

Collider Physics

with an Introduction to Higgs Hunting

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Part I: Higgs Hunting and Beyond

- 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?
- Other big questions

Part II: The Experiments

- CDF and ATLAS
- Penn activities on ATLAS

Part III: A Real Example

H → *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

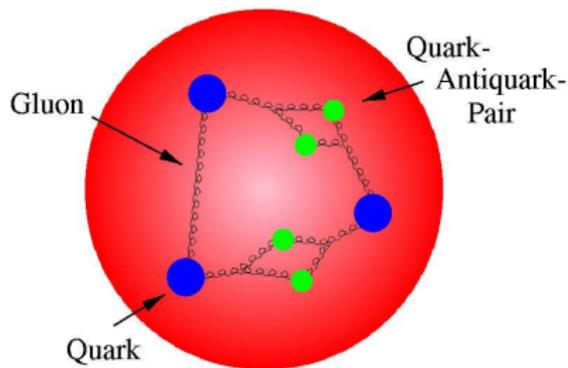
		Mass	Spin	EM Chg
$\begin{pmatrix} p \\ n \end{pmatrix}$	Proton	938.3 MeV/c ²	$\frac{1}{2}$	+1
	Neutron	939.6 MeV/c ²	$\frac{1}{2}$	0

- 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

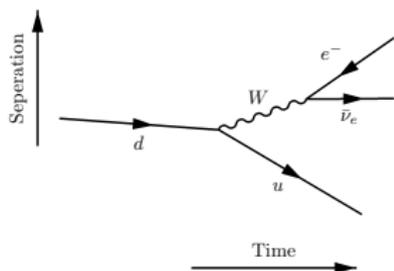
Strong Nuclear g =gluon

Weak Nuclear W and Z

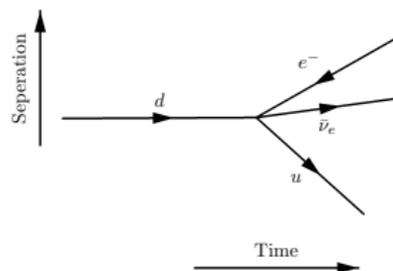
plus the Higgs...

A More Theoretical View

- The Gauge Principle relates **Symmetries** to **Forces** to **Massless Bosons**
 - Generalization of familiar 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
 - achieved mathematically by giving the force carrier mass



Can't produce W -mass
→
Uncertainty/Tunneling →
short distance

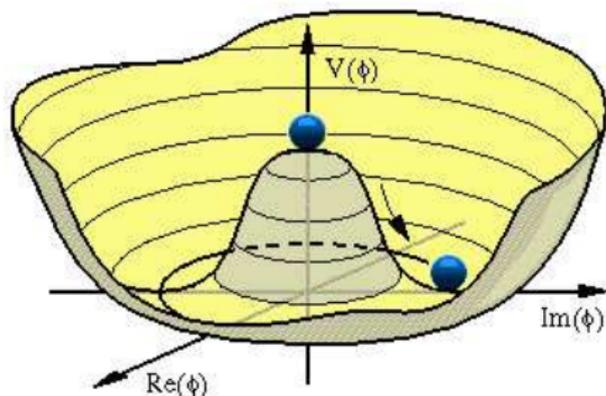


- But the gauge principle only works for massless particles
- The solution: put in a symmetry into the theory using the gauge principle, **but have the solution to the equations spontaneously violate the symmetry**

Higgs = 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

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

Massless Gauge
Bosons



Spontaneous
Symmetry
Breaking

Weak Force
 W^+ , W^- , Z

Acquire Mass

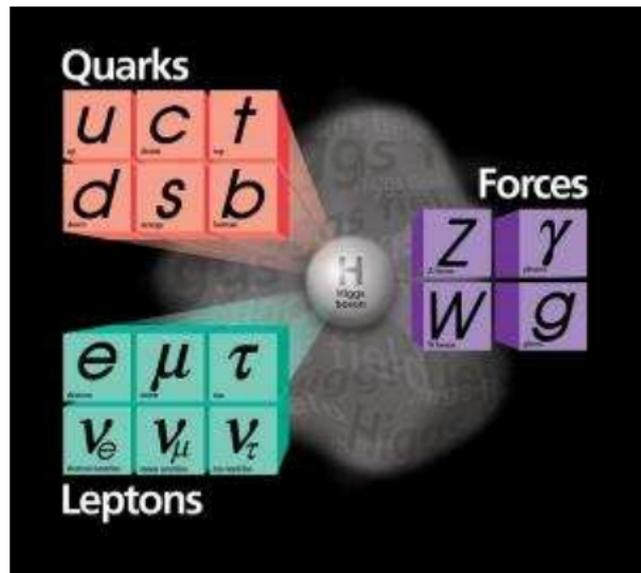
Electromagnetic
Force:
Mix of B^0 and W^0

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

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 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

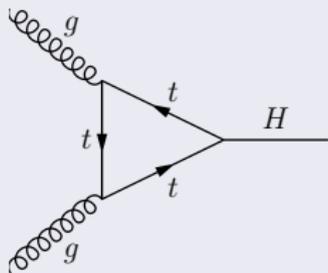
- 1 Things that couple strongly to the Higgs have large masses
- 2 Things with large masses decay rapidly (subject to quantum numbers)
- 3 We can only collide long-lived particles

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

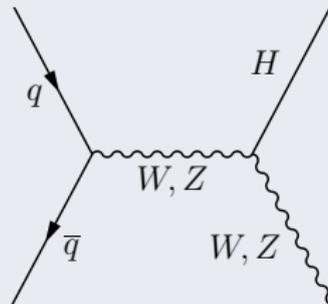
Why is the Higgs so Hard to Find?

Some of the possible solutions...

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



Produce the Higgs in association with W or Z

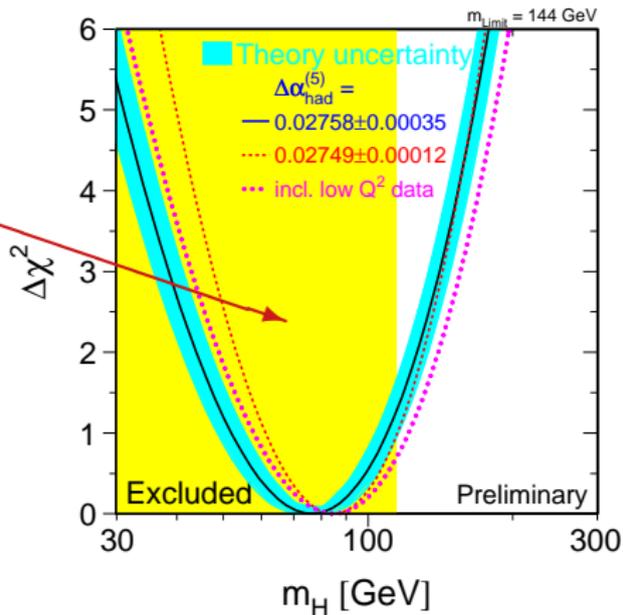
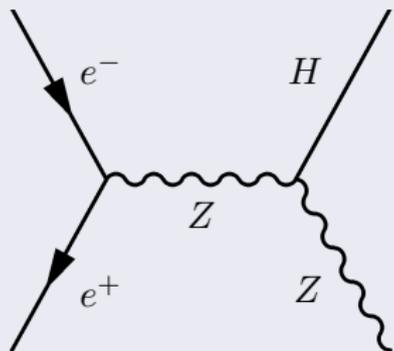


Both processes are analogous to tunneling.
They are not allowed classically.

What is already known about the Higgs?

Direct Limits

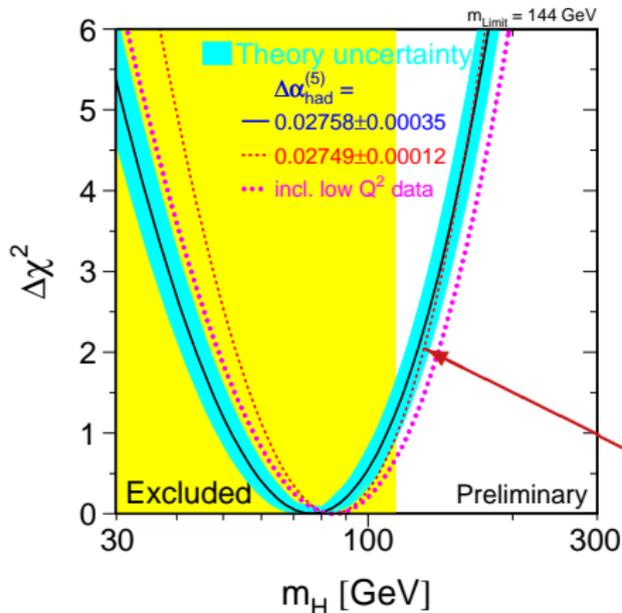
Yellow area excluded by LEP experiments using e^+e^- collisions at 207 GeV/c²



$$m_H \text{ limit} \approx \text{collision energy} - m_Z$$

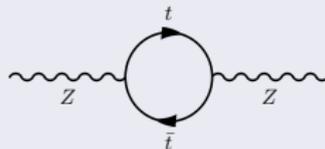
What is already known about the Higgs?

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



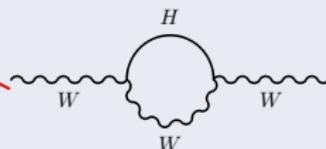
Indirect Limits

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

Big Questions beyond the Higgs

- Higgs mass naturally gets large quantum corrections
 - If it exists, stabilizes it's mass?
 - If it doesn't exists, what breaks electroweak symmetry?
- Cosmology and astronomy see evidence of Dark Matter
 - Can we product it in the lab?
- Why is Gravity so weak compared to the other forces?
- Why three generations of quarks and leptons?

There are ideas to answer some of these questions:
Super-symmetry, extra-dimensions, new substructure or forces,... only one way to find out which is right

Part II: The Experiments

- CDF and ATLAS
- Penn activities on ATLAS

Two large experiments

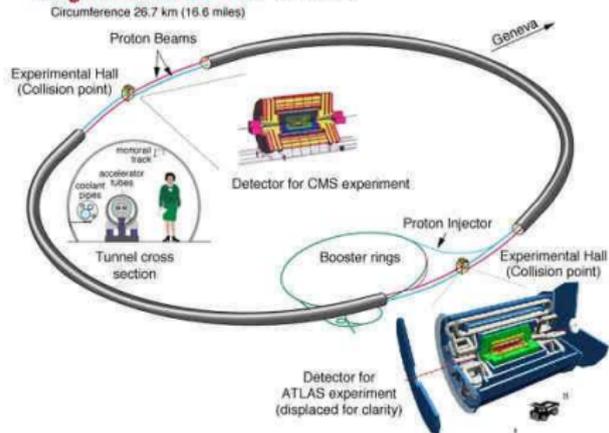


Now: The Tevatron collides protons with anti-protons ($p\bar{p}$) at 2 TeV of center of mass energy

Two detectors: CDF and DØ

CDF results in this talk

Large Hadron Collider at CERN



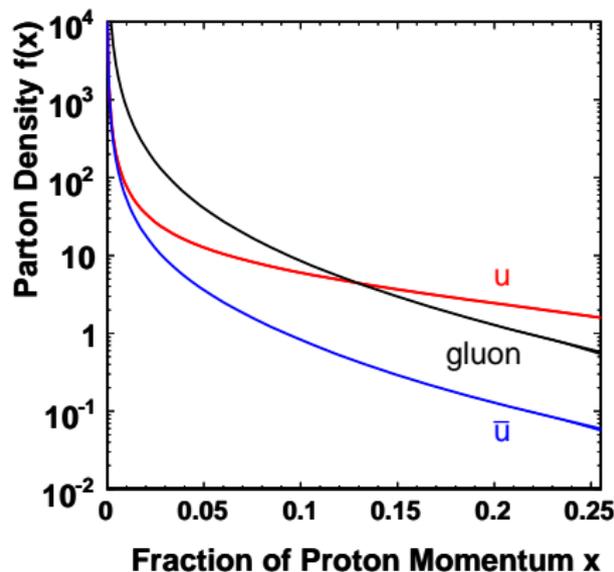
The Future: The LHC collides protons with protons (pp) at 14 TeV of center of mass energy

Your opportunity to discover the Higgs here

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:
Rich Variety of Physics
- Bad:
Don't know what collided

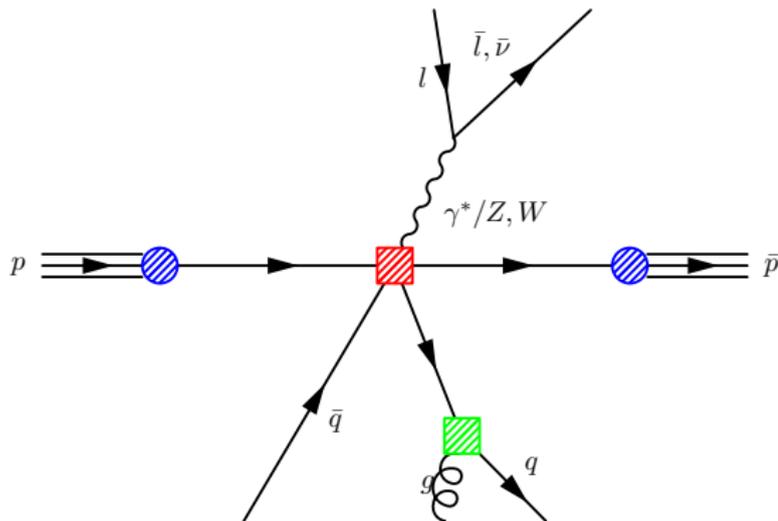
The Guts of a Proton Collision

- **Electroweak Physics**

- This is what we are after

- **Nonperturbative (hard to calculate) Strong Force Effects**

- Lots of different configurations and effects
- Extra quarks and gluons turn into “jets” of particles



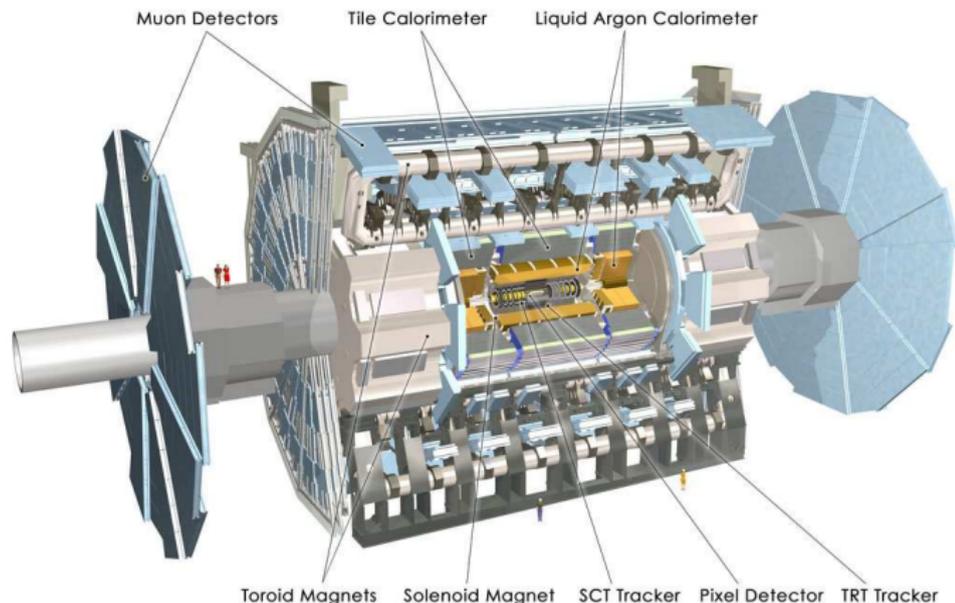
- **Parton Distribution Functions \equiv Structure of the Proton**

- All the events are “boosted” along the beam line

Multipurpose Detectors

Spray of particles emerges from collision point

Concentric cylinders of sub-detectors



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

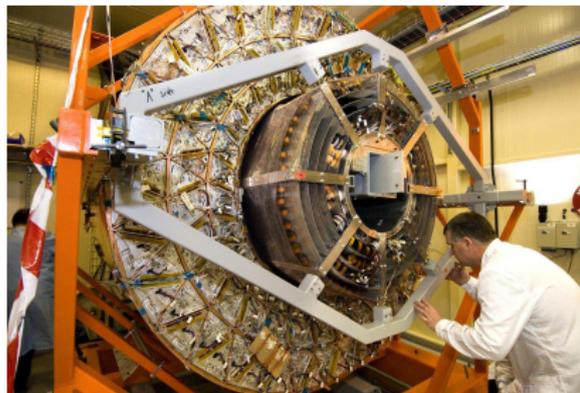
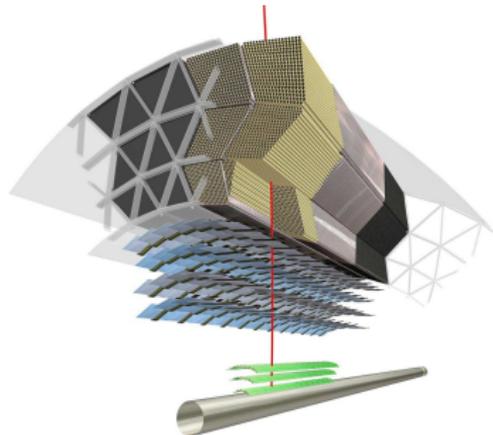
Charge Particle Tracking

Gas-based device

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

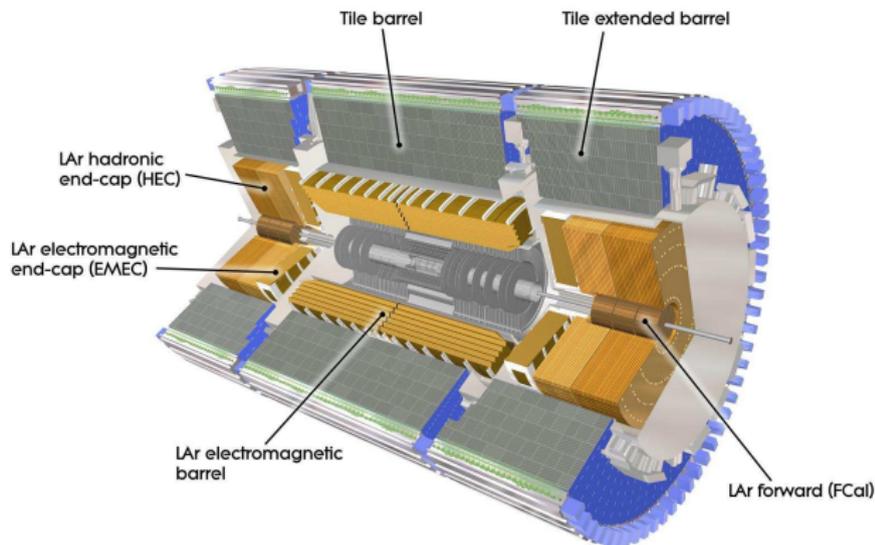


Calorimeters

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

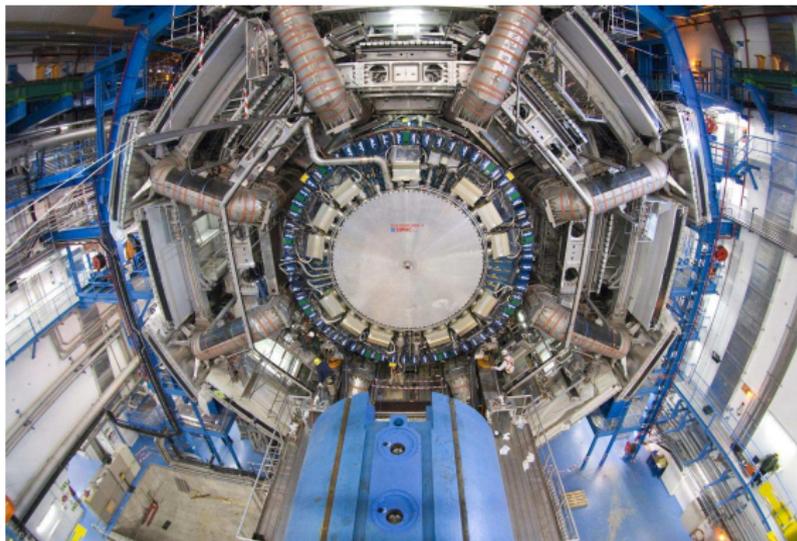
e and γ make small showers

Hadrons (made out of quarks) make big showers



- Inner Cylinder: Charge collected from ionized Liquid Argon
- Outer Cylinder: Scintillation, electrons knocked into higher orbitals of molecules de-excite, emitting light in proportion to energy

Muons make it all the way through

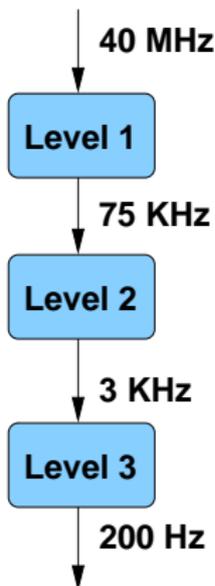


- Special “Muon” chambers are a variety of gas-based tracking devices
- ATLAS two magnets systems: Solenoid inside and Toroids outside



Triggering

- Beams cross at 40 MHz with multiple collisions per crossing
- Can store at most 200 Hz of the crossings, “events”
- **Sophisticated system selects the events to store \implies “trigger”**



- Level 1 hardware with simple algorithms, decision made in $2.5\mu s$
- Level 2 computer farm with the decisions made in $\approx 50ms$
- Level 3 bigger computer farm with the decisions made in $\approx 3s$

Penn involvement: Triggering and Electronics

Trigger

- Studies to make sure we store the interesting events (and can understand what we stored)
- Also study how much resources the decision algorithms use
- Rate of collisions will increase ≈ 1000 fold in next 3-5 years
- Designing new trigger system for the ATLAS upgrade that deals with ≈ 400 collisions or $\approx 10,000$ particles per crossing

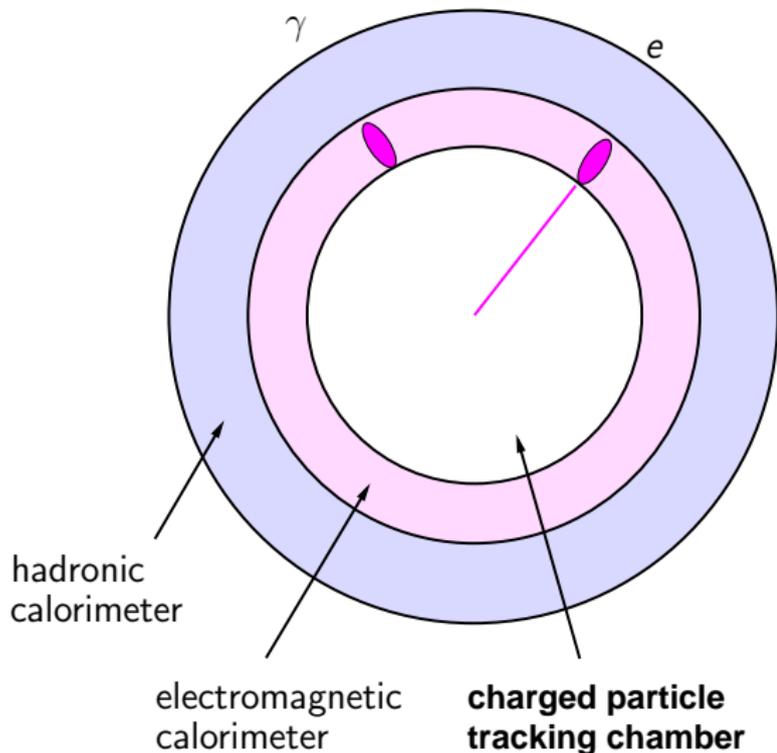
Electronics and TRT (gas-based tracking chamber)

- Designed, built, and are making the electronics work
- Understanding data the now build system is providing
- Working on the electronics for a replacement in the upgrade

Electrons and Photons in the Detector

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

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

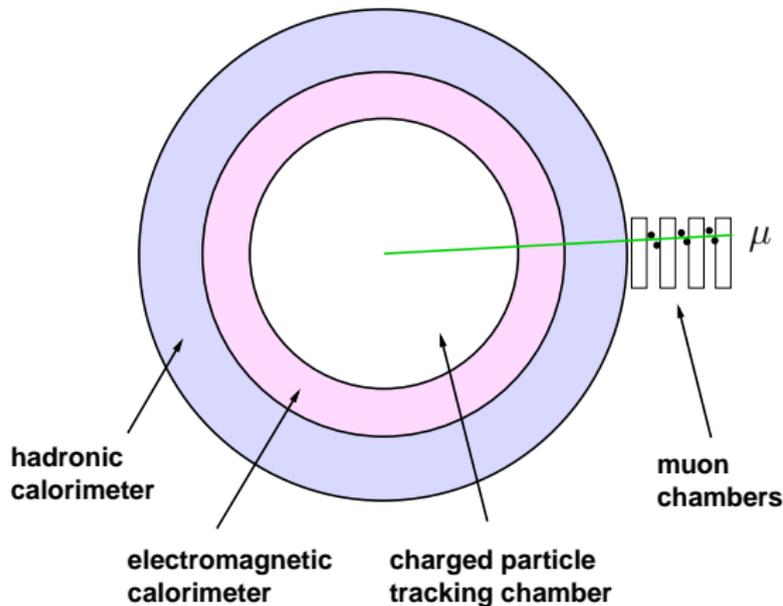


Muons

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

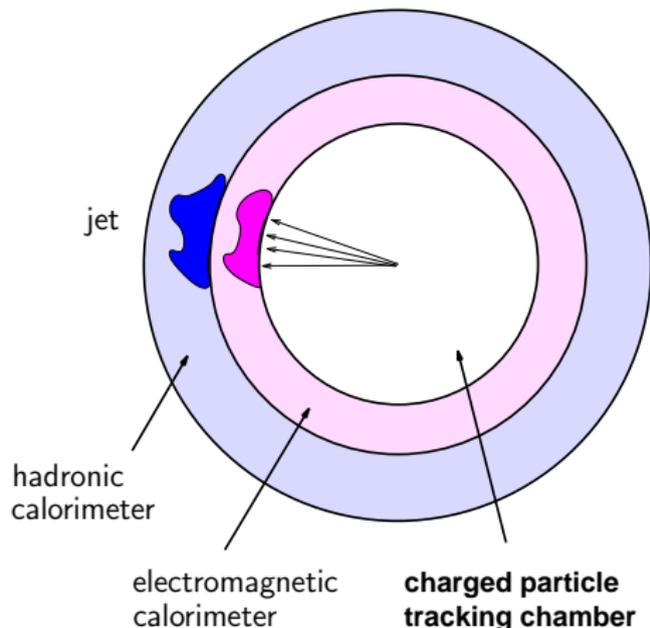


Jets

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!

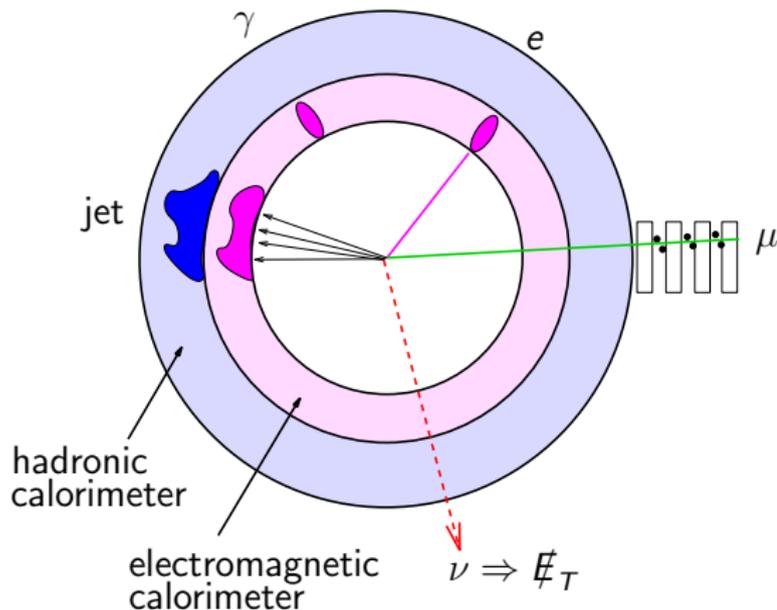
Neutrinos will go through the earth with no problem

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



Part III: A Real Example

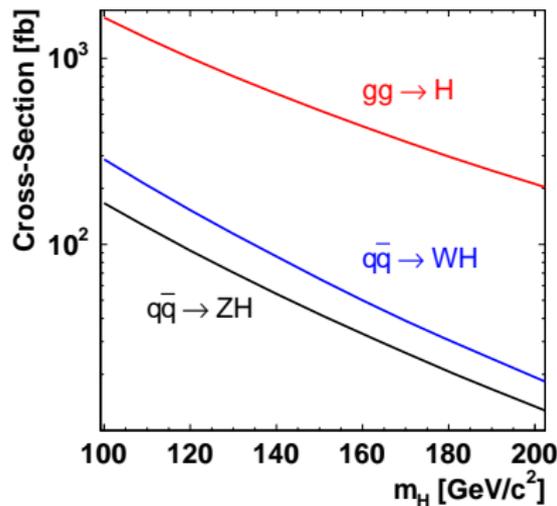
H → *WW* in the CDF Detector
at the Fermilab Tevatron

- The search channel
- Finding *W*-pairs
- Searching for *H* → *WW*
- Results!
- The Future of *H* → *WW*

Wide Variety of Options

Pick one from each column

Production

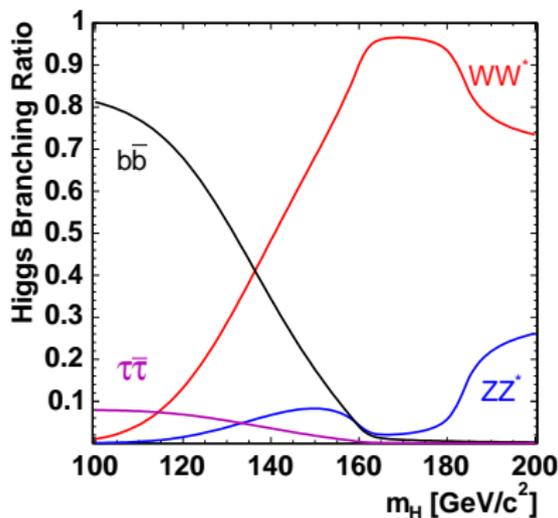


Cross-sections at Tevatron

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

LHC has many more options

Decay



Interesting Branching Fractions

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

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

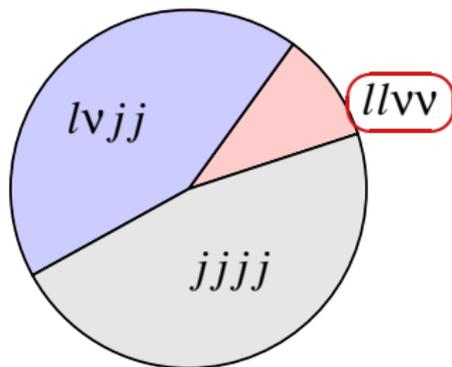
- Small branching fractions
- Low backgrounds

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

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

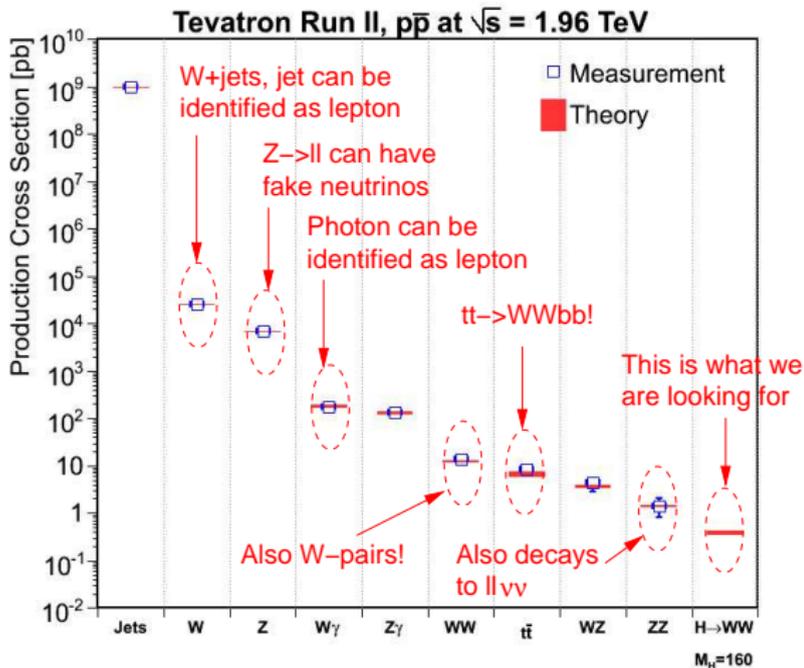
Fully Hadronic: $q\bar{q}'q\bar{q}'$

- Forget about it!

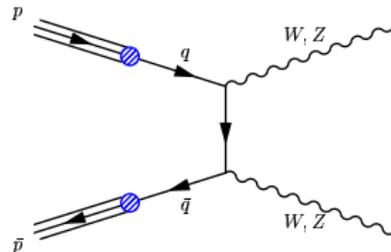


WW and $H \rightarrow WW$

Look at this again

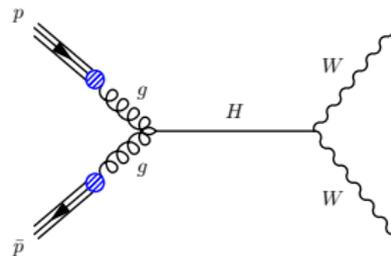


We have to account for all of this when we look at data



$$qq \rightarrow WW$$

Already a needle in a hay stack



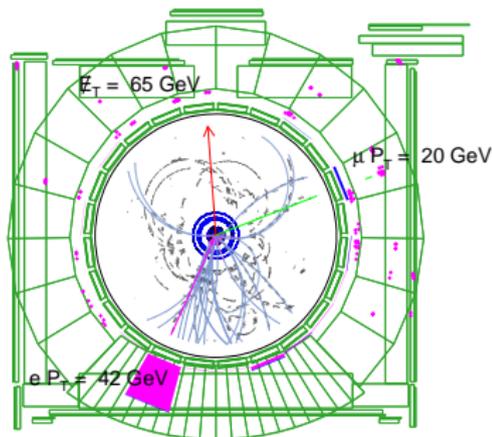
$$gg \rightarrow H \rightarrow WW$$

Underneath the needle

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

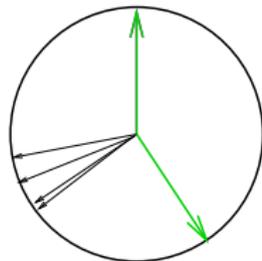
... in trillions of collisions

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



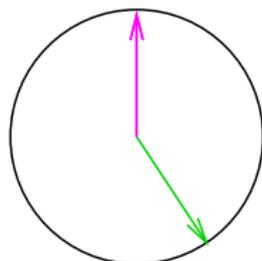
Beam's Eye View of CDF

Collision
Cartoons



$Z \rightarrow ll$

1000 times
more of
these

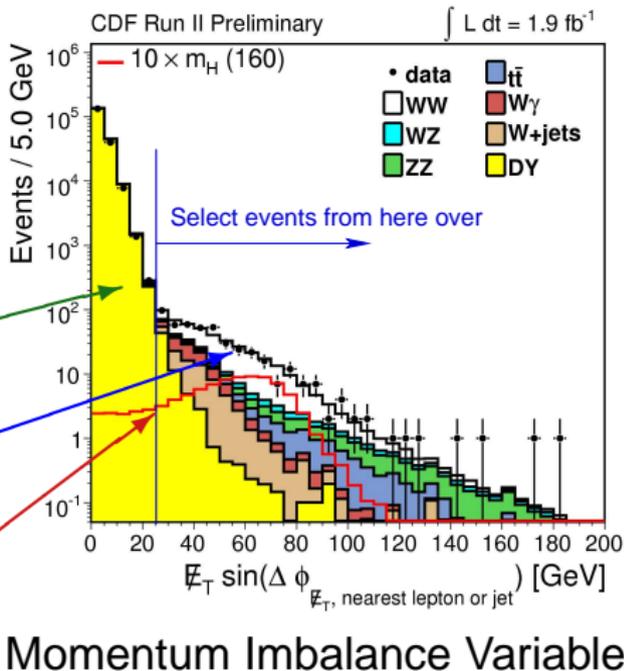


$WW \rightarrow ll\nu\nu$

than of
these

$WW \rightarrow ll\nu\nu$ 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!**

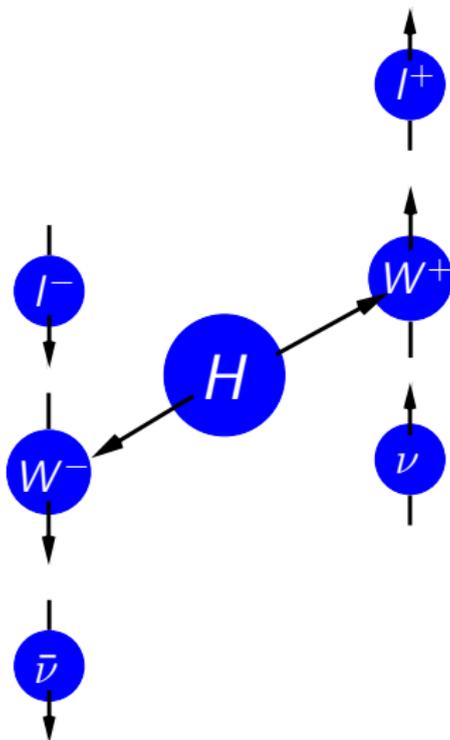


Looking for at most 8 Higgs events in ≈ 500 background events
 ...and we've already made a selection of 1 in 10 billion

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

The differences are subtle

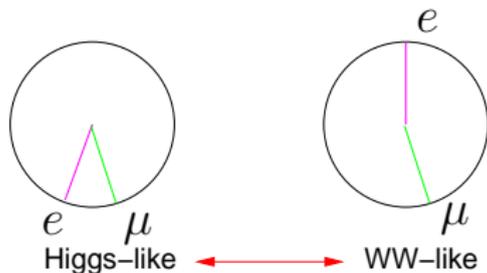
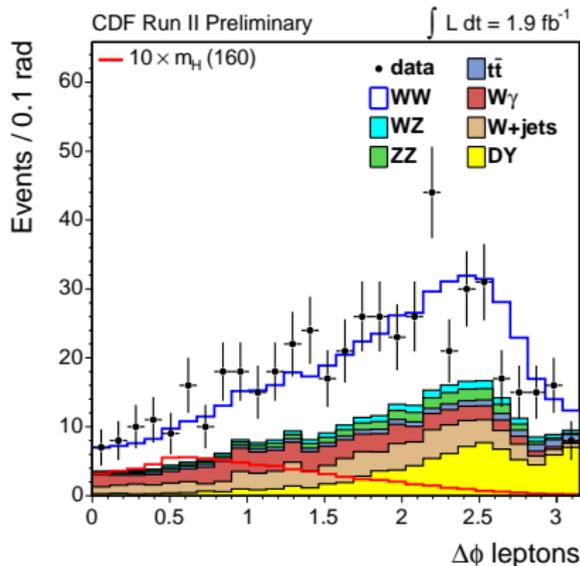
- Higgs is a spinless particle
- W has spin one
 - \Rightarrow W s must be spinning in opposite directions
- Parity Violation:
 - Positively charged leptons tend to go along W^+ spin direction
 - Negatively charged leptons tend to go away from W^- spin direction
 - \Rightarrow charge leptons tend to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



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

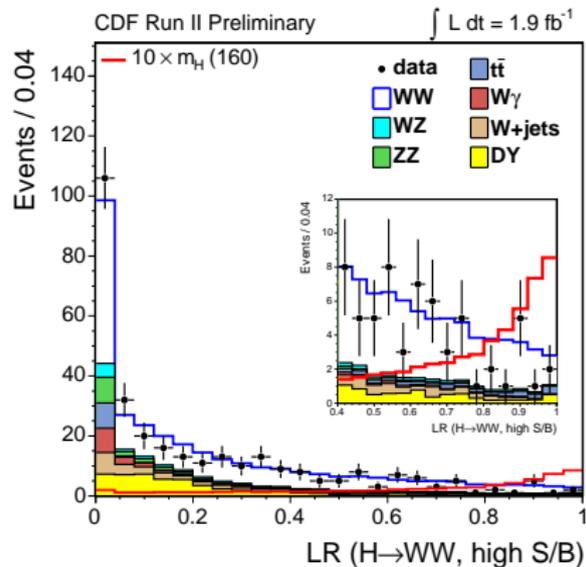
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Advanced Technique for Separating $H \rightarrow WW \rightarrow ll\nu\nu$ from $WW \rightarrow ll\nu\nu$

- 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”



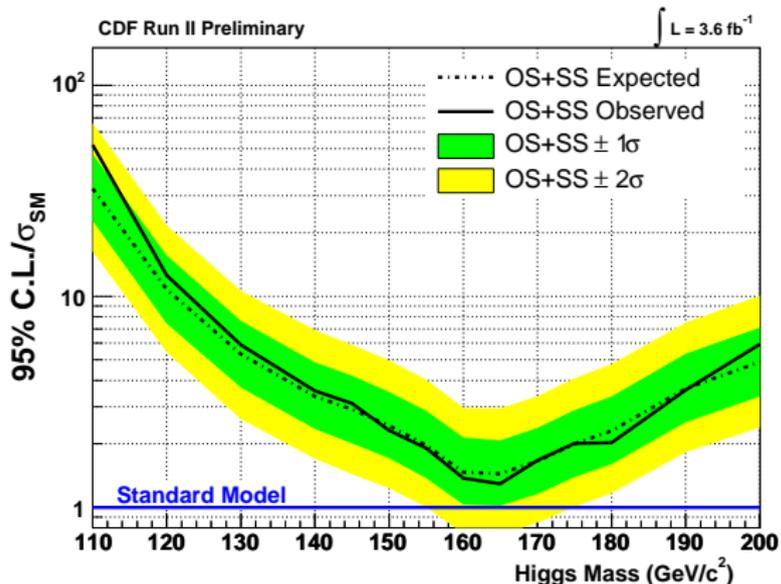
WW-like \longleftrightarrow Higgs-like

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

Results = Limits on Higgs Production

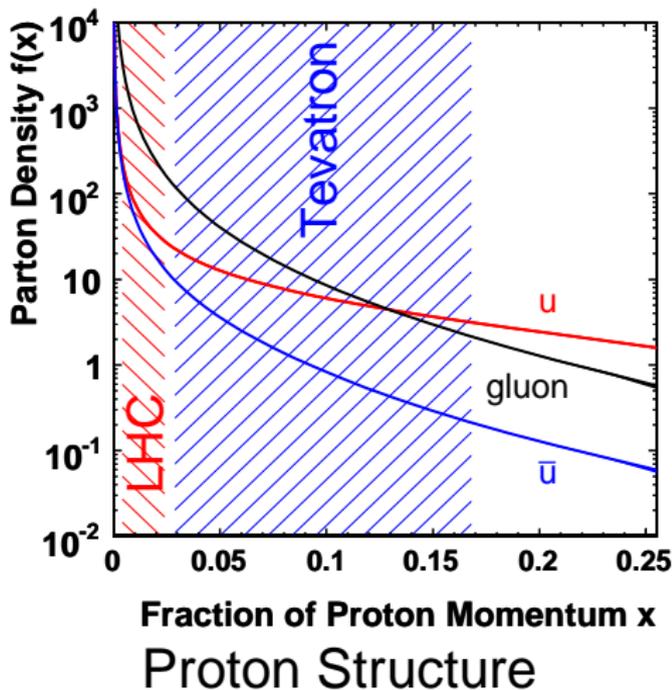
Limits shown as a ratio to the Standard Model expectation

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



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 ≈ 60 times
- $q\bar{q} \rightarrow WW$ only goes up 9 times



Summary

Your chance to discover the Higgs
... or something even better!

