Effects of Higgs in Electroweak Chiral Lagrangian

Qing Wang

Tsinghua University, Beijing

Oct 5, 2006, NCTS and NTHU


物理

Effects of Higgs in Electroweak Chiral Lagrangian

Standard Model and Beyond

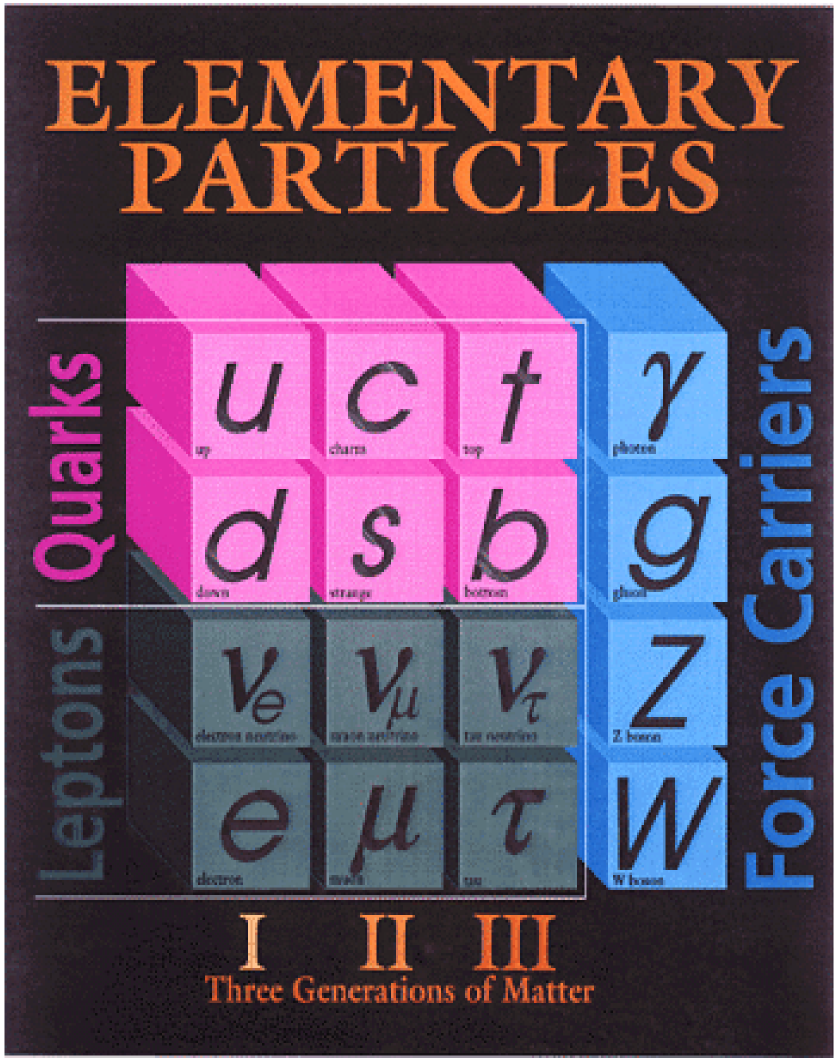
Model Independent Description of New Physics

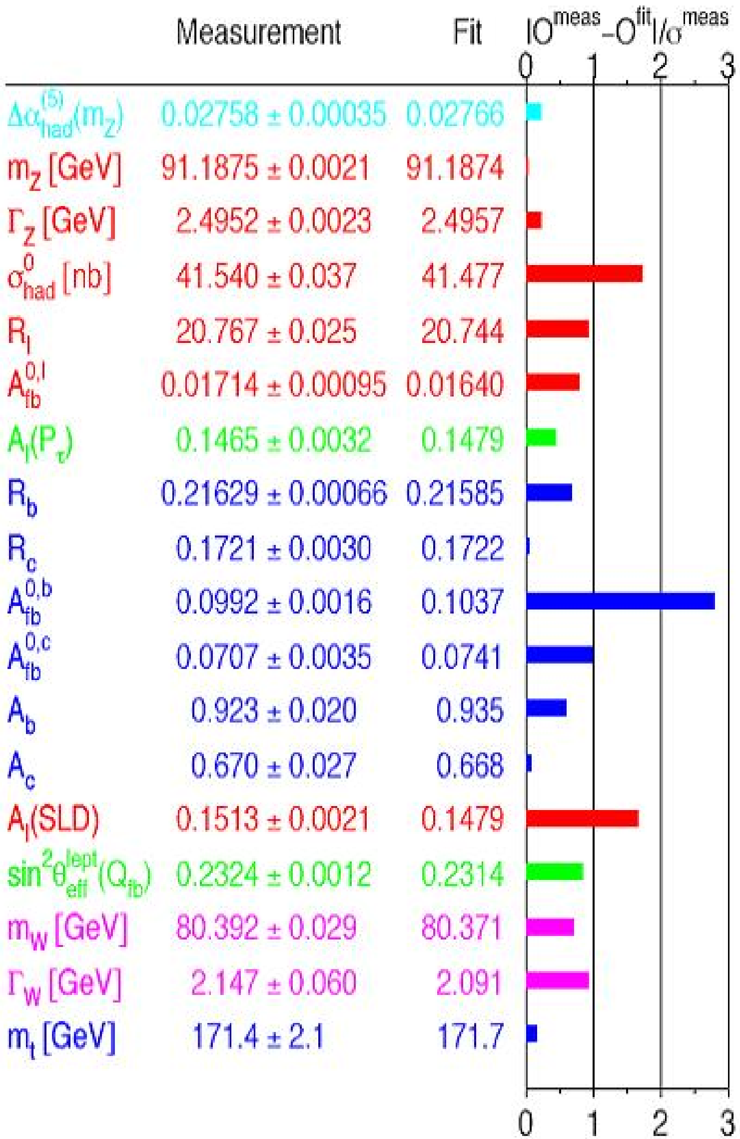
Equivalence between Linear and Nonlinear Realizations of EWCL with Higgs

Extended EWCL and Integrating out Higgs

Effects of Higgs in EWCL

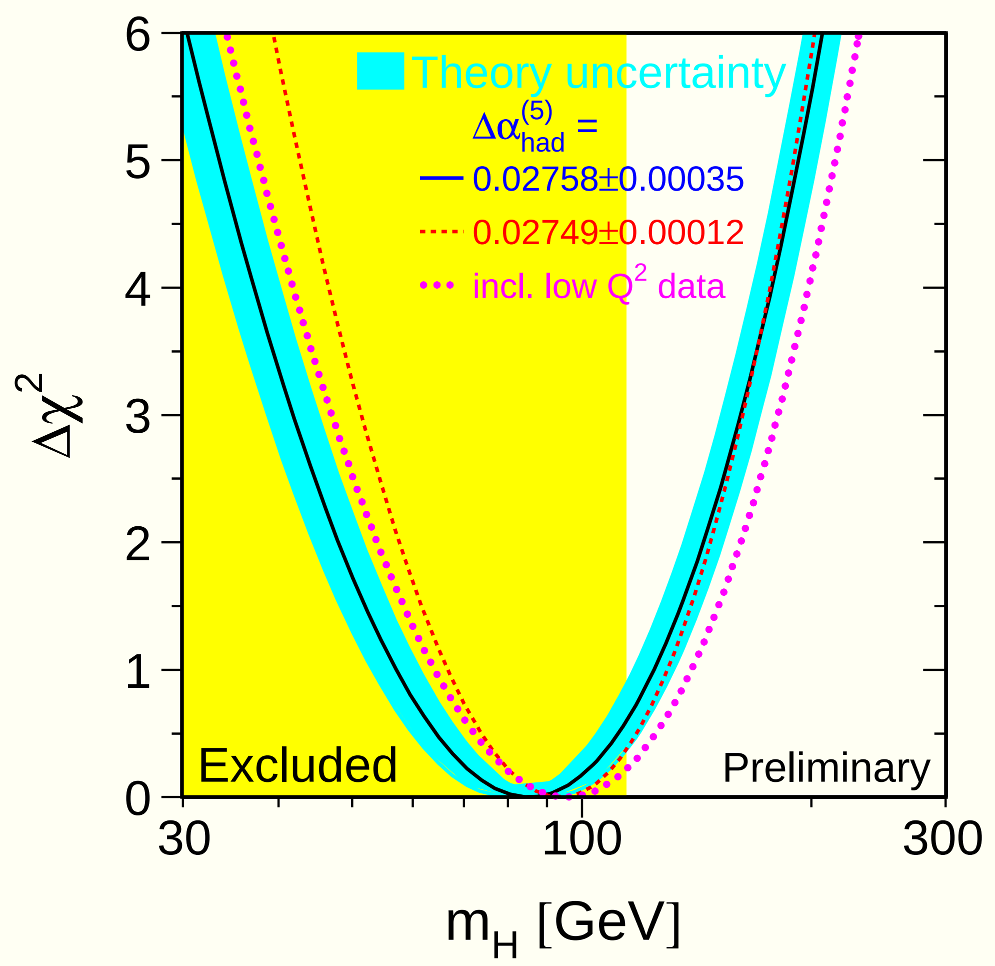
Standard Model and Beyond

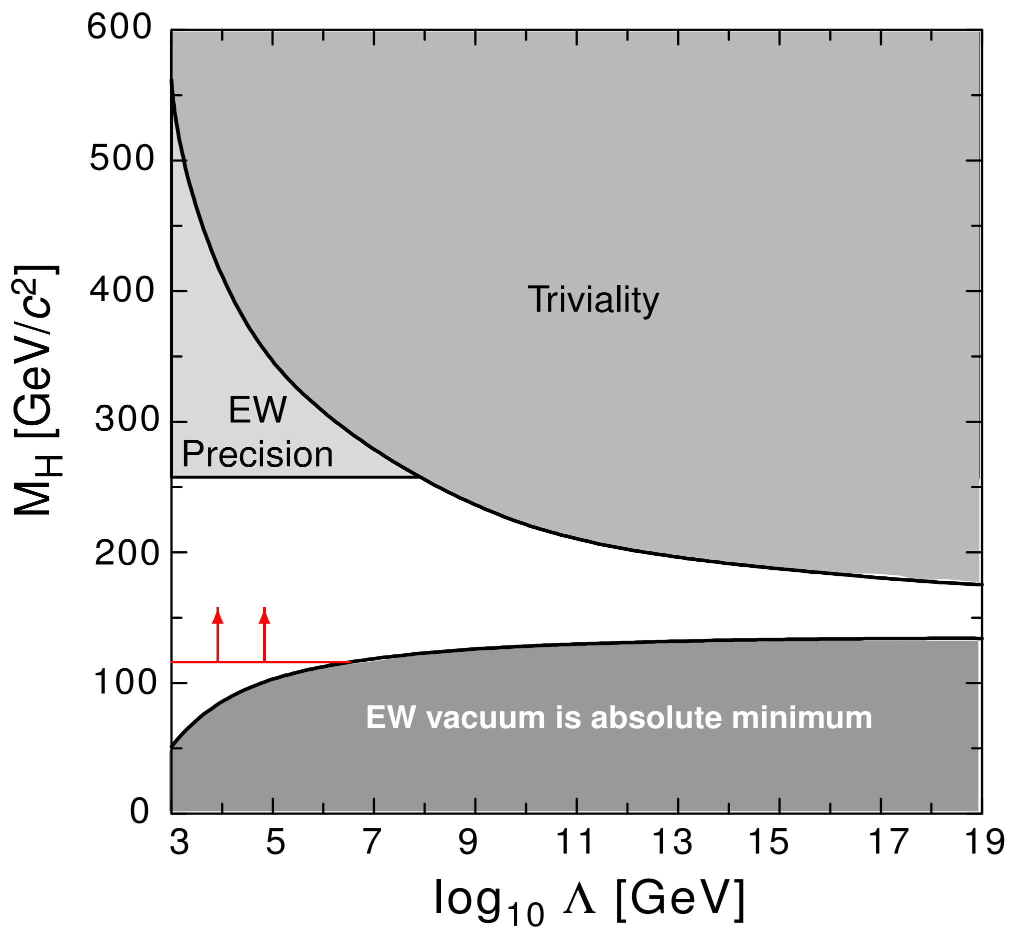




Standard Model and Beyond

Unknown **Scalar field**: linear representation of $SU(2)_L \otimes U(1)_Y = 3$ longitudinal $W^{\pm}, Z$ $+ 1$ Higgs





Standard Model and Beyond

Fig. 1: The flowering of the Higgs physics that is expected to bloom at the TeV scale.

Questions

- **Is it possible to find Higgs particle in future experiments ?**

- **If we do not find Higgs, what does it imply ?**

- **If we do find Higgs, can we judge whether it is SM or non-SM Higgs ?**

TeV Working Group in China http://hep.tsinghua.edu.cn/tevworkinggroup

- organized and first meeting in Dec, 2005
- more than 40 professors THU, PKU, USTC, ZJU, SDU, Nankai, ITP, IHEP...
- lead by Prof.Y.P.Kuang in THU and several subgroups

High Energy Physics in Tsinghua University http://hep.tsinghua.edu.cn

- lead by Center for High Energy Physics, Tsinghua University TUHEP
- New Physics and EWSSB; Collider phenomenology; Top; neutrino; Extra Dim; SUSY; QCD and Nonperturb; Quarkonium
- LHCb and CPV ; Rich Star and QGP; SuperK and Neutrino; BES and tau-charm

Model Independent Description of New Physics

High Energy Colliders

- **LEPII:** electroweak precision measurements; signals at 115GeV

  shut down

- **Tevatron RunII:** try best to search for Higgs, SUSY, extra dim, ...

  operating

- **LHC(2007):** an expected discovery machine for new physics !

  building up

- **ILC:** synergy with LHC, expect to fully investigate EWSB !

  planning

An expected data rich era is coming !

Model Independent Description of New Physics

New Physics Models

- **SUSY:** too many free parameters!

  MSSM predicts $M_H \leq$135GeV

- **Dynamical EWSB:** technicolor, topcolor/topseesaw . . .heavy composite Higgs

  no light Higgs

- **Extra Dimension:** High dimension space induced Higgsless models!

  new spin 1 gauge field

- **Little Higgs:** Higgs as pseudo goldstone particle!

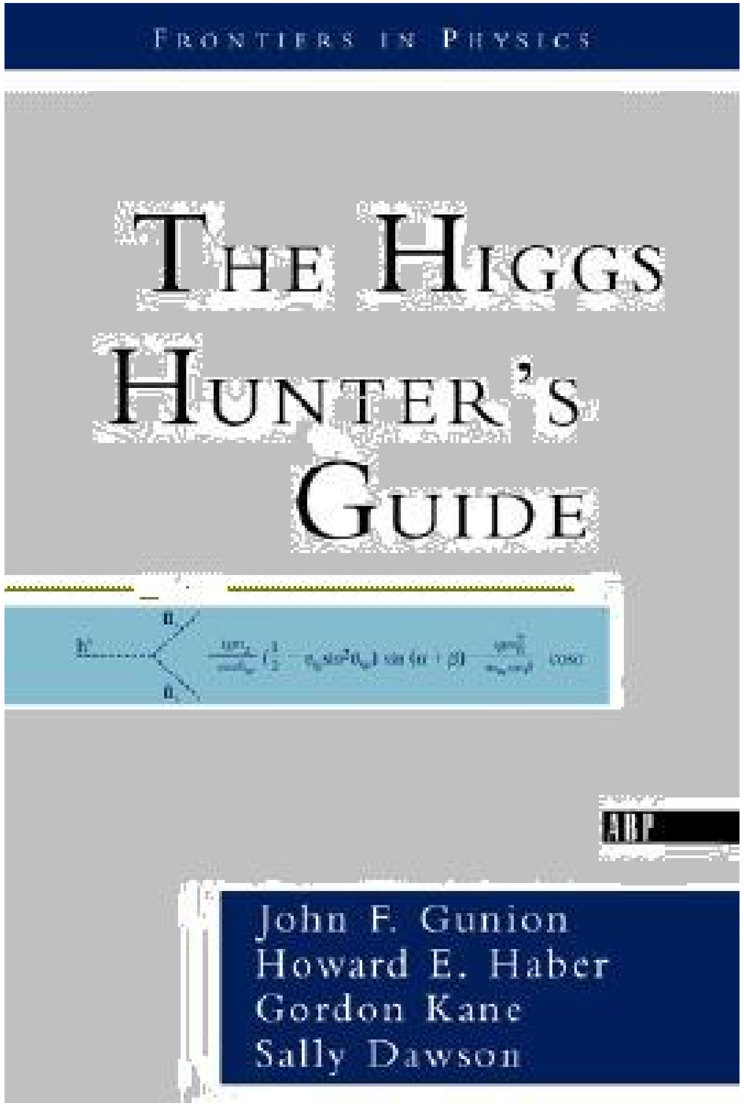
  $\mathrm{M_H} \sim 100 - 200$GeV

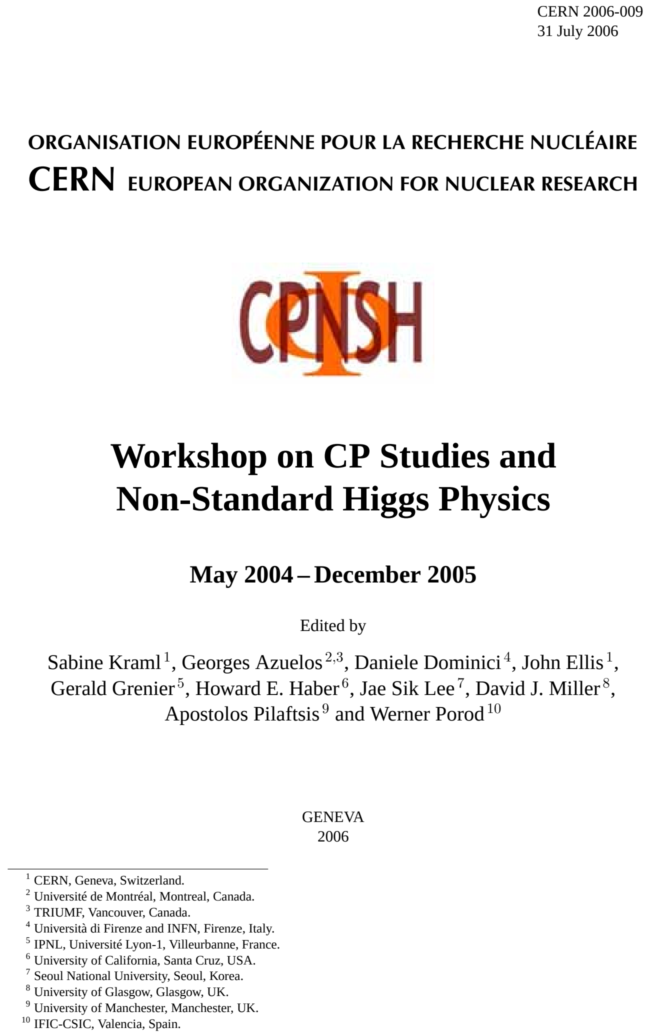
- . . . . . .

Too many models on the market !

Model Independent Description of New Physics

Model Independent Description of New Physics




CERN 2006-009
31 July 2006

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CPNSH

Workshop on CP Studies and Non-Standard Higgs Physics

May 2004 – December 2005

Edited by

Sabine Kraml[1], Georges Azuelos[2,3], Daniele Dominici[4], John Ellis[1], Gerald Grenier[5], Howard E. Haber[6], Jae Sik Lee[7], David J. Miller[8], Apostolos Pilaftsis[9] and Werner Porod[10]

GENEVA
2006

[1] CERN, Geneva, Switzerland.
[2] Université de Montréal, Montreal, Canada.
[3] TRIUMF, Vancouver, Canada.
[4] Università di Firenze and INFN, Firenze, Italy.
[5] IPNL, Université Lyon-1, Villeurbanne, France.
[6] University of California, Santa Cruz, USA.
[7] Seoul National University, Seoul, Korea.
[8] University of Glasgow, Glasgow, UK.
[9] University of Manchester, Manchester, UK.
[10] IFIC-CSIC, Valencia, Spain.

Model Independent Description of New Physics

Effective Electroweak Chiral Lagrangian–EWCL

- To respect present status of SM:
  Higgs not found! Its self coupling and Yukawa terms not tested !
- Need a theory describe present status of experiment:
  need three goldstone bosons and their coupling with fermions!
- Subtract out Higgs in Standard Model:
  EW symmetry and its breaking must be realized nonlinearly!
- Without Higgs makes theory model independent:
  Underlying models are parameterized by choice of different coefficients.

Model Independent Description of New Physics

EW Chiral Lagrangian: boson part

$\mathcal{L}_{\rm Scalar} \rightarrow \mathcal{L}_{\rm EWCL}^{\rm boson}$ $\quad T = U\tau^3 U^\dagger \quad V_\mu = (D_\mu U)U^\dagger \quad D_\mu U = \partial_\mu U + ig_2 W_\mu U - ig_1 B_\mu \tau^3/2$

$$\begin{aligned}
\mathcal{L}_{\rm EWCL}^{\rm boson} = & -(f^2/4){\rm tr}(V_\mu V^\mu) + (f^2/4)\beta_1[{\rm tr}(TV_\mu)]^2 + (1/2)\alpha_1 g_2 g_1 B_{\mu\nu}{\rm tr}(TW^{\mu\nu}) \\
& + (i/2)\alpha_2 g_1 B_{\mu\nu}{\rm tr}(T[V^\mu,V^\nu]) + i\alpha_3 g_2 {\rm tr}(W_{\mu\nu}[V^\mu,V^\nu]) + \alpha_4[{\rm tr}(V_\mu V_\nu)]^2 + \alpha_5[{\rm tr}(V_\mu V^\mu)]^2 \\
& + \alpha_6 {\rm tr}(V_\mu V_\nu){\rm tr}(TV^\mu)(TV^\nu) + \alpha_7 {\rm tr}(V_\mu V^\mu){\rm tr}(TV_\nu)(TV^\nu) + (1/4)\alpha_8 g_2^2[{\rm tr}(TW_{\mu\nu})]^2 \\
& + (i/2)\alpha_9 g_2 {\rm tr}(TW_{\mu\nu}){\rm tr}(T[V^\mu,V^\nu]) + (1/2)\alpha_{10}[{\rm tr}(TV_\mu){\rm tr}(TV_\nu)]^2 \\
& + \alpha_{11} g_2 \epsilon^{\mu\nu\rho\lambda}{\rm tr}(TV_\mu){\rm tr}(V_\nu W_{\rho\lambda}) + \alpha_{12}{\rm tr}(TV_\mu){\rm tr}(V_\nu W^{\mu\nu}) + \alpha_{13} g_2 g_1 \epsilon^{\mu\nu\rho\sigma}B_{\mu\nu}{\rm tr}(TW_{\rho\sigma}) \\
& + \alpha_{14} g_2^2 \epsilon^{\mu\nu\rho\sigma}{\rm tr}(TW_{\mu\nu}){\rm tr}(TW_{\rho\sigma}) + 2i\alpha_{15} g_2 \epsilon^{\mu\nu\rho\sigma}{\rm tr}(W_{\mu\nu}V_\rho V_\sigma) \\
& + \alpha_{16} g_2^2 \epsilon^{\mu\nu\rho\sigma}{\rm tr}(TW_{\mu\nu}){\rm tr}(TW_{\rho\sigma}) + 2i\alpha_{17} g_{12} g_2^2 \epsilon^{\mu\nu\rho\sigma}{\rm tr}(TW_{\mu\nu}{\rm tr}(TV_\rho V_\sigma) \\
& + \alpha_{18} g_1^2 \epsilon^{\mu\nu\rho\sigma}B_{\mu\nu}B_{\rho\sigma} + \alpha_{19} g_2^2 \epsilon^{\mu\nu\rho\sigma}{\rm tr}(W_{\mu\nu}W_{\rho\sigma}) + (g_1^2/4)Z_1 B_{\mu\nu}B^{\mu\nu} + (g_2^2/2)Z_2 {\rm tr}(W_{\mu\nu}W^{\mu\nu}) + O(p^6)
\end{aligned}$$

Model Independent Description of New Physics

EW Chiral Lagrangian: fermion part

$$L_i = \begin{pmatrix} \nu_i \\ E_i \end{pmatrix} \qquad Q_i = \begin{pmatrix} U_i \\ D_i \end{pmatrix} \qquad \Phi = U \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}$$

$$\mathcal{L}_{\rm Yukawa} \to \mathcal{L}^{\rm fermion}_{\rm EWCL} = \overline{L}_i \begin{pmatrix} 0 & 0 \\ 0 & f_i^e \end{pmatrix} U P_R L_i + \overline{Q}_i \begin{pmatrix} f_i^u & 0 \\ 0 & f_i^d \end{pmatrix} U P_R Q_i \; + \; \textbf{h.c.}$$

$$+ f_{ij}^{\nu} L^{\alpha T} C L_j^{\beta} \Phi^{\alpha'} \Phi^{\beta'} \epsilon^{\alpha\alpha'} \epsilon^{\beta\beta'} \; + \; \textbf{h.c.}$$ Neutrino Majorana mass

$+$**high order terms**

high order terms: self interactions; interactions with gauge fields !

Model Independent Description of New Physics

Experimental Tests

$$S=-16\pi\Pi'_{3B}(0)=-16\pi\alpha_1 \quad \alpha T=\frac{e^2[\Pi_{11}(0)-\Pi_{33}(0)]}{c^2s^2m_Z^2}=2\beta_1 \quad U=16\pi[\Pi'_{11}(0)-\Pi'_{33}(0)]=-16\pi\alpha_8$$

$$\frac{\mathcal{L}_{WWV}}{g_{WWV}}=ig_1^V(W^V_{\mu\nu}W^{-\mu}V^\nu-W^-_{\mu\nu}W^{+\mu}V^\nu)+i\kappa_VW^+_\mu W^-_\nu V^{\mu\nu}-g_4^VW^+_\mu W^-_\nu(\partial^\mu V^\nu+\partial^\nu V^\mu)$$
$$+g_5^V\epsilon^{\mu\nu\rho\sigma}[W^+_\mu(\partial_\rho W^-_\nu)-(\partial_\rho W^+_\mu)W^-_\nu]V_\lambda+i\tilde{\kappa}_VW^+_\mu W^-_\nu\tilde{V}^{\mu\nu}$$

$$g_1^Z-1=\frac{\beta_1}{c^2-s^2}+\frac{e^2\alpha_1}{c^2(c^2-s^2)}+\frac{e^2\alpha_3}{s^2c^2} \qquad g_1^\gamma-1=0 \qquad g_5^Z=\frac{e^2\alpha_{11}}{s^2c^2} \qquad g_5^\gamma=0$$

$$\kappa_\gamma-1=\frac{e^2(-\alpha_1+\alpha_2+\alpha_3-\alpha_8+\alpha_9)}{s^2} \qquad \kappa_Z-1=\frac{\beta_1}{c^2-s^2}+\frac{e^2\alpha_1}{c^2(c^2-s^2)}+\frac{e^2(\alpha_1-\alpha_2)}{c^2}+\frac{e^2(\alpha_3-\alpha_8+\alpha_9)}{s^2}$$

Model Independent Description of New Physics

Two Future Possibilities

- **Within SM:** Higgs is not found
- **Beyond SM:** Many models, but no new particle is found now

In Future, next generation colliders will all work at TeV energy region

- **Possibility One:** No new particle is found in TeV energy region worst case

  violate unitarity

- **Possibility Two:** New particle is found in TeV energy region

  probability: Z' >SUSY>Higgs; people will be excited and busy

Model Independent Description of New Physics

- New particle discovery needs time: at least 3 years
- Before discovery of new particle: EWCL works !
- Once new particle is found: need go beyond EWCL not urgent now

During the time before discovery of new particle: urgent

- Can we test effects of new particle below its threshold ?
- New particles as virtual particle contribute to physics! $\Rightarrow$ EWCL
- It is most economical and effective theory to investigate new physics !

Model Independent Description of New Physics

Investigating New Physics in terms of EWCL

- **Experimentally:** test and fix coefficients of the EWCL

  need to analyze and choose the best process He,Kuang,Yuan,hep-ph/9704276

- **Theoretically:** calculate coefficients of the EWCL

  need to perform computation: integrate out new particles QCD experience

  PRD61,54011(00); PRD66,14019(02); PLB532,240(02); PLB560,188(03)

  Each underlying model is corresponding to a group of coefficents!

Operators	$\mathcal{L}^{(2)\prime}$	$\mathcal{L}_{1,13}$	$\mathcal{L}_2$	$\mathcal{L}_3$	$\mathcal{L}_{4,5}$	$\mathcal{L}_{6,7}$	$\mathcal{L}_{8,14}$	$\mathcal{L}_9$	$\mathcal{L}_{10}$	$\mathcal{L}_{11,12}$	$T_1 \parallel B$	Processes
LEP-I (S,T,U)	⊥	⊥ †					⊥ †				$g^4\frac{f_\pi^2}{\Lambda^2}$	$e^-e^+ \to Z \to f\bar{f}$
LEP-II	⊥	⊥	⊥	⊥			⊥	⊥		⊥	$g^4\frac{f_\pi^2}{\Lambda^2}$	$e^-e^+ \to W^-W^+$
LC(0.5)/LHC(14)			√	√				√			$g^2\frac{E^2}{\Lambda^2} \parallel g^2\frac{M_W^2}{E^2}$	$f\bar{f} \to W^-W^+/(LL)$
		△	△	△			△	△		△	$g^3\frac{Ef_\pi}{\Lambda^2} \parallel g^2\frac{M_W}{E}$	$f\bar{f} \to W^-W^+/(LT)$
LC(1.5)/LHC(14)				√	√	√		√		√	$g^2\frac{1}{f_\pi}\frac{E^2}{\Lambda^2} \parallel g^3\frac{M_W}{E^2}$	$f\bar{f} \to W^-W^+Z/(LLL)$
		△	△	△	△	△	△	△		△	$g^3\frac{E}{\Lambda^2} \parallel g^3\frac{M_W^2}{E^3}$	$f\bar{f} \to W^-W^+Z/(LLT)$
				√	√	√			√		$g^2\frac{1}{f_\pi}\frac{E^2}{\Lambda^2} \parallel g^3\frac{M_W}{E^2}$	$f\bar{f} \to ZZZ/(LLL)$
					△	△			△		$g^3\frac{E}{\Lambda^2} \parallel g^3\frac{f_\pi}{\Lambda^2}\frac{M_W}{E}$	$f\bar{f} \to ZZZ/(LLT)$
					√						$\frac{E^2}{f_\pi^2}\frac{E^2}{\Lambda^2} \parallel g^2$	$W^-W^\pm \to W^-W^\pm/(LLLL)$ ‡
				△	△			△		△	$g\frac{E}{f_\pi}\frac{E^2}{\Lambda^2} \parallel g^2\frac{M_W}{E}$	$W^-W^\pm \to W^-W^\pm/(LLLT)$ ‡
					√	√					$\frac{E^2}{f_\pi^2}\frac{E^2}{\Lambda^2} \parallel g^2$	$W^-W^+ \to ZZ$ & perm./$(LLLL)$
			△	△	△	△		△		△	$g\frac{E}{f_\pi}\frac{E^2}{\Lambda^2} \parallel g^2\frac{M_W}{E}$	$W^-W^+ \to ZZ$ & perm./$(LLLT)$
					√	√			√		$\frac{E^2}{f_\pi^2}\frac{E^2}{\Lambda^2} \parallel g^2\frac{E^2}{\Lambda^2}$	$ZZ \to ZZ/(LLLL)$
				△	△	△			△		$g\frac{E}{f_\pi}\frac{E^2}{\Lambda^2} \parallel g^2\frac{M_W E}{\Lambda^2}$	$ZZ \to ZZ/(LLLT)$
LHC(14)				√						√	$g^2\frac{E^2}{\Lambda^2} \parallel g^2\frac{M_W^2}{E^2}$	$q\bar{q}' \to W^\pm Z/(LL)$
		△	△	△			△	△		△	$g^3\frac{Ef_\pi}{\Lambda^2} \parallel g^2\frac{M_W}{E}$	$q\bar{q}' \to W^\pm Z/(LT)$
				√	√			√		√	$g^2\frac{1}{f_\pi}\frac{E^2}{\Lambda^2} \parallel g^3\frac{M_W}{E^2}$	$q\bar{q}' \to W^-W^+W^\pm/(LLL)$
			△	△	△		△	△		△	$g^3\frac{E}{\Lambda^2} \parallel g^3\frac{M_W^2}{E^3}$	$q\bar{q}' \to W^-W^+W^\pm/(LLT)$
				√	√	√				√	$g^2\frac{1}{f_\pi}\frac{E^2}{\Lambda^2} \parallel g^3\frac{M_W}{E^2}$	$q\bar{q}' \to W^\pm ZZ/(LLL)$
		△	△	△	△	△	△	△		△	$g^3\frac{E}{\Lambda^2} \parallel g^3\frac{M_W^2}{E^3}$	$q\bar{q}' \to W^\pm ZZ/(LLT)$
LC($e^-\gamma$)		√	√	√			√	√		√	$eg^2\frac{E}{\Lambda^2} \parallel eg^2\frac{M_W^2}{E^3}$	$e^-\gamma \to \nu_e W^- Z, e^- WW/(LL)$
LC($\gamma\gamma$)		√	√	√			√	√			$e^2\frac{E^2}{\Lambda^2} \parallel e^2\frac{M_W^2}{E^2}$	$\gamma\gamma \to W^-W^+/(LL)$
		△	△	△			△	△			$e^2 g\frac{Ef_\pi}{\Lambda^2} \parallel e^2\frac{M_W}{E}$	$\gamma\gamma \to W^-W^+/(LT)$

Table VII. Probing the EWSB Sector at High Energy Colliders: A Global Classification for the NLO Bosonic Operators.

(Notation: √ = Leading contributions, △ = Sub-leading contributions, and ⊥ = Low-energy contributions. Notes: †Here, $\mathcal{L}_{13}$ or $\mathcal{L}_{14}$ does not contribute at $O(1/\Lambda^2)$. ‡At LHC(14), $W^+W^+ \to W^+W^+$ should also be included.)

Model Independent Description of New Physics

Calculate Coefficients of EWCL from Different Models

- **SM:** need to integrate out Higgs
- **One doublet technicolor model:** reproduce scale up result
- **One family technicolor model:** find difference with scale up result
- **Top color assisted technicolor model**
- **Little higgs models** . . . . . . Hard and tedious work !

Model Independent Description of New Physics

Investigating New Physics beyond EWCL

- **Model dependent research:** . . . . . .
- **Model independent research:** The first discovered particles may be $\mathbf{Z}', \mathbf{h}, \rho$
  - **Adding in EWCL a** Z'
  - **Adding in EWCL a Higgs :** either linearly or nonlinearly
  - **Adding in EWCL a vector boson :** Like QCD CL with ρ

Equivalence between Linear and Nonlinear Realizations of EWCL with Higgs

Adding in Higgs to EWCL: Two Types of Effective Theory

- **Linear Realization:** **SM + high dimension operators !**

$$\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix}\phi^+ \\ \phi^0\end{pmatrix} \qquad \mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_n \frac{f_n}{\Lambda_H^2}\mathcal{O}_n$$

- **Nonlinear Realization:** **electroweak chiral Lagrangian**

$$\Phi^c \equiv i\tau^2\Phi^* \quad \Sigma \equiv (\Phi^c,\Phi) \equiv \frac{h+v}{\sqrt{2}}U \quad U = e^{i\pi^i\tau^i}, \quad i = 1,2,3$$

They are equivalent or not ?

Equivalence between Linear and Nonlinear Realizations of EWCL with Higgs

Dimension Six Operators in Linear Realization

$$\mathcal{O}_{DW} = Tr([D_\mu, \hat{W}_{\nu\rho}][D^\mu, \hat{W}^{\nu\rho}]) \qquad \mathcal{O}_{DB} = -\frac{g'^2}{2}\partial_\mu B_{\nu\rho}\partial^\mu B^{\nu\rho}$$

$$\mathcal{O}_{BW} = \Phi^+\hat{B}_{\mu\nu}\hat{W}^{\mu\nu}\Phi \qquad \mathcal{O}_{\Phi,1} = \left[(D_\mu\Phi)^+\Phi\right]\left[\Phi^+D^\mu\Phi\right]$$

$$\mathcal{O}_{WWW} = Tr(\hat{W}_{\mu\nu}\hat{W}^{\nu\rho}\hat{W}_\rho^\mu) \qquad \mathcal{O}_{WW} = \Phi^+\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\Phi$$

$$\mathcal{O}_{BB} = \Phi^+\hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\Phi \qquad \mathcal{O}_W = (D_\mu\Phi)^+\hat{W}^{\mu\nu}(D_\nu\Phi)$$

$$\mathcal{O}_B = (D_\mu\Phi)^+\hat{B}^{\mu\nu}(D_\nu\Phi) \qquad \mathcal{O}_{\Phi,2} = \frac{1}{2}\partial_\mu(\Phi^+\Phi)\partial^\mu(\Phi^+\Phi)$$

$$\mathcal{O}_{\Phi,3} = \frac{1}{3}(\Phi^+\Phi)^3 \qquad \mathcal{O}_{\Phi,4} = (\Phi^+\Phi)\left[(D_\mu\Phi)^+(D^\mu\Phi)\right]$$

$$D_\mu = \partial_\mu + igT^aW_\mu^a + ig'YB_\mu \qquad \hat{W}_{\mu\nu} = igT^aW_{\mu\nu}^a \quad \hat{B}_{\mu\nu} = ig'B_{\mu\nu}$$

Equivalence between Linear and Nonlinear Realizations of EWCL with Higgs

O(p^4) Operators in Nonlinear Realization

$$l_4^1 \equiv B_{\mu\nu}Tr(TW^{\mu\nu}) \qquad l_4^2 \equiv B_{\mu\nu}Tr(T[V^\mu, V^\nu])$$

$$l_4^3 \equiv Tr(W_{\mu\nu}[V^\mu, V^\nu]) \qquad l_4^4 \equiv [Tr(V_\mu V_\nu)]^2$$

$$l_4^5 \equiv [Tr(V_\mu V^\mu)]^2 \qquad l_4^6 \equiv Tr(V_\mu V_\nu)Tr(TV^\mu)Tr(TV^\nu)$$

$$l_4^7 \equiv Tr(V_\mu V^\mu)Tr(TV_\nu)Tr(TV^\nu) \qquad l_4^8 \equiv [Tr(TW_{\mu\nu})]^2$$

$$l_4^9 \equiv Tr(TW_{\mu\nu})Tr(T[V^\mu, V^\nu]) \qquad l_4^{10} \equiv [Tr(TV_\mu)Tr(TV_\nu)]^2$$

$$l_4^{11} \equiv \epsilon_{\mu\nu\rho\lambda}Tr(TV^\mu)Tr(V^\nu W_{\rho\lambda}) \qquad l_4^{12} \equiv Tr(TV^\mu)Tr(V_\nu W^{\mu\nu})$$

$$l_4^{13} \equiv \epsilon_{\mu\nu\rho\lambda}B^{\mu\nu}Tr(TW^{\rho\lambda}) \qquad l_4^{14} \equiv \epsilon_{\mu\nu\rho\lambda}Tr(TW^{\mu\nu})Tr(TW^{\rho\lambda})$$

Equivalence between Linear and Nonlinear Realizations of EWCL with Higgs

Linear Realization ⇒ Nonlinear Realization

$$
\begin{aligned}
2(D_\mu\Phi)^+\Phi &= \partial_\mu h^2 + h^2 Tr(TV_\mu) \\
2\Phi^+ W_{\mu\nu}\Phi &= h^2 Tr(TW_{\mu\nu}) \\
2(D_\mu\Phi)^+(D_\nu\Phi) &= h^2[Tr(TV_\mu V_\nu) - Tr(V_\mu V_\nu)] + 2(\partial_\mu h)(\partial_\nu h) \\
2(D_\mu\Phi)^+ W^{\mu\nu}(D_\nu\Phi) &= h^2 Tr(W^{\mu\nu}V_\mu V_\nu) - (\partial_\mu h^2) Tr(W^{\mu\nu}V_\nu) \\
2\Phi^+ W^{\nu\rho}(D^\mu\Phi) &= h^2[Tr(TV^\mu W^{\nu\rho}) + Tr(V^\mu W^{\nu\rho})] \\
2(D^\mu\Phi)^+ W^{\nu\rho}\Phi &= h^2[Tr(TV^\mu W^{\nu\rho}) - Tr(V^\mu W^{\nu\rho})]
\end{aligned}
$$

Equivalence between Linear and Nonlinear Realizations of EWCL with Higgs

Nonlinear Realization ⇒ Linear Realization

$$Tr(TV_\mu) = (\Phi^+\Phi)^{-1}[2(D_\mu\Phi)^+\Phi - \partial_\mu(\Phi^+\Phi)]$$

$$Tr(TW_{\mu\nu}) = 2(\Phi^+\Phi)^{-1}[\Phi^+W_{\mu\nu}\Phi]$$

$$Tr(V_\mu V_\nu) = \frac{1}{2}(\Phi^+\Phi)^{-2}\partial_\mu(\Phi^+\Phi)\partial_\nu(\Phi^+\Phi) - (\Phi^\dagger\Phi)^{-1}[(D_\mu\Phi)^\dagger(D_\nu\Phi) + h.c.]$$

$$Tr(TV_\mu V_\nu) = (\Phi^+\Phi)^{-1}[(D_\mu\Phi)^+(D_\nu\Phi) - h.c.]$$

$$Tr(V^\mu W^{\nu\rho}) = (\Phi^+\Phi)^{-1}[-(D^\mu\Phi)^+W^{\nu\rho}\Phi + h.c.]$$

$$Tr(TV^\mu W^{\nu\rho}) = (\Phi^+\Phi)^{-1}[(D^\mu\Phi)^+W^{\nu\rho}\Phi + h.c.]$$

$$Tr(W^{\mu\nu}V_\mu V_\nu) = 2(\Phi^+\Phi)^{-1}[(D_\mu\Phi)^+W^{\mu\nu}(D_\nu\Phi)] + (\Phi^+\Phi)^{-2}\partial_\mu(\Phi^+\Phi)[-(D^\mu\Phi)^+W^{\nu\rho}\Phi + h.c.]$$

Equivalence between Linear and Nonlinear Realizations of EWCL with Higgs

- Mathematically linear and nonlinear representations are equivalent
- $m_h \propto$ higgs self coupling in linear representation
- Perturbation expansion converge $\Rightarrow$ light higgs
- Discussion of light higgs favors linear repersentation
- Heavy higgs can only be discussed in nonlinear representation
- Nonlinear representation can discuss light higgs in principle

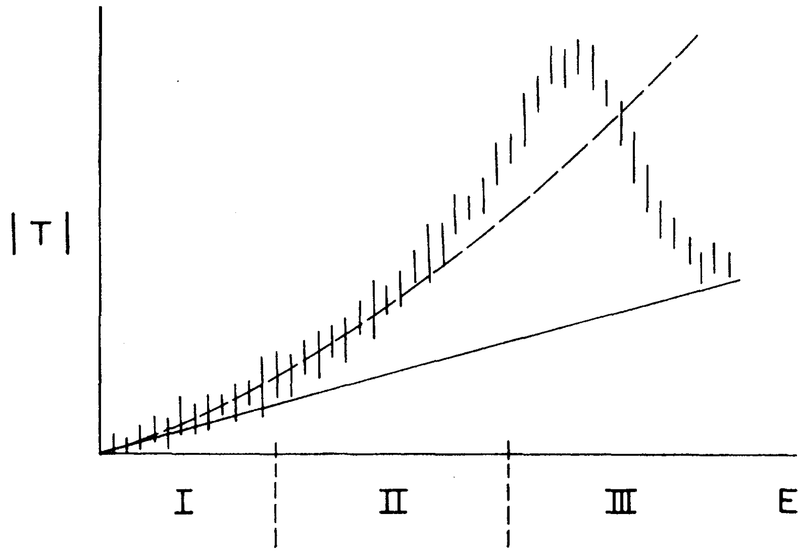
Extended EWCL and Integrating out Higgs

EEWCL: EWCL include in Higgs field

- Writing done most general EEWCL previous works only focus on special terms
- Integrating out Higgs field
- investigate its effects on EWCL coefficients

Problems

- Higgs dependence in EEWCL is rather arbitrary
- Higgs field cannot be exactly integrated out!
- Can we make estimations on Higgs Effects?



Extended EWCL and Integrating out Higgs

- Take low energy expansion
- VEV part of Higgs field is order of p^0
- Quantum fluctuation part of Higgs field h is at least order of p^2
- Only accurate to 1-loop precision
- Use dimensional regularization
- Apply equation of motion

Extended EWCL and Integrating out Higgs

All terms contribute to p^4 EWCL at 1-loop

$$\mathcal{L}^{(2)} = m^2[(f_1 - f_3\delta c)A_\mu^2 + (f_2 - f_4\delta c)Tr(V_\mu^2)]$$

$$\delta c = \frac{a}{32\pi^2}\left(\frac{1}{2-\frac{D}{2}} - \gamma + 1 + \ln\frac{4\pi\mu^2}{m^2}\right)$$

$$\mathcal{L}^{(4)} = -\frac{1}{2}m^2(1-a\delta c)h^2 + mh[(f_3-f_5\delta c)A_\mu^2 + (f_4-f_6\delta c)Tr(V_\mu^2)] + [g_0^i-(g_0^i)'\delta c]l_4^i$$

$$\mathcal{L}^{(6)} = \frac{1}{2}(\partial_\mu h)^2 - \frac{1}{6}amh^3 + \frac{1}{2}f_5h^2A_\mu^2 + \frac{1}{2}f_6h^2Tr(V_\mu^2)$$

$$\mathcal{L}^{(8)} = -\frac{1}{12}bh^4 + \frac{1}{6m}h^3[f_7A_\mu^2 + f_8Tr(V_\mu^2)] + \frac{1}{2}(g_0^i)''h^2l_4^i + \frac{1}{2m^2}g_2^k(\partial_\mu h)(\partial_\nu h)l_2^{\mu\nu}$$

$$\mathcal{L}^{(10)} = \frac{1}{2}(g_2^k)'m^{-3}(\partial_\mu h)(\partial_\nu h)hl_2^{k\mu\nu}$$

Extended EWCL and Integrating out Higgs

$$A_\mu = tr(TV_\mu)$$

$$l_2^{1\mu\nu} = Tr(TV^\mu)Tr(TV^\nu) \qquad l_2^{2\mu\nu} = Tr(V^\mu V^\nu)$$

$$l_3^{1\mu} = Tr(TV^\mu)Tr(V^\nu V_\nu) \qquad l_3^{2\mu} = Tr(TV^\nu)Tr(V^\mu V_\nu)$$

$$l_3^{3\mu} = Tr(TV^\nu)Tr(TV^\mu V_\nu) \qquad l_3^{4\mu} = Tr(TV_\nu)Tr(TW^{\mu\nu})$$

$$l_3^{5\mu} = B^{\mu\nu}Tr(TV_\nu) \qquad l_3^{6\mu} = Tr(TW^{\mu\nu}V_\nu)$$

$$l_3^{7\mu} = Tr(W^{\mu\nu}V_\nu)$$

Extended EWCL and Integrating out Higgs

Integrating out Higgs: **loop expansion**

$$\Gamma^{1loop} = \int d^4x\mathcal{L}_{EEWCL} + \frac{i}{2}\ln Det\hat{D}$$

$$\hat{D}(x,y) \equiv \frac{\delta^2 S}{\delta h(x)\delta h(y)} = -[\partial_x^2 + m^2 - A(x) + C_{\mu\nu}(x)\partial_x^\mu\partial_x^\nu]\delta(x-y)$$

$$A(x) = -amh(x) + f_5 A_\mu^2(x) + f_6 Tr[V_\mu^2(x)] - bh^2(x) + f_7 m^{-1}h(x)A_\mu^2(x) + f_8 m^{-1}h(x)Tr[V_\mu^2(x)] + m^{-2}(g_0^i)'' l_4^i(x)$$

$$C^{\mu\nu}(x) = g_2^k m^{-2} l_2^{k\mu\nu}(x) + (g_2^k)' m^{-3} h l_2^{k\mu\nu}(x)$$

Extended EWCL and Integrating out Higgs

Integrating out Higgs: loop expansion

$$\Gamma^{1loop} = \int d^4x \mathcal{L}_{EEWCL} + \frac{i}{2} \ln Det\hat{D} = \int d^4x [\mathcal{L}^{(2)} + \mathcal{L}^{(2)} + \cdots]$$

$$\mathcal{L}^{(2)} = m^2[\bar{f}_1 A_\mu^2 + \bar{f}_2 Tr(V_\mu^2)]$$

$$\mathcal{L}^{(4)} = -\frac{1}{2} m_h^2 h^2 + m[\bar{f}_3 h A_\mu^2 + \bar{f}_4 h Tr(V_\mu^2)] + \bar{g}_0^i l_4^i$$

Extended EWCL and Integrating out Higgs

$$L \equiv \frac{1}{2-\frac{D}{2}} - \gamma + \ln\frac{4\pi\mu^2}{m^2}$$

$$\bar{f}_1 = f_1 + \frac{1}{32\pi^2}\left[-\frac{(L+3/2)}{4}g_2^1 - (L+1)(f_5 + af_3)\right]$$

$$\bar{f}_2 = f_2 + \frac{1}{32\pi^2}\left[-\frac{(L+3/2)}{4}g_2^2 - (L+1)(f_6 + af_4)\right]$$

$$m_h^2 = m^2\left[1 - \frac{1}{16\pi^2}(L+1)(a^2+b) - \frac{a^2}{32\pi^2}\right]$$

$$\bar{f}_3 = f_3 + \frac{1}{32\pi^2}\left[-(L+1)f_7 - \frac{L+3/2}{4}(g_2^1)' - \frac{L+1}{2}ag_2^1 - (2L+1)af_5\right]$$

$$\bar{f}_4 = f_4 + \frac{1}{32\pi^2}\left[-(L+1)f_8 - \frac{L+3/2}{4}(g_2^2)' - \frac{L+1}{2}ag_2^2 - (2L+1)af_6\right]$$

Extended EWCL and Integrating out Higgs

$$\bar{g}_0^4 = g_0^4 + \frac{1}{32\pi^2}\Big[-(L+1)\left[(g_0^4)'' + a(g_0^4)'\right] + \frac{L+3/2}{8}(g_2^2)^2\Big]$$

$$\bar{g}_0^6 = g_0^6 + \frac{1}{32\pi^2}\Big[-(L+1)\left[(g_0^6)'' + a(g_0^6)'\right] + \frac{L+3/2}{4}g_2^1 g_2^2\Big]$$

$$\bar{g}_0^5 = g_0^5 + \frac{1}{32\pi^2}\Big[-(L+1)\left[(g_0^5)'' + a(g_0^5)'\right] + \frac{L}{2}(f_6)^2 + \frac{L+1}{2}f_6 g_2^2 + \frac{L+3/2}{16}(g_2^2)^2\Big]$$

$$\bar{g}_0^7 = g_0^7 + \frac{1}{32\pi^2}\Big[-(L+1)\left[(g_0^7)'' + a(g_0^7)'\right] + L f_5 f_6 + \frac{L+1}{2}(f_5 g_2^2 + f_6 g_2^1) + \frac{L+3/2}{8}g_2^1 g_2^2\Big]$$

$$\bar{g}_0^{10} = g_0^{10} + \frac{1}{32\pi^2}\Big[-(L+1)\left[(g_0^{10})'' + a(g_0^{10})'\right] + \frac{L}{2}(f_5)^2 + \frac{L+1}{2}f_5 g_2^1 + \frac{3(L+3/2)}{16}(g_2^1)^2\Big]$$

$$\bar{g}_0^i = g_0^i + \frac{1}{32\pi^2}\Big[-(L+1)\left[(g_0^i)'' + a(g_0^i)'\right]\Big] \qquad i = 1,2,3,8,9,11,12,13,14$$

Extended EWCL and Integrating out Higgs

$$h_c = \frac{m}{m_h^2}[\bar{f}_3 Tr(TV_\mu)Tr(TV^\mu) + \bar{f}_4 Tr(V_\mu V^\mu)]$$

$$\mathcal{L}_{EWCL} = m^2 \left[\bar{f}_1 Tr(TV_\mu)Tr(TV^\mu) + \bar{f}_2 Tr(V_\mu^2)\right] + (g_0^i + \Delta g_0^i) l_4^i$$

$$\Delta g_0^5 = \frac{m^2}{2m_h^2}(\bar{f}_4)^2 + \delta g_0^5 \qquad \Delta g_0^7 = \frac{m^2}{m_h^2}\bar{f}_3\bar{f}_4 + \delta g_0^7 \qquad \Delta g_0^{10} = \frac{m^2}{2m_h^2}(\bar{f}_3)^2 + \delta g_0^{10}$$

$$\Delta g_0^j = \delta g_0^j \qquad j \neq 5, 7, 10$$

$$\delta f_i = \bar{f}_i - f_i \qquad \delta g_0^i = \bar{g}_0^i - g_0^i \qquad \delta m^2 = m_h^2 - m^2$$

Effects of Higgs in EWCL

$$\mathcal{L}_{EWCL} = m^2\left[\bar{f}_1 Tr(TV_\mu)Tr(TV^\mu) + \bar{f}_2 Tr(V_\mu^2)\right] + (g_0^i + \Delta g_0^i) l_4^i$$

$$\Delta g_0^5 = \frac{m^2}{2m_h^2}(\bar{f}_4)^2 + \delta g_0^5 \quad \Delta g_0^7 = \frac{m^2}{m_h^2}\bar{f}_3\bar{f}_4 + \delta g_0^7 \quad \Delta g_0^{10} = \frac{m^2}{2m_h^2}(\bar{f}_3)^2 + \delta g_0^{10}$$

Effects of Higgs

♣ **From loop** ♠ **From equation of motion for Higgs**

Assumption

higgs will be the next new particle we find in future experiment!

$\Rightarrow$ **Some of f_l and g_0^i may be small**

Effects of Higgs in EWCL

Higgs decay and four-gauge-boson coupling

$$\Gamma_{h\to ZZ}=\frac{(2\bar{f}_3+\bar{f}_4)^2e^4m_h}{32s^4c^4}(1-\frac{4m_Z^2}{m_h^2})^{\frac{1}{2}}\qquad \Gamma_{h\to WW}=\frac{(\bar{f}_4)^2e^4m_h}{32s^4}(1-\frac{4m_W^2}{m_h^2})^{\frac{1}{2}}$$

$$\begin{aligned}\mathcal{L}_{EWCL}\Big|_{5,7,10}=&\frac{32s^4}{e^4m_h}\bigg[(1-\frac{4m_W^2}{m_h^2})^{-\frac{1}{2}}\Gamma_{h\to WW}-2c^4(1-\frac{4m_Z^2}{m_h^2})^{-\frac{1}{2}}\Gamma_{h\to ZZ}\\&+c^8(1-\frac{4m_W^2}{m_h^2})^{\frac{1}{2}}(1-\frac{4m_Z^2}{m_h^2})^{-1}\frac{(\Gamma_{h\to ZZ})^2}{\Gamma_{h\to WW}}\bigg][Tr(TV_\mu)Tr(TV_\nu)]^2\\&+\frac{16s^4}{e^4m_h}\bigg[c^4(1-\frac{4m_Z^2}{m_h^2})^{-\frac{1}{2}}\Gamma_{h\to ZZ}-(1-\frac{4m_W^2}{m_h^2})^{-\frac{1}{2}}\Gamma_{h\to WW}\bigg]Tr(V_\mu V^\mu)[Tr(TV_\nu)]^2\\&+\frac{4s^4}{e^4m_h}(1-\frac{4m_W^2}{m_h^2})^{-\frac{1}{2}}\Gamma_{h\to WW}[Tr(V_\mu V^\mu)]^2\end{aligned}$$

Dominate if we ignore g_0^i and δg_0^i

Effects of Higgs in EWCL

higgs mass dependence

$$\frac{d\bar{f}_1}{dm^2}=\frac{1}{32\pi^2}\frac{1}{m^2}\left[\frac{1}{4}g_2^1+f_5+af_3\right]\qquad\frac{d\bar{f}_2}{dm^2}=\frac{1}{32\pi^2}\frac{1}{m^2}\left[\frac{1}{4}g_2^2+f_6+af_4\right]$$

$$-\beta_1=\bar{f}_1/\bar{f}_2\quad\Rightarrow\quad m^2\frac{d\alpha T}{dm^2}=2\frac{d\beta_1}{dm^2}\approx\frac{1}{16\pi^2}\frac{1}{\bar{f}_2}[f_5+\beta_1 f_6]$$

$$m^2\frac{d\bar{g}_0^1}{dm^2}=\frac{1}{32\pi^2}[(g_0^1)''+a(g_0^1)']$$

$$\frac{1}{2}gg'\alpha_1=\bar{g}_0^1\quad\Rightarrow\quad m^2\frac{d(gg'S)}{dm^2}=-16\pi\frac{dgg'\alpha_1}{dm^2}=-\frac{1}{\pi}[(g_0^1)''+a(g_0^1)']$$

Effects of Higgs in EWCL

higgs mass dependence

C	$16\pi^2\frac{dC}{d\ln m}\|_{p^6}$	$16\pi^2\frac{dC}{d\ln m}\|_{p^8}$	$16\pi^2\frac{dC}{d\ln m}\|_{p^{10}}$	$16\pi^2\frac{dC}{d\ln m}\|_{p^{12}}$
$\bar{f}_1$	f_5	$\frac{g_2^1}{4}$	af_3	
$\bar{f}_2$	f_6	$\frac{g_2^2}{4}$	af_4	
$\bar{f}_3$		f_7	$\frac{(g_2^1)'}{4}$	$2af_5$
$\bar{f}_4$		f_8	$\frac{(g_2^2)'}{4}$	$2af_6$
$\tilde{g}_0^4$		$(g_0^4)''$		$a(g_0^4)'$
$\tilde{g}_0^6$		$(g_0^6)''$		$a(g_0^4)'$
$\tilde{g}_0^5$		$(g_0^5)''$		$f_4f_8+a(g_0^5)'-\frac{(f_6)^2}{2}$
$\tilde{g}_0^7$		$(g_0^7)''$		$f_3f_7+f_4f_8+a(g_0^7)'+f_5f_6$
$\tilde{g}_0^{10}$		$(g_0^{10})''$		$f_3f_7+a(g_0^{10})'-\frac{(f_5)^2}{2}$
$\tilde{g}_0^i$		$(g_0^i)''$		$a(g_0^i)'$

Summary

- R&E of Theory and exp all asked for M Ind investigation for Higgs
- Before higgs is discovered, EWCL is a good tool to do research
- We have calculated effects from comprehensive higgs 1-loop
- Wait for exp data and more detail phenomenology analysis
- Also need to estimate effects of other new physics particles

Thanks!