Testing the Higgs potential, electroweak phase transition and electroweak baryogenesis at LHC and CEPC

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Outline

- Motivation
- EW baryogenesis in a nutshell
- The lagrangian in EFT and concrete model
- Hints at LHC
- Testing at the CEPC
- Summary and outlook

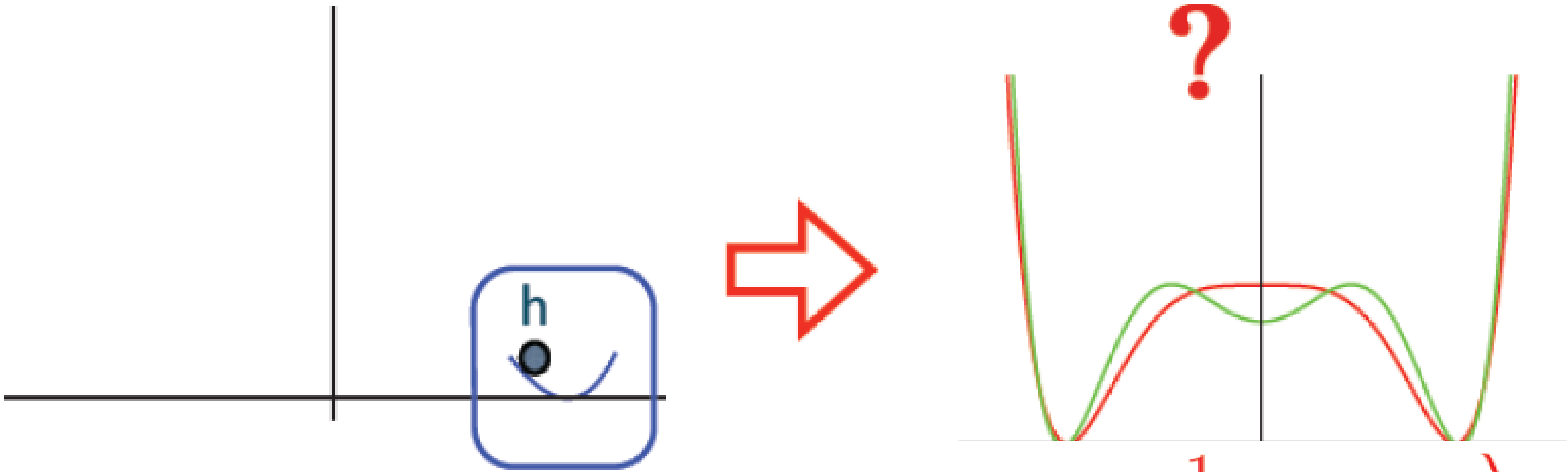
Motivation I: origin of the baryon asymmetry of the universe

A long standing problem in cosmology and particle physics is to unravel the origin of baryon asymmetry of the universe (BAU)

After the discovery of the 125 GeV Higgs boson at the LHC, electroweak (EW) baryogenesis becomes a timely and testable scenario for explaining the BAU.

$$\eta = n_B/n_\gamma = 6.05(7) \times 10^{-10} \quad (\text{ CMB })$$

Motivation II: the true shape of the Higgs potential and the type of phase transition



For the Higgs potential, we know nothing but the quadratic oscillation around the vev v with the mass 125 GeV.

$$V(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4} h^4$$

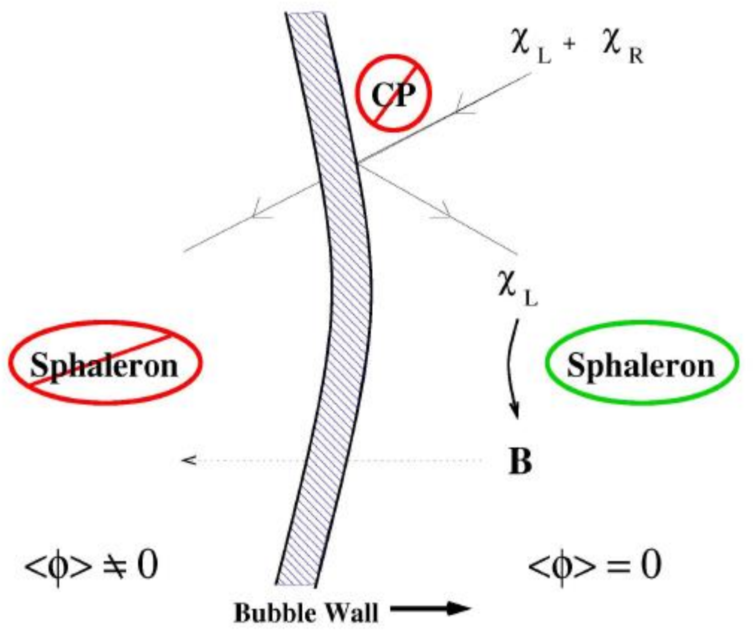
or $$V(h) = \frac{1}{2}\mu^2 h^2 - \frac{\lambda}{4} h^4 + \frac{1}{\Lambda^2} h^6$$

Baryogenesis-Sakharov conditions

Sakharov Conditions for baryogenesis (1967)

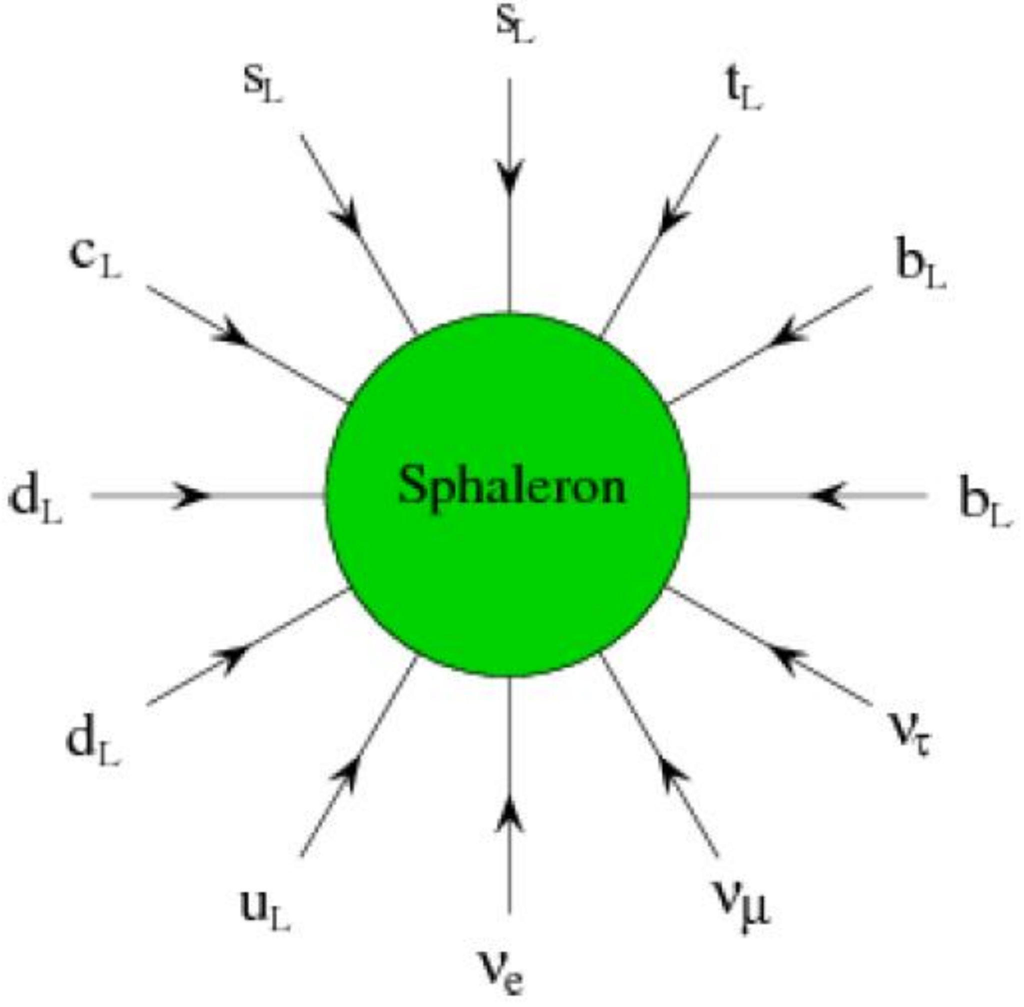
- violation of baryon number–create baryonic charge;
- CP-violation and C violation–distinguish matter from antimatter;
- departure from equilibrium dynamics or CPT violation–provide a time arrow.

EW baryogenesis in SM



- anomaly in B + L-current;
- C-violation (chiral gauge) CP-violation in KM matrix or extension of SM;
- First-order EWPT with expanding bubble walls.

B-violation in SM——Sphaleron



CP-violation souce in SM

The anomalous top coupling may provide the CP-violation source for baryogenesis. The current data still leave room for this source.

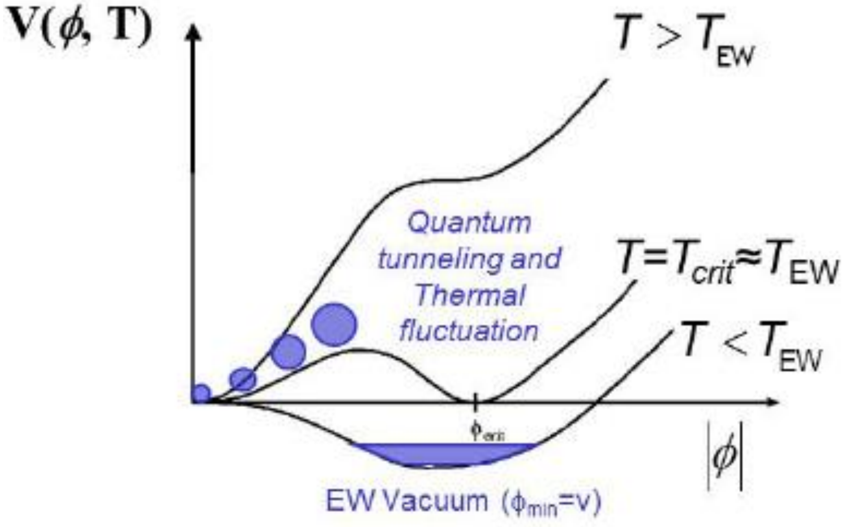
Top quark decay via flavor changing neutral currents at hadron colliders , Tao Han, R.D. Peccei, X. Zhang. Nucl.Phys. B454 (1995) 527-540
Nonstandard couplings of the top quark and precision measurements of the electroweak theory R.D. Peccei, S. Peris, X. Zhang. Nucl.Phys. B349 (1991) 305-322

Dynamical Symmetry Breaking and Universality Breakdown R.D. Peccei, X. Zhang. Nucl.Phys. B337 (1990)

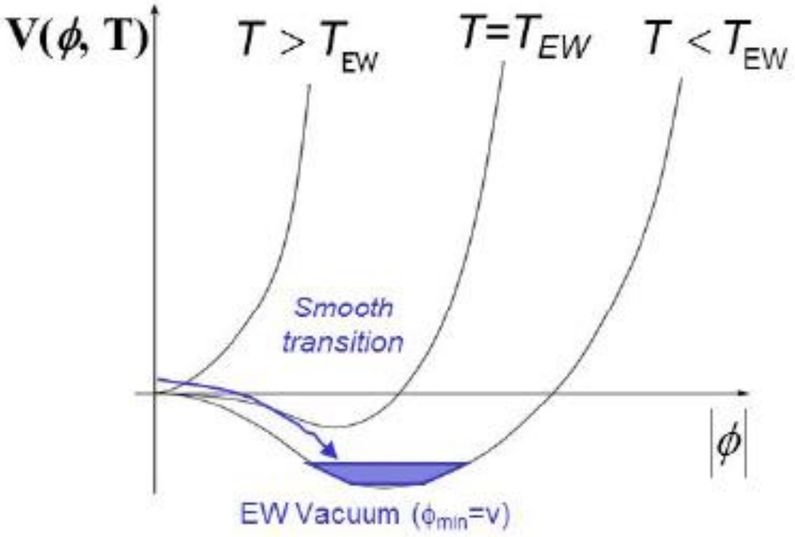
269-283 CP-violation FCNC process Yan Wan, Fa Peng Huang,et,al. Phys. Rev. D86, 094014 (2012)

Departure from thermal equilibrium —— Strong first order phase transition

Strong First Order phase transition for $m_H < 75$ GeV



Second Order phase transition for $m_H > 75$ GeV



Extension of the Higgs sector is needed to produce strong first order phase transition for 125 GeV Higgs boson.

[Operators analysis for Higgs potential and cosmological bound on Higgs mass]
[Xin-min Zhang] ([Maryland U.]). **Phys.Rev. D47 (1993) 3065-3067**

Extending the Higgs sector taking the effective field theory approach

$$\delta\mathcal{L} = -x_u^{ij}\frac{\phi^\dagger\phi}{\Lambda^2}\bar{q}_{Li}\tilde{\phi}u_{Rj} + \text{H.c.} - \frac{\kappa}{\Lambda^2}(\phi^\dagger\phi)^3$$

provide sizable CP violation source

provide another possible Higgs potential or EW symmetry breaking

Provide Strong first order phase transition

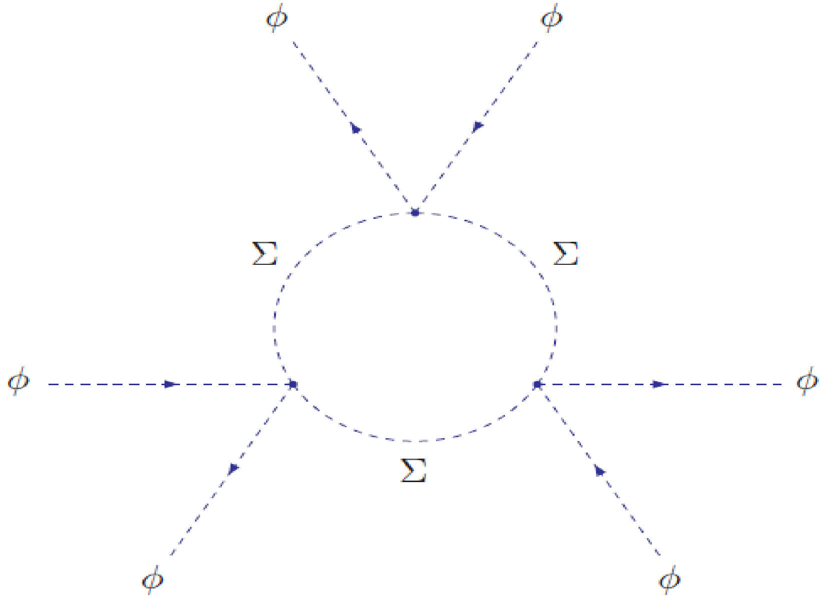
Cedric Delaunay, Christophe Grojean, James D. Wells
JHEP 0804:029,2008

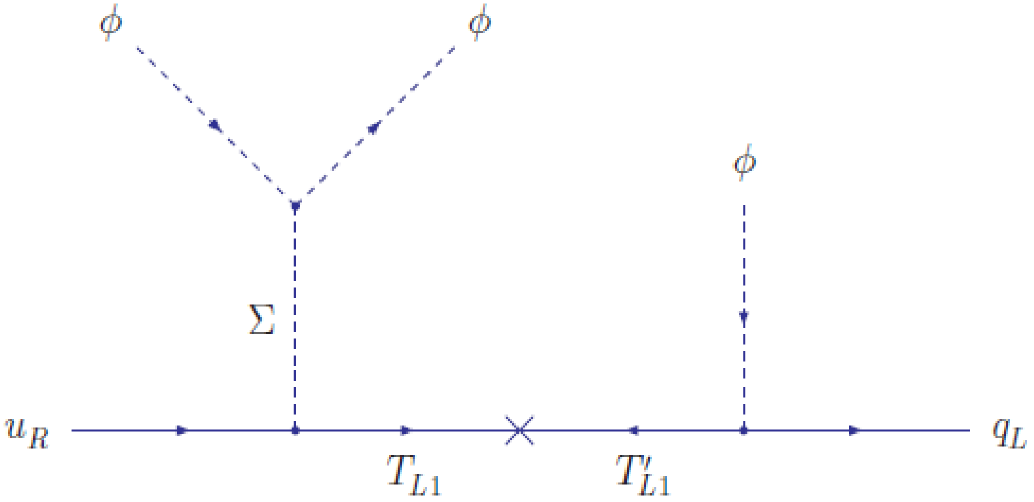
X. m. Zhang, Phys. Rev. D **47**, 3065 (1993) [hep-ph/9301277].
X. Zhang and B. L. Young, Phys. Rev. D **49**, 563 (1994) [hep-ph/9309269].
K. Whisnant, B. L. Young and X. Zhang, Phys. Rev. D **52**, 3115 (1995) [hep-ph/9410369].
X. Zhang, S. K. Lee, K. Whisnant and B. L. Young, Phys. Rev. D **50**, 7042 (1994) [hep-ph/9407259]

Fa Peng Huang, Chong Sheng Li, Phys.Rev. D92 (2015) 7, 075014

Renormalizable realization of the EFT

- The concerned dim-6 operators can be induced from certain renormalizable extension of the SM.
- We built a model with vector-like quark and triplet Higgs.





New Higgs potential and EW phase transition

$$V_{\text{tree}}(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4}h^4 + \frac{\kappa}{8\Lambda^2}h^6$$

$$V_{\text{eff}}(h,T) \approx \frac{1}{2}\left(\mu^2 + cT^2\right)h^2 + \frac{\lambda}{4}h^4 + \frac{\kappa}{8\Lambda^2}h^6$$

$$c = \frac{1}{16}\left(g'^2 + 3g^2 + 4y_t^2 + 4\frac{m_h^2}{v^2} - 12\frac{\kappa v^2}{\Lambda^2}\right)$$

New Higgs potential and EW phase transition

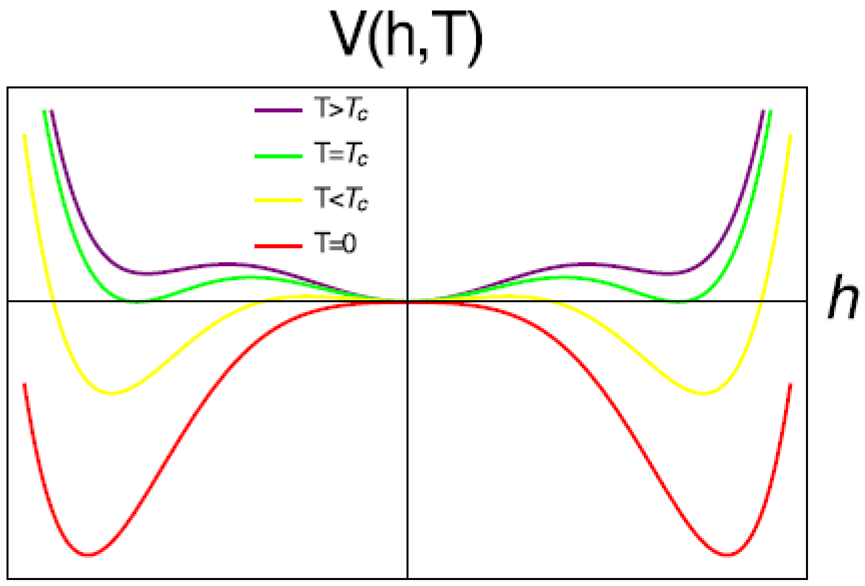
- This shape of Higgs potential may be the possible Higgs potential, which could trigger the desired spontaneous symmetry breaking as in the SM.
- To realize the SFOPT, it needs μ^2+c $T^2 > 0$ to make the EW-symmetric vacuum stable,

  $\lambda < 0$ to reverse the potential,

  and the h^6 term to stabilize the EW-broken vacuum

New Higgs potential and EW phase transition

For the Higgs potential, we know nothing but the quadratic oscillation around the vev v with the mass 125 GeV.



$$\lambda = \frac{m_h^2}{2v^2}\left(1 - \frac{\Lambda_{\rm max}^2}{\Lambda^2}\right) \qquad \lambda(\Lambda \to \infty) = \frac{m_h^2}{2v^2},$$

$$\mu^2 = \frac{m_h^2}{2}\left(-1 + \frac{\Lambda_{\rm max}^2}{2\Lambda^2}\right) \qquad \mu^2(\Lambda \to \infty) = -\frac{m_h^2}{2}$$

Strong first order phase transition

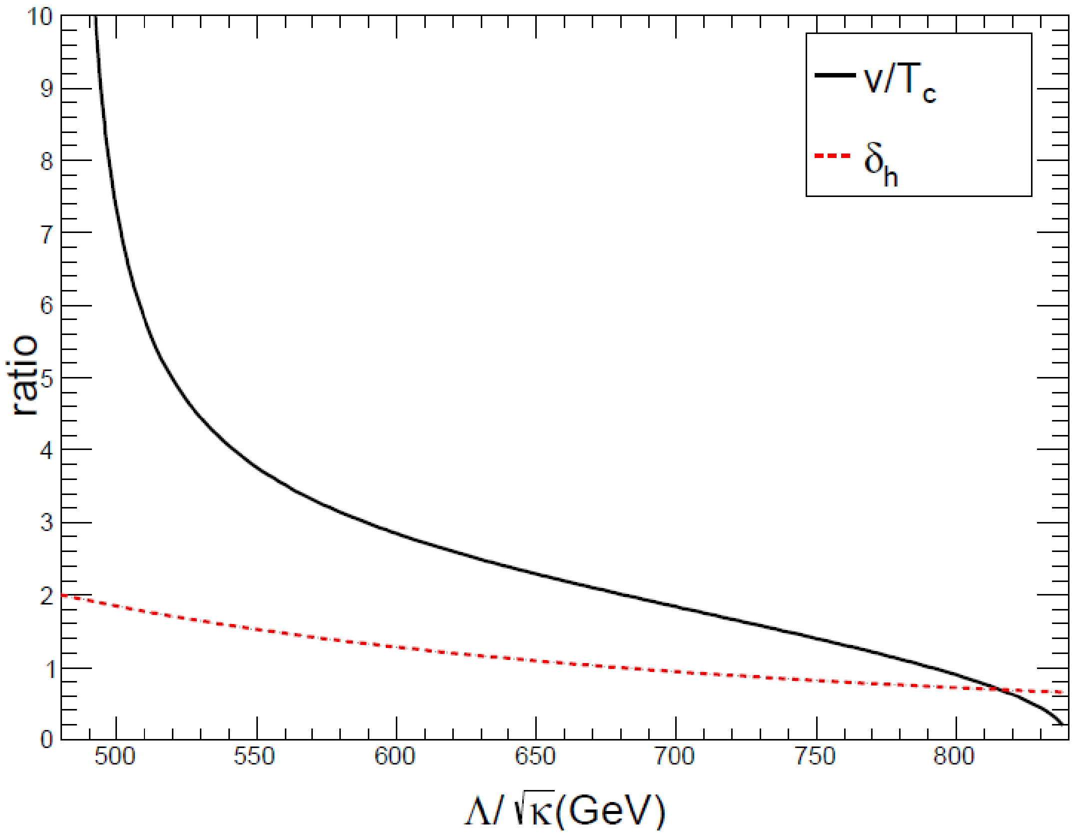
$$T_c = \frac{\sqrt{\lambda^2\Lambda^2 - 4\kappa\mu^2}}{2\sqrt{c\kappa}} > 0 \quad \frac{v(T_c)}{T_c} = \frac{2\Lambda\sqrt{-c\lambda}}{\sqrt{\lambda^2\Lambda^2 - 4\kappa\mu^2}} \gtrsim 1$$

$$\Lambda_{\max} = \sqrt{3\kappa v^2}/m_h \approx 840\sqrt{\kappa}\ \mathrm{GeV}$$

$$\Lambda_{\min} \equiv \Lambda_{\max}/\sqrt{3} = \sqrt{\kappa v^2}/m_h$$
$$\approx 480\sqrt{\kappa}\ \mathrm{GeV}$$

Strong first order phase transition leads to obvious deviation of the tri-linear Higgs coupling

$$\mathcal{L}_{hhh} = -\frac{1}{3!}(1+\delta_h)A_h h^3$$



Easy to realize the strong first order phase transition

$$\boldsymbol{\delta_h \in (\frac{2}{3}, 2)}$$

CP violation source

$$-x_u^{ij}\frac{\phi^\dagger\phi}{\Lambda^2}\bar{q}_{Li}\tilde{\phi}u_{Rj}+\mathrm{H.c.}$$

Provide sizable CP violation source

We only consider the top quark case , and then the operator can be parameterized as

$$\mathcal{L}=-\frac{m_t}{v}h\bar{t}(1+\delta_t^+ + i\delta_t^-\gamma^5)t$$

CP violation source

The top quark aquires a complex mass inside the bubble during the phase transition:

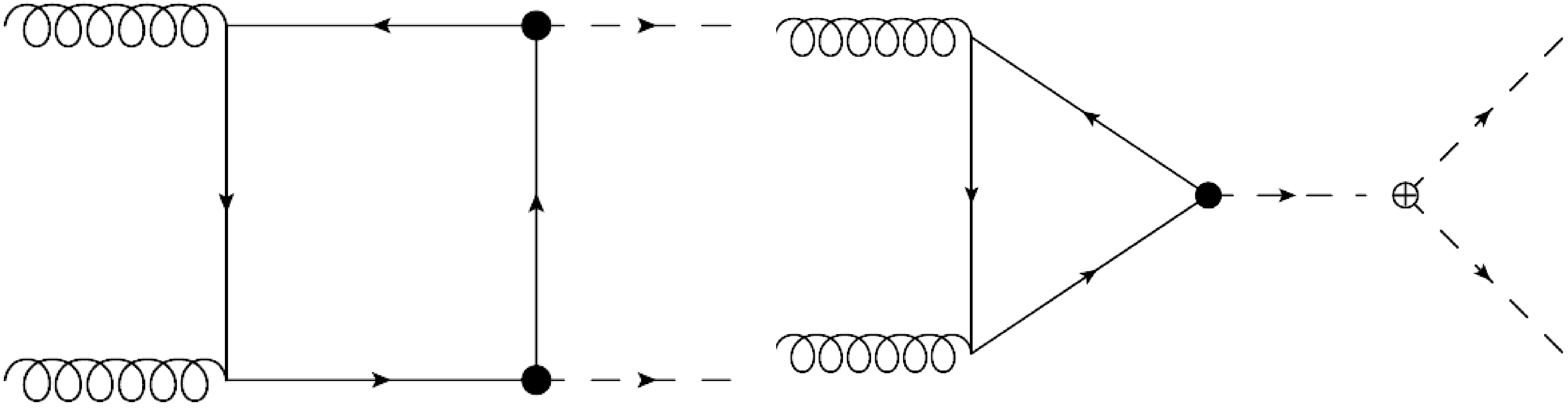
$$m_t(z) = \frac{m_t}{v}(1 + \delta_t^+ + i\delta_t^- \gamma^5)h(z)$$

$$\eta = 6.05(7) \times 10^{-10} \Longrightarrow \delta_t^- = \mathcal{O}(0.01 - 1)$$

We assume that the severe constraints from the EDM are relaxed by other new physics beyond the SM .

Hints at the LHC: Higgs pair production!

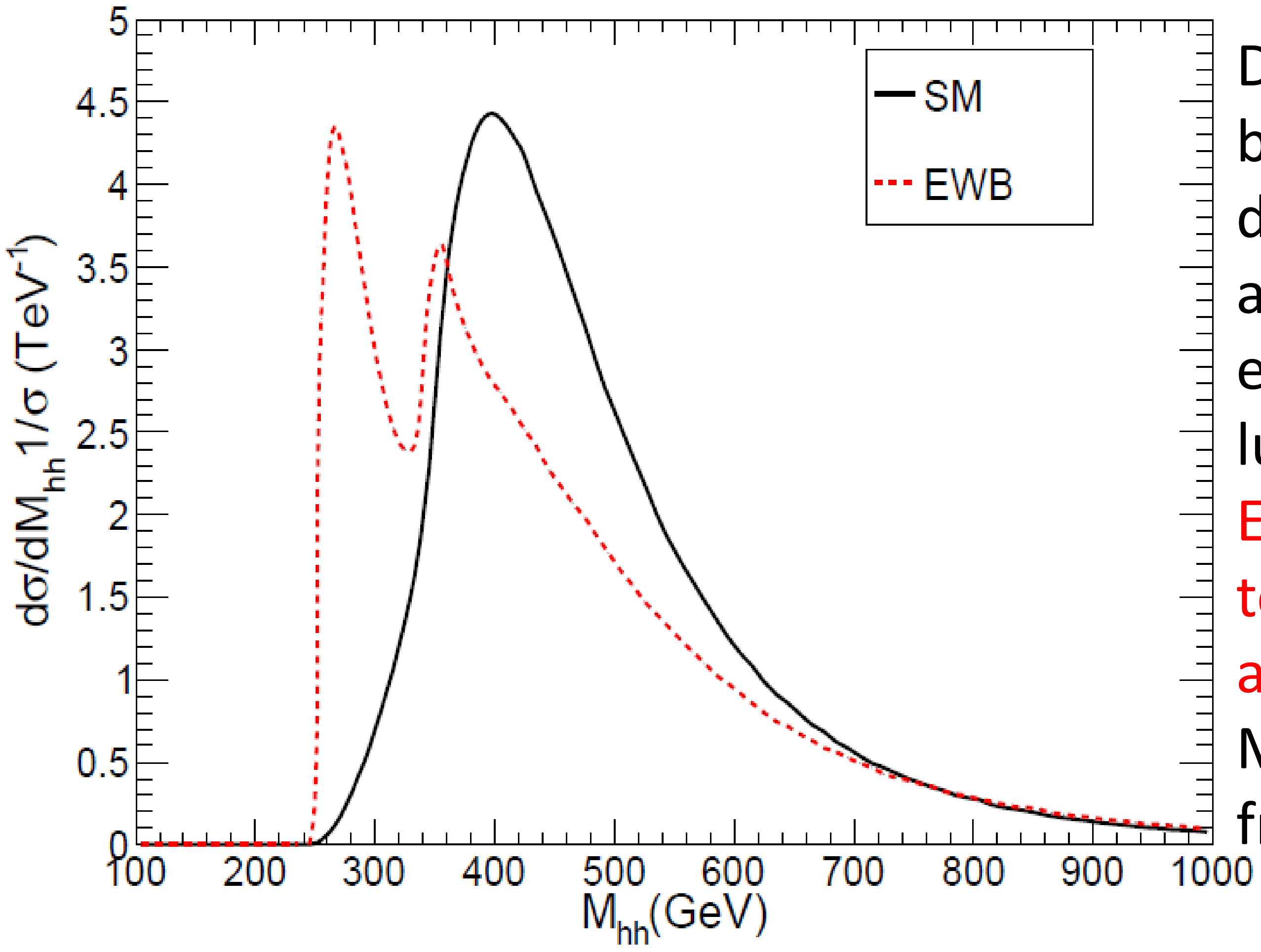
$$-\mathcal{L} = \frac{1}{3!}\left(\frac{3m_h^2}{v}\right)(1+\delta_h)\,h^3 \;+\; \frac{m_t}{v}h\bar{t}(1+\delta_t^+ + i\delta_t^-\gamma^5)t$$



Modify the Higgs pair production at the LHC

$$
\begin{aligned}
\frac{d\hat{\sigma}(gg \to hh)}{d\hat{t}} = \frac{G_F^2 \alpha_s^2}{512(2\pi)^3} \Bigg\{ \Big| & (1+\delta_h)(1+\delta_t^+)\mathcal{P}(\hat{s}) F_\triangle^A \\
& + (1+\delta_t^+)^2 F_\Box^{AA} + (\delta_t^-)^2 F_\Box^{BB} \Big|^2 \\
+ \Big| (1+\delta_t^+)\delta_t^- G_\Box^{AB} \Big|^2 & + \Big| (1+\delta_t^+)^2 G_\Box^{AA} + (\delta_t^-)^2 G_\Box^{BB} \Big|^2 \\
+ \Big| (1+\delta_h)\delta_t^- \mathcal{P}(\hat{s}) F_\triangle^B & + (1+\delta_t^+)\delta_t^- F_\Box^{AB} \Big|^2 \Bigg\},
\end{aligned}
$$

Invariant mass distribution of Higgs pair production at the LHC induced by the dim-6 operators



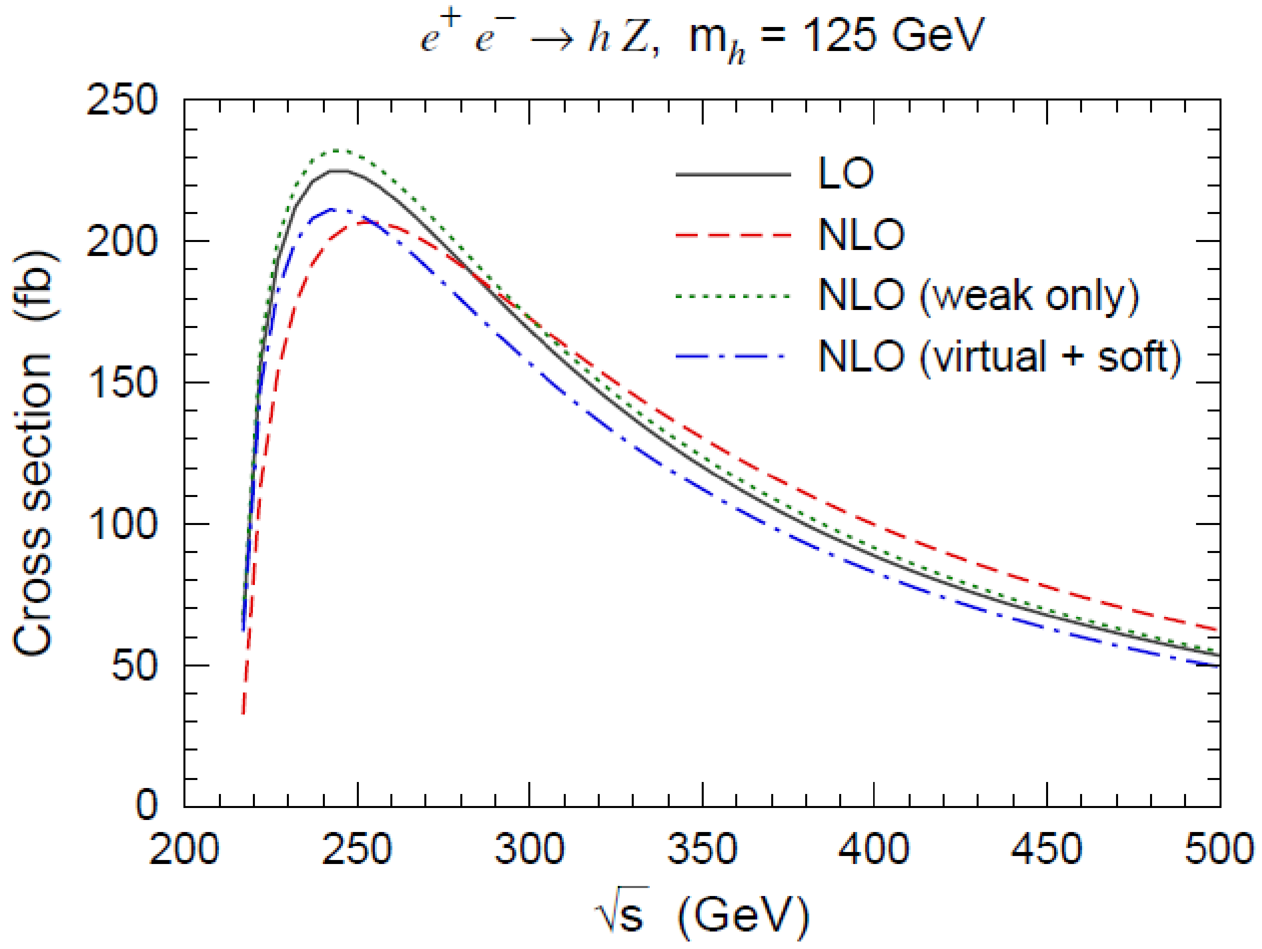
Due to the difficulties to suppress the backgrounds at the LHC, it will be difficult to completely pin down these anomalous couplings at the 14TeV LHC, even with 3000 fb^{-1} integrated luminosity.

Exploiting the boosted tricks may help to increase the ability to extract the anomalous couplings.

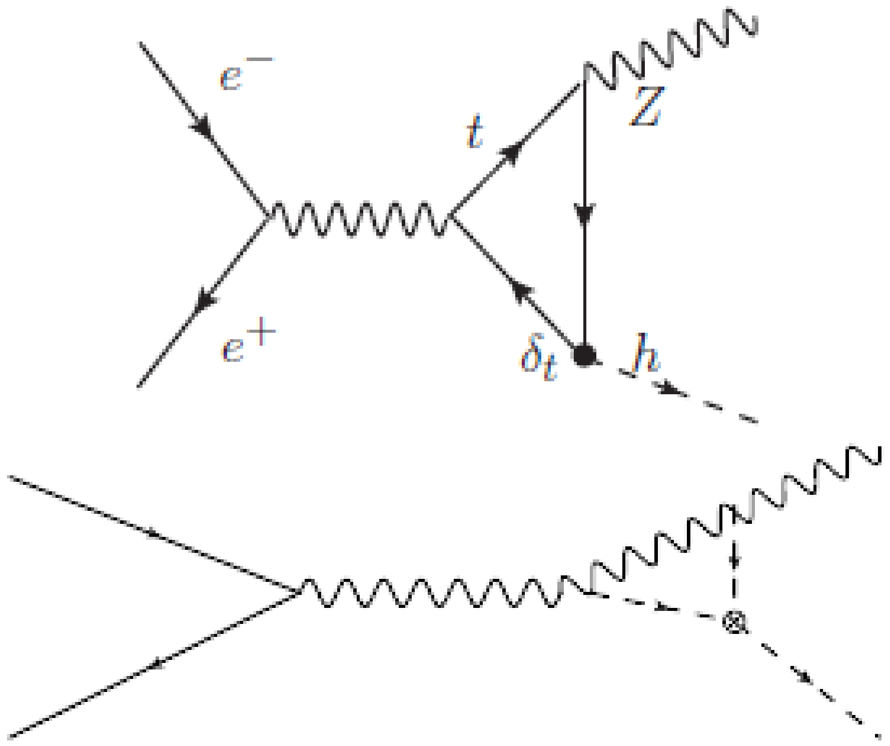
More precise information may come from the future CEPC experiments.

The Circular Electron Positron Collider (CEPC) can precisely test this scenario through precise measurements of the Zh production.

The NLO Zh cross section cross section in the SM.

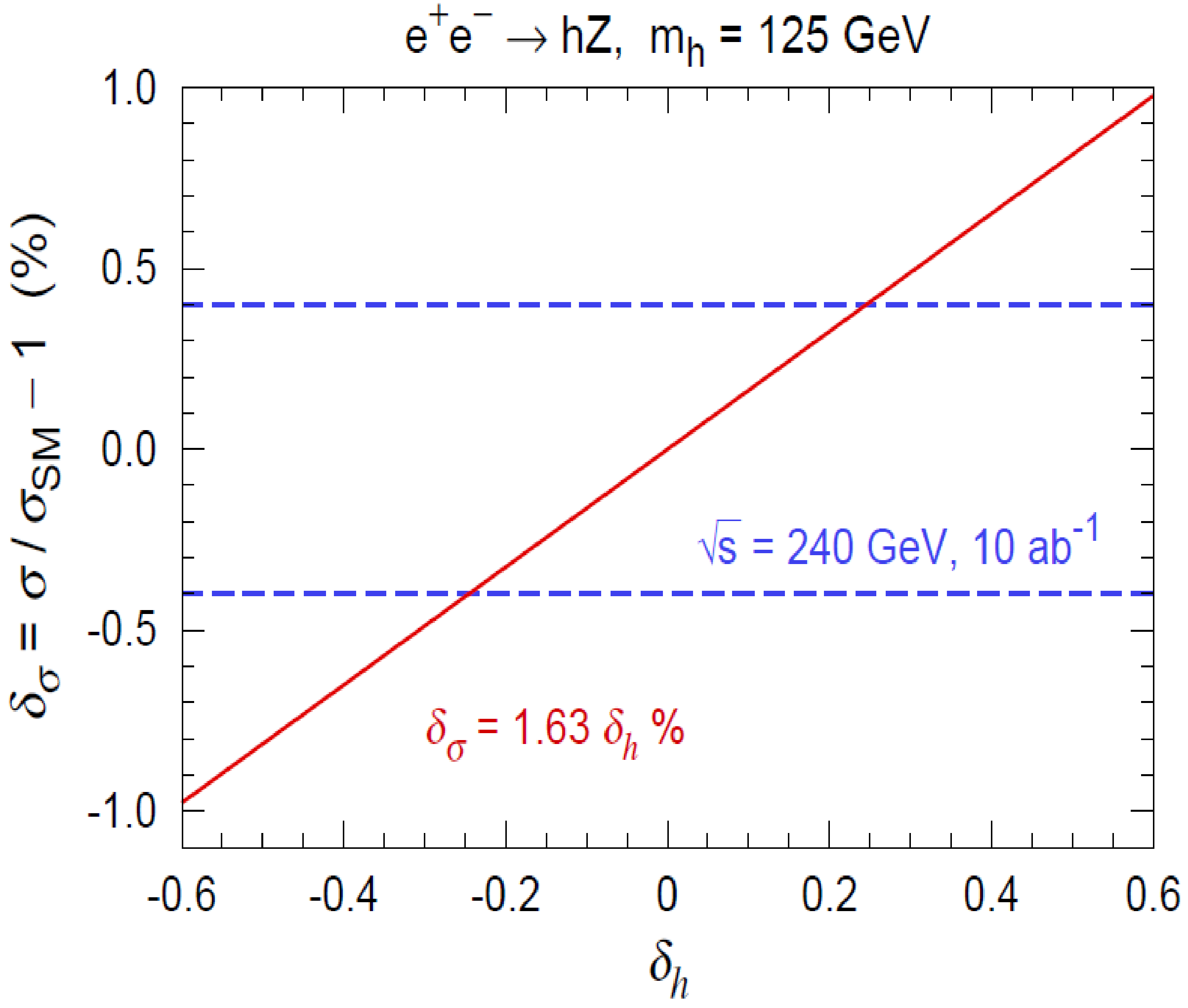


In this scenario for explaining the EW phase and EW baryogenesis, the anomalous tri-linear Higgs coupling and top quark Yukawa coupling will contribute to the cross section of Zh.



Firstly, we extract the anomalous Higgs tri-linear coupling at 240 GeV.

$$\delta_\sigma = \frac{\sigma_{hz,\delta_h \neq 0}}{\sigma_{hz,SM}} - 1$$



Pin down the tri-linear Higgs coupling

For the future CEPC with the integrated luminosity of 10 ab^{-1} at $\sqrt{s} =$ 240 GeV , the precision of the σ_{zh} may be about 0.4% . Therefore, it is possible to test the δ_h $\sim 25\%$ at the CEPC.

Matthew McCullough arXiv:1312.3322

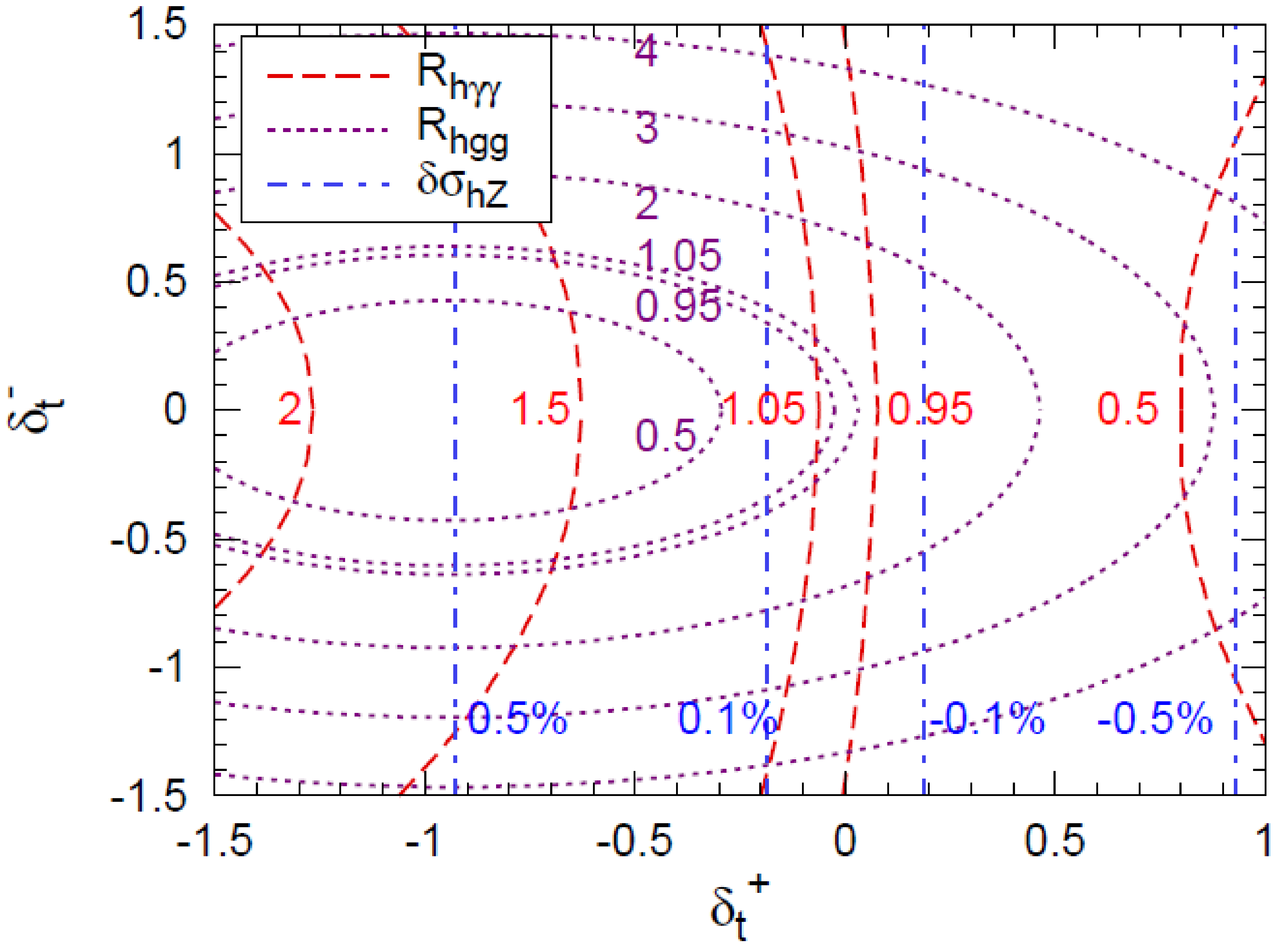
Since the new type of the Higgs potential (or the strong first order phase transition) leads to the modification of the tri-linear Higgs boson coupling from 2/3 to 2, which is well within the CEPC's precision.

Thus, the CEPC has the ability to test the shape of the Higgs potential and the type of the EW phase transition.

Challenging to test the anomalous top quark Yukawa coupling :need precise measurements of the Higgs partial decay width

$$g^2_{hgg}/g^2_{hgg,SM} \simeq (1+\delta_t^+)^2 + 0.11\delta_t^+(1+\delta_t^+) + 2.6(\delta_t^-)^2$$
$$g^2_{h\gamma\gamma}/g^2_{h\gamma\gamma,SM} \simeq (1-0.28\delta_t^+)^2 + (0.43\delta_t^-)^2.$$

$$R_{hXX} = \frac{\sigma_h \times Br(h\to XX)}{\sigma_h^{SM} \times Br(h\to XX)^{SM}} = \frac{\sigma_h}{\sigma_h^{SM}}\frac{\Gamma_{hXX}}{\Gamma_{hXX}^{SM}}\frac{\Gamma_{tot}^{SM}}{\Gamma_{tot}},$$



$R_{h\gamma\gamma}$
R_{hgg}
$\delta\sigma_{hZ}$
4
3
2
1.05
0.95
0.5
2
1.5
1.05
0.95
0.5
0.5%
0.1%
-0.1%
-0.5%
1.5
1
0.5
0
-0.5
-1
-1.5
-1.5
-1
-0.5
0
0.5
1
δ_t^-
δ_t^+

Summary and outlook

- The SM Higgs sector is extended using the EFT approach and a concrete renormalizable model is built to realize the EFT .

- The dim-6 effective operator can provide another possible Higgs potential, which can triger the EW symmetry breaking , which can keep the Higgs mass and vev.

- The dim-6 effective operator can enforce the strong first order phase transition and provide sizable CP violation to realize a successful electroweak baryogenesis.

- In this scenario, the trilinear Higgs coupling and the top quark Yukawa coupling can be modified obviously, which leads to different Higgs pair invariant mass distribution at the LHC and Zh cross section at the CEPC.

- The CEPC may precisely test this scenario.

Summary and outlook

- Since the 125 GeV Higgs boson has been discovered at the LHC, it becomes a central issue to unravel the structure of the Higgs potential and the nature of the EW baryogenesis at the LHC and the CEPC.

- However, there are so many possibilities, related to all possibilities of the Higgs sector extension.

- Each type of extension is need to study in detail at LHC and CEPC.

- Just at the corner with the improvement the experimental precision.

Thanks for your attention！