

# New collider implications on a strongly first order EWPT.

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- **Problem:** Baryon Asymmetry of the Universe (BAU) [Planck, 2020]
- **Solution:** Electroweak Baryogenesis (EWBG) [Kuzmin et al., 1985]
- **Requirement:** Strongly First Order Phase Transition (SFOPT) [Sakharov, 1991]
- **Experimental Implications:**
- **Non-decoupling effects at colliders:**
  - $h\gamma\gamma$   
.[Shifman et al., 1979]
  - $hhh$   
.[Kanemura et al., 2005, Grojean et al., 2005]
- **Cosmological Imprints:**
  - Gravitational Waves  
.[Grojean and Servant, 2007]
  - Primordial Black Holes  
.[Hashino et al., 2022]

# Why naHEFT

nearly-aligned Higgs EFT (naHEFT)  
[Kanemura and Nagai, 2022]

- **Motivation:**  
LHC measurements overwhelmingly aligned with the SM predictions.
- **Assumption:**  
All coupling deviations arise from loop corrections of new physics.  
(No tree level mixing.)
- **Advantage 1:**  
It's better than SMEFT at describing non-decoupling new physics.
- **Advantage 2:**  
It's a simpler framework than HEFT with more predictability.

- One-loop corrected Lagrangian:

$$\mathcal{L}_{naHEFT} = \mathcal{L}_{SM} + \xi(\mathcal{L}_S + \mathcal{L}_V) \quad \left( \xi = \frac{1}{(4\pi)^2} \right)$$

- One-loop scalar potential:

$$\begin{aligned} \mathcal{L}_S = & -\frac{N}{4} [\mathcal{M}^2(h)]^2 \log \frac{\mathcal{M}^2(h)}{\mu^2} \\ & + \frac{v^2}{2} \mathcal{F}(h) \text{Tr}[D_\mu U^\dagger D^\mu U] + \frac{1}{2} \mathcal{K}(h) (\partial_\mu h) (\partial^\mu h) \end{aligned}$$

- One-loop scalar-vector potential:

$$\begin{aligned} \mathcal{L}_V = & g^2 \mathcal{F}_W(h) \text{Tr}[\mathbf{W}_{\mu\nu} \mathbf{W}^{\mu\nu}] + g'^2 \mathcal{F}_B(h) \text{Tr}[\mathbf{B}_{\mu\nu} \mathbf{B}^{\mu\nu}] \\ & - gg' \mathcal{F}_{BW}(h) \text{Tr}[U \mathbf{B}_{\mu\nu} U^\dagger \mathbf{W}^{\mu\nu}] \end{aligned}$$

# Further Assumptions

- Free parameters:
  - BSM degrees of freedom:  $\kappa_0 = n_0 + 2n_+ + 2n_{++}$
  - Mass scale:  $\Lambda^2 = M^2 + \lambda_g v^2$
  - Non-decouplingness:  $r = \lambda_g v^2 / \Lambda^2$
- Polynomials from integrated out heavy particles:

$$\mathcal{F}(h) = \mathcal{F}_{BW}(h) = 0$$

$$\mathcal{M}^2(h) = M^2 + \lambda_g (v + h)^2$$

$$\mathcal{K}(h) = \kappa_0 \frac{\Lambda^2}{3v^2} r \left[ 1 - (1 - r) \frac{\Lambda^2}{\mathcal{M}^2(h)} \right]$$

$$\mathcal{F}_W(h) = \mathcal{F}_B(h) = \frac{b}{2} \ln \left[ 1 - r + r \left( 1 + \frac{h}{v} \right)^2 \right], \quad b = \frac{n_+ + 4n_{++}}{3}$$

# Cosmological Constraints

- Condition for SFOPT:

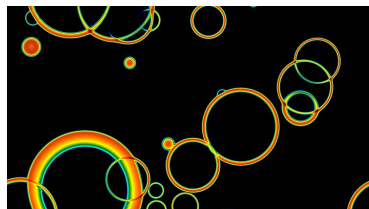
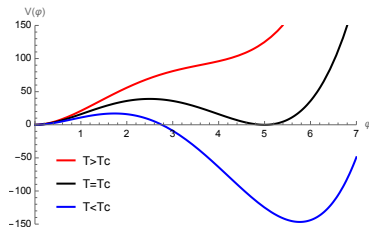
$$\frac{v_c}{T_c} > 1 \quad \left( SM : \frac{v_c}{T_c} < 1 \right)$$

EWPT must be strong enough for EWBG

- Completion Condition:

$$\frac{\Gamma}{H^4} > 1$$

Transition rate high enough to finish PT



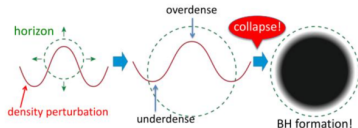
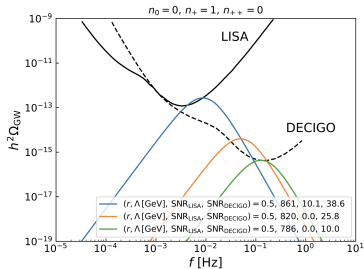
# Cosmological Observables

- Gravitational Waves:

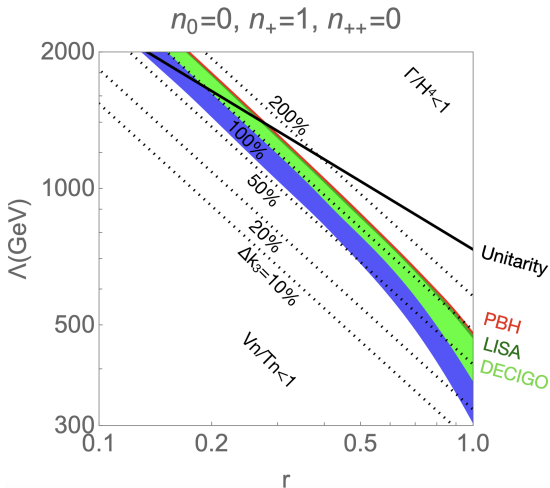
GW released during the EWPT can be detected by future observatories like LISA and DECIGO

- Primordial Black Holes:

PBH can be formed by large density contrasts after cosmological phase transitions.



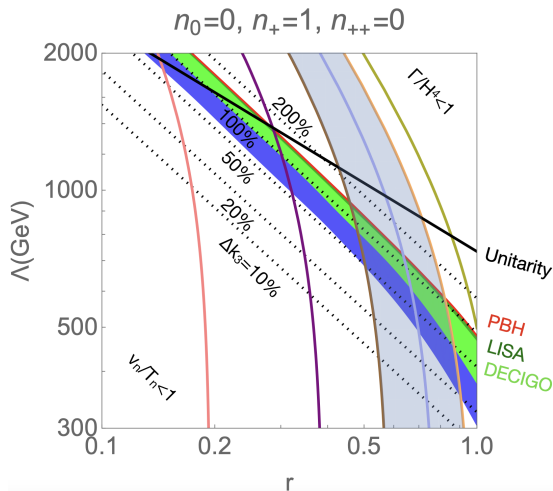
# Results



- Coloured regions can realise SFOPT.
- Higgs couplings probe the overall area.
- GW and PBH can probe only specific parts.
- Unitarity forbids too high new physics scale in realistic models.



# Results



- Future  $h \rightarrow \gamma\gamma$  precision measurements will constrain SF OPT parameter space.

- Measuring:

- $\Delta\kappa_{\gamma\gamma} = (-4 \pm 1)\%$

- Implies:

- $\Lambda \lesssim 1\text{TeV}$

- $r \gtrsim 0.5$

- $21\% < \Delta\kappa_3 < 137\%$

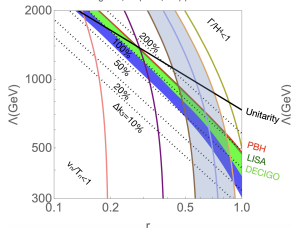
(HL-LHC  $\Delta\kappa_{\gamma\gamma} = 1.8\%$ ,  $1\sigma$ )  
.[Cepeda et al., 2019]



# Results

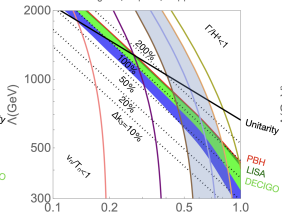
## Charged Singlet

$$n_0=0, n_+=1, n_{++}=0$$



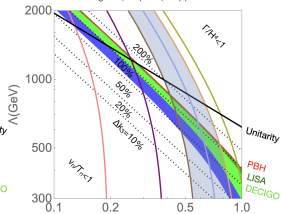
## Real Triplet

$$n_0=1, n_+=1, n_{++}=0$$

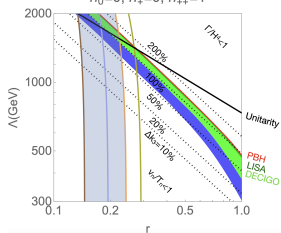


## 2HDM

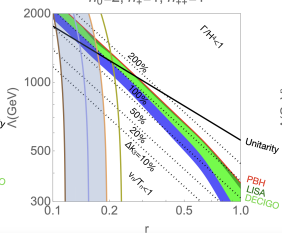
$$n_0=2, n_+=1, n_{++}=0$$



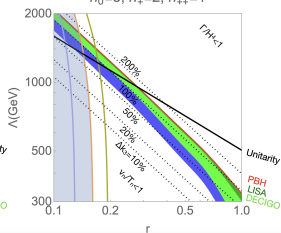
$$n_0=0, n_+=0, n_{++}=1$$



$$n_0=2, n_+=1, n_{++}=1$$



$$n_0=3, n_+=2, n_{++}=1$$



Doubly C.S.

Complex Triplet

Georgi-Machacek

# Results

- $\Delta\kappa_{\gamma\gamma} = (-4 \pm 1)\%$

$(n_0, n_+, n_{++})$	Required by $\frac{v_n}{T_n} > 1$ & $\frac{\Gamma}{H^4} < 1$	Conservative bound	Example of SM extension
(0, 1, 0)	137% > $\Delta\kappa_3$ > 21%	114% > $\Delta\kappa_3$ > 50%	A singly charged scalar
(1, 1, 0)	143% > $\Delta\kappa_3$ > 19%	115% > $\Delta\kappa_3$ > 47%	A real triplet scalar
(2, 1, 0)	135% > $\Delta\kappa_3$ > 18%	114% > $\Delta\kappa_3$ > 44%	A doublet scalar
(0, 0, 1)	153% > $\Delta\kappa_3$ > 62%	148% > $\Delta\kappa_3$ > 65%	A doubly charged scalar
(2, 1, 1)	160% > $\Delta\kappa_3$ > 65%	150% > $\Delta\kappa_3$ > 75%	A complex triplet scalar
(3, 2, 1)	136% > $\Delta\kappa_3$ > 59%	153% > $\Delta\kappa_3$ > 63%	Gerogi-Machacek model

- Required by  $\frac{v_n}{T_n} > 1$  &  $\frac{\Gamma}{H^4} < 1$ :

Interval for which EWPT *can be* SFO. (Important to deny SFOPT.)

- Conservative bound:

Interval for which EWPT *is* SFO. (Important to confirm SFOPT.)

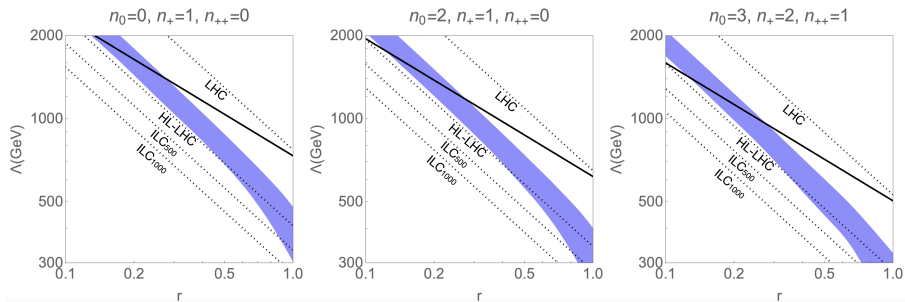
# Future colliders

Collider	HL-LHC	ILC <sub>250</sub>	ILC <sub>500</sub>	ILC <sub>1000</sub>
$\Delta\kappa_3(1\sigma)$	50%	49%	22%	10%

LHC
$-0.4 < \kappa_3 < 6.3$

[Micco et al., 2020]

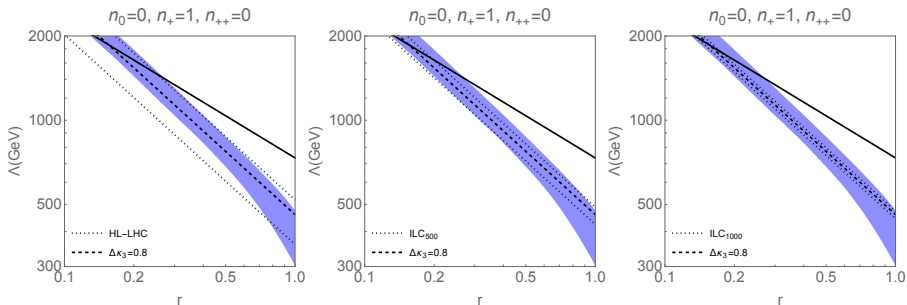
[ATLAS Coll., 2023]



- Assuming  $\langle \Delta\kappa_3 \rangle = 0$  only ILC<sub>1000</sub> can deny SFOEWPT.

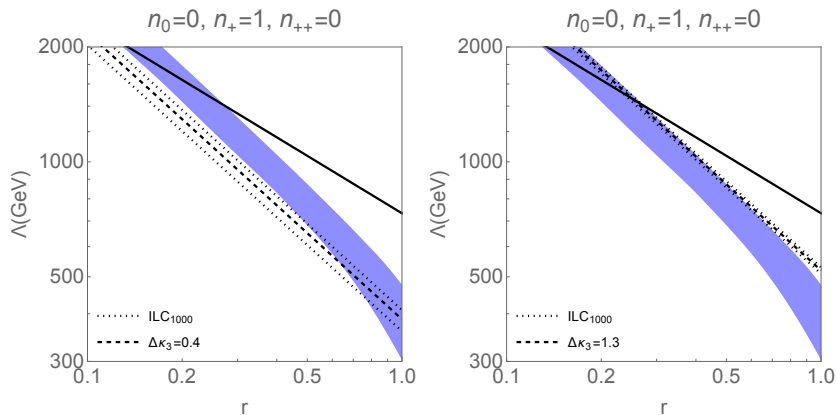
# Future colliders

- Around  $\Delta\kappa_3 = 0.8$  is the ideal value for SFOEWPT.



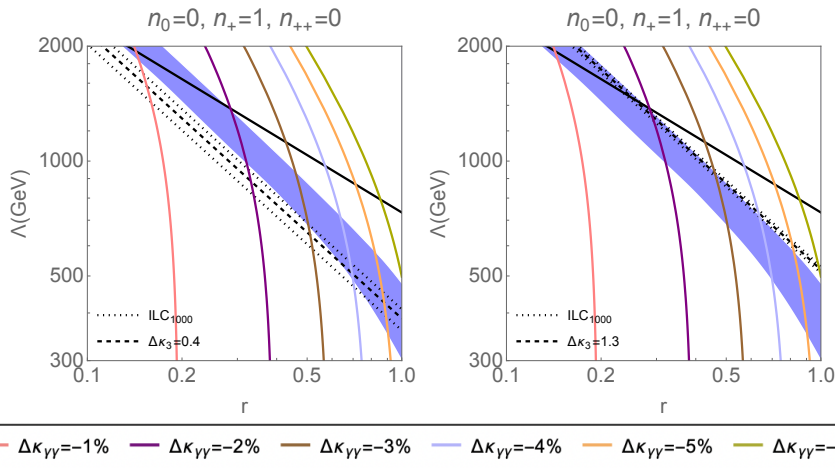
- Still, assuming  $\langle \Delta\kappa_3 \rangle = 0.8$  only  $ILC_{1000}$  can confirm SFOEWPT.

# Future colliders



- For other values of  $\langle \Delta\kappa_3 \rangle$  not even  $\kappa_3$  ILC<sub>1000</sub> measurement can confirm/deny SFOEWPT.

# Future colliders



- Measurements of  $\kappa_{\gamma\gamma}$  can solve this problem by reducing the allowed parameter space for each model, by complementing  $\kappa_3$  measurements.

# Conclusions

- We used naHEFT extended with Higgs-gauge couplings.
- We studied collider and cosmological implications on SFOPT.
- We demonstrated how future  $h \rightarrow \gamma\gamma$  precision measurements will be crucial to constrain SFOPT.
- We further calculated example required and conservative bounds on  $hhh$  in various benchmark models.
- We show how to use  $\kappa_3$  measurements at future colliders to constrain SFOPT, and again motivate  $h \rightarrow \gamma\gamma$  as a crucial complementary measurement.



Charged Singlet ( $n_0 = 0$ ):

$$V(\chi^\pm) = m_s^2 \chi^+ \chi^- + \lambda_s (\chi^+ \chi^-)^2 + \lambda_{hs} \chi^+ \chi^- \Phi^\dagger \Phi$$
$$\Lambda^2 = m_s^2 + \lambda_{hs} v^2, \quad r = \frac{\lambda_{hs} v^2}{\Lambda^2}$$

2HDM ( $n_0 = 2$ ):

$$V(H^\pm, H^0, A) = m_D^2 \phi^\dagger \phi + \lambda_{D2} (\phi^\dagger \phi)^2 + \lambda_{D3} \phi^\dagger \phi \Phi^\dagger \Phi$$
$$+ \lambda_{D4} \phi^\dagger \Phi \Phi^\dagger \phi + \frac{\lambda_{D5}}{2} \left( ((\phi^\dagger \Phi)^2 + (\Phi^\dagger \phi)^2) \right)$$
$$\Lambda_+^2 = m_D^2 + \lambda_{D3} v^2, \quad r_+ = \frac{\lambda_{D3} v^2}{\Lambda^2}$$

(Figure:  $\Lambda_+ \sim \Lambda_0 \sim \Lambda_A$ ,  $r_+ \sim r_0 \sim r_A$ )

## Extra: Coupling scaling factors

$$k_3 = \frac{g_{hhh}^{EFT}}{g_{hhh}^{SM}}, \quad k_{p=f,V} = \frac{g_{hpp}^{EFT}}{g_{hpp}^{SM}}, \quad k_{VV'=\gamma\gamma,Z\gamma} = \frac{\Gamma_{h \rightarrow VV'}^{EFT}}{\Gamma_{h \rightarrow VV'}^{SM}}$$

$$\kappa_V = \kappa_f = 1 - \kappa_2 \frac{\xi \Lambda^2}{6 v^2} r^2$$

$$\kappa_3 = 1 + \kappa_0 \frac{4\xi \Lambda^4}{3 v^2 m_h^2} \left[ r^3 - \frac{m_h^2}{8\Lambda^2} r^2 (3 - 2r) \right]$$

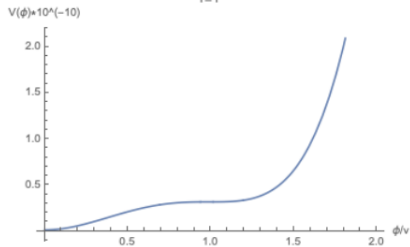
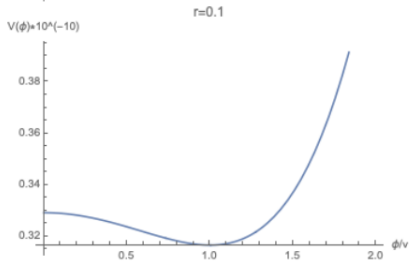
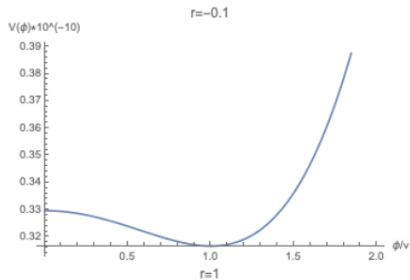
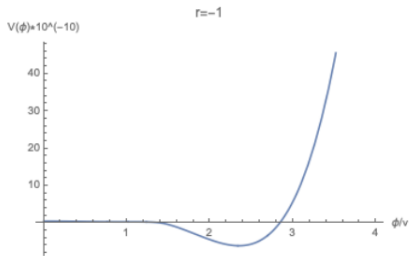
$$\kappa_{\gamma\gamma}^2 \simeq \left| \kappa_V - \frac{br}{F_{SM}} \right|^2,$$

$$F_{SM} = 6.492$$

$$\kappa_{Z\gamma}^2 \simeq \left| \kappa_V - \frac{br}{G_{SM}} (J_3^{\text{new}} - s_W^2) \right|^2,$$

$$G_{SM} = 11.65$$

# Extra 2



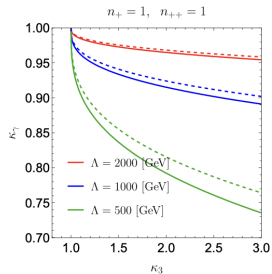
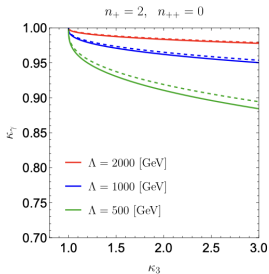
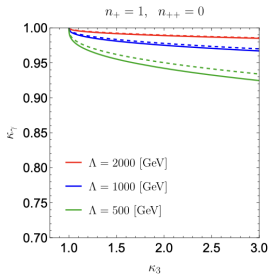
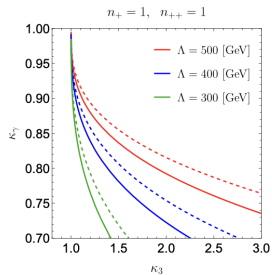
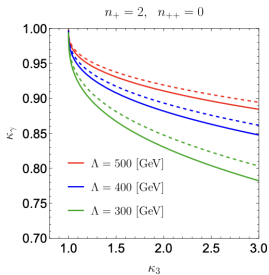
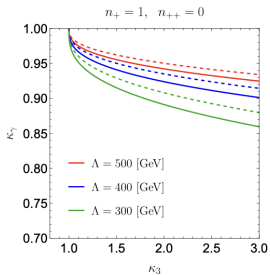
$$\mathcal{L} = \xi \left[ \mathcal{F}_B \text{Tr}\{B_{\mu\nu} B^{\mu\nu}\} + \mathcal{F}_W \text{Tr}\{W_{\mu\nu} W^{\mu\nu}\} + \mathcal{F}_{BW} \text{Tr}\{UB_{\mu\nu} U^\dagger W^{\mu\nu}\} \right]$$

$$\mathcal{L} = -\frac{1}{2} \frac{e^2}{v} a_{h\gamma\gamma} h F_{\mu\nu} F^{\mu\nu} - \frac{egc_W}{v} a_{hZ\gamma} h F_{\mu\nu} Z^{\mu\nu} + \dots$$

$$a_{h\gamma\gamma} = a_{hBB} + a_{hWW} - a_{hBW}$$

$$a_{hZ\gamma} = \frac{1}{c_W^2} \left[ -a_{hBB} s_W^2 + a_{hWW} c_W^2 - \frac{1}{2} a_{hBW} (c_W^2 - s_W^2) \right]$$

# Extra 4



# Extra 5

