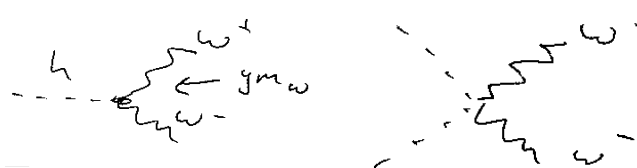


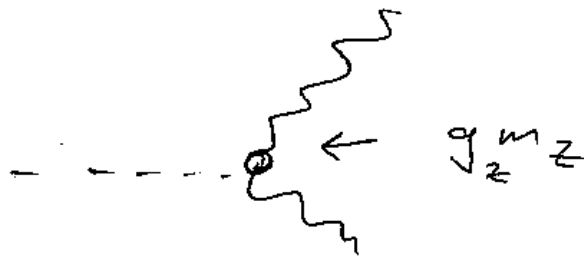
Lecture 31

The Higgs Boson

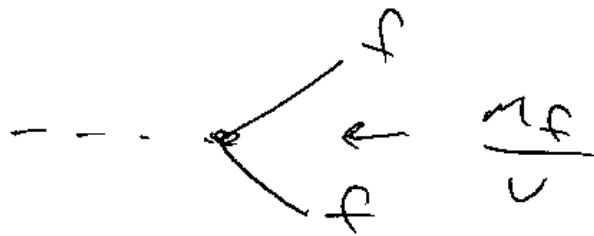
After Symmetry Breaking

$$\mathcal{L} \subset \frac{1}{4}g^2 W_\mu^- W^{+\mu} (v+h)^2 = \underbrace{\frac{1}{4}g^2 v^2 W_\mu^- W^{+\mu}}_{\text{W's Mass Term}} + \underbrace{\frac{1}{2}g^2 v W_\mu^- W^{+\mu} h}_{\text{Diagram 1}} + \underbrace{\frac{1}{4}g^2 W_\mu^- W^{+\mu} h h}_{\text{Diagram 2}}$$


Same for the Z



Saw last time Yukawa coupling leads to interactions with Higgs



Higgs Boson in SM is a massive neutral Spin = 0 particle. Its mass is free parameter ($m_H = 2\lambda v^2$)

H decays

$$\begin{array}{ll}
 H \rightarrow ff & \text{if } m_H > 2m_f \\
 H \rightarrow WW, ZZ & \text{if Massive enough}
 \end{array}$$

Now, because the Higgs couples according to mass, the Higgs wants to decay to the most massive thing it can.

For 125 GeV

$$\text{Br}(h \rightarrow bb) \sim 60\%$$

$$\text{Br}(h \rightarrow WW) \sim 20\%$$

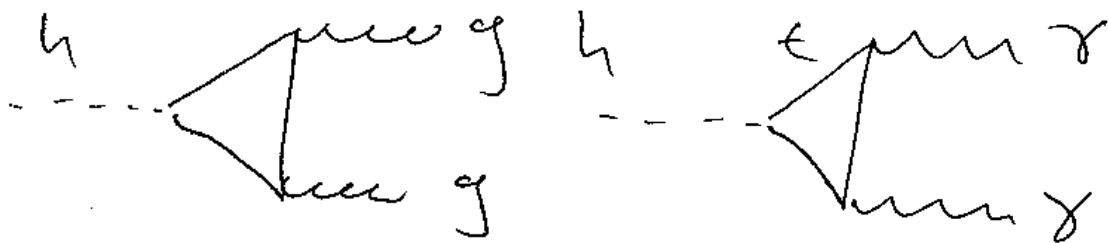
$$\text{Br}(h \rightarrow gg) \sim 10\%$$

$$\text{Br}(h \rightarrow \tau\tau) \sim 6\%$$

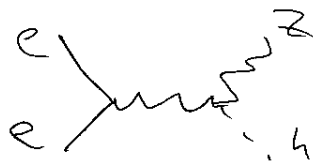
$$\text{Br}(h \rightarrow ZZ) \sim 3\%$$

$$\text{Br}(h \rightarrow \gamma\gamma) \sim 0.2\%$$

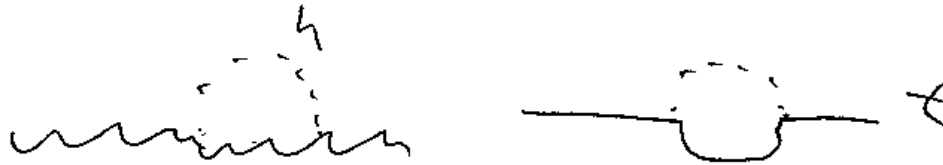
Decays to massless particles



Prior to LHC searched directly for the Higgs at LEP $\Rightarrow m_h > 115\text{GeV}$



Also studied m_{top} and m_W which put a limit on size of m_h .



$$\Rightarrow m_h < 150 \text{ GeV}$$

Now, Major goal of LHC was to discover Higgs.

How to make Higgs Bosons at the LHC?

The LHC collides protons (quarks/gluons).

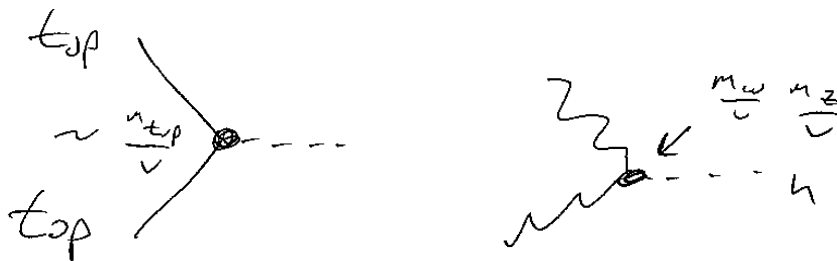
The stuff in the proton is light:

\Rightarrow small coupling to the Higgs

\Rightarrow small cross section to produce the Higgs

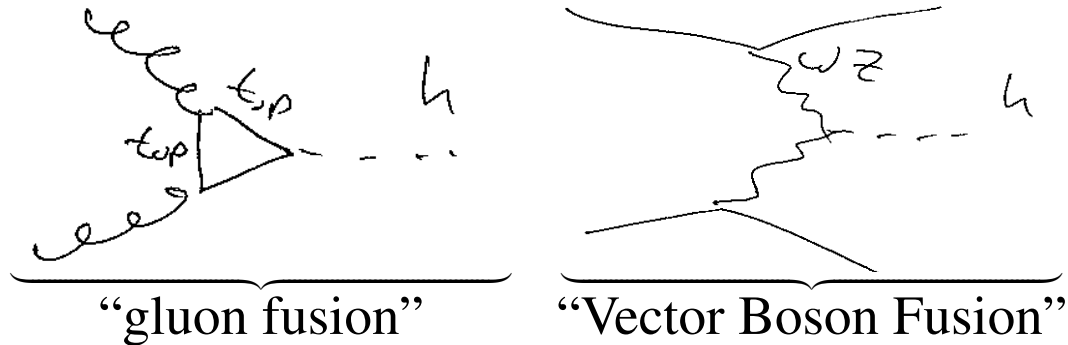
top, W, and Z are the heaviest particles in the theory \Rightarrow they have the largest coupling to the higgs

Would really like to use processes like:



Problem is we don't have a top/W/Z colliders.

So, at the LHC we first have to make the Ws and Zs from protons, then make the Higgs boson. eg:



This is one reason the Higgs was so hard to find. The leading production diagrams are from higher order processes.
 (“god particle” vs “god-damned particle”)

How much data is needed?

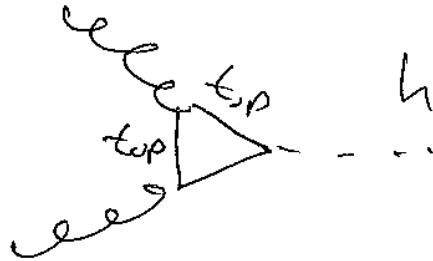
Lets estimate how often we make a Higgs.

Warm-up How often do we make a W/Z?

$$\begin{aligned}\sigma_{W/Z} &\sim \frac{\alpha_W}{m_{W/Z}^2} \sim \frac{1}{50} \frac{1}{100^2} \text{ GeV}^{-2} \\ &\sim 10^{-6} \text{ GeV}^{-2}\end{aligned}$$

$$\sigma_{pp} \sim \text{GeV}^{-2} \Rightarrow 1 W/Z \text{ for every } 1 \text{ Million } pp \text{ collisions}$$

Now lets do the same thing for the Higgs



$$\sigma_H \sim \frac{1}{16\pi^2} \frac{\alpha_s^2 \alpha_W}{m_H^2}$$

$$\sim \frac{1}{160} \left(\frac{1}{10}\right)^2 \left(\frac{1}{50}\right) \left(\frac{1}{100}\right)^2 \text{GeV}^{-2} \sim 10^{-10} \text{GeV}^{-2}$$

1 Higgs for every billion proton collisions.

How to look for it

$h \rightarrow b\bar{b}$	60%
$h \rightarrow W W$	20%
$h \rightarrow \gamma\gamma$	10%
$h \rightarrow \tau\tau$	8%
$h \rightarrow Z Z$	3%
$h \rightarrow \gamma\gamma$	0.2%

Good target is $\sim 100 \frac{h \rightarrow \gamma\gamma}{\text{year}}$

$$\Rightarrow 10^5 \frac{\text{higgs}}{\text{year}} \sim 1 \frac{\text{higgs}}{s}$$

\Rightarrow Need a billion proton collisions per second.

Only have beams that cross at 40 million times/s
 \Rightarrow need at least 25 proton collisions per crossing.

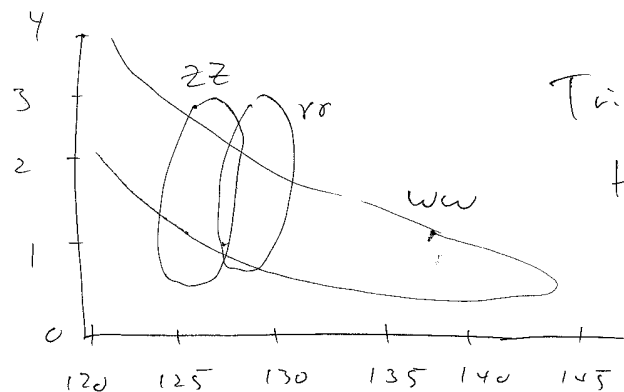
This is why we have to live with pile-up.

In 2012, Higgs discovered

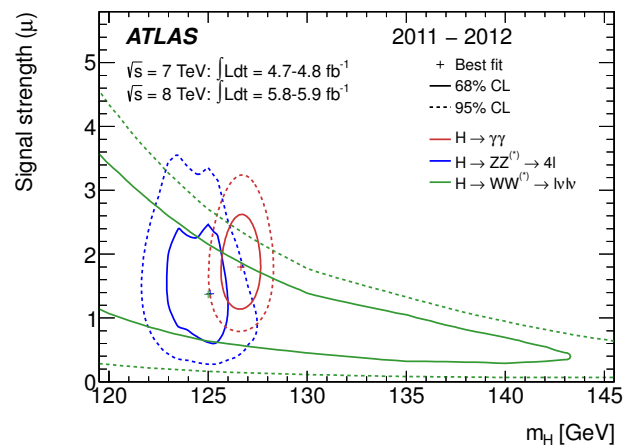
- $h \rightarrow WW \rightarrow \ell\nu\ell\nu$ (Hard)
- $h \rightarrow ZZ \rightarrow \ell\ell\ell\ell$ (easy)
- $h \rightarrow \gamma\gamma$ (straight forward)

Triumph of Humanity!!!

Cartoon:



Real Data:



So far looks like SM Higgs in every way. (stupidest version)

What we don't know

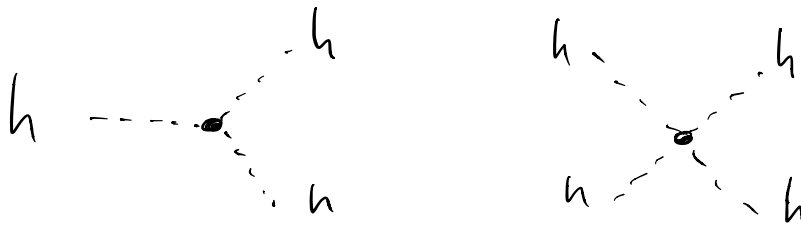
- if established couplings are modified at the $\sim 10 - 20\%$ level

-

$$\begin{pmatrix} \nu \\ e \end{pmatrix} \begin{pmatrix} \nu \\ \mu \end{pmatrix} \begin{pmatrix} \nu \\ \tau \end{pmatrix} \quad \begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$$

$$\gamma \quad W \quad Z \quad g$$

- if Higgs decays in unexpected way $\sim 20\%$ of the time
- Very important unobserved interaction



Higgs self-interaction.

Di-Higgs Production / Next Frontier.