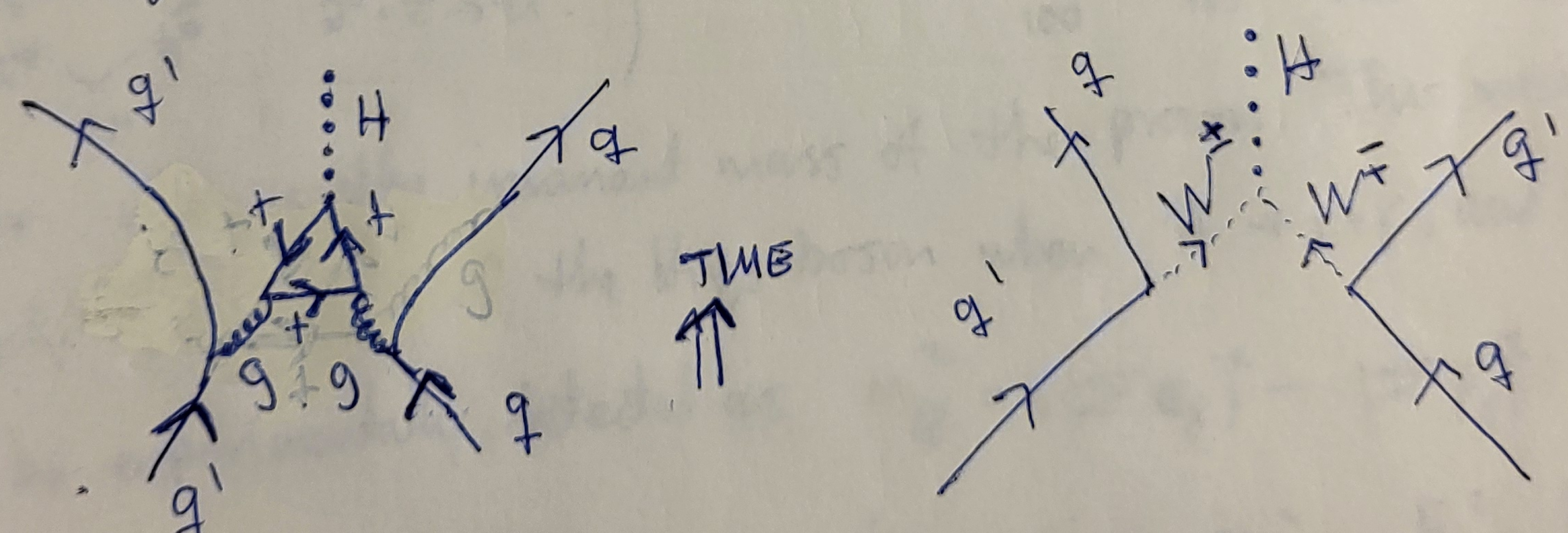
The discovery of the Higgs boson

Prior to the large hadron collider (LHC) at CERN, searches at the large electron-positron (LEP) collider (also at CERN) had placed a limit on the Higgs boson mass at $m_H > 114$ GeV.

Simultaneously, electroweak measurements at LEP suggested $m_H \lesssim 150$ GeV and at least not exceeding 200 GeV.

LHC was the highest-energy particle collider ever built, and could operate at CoM energies up to 8 TeV.

The Higgs boson could be produced at LHC through a number of different processes, for instance:



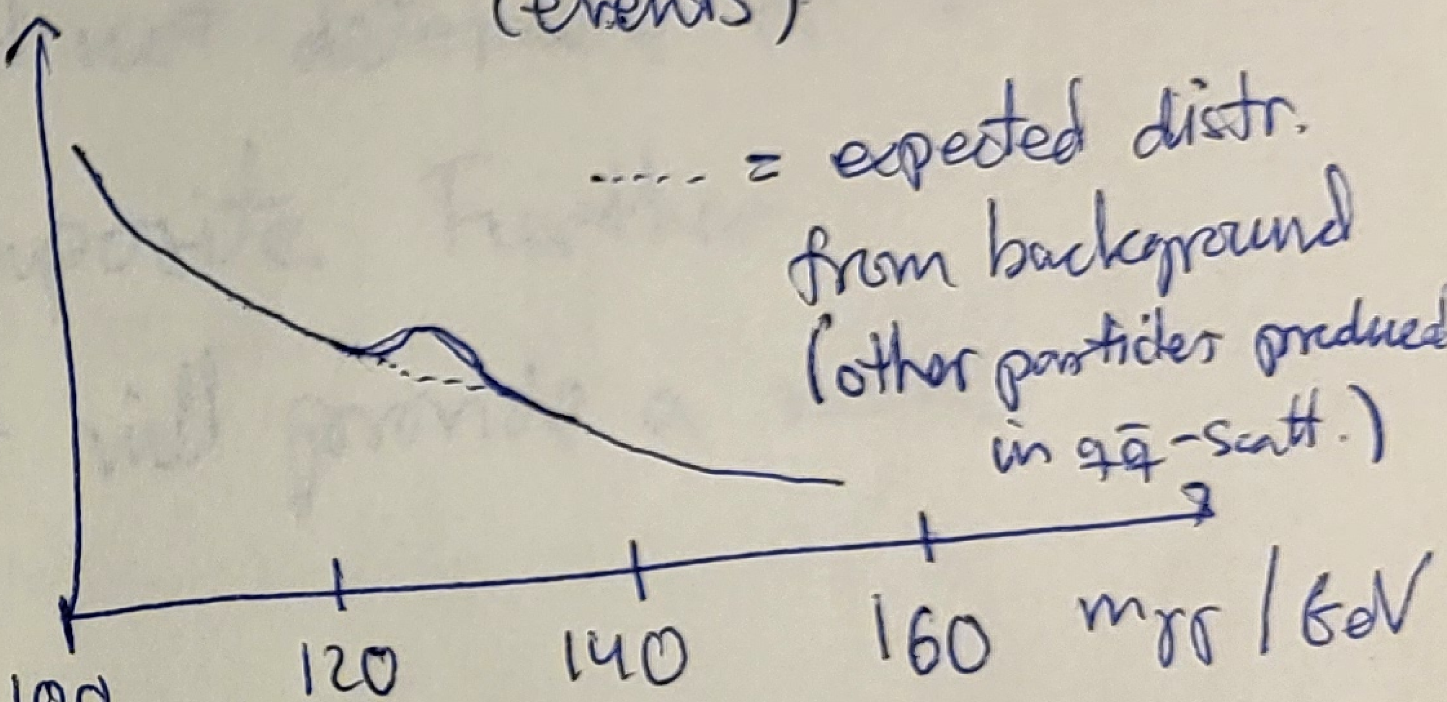
where q, q' are quarks, $W = \{W^+, W^-\}$, t = top quark, g = gluon, and H = Higgs boson.

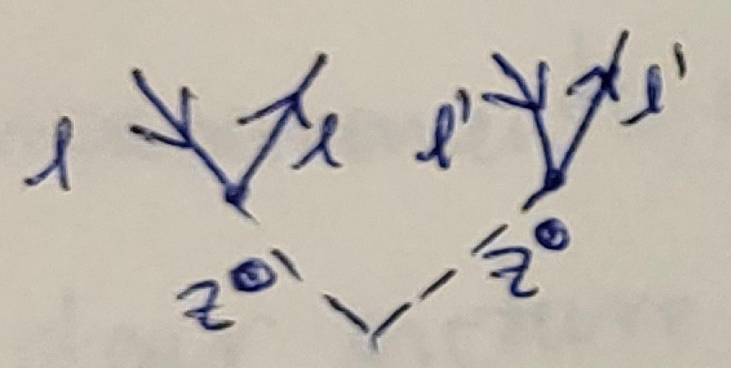
One could then perform sensitive searches for various decays of the Higgs boson, such as $H \to \gamma + \gamma$, $H \to Z^0 + Z^0$; $H \to W^+ + W^-$, $H \to l^+ + l^- + l'^+ + l'^-$ where l, l' are leptons.

The two decay channels which ultimately turned out to produce the statistically most significant evidence for H turned out to be $H \to \gamma + \gamma$ and $H \to Z^0 + Z^0 \to 4l$. In these channels, one then would reconstruct what m_H would have to be based on the energy of the decay products.

In the end, one observed plots like:

Observed mass distribution (events)





$Z^0 + Z^0 \to 4l$.

where $m_{\gamma\gamma}$ is the invariant mass of the process. This would simply be the mass of the Higgs boson when $H \to \gamma + \gamma$, and it can be experimentally detected as $m_{\gamma\gamma}^2 = \left(\sum E_\gamma\right)^2 - \left|\sum \vec{p}_\gamma\right|^2$ due to energy-momentum conservation, since $m_H^2 = E_H^2 - |\vec{p}_H|^2$.

Compared to the expected background, an excess of events were observed at $m_{\gamma\gamma} \approx 126$ GeV. An excess at the same invariant mass was observed separately for the $H \to Z^0 + Z^0 \to 4l$ channel.

Based on the statistical likelihood of this excess of events being observed in multiple decay channels, compelling evidence was therefore obtained that the Higgs boson exists and its mass is $m_H \approx 126$ GeV.

While a tremendous triumph, completing the particle spectrum in the Standard Model, more remains to be learned about the Higgs boson. For instance, in a popular extension of SM called Supersymmetry, there are 5 Higgs bosons. Moreover, the LHC measurements could not determine if H is a fundamental scalar particle or composite. Further measurements of branching ratios for H will provide a more clear picture in years to come.

Fermion masses

Let us briefly sketch how the Higgs field generates masses for fermions and what this fifth fundamental force is.

Assume you have a Lagrangian describing the fermion sector. We now say that there also exists a Higgs field, which for technical reasons is a two-comp. complex field: $\varphi(x) = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix}$

The upper component has charge $Q=+1$ and the lower $Q=0$

The Lagrangian of the Higgs field is : $\left(D_\mu = \partial_\mu + \frac{ig'}{2}B_\mu + \frac{ig_W}{2}\vec{\tau}\cdot\vec{W}_\mu\right)$

$$\mathcal{L}_H = (D_\mu\varphi)^\dagger(D^\mu\varphi) - \mu^2\varphi^\dagger\varphi - \lambda(\varphi^\dagger\varphi)^2 \qquad (\mu^2<0, \lambda>0)$$

so that the potential minimum is at $\varphi^\dagger\varphi = \frac{-\mu^2}{2\lambda}$. We now perform SSB so that the vacuum state realized is $\varphi = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v\end{pmatrix}$, $v^2 = -\frac{\mu^2}{\lambda}$.

Thus, the charge of this Higgs field configuration is zero.

This choice is needed so that the photon remains massless as it does not couple to the Higgs field (since it has no charge in this config.)

Now, look at the fermion part of $\mathcal{L}$. There can exist no mass term $m\bar{\psi}\psi = m(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L)$ because this would violate the $SU(2)_L$ symmetry required for electroweak interactions, since ψ_L and ψ_R transform differently. So how do we give the fermions masses?

The solution is that the masses come from a coupling to the Higgs field.

This is called a Yukawa coupling : $\mathcal{L}_Y = -G_e(\bar{\nu}_e, \bar{e}^-)_L\begin{pmatrix}\varphi_+\\ \varphi_0\end{pmatrix}e_R^- + \text{h.c.}$

(plus the same for muon and tauon fields). Note how these terms are invariant under an $SU(2)_L$ transformation since a local $SU_L(2)$ transformation applied to both $(\bar{\nu}_e, \bar{e})$ and $\begin{pmatrix}\varphi_+\\ \varphi_0\end{pmatrix}$ leaves their inner product invariant (just like $\underbrace{\bar{a}\,U^{-1}Ub}_{\bar{a}'b'=} = \bar{a}b$)

Spontaneously breaking the SU(2) symmetry of the Higgs field.

$$\begin{pmatrix}\varphi^+\\ \varphi^0\end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v+\rho(x)\end{pmatrix}$$ where $\rho(x)$ is the fluctuation around

↑ Note to self: when neglecting phase-fluctuations, we have performed a gauge-fixing of the Higgs field (i.e. we fixed $\varphi^+=0$) and $\rho\in\mathbb{R}$

the vacuum state, we get

$$\mathcal{L}_Y = -\underbrace{\frac{G_e v}{\sqrt{2}}}_{\text{mass}}\bar{e}\cdot e - \underbrace{\frac{G_e}{\sqrt{2}}\rho\,\bar{e}\cdot e}_{\text{remaining Yukawa coupling}}$$

where ρ is the Higgs boson and the electron mass is $m_e = \frac{G_e v}{\sqrt{2}}$.
The fifth fundamental interaction is thus the coupling between fields that have mass and the Higgs field. The Higgs field is the mediating field, but the Higgs boson is not a gauge boson like the fields describing $W^\pm$, Z^0, and γ.

~~Since the latter arise due to a local symmetry requirement for the particle field themselves. In contrast the Higgs boson arises from SSB of the Higgs field itself.~~

These fields have a redundancy in how we describe them (e.g. $A_\mu \to A_\mu + \partial_\mu\lambda$). This is not the case for the Higgs boson which is a scalar, neutral field ρ and thus a real number. There is no redundancy in our description of ρ, unlike A_μ.
Also, gauge bosons arise due to the need to ensure that a local cont. symmetry holds. The Higgs boson does not arise in this way: it was generated during the SSB procedure, and is the deviation from the GS in the radial direction of the sombrero-potential.