Closing in on the Higgs Particle with the Tevatron

Outline

Standard Model of Physics

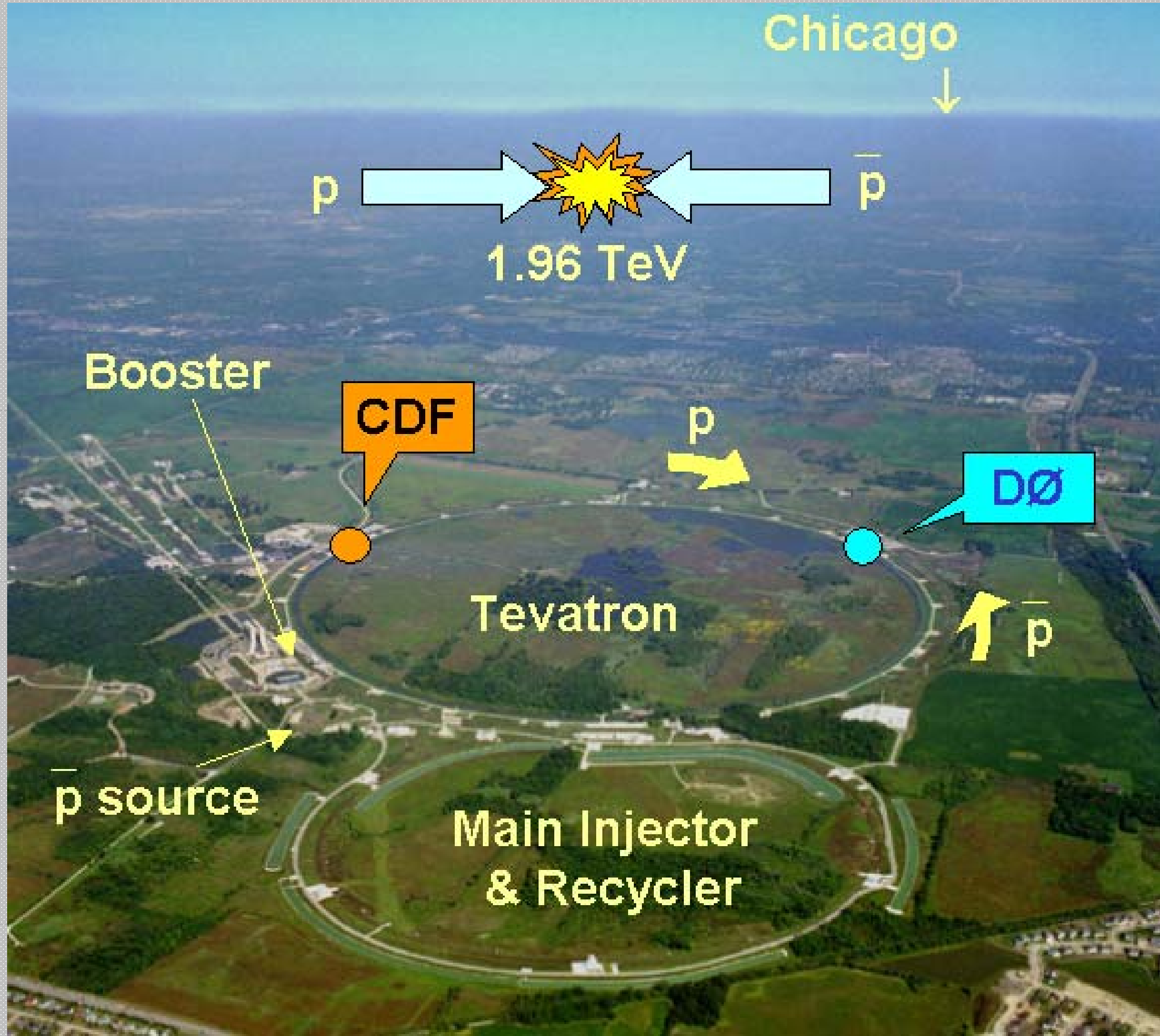
Higgs Particle and Mass

Challenges of finding the Higgs

How the search is performed

Current status – the race is on!

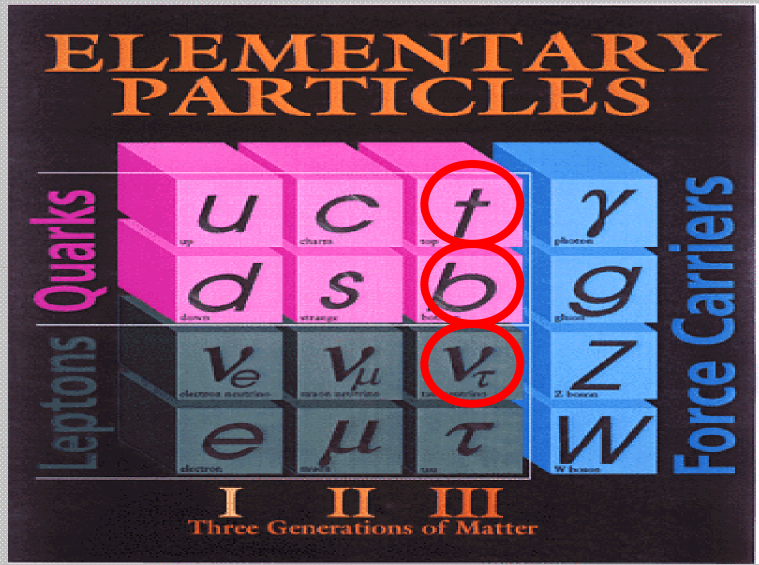
Future projections



2009 America Association for Advancement of Science Annual Meeting
Chicago, February 15 2009
Dmitri Denisov, Fermilab

Standard Model Of Physics

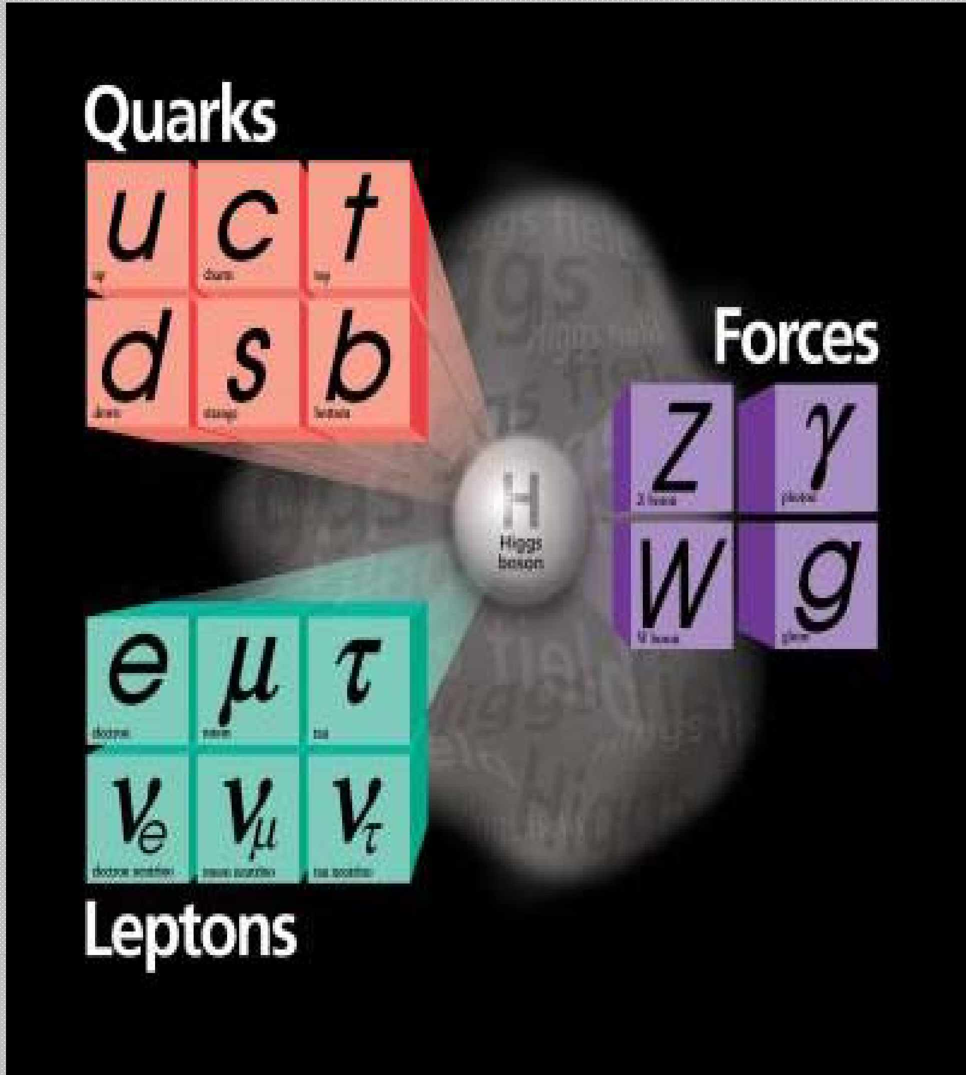
- The Standard Model is the modern theory of particles and interactions
  - Describes absolute majority of phenomena in Nature
  - Makes everything of a small number of objects
    - Quarks and leptons
  - Forces are carried by
    - photon - electromagnetic
    - gluons - strong
    - W/Z bosons - weak
  - Accurate to a very high precision
    - Better than 10^{-10}
- Three basic blocks have been discovered at Fermilab
    - B quark
    - Top quark
    - τ neutrino



- But the Standard Model is incomplete
  - Can't explain observed number of quarks/leptons, dark energy/matter
  - Model parameters can't be predicted
  - Mechanism for particles to acquire masses is not (yet) understood
- Nothing wrong with the Standard Model!
  - Similar to Newtonian mechanics - it has limitations
  - The goal is to define limits of applicability and… find what lies beyond…

Introducing the Higgs Particle

- **Mass** is a fundamental parameter of any object
  - Inertia, gravitational force, energy
- The fundamental forces of the Standard Model are symmetric (do not depend) upon mass
  - In order to provide particles with masses the symmetry breaking mechanism has been developed
- The “Higgs mechanism” provides mathematical description of mass via “Higgs field”
  - The whole Universe is filled with “Higgs Field”
  - Particles acquire mass by interacting with this field
- The Higgs mechanism predicts existence of new fundamental particle
  - The Higgs particle!



It is now challenge for experimental physicists to find this particle – the last undiscovered particle of the Standard Model!

Experimental Tools - Accelerators

- Accelerators are giant microscopes to study extremely small objects ~10^{-16}cm

Wavelength=h/E

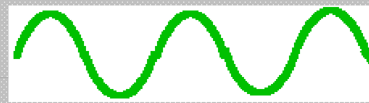
Electron microscope is better than optical!

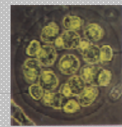
- Accelerators are "converters" if energy into mass

$E=mc^2$

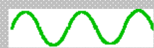
Objects with masses up to

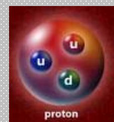
Mass = $2E_{beam}/c^2$ could be created

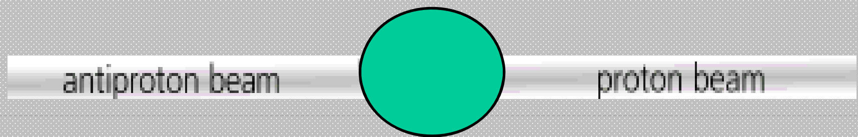




Cell







E_{beam} Mass E_{beam}

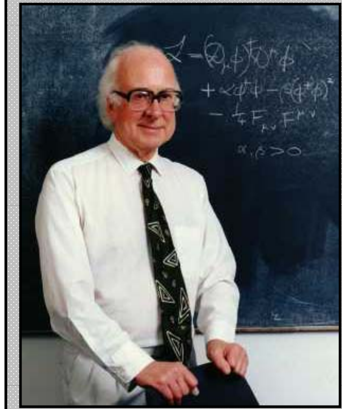
Tevatron is the world highest energy accelerator

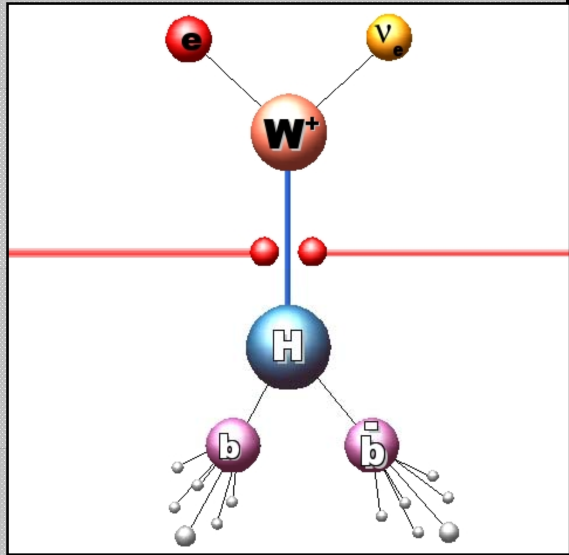
Energy is 2000 GeV or ~2000 proton masses

1 GeV = 1 proton mass

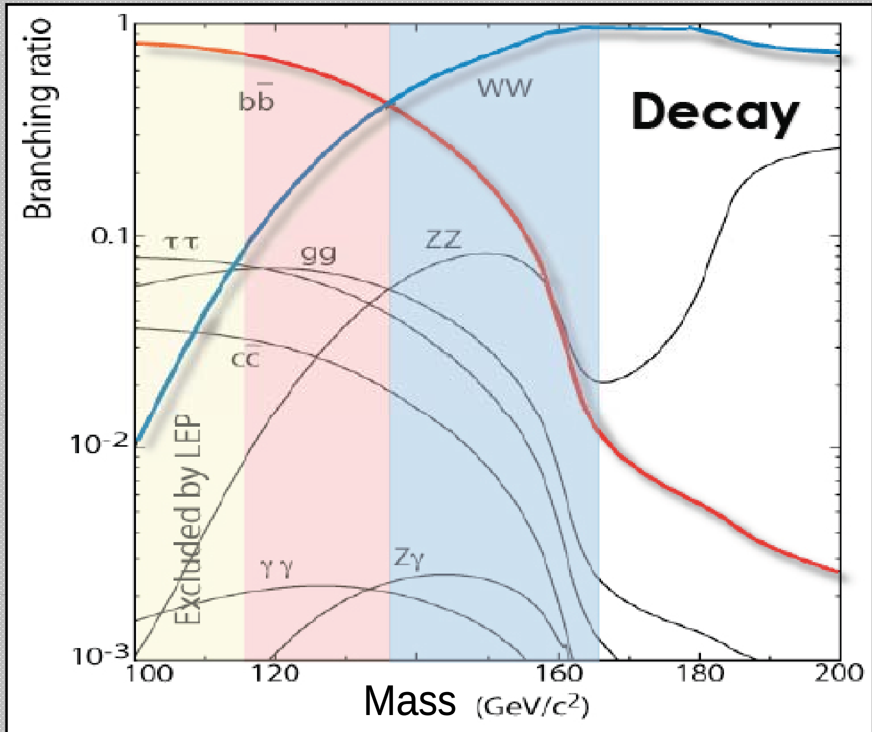
What Will the Higgs Particle Look Like?

- Not exactly like Peter Higgs…
- Theory predicts Higgs particle properties
- Higgs will decay very quickly in 10^{-24} sec into other particles
  - Could not be "directly" seen
  - Observed through decays into other well known particles





- Mass of the Higgs is not predicted
  - Serious challenge as Higgs decays depend on the mass
    - There are hints available…
- Higgs "likes" mass and decays into heaviest objects energy conservation permits
- Most probable modes are
  - Two b-quarks (low mass)
  - Two W bosons (high mass)
- Recipe: search for events with two b-quarks or two W bosons coming from decay of an object with specific mass



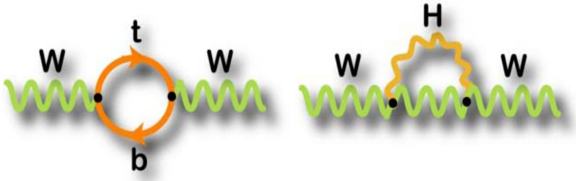
Why Search for the Higgs at the Tevatron?

Available experimental limits

- Direct searches at the Large Electron Positron Collider at CERN

M_{Higgs} >114 GeV with 95% probability

- Precision measurements of the Standard Model parameters



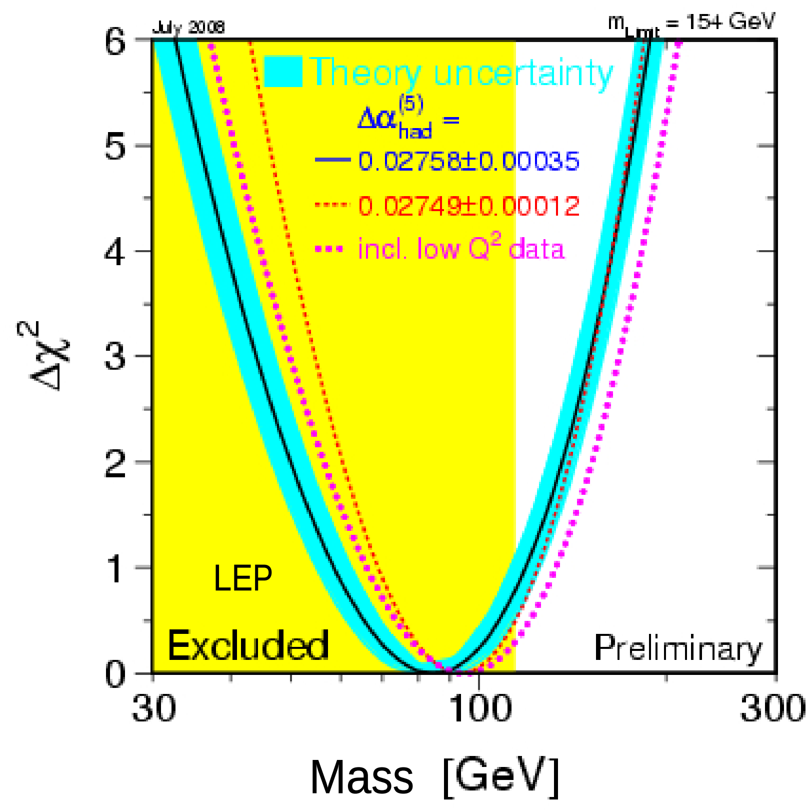
M_{Higgs} < 185 GeV with 95% probability

- Existing results are pointing to the mass range from 114 GeV to 185 GeV

Excellent as Tevatron can create objects with such mass with reasonable probabilities!

The hunt is on!

Higgs Mass Probability



Experimental Challenges

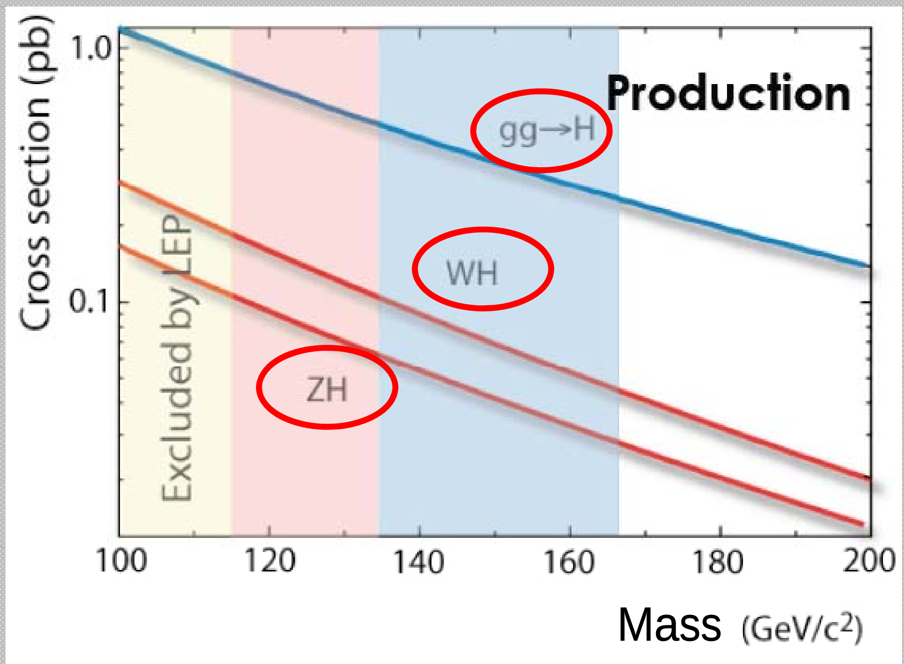
- Probability of producing Higgs particle is low

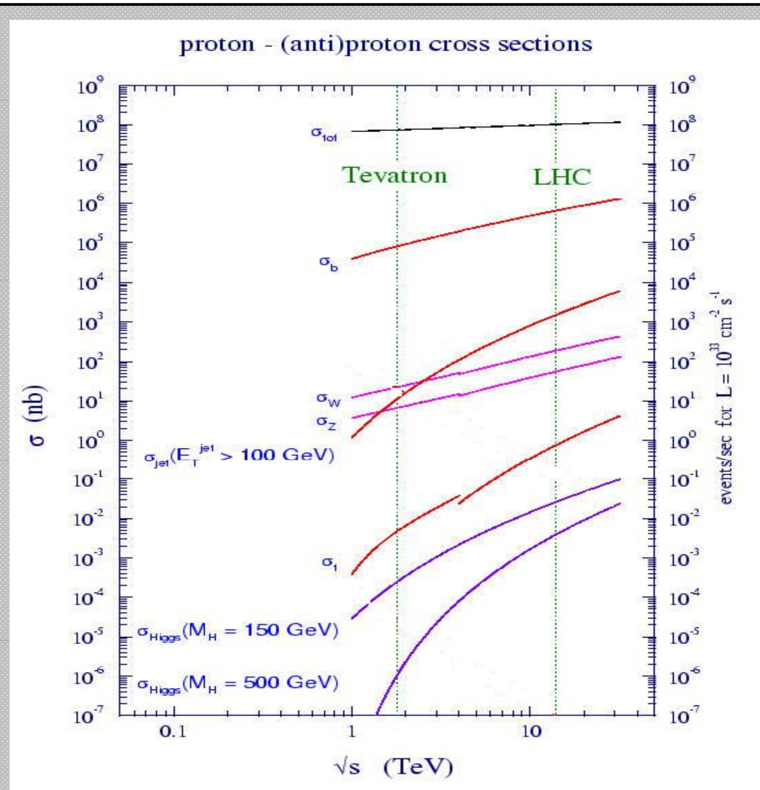
$$N_{events} = L \times \sigma$$

L is intensity of colliding beams or "Tevatron luminosity", σ is "cross section"

- To increase number of produced Higgses we need a lot of luminosity or number of proton-antiproton collisions
- High luminosity of the Tevatron is critical

- Backgrounds from known Standard Model processes are high
  - Quantum dice – outcome of a specific collision is unpredictable
  - Only one out of 1000000000000 collisions might contain Higgs particle
- Separation of backgrounds is one of the main challenges in hunt for the Higgs

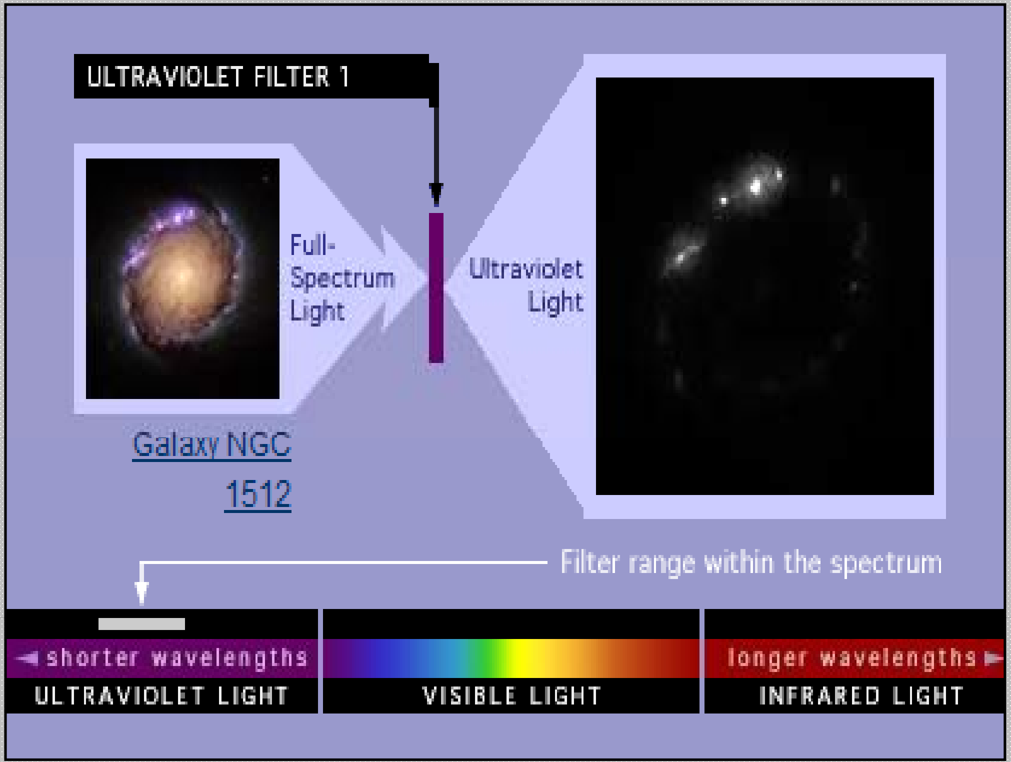




How to Separate Signal from Backgrounds?

- We can't turn backgrounds off...
  - develop "filters" which reject background events with higher probability than Higgs events
- Higgs search "recipe"
  - Get as many collisions as possible
  - Use advanced analysis methods to separate Higgs events from trillions of events produced by know processes

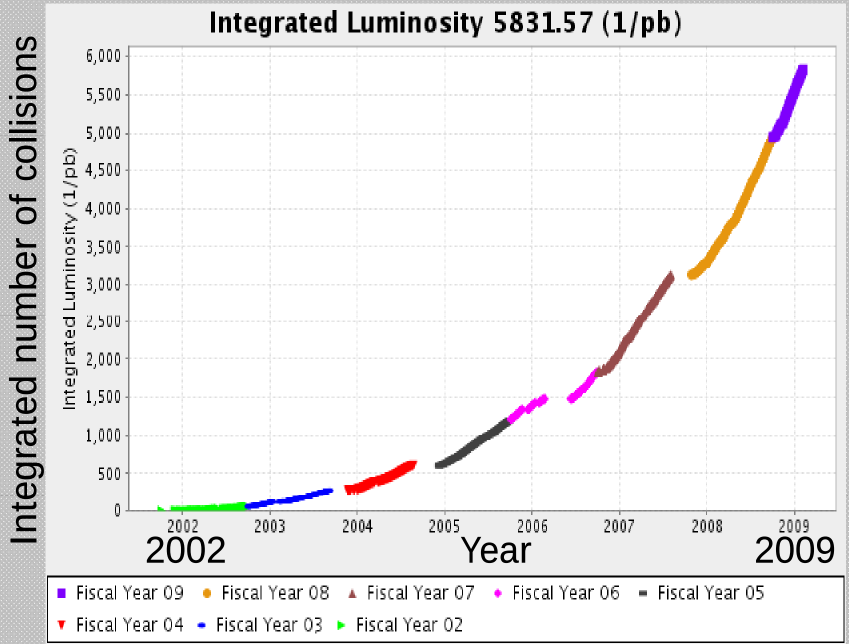
Optical Analogy



Performance of the Tevatron accelerator and CDF and DØ detectors are two major factors which shape the search for the Higgs boson at Fermilab

Tevatron Performance

- Tevatron collides protons and antiprotons with world highest energy of 2000 GeV
- Constructed in 1980's with major upgrade in late 1990's
- Tevatron accelerator complex consists of five accelerators with main accelerator 6 km in circumference
- The complex accelerates protons (and makes anti-protons) from a fraction of eV energy (hydrogen bottle) to 1000 GeV kinetic energy
  - 1000 times more than rest mass of a proton
- Tevatron is rapidly increasing number of collisions delivered

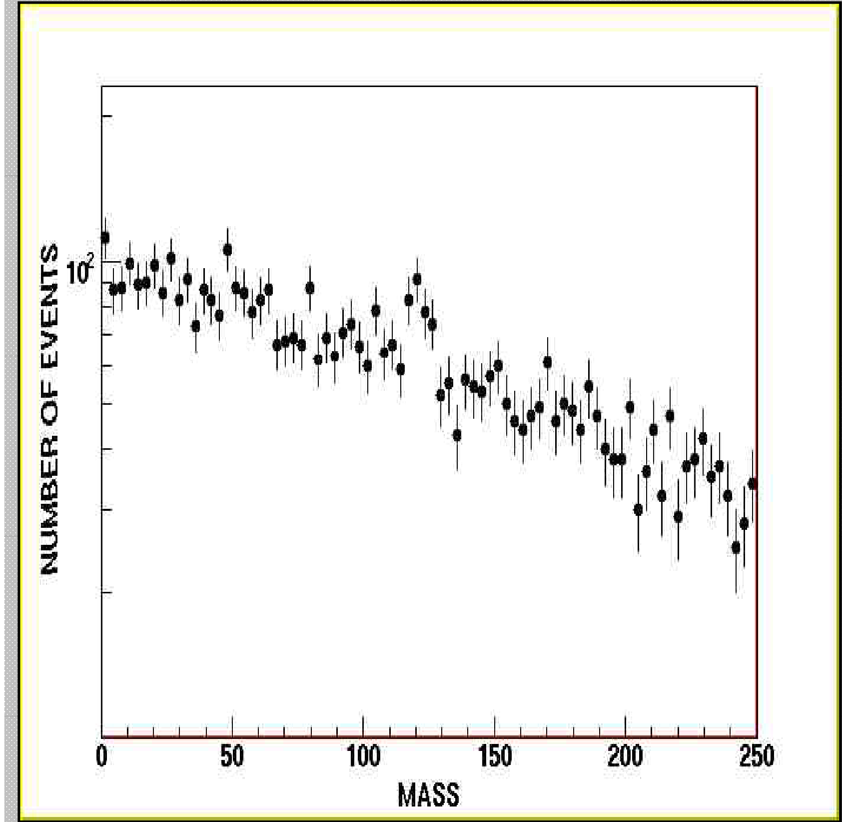


Statistical Power of Large Data Set

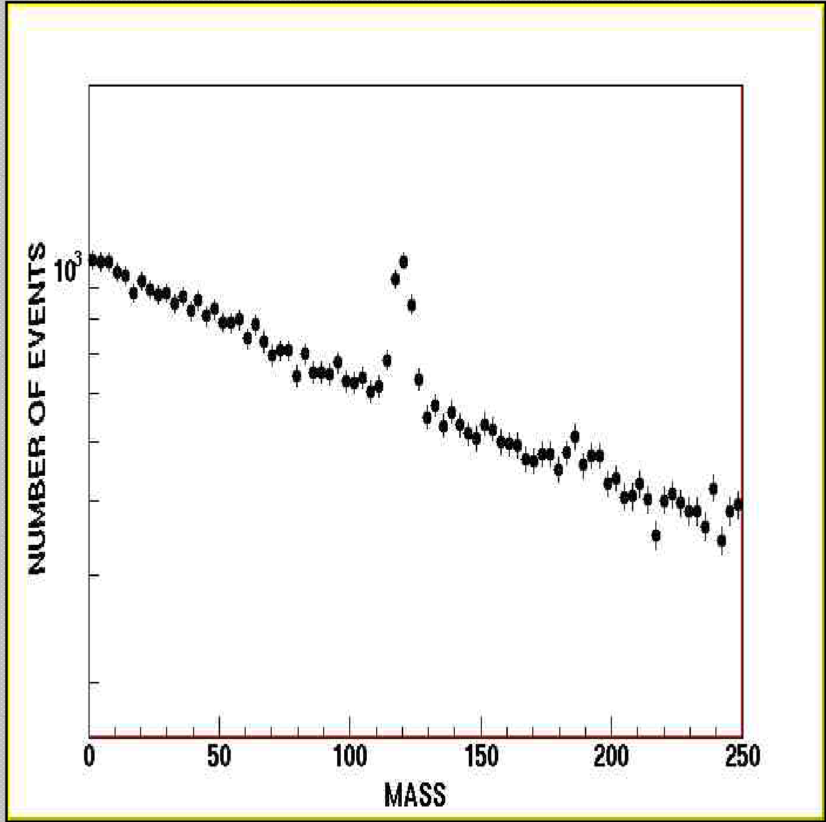
All studies in particle physics are subject to statistical fluctuations

Probabilistic nature of results with small number of events

Simulation Example



x10 data →

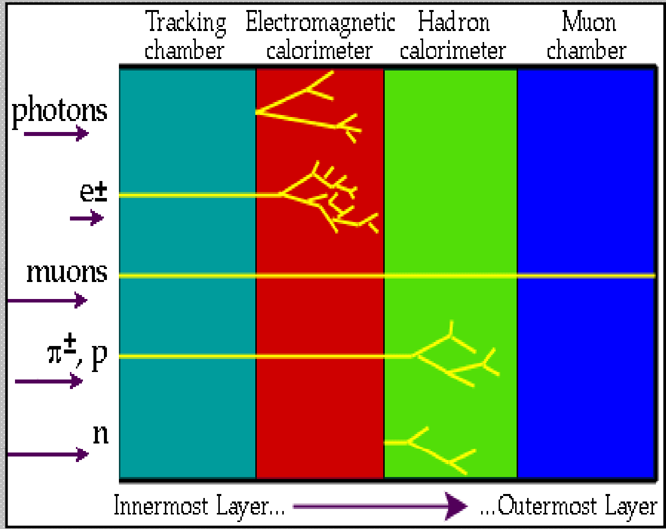


Increase in the data set could make “hints of a signal” obvious and statistically significant

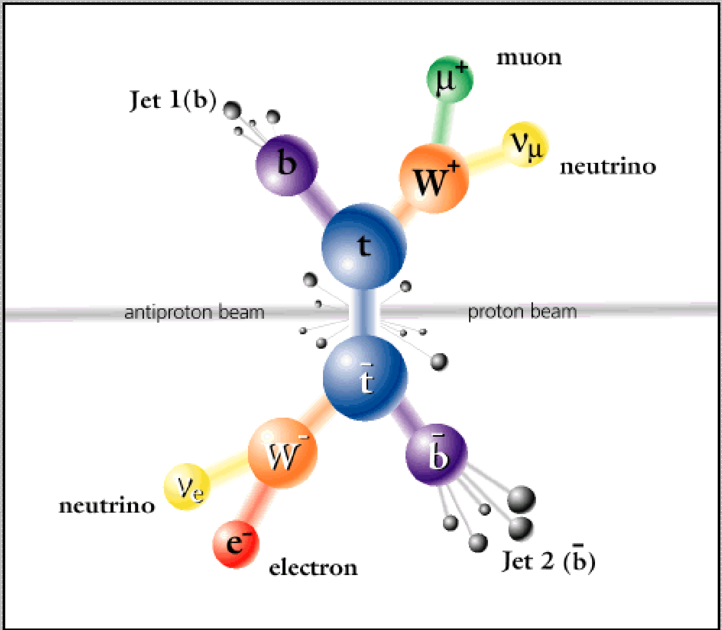
Continuing operation of the Tevatron is absolutely critical component of the Higgs search

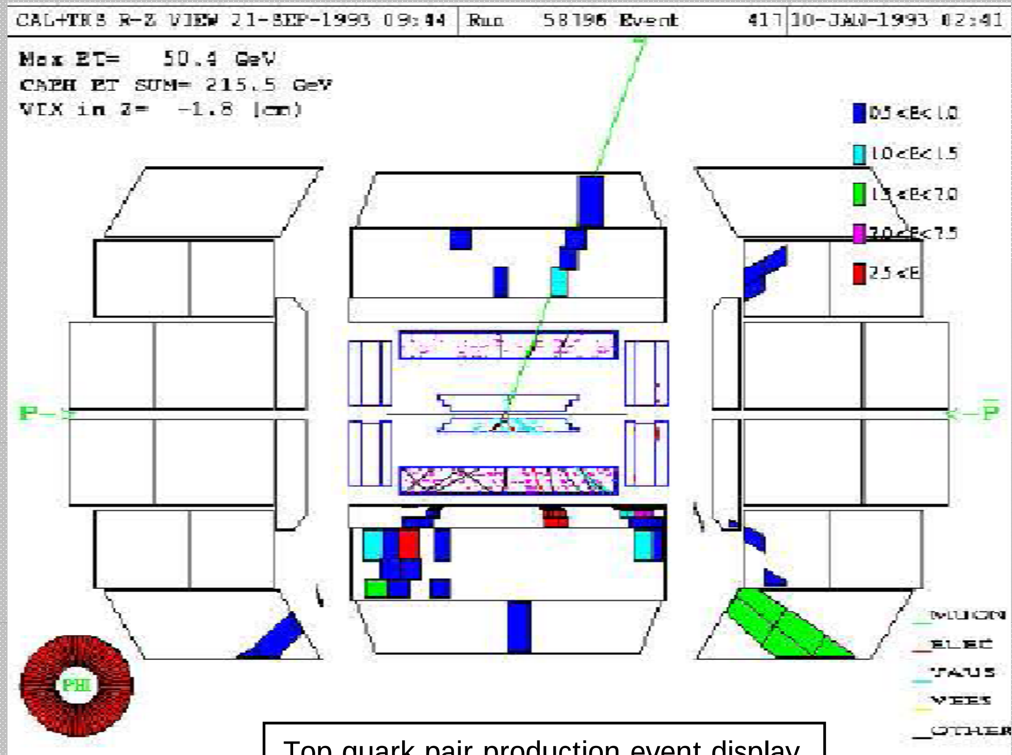
How Physicists Detect Particles

- Higgs decays into other particles almost immediately
  - Detectors surround interaction region
  - Many layers to detect different species
- Particles we study have very high energies large detectors are needed to absorb them
- We are taking millions of “pictures” per second to analyze collected data “off-line”



Top quark pair production

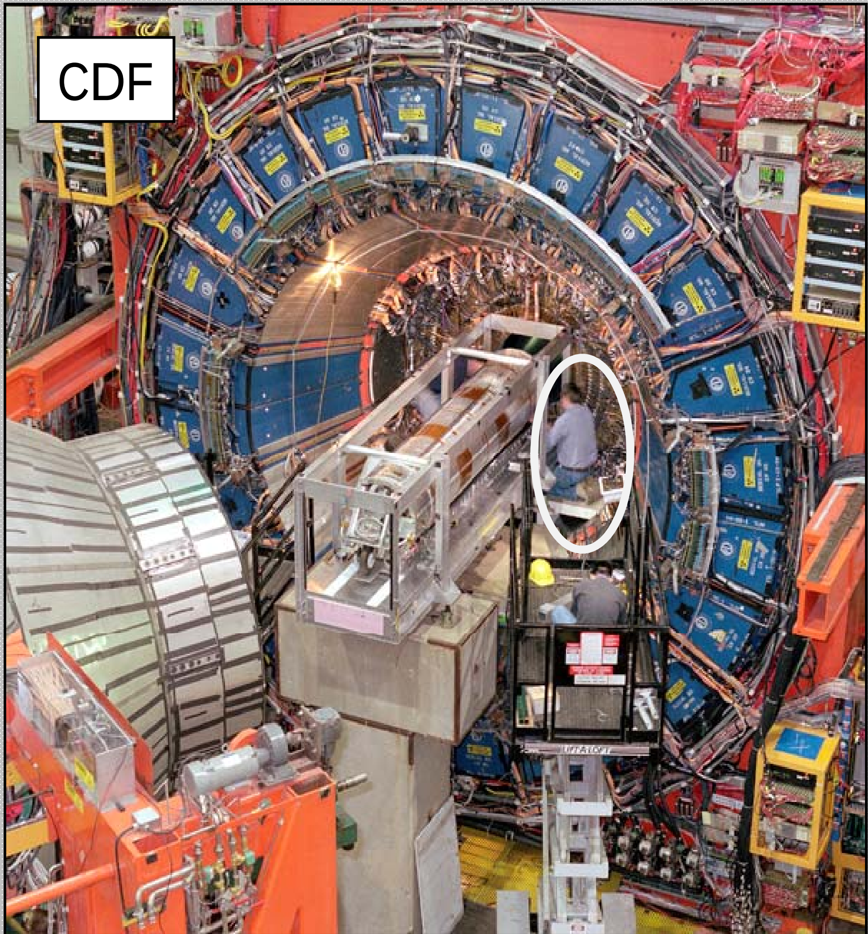


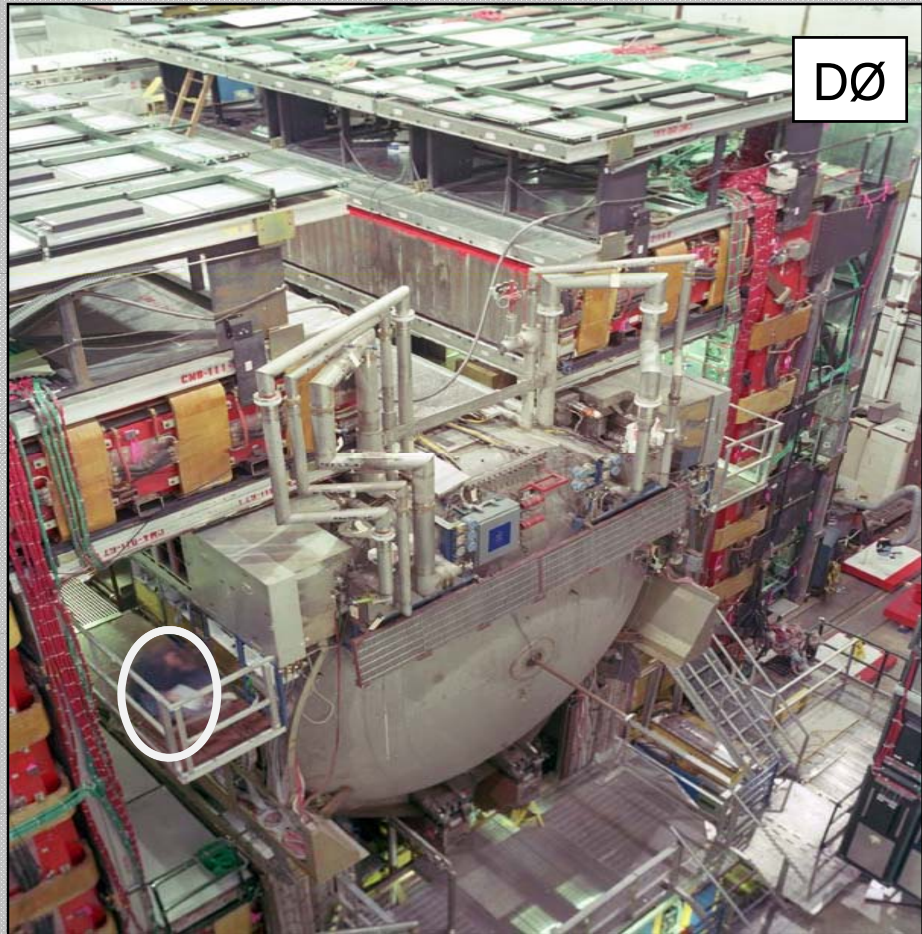


Top quark pair production event display

CDF and DØ Detectors

In order to analyze millions of interactions per second with particles carrying kinetic energies 100’s times above their rest mass two complex detectors have been built at Fermilab





Why two detectors?
To verify results, to increase chances to detect Higgs, and to create healthy competition

Scientists Behind the Higgs Hunt

Behind all technical complexity there are 100's of excellent scientists from all over the world working closely together excited by the challenge of pushing limits of knowledge and discovering unknown

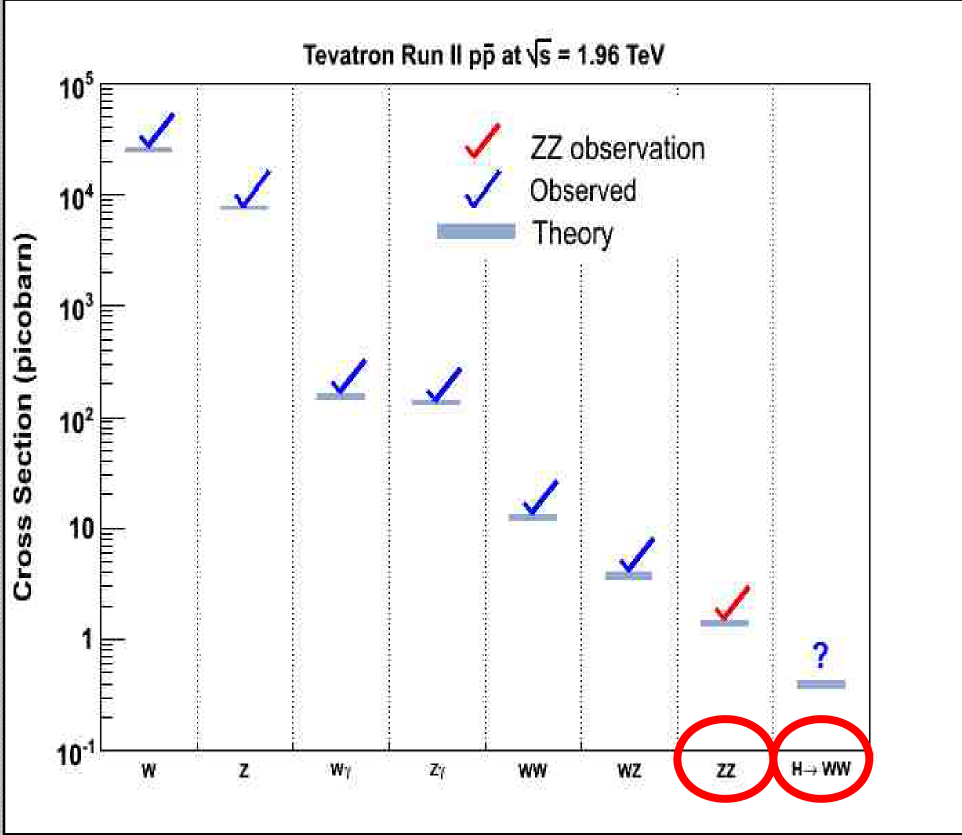
CDF : 602 physicists, 15 countries, 63 institutions

DØ : 554 physicists, 18 countries, 90 institutions

- Physics research at Fermilab is an excellent example of productive international cooperation
  - Over 100 publications in refereed journals per year!
  - Over 60 PhDs obtained based on Tevatron results per year!

Stepping Stones to the Higgs

- How to verify proper detectors and algorithm performance?
  - Detection and studies of well known Standard Model objects
  - Observation of expected, but not previously seen Standard Model phenomena
- Production of pairs of bosons, WW, WZ, ZZ is one of them
  - Final states have masses and cross sections similar to the Higgs

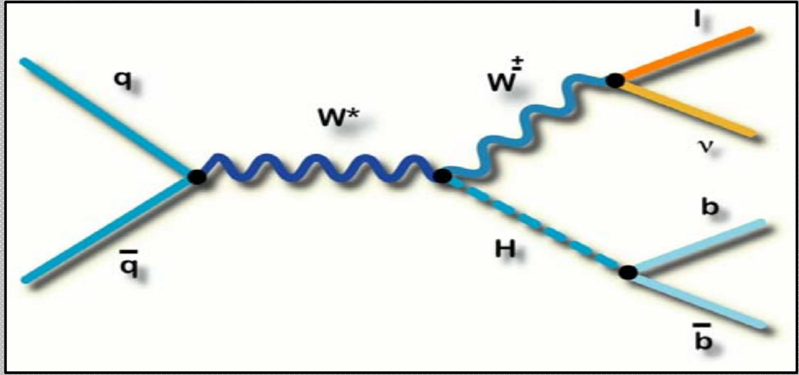


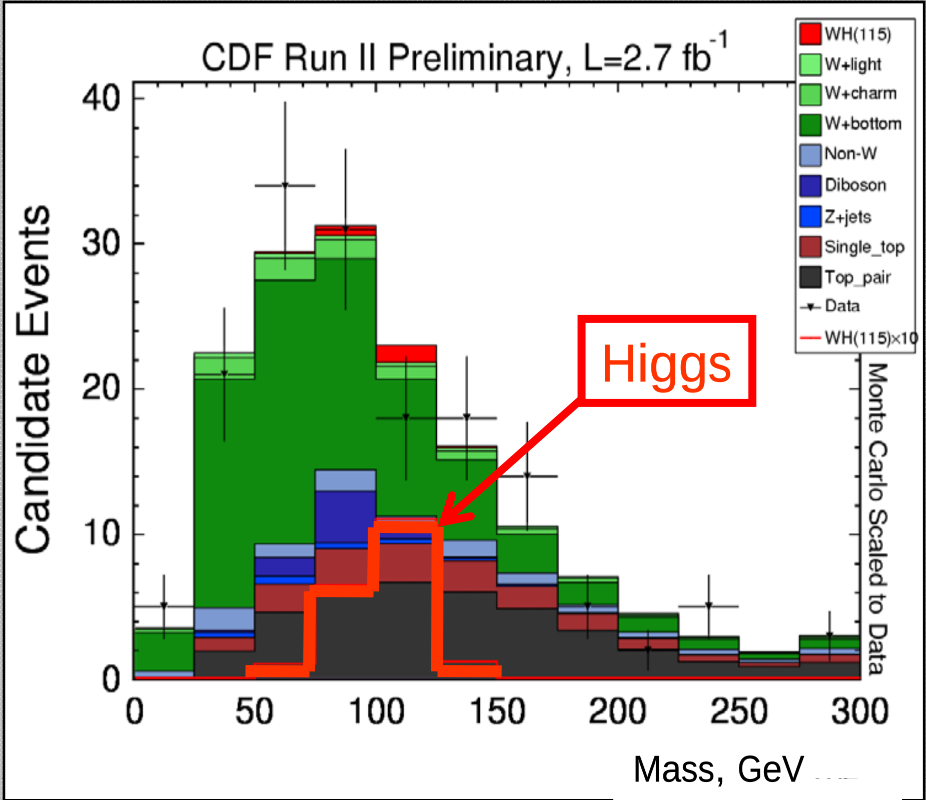
- Summer 2008: ZZ pair production was observed at Fermilab
  - Lowest boson pairs production cross section
  - In good agreement with Standard Model expectations
- We are ready to make the next step…

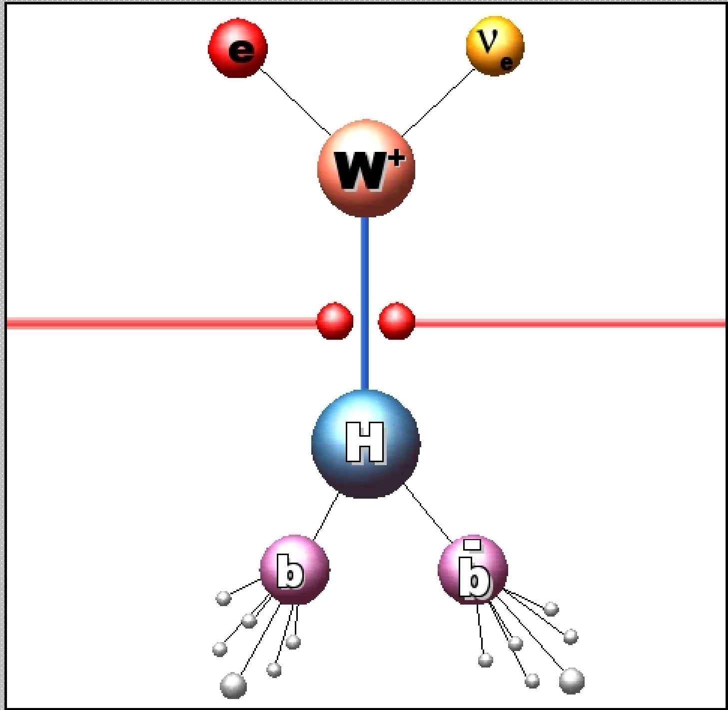
Channel	4e	4μ	2e+2μ	All channels
Expected Signal	0.45	0.60	1.08	2.13
Total background	0.05	0.0003	0.095	0.14
Observed events	2	1	0	3

Higgs Search: W boson and Higgs Channel

- Channel most sensitive in the ~110-130 GeV mass range
- Select events with lepton (muon or electron), neutrino (missing energy) and pair of jets from b-quarks
- Dijet mass → any peaks?



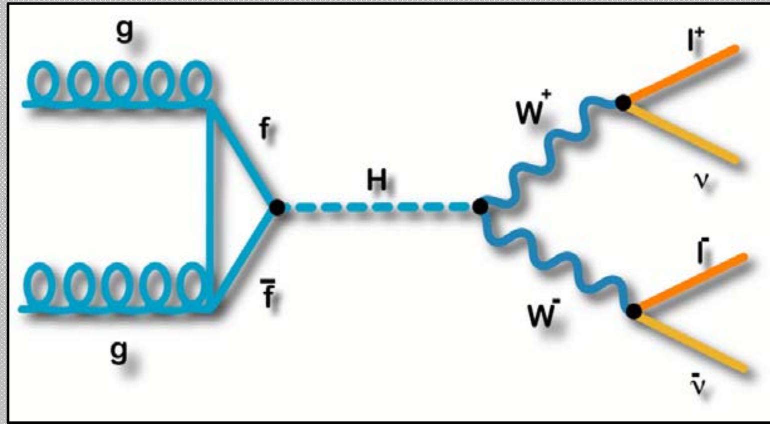


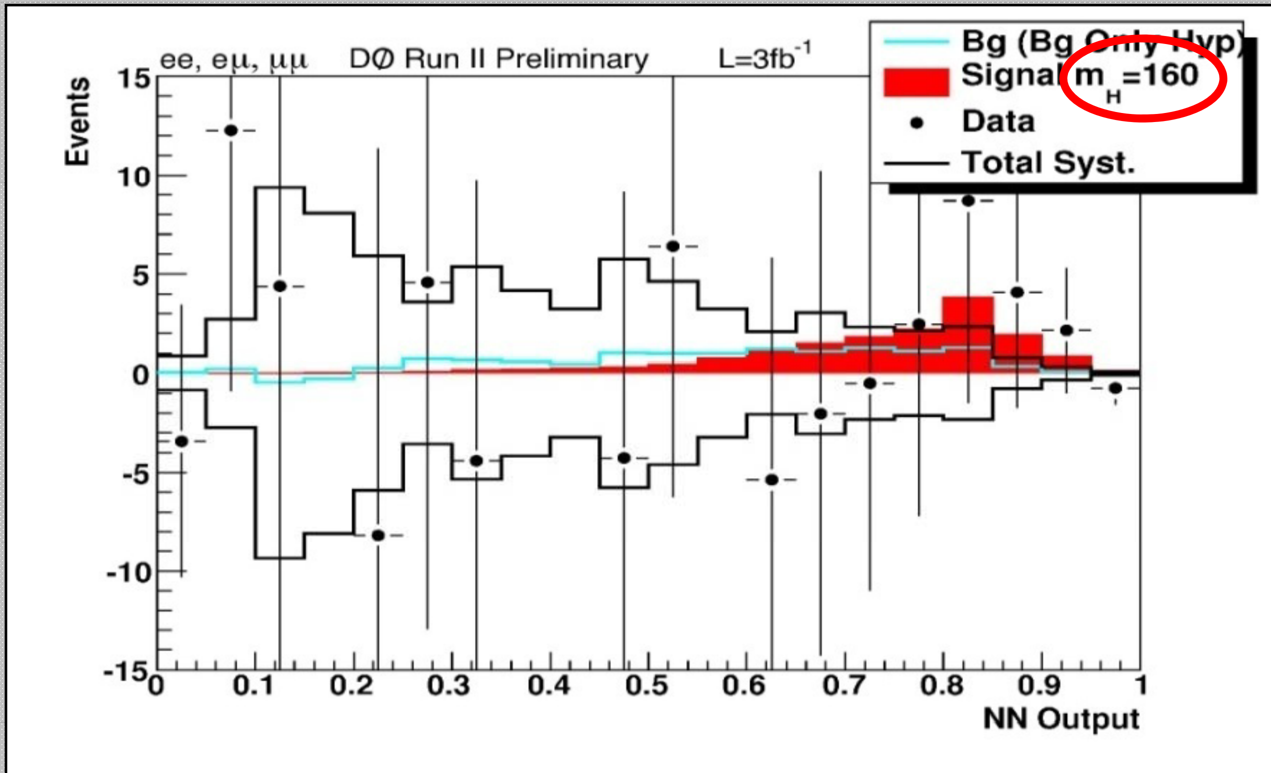


Power of multivariate analysis provides extra ability to separate signal from backgrounds

Higgs Search: Two W Bosons Channel

- Channel most sensitive in the ~130-180 GeV mass range
- Select events with two leptons (muon or electron) and two neutrino (missing energy)
- Angle between leptons ➔ multivariate discriminant

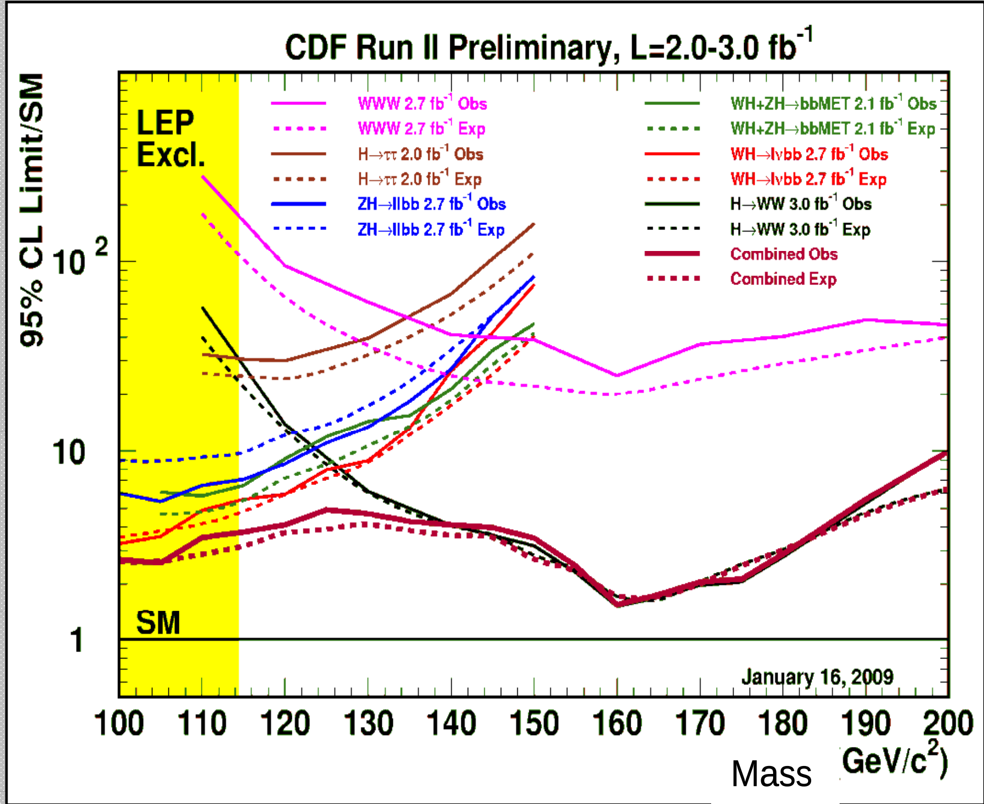


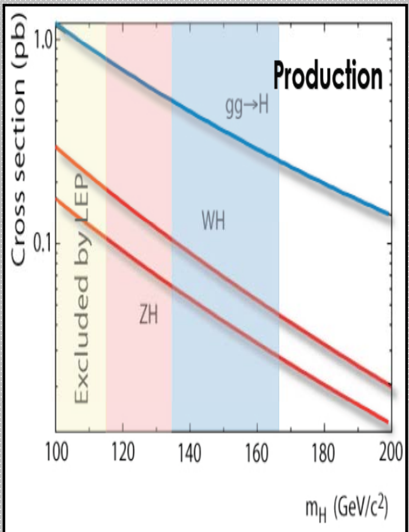


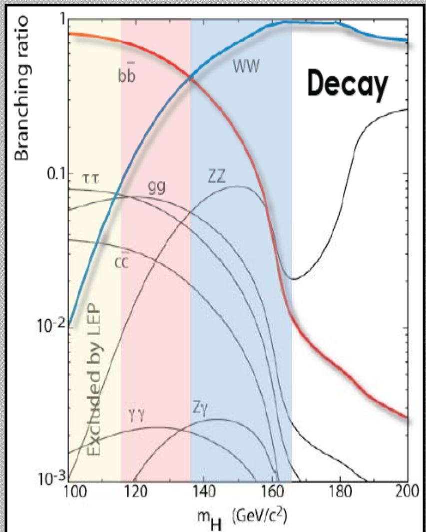
Gaining sensitivity to the Higgs boson at masses of ~160 GeV !

Power of Combination

- Many different channels of Higgs production and decay are searched for at the Tevatron
- All channels are combined to increase probability of exclusion (at one mass) or evidence (at another mass)
- CDF and DØ are combining their (independently observed) results as well





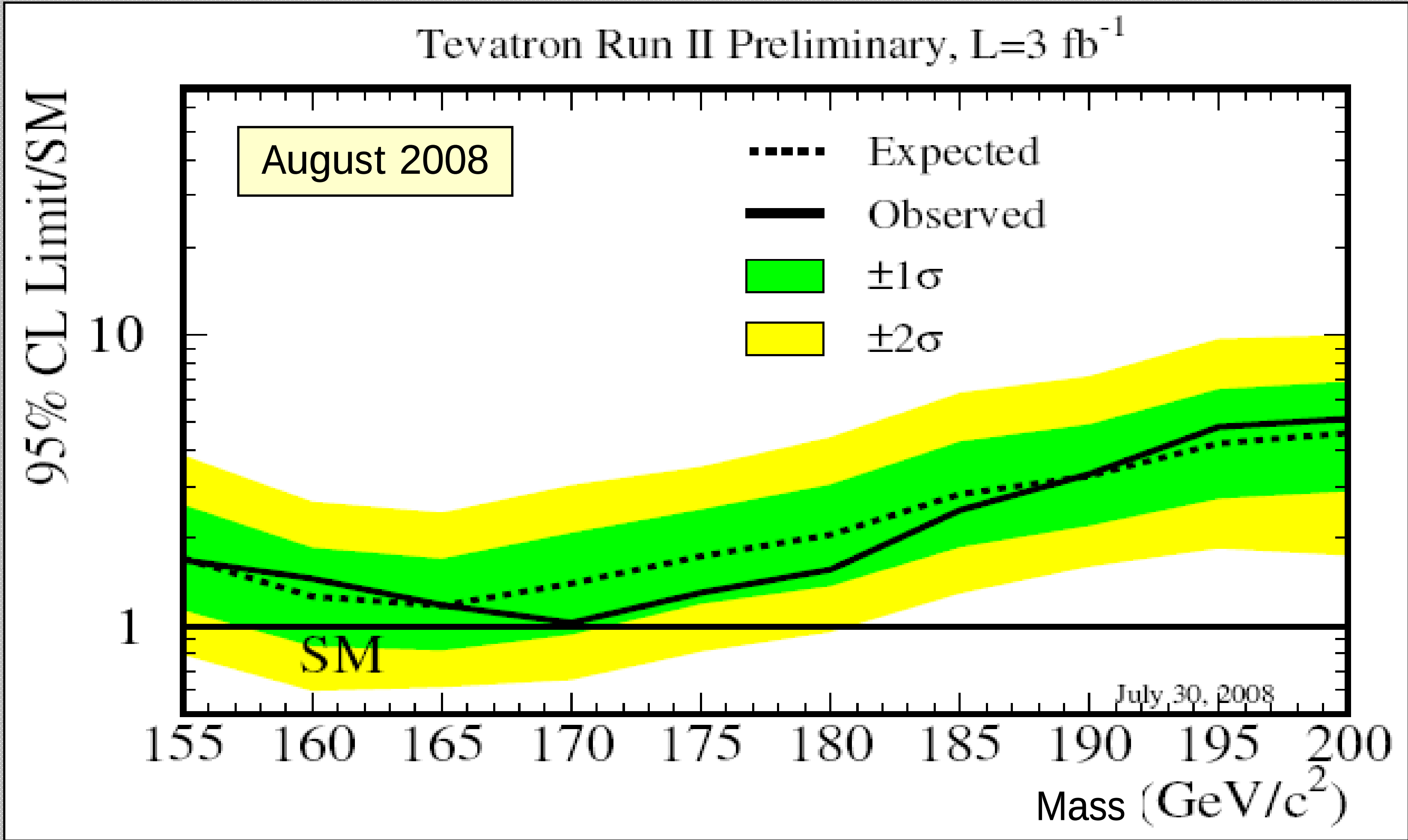


Higgs production with probability above solid curves is excluded

When the exclusion curve crosses “1”, it means that Higgs boson with that specific mass does not exist

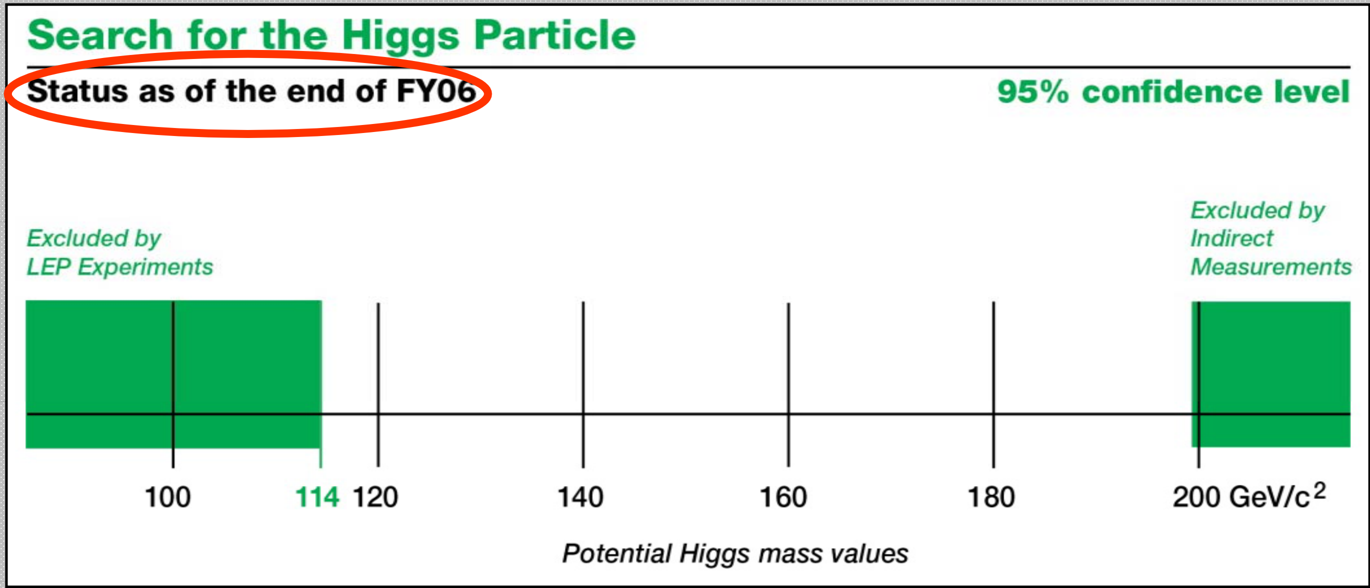
Summer 2008 Tevatron Higgs Search Combination

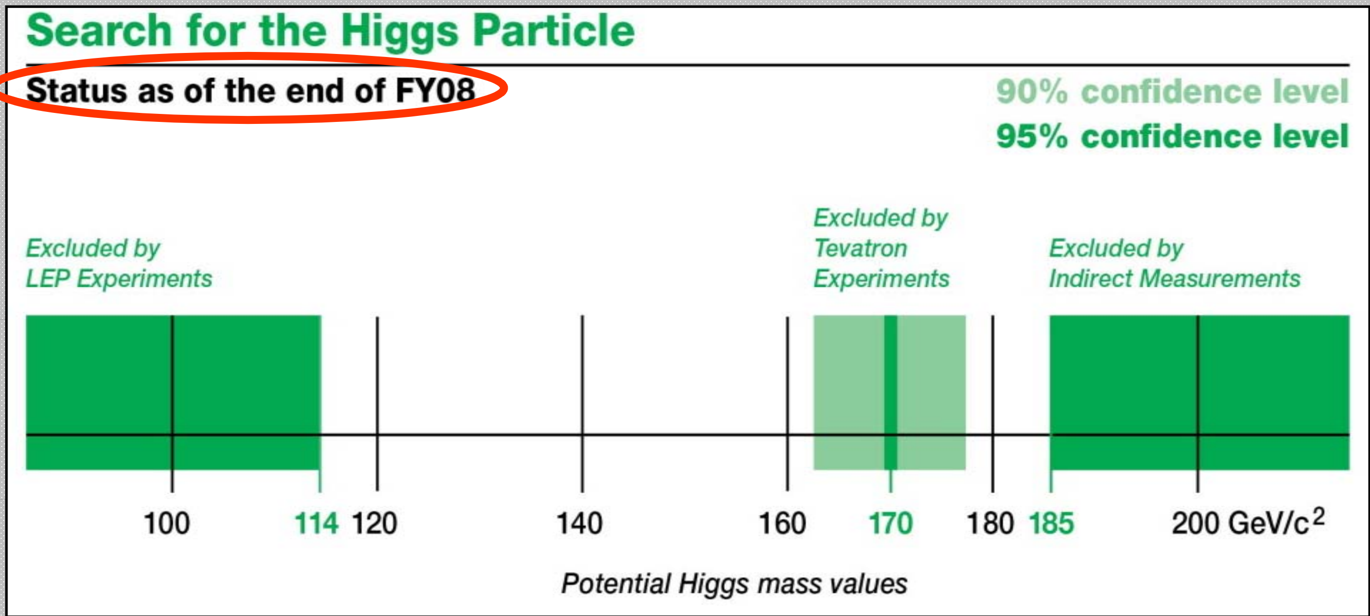
Excluded Higgs with mass of 170 GeV!



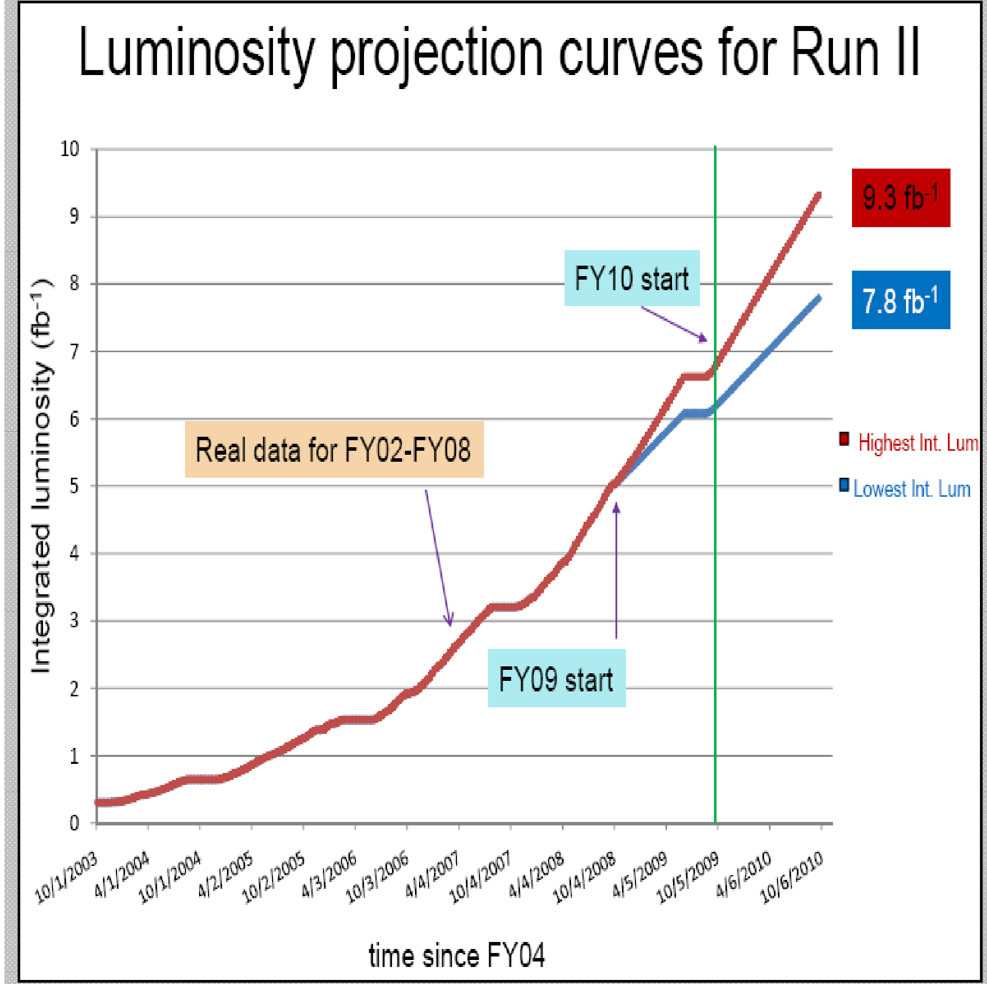
Tevatron demonstrated sensitivity to the Higgs search and from now will increase exclusion region or...find the Higgs

Closing the Range Where Higgs Hides



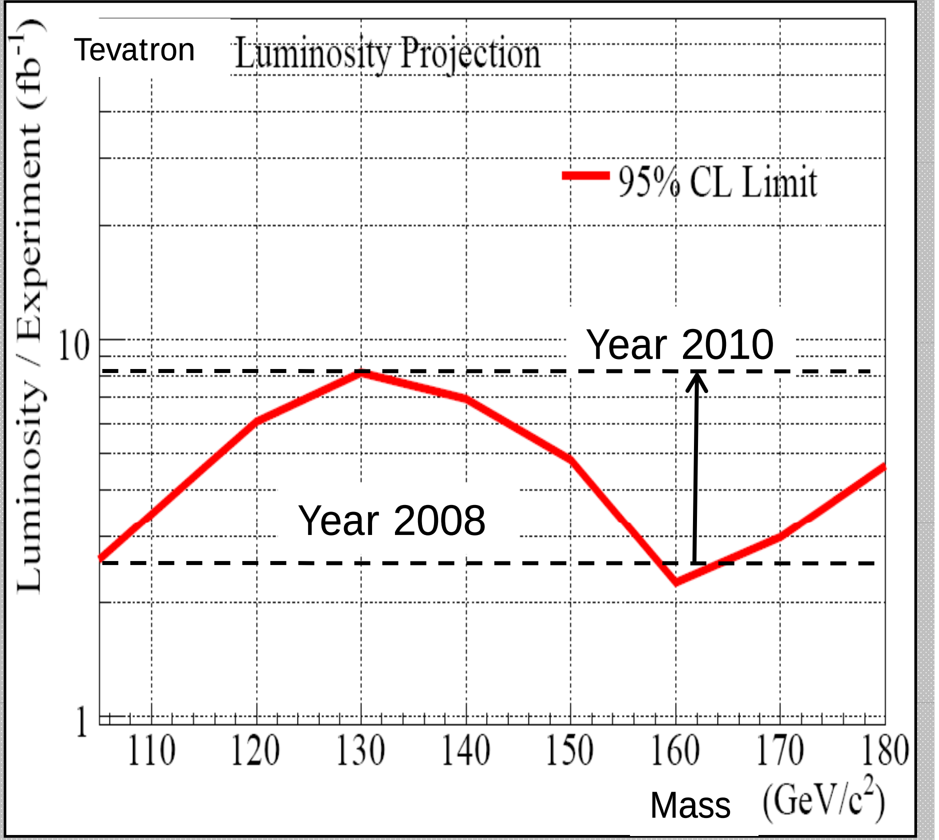


Future Higgs Search Projections



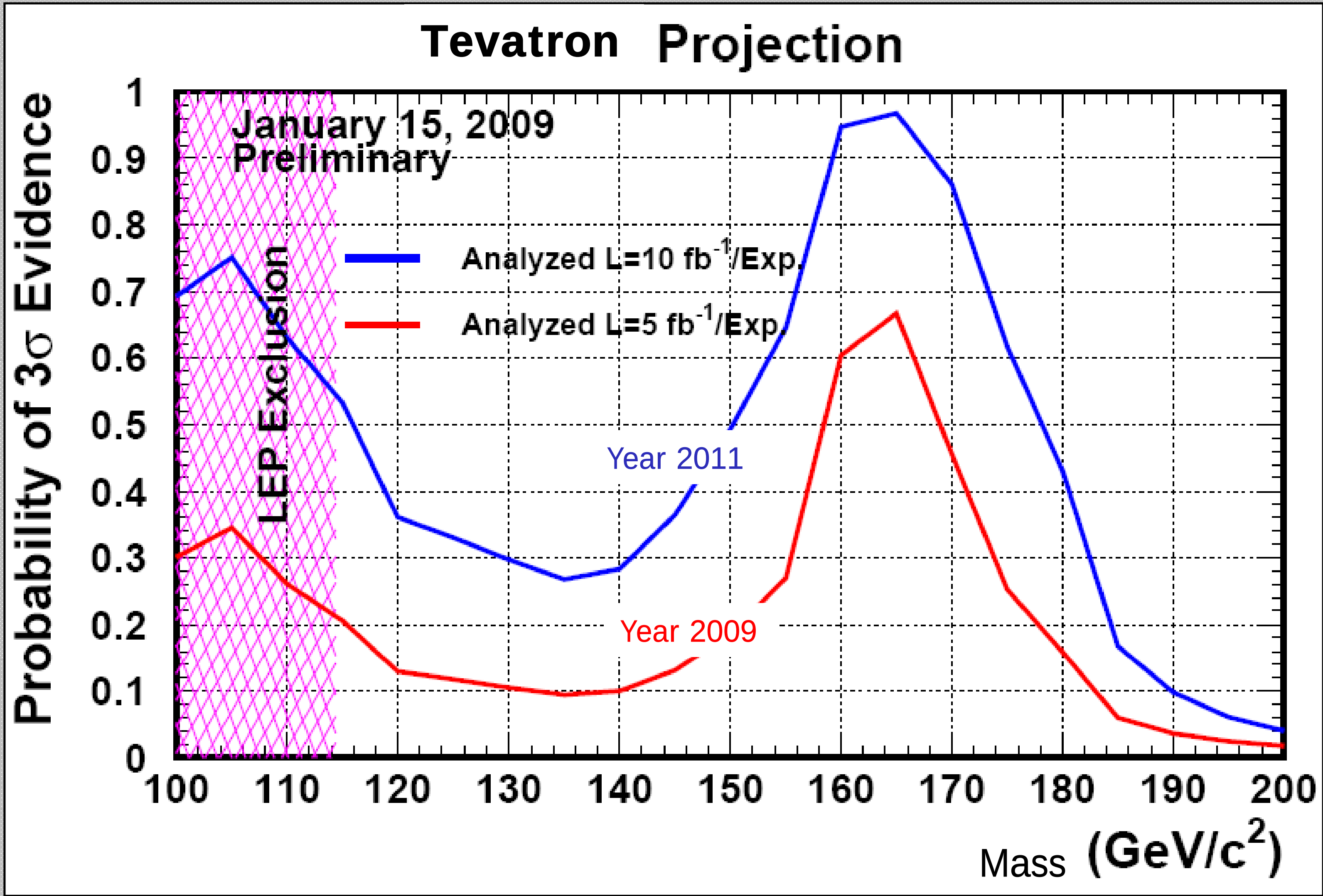
- What next few years will bring us?
  - Many more collisions delivered by the Tevatron
  - Better analysis tools

Higgs Exclusion Projections



With data accumulated by the end of 2010 we will be able to exclude Higgs over entire expected mass range… or…

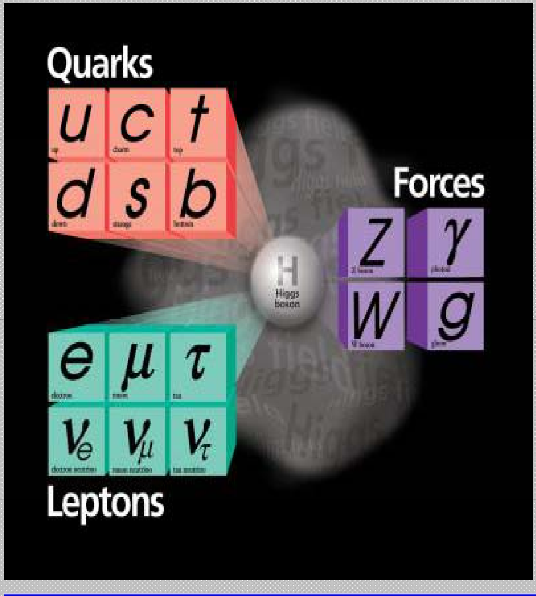
Tevatron Higgs Evidence Potential



With high probability will see evidence of the Higgs and measure its mass in practically full allowed mass range

Tevatron Higgs Searches: Summary

Scientists at the Tevatron are actively searching for the Higgs – the last undiscovered particle of the Standard Model



CDF and DØ experiments reached sensitivity needed to see the Higgs in previously unexplored mass range

Direct exclusion of Higgs with mass of ~170 GeV

In the next few years if Higgs with expected mass exists in Nature

We will see evidence of it existence

This time at the Tevatron is exciting and we are looking forward for new results about most fundamental laws of Nature, including origin of the mass, to come!

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