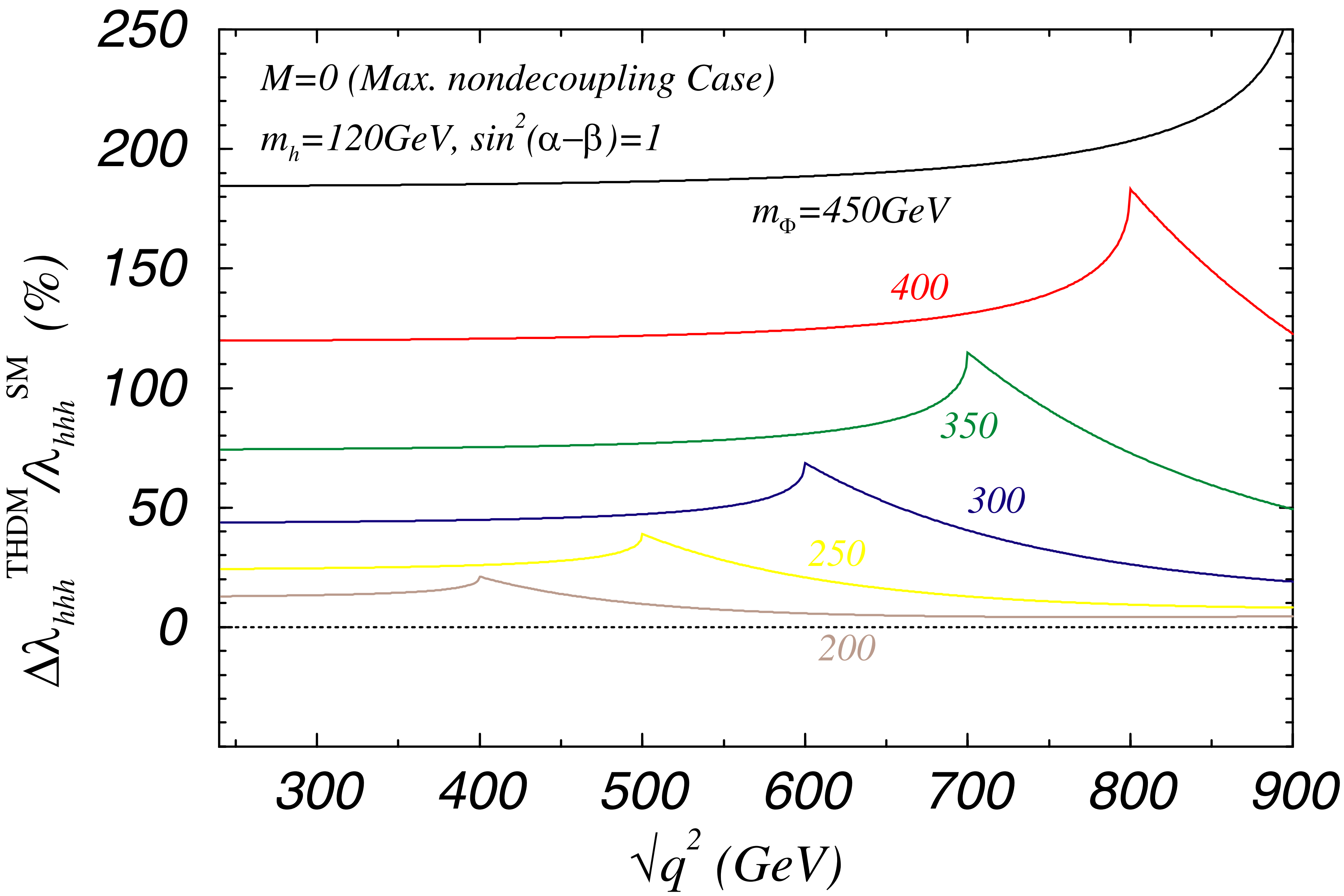
Higgs couplings in the naHEFT

[Kanemura and Nagai, JHEP 03 (2022)]



Momentum dependence on hhh coupling

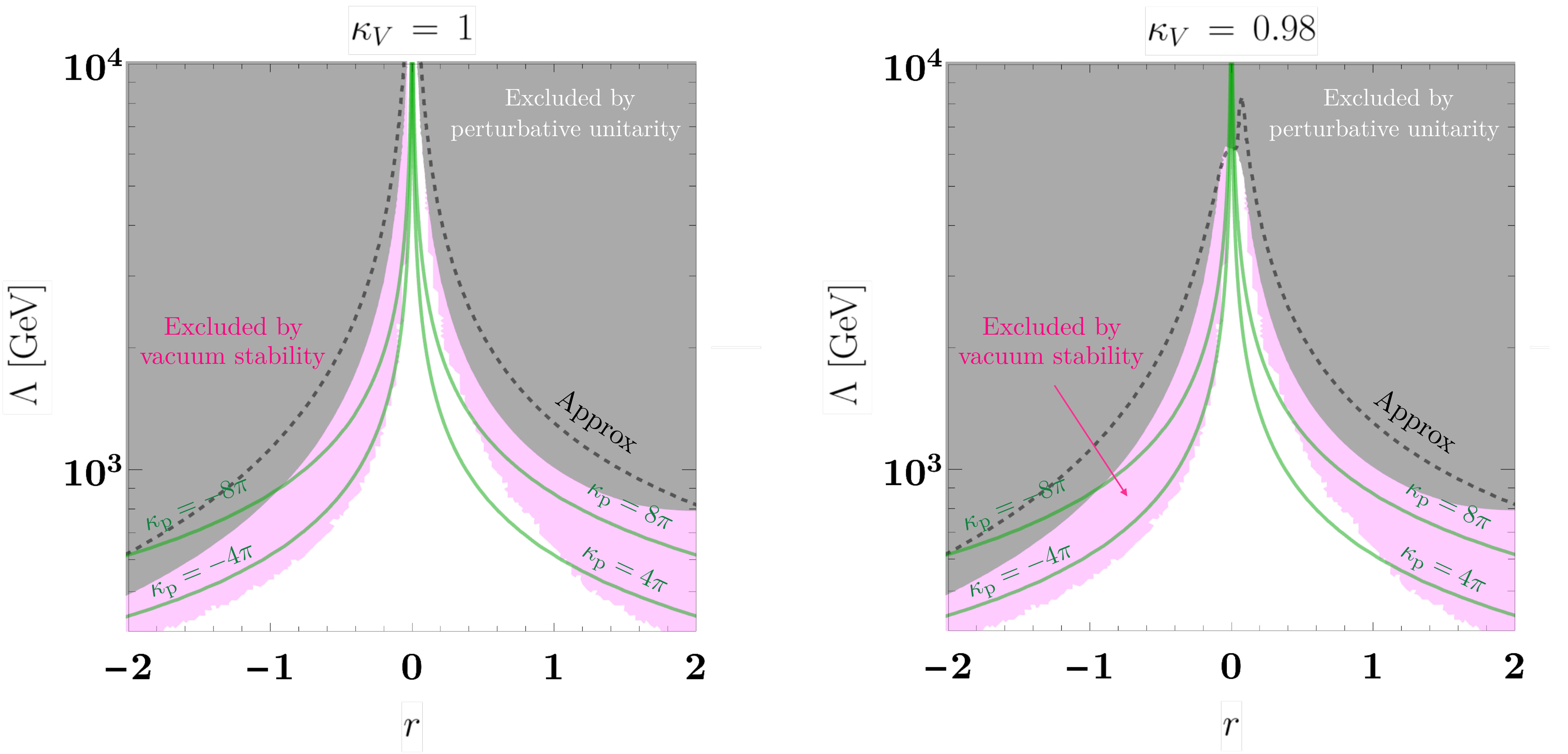
[Kanemura, Okada, Senaha and Yuan, PRD 70 (2004)]



Theoretical bounds in the naHEFT

[Kanemura and Nagai, JHEP 03 (2022)]

$$g^{\text{new}}_{hVV}/g^{\text{SM}}_{hVV} = \kappa_v$$



Nearly aligned Higgs EFT

Nearly aligned Higgs EFT (naHEFT)

[Kanemura and Nagai, JHEP 03 (2022)]

$$
\begin{aligned}
\mathcal{L}_{\rm BSM} = \xi \Bigg[& -\frac{\kappa_0}{4} [\mathcal{M}^2(h)]^2 \ln \frac{\mathcal{M}^2(h)}{\mu^2} \\
& + \frac{v^2}{2} \mathcal{F}(h)\, {\rm Tr}[D_\mu U^\dagger D^\mu U] + \frac{1}{2} \mathcal{K}(h) (\partial_\mu h)(\partial^\mu h) \\
& - v \left(\bar{q}_L^i U \left[\mathcal{Y}_q^{ij}(h) + \hat{\mathcal{Y}}_q^{ij}(h) \tau^3 \right] q_R^j + h.c. \right) \\
& - v \left(\bar{l}_L^i U \left[\mathcal{Y}_l^{ij}(h) + \hat{\mathcal{Y}}_l^{ij}(h) \tau^3 \right] l_R^j + h.c. \right) \Bigg],
\end{aligned}
$$

$$\xi = 1/(4\pi)^2$$

$$U = \exp\left(\frac{i}{v} \pi^a \tau^a \right)$$

When we consider the case violating the custodial symmetry, we should add

$$\mathcal{F}_Z(h)\, ({\rm Tr}[U^\dagger D_\mu U \tau^3])^2$$

Nearly aligned Higgs EFT

$$V_{\rm EFT} = V_{\rm SM} + \frac{\kappa_0}{64\pi^2}\left[\mathcal{M}^2(\phi)\right]^2 \ln\frac{\mathcal{M}^2(\phi)}{\mu^2}$$

Up to dimension six

$$V_{\rm BSM}(\Phi) = \frac{1}{f^2}\left(|\Phi|^2 - \frac{v^2}{2}\right)^3 , \quad \frac{1}{f^2} = \frac{2}{3}\,\xi\,\kappa_0\,\frac{\Lambda^4}{v^6}\frac{r^3}{1-r} .$$

Up to dimension eight

$$V_{\rm BSM}(\Phi) = \frac{1}{f_6^2}\left(|\Phi|^2 - \frac{v^2}{2}\right)^3 - \frac{1}{f_8^4}\left(|\Phi|^2 - \frac{v^2}{2}\right)^4$$

$$\frac{1}{f_6^2} = \frac{1}{f^2}\,\frac{1-2r}{1-r} , \quad \frac{1}{f_8^4} = \frac{\xi}{3}\,\kappa_0\,\frac{\Lambda^4}{v^8}\frac{r^4}{(1-r)^2} .$$