Probing the nature of electroweak phase transition from CEPC to gravitational waves detectors

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based on arXiv:1511.03969 with Pei-Hong Gu, Peng-Fei Yin, Zhao-Huan Yu Xinmin Zhang and arXiv:1601.01640 with Youping Wan,Dong-Gang Wang, Yifu Cai, Xinmin Zhang

CEPC/SPPC Conference

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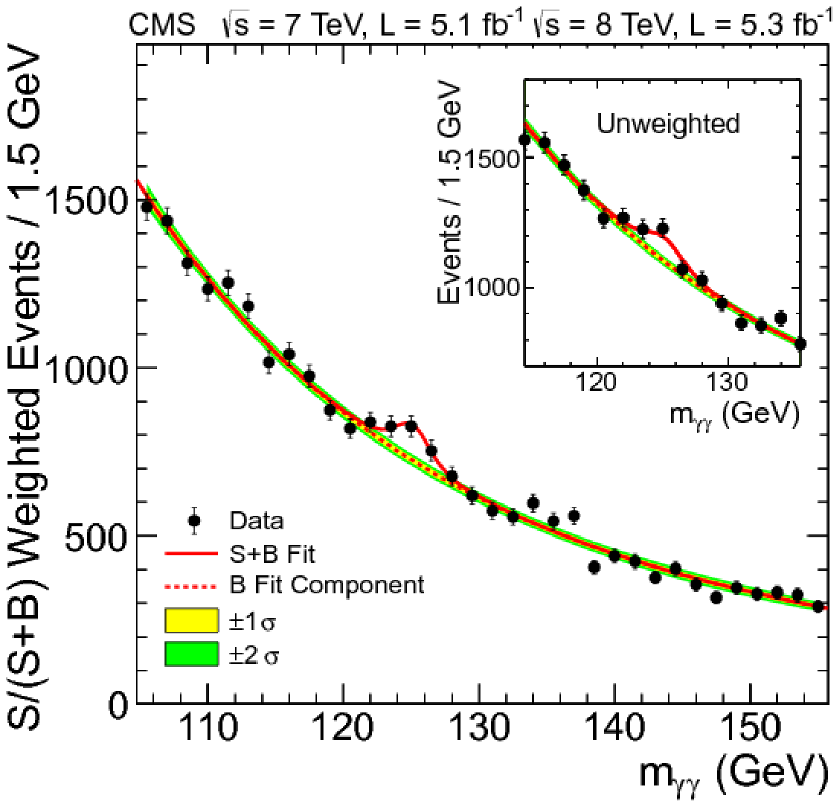
Outline

- **Motivation**
- **Electroweak baryogenesis in a nutshell**
- **The effective Lagrangian and concrete model**
- **Hints at the hadron collider**
- **Testing at the lepton collider**
- **Gravitational wave detection**
- **Summary and outlook**

Higgs Independence Day:4 July 2012@LHC

coincidence or deliberate ?

Post-Higgs era



- The discovery of 125 GeV scalar at the LHC opens a new window to study the fundamental physics, such as **neutrino mass**, **Higgs (portal) inflation**, **Higgs dark energy**, **Higgs baryogenesis(Higgs cosmology)**, and **the 2015 theory highlight "relaxation"**…….
- However, there still exists urgent problem in particle physics of post-Higgs era, namely exploring the true shape of the Higgs potential, the nature of the EW SSB, and the type of the EW phase transition.

The nature of the Higgs potential may related to all the fundamental problems!

Cosmological Constant problem:inflation,dark energy;
the largest hierarchy:

The 125 GeV Higgs boson–so simple, yet not so natural !
CEPC/SPPC helps to understand these problems.

$$C_0 \approx (2 \times 10^{-3}\mathrm{eV})^4 \ll \mathrm{M_P^4}$$

hierarchy problem,
the order of EW phase transition, baryogenesis(This talk focuses on this topic.)

$$\mathcal{L}_{Higgssector} = C_0 - \mu^2 H^\dagger H + \lambda (H^\dagger H)^2 + (y_{ij}\bar{\Psi}_{Li}\Psi_{Rj} + h.c.)$$

triviality/stability of EW vacuum

flavor;
CP-violation;
mass and mixing hierarchy

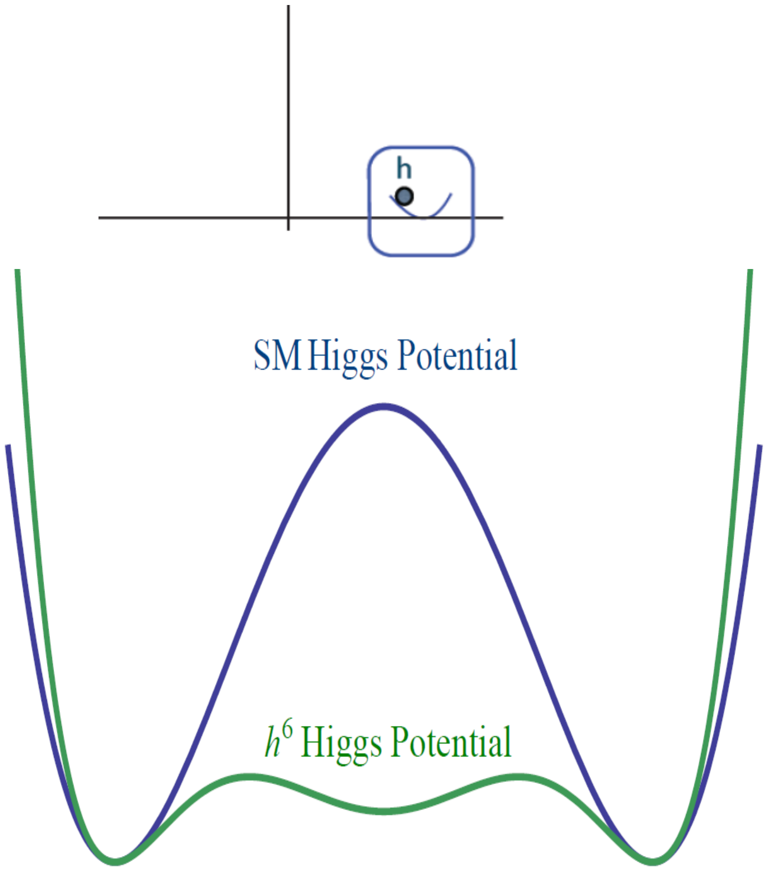
$$+\mathcal{O}_{hidden} H^\dagger H$$

Higgs portal scenario,hidden sector of new physics,Higgs inflation......

Precise higher order calculations in SM.

Phenomenology of new physics.

What is the true shape of the Higgs potential and the type of EW phase transition?



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

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

or

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

Pre CDR of CEPC

arXiv:1511.06495 Nima Arkani-Hamed, Tao Han, Michelangelo Mangano, Lian-Tao Wang

The true shape of the Higgs potential and the type of EW phase transition

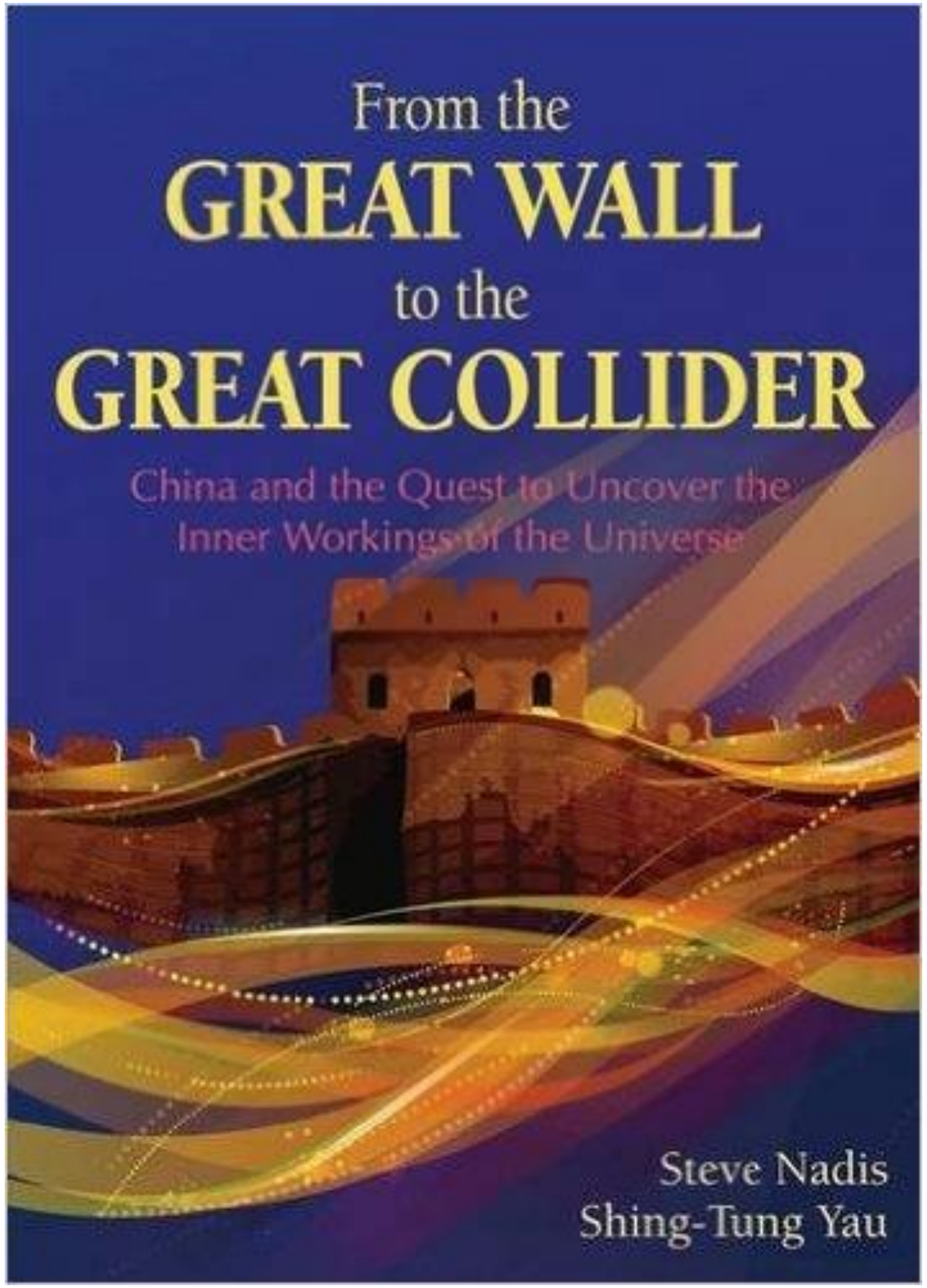
The baryon asymmetry of the universe (BAU) may be generated by some combination of other baryogenesis mechanisms.
However, EW phase transition is the last period to affect the BAU.

First order EW phase transition ⟺

- **The true shape of Higgs potential**
- Baryon **asymmetry of the universe**
- **Gravitational wave**

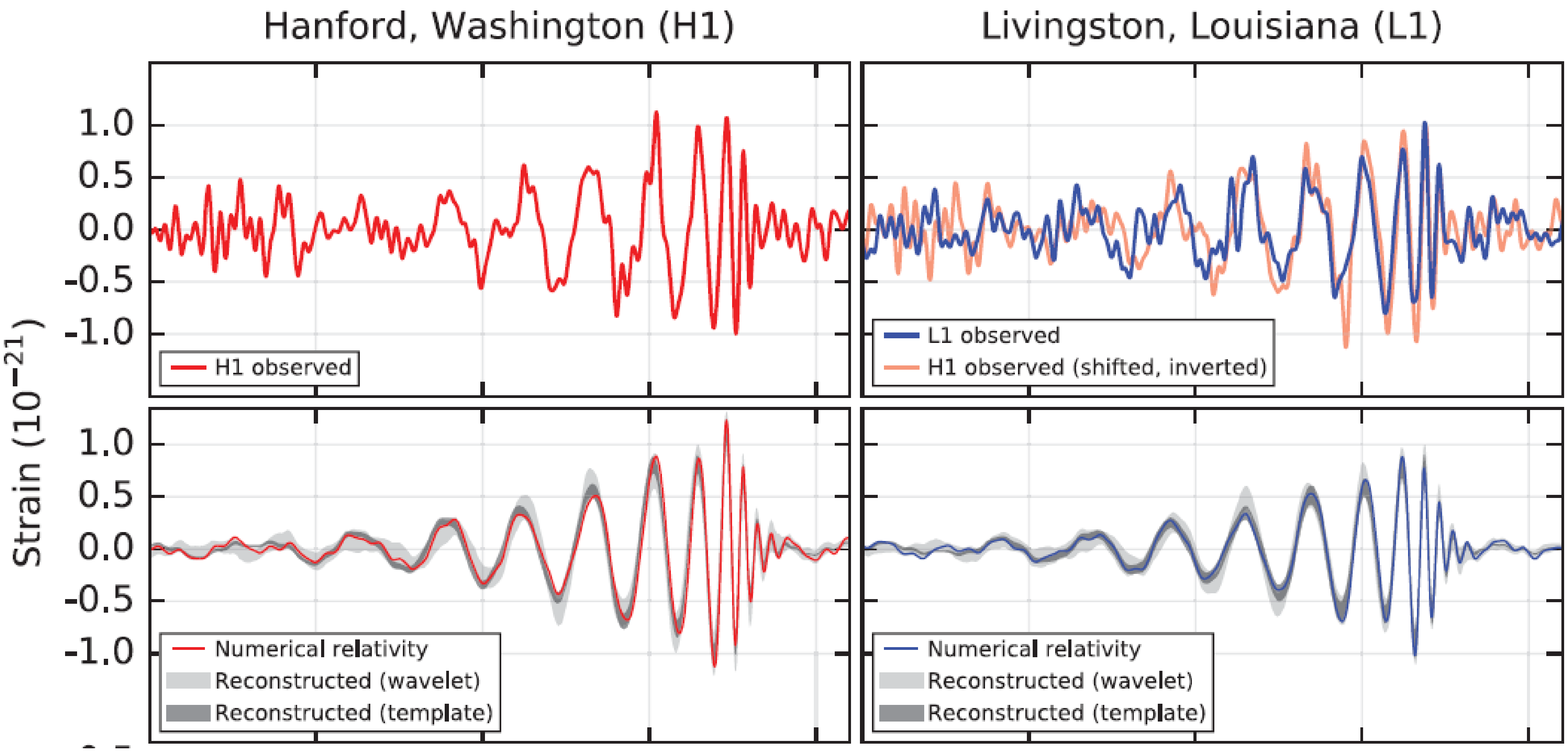
The current particle collider has no ability to unravel the true shape of the Higgs potential, we need new experimental approaches.

A： Directly, we can build more powerfull colliders, such as the planned CEPC/SPPC in China.



B:Indirectly, GW detectors can test true Higgs potential as complementary approach.

The Dawn of the Gravitational Wave physics:



Motivation from cosmology: origin of the baryon asymmetry of the universe

A long standing problem in particle cosmology 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.

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

Baryogenesis-Sakharov conditions(1967)

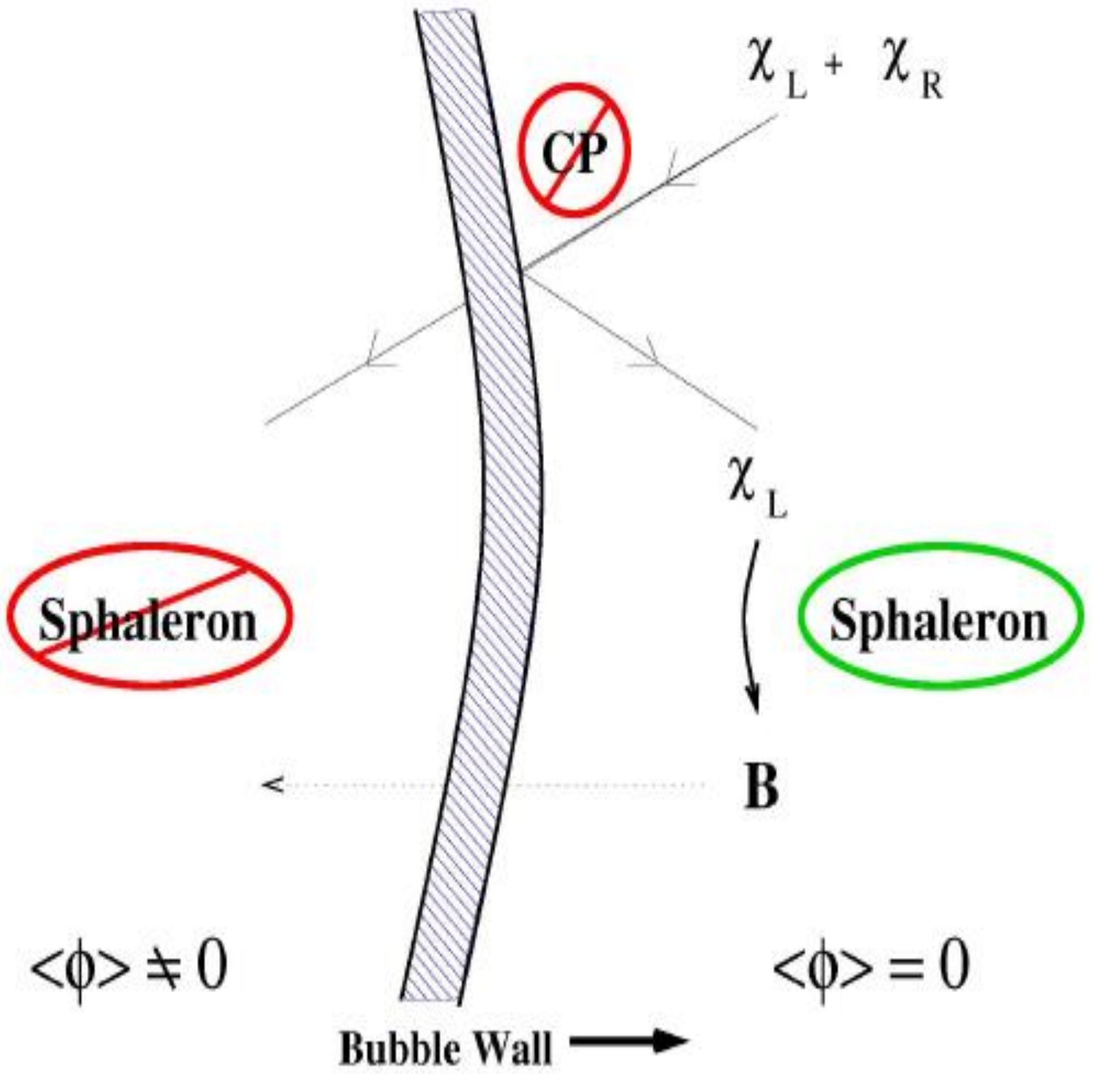
To produced the observed BAU, three necessary conditions are needed at the same cosmic epoch:

- Baryon number violation: create baryonic charge
- C and CP violation: distinguish matter from anti-matter
- Departure from thermal equilibrium or CPT violation: provide a time arrow

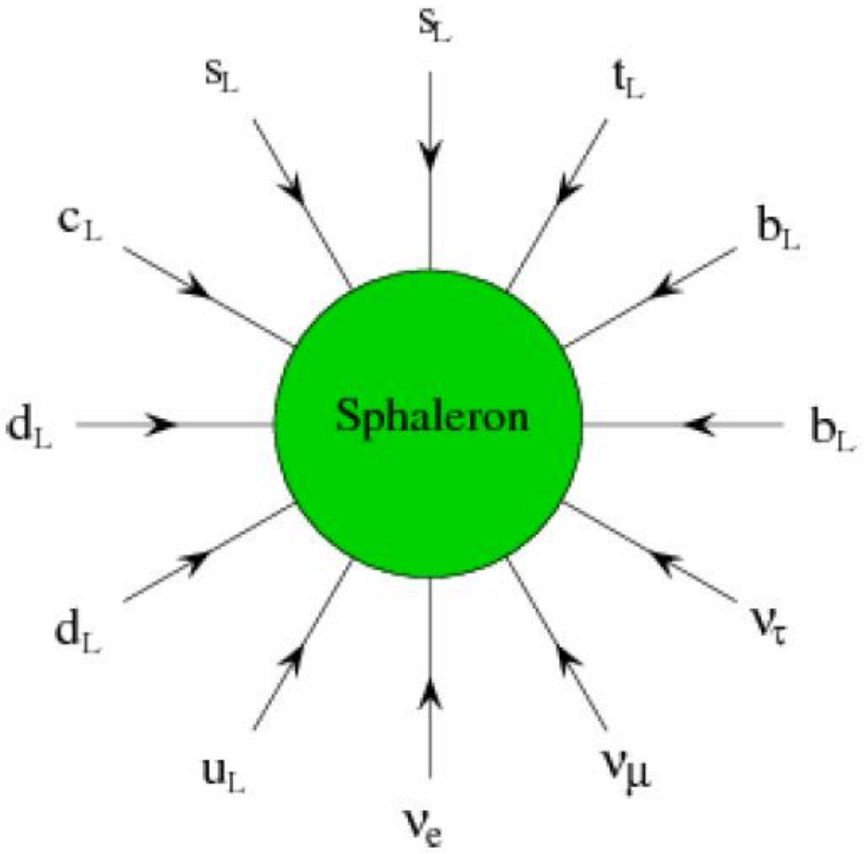
EW baryogenesis:

SM technically has all the three elements for baryogenesis , but not enough.

- B violation from anomaly in B+L current.
- CKM matrix, but too weak.
- First order phase transition with expanding Higgs Bubble wall.



B-violation in SM——Sphaleron process



$$\partial_\mu J^\mu_{B_L+L_L} = \frac{3g^2}{32\pi^2}\epsilon_{\alpha\beta\gamma\delta}W_a^{\alpha\beta}W_a^{\gamma\delta}$$

Baryon number is violated in electroweak interactions through non-perturbative effect ,i.e.triangle anomaly in baryonic current

This process trades three leptons, one from each generation, for nine quarks, three within each generation, and one of each color per generation

Manton, P.R.D28(‘83)

Boris M. Kastening, R.D. Peccei, X. Zhang (UCLA)

Phys.Lett. B266 (1991) 413-418

CP-violation souce in SM

Driven by the current LHC data, it still leaves room for the anomalous top quark Yukawa coupling, which may provide the CP-violation source for EW baryogenesis.

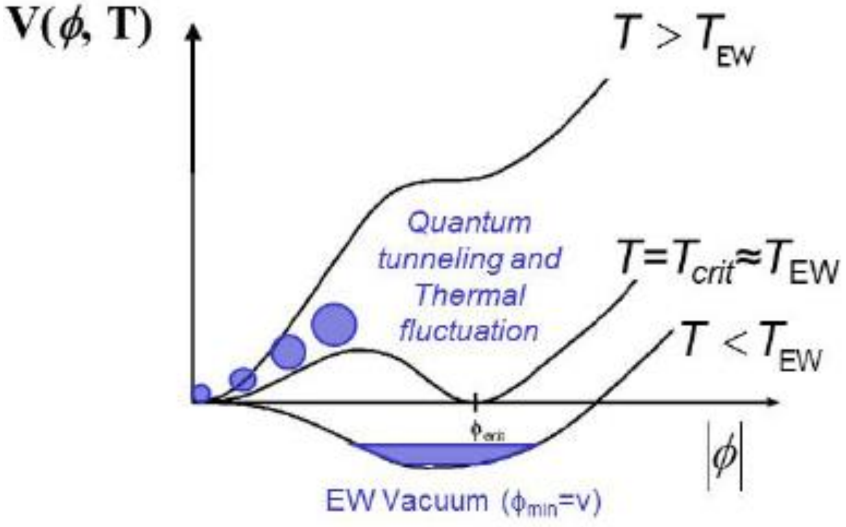
Top quark decay via flavor changing neutral currents at hadron colliders , Tao Han, R.D. Peccei, X. Zhang. Nucl.Phys. B454 (1995) 527-540
Nonstandard couplings of the top quark and precision measurements of the electroweak theory R.D. Peccei, S. Peris, X. Zhang. Nucl.Phys. B349 (1991) 305-322

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

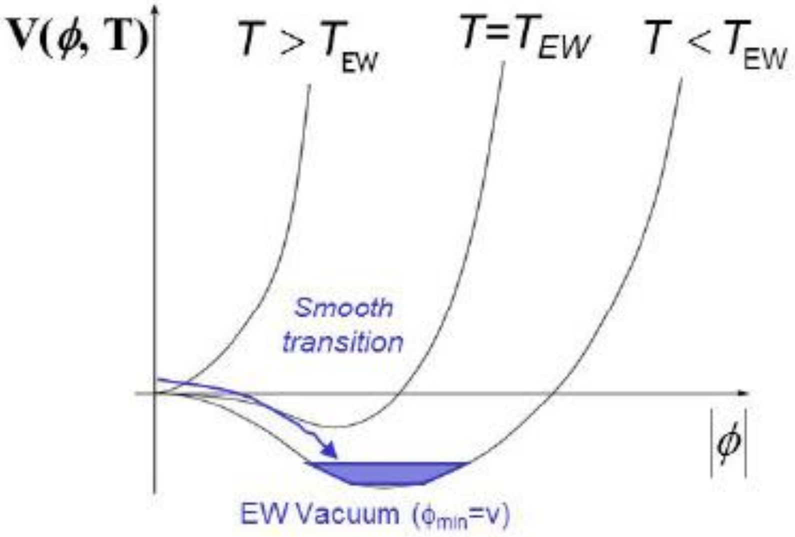
269-283 CP-violation FCNC process Yan Wan, Fa Peng Huang,et,al. Phys. Rev. D86, 094014 (2012)

Departure from thermal equilibrium —— Strong first order phase transition

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



Cross over or 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

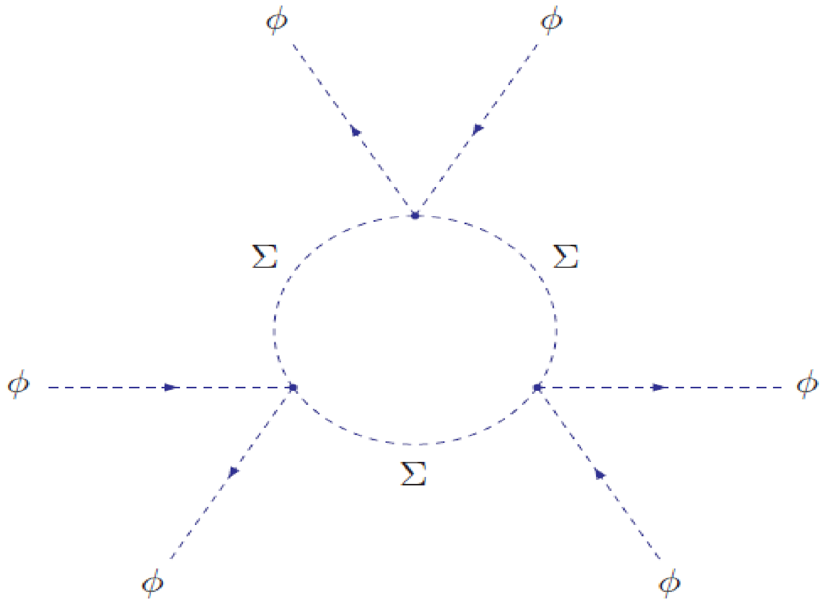
Cedric Delaunay, Christophe Grojean, James D. Wells
JHEP 0804:029,2008

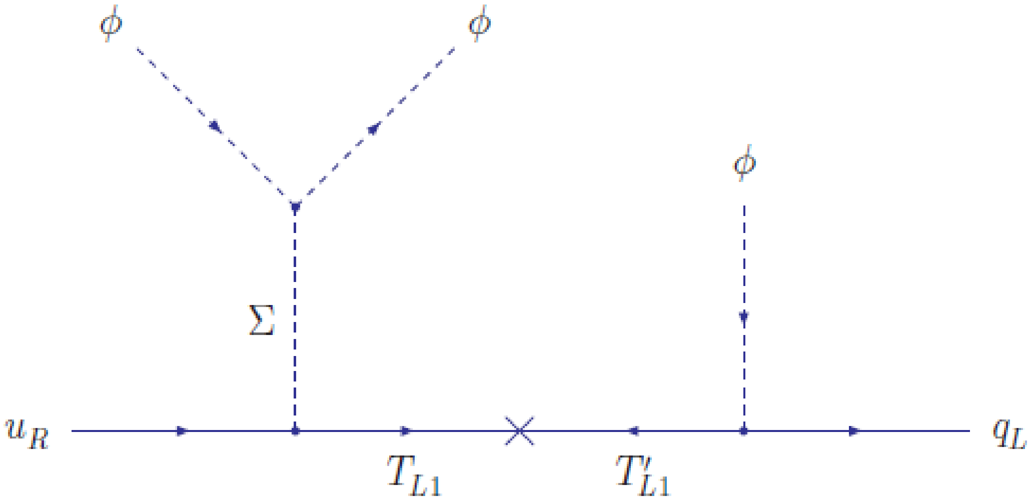
X. m. Zhang, Phys. Rev. D **47**, 3065 (1993) [hep-ph/9301277].
X. Zhang and B. L. Young, Phys. Rev. D **49**, 563 (1994) [hep-ph/9309269].
K. Whisnant, B. L. Young and X. Zhang, Phys. Rev. D **52**, 3115 (1995) [hep-ph/9410369].
X. Zhang, S. K. Lee, K. Whisnant and B. L. Young, Phys. Rev. D **50**,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

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

Renormalizable realization of the effective Lagrangian

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





New Higgs potential and EW phase transition

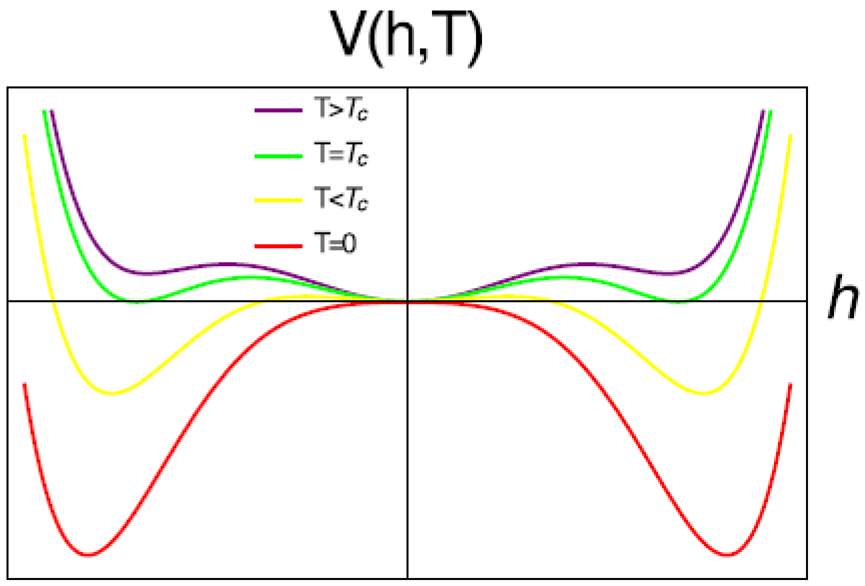
$$V_{\text{tree}}(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4}h^4 + \frac{\kappa}{8\Lambda^2}h^6$$

To study the EW phase transition, we need to calculate the one-loop finite temperature effective potential using the finite temperature field theory:

$$V_{\text{eff}}(h,T) = V_{\text{tree}}(h) + V_1^{T=0}(h) + \Delta V_1^{T\neq 0}(h,T)$$

New Higgs potential and EW phase transition

For the Higgs potential, we know nothing but the quadratic oscillation around the vev v (246GeV) with the mass 125 GeV.



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

$$\lambda(\Lambda \to \infty) = \frac{m_h^2}{2v^2},$$

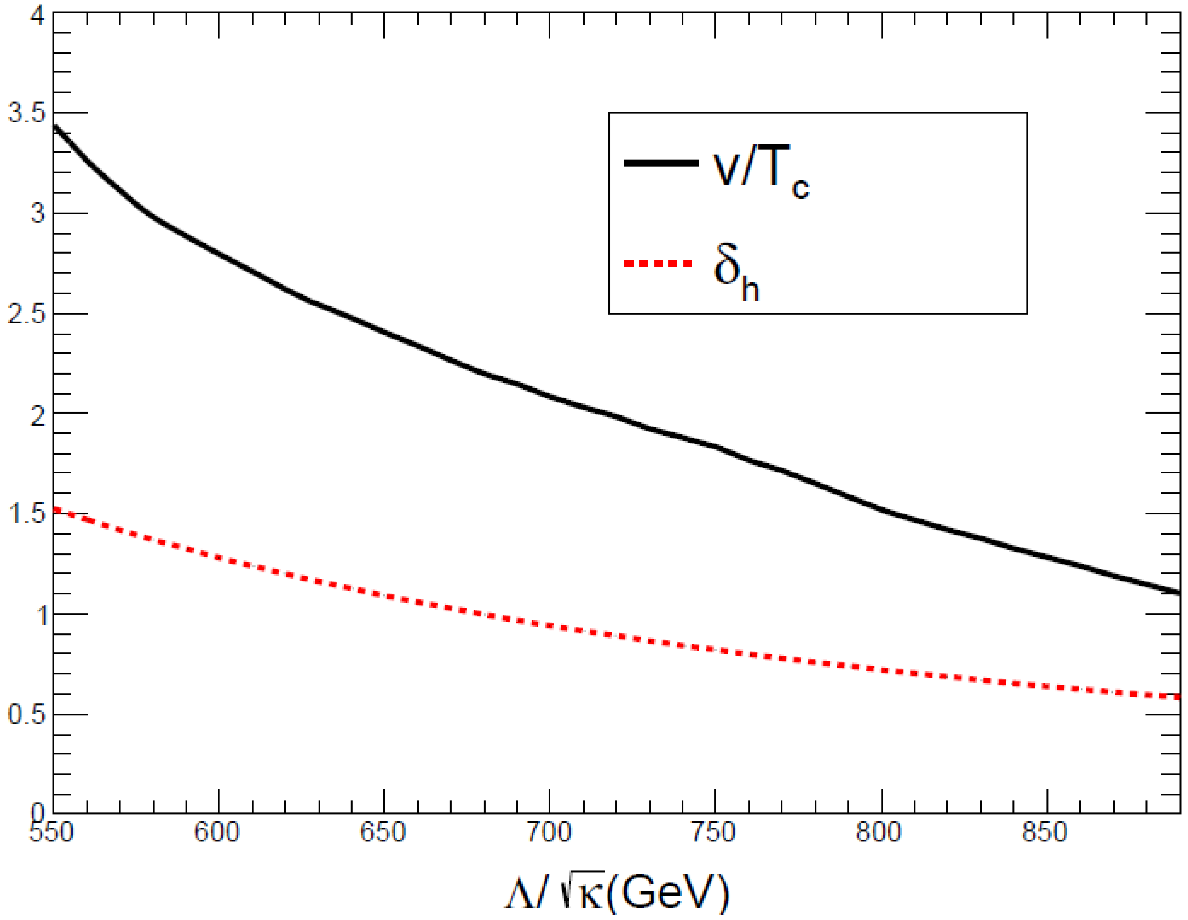
$$\mu^2 = \frac{m_h^2}{2}\left(-1 + \frac{\Lambda_{\max}^2}{2\Lambda^2}\right)$$

$$\mu^2(\Lambda \to \infty) = -\frac{m_h^2}{2}$$

Strong first order phase transition

$$T_c = \frac{\sqrt{\lambda^2\Lambda^2 - 4\kappa\mu^2}}{2\sqrt{c\kappa}} > 0$$

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



Dynamics of the EW phase transition

At the critical temperature Tc, the two minma are degenerate.
Phase transition and bubble nucleate at T<Tc with rate :

$$\Gamma = A T^4 e^{-S_3/T}$$

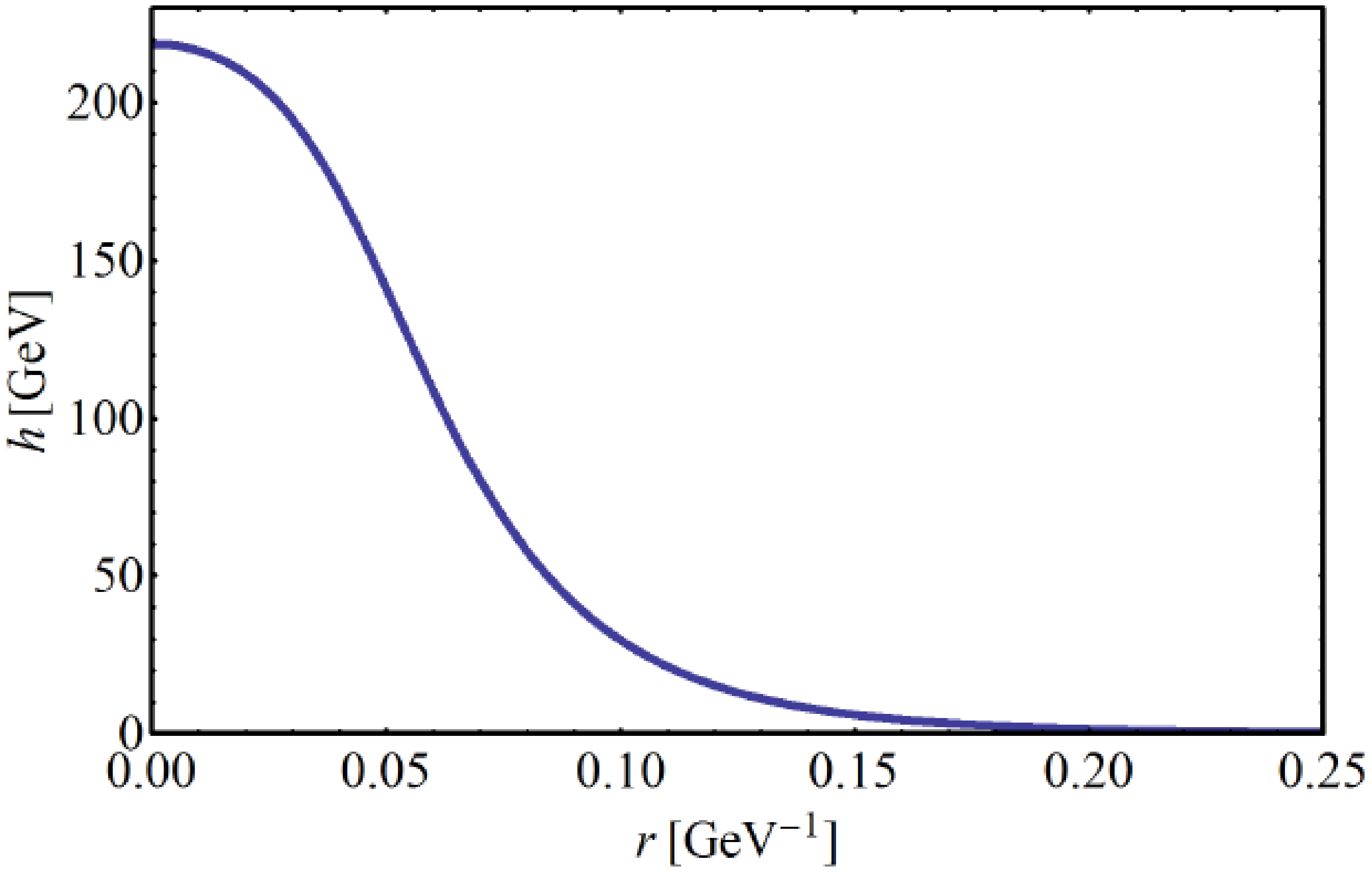
Here, the Higgs bubble energy is $$S_3 = \int dr 4\pi r^2 \left[\frac{1}{2} \left(\frac{d\phi_b}{dr} \right)^2 + V(\phi_b, T) \right]$$

$$\frac{d^2\phi_b}{dr^2} + \frac{2}{r}\frac{d\phi_b}{dr} = \frac{\partial V(\phi_b, T)}{\partial \phi_b}$$

$$\phi_b(r \to \infty) = 0 \text{ and } \frac{d\phi_b(r=0)}{dr} = 0$$

Profile of the Higgs field

Using the over-shoot/
Under-shoot method, we can obtain the Higgs profile. For T=51.94 GeV and Λ=600 GeV.



Dynamics of the EW phase transition

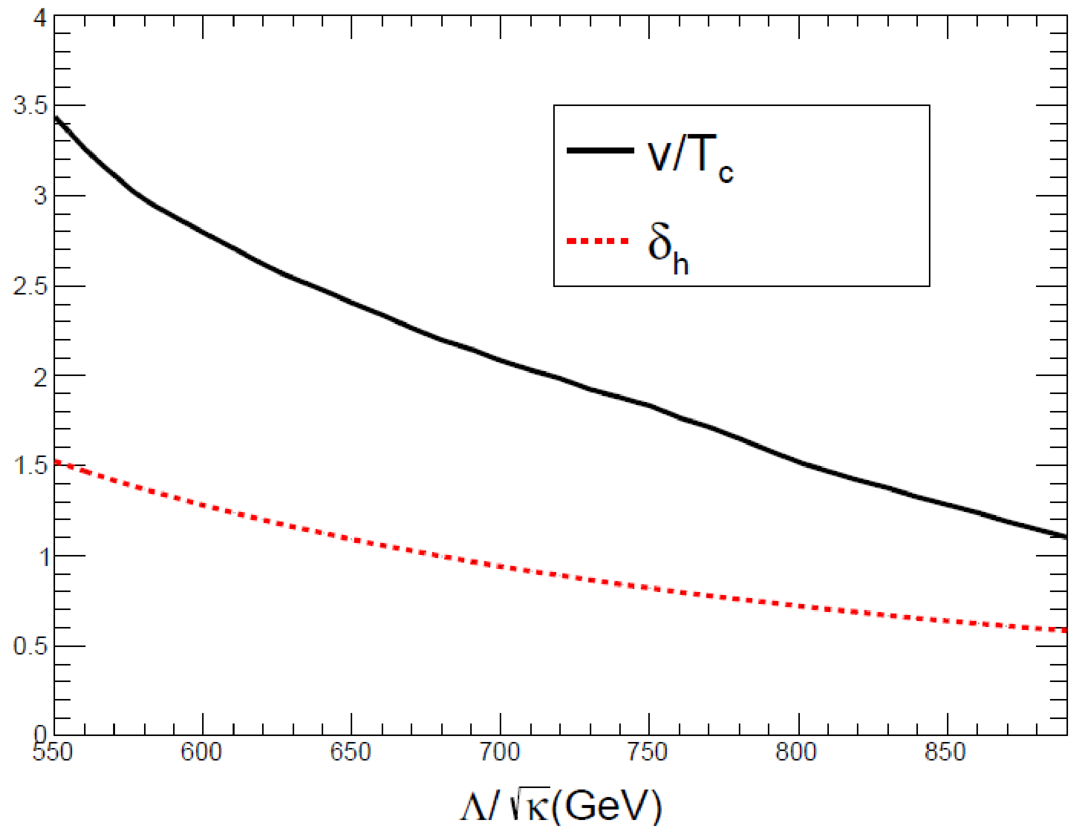
Two import parameters α *and* β

$$\alpha \equiv \frac{\epsilon(T)}{\rho_{\rm rad}(T)} \quad \tilde{\beta} \equiv \frac{\beta}{H_*} = T_* \left.\frac{dS}{dT}\right|_{T_*} = T_* \frac{d}{dT}\left(\frac{S_3}{T}\right)\Bigg|_{T_*}$$

$$v_b(\alpha) = \frac{\frac{1}{\sqrt{3}} + \sqrt{\alpha^2 + \frac{2\alpha}{3}}}{1+\alpha}$$

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 (at one-loop leve)

$$\boldsymbol{\delta_h \in (0.6, 1.5)}$$

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:

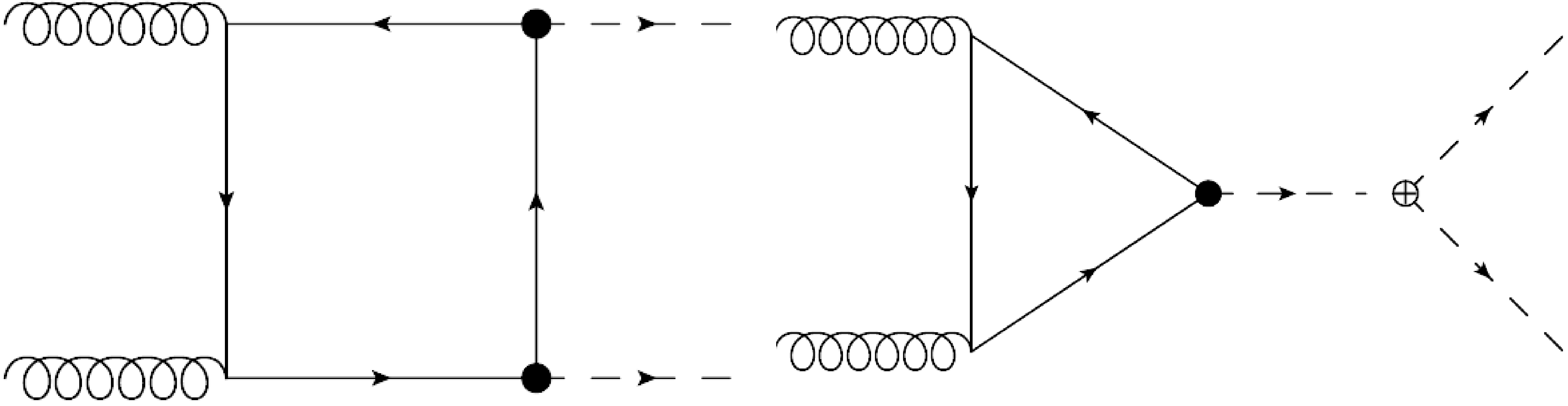
$$m_t(z) = \frac{m_t}{v}(1 + \delta_t^+ + i\delta_t^- \gamma^5)h(z)$$

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

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

Hints at the large hardron collider (LHC): Higgs pair production!

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

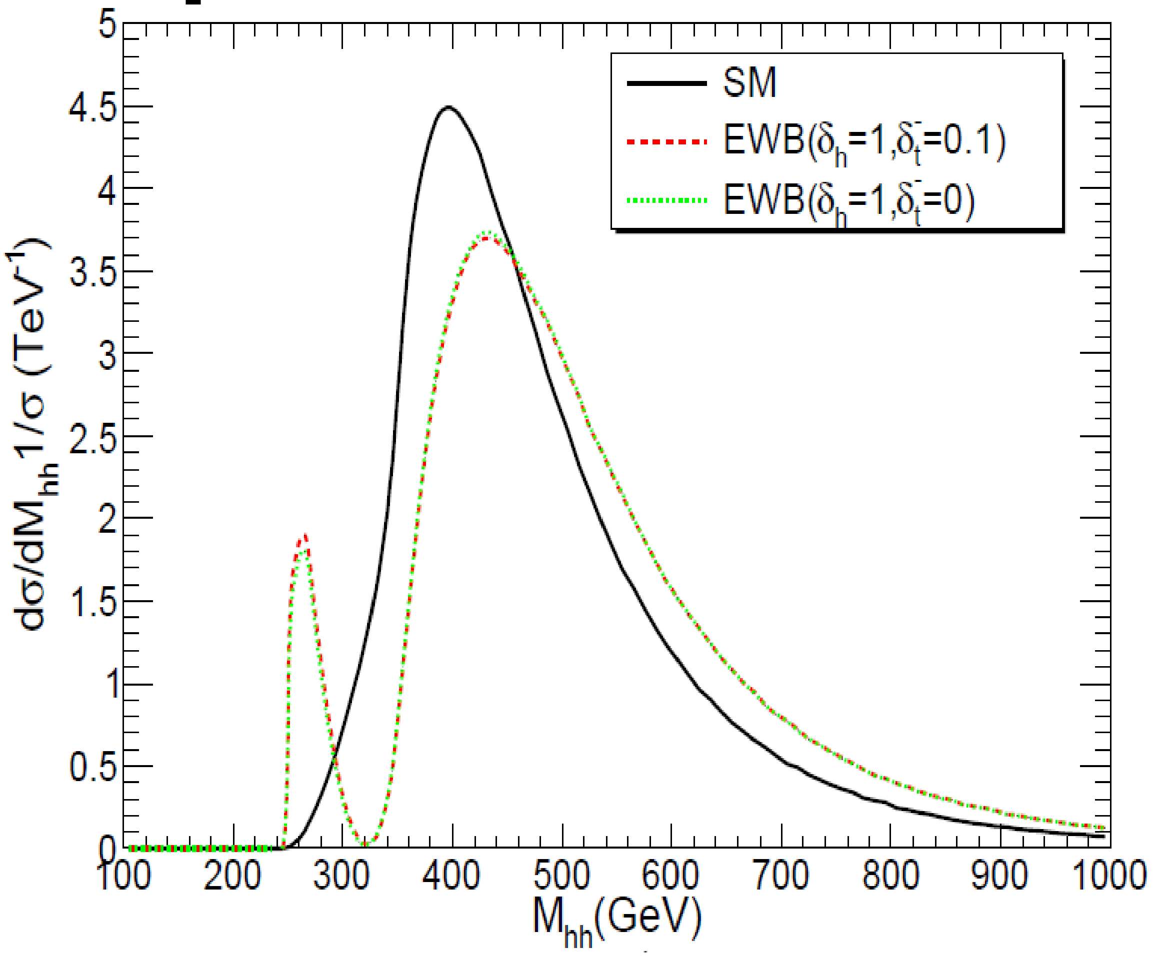


Modify the Higgs pair production at the LHC

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

F and G are the 8 form factors after loop calculation, respectively.

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



Q. Li, Z. Li, Q. S. Yan and X. Zhao

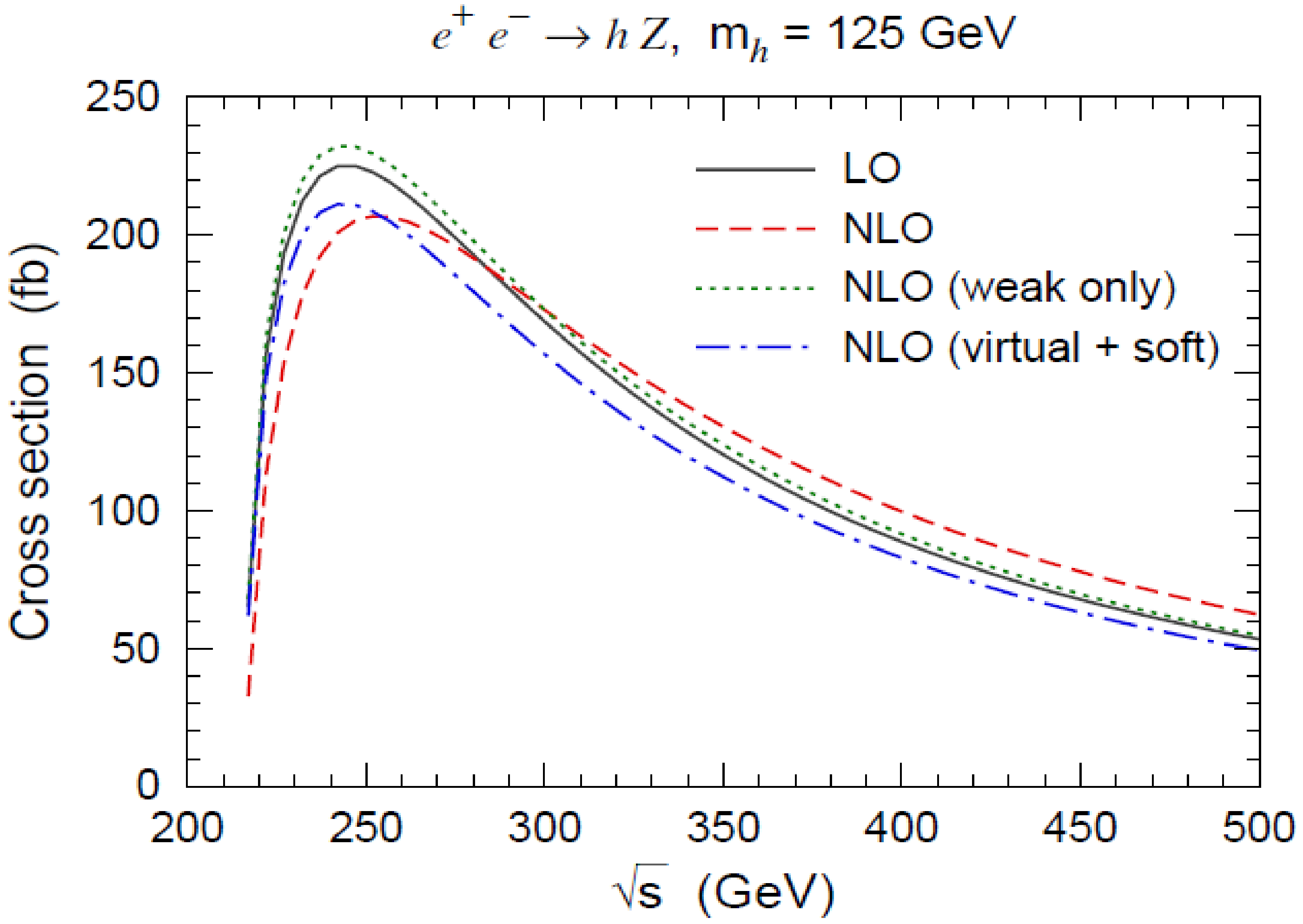
- Due to the difficulties to suppress the backgrounds at the LHC, it will be difficult to completely pin down these anomalous couplings at the 14TeV LHC, even with 3000 fb^{-1} integrated luminosity.
- Exploiting the boosted tricks may help to increase the ability to extract the anomalous couplings.
- More precise information may come from the future lepton collider, such as CEPC or 100 TeV hadron collider, such as SPPC.

H. J. He, J. Ren and W. Yao, arXiv:1506.03302

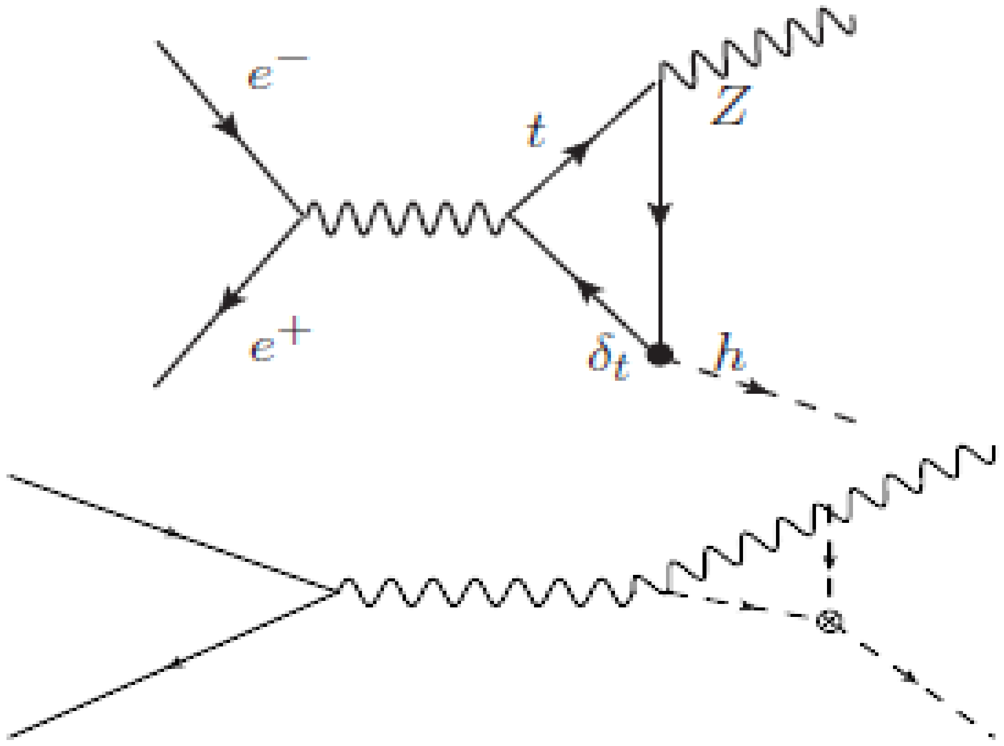
Q. H. Cao, Y. Liu and B. Yan, arXiv:1511.03311

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.

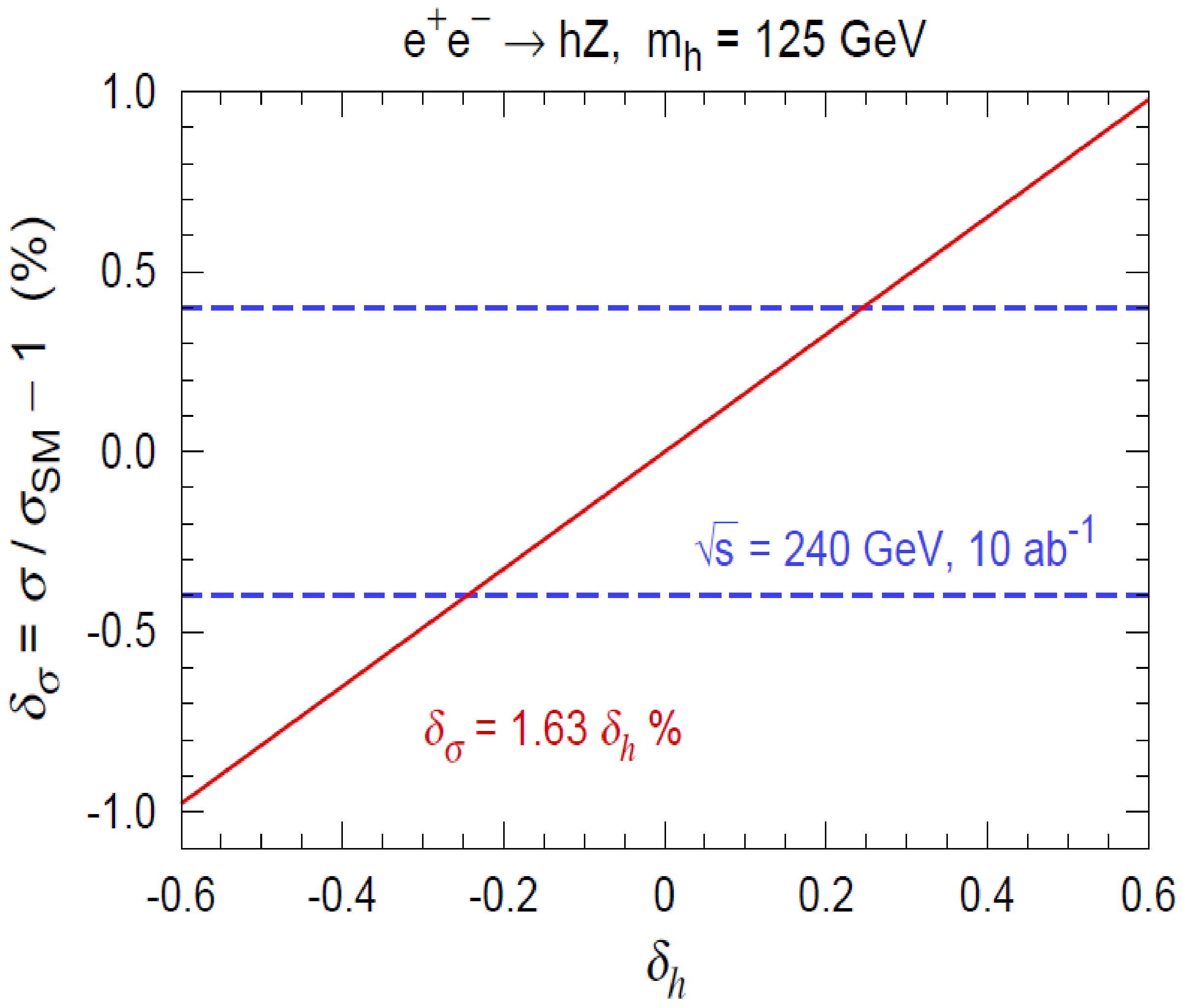


In this scenario for explaining the EW phase transition and EW baryogenesis, the anomalous tri-linear Higgs coupling and top quark Yukawa coupling will contribute to the cross section of Zh production.



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 ~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

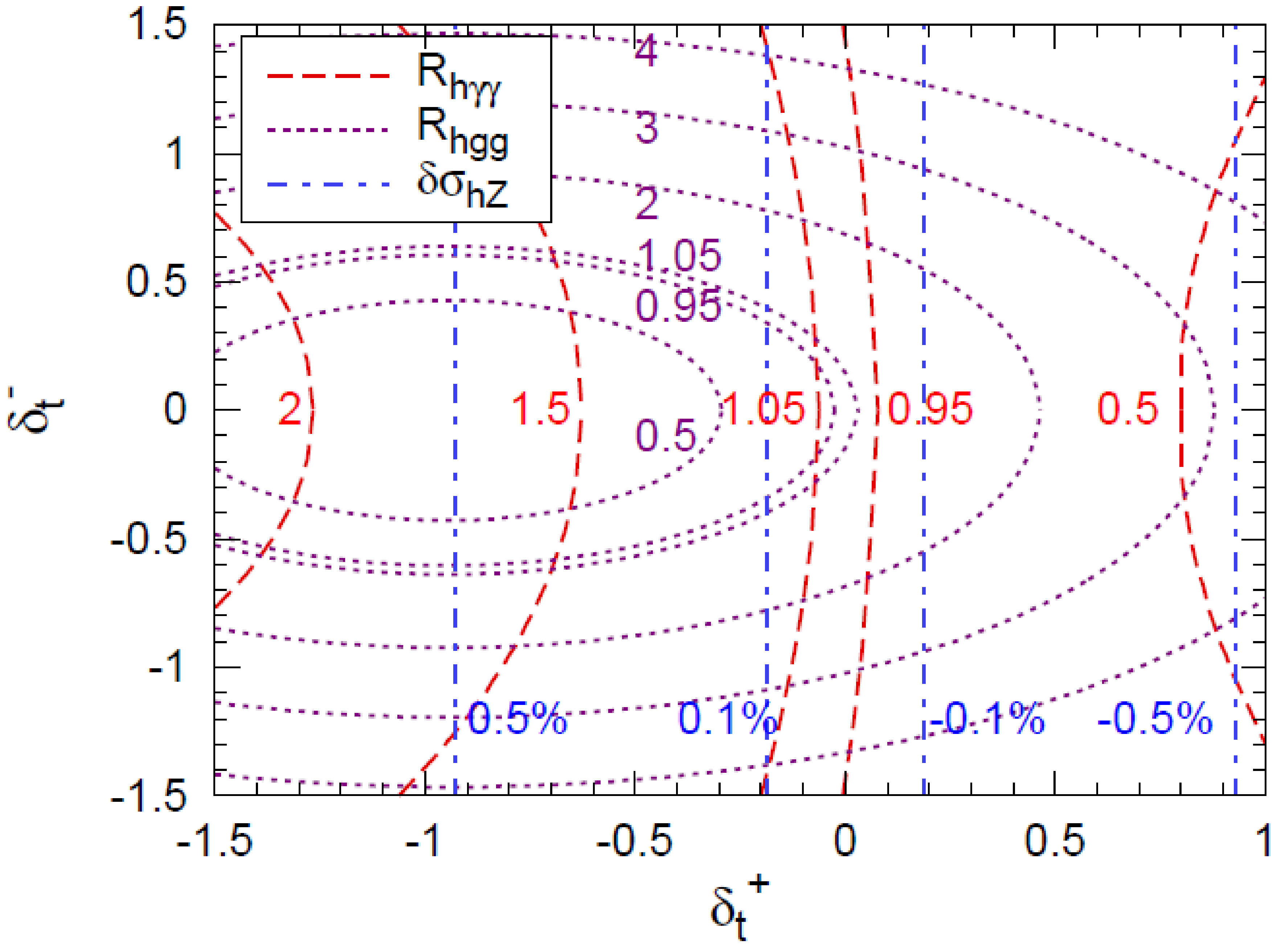
coupling from 0.6 to 1.5, which is well within the CEPC's precision.

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

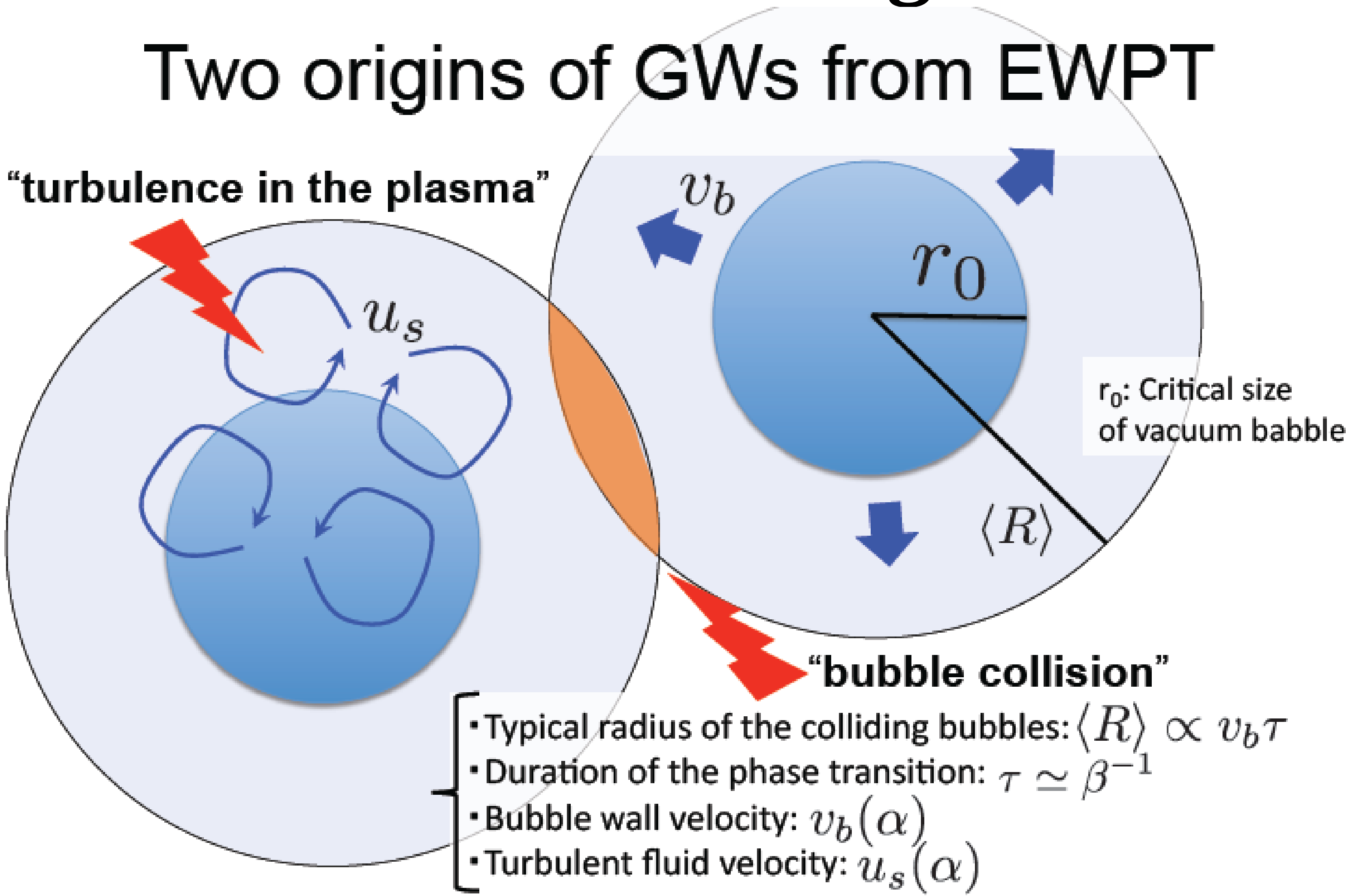
$$g^2_{hgg}/g^2_{hgg,SM} \simeq (1+\delta_t^+)^2 + 0.11\delta_t^+(1+\delta_t^+) + 2.6(\delta_t^-)^2$$
$$g^2_{h\gamma\gamma}/g^2_{h\gamma\gamma,SM} \simeq (1-0.28\delta_t^+)^2 + (0.43\delta_t^-)^2.$$

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



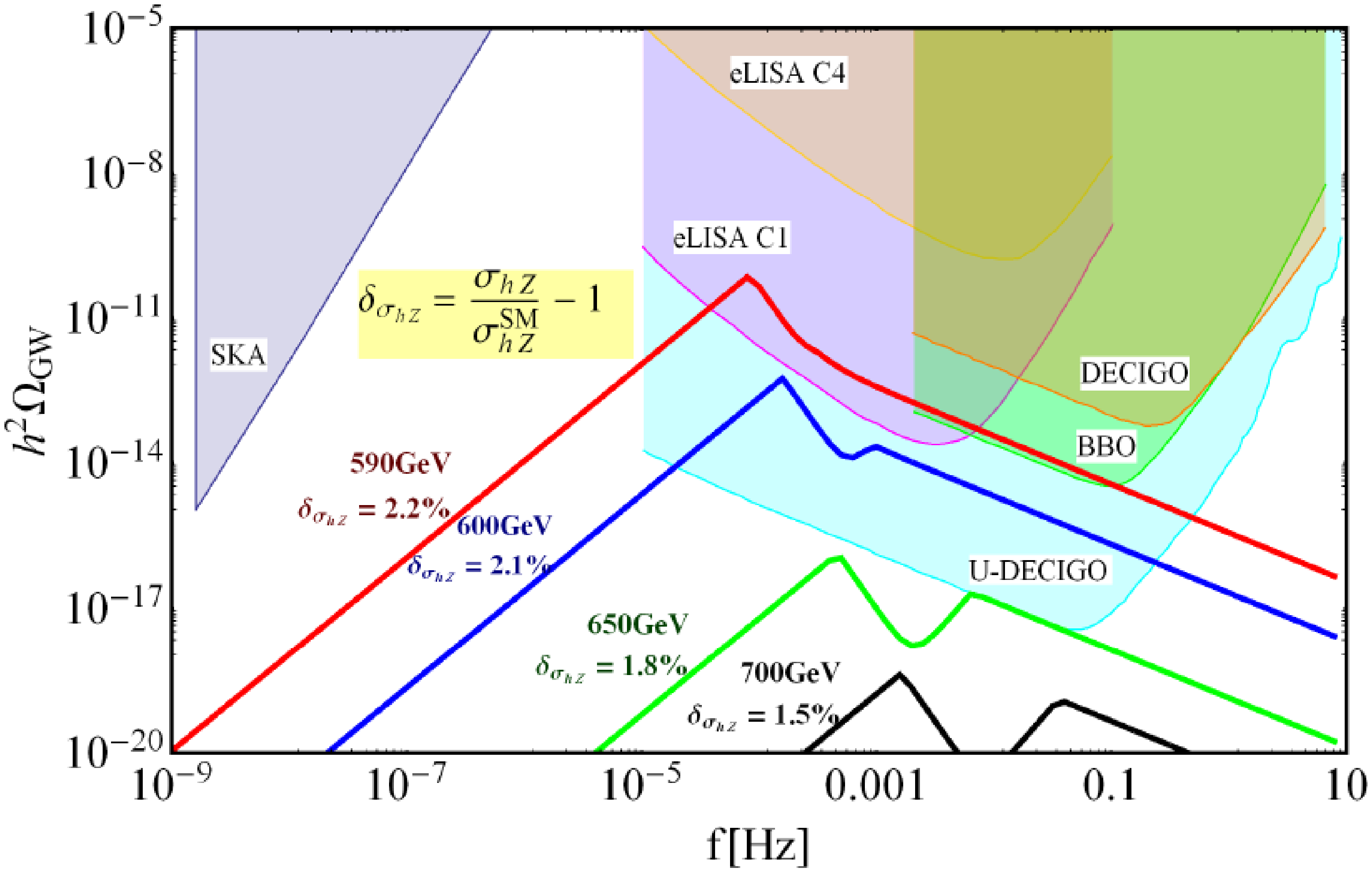
$R_{h\gamma\gamma}$
R_{hgg}
$\delta\sigma_{hZ}$
4
3
2
1.05
0.95
0.5
2
1.5
1.05
0.95
0.5
0.5%
0.1%
-0.1%
-0.5%
δ_t^-
δ_t^+
1.5
1
0.5
0
-0.5
-1
-1.5
-1.5
-1
-0.5
0
0.5
1

Complementary probing of the electroweak phase transition with relic gravitational wave



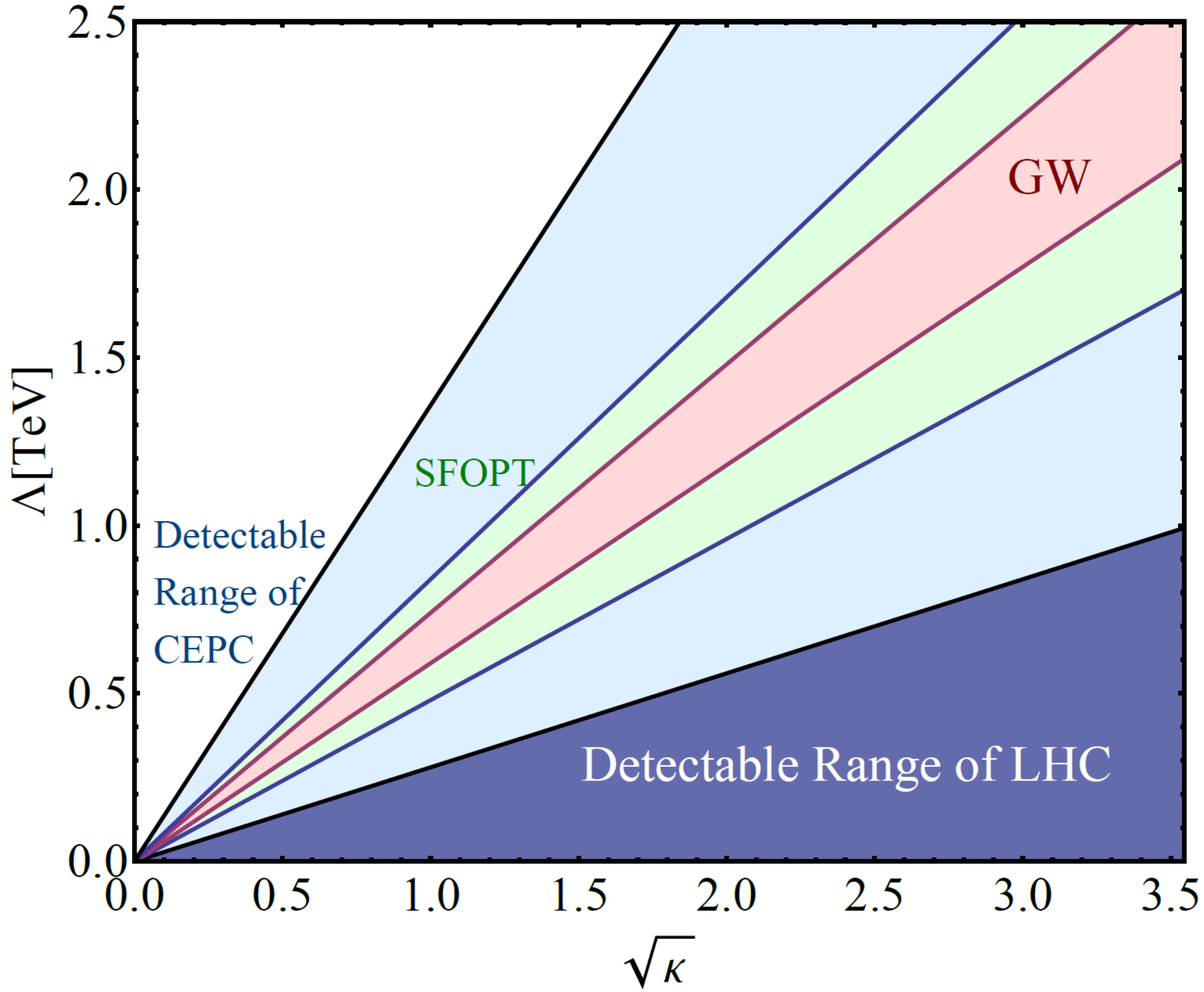
Matsui'15

Complementary probing of the electroweak phase transition with relic gravitational wave



- eLISA, BBO and U-DECIGO are capable of detecting the GW from the EWPT
- The study on the EWPT bridges the particle physics at colliders with the astrophysics and cosmology in the early universe.

Complementary probing of the electroweak phase transition with relic gravitational wave



The observational abilities of different from particle colliders to GW detectors.

Summary

- 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 operators can enforce the strong first order phase transition and provide sizable CP violation to realize a successful EW baryogenesis.
- In this scenario, the tril-inear 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 and GW experiments may provide a complementary test.

Summary

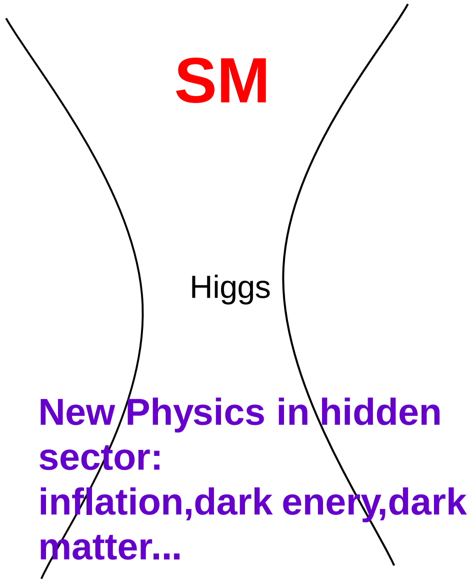
- Since the 125 GeV Higgs boson has been discovered at the LHC, it becomes a central issue to unravel the structure of the Higgs potential and the nature of the EW baryogenesis at the CEPC.
- However, there are so many possibilities, related to all possibilities of the Higgs sector extension.
- Each type of extension is need to study in detail at CEPC/SPPC.
- Just at the corner with the improvement the experimental precision.
- The analysis will contribute to deeply understand the Higgs physics, such as the EW baryogenesis, which can build an innovative connection between astrophysics and particle physics. Our joint study will enable novel insights into the astrophysics, GW physics and fundamental particle physics.

Outlook

Theoretical study?

A:Higgs as a portal to search for the new physics beyond the SM!

B:Unravel the nature of spontaneous symmetry breaking, the order of the EW phase transition and the true potential of the Higgs boson.



$$\mathcal{L} = \mathcal{O}_{hidden} H^\dagger H$$

Outlook

Experimental test?

Two complementary approaches to study the Higgs physics:

- Particle Colliers, such as CEPC-SppC: Build higher energy collider with high energy and high luminosity.

- Gravitational Wave Detectors, such as eLisa, Ali:

The recently announced aLIGO observation has initiated a new era of exploring fundamental physics with GW detectors.

Thanks for your attention！