1. The SM of Particle Physics in a Nutshell

The electroweak and strong interactions of quarks and leptons are described by renormalizable quantum gauge theories.

The principle of invariance of the theory under the transformation of a local gauge symmetry group fixes the dynamics.

The particles that transmit the forces are thus called gauge bosons. They have spin 1 and have to be quantized according to Bose-Einstein spin statistics (*bosons*).

The matter particles, the quarks and leptons, have spin $\frac{1}{2}$ and have to be quantized according to Fermi-Dirac spin statistics (*fermions*).

Force	acts on	transmitted by
electromagnetic	all electrically charged particles	photon (massless, spin 1)
weak	quarks, leptons, $W^{\pm}$, Z	$W^{\pm}$, Z (massive, spin 1)
strong	all colored particles (quarks and gluons)	8 gluons (massless, spin 1)

Symmetries are mathematically formulated using group theoretical methods:

The transformations of local gauge symmetries are described by unitary $n \times n$ matrices, $U = e^{iH}$ (H: hermitian, quadratic $n \times n$ matrix), with real, space-time dependent elements.

The matrices U form a group called U(n), SU(n) (det(U)=1).

U(n) has n^2 and SU(n) $n^2 - 1$ parameters, $\alpha_j(x)$, and generators, λ_j, and can be written in terms of infinitesimal transformations as follows ($x = (t, \vec{x})$):

U(n): $U(\alpha_j) = 1 + i\sum_{j=1}^{n^2} \delta\alpha_j(x)\lambda_j$

SU(n): $U(\alpha_j) = 1 + i\sum_{j=1}^{n^2-1} \delta\alpha_j(x)\lambda_j$

Example:

Gauge group of the electromagnetic interaction: U(1) with $U(\alpha) = 1 + iQ\delta\alpha(x)$. Q is the electric charge.

Requiring the Dirac equation, which describes free electrons, to be invariant under these transformations leads to electron-photon interaction and the existence of massless photons.

Interaction	symmetry group	gauge theory
electromagnetic	unbroken local U(1): invariance under space-time dep. phase transitions generated by the electric charge	QED
strong	unbroken local SU(3): invariance under space-time dep. rotations in the 8-dimensional color space	QCD
electroweak	(spontaneously broken) SU(2)$\otimes$U(1): invariance under space-time dep. rotations in the 3-dim. (weak) isospin space and under phase transitions generated by the (weak) hypercharge, Y ($Q = I_3 + Y/2$)	SM of electroweak interactions

Leptons and quarks are arranged in three families (generations) of left-handed doublets of the symmetry group of the weak isospin, SU(2) ($I_3 = \pm 1/2$):

$\Psi_L = (1-\gamma_5)\Psi$	I_3	Q	L	B
Leptons				
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	$+\frac{1}{2}$ $-\frac{1}{2}$	0 -1	$+1$ $+1$	0 0
Quarks				
$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} c \\ s \end{pmatrix}_L \quad \begin{pmatrix} t \\ b \end{pmatrix}_L$	$+\frac{1}{2}$ $-\frac{1}{2}$	$+\frac{2}{3}$ $-\frac{1}{3}$	0 0	$+\frac{1}{3}$ $+\frac{1}{3}$

Right-handed quarks and leptons ($\Psi_R = (1+\gamma_5)\Psi$) form singlets under SU(2) ($I_3 = 0$).

I_3: third component of the weak isospin

Q: electric charge in units of e, $e = \sqrt{4\pi\alpha}$ (α is the Sommerfeld fine structure constant).

L, $L_{i=e,\mu,\tau}$: Lepton number is separately conserved for each family (with, e.g., $L_e = 0$ for ν_μ, μ, ν_τ, τ) and $L = L_e + L_\mu + L_\tau$. B: Baryon number is observed experimentally to be conserved.

The antiparticles of the quarks and leptons have the same mass and spin as the particles but the quantum numbers Q, L, B are reversed in sign.

In the SM the neutrinos (ν_e, ν_μ, ν_τ) are considered to be massless. However, recently, strong experimental evidence has been found that this might not be the case. This could be the first signal of physics beyond the SM (term paper).

Leptons do not carry color charge and thus do not feel the strong force. Quarks carry color charge and each quark flavor comes in three colors.

Colored particles are permanently bound in colorless hadrons (“confinement”) (mesons: $q\bar{q}$ bound states, baryons: qqq bound states).

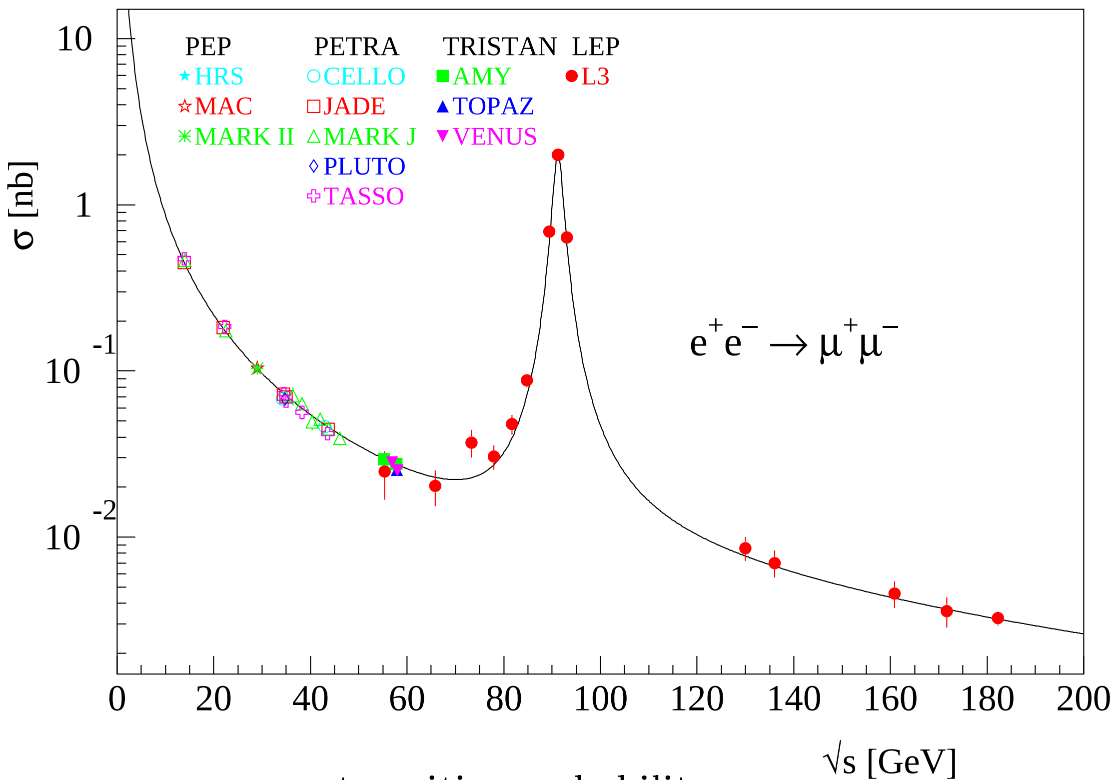
As a consequence of QCD, quarks are asymptotically free, i.e. the strength of the coupling decreases with increasing momentum transfer of the interaction discussed (term paper).

As a consequence of the mechanism which generates mass for the electroweak gauge bosons, $W^\pm, Z$, (Higgs-Kibble mechanism), the SM predicts the existence of a massive, neutral, spin 0 particle, the Higgs boson (term paper).

The Higgs boson is the only SM particle that has not been experimentally observed (yet) (term paper).

An example:

$$e^+e^- \to \gamma, Z \to \mu^+\mu^-(\gamma)$$



σ = (total) cross section= $\frac{\text{transition probability}}{\text{flux of incoming particles}}$

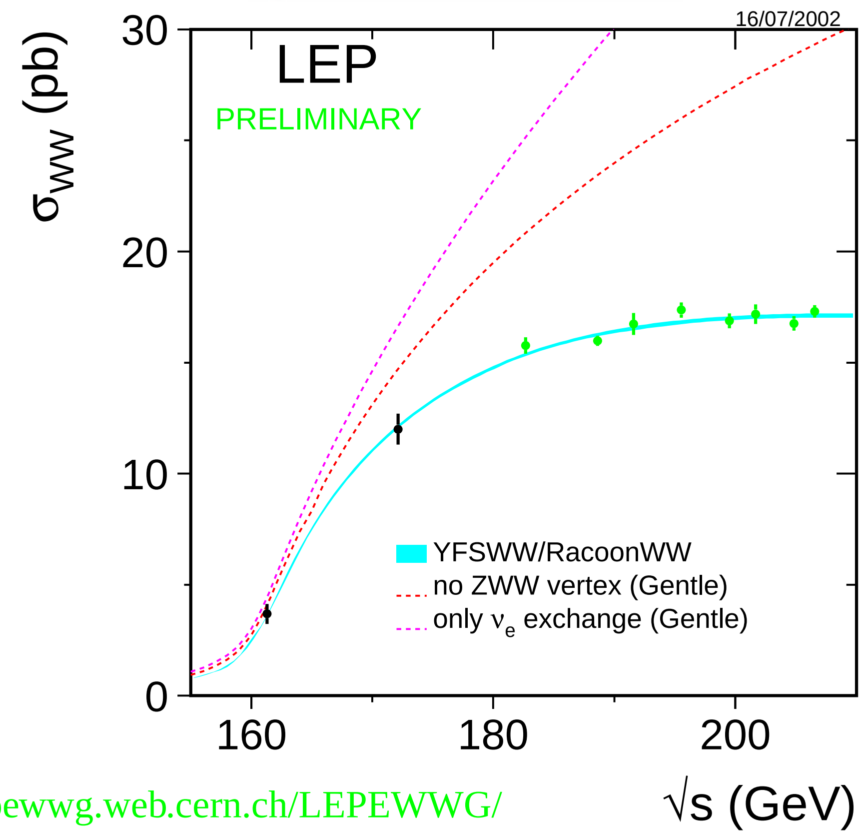
$\sqrt{s}$ = center-of-mass energy

from http://l3.web.cern.ch/l3/analysis/lineshape/wwwls.html

SM prediction versus experiment

An example:

$$e^+e^- \to \gamma, Z \to W^+W^- \to f\bar{f}f\bar{f}(\gamma)$$

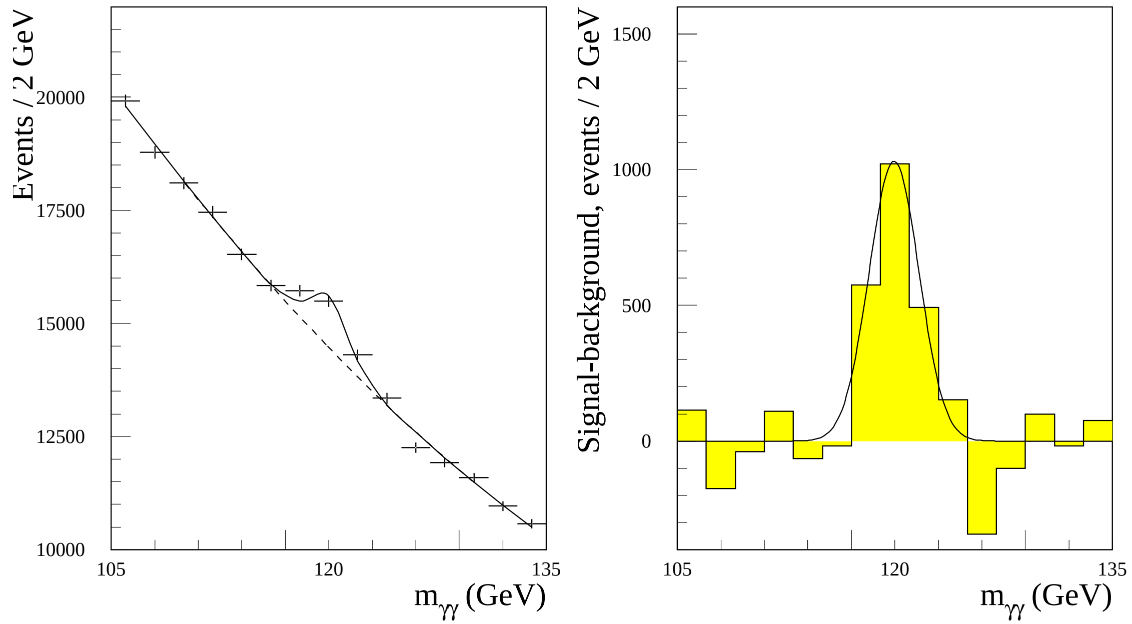


from http://lepewwg.web.cern.ch/LEPEWWG/

SM prediction versus experiment: A possible Higgs signal

An example:

$$pp \rightarrow (\text{Higgs} \rightarrow)\gamma\gamma \text{ at the LHC}$$



from the ATLAS TDR, CERN-LHCC 99-14