Beyond Standard Model Higgs

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Outline

1. Standard Model Higgs Particle
2. Beyond Standard Model Higgs
3. Higgs Particle as Partner of Guage Boson

Standard Model Higgs Particle

Left-handed fermions

$$l_{iL} = \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L, \qquad l_{iR} = e_R,\ \mu_R,\ \tau_R$$

$$q_{iL} = \begin{pmatrix} u' \\ d \end{pmatrix}_L \begin{pmatrix} c' \\ s \end{pmatrix}_L \begin{pmatrix} t' \\ b \end{pmatrix}_L, \qquad q_{iR} = u_R,\ c_R,\ t_R\ \cdots$$

Higgs Scalar

$$\phi = \begin{pmatrix} \phi^0 \\ \phi^- \end{pmatrix}, \qquad \langle\phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} v \\ 0 \end{pmatrix}, \qquad v = 246\ Gev$$

Important roles of Higgs scalar:

1. Break the gauge symmetry: $SU(2) \times U(1) \rightarrow U(1)_{em}$
   Only $h = \mathrm{Re}\,\phi^0$ left over after spontaneous symmetry breaking
   Gauge boson masses ratio
   $$\rho = \frac{M_W^2}{M_Z^2 \cos^2\theta_W} = 1$$
   This is a property of Higgs in doublet.
2. Give fermion masses
   Yukawa coupling
   $$L_Y = \left(f_{ij} \bar{l}_{iL} l_{jR} \phi + \cdots \right)$$
   fermion mass matrices
   $$m_{ij} = f_{ij} \frac{v}{2},$$
   Diagonalization of $m_{ij} \Longrightarrow$ Yukawa coupling conserves flavor & magnitude is proportional to fermio mass⇒favor heavy particles

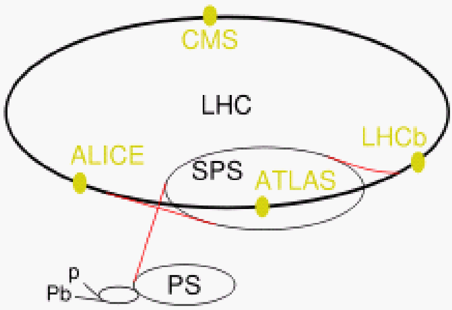
Higgs mass–not determined by theory and data indicates

$$m_H > 114 \ Gev/c^2$$

Search for Higgs

LHC(Large Hadron Collider) : 7 *Tev* on 7 *Tev* proton machine

Large Hadron Collider (LHC)

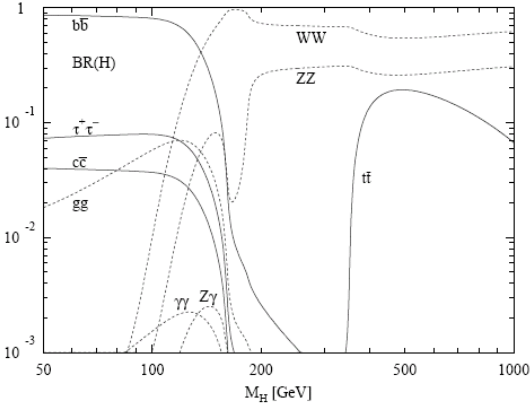


The accelerator chain of the Large Hadron Collider

- Production at hadron machine:

$$\begin{array}{lll} (i) & \text{Gluon fusion :} & pp \longrightarrow gg \longrightarrow H + \cdots, \\ (ii) & \text{V V fusion :} & pp \longrightarrow VV \longrightarrow H + \cdots, \\ (iii) & \text{Association with V} & pp \longrightarrow qq\prime \longrightarrow VH + \cdots. \end{array}$$

Decay of Higgs



2) Beyond Standard Model Higgs

Motivations for extra Higgs:

1. Neutrino mass(Majorana mass)–leptonic number violation
2. Supersymmetry
3. Spontaneous CP violation
4. Breaking of larger symmetries–

- Left-Right model
- Grand Unified Theory(GUT)
- Little Higgs
- $\cdots$

Neutrino mass:

Leptons:

$$l_{aL} = \begin{pmatrix} \nu_a \\ l_a^- \end{pmatrix}_L \sim \left(\mathbf{2}, -\frac{1}{2}\right), \quad l_{aR}^- \sim (\mathbf{1}, -1), \quad \phi = \begin{pmatrix} \phi^0 \\ \phi^- \end{pmatrix} \sim \left(\mathbf{2}, -\frac{1}{2}\right)$$

leptonic bilinears:

$$\overline{l_a}_L l_{bR}^- \sim \left(\mathbf{2}, -\frac{1}{2}\right), \qquad \text{usual doublet with lepton number L=0}$$

$$\overline{l_a}_L^c l_{bL} \sim (\mathbf{1}, -1) + (\mathbf{3}, -1), \qquad \text{triplet and singlet, L=2}$$

$$\overline{l_a}_R^c l_{bR}^- \sim (\mathbf{1}, -2), \qquad \text{doubley charged singlet, L=2}$$

To get neutrino masses, we need lepton number violation. This can be achieved by trilinear coupling

$$\phi\phi h$$

where h is one of L=2 Higgs singlet or triplet.

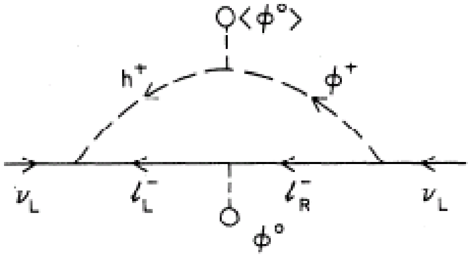
Example : Zee model—singlet charged Higgs h +one additional doublet ϕ_2
Yukawa coupling

$$L_Y = f_{ab}\overline{l_a}^c_{iL} l_{bjL}\varepsilon_{ij} h + h..c.$$

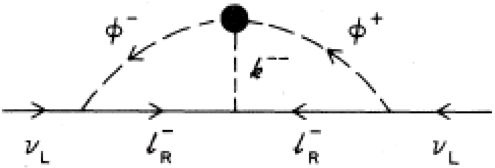
Note that h has 2 units of lepton number. To generate leptons number we need the trilinear coupling

$$L_\phi = \varepsilon_{ij}\phi_{1i}\phi_{2j} h + h.c.$$

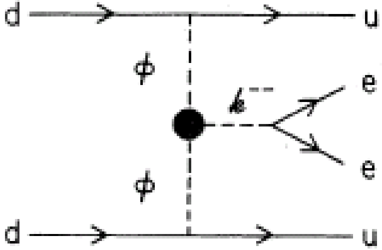
Due to the antisymmetric nature of ε_{ij} we need 2 doublets of Higgs. The neutrino masses is generated through 1-loop diagram,



Doubly charged singlet k^{++} can give rise to neutrino masses



and also contribute to nuclear $\beta\beta$ decays,



k^{++} can also contribute to many $\Delta L = 2$ processes similar to nuclear $\beta\beta$ decays,

$\Delta S = 0$	$\Delta S = 1$	$\Delta S = 2$
$\Sigma^- \longrightarrow \Sigma^+ e^- e^-$	$\Sigma^- \longrightarrow p e^- e^-$	$\Xi^- \longrightarrow p e^- e^-$
	$\Sigma^- \longrightarrow p \mu^- \mu^-$	$\Xi^- \longrightarrow p \mu^- \mu^-$
	$\Xi^- \longrightarrow \Sigma^+ e^- e^-$	

Supersymmetry:
Quarks:

$$q_{aL} = \begin{pmatrix} u_a \\ d_a \end{pmatrix}_L \sim \left(\mathbf{2}, -\frac{1}{6}\right), \qquad u_{aR} \sim \left(\mathbf{1}, \frac{2}{3}\right), \qquad d_{aR} \sim \left(\mathbf{1}, -\frac{1}{3}\right)$$

quarks bilinear

$$\overline{q}_{aL} u_{bR} \sim \left(\mathbf{2}, \frac{1}{2}\right) \sim \phi^{\dagger}, \qquad \overline{q}_{aL} u_{aR} \sim \left(\mathbf{2}, -\frac{1}{2}\right) \sim \phi$$

But in supersymmetry ϕ and $\phi^{\dagger}$ belongs to two different chiral multiplets $\Rightarrow$ two different doublets of Higgs–one gives masses to up-type of quarks and the other to down-type of quarks
After spontaneous symmetry breaking, 5 scalar particles left-over, 3 neutral and 2 charged

Spontaneous CP violation:(TD Lee 1973)
Two doublet of Higgs with vacuum expectation value

$$\phi_1 = \begin{pmatrix} 0 \\ \rho_1 \end{pmatrix}, \qquad \phi_2 = \begin{pmatrix} 0 \\ \rho_2 e^{i\theta} \end{pmatrix}$$

The CP violation comes from the phase $e^{i\theta}$.

Problem: the Higgs couplings will not conserve flavors
Breaking larger symmetries:
Left-right symmetric model: spontaneous violation of parity
Grand unification theory: unifies strong, electroweak interactions

Higgs scalar as partner of gauge field in higher dimension

Abelian case

Field tensor:

$$F_{ab} = \partial_a A_b - \partial_b A_a, \qquad A_a = \left(A_0, \vec{A}, \phi \right)$$

The part which contains the scalar field ϕ is

$$F_{\mu 4} = \partial_\mu \phi - \partial_4 A_\mu$$

There is no scalar field self interaction. This is true in any dimension.

Non-Abelian case

(a) 5-dimension

Field tensor:

$$F_{CD}^{a}=\partial_{C}A_{D}^{a}-\partial_{D}A_{C}^{a}+igf^{abc}A_{C}^{b}A_{D}^{c},\qquad A_{C}^{a}=\left(A_{0}^{a},\overrightarrow{A}^{a},\phi^{a}\right)$$

The part contains scalar fields is

$$\begin{aligned} F_{\mu 4}^{a} &= \partial_{\mu}\phi^{a}-\partial_{4}A_{\mu}^{a}+igf^{abc}A_{\mu}^{b}\phi^{c} \\ &= \partial_{\mu}\phi^{a}+gf^{abc}A_{\mu}^{b}\phi^{c} \qquad \text{covariant derivative} \end{aligned}$$

where A_{μ}^{a} is assumed to be independent of x_4.

Again there is no self interaction of scalar field ϕ^{a}.

(b) 6-dimension $A_{C}^{a}=\left(A_{0}^{a},\overrightarrow{A}^{a},\phi_{1}^{a},\phi_{2}^{a}\right)$

$$F_{45}^{a}=\partial_{4}\phi_{1}^{a}-\partial_{5}\phi_{2}^{a}+gf^{abc}\phi_{1}^{b}\phi_{2}^{c}$$

Now we get scalar fields self interaction,

$$F_{45}^{a}F^{a45}\longrightarrow g^{2}f^{abc}f^{ade}\phi_{1}^{b}\phi_{2}^{c}\phi_{1}^{d}\phi_{2}^{e}$$

The quadratic term can come from the $\partial_{4}\phi_{1}^{a}-\partial_{5}\phi_{2}^{a}$ part of the field