An Introduction to Higgs Hunting

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Part I: General Higgs Hunting

- What is the Higgs and why is it so important?
- Why is the Higgs so hard to find?
- What is already known about the Higgs?
- How do people look for the Higgs?

Part II: A Real Example

$H \rightarrow WW$ in the CDF Detector
at the Fermilab Tevatron

The Story of a Broken Symmetry

- Interesting Observation: The Proton and the Neutron are almost the same except for charge

$$\begin{pmatrix} p \\ n \end{pmatrix}$$

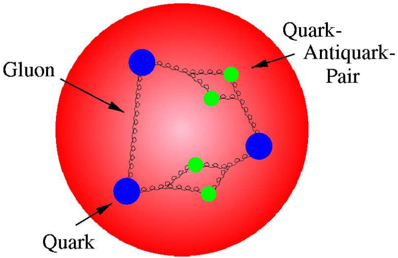
	Mass	Spin	EM Chg
Proton	938.3 MeV/c^2	$\frac{1}{2}$	+1
Neutron	939.6 MeV/c^2	$\frac{1}{2}$	0

- The similarity suggests an underlying symmetry
- The imperfection of the symmetry suggests that it's broken
- Weak nuclear interactions, e.g. "β-decay", can transform one to the other
  - Suggests that this has to do with the weak force

The Standard Model of particle physics says:

There is an Electroweak Symmetry
...but it's broken by the Higgs.

...okay, it's not quite that simple



- Protons and Neutrons are not fundamental particles
- Most of the mass of the proton and neutron are in gluons and "sea" quarks (non-valence)
- The strong force hides the size of the symmetry breaking

The Standard Model

Particles: Quarks

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$$

Particles: Leptons

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$$

Forces

Electromagnetic γ

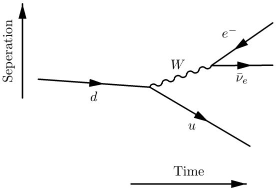
Strong Nuclear g=gluon

Weak Nuclear W and Z

plus the Higgs...

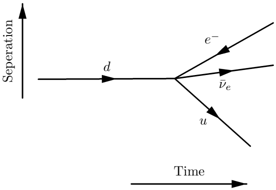
A More Theorectical View

- The Gauge Principal relates
  Symmetries to Forces to Massless Bosons
  - Generalization of familar classical gauge symmetry in E&M
  - Field choosing a different Gauge at every point becomes γ
  - Successful description Quantum Electromagnetism (QED)
- The Weak Force is short range
  - acheived mathematically by giving the force carrier mass



Can't produce W-mass

Uncertainty/Tunneling $\rightarrow$ short distance

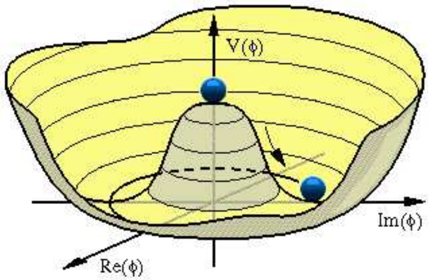


  - But the gauge principal only works for massless particles
  - The solution: put in a symmetry into the theory using the gauge principle, but have the solution to the equations spontaneously violate the symmetry

Agent of the Symmetry Breaking

Added to the theory in order to break the symmetry

- Complex scalar (spin=0) field
- Higgs interacts with itself to make zero field a higher energy state



- The Higgs acquires a vacuum expectation and chooses a phase
- The particle interactions are symmetric, but the vacuum isn't
- Vacuum isn't empty, it's full of the Higgs field!

This is known as spontaneous symmetry breaking

Effect of the Symmetry Breaking

Two phenomena are unified into one

Carriers of
Electroweak Force

$$\underbrace{\begin{pmatrix} W^+ \\ W^0 \\ W^- \end{pmatrix}}_{SU(2)_L} \quad \underbrace{B^0}_{U(1)_Y}$$

Massless Gauge
Bosons

Spontaneous
Symmetry
Breaking

Weak Force
W^+, W^-, Z

Acquire Mass

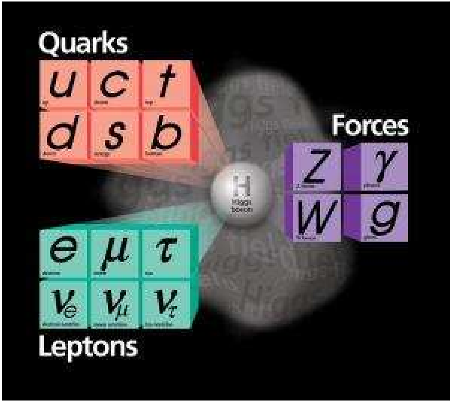
Electromagnetic
Force:
Mix of B^0 and W^0

$$\underbrace{\gamma}_{U(1)_{EM}}$$

Still Massless

- Coupling of electroweak bosons to Higgs vacuum expectation gives them mass and breaks the symmetry
- Right quantum numbers to also give fermions masses

Standard Model in it's Full Glory



Electroweak symmetry breaking predicts relationships between *W* and *Z* masses and couplings

Tested extensively for $>$ 30 years

Higgs Summary

1. Agent of symmetry breaking
2. Gives mass to boson and fermions
3. Occam's razor solution

- There are many other possible ways to break electroweak symmetry
- All these particles have been seen except for the Higgs

Why is the Higgs to So Hard to Find?

We make new particles in the lab by colliding particles at very high center of mass energies ($E = mc^2$), but...

The problem

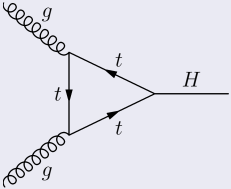
1. Things that couple strongly to the Higgs have large masses
2. Things with large masses decay rapidly (subject to quantum numbers)
3. We can only collide long-lived particles

So...We can't collide anything that couples well to the Higgs

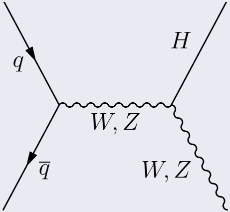
Why is the Higgs to So Hard to Find?

Some of the possible solutions...

Produce the Higgs via heavy quark loops $gg \to H$



Produce the Higgs in association with W or Z

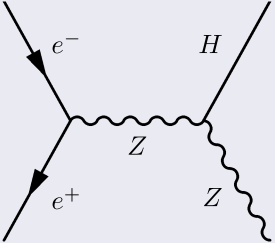


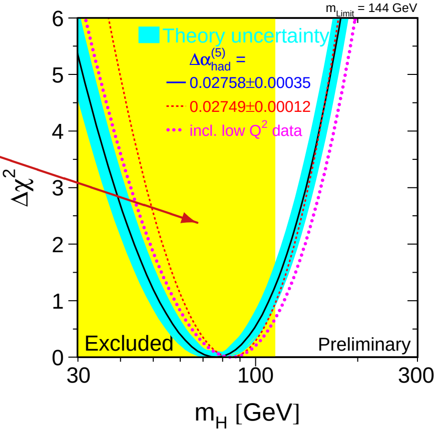
Both processes are analogous to tunneling. They are not allowed classically.

What is already known about the Higgs?

Direct Limits

Yellow area excluded by LEP experiments using e^+e^- collisions at 207 GeV/c^2

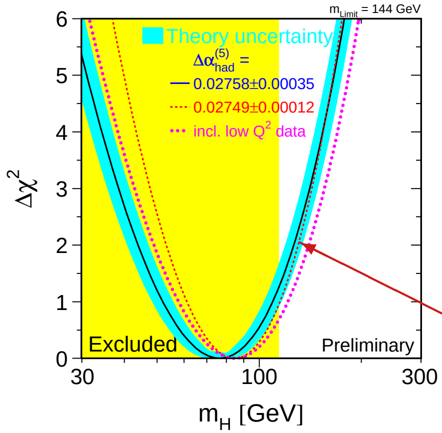




m_H limit ≈ collision energy - m_Z

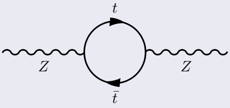
What is already known about the Higgs?

Combination LEP and Tevatron experiments measure the effect of particles we can't produce!



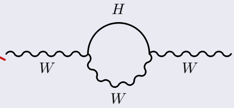
Indirect Limits

Effect of *t*-quark on *Z* mass



Successful prediction of top quark mass,

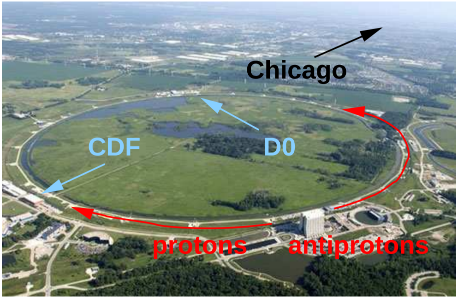
Effect of Higgs on *W* mass

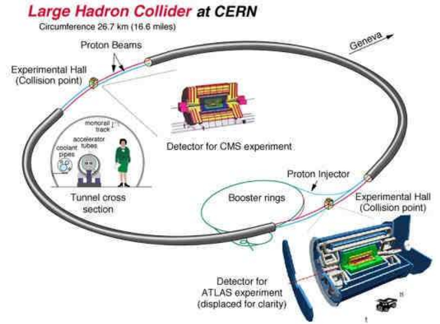


Now add in measured top quark mass and predict the Higgs mass

How do people look for the Higgs?

Two large experiments





Now: The Tevatron collides protons with anti-protons ($p\bar{p}$) at 2 TeV of center of mass energy

Two detectors: CDF and DØ

CDF results in this talk

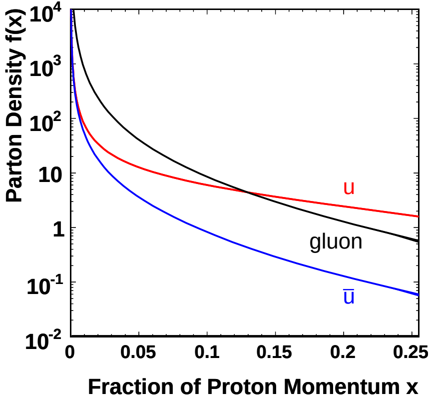
The Future: The LHC collides protons with protons (pp) at 14 TeV of center of mass energy

Two detectors (for Higgs): CMS and Atlas

Colliding Bags of Particles

Protons aren't fundamental particles

- They contain quarks, anti-quarks, and gluons (the carrier of the strong force)
- Each *pp* or $p\bar{p}$ collision can have contain a collision of any combination of these
- Collision have a variety of energies corresponding to how much of the *pp* ($p\bar{p}$) energy was in the colliding particles

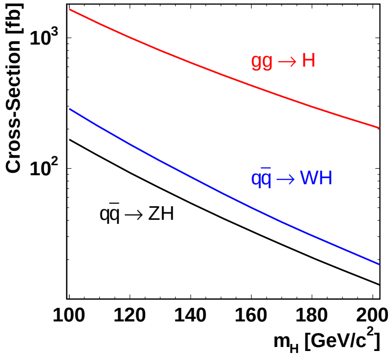


- Good:
  All kinds of collisions
- Bad:
  Don't know what collided

Wide Variety of Options

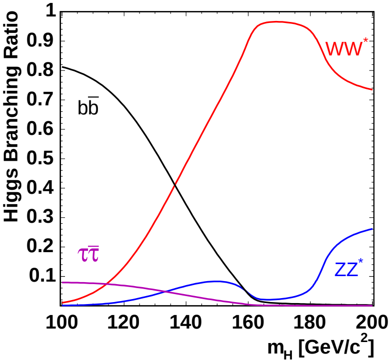
Pick one from each column

Production



Cross-sections at Tevatron

Decay



Interesting Branching Fractions

Remember Constraints on SM Higgs: $114 < m_H <\approx 180$ GeV/c^2

LHC has many more options

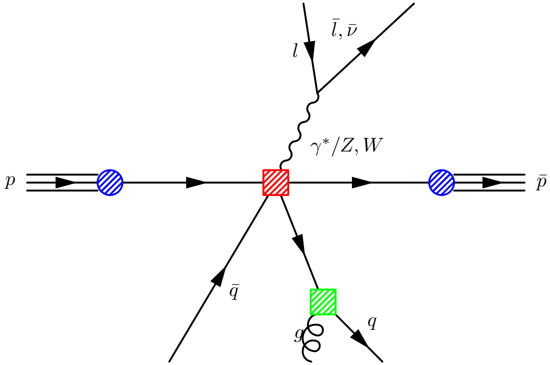
Part II: A Real Example

$H \rightarrow WW$ in the CDF Detector
at the Fermilab Tevatron

- More on Proton Collisions
- The CDF Detector
- Finding W-pairs
- Searching for $H \rightarrow WW$
- Results!
- The Future of $H \rightarrow WW$

The Guts of a Proton Collision

- Electroweak Physics
  - This is what we are after
- Nonperturbative (hard to calculate) Strong Force Effects
  - Lots of different confi gurations and effects
  - Extra quarks and gluons turn into “jets” of particles



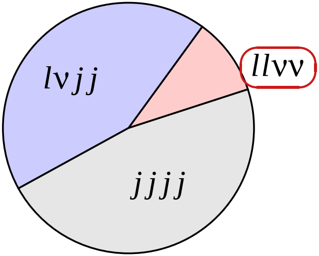
- Parton Distribution Functions $\equiv$ Structure of the Proton
  - All the events are “boosted” along the beam line

Choosing a Decay Mode to Use

Protons are made of quarks and gluons, which couple **strongly** to quarks and gluons, $\Rightarrow$ there are lots of them around

W-decay

70 %	$W^- \to q\bar{q}'$
30 %	$W^- \to l^-\bar{\nu}_l$



WW and $H \to WW$

Fully Leptonic: $l^-\bar{\nu}_l l^+\nu_l$

- Small branching fractions
- Low backgrounds

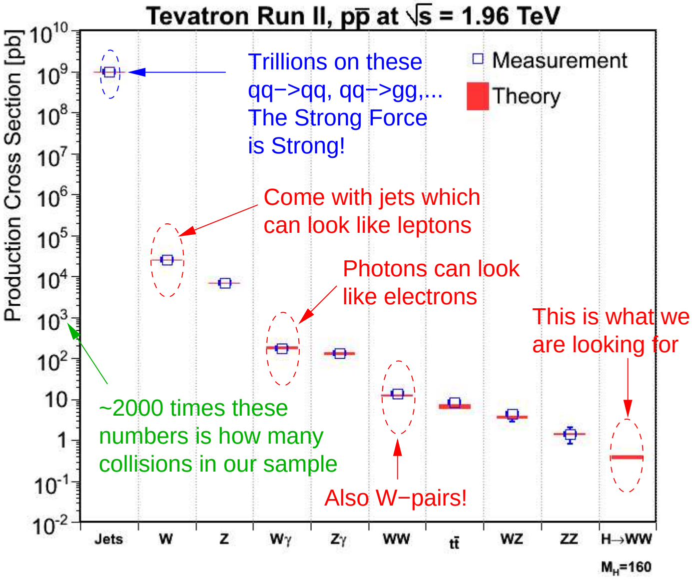
Semileptonic: $l^-\bar{\nu}_l q\bar{q}'$

- $\approx 5 - 10\times$ branching fractions
- $\approx 1000\times$ backgrounds
- Backgrounds hard to understand

Fully Hadronic: $q\bar{q}'q\bar{q}'$

- Forget about it!

A Huge Data Sample



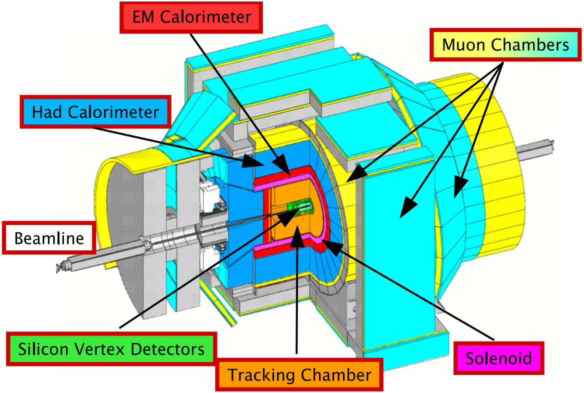
Looking for ≈8 events (=collisions) in a trillion!

≈ 1 petabyte = 1000 terabytes of data

The CDF Detector: A Multipurpose Detector

Spray of particles emerges from collision point

Concentric cylinders of subdetectors



- Inner subdetectors: Low density detectors to measure charged particle paths in a magnetic field $\rightarrow$ momentum
- Outer subdetectors: Measure neutral and charged particle energy deposition using dense material

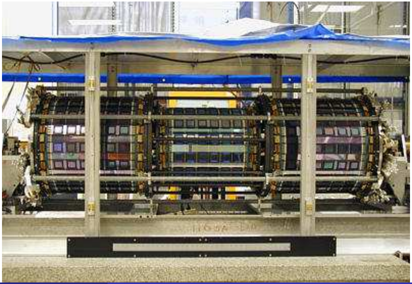
Charge Particle Tracking

Gas-based device

- Charged particles knock electrons off molecules in gas
- Electrons fall towards wires in large electric field, knocking of more electrons
- Electrons collected on wires

Silicon Vertex Detector

- Electron-hole pairs created in silicon semiconductor by passing charged particles
- Electrons and holes drift collected on surface of wafers

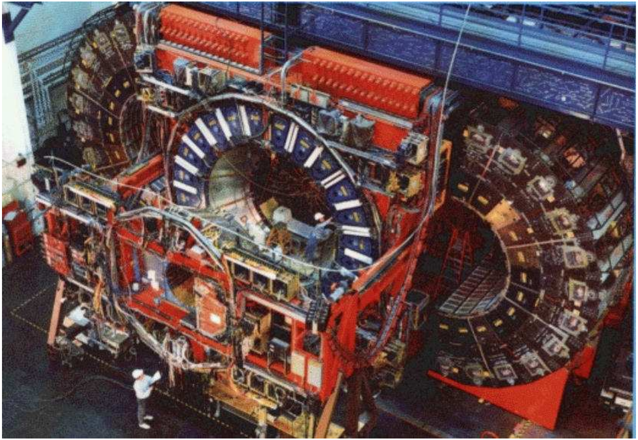


Calorimeters

Particles hitting material make more lower energy particles, cascading into showers

e and γ make small showers

Hadrons (made out of quarks) make big showers



- Plastic scintillation counters embedded in layers of lead and iron absorber
- Scintillation: electrons knocked into higher orbitals of molecules de-excite, emitting light in proportion to energy

Muons make it all the way through

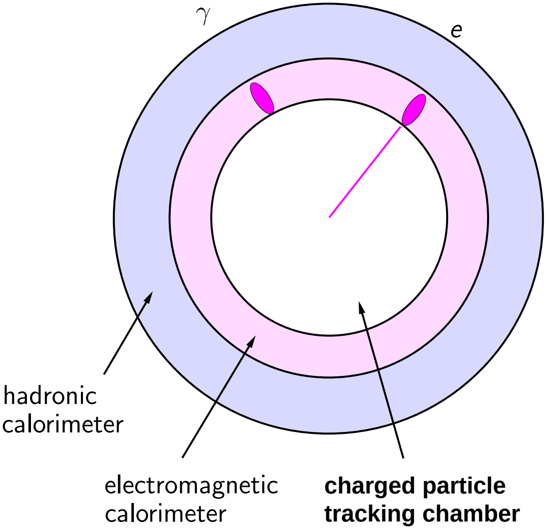
- Special “Muon” chambers are a combination of gas-based tracking devices and scintillation counters
- Extra iron to make sure

Electrons and Photons in the Detector

Both leave small showers in the EM calorimeter and do not make it to hadronic calorimeter

$W\gamma \approx 100$ bigger than signal

- photons convert to e^+e^- in material

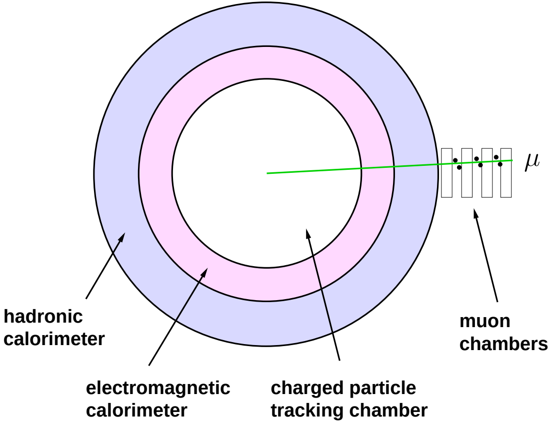


Muons

Muons are just like electrons but heavier

The mass makes a huge difference in how they interact in the detector...they are very hard to stop

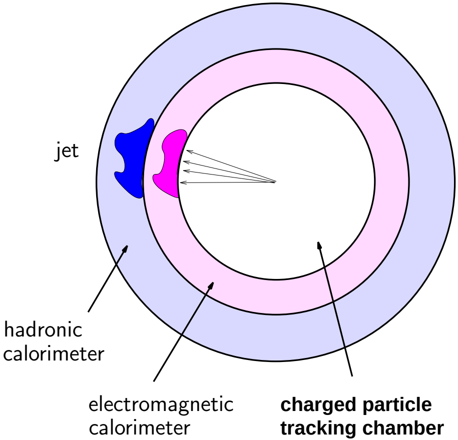
They are the only things to make it to the muon chambers



Jets

Quarks and gluons don't like to be alone

- When pulled apart more quarks and gluons show up to make pairs and triplets
- They show up as clusters of particles called "jets"
- Fluctuations in this process can make them look like electrons or muons



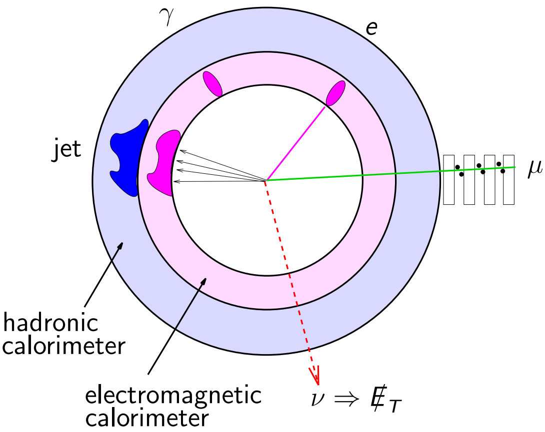
There are ≈ 1000 times more jets than leptons

Neutrinos!

Neutrinos will go through the earth with no problem

Detected by the lack of momentum conservation in the plane transverse to the beam

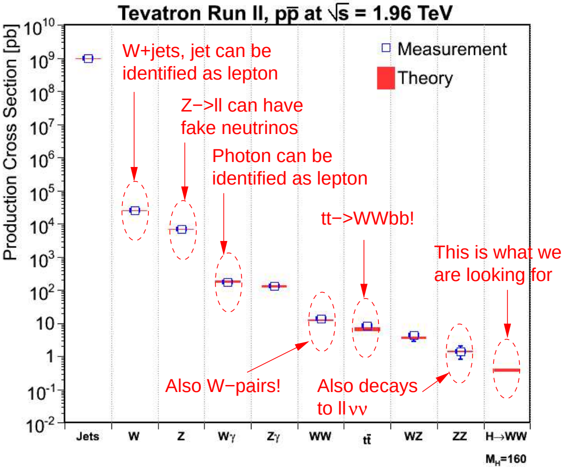
Lack of momentum conservation is, after all, how they were discovered

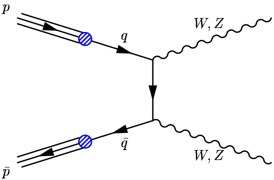


"I have committed the ultimate sin, I have predicted the existence of a particle that can never be observed."

- Wolfgang Pauli

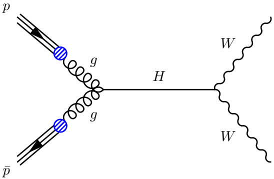
Look at this again





$qq \rightarrow WW$

Already a needle in a hay stack



$gg \rightarrow H \rightarrow WW$

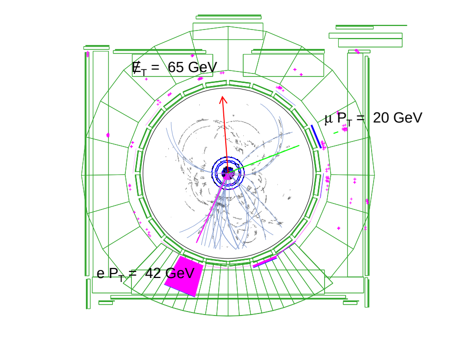
Underneath the needle

We have to account for all of this when we look at data

Finding $(H \rightarrow) WW \rightarrow ll\nu\nu$

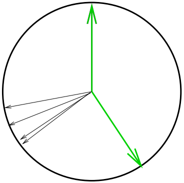
... in trillions of collisions

- Select collisions with two charged-leptons (electrons or muons)
- Require momentum imbalance to indicate presence of neutrinos



Beam's Eye View of CDF

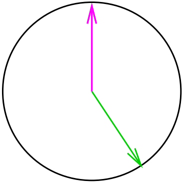
Collision Cartoons



$Z \rightarrow ll$

1000 times more of these

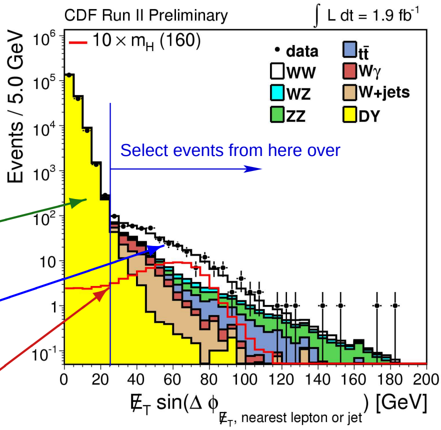
than of these



$WW \rightarrow ll\nu\nu$

$WW \rightarrow ll\nu\nu$ and $H \rightarrow WW \rightarrow ll\nu\nu$

- Backgrounds stacked on top of each other to predict to number of events (collisions) in sample
- $Z \rightarrow ll$ (also called Drell-Yan or DY)
- $q\bar{q} \rightarrow WW \rightarrow ll\nu\nu$ is white area
- Red line is predicted Higgs signal **times 10!**



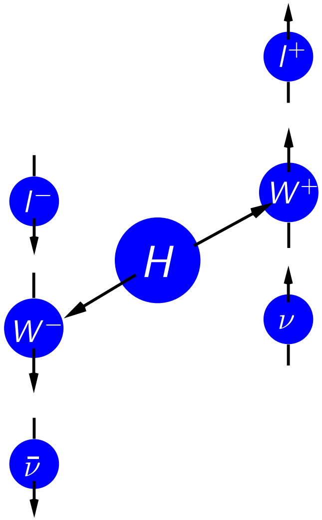
Momentum Imbalance Variable

Lookings for at most 8 Higgs events in ≈ 500 background events ...and we've already made a selection of 1 in 10 billion

Separating $gg \to H \to WW$ from $q\bar{q} \to WW$

The differences are subtle

- Higgs is a spinless particle
- W has spin one
  - $\Rightarrow$ Ws must be spinning in opposite directions
- Parity Violation:
  - Positively charged leptons tend to go along W^+ spin direction
  - Negatively charged leptons tend to go away from W^- spin direction
  - $\Rightarrow$ charge leptons tend to go in the same direction



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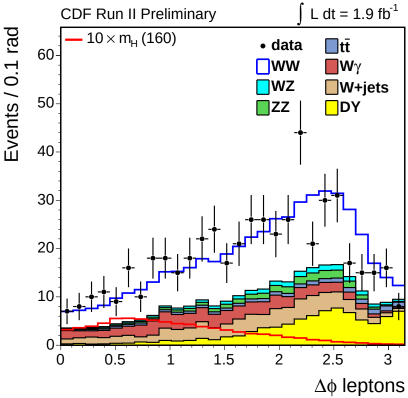
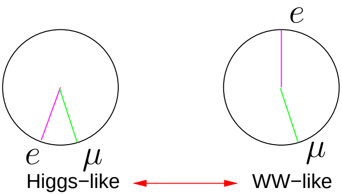
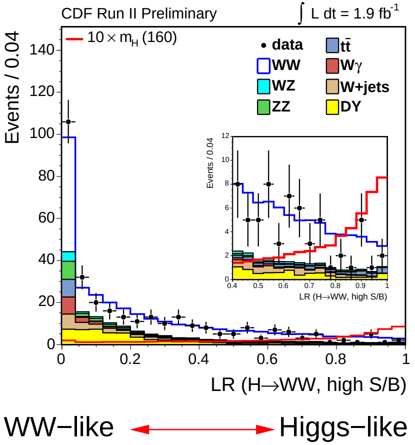




Advanced Technique for Separating $H \to WW \to ll\nu\nu$ from $WW \to ll\nu\nu$

- Use all the measured kinematic information
  - Charged-lepton momentum and directions
  - Missing transverse momentum size and direction
- Construct probabilities based on theoretical predictions of processes and model of the detector response
- Make a “likelihood ratio”

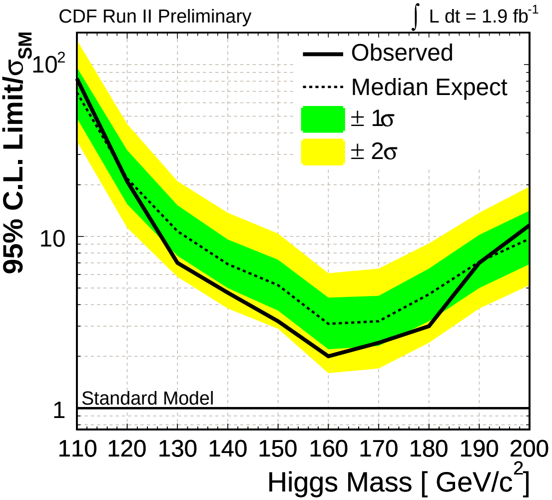


$$\text{Likelihood Ratio} = \frac{\text{Event Probability from Higgs}}{\text{Event Probability from either Higgs or Background}}$$

Results = Limits on Higgs Production

Limits shown as a ratio to the Standard Model expectation

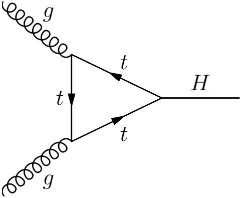
Not yet ruling out values of the Higgs mass in the Standard Model, but we are getting close

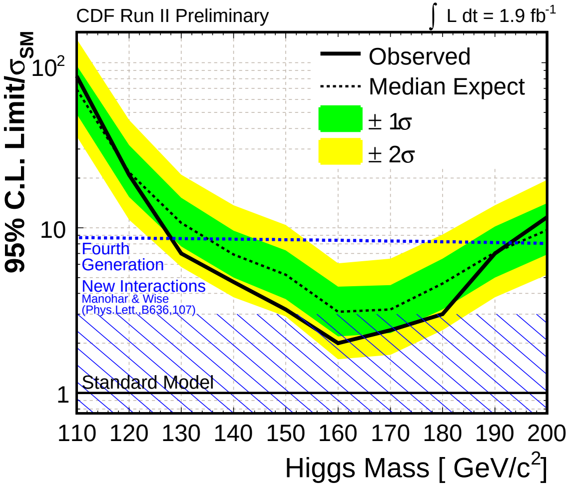


Results = Limits on Higgs Production

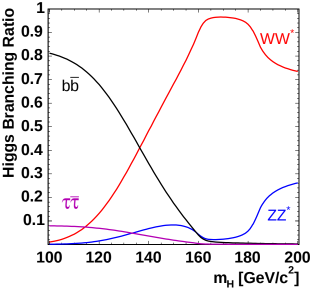
The Standard Model may not be right!

Models with more particles can change the gluon-gluon to Higgs *ggH* coupling: There could be something else in this loop



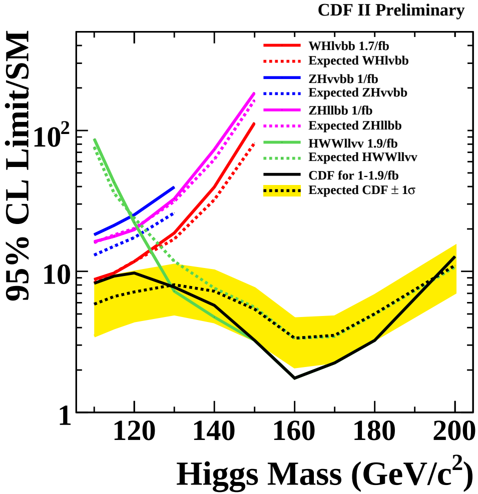


Remember this:



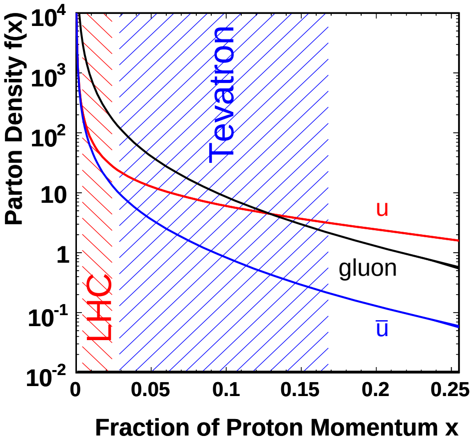
Interesting Branching Fractions

At low mass *WW* disappears and $b\bar{b}$ appears



Scaling this to the LHC

- LHC collides at 14 TeV instead of the Tevatron's 2 TeV
- Need smaller fraction of proton momentum to make the same Higgs mass
- $gg \rightarrow H \rightarrow WW$ signal goes up $\approx$ 60 times
- $q\bar{q} \rightarrow WW$ only goes up 9 times

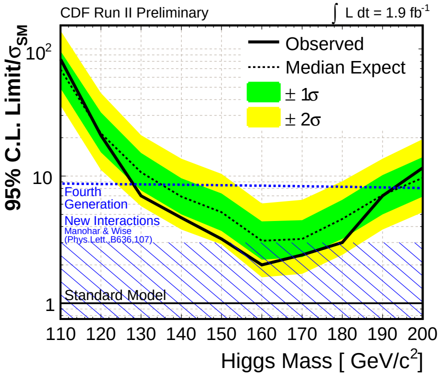


Proton Structure

Summary

Tevatron: Closing in on the Higgs

Ruling out non-standard model physics on the way



LHC: About to turn on

Will find or rule out the Standard Model Higgs!