Spontaneous Symmetry Breaking and Higgs Physics

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Part I **Spontaneous Symmetry Breaking**

Part I **Standard Model and Higgs Particle**

1. Construction of Standard Model
2. Properties of Higgs Particle
3. Production of Higgs Particle in LHC
4. Higgs Decays

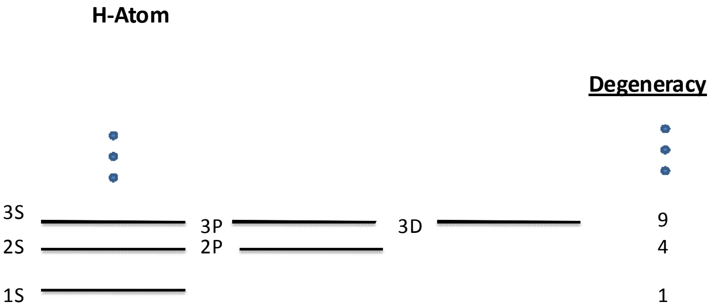
Introduction

Symmetry can be realized in 2 different modes:

Weyl-Wigner mode

$$Symmetry\ \ of\ \ Hamiltonian = Symmetry\ \ of\ \ States$$

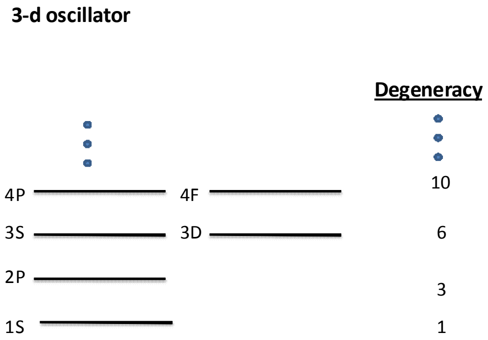
Example 1:Hydrogen Atom Spectrum



$O(4)$: angular momentum $\vec{L}$ & Lenz vector $\vec{M} = \vec{P} \times \vec{L} - \vec{r}\,\frac{4\pi\varepsilon}{e^2}$

Example 2: Three dimensioal Isotropic Harmonic oscillator

$$H = \hbar\omega\left(a_1^\dagger a_1 + a_2^\dagger a_2 + a_3^\dagger a_3\right) + \frac{3}{2}\hbar\omega$$



Extra degeneracies can be understood with $SU(3)$ symmetry.
Nambu-Goldstone mode:

$$Symmetry\ of\ Hamiltonian > Symmetry\ of\ States$$

Symmetry of interaction not realized in states & ground state not invariant

Example: Ferromagnetism
$T > T_C$ (Curie Temp) all magnetic dipoles are randomly oriented
$T < T_C$ all magnetic dipoles are in same direction
Ginsburg-Landau theory:

Write free energy u as function of magnetization $\overrightarrow{M}$,

$$u(\overrightarrow{M}) = (\partial_t \overrightarrow{M})^2 + \alpha_1 (T) (\overrightarrow{M} \cdot \overrightarrow{M}) + \alpha_2 (\overrightarrow{M} \cdot \overrightarrow{M})^2,$$

where

$$\alpha_2 > 0, \qquad \alpha_1 = \alpha (T - T_C) \qquad \alpha > 0$$

Here u has $O(3)$ rotational symmetry. The ground state is at

$$\overrightarrow{M}(\alpha_1 + 2\alpha_2 \overrightarrow{M} \cdot \overrightarrow{M}) = 0$$

.$T > T_C$ minimum at $\overrightarrow{M} = 0$.
$T < T_C$ minimum at $\left|\overrightarrow{M}\right| = \sqrt{\alpha_1 / 2\alpha_2} \neq 0$. If we choose $\overrightarrow{M}$ to be in some direction the rotational symmetry is broken.

Goldstone Theorem

Noether theorem: continuous symmetry $\Longrightarrow$ conserved current,

$$\partial_\mu J^\mu = 0, \qquad Q = \int d^3 x J^0 (x) , \qquad \frac{dQ}{dt} = 0$$

Suppose

$$\langle 0 | [Q, \phi (0)] | 0 \rangle = v \neq 0, \qquad \text{and } v \text{ indep of time}$$

then

$$\sum_n (2\pi)^3 \delta^3 (\vec{p}_n) [\left\langle 0 \left| J^0 \right| n \right\rangle \langle n | \phi | 0 \rangle e^{-iE_n t} - \langle 0 | \phi | n \rangle \left\langle n \left| J^0 \right| 0 \right\rangle e^{iE_n t} = \upsilon \neq 0$$

To make LHS t independent, we need

$$E_n = 0, \qquad \text{as} \qquad \vec{p}_n = 0, \quad \text{for some state } n$$

For relativistic system, energy momentum relation,

$$E_n = \sqrt{\vec{p}_n^{\,2} + m_n^2} \qquad \Rightarrow \qquad m_n = 0, \quad \text{Goldstone boson}$$

Heisenberg Ferromagnets

Hamiltonian is

$$H = -\frac{1}{2}\sum_{RR'} J(\overrightarrow{R} - \overrightarrow{R}')\overrightarrow{S}(\overrightarrow{R}) \cdot \overrightarrow{S}(\overrightarrow{R}')$$

Hamiltonian is symmetric under the rotations of the whole system. Write

$$\overrightarrow{S}(\overrightarrow{R}) \cdot \overrightarrow{S}(\overrightarrow{R}') = S_z(\overrightarrow{R}) \cdot S_z(\overrightarrow{R}') + S_-(\overrightarrow{R}) \cdot S_+(\overrightarrow{R}')$$

Ground state,

$$|g\rangle = \prod_R |S\rangle_R , \qquad S_z(\overrightarrow{R})\,|S\rangle_R = S\,|S\rangle_R$$

all spins aligned in same direction, not invariant under rotation.
Excited states:one of the spin is lowered by 1.
Define

$$\left|\overrightarrow{R}\right\rangle = \frac{1}{\sqrt{2S}} S_-(\overrightarrow{R})\,|g\rangle$$

It turns out that the combination (spin wave)

$$\left|\overrightarrow{k}\right\rangle = \frac{1}{\sqrt{N}}\sum_k e^{i\overrightarrow{k}\cdot\overrightarrow{R}}\left|\overrightarrow{R}\right\rangle , \qquad N\text{–total number of spin}, \overrightarrow{k} \text{ arbitrary vector}$$

is an eigenstate of the Hamiltonian with energy,

$$E_k - E_0 = 2S \sum_R J(\overrightarrow{R}) \sin^2 \left(\frac{\overrightarrow{k} \cdot \overrightarrow{R}}{2} \right)$$

which goes to 0 as $k \longrightarrow 0$, i. e. Goldstone excitations.

Superfluid

Helium atoms Hamiltonian,

$$H = -\frac{1}{2m}\int d^3x\psi^\dagger\nabla^2\psi + \frac{1}{2}\int d^3xd^3y\psi^\dagger(x)\psi^\dagger(y)v(x-y)\psi(x)\psi(y)$$

$v(x)$ effective potential. System in volume Ω .
H is invariant under phase transformation,

$$\psi(x) \to \psi'(x) = e^{i\alpha}\psi(x), \qquad U(1) \text{ symmetry}$$

Conserved charge,

$$Q = \int d^3x\psi^\dagger(x)\psi(x) \qquad \text{number operator}$$

and

$$[Q, \psi(x)] = \psi(x), \qquad \left[Q, \psi^\dagger(x)\right] = -\psi^\dagger(x). \tag{1}$$

In terms of creation and annihilation operators,

$$H = \sum_k \frac{\hbar^2 k^2}{2m} a_k^\dagger a_k + \frac{1}{2\Omega} \sum_{k_i} \overline{v} \left(k_1 - k_3\right) \delta_{k_1+k_2,k_3+k_4} a_{k_1}^\dagger a_{k_2}^\dagger a_{k_3} a_{k_4}$$

where

$$\overline{v}\left(k\right) = \int d^3 x e^{i\vec{k}\cdot\vec{x}} v\left(x\right)$$

If $v\left(x\right)$ is weak, most particles in $k = 0$ state,

$$< n_0 > \gg < n_k > \qquad \text{with} \qquad k \neq 0.$$

and we can approximate

$$a_0 \simeq a_0^\dagger \simeq \sqrt{n_0} = \left(c - number\right)$$

To leading order in $n_{0,}$

$$H = \sum_{k\neq 0} \omega_k a_k^\dagger a_k + \frac{n_0}{2\Omega} \sum_{k\neq 0} \overline{v}\left(k\right) \left(a_k^\dagger a_{-k}^\dagger + a_k a_{-k}\right) + \frac{N^2}{2\Omega} \overline{v}\left(0\right)$$

where

$$\omega_k = \frac{\hbar^2 k^2}{2m} + \frac{n_0}{\Omega}\bar{v}(k), \qquad N: \text{ total number of particles}$$

H can be diagonalized by Bogoliubov transformation,

$$\alpha_k = \cosh\theta_k \ a_k + \sinh\theta_k \ a^\dagger_{-k}$$

$$\alpha^\dagger_k = \cosh\theta_k \ a^\dagger_k + \sinh\theta_k \ a_{-k}$$

α_k new quasi-particle operator.
With the choice

$$\tanh 2\theta_k = \frac{\frac{n_0 \bar{v}}{\Omega}}{\omega_k}$$

Hamiltonian is diagonal,

$$H = \sum_{k\neq 0} \varepsilon_k \alpha^\dagger_k \alpha_k + \frac{N^2 v(0)}{2\Omega} + \frac{1}{2}\sum_{k\neq 0}(\varepsilon_k - \omega_k)$$

where

$$\varepsilon_k = \sqrt{\left(\frac{\hbar^2 k^2}{2m}\right)^2 + 2\left(\frac{\hbar^2 k^2}{2m}\right)\left(\frac{n_0 \bar{v}(k)}{\Omega}\right)}$$

Energy eigenvalues,

$$E = \sum_k n_k \varepsilon_k + \text{const}$$

The quai-particle energy excitation has the property that

$$\varepsilon_k \longrightarrow 0, \qquad \text{as} \qquad k \longrightarrow 0 \qquad \text{Goldstone excitation}$$

The ground state is

$$\alpha_k |\Psi_0 >= 0 \qquad \forall\, k$$

and $\psi(0)$ in the ground state is non-zero, $< \Psi_0 | \psi(0) | \Psi_0 >= \sqrt{\frac{n_0}{\Omega}} \neq 0$.

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Spontaneous Symmetry Breaking in Relativistic system

1)Global symmetry

Consider

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

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 Lagrangian is invariant under the $O(2)$ rotation

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

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 the case $\mu^2 > 0$, the minimum is at

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

points on a circle with radius v in the (σ, π) plane. They are all related to each other through $O(2)$ rotations and are all equivalent.
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 the true minimum and define a shifted field

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

The Lagrangian is

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

no quadratic term in the $\pi-$field $\quad \Rightarrow \quad \pi$ massless Goldstone boson.
Note that

massless particle $\Longrightarrow$ long range force

Nambu-Jona-Lasinio Model

Lagrangina is of the form,

$$L = \bar{\psi} i\gamma^{\mu}\partial_{\mu}\psi + G\left[\left(\bar{\psi}\psi\right)^{2} - \left(\bar{\psi}\gamma_{5}\psi\right)^{2}\right]$$

Rewrite this as

$$L = \bar{\psi}_{L} i\gamma^{\mu}\partial_{\mu}\psi_{L} + \bar{\psi}_{R} i\gamma^{\mu}\partial_{\mu}\psi_{R} + 4G\left(\bar{\psi}_{R}\psi_{L}\right)\left(\bar{\psi}_{L}\psi_{R}\right)$$

This has chiral $U(1)_{L} \times U(1)_{R}$ symmetry.
To anticipate the spontaneous generateion of fermion mass, split this as

$$L = L_{0} + L_{int}$$

with

$$L_{0} = \bar{\psi}\left(i\gamma^{\mu}\partial_{\mu} - m\right)\psi, \qquad L_{int} = m\bar{\psi}\psi + G\left[\left(\bar{\psi}\psi\right)^{2} - \left(\bar{\psi}\gamma_{5}\psi\right)^{2}\right]$$

parameter m is arbitrary

Fermion propagator is ,

$$iS_F(p) = \frac{i}{\not{p} - \Sigma(p, m)}$$

where $\Sigma(p, m)$ one-particle-irreducible self energy graphs. Take m to be the physical mass, then

$$m = \Sigma(p, m)|_{\not{p}=m}$$

Nambu and Jona-Lasinio take lowest order contribution,

$$\Sigma(p, m)|_{\not{p}=m} = 4Gi \int \frac{d^4k}{(2\pi)^4} \frac{m}{k^2 - m^2}$$

Then

$$m = 4Gi \int \frac{d^4k}{(2\pi)^4} \frac{m}{k^2 - m^2}$$

Certainly, $m = 0$ is a solution $\Longrightarrow$ unbroken symmetry.
There is also a non-trivial solution,

$$1 = 4Gi \int \frac{d^4k}{(2\pi)^4} \frac{1}{k^2 - m^2} \qquad (2)$$

where m is non-zero and symmetry is broken spontaneously. Use an ultraviolet cutoff Λ, we get

$$\frac{4\pi^2}{G\Lambda^2} = 1 - \frac{m^2}{\Lambda^2} \ln\left(\frac{\Lambda^2}{m^2} + 1\right)$$

Since LHS<1, we need

$$G > \frac{4\pi^2}{\Lambda^2} \qquad \text{critical strength} \tag{3}$$

Then Fermion is massive and chiral symmetry is broken spontaneously.
It can also be shown that the vacuum expectation value

$$\left\langle \bar{\psi}\psi \right\rangle \neq 0, \qquad \bar{\psi}\gamma_5\psi - \text{Goldstone mode}$$

Here symmetry breaking is due to the vaccum expectation value of a composite operator, called fermion condensate and Goldstone boson corresponds to a composite operator

QCD at low energies

Approximate chiral $SU(3) \times SU(3)$ symmetry broken by quark condensate $\langle \bar{q}q \rangle$ and pseudoscalar meson, π, K and η are approxiamte Goldstone bosons.

2) Local Symmetry

The Lagrangian for a simple $U(1)$ local 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

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

This is invariant under local $U(1)$ 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

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

is

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

Write

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

choose

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

$\Rightarrow \phi_2$ Goldstone boson.
New feature : covariant derivative produces mass term for the gauge boson,

$$|D_\mu \phi|^2 = |(\partial_\mu - igA_\mu) \phi|^2 \simeq \dots \frac{g^2 v^2}{2} A^\mu A_\mu + \dots \qquad (4)$$

Guage boson mass

$$M = gv$$

Instead of ϕ_1' and ϕ_2' fields we use η and ξ. We can now use gauge transformation to transform away ξ. Define

$$\phi^{''} = \exp(-i\xi/v) \phi = \frac{1}{\sqrt{2}} [v + \eta(x)] \qquad (5)$$

and

$$B_\mu = A_\mu - \frac{1}{gv} \partial_\mu \xi$$

ξ disappears. In fact ξ becomes the longitudinal component of B_μ.
massless gauge boson + Goldstone boson= massive vector meson
all long range forces disappear.

Connection with superconductivity

Equation of motion for this theory,

$$\vec{\nabla} \times \vec{B} = \vec{J}$$

with

$$\vec{J} = ie\left[\phi^\dagger\left(\vec{\nabla} - ie\vec{A}\right)\phi - \left(\vec{\nabla} + ie\vec{A}\right)\phi^\dagger\phi\right]$$

where we have replace g by e.
Spontaneous symmetry breaking $\Rightarrow \phi = v$ and

$$\vec{J} = e^2 v^2 \vec{A}$$

This is just the London equation. Then

$$\vec{\nabla} \times \left(\vec{\nabla} \times \vec{B}\right) = \vec{\nabla} \times \vec{J}, \qquad \Longrightarrow \qquad \nabla^2 \vec{B} = e^2 v^2 \vec{B}$$

This gives Meissner effect.

For the static case, $\partial_0 \overrightarrow{A} = 0$, $A_0 = 0$, we get $\overrightarrow{E} = 0$ and from Ohm's law

$$\overrightarrow{E} = \rho \overrightarrow{J}, \qquad \rho \text{ resistivity}$$

we have $\rho = 0$, i.e. superconductivity.

Standard Model of Electroweak Interaction

Construction of Standard Model (Weinberg 1967, 't Hooft 1971)

This is a gauge theory with spontaneous symmetry breaking.

Gauge group: $SU(2) \times U(1)$ gauge bosons: $\vec{A}_\mu, B_\mu$

Scalar field: $\phi = \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix}$,

Spontaneous symmetry breaking: $SU(2) \times U(1) \longrightarrow U(1)_{em}$

$$\phi = \exp\left(i\vec{\tau} \cdot \vec{\xi}(x)/v\right) \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$$

Here $\vec{\xi}(x)$, Goldstone bosons eaten up by gauge bosons to become massive. The left over field $H(x)$ is usually called **Higgs Particle.**

Massive gauge bosons:

$$\begin{aligned} W_\mu^\pm &= \frac{1}{\sqrt{2}}\left(A_\mu^1 \mp iA_\mu^2\right) & \quad & W - \text{boson} \\ Z_\mu &= \cos\theta_W A_\mu^3 - \sin\theta_W B_\mu & & Z - \text{boson} \\ A_\mu &= \sin\theta_W A_\mu^3 + \cos\theta_W B_\mu & & \text{Photon} \end{aligned}$$

Fermions:

a) Leptons

$$L_i = \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L, \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L, \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L, \qquad R_i = e_R, \mu_R, \tau_R,$$

b) Quarks (Glashow, Iliopoupos, and Maiani, Kobayashi and Maskawa)

$$q_{iL} = \begin{pmatrix} u' \\ d \end{pmatrix}_L, \begin{pmatrix} c' \\ s \end{pmatrix}_L, \begin{pmatrix} t' \\ b \end{pmatrix}_L, \qquad U_{iR} = u_R, c_R, t_R, \quad D_{iR} = d_R, s_R, b_R$$

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

Cabbibo-Kobayashi-Maskawa mixing matrix or CKM matrix for short.

Yukawa coupling:

$$\mathcal{L}_Y = f_{ij} \overline{L}_i R_j \phi + h.c. + \cdots$$

Fermions get their masses from spontaneous symmetry breaking through Yukawa couplings,

$$m_{ij} = f_{ij} v$$

This implies that the Yukawa couplings $\propto$ masses.

Highlights of the Success of Standard Model

- W and Z were discovered in1983 at SPS in CERN,
- Z boson mediates weak neutral current interactions,e.g.

$$\nu_\mu + e \longrightarrow \nu_\mu + e, \qquad \nu + N \longrightarrow \nu + X, \cdots$$

  These processes were discovered and being studies extensively in 1970's.
- t and b quarks were predicted and subsequently found
- Z bosons are studied extensively in e^+e^- machine and the results agree with theory
- ...

LHC: look for Higgs,

1. $Hf\bar{f}$ coupling $\propto m_f$ and conserves flavor
2. HVV coupling $\propto M_V$

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

Mass of Higgs particle

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

$$v = \sqrt{\frac{\sqrt{2}}{G_F}} = 246\, Gev$$

Higgs Mass

1. Bound from experimental serach
   Direct search at LEP $\Rightarrow \quad M_H > 114.4\ Gev/c^2$ ([?]).
   Indirectly, loop correction from high precision electroweak data gives $76^{+33}_{-24}\ Gev/c^2$.
2. Theoretical constraints
   1. Pertubative unitarity
      Polarization of longituinal W grows with energy.
      Lowest order W_L scattering grow with energies and eventually violates the unitarity
      $$M_H \leq 870\ Gev$$
      This is probably not a true bound but rather a limit on our ability to calculate perturbatively.

2. Triviality bound
From the renormaliztion groupe quation, to lowest order, effective quartic Higgs self coupling $\lambda\left(Q^2\right)$,

$$\lambda\left(Q^2\right) = \frac{\lambda\left(v^2\right)}{1 - \frac{3}{4\pi^2}\lambda\left(v^2\right)\log\frac{Q^2}{v^2}}$$

if neglect all other couplings which are small when M_H large.
Taken seriously, , $Q^2 \ll v^2$, $\lambda\left(Q^2\right) \to 0$. We say that the theory is trivial
But,$\lambda\left(Q^2\right) \to \infty$ at

$$Q = \Lambda_C = v \exp\left(\frac{2\pi^2}{3\lambda}\right) = v \exp\left(\frac{4\pi^2 v^2}{3M_H^2}\right)$$

This called Landau pole.
Usual argument : new physics should appear to prevent the instability to develop : the cutoff of Standard Model.
For example $\Lambda_C \sim 10^{16}\,Gev$ if $M_H \leq 200$ Gev.

3. Naturalness problem
Contribution to Higgs self energy diverges quadratically, $\Sigma_H \sim \Lambda_H^2$ and leads to a shift of Higgs mass,

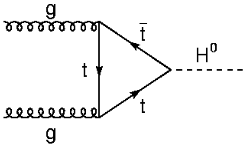
$$M_H^2 = M_{H,0}^2 + \frac{3\lambda}{16\pi^2}\Lambda_H^2$$

Treat Λ_H as scale where the Standard Model should be cutoff by some unknow new physics.
If $\Lambda_H \sim 10^{19} Gev$, then to get $M_H \leq 1 Tev$, fine tune $M_{H,0}^2$ to 30 decimal places– naturalness problem
Supersymmetry–no Λ_H^2 term

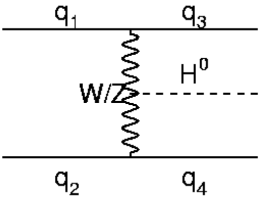
Production of Higgs Paticle

Higgs couplings $\propto$ masses $\Longrightarrow$ production through t quarks, W and Z. :

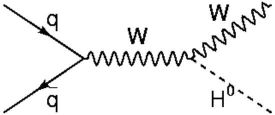
1. Gluon fusion through $t-$quark loop;



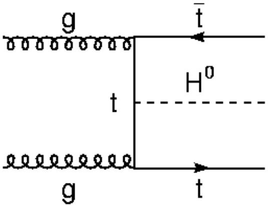
2. Vector meson fusion; $qq \longrightarrow qqH$



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

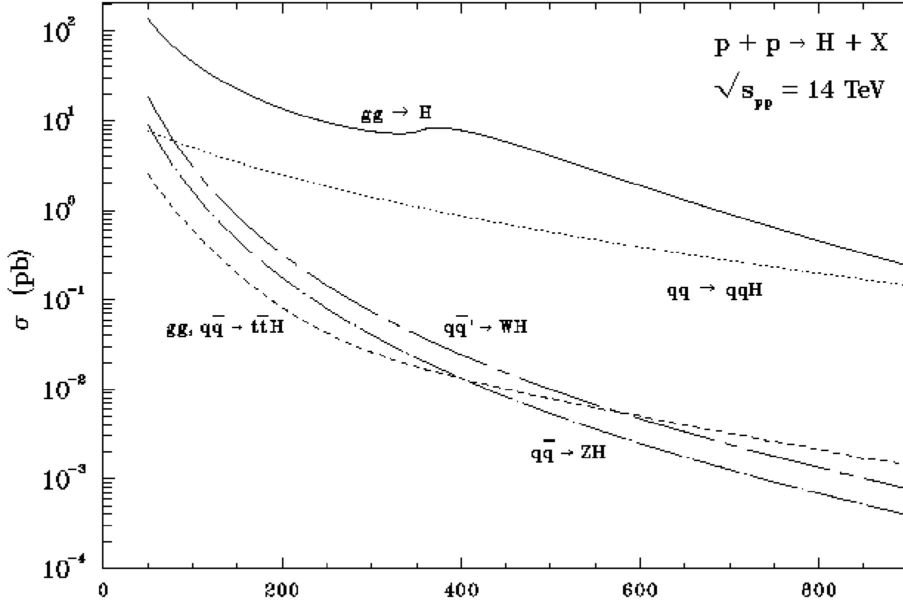


4. Associated Higgs production with heavy quarks $gg \longrightarrow ttH$



The leading order production cross sections for these 4 processes as a function of Higgs boson mass are shown below

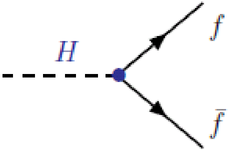
Figure 2.2: The production cross section of the standard model Higgs boson. Across the compl
mass range the gluon fusion process is dominating.



Higgs Decay

Decay into heaviest particles allowed by kinematics.

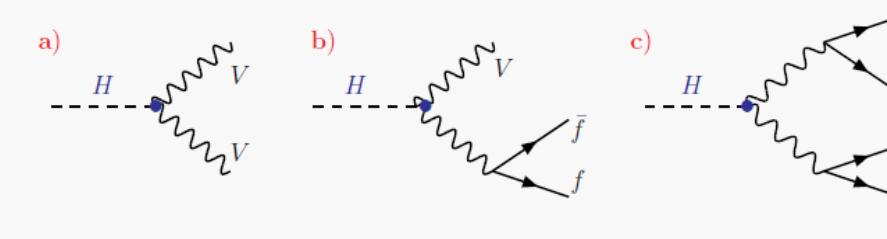
1. $H \rightarrow f\bar{f}$



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

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

2. $H \rightarrow$ gauge bosons



$H \longrightarrow VV \quad$ if $M_H > 2M_V$

Since longitudinal polarization

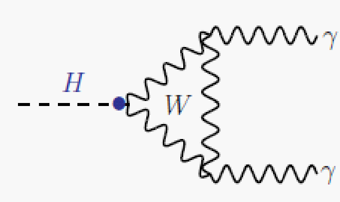
$$\varepsilon_\mu^{(L)} \simeq \frac{k_\mu}{M_V} + O\left(\frac{M_V}{E}\right), \qquad \text{with } k_\mu \text{ momentum of } V$$

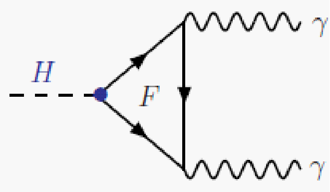
for large Higgs masses, the vector bosons are longitudinal polarized.

1. $H \longrightarrow VV^* \longrightarrow Vf\bar{f} \quad$ for $M_H < 2M_V$
   For $M_H \gtrsim 130$ Gev, $H \longrightarrow WW \longrightarrow Wf\bar{f}$ dominate over $H \longrightarrow b\bar{b}$, because HWW coupling is large enough to compensate the additional coupling constant. and

2. $H \longrightarrow V^*V^* \longrightarrow f\bar{f}, ff$
   These modes is generally small

3. Decays into $\gamma\gamma$
   This decay is of special interest due to their relatively clean experimenal signaure.





branching fractions of various Higgs decay modes are plotted as function of Higgs mass