Electroweak phase transition in the nearly aligned Higgs EFT

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S. Kanemura, R. Nagai and M. Tanaka: JHEP 06 (2022)

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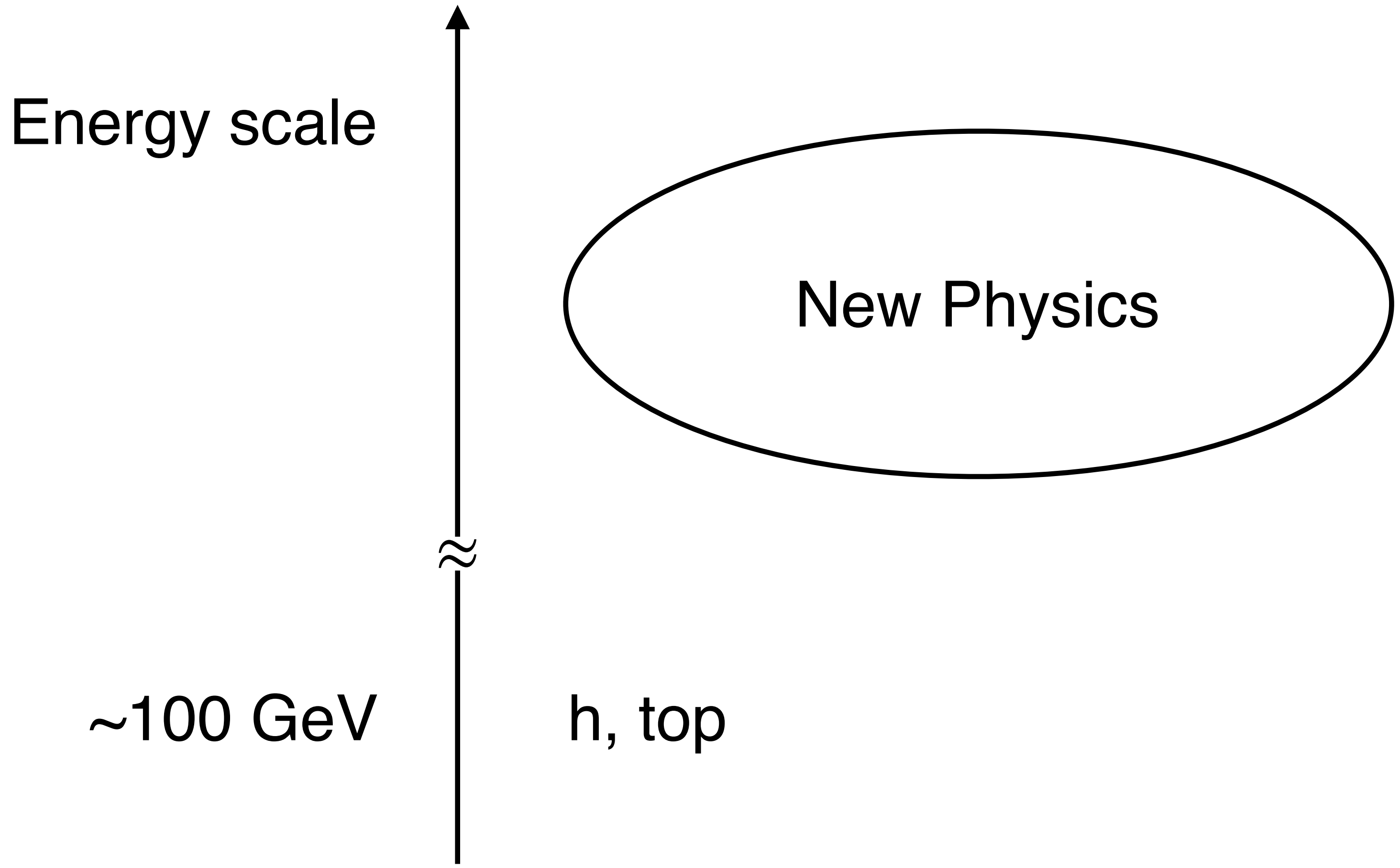
Introduction

Standard Model (SM) is consistent with the result in LHC

Unsolved problems: baryon asymmetry of the Universe, dark matter etc…



Contributions from heavy new particles can be described by EFT frameworks

e.g., Standard Model Effective Field Theory (SMEFT), Higgs EFT (HEFT)

[Buchmuller and Wyler: Nucl. Phys. B268 (1986)]
[Grzadkowski et al.: JHEP 10 (2010)]

[Feruglio: Int. J. Mod. Phys. A 8 (1993)]

Introduction

- The framework of the SMEFT is often used

[Buchmuller and Wyler: Nucl. Phys. B268 (1986)]
[Grzadkowski et al.: JHEP 10 (2010)]

→ SMEFT is a good EFT framework for the decoupling new physics

[Appelquist and Carazzone, PRD 11 (1975)]

- Heavy particles can cause large quantum effects (non-decoupling effects)

[Kanemura et al.: PRD 70 (2004)]

→ SMEFT does not work well in such the case

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

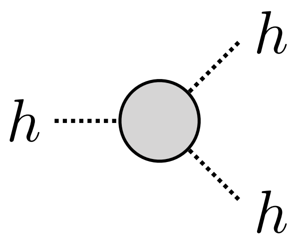
- HEFT can describe the new physics with the large quantum effects

[Feruglio: Int. J. Mod. Phys. A 8 (1993)]

We discuss an development of the HEFT to discuss the non-decoupling effects

Non-decoupling effects in hhh coupling

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



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

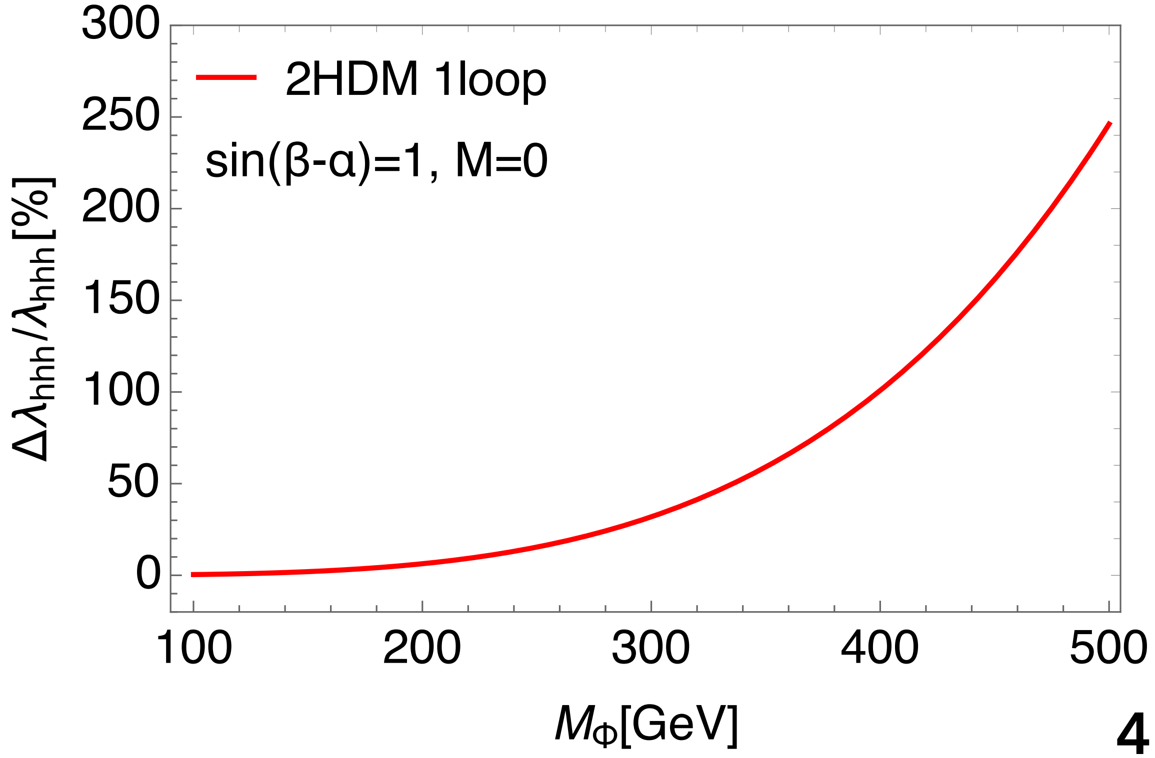
$$\frac{\Delta\lambda_{hhh}^{\rm 2HDM}}{\lambda_{hhh}^{\rm SM}} \simeq \sum_{\Phi=H,A,H^\pm} \frac{n_\Phi m_\Phi^4}{12\pi^2 m_h^2 v^2}\left(1-\frac{M^2}{m_\Phi^2}\right)^3 \simeq \begin{cases} \displaystyle\sum_\Phi \frac{n_\Phi \lambda_\Phi^3 v^4}{12\pi^2 m_h^2 m_\Phi^2} & (\lambda_\Phi v^2 \ll M^2)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

Large hhh coupling is required to realize the strongly 1st order phase transition

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

$$\frac{\Delta\lambda_{hhh}^{\rm 2HDM}}{\lambda_{hhh}^{\rm SM}} > 20 - 30\ \%$$

The non-decoupling effect is very important



Non-decoupling effects and new EFT

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

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

Important to describe the non-decoupling effects

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

$$V_{\rm CW}(\varphi) \ni \frac{\lambda_\Phi^3}{64\pi^2 M^2}\varphi^6 = \frac{1}{\Lambda^2}\varphi^6$$

⇒ SMEFT is a good approximation

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

⇒ 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)

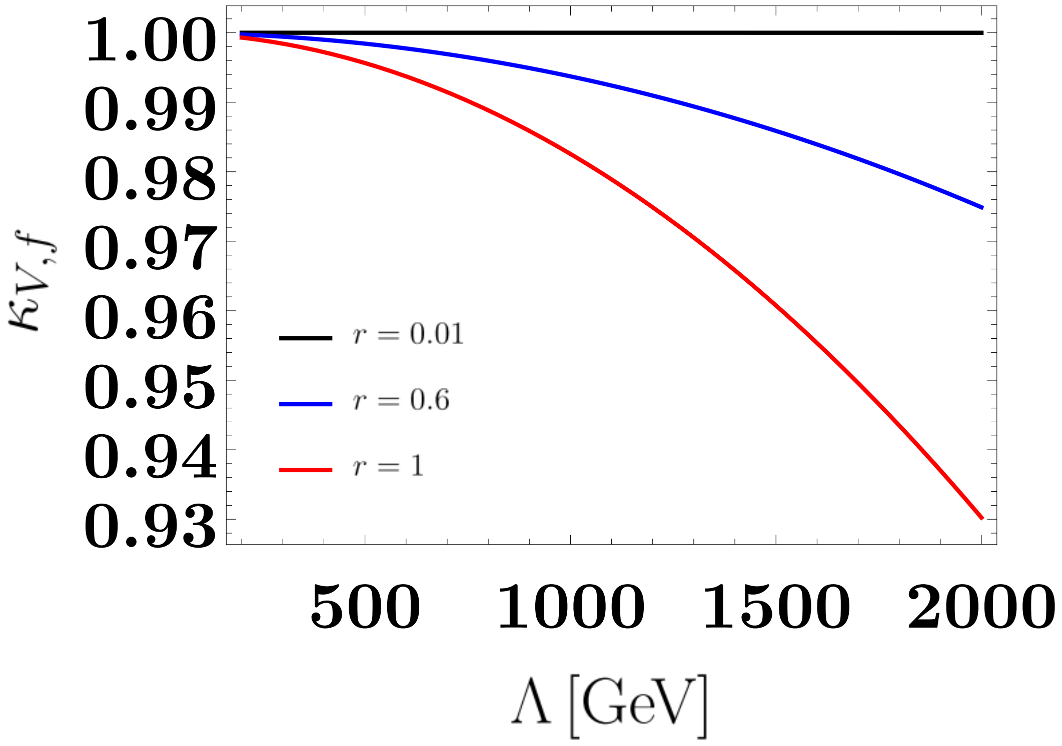
The naHEFT can describe the non-decoupling effects independent of models

[Kanemura and Nagai, JHEP 03 (2022)]

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

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

[Kanemura and Nagai, JHEP 03 (2022)]



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

polynomial in terms of h

What is the meaning of “nearly aligned”?

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

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

naHEFT vs. SMEFT: hhh coupling

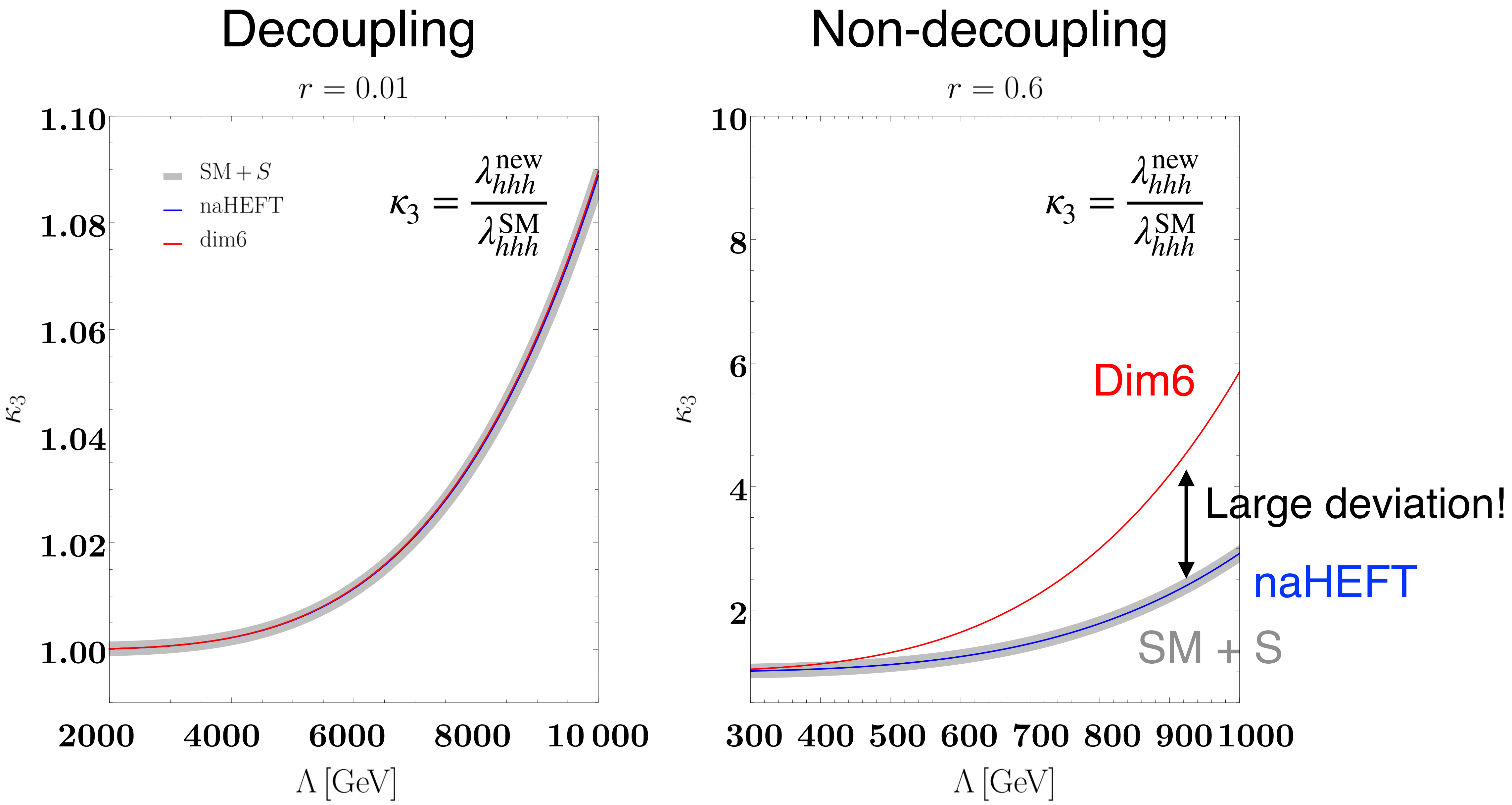
[Kanemura and Nagai, JHEP 03 (2022)]

- Non-decouplingness: $\boxed{r = \frac{\kappa_p v^2}{2}/\Lambda^2}$

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

$r \sim 0 \Rightarrow M^2 \gg \frac{\kappa_p}{2}v^2$ Decoupling

$r \sim 1 \Rightarrow M^2 \ll \frac{\kappa_p}{2}v^2$ Non-decoupling



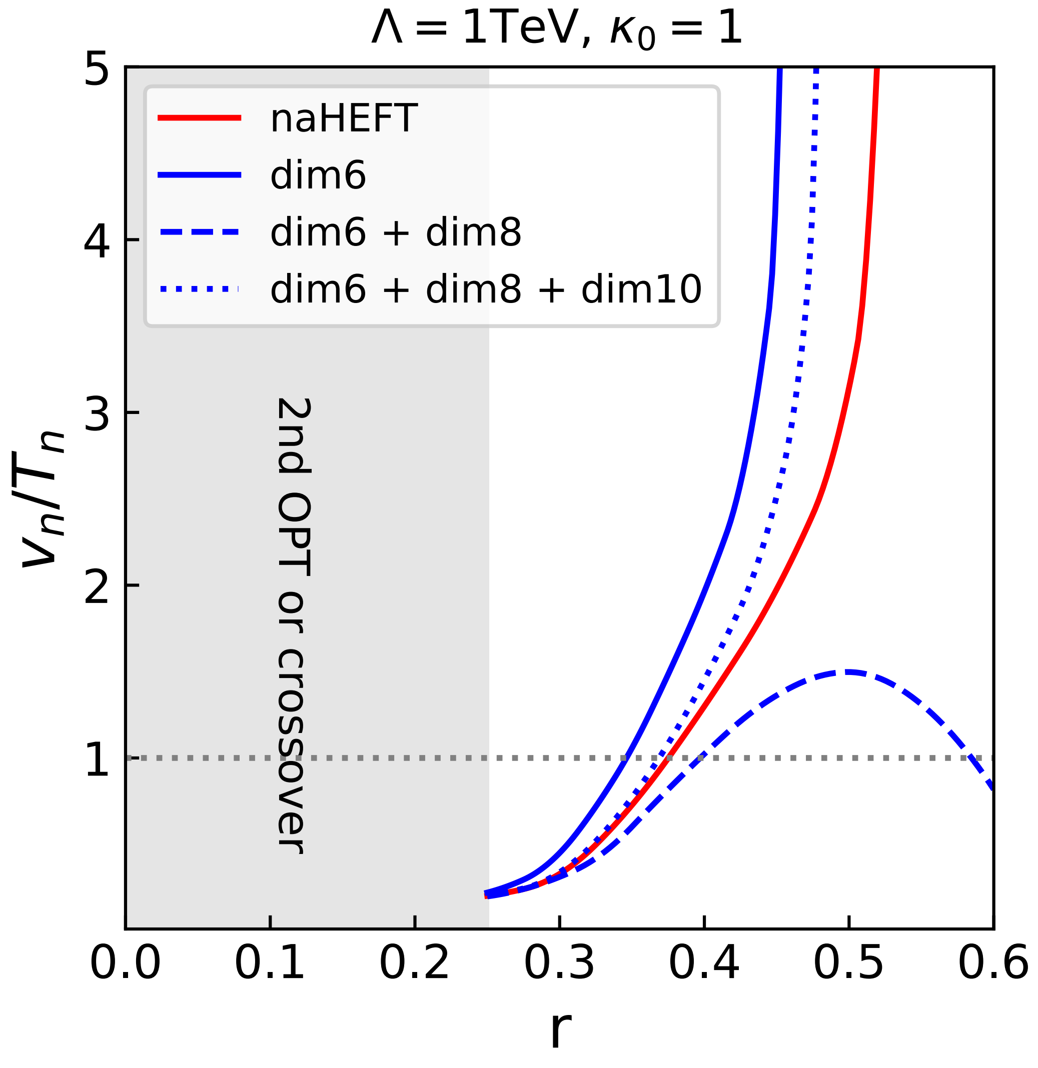
naHEFT at the finite temperature

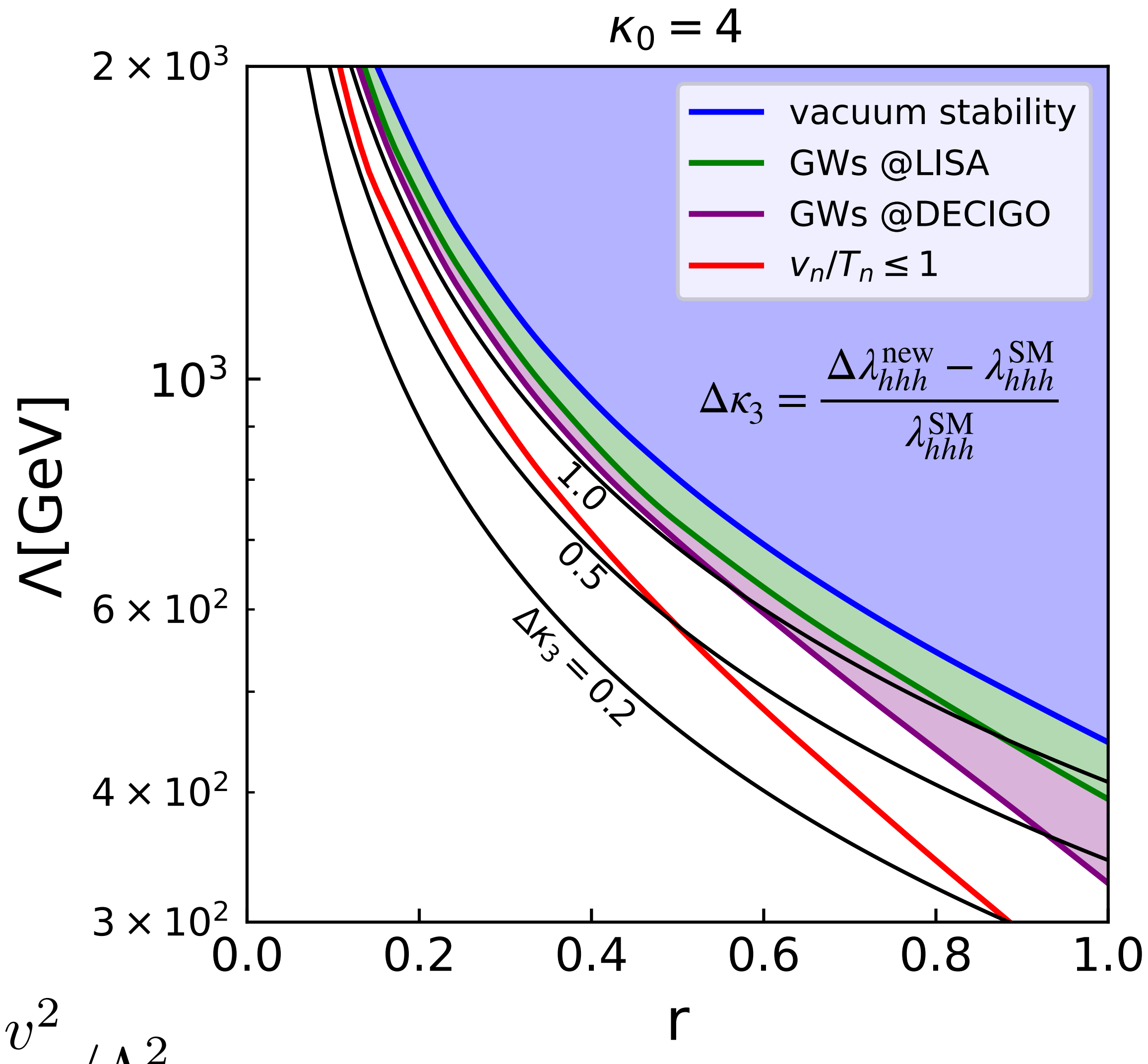
- We extend the naHEFT at finite temperature systems

[Kanemura, Nagai and Tanaka, JHEP 06 (2022)]

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

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





$$r = \frac{\kappa_p v^2}{2}/\Lambda^2$$

Summary

- We proposed the nearly aligned Higgs EFT

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

→ The naHEFT can describe models with the non-decoupling effects

- We discussed the hhh coupling and the gravitational waves by first-order phase transitions in the naHEFT

→ SMEFT is not appropriate when we discuss phenomena related to the non-decoupling quantum effects

- We can test extended models with the non-decoupling effects via the hhh coupling measurement and the gravitational wave observation

Backup

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)]

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

Sakharov's condition

①Baryon # violation
②C and CP violation
③Departure from equilibrium

- 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)]

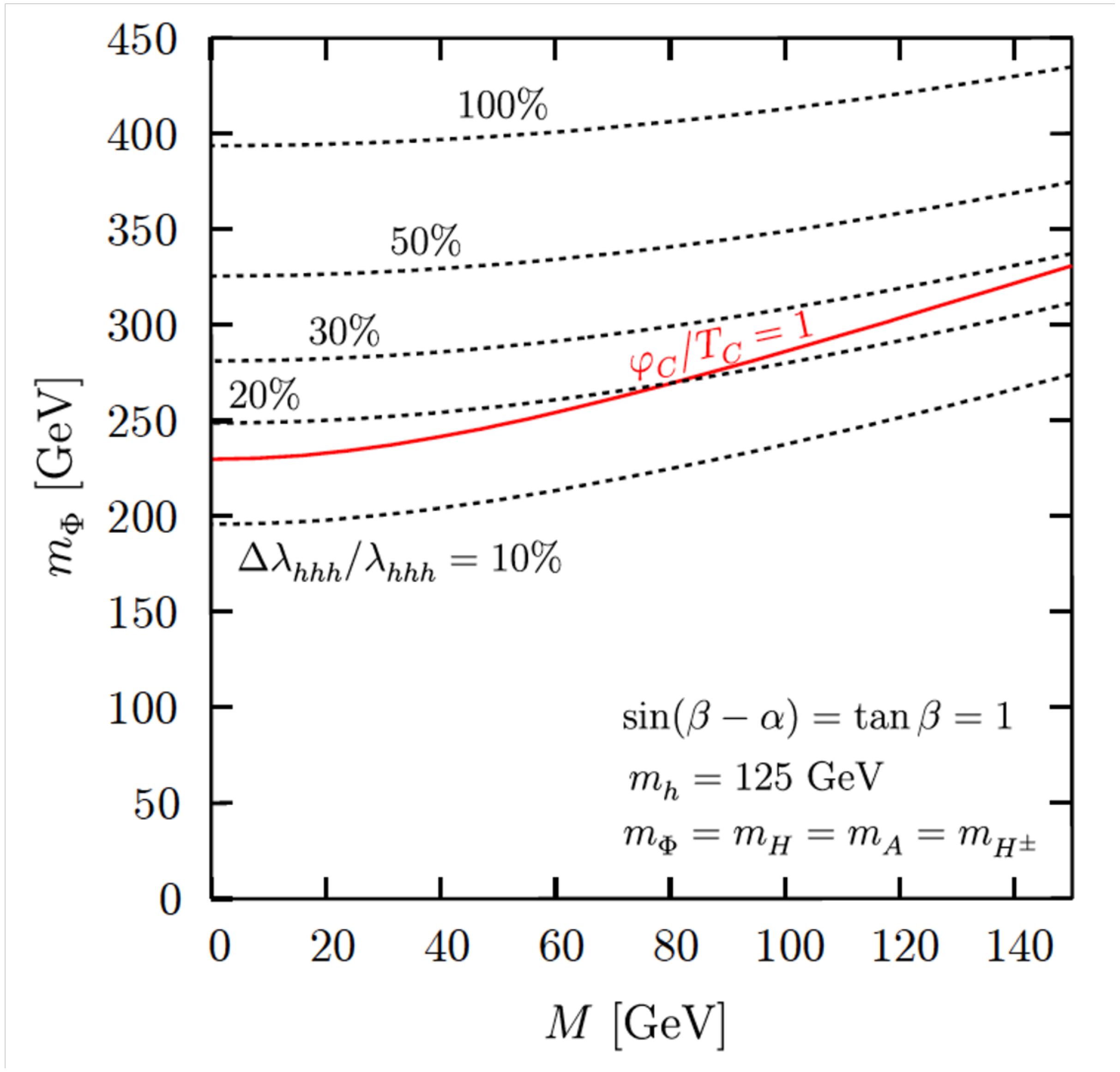
Extension of the Higgs sector is needed

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)]



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

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

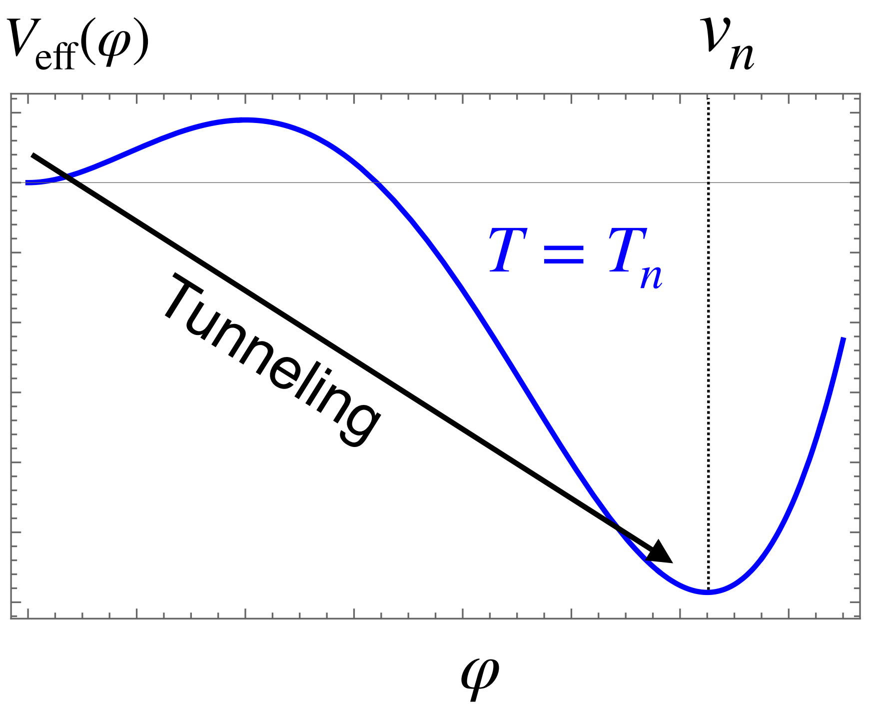
Strongly 1st order phase transition

- Effective potential (High temperature expansion)

[Anderson and Hall, PRD 45 (1992)]

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

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

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

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

[Funakubo and Senaha, PRD 79 (2009)]

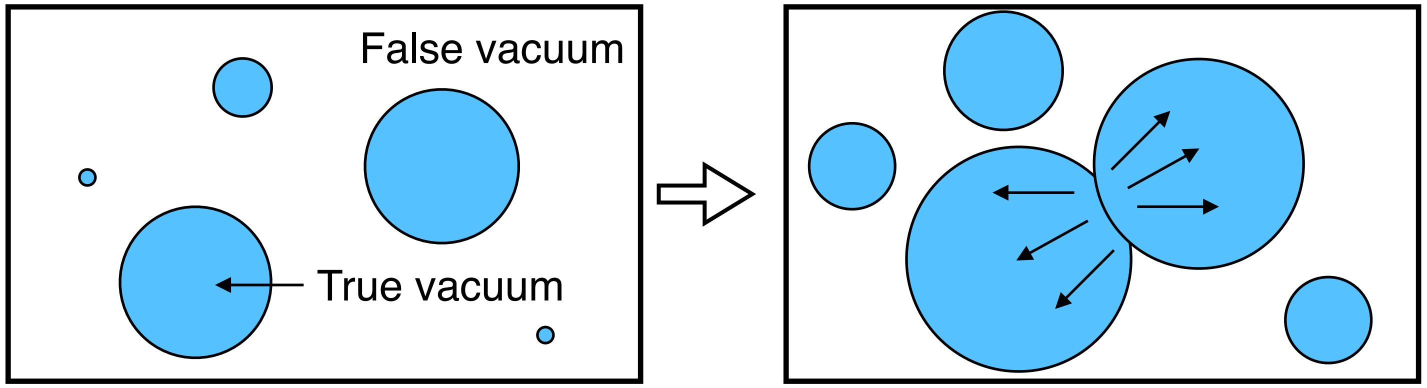
Gravitational waves from 1st OPT

Origin of the gravitational waves (GWs) from 1st OPT [Caprini et al., JCAP 04 (2016)]

① Bubble collisions

② Compression wave of plasma

③ Plasma turbulence



Eg) Compression wave (leading contribution)

$$\Omega_{\rm SW}(f)h^2 = \tilde{\Omega}_{\rm SW}^{\rm peak}h^2 \times (f/\tilde{f}_{\rm SW})^3 \left(\frac{7}{4+3\,(f/\tilde{f}_{\rm SW})^2}\right)^{7/2}$$

The peak height

$$\tilde{\Omega}_{\rm sw}^{\rm peak}h^2 \simeq 2.65\times 10^{-6} v_b \tilde{\beta}_{\rm GW}^{-1}\left(\frac{\kappa_{\rm sw}\alpha_{\rm GW}}{1+\alpha_{\rm GW}}\right)^2\left(\frac{100}{g_*}\right)^{1/3}$$

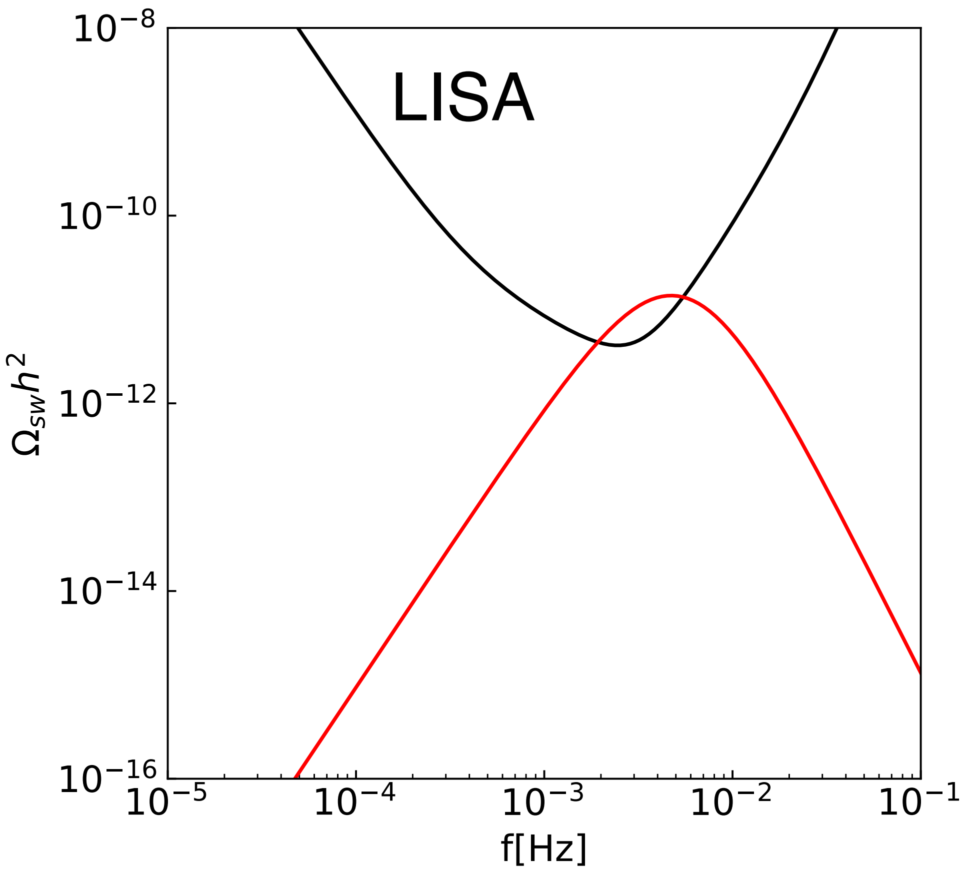
The peak frequency

$\kappa_{\rm sw}$: efficiency factor

$$\tilde{f}_{\rm sw} \simeq 1.9\times 10^{-2}\frac{1}{v_b}\tilde{\beta}_{\rm GW}\left(\frac{T_n}{100{\rm GeV}}\right)\left(\frac{g_*}{100}\right)^{1/6} \quad {\rm mHz}$$

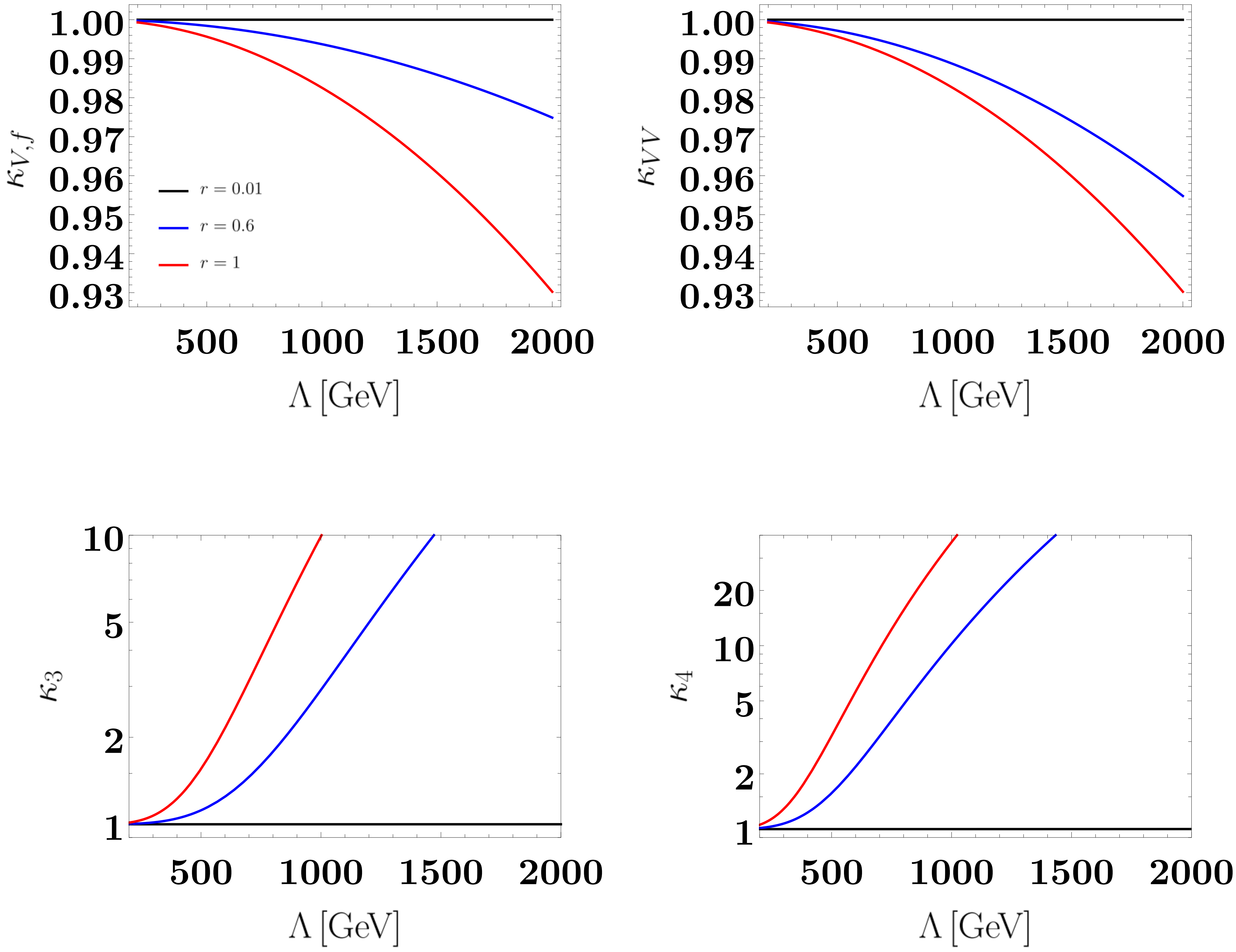
PTPlot used [Caprini et al., JCAP 03 (2020) 024]

[LISA: arXiv:1702.00786]



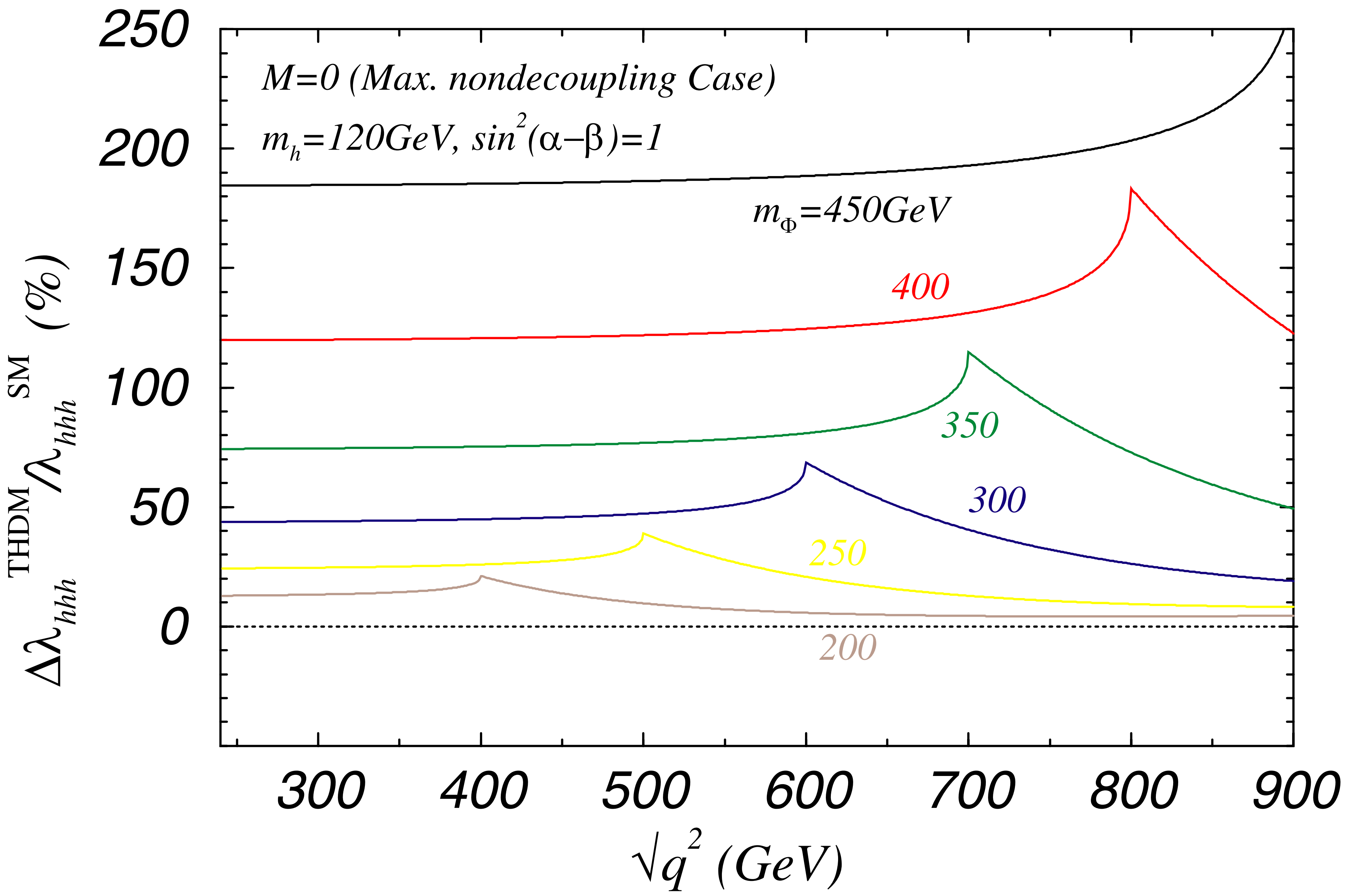
Higgs couplings in the naHEFT

[Kanemura and Nagai, JHEP 03 (2022)]



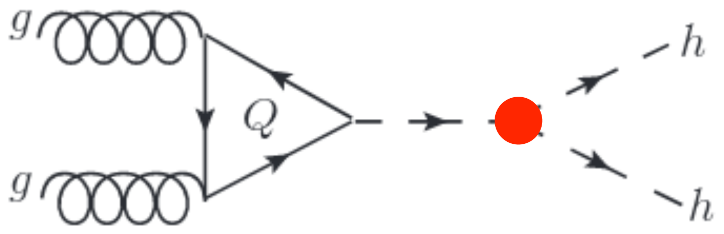
Momentum dependence on hhh coupling

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

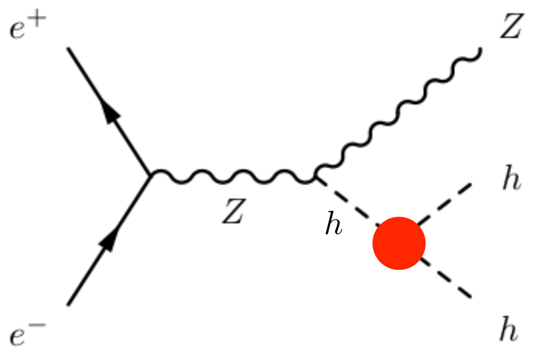


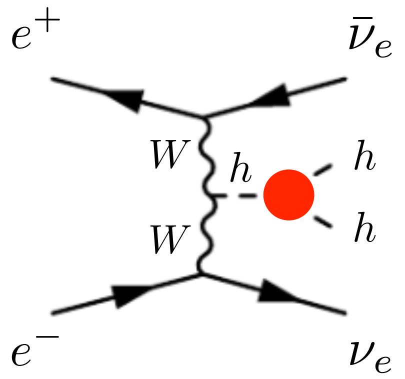
hhh measurement at future colliders

- Hadron colliders

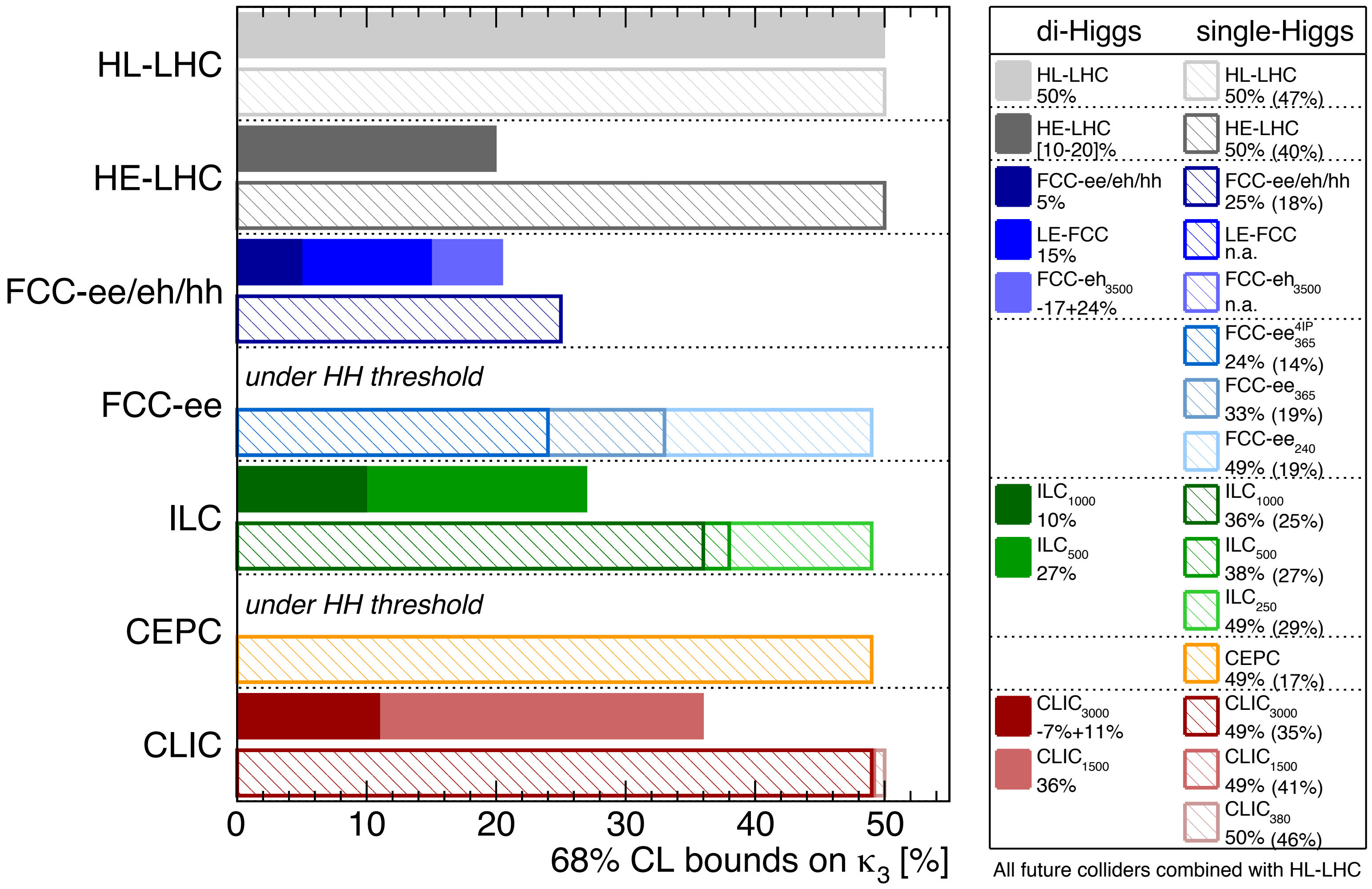


- Lepton colliders





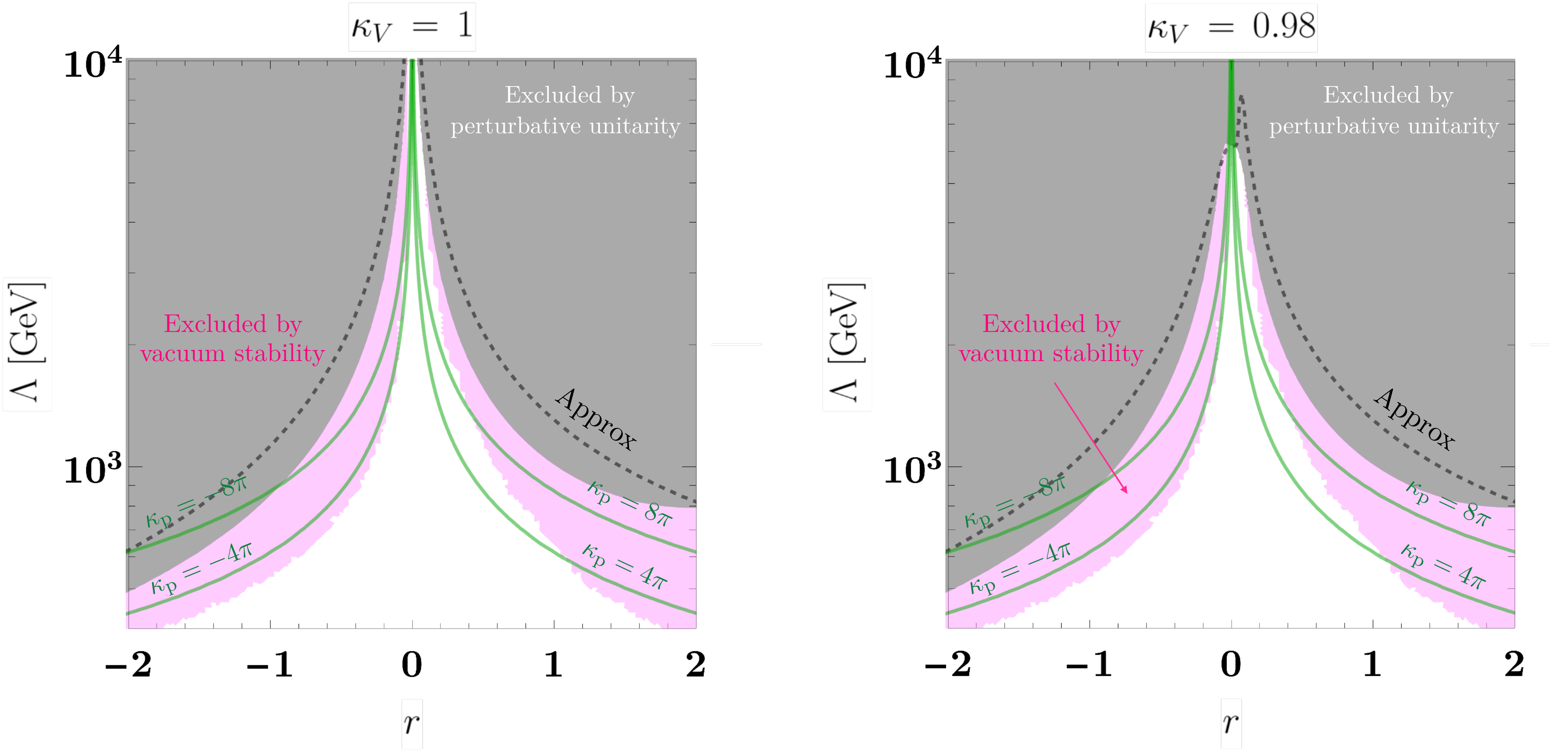
[arXiv: 1905.03764]



Theoretical bounds in the naHEFT

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

[Kanemura and Nagai, JHEP 03 (2022)]



Mass upper bound exists in models without alignment

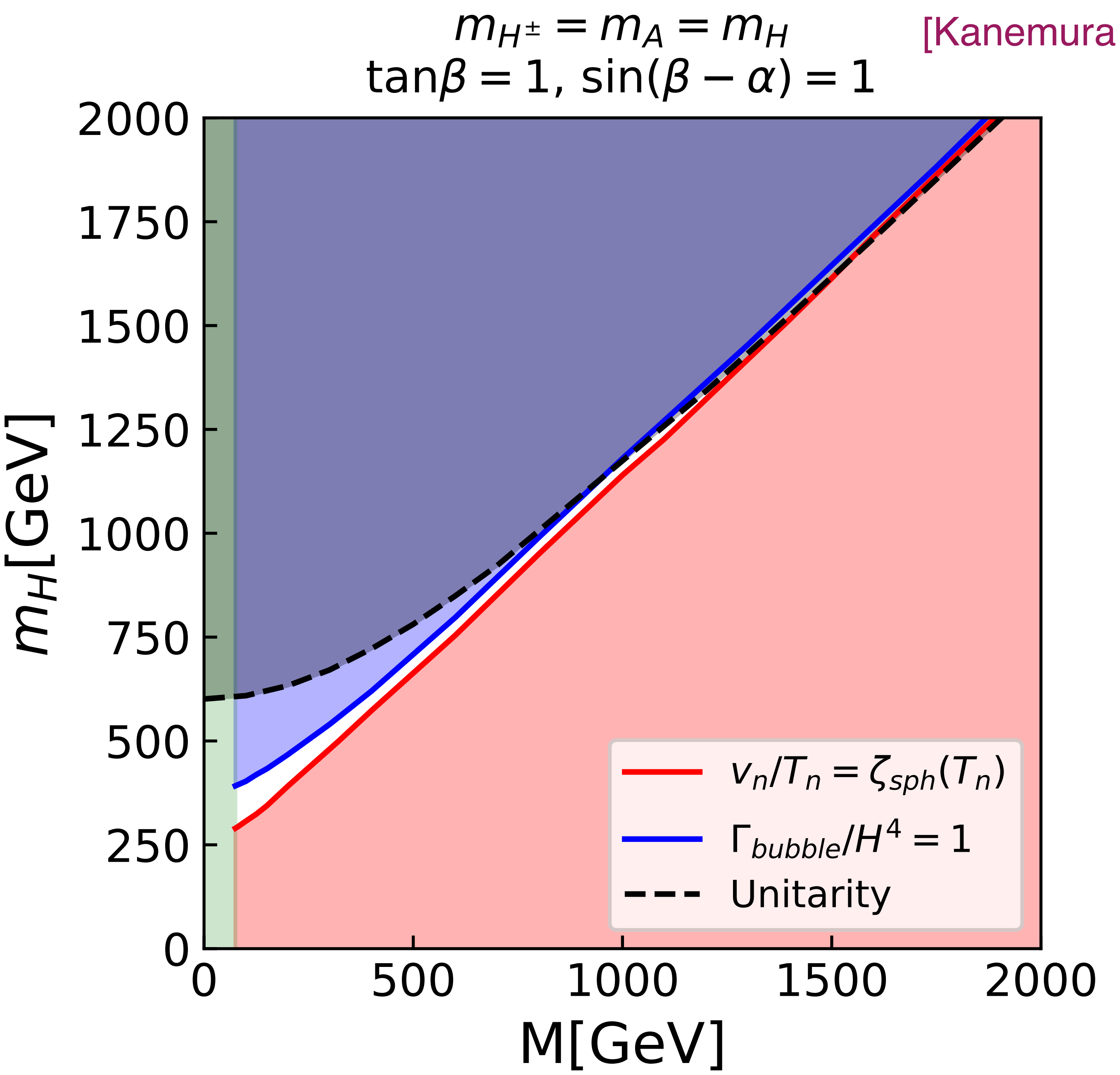
→ New no-lose theorem

EW Phase transition in the 2HDM

To realize the strongly 1st OPT while satisfying the unitarity bound,

Masses of additional Higgs bosons < 1.6-2 TeV

[Kanemura and Tanaka, arXiv:2201.04791]



$$M_\Phi^2 = M^2 + \lambda_\Phi v^2$$

Nearly aligned Higgs EFT

- Lagrangian for the nearly aligned Higgs EFT (naHEFT)

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm BSM}$$

[Kanemura and Nagai, JHEP 03 (2022)]

- BSM part in the naHEFT

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

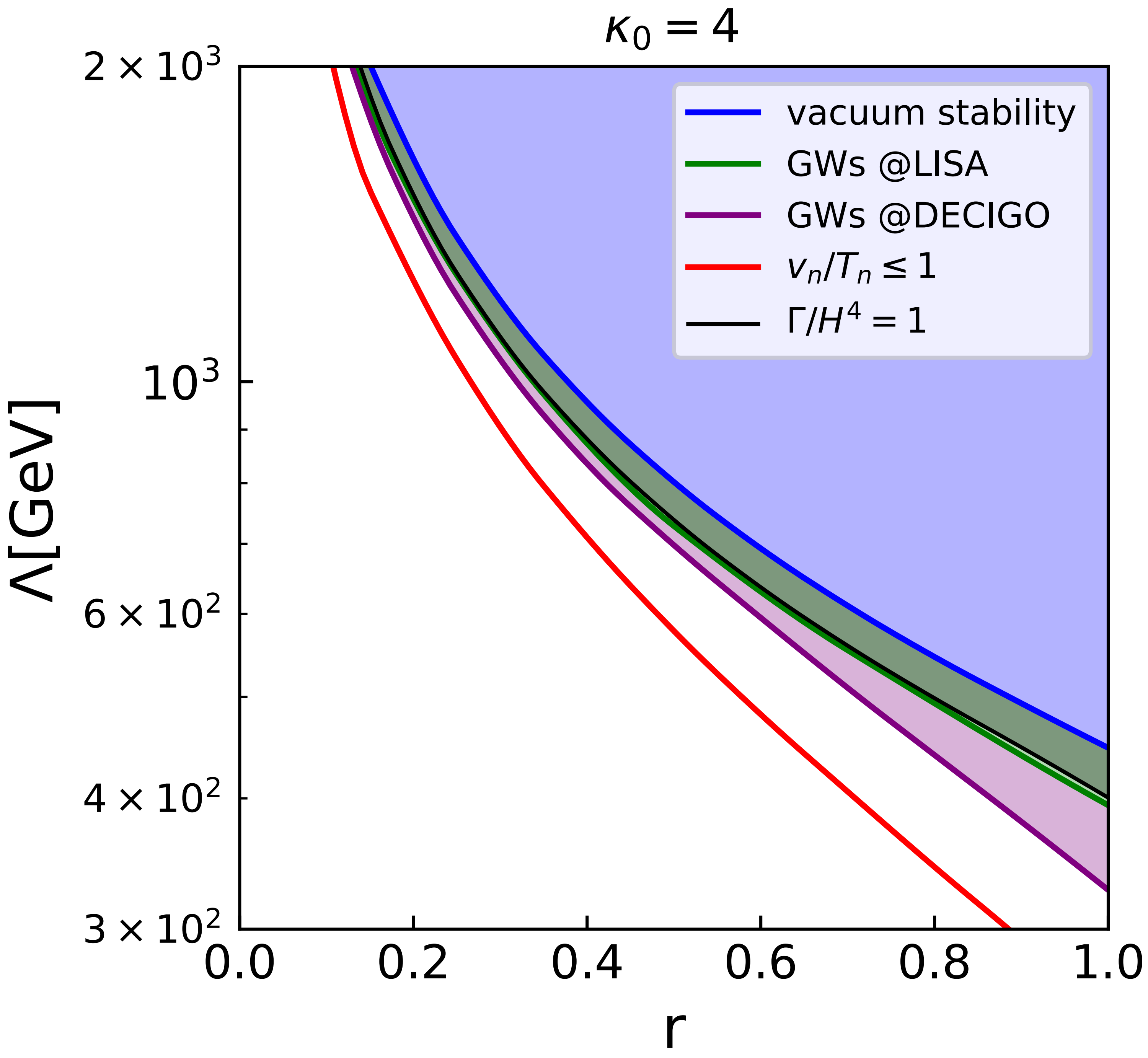
$$U = \exp\left(\frac{i}{v}\pi^a\tau^a\right)$$

$\mathcal{M}^2(h),\ \mathcal{F}(h),\ \mathcal{K}(h),\ \mathcal{Y}^{ij}_\psi(h),\ \hat{\mathcal{Y}}^{ij}_\psi(h)$: polynomial in terms of h

- The custodial symmetry breaking term $\mathcal{F}_Z(h)\,({\rm Tr}[U^\dagger D_\mu U\tau^3])^2$

Nearly aligned Higgs effective field theory

[Kanemura, Nagai and Tanaka, arXiv: 2202.12774]



Nearly aligned Higgs EFT

- Since we are interested in the phase transition, we focus on the potential part

d.o.f of BSM particle

$$V_{\rm BSM} = \frac{\kappa_0}{64\pi^2}[\mathcal{M}^2(\phi)]^2 \ln \frac{\mathcal{M}^2(\phi)}{\mu^2} \longleftarrow$$

field dependent mass of BSM particle

renormalization scale

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

- The square mass of the BSM particle (cutoff scale): $\mathcal{M}^2(v) \equiv \Lambda^2$

- Important parameter in the naHEFT: Non-decouplingness $r = \frac{\frac{\kappa_p v^2}{2}}{\Lambda^2}$

$r \sim 0 \;\Rightarrow\; M^2 \gg \frac{\kappa_p}{2} v^2$ Decoupling region

$r \sim 1 \;\Rightarrow\; M^2 \ll \frac{\kappa_p}{2} v^2$ Non-decoupling region

SMEFT and naHEFT

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

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

$$\mathcal{M}^2(v) \equiv \Lambda^2 \qquad r = \frac{\frac{\kappa_p v^2}{2}}{\Lambda^2}$$

Expand the logarithmic part in terms of ϕ

- Up to dimension six

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

- Up to dimension eight

$$\xi = \frac{1}{16\pi^2}$$

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

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

The log part cannot be expanded in terms of ϕ in r > 1/2

Difference b/w naHEFT and SMEFT

- SMEFT

$$V(\Phi) = \mu^2 |\Phi|^2 + \lambda |\Phi|^4 + \frac{c_6}{\Lambda^2} |\Phi|^6 + \frac{c_8 v^2}{\Lambda^4} |\Phi|^8$$

c_6 and c_8 are independent

- naHEFT

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

$$\frac{1}{f_6^2} = \frac{1}{f^2}\frac{1-2r}{1-r}, \quad \frac{1}{f_8^4} = \frac{\xi}{3}\kappa_0 \frac{\Lambda^4}{v^8}\frac{r^4}{(1-r)^2} \quad \frac{1}{f^2} = \frac{2}{3}\xi\,\kappa_0 \frac{\Lambda^4}{v^6}\frac{r^3}{1-r}\,.$$

c_6 and c_8 are NOT independent