Lecture 17 - The Higgs Boson

- Spontaneous Symmetry Breaking
- The Higgs Mechanism
- Higgs Couplings to Fermions
- Electroweak Constraints on the Higgs
- Direct Searches for Higgs Bosons
- Higgs signatures at the LHC

Spontaneous Symmetry Breaking

The ground state configuration of a system does not always display the full symmetry that might be expected.

The symmetry is **spontaneously broken**, and is "hidden".

Everyday example:
A circle of people are sitting at a dining table. The first person who picks up a napkin (with Left Hand or Right Hand), breaks rotational symmetry.

Physics example:
In a ferromagnet spins align in a random direction until an external magnetic field is applied which breaks rotational symmetry.

The Higgs Potential

In electroweak theory the difference between the physical $\gamma, W^{\pm}, Z^0$ boson masses is created by spontaneous symmetry breaking of the Higgs field ϕ.

The potential energy of the Higgs field is:

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2 \qquad \mu^2 < 0 \quad \lambda > 0$$

The Higgs is a scalar field that exists in a vacuum

The potential is symmetric under rotations in ϕ space

The free energy of a ferromagnet is related to its magnetization M:

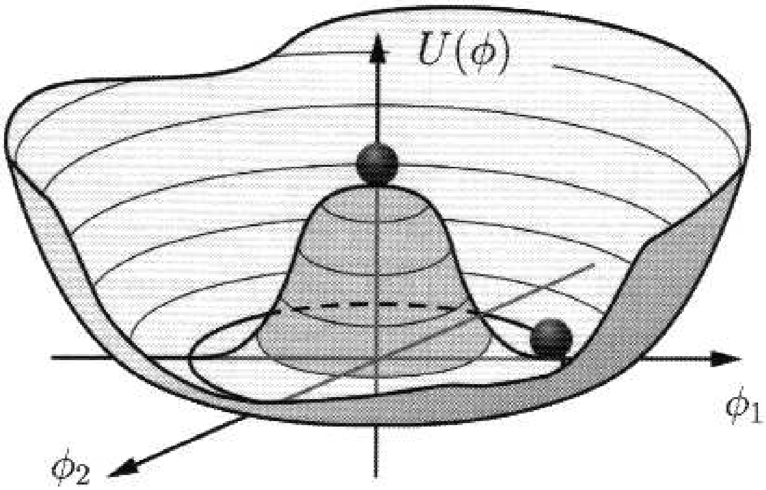
$$G = \alpha M^2 + \beta M^4 \qquad \alpha < 0 \quad \beta > 0$$

The magnetization exists in the absence of an external field

The free energy is symmetric under rotations in space

Vacuum Expectation Value

The Higgs potential has the shape of a "mexican hat"



It has a minimum which is not at $<\phi>= 0$

Known as the vacuum expectation value v

$$v = \frac{|\mu|}{\sqrt{\lambda}} = \frac{2M_W}{g} = 246\text{GeV}$$

This parameter defines the **electroweak scale**

The Standard Model Higgs Field

The Higgs field is a weak isospin doublet with four components:

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$$

A fluctuation around the minimum v **spontaneously breaks** the rotational symmetry of the Higgs field.

Choose direction of fluctuation so that vacuum Higgs field is:

$$\phi_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

Breaking the symmetry "eats" three of the four ϕ components!

The Higgs Boson

The fluctuation around the minimum v is written as:

$$\phi(x) = \phi_0 + h(x) \qquad \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} \Rightarrow \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

The scalar field $h(x)$ describes a physical Higgs boson

Expanding the Higgs potential to second order in h^2:

$$V = V_0 + \frac{\mu^2}{2}(2vh + h^2) + \frac{\lambda}{4}(4v^3 h + 6v^2 h^2) = V_0 + \lambda v^2 h^2$$

The additional term from h^2 gives the Higgs boson mass:

$$M_H^2 = 2\lambda v^2 \qquad M_H = \sqrt{2}|\mu|$$

This mass still has to be determined experimentally!

Vector Boson Masses

Couplings of vacuum Higgs field ϕ_0 to electroweak bosons:

$$\left(\frac{g}{2}\vec{\tau}.\vec{W} + \frac{g'}{2}B\right)\phi_0$$

$$\mathcal{L}_{\mathcal{H}} = \frac{1}{8}\left|\begin{pmatrix} gW^3 + g'B & g(W^1 - iW^2) \\ g(W^1 + iW^2) & -gW^3 + g'B \end{pmatrix}\begin{pmatrix} 0 \\ v \end{pmatrix}\right|^2$$

In terms of the physical W and Z bosons this gives:

$$\left(\frac{gv}{2}\right)^2 W^+W^- + \frac{v^2}{8}Z^0Z^0 \qquad Z^0 = -gW^3 + g'B$$

We identify these as vector boson mass terms:

$$M_W = \frac{vg}{2} \qquad M_Z = \frac{v\sqrt{g^2 + g'^2}}{2}$$

Note that the coupling of photon $A^0 = gW^3 + g'B$ to ϕ_0 is zero!

Higgs Couplings to Fermions

The scalar Higgs field ϕ couples fermion states of *opposite helicity*

In the Lagrangian there are new fermion terms:

$$\mathcal{L}_f = \frac{g_f}{\sqrt{2}}(\bar{f}_L f_R + \bar{f}_R f_L)v + \frac{g_f}{\sqrt{2}}(\bar{f}_L f_R + \bar{f}_R f_L)h$$

The first term is treated as a fermion mass term:

$$m_f = \frac{g_f v}{\sqrt{2}} = \frac{\sqrt{2} g_f M_W \sin\theta_W}{e}$$

The vacuum Higgs field v generates the fermion masses m_f

The second term is the fermion coupling to the Higgs boson h

The coupling constant g_f, describing the Higgs boson coupling to $f\bar{f}$, is proportional to m_f!

Upper Bound on Higgs Boson Mass

The Higgs boson width Γ_H is the sum of all its couplings:

$$\sum_f \Gamma(H \to f\bar{f}) + \Gamma(H \to W^+W^-) + \Gamma(H \to Z^0Z^0) + \Gamma(H \to HH)$$

The last term is from the Higgs self-couplings.

For a very large Higgs mass $M_H \gg v$ the self-coupling dominates

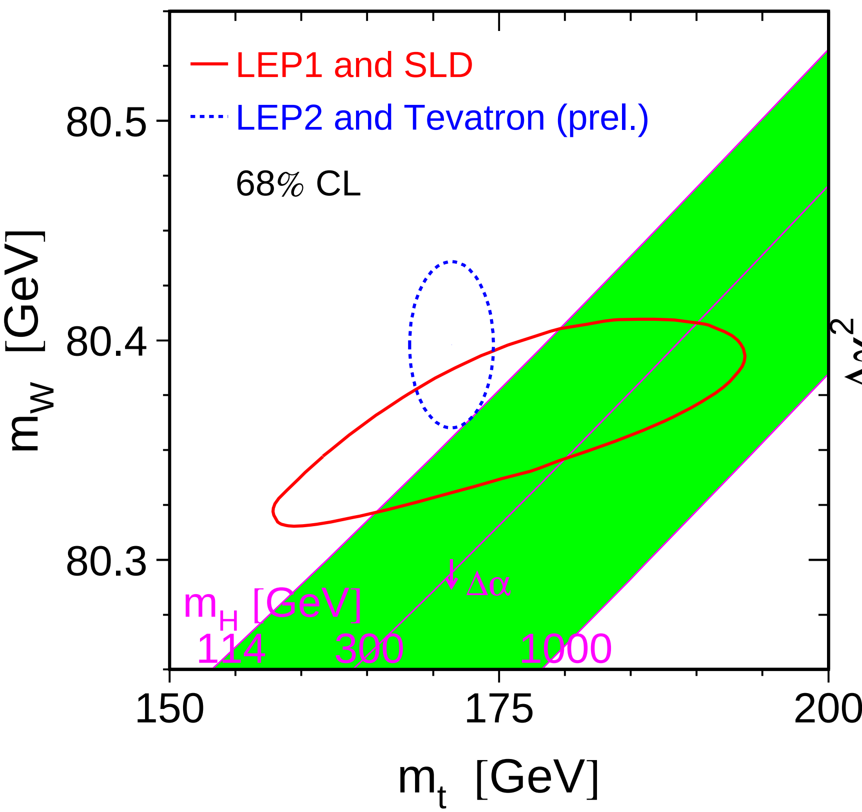
To satisfy unitarity $\Gamma_H < M_H$:

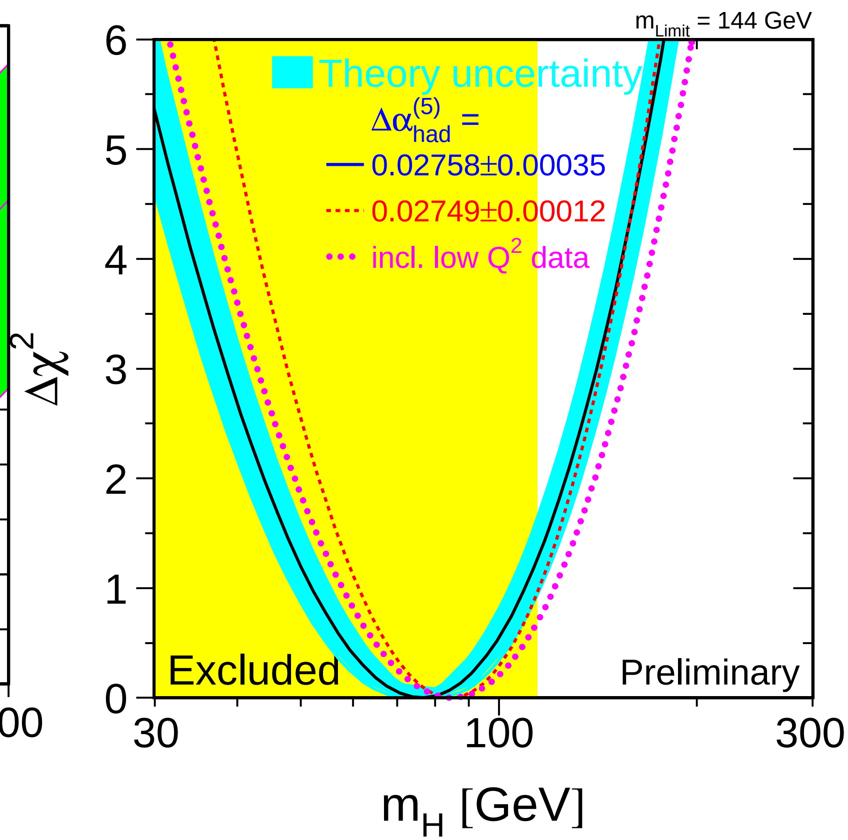
$$G_F M_H^3 < M_H \qquad M_H < \frac{1}{\sqrt{G_F}}$$

A more precise calculation gives $M_H < 1.2$ TeV

Precision Electroweak Bounds on Higgs Mass

Higher order diagrams involving Higgs Bosons enter as corrections to Standard Model predictions for electroweak processes.



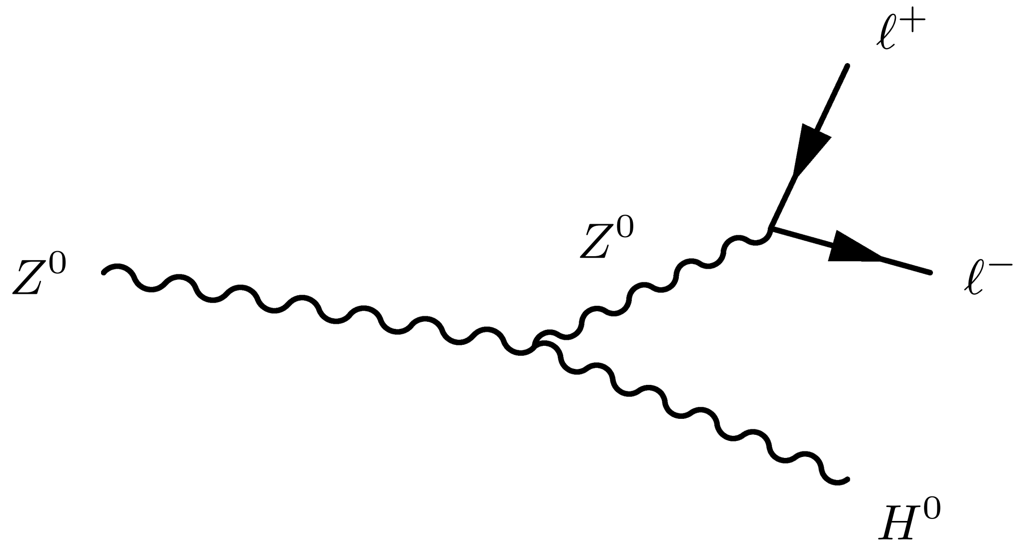


Higgs mass $M_H = 85^{+39}_{-28}$ GeV

$M_H < 144$ GeV (90% C.L.)

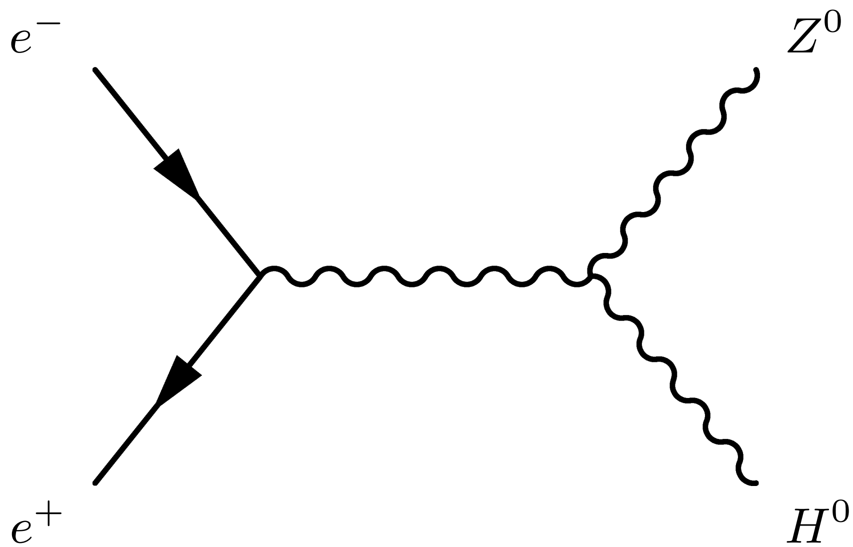
Direct Search for Higgs at LEP (1989-1995)

At the Z^0 peak look for associated production of a Higgs and a lepton pair from a virtual Z^0 (Higgsstrahlung)



No signal for a light Higgs with $M_H < 46$ GeV $(M_Z/2)$

Direct Search for Higgs at LEP-2 (1996-2001)



Associated production $e^+e^- \rightarrow Z^0H^0$ at $\sqrt{s} \approx 200$ GeV

A few candidates caused a lot of excitement in 2001!

Lower limit $M_H > 114$ GeV (90%C.L.)

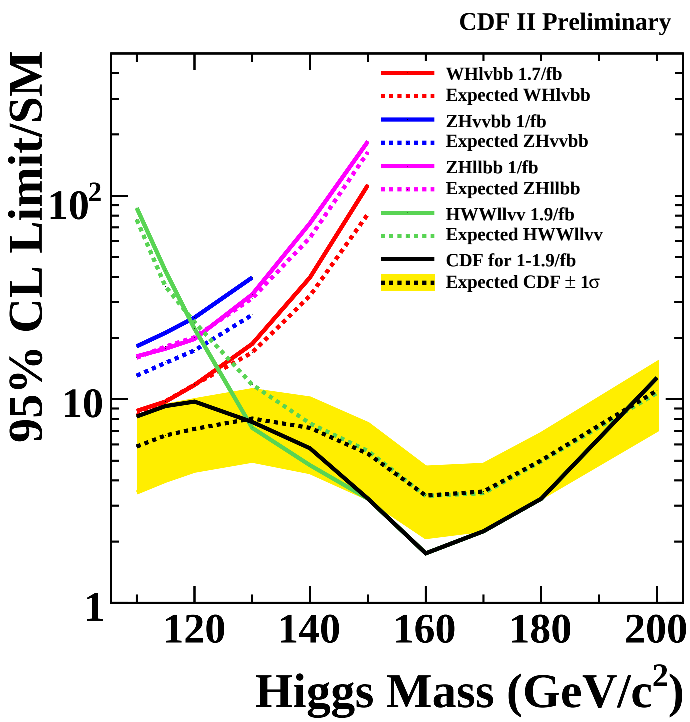
Higgs Production at Tevatron

At the Tevatron Higgs searches use three different channels:

Gluon-gluon fusion: $gg \to H^0 \to W^+W^- \to \ell^+\ell^-\nu\bar{\nu}$

Associated W-Higgs production: $q\bar{q} \to WH \to \ell\nu b\bar{b}$

Associated Z-Higgs production: $q\bar{q} \to ZH \to \ell\ell b\bar{b}$



CDF limits compared to Standard Model (SM):

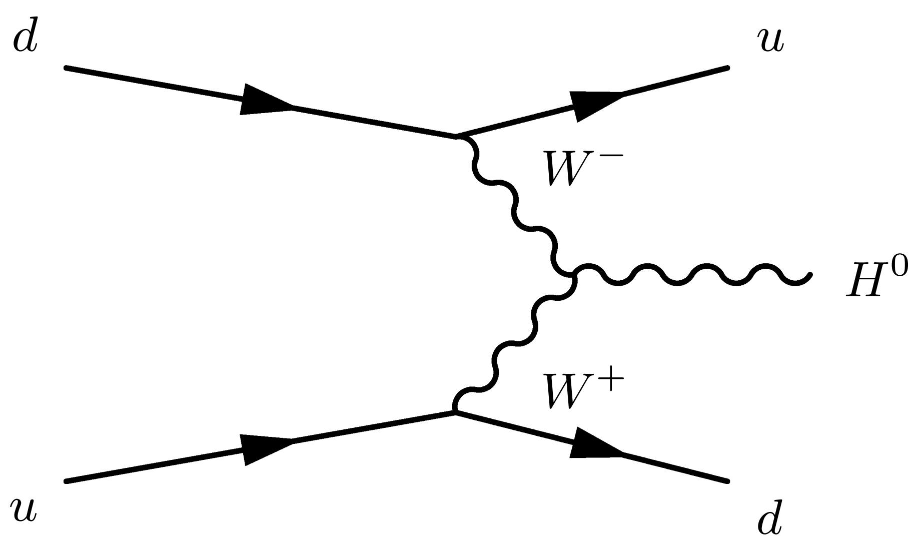
No signal yet...

$< 2\times$SM for $M_H \approx 160$ GeV

Tevatron expects to rule out $M_H > 140$ GeV and may observe a signal!

Higgs Production at LHC

At the LHC W^+W^- fusion will be a significant process:



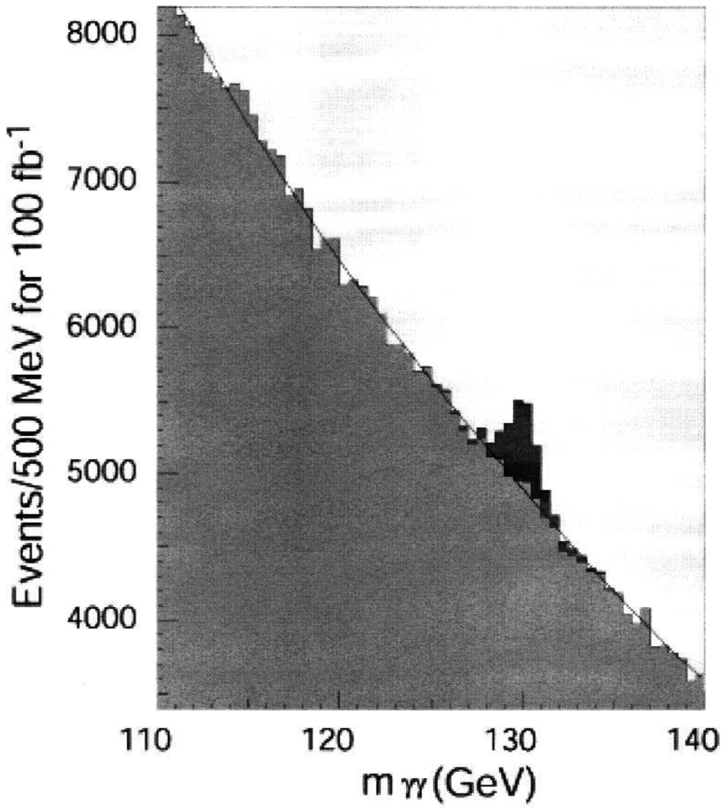
Identify these events by:

- *forward-tagging* of jets from protons
- *central production* and decay of Higgs boson

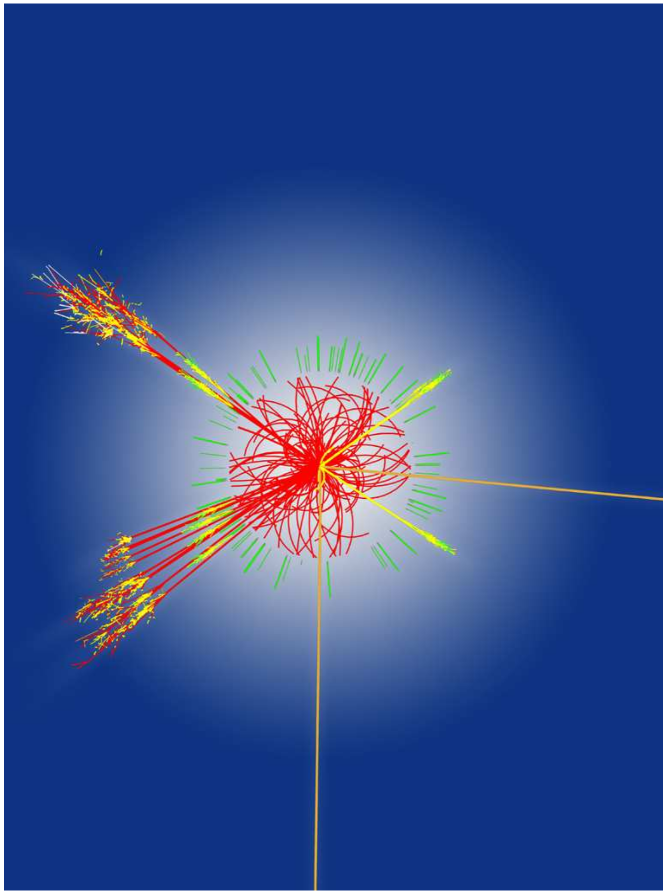
Higgs Signatures at LHC

- $M_H > 2M_Z$. Coupling to ZZ is proportional to M_Z.
  Large decay rate. Clear signature from $ZZ \to \ell^+\ell^-\ell^+\ell^-$.
- $M_H \approx 2M_W$. Coupling to W^+W^- is proportional to M_W.
  Large decay rate. Clear signature in W^+W^- to $q\bar{q}\ell\nu$.
- $M_H \approx 120$ GeV.
  - Largest coupling is to $b\bar{b}$.
    There is a lot of background from QCD jets.
  - Next largest coupling to $\tau^+\tau^-$
    Difficult because of missing neutrinos.
  - Also looking at small rate $H \to \gamma\gamma$.

First LHC data in 2009/10. High mass Higgs found quickly.
Low mass Higgs will take several years!



Simulated $H \to \gamma\gamma$ at CMS



Simulated Higgs at ATLAS