Results from the Tevatron:
Standard Model Measurements and Searches for the Higgs

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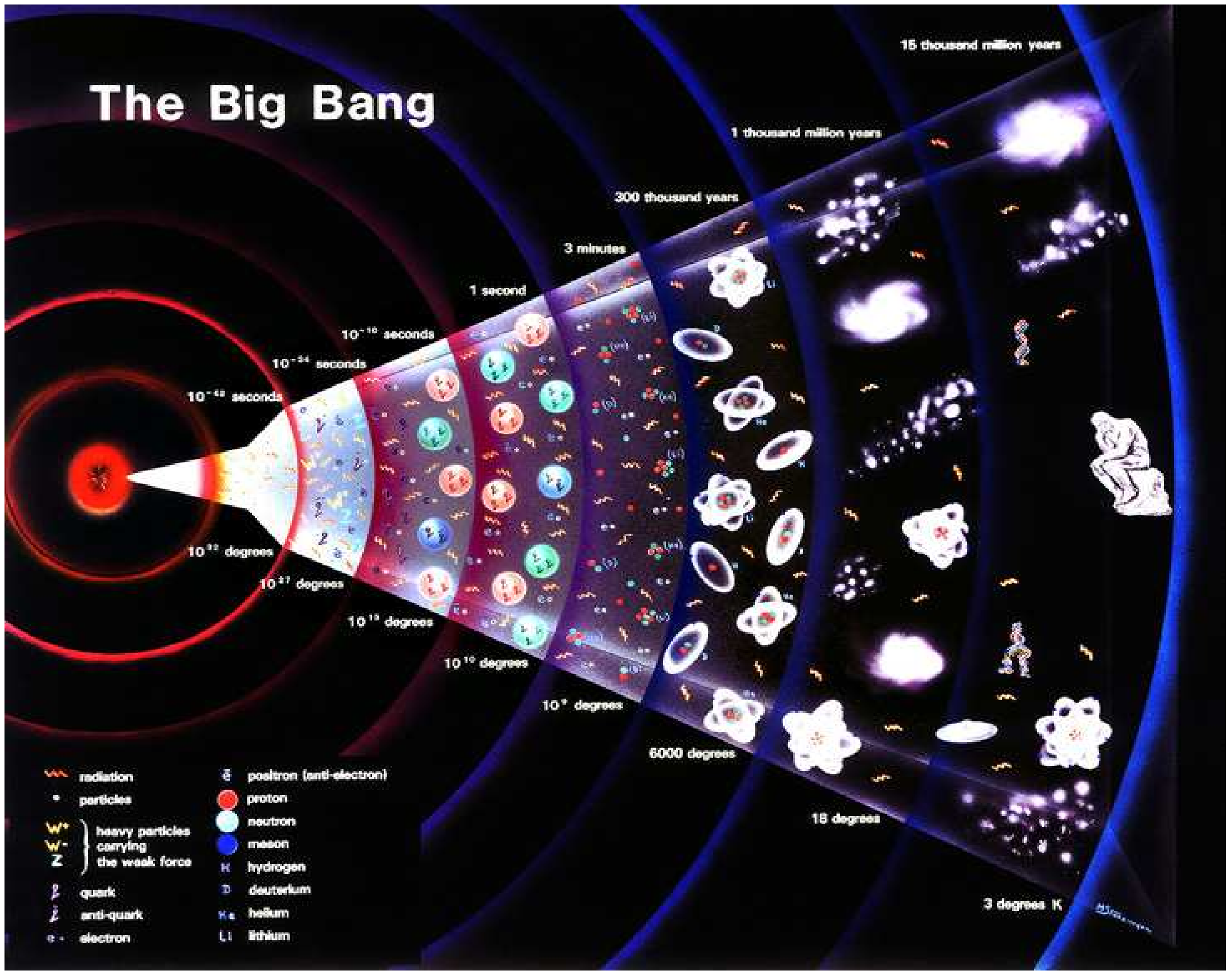
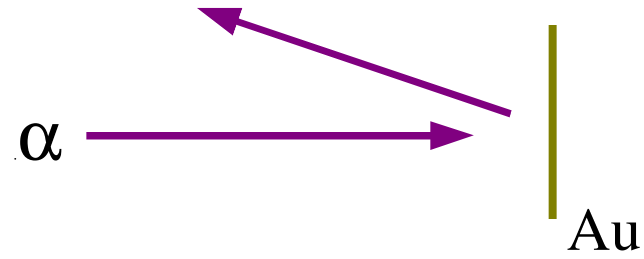


SLAC Summer Institute
31 July 2007

Why Build Accelerators?
From Atoms to Quarks

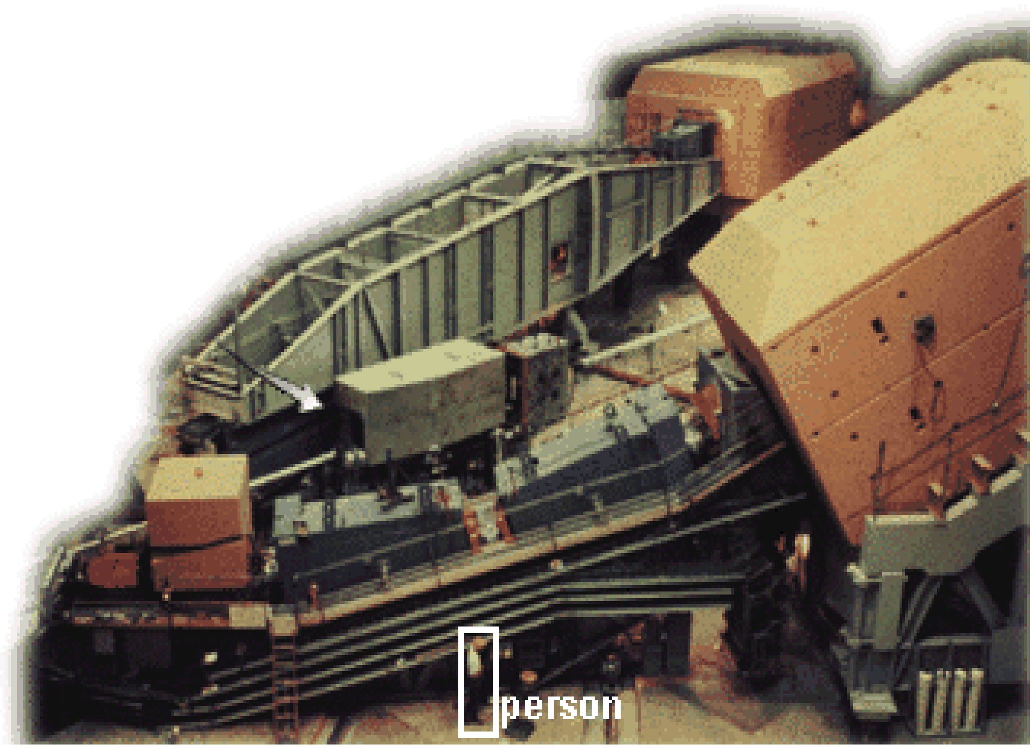
- Scattering of probe particles off matter to investigate substructure, i.e. "look inside"
- Rutherford did it, shooting α particles at a gold foil, to tell us the structure of the atom (1911)
- Quantum mechanics: $\Delta r \sim h / \Delta p$



	Radius	Accelerator energy
atom ↓	10^{-10} m	10 electron-volts (eV)
nucleus ↓	10^{-15} m	10^{6} eV (MeV)
proton, neutron ↓	10^{-18} m	10^{9} eV (GeV)
quarks	$<10^{-18}$ m	> GeV

A Century of Particle Physics

- Quark constituents of nucleons established in high energy electron scattering experiments at SLAC, 1966-1978
  - Point-like particles explain high scattering rate at large energy and angle



A Century of Particle Physics

- Success # 1: discovery of 6 quarks and 6 leptons
- 12 fundamental matter particles (and their antimatter counterparts) fit neatly into an elegant mathematical framework

<u>Quarks</u>

$$\begin{array}{lll} u < 1\ \text{GeV} & c \sim 1.5\ \text{GeV} & t \sim 175\ \text{GeV} \\ d < 1\ \text{GeV} & s < 1\ \text{GeV} & b \sim 4.5\ \text{GeV} \end{array}$$

But note the intriguing pattern of mass values; not explained:

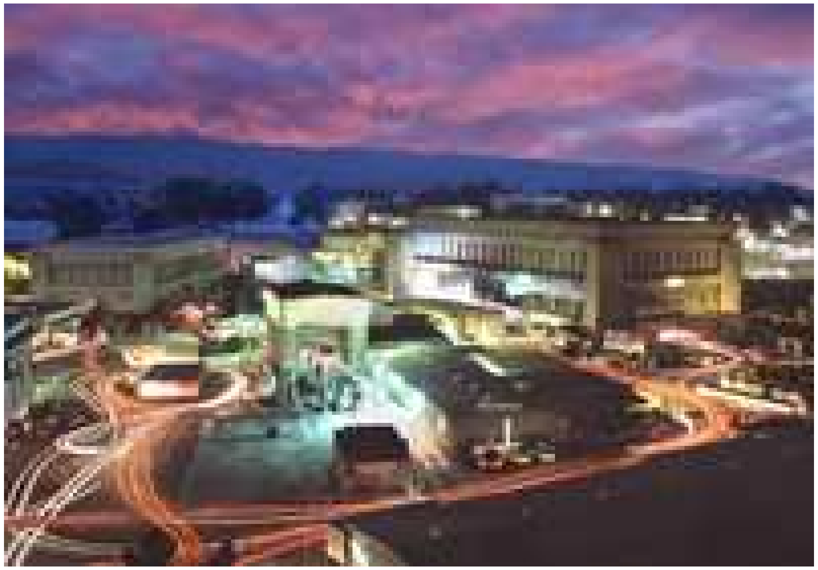
<u>Leptons</u>

$$\begin{array}{lll} \nu_e < 1\ \text{eV} & \nu_\mu < 0.17\ \text{MeV} & \nu_\tau < 24\ \text{MeV} \\ e\ 0.5\ \text{MeV} & \mu\ 106\ \text{MeV} & \tau\ 1.8\ \text{GeV} \end{array}$$

A Century of Particle Physics

- The "charm quark" (*c*) discovered at SLAC in 1974

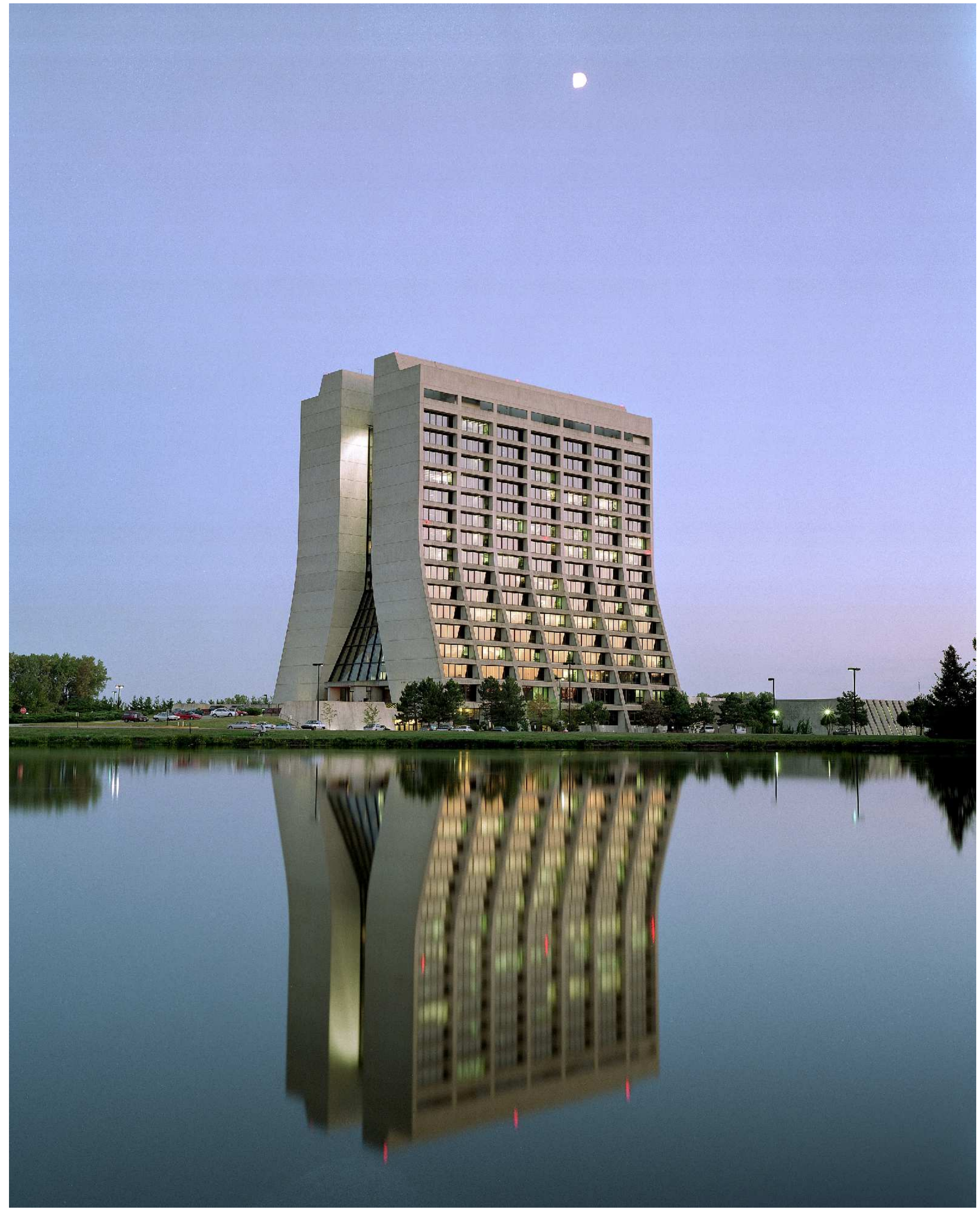
- The heaviest lepton, "τ" was also discovered at SLAC in 1975



A Century of Particle Physics

- The heaviest "top quark" (*t*) discovered at Fermilab in 1995

- The next heaviest, "bottom quark" (*b*) was also discovered at Fermilab in 1977



A Century of Particle Physics

- Success # 2: a really elegant framework for *predicting* the nature of fundamental forces
  - matter particles (quarks and leptons) transform in *curved* internal spaces
  - The equations of motion *predict* terms that describe particle interactions with force fields

- Analogous to the Coriolis and Centrifugal forces generated in rotating frames of reference

A Century of Particle Physics

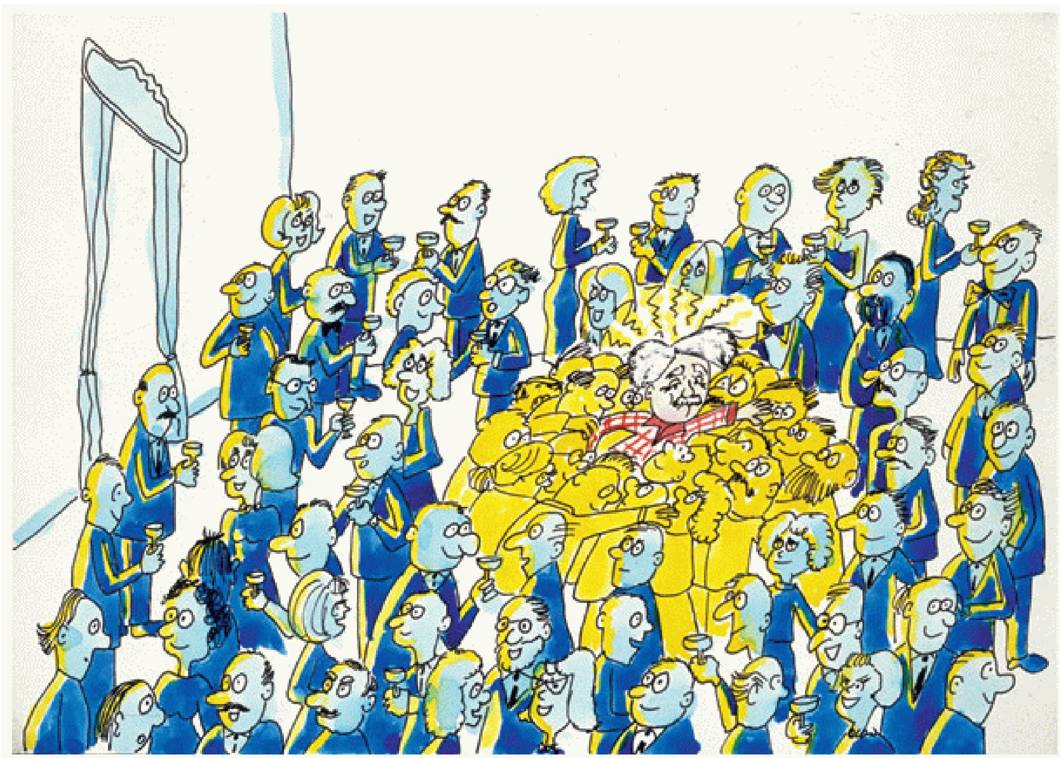
- Notion of symmetry of equations under “gauge transformations” not just a theoretical success: beautifully confirmed by large amount of experimental particle physics measurements, for
  - Electromagnetic force $\psi(x) \longrightarrow e^{i\phi(x)}\,\psi(x)$

  - Weak force (radioactivity)

  - Strong (nuclear) force

The "Problem", thus Excitement, of Particle Physics

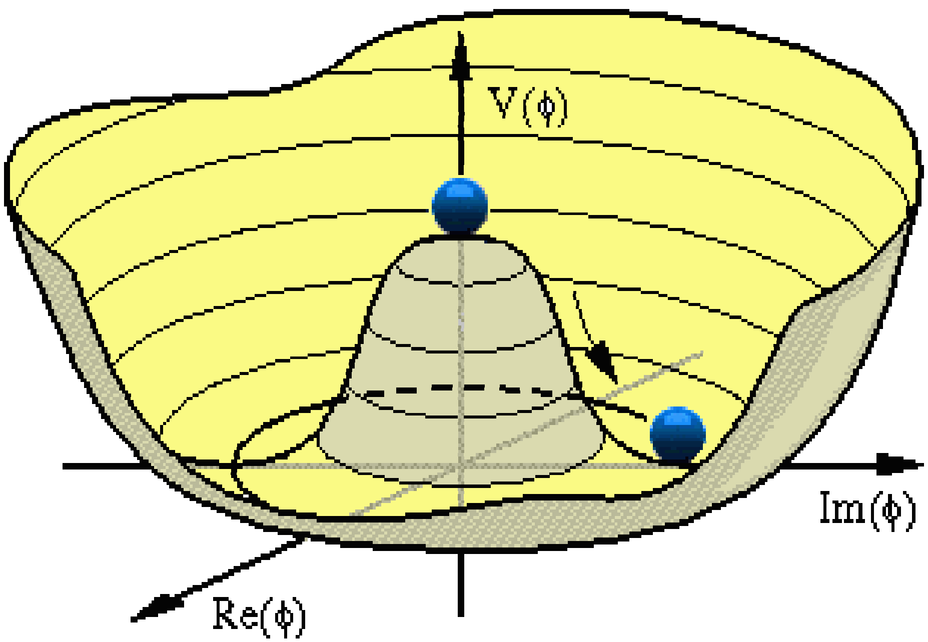
- This highly successful theory predicts that particles should be massless!
  - Obviously not true in nature
  - Not just "Dark Matter", we do not know the origin of "Visible Matter"
- Theory rescued by postulating a new "Higgs" field, which permeates all space
  - A sticky field, particles moving through space scatter off the Higgs field, thereby *appearing* to be massive



[Image proposed by David Miller, University College London]

The "Problem", thus Excitement, of Particle Physics

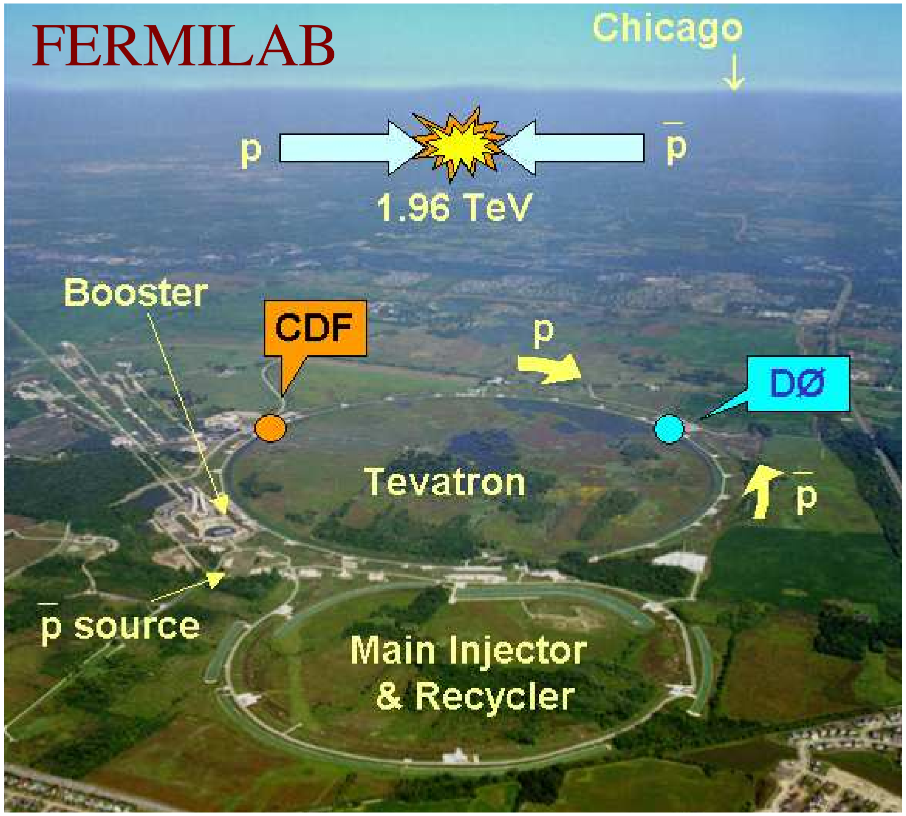
- Proof of the concept: superconductivity
  - Normally massless photon (quantum of electromagnetic force) becomes massive in a superconductor
- Conclusion: our vacuum is not a true vacuum
  - Its a "false vacuum", behaving like a superconductor!

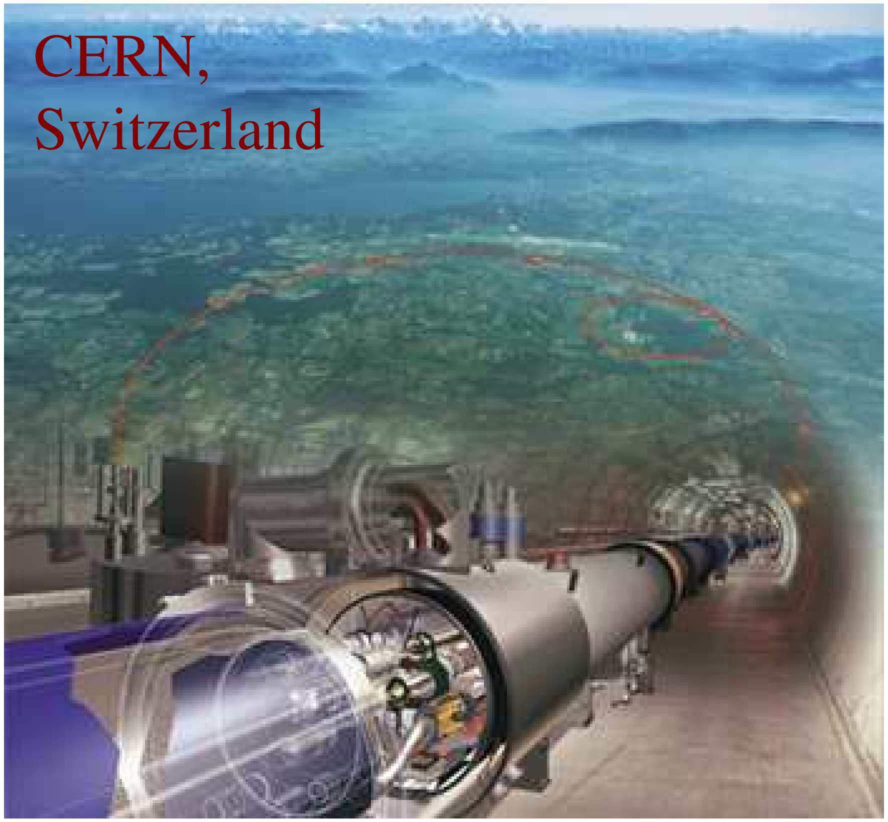


Crossing the Energy Threshold for Discoveries

"Critical Temperature" for superconducting vacuum ~ 1 TeV

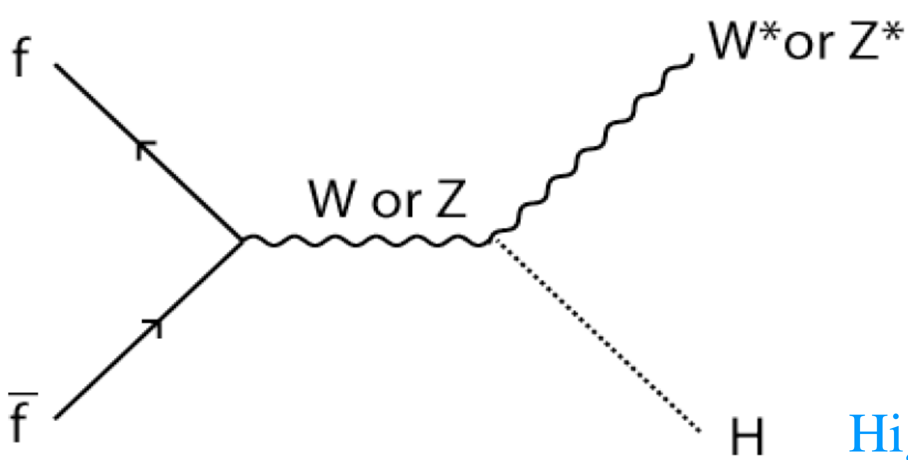
Accelerators at Fermilab (running now with 2 TeV energy) and CERN (start running in 2007 with 14 TeV energy) are at the energy at which the "Higgs Boson" is expected to show up





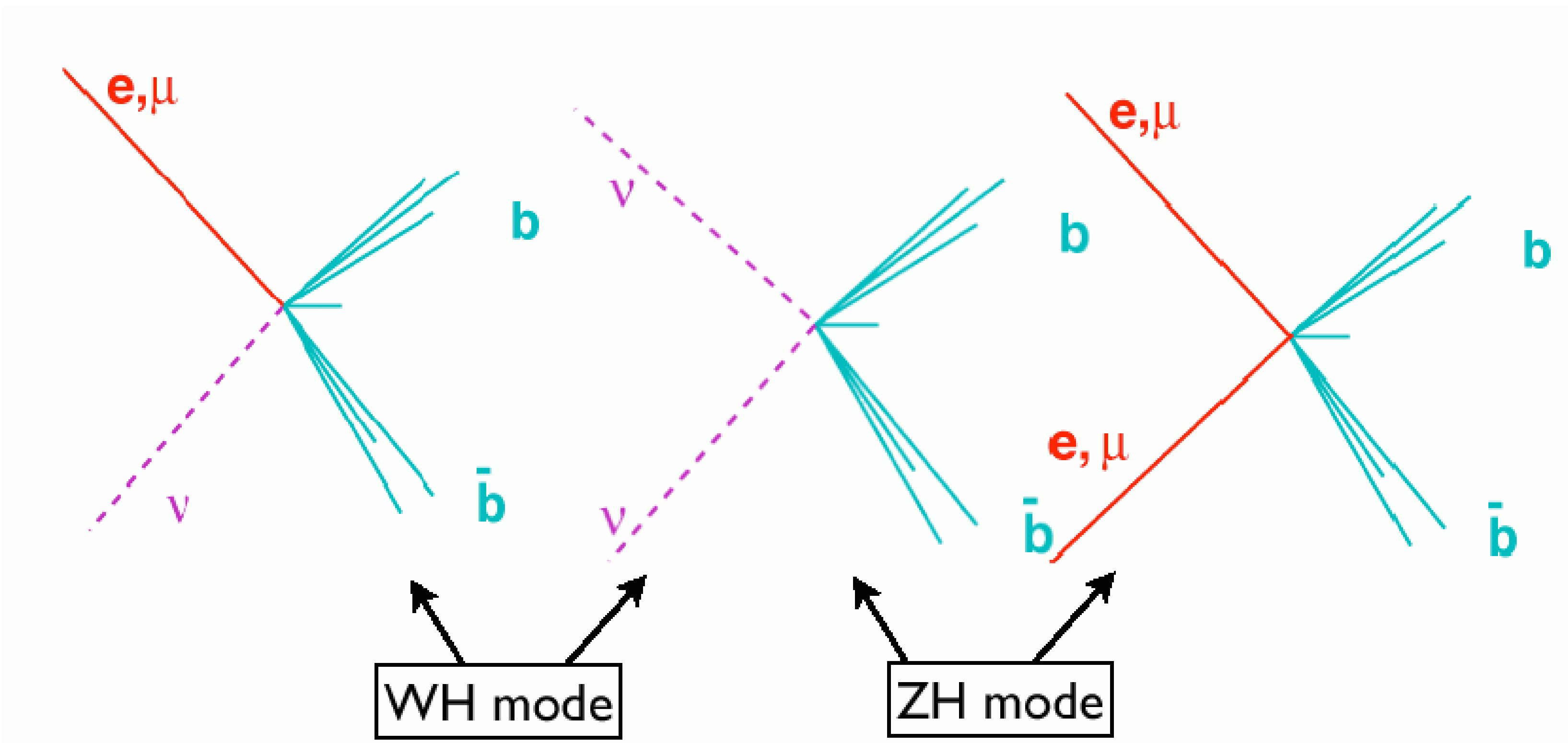
Search for Higgs boson is a key mission of the HEP program

Light Higgs Boson Production and Decay

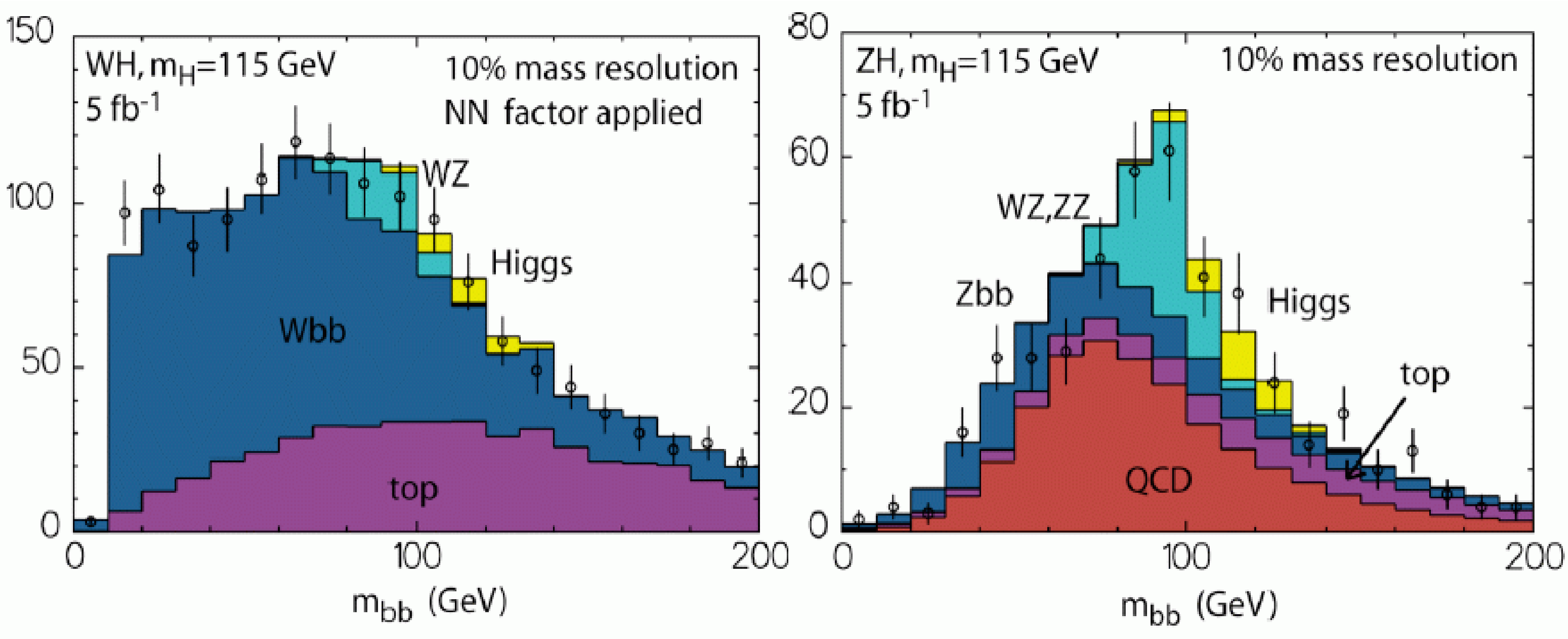


W, Z decay to electrons, muons and/or neutrinos

Higgs boson decays to bottom quarks



Simulated Higgs Signal on Expected Backgrounds



Key requirements for observing signal:

Good reconstruction of decay particle momentum vectors

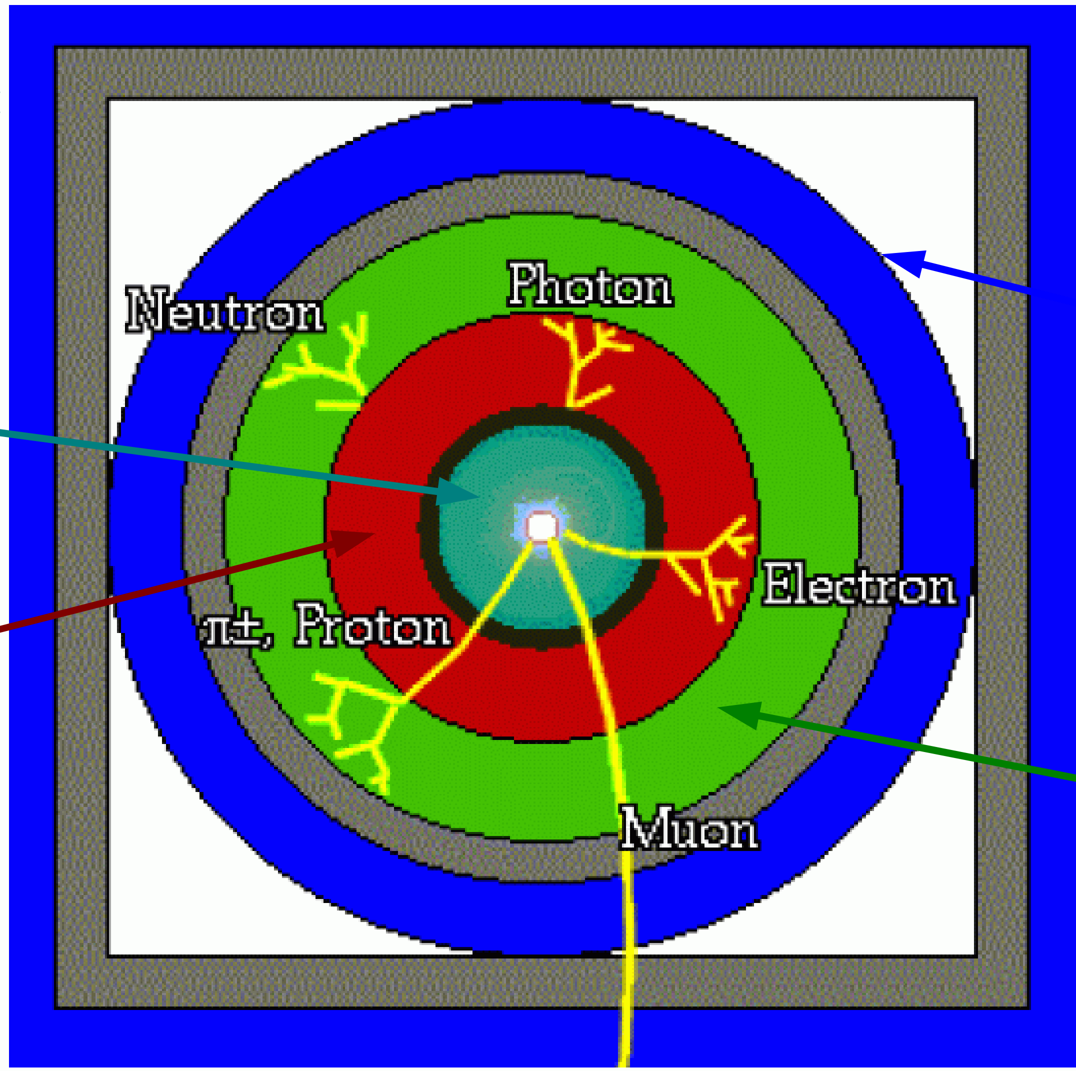
Good simulation of signal and background events

Observation of standard model ZZ and WZ production an important milestone

Particle Detection

Drift chamber (COT): reconstuct particle trajectory by sensing ionization in gas on high voltage wires

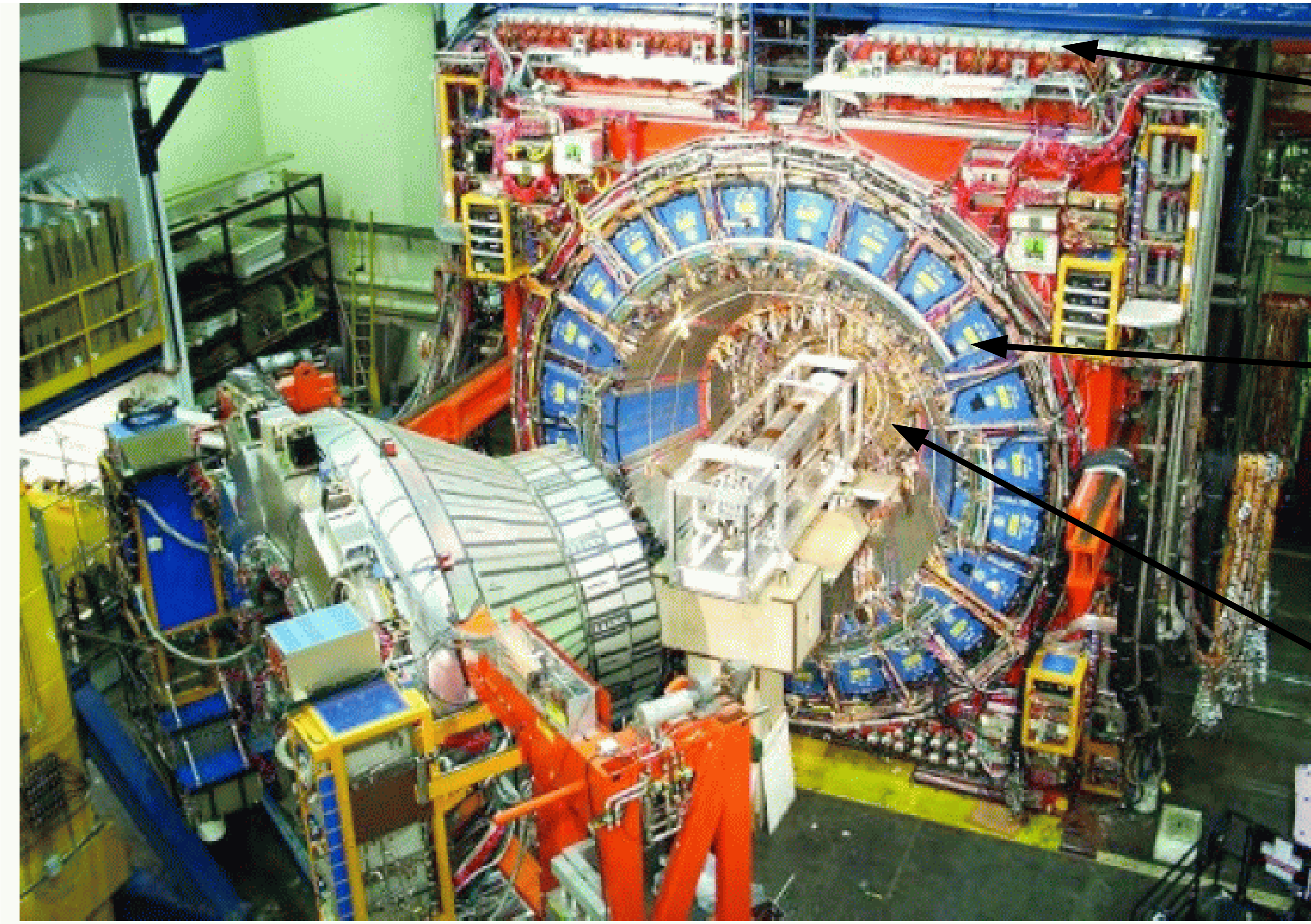
Electromagnetic (EM) calorimeter: lead sheets cause *e*/γ shower, sense light in alternating scintillator sheets



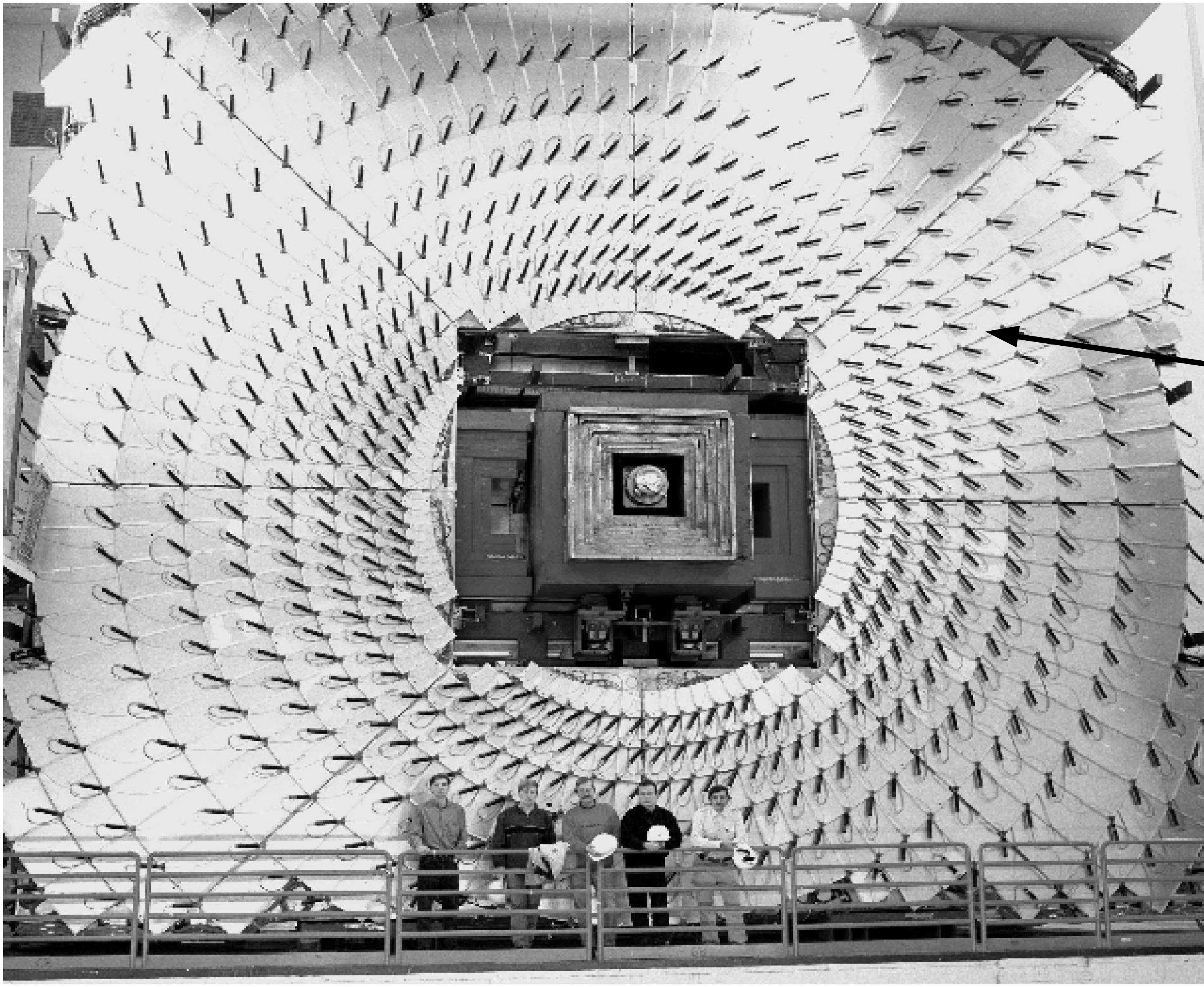
Muon chambers: detect penetrating particles behind shielding

Hadronic calorimeter: steel sheets cause hadronic showers, sense scintillator light

Collider Detector at Fermilab (CDF)



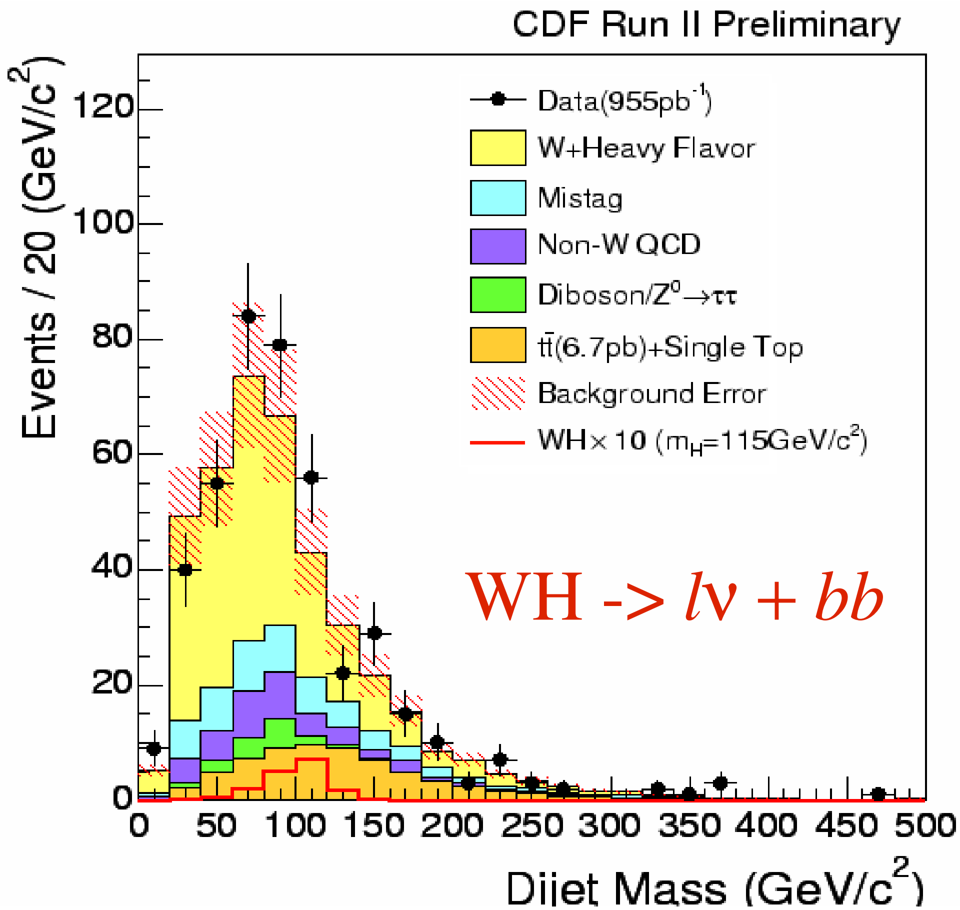
D0 Detector

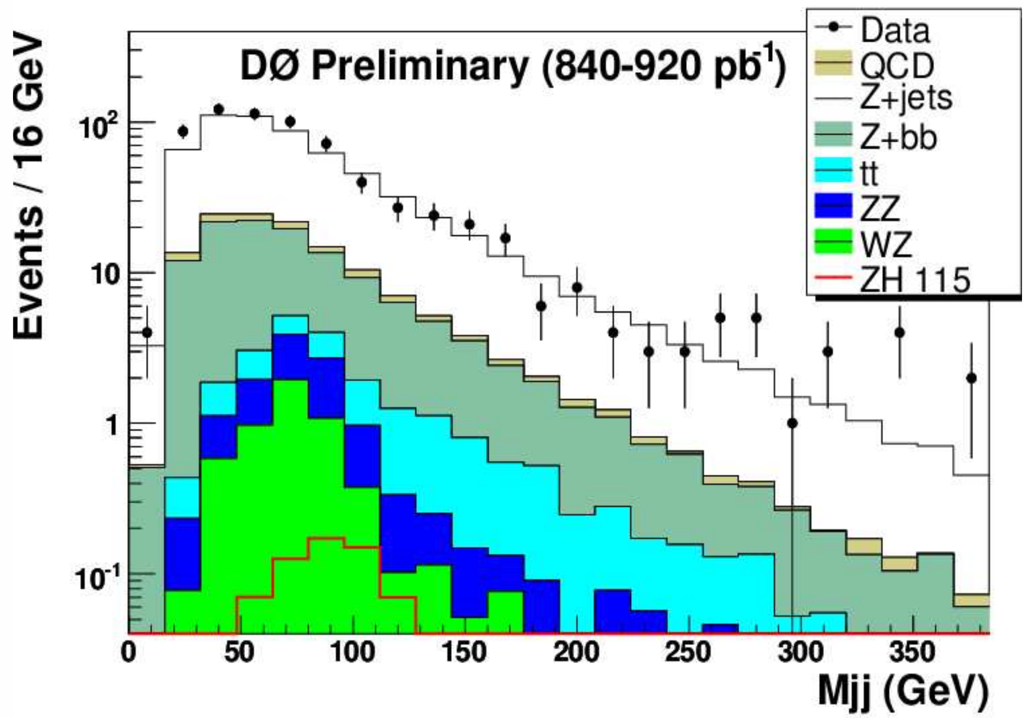


Forward muon detectors

CDF Tracking Chamber

Search for the Higgs Boson

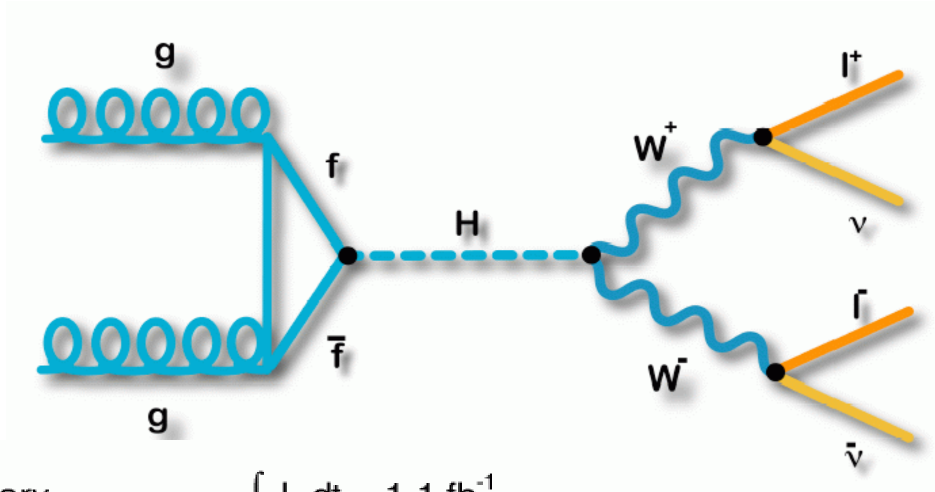


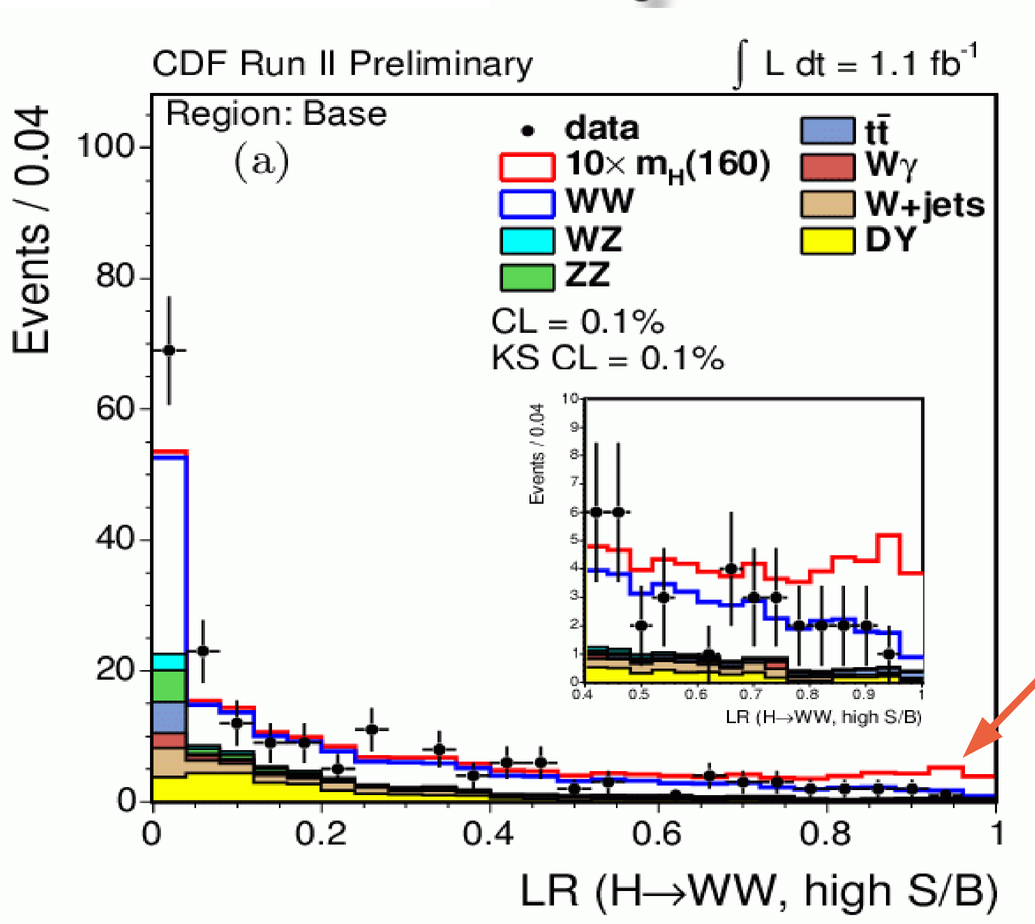


ZH -> ll + bb

Searches with 1 fb^{-1} of data show no statistically significant excess of events due to Higgs boson production, above expected backgrounds

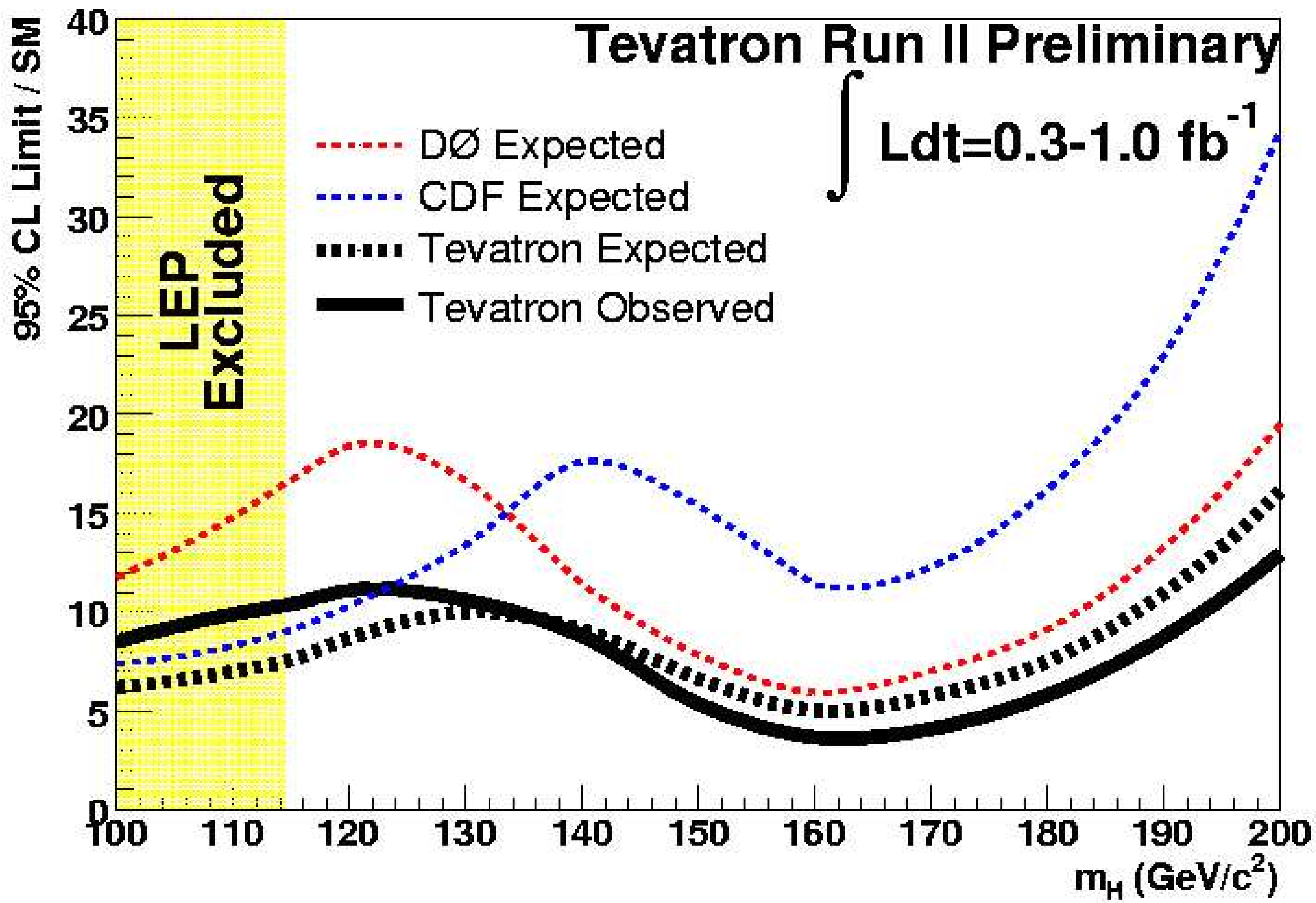
Heavy Higgs Boson Production and Decay





event topology "Likelihood" of hypothetical H -> WW signal (x10), compared to data and backgrounds

Higgs Boson Production Limits

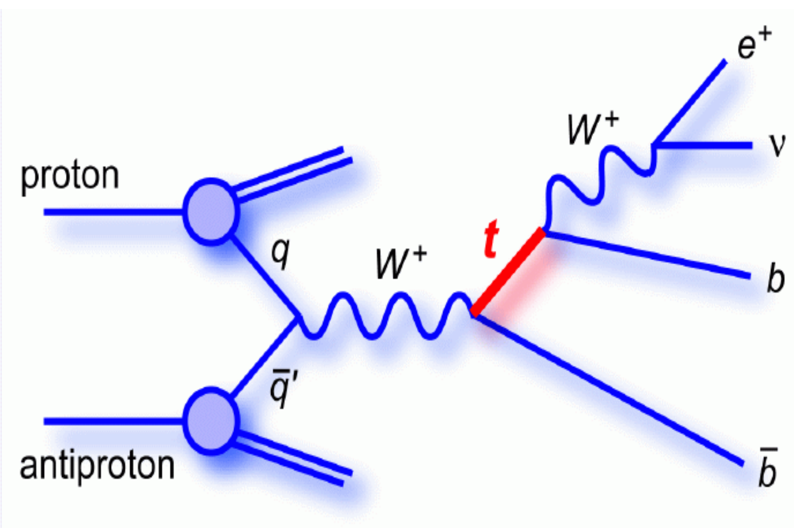


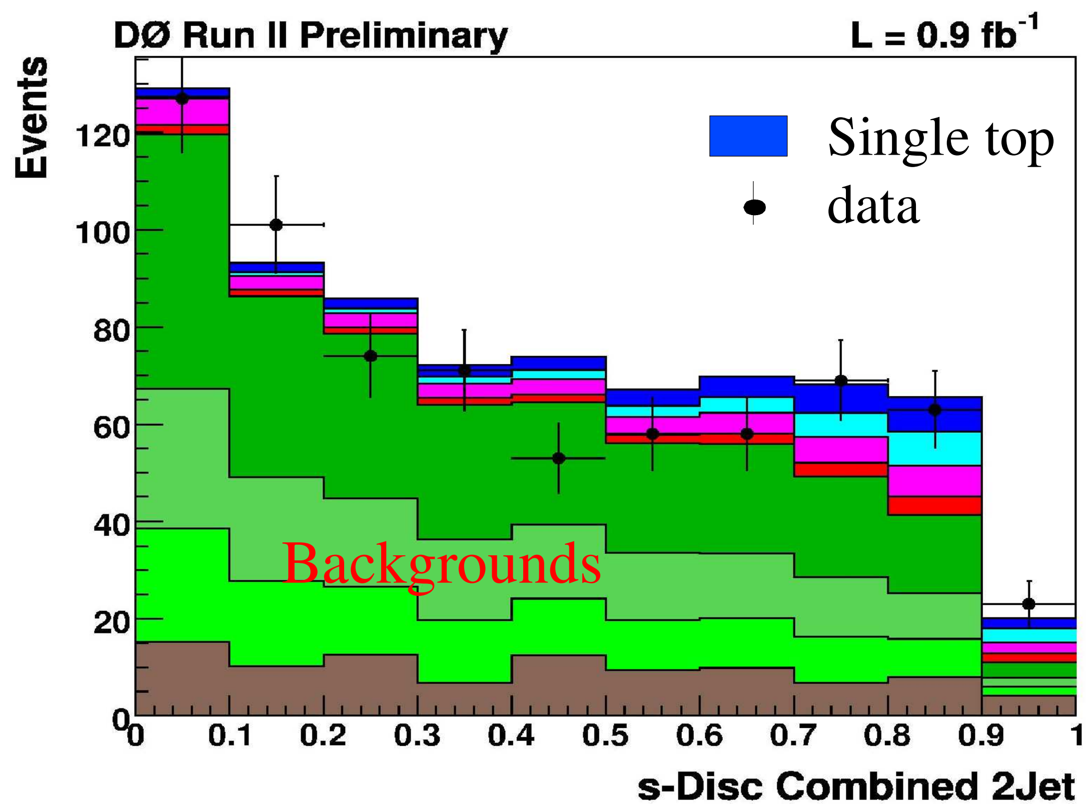
- Comparison of Higgs boson production cross section upper limit to the theoretical expectation
- Shows that analysis of x5-10 more data at the Tevatron has a good chance of discovering the Higgs boson

Milestones in Standard Model Observations towards the Higgs

Single Top Production

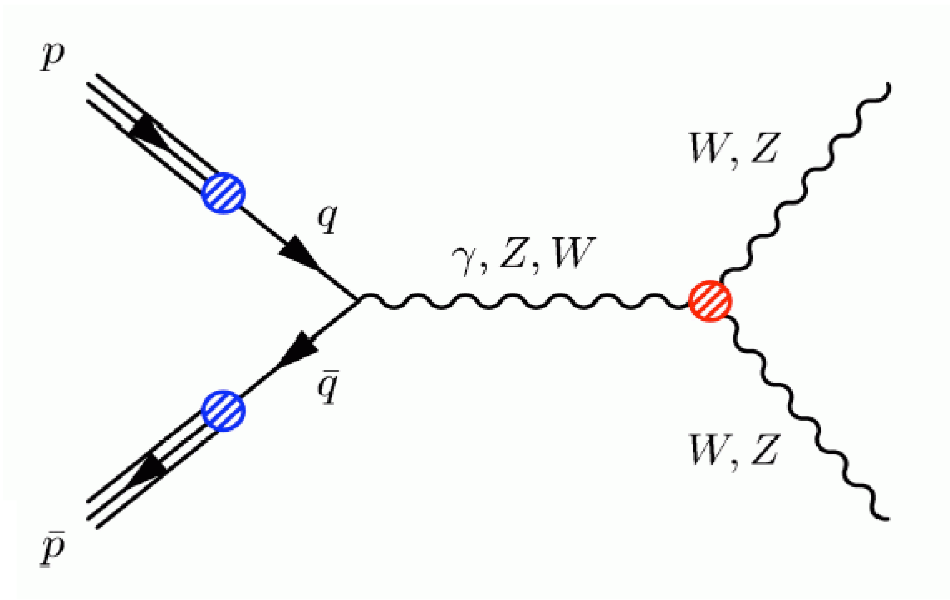
- Top quark discovered in 1995 at the Tevatron using the pair production mode
- Evidence (3.2σ) of single top quark production in D0 data
- Important measurement of the t-b coupling
- Similar final state as WH -> $l\nu$ + bb search
  - Therefore also a key milestone in the Higgs search

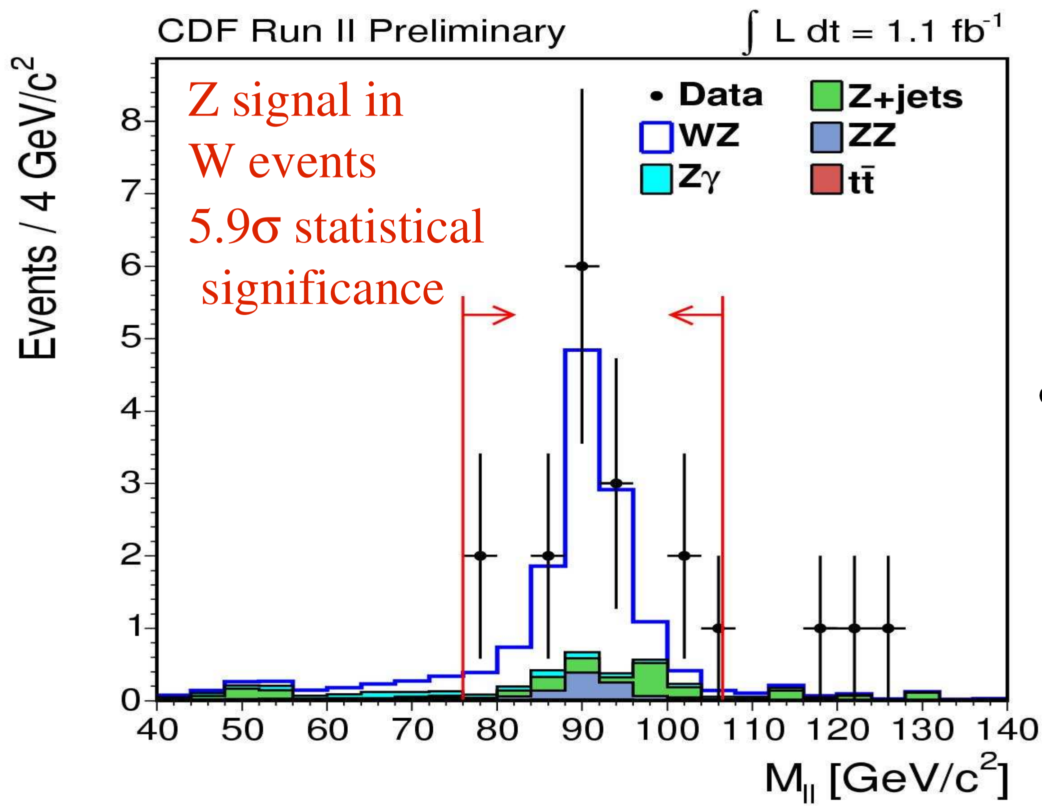




Observation of W+Z Associated Production

- Recent confirmation of this fundamental prediction of the standard model provided by ~1 fb^{-1} of CDF data



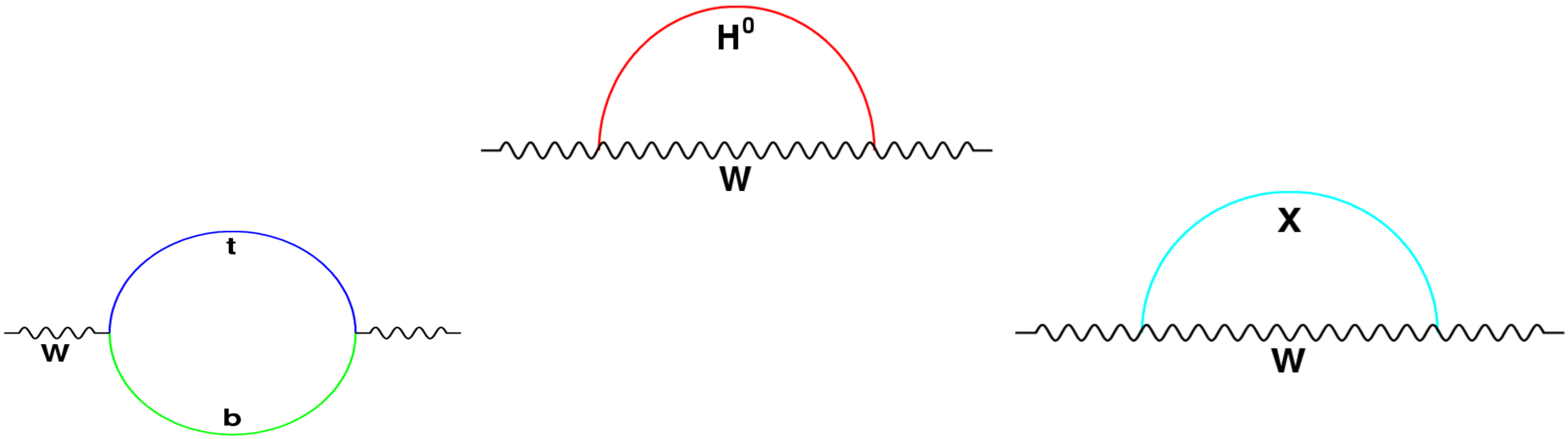


- Another key milestone in the Higgs boson search

Precision Standard Model Measurements
Constraining the Higgs and New Physics

Precision Measurements of W boson and top quark masses

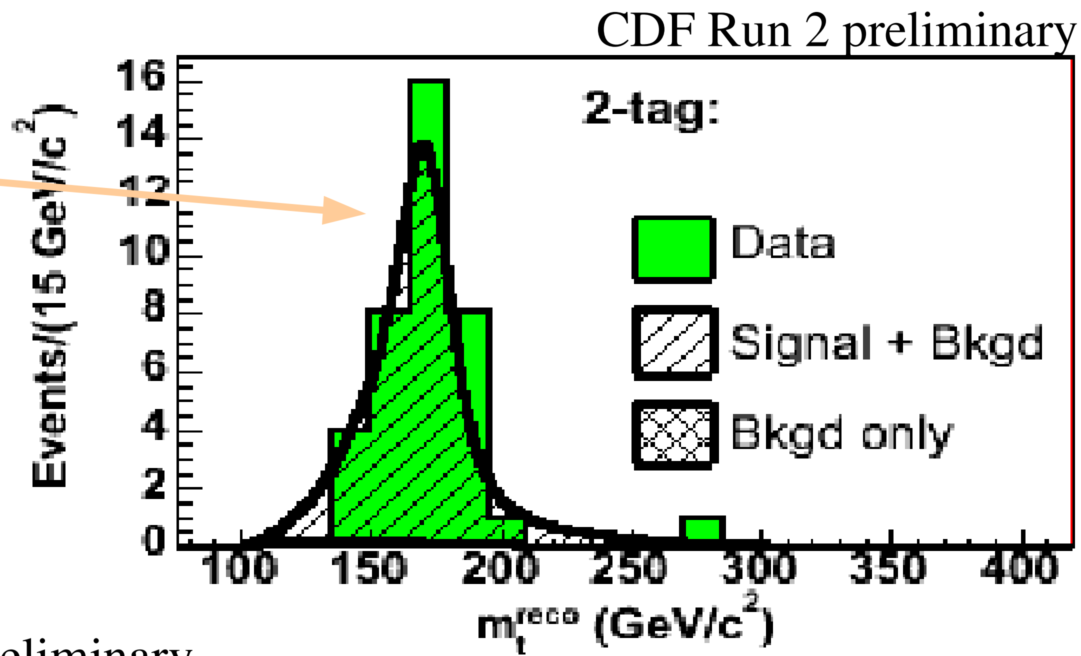
- Radiative corrections due to heavy quark and Higgs loops and exotica

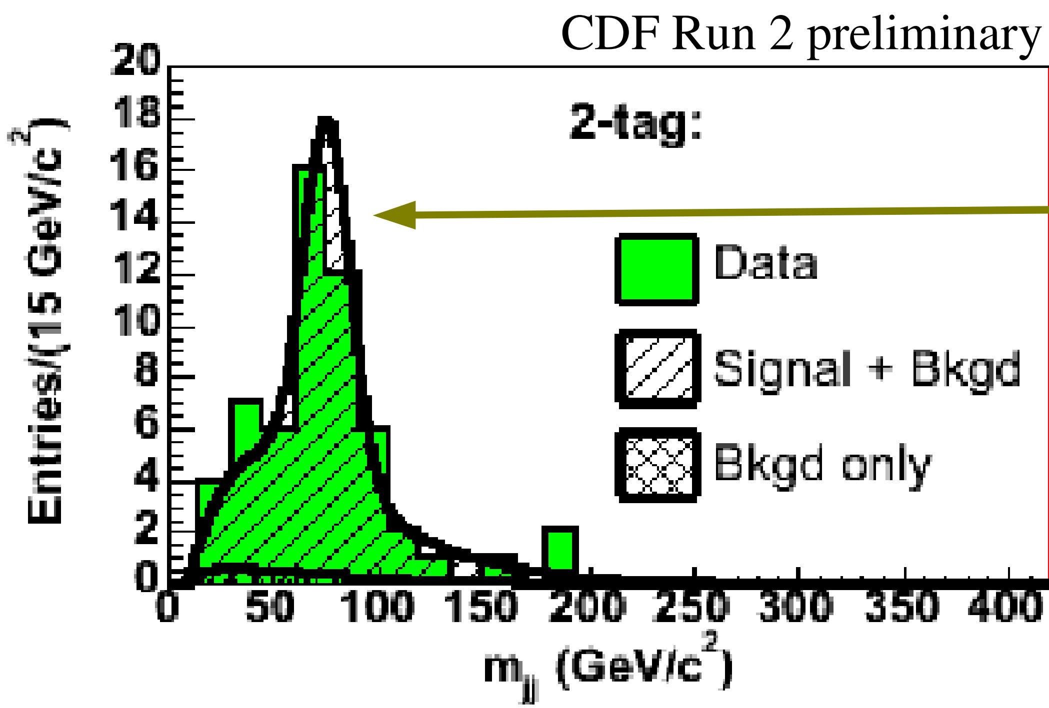


- Top quark mass and W boson mass constrain the mass of the Higgs boson, and possibly new particles beyond the standard model
- Precision measurements of weak mixing angle at SLD and LEP also constrain the Higgs and new physics

Progress on M_{top} at the Tevatron

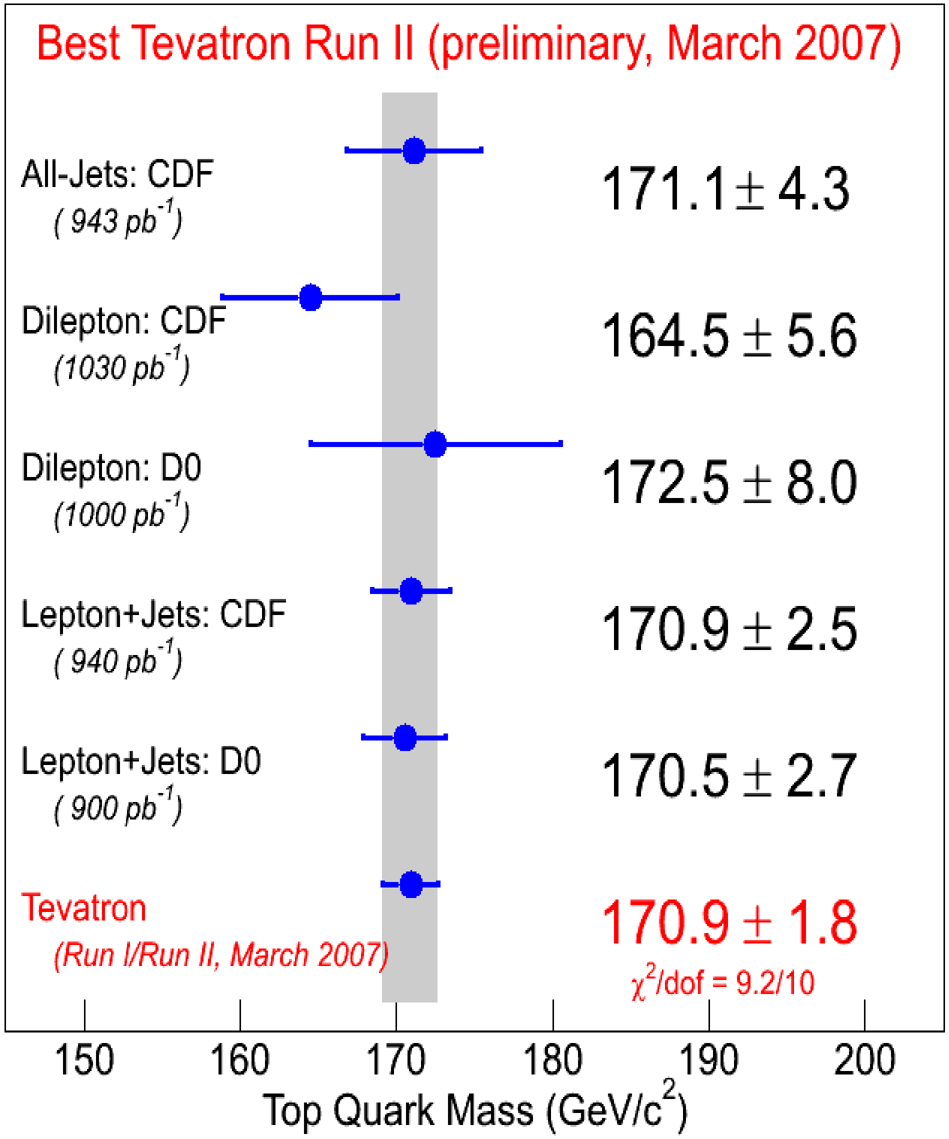
Reconstructed top mass in 680 pb^{-1} of CDF data, fit with simulated lineshape





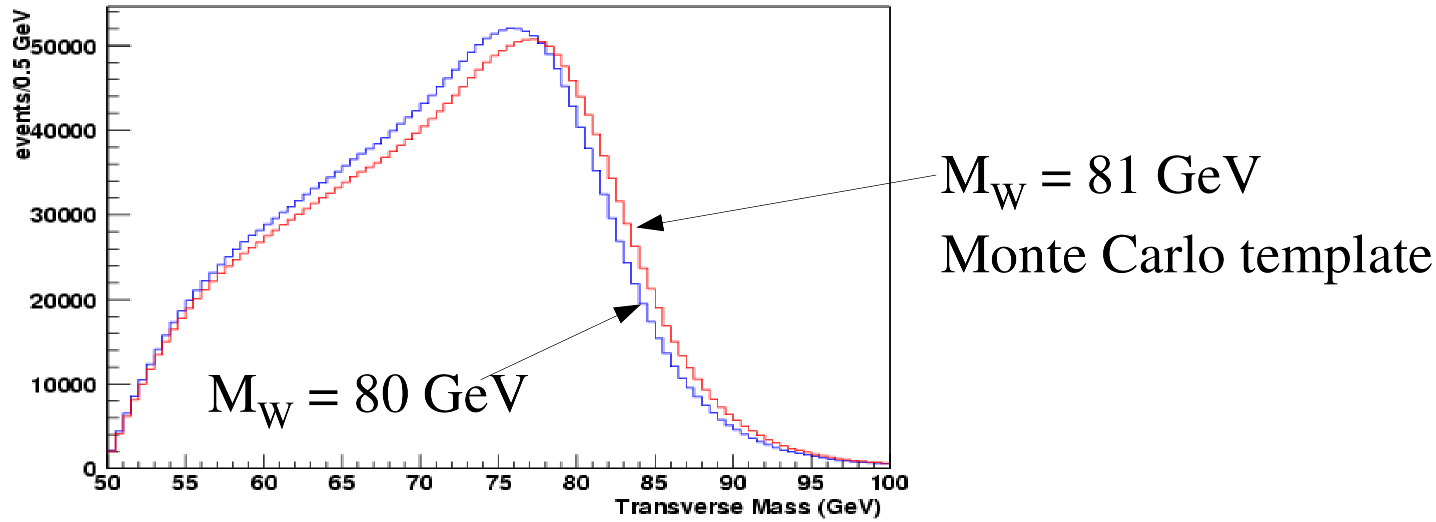
Improved top mass precision due to in-situ calibration of jet energy using W->jj decays in the same events

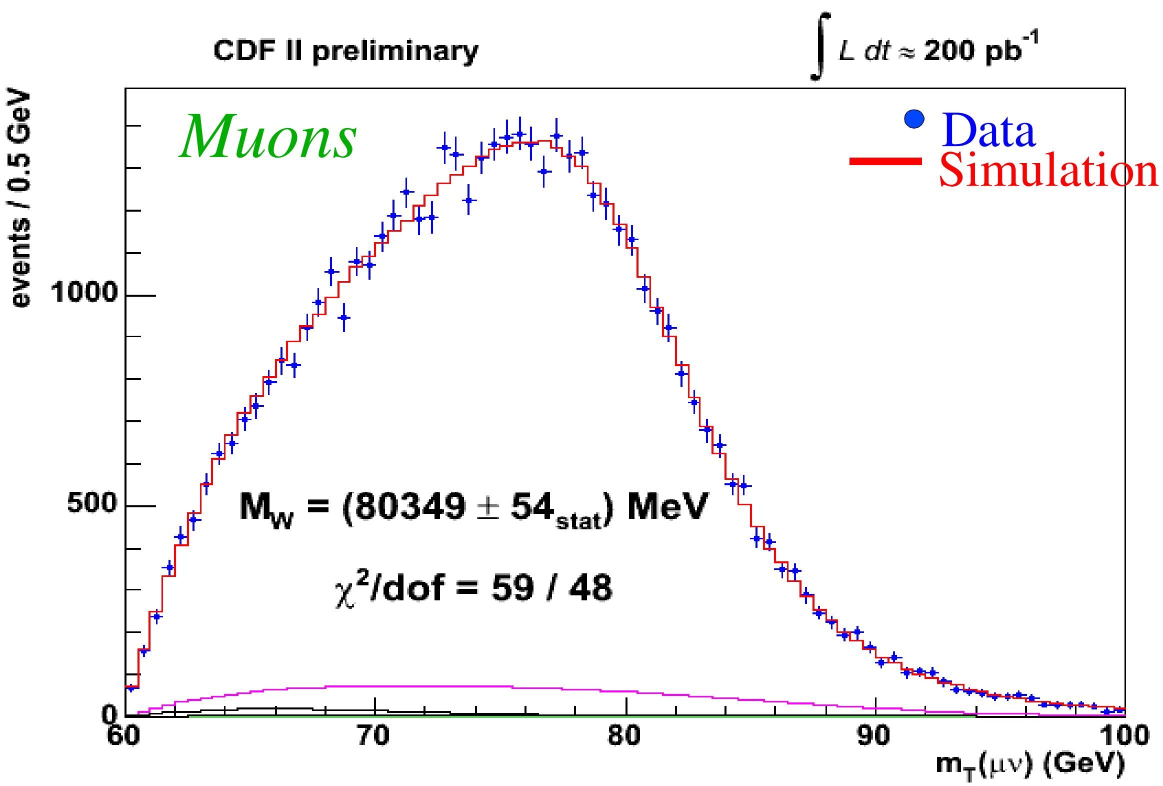
Progress on M_{top} at the Tevatron



- δM_{top} = 1.8 GeV, the best-measured quark mass (smallest % error)

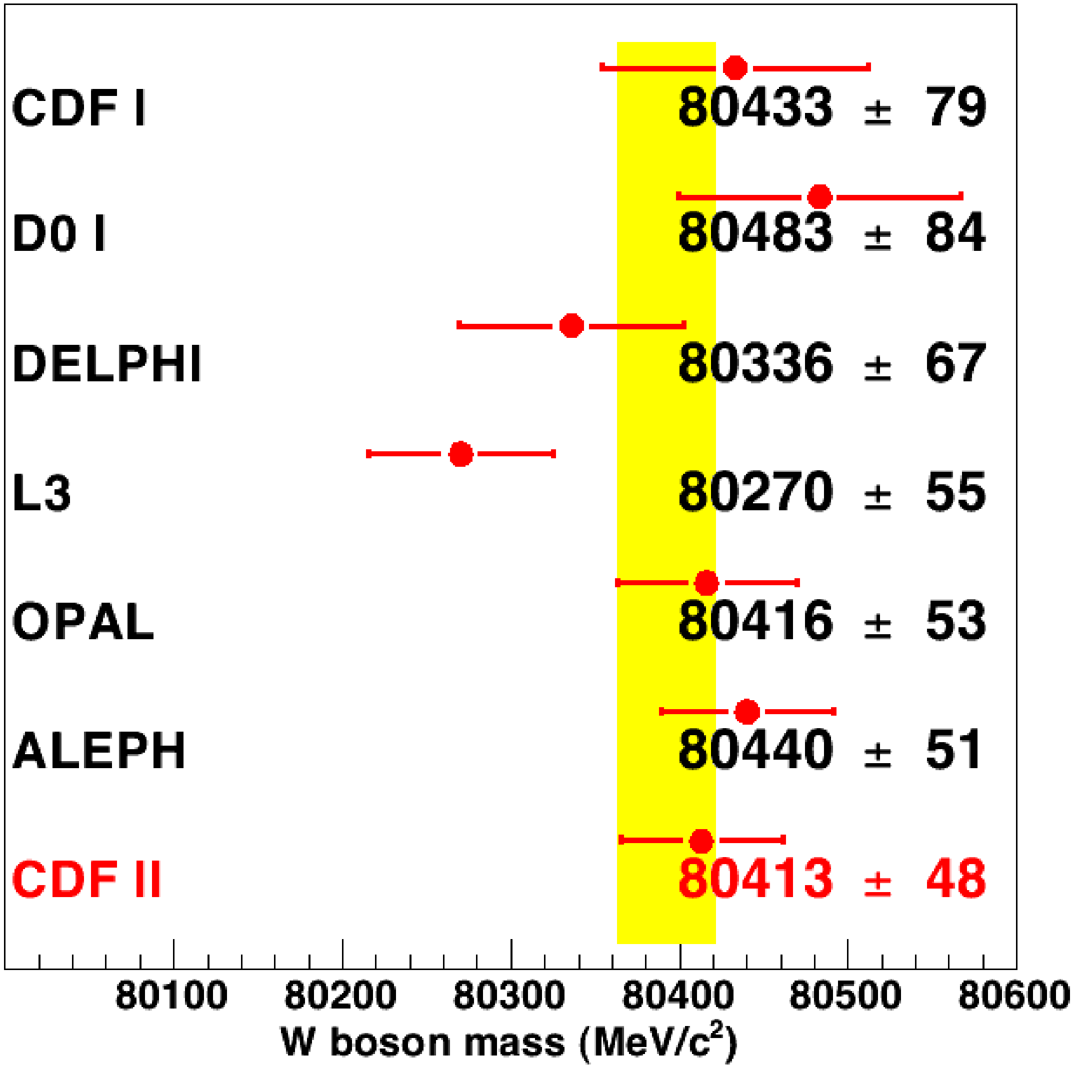
Fitting for the *W* Boson Mass





Perform fits to kinematic distributions sensitive to the W boson mass

W boson mass measurement

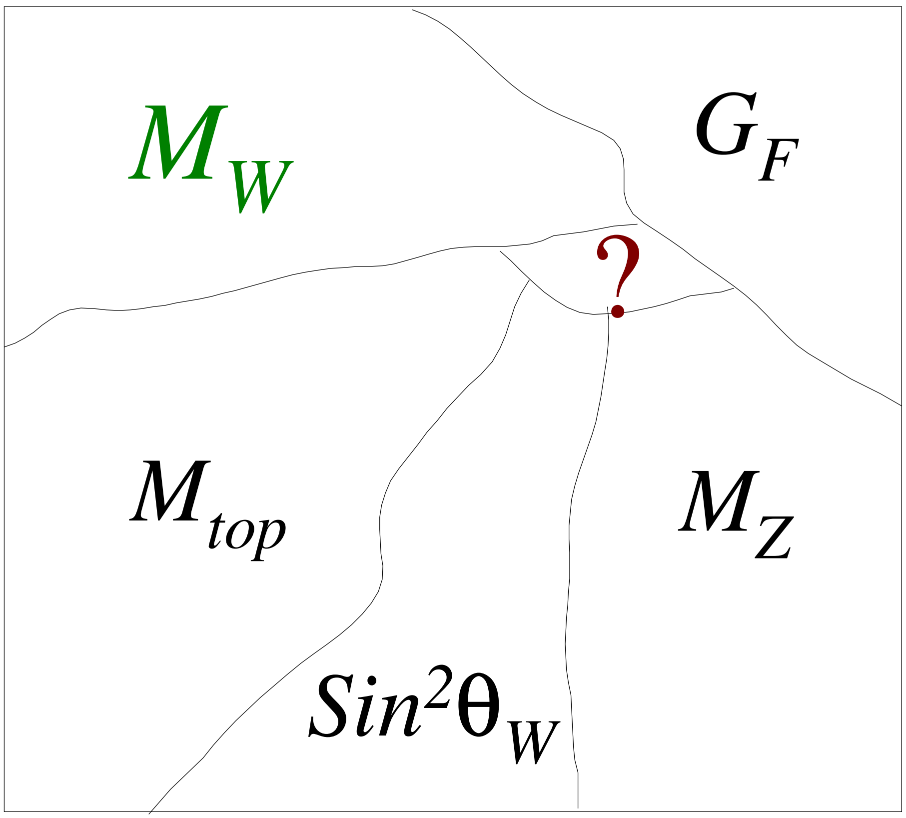


The CDF Run 2 result is the most precise single measurement of the W mass

... and factor of 10 more data being analyzed now!

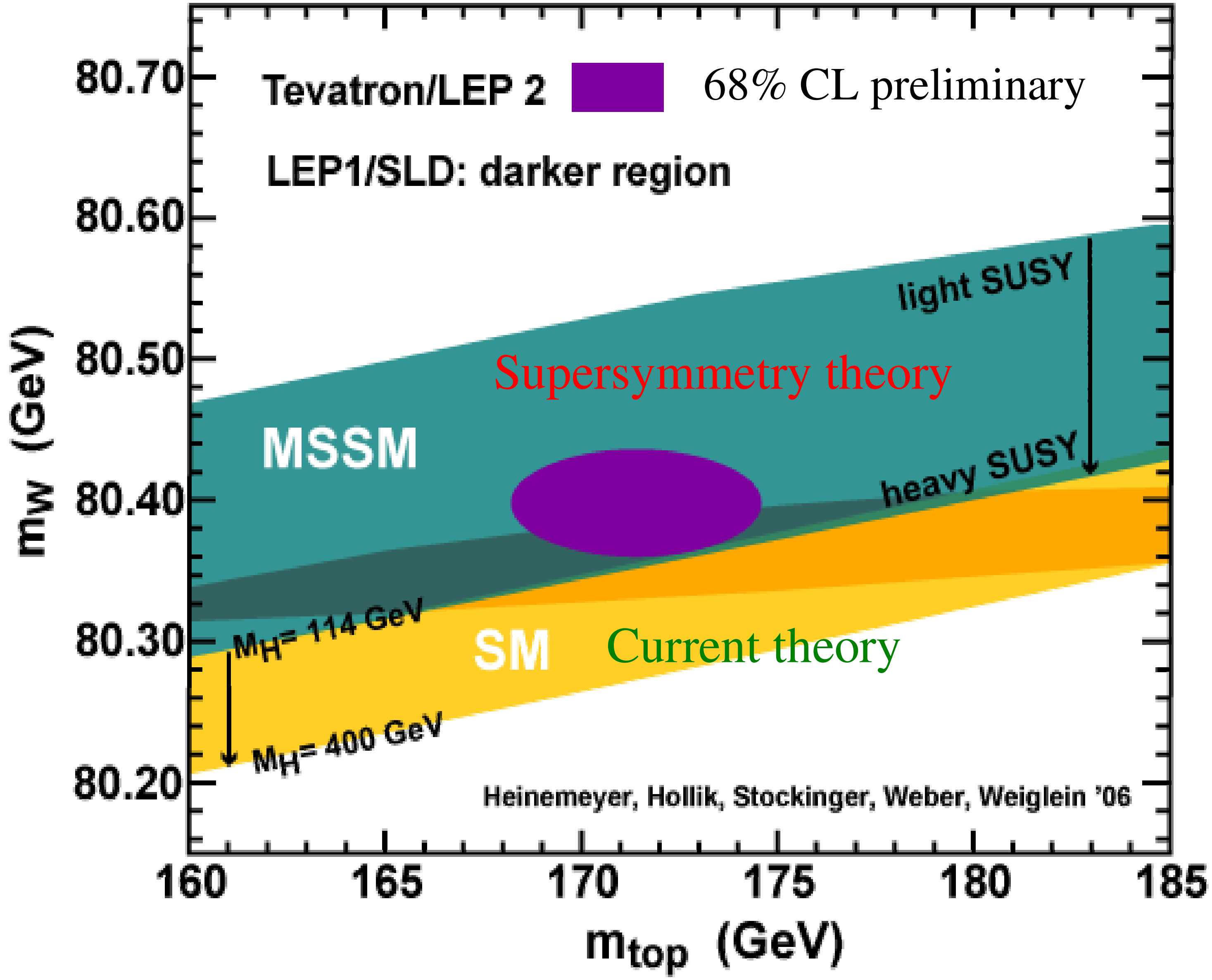
Higgs Mass Constraints from Precision Measurements

- SM Higgs fit: $M_H = 76^{+33}_{-24}$ GeV
- LEPII direct searches exclude $M_H < 114.4$ GeV @ 95% CL (PLB 565, 61)



In addition to the Higgs, is there another missing piece in this puzzle?

M_W *vs* M_{top}



Lightest neutral supersymmetric particle could be dark matter candidate!

Summary

- CDF and D0 at the Fermilab Tevatron in pursuit of the mass-generating mechanism:
  - Are closing in on the Higgs boson using direct searches
  - Are constraining the Higgs boson mass by making precision measurements of the top quark and W boson masses
  - Are confirming key theoretical predictions of current theory
    - Production of single top quarks
    - Associated production of W+Z bosons
    - Matter-antimatter oscillations in bound states of *b* quarks
    - Discovering new nucleonic bound states of *b* quarks
  - Searching for new fundamental symmetries of nature
    - Supersymmetry
    - Substructure
    - New forces
    - Additional spatial dimensions
- CDF and D0 continue to collect and analyze x5 more data in the next few years – nature may reveal more of its secrets!