Higgs Boson Phenomenology
Lecture I

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Outline of Lecture I

- Understanding the Electroweak Symmetry Breaking as a first step towards a more fundamental theory of particle physics.

- The Higgs mechanism and the breaking of the Electroweak Symmetry in the Standard Model.

  $\longrightarrow$ Toy model: breaking of an abelian gauge symmetry.
  $\longrightarrow$ Quantum effects in spontaneously broken gauge theories.
  $\longrightarrow$ The Standard Model: breaking of the $SU(2)_L \times U(1)_Y$ symmetry.
  $\longrightarrow$ Fermion masses through Yukawa-like couplings to the Higgs field.

- First step: calculate the SM Higgs boson decay branching ratios.

Some References for Part I

- Spontaneous Symmetry Breaking of global and local symmetries:
  - ▷ An Introduction to Quantum Field Theory,
    M.E. Peskin and D.V. Schroeder
  - ▷ The Quantum Theory of Fields, V. II, S. Weinberg
- Theory and Phenomenology of the Higgs boson(s):
  - ▷ The anatomy of the electro-weak symmetry breaking I: the Higgs boson in the standard model,
    A. Djouadi, Phys. Rep. 457 (2008) 1, hep-ph/0503172
  - ▷ The anatomy of the electro-weak symmetry breaking II: the Higgs bosons in the minimal supersymmetric model A. Djouadi,
    Phys. Rep. 457 (2008) 1, hep-ph/0503172
  - ▷ Higgs boson physics,
    L. Reina, lectures given at TASI 2004, hep-ph/0512377

Breaking the Electroweak Symmetry: Why and How?

- The gauge symmetry of the Standard Model (SM) forbids gauge boson mass terms, but:

$$M_{W^\pm} = 80.399 \pm 0.023\,\mathrm{GeV} \quad \text{and} \quad M_Z = 91.1875 \pm 0.0021\,\mathrm{GeV}$$

$$\Downarrow$$

Electroweak Symmetry Breaking (EWSB)

- Broad spectrum of ideas proposed to explain the EWSB:
  - ▷ Weakly coupled dynamics embedded into some more fundamental theory at a scale Λ (probably $\simeq$ TeV):
    $\Longrightarrow$ Higgs Mechanism in the SM or its extensions (MSSM, etc.)
    $\longrightarrow$ Little Higgs models
  - ▷ Strongly coupled dynamics at the TeV scale:
    $\longrightarrow$ Technicolor in its multiple realizations.
  - ▷ Extra dimensions beyond the 3+1 space-time dimensions

Different but related .....

- Explicit fermion mass terms also violate the gauge symmetry of the SM:

  $\longrightarrow$ introduced through new gauge invariant interactions, as dictated by the mechanism of EWSB

  $\longrightarrow$ intimately related to flavor mixing and the origin of CP-violation: new experimental evidence on this side will give further insight.

The story begins in 1964 . . .

with Englert and Brout; Higgs; Hagen, Guralnik and Kibble

VOLUME 13, NUMBER 9 PHYSICAL REVIEW LETTERS 31 AUGUST 1964

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

VOLUME 13, NUMBER 20 PHYSICAL REVIEW LETTERS 16 NOVEMBER 1964

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

Spontaneous Breaking of a Gauge Symmetry

Abelian Higgs mechanism: one vector field $A^\mu(x)$ and one complex scalar field $\phi(x)$:

$$\boxed{\mathcal{L} = \mathcal{L}_A + \mathcal{L}_\phi}$$

where

$$\mathcal{L}_A = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} = -\frac{1}{4}(\partial^\mu A^\nu - \partial^\nu A^\mu)(\partial_\mu A_\nu - \partial_\nu A_\mu)$$

and ($D^\mu = \partial^\mu + igA^\mu$)

$$\mathcal{L}_\phi = (D^\mu\phi)^* D_\mu\phi - V(\phi) = (D^\mu\phi)^* D_\mu\phi - \mu^2\phi^*\phi - \lambda(\phi^*\phi)^2$$

$\mathcal{L}$ invariant under local phase transformation, or local $U(1)$ symmetry:

$$\begin{aligned} \phi(x) &\rightarrow e^{i\alpha(x)}\phi(x) \\ A^\mu(x) &\rightarrow A^\mu(x) + \frac{1}{g}\partial^\mu\alpha(x) \end{aligned}$$

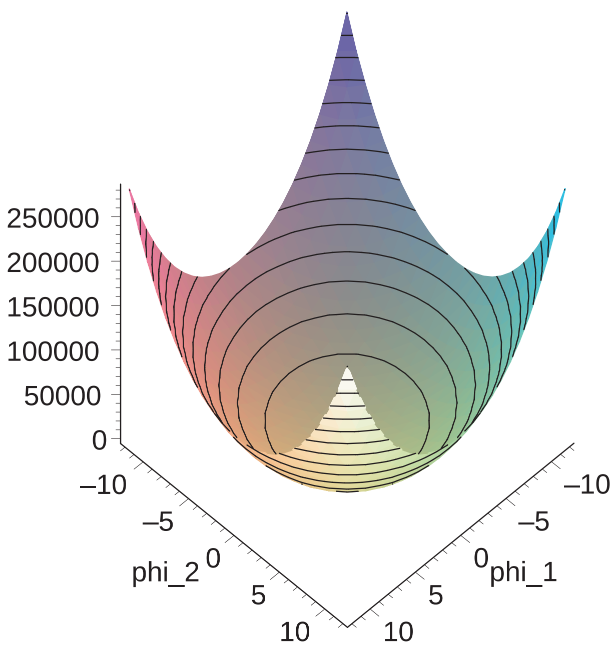
Mass term for A^μ breaks the $U(1)$ gauge invariance.

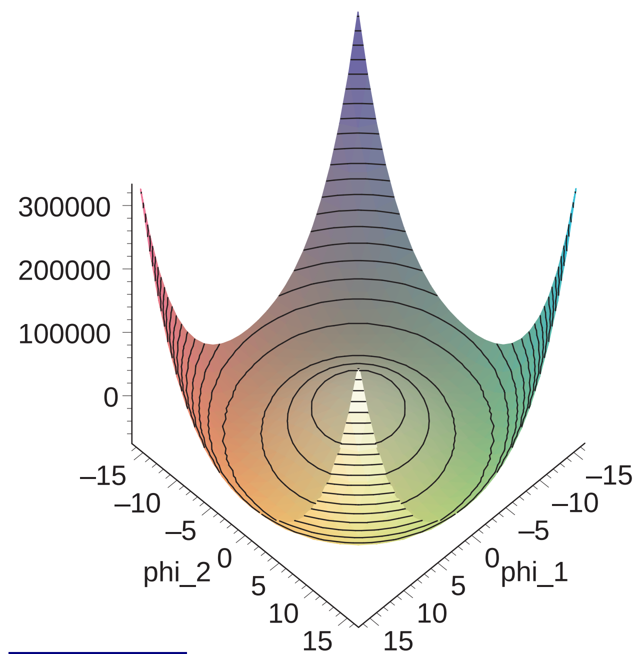
Can we build a gauge invariant massive theory? Yes.

Consider the potential of the scalar field:

$$V(\phi) = \mu^2 \phi^* \phi + \lambda(\phi^* \phi)^2$$

where $\lambda > 0$ (to be bounded from below), and observe that:





$\mu^2 > 0$ → unique minimum:

$$\phi^* \phi = 0$$

$\mu^2 < 0$ → degeneracy of minima:

$$\phi^* \phi = \frac{-\mu^2}{2\lambda}$$

- $\mu^2 > 0 \longrightarrow$ electrodynamics of a massless photon and a massive scalar field of mass μ ($g = -e$).

- $\mu^2 < 0 \longrightarrow$ when we choose a minimum, the original $U(1)$ symmetry is spontaneously broken or hidden.

$$\phi_0 = \left(-\frac{\mu^2}{2\lambda}\right)^{1/2} = \frac{v}{\sqrt{2}} \quad \longrightarrow \quad \phi(x) = \phi_0 + \frac{1}{\sqrt{2}}(\phi_1(x) + i\phi_2(x))$$

$$\Downarrow$$

$$\mathcal{L} = \underbrace{-\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}g^2v^2A^\mu A_\mu}_{\text{massive vector field}} + \underbrace{\frac{1}{2}(\partial^\mu\phi_1)^2 + \mu^2\phi_1^2}_{\text{massive scalar field}} + \underbrace{\frac{1}{2}(\partial^\mu\phi_2)^2 + gvA_\mu\partial^\mu\phi_2}_{\text{Goldstone boson}} + \ldots$$

Side remark: The ϕ_2 field actually generates the correct transverse structure for the mass term of the (now massive) A^μ field propagator:

$$\langle A^\mu(k)A^\nu(-k)\rangle = \frac{-i}{k^2 - m_A^2}\left(g^{\mu\nu} - \frac{k^\mu k^\nu}{k^2}\right) + \cdots$$

More convenient parameterization (unitary gauge):

$$\phi(x) = \frac{e^{i\frac{\chi(x)}{v}}}{\sqrt{2}}(v + H(x)) \quad \xrightarrow{U(1)} \quad \frac{1}{\sqrt{2}}(v + H(x))$$

The $\chi(x)$ degree of freedom (Goldstone boson) is rotated away using gauge invariance, while the original Lagrangian becomes:

$$\mathcal{L} = \mathcal{L}_A + \frac{g^2 v^2}{2} A^\mu A_\mu + \frac{1}{2}\left(\partial^\mu H \partial_\mu H + 2\mu^2 H^2\right) + \dots$$

which describes now the dynamics of a system made of:

- a massive vector field A^μ with $m_A^2 = g^2 v^2$;
- a real scalar field H of mass $m_H^2 = -2\mu^2 = 2\lambda v^2$: the Higgs field.

$$\Downarrow$$

Total number of degrees of freedom is balanced

Non-Abelian Higgs mechanism: several vector fields $A^a_\mu(x)$ and several (real) scalar field $\phi_i(x)$:

$$\mathcal{L} = \mathcal{L}_A + \mathcal{L}_\phi \quad , \quad \mathcal{L}_\phi = \frac{1}{2}(D^\mu\phi)^2 - V(\phi) \quad , \quad V(\phi) = \mu^2\phi^2 + \frac{\lambda}{2}\phi^4$$

($\mu^2 < 0$, $\lambda > 0$) invariant under a non-Abelian symmetry group G:

$$\phi_i \longrightarrow (1 + i\alpha^a t^a)_{ij}\phi_j \stackrel{t^a = iT^a}{\longrightarrow} (1 - \alpha^a T^a)_{ij}\phi_j$$

(s.t. $D_\mu = \partial_\mu + gA^a_\mu T^a$). In analogy to the Abelian case:

$$\begin{aligned} \frac{1}{2}(D_\mu\phi)^2 \quad &\longrightarrow \quad \ldots + \frac{1}{2}g^2(T^a\phi)_i(T^b\phi)_i A^a_\mu A^{b\mu} + \ldots \\ &\stackrel{\phi_{min}=\phi_0}{\longrightarrow} \quad \ldots + \frac{1}{2}\underbrace{g^2(T^a\phi_0)_i(T^b\phi_0)_i}_{m^2_{ab}} A^a_\mu A^{b\mu} + \ldots = \end{aligned}$$

$\boxed{T^a\phi_0 \neq 0}$ $\longrightarrow$ massive vector boson + (Goldstone boson)

$\boxed{T^a\phi_0 = 0}$ $\longrightarrow$ massless vector boson + massive scalar field

Classical $\longrightarrow$ Quantum : $\boxed{V(\phi) \longrightarrow V_{eff}(\varphi_{cl})}$

The stable vacuum configurations of the theory are now determined by the extrema of the Effective Potential:

$$V_{eff}(\varphi_{cl}) = -\frac{1}{VT}\Gamma_{eff}[\phi_{cl}] \;\;,\;\; \phi_{cl} = \text{constant} = \varphi_{cl}$$

where

$$\Gamma_{eff}[\phi_{cl}] = W[J] - \int d^4y J(y)\phi_{cl}(y) \quad , \quad \phi_{cl}(x) = \frac{\delta W[J]}{\delta J(x)} = \langle 0|\phi(x)|0\rangle_J$$

$W[J] \longrightarrow$ generating functional of connected correlation functions

$\Gamma_{eff}[\phi_{cl}] \longrightarrow$ generating functional of 1PI connected correlation functions

$V_{eff}(\varphi_{cl})$ can be organized as a loop expansion (expansion in $\hbar$), s.t.:

$$V_{eff}(\varphi_{cl}) = V(\varphi_{cl}) + \text{loop effects}$$

SSB $\longrightarrow$ non trivial vacuum configurations

Gauge fixing : the R_ξ gauges. Consider the abelian case:

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

upon SSB:

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

$$\Downarrow$$

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}(\partial^\mu\phi_1 + gA^\mu\phi_2)^2 + \frac{1}{2}(\partial^\mu\phi_2 - gA^\mu(v + \phi_1))^2 - V(\phi)$$

Quantizing using the gauge fixing condition:

$$G = \frac{1}{\sqrt{\xi}}(\partial_\mu A^\mu + \xi g v\phi_2)$$

in the generating functional

$$Z = C\int \mathcal{D}A\mathcal{D}\phi_1\mathcal{D}\phi_2 \exp\left[\int d^4x\left(\mathcal{L} - \frac{1}{2}G^2\right)\right]\det\left(\frac{\delta G}{\delta\alpha}\right)$$

($\alpha \longrightarrow$ gauge transformation parameter)

$$\begin{aligned}\mathcal{L} - \frac{1}{2}G^2 &= -\frac{1}{2}A_\mu \left(-g^{\mu\nu}\partial^2 + \left(1 - \frac{1}{\xi}\right)\partial^\mu\partial^\nu - (gv)^2 g^{\mu\nu}\right)A_\nu \\ &\quad \frac{1}{2}(\partial_\mu\phi_1)^2 - \frac{1}{2}m_{\phi_1}^2\phi_1^2 + \frac{1}{2}(\partial_\mu\phi_2)^2 - \frac{\xi}{2}(gv)^2\phi_2^2 + \cdots \\ &+ \\ \mathcal{L}_{ghost} &= \bar{c}\left[-\partial^2 - \xi(gv)^2\left(1 + \frac{\phi_1}{v}\right)\right]c\end{aligned}$$

such that:

$$\begin{aligned}\langle A^\mu(k)A^\nu(-k)\rangle &= \frac{-i}{k^2 - m_A^2}\left(g^{\mu\nu} - \frac{k^\mu k^\nu}{k^2}\right) + \frac{-i\xi}{k^2 - \xi m_A^2}\left(\frac{k^\mu k^\nu}{k^2}\right) \\ \langle \phi_1(k)\phi_1(-k)\rangle &= \frac{-i}{k^2 - m_{\phi_1}^2} \\ \langle \phi_2(k)\phi_2(-k)\rangle &= \langle c(k)\bar{c}(-k)\rangle = \frac{-i}{k^2 - \xi m_A^2}\end{aligned}$$

Goldtone boson ϕ_2, $\Longleftrightarrow$ longitudinal gauge bosons

The Higgs sector of the Standard Model :
$SU(2)_L \times U(1)_Y \xrightarrow{SSB} U(1)_Q$

Introduce one complex scalar doublet of $SU(2)_L$ with $Y=1/2$:

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad \longleftrightarrow \quad \mathcal{L} = (D^\mu\phi)^\dagger D_\mu\phi - \mu^2\phi^\dagger\phi - \lambda(\phi^\dagger\phi)^2$$

where $D_\mu\phi = (\partial_\mu - igA_\mu^a\tau^a - ig'Y_\phi B_\mu)$, ($\tau^a = \sigma^a/2$, $a=1,2,3$).

The SM symmetry is spontaneously broken when $\langle\phi\rangle$ is chosen to be (e.g.):

$$\langle\phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix} \quad \text{with} \quad v = \left(\frac{-\mu^2}{\lambda}\right)^{1/2} \quad (\mu^2 < 0,\ \lambda > 0)$$

The gauge boson mass terms arise from:

$$(D^\mu\phi)^\dagger D_\mu\phi \quad \longrightarrow \quad \cdots + \frac{1}{8}(0\ \ v)\left(gA_\mu^a\sigma^a + g'B_\mu\right)\left(gA^{b\mu}\sigma^b + g'B^\mu\right)\begin{pmatrix} 0 \\ v \end{pmatrix} + \cdots$$

$$\longrightarrow \quad \cdots + \frac{1}{2}\frac{v^2}{4}\left[g^2(A_\mu^1)^2 + g^2(A_\mu^2)^2 + (-gA_\mu^3 + g'B_\mu)^2\right] + \cdots$$

And correspond to the weak gauge bosons:

$$W^{\pm}_{\mu} = \frac{1}{\sqrt{2}}(A^1_\mu \pm A^2_\mu) \longrightarrow \boxed{M_W = g\frac{v}{2}}$$

$$Z^0_\mu = \frac{1}{\sqrt{g^2+g'^2}}(gA^3_\mu - g'B_\mu) \longrightarrow \boxed{M_Z = \sqrt{g^2+g'^2}\frac{v}{2}}$$

while the linear combination orthogonal to Z^0_μ remains massless and corresponds to the photon field:

$$A_\mu = \frac{1}{\sqrt{g^2+g'^2}}(g'A^3_\mu + gB_\mu) \longrightarrow \boxed{M_A = 0}$$

Notice: using the definition of the weak mixing angle, θ_w:

$$\cos\theta_w = \frac{g}{\sqrt{g^2+g'^2}} \quad , \quad \sin\theta_w = \frac{g'}{\sqrt{g^2+g'^2}}$$

the W and Z masses are related by: $\boxed{M_W = M_Z\cos\theta_w}$

The scalar sector becomes more transparent in the unitary gauge:

$$\phi(x) = \frac{e^{\frac{i}{v}\vec{\chi}(x)\cdot\vec{\tau}}}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix} \quad \xrightarrow{SU(2)} \quad \phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$$

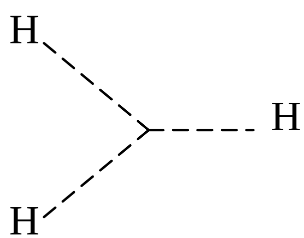
after which the Lagrangian becomes

$$\mathcal{L} = \mu^2 H^2 - \lambda v H^3 - \frac{1}{4} H^4 = -\frac{1}{2} M_H^2 H^2 - \sqrt{\frac{\lambda}{2}} M_H H^3 - \frac{1}{4} \lambda H^4$$

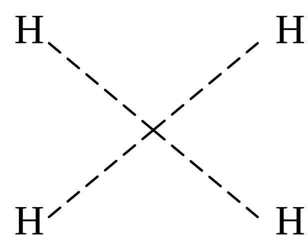
Three degrees of freedom, the $\chi^a(x)$ Goldstone bosons, have been reabsorbed into the longitudinal components of the $W_\mu^\pm$ and Z_μ^0 weak gauge bosons. One real scalar field remains:

the Higgs boson, H, with mass $\boxed{M_H^2 = -2\mu^2 = 2\lambda v^2}$

and self-couplings:

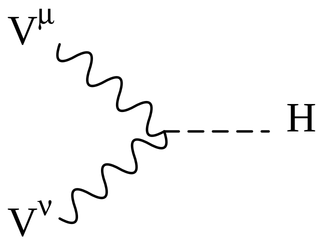


$= -3i\frac{M_H^2}{v}$

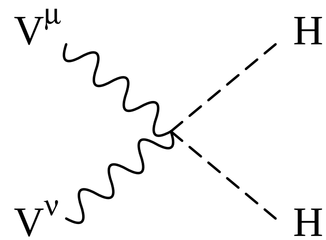


$= -3i\frac{M_H^2}{v^2}$

From $(D^\mu\phi)^\dagger D_\mu\phi \longrightarrow$ Higgs-Gauge boson couplings:



$$= 2i\frac{M_V^2}{v}g^{\mu\nu}$$



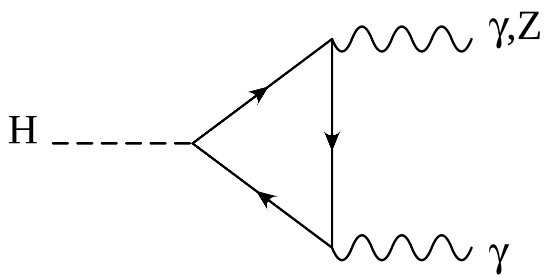
$$= 2i\frac{M_V^2}{v^2}g^{\mu\nu}$$

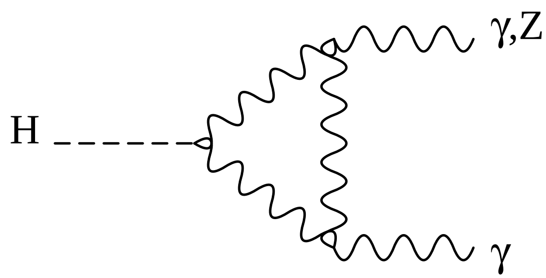
Notice: The entire Higgs sector depends on only two parameters, e.g.

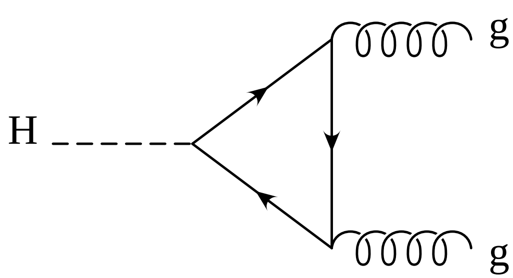
$$M_H \text{ and } v$$

v measured in μ-decay:
$v = (\sqrt{2}G_F)^{-1/2} = 246$ GeV $\longrightarrow$ SM Higgs Physics depends on M_H

Also: remember Higgs-gauge boson loop-induced couplings:







They will be discussed in the context of Higgs boson decays.

Finally: Higgs boson couplings to quarks and leptons

The gauge symmetry of the SM also forbids fermion mass terms $(m_{Q_i} Q_L^i u_R^i, \ldots)$, but all fermions are massive.

$$\Downarrow$$

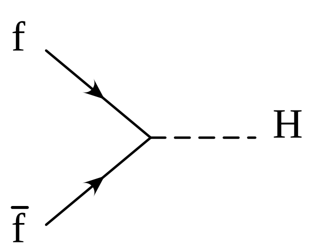
Fermion masses are generated via gauge invariant Yukawa couplings:

$$\mathcal{L}_{Yukawa} = -\Gamma_u^{ij} \bar{Q}_L^i \phi^c u_R^j - \Gamma_d^{ij} \bar{Q}_L^i \phi d_R^j - \Gamma_e^{ij} \bar{L}_L^i \phi l_R^j + h.c.$$

such that, upon spontaneous symmetry breaking:

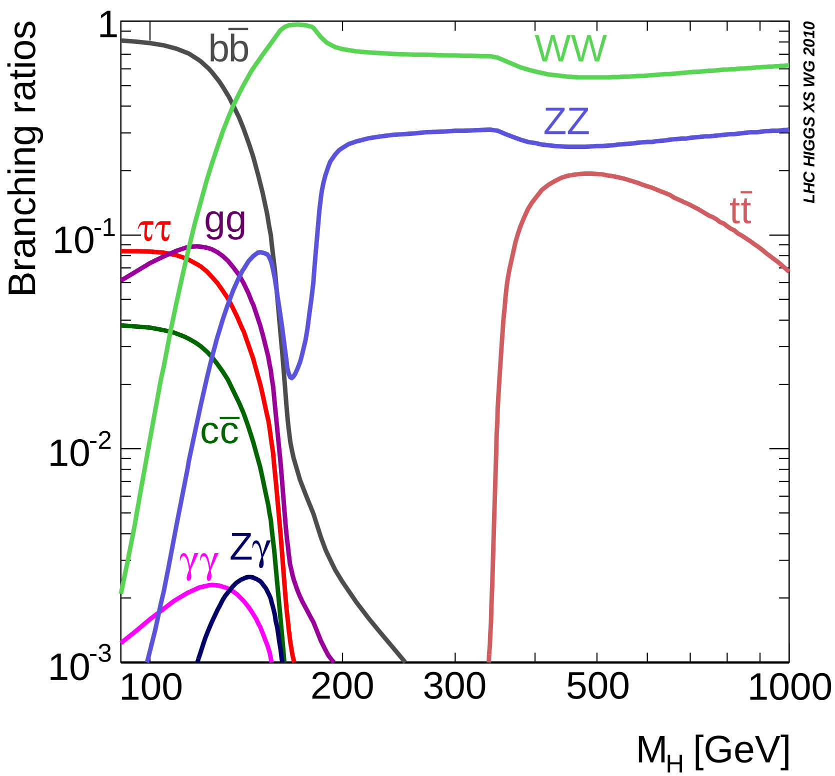
$$\phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix} \longrightarrow \boxed{m_f = \Gamma_f \frac{v}{\sqrt{2}}}$$

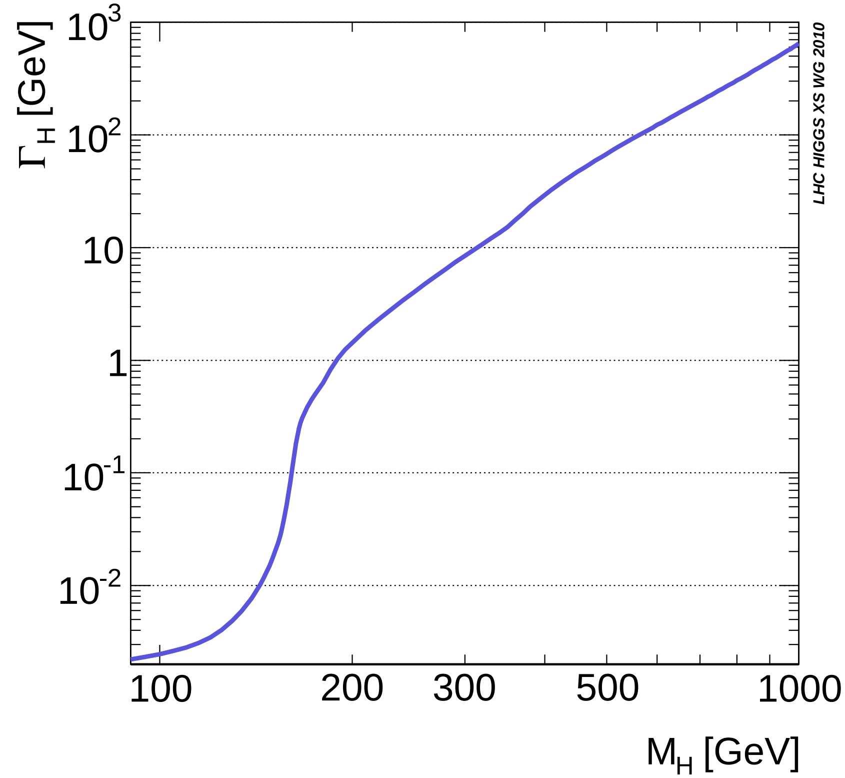
and



$$= -i \frac{m_f}{v} = -i y_t$$

SM Higgs boson decay branching ratios and width





Observe difference between light and heavy Higgs

These curves include: tree level + QCD and EW loop corrections.

Exercise: Calculate first order predictions and compare to HDECAY (M. Spira).