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Probing the nature of electroweak phase transition/baryogenesis from particle colliders to gravitational wave detectors

Fa Peng Huang

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

TeV Particle Astrophysics 2016@CERN, 13 Sep. 2016

Outline

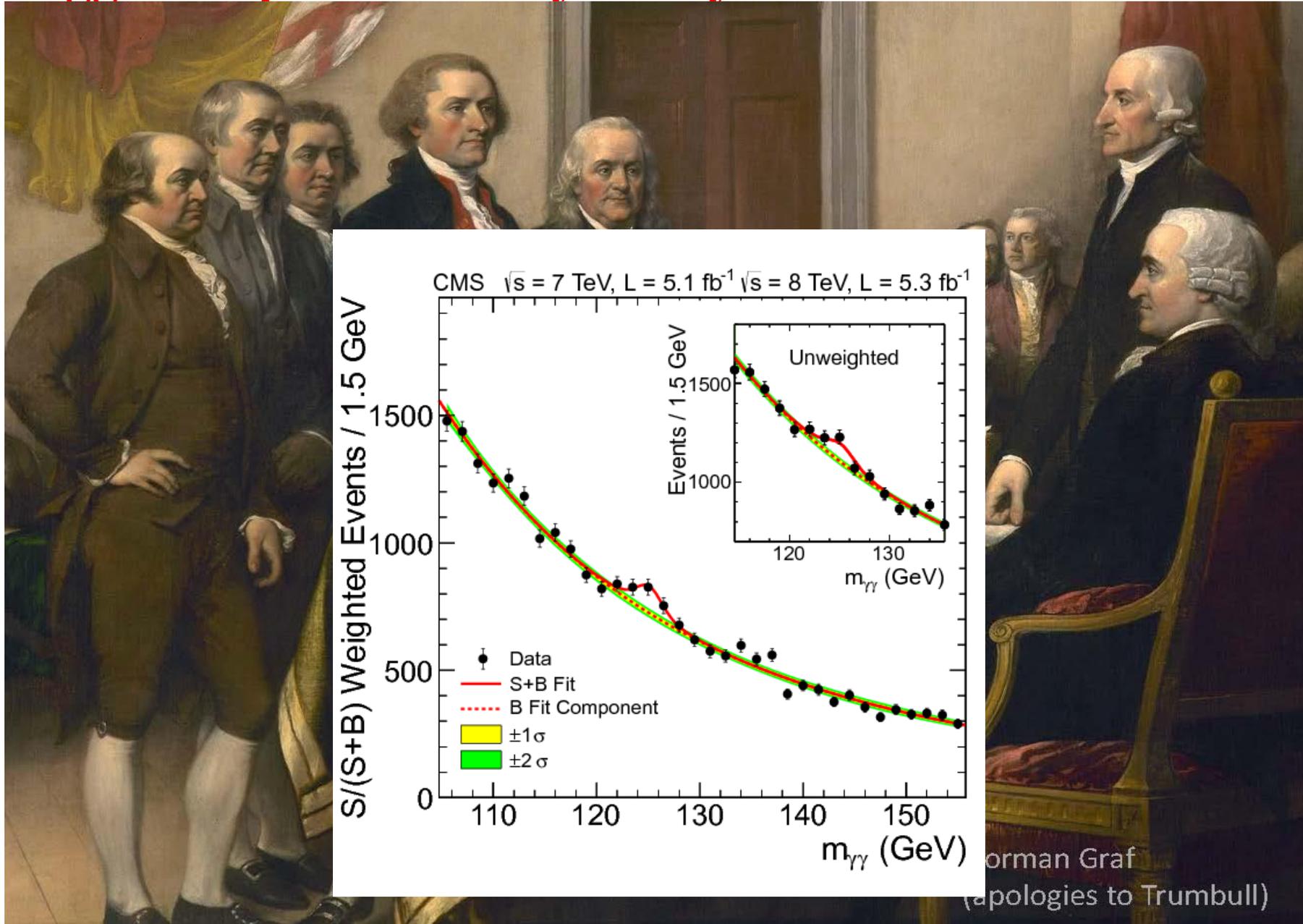
- **Motivation**
- **Electroweak baryogenesis in a nutshell**
- **The effective Lagrangian and concrete model**
- **Hints at the hadron collider**
- **Testing at the lepton collider**
- **Gravitational wave detection**
- **Summary**

Higgs Independence Day: 4 July 2012 @ LHC deliberate !



Norman Graf
(apologies to Trumbull)

Higgs Independence Day: 4 July 2012 @ LHC deliberate !

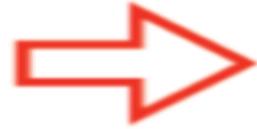
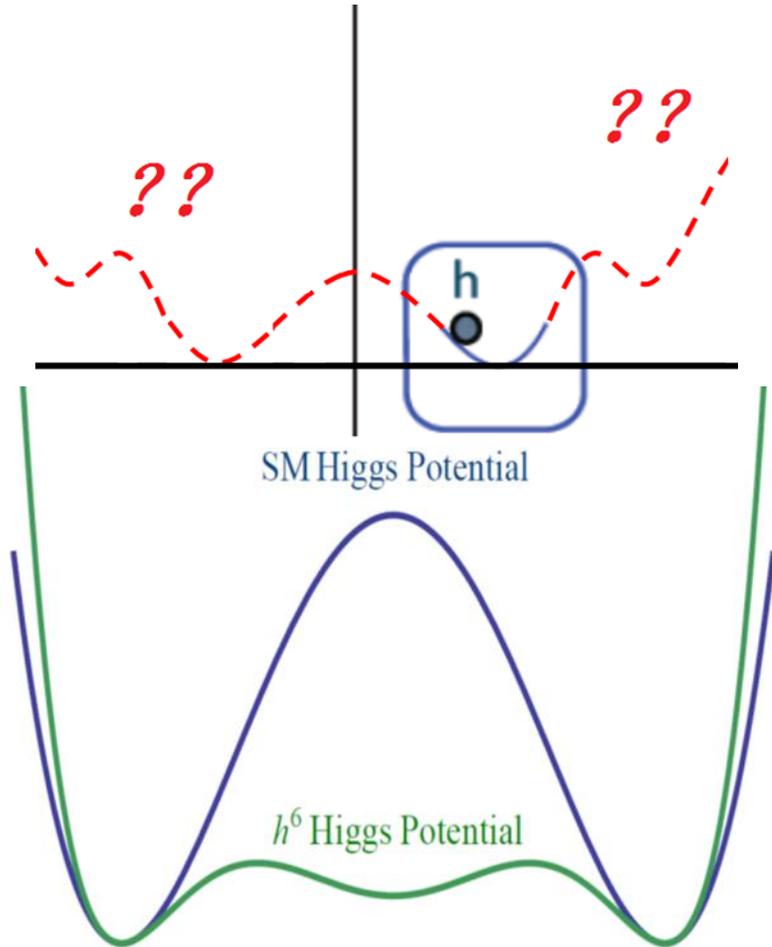


Physics after Higgs Independence Day

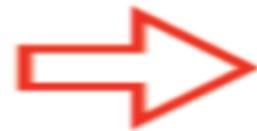
- The discovery of 125 GeV scalar at the LHC opens a new window to study the fundamental physics, such as neutrino mass, Higgs (portal) inflation, Higgs dark energy, baryogenesis (Higgs cosmology), and **the “cosmological relaxion”, Nnaturalness...**
- However, these fundamental problems may related 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.

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

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 $v_{ev}=246\text{GeV}$ 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

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

First order
EW phase
transition

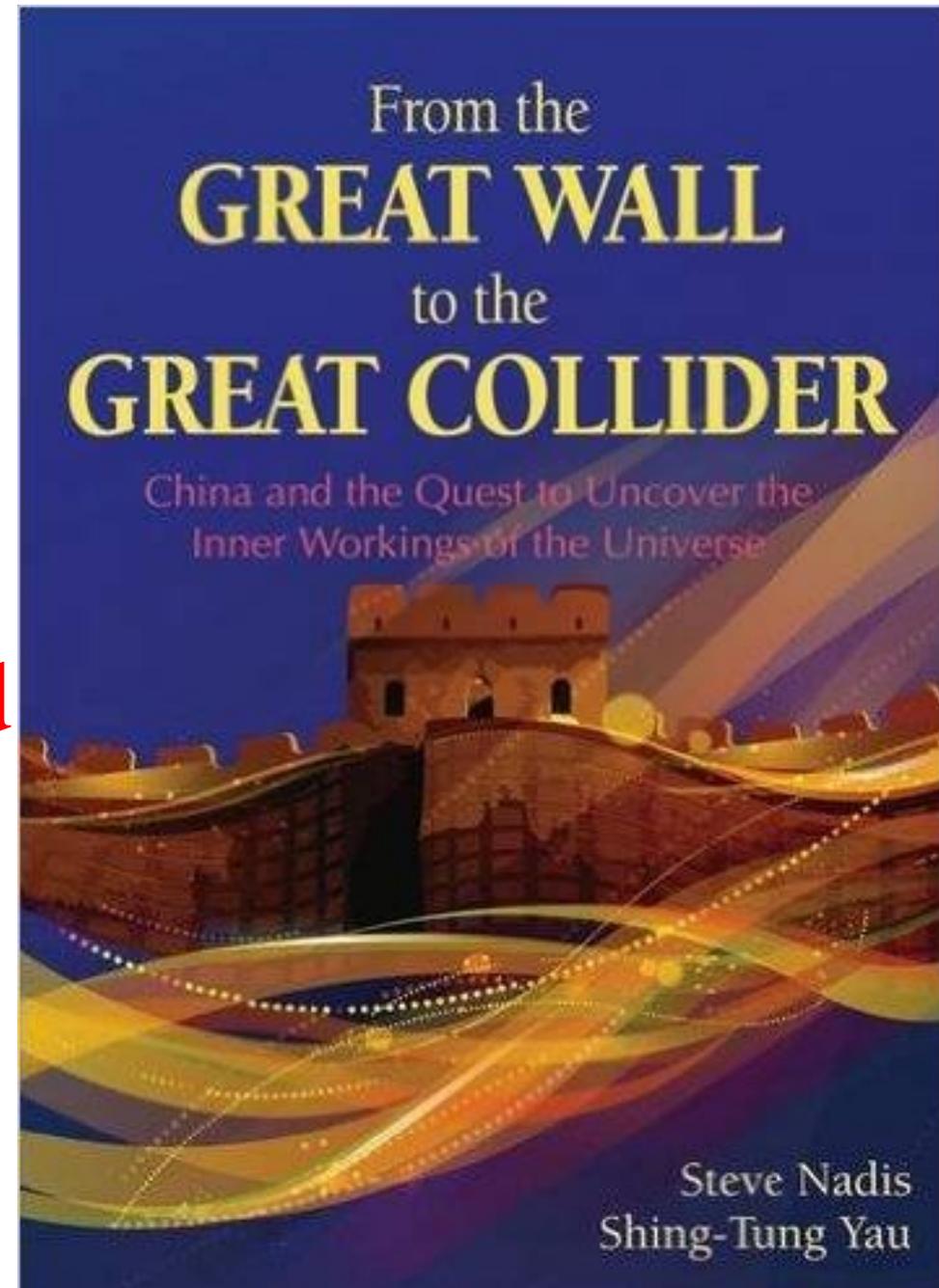


- The true shape of Higgs potential
- Baryon asymmetry of the universe (baryogenesis)
- Gravitational wave

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

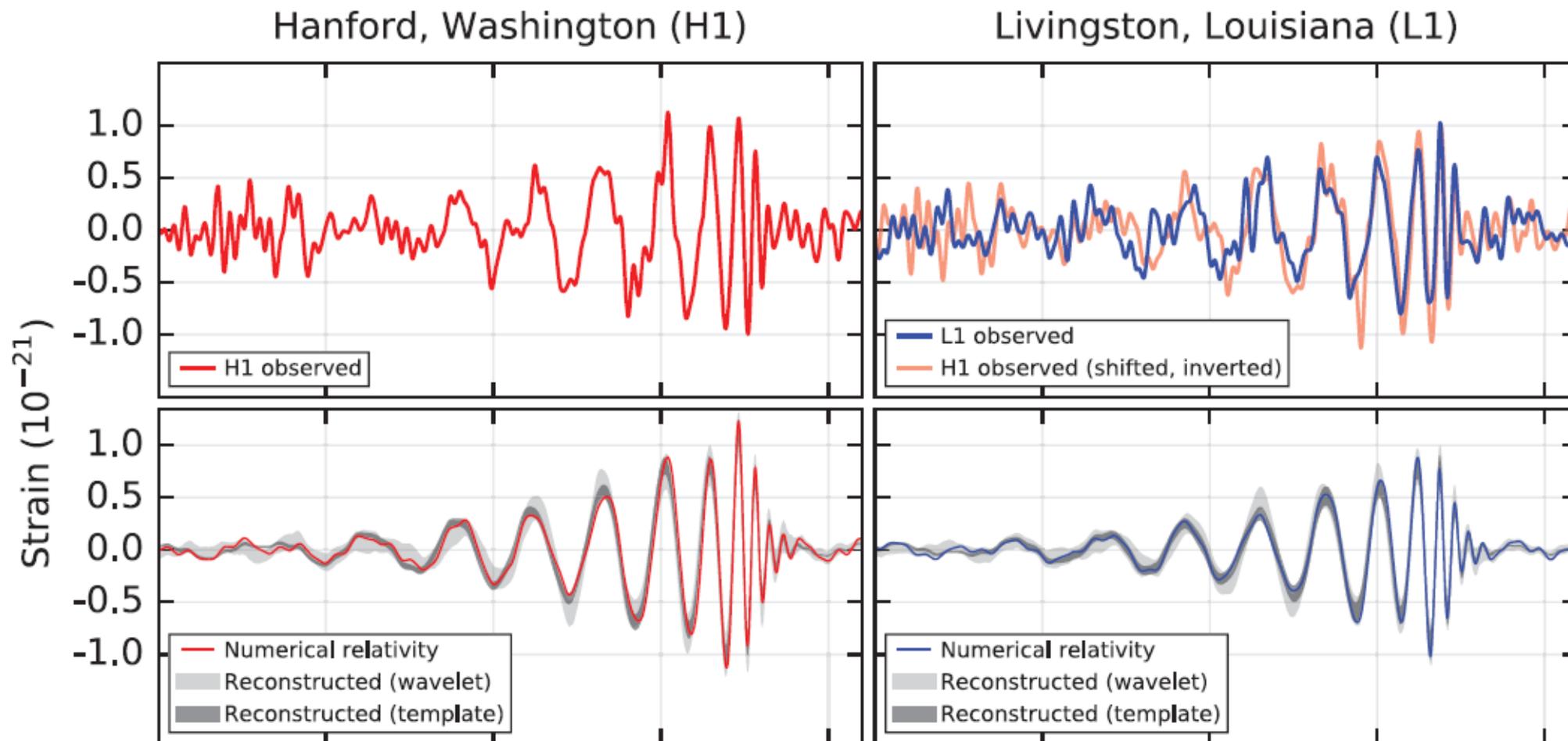
A: Directly, we can build more powerful colliders, such as the planned CEPC/SppC.

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)

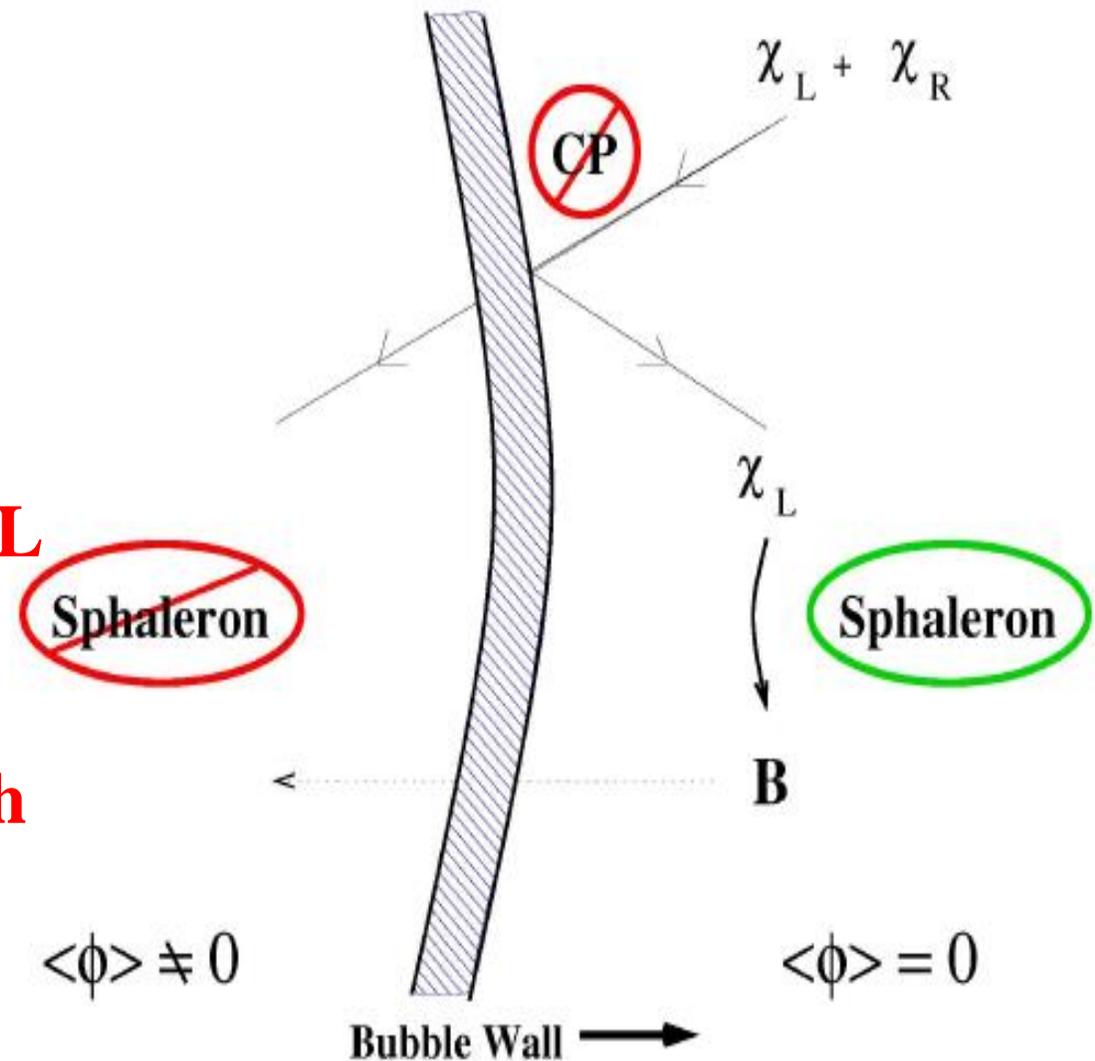
To produce the observed BAU, three necessary conditions are needed at the same cosmic epoch:

- 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**

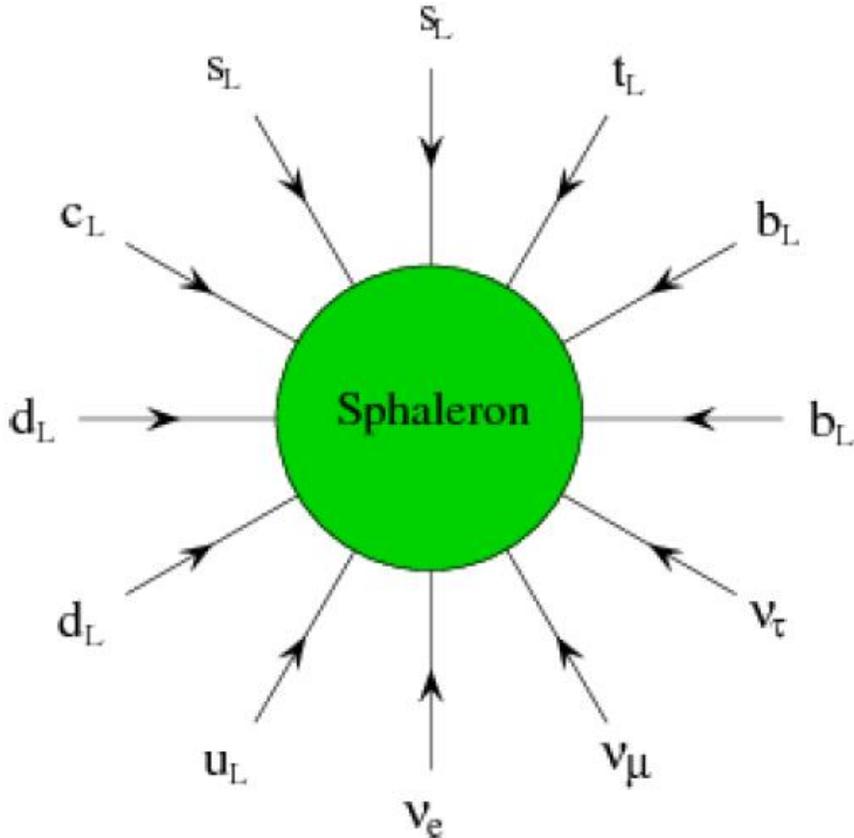
EW baryogenesis:
SM technically has all
the three elements for
baryogenesis ,
but not enough.

- **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, X. Zhang \(UCLA\)](#)

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

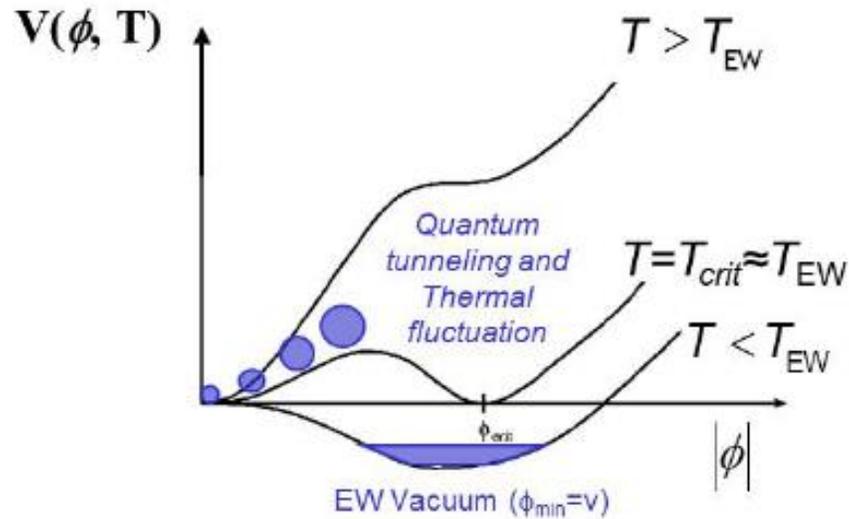
Dynamical Symmetry Breaking and Universality Breakdown R.D. Peccei, X. Zhang. Nucl.Phys. B337 (1990)

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

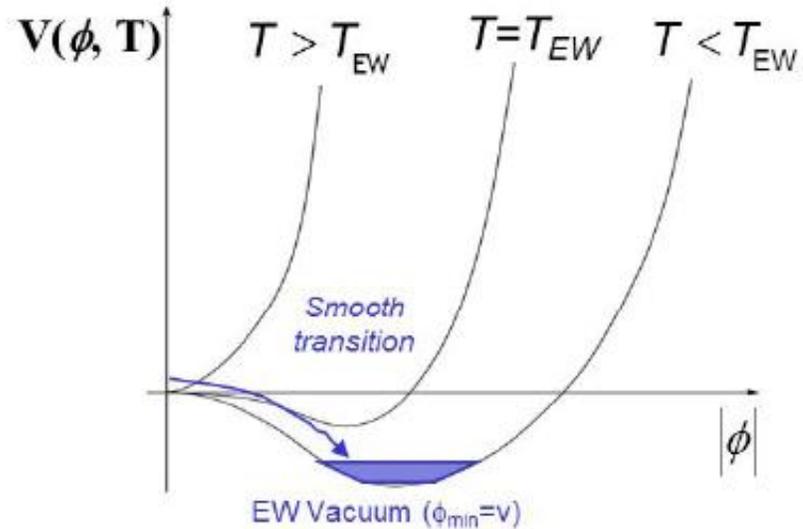
Departure from thermal equilibrium ———

Strong first order phase transition

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](#)

Xinmin 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]

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

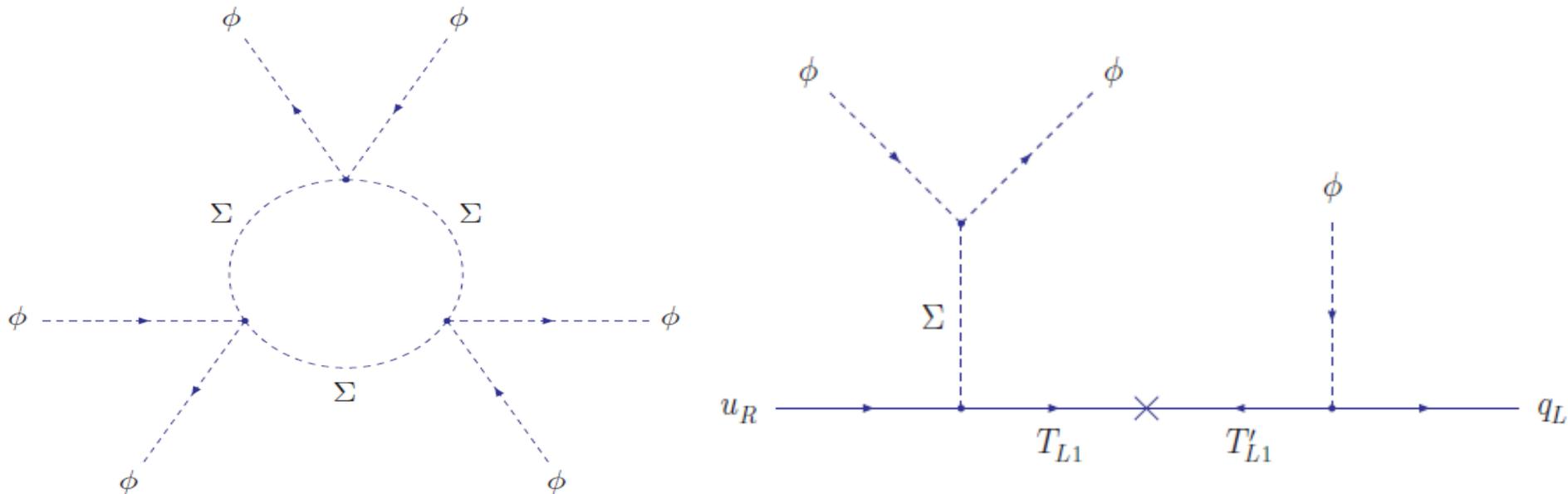
FPH, P.H. Gu, P.F. Yin, Z. H. Yu, Xinmin Zhang Phys.Rev. D93 (2016) 103515

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 quarks and triplet Higgs.

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



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:

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

C. Grojean, G. Servant, J. Well PRD71(2005)036001

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

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

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

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

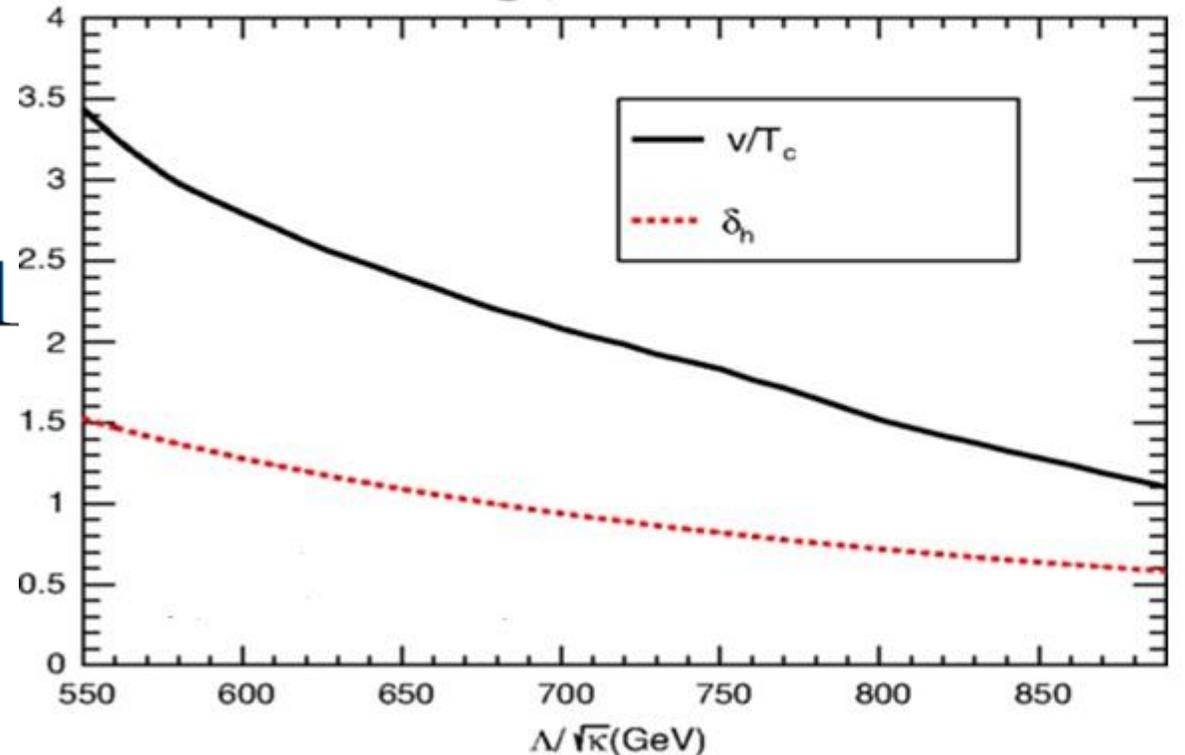
$$T_c = \frac{\sqrt{\lambda^2 \Lambda^2 - 4\kappa\mu^2}}{2\sqrt{c\kappa}} > 0$$

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

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

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

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



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:

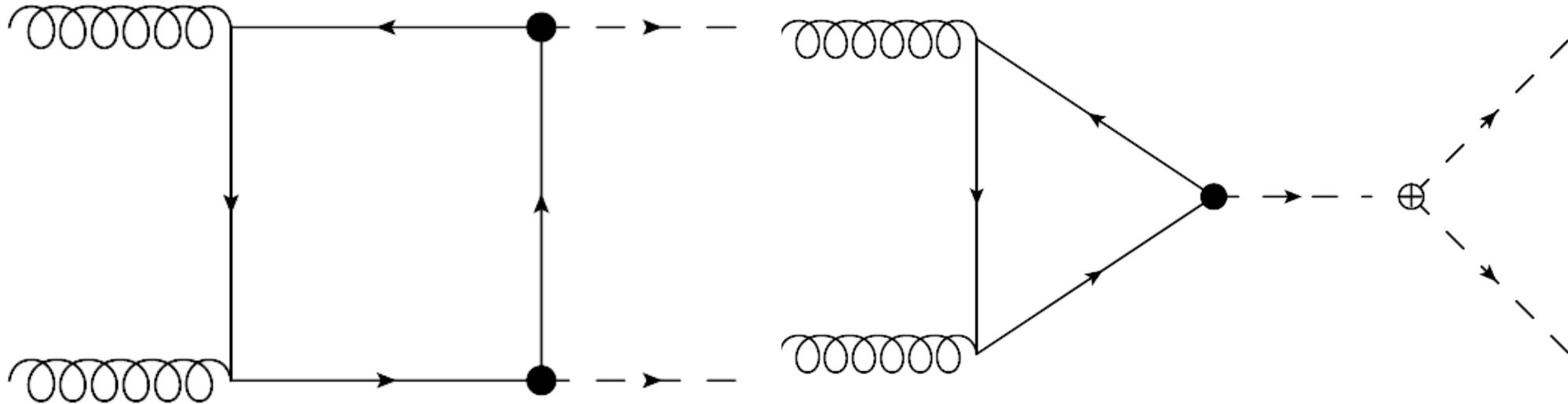
$$m_t(z) = \frac{m_t}{v} (1 + \delta_t^+ + i\delta_t^- \gamma^5) h(z)$$

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

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!

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

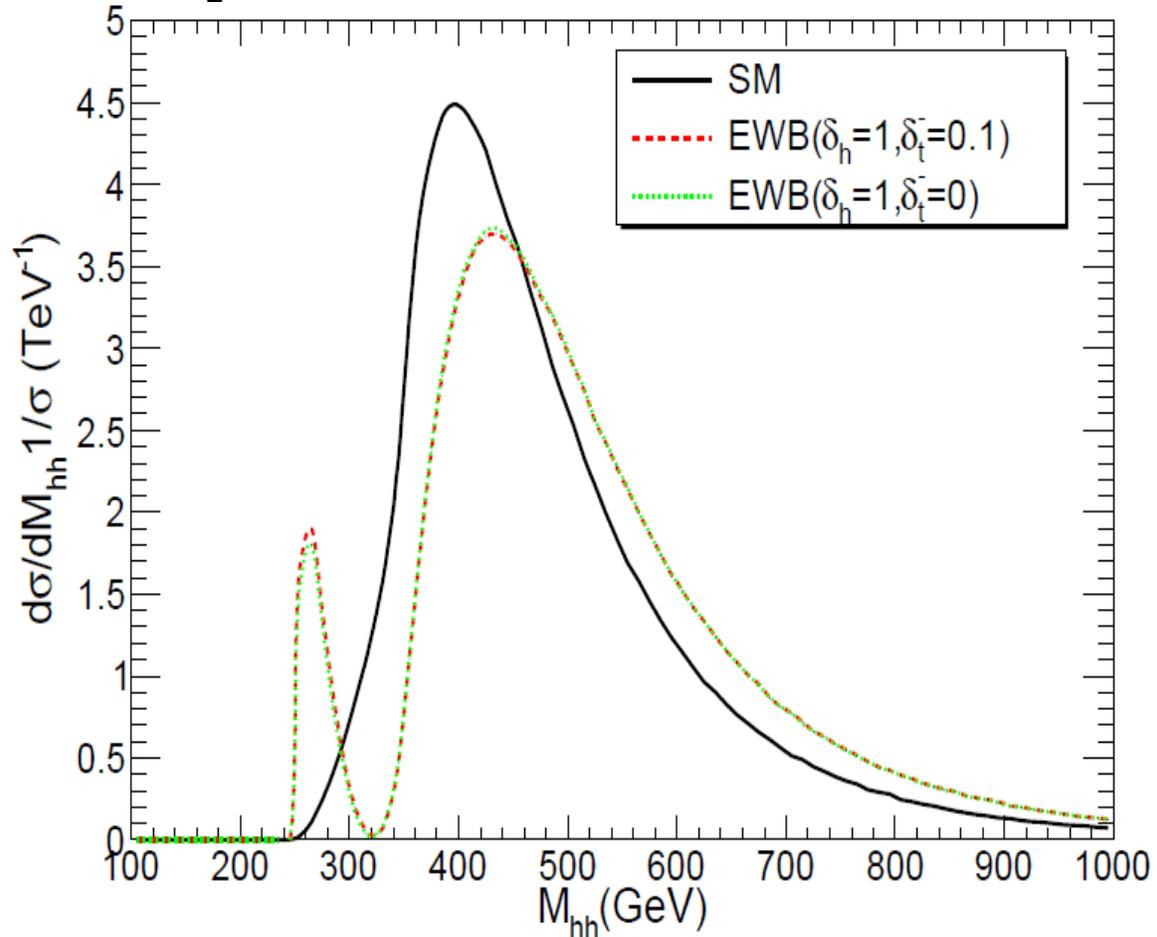


Modify the Higgs pair production at the LHC

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

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 at TeV LHC, even with 3000 fb^{-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.

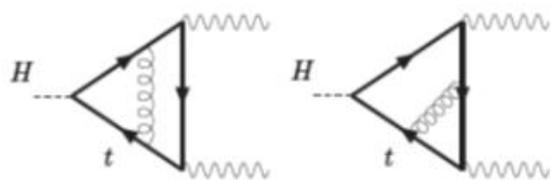
The Circular Electron Positron Collider (CEPC) can precisely test this scenario through precise measurements of the Zh production.

The NLO Zh cross section (reduce the LO result about 10%) **in the SM.**

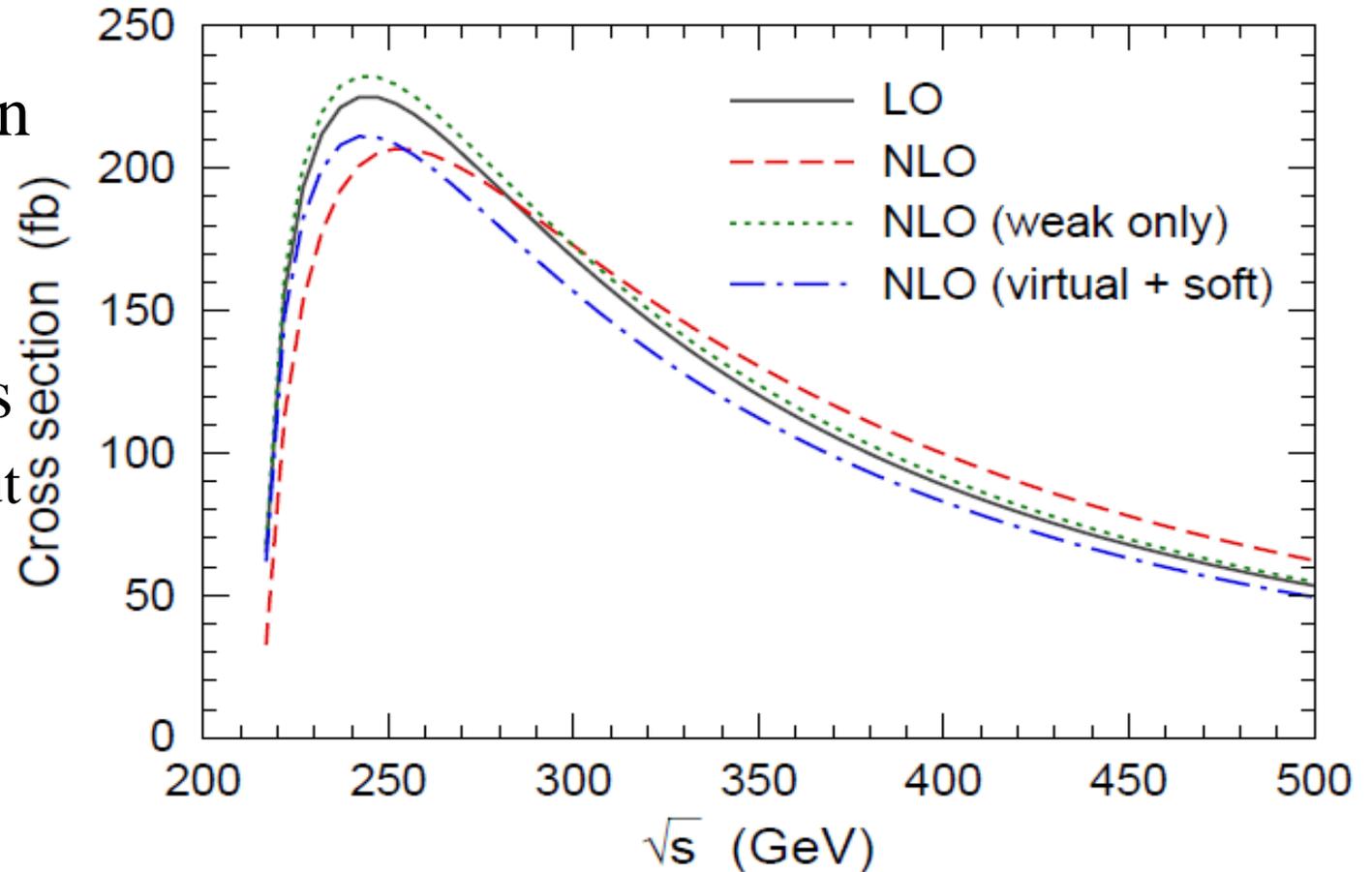
Towards NNLO Zh cross section (correction is about the 1% for 240 GeV CEPC)

Lilin Yang, et al [arXiv:1609.xxxxx](https://arxiv.org/abs/1609.xxxxx)

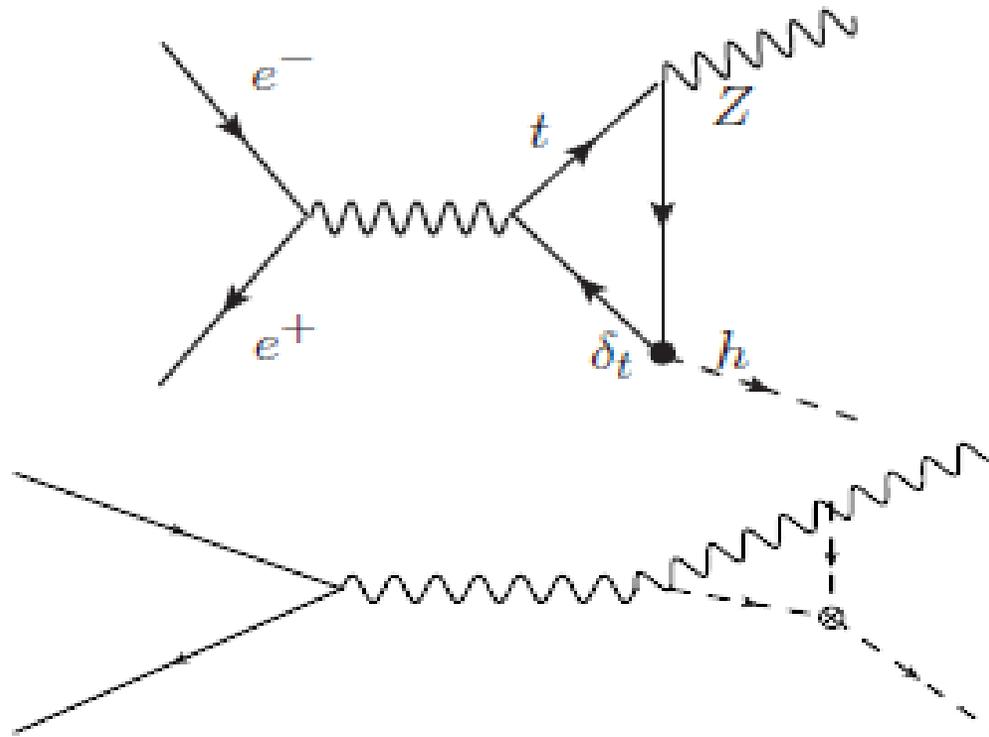
The "simpler": $O(\alpha\alpha_s)$



$$e^+ e^- \rightarrow h Z, m_h = 125 \text{ GeV}$$

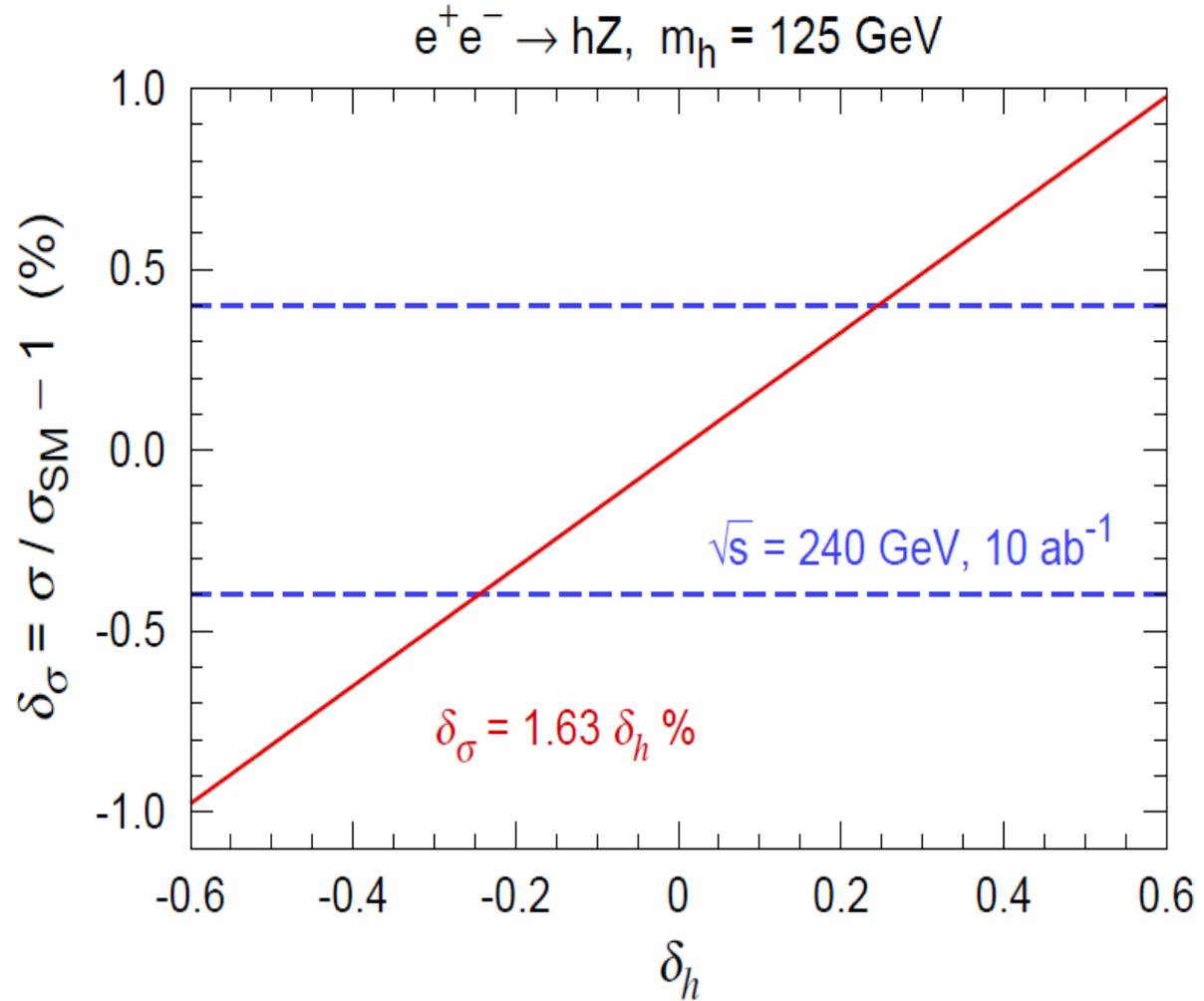


At lepton collider, for the EW phase transition /baryogenesis, the anomalous tri-linear Higgs coupling and top quark Yukawa coupling will contribute to the of Zh production.



**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

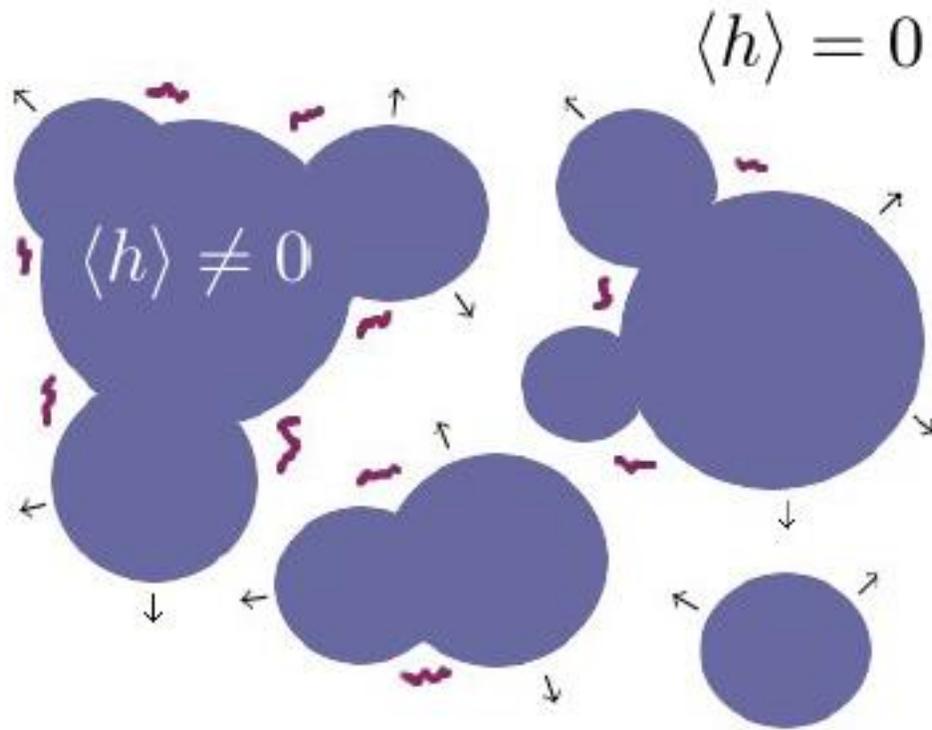
For the future CEPC with the integrated luminosity of 10 ab^{-1} at $\sqrt{s} = 240 \text{ GeV}$, the precision of the σ_{zh} may be about 0.4%. Therefore, it is possible to test the $\delta_h \sim 25\%$ at the CEPC.

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))

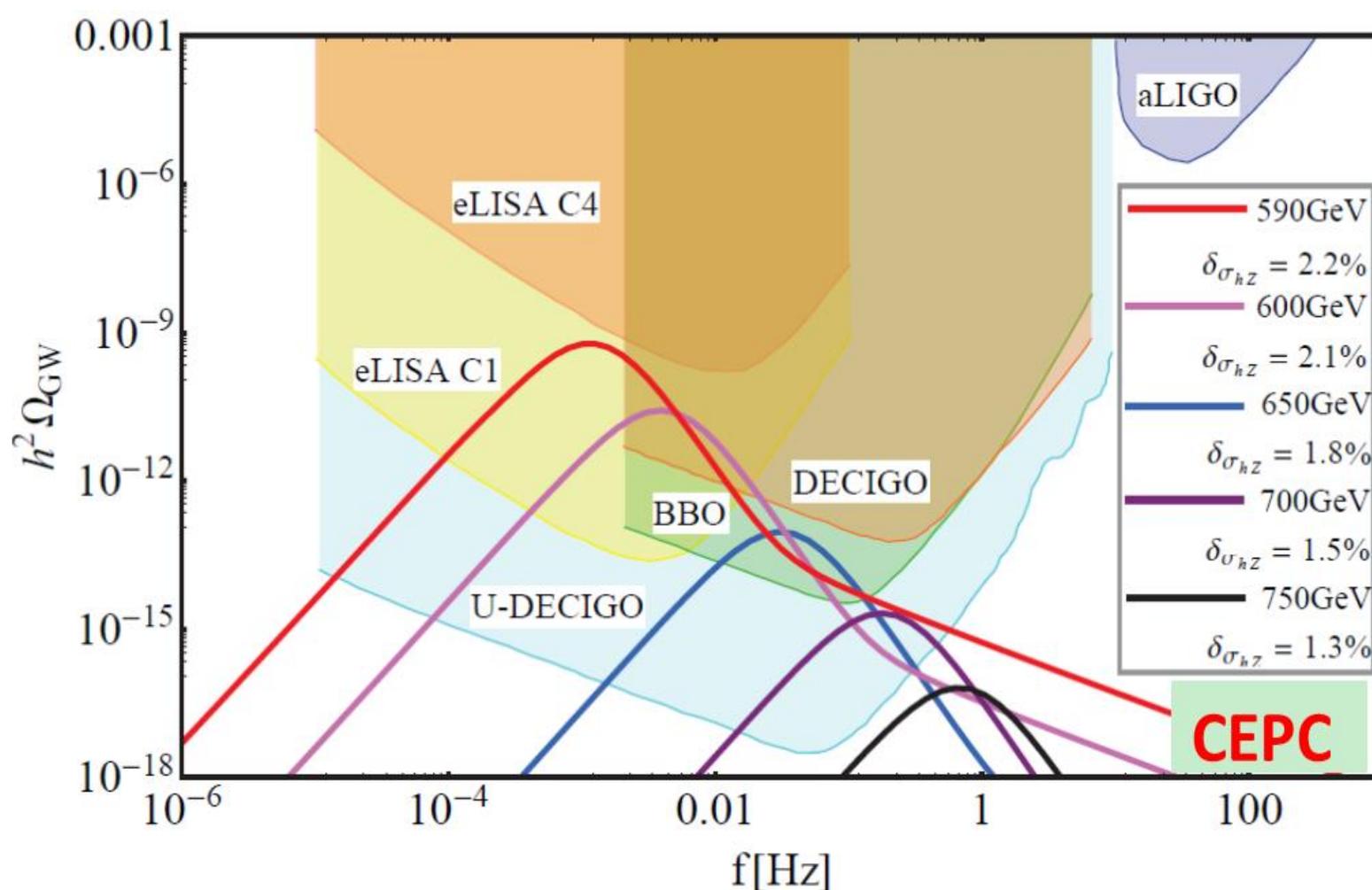
**EW phase transition
GW becomes more
interesting and realistic
after the discovery of
Higgs boson by LHC
and GW by LIGO.**

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.**

FPH, et,al 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.
- 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.**
- 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.

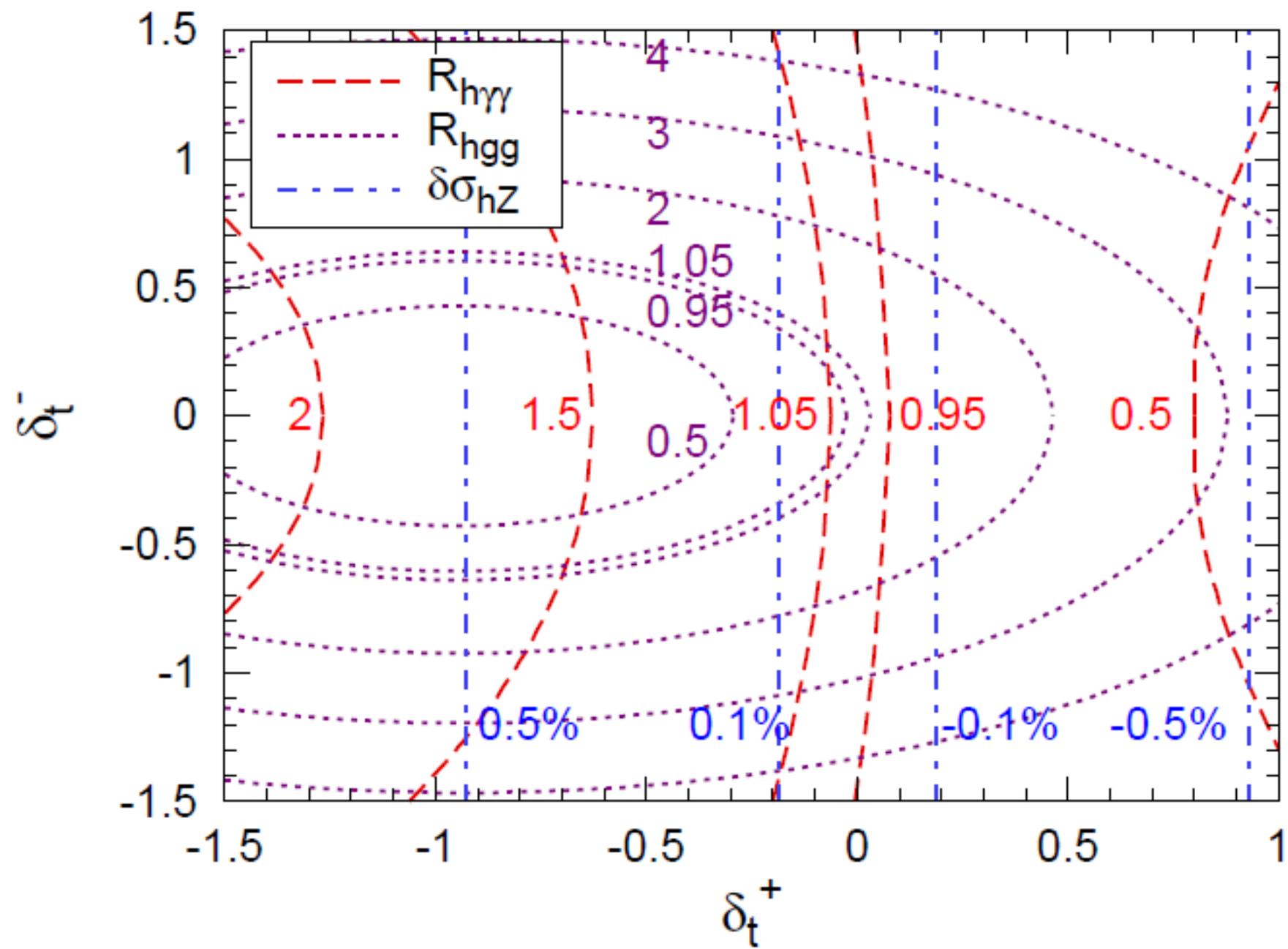
Thanks for your attention !

Backup Slides

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

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

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



Dynamics of the EW phase transition

At the critical temperature T_c , the two minima are degenerate.
Phase transition and bubble nucleate at $T < T_c$ with rate : $\Gamma = AT^4 e^{-S_3/T}$

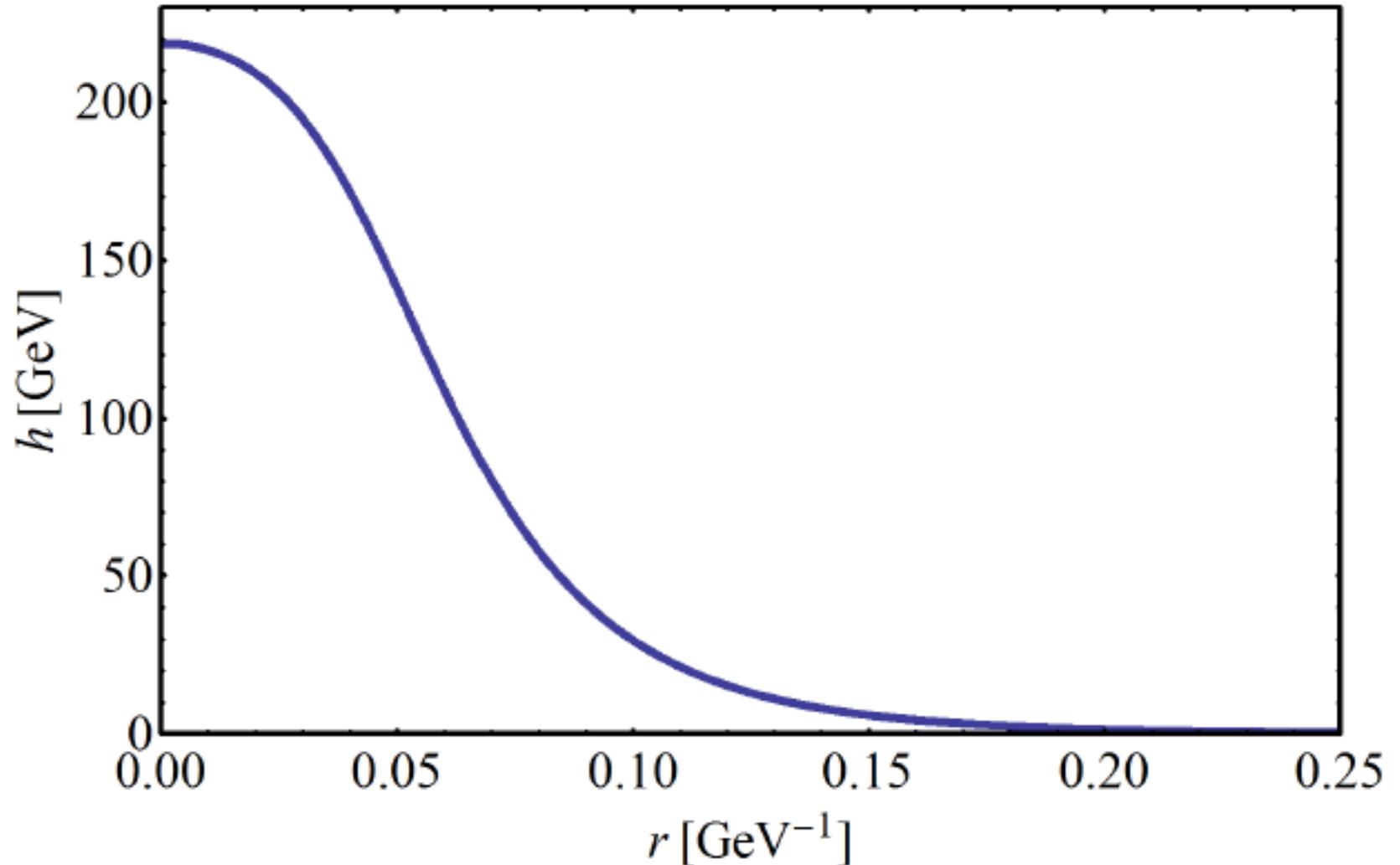
Here, the Higgs bubble energy is $S_3 = \int dr 4\pi r^2 \left[\frac{1}{2} \left(\frac{d\phi_b}{dr} \right)^2 + V(\phi_b, T) \right]$

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

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

Profile of the Higgs field

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



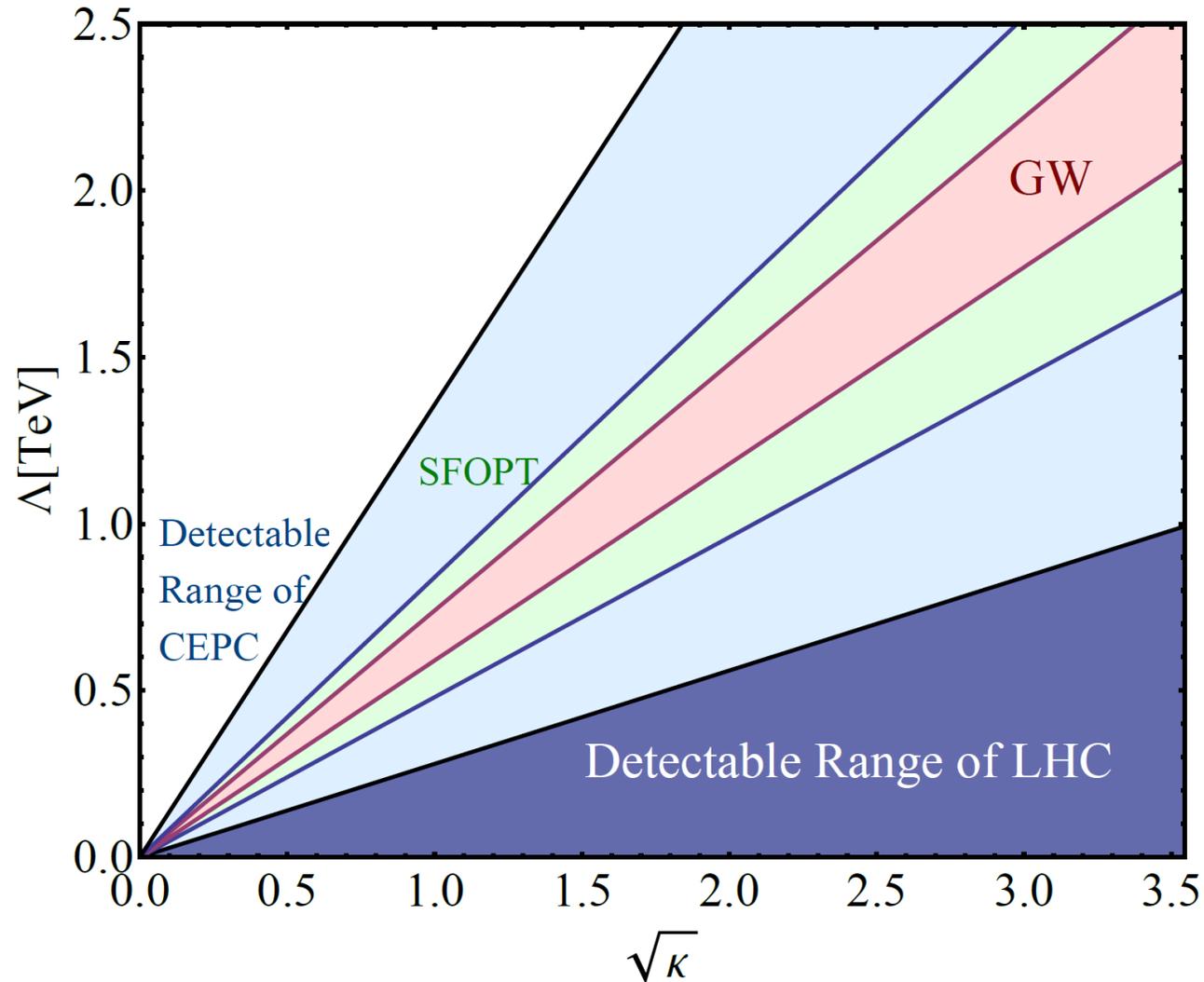
Dynamics of the EW phase transition

Two important parameters α and β

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

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

Complementary probing of the electroweak phase transition with relic gravitational wave



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