Exploring first-order electroweak phase transition in the nearly aligned Higgs effective field theory

Ricardo R. Florentino

Particle Physics Theory Group
Graduate School of Science
Osaka University

Collaborators: Prof. Shinya Kanemura; Dr. Masanori Tanaka

Workshop on Multi-Higgs Models 2024

Phys.Lett.B 856 (2024) 138940 [arXiv:2406.03957]

Introduction

- 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.

naHEFT Lagrangian

- One-loop corrected Lagrangian:

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

- One-loop scalar potential:

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

- One-loop scalar-vector potential:

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

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:

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

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

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

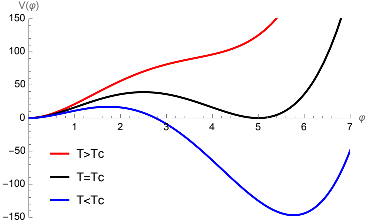
$$\mathcal{F}_W(h) = \mathcal{F}_B(h) = \frac{b}{2} \ln \left[1 - r + r\left(1 + \frac{h}{v}\right)^2\right], \quad b = \frac{n_+ + 4n_{++}}{3}$$

Cosmological Constraints

- Condition for SFOPT:

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

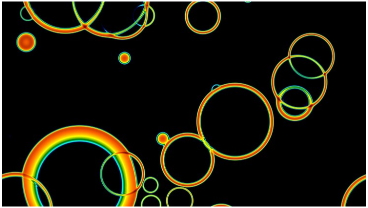
EWPT must be strong enough for EWBG



- Completion Condition:

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

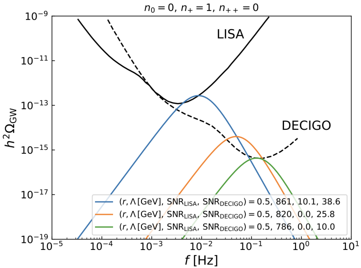
Transition rate high enough to finish PT



Cosmological Observables

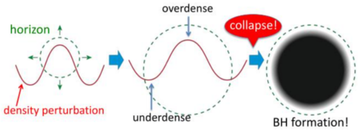
- Gravitational Waves:

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

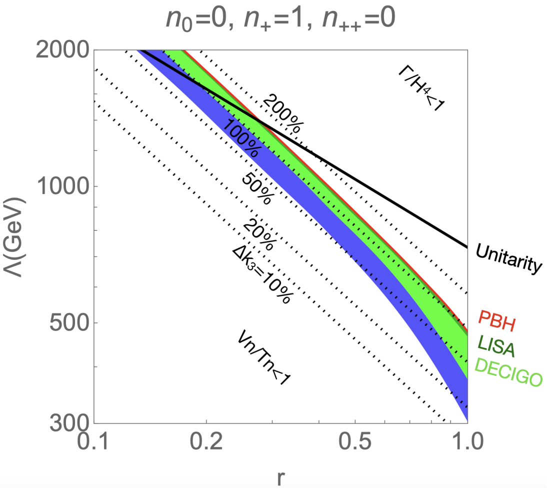


- Primordial Black Holes:

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

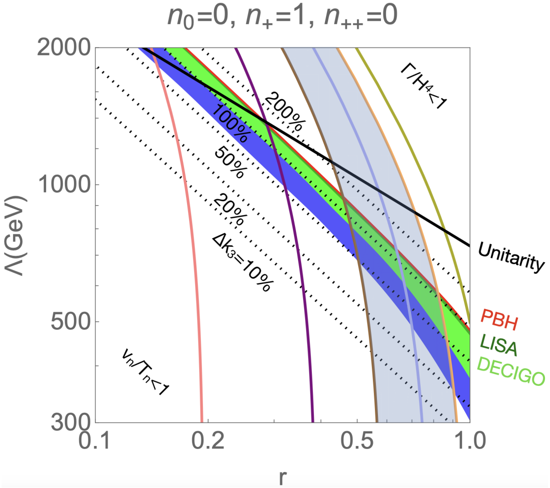


Results



- 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

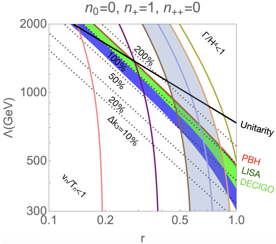


- Future $h \to \gamma\gamma$ precision measurements will constrain SFOPT parameter space.
- Measuring:
  - $\Delta\kappa_{\gamma\gamma} = (-4 \pm 1)\%$
- Implies:
  - $\Lambda \lesssim 1\,TeV$
  - $r \gtrsim 0.5$
  - $21\% < \Delta\kappa_3 < 137\%$

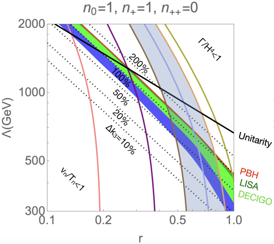
(HL-LHC $\Delta\kappa_{\gamma\gamma}$=1.8%, 1$\sigma$) .[Cepeda et al., 2019]

Results

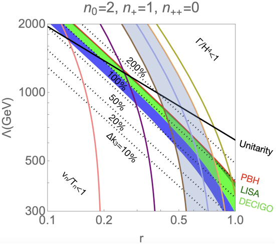
Charged Singlet

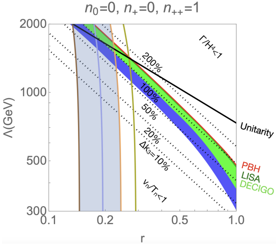


Real Triplet

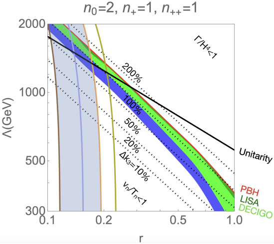


2HDM

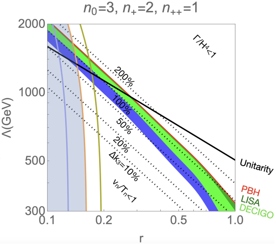




Doubly C.S.



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.)

Conclusions

- We used naHEFT extended with Higgs-gauge couplings.
- We studied collider and cosmological implications on SFOPT.
- We demonstrated how future $h \to \gamma\gamma$ precision measurements will be crucial to constrain SFOPT.
- Finally, we calculated example required and conservative bounds on *hhh* in various benchmark models.

Extra: Example models

Charged Singlet ($n_0 = 0$):

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

2HDM ($n_0 = 2$):

$$\begin{aligned} V(H^{\pm}, H^0, A) =& m_D^2 \phi^\dagger \phi + \lambda_{D2} (\phi^\dagger \phi)^2 + \lambda_{D3} \phi^\dagger \phi \Phi^\dagger \Phi \\ & + \lambda_{D4} \phi^\dagger \Phi \Phi^\dagger \phi + \frac{\lambda_{D5}}{2} \Big(((\phi^\dagger \Phi)^2 + (\Phi^\dagger \phi)^2 \Big) \\ \Lambda_+^2 =& m_D^2 + \lambda_{D3} v^2, \qquad r_+ = \frac{\lambda_{D3} v^2}{\Lambda^2} \end{aligned}$$

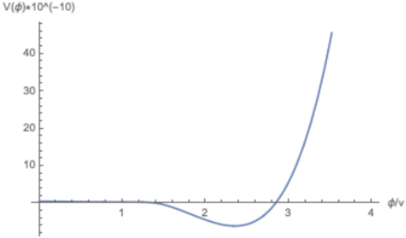
(Figure: $\Lambda_+ \sim \Lambda_0 \sim \Lambda_A$, $r_+ \sim r_0 \sim r_A$)

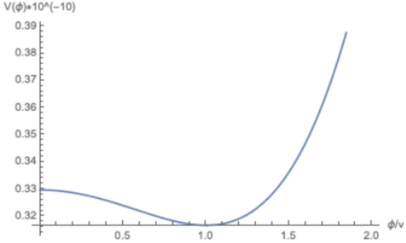
Extra: Coupling scaling factors

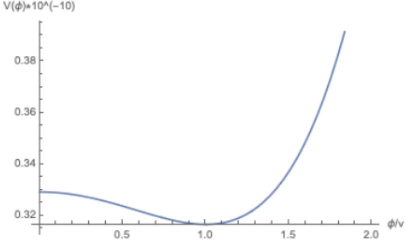
$$k_3 = \frac{g_{hhh}^{EFT}}{g_{hhh}^{SM}}, \qquad k_{p=f,V} = \frac{g_{hpp}^{EFT}}{g_{hpp}^{SM}}, \qquad k_{VV'=\gamma\gamma,Z\gamma} = \frac{\Gamma_{h\to VV'}^{EFT}}{\Gamma_{h\to VV'}^{SM}}$$

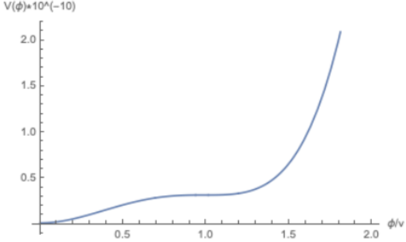
$$\begin{aligned}
\kappa_V =& \kappa_f = 1 - \kappa_2 \frac{\xi}{6}\frac{\Lambda^2}{v^2} r^2 \\
\kappa_3 =& 1 + \kappa_0 \frac{4\xi}{3}\frac{\Lambda^4}{v^2 m_h^2}\left[r^3 - \frac{m_h^2}{8\Lambda^2} r^2 (3-2r)\right] \\
\kappa_{\gamma\gamma}^2 \simeq& \left|\kappa_V - \frac{br}{F_{SM}}\right|^2, \qquad\qquad F_{SM} = 6.492 \\
\kappa_{Z\gamma}^2 \simeq& \left|\kappa_V - \frac{br}{G_{SM}}(J_3^{new} - s_W^2)\right|^2, \qquad G_{SM} = 11.65
\end{aligned}$$

Extra 2


r=−1


r=−0.1


r=0.1

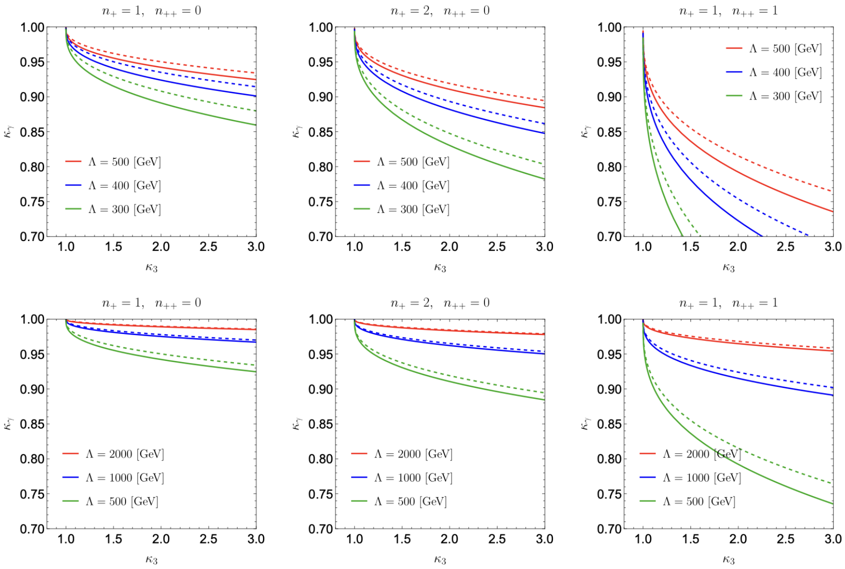

r=1

Extra 3

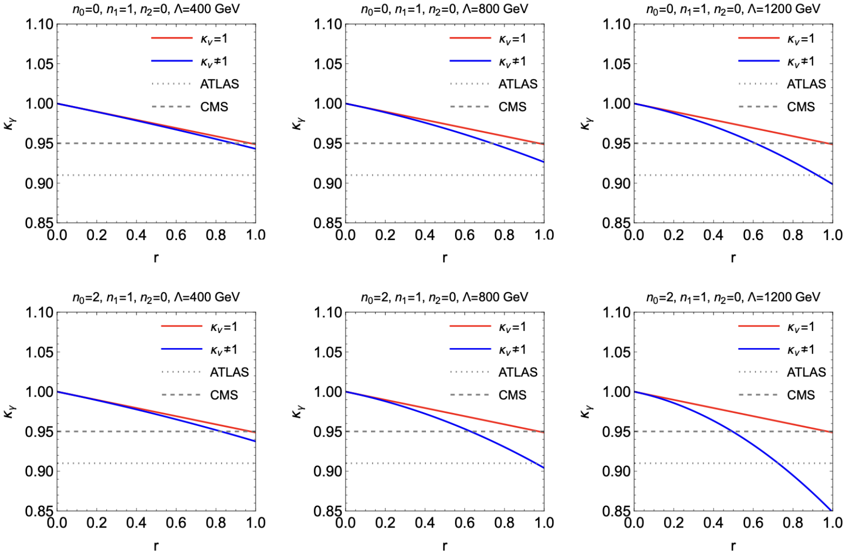
$$\begin{aligned}\mathcal{L} =& \xi \left[\mathcal{F}_B \operatorname{Tr}\{B_{\mu\nu} B^{\mu\nu}\} + \mathcal{F}_W \operatorname{Tr}\{W_{\mu\nu} W^{\mu\nu}\} + \mathcal{F}_{BW} \operatorname{Tr}\Big\{U B_{\mu\nu} U^\dagger W^{\mu\nu}\Big\}\right] \\ \mathcal{L} =& -\frac{1}{2}\frac{e^2}{v} a_{h\gamma\gamma} h F_{\mu\nu} F^{\mu\nu} - \frac{e g c_W}{v} a_{hZ\gamma} h F_{\mu\nu} Z^{\mu\nu} + \ldots\end{aligned}$$

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

Extra 4


$n_+ = 1, \quad n_{++} = 0$
$n_+ = 2, \quad n_{++} = 0$
$n_+ = 1, \quad n_{++} = 1$
κ_γ
κ_3
1.00
0.95
0.90
0.85
0.80
0.75
0.70
1.0
1.5
2.0
2.5
3.0
$\Lambda = 500$ [GeV]
$\Lambda = 400$ [GeV]
$\Lambda = 300$ [GeV]
$\Lambda = 2000$ [GeV]
$\Lambda = 1000$ [GeV]
$\Lambda = 500$ [GeV]

Extra 5


n_0=0, n_1=1, n_2=0, Λ=400 GeV
n_0=0, n_1=1, n_2=0, Λ=800 GeV
n_0=0, n_1=1, n_2=0, Λ=1200 GeV
n_0=2, n_1=1, n_2=0, Λ=400 GeV
n_0=2, n_1=1, n_2=0, Λ=800 GeV
n_0=2, n_1=1, n_2=0, Λ=1200 GeV
κ_V=1
κ_V≠1
ATLAS
CMS
κ_γ
r
1.10
1.05
1.00
0.95
0.90
0.85
0.0
0.2
0.4
0.6
0.8
1.0

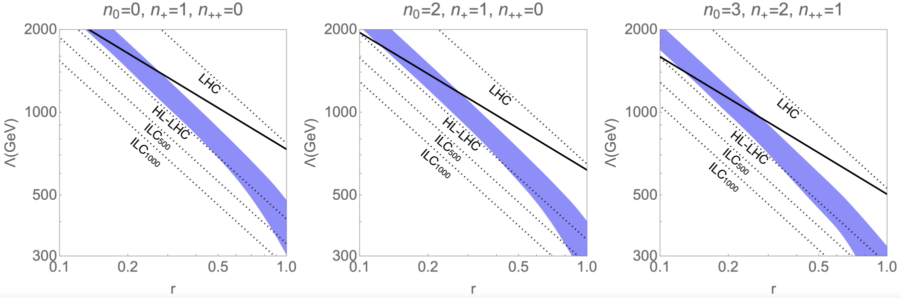
Future colliders

Collider	HL-LHC	ILC_{250}	ILC_{500}	ILC_{1000}
$\Delta\kappa_3(1\sigma)$	50%	49%	22%	10%

LHC
$-0.4 < \kappa_3 < 6.3$

[Micco et al., 2020]

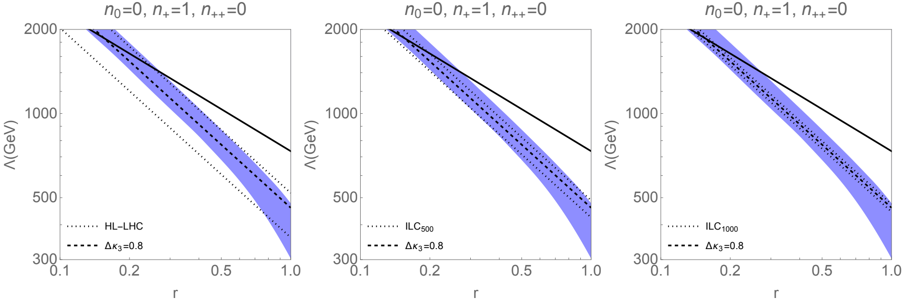
[ATLAS Coll., 2023]



- Assuming $< \Delta\kappa_3 >= 0$ only ILC_{1000} can deny SFOEWPT.

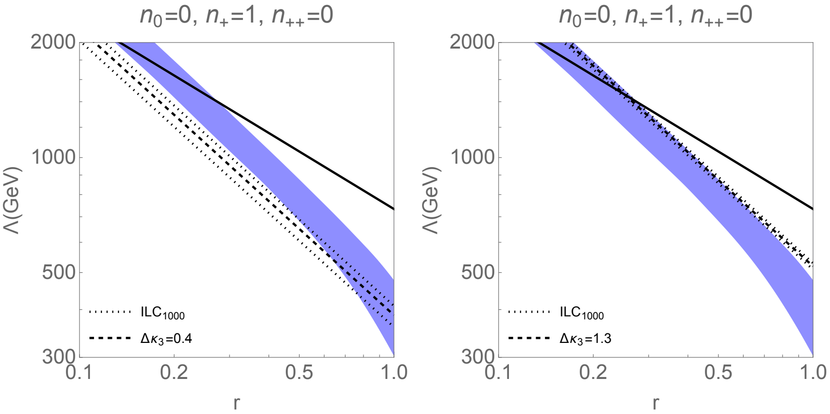
Future colliders

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



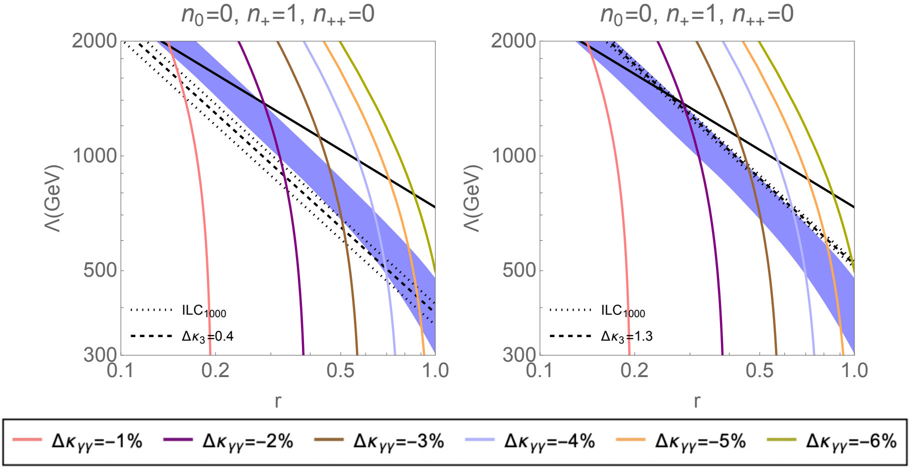
- Still, assuming $< \Delta\kappa_3 >= 0.8$ only ILC_{1000} can confirm SFOEWPT.

Future colliders



- For other values of $< \Delta\kappa_3 >$ not even κ_3 ILC_{1000} 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 κ_3 measurements.