Introduction to Standard Model

Ling-Fong Li

National Center for Theoretical Science (NCTS)

Introduction to Standard Model of Electroweak Interaction

Lecture 1 Symmetries–Global and Local

Lecture 2 Spontaneous Symmetry Breaking

Lecture 3 Standard Model

History

- Standard Model = Non-Abelian Gauge Theory + Spontaneous Symmetry Breaking
- Non-Abelian Gauge Theory– Yang Mills 1954
- Spontaneous Symmetry Breaking (SSB)— Nanbu, Goldstone, Salam, Weinberg, ~1960's
- SSB + Gauge theory– Higgs, Englert and Brout, Guralnik, Hagen, and Kibble, Anderson~1964
- Renormalization of Yang-Mills theory– Fadeev and Popov, t' Hooft 1971
- Electroweak Model– Weinberg, Salam, 1967

Symmetry

Symmetries play important roles in high energy physics.

Global symmetry

Consider Lagrangian,

$$\mathcal{L} = \frac{1}{2}\left[\left(\partial_\mu \phi_1\right)^2 + \left(\partial_\mu \phi_2\right)^2\right] - \frac{\mu^2}{2}\left(\phi_1^2 + \phi_2^2\right) - \frac{\lambda}{4}\left(\phi_1^2 + \phi_2^2\right)^2$$

this is invariant under rotation in (ϕ_1, ϕ_2) plane, $O(2)$ symmetry,

$$\begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} \longrightarrow \begin{pmatrix} \phi_1' \\ \phi_2' \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix}$$

θ is independent of x^μ and is called **global** transformation.

Another way is to write

$$\phi = \frac{1}{\sqrt{2}}\left(\phi_1 + i\phi_2\right)$$

and

$$\mathcal{L} = \partial_\mu \phi^\dagger \partial_\mu \phi - \mu^2 \phi^\dagger \phi - \lambda\left(\phi^\dagger \phi\right)^2$$

This is a phase transformation,

$$\phi \longrightarrow \phi' = e^{-i\theta}\phi$$

This is called the $U(1)$ symmetry.
Example, charge conservation.
Approximate symmetries, e.g. lepton number, isospin, Baryon number,$\cdots$ are probably realized in the form of global symmtries.

Local Symmetry

Local symmetry: transformation parameters, e.g. angle θ, depend on x^μ. This originates from electromagnetic theory.

Maxwell Equations:

$$\vec{\nabla} \cdot \vec{E} = \frac{\rho}{\varepsilon_0}, \qquad \vec{\nabla} \cdot \vec{B} = 0$$

$$\vec{\nabla} \times \vec{E} + \frac{\partial \vec{B}}{\partial t} = 0, \qquad \frac{1}{\mu_0}\vec{\nabla} \times \vec{B} = \varepsilon_0 \frac{\partial \vec{E}}{\partial t} + \vec{J}$$

Introduce ϕ, $\vec{A}$ to solve those equations without source,

$$\vec{B} = \vec{\nabla} \times \vec{A}, \qquad \vec{E} = -\vec{\nabla}\phi - \frac{\partial \vec{A}}{\partial t}$$

These are not unique because of **gauge** tranformation

$$\phi \longrightarrow \phi - \frac{\partial \alpha}{\partial t}, \qquad \vec{A} \longrightarrow \vec{A} + \vec{\nabla}\alpha$$

Or

$$A_\mu \longrightarrow A_\mu - \partial_\mu \alpha$$

will give the same electromagnetic fields
In quantum mechanics, Schrodinger equation for charged particle,

$$\left[\frac{1}{2m} \left(\frac{\hbar}{i} \vec{\nabla} - e \vec{A} \right)^2 - e\phi \right] \psi = i\hbar \frac{\partial \psi}{\partial t}$$

This requires transformation of wave function,

$$\psi \longrightarrow \exp\left(i \frac{e}{\hbar} \alpha \right) \psi$$

to get same physics.
Thus gauge transformation is connected to **symmetry** (local) transformation.

In field theory, gauge fields are needed to contruct covariant derivatives.
Consider Lagrangian with global $U(1)$ symmetry,

$$\mathcal{L} = \left(\partial_\mu \phi\right)^\dagger \left(\partial^\mu \phi\right) + \mu^2 \phi^\dagger \phi - \lambda \left(\phi^\dagger \phi\right)^2$$

Suppose phase transformation depends on x^μ,

$$\phi \longrightarrow \phi' = e^{ig\alpha(x)}\phi$$

The derivative transforms as

$$\partial^\mu \phi \longrightarrow \partial^\mu \phi' = e^{i\alpha(x)} \left[\partial^\mu \phi + ig\left(\partial^\mu \alpha\right)\phi\right],$$

not a phase transformation.
Introduce gauge field A^μ, with transformation

$$A^\mu \longrightarrow A'^\mu = A^\mu - \partial^\mu \alpha$$

The combination

$$D^\mu \phi \equiv \left(\partial^\mu - igA^\mu\right)\phi, \qquad \text{covariant derivative}$$

will be transformed by a phase,

$$D^{\mu}\phi' = e^{ig\alpha(x)}\left(D^{\mu}\phi\right)$$

and the combination

$$D_{\mu}\phi^{\dagger}D^{\mu}\phi$$

is invarianat under local phase transformation.
Define anti-symmetric tensor for the gauge field

$$\left(D_{\mu}D_{\nu} - D_{\nu}D_{\mu}\right)\phi = gF_{\mu\nu}\phi, \qquad \text{with} \qquad F_{\mu\nu} = \partial_{\mu}A_{\nu} - \partial_{\nu}A_{\mu}$$

We can use the property of the covariant derivative to show that

$$F'_{\mu\nu} = F_{\mu\nu}$$

Complete Lagragian is

$$\mathcal{L} = D_{\mu}\phi^{\dagger}D^{\mu}\phi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - V\left(\phi\right)$$

where $V\left(\phi\right)$ does not depend on derivative of ϕ.

- mass term $A^{\mu}A_{\mu}$ is not gauge invariant $\Rightarrow$ massless particle$\Rightarrow$long range force
- coupling of gauge field to other field is universal

Non-Abelian gauge symmetry(Yang-Mills field)

In 1954, Yang and Mills generalized $U(1)$ local symmetry to non-Abelian symmetry.

Consider $SU(2)$ doublet,

$$\psi = \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix}$$

Under $SU(2)$ transformation,

$$\psi \rightarrow \psi' = \exp\left\{ -i\frac{\vec{\tau} \cdot \vec{\theta}}{2} \right\} \psi$$

$\vec{\tau} = (\tau_1, \tau_2, \tau_3)$ are Pauli matrices

Start from

$$\mathcal{L} = \bar{\psi}(x)\left(i\gamma^\mu \partial_\mu - m\right)\psi$$

Under local symmetry transformation,

$$\psi(x) \longrightarrow \psi'(x) = U(\theta)\psi, \qquad \text{where} \qquad U(\theta) = \exp\left\{ -i\frac{\vec{\tau} \cdot \vec{\theta}(x)}{2} \right\}$$

But for derivative,

$$\partial_\mu \psi\left(x\right) \longrightarrow \partial_\mu \psi'\left(x\right) = \left(\partial_\mu U\right)\psi + U\partial_\mu \psi$$

Introduce gauge fields $\overrightarrow{A}_\mu$ to form convariant derivative,

$$D_\mu \psi \equiv \left(\partial_\mu - ig\frac{\overrightarrow{\tau}\cdot\overrightarrow{A_\mu}}{2}\right)\psi$$

require that $D_\mu \psi$ has the same transformation as ψ, $i.e.$

$$\left[D_\mu \psi\right]' = U\left[D_\mu \psi\right]$$

then

$$\left(\partial_\mu - ig\frac{\overrightarrow{\tau}\cdot\overrightarrow{A'_\mu}}{2}\right)U\psi = U\left(\partial_\mu - ig\frac{\overrightarrow{\tau}\cdot\overrightarrow{A_\mu}}{2}\right)\psi$$

This can be simplified to give

$$\frac{\overrightarrow{\tau}\cdot\overrightarrow{A'_\mu}}{2} = U\left(\frac{\overrightarrow{\tau}\cdot\overrightarrow{A_\mu}}{2}\right)U^{-1} - \frac{i}{g}\left(\partial_\mu U\right)U^{-1}$$

Use covariant derivatives to get field tensor

$$\left(D_\mu D_\nu - D_\nu D_\mu\right)\psi \equiv ig\left(\frac{\vec{\tau}\cdot\vec{F}_{\mu\nu}}{2}\right)\psi$$

and

$$\frac{\vec{\tau}\cdot\vec{F}_{\mu\nu}}{2} = \frac{\vec{\tau}}{2}\cdot\left(\partial_\mu\vec{A}_\nu - \partial_\nu\vec{A}_\mu\right) - ig\left[\frac{\vec{\tau}\cdot\vec{A}_\mu}{2}, \frac{\vec{\tau}\cdot\vec{A}_\nu}{2}\right]$$

Or

$$F^i_{\mu\nu} = \partial_\mu A^i_\nu - \partial_\nu A^i_\mu + g\varepsilon^{ijk}A^j_\mu A^k_\nu$$

Under gauge transformation

$$\vec{\tau}\cdot\vec{F}'_{\mu\nu} = U\left(\vec{\tau}\cdot\vec{F}_{\mu\nu}\right)U^{-1}$$

Then the combination

$$Tr\left[\left(\vec{\tau}\cdot\vec{F}_{\mu\nu}\right)\left(\vec{\tau}\cdot\vec{F}^{\mu\nu}\right)\right] = 2\left(\vec{F}_{\mu\nu}\cdot\vec{F}^{\mu\nu}\right)$$

is invariant. For infinitesmal transformtion $\theta(x) \ll 1$,

$$A'^{i}_{\mu} = A_{\mu} + \varepsilon^{ijk}\theta^{j} A^{k}_{\mu} - \frac{1}{g}\partial_{\mu}\theta^{i}$$

$$F'^{i}_{\mu\nu} = F^{i}_{\mu\nu} + \varepsilon^{ijk}\theta^{j} F^{k}_{\mu\nu}$$

- $A^{i\mu}A^{i}_{\mu}$ is not gauge invariant ⇒ massless particle⇒long range force
- coupling to other field is also universal.

Spontaneous Symmetry Breaking

Usually symmetry of Lagrangin or Hamiltonian $\Longrightarrow$ physicial states degenercy.
Spontaneous symmetry breaking(SSB): the symm of interaction $>$ symm of spectrum.

$\Longrightarrow$ massless excitation, called the Nambu-Goldstone boson,

in 1964 Higgs and others : in local symmetry, SSB convert the long range force in gauge theory into a short range force.
Weinberg, Salam construct a model of electromagnetic and weak interactions.
t' Hooft : 1971 it is renomalizable and all the higher order effects are calculable

Goldstone Theorem

Example: ferromagnetism near Curie tempeture T_C.
Landau-Ginzberg's mean field theory
free energy density ,

$$u\left(\vec{M}\right)=\left(\partial_t\vec{M}\right)^2+V\left(\vec{M}\right)$$

where

$$V\left(\vec{M}\right)=\alpha_1\left(T\right)\left(\vec{M}\cdot\vec{M}\right)+\alpha_2\left(\vec{M}\cdot\vec{M}\right)^2$$

u and V rotationally invariant. assume

$$\alpha_1(T) = \alpha(T - T_C) \qquad \text{with } \alpha > 0$$

minimize $V\left(\vec{M}\right)$,

$$\frac{\partial V}{\partial M_i} = 0 \qquad \Longrightarrow \qquad M_i\left(\alpha_1 + 2\alpha_2 \vec{M}\cdot\vec{M}\right) = 0$$

For $T > T_C$ (i.e. $\alpha_1 > 0$), the solution is at $M_i = 0$. For $T < T_C$ (i.e. $\alpha_1 < 0$), the minimum is at

$$\left|\vec{M}\right| = \sqrt{-\frac{\alpha_1}{2\alpha_2}}$$

direction can be arbitrary. rotational symmetry spontaneously broken.
Goldstone theorem: spontaneous breaking of continuous symmetry zero energy excitations.
In particle physics, this means massless particle $\Longrightarrow$ long range force

Spontaneous Symmetry Breaking

Global symmetry

Suppose

$$L = \frac{1}{2}\left[\left(\partial_\mu \sigma\right)^2 + \left(\partial_\mu \phi\right)^2\right] - V\left(\sigma^2 + \pi^2\right)$$

with

$$V\left(\sigma^2 + \pi^2\right) = -\frac{\mu^2}{2}\left(\sigma^2 + \pi^2\right) + \frac{\lambda}{4}\left(\sigma^2 + \pi^2\right)^2$$

This is invariant under $O(2)$ rotation

$$\begin{pmatrix} \sigma \\ \pi \end{pmatrix} \longrightarrow \begin{pmatrix} \sigma' \\ \pi' \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \sigma \\ \pi \end{pmatrix}$$

rotation angle α independent of spacetime, global transformation. Minimize the potential energy V,

$$\frac{\partial V}{\partial \sigma} = \sigma\left[-\mu^2 + \lambda\left(\sigma^2 + \pi^2\right)\right] = 0$$

$$\frac{\partial V}{\partial \pi} = \pi\left[-\mu^2 + \lambda\left(\sigma^2 + \pi^2\right)\right] = 0$$

For $\mu^2 > 0$, the minimum at

$$\sigma^2 + \pi^2 = v^2, \qquad \text{with} \;\; v^2 = \frac{\mu^2}{\lambda}$$

minima is at circle with radius v in the (σ, π) plane.Pick for example,

$$\langle 0 \, | \sigma | \, 0 \rangle = \nu, \qquad \langle 0 \, | \pi | \, 0 \rangle = 0$$

$O\,(2)$ symmetry is broken by the vacuum state.
Consider small oscillations around true minimum and define a shifted field

$$\sigma' = \sigma - v$$

Lagrangian density

$$L = \frac{1}{2}\left[\left(\partial_\mu \sigma'\right)^2 + \left(\partial_\mu \phi\right)^2 \right] - \mu^2 \sigma'^2 - \lambda v \sigma' \left(\sigma'^2 + \pi^2\right) - \frac{\lambda}{4}\left(\sigma'^2 + \pi^2\right)^2$$

no quadratic term in $\pi-$field and π is the massless **Goldstone boson**.
massless particle $\Longrightarrow$ long range force .

Local Symmetry

Consider local $U(1)$ symmetry

$$L = \left(D_\mu\phi\right)^\dagger \left(D^\mu\phi\right) + \mu^2\phi^\dagger\phi - \lambda\left(\phi^\dagger\phi\right)^2 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

where

$$D_\mu\phi = \left(\partial_\mu - igA_\mu\right)\phi, \qquad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

Local transformation

$$\phi(x) \longrightarrow \phi'(x) = e^{-i\alpha}\phi(x)$$

$$A_\mu(x) \longrightarrow A'_\mu(x) = A_\mu(x) - \partial_\mu\alpha(x)$$

When $\mu^2 > 0$, minimum of potential

$$V(\phi) = -\mu^2\phi^\dagger\phi + \lambda\left(\phi^\dagger\phi\right)^2$$

at

$$\phi^\dagger\phi = \frac{v^2}{2}, \qquad \text{with} \qquad v^2 = \frac{\mu^2}{\lambda}$$

Thus ϕ has a vacuum expectation value

$$|\langle 0 |\phi| 0\rangle| = \frac{v}{\sqrt{2}}$$

write ϕ as,

$$\phi = \frac{1}{\sqrt{2}}(\phi_1 + i\phi_2)$$

choose

$$\langle 0 |\phi_1| 0\rangle = v, \qquad \langle 0 |\phi_2| 0\rangle = 0$$

define the shifted fields as

$$\phi_1' = \phi_1 - v, \qquad \phi_2' = \phi_2$$

ϕ_2' Goldstone boson.

New feature: covariant derivative term produce mass term for gauge boson,

$$\left|D_\mu \phi\right|^2 = \left|\left(\partial_\mu - igA_\mu\right)\phi\right|^2 \longrightarrow \frac{g^2 v^2}{2} A^\mu A_\mu + \cdots \quad (1)$$

guage boson mass

$$M = gv$$

write scalar field as

$$\phi(x) = \frac{1}{\sqrt{2}}\left[v + \eta(x)\right] e^{i\xi(x)/v}$$

use gauge transformation to transform away ξ.

$$\phi^{''} = \exp\left(-i\xi/v\right)\phi = \frac{1}{\sqrt{2}}\left[v + \eta(x)\right] \quad (2)$$

and

$$B_\mu = A_\mu - \frac{1}{gv}\partial_\mu \xi \quad (3)$$

massless gauge boson+Goldstone boson= massive gaue boson

Standard Model of Electroweak Interaction

- weak interaction is mediated by massive vector mesons.
- universality of weak couplings $\Longrightarrow$ local symmetries.
  spontaneous symmetry breaking in gauge theory has both universality and massive vector mesons.

The gauge group is $SU(2) \times U(1)$ with gauge bosons $\overrightarrow{A}_\mu$ and B_μ .

$$L_1 = -\frac{1}{4} F^i_{\mu\nu} F^{i\mu\nu} - \frac{1}{4} G^{\mu\nu} G_{\mu\nu}$$

where

$$F^i_{\mu\nu} = \partial_\mu A^i_\nu - \partial_\nu A^i_\mu + g\varepsilon^{ijk} A^j_\mu A^k_\nu$$

$$G_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\nu$$

Here g gauge coupling for the $SU(2)$ group.
scalar fields is $SU(2)$ doublet with hypercharge $Y = 1$,

$$\begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \qquad Y = 1$$

Lagrangian containing ϕ is

$$L_2 = \left(D_\mu \phi\right)^\dagger \left(D^\mu \phi\right) - V\left(\phi\right)$$

where

$$D_\mu \phi = \left(\partial_\mu - \frac{ig}{2}\vec{\tau} \cdot \vec{A}_\mu - \frac{ig'}{2} B_\mu\right)\phi$$

$$V\left(\phi\right) = -\mu^2 \left(\phi^\dagger \phi\right) + \lambda \left(\phi^\dagger \phi\right)^2$$

Spontaneous Symmetry Breaking

$$\langle \phi \rangle_0 \equiv \langle 0 \left| \phi \right| 0 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}, \qquad v = \sqrt{\frac{\mu^2}{\lambda}}$$

Write the scalar fields

$$\phi(x) = U^{-1}\left(\vec{\xi}\right) \begin{pmatrix} 0 \\ \frac{v + H(x)}{\sqrt{2}} \end{pmatrix}, \qquad \text{with} \quad U\left(\vec{\xi}\right) = \exp\left[\frac{i\vec{\xi}(x) \cdot \vec{\tau}}{v}\right]$$

where $\vec{\xi}(x)$ Goldstone bosons. use the gauge transformation to remove $\vec{\xi}(x)$

$$\phi' = U\left(\vec{\xi}\right)\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$$

Then $\vec{\xi}(x)$ disappear, left-over field $H(x)$, usually called Higgs field,

Fermions and CKM mixing

ψ_L are all in $SU(2)$ doublets and ψ_R are all $SU(2)$ singlets $\bar{\psi}_L \psi_R + h.c.$ is not $SU(2)$ invariant$\Longrightarrow$ no bare mass terms

However fermions couple to scalar fields ϕ through Yukawa couplings . ,

$$L_Y = f_{ij}\bar{q}'_{iL}\phi u'_{Rj} + f'_{ij}\bar{q}'_{iL}\phi d'_{Rj} + h.c.$$

where

$$q'_{1L} = \begin{pmatrix} u' \\ d' \end{pmatrix}_L, \qquad q'_{2L} = \begin{pmatrix} c' \\ s' \end{pmatrix}_L, \qquad q'_{3L} = \begin{pmatrix} t' \\ b' \end{pmatrix}_L$$

$$\begin{aligned} u_{1R} &= u'_R, \qquad u_{2R} = c'_R, \qquad u_{3R} = t'_R, \\ d_{1R} &= d'_R, \qquad d_{2R} = s'_R, \qquad d_{3R} = b'_R \end{aligned}$$

Yukawa coupling constants f_{ij} and f'_{ij} are arbitrary, the quark mass matrices are not diagonal. The mass matrices in the up and down sectors are

$$m^{(u)}_{ij} = f_{ij}\frac{v}{\sqrt{2}}, \qquad m^{(d)}_{ij} = f'_{ij}\frac{v}{\sqrt{2}}$$

These matrices can be diagonlized by bi-unitary transformations,

$$U_u m^{(u)} V_u = m^{(u)}_d, \qquad U_d m^{(d)} V_d = m^{(d)}_d$$

redefine the left-handed doublets to put all the unitary matrices in the down sector,

$$q_{iL}: \begin{pmatrix} u \\ d' \end{pmatrix}_L, \qquad \begin{pmatrix} c \\ s' \end{pmatrix}_L, \qquad \begin{pmatrix} t \\ b' \end{pmatrix}_L$$

where

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}_L = U_u^\dagger U_d \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

where

$$U_u^\dagger U_d = U_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

CKM(Cabbibo-Kobayashi-Maskawa) matrix .
Note that when mass matrices are diagonalized, Yukawa couplings become diagonal as well,

$$L_Y = \sum_i \left(m_i \bar{q}_i q_i + \frac{m_i}{v} H(x) \bar{q}_i q_i \right) \tag{4}$$

Higgs particle prefers to decay into heaviest fermions allowed by kinematics.

Higgs Physics

top priority at LHC is to look for Higgs particle.

1. Higgs coupling to fermion is proportional to fermion mass
2. Higgs coupling to gauge boson is also proportional to gauge boson mass,

$$L_{HVV} = gH(x)\left[M_W W_\mu^+ W + \frac{1}{2\cos\theta_W} M_Z Z^\mu Z_\mu\right]$$

Mass of Higgs particle can be written as

$$m_H = \sqrt{2\mu^2} = \sqrt{2\lambda}v,$$

where $v = 246$ Gev is related to Fermi coupling constant G_F by

$$v = \sqrt{\frac{\sqrt{2}}{G_F}}$$

Higgs Mass

Bound from experimental serach

direct search at e^+e^- collider LEP $m_H > 114.4\ Gev/c^2$ ..

Theoretical constraints

Pertubative unitarity

W_L scattering grow with energies and eventually violates the unitarity.
the amplitude satifies unitarity if

$$M_H \leq 870\ Gev$$

Naturalness problem

contribution to Higgs mass from compling $\lambda\phi^4$ diverges quadratically, $\Sigma_H \sim \Lambda_H^2$,

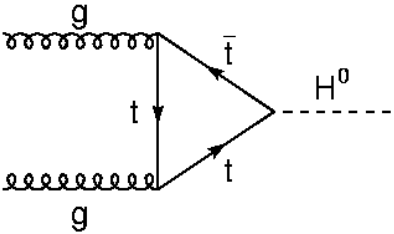
$$M_H^2 = M_{H,0}^2 + \frac{3\lambda}{16\pi^2}\Lambda_H^2$$

treat the cutoff Λ_H as mass scale where the Standard Model should be cutoff by some unknow new physics. If $\Lambda_H \sim 10^{19}Gev$, then to get M_H to be of order of weak scale $\leq 1Tev$, we need to fine tune the bare mass $M_{H,0}^2$ to 30 decimal places to cancel the huge contribution from Λ_H^2.
supersymmetric theory

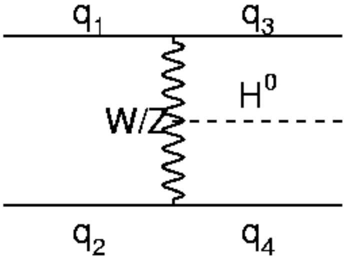
Production of Higgs Paticle

Higgs coupling is strongest for t quarks. There are 4 mechanisms for Higgs productions:

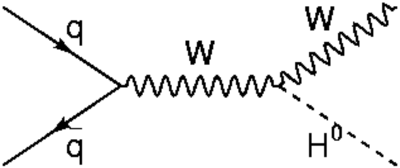
1. Gluon fusion through $t-$quark loop;



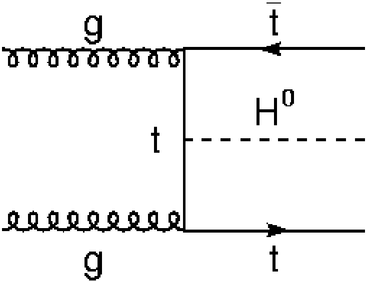
2. Vector meson fusion; $qq \longrightarrow qqH$



3. Associated production of H with a gauge boson, $qq \longrightarrow HW/Z$



4. Associated Higgs production with heavy quarks $gg \longrightarrow ttH$



production cross sections for these 4 processes are shown below,

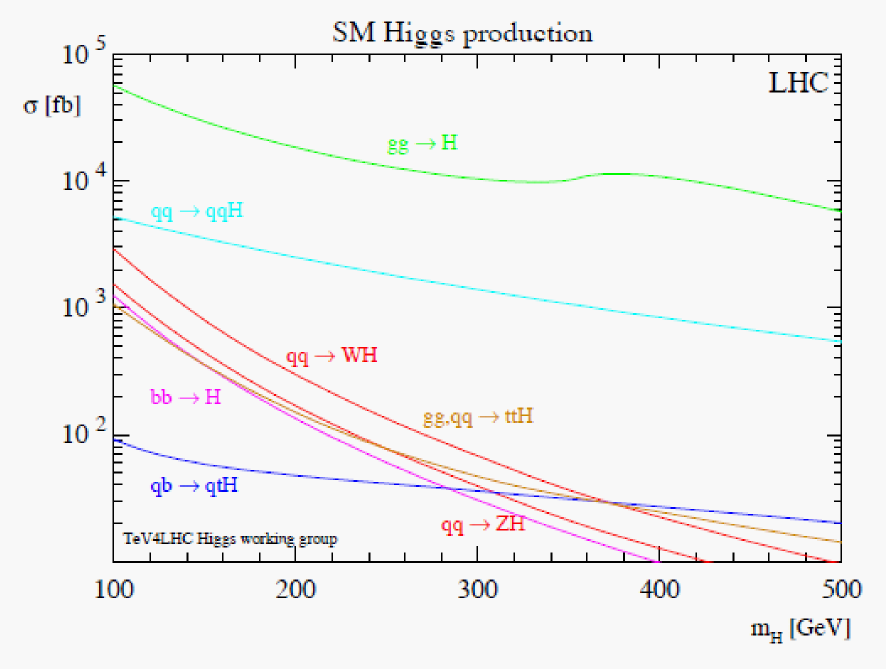


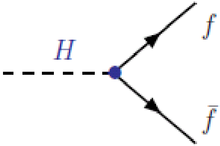
Fig: Higgs Production Cross Section for PP collison at 14 Tev

Higgs Decay

Higgs will decay into heaviest particles allowed by kinematics.

1. **Decays into quarks and leptons**

   To lowest order, the diagram is just

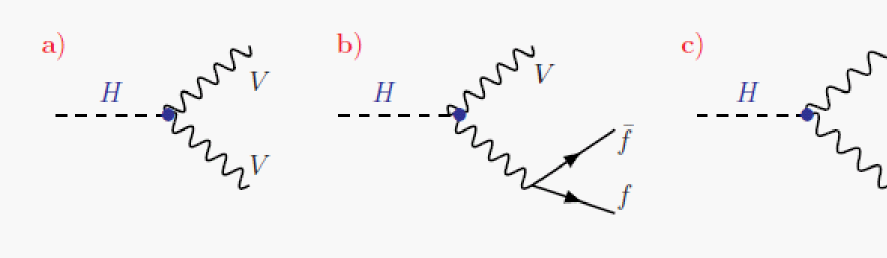


Use the Higgs coupling given in Eq(4) we can compute the decay width to give

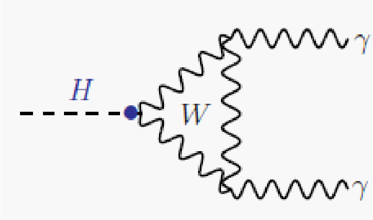
$$\Gamma\left(H \longrightarrow f\bar{f}\right) = \frac{G_F N_c}{4\sqrt{2}} M_H m_f^2 \left(1 - \frac{4m_f^2}{M_H^2}\right)^{3/2}$$

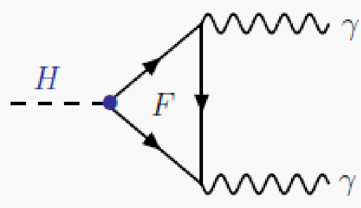
wher $N_c = 3$ for quarks and $N_c = 1$ for leptons.

2. **Decays into electroweak gauge bosons**
The diagrams for decays into gauge boson pair and subsequent decay of gauge boson into leptons are given by

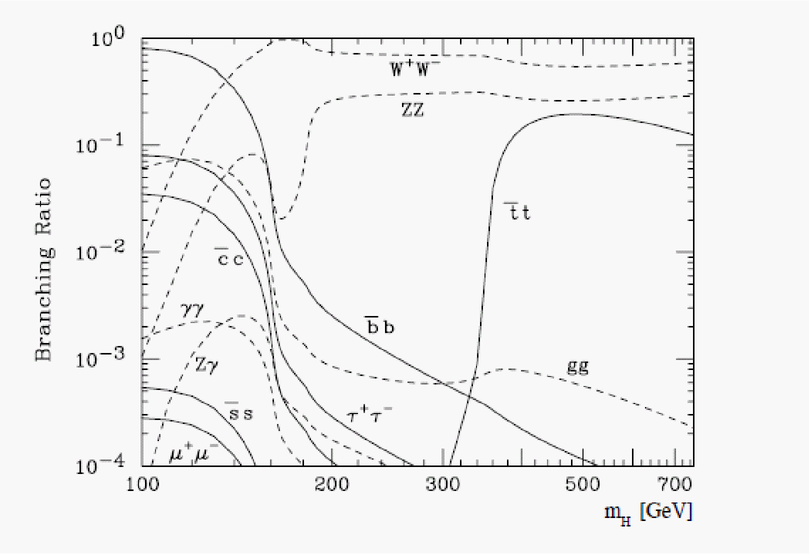


3. **Decays into $\gamma\gamma$**
This decay induced by the gauge boson or heavy fermion loop as shown in the graphs
below can be important due to the large Higgs couplings to the heavy particles.





relative importance of each decay mode,



- decays of Higgs into *WW* or *ZZ* dominate .

- below the WW threshold $H \longrightarrow b\bar{b}$ dominates.
- decay $H \longrightarrow \gamma\gamma$ is of special interest due to their relatively clean experimenal signaure.