Testing the Electroweak Baryogenesis at the LHC and CEPC

Fa Peng Huang
based on the works of *arXiv* : 1511.*xxxxx* with Xinmin Zhang, Xiaojun Bi, PeiHong Gu and PengFei Yin
and *Phy*.*Rev*.*D*92, 075014(2015)(*arXiv* : 1507.08168) with Chong Sheng Li

The mini-workshop at IHEP
Oct 19, 2015

Testing the Electroweak Baryogenesis at the LHC and CEPC

Fa Peng Huang

based on the works of $arXiv: 1511.xxxxx$ with Xinmin Zhang,
Xiaojun Bi, PeiHong Gu and PengFei Yin
and $Phy.Rev.D92, 075014(2015)(arXiv: 1507.08168)$ with
Chong Sheng Li

The mini-workshop at IHEP
Oct 19, 2015

Outline

- Motivation
- Electroweak baryogenesis in a nutshell
- scenario I
- scenario II
- Conclusion

Motivation–Baryogenesis

How to explain the baryon asymmetry of the universe*Baryogenesis*

$$\eta = \frac{n_B}{n_\gamma} = \frac{n_b - b_{\bar{b}}}{n_\gamma} = 6.05(7) \times 10^{-10} (\mathrm{CMB}) (\mathit{Planck})$$

η can be determined from the CMB or BBN.

Baryogenesis–Sakharvov Conditions

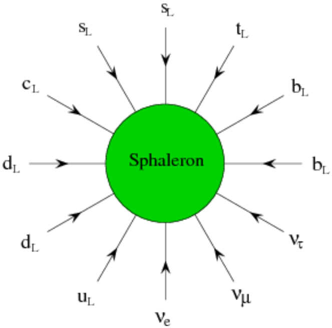
Sakharov Conditions for baryogenesis (1967)

- 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.

Baryogenesis–Sakharvov Conditions 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 Process



*Phys.Lett.B*266(1991)413 – 418 Sphalerons in the two doublet Higgs model Pecci, Zhang and Kastening
*Phys.RevD*45, 8(1992) QCD sphalerons at high temperature and baryogenesis at the electroweak scale Rabindra N. Mohapatra and Xinmin Zhang

CP-violation

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

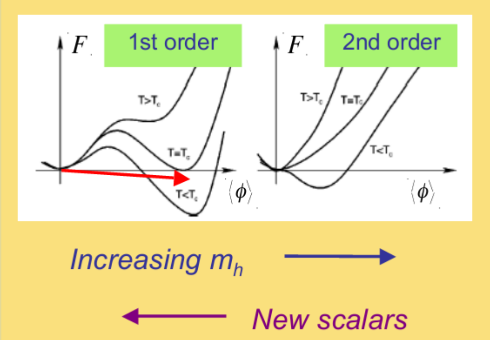
Top quark decay via flavor changing neutral currents at hadron colliders , Tao Han, R.D. Peccei, X. Zhang. Nucl.Phys. B454 (1995) 527-540
Nonstandard couplings of the top quark and precision measurements of the electroweak theory R.D. Peccei, S. Peris, X. Zhang. Nucl.Phys. B349 (1991) 305-322

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

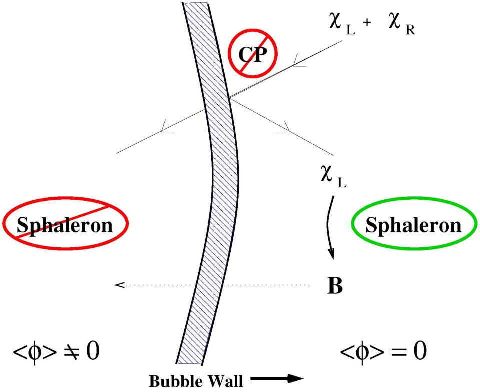
269-283 CP-violation FCNC process Yan Wan, Fa Peng Huang,et,al. Phys. Rev. D86, 094014 (2012)

Departure from equilibrium dynamics–Strong First Order Phase Transition

Unravel the essence of the electroweak phase transition or the true potential of the Higgs field is the leading goal of the CEPC as shown in Nima's outlook talk for CEPC.



Electroweak baryogenesis scenario



This electroweak baryogenesis can be tested at CEPC?

Implications on Electroweak baryogenesis for 125 GeV Higgs boson

- The discovery of the Higgs boson opens the door for studying the scalar sector of the SM(the Higgs potential), which can help us to understand the true mechanism of the electroweak phase transition and the origin of baryon asymmetry of the universe.
- The eletroweak baryogenesis becomes a particularly timely, interesting and testable scenario to explain the baryon asymmetry of our universe.
- However, the 125 GeV is too heavy for eletroweak baryogenesis.
- Any Extension of the Higgs sector is needed to be discussed.

Scenario I

we follow the effective Lagrangian approaches to investigate the EWB in JCAP 1201 (2012) 012,

$$\begin{aligned}\mathcal{L} &= \mathcal{L}_{\mathrm{SM}} + \frac{1}{2}\partial_\mu S \partial^\mu S + \frac{1}{2}\mu^2 S^2 - \frac{1}{4}\lambda S^4 - \frac{1}{2}\kappa S^2 (\Phi^\dagger \Phi) \quad (1)\\ &+ y_t \frac{\eta}{\Lambda} S \bar{Q}_L \tilde{\Phi} t_R + \mathrm{H.c.}\end{aligned}$$

where $\eta = a + ib$ is a complex parameter, S is a very light singlet scalar particle beyond the SM, λ and λ_{SM} are assumed to be positive here.
based on the works of the Phy. Rev D 92, 075014 (2015)(arXiv:1507.08168)
Fa Peng Huang, Chong Sheng Li

Scenario I

The full finite-temperature effective potential up to one-loop levlel

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

$V_1^{T=0}(H,\sigma)$ is the Coleman-Weinberg potential; and $\Delta V_1^{T\neq 0}(H,\sigma,T)$ is the leading thermal correction. Using the high-temperature expansion up to $\mathcal{O}(T^2)$,

$$V_{eff} = D_H(T^2 - T_{0H}^2)H^2 + D_\sigma(T^2 - T_{0\sigma}^2)\sigma^2 + \frac{1}{4}(\lambda_{SM}H^4 + \kappa H^2\sigma^2 + \lambda\sigma^4),$$

$$D_H = \frac{1}{32}(8\lambda_{SM} + g'^2 + 3g^2 + 4y_t^2 + 2\kappa),$$
$$D_\sigma = \frac{1}{24}(2\kappa + 5\lambda + 6g_2^2),$$

Scenario I

The condition of the SFOPT is

$$\frac{v(T_c)}{T_c} \gtrsim 1 \tag{2}$$

By observing the vacuum structure of the Higgs sector at zero temperature, we find that $\mu^2 = \mu_{SM}^2 \frac{\mathscr{G}}{2\lambda_{SM}}(1+\delta_{\mu^2}), \lambda = (\frac{\mathscr{G}}{2\lambda_{SM}})^2 \lambda_{SM}(1+\delta_\lambda)$ will produce SFOPT.

Scenario I

Here, the phase transition critical temperature is

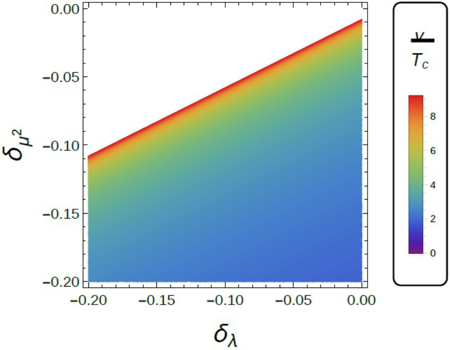
$$T_c \approx \frac{m_H\sqrt{\delta_\lambda - 2\delta_{\mu^2}}}{2\sqrt{D_h - D_\sigma}}, \tag{3}$$

and the washout parameter is given by

$$\frac{v(T_c)}{T_c} \approx \frac{2\sqrt{D_H - D_\sigma}v}{m_H\sqrt{\delta_\lambda - 2\delta_{\mu^2}}} \tag{4}$$

Scenario I

As long as $\delta_\lambda - 2\delta_{\mu^2} << 1$, $v(T_c)/T_c > 1$ and the SFOPT can be realized.

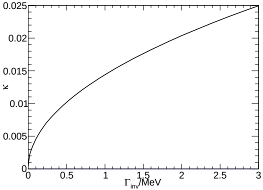


Scenario I

Higgs invisible decay

$$\mathcal{L}_{H\to SS} = -\frac{\kappa\langle\Phi\rangle S^2 H}{4}, \tag{5}$$

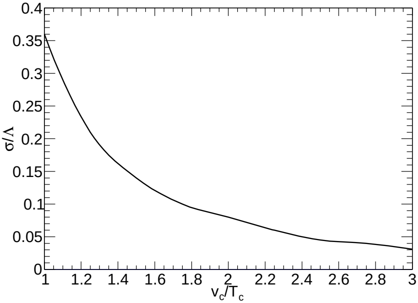
$$\Gamma_{inv}(\mathrm{H}\to\mathrm{SS}) = \frac{\kappa^2\langle\Phi\rangle^2}{32\pi \mathrm{m_H}}\sqrt{1-\frac{4\mathrm{m_S^2}}{\mathrm{m_H^2}}} \simeq \frac{\kappa^2\langle\Phi\rangle^2}{32\pi \mathrm{m_H}}. \tag{6}$$



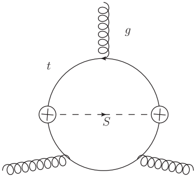
We expect precise width of Higgs invisible decay at CEPC to obtain more straight constraints of κ.

Scenario I

$$\eta_B = \frac{405\Gamma_{\rm sph}}{4\pi^2 v_\sigma g_* T} \int dz\, \mu_{B_L} f_{\rm sph}\, e^{-45\,\Gamma_{\rm sph}|z|/(4v_\sigma)}, \qquad (7)$$



Scenario I



The numerical calculation gives

$$\frac{d_n}{e} = (22 \pm 10) \times 2.1 \times 10^{-2} \times \frac{abv^2}{\Lambda^2} \times 10^{-25}\ cm. \tag{8}$$

$$\mid \frac{d_n}{e} \mid < 2.9 \times 10^{-26}\ cm, \tag{9}$$

Combining the numerical prediction and the experimental bound, we obtain the constraints on the NP scale Λ:

$$\Lambda > [229, 374]\sqrt{ab}\ \mathrm{GeV}. \tag{10}$$

Scenario I

Constaints from LHC

$$\sigma(pp \to \mathrm{MET} + \mathrm{jet}) < 6.1 \ \mathrm{fb}, \tag{11}$$

Table: Sample results of the 95% C.L. lower limits on the NP scale Λ from the CMS analysis [**?**].

m_S (GeV)	Λ (GeV) for $a = b = 1$ at 8 TeV LHC [**?**]
6	820
12	500

conclusion of scenario I

- The dimsion-5 effective Lagrangian is introduced to explain the eletroweak baryogesis.
- Both the SFOPT and the CP-violation source can be provided.
- The constraints from the LHC and neutron EDM are discussed.

Scenario II

Follow xinmin zhang's early work in 90' ,

$$\delta\mathcal{L} \;=\; -(a+ib)\frac{\phi^\dagger\phi}{\Lambda^2}\bar{q}_L\tilde{\phi}t_R + \mathrm{H.c.} - \frac{\kappa}{\Lambda^2}(\phi^\dagger\phi)^3\,, \qquad (12)$$

arXiv:1511.xxxxx with Xinmin Zhang, Xiaojun Bi, PeiHong Gu and PengFei Yin(work in progress)

Scenario II

$$V_{\rm tree}(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4} h^4 + \frac{\kappa}{8\Lambda^2} h^6. \tag{13}$$

$$V_{\rm eff}(h, T) \approx \frac{1}{2}\left(\mu^2 + c\, T^2\right) h^2 + \frac{\lambda}{4} h^4 + \frac{\kappa}{8\Lambda^2} h^6. \tag{14}$$

The finite temperature effects are in

$$c = \frac{1}{16}(4y_t^2 + 3g^2 + g'^2 + 4\frac{m_h^2}{v^2} - 12\frac{\kappa v^2}{\Lambda^2}), \tag{15}$$

To keep the observed m_h and $\mathrm{vev}\ v$, λ and μ^2 should be changed as

$$\lambda = \frac{m_h^2}{2v^2}\left(1 - \frac{\Lambda_{\rm max}^2}{\Lambda^2}\right), \tag{16}$$

$$\mu^2 = \frac{m_h^2}{2}\left(\frac{\Lambda_{\rm max}^2}{2\Lambda^2} - 1\right), \tag{17}$$

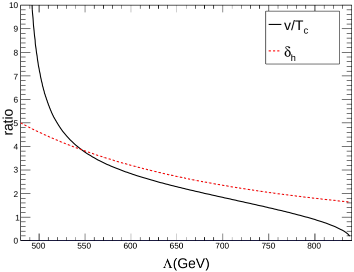
Scenario II

$$
\begin{aligned}
T_c &= \sqrt{\frac{\mu^2}{c}}\sqrt{\frac{\lambda^2\Lambda^2}{4\mu^2}-1}, && (18)\\
\frac{v(T_c)}{T_c} &= \sqrt{\frac{c}{-\lambda}}\frac{2}{\sqrt{1-\frac{4\mu^2}{\lambda^2\Lambda^2}}}\,. && (19)
\end{aligned}
$$

Scenario II

- In order to guarantee the SFOPT, it needs $\mu^2 + cT^2 > 0$, $\lambda < 0$ and the h^6 term to stabilize the EW-broken vacuum, namely $\Lambda < \Lambda_{\rm max} = \sqrt{3\kappa} v^2/m_h \approx 840 GeV$ when $\kappa = 1$.
- From the requirements of perturbativity, $\kappa < 4\pi$. If we choose a larger κ, we can get a larger upper bound $\Lambda_{\rm max}$. For example, if $\kappa = 12.5$, then $\Lambda_{\rm max} = 3$ $\rm TeV$.
- $T_c > 0$ gives the lower bound of $\Lambda_{min} = \Lambda_{max}/\sqrt{3}$

Scenario II



$$\frac{v(T_c)}{T_c} \gtrsim 1. \tag{20}$$

$$\mathcal{L}_{hhh} = -3\frac{m_h^2}{v}\left(1 + 5\frac{\Lambda_{\rm min}^2}{\Lambda^2}\right)\frac{h^3}{3!} \tag{21}$$

The large deviation of the trilinear Higgs coupling may be test at HL-LHC and CEPC(SPPC).

CP-violation source

the Lagrangian for top-Higgs coupling is parameterized as

$$\mathcal{L} = -\frac{m_t}{v} h \bar{t} (1 + \delta_t^+ + i \delta_t^- \gamma^5) t, \tag{22}$$

The $i\gamma^5$ term is CP-odd, and would provide the CPV source for the baryogenisis.

$$\delta_t^+ = \frac{a v^3}{2 \Lambda^2 m_t} \tag{23}$$

$$\delta_t^- = \frac{b v^3}{2 \Lambda^2 m_t} \tag{24}$$

CP-violation source

$$m_t(z) = \frac{m_t}{v}(1 + \delta_t^+ + i\delta_t^- \gamma^5) h(z) \equiv |m_t(z)| e^{i\Theta(z)}, \tag{25}$$

$$\eta_B = \frac{405\Gamma_{\rm sph}}{4\pi^2 v_\sigma g_* T} \int dz\, \mu_{B_L} f_{\rm sph}\, e^{-45\,\Gamma_{\rm sph}|z|/(4v_\sigma)}, \tag{26}$$

From the preliminary numerical estimation, we can further take

$$\delta_t^- = \mathcal{O}(0.1 - 1)\,, \tag{27}$$

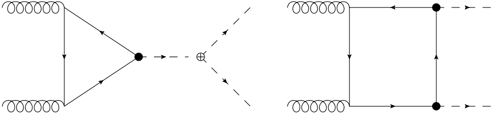
to provide the CP violation source for a successful baryogenesis.

Higgs pair production

The deviation from the SM case can be written as

$$-\mathcal{L} = \frac{1}{3!}\left(\frac{3m_h^2}{v}\right)\lambda_{3h}\, h^3 \;+\; \frac{m_t}{v} h\bar{t}(1+\delta_t^+ + i\delta_t^-\gamma^5)t\,, \qquad (28)$$

which $\lambda_{3h} = (1+\delta_h)$ and $\delta_h = 5\frac{\Lambda_{min}^2}{\Lambda^2}$. In the SM, $\lambda_{3h} = 1, \delta_t^+ = 0$ and $\delta_t^- = 0$.



Higgs pair production

Using Feycalc, the partonic differential cross section for the $g(p_a)g(p_b) \to h(p_c)h(p_d)$ process can be obtained

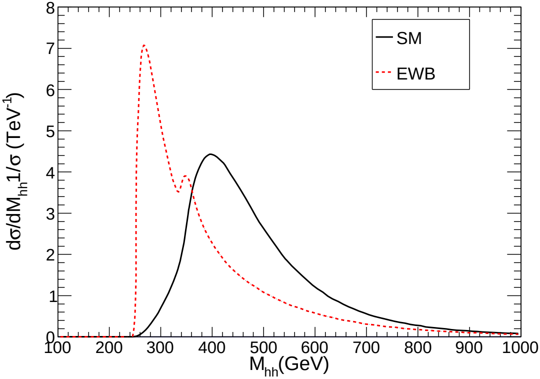
$$
\begin{aligned}
& \frac{d\hat{\sigma}(gg \to hh)}{d\hat{t}} \qquad (29) \\
= \;& \frac{G_F^2 \alpha_s^2}{512(2\pi)^3} \Bigg\{ \Big| (1+\delta_h)(1+\delta_t^+)\mathcal{P}(\hat{s}) F_\triangle^A \\
+ \;& (1+\delta_t^+)^2 F_\square^{AA} + (\delta_t^-)^2 F_\square^{BB} \Big|^2 \\
+ \;& \Big| (1+\delta_t^+)^2 G_\square^{AA} + (\delta_t^-)^2 G_\square^{BB} \Big|^2 \\
+ \;& \Big| (1+\delta_h)\delta_t^- \mathcal{P}(\hat{s}) F_\triangle^B + (1+\delta_t^+)\delta_t^- F_\square^{AB} \Big|^2 + \Big| (1+\delta_t^+)\delta_t^- G_\square^{AB} \Big|^2 \Bigg\},
\end{aligned}
$$

$Chien - YiChen, Qi - ShuYan, XiaoranZhao, Yi - MingZhong, arXiv : 1510.04013$

$QiangLi, ZhaoLi, Qi - ShuYan, XiaoranZhaoPhys.Rev.D92(2015)1, 014015$

Higgs pair production

The invariant mass distribution of the Higgs boson pair for $PP \to hh$ at 14 TeV LHC, choosing the benchmark point $\delta_h = 3, \delta_t^+ = 0.01, \delta_t^- = 0.2$.

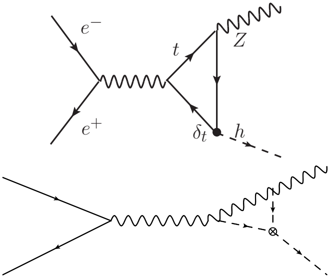


Top-Higgs coupling

The anomalous top-Higgs coupling would modify the Higgs couplings to gg and $\gamma\gamma$.
Thus, the loop induced Higgs couplings c_{hgg} and $c_{h_\gamma\gamma}$ can be parameterized as

$$\begin{aligned} g^2_{hgg} &\simeq (1+\delta_t^+)^2 + 0.11\delta_t^+(1+\delta_t^+) + 2.6\delta_t^-, \\ g^2_{h\gamma\gamma} &\simeq (1.28 - 0.28\delta_t^+)^2 + (0.43\delta_t^-)^2. \end{aligned}$$

ZH production at CEPC



ZH production at CEPC

Define the deviation of σ_{hZ} as

$$\delta_\sigma = \frac{\sigma_{hz,\delta_h \neq 0}}{\sigma_{hz,SM}} - 1. \tag{30}$$

We can see that δ_σ is approximately proportional to δ_h as $\delta_\sigma \sim 1.6\delta_h\%$. For the future CEPC with the integrate luminosity of 10 ab^{-1}, the precession of σ_{zh} can be 0.4%. Therefore, it is possible to test $\delta_h \sim 25\%$ at the CEPC.

ZH product at CEPC

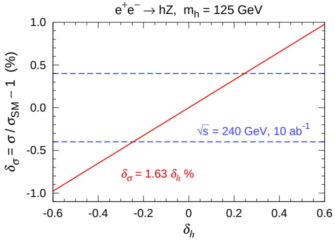


Figure: The modification of the Higgs associated production cross section as a function of the anomalous trilinear coupling δ_h (solid line) at the e^+e^- collider with $\sqrt{s} = 240$ GeV. The dashed lines denote the sensitivity to $\delta_{\sigma_{hZ}}$ of the e^+e^- collider with the luminosity of 10 ab^{-1}.

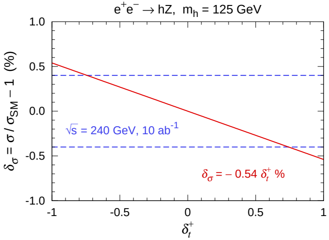
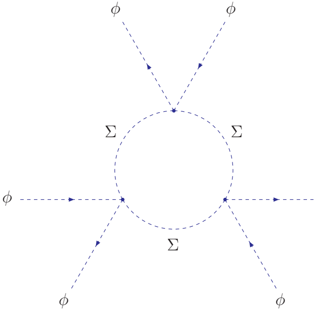
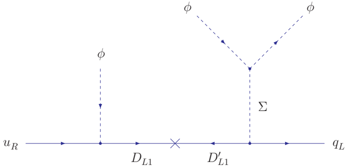


Figure: The modification of the Higgs associated production cross section as a function of the anomalous CP-even top-Higgs coupling δ_t^+ (solid line) at the e^+e^- collider with $\sqrt{s} = 240$ GeV. The dashed lines denote the sensitivity to $\delta_{\sigma_{hZ}}$ of the e^+e^- collider with the luminosity of 10 ab^{-1}.

Renormalizable model

The dimension-6 operators can be induced from certain renormalizable extensions of the SM. Such as a class of realistic models with vector-like quarks and triplet Higgs.





Future collider signature

Precise measurement of the following couplings are needed to test this scenario in HL-LHC and CEPC(SPPC):

- Higgs tri-linear coupling
- $t\bar{t}H, Ht, H\bar{t}$ production with CP-violation top Yukawa coupling:crosssecion, polarization...
- precise ZH measurement at CEPC.

Conclusion

- Since the 125 GeV Higgs boson has bee seen at the LHC, we might be able to test the Higgs potential and the EWB scenario just at the corner;
- But, there are so many possible concrete realization in this scenario, related to all the possibilities for the Higgs sector and the related BSM physics;
- concentrating on the key physics required to make EWG work
- Still challenge in experiments, e.g. the precise test of Higgs tri-linear coupling and the top quark coupling.

Thanks!