



中国科学院高能物理研究所

Institute of High Energy Physics Chinese Academy of Sciences

# Probing the nature of Higgs boson from particle colliders to gravitational wave detectors

**Fa Peng Huang(黄发朋)**

based on our recent work Phys. Rev. D 93, 103515 ( 2016) ,  
Phys. Rev. D 94, 041702(R)(2016) and work in progress  
with Prof. Xinmin Zhang et al

CLHCP 2016@Peking University, 17 Dec. 2016

感谢李老师一直以来的  
指引和关心，  
祝李老师  
生日快乐，福寿安康

# Outline

- Research background
- Electroweak baryogenesis in a nutshell
- The effective Lagrangian and concrete model
- Hints at the hadron collider
- Test at the lepton collider
- Gravitational wave from EWPT
- Summary and outlook

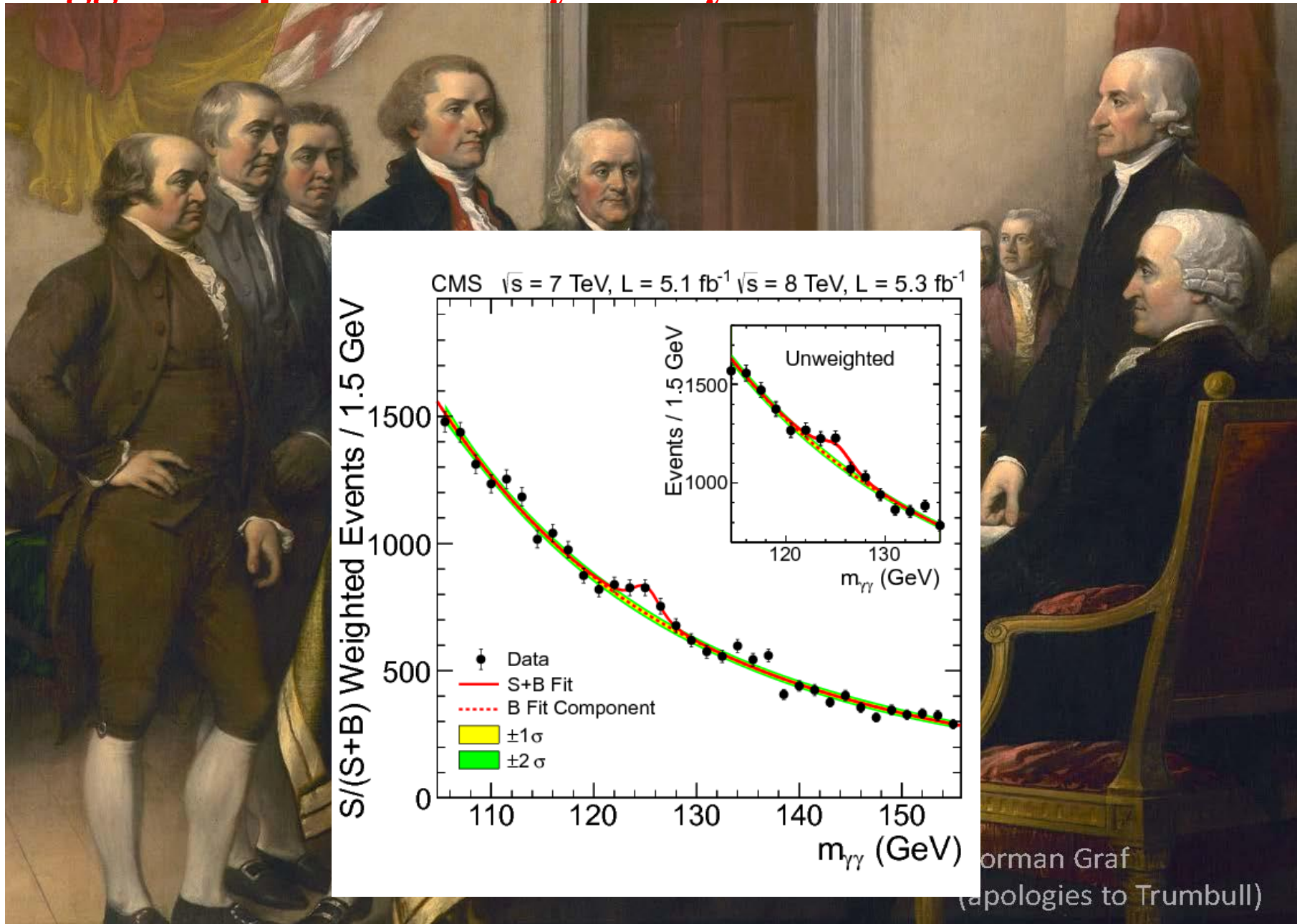
# Higgs Independence Day: 4 July 2012 @ LHC deliberate !



Norman Graf  
(apologies to Trumbull)



# Higgs Independence Day: 4 July 2012 @ LHC deliberate !



# Physics after Higgs Independence Day

- 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, baryogenesis (Higgs cosmology), and **the “cosmological relaxion”, Nnaturalness...**
- However, these fundamental problems may related to the nature of Higgs potential, namely, the true shape of Higgs potential, the nature of 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 by precise measurement of the Higgs properties.**

$$C_0 \approx (2 \times 10^{-3} \text{eV})^4 \ll M_{\text{P}}^4$$

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

triviality/stability  
of EW vacuum

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

flavor;  
CP-violation;  
mass and mixing hierarchy

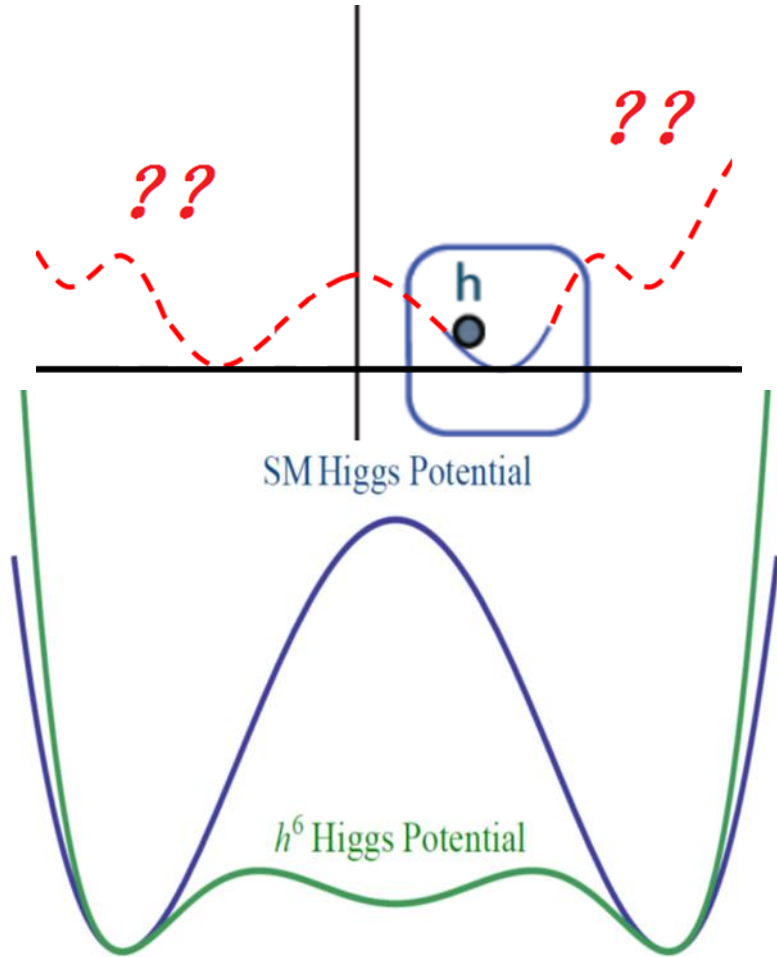
$$+ \mathcal{O}_{hidden} H^\dagger H$$

Higgs inflation(Alì).....  
**Higgs portal scenario,hidden sector of new physics,**

Precise higher order calculations in SM.

Case by case study of new physics Phenomenology.

# What is the nature of Higgs potential and the type of EW phase transition?



For the Higgs potential, we know nothing but the quadratic oscillation around the  $v_{\text{ev}}=246\text{GeV}$  with the mass  $125\text{ GeV}$  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



# The nature of Higgs potential and the type of EW phase transition

First order  
EW phase  
transition

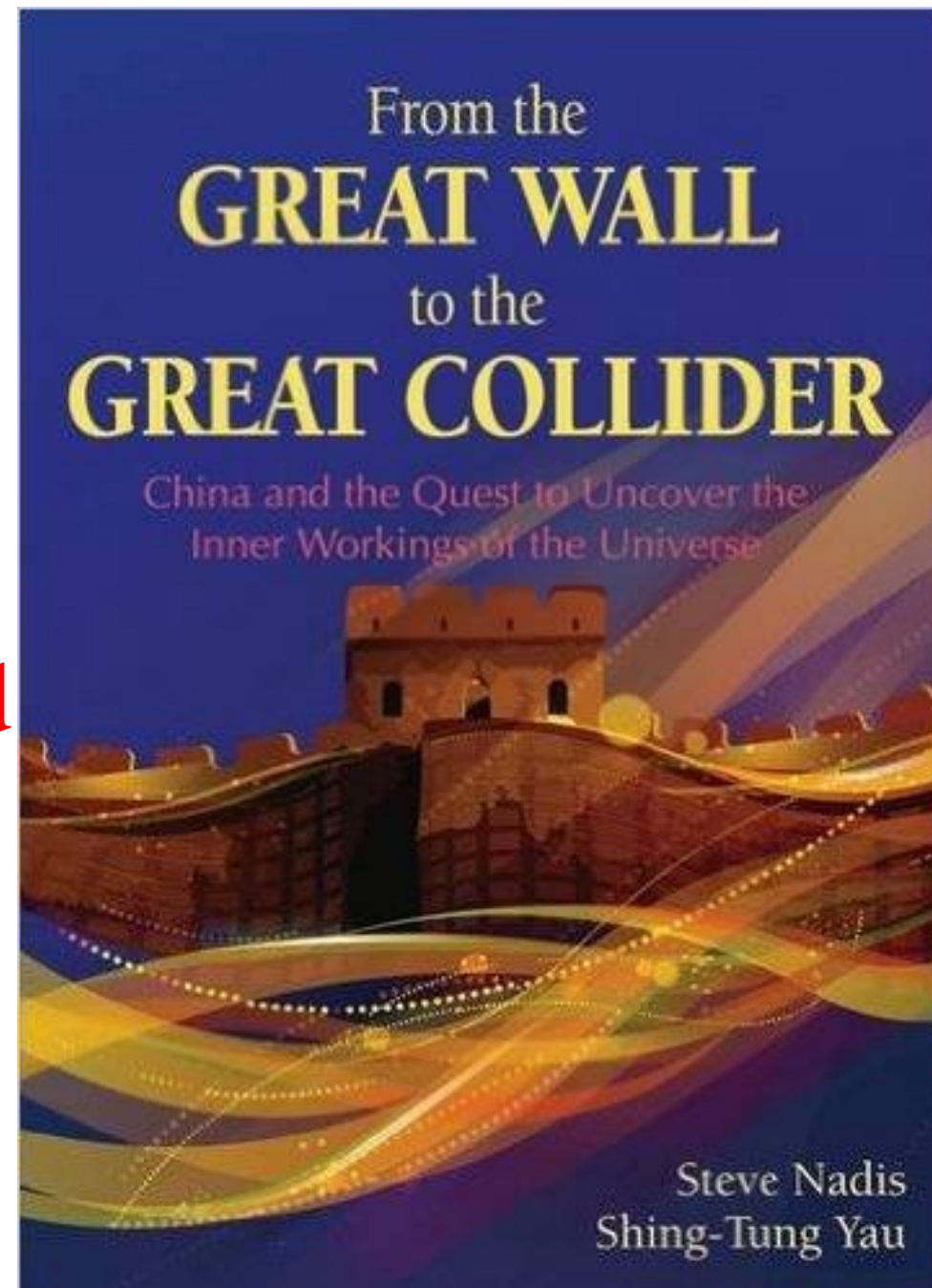


- The true shape of Higgs potential
- Baryon asymmetry of the universe (baryogenesis)
- Gravitational wave
- Help to know the evolution history of the universe at hundred GeV temperature.

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

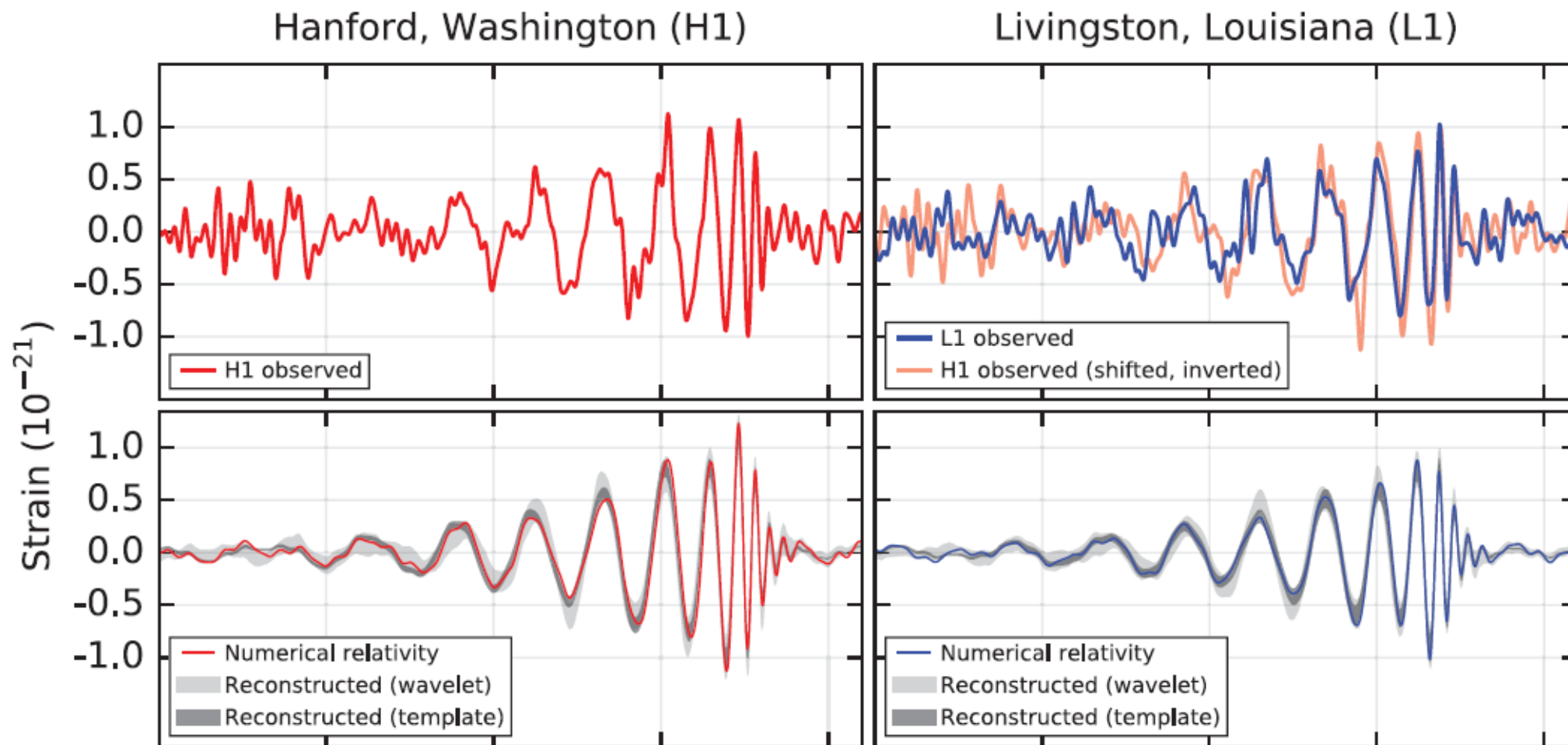
**A:** Directly, we can build more powerful colliders, such as the planned CEPC/SppC.

**Pre CDR of CEPC**



**B:Indirectly, GW detectors can test 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.



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

# **Baryogenesis-Sakharov conditions(1967)**

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

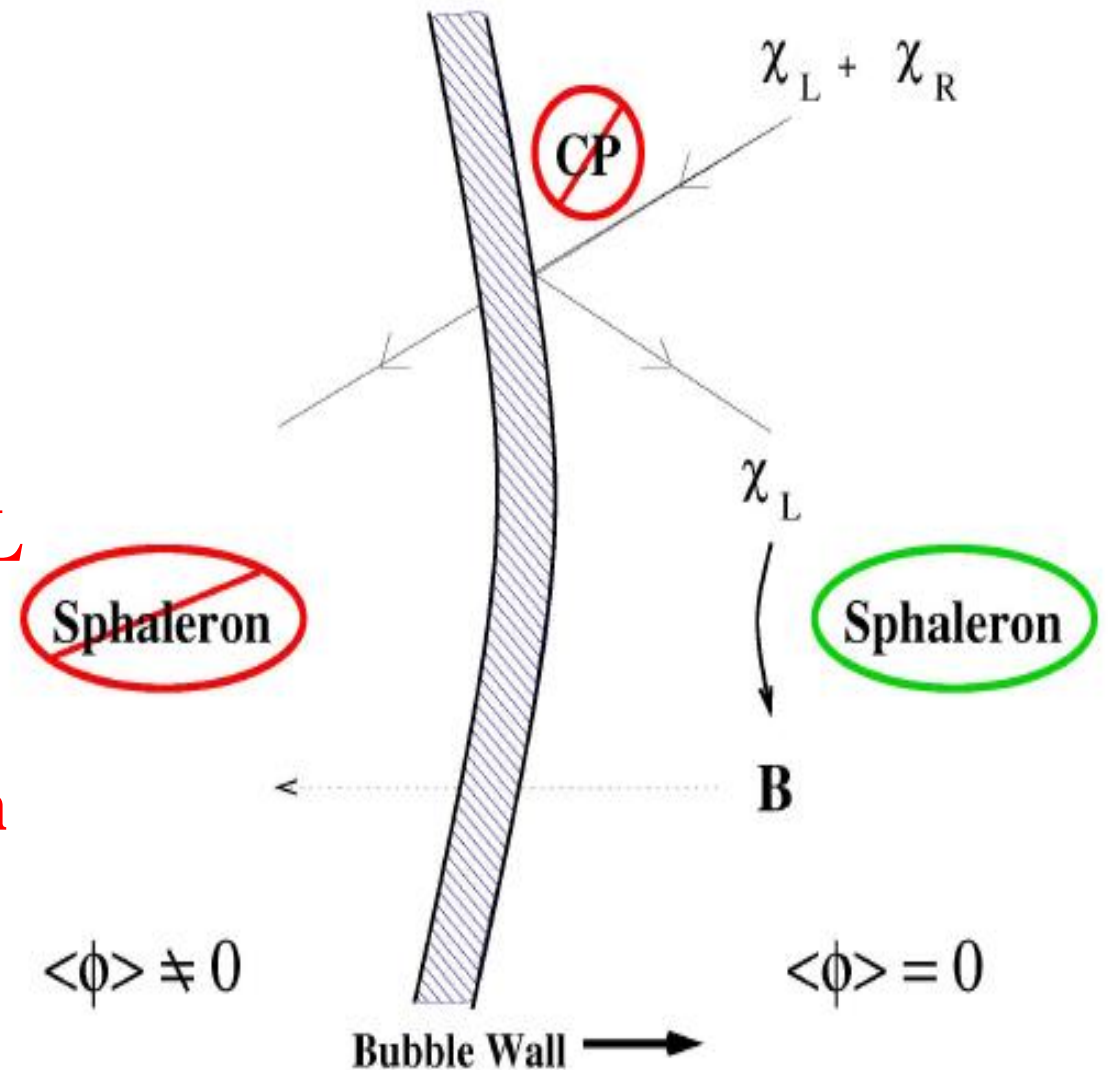
- Baryon number violation: create baryonic charge**
- C and CP violation: distinguish matter from anti-matter**
- Departure from thermal equilibrium or CPT violation:  
provide a time arrow**



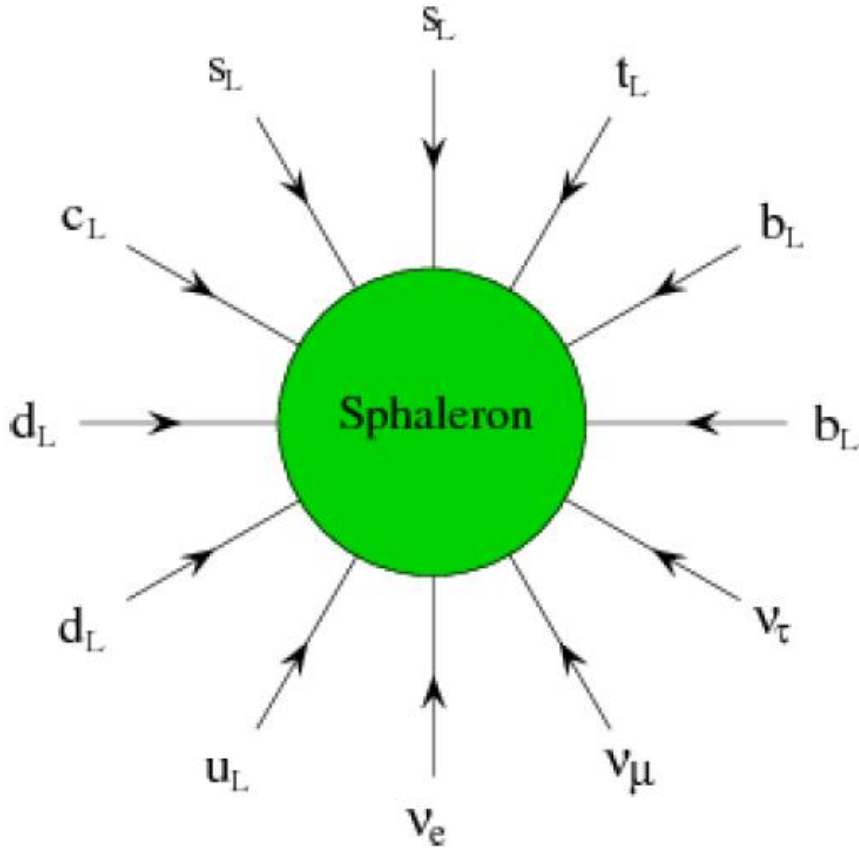
**EW baryogenesis:**  
SM technically has all  
the three elements for  
baryogenesis ,  
but not enough.

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

From D. E. Morrissey and M. J. Ramsey-Musolf,  
New J. Phys. 14, 125003 (2012).



# B-violation in SM——Sphaleron process



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

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](#), [Xinmin. Zhang](#)

Phys.Lett. B266 (1991) 413-418

# CP-violation source

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

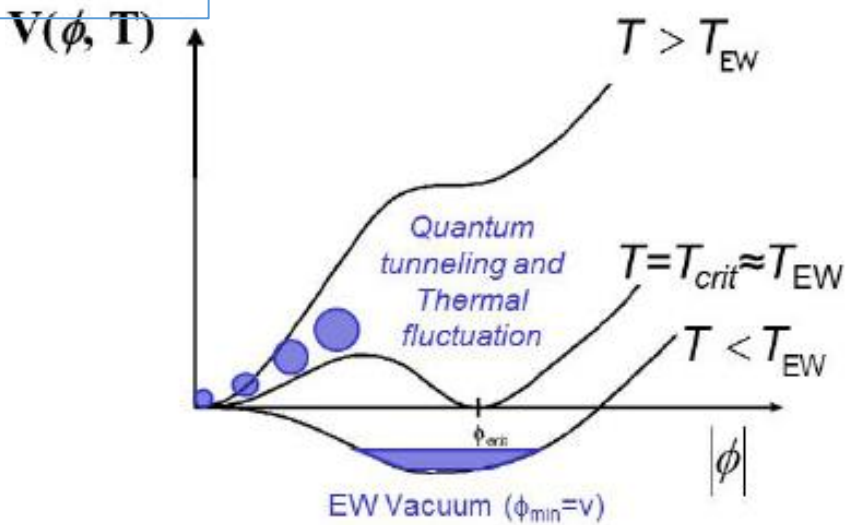
Dynamical Symmetry Breaking and Universality Breakdown R.D. Peccei, X. Zhang. Nucl.Phys. B337 (1990)

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

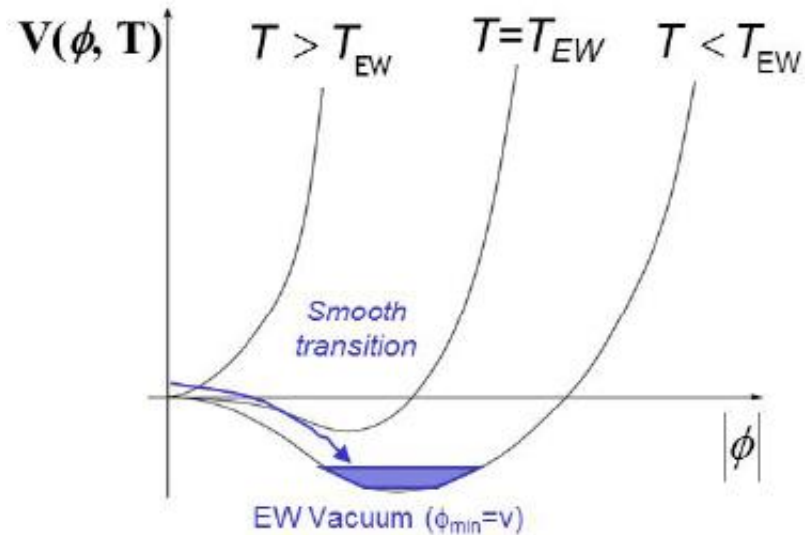
# Departure from thermal equilibrium — Strong first order phase transition

From  
lattice  
simulation

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



Cross over 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

Xinmin Zhang 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]

**FPH, C.S. Li, Phys.Rev. D92 (2015) , 075014**

**FPH, P.H. Gu, P.F. Yin, Z. H. Yu, Xinmin Zhang Phys.Rev. D93 (2016) 103515**

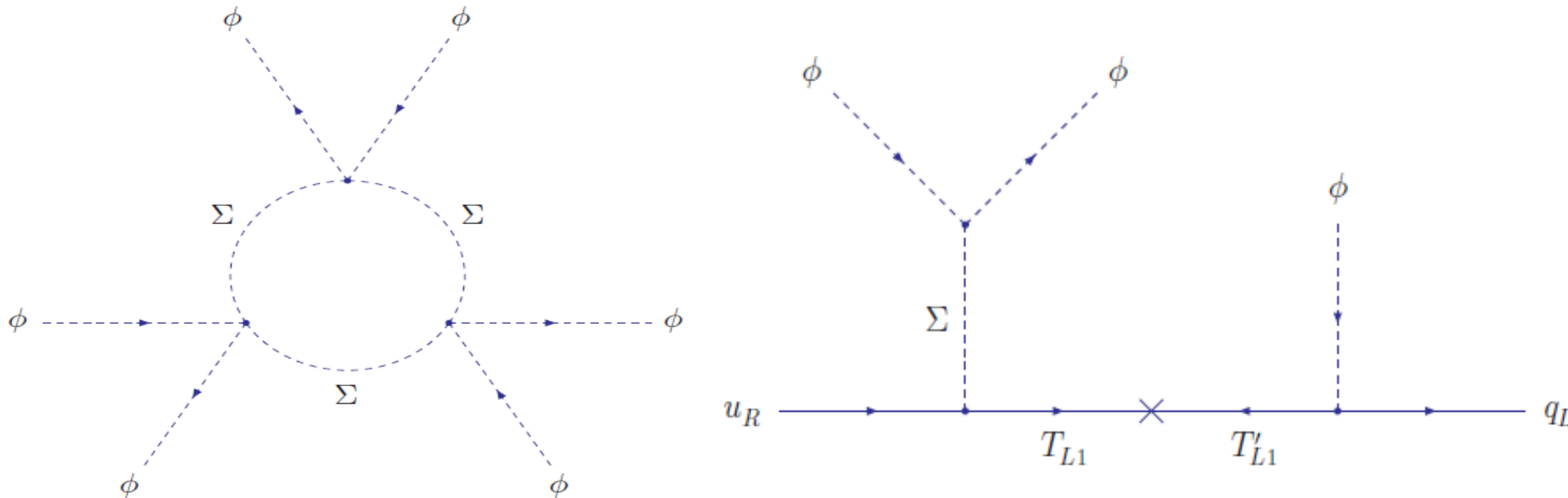
**FPH, Y. Wan, D.G. Wang, Y.F. Cai, Xinmin Zhang Phys. Rev. D 94, 041702(R) 2016**



# 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 scalar.

model details see **FPH**, et. al **Phys.Rev. D93 (2016) 103515**



# Renormalizable realization of the effective Lagrangian: an example to get $h^6$ term

The model with an  $SU(2)_L$  triplet scalar without hypercharge  $\Sigma(1, 3, 0)$

$$\delta\mathcal{L} = \xi_\Sigma \phi^\dagger \sigma^a \phi \Sigma^a + \frac{1}{2} \text{Tr}[(D^\mu \Sigma)^\dagger D_\mu \Sigma] - \frac{1}{2} M_\Sigma^2 \text{Tr}(\Sigma^2) - \kappa_\Sigma \phi^\dagger \phi \text{Tr}(\Sigma^2)$$

dimension-6 operator	tree-level and one-loop matching
$\mathcal{O}_{WW} = g^2  H ^2 W_{\mu\nu}^a W^{a,\mu\nu}$	$c_{WW} = \frac{\kappa_\Sigma}{96\pi^2 M_\Sigma^2}$
$\mathcal{O}_{2W} = -\frac{1}{2} (D^\mu W_{\mu\nu}^a)^2$	$c_{2W} = \frac{g^2}{480\pi^2 M_\Sigma^2}$
$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon^{abc} W_\rho^{a\mu} W_\mu^{b\nu} W_\nu^{c\rho}$	$c_{3W} = \frac{g^2}{480\pi^2 M_\Sigma^2}$
$\mathcal{O}_H = \frac{1}{2} (\partial_\mu  H ^2)^2$	$c_H = \frac{\kappa_\Sigma^2}{16\pi^2 M_\Sigma^2}$
$\mathcal{O}_T = \frac{1}{2} (H^\dagger \overleftrightarrow{D}_\mu H)^2$	$c_T = \frac{\xi_\Sigma^2}{M_\Sigma^4}$
$\mathcal{O}_6 = (H^\dagger H)^3$	$c_6 = \frac{\kappa_\Sigma \xi_\Sigma^2}{M_\Sigma^4} + \frac{\kappa_\Sigma^3}{8\pi^2 M_\Sigma^2}$

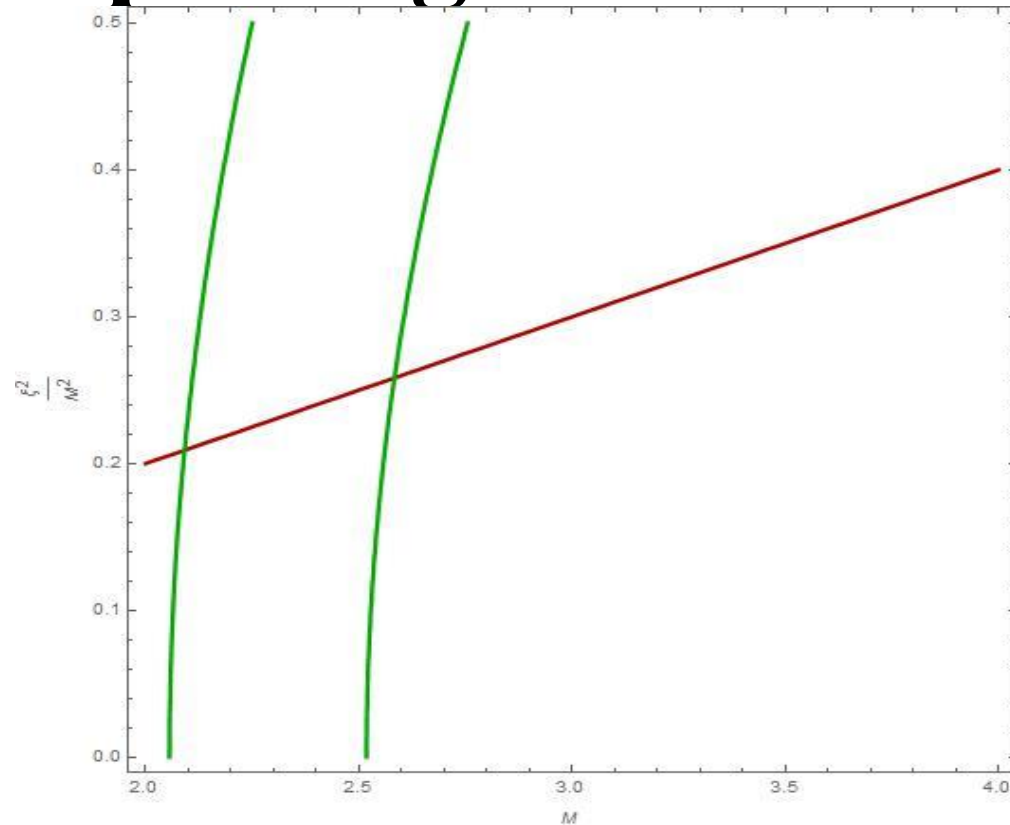
# Renormalizable realization of the effective Lagrangian: an example to get $h^6$ term

Considering the existed electroweak precise observables (work in progress)  
There exists parameter space to get the needed size of  $h^6$  term.

Next step: compare the EFT and the UV Completed model

$$T = 0.08 \pm 0.12 \quad T \approx -7.8c_T$$

$$\frac{\sigma_{ZH} - \sigma_{ZH}^{SM}}{\sigma_{ZH}^{SM}} \approx (0.26c_{WW} + 0.01c_{BB} + 0.04c_{WB} - 0.06c_H - 0.04c_T)(\text{TeV})^2 + 0.016\delta_h$$



# New Higgs potential and EW phase transition

For simplicity to investigate the signals from particle colliders to GW detector, we use the effective Lagrangian form for future discussion.

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

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

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

C. Grojean, G. Servant, J. Well PRD/1(2005)036001

[A.Noble](#), [M. Perelstein](#) Phys.Rev. D78 (2008) 063518

D. Bodeker, L. Fromme, S.J. Huber, M. Seniuch, JHEP 0502 (2005) 026

D.J.H. Chung, Andrew J. Long, Lian-tao Wang Phys.Rev. D87 (2013) , 023509

Lots of discussions, sorry that I can't cover all

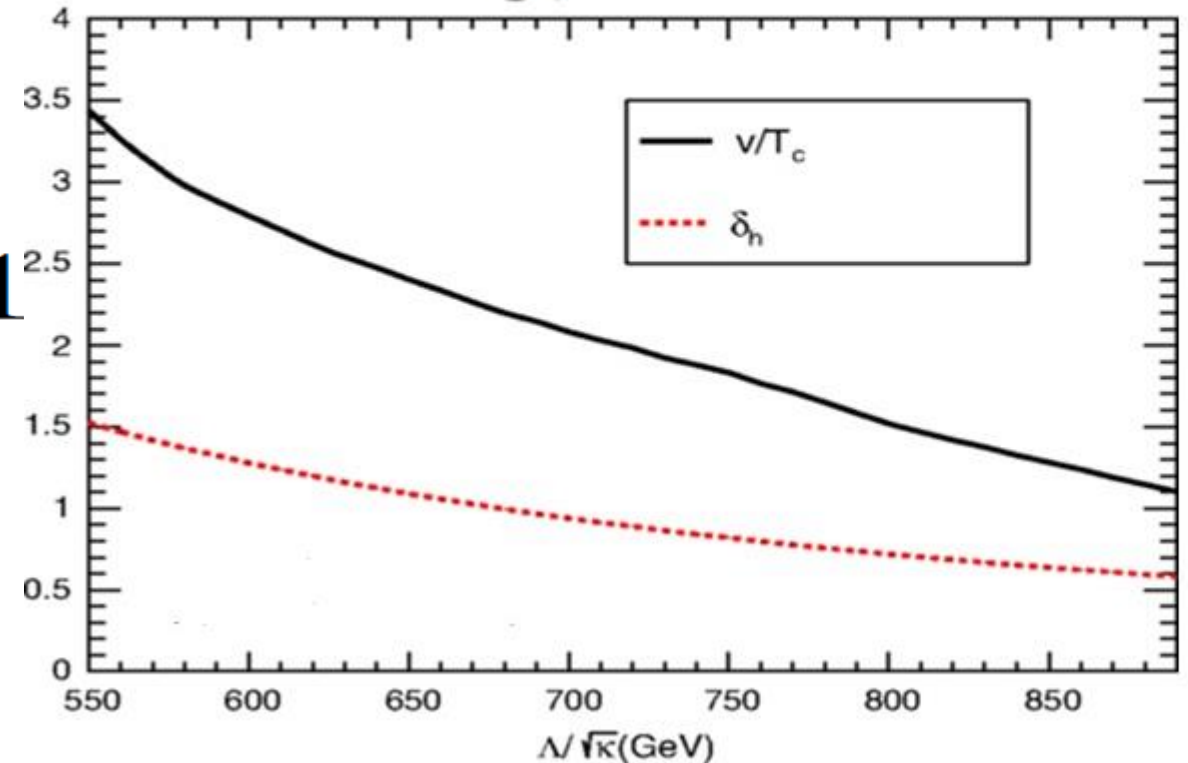
# Strong first order phase transition leads to obvious deviation of tri-linear Higgs coupling

$$T_c = \frac{\sqrt{\lambda^2 \Lambda^2 - 4\kappa \mu^2}}{2\sqrt{c\kappa}} > 0 \quad \mathcal{L}_{hhh} = -\frac{1}{3!}(1 + \delta_h)A_h h^3$$

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

At one loop level, deviation of the tri-linear Higgs coupling

$$\delta_h \in (0.6, 1.5)$$





# CP violation source

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

Provide sizable  
CP violation  
source

We only consider the top quark, 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 acquires a complex mass inside the bubble during the phase transition:

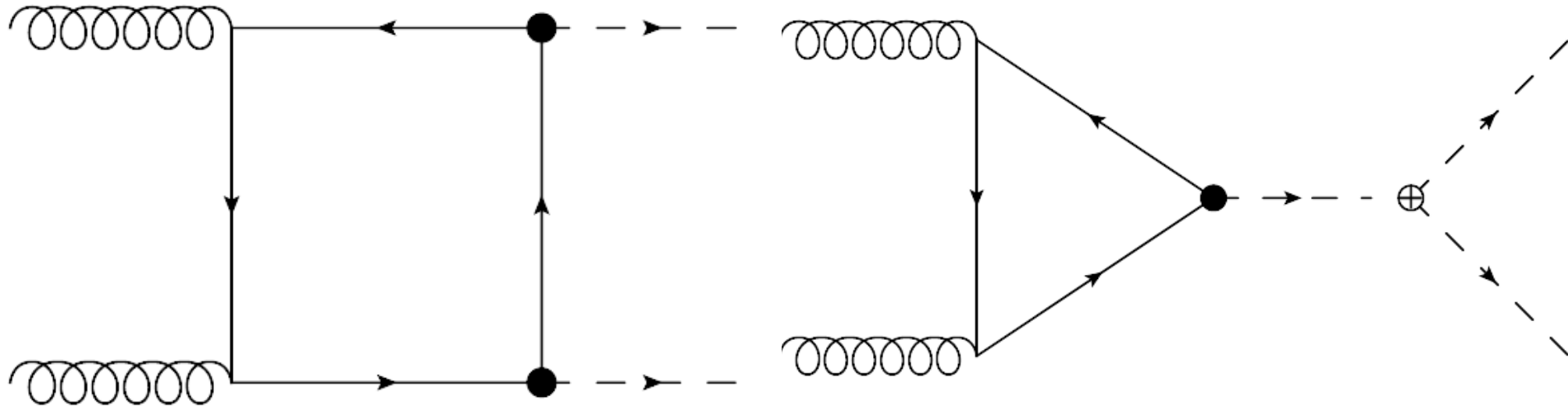
$$m_t(z) = \frac{m_t}{v} (1 + \delta_t^+ + i\delta_t^- \gamma^5) h(z)$$

$$\eta = 6.0\tilde{5}(7) \times 10^{-10} \longrightarrow \delta_t^- = \mathcal{O}(0.01 - 1)$$

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

# Hints at the large hadron collider (LHC): Higgs pair production

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

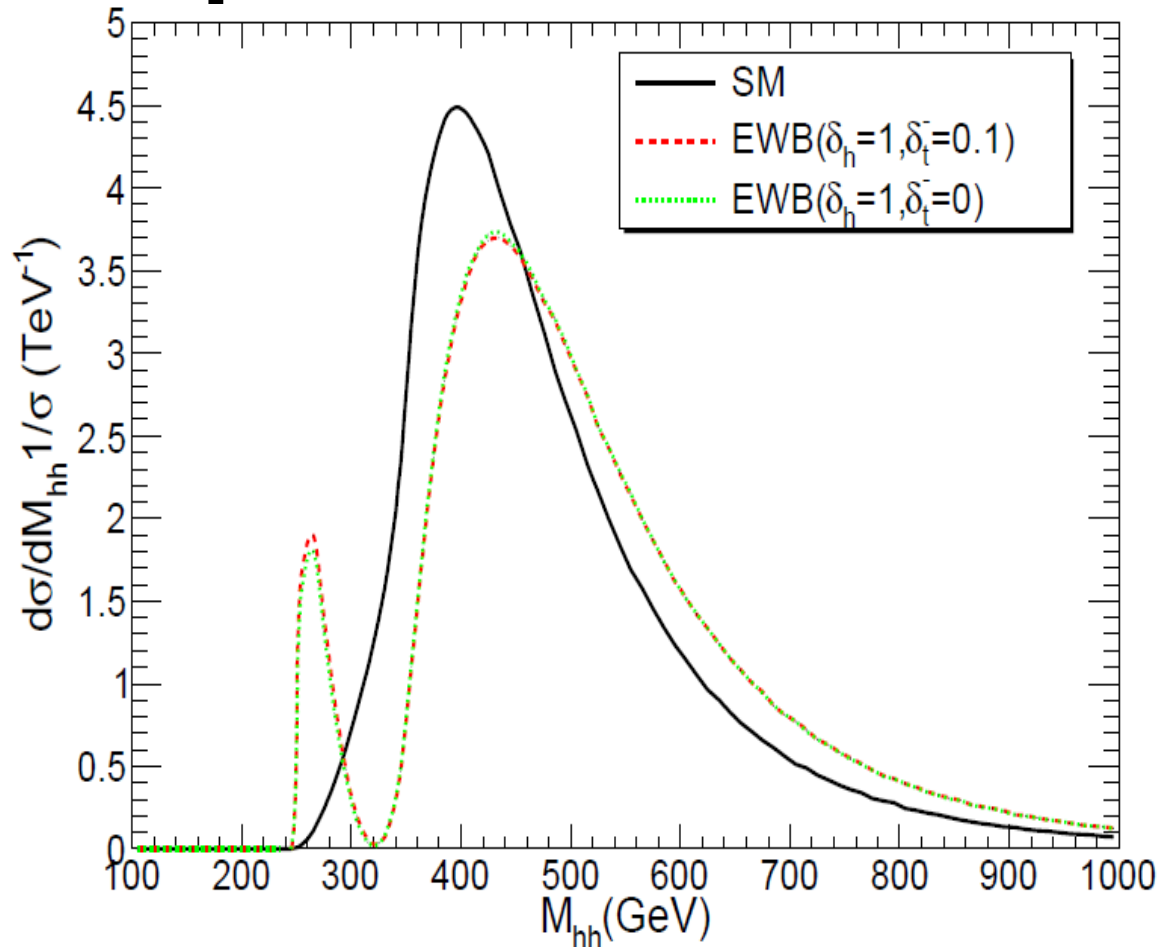


# Modify the Higgs pair production at the LHC

$$\begin{aligned} \frac{d\hat{\sigma}(gg \rightarrow hh)}{d\hat{t}} = & \frac{G_F^2 \alpha_s^2}{512(2\pi)^3} \left\{ \left| (1 + \delta_h)(1 + \delta_t^+) \mathcal{P}(\hat{s}) F_{\Delta}^A \right. \right. \\ & \left. \left. + (1 + \delta_t^+)^2 F_{\square}^{AA} + (\delta_t^-)^2 F_{\square}^{BB} \right|^2 \right. \\ & \left. + \left| (1 + \delta_t^+) \delta_t^- G_{\square}^{AB} \right|^2 + \left| (1 + \delta_t^+)^2 G_{\square}^{AA} + (\delta_t^-)^2 G_{\square}^{BB} \right|^2 \right. \\ & \left. + \left| (1 + \delta_h) \delta_t^- \mathcal{P}(\hat{s}) F_{\Delta}^B + (1 + \delta_t^+) \delta_t^- F_{\square}^{AB} \right|^2 \right\}, \end{aligned}$$

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



- Two peaks for the baryogenesis scenario, one peak for the SM.
- Due to the difficulties to suppress backgrounds at the LHC, it will be difficult to completely pin down these anomalous coupling at 14 TeV LHC, even with  $3000 \text{ ab}^{-1}$  integrated luminosity.
- Exploiting boosted tricks helps to increase ability to extract the anomalous couplings.
- More precise information may come from future 100 TeV hadron collider, such as SppC, or future lepton collider, such as CEPC.

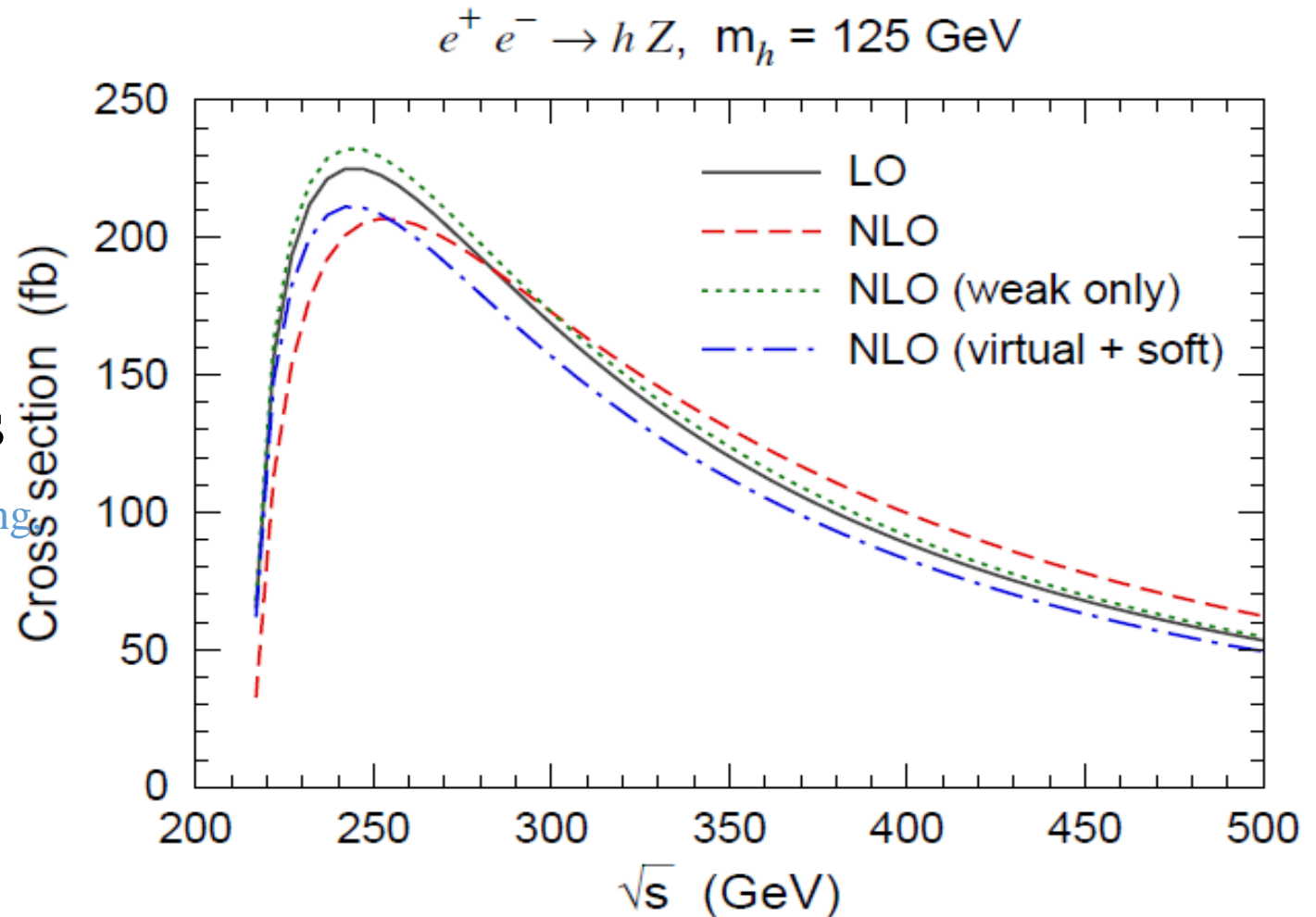
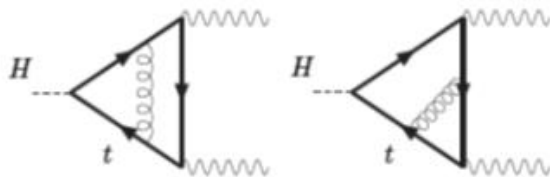


**The Circular Electron Positron Collider (CEPC) can precisely test this scenario through precise measurements of the Zh production.**

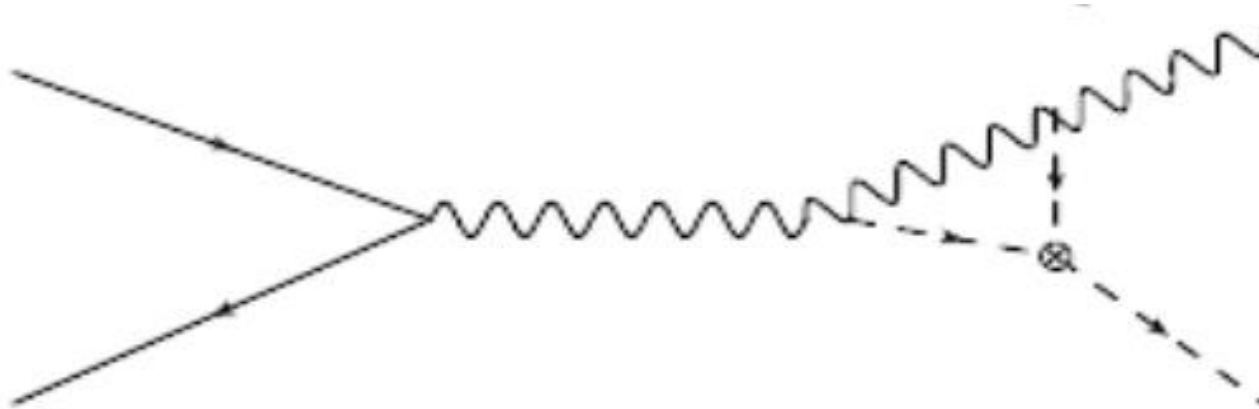
**The NLO Zh cross-section in the SM.**

Towards NNLO Zh cross section recently by [Lilin Yang et al 2016](#)  
[Yu Jia et al 2016](#)

The “simpler”:  $O(\alpha\alpha_s)$

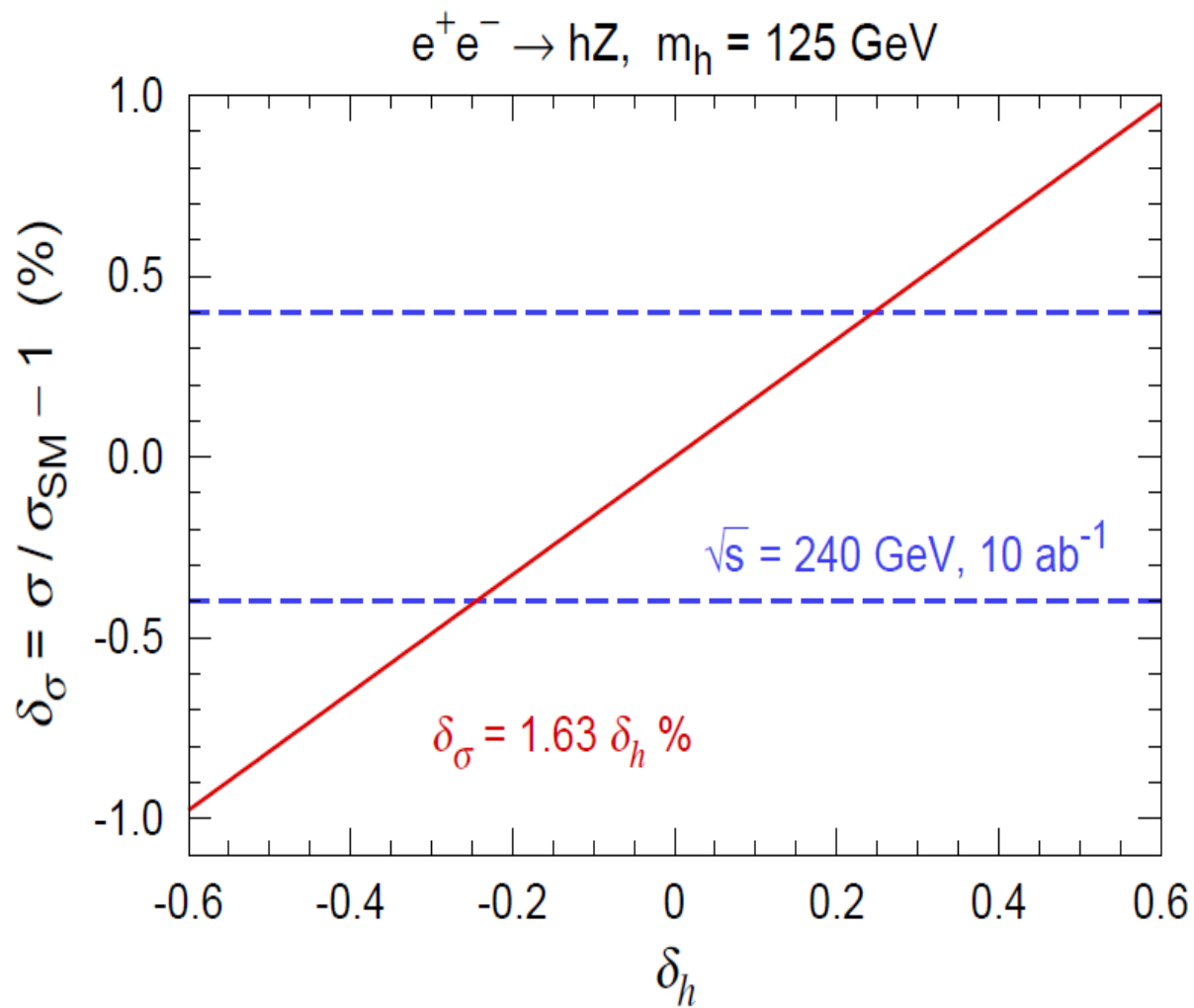


**At CEPC, for the EW phase transition  
/baryogenesis scenario, the anomalous tri-linear  
Higgs coupling will contribute to the Zh production  
beyond the SM.**



**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

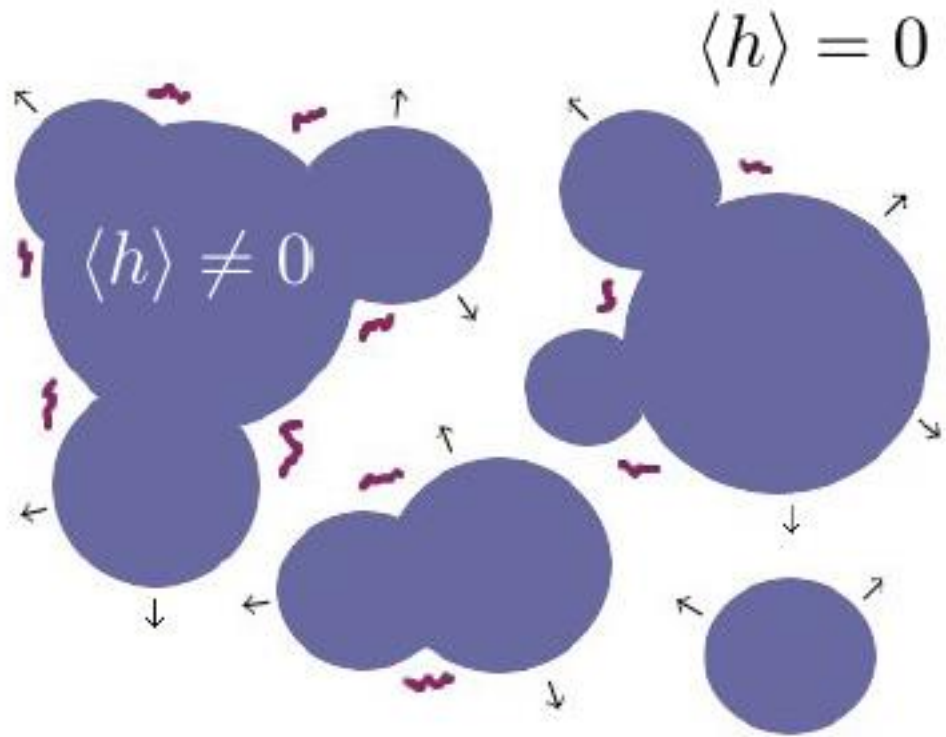
For the future CEPC with the integrated luminosity of  $10 \text{ ab}^{-1}$  at  $\sqrt{s} = 240 \text{ GeV}$ , the precision of the  $\sigma_{zh}$  may be about 0.4%. Therefore, it is possible to test the  $\delta_h \sim 25\%$  at the CEPC.

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 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)



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.

Pictures from Prof. Huber and Konstandin

**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 more  
interesting and realistic  
after the discovery of  
Higgs boson by LHC  
and GW by LIGO.**

# Source of GW during EW phase transition

- **Bubble collision:** well-known source
- **Turbulence in the plasma fluid:** a fraction of the bubble wall energy converted into turbulence.
- **Sound wave in the plasma fluid :** after the collision a fraction of bubble wall energy converted into motion of the fluid (and is only later dissipated).

New source of GW:  
sound wave

M.Hindmarsh, *et al.*, PRL  
**112**, 041301 (2014);

[G. Christophe](#) *et al.* Phys.Rev. D75 (2007)

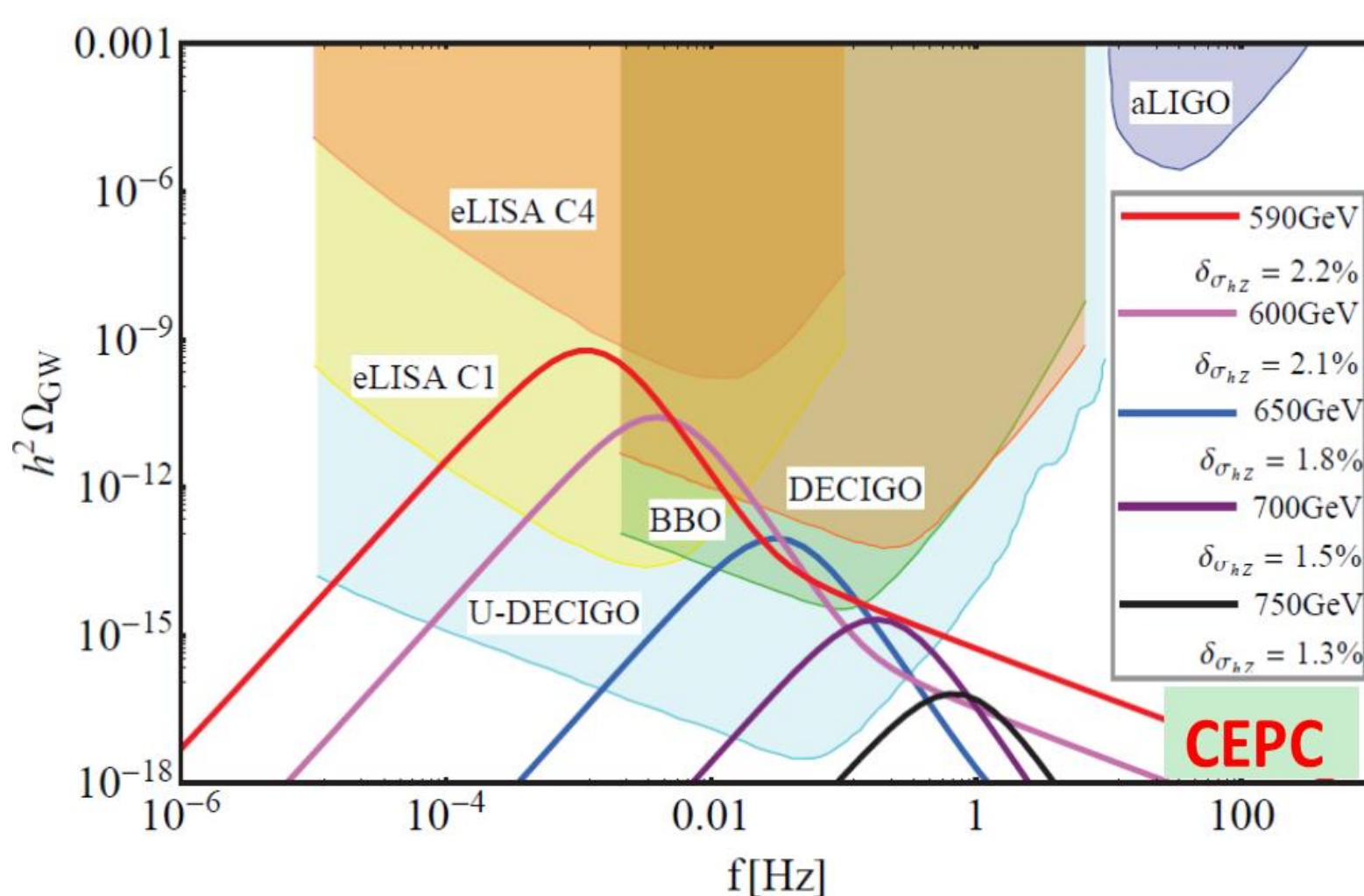
[Caprini, Chiara](#) *et al.* JCAP 1604 (2016)

**Detectable GW signals  
will be produced  
during the EW phase  
transition.**



# Correlate particle collider and GW signals

## Double test on Higgs nature from particle to wave



➤ eLISA, BBO, U-DECIGO are capable of detecting the GW from EWPT

➤ The study on EWPT naturally bridges the particle physics at collider with GW survey, astrophysics and cosmology.

We shown the combined results in this Figure:

The colored regions correspond to the expected sensitivities of GW detectors eLISA, BBO, and U-DECIGO.

The colored lines represents the GW spectrum for different cutoff scales, which also corresponds the deviation of hZ cross section at CEPC, respectively.

**Firstly**, we can see that the eLISA, BBO, U-DECIGO are capable of detecting the GW from EWPT.

**Secondly**, the study on EWPT naturally bridges the particle physics at collider with GW survey, astrophysics and cosmology. For example, the red line depicts the GW spectrum for 590 GeV, which corresponds collider signal of the deviation of hZ cross section 2.2% at the CEPC.

**Last but not the least**, the GW survey can provide a complementary approach to probe the nature of the EWPT alternative to particle colliders, and vice versa.

**The future lepton collider and GW detector can make a double check on the nature of the Higgs boson.**

# 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.
- The SM Higgs sector is extended using the EFT approach and a concrete renormalizable model is also built to realize the EFT . The Collider and GW signals and their correlation are investigated.
- However, there are so many possibilities, related to all possibilities of the extending the Higgs sector. **Each type of extension is need to study in detail both at colliders and GW detectors. (See Andrew's talk)**
- The joint analysis will contribute to deeply understand the nature of Higgs boson, which can build an deep connection between astrophysics a particle physics, and GW physics in fundamental physics.

# Thanks for your attention !

