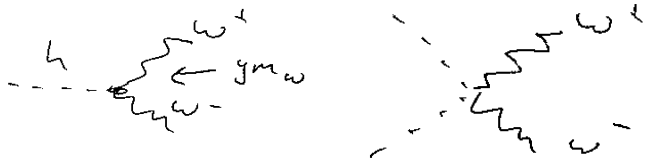
Lecture 31

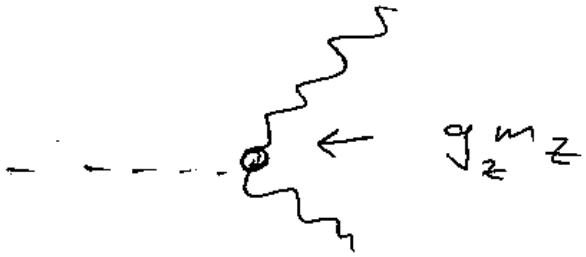
The Higgs Boson

After Symnmetry Breaking

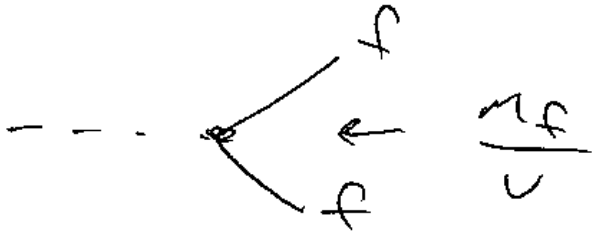
$$\mathcal{L} \subset \frac{1}{4}g^2 W_\mu^- W^{+\mu}(v+h)^2 = \underbrace{\frac{1}{4}g^2 v^2 W_\mu^- W^{+\mu}}_{\text{W's Mass Term}} + \underbrace{\frac{1}{2}g^2 v W_\mu^- W^{+\mu} h}_{} + \underbrace{\frac{1}{4}g^2 W_\mu^- W^{+\mu} hh}_{}$$



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

$$H \rightarrow ff \qquad \text{if } m_H > 2m_f$$
$$H \rightarrow WW, ZZ \qquad \text{if Massive enough}$$

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

For 125 GeV

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

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

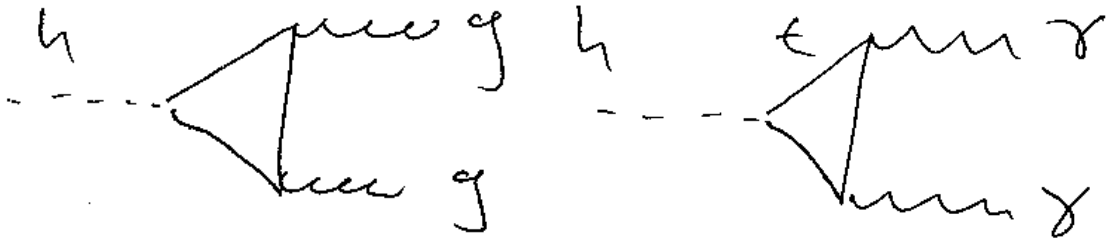
$\text{Br}(h \rightarrow gg) \sim 10\%$

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

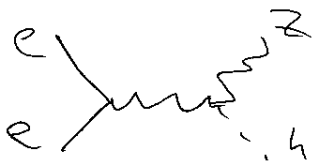
$\text{Br}(h \rightarrow ZZ) \sim 3\%$

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

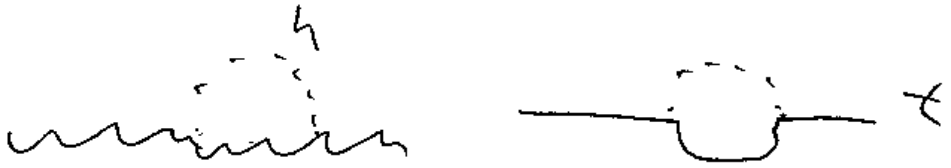
Decays to massless particles



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.



$\Rightarrow m_h < 150$ GeV

Now, Major goal of LHC was to discover Higgs.

How to make Higgs Bosons at the LHC?

The LHC collides protons (quarks/gluons).

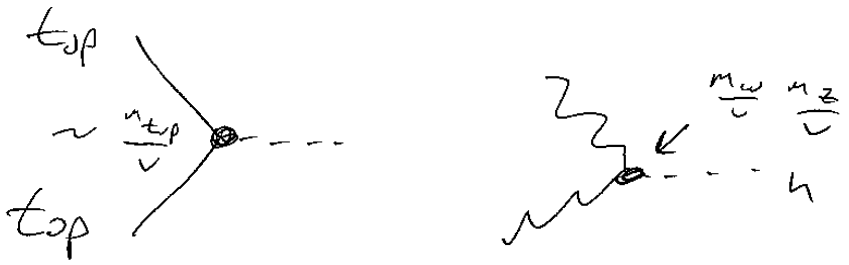
The stuff in the proton is light:

$\Rightarrow$ small coupling to the Higgs

$\Rightarrow$ small cross section to produce the Higgs

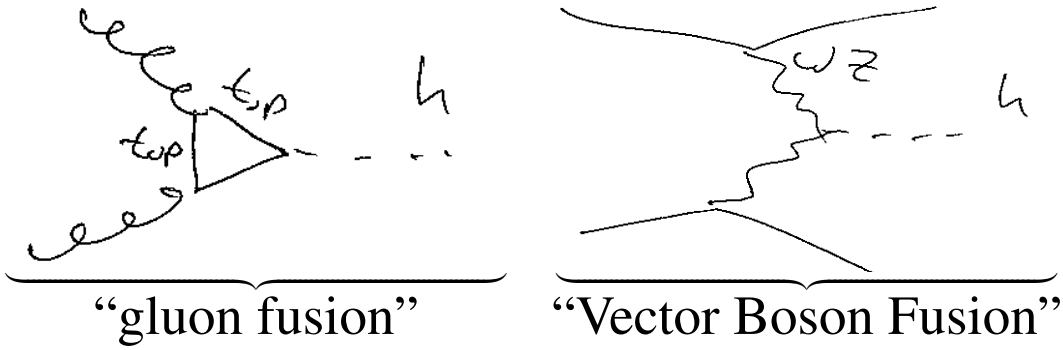
top, W, and Z are the heaviest particles in the theory $\Rightarrow$ they have the largest coupling to the higgs

Would really like to use processes like:



Problem is we dont have a top/W/Z colliders.

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



"gluon fusion" "Vector Boson Fusion"

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

How much data is needed?

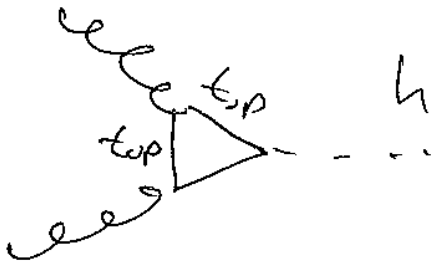
Lets estimate how often we make a Higgs.

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

$$\sigma_{W/Z} \sim \frac{\alpha_W}{m^2_{W/Z}} \sim \frac{1}{50}\frac{1}{100^2}\,\text{GeV}^{-2}$$
$$\sim 10^{-6}\,\text{GeV}^{-2}$$

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

~~$h \to bb$ 60%~~
$h \to WW$ 20%
~~$h \to gg$ 10%~~
~~$h \to \tau\tau$ 8%~~
$h \to ZZ$ 3%
$h \to \gamma\gamma$ 0.2%

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

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

$\Rightarrow$ Need a billion proton collisions per second.

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

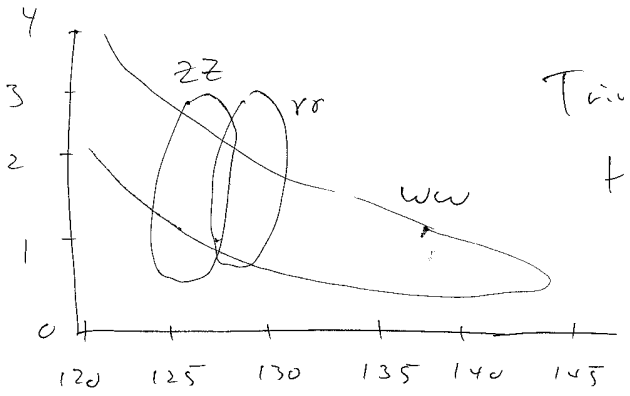
This is why we have to live with pile-up.

In 2012, Higgs discovered

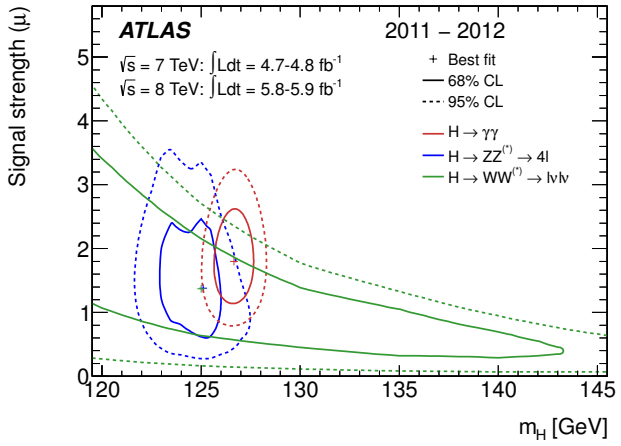
- $h \to WW \to \ell\nu\ell\nu$ (Hard)
- $h \to ZZ \to \ell\ell\ell\ell$ (easy)
- $h \to \gamma\gamma$ (straight forward)

Triumph of Humanity!!!

Cartoon:



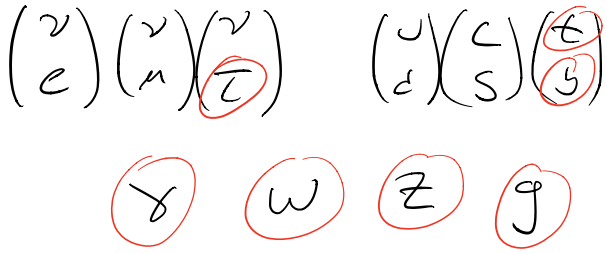
Real Data:



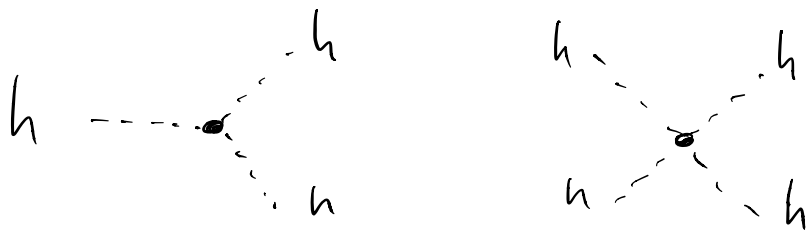
So far looks like SM Higgs in every way. (stupidest version)

What we dont know

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



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



Higgs self-interaction.

Di-Higgs Production / Next Frontier.