中国科学院高能物理研究所
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Probing the nature of Higgs boson from Great Collider(CEPC/SppC) to Gravitational Wave

Fa Peng Huang(黄发朋)

based on our recent work Phys. Rev. D 93, 103515 (2016) and Phys. Rev. D 94, 041702(R)(2016) with Xinmin Zhang etc.

International Symposium on Higgs Boson and Beyond Standard Model Physics

Shandong University, Weihai
17.Aug.2016

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 deliberate ！

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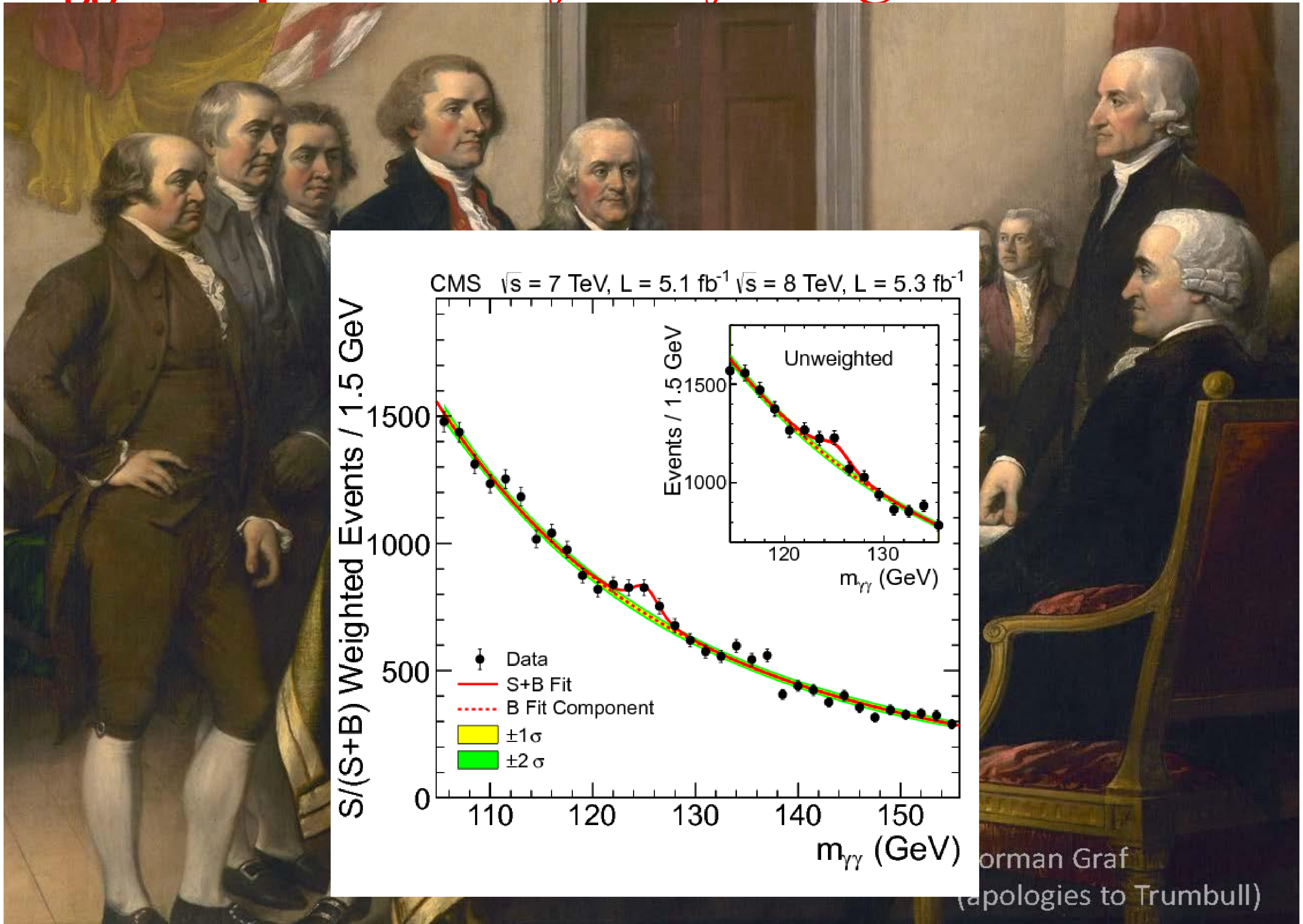


Higgs physics in Post-Higgs era:

- **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”,Nnaturalness…**
- **However, there still exists urgent problem in particle physics , namely exploring the true shape of the Higgs potential, the nature of the EW SSB, and the type of the EW phase transition, the EW baryogenesis.**

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.

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

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

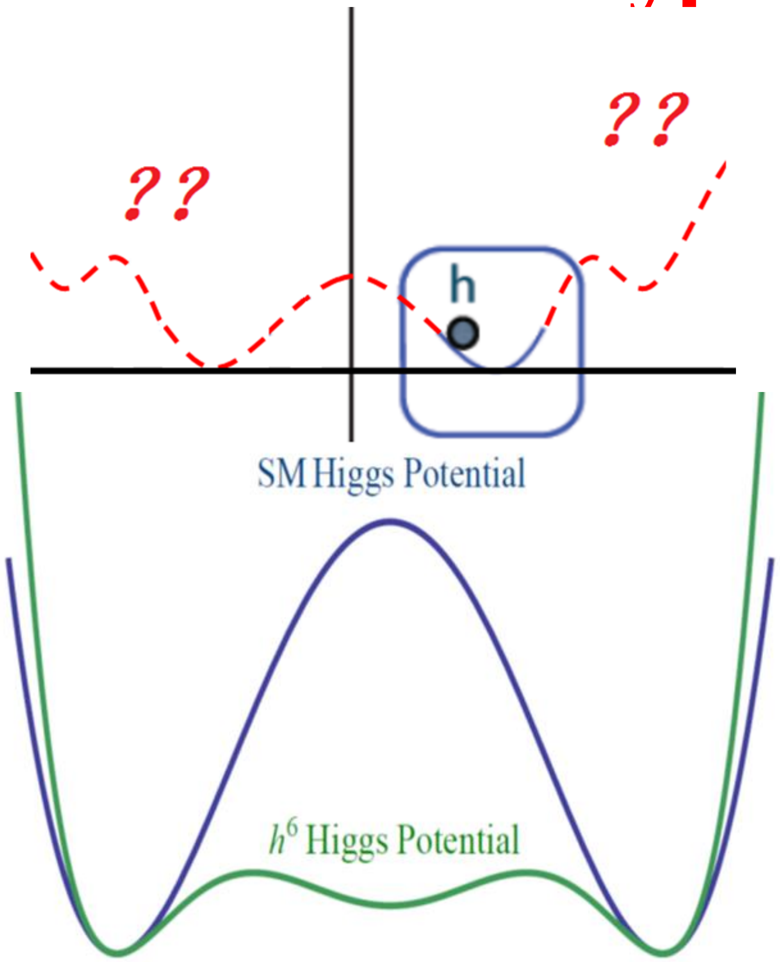
$$+\mathcal{O}_{hidden} H^\dagger H$$

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

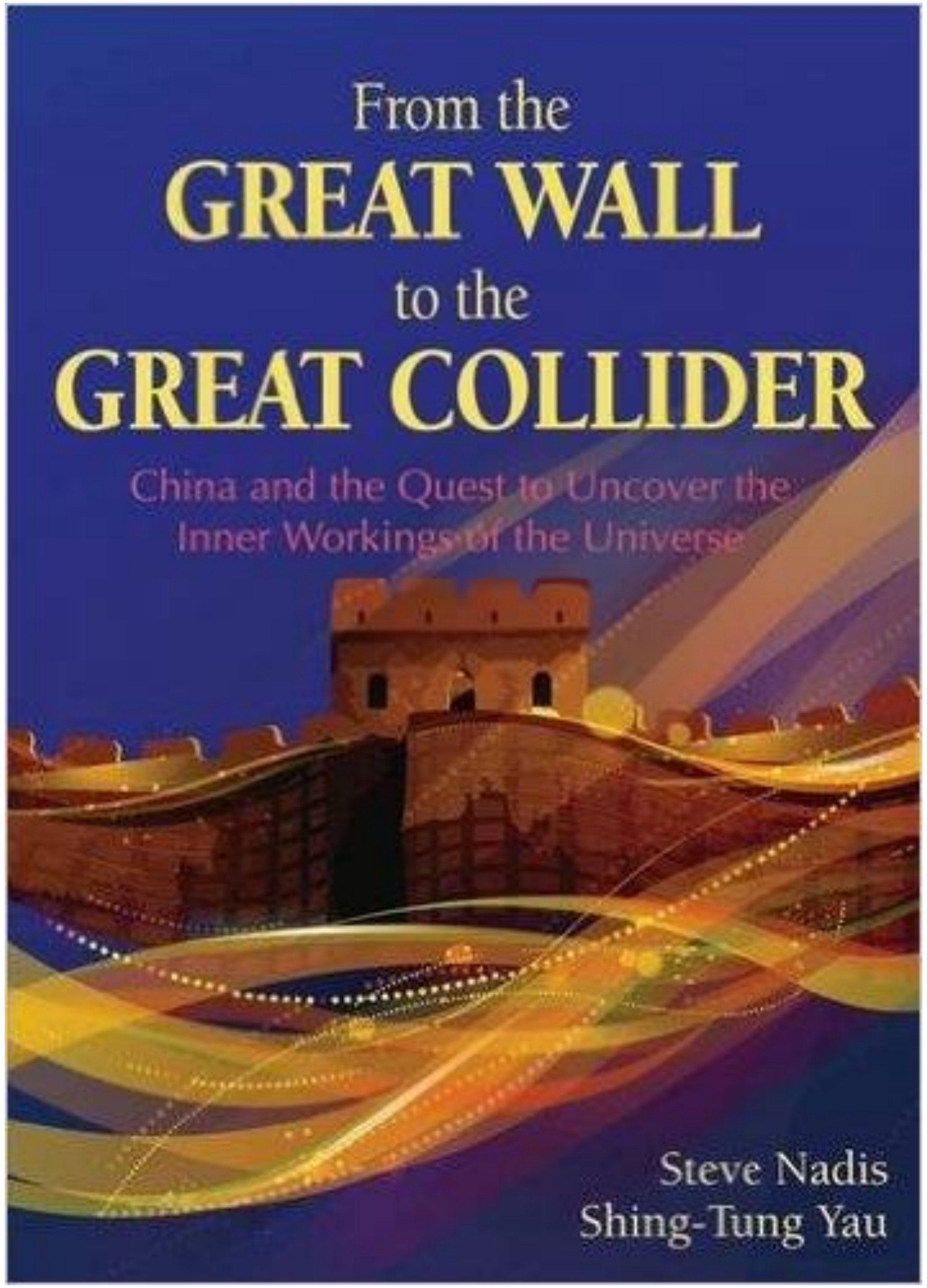
The baryon asymmetry of the universe (BAU) may be generated by some combination of other baryogenesis mechanisms.
However, EW phase transition is the last period to affect the BAU.

First order EW phase transition ⟺

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

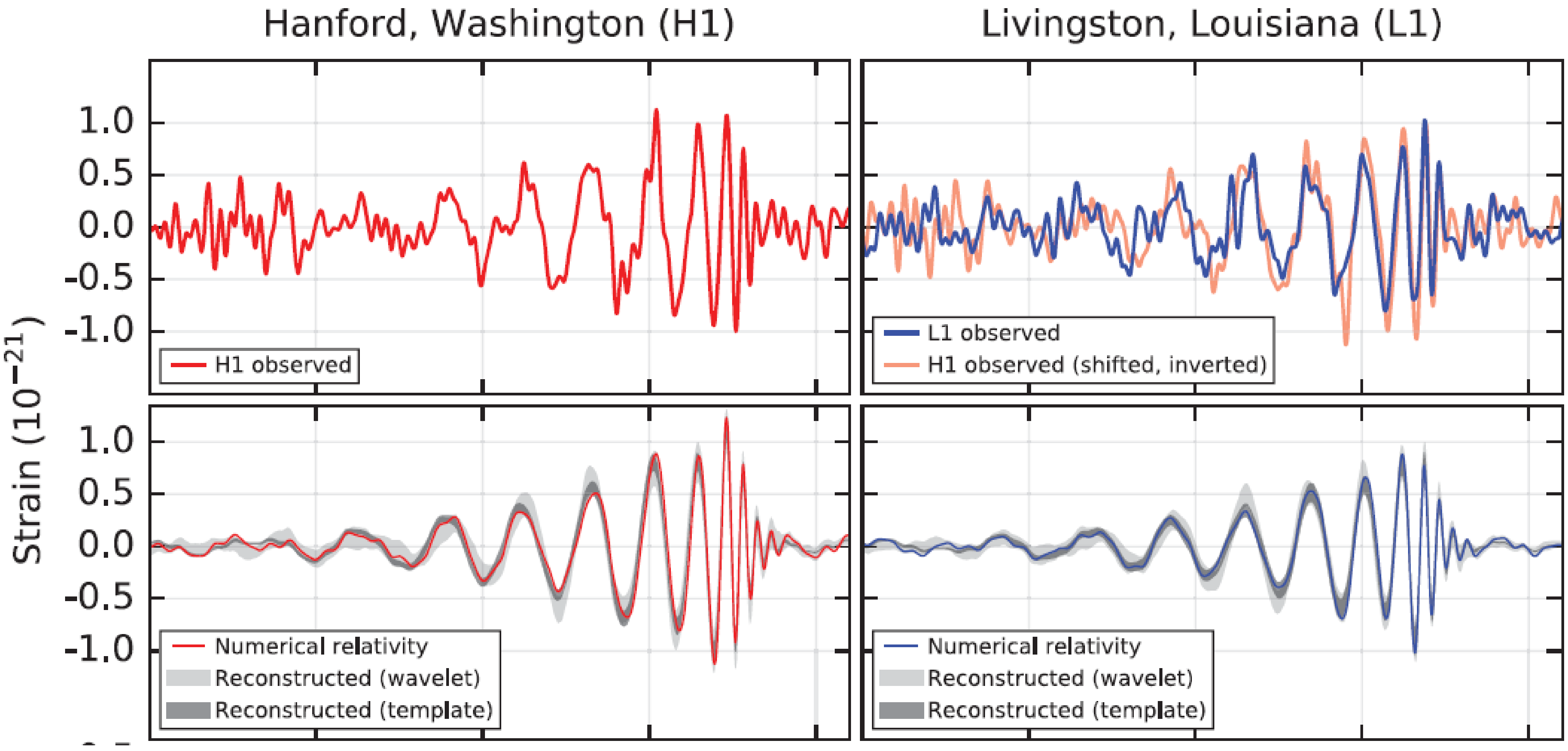
Current particle collider has no ability to unravel the true potential of the Higgs boson, we need new experiments.

A： Directly, we can build more powerfull colliders, such as the CEPC/SppC.



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, electroweak (EW) baryogenesis becomes a timely and testable scenario for explaining the BAU.

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

Baryogenesis-Sakharov conditions(1967)

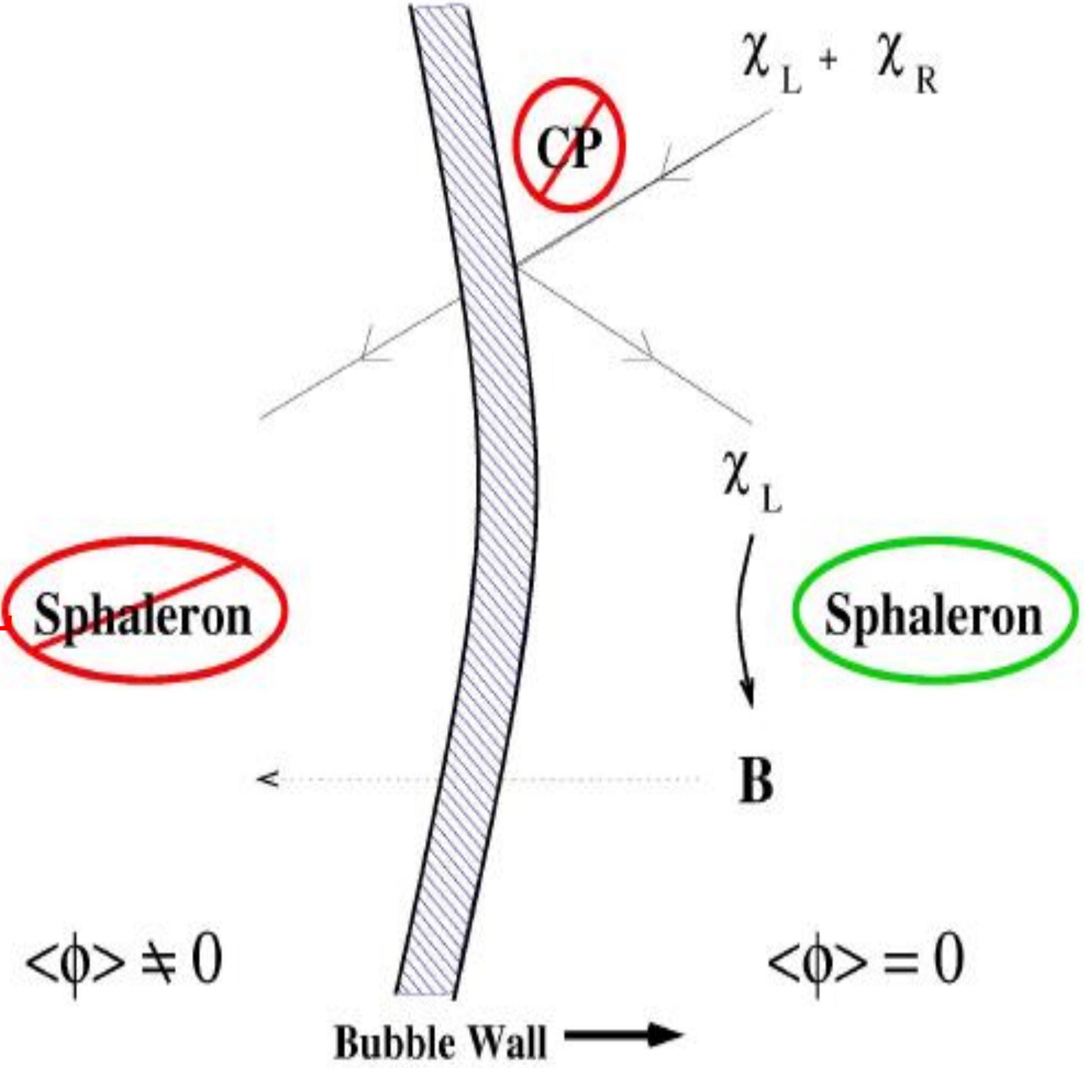
To produce the observed BAU, three necessary conditions are needed at the same cosmic epoch:

- **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**

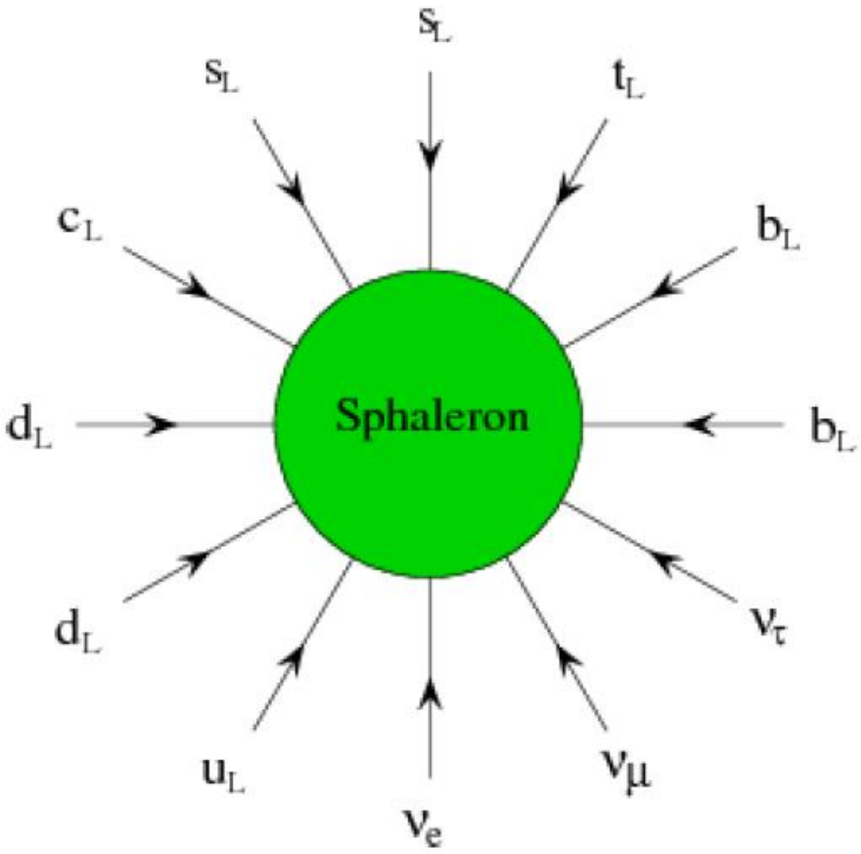
EW baryogenesis:

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

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

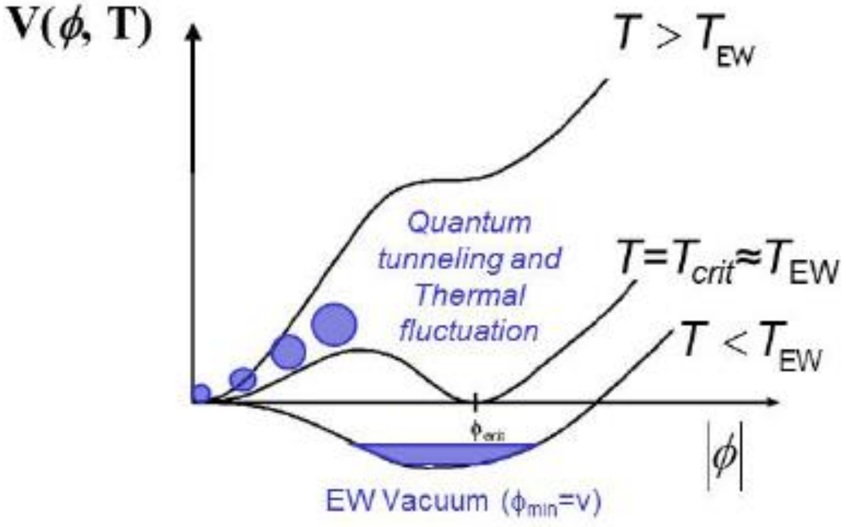
Nonstandard couplings of the top quark and precision measurements of the electroweak theory R.D. Peccei, S. Peris, X. Zhang. Nucl.Phys. B349 (1991) 305-322

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

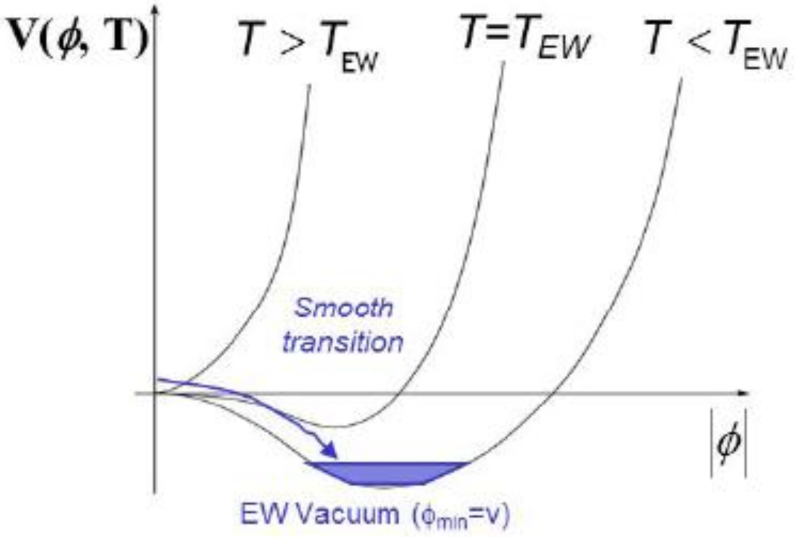
269-283 CP-violation FCNC process Yan Wan, Fa Peng Huang,et,al. Phys. Rev. D86, 094014 (2012)

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

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

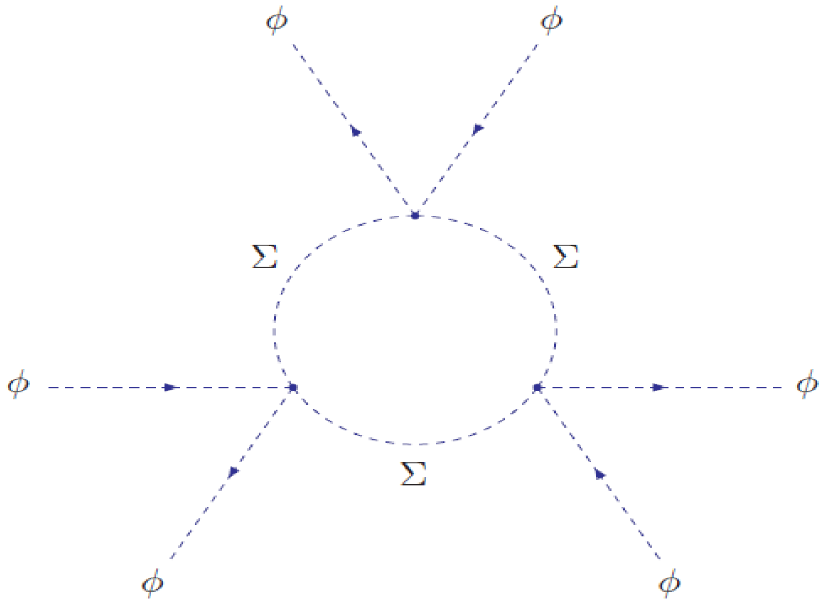
provide another possible Higgs potential or EW symmetry breaking; provide strong first order phase transition

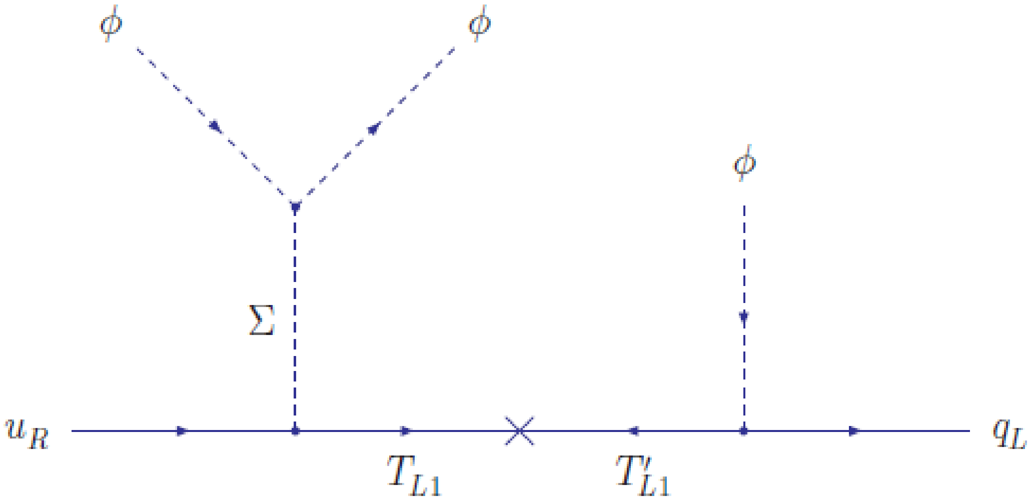
X. m. Zhang, Phys. Rev. D **47**, 3065 (1993) [hep-ph/9301277].
X. Zhang and B. L. Young, Phys. Rev. D **49**, 563 (1994) [hep-ph/9309269].
K. Whisnant, B. L. Young and X. Zhang, Phys. Rev. D **52**, 3115 (1995) [hep-ph/9410369].
X. Zhang, S. K. Lee, K. Whisnant and B. L. Young, Phys. Rev. D **50**,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

Fa Peng Huang, Chong Sheng Li, Phys.Rev. D92 (2015) , 075014
Fa Peng Huang, Pei-Hong Gu, Peng-Fei Yin, Zhao Huan Yu,Xinmin Zhang **Phys.Rev. D93 (2016) 103515**
Fa Peng Huang, Youping Wan, Dong-Gang Wang, Yifu Cai,Xinmin Zhang **Phys. Rev. D 94, 041702(R) 2016**

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

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

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

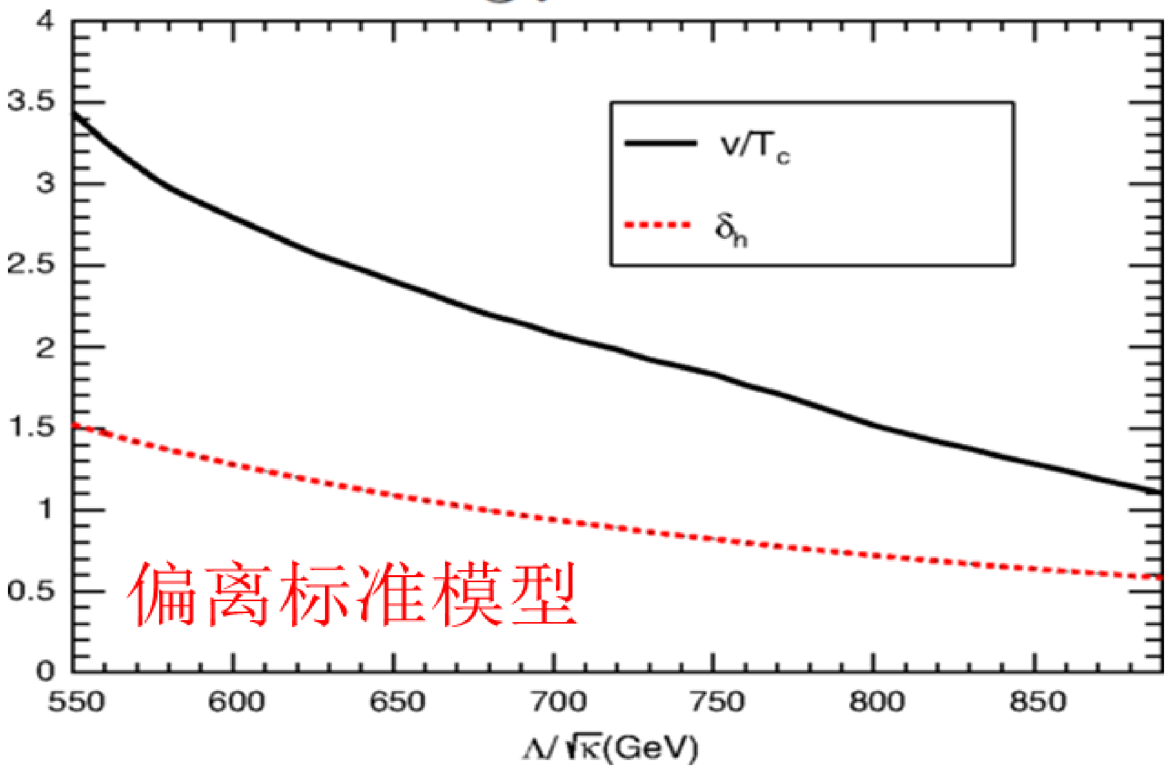
$$V_{\rm eff}(h,T) = V_{\rm tree}(h) + V_1^{T=0}(h) + \Delta V_1^{T\neq 0}(h,T)$$

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

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

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

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



At one loop level

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

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:

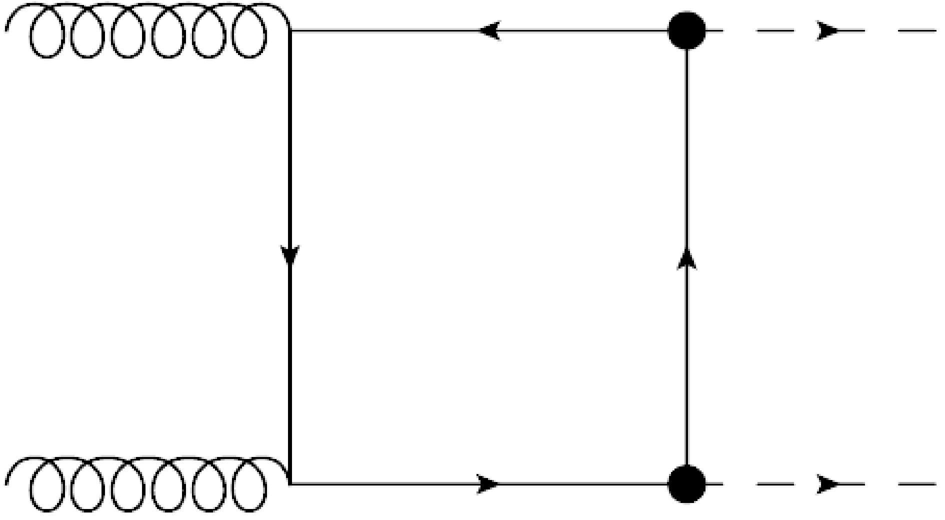
$$m_t(z) = \frac{m_t}{v}(1 + \delta_t^+ + i\delta_t^- \gamma^5)h(z)$$

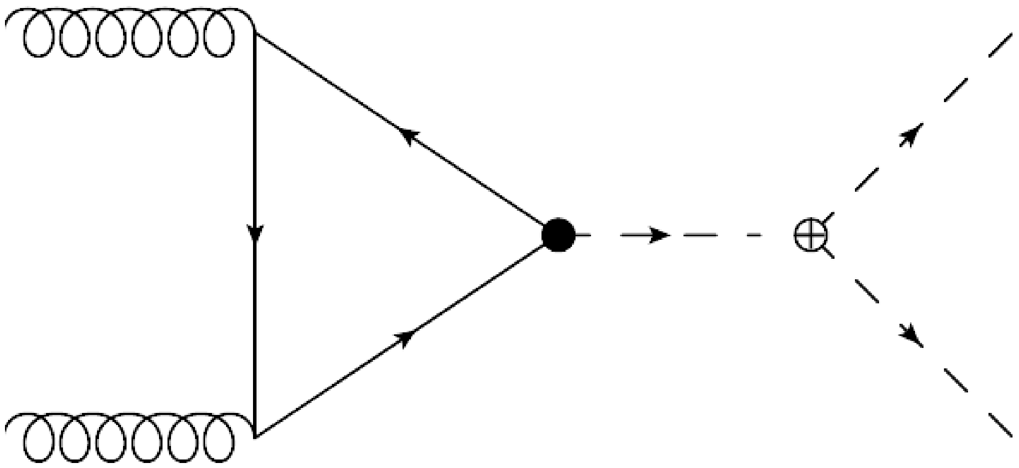
$$\eta = 6.05(7) \times 10^{-10} \Longrightarrow \delta_t^- = \mathcal{O}(0.01 - 1)$$

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!

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



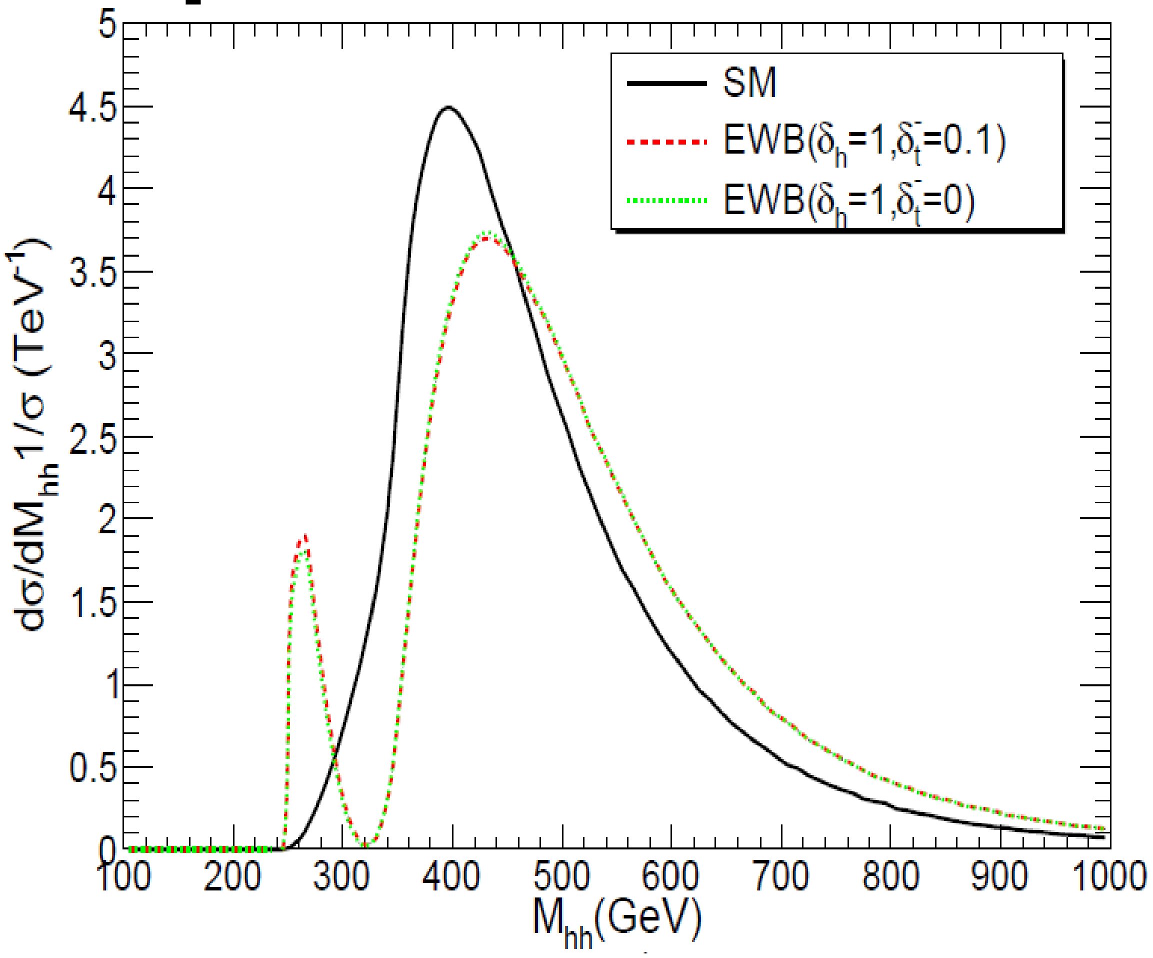


Modify the Higgs pair production at the LHC

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

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

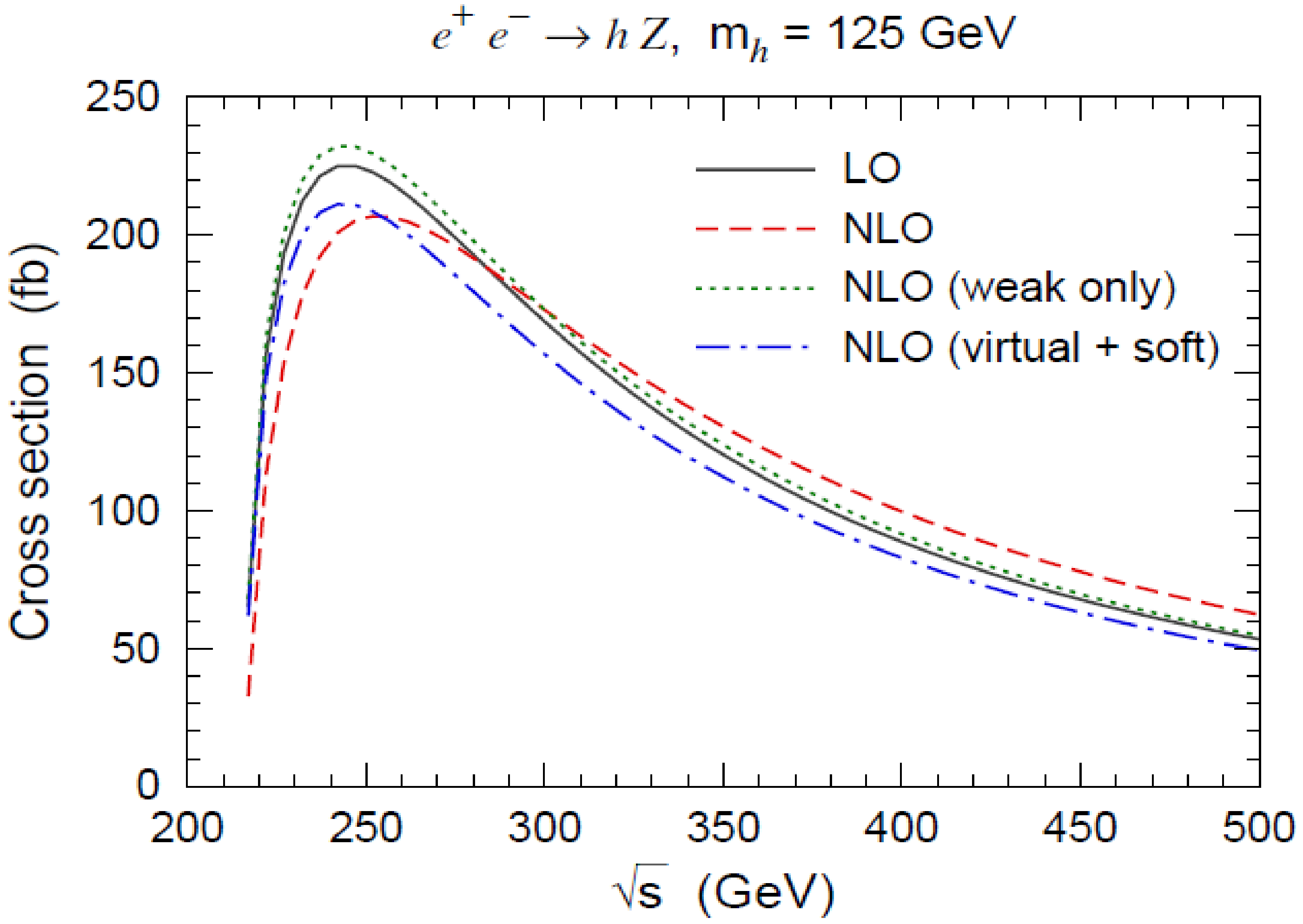
- Due to the difficulties to suppress the backgrounds at the LHC, it will be difficult to completely pin down these anomalous couplings at the 14TeV LHC, even with 3000 fb^{-1} integrated luminosity.
- Exploiting boosted tricks helps to increase the ability to extract the anomalous couplings.
- More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

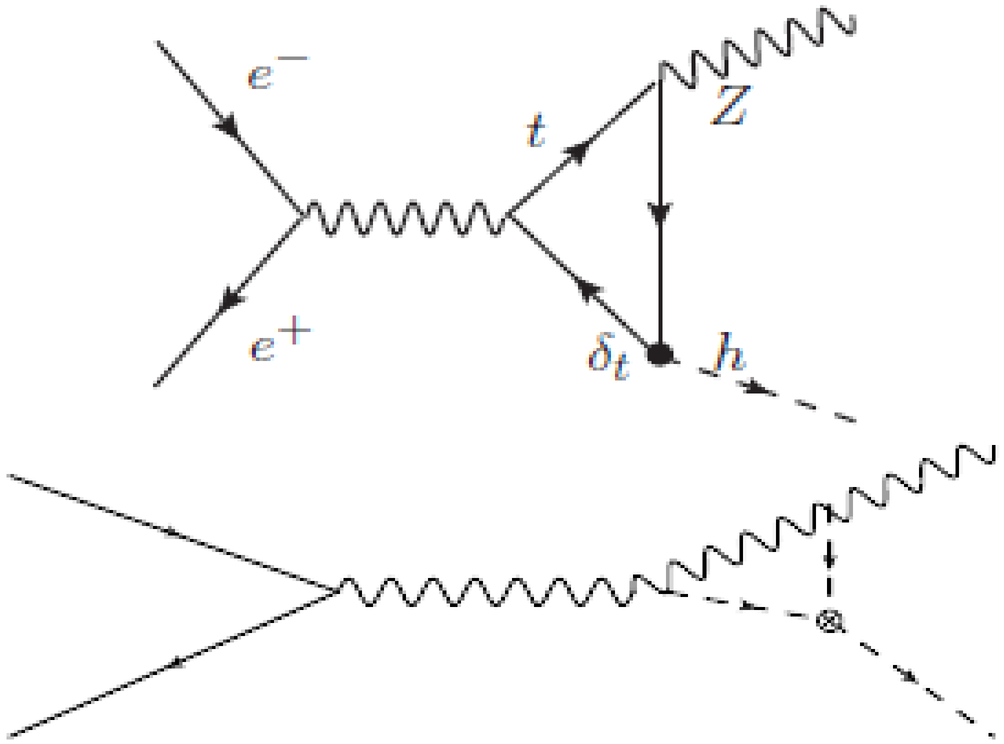
Q. H. Cao, Y. Liu and B. Yan, arXiv:1511.03311

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.

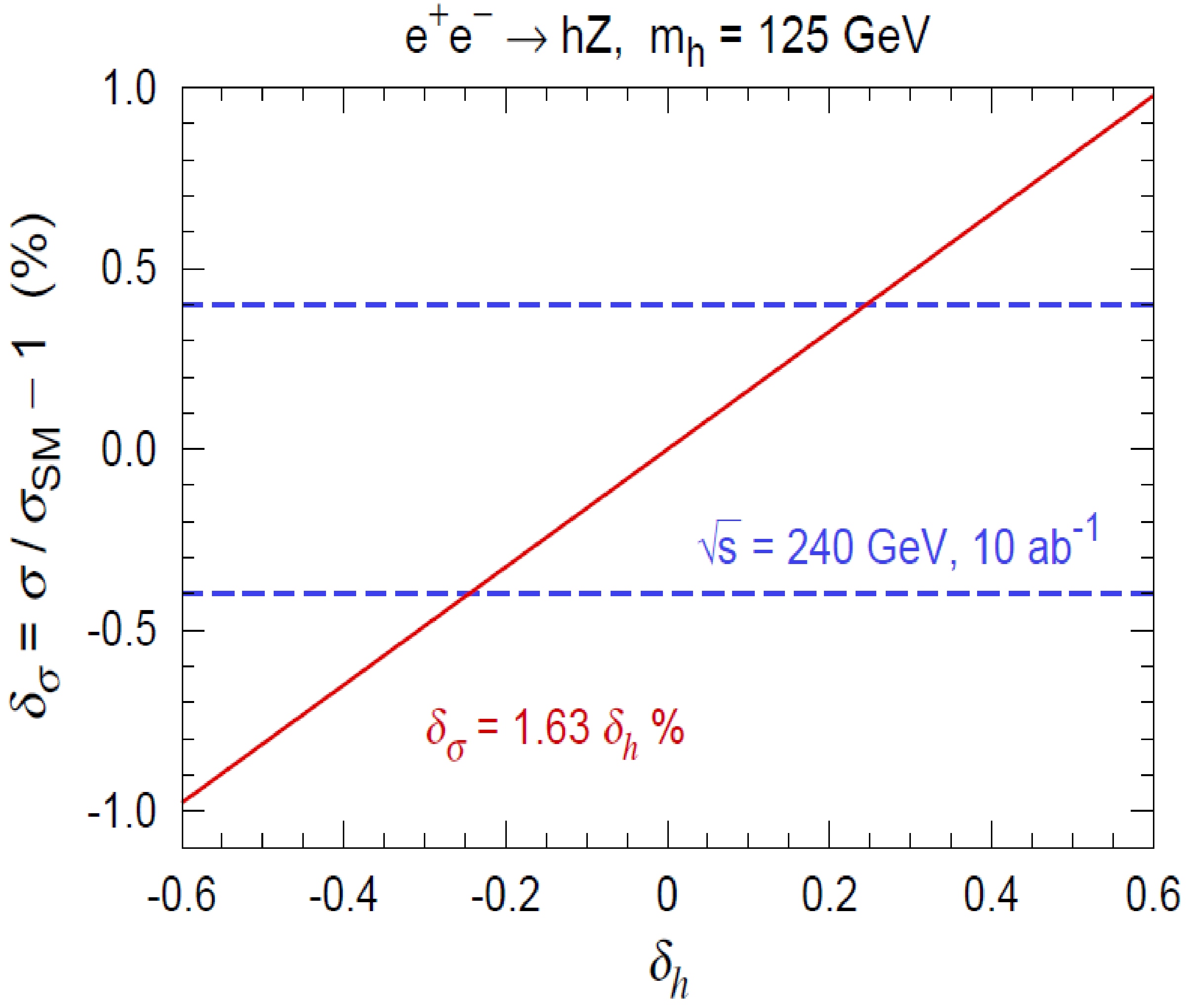


In this scenario for explaining the EW phase transition and EW baryogenesis, the anomalous tri-linear Higgs coupling and top quark Yukawa coupling will contribute to the cross section of Zh production.



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

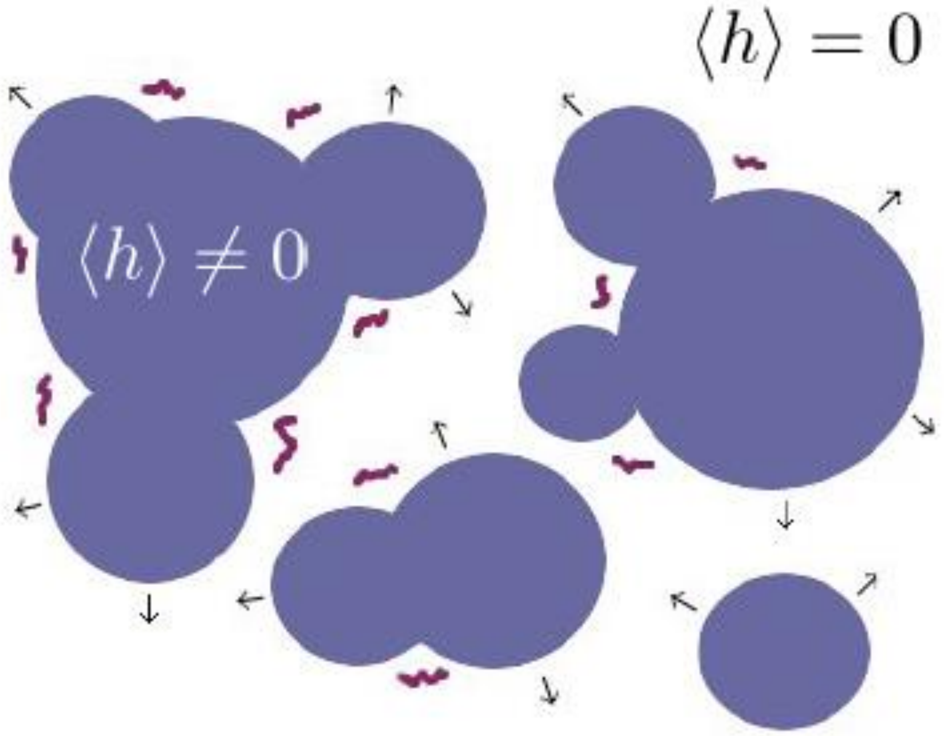
For the future CEPC with the integrated luminosity of 10 ab^{-1} at $\sqrt{s} =$ 240 GeV , the precision of the σ_{zh} may be about 0.4% . Therefore, it is possible to test the δ_h ~25% at the CEPC.

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.

EW phase transition gravitational wave(GW)

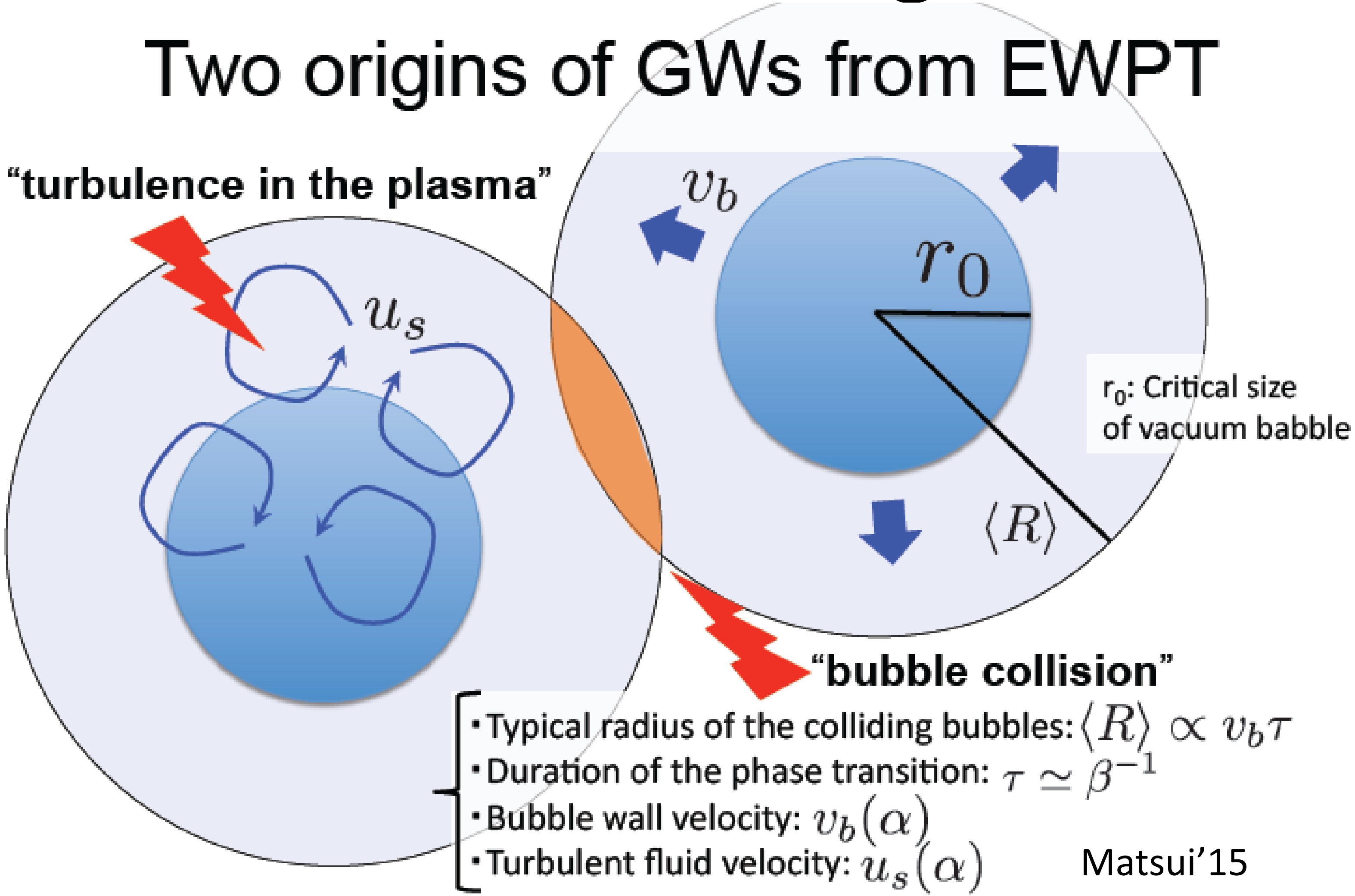


E. Witten, Phys. Rev. D 30, 272 (1984)
C. J. Hogan, Phys. Lett. B 133, 172 (1983);
M. Kamionkowski, A. Kosowsky and M. S. Turner, Phys. Rev. D 49, 2837 (1994))

EW phase transition GW becomes a hot topic after the discovery of Higgs boson and GW

First order EW phase transition can drive the plasma of the early universe out of thermal equilibrium, and Higgs bubble nucleate during it, which will produce GW.

Complementary probing of the electroweak phase transition with relic gravitational wave



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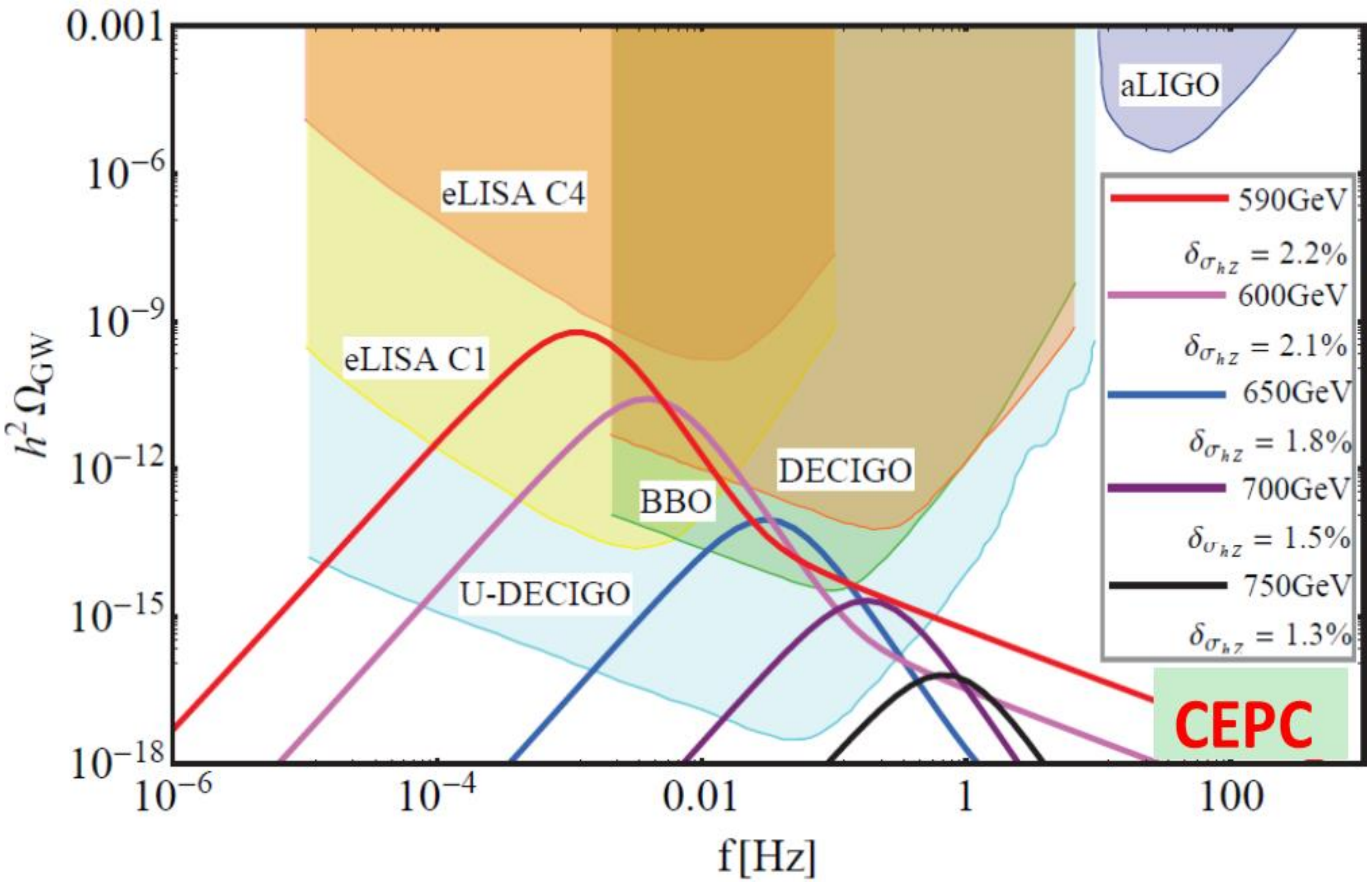


- eLISA, BBO are capable of detecting the GW from the EWPT
- The study on the EWPT bridges the particle physics at colliders with the astrophysics and cosmology in the early universe.

Fa Peng Huang, etc Phys. Rev. D 94, 041702(R) 2016

Summary

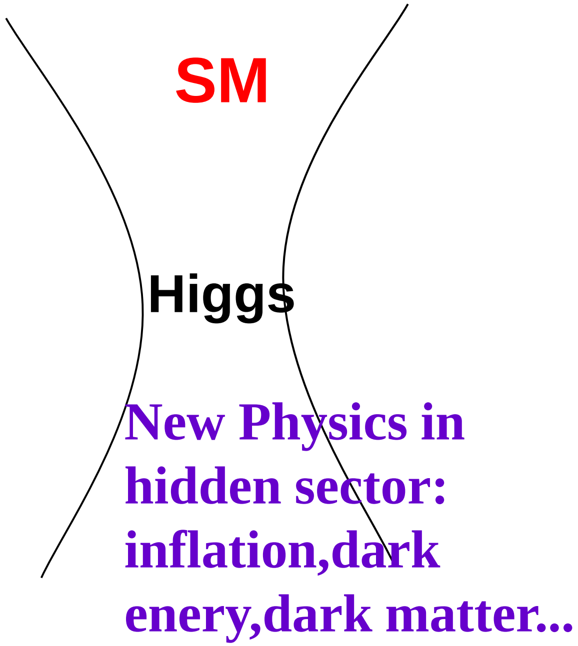
- Since the 125 GeV Higgs boson has been discovered at the LHC, it becomes a central issue to unravel the structure of the Higgs potential and the nature of the EW baryogenesis at the CEPC.
- However, there are so many possibilities, related to all possibilities of the Higgs sector extension.
- Each 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:Unravel the nature of spontaneous symmetry breaking, the order of the EW phase transition and the true potential of the Higgs boson.

B:Higgs as a portal to study the unsolved problem, which can not be explained by SM!



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

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:**

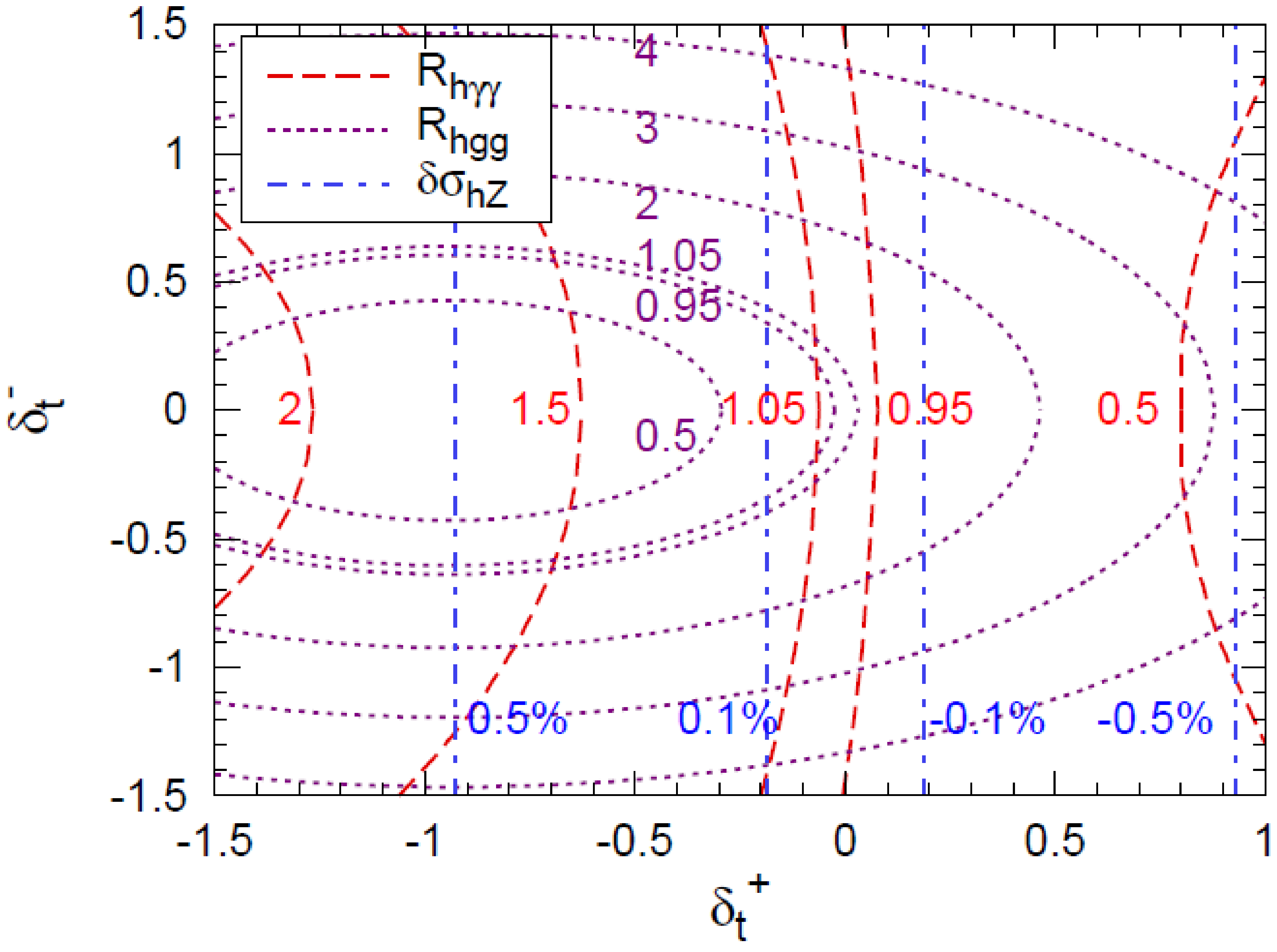
The recently announced aLIGO observation has initiated a new era of exploring fundamental physics with GW detectors.

Thanks for your attention !

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

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

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



R_hγγ
R_hgg
δσ_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^-

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

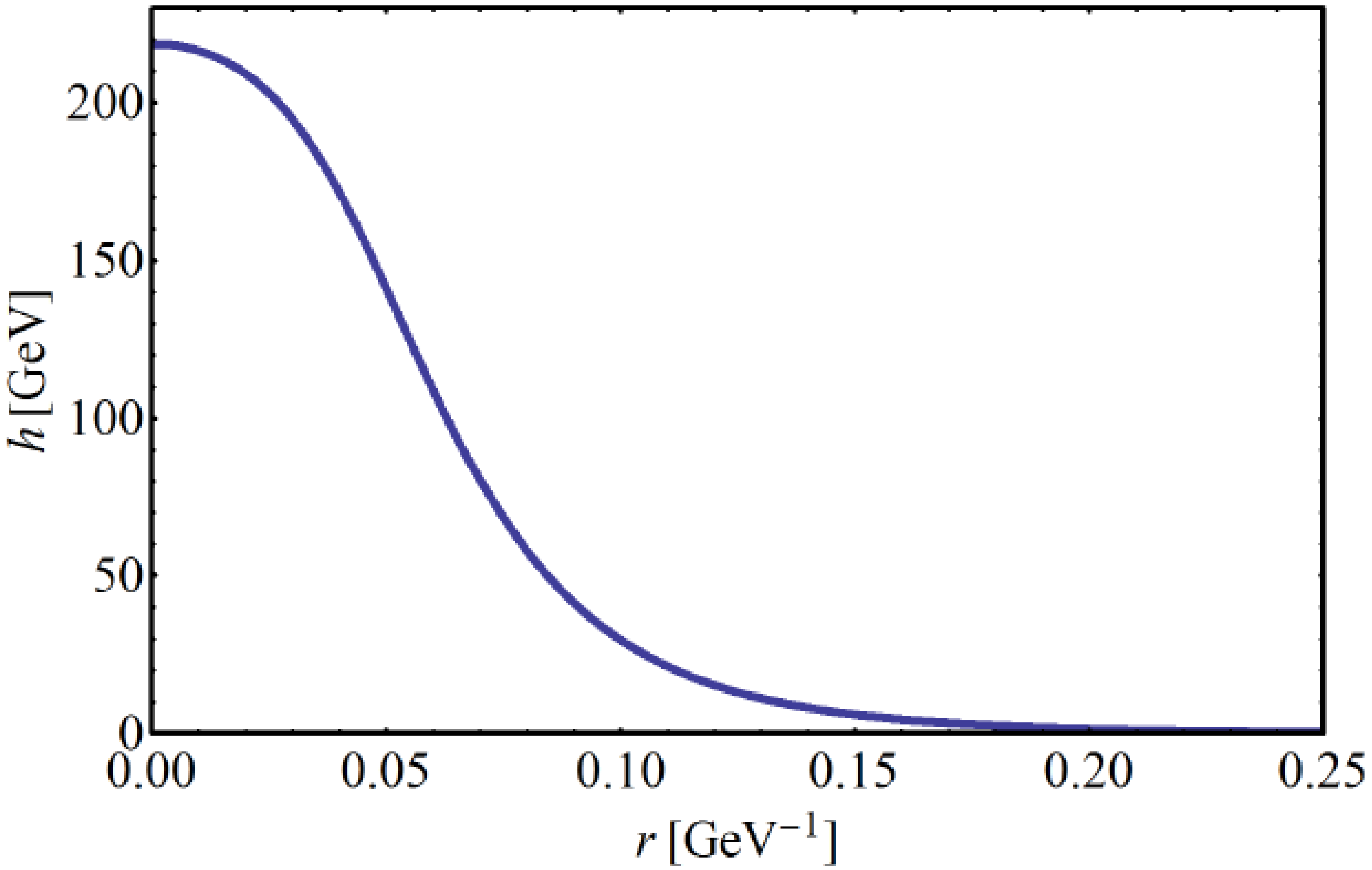
Here, the Higgs bubble energy is $$S_3 = \int dr 4\pi r^2 \left[\frac{1}{2} \left(\frac{d\phi_b}{dr} \right)^2 + V(\phi_b, T) \right]$$

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

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

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.



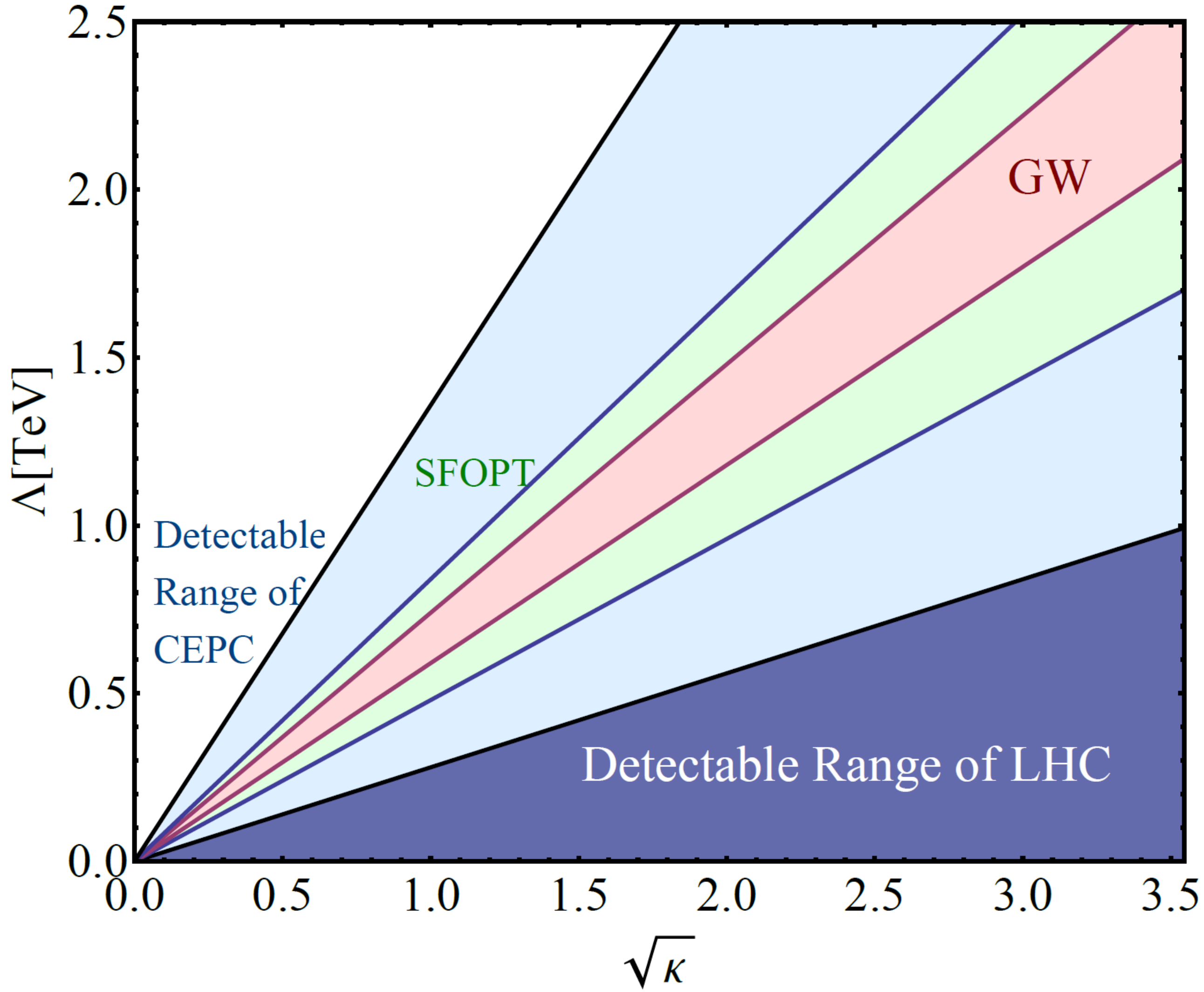
Dynamics of the EW phase transition

Two import parameters α and β

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

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

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.