Understanding the nature of Electroweak Symmetry Breaking with CEPC-SPPC

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Discovery of the Higgs-like particle at LHC

*) Important to particle physics and cosmology

*) Congradulation again to you (all) the experimentalists
made contributions directly or indirectly!

*) Most significant, however
having proven a lot of theoretician including me
(many theoretician like dynamical breaking)
to be wrong!

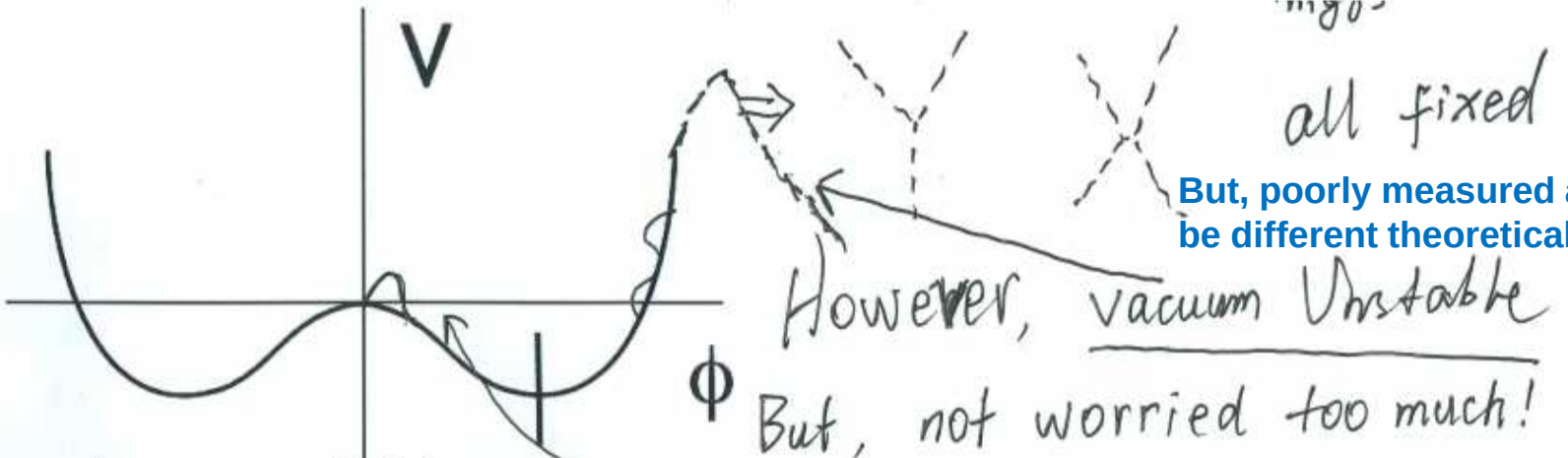
+) will tell you a new idea
hope be proven to be wrong again at CEPC-SPPC
(HL-LHC…)

On the nature of Electroweak Symmetry Breaking

In the standard model, the symmetry is broken by

$$V(\phi) = \mu^2|\varphi|^2 + \lambda|\varphi|^4$$

two parameters μ^2, λ fixed by v, m_{higgs}



all fixed

But, poorly measured and could be different theoretically

However, vacuum Unstable

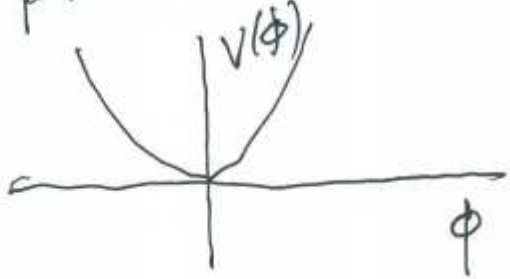
But, not worried too much!

Interesting Possibility

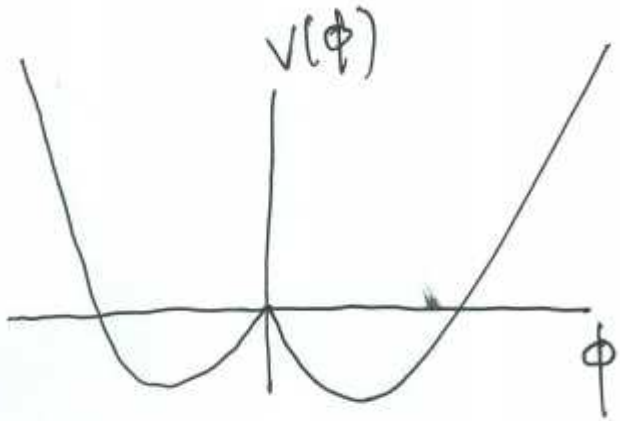
$$V(\phi) = \mu^2|\varphi|^2 + \lambda|\varphi|^4 + \frac{|\phi|^6}{\Lambda^2} \Rightarrow$$



phase transition in cosmology

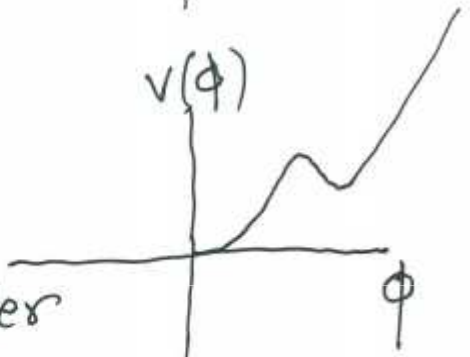


2nd order phase transition

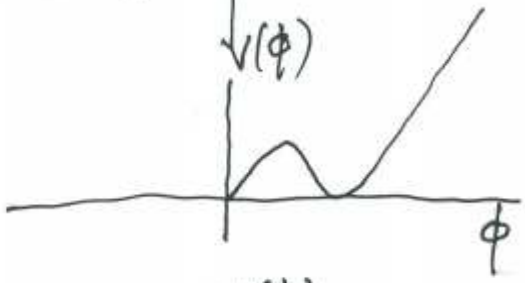


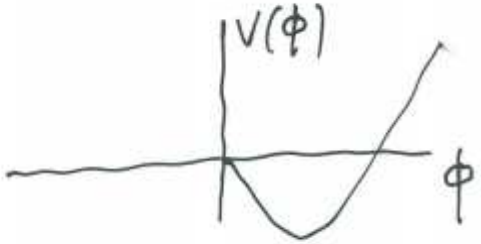






1st order





Sources of $\frac{|\varphi|^6}{\Lambda^2}$?

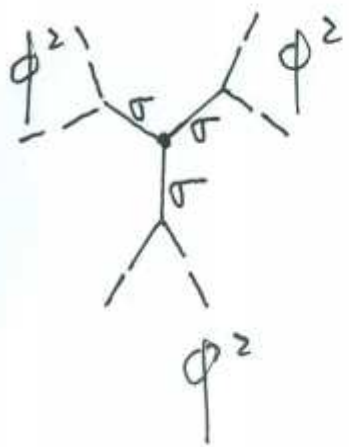
1, Composite Higgs theory

like linear σ model for QCD

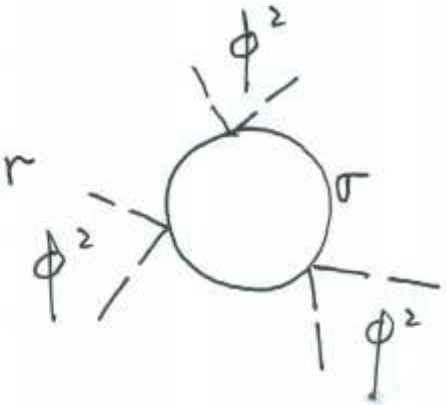
2, Loop effects of heavy particles

a, Singlet σ

$$\mathcal{L}_\sigma \sim m_\sigma^2 \sigma^2 + g|\varphi|^2\sigma^2 + f\sigma^3 + \delta|\varphi|^2\sigma$$



or

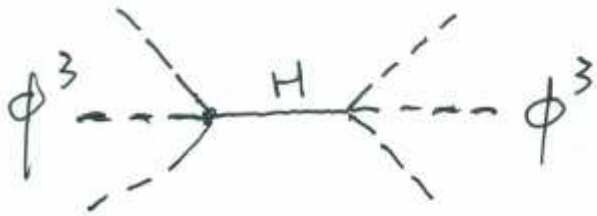


$\Longrightarrow \frac{|\varphi|^6}{\Lambda^2}$

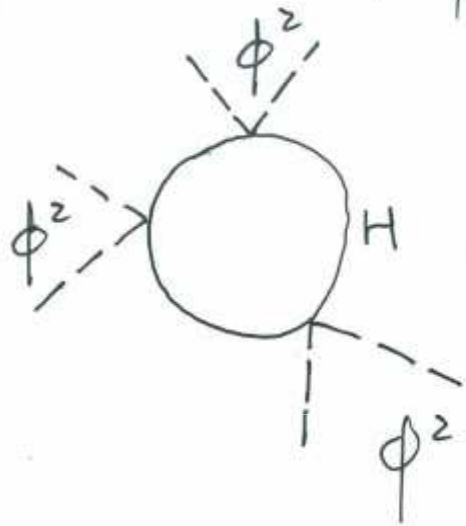
With $\Lambda \sim m_\sigma$

b, Doublet H

$$\mathcal{L} \sim m_H^2 H^2 + g|\phi|^2 H^2 + f\phi^3 H + \cdots$$

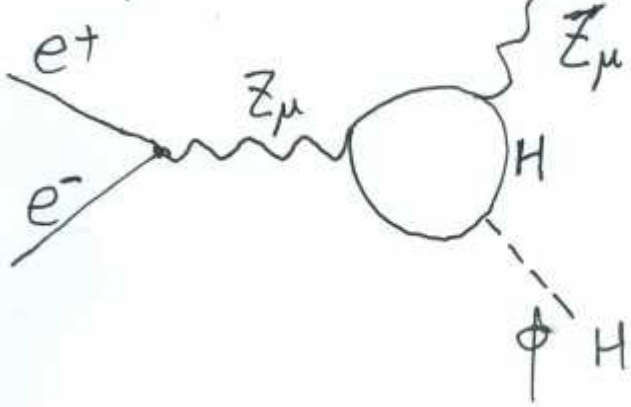


or

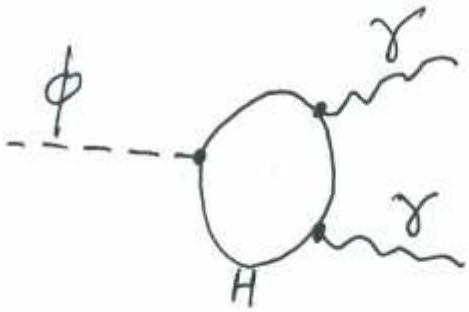


$\Longrightarrow \dfrac{|\phi|^6}{\Lambda^2}$ where $\Lambda \sim M_H$

Further More,



or



C) **There are more examples with heavy particles like triplets, colored singlets、 doublets ……. Which will modify the couplings of Higgs itself and also to W、Z……..**

- Thus in general

$$\mathcal{L}^{\text{new}} = \frac{1}{\Lambda^2} c_{\Phi,3} (\Phi^+\Phi - \tfrac{1}{2}v^2)^3 + \frac{1}{\Lambda^2}\Big[c_{\Phi,1}(D_\mu\Phi)^+\Phi\Phi^+(D^\mu\Phi) + \tfrac{1}{2}c_{\Phi,2}\partial_\mu(\Phi^+\Phi)\partial^\mu(\Phi^+\Phi)\Big] + \frac{1}{\Lambda^2}\Big[c_{BW}\Phi^+\widehat{B}_{\mu\nu}\widehat{W}^{\mu\nu}\Phi + c_W(D_\mu\Phi)^+\widehat{W}^{\mu\nu}(D_\nu\Phi)\Big] + \frac{1}{\Lambda^2}\Big[c_B(D_\mu\Phi)^+\widehat{B}^{\mu\nu}(D_\nu\Phi) + c_{WW}\Phi^+\widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\Phi\Big] + \frac{1}{\Lambda^2}c_{BB}\Phi^+\widehat{B}_{\mu\nu}\widehat{B}^{\mu\nu}\Phi.$$

Will change the rate of Higgs + Z production at CEPC

$$\mathcal{L}_{\text{eff}} = \frac{gM_W}{\Lambda^2}[T_1 H Z_\mu Z^\mu + T_2 Z_{\mu\nu}Z^\mu(\partial^\nu H) + T_3 H Z_{\mu\nu}Z^{\mu\nu} + T_4 A_{\mu\nu}Z^\mu(\partial^\nu H) + T_5 H A_{\mu\nu}Z^{\mu\nu}],$$

with

$$T_1 = \frac{2m_W^2}{g^2}\frac{c_{\Phi,1}}{c^2},$$

$$T_2 = \frac{c^2 c_W + s^2 c_B}{2c^2},$$

$$T_3 = -\frac{c^4 c_{WW} + s^4 c_{BB} + s^2 c^2 c_{BW}}{2c^2},$$

$$T_4 = \frac{s(c_W - c_B)}{2c},$$

$$T_5 = \frac{s(-2c^2 c_{WW} + 2s^2 c_{BB} + (c^2 - s^2)c_{BW})}{2c},$$

How larger is the \Lambda ?

- Naturalness argue \Lambda around TeV

  however, is 1 TeV or 5 TeV

  --→a big difference for experiment

  And the theory is proven already not very natural
- Neutrino Mass requires new physics

  however, generally the scale \Lambda

  could be much higher than TeV
- Cosmology arguments:

  Inflation 、 Dark energy

  Dark matter (axion, gravitino…..

  WIMPs but need new particles with mass unkown

  Electroweak baryogenesis

Electroweak Baryogenesis
requires new physics in the Higgs
and Top sector ……..which
will be detected at CEPC-SPPC

CEPC: detecting the anomalous couplings

SPPC: searching for directly the new particles which generate the anomalous couplings

baryogenesis
三个条件

Andrei Sakharov （1967年） 三个条件：

i) B violation

ii) C and CP violation

iii)Out of thermo-equilibrium (CPT conserved)

Freezing out of the heavy particles

$$\begin{aligned}\langle B\rangle &= \mathrm{Tr}(\rho B) = \mathrm{Tr}\left((CPT)(CPT)^{-1}\exp(-\beta H)B\right)\\ &= \mathrm{Tr}\left(\exp(-\beta H)(CPT)^{-1}B(CPT)\right) = -\mathrm{Tr}(\rho B) = 0\end{aligned}$$

If CPT is broken, can be generated in thermo-equilibrium

Baryon and Lepton Sym in SM.

$\mathcal{L}^{S.M.} \sim Y_e \bar{l} e \phi + Y_d \bar{q} d \phi + Y_u \bar{q} u \phi$

Global symmetries: 整体对称性

$\begin{matrix} q \\ u \\ d \end{matrix} \rightarrow e^{iQ\alpha} \begin{matrix} q \\ u \\ d \end{matrix}$ 重子数

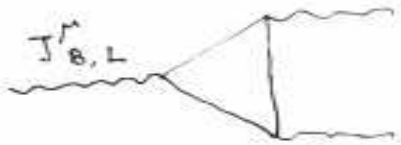
同样: $l_i \rightarrow e^{iQ_i\alpha} l_i$ 轻子味对称性

问题: triangle anomaly

$J^\mu_B = \frac{1}{3} \sum_i \left(\bar{q}_L \gamma^\mu q_L + \bar{u}_R \gamma^\mu u_R + \bar{d}_R \gamma^\mu d_R \right)$

$J^\mu_L = \sum_i \left(\bar{l}_L \gamma^\mu l_L + \bar{e}_R \gamma^\mu e_R \right)$

$\partial^\mu J^B_\mu = \partial^\mu J^L_\mu = \frac{N_f}{32\pi^2} \left(-g^2 W^a_{\mu\nu} \tilde{W}^{a\mu\nu} + g'^2 B_{\mu\nu} \tilde{B}^{\mu\nu} \right)$



More on Symmetry breaking via anomaly

$\partial_\mu J^\mu_B = \partial_\mu J^\mu_L \sim W^I_{\mu\nu} \tilde{W}^{I,\nu}$

$\oplus \quad B_{\mu\nu} \tilde{B}^{\mu\nu}$

注意：$B_{\mu\nu} \tilde{B}^{\mu\nu} \sim \partial_\mu K^\mu$

$\mathcal{L} \supset \epsilon^{\mu\nu\alpha\beta} A_\nu \partial_\alpha A_\beta$

$\int d^4x \, \partial_\mu K^\mu = ?$

SU(2)真空：θ真空



$N_{CS} = \frac{g^3}{96\pi^2} \int d^3x \, \epsilon_{ijk} \epsilon^{IJK} W^{Ii} W^{Jj} W^{Kk}$

$\Delta B = \Delta L = 3 \Delta N_{CS}$

Physics Letters B 266 (1991) 413–418
North-Holland

PHYSICS LETTERS B

Sphalerons in the two-doublet Higgs model

B. Kastening, R.D. Peccei and X. Zhang
Department of Physics, University of California, Los Angeles, CA 90024, USA

$$\mathcal{L} = -\tfrac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} - \tfrac{1}{4}f_{\mu\nu}f^{\mu\nu} + (\mathrm{D}_\mu\Phi_1)^\dagger(\mathrm{D}^\mu\Phi_1) + (\mathrm{D}_\mu\Phi_2)^\dagger(\mathrm{D}^\mu\Phi_2) - V(\Phi_1, \Phi_2)\,, \qquad (1)$$

where $F^a_{\mu\nu}$ are the SU(2) field strength, $f_{\mu\nu}$ the $\mathrm{U}_Y(1)$ field strength, $V(\Phi_1, \Phi_2)$ the Higgs potential and $\mathrm{D}_\mu\Phi_{(1,2)}$ the covariant derivative. Our Minkowski space metric is $g_{\mu\nu} = \mathrm{diag}(1, -1, -1, -1)$.

We seek to minimize the energy functional (4) with fields of the general form

$$\boldsymbol{W}_i\cdot\boldsymbol{\tau}\,\mathrm{d}x^i = -\frac{2\mathrm{i}}{g}f(gvr)\,\mathrm{d}U^\infty(U^\infty)^{-1}\,,$$

$$\Phi_1 = \frac{v_1}{\sqrt{2}}h_1(gvr)U^\infty\begin{pmatrix}0\\1\end{pmatrix},$$

$$\Phi_2 = \frac{v_2}{\sqrt{2}}h_2(gvr)U^\infty\begin{pmatrix}0\\1\end{pmatrix}\mathrm{e}^{\mathrm{i}\rho}\,, \qquad (5)$$

where

$$U^\infty = \frac{1}{r}\begin{pmatrix} z & x+\mathrm{i}y \\ -x+\mathrm{i}y & z\end{pmatrix}. \qquad (6)$$

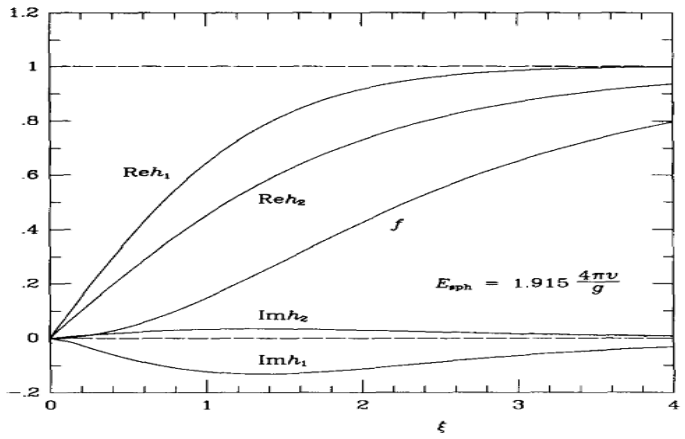


Fig. 1. Radial functions f, h_1 and h_2 for $\lambda_1/g^2 = 4$, $\lambda_2/g^2 = 0.1$, $\lambda_3/g^2 = 0.04$, $\lambda_5/g^2 = 0.3$, $\lambda_6/g^2 = 5$, $\cos^2\beta = 0.2$ and $\rho = 30°$.

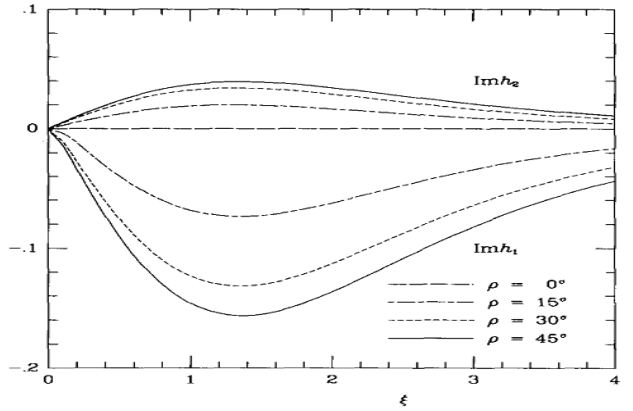
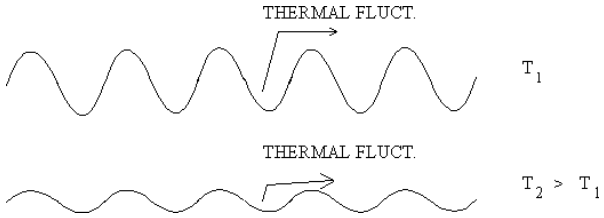


Fig. 2. Imaginary parts of h_1 and h_2 for different ρ, with the other parameters being the same as in fig. 1.

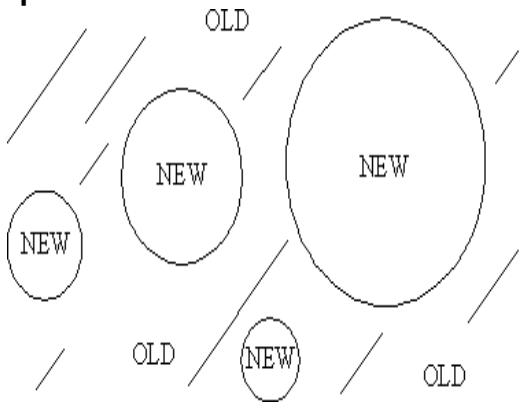
Electroweak baryogenesis

i) B violation ←----anomaly, non-trivial vacuum, sphaleron



ii) C and CP violation ←-----CKM mechanism
(however, too small-→new physics)

iii) First order phase transition



Need Higgs mass
< 35 GeV!

重要预言：
Higgs质量
新物理

Electroweak Baryogenesis and New Physics

i) Early 90's and later on, many studies with new physics models like 2- Higgs，L-R symmetry, SUSY

ii) Effective Lagrangian Method

1) Xinmin Zhang, Phys. Rev. D47, (1993) 3065 (**hep-ph/9301277)**
"Operator Analysis for the Higgs Potential and Cosmological Bound on the Higgs-Boson Mass"

2) Bing-Lin Young and Xinmin Zhang, PRD49 (1994) 563 (**hep-ph/9309269)**
"Effective Lagrangian Approach to Electroweak Baryogenesis: Higgs mass limit and Electric dipole moments of fermion "

3) Xinmin Zhang, S.K. Lee, K. Whisnant and B.-L. Young
Phys.Rev. D50 (1994) 7042-7047 (hep-ph/9407259)
"Phenomenology of a non-standard top quark Yukawa coupling "

Effective Theory

- Chiral lagrangian for strong interaction

(S. Weinberg, 1968)

SU(2)_L X SU(2)_R is broken down

by quark condensate to SU(2)_{L+R}

Pion interaction, scattering…..

Pion nucleon (constituent quarks) interaction

- Chiral lagrangian for electroweak theory

SU_L（2） X U_Y(1) is broken

by some condensate (???) down to U_em(1)

There are three goldstone bosons which become the longitudinal components of gauge bosons W and Z

(Peccei, Zhang; Zhang Ph.D thesis)

$$\Sigma = \exp\left(i\frac{\tau_i \xi_i}{v_i}\right) \qquad \Sigma \to \Sigma' = \exp\left(i\boldsymbol{\alpha}_{\mathrm{L}} \cdot \frac{\boldsymbol{\tau}}{2}\right)\Sigma \exp\left(-iy\frac{\tau_3}{2}\right)$$

$$\Psi_{\mathrm{L}} = \Sigma F_{\mathrm{L}} = \exp\left(i\frac{\tau_i \xi_i}{v_i}\right)\begin{pmatrix} f \\ f' \end{pmatrix}_{\mathrm{L}}$$

under an $\mathrm{SU}(2) \times \mathrm{U}(1)$ transformation g, transforms as

$$\Psi_{\mathrm{L}} \to \Psi'_{\mathrm{L}} = (\Sigma' F'_{\mathrm{L}}) = g(\Sigma F_{\mathrm{L}}) = g\Psi_{\mathrm{L}}$$

$$\mathscr{L}_1 = -\overline{F_{\mathrm{L}i}}\,\gamma_\mu\left(\kappa_{\mathrm{L}}^{\mathrm{NC}}\right)_{ij}F_{\mathrm{L}j}\Sigma_3^\mu - \overline{F_{\mathrm{R}i}}\,\gamma_\mu\left(\kappa_{\mathrm{R}}^{\mathrm{NC}}\right)_{ij}F_{\mathrm{R}j}\Sigma_3^\mu$$

$$-\sqrt{2}\,\overline{F_{\mathrm{L}i}}\,\gamma_\mu\tau_-\left(\kappa_{\mathrm{L}}^{\mathrm{CC}}\right)_{ij}F_{\mathrm{L}j}\Sigma_+^\mu - \sqrt{2}\,\overline{F_{\mathrm{L}i}}\,\gamma_\mu\tau_+\left(\kappa_{\mathrm{L}}^{\mathrm{CC}}\right)_{ij}^\dagger F_{\mathrm{L}j}\Sigma_-^\mu$$

$$-\sqrt{2}\,\overline{F_{\mathrm{R}i}}\,\gamma_\mu\tau_-\left(\kappa_{\mathrm{R}}^{\mathrm{CC}}\right)_{ij}F_{\mathrm{R}j}\Sigma_+^\mu - \sqrt{2}\,\overline{F_{\mathrm{R}i}}\,\gamma_\mu\tau_+\left(\kappa_{\mathrm{R}}^{\mathrm{CC}}\right)_{ij}^\dagger F_{\mathrm{R}j}\Sigma_-^\mu\ .$$

How to break the SU_L(2) X U_Y(1) down to U_{em}(1) ?

Assuming the top is composite, then the residual interaction between the top makes the top condensate.

Phenomenologically, expect large anomalous top quark couplings!!!

$$\kappa \sim (1/v)M$$

Top quark physics

- **Top quark decay via flavor changing neutral currents at hadron colliders** , Tao Han (UC, Davis), R.D. Peccei (UCLA), X. Zhang (Iowa State U. & Fermilab). **Nucl.Phys. B454 (1995) 527-540 (citation:** 138)
- **Nonstandard couplings of the top quark and precision measurements of the electroweak theory**
  R.D. Peccei, S. Peris, X. Zhang (UCLA).
  Nucl.Phys. B349 (1991) 305-322 (citation: 155)
- **Dynamical Symmetry Breaking and Universality Breakdown**
  R.D. Peccei, X. Zhang (UCLA).
  Nucl.Phys. B337 (1990) 269-283 (citation: 208)

At CEPC-SPPC the anomalous top couplings will be measured with a high Precision.

However, for CEPC with 240 GeV, top pair can not be produced, but single top might be produced via FCNC

e^+ e^- ------Z (or \gamma) --→ \bar t c

Effective Lagrangian with a light Higgs

- With non-linearly realized SU_L(1)XU_Y(1), a light Higgs boson can be easily added on by taking h to be a singlet

(C.-P. Yuan ….Hong-Jian He …)

*) With linearly realized SU_L(1)XU_Y(1), the Higgs forms a SU_L(2) doublet with other three goldstones.

$$\mathcal{L}^{\text{new}} = \sum_i \frac{c_i}{\Lambda^{d_i-4}} O^i \,,$$

An example: neutrino mass in effective theory

$$\hat{O}_{\text{dim}=5} = \ell^T C \epsilon \varphi \; \varphi^T \epsilon \ell \qquad C = i\gamma_2\gamma_0$$

(Weinberg '79)

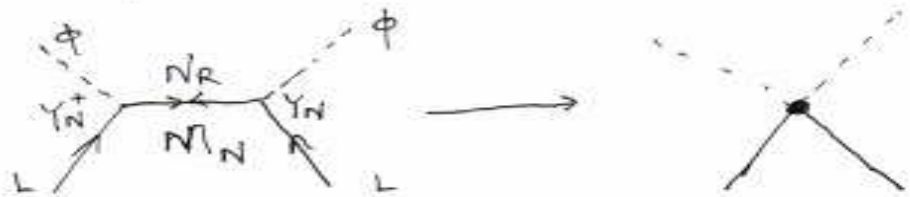
$$\frac{1}{\Lambda}\hat{O}_{\text{dim}=5} \xrightarrow{\langle\varphi\rangle = \begin{pmatrix} 0 \\ v \end{pmatrix}} \frac{v^2}{\Lambda}\nu_L^T C \nu_L$$

$$m_\nu \sim 1\,\text{eV} \;\rightarrow\; \Lambda \sim 10^{13}\,\text{GeV}$$

See Saw 机制

$\longrightarrow$ dim-5 operator $\frac{1}{\Lambda} L\phi L\phi$

I, 引入右手中微子



$\Rightarrow m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2$

II, 引入 triplet 标量场



$\Rightarrow m_\nu = Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2$

III, ... 很多小的中微子质量"产生模型 .....

Electroweak phase transition in effective theory:
------ Operator relevant to Higgs mass limit

$$O_3 = \alpha \frac{\phi^6}{\Lambda^2} ,$$

Effective potential:

$$V_T^{\text{eff}} = D(T^2 - T_0^2)\phi^2 - ET\phi^3 + \tfrac{1}{4}\lambda_T \phi^4 ,$$

where

$$D = \frac{1}{8v^2}(2M_W^2 + 2m_t^2 + M_Z^2) ,$$

$$T_0^2 = \frac{1}{D}\left(\frac{m_H^2}{4} - 2Bv^2\right) ,$$

$$B = \frac{3}{64\pi^2 v^4}(2M_W^4 + M_Z^4 - 4m_t^4) ,$$

$$E = \frac{1}{6\pi v^3}(2M_W^3 + M_Z^3) ,$$

$$\lambda_T = \lambda - \frac{3}{16\pi^2 v^4}\left[2M_W^4 \ln\frac{M_W^2}{\alpha_B T^2} + M_z^4 \ln\frac{M_Z^2}{\alpha_B T^2} - 4m_t^4 \ln\frac{m_t^2}{\alpha_F T^2}\right] ,$$

where $\ln\alpha_B = 2\ln 4\pi - 2\gamma \simeq 3.91$ and $\ln\alpha_F = 2\ln\pi - 2\gamma \simeq 1.14$.

$$V_3^{(T)} = \alpha \frac{v^2}{\Lambda^2}\phi^2\left[-\phi^2 + v^2 + \frac{1}{3}\frac{\phi^4}{v^2}\right] .$$

弱电相变

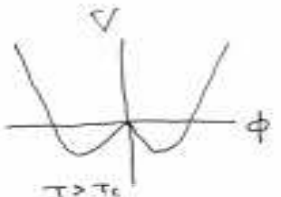
$SU(2) \times U(1) \xrightarrow[\langle\phi\rangle = v]{} U_{em}(1)$

$T > T_c \quad \langle\phi\rangle \neq 0$

$T < T_c \quad \langle\phi\rangle = 0$

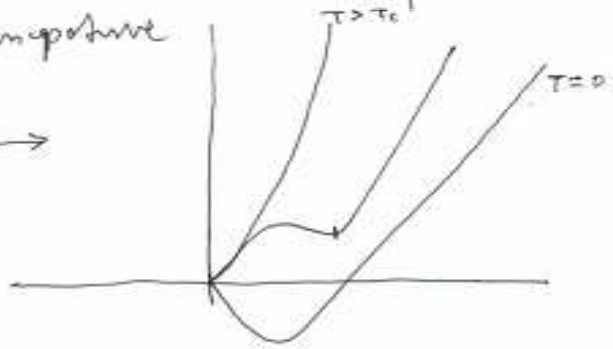
I, potential at tree level

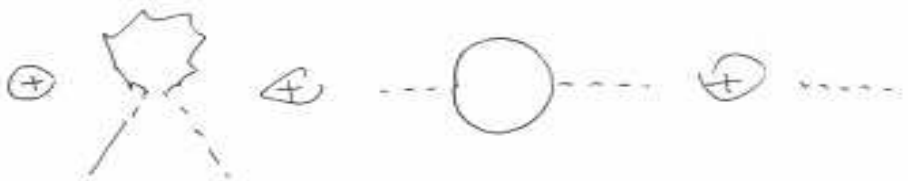
$$V(\phi) = \lambda \left(\phi^+ \phi - \frac{v^2}{2} \right)^2$$



II, At finite temperature

$\longrightarrow$





$$O_3 = \alpha \frac{\phi^6}{\Lambda^2} \quad \Longrightarrow \quad m_H^2 < (35\ GeV)^2 + 8\alpha \frac{v^4}{\Lambda^2}$$

Prediction for a light Higgs !!!

重要预言：

Higgs质量：

115 GeV ~ 132 GeV

Xinmin Zhang PRD47, 3065 (1993)

Cedric Delaunay, Christophe Grojean, James D. Wells

JHEP 0804:029,2008

PHYSICAL REVIEW D, VOLUME 70, 093007

Electroweak phase transition in the standard model with a dimension-six Higgs operator at the one-loop level

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[2]*Department of Physics, Konkuk University, Seoul 143-701, Korea*

(Received 29 August 2004; published 11 November 2004)

The possibility of a strongly first-order electroweak phase transition by means of a dimension-six Higgs operator in the Higgs potential of the standard model is studied at finite temperature at the one-loop level. Exact calculation of the one-loop effective Higgs potential at finite temperature suggests that for the Higgs boson with its mass between 115 and 132 GeV the strongly first-order electroweak phase transition is possible if a dimension-six operator is present.

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I. INTRO

comparable to 1 for $115 \lesssim m_H \lesssim 132$ GeV. Thus, our study suggests that the SM Higgs potential at the one-loop level with a dimension-six operator allows a strongly first-order electroweak phase transition, for the Higgs boson mass between 115 and 132 GeV. A Higgs boson with this mass range might easily be searched in future high energy experiments.

in the Higgs

ACKNOWLEDGMENTS

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Anomalous Higgs self couplings

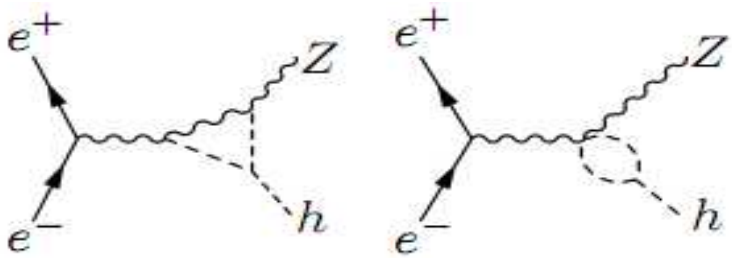
$$O_3 = \alpha \frac{\phi^6}{\Lambda^2} \ ,$$

My result in 1993: $m_H^2 < (35\ GeV)^2 + 8\alpha \frac{v^4}{\Lambda^2}$

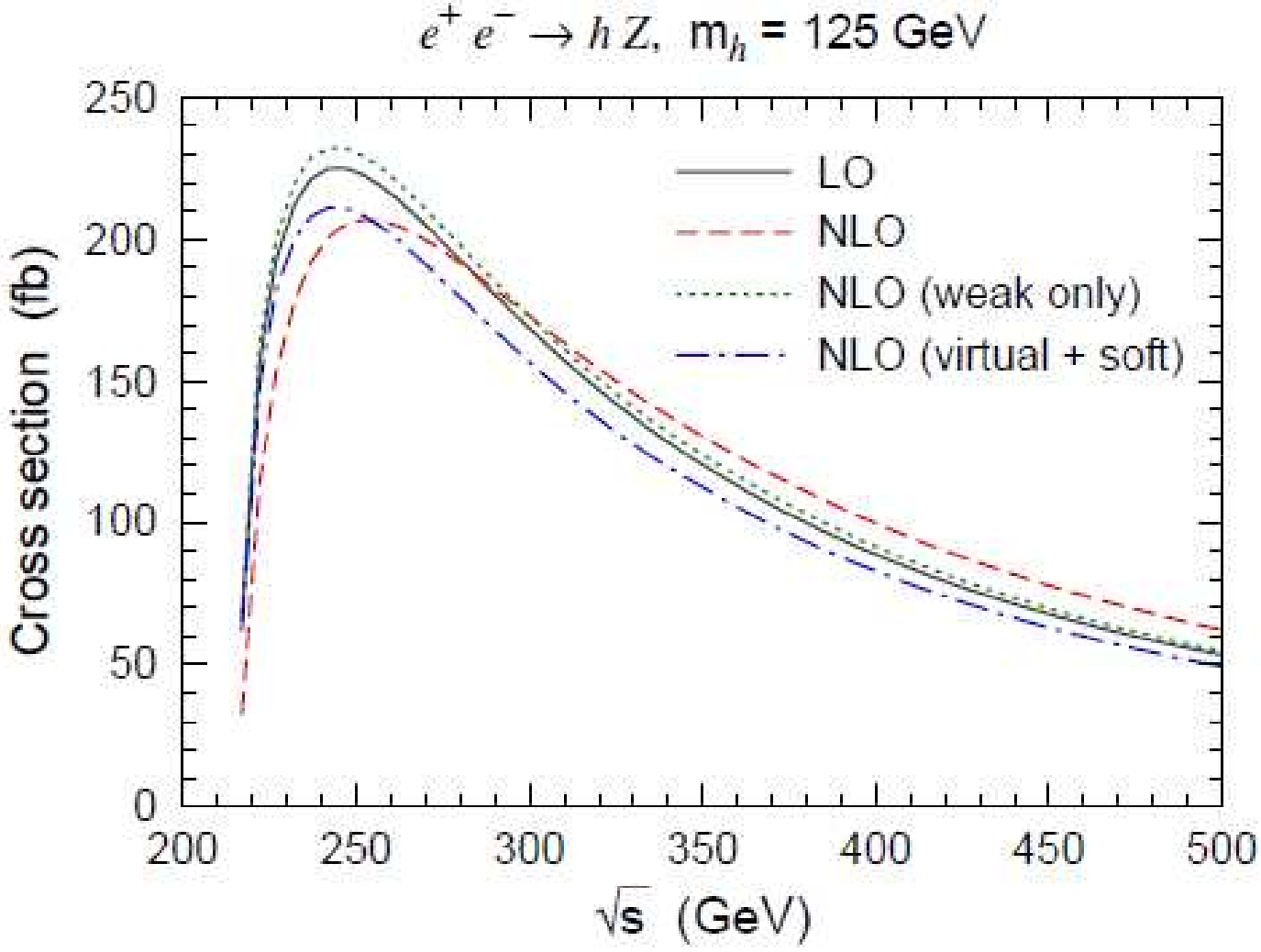
taking Higgs mass 125 GeV, I obtain \Lambda should be
no more than 1.5 TeV for \alpha ~ O(1)
which gives a correct to the triplet Higgs coupling about 90%

My result is consistent with the recent analysis (C. Grojean, G. Servant, J. Wells; S. W. Ham, S. K. Oh; Dietrich Bodeker, Lars Fromme, Stephan J. Huber, Michael Seniuch ; Daniel J. H. Chung, Andrew J. Long, Lian-Tao Wang ……)

The anomalous Higgs self coupling is claimed to be measured with precision O (30 %) at TLEP in Matthew McCullough arXiv:1312.3322
(For CEPC, see P. Yin, X Bi, P. Gu and X. Zhang in preparation)



Higgs production at the electron-positron collider

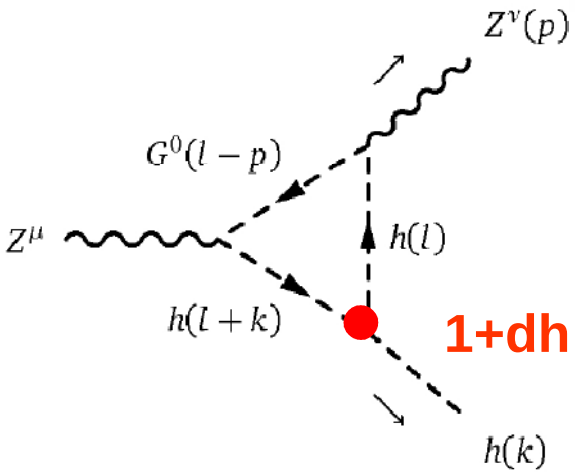


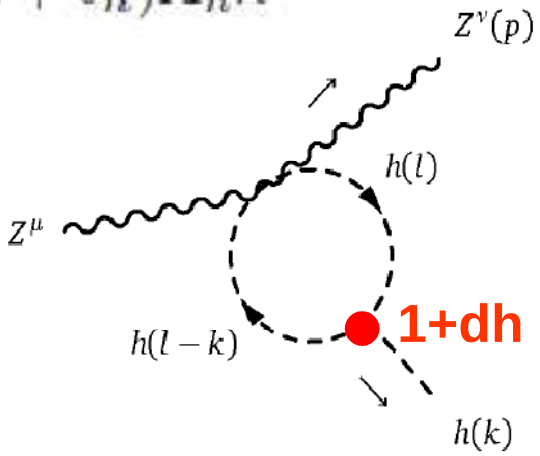
$$\sigma_{NLO} = \sigma_{born} + \sigma_{weak} + \sigma_{EM}$$

$$\sigma_{EM} = \sigma_{vir} + \sigma_{soft} + \sigma_{coll} + \sigma_{finite}$$

Higgs loop contribution with anomalous coupling

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





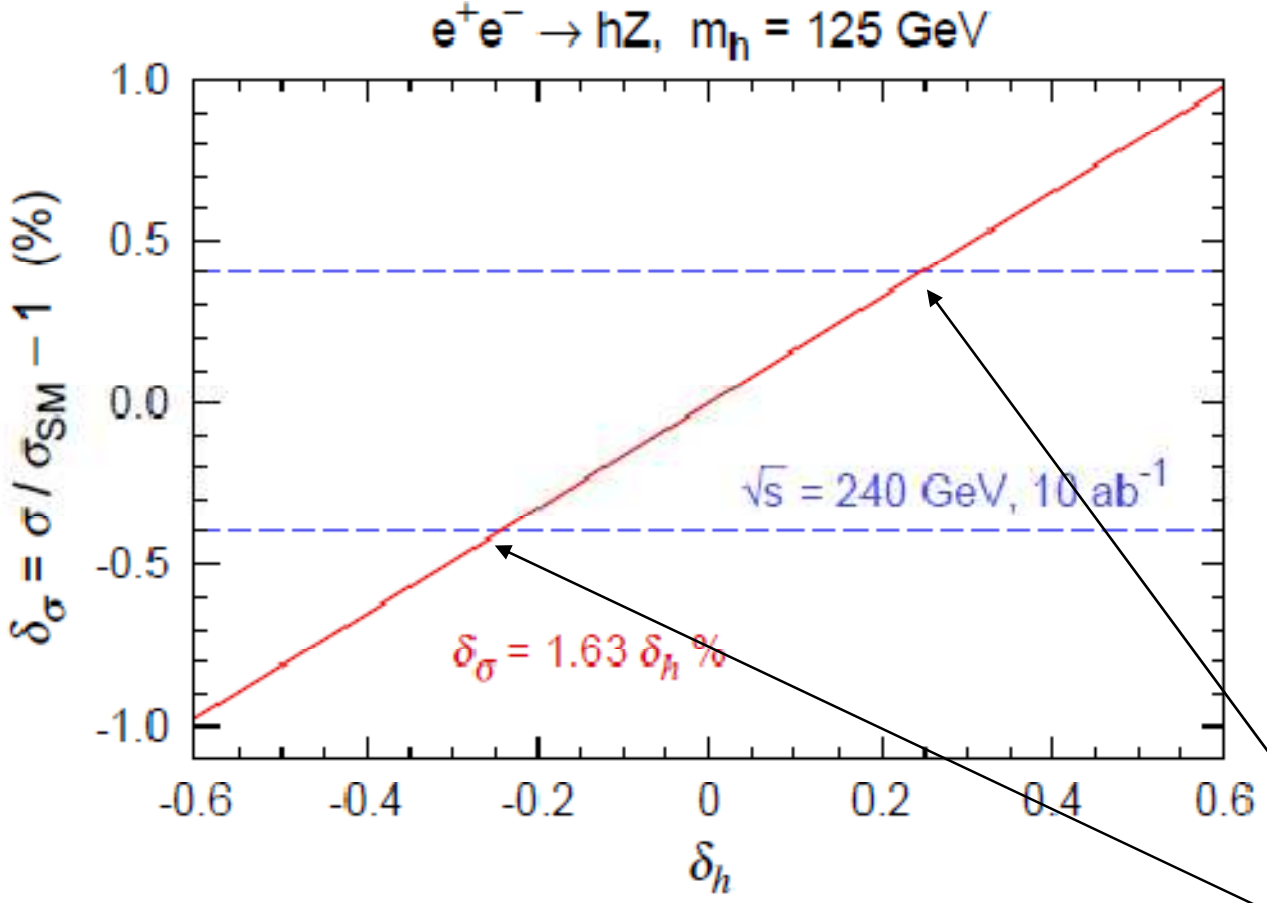
$$\frac{3\,i\,\Delta\,el^3\,m_h^2\,g^{\mu\nu}}{128\,\pi^2\,c_W^2\,m_W\,s_W^3}$$ X(1+dh)

$$-\frac{3\,i\,\Delta\,el^3\,m_h^2\,g^{\mu\nu}}{128\,\pi^2\,c_W^2\,m_W\,s_W^3}$$ X(1+dh)

- No contribution from the counter terms
- Divergence also cancelled after introducing anomalous triple Higgs coupling

Higgs production at the electron-positron collider

- Consider anomalous triple Higgs coupling



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

- **If the precision of Higgs associated production cross section is ~0.4%, it is possible to determine the anomalous Higgs coupling to ~25%**
  - **Proposed by McCullough, 1312.3322**

Predictions by electroweak baryogenesis and strong first order phase transition

A model independent analysis gives:

1) Anomalous Higgs coupling is 90%,

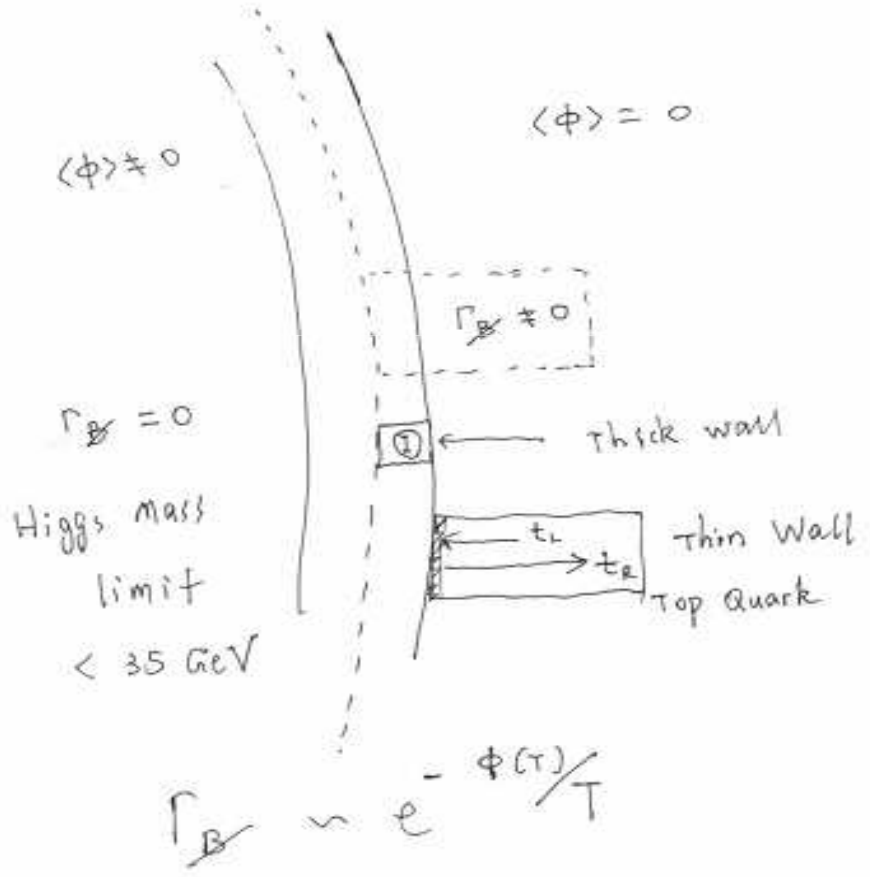
   which will be confirmed at 3 sigma at CEPC

2) \Lambda be smaller than 1.5 TeV,

   New particles (scalars, fermions, vector fields….) will be directly searched at SPPC.

========➔ “no lose” theorem

Electroweak Baryogenesis



$\mathcal{L}^{eff}$ 方法

① 定义

$$\Delta B \sim \Delta N_{CS} \sim \frac{\alpha_W}{4\pi} \int_{t_c}^{\infty} d^4x \, W_{\mu\nu} \tilde{W}^{\mu\nu}$$

↑ 相变开始

$$\tilde{W}_{\mu\nu} = \frac{1}{2} \varepsilon_{\mu\nu\alpha\beta} W^{\alpha\beta}$$

$$\Delta \mathcal{L}^{\text{New Phys}} = C_W \frac{g^2}{8\pi^2} \frac{\Phi^2}{\Lambda^2} \operatorname{Tr} W_{\mu\nu} \tilde{W}^{\mu\nu}$$

$$\downarrow$$

$$\partial_\mu K^\mu$$

$$n_B = 3 \int \frac{\Gamma_{sph}}{T} \frac{d}{dt} \left(C_W \frac{\Phi^2}{\Lambda^2} \right) dt = 3 \int \frac{\Gamma_{sph}}{T} \alpha \left(C_W \frac{\Phi^2}{\Lambda^2} \right)$$

$$\Gamma_{sph} = K (\alpha_W T)^4 \qquad K \approx 0.1 \sim 1$$

$$\frac{n_B}{s} \sim 4 \times 10^{-2} \, K \, C_W \, \alpha_W^4 \, (T/\Lambda)^2$$

$$\sim (0.4 - 1.4) \times 10^{-10}$$

要求: $\Lambda \sim 1$ TeV $\quad C_W \geq 0.1 - 1$

$$\Delta \mathcal{L}^{\text{New phys}} \longrightarrow C_W \frac{\alpha_{em}}{32\pi} \frac{H}{v} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

$$H \to \gamma\gamma$$

Higgs mass limit:

$$m_H^2 < (35\,\text{GeV})^2 + 8\alpha \frac{v^4}{\Lambda^2}$$

$$\downarrow \quad \alpha \frac{\Phi^6}{\Lambda^2}$$

$$\langle \Phi \rangle \sim \frac{1}{\sqrt{2}} v \sim \frac{1}{\sqrt{2}} 250\,\text{GeV}$$

$\Rightarrow$ i) light Higgs $\sim$ 125 GeV

ii) New $H \to \gamma\gamma$

$$O^{\text{New}} \sim \frac{\Phi^2}{\Lambda^2} F_{\mu\nu} F^{\mu\nu}$$

Operator relevant to baryon number generation

$$\mathcal{O}^t = c_t e^{i\xi} \frac{\phi^2 - v^2/2}{\Lambda^2} \Gamma_t \bar{\Psi}_L \tilde{\Phi} t_R, \qquad \Longrightarrow \qquad \Gamma_t^{\rm eff} = \Gamma_t \left\{ 1 + c_t e^{i\xi} \frac{\phi^2 - v^2/2}{\Lambda^2} \right\}.$$

$$\frac{n_B}{s} \sim \kappa c_t \sin\xi \times 10^{-9}.$$

Anomalous top-Higgs couplings:

$$\mathcal{L}^{\rm eff} \sim \frac{m_t}{t} \bar{t} \left\{ \left[1 + \left(\frac{c_t}{16} \right) \cos\xi \right] + i \left(\frac{c_t}{16} \right) \sin\xi \gamma_5 \right\} t H,$$

For \Lambda ~ 1 TeV.

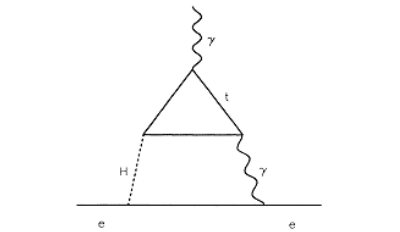
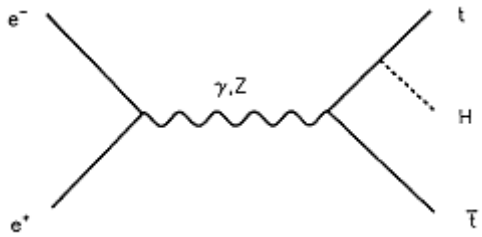


FIG. 1. Dominant contribution to d_e, the electric dipole moment of the electron.



X. Zhang et al, PRD 50, 7042 (1994)
Lars Fromme, Stephan J. Huber, JHEP 0703:049,2007
Lianyou Shan et al (In preparation)

Note: Non-universal couplings induce FCNC couplings

t t\bar h (\gamma, Z) --→ t\bar c h (\gamma, Z)
T. Han, R. Peccei, X. Zhang et al…..
C.-P., Yuan et al

Comments

I) The generation of baryon number asymmetry

predict CP violating

anomalous Higgs couplings

anomalous htt couplings

II) anomalous htt couplings can be probed at HL-LHC, SPPC,

but hard at CEPC (with loop effect);

Interesting: Top decay into Higgs and charm quark…..

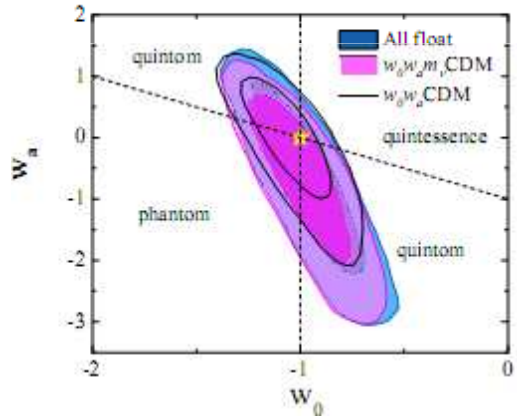
III) If found nothing, should disappointed ?

discover the 2rd order phase transition of

the electroweak theory!!!

More on if found nothing

- Understanding the universe evolution up to TeV scale
- Analogy with the dark energy study



Wish to discover the dynamics of dark energy. However, if still the cosmological constant, seems find nothing, but a big discovery

======understood the nature of accelerated universe!!

Neutrino mass and Higgs invisible decay

- Effective theory: Heavy particles decoupled $M \sim \Lambda$
- Goldstone Bosons : $m \sim 0$
- In the S.M. $U(1)_{B+L}$ anomalous; $U(1)^{\text{Global}}_{B-L}$
- ν masses : See-Saw mechanism

$$\bar{\nu}_R^c \nu_R \xrightarrow{\text{Introducing } \sigma} \bar{\nu}_R^c \nu_R \sigma$$

$\langle \sigma \rangle \neq 0 \rightarrow$ Breaking $U_{B-L}(1)$ symmetry $\rightarrow$ Goldstone $J \sim \text{Im}\,\sigma$

$$m \bar{\nu}_L \nu_R + M \bar{\nu}_R^c \nu_R \longrightarrow m_\nu \sim \frac{m^2}{M}$$

where $M \sim y \langle \sigma \rangle$

Singlet Majoron Model:

Y. Chikashige (Munich, Max Planck Inst.), Rabindra N. Mohapatra (Munich, Max Planck Inst. & Munich U.), R.D. Peccei (Munich, Max Planck Inst.)

Phys.Lett. B98 (1981) 265

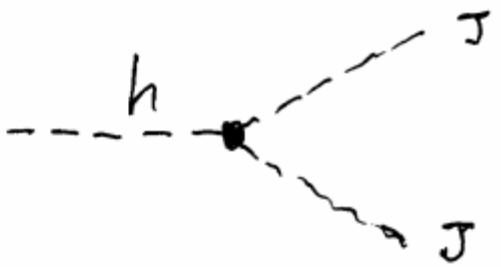
SUSY singlet Majoron model:

R. Mohapatra and X. Zhang (Maryland)

Phys. Rev. D49, (1994) 1163

$$V(\phi, \sigma) \sim \lambda\left(|\phi|^2 - v^2\right)^2 + \tilde{\lambda}\left(|\sigma|^2 - f^2\right)^2 + g|\phi|^2|\sigma|^2$$

$h \longrightarrow J\ J$



Discussions

*) SM works well so far

**) Motivations for new physics

Naturalness: not so convincing as before

neutrino mass

Cosmology (inflation, dark matter, dark energy ….)

Much relevant: WIMP dark matter

elecroweak baryogenesis

Particle Cosmology!!!

***) For SPPC, no doubt on the potential of discovery

For CEPC, improving the precision of the measurements

however, need to understand the physical significance?

Answer the question “so what?”

*) In this talk, I explain hopefully one of the answers to the "so what" question based on the arguments on the strong phase transition and electroweak baryogenesis.

**) If no new particle found, is it still a discovery?

"condense matter physics"

discover the dynamics of the phase transition!!

Even if found nothing =➔ a big discovery:

the nature choose such a simple and "boring" mechanism!!

(similarly, cosmological constant for dark energy?!)

***) No lose theorem for the study of phase transition?

generally, Yes for CEPC-SPPC

NEED much more works!

(0) New Machines for a new Frontier

(1) The Ewk Phase Transition

(2) Naturalness + deep origin of EWSB

(3) Dark Matter(s)

[(4) New world of Flavor + CP]

{Throughout: interplay with LHC}

---------- From Nima Arkani-Hamed's talk

1. We must study the Higgs boson itself in as much detail as possible, searching for signs of a larger Higgs sector and the effects of new heavy particles.

2. We must search for the imprint of the Higgs boson and its possible partners on the couplings of the W and Z bosons and the top quark.

3. We must search directly for new particles with TeV masses that can address important problems in fundamental physics.

---------From Peskin's talk

Thank you !