New Physics Beyond the Standard Model

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I. INTRODUCTION

1. The EWSB sector of the SM

Although the SM has passed a lot of precision experiemntal tests, Its *electroweak symmetry breaking* (EWSB) sector is still *not clear*. The SM introduces a Higgs doublet to implement EWSB. So far, H is not found. The LEP bound is

$$m_H > 114.3 \text{ GeV}.$$

Precision data + SM $\Longrightarrow$ $m_H < 196$ GeV (95% CL).

Furthermore, elementary Higgs field theory suffers from theoretical problems:

i Triviality:

RGE$\Longrightarrow$renormalized running coupling constant $\lambda(Q^2)$ [Λ_r: regularization UV cutoff ($\Lambda_r \to \infty$)].

$$\lambda(Q^2) = \frac{\lambda(\Lambda_r)}{1 - \frac{3}{2\pi^2}\lambda(\Lambda_r)\ln\frac{Q^2}{\Lambda_r^2}}$$

$$\Downarrow$$

$$\lambda(Q^2) \xrightarrow{\Lambda_r \to \infty} 0, \quad \text{at any scale } Q^2 \quad (\textit{triviality}),$$

Nonperturbative lattice calculation$\Longrightarrow$ same conclusion.

Usual point of view: *SM is a low energy effective theory below a certain new physics scale* $\Lambda \not\to \infty$ of a *more fundamental theory of new physics.*

ii Unnatrualness:

Consider M_W^2 (EWSB scale) in the SM below Λ (e.g. $\Lambda = \Lambda_{GUT}$).

$WW\phi\phi$ interaction$\Longrightarrow$ $\delta M_W^2 = O\left(\frac{\alpha}{\pi}\right)A\Lambda^2$, $[A \sim O(1)]$.

$$M_W^2 = M_{0W}^2 + \delta M_W^2 \sim 10^2\ \mathrm{GeV} \ll \Lambda^2 \Longrightarrow M_{0W}^2 = O\Big(\frac{\alpha}{\pi}\Big) B\Lambda^2,\ [B \sim O(1)].$$

$$A + B \approx \frac{\pi}{\alpha}\frac{M_W^2}{\Lambda^2} \approx \frac{10^6}{10^{32}} \Longrightarrow A,\ B \text{ fine tuned to 26 digits.}$$

This is very *unnatural* in physics. In GUT, this causes the so-called *hierarchy* prblem.

iii, Too Many Free Parameters

The SM contains 19 (26) free parameters, and at least 10 (13) of which are from the EWSB sector.

New physics beyond the SM is required to solve the above problems.

Actually, the fit of the SM to the precision data is not so perfect, e.g. there is a 3σ *deviation in* A_{FB}^b. So that *there is room for new physics.* New physics effect cannot be so significant at present energies, so that *future high energy colliders are needed to probe the new physics.*

II. Supersymmetry

- The way of keeping elementary Higgs and avoiding *unnaturalness* is to introduce *supersymmetry* (SUSY) in which $\delta M_W^2 = A\Lambda^2$ is canceled by the contribution of the SUSY partner.
- SUSY relates the coupling of $|\phi|^4$ to the gauge coupling g, so that *triviality* of $|\phi|^4$ coupling is avoided.
- SUSY GUT is possible, and the running coefficient of $|\phi|^2$ can be driven to negative at the scale of M_Z from the RGE$\Longrightarrow$*radiative* EWSB.
- SUSY appears in superstring.

- Weakly interacting EWSB mechnism (perturbative calculable).

- *SUSY breaking mechnism* is *even more unclear*, and there are *even more free parqameters* in SUSY models than in the SM !

1, Particles in the MSSM

- *Anomaly free* and SUSY $\Longrightarrow$ two Higgs doublets, H_1 and H_2.

- MSSM contains the following superfields:

	gauge field			leptons		quarks			Higgs	
superfield	$\hat{G}$	$\hat{V}^a$	$\hat{V}'$	$\hat{L}$	$\hat{E}$	$\hat{Q}$	$\hat{U}$	$\hat{D}$	$\hat{H}_1$	$\hat{H}_2$
bosonic	g	W^a	B	$\tilde{L}^j = \begin{pmatrix} \tilde{\nu} \\ \tilde{e}^- \end{pmatrix}_L$	$\tilde{E} = \tilde{e}^+_R$	$\tilde{Q}^j = \begin{pmatrix} \tilde{u}_L \\ \tilde{d}_L \end{pmatrix}$	$\tilde{U} = \tilde{u}^*_R$	$\tilde{D} = \tilde{d}^*_R$	$\tilde{H}^i_1$	$\tilde{H}^i_2$
fermionic	$\tilde{g}$	$\tilde{W}^a$	$\tilde{B}$	$\begin{pmatrix} \nu \\ e^- \end{pmatrix}_L$	e^c_L	$\begin{pmatrix} u \\ d \end{pmatrix}_L$	u^c_L	d^c_L	$\begin{pmatrix} \tilde{H}^0_1 \\ \tilde{H}^-_1 \end{pmatrix}_L$	$\begin{pmatrix} \tilde{H}^+_2 \\ \tilde{H}^0_2 \end{pmatrix}_L$

- To have B and L conservation, R-parity $[R = (-1)^{2s+3B+L}]$ is usually imposed.

Ordinary particles: $R = 1$ SUSY particles: $R = -1$.

2, Soft SUSY Breaking

- All sparticles are not seen yet$\Longrightarrow$SUSY should be broken.

- It is very difficult (perhaps impossible) to construct spontaneous SUSY breaking models within the content of the MSSM.

$$DSB\ sector\ (hidden\ sector) \longrightarrow messenger\ sector \longrightarrow MSSM\ sector.$$

- Broken SUSY$\Longrightarrow$ $\delta M_W^2 = O\left(\frac{\alpha}{\pi}\right)|m_B^2 - m_F^2| \ln \frac{\Lambda^2}{(m_B, m_F)^2}$ $\Longrightarrow$$m_{spart.} \lesssim O(1\ \mathrm{TeV})$ to solve *unnaturalness* problem.

- Avoiding extra quadratic divergence$\Longrightarrow$ *soft SUSY breaking.*

  General soft-SUSY-breaking terms (R-parity concerving):

$$
\begin{aligned}
V_{\text{soft}} &= m_1^2|H_1|^2 + m_2^2|H_2|^2 - m_{12}^2(\epsilon_{ij}H_1^iH_2^j + h.c.) \\
&+(M_{\tilde{Q}}^2)_{mn}\tilde{Q}_m^{i*}\tilde{Q}_n^i + (M_{\tilde{U}}^2)_{mn}\tilde{U}_m^*\tilde{U}_n + (M_{\tilde{D}}^2)_{mn}\tilde{D}_m^*\tilde{D}_n + (M_{\tilde{L}}^2)_{mn}\tilde{L}_m^{i*}\tilde{L}_n^i + (M_{\tilde{E}}^2)_{mn}\tilde{E}_m^*\tilde{E}_n \\
&+\epsilon_{ij}[(h_LA_L)_{mn}\tilde{H}_1^i\tilde{L}_m^j\tilde{E}_n + (h_DA_D)_{mn}\tilde{H}_1^i\tilde{Q}_m^j\tilde{D}_n - (h_UA_U)_{mn}\tilde{H}_2^i\tilde{Q}_m^j\tilde{U}_n + h.c.] \\
&+\frac{1}{2}[M_3\tilde{g}\tilde{g} + M_2\tilde{W}^a\tilde{W}^a + M_1\tilde{B}\tilde{B} + h.c.].
\end{aligned}
$$

The coefficients are complex matrices. *Total number of free parameters* in the MSSM is 124 (19 *SM parameters* and 105 *additional new parameters*).

- To reduce the number of free parameters$\Longrightarrow$ certain SUSY breaking models:

i, Gravity-mediated SUSY breaking.

messemger=gravitation.

In *minimal* supergravity (mSUGRA) framework, the constrained MSSM (CMSSM):

At M_P,

$$
\begin{aligned}
&M_{\tilde{Q}}^2(M_P) = M_{\tilde{U}}^2(M_P) = M_{\tilde{D}}^2(M_P) = M_{\tilde{L}}^2(M_P) = M_{\tilde{E}}^2(M_P) = m_0^2\ \mathbf{1}\,, \\
&m_1^2(M_P) = m_2^2(M_P) = m_0^2\,, \\
&A_U(M_P) = A_D(M_P) = A_L(M_P) = A_0\ \mathbf{1},
\end{aligned}
$$

and at GUT scale M_X,

$$
\begin{aligned}
&\sqrt{5/3}\ g_1(M_X) = g_2(M_X) = g_3(M_X) = g_U\,, \\
&M_1(M_X) = M_2(M_X) = M_3(M_X) = m_{1/2}.
\end{aligned}
$$

5 *new parameters* in addition to the SM parameters:

$$
m_0,\ m_{1/2},\ A_0,\ \tan\beta \equiv \frac{v_2}{v_1},\ sgn(\mu).
$$

For obtaining *radiative* EWSB,

$$1 \lesssim \tan\beta \lesssim \frac{m_t}{m_b}.$$

ii, Gauge-mediated SUSY-breaking

messenger=gauge-fields with $SU(3)_c \times SU(2) \times U(1)$ quantum numbers.

The *minimal* gauge-mediated SUSY-breaking (mGMSB) model contains an effective mass scale Λ [$\Lambda \sim 100$ TeV for obtaining $m_{spart.} \lesssim O(1\ \mathrm{TeV})$] and an averaged messenger mass scale M ($\Lambda < M < 10^{16}$ GeV). 4 *new parameters* in addition to the SM parameters:

$$\Lambda,\ M,\ \tan\beta \equiv \frac{v_2}{v_1},\ sgn(\mu).$$

Different approaches leads to different SUSY particle spectra. Particles with the same $SU(3) \times U(1)_{em}$ quantum numbers may mix to form mass eigen-states. For example,

charginos $\tilde{\chi}_j^{\pm}$, $(j = 1, 2)$ are linear combinations of $\tilde{W}^{\pm}$ and $\tilde{H}^{\pm}$,

neutralinos $\tilde{\chi}_k^0$ $(k = 1, \cdots, 4)$ are linear combinations of $\tilde{W}^0$, $\tilde{B}$, $\tilde{H}_1^0$ and $\tilde{H}_2^0$.

Cosmology$\Longrightarrow$LSP: *neutral* and *colorless.*

CMSSM: LSP is χ_1^0, mGMSB: LSP is $\tilde{G}$.

3. Constraints on MSSM Parameters

- LEP and Tevatron experiments give severe constraints on the mSUGRA parameter space [B. Clerbaux (LEPSUSY WG, 13/06/2002)].

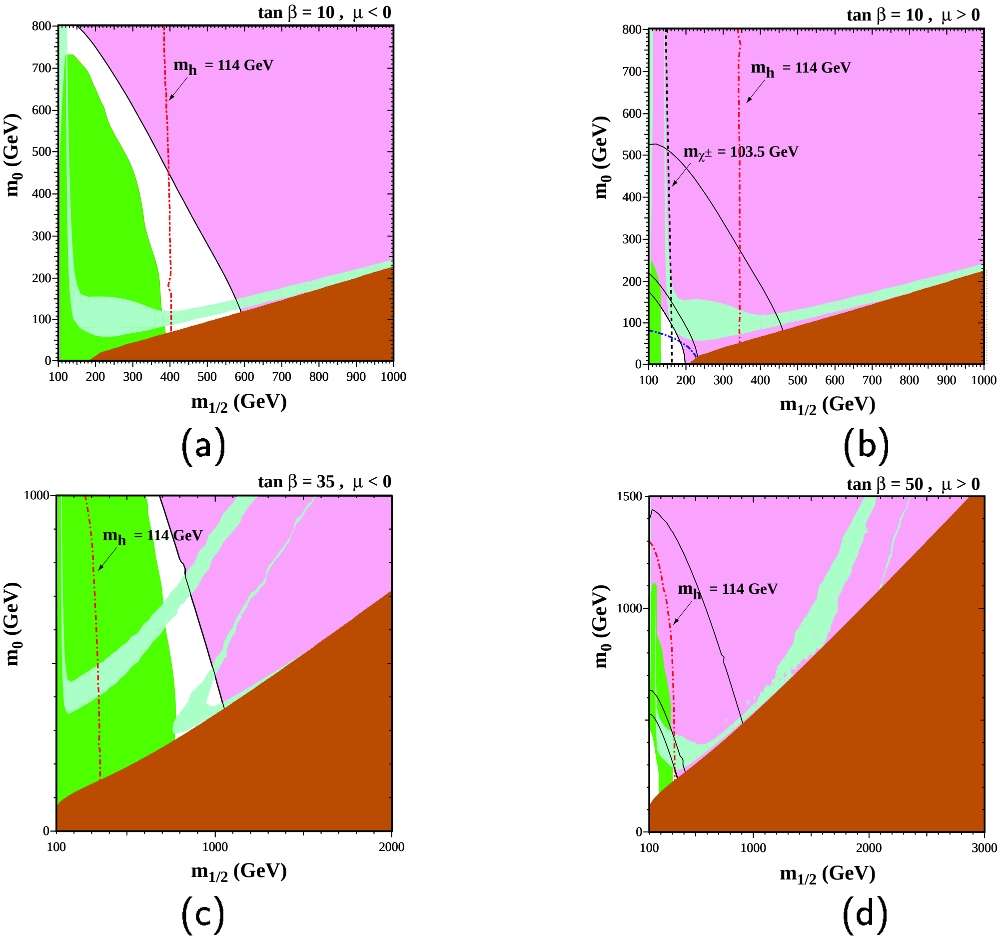


Fig. 1. Compilations of phenomenological constraints on the CMSSM for (a) $\tan\beta = 10$, $\mu < 0$, (b) $\tan\beta = 10$, $\mu > 0$, (c) $\tan\beta = 35$, $\mu < 0$, (d) $\tan\beta = 50$, $\mu > 0$, assuming $A_0 = 0$, $m_t = 175$ GeV and $m_b = 4.25$ GeV. The lower right dark (brick red) shaded regions are excluded since the LSP in it is the charged $\tilde{\tau}_1$. The left medium (dark green) shaded regions are excluded by $b \to s\gamma$. The upper right (pink) shaded regions are excluded by the $\pm 2\sigma$ ranges of $g_\mu - 2$. The light (turquoise) shaded regions are the cosmologivally prefered regions with $0.1 \lesssim \Omega_\chi h^2 \lesssim 0.3$. (quoted from [J. Eliss, K.A. Olive and Y. Santoso, New J. Phys. **4** (2002) 32]).

LEP:

$m_{\chi^\pm} - m_{\chi_1^0} > 5$ GeV : $m_{\chi^\pm} > 103.5$ GeV,

$m_{\chi^\pm} - m_{\chi_1^0} < 5$ GeV :

$m_{\chi^\pm} > 92.4$ GeV (Higgsino – like), $m_{\chi^\pm} < 91.9$ GeV (Gaugino – like),

$m_{\chi_1^0} > 59$ GeV, for $\tan\beta > 10$,

$m_{\tilde{e}_R} > 99.6$ GeV, $m_{\tilde{\mu}_R} > 94.9$ GeV, $m_{\tilde{\tau}_R} > 85.9$ GeV, for $\mathrm{m}_{\chi^0} = 0$,

$m_{\tilde{q}} > 100$ GeV.

Tevatron: degenerate $m_{\tilde{q}} = m_{\tilde{g}}$

CDF: $m_{\tilde{q}} > 300$ GeV, D0: $m_{\tilde{q}} > 200$ GeV.

- CLEO $b \to s\gamma$ data gives strong constraint on $\mu < 0$; weak constraint on $\mu > 0$

4. SUSY Higgs Bosons

- The 2 Higgs doublets H_1 and H_2 in MSSM contain 8 real components:

  3 Goldstone bosons "eaten" by $W^\pm$ and Z^0,

  5 physical Higgs bosons:

  CP-even: h^0, H^0, CP-odd: A^0, charged: $H^\pm$.

- When $m_{A^0} \gg 150$ GeV, m_{A^0}, m_{H^0}, $m_{H^\pm}$ nearly *degenerate* and $m_{h^0} \to m_{h^0}^{max}(\tan\beta)$ – *decoupling limit.*

- LEP bounds [U. Schwickerath, hep-ph/0205126]:

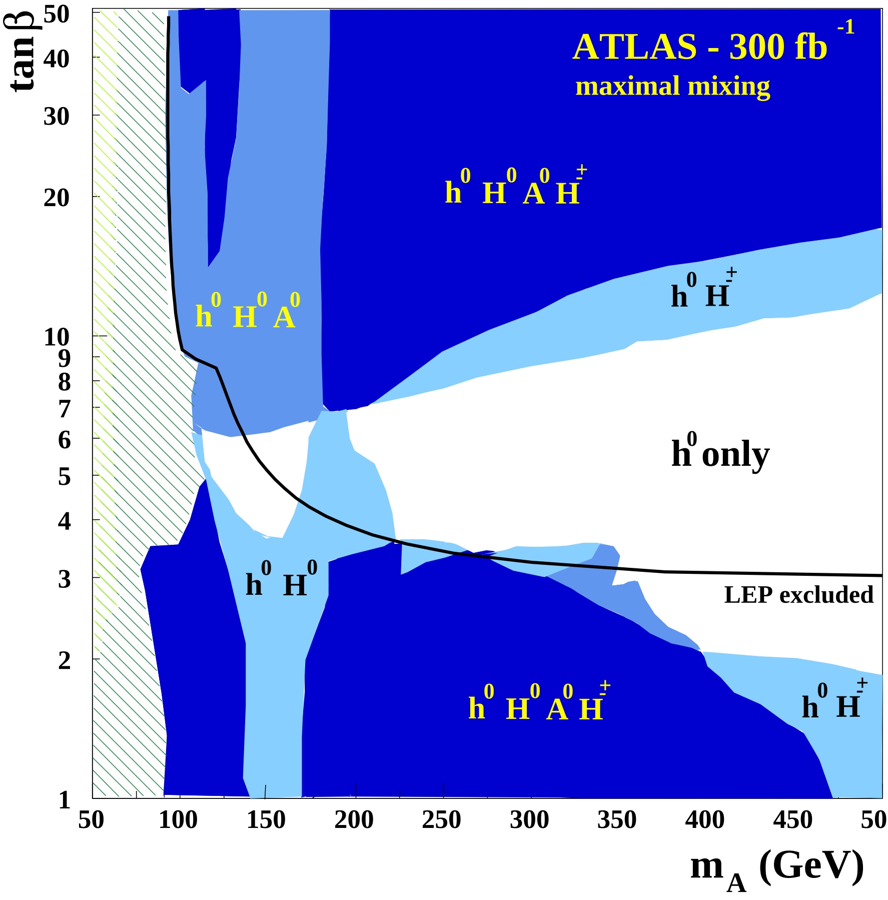
$$m_{h^0}(m_{H^0}) > 91.0 \text{ GeV}, \qquad m_{A^0} > 91.9 \text{ GeV}, \qquad m_{H^\pm} > 78.6 \text{ GeV}.$$

- Theoretically, up to 2-loop corrections,

$$m_{h^0}^{max} \simeq 135 \text{ GeV}.$$

Within the searching ability of Tevatron, LHC, LC.

- LHC coverage of the MSSM Higgs Bosons:



- At LC, MSSM can be searched for via

$e^+e^- \to Z + h^0/H^0$ (Higss-strahlung), $e^+e^- \to \nu_e\bar{\nu}_e + h^0/H^0$ (WW fusion), $e^+e^- \to A^0 + h^0/H^0$ (associated production), $e^+e^- \to H^+H^-$ (pair production), or $t \to b + H^+$ (if $m_{H^+} < m_t - m_b$).

$\gamma\gamma$ collider is *the best for detecting MSSM Higgs bosons.*

- If *no Higgs boson is found below 135 GeV*, MSSM will be *in trouble.* Simplest non-minimal SUSY SM (adding a Higgs singlet) will lead to $m_{h^0} \lesssim 200$ GeV.

5. SUSY particle Searches

- Searching for *sparticles* is crucial for testing SUSY. Signals in different models may be different.

- R-parity conserving,

$$p/e^+ + p(\bar{p})/e^- \rightarrow \quad sparticle \ (\text{R=-1}) \quad + \quad sparticle \ (\text{R=-1}),$$

$$sparticle \rightarrow sparticle' \ + \ particle \rightarrow \cdots \rightarrow \text{LSP} \ (\not{E}) \ + \ leptons/jets$$

If NLSP is charged (detectable) and long-lived ($m_{\text{NLSP}} \gtrsim m_{\text{LSP}}$),

$$sparticle \rightarrow sparticle' \ + \ particle \rightarrow \cdots \rightarrow \text{NLSP} + \ leptons/jets.$$

- R-parity violating:

LSP is no longer $\not{E}$, and can decay into *leptons and/or jets*. There may be lepton number violating processes. Squark may behave as *leptoquark* ($e^+\bar{u} \rightarrow \tilde{\bar{d}}$).

- LHC can only detect $\not{E}_T$ ($\sqrt{\hat{s}}$ not definite). LHC is good for the search for *colored* sparticles, e.g., it can search for $\tilde{q}(\tilde{g})$ up to $m_{\tilde{q}(\tilde{g})} \lesssim 3.6$ TeV.

- LC is good for the search for *colorless* sparticles and for precision measurement up to $m_{sparticle} \lesssim 1$ TeV. TESLA can reach the precision:

$\delta m_{\tilde{\chi}^{\pm,0}} = 0.1 - 1$ GeV, $\quad \delta m_{\tilde{l},\tilde{\nu}} = 0.05 - 0.3$ GeV,

$\delta m_{\tilde{\tau},\tilde{\nu}_\tau} = 0.6$ GeV, $\quad \delta m_{\tilde{t},\tilde{b}} = 1$ GeV.

Precision $m_{sparticle}$ can serve as initial conditions for RGE to obtain running sparticle masses at M_X and M_P to test SUSY breaking models.

- If no sparticle is found below 1 TeV, SUSY will be *irrelevant to the solution of unnaturalness problem*, and other solution is needed.

III. Strongly Interaction EWSB Mechanism

- The way of completely avoiding *triviality* and *unnaturalness* is to abandon elementary Higgs field and introduce new *strong non-Abelian gauge interaction*$\Longrightarrow$ $\langle\bar{\psi}\psi\rangle \neq 0$ to break the EW symmetry, just like quark condensate breaks chiral symmetry in QCD.
- Simpest example is the original QCD-like *technicolor* (TC) model. But it is ruled out by LEP experiments. Two improved models are in order:

i. Topcolor-Assisted Technicolor Model (TC2)

- This model combines the *technicolor* and *topcolor* ideas. Assume that above $\Lambda \sim 1$ TeV, the gauge interactions are

$$\begin{array}{ccccc} \underline{SU(3)_1 \times SU(3)_2} & \times & \underline{U(1)_1 \times U(1)_2} & \times & SU(2)_L \\ \Downarrow \text{TC (at } \Lambda) & & \Downarrow \text{TC (at } \Lambda) & & \\ SU(3)_c & \times & U(1)_Y & \times & SU(2)_L \end{array}$$

- $SU(3)_2 \times U(1)_2$ for first two families. *Topcolor* $SU(3)_1 \times U(1)_1$ (much stronger) for 3rd family. Adjust the two couplings to form $\langle\bar{t}t\rangle \neq 0$ but $\langle\bar{b}b\rangle = 0$.
- TC $\Longrightarrow$EWSB and common quark masses of order GeV.
- Topcolor$\Longrightarrow$ $\langle t\bar{t}\rangle$ $\Longrightarrow$constituent top quark mass $\Longrightarrow$ $m_t = 175$ GeV.
- This model can be consistent with LEP data.
- Construction of TC2 model including generating CKM matrix is in progress.

- Different models contain different *pseudo Goldstone bosons* (PGBs) coupling strongly to t-quark, and can be tested via t-quark productions at LHC and photon colliders at LC. *Different models can be distinguished.*

ii. Top Quark Seesaw Theory

[R.S. Chivukula, B.A. Dobrescu, H. Georgi, and C.T. Hill, Phys. Rev. D **59** (1999) 075003]

- Gauge group in this theory is:

$$G \times SU(3)_1 \times SU(3)_2 \times SU(2)_W \times U(1)_Y \overset{G \text{ at } \Lambda}{\Longrightarrow} SU(3)_c \times U(1)_Y .$$

Topcolor is in charge of both EWSB and giving large m_t.

- Instead of techniquarks, the theory introduces certain $SU(2)_W$-singlet fermions, $\chi, \cdots$. Simplest model:

$$\psi_L = (t_L,\ b_L):\ (\mathbf{3},\ \mathbf{1},\ \mathbf{2},\ +1/3),$$

$$\chi_R:\ (\mathbf{3},\ \mathbf{1},\ \mathbf{1},,\ +4/3)\,, \quad t_R,\ \chi_L:\ (\mathbf{1},\ \mathbf{3},\ \mathbf{1},\ +4/3)$$

$$\Downarrow \text{topcolor}$$

$$\text{composite scalar } \varphi = \begin{pmatrix} \overline{\chi_R}\, t_L \\ \overline{\chi_R}\, b_L \end{pmatrix}$$

behaving like a Higgs doublet whose VEV breaks EW symmetry.

- VEV of φ causes a dynamical mass $m_{t\chi} \sim$ 700 GeV, and the dynamics causes mass terms $-\mu_{\chi\chi}\overline{\chi_L}\chi_R - \mu_{\chi t}\overline{\chi_L}t_R + h.c.$ in the $\chi - t$ sector. Then the mass matrix of the heavy charge $2/3$ quarks is

$$(\overline{t_L}\ \ \overline{\chi_L})\begin{pmatrix} 0 & m_{t\chi} \\ \mu_{\chi t} & \mu_{\chi\chi} \end{pmatrix}\begin{pmatrix} t_R \\ \chi_R \end{pmatrix}.$$

Diagonalization (for $\mu_{\chi\chi} \gg m_{t\chi}$) $\Longrightarrow$ $\mathbf{m}_\mathrm{t} \approx \mathbf{m}_{\mathrm{t}\chi}\frac{\mu_{\chi t}}{\mu_{\chi\chi}}$ (*seesaw mechanism*). Desired top quark mass can be obtained for appropriate dynamical value of $\mu_{\chi t}/\mu_{\chi\chi}$.

- The simple model can be extended to include the generation of m_b by introducing an additional $SU(2)_W$-singlet fermion ω with

$$\omega_R:\ (\mathbf{3},\ \mathbf{1},\ \mathbf{1},\ -2/3), \qquad b_R, \omega_L:\ (\mathbf{1},\ \mathbf{3},\ \mathbf{1},\ -2/3).$$

This model is *anomaly free.*

- Advantages of this model:

(a) The known t-quark is responsible for EWSB.

$(t_L,\ b_L) \Longrightarrow SU(2)_W$-doublet nature of φ.

(b) $SU(2)_W$-singlet χ, ω $\Longrightarrow$no large custodial $SU(2)$ breaking.

(c) Only $\langle \bar{t}t\rangle \neq 0 \Longrightarrow$ no large contribution to S parameter.

(d) Desired m_t can be obtained from the seesaw mechanism.

- Realistic models consistent with precision EW data [H.-J. He and C.T. Hill, Phys. Rev. D **65** (2002) 055006]:

m_χ, m_ω: few TeV $\lesssim m_\chi, m_\omega \lesssim 30$ TeV.

Two composite Higgs doublets with five observable Higgs bosons: h^0 , H^0, A^0, $H^\pm$. Masses:

$m_{h^0} \sim 1$ TeV, $\quad m_{H^0}, m_{H^\pm} \sim$ few TeV.

$m_{A^0} \propto \Lambda$ (for 1 TeV $\lesssim \Lambda \lesssim 10$ TeV, 10^2 TeV $\lesssim m_{A^0} \lesssim 10^3$ TeV).

These heavy Higgs effects can be tested via $V_L V_L$ scatterings ($V_L:\ W_L^\pm, Z_L^0$) at LHC and LC.

For 1 TeV $\lesssim \Lambda \lesssim 10$ TeV, effective $ht\bar{t}$ and $Wt\bar{b}$ couplings are smaller than the SM values. Can be tested in future precision expereiments at the LC.

IV. Other New physics

1. Large Extra Dimensions

- Recent investigation [I. Antoniadis, N. Arkani-Hammed, S. Dimopoulos, and G dvali, Phys. Lett. **B 429** (1998) 263; L. Randall and R Sundrum, Phys. Rev. Lett. **83** (1999)3370]:

some extra dimensions can be large

$$\Downarrow$$

Unification with gravity at TeV scale (*no hierarchy problem and triviality*).

- An interesting application [H.C. Cheng, B.A.Dobrescu, and C.T. Hill, Nucl. Phys. **B 589** (2000) 249]:

$(4+\delta)$-dim. SM (no Higgs)$\Longrightarrow$top quark seesaw model, $\quad \delta \geq 3$

$\star$ t_R lives in $4+1$ dim. Kaluza-Klein (KK) modes$-SU(2)_W$-singlet quarks

$\star$ gluons live in $4+\delta$ dim. KK modes$-SU(3)_1$ colorons

$\star$ $1/\sqrt{n_{KK}}$ suppresses m_t (seesaw not needed).

- (De)Constructing Dimensions [N. Arkani-Hammed, A. Cohen, and H. Georgi, Phys. Rev. Lett. **86** (2001) 4757]:

4-dim.$\mathbf{G}^N \times \mathbf{G}_s^N \overset{\mathbf{G}_s^N}{\Longrightarrow} \mathbf{G}^N$ coupled to GBs (nlσm)$\sim$ reduction of 5-dim. $\mathbf{G}$ theory.

- "Little Higgs" models [N. Arkani-Hammed, A.G. Cohen, and H. Georgi, Phys. Lett. **B 513** (2001) 232; T. Gregoire and J.G. Wacker, hep-ph/0207164]:

4-dim.$\mathbf{G}^{N\times N} \times \mathbf{G}_s^{N\times N} \overset{\Lambda\sim 10\text{TeV}}{\Longrightarrow} \mathbf{G}^{N\times N}$ coupled to 2 GB fields $U_{(i,j)}$ and $V_{(i,j)}$

($\sim$reduction of (4+2)-dim.$\mathbf{G}$ theory),

$U_{(i,j)} = \exp\{iu/(Nf)\}$, $V_{(i,j)} = \exp\{iv/(Nf)\}$.

$$\mathcal{H} = \frac{u+iv}{\sqrt{2}} = \begin{pmatrix} \varphi + \eta & h_1 \\ h_2^\dagger & -\eta \end{pmatrix}$$

3 energy regions:

$E \geq \Lambda = 4\pi f \sim 10 - 30$ TeV: strong coupling

$\Lambda \geq E \geq gf \sim 1 - 3$ TeV: new gauge bosons W', Z', new scalars ϕ, η, h_2, and new fermions χ cancelling Λ^2 divergences.

$gf \geq E \geq \frac{g^2 f}{4\pi} \sim 100 - 200$ GeV: SM gauge fields, fermions and "little Higgs" h_1 with $m_{h_1} \sim 100 - 200$ GeV without fine tuning.

If LHC sees only SM particles, it is likely this "little Higgs" model (no *triviality* and *unnaturalness*).

2. Noncommutative geometry [talk by N.S. Kersting]

V. General Probe of New Physics Effects

- SUSY topcolor extra dim ······

  $\searrow$ $\searrow$ $\swarrow$ $\swarrow$

  nature=?

  Merely test known models *not sufficient.*

  General *no lose* probe of new physics is needed

- Effective Lagrangian $\mathcal{L}_{eff}$ below Λ:

  integrate out new particles above $\Lambda \Longrightarrow \mathcal{L}_{eff}$ *below* Λ

coefficients in $\mathcal{L}_{eff}$ reflect new physics models

- General probe $--$ 2 steps:

◇ *first step*:

Start from general $\mathcal{L}_{eff}$ (*coefficients* unspesified).

Find processes to measure *coefficients* experimentally$\Longrightarrow$ $\mathcal{L}_{eff}$ reflecting *nature.*

◇ *second step*:

Integrate out new particles above Λ in various new physics models and see which one (kind) can lead to the measured coefficients. *Developing new techniques* is needed.

- **First step**:

1. The Case of No Light Higgs Boson below Λ

The most challenging case for expt. General EW effective Lagrangian in this case [*EW chiral Lagrangian* (EWCL)] containing the GBs π^a in nonlinear realization $U = \exp\{i\tau^a\pi^a/f_\pi\}$ $(f_\pi = v)$ and gauge fields is:

$$\mathcal{L}_{eff}(\pi^a, W^\pm, Z^0, \gamma) = \mathcal{L}_G(W^\pm, Z^0, \gamma) + \sum_{i=1}^{16} \ell_i \mathcal{O}_i(\pi^a, W^\pm, Z^0, \gamma),$$

ℓ_i- effective coupling constants of π^a-interactions.
Examples: ℓs (at scale $\mu = 1.5$ TeV) from integrating out heavy *scalar* and *vector* [J. Bagger, S. Dawson, G. Valencia, nucl. Phys. **B 399** (1993) 364]:

integrated out particle	ℓ_1	ℓ_3	ℓ_4	ℓ_5
scalar(m=2.0 TeV)	-0.02	-0.01	0.01	0.33
scalar(m=1.5 TeV)	0.00	0.00	0.00	0.55
vector(m=2.0 TeV)	-3.0	-1.4	0.38	-0.31
vector(m=1.5 TeV)	-5.0	-2.4	0.60	-0.60

π^a are not physical particles (not observable). However, π^a degrees fo freedom reside in observables V_L $(W_L^\pm, Z_L^0)$. So ℓ_i can be measured via V_L reactions.

Relation between $T(V_L^a)$ and $T(i\pi^a)$ is the *equivalence theorem* (ET) [H.-J. He, Y.-P. Kuang, and X. Li, Phys. Rev. Lett. **69** (1992) 2619; Phys. Lett. **B 329** (1994) 278; Phys. Rev. D **49** 91994) 4842].

Based on the ET, it is shown that sensitive V_L-reaction processes at LHC, LC (including $e\gamma$ collider) for measuring all ℓs can be found [H.-J. He, Y.-P. Kuang, and C.-P. Yuan, Phys. Lett. **B 382** (1996) 149; Phys. Rev. D **55** (1997) 3038].

Monte Carlo simulations for the sensitivities of determining ℓ_4 and ℓ_5 at LHC and TESLA have also been done [TESLA Technical Design Report]. ℓ_4 and ℓ_5 can be measured outside the following ranges:

LHC (100 fb^{-1}): $-0.17 \leq \ell_4 \leq +1.7, \quad -0.35 \leq \ell_5 \leq +1.2,$

800 GeV TESLA (1000 fb^{-1}): $-1.1 \leq \ell_4 \leq +0.8, \quad -0.4 \leq \ell_5 \leq +0.3.$

Improvement of the measurements has been studied [J.M. Butterworth, B.E. cox, and J.R. Forshaw, Phys. Rev. D **65** (2002) 096014]

• 2. The Case with Light Higgs Boson below Λ

Once a light Higgs boson candidate is found, the crucial thing is to test whether it is the SM Higgs or a Higgs in new physics models. This requires *testing Higgs interactions*. Consider testing anomalous HVV couplings.

In linearly realizes effective Lagrangian containing light Hggs H, anomalous HVV couplings are composed of dim-5 operators

$$\mathcal{L}^H_{eff} = g_{H\gamma\gamma} H A_{\mu\nu} A^{\mu\nu} + g^{(1)}_{HZ\gamma} A_{\mu\nu} Z^\mu \partial^\nu H + g^{(2)}_{HZ\gamma} H A_{\mu\nu} Z^{\mu\nu} + g^{(1)}_{HZZ} Z_{\mu\nu} Z^\mu \partial^\nu H$$
$$+ g^{(2)}_{HZZ} H Z_{\mu\nu} Z^{\mu\nu} + g^{(1)}_{HWW} (W^+_{\mu\nu} W^\mu_- \partial^\nu H + h.c.) + g^{(2)}_{HWW} H W^+_{\mu\nu} W^{\mu\nu}_-,$$

Existing studies:

LHC: [O.J.P. Éboli *et al.*, Phys. Lett. **B 478** (2000) 199; T. Plehn *et al.*, Phys. Rev. Lett. **88** (2002) 051801]:

$pp \to H + X,\ H \to \gamma\gamma,\ \tau^+\tau^- \Longrightarrow g^{(i)}_{HVV} \neq 0$ effect can be detected if

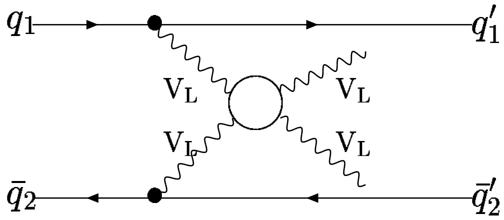
$$|g^{(i)}_{HVV}| \geq 10^{-1}\ \text{TeV}^{-1}$$

LC: [K. Hagiwara *et al.*, Eur. phys. J. C **14** (2000) 457]:

$e^+e^- \to ZH$, $Z \to f\bar{f} \Longrightarrow g(i)_{HZZ}$ effect can be detected if

$$|g^{(i)}_{HZZ}| \geq (10^{-3} - 10^{-2})\ \text{TeV}^{-1}.$$

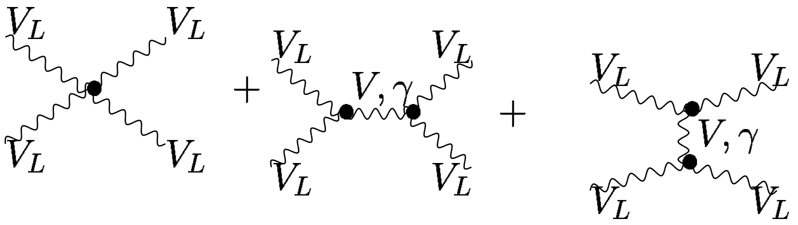
New suggestion [B. Zhang, Y.-P. Kuang, H.-J. He, and C.-P. Yuan, TUHEP-TH-01127]: testing $|g^{(i)}_{HVV}$ via V_LV_L scatterings at LHC.



Scattering amplitude contains two parts:

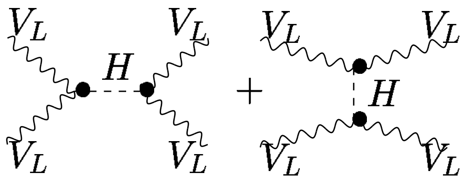
(a) the amplitude $T(V,\gamma)$, (b) the amplitude $T(H)$:

$T(V,\gamma)$:



+ cross diagrams

$T(H)$:



+ cross diagrams

At high energies,

$$\begin{tikzcd}
T(V,\gamma), \quad T(H) \arrow[d, Rightarrow, "SM\ HVV"] & \sim & E^2 \arrow[d, Rightarrow, "anom.HVV"] \\
T(V,\gamma)+T(H)\sim E^0 \arrow[dr] & & T(V,\gamma)+T(H)\sim E^2 \arrow[dl] \\
 & \text{this difference is sensitive to } |g^{(i)}_{HVV}| &
\end{tikzcd}$$

Taking kinematical cuts for reducing backgrounds [J. Bagger *et al.*, Phys. Rev. D **52** (19950 3878], the $W_L^+W_L^+$ gives the most sensitive test (mainly testing $|f_{WW}/\Lambda^2|$). For integrated luminosity 300 fb^{-1}, the obtained sensitivity is: $|g^{(2)}_{HWW}|\neq 0$ effect can be detected if

$$|g^{(2)}_{HWW}|\geq 2.6\times 10^{-3}\ \text{TeV}^{-1},$$

of the same order as for the HZZ anomalous coupling at LC.

3. Anomalous Couplings of the Top Quark

Yukawa coupling of top quark $y_t=\sqrt{2}m_t/v\approx 1$. Top quark couples strongly to EWSB sector, and is sensitive to new physics related to EWSB. Studying effective anomalous couplings of top quark will also be very useful for probing new physics. This kind of study has been carried out in various papers [including T. Han, T. Huang, Z.-H. Lin, J.-X. Wang, and X.-M. Zhang, phys. Rev. D **61** (2000) 015006; Z.-H. Lin, T. Han, T. Huang, J.-X. Wang, and X.-M. Zhang, Phys. Rev. D **65** (2002) 014008.]

- **Second step**:

Having measured the coefficients in $\mathcal{L}_{eff}$, the next step is to examine *what new physics model above* Λ *can lead to the measured effective Lagrangian coefficients* to specify the new physics model (difficult due to the nonperturbative dynamics in integrating out the heavy particle contributions).

This is similar to the problem of calculating the chiral Lagrangian coefficients from QCD. New techniques for calculating the chiral Lagrangian coefficients from QCD has been developed recently [Q. Wang, Y.-P. Kuang, X.-L. Wang, and M. Xiao, Phys. Rev. D **61** (2000) 054001; H. Yang, Q. Wang, Y.-P. Kuang, and Q. Lu, Phys. Rev. D **66** (2002) 094019; Q. Wang, Y.-P. Kuang, H. Yang, and Q. Lu, J. Phys. G **28** (2002) L55].

With certain approximation, *the calculated chiral Lagrangian coefficients are quite consistent with the values determined by experiments.* Such techniques can be applied to the study in the *second step*, and is in progress.

VI. Conclusions

• SM Higgs not found. SM suffers from *triviality, unnaturalness,* etc. New physics is needed to solve the problems.

• Various new physics models have been proposed: *SUSY, topcolor-assisted technicolor models, top quark seesaw models, large extra dimension models, noncommutative geometry, and other possibilities.* their characteristic signals can be tested at high energy colliders.

• We do not know if the *nature* really behave like one of the proposed new physics models or not. *merely testing known models is not sufficient.*

• General probe of new physics:

first step: start from general $\mathcal{L}_{eff}$, and find sensitive processes to determine the coefficients in $\mathcal{L}_{eff}$ experimentally.

second step: Integrate out new heavy particle contributions above Λ for various new physics models to obtain corresponding coefficients in $\mathcal{L}_{eff}$ and see which kind of model can lead to the measured coefficients. *new calculation technique is needed.*

• Particle physics is in a crucial status of clarifying the choice of different directions of new physics. LHC and LC will be important equipment for studying it. Further theoretical and experimental studies are needed.