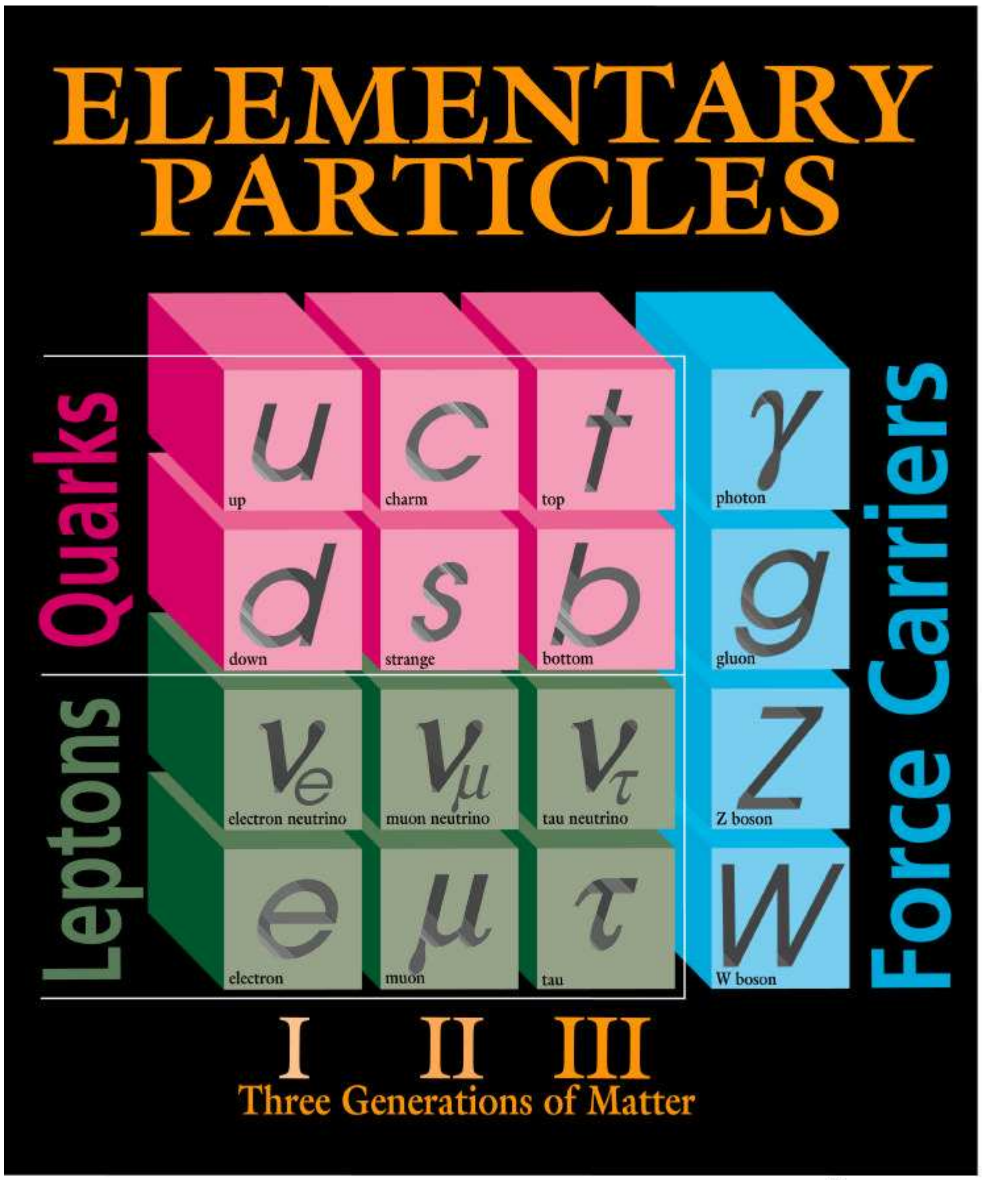
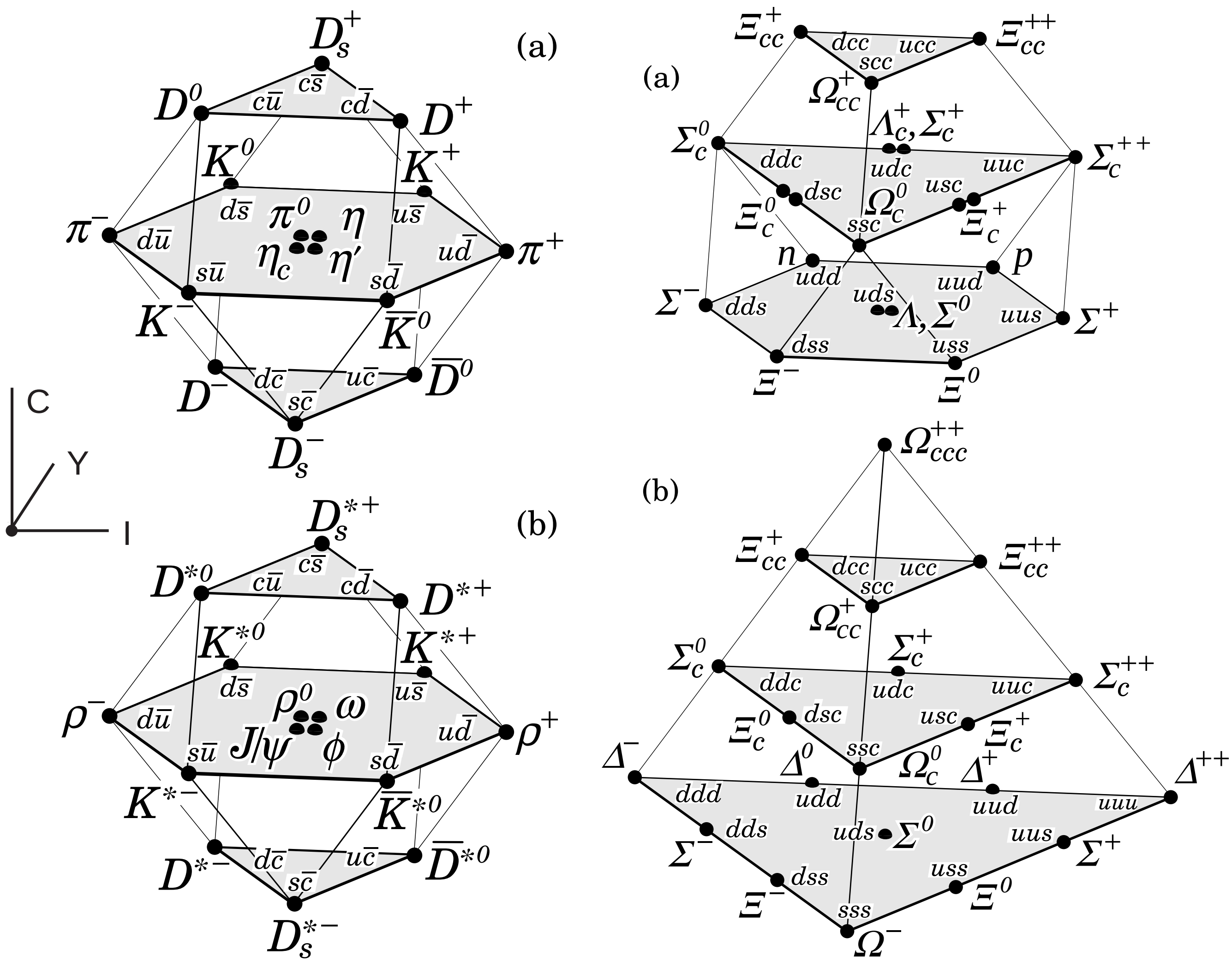
Standard Model



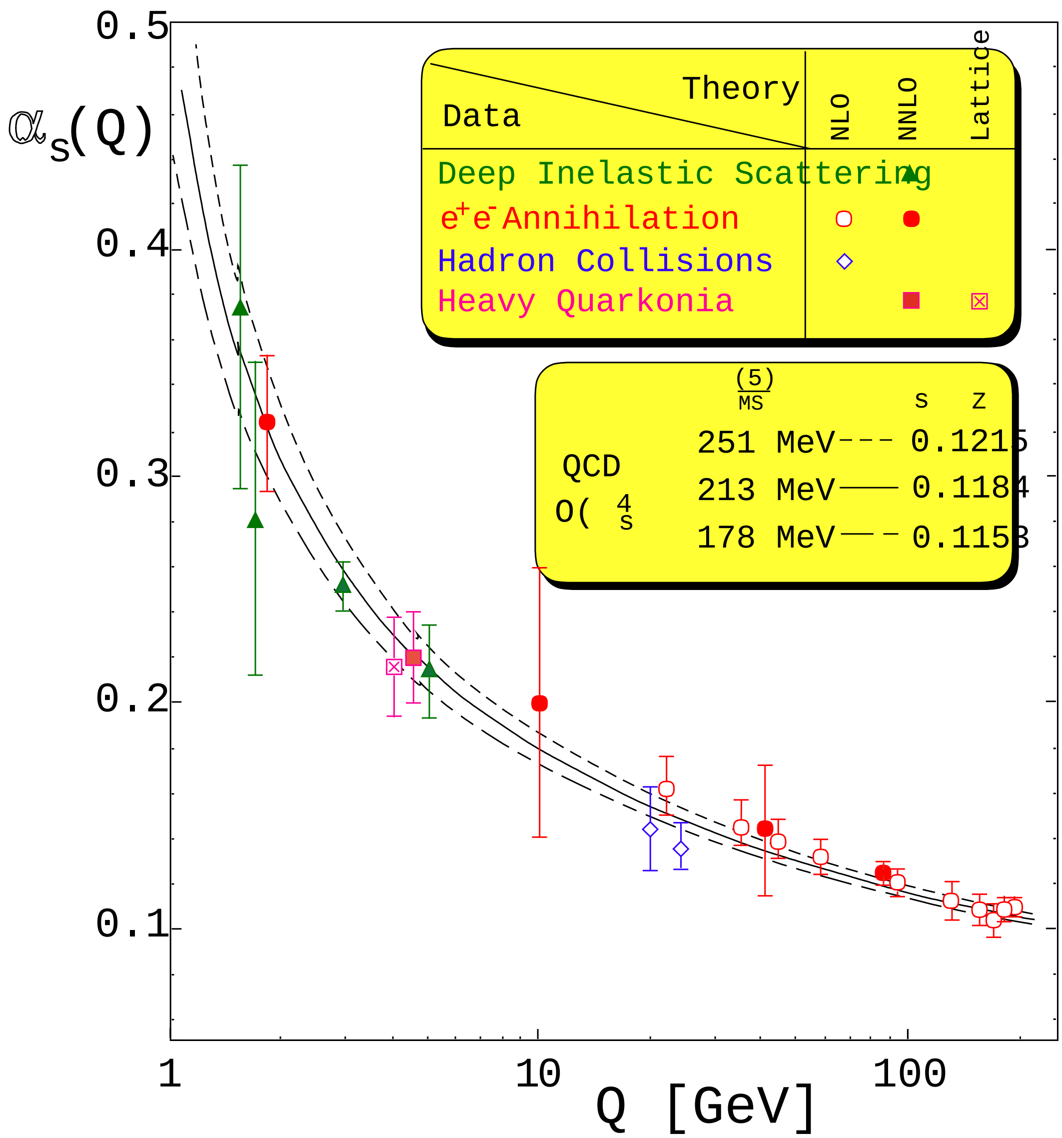
Fermilab 95-759

Quantum Chromodynamics

Hadrons – mesons and baryons – are "bound states" of quarks and gluons.



- Asymptotic freedom : the effective coupling vanishes at high energies



– Interactions of quarks and gluons visible at high energies

– Perturbation applicable, but parameters connecting quarks/gluons to hadrons need to be known

  * structure functions (parton distributions)
  * decay constants ($f_\pi, \cdots$)
  * wave functions (quarkonia)

⋮

- Color confinement : neither free quarks nor free gluons
  - Crucial to separate short– and long–distance physics
- QCD Lagrangian
  - Gauge group : SU(3)

    gluons 8

    quarks $(3_L + 3_R) \times n_f$

    n_f : #(flavors)
  - Parameters : masses generated by Higgs mechanism

    gauge coupling $\alpha_s = \frac{g_s^2}{4\pi}$

    quark masses $m_u, m_d, m_s, m_c, m_b, m_t$

$$\mathcal{L}_{\rm QCD} = -\frac{1}{4} G^a_{\mu\nu} G^{a\,\mu\nu} + \sum_q \bar{q}(i\not{D} - m_q) q$$

Gauged Higgs System

- SU(2)$_L$ doublet : φ with hypercharge $Y = 1/2$

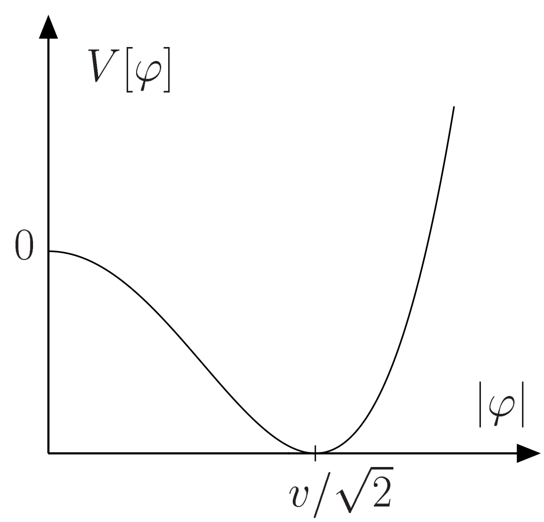
$$\varphi = \frac{1}{\sqrt{2}} \begin{pmatrix} i(\varphi_1 - i\varphi_2) \\ \varphi_0 - i\varphi_3 \end{pmatrix} \qquad \begin{array}{ll} \mathrm{SU}(2) & : \ \varphi \rightarrow \exp(iT_a\theta^a)\,\varphi \\ \mathrm{U}(1) & : \ \varphi \rightarrow \exp(iY\theta)\,\varphi \end{array}$$

- Potential : The gauge invariant and renormalizable Lagrangian

$$\mathcal{L}_{Higgs} = (D^\mu\varphi)^\dagger D_\mu\varphi - V(\varphi)$$

for the Higgs doublet is given by the most general potential

$$V(\varphi) = \mu^2\varphi^\dagger\varphi + \lambda(\varphi^\dagger\varphi)^2$$



– O(4) ≡ SU(2)$_L$×SU(2)$_R$: $\varphi^\dagger\varphi = \frac{1}{2}\left(\varphi_0^2 + \varphi_1^2 + \varphi_2^2 + \varphi_3^2\right) \equiv \frac{1}{2}\eta$

Spontaneous Breaking of SU(2)$_L\times$U(1)$_Y$

- $\boxed{\mu^2 < 0 \text{ and } \lambda > 0}$ (vacuum stability) :

$$\frac{\partial V}{\partial \eta} = \frac{1}{2}\mu^2 + \frac{1}{2}\lambda\eta = 0 \;\Rightarrow\; \eta = -\frac{\mu^2}{\lambda} \equiv v^2$$

$$\varphi_0 = v, \quad \varphi_a = 0 \quad (a = 1,2,3)$$

with losing the generality leading to the vacuum expectation value (vev) of the Higgs doublet

$$\langle\varphi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix}$$

- Unbroken gauge symmetry leaving $\langle\varphi\rangle$ invariant

$$Q = T_3 + Y = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \;\Rightarrow\; SU(2)_L \times U(1)_Y \to U(1)_{EM}$$

- The potential itself has the custodial SU(2)$_D$ symmetry.

$$SU(2)_L \times SU(2)_R \to SU(2)_D$$

This group is the symmetry of the Higgs potential only; in the full theory SU(2)$_R$ and SU(2)$_D$ are explicitly broken by the U(1)$_Y$ gauge interactions.

Gauge Boson Masses

- SU(2)$_L\times$U(1)$_Y$ covariant derivative

$$D_\mu\varphi = \left(\partial_\mu + ig\frac{\tau_a}{2}W_\mu^a + ig'\frac{1}{2}B_\mu\right)\varphi$$

- Gauge boson mass terms come from the Higgs kinetic term :

$$\mathcal{L} = (\mathcal{D}^\mu\langle\varphi\rangle)^\dagger\mathcal{D}_\mu\langle\varphi\rangle \Leftarrow \langle\varphi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v\end{pmatrix}$$

$$= \frac{v^2}{8}\left\{g^2\left[(W_\mu^1)^2+(W_\mu^2)^2\right]+(gW_\mu^3-g'B_\mu)^2\right\}$$

$$W_\mu^\pm = \frac{1}{\sqrt{2}}\left(W_\mu^1 \mp iW_\mu^2\right)$$

$$Z_\mu = \frac{1}{\sqrt{g^2+g'^2}}\left(gW_\mu^3 - g'B_\mu\right)$$

$$= \frac{1}{4}g^2v^2W_\mu^\dagger W^\mu + \frac{1}{8}(g^2+g'^2)v^2Z^\mu Z_\mu \equiv m_W^2W_\mu^\dagger W^\mu + \frac{1}{2}m_Z^2Z^\mu Z_\mu$$

$$m_W = \frac{1}{2}gv \qquad v \approx 246\ \text{GeV}$$

$$m_Z = \frac{1}{2}\sqrt{g^2+g'^2}\,v > m_W$$

  - The state orthogonal to Z_μ

$$A_\mu = \frac{1}{\sqrt{g^2+g'^2}}\left(g'W_\mu^3 + gB_\mu\right)$$

is massless so that it is nothing but the photon field.

– The weak mixing angle θ_W is defined as

$$\tan\theta_W = \frac{g'}{g} \Rightarrow \begin{cases} Z_\mu = W_\mu^3 \cos\theta_W - B_\mu \sin\theta_W \\ A_\mu = W_\mu^3 \sin\theta_W + B_\mu \cos\theta_W \end{cases}$$

- Among the four scalar fields $\varphi_i (i = 0, 1, 2, 3)$ the three fields $(\varphi_1, \varphi_2, \varphi_3)$ become the longitudinal components of the massive gauge bosons $(W^\pm, Z)$ while $\varphi_0 = (v + H)/\sqrt{2}$ remains as a physical field - this is called the Higgs boson.

- The so–called ρ parameter

$$\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = \frac{g_Z^2/m_Z^2}{g^2/m_W^2} = \frac{\text{NC Fermi coupling}}{\text{CC Fermi coupling}}$$

– SM Higgs : $\rho = 1$

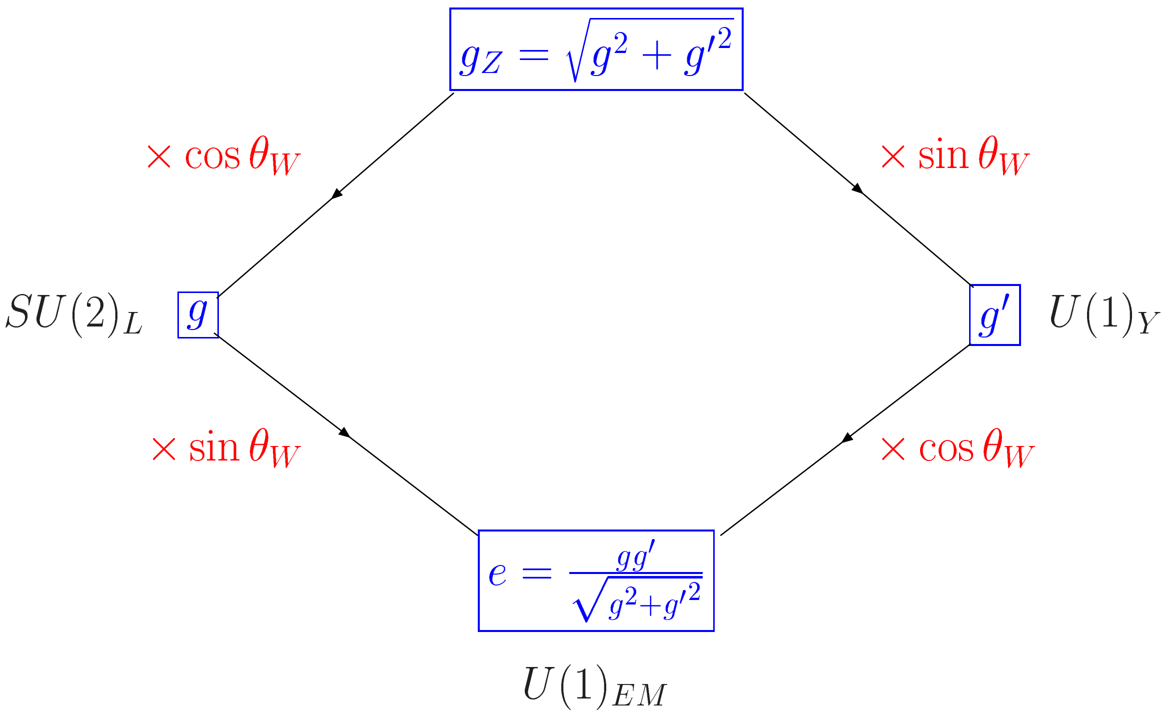
– General Higgs :

$$\begin{aligned} m_W^2 &= \frac{1}{2}\langle I_3|(I^+I^- + I^-I^+)|I_3\rangle g^2\langle\varphi\rangle^2 \\ &= \left[I(I+1) - I_3^2\right] g^2\langle\varphi\rangle^2 \qquad\qquad I^\pm = I^1 \pm iI^2 \\ m_Z^2 &= 2I_3^2\,(g^2 + g'^2)\langle\varphi\rangle^2 \end{aligned}$$

$$\Rightarrow \rho = \frac{m_W^2}{m_Z^2\cos^2\theta_W} = \frac{I(I+1) - I_3^2}{2I_3^2}$$

$$\begin{aligned} (I, I_3) &= \left(\frac{1}{2}, \pm\frac{1}{2}\right) \to \rho = 1 \qquad (1,\ \pm 1) \to \rho = \frac{1}{2} \\ & \quad (1,\ 0) \to \rho = \infty \qquad \left(\frac{3}{2}, \pm\frac{3}{2}\right) \to \rho = \frac{1}{3} \quad \cdots \end{aligned}$$

$$\boxed{\tan\theta_W = \frac{g'}{g}} \qquad \sin/\cos\theta_W = \frac{g'/g}{\sqrt{g^2+g'^2}}$$



SU(2)×U(1) Gauge Interactions

- Covariant derivative in terms of physical gauge bosons

$$D_\mu = \partial_\mu + \frac{ig}{\sqrt{2}}\left(I^+ W_\mu + I^- W_\mu^\dagger\right) + igI_3 W_\mu^3 + ig' Y B_\mu$$

$$Y = Q - I_3 \qquad \{W^3, B\} \to \{Z, A\}$$

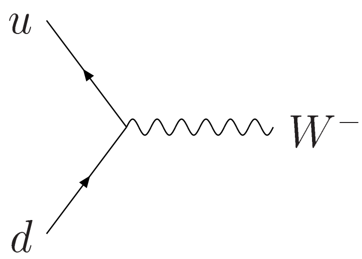
$$= \partial_\mu + \frac{ig}{\sqrt{2}}\left(I^+ W_\mu + I^- W_\mu^\dagger\right) + ig_Z\left(I_3 - Q\sin^2\theta_W\right) Z_\mu + ieQA_\mu$$

  - $W^\pm$ couples with pure SU(2) gauge coupling
  - Z couples to a linear combination of SU(2) and EM charge
  - γ couples to the electric charge $Q \Rightarrow$ QED

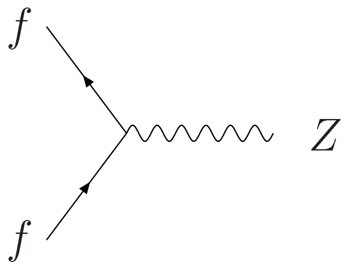
Particle Names	I	$Y = \langle Q \rangle$	$SU(3)_C$
$l_L = \begin{bmatrix} \nu \\ e \end{bmatrix}_L$	$\frac{1}{2}$	$-\frac{1}{2}$	1
e_R	0	-1	1
$q_L = \begin{bmatrix} u \\ d \end{bmatrix}_L$	$\frac{1}{2}$	$\frac{1}{6}$	3
u_R	0	$\frac{2}{3}$	3
d_R	0	$-\frac{1}{3}$	3
$\varphi = \begin{bmatrix} \varphi^+ \\ \varphi^0 \end{bmatrix}$	$\frac{1}{2}$	$\frac{1}{2}$	1
$\tilde{\varphi} = \begin{bmatrix} -\varphi^{0*} \\ \varphi^- \end{bmatrix}$	$\frac{1}{2}$	$-\frac{1}{2}$	1

- Fermion gauge interactions

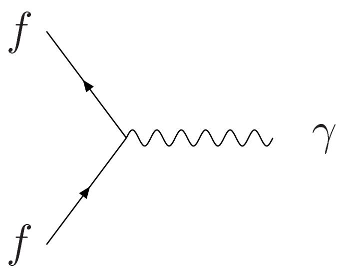
$$\mathcal{L} = \sum_{\text{fermions}} \bar{\psi}_L\, i\, \not{D} \psi_L + \bar{\psi}_R\, i\, \not{D} \psi_R$$



$$-\frac{i}{\sqrt{2}}\, g\gamma_\mu P_L$$



$$-ig_Z\gamma_\mu\left(I_3 P_L - Q\sin^2\theta_W\right)$$



$$-ieQ\gamma_\mu$$

- Yang–Mills Interactions

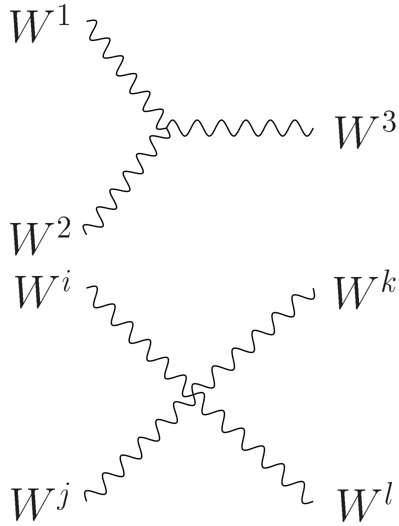
$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f^{abc} A^b_\mu A^c_\nu$$

$$[\mathsf{T}^a, \mathsf{T}^b] = i\, f^{abc}\mathsf{T}^c \qquad \mathrm{Tr}(\mathsf{T}^a\mathsf{T}^b) = \frac{1}{2}\delta^{ab}$$

$$\begin{aligned}\mathcal{L} &= -\frac{1}{4} F^a_{\mu\nu} F^{a\,\mu\nu} \\ &= -\frac{1}{4}\left(\partial_\mu A^a_\nu - \partial_\nu A^a_\mu\right)^2 - g f^{abc}\partial_\mu A^a_\nu A^{b\,\mu} A^{c\,\nu} \\ &\quad -\frac{1}{4} g^2 f^{abe} f^{cde} A^a_\mu A^b_\nu A^{c\mu} A^{d\nu}\end{aligned}$$

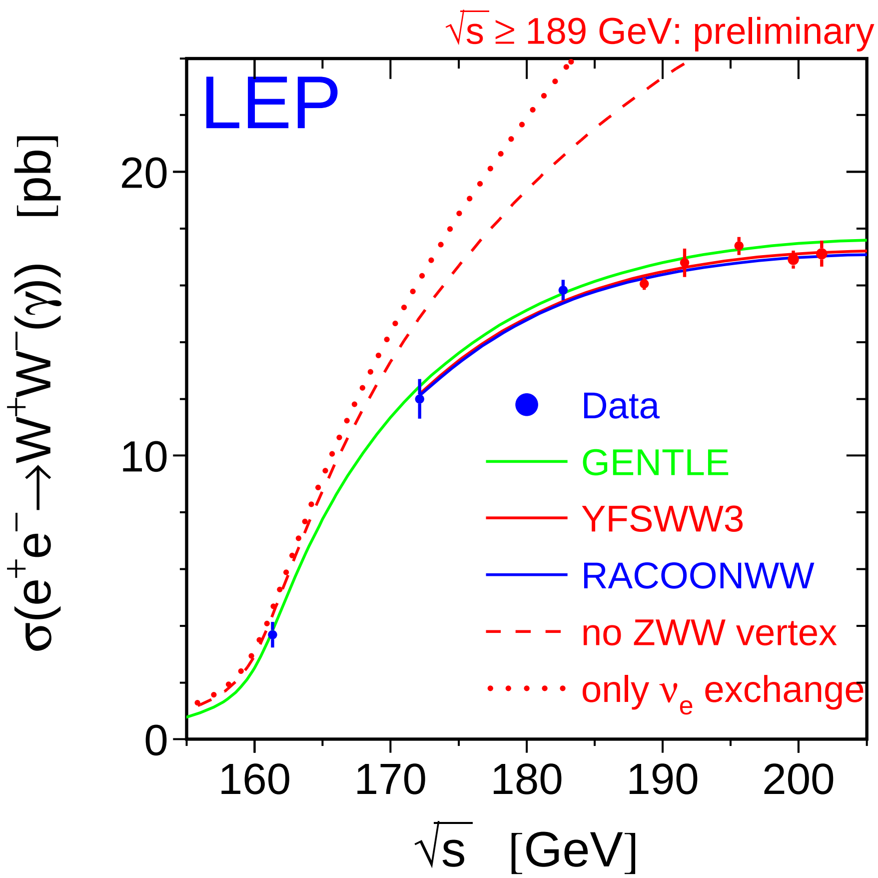
  – SU(2) : $f^{abc} = \epsilon^{abc}$ $[a = 1, 2, 3]$
  – Gauge boson self couplings*

*Higgs–gauge/Higgs–fermion interactions later



$W^+W^-[Z/\gamma]$

$W^+W^-[W^+W^-/ZZ/Z\gamma/\gamma\gamma]$



Fermion Masses

- Only Higgs doublets can give known fermion masses while any nontrivial Higgs representation can give gauge boson masses
- Fermions cannot have SU(2)×U(1) invariant mass term, i.e. quarks and leptons are massless before symmetry breaking
- A single doublet φ can generate masses of all quarks, leptons and $W^\pm, Z$
- Yukawa interactions [only one generation is considered] :

$$
\begin{aligned}
-\mathcal{L} &= f\,(\bar{q}_L \bar{d})\,\varphi - h\,(\bar{q}_L \bar{u})\,\tilde{\varphi} + \text{h.c.} \\
&\qquad \langle\varphi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix} \qquad \langle\tilde{\varphi}\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} -v \\ 0 \end{pmatrix} \\
&= \frac{1}{\sqrt{2}} f v (\bar{d} d) + \frac{1}{\sqrt{2}} h v (\bar{u} u) \equiv \mathrm{m_d \bar{d} d + m_u \bar{u} u}
\end{aligned}
$$

$$
\Rightarrow \mathrm{m_d} = \frac{1}{\sqrt{2}}\mathrm{fv} \quad \mathrm{m_u} = \frac{1}{\sqrt{2}}\mathrm{hv}
$$

Minimal Model based on SU(2)×U(1)×SU(3)

- The only dimensionful parameter is v; all other masses are secondary

$$
\begin{aligned}
m_W &= \tfrac{1}{2} g v & m_Z &= \tfrac{1}{2} g_Z v \\
m_u &= \tfrac{1}{\sqrt{2}} h_u v & m_d &= \tfrac{1}{\sqrt{2}} f_d v \\
m_l &= \tfrac{1}{\sqrt{2}} f_l v & m_H &= \sqrt{2}\lambda^{1/2} v
\end{aligned}
$$

- Neutrinos were exactly massless within the SM ⇒ Not any more
- Baryon and lepton numbers are automatically conserved (no renormalizable B/L–violating interactions) ⇒ Probably not any more

Quark Masses and Mixings

Consider n generations of quarks $\{ \underbrace{q^0_{Li} = (u^0_{Li}, d^0_{Li}), \; u^0_{Ri}, \; d^0_{Ri}}_{\text{complex fields}} \}$, $i = 1 - n$

① Kinetic + gauge terms for these fields is symmetric under $U(n) \times U(n) \times U(n)$

$$q^0_L \to \underset{n\times n}{U_1} q^0_L, \quad u^0_R \to \underset{n\times n}{U_2} u^0_R, \quad d^0_R \to \underset{n\times n}{U_3} d^0_R \; ; \quad U_{1,2,3} : \text{unitary} \quad \text{i.e. } U_i^+ U_i = 1$$

- Gauge bosons are blind of generations $\quad q^0_L = \begin{pmatrix} q^0_{L1} \\ \vdots \\ q^0_{Ln} \end{pmatrix}$ etc
- Every generation cannot be distinguished from one another

② Yukawa interactions break the symmetry (generally)

$$-\mathcal{L}_Y = f_{ij} \bar{d}^0_{Ri} \phi^+ q^0_{Lj} + h_{ij} \bar{u}^0_{Ri} \tilde{\phi}^+ q^0_{Lj} + h.c.$$

- Yukawa terms are the ONLY source of symmetry breaking in SM with $\langle \varphi^0 \rangle = v/\sqrt{2}$

③ f's and h's have $4n^2$ (real) parameters in total. But not all of them are physically observable. The symmetry of the kinetic term implies a kind of reparametrization invariance :

The transformation $f \to U_3^\dagger f U_1$, $h \to U_2^\dagger h U_1$ leaves the physics unchanged.

④ A $U(1)$ subgroup of $U(n)^3$, with $U_1 = U_2 = U_3 = e^{i\alpha}$ does NOT change f and h.

The effective reparametrization group is thus $U(n)^3 / U(1)$.

⑤ The space of physical parameters is therefore $\boxed{\mathbb{R}^{4n^2} / \left(U(n)^3 / U(1) \right)}$

- Dimension $= 4n^2 - (3 \times n^2 - 1) = n^2 + 1$

- $n^2 + 1 = 2n + \frac{1}{2} n(n-1) + \frac{1}{2}(n-1)(n-2)$

	particle masses	mixing angles (flavor violation)	phases (CP violation)
$n =$ 2	4	1	0 (no $\not{CP}$)
3	6	3	1 ($\not{CP}$) — realized in Nature
4	8	6	3 (〃)
⋮	⋮	⋮	⋮

(Cabibbo-)Kobayashi-Maskawa Matrix $\equiv$ KM matrix

① Gauge symmetry breaking $\langle \varphi^0 \rangle = \frac{v}{\sqrt{2}}$: $M_d = \frac{v}{\sqrt{2}} f$, $M_u = \frac{v}{\sqrt{2}} h$: $n \times n$

$$-\mathcal{L}_m = \bar{d}^0_R M_d d^0_L + \bar{u}^0_R M_u u^0_L + \text{h.c.}$$

Theorem (SVD): A complex $n \times n$ matrix M can be written as
$M = U^{+} D U'$ with unitary U and U'
D : diagonal with its diagonal elements ≥ 0

∇

$$M_u = U_R^{+} M_u^D U_L \qquad M_d = V_R^{+} M_d^D V_L$$

with $u_{R,L} = U_{R,L} u^0_{R,L}$ and $d_{R,L} = V_{R,L} d^0_{R,L}$

$M_u^D = \text{diag}(m_{u_1}, \ldots, m_{u_n})$
$M_d^D = \text{diag}(m_{d_1}, \ldots, m_{d_n})$

$$\Rightarrow \quad -\mathcal{L}_m = m_{u_i}(\bar{u}_{R_i} u_{L_i} + \bar{u}_{L_i} u_{R_i}) + m_{d_i}(\bar{d}_{R_i} d_{L_i} + \bar{d}_{L_i} d_{R_i}) \quad : \text{diagonal}$$

$$U_L \cdot \begin{pmatrix} u^0_L \\ d^0_L \end{pmatrix} = \begin{pmatrix} U_L u^0_L \\ U_L d^0_L \end{pmatrix} = \begin{pmatrix} u_L \\ U_L V_L^{+} d_L \end{pmatrix} \equiv \begin{pmatrix} u_L \\ K d_L \end{pmatrix} = \begin{pmatrix} u_L \\ d'_L \end{pmatrix}$$

$\Rightarrow$ **KM matrix $K \equiv U_L V_L^{+}$ linking d'_L to d_L : $n \times n$ complex !**

② Standard parameters : three Euler angles (θ_{12}, θ_{23}, θ_{31}) and one phase (δ_{13})

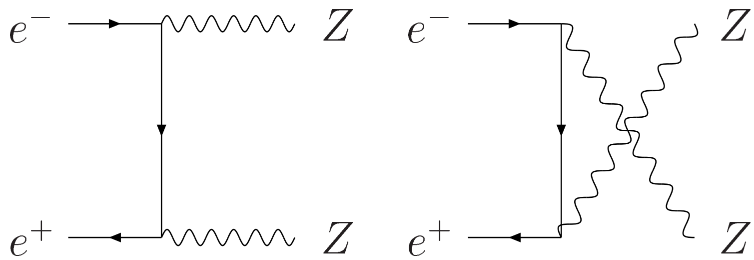
$$K = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{bmatrix}$$

Higgs Phenomenology

Minimal Higgs Boson

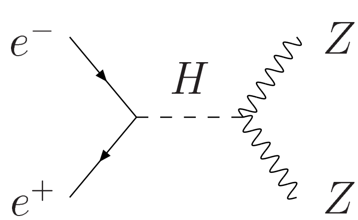
Something needed in $J = 0$ sector

- Assume SU(2)×U(1) without Higgs and with $W^{\pm}, Z$ masses put by hand
  - $e^+e^- \to ZZ$

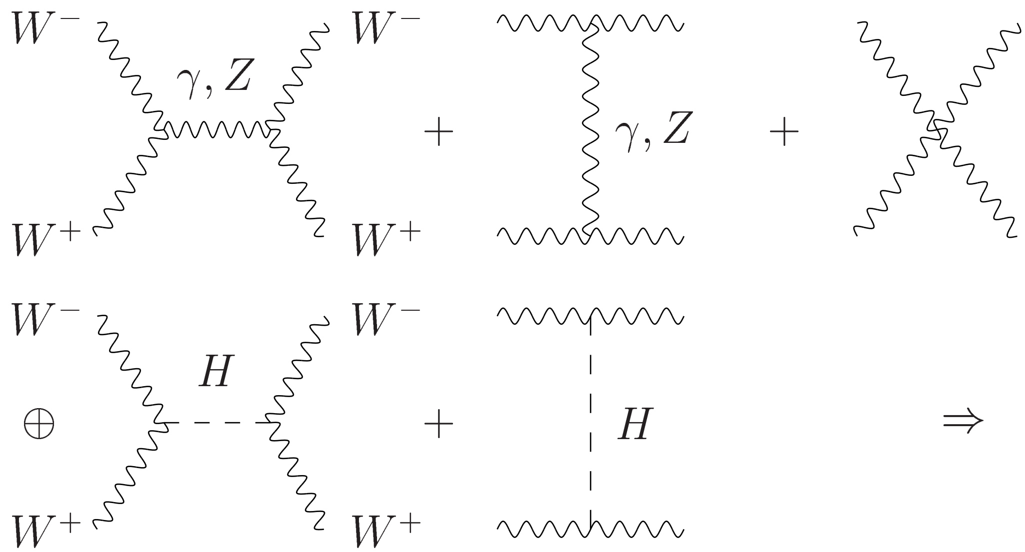


$$\frac{d\sigma}{d\cos\theta} \sim \frac{\pi\alpha}{16 s_W^2 c_W^2} \frac{m_e^2}{m_Z^4}$$

This comes from $J = 0$ partial wave and eventually violates unitarity at high energies; so something is needed to cure the $J = 0$ part. Adding the standard Higgs cancels the ill behavior entirely. [Higgs–fermion coupling must be proportional to the fermion mass !]



– $W^+W^- \to W^+W^-$



$\mathcal{M} \sim E^2$

$\frac{d\sigma}{d\cos\theta} \sim s$

$\Rightarrow$ $\mathcal{M} \sim$ constant

$\frac{d\sigma}{d\cos\theta} \sim 1/s$

- SU(2) doublet with 4 components - 1 physical $H \oplus$ 3 unphysical $(W^\pm, Z)$
- Higgs : vibration of the vacuum

$$J = 0,\ P = +,\ C = +,\ Q = 0,\ \cdots$$

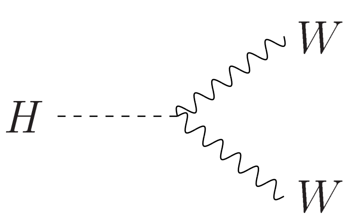
Higgs Couplings

Higgs couplings can be derived by replacing v by $v + H$

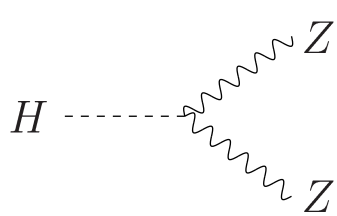
$$m \Rightarrow m\left(1 + \frac{g}{2m_W}H\right)$$

- With gauge bosons

$$\begin{aligned}
\mathcal{L} &= m_W^2 W_\mu^\dagger W^\mu + \frac{1}{2}m_Z^2 Z^\mu Z_\mu \\
&\to m_W^2\left(1 + \frac{g}{2m_W}H\right) W_\mu^\dagger W^\mu + \frac{1}{2}m_Z^2\left(1 + \frac{g_Z}{2m_Z}H\right) Z^\mu Z_\mu \\
&= (\text{masses}) + g m_W H W_\mu^\dagger W^\mu + \frac{1}{2} g_Z m_Z H Z_\mu Z^\mu \\
&\qquad + \frac{1}{4}g^2 H^2 W_\mu^\dagger W_\mu + \frac{1}{8}g_Z^2 H^2 Z_\mu Z^\mu
\end{aligned}$$



$i g m_W g_{\alpha\beta}$

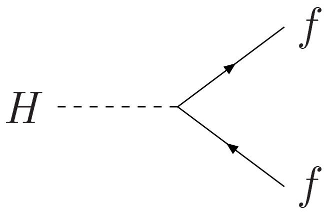


$i g_Z m_Z g_{\alpha\beta}$

No $HZ\gamma$, $H\gamma\gamma$, Hgg at tree level

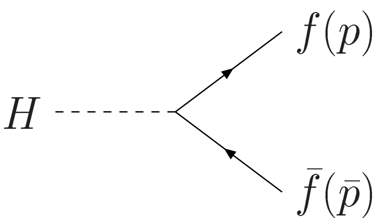
- With fermions

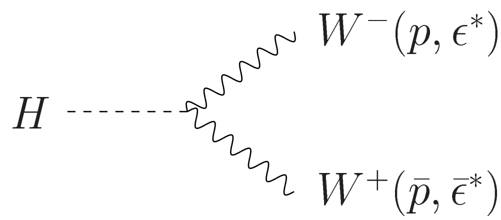
$$\begin{aligned}
\mathcal{L} &= -m_f \bar{f} f \\
&\to -m_f\left(1 + \frac{g}{2m_W}H\right)\bar{f} f = (\text{mass}) - \frac{g m_f}{2m_W} H \bar{f} f
\end{aligned}$$



$-i\,\frac{gm_f}{2m_W}$ flavor–conserving scalar coupling (Q^{++})

Higgs Decays





$$\mathcal{M} = -\frac{gm_f}{2m_W}\,\bar{u}(p)v(\bar{p})$$

$$\mathcal{M} = gm_{_W}\,\epsilon^*\cdot\bar{\epsilon}^*$$

Partial Decay Widths

$$\begin{aligned}\Gamma(H\to f\bar{f}) &= \frac{\alpha m_f^2 m_H}{8m_{_W}^2\sin^2\theta_W}N_C^f\beta_f^3 \\ &= \frac{G_F m_f^2 m_H}{4\sqrt{2}\pi}N_C^f\beta_f^3 \qquad \beta_f = \sqrt{1-\frac{4m_f^2}{m_H^2}}\end{aligned}$$

$$\Gamma(\mathsf{H} \to \mathsf{W}_\mathsf{T}^+\mathsf{W}_\mathsf{T}^-) = \frac{\alpha \mathsf{m}_\mathsf{W}^2 \beta_\mathsf{W}}{2\mathsf{m}_\mathsf{H} \sin^2\theta_\mathsf{W}} \qquad \beta_\mathsf{W} = \sqrt{1 - \frac{4\mathsf{m}_\mathsf{W}^2}{\mathsf{m}_\mathsf{H}^2}}$$

$$\Gamma(\mathsf{H} \to \mathsf{W}_\mathsf{L}^+\mathsf{W}_\mathsf{L}^-) = \frac{\alpha \mathsf{m}_\mathsf{H}^3 \beta_\mathsf{W}}{16\mathsf{m}_\mathsf{W}^2 \sin^2\theta_\mathsf{W}} \left(1 - \frac{2\mathsf{m}_\mathsf{W}^2}{\mathsf{m}_\mathsf{H}^2}\right)$$

$$\Gamma(H \to W^+W^-) = \frac{\alpha m_H^3 \beta_W}{16 m_W^2 \sin^2\theta_W}\left(1 - \frac{4m_W^2}{m_H^2} + \frac{12 m_W^4}{m_H^4}\right)$$
$$= \frac{G_F m_H^3 \beta_W}{8\sqrt{2}\pi}\left(1 - \frac{4m_W^2}{m_H^2} + \frac{12 m_W^4}{m_H^4}\right)$$

$$\Gamma(H \to ZZ) = \frac{1}{2} \cdot \frac{G_F m_H^3 \beta_Z}{8\sqrt{2}\pi}\left(1 - \frac{4m_Z^2}{m_H^2} + \frac{12 m_Z^4}{m_H^4}\right)$$

- In the limit of $m_H \gg m_W, m_Z$

$$\Gamma(H \to ZZ) = \frac{1}{2}\Gamma(H \to WW)$$

- $H \to \gamma\gamma, Z\gamma, gg$: only via fermion and/or W loops leading to small branching ratios in general

- Equivalence theorem : $\Gamma(H \to V_L V_L) \gg \Gamma(H \to V_T V_T)$

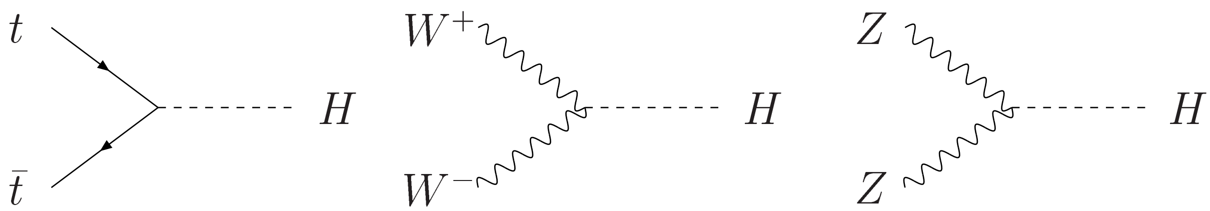
$$\Gamma(H \to f\bar{f}) \sim \alpha_W m_H \times \left(\frac{m_f}{m_W}\right)^2 \sim (\text{Yukawa})^2 m_H$$

$$\Gamma(H \to VV) \sim \alpha_W m_H \times \left(\frac{m_H}{m_V}\right)^2 \sim \lambda m_H \not\sim (\text{gauge})^2 m_H$$

in the limit of $m_H \gg m_V$.

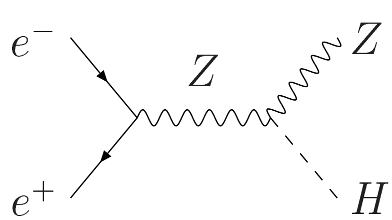
Higgs Boson Production

- 1st and 2nd generation quarks/leptons couple extremely weakly to H
- "Large" coupling required, i.e. production via heavy particles



- Main production modes

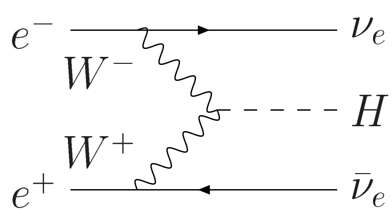
(a) Higgs–strahlung :



$\sigma \sim \frac{G_F^2 M_Z^4}{96\pi s} \kappa_S \beta$

$\sqrt{s}$ lower part

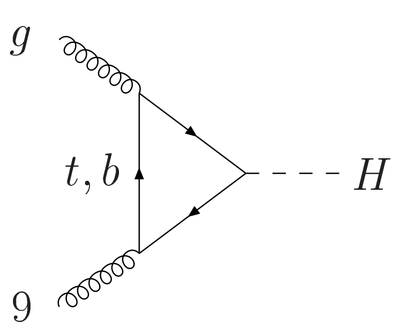
(b) W fusion :



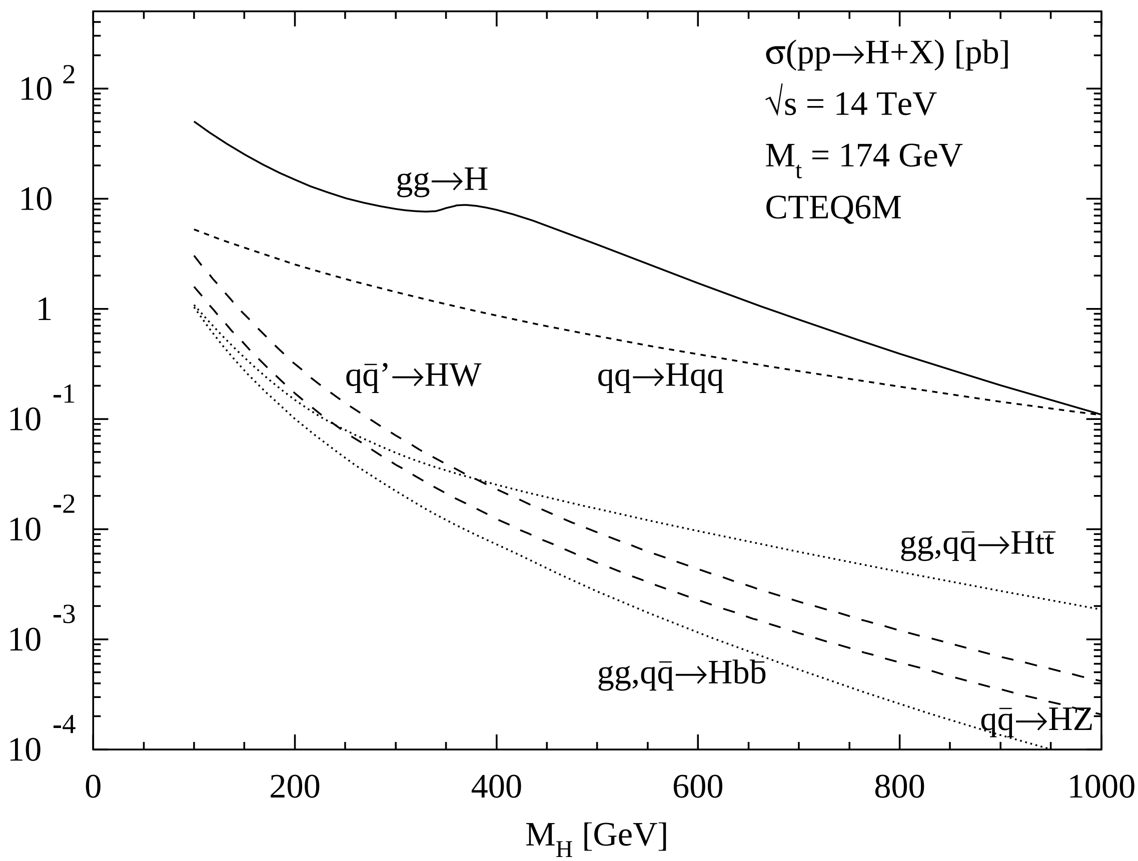
$\sigma \sim \frac{G_F^3 M_W^4}{4\sqrt{2}\pi^3} \log \frac{s}{M_H^2}$

$\sqrt{s}$ upper part

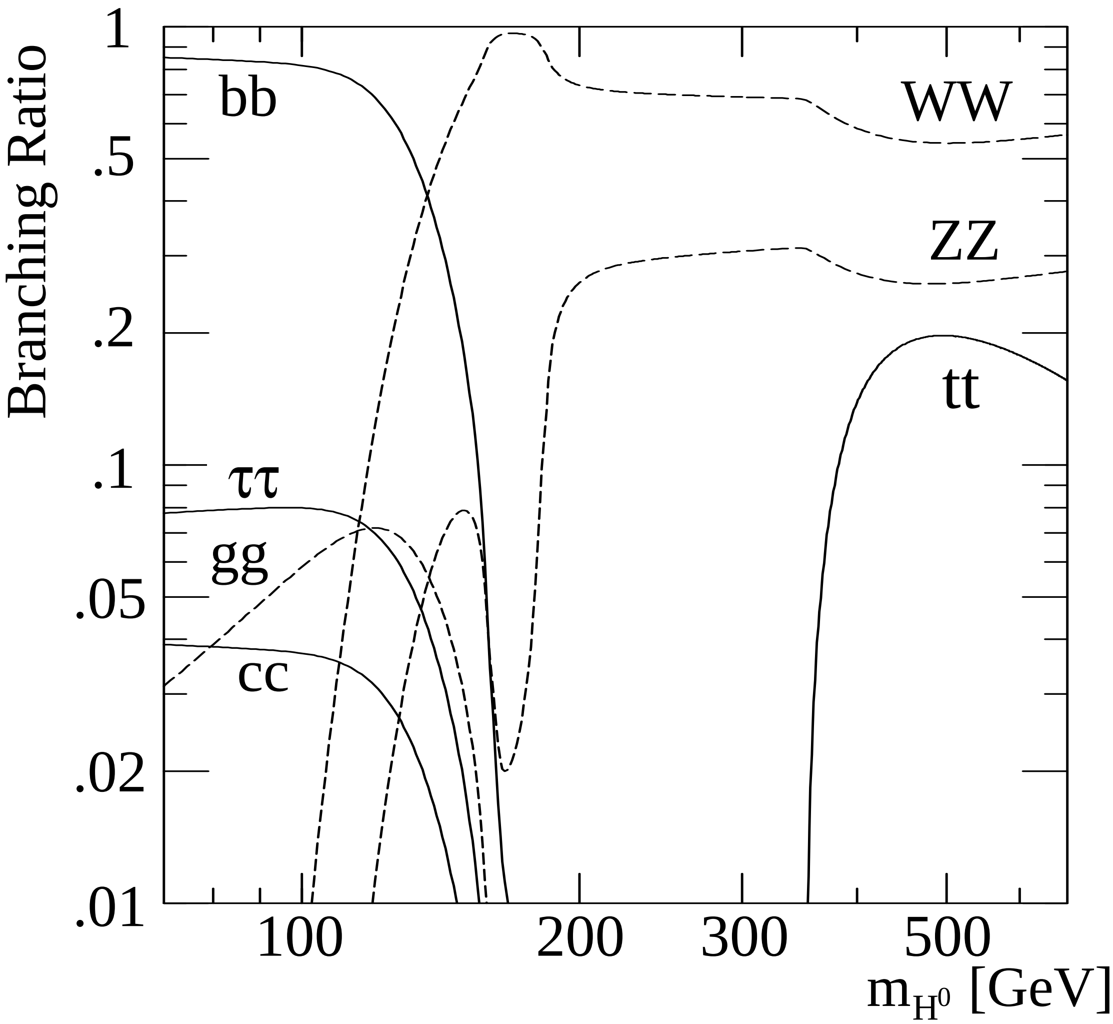
(c) Gluon fusion :



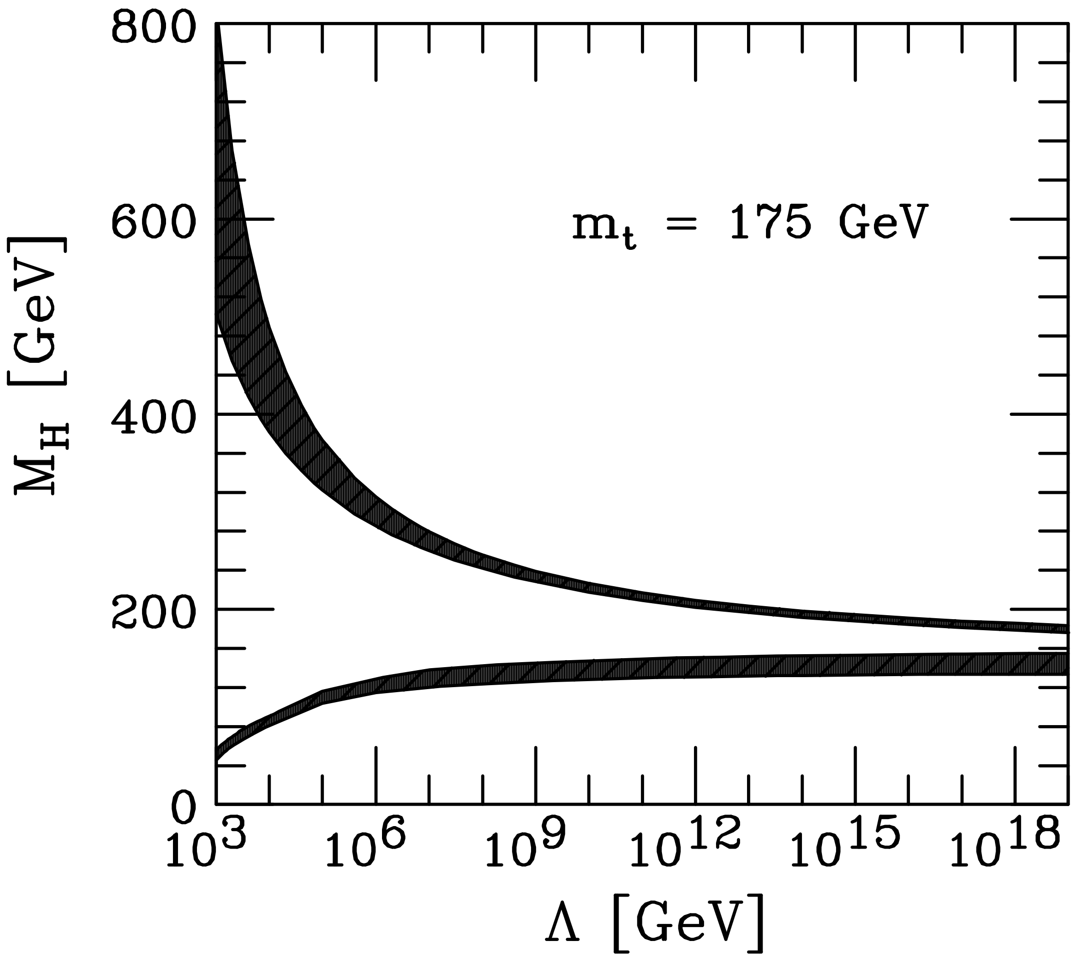
LHC



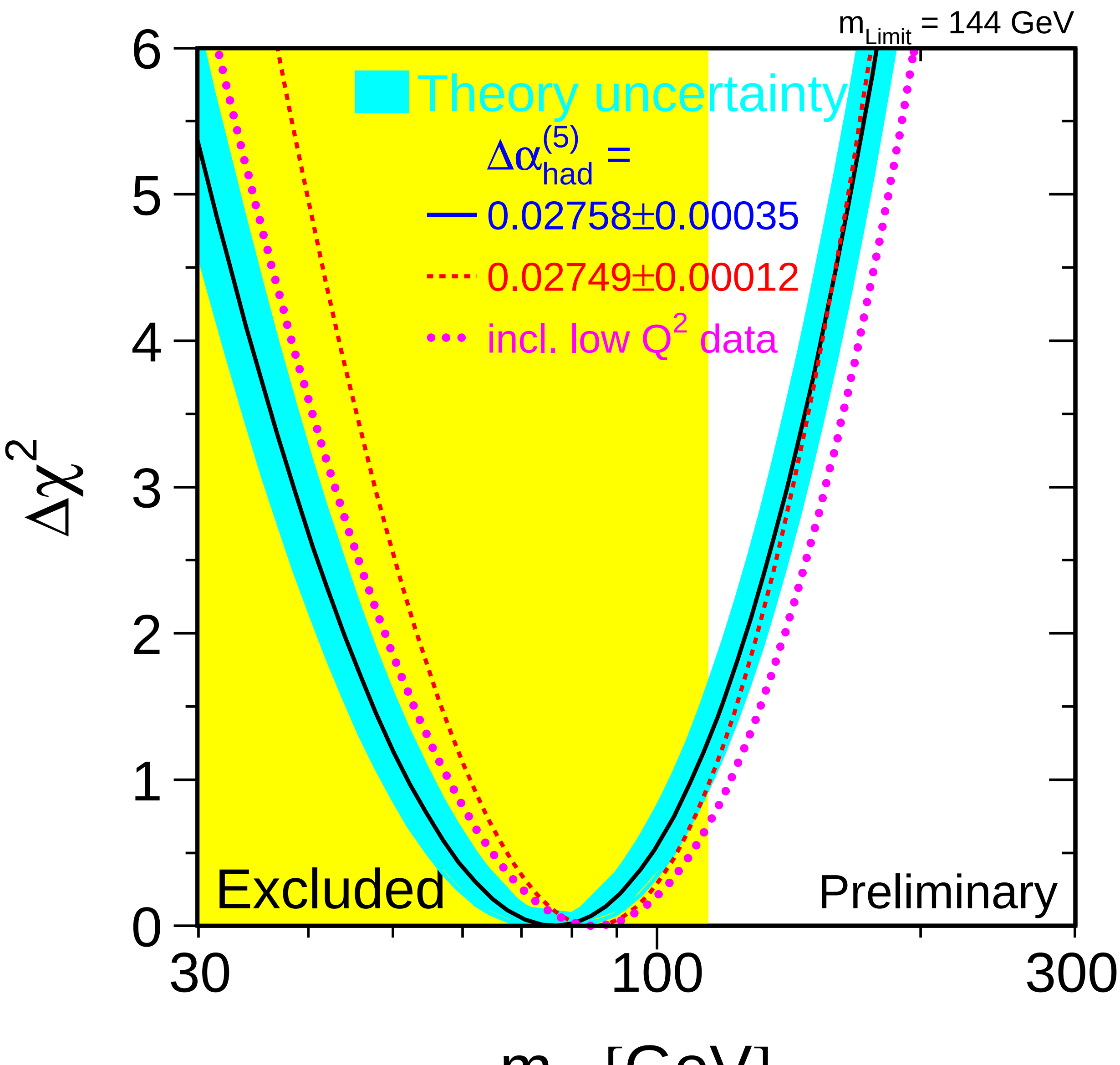
σ(pp→H+X) [pb]
√s = 14 TeV
M_t = 174 GeV
CTEQ6M
gg→H
qq̄'→HW
qq→Hqq
gg,qq̄→Htt̄
gg,qq̄→Hbb̄
qq̄→HZ
10 2
10
1
10 -1
10 -2
10 -3
10 -4
0
200
400
600
800
1000
M_H [GeV]



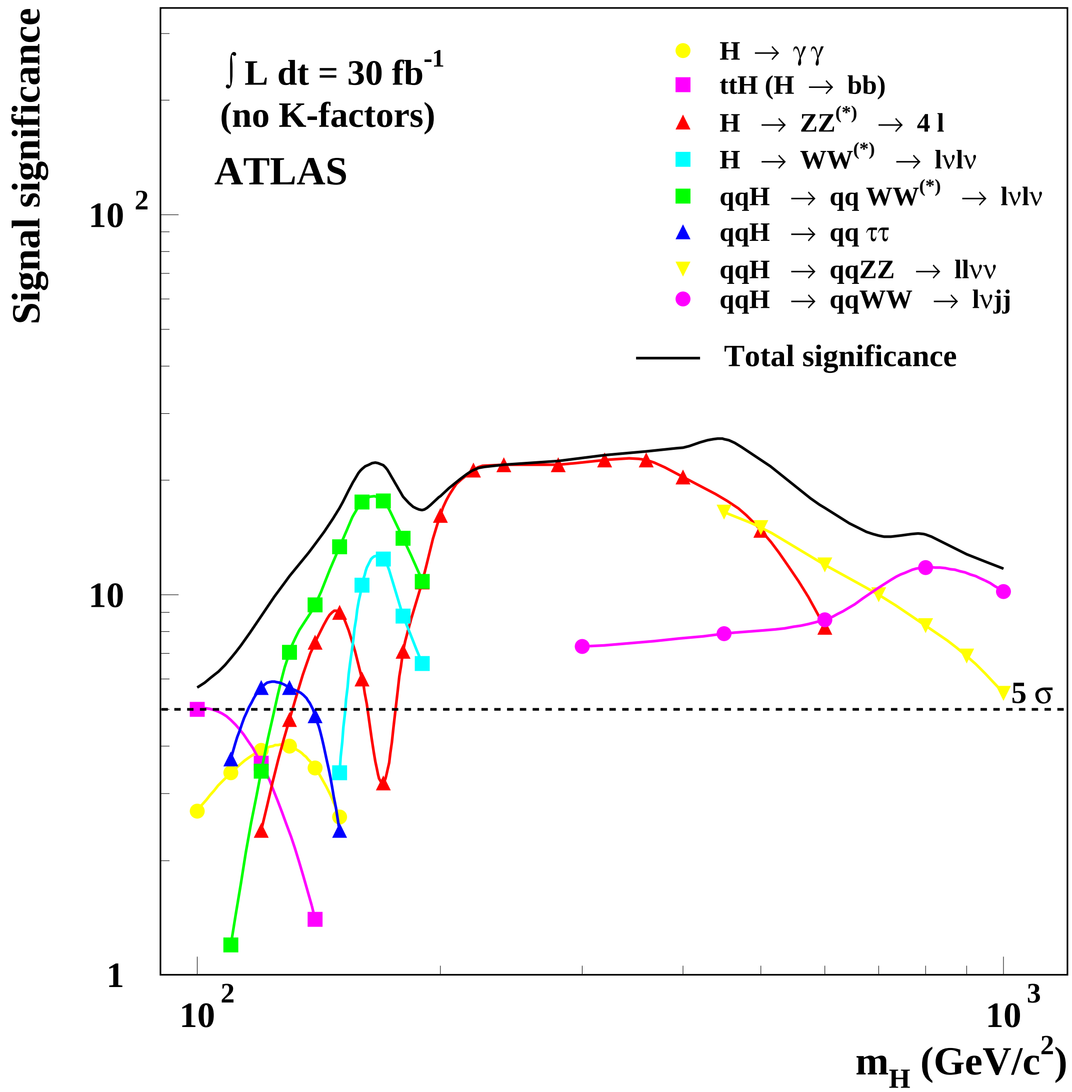
Branching Ratio
1
.5
.2
.1
.05
.02
.01
bb
WW
ZZ
tt
ττ
gg
cc
100
200
300
500
m_{H^0} [GeV]



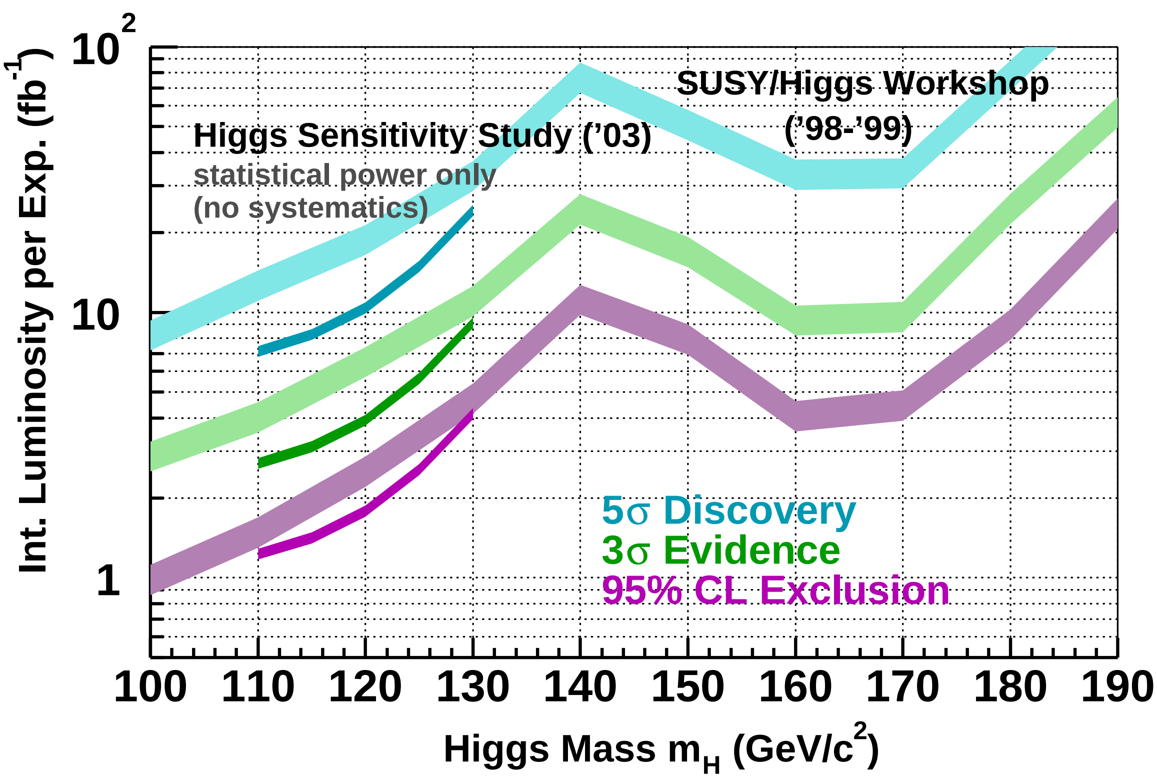
800
600
400
200
0
m_t = 175 GeV
M_H [GeV]
10^3
10^6
10^9
10^{12}
10^{15}
10^{18}
Λ [GeV]



m_Limit = 144 GeV
Theory uncertainty
Δα_had^(5) =
0.02758±0.00035
0.02749±0.00012
incl. low Q^2 data
Excluded
Preliminary
Δχ^2
m_H [GeV]
0
1
2
3
4
5
6
30
100
300



Signal significance
∫ L dt = 30 fb-1
(no K-factors)
ATLAS
H → γγ
ttH (H → bb)
H → ZZ(*) → 4 l
H → WW(*) → lνlν
qqH → qq WW(*) → lνlν
qqH → qq ττ
qqH → qqZZ → llνν
qqH → qqWW → lνjj
Total significance
5 σ
10 2
10
1
10 2
10 3
mH (GeV/c2)



Int. Luminosity per Exp. (fb^{-1})
10^2
10
1
100
110
120
130
140
150
160
170
180
190
Higgs Mass m_H (GeV/c^2)
SUSY/Higgs Workshop
('98-'99)
Higgs Sensitivity Study ('03)
statistical power only
(no systematics)
5σ Discovery
3σ Evidence
95% CL Exclusion

Higgs Physics Menu

m_H

elementary or composite ?
electroweak physics
$t\bar{t}$ condensation ?

Γ_H

Higgs sector
Resonance shape (if wide)
How to measure ? (if narrow)

$J^{PC} = 0^{++}$

Branching Ratios

$H \to W^+W^-/ZZ \to$ custodial SU(2) symmetry
$H \to t\bar{t}, \tau^+\tau^-, \cdots \to$ Yukawa; minimal or not ?
$H \to \gamma\gamma, Z\gamma, gg \to$ one–loop structure