Search for the Higgs Boson

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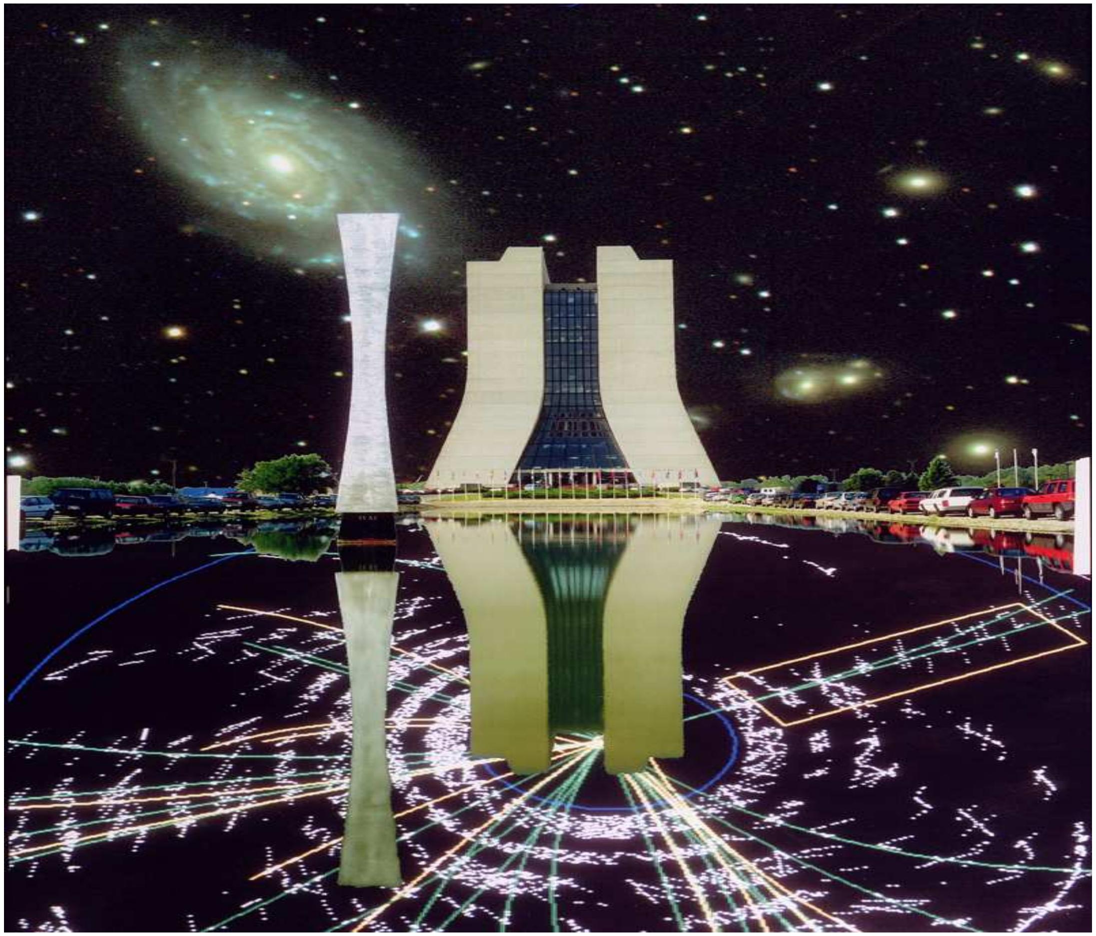
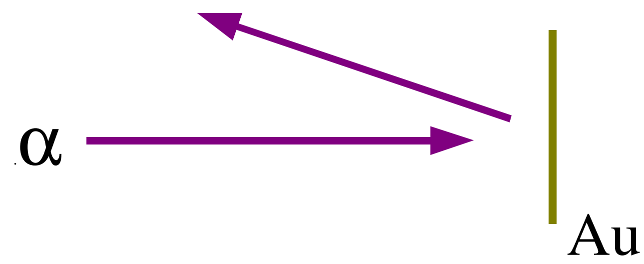


The Inter-University Centre for Astronomy and Astrophysics
24 December 2008

Why Build Accelerators?
From Atoms to Quarks

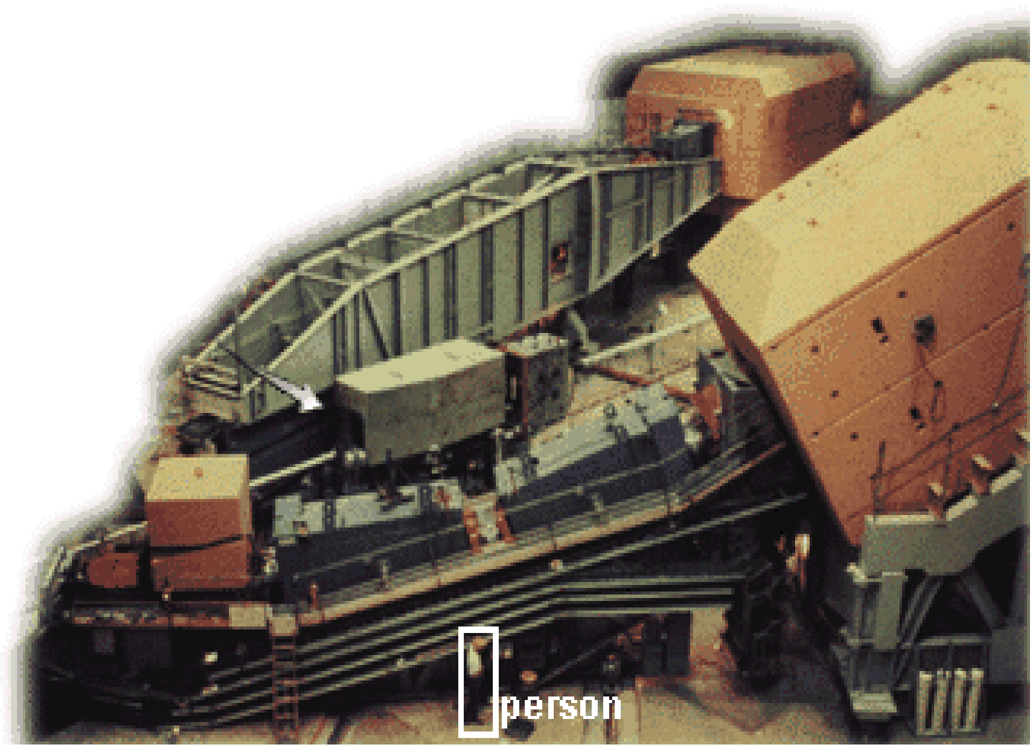
- Scattering of probe particles off matter to investigate substructure, i.e. "look inside"
- Rutherford did it, shooting α particles at a gold foil, to tell us the structure of the atom (1911)
- Quantum mechanics: $\Delta r \sim h / \Delta p$



	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: Standard Model

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



A Century of Particle Physics: Standard Model

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

Quarks

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

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

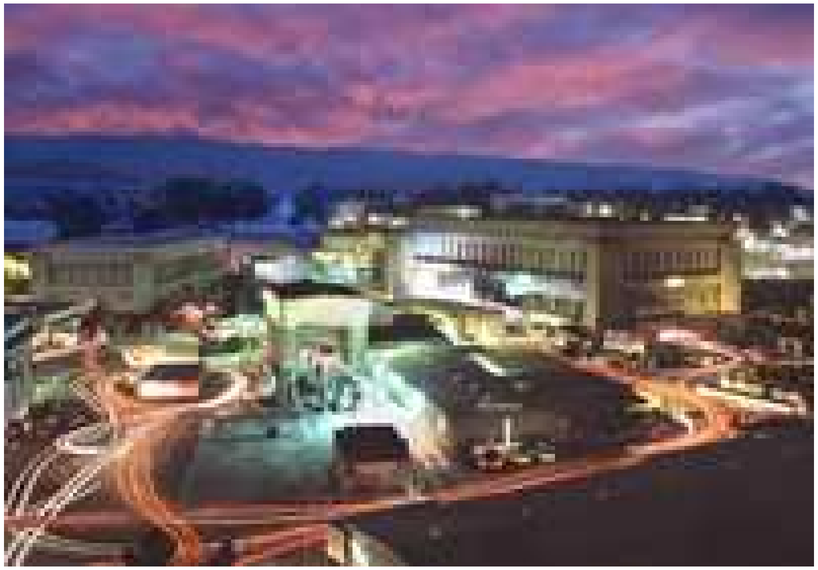
Leptons

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

A Century of Particle Physics: Standard Model

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

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

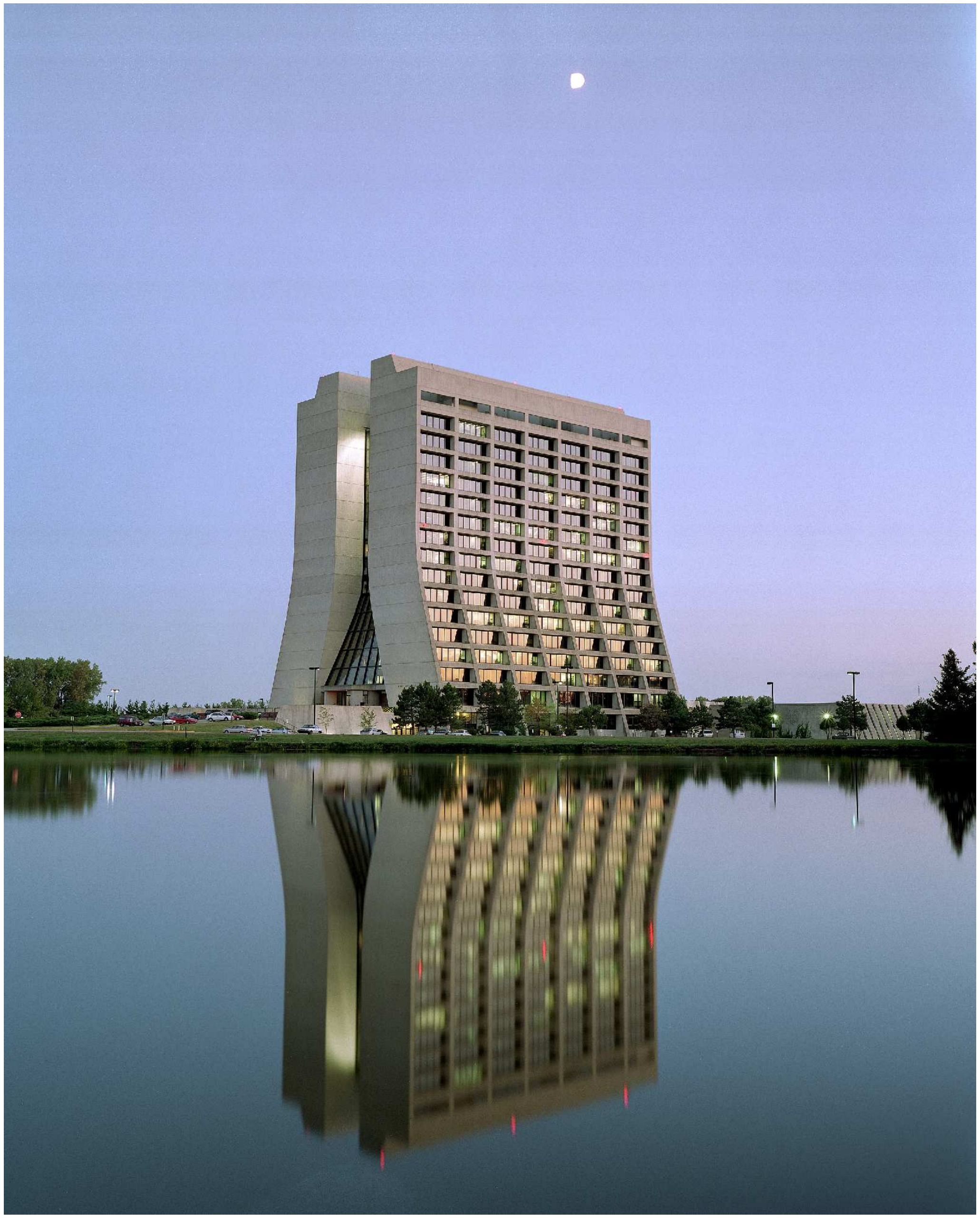


A Century of Particle Physics: Standard Model

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

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

- Appearance of τ lepton in ν_τ beam established at Fermilab



A Century of Particle Physics: Standard Model

- 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: Standard Model

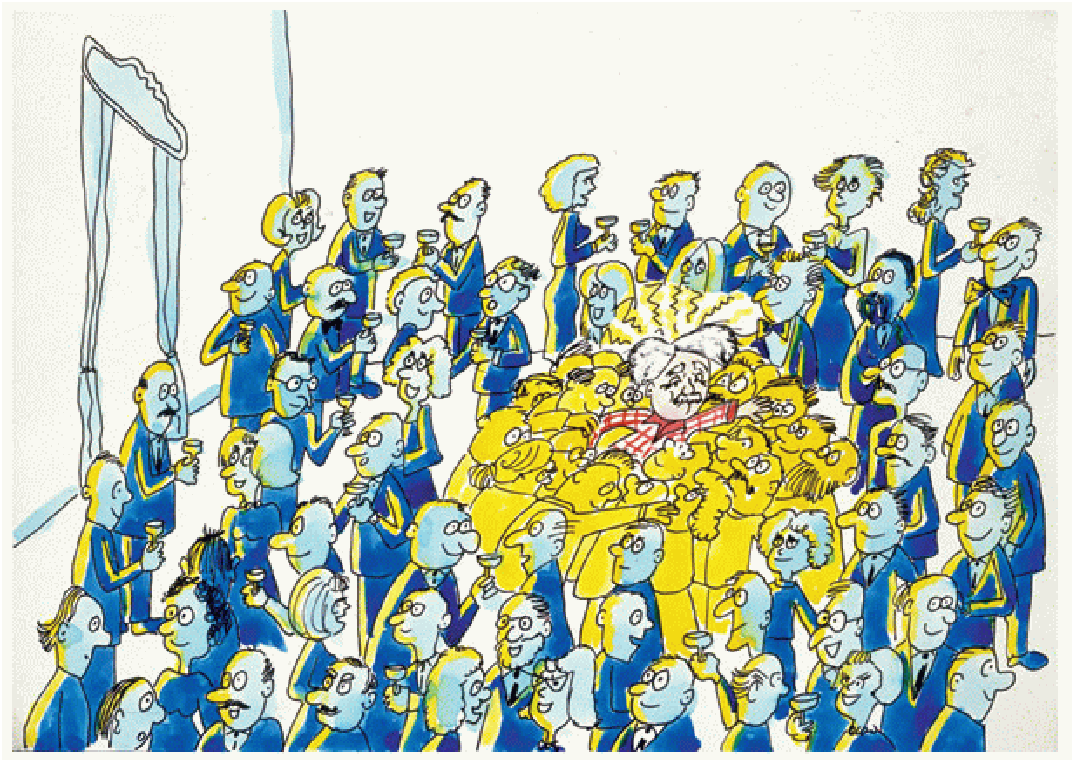
- Notion of symmetry of equations under “gauge transformations” not just a theoretical success: beautifully confirmed by large amount of experimental particle physics measurements, for
  - Electromagnetic force $\psi(x) \longrightarrow e^{i\phi(x)}\,\psi(x)$

  - Weak force (radioactivity)

  - Strong (nuclear) force: internal space is 3D spherical surface

The “Problem”, thus Excitement, of Particle Physics

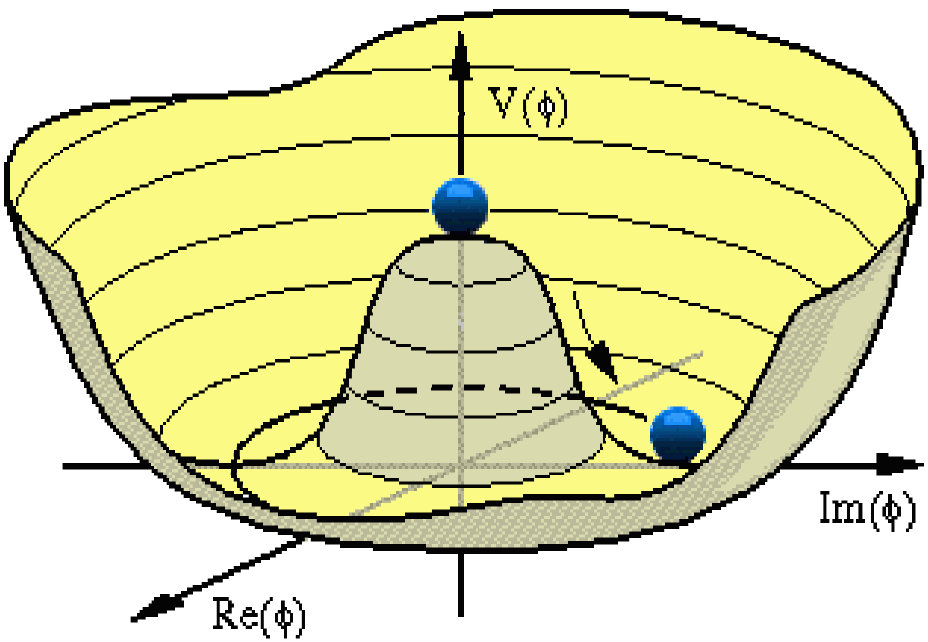
- This highly successful theory predicts that particles should be massless!
  - Obviously not true in nature
  - Not just “Dark Matter”, we do not know the origin of “Visible Matter”
- Theory rescued by postulating a new “Higgs” field, which permeates all space
  - A sticky field, particles moving through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

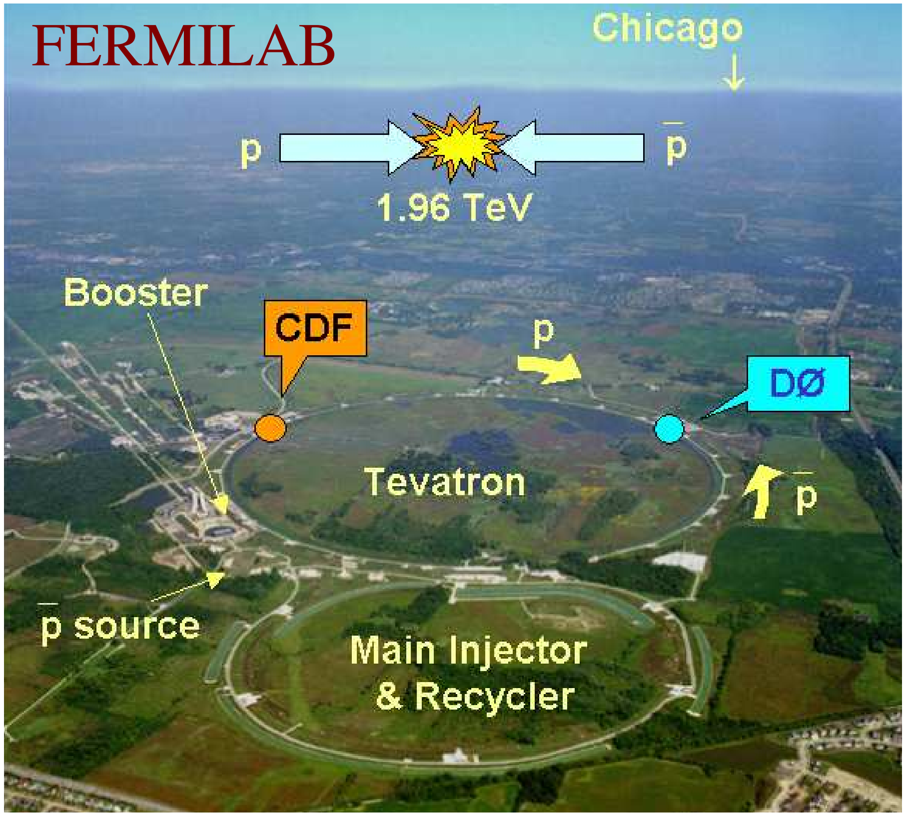
- Proof of the concept: superconductivity
  - Normally massless photon (quantum of electromagnetic force) becomes massive in a superconductor
- Conclusion: our vacuum is not a true vacuum
  - Its a "false vacuum", behaving like a superconductor



Crossing the Energy Threshold for Discoveries

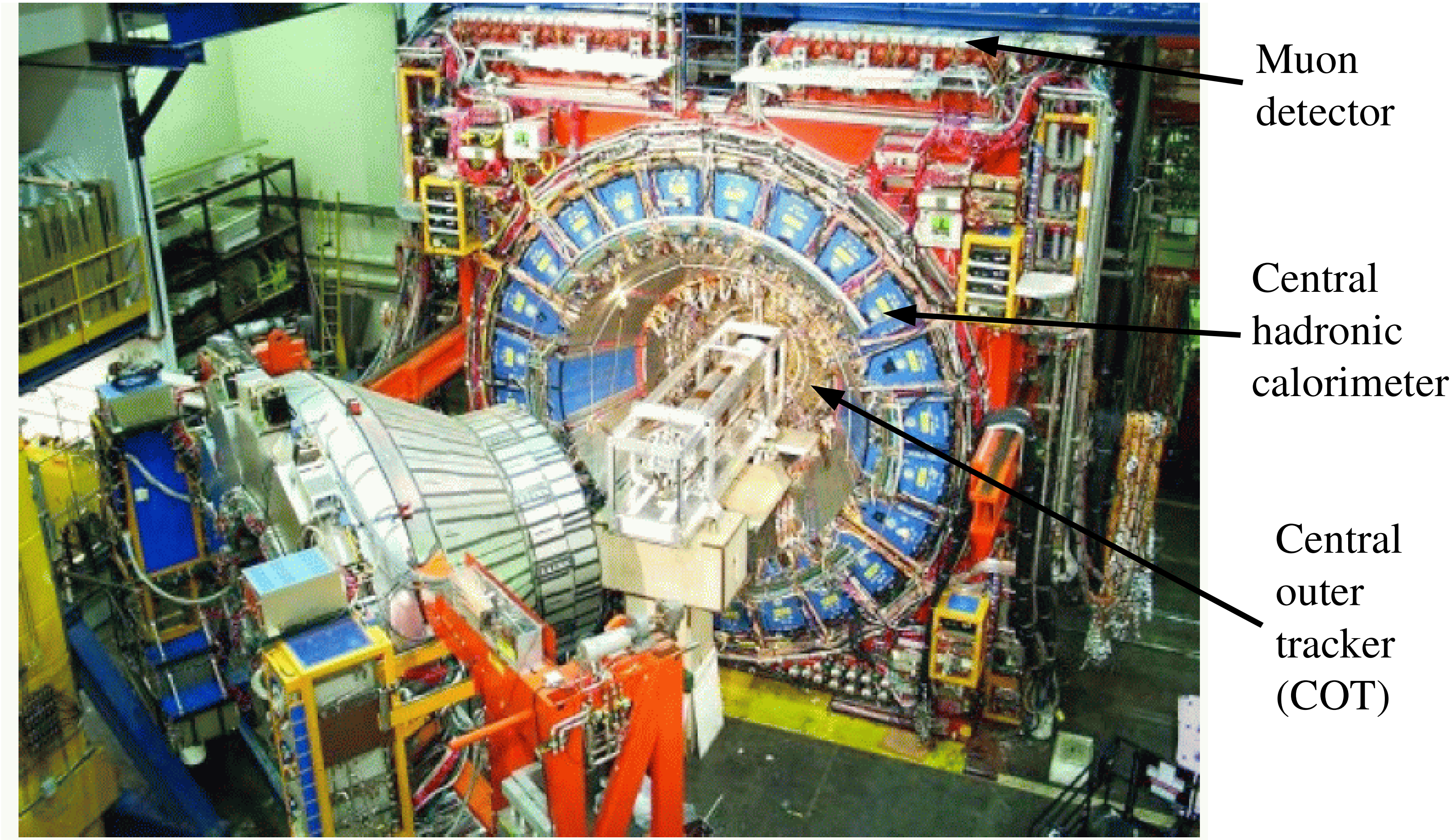
"Critical Temperature" for superconducting vacuum ~ 1 TeV

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 High Energy Physics program

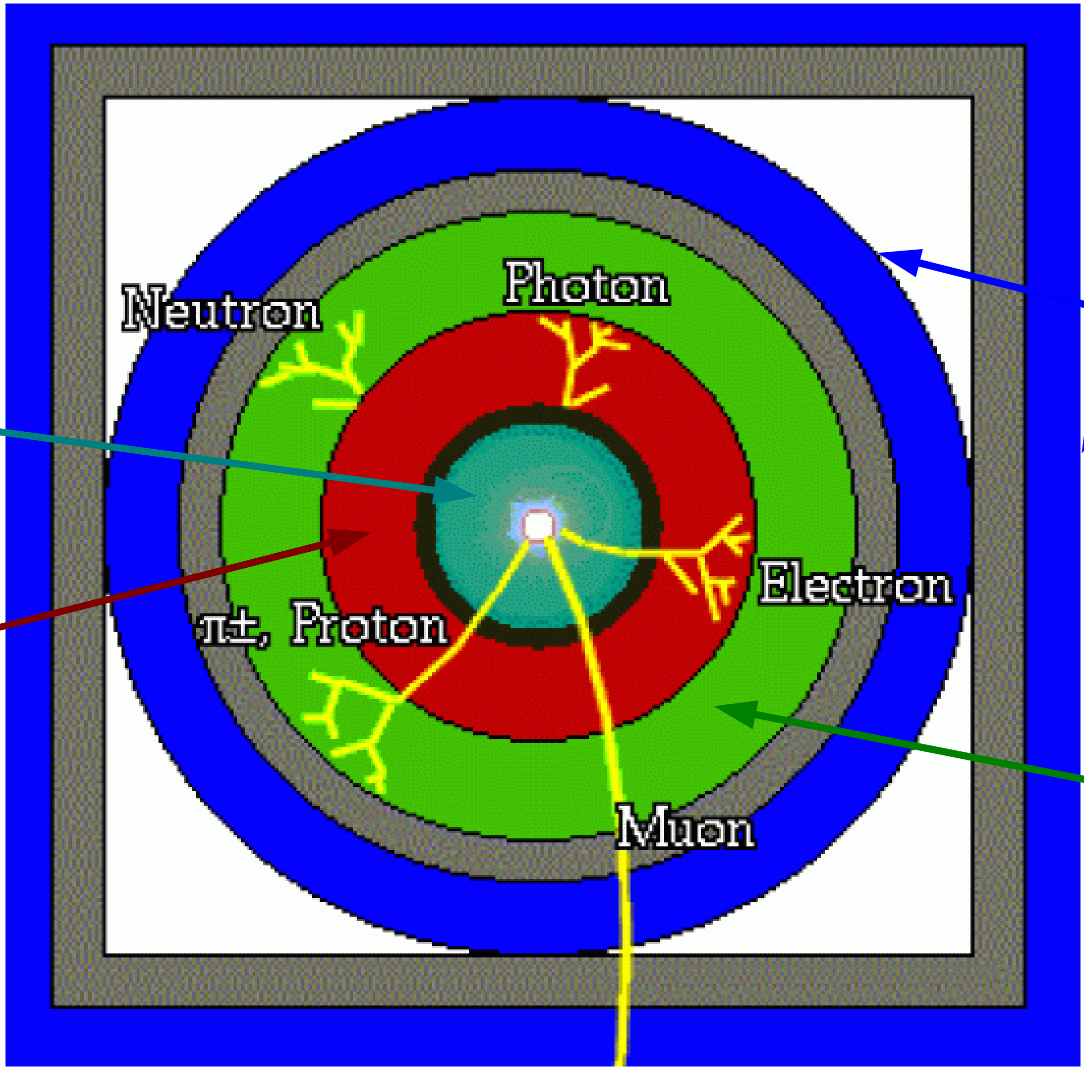
Collider Detector at Fermilab (CDF)



Particle Detection

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

Muon chambers: detect penetrating particles behind shielding



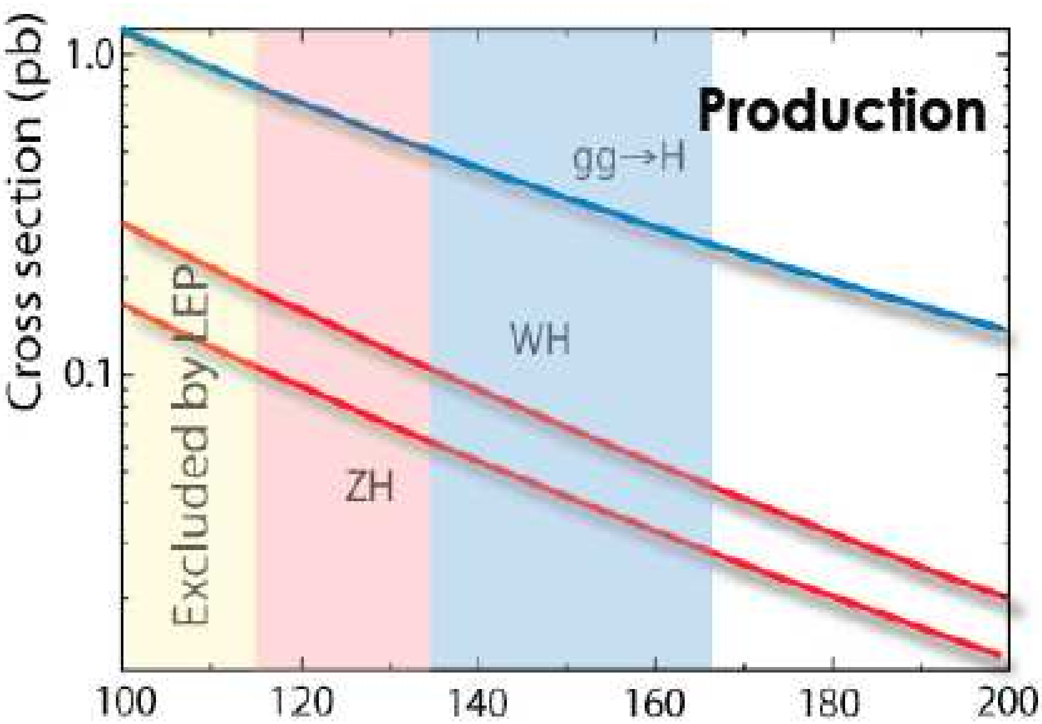
Electromagnetic (EM) calorimeter: lead sheets cause *e*/γ shower, sense light in alternating scintillator sheets

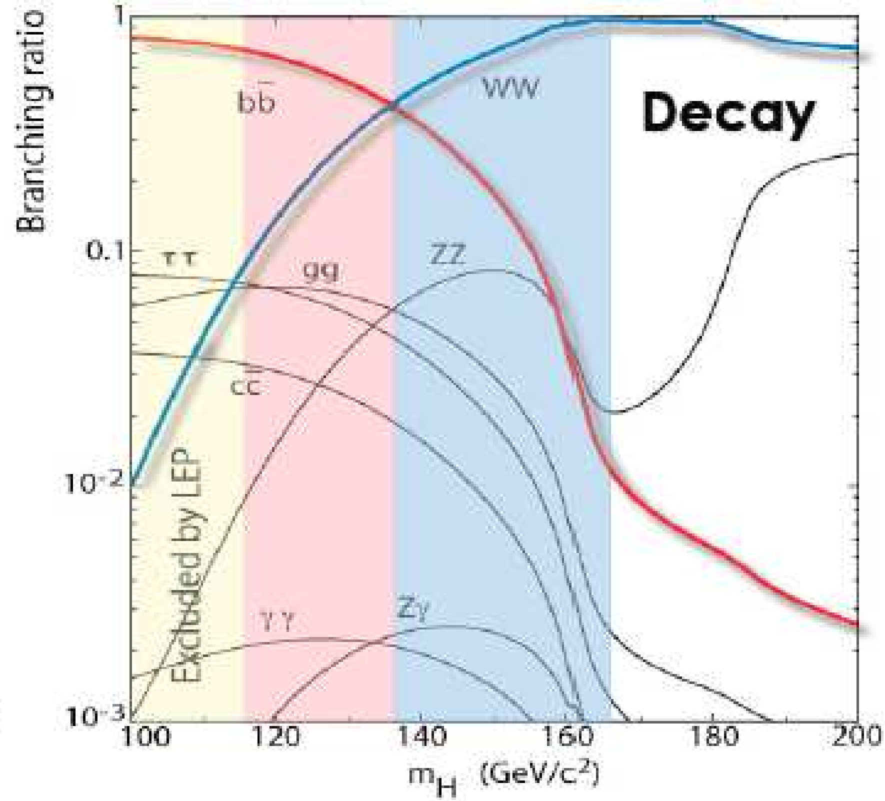
Hadronic calorimeter: steel sheets cause hadronic showers, sense scintillator light

CDF Tracking Chamber

Standard Model Higgs Boson Production and Decay

Higgs Boson Production and Decay

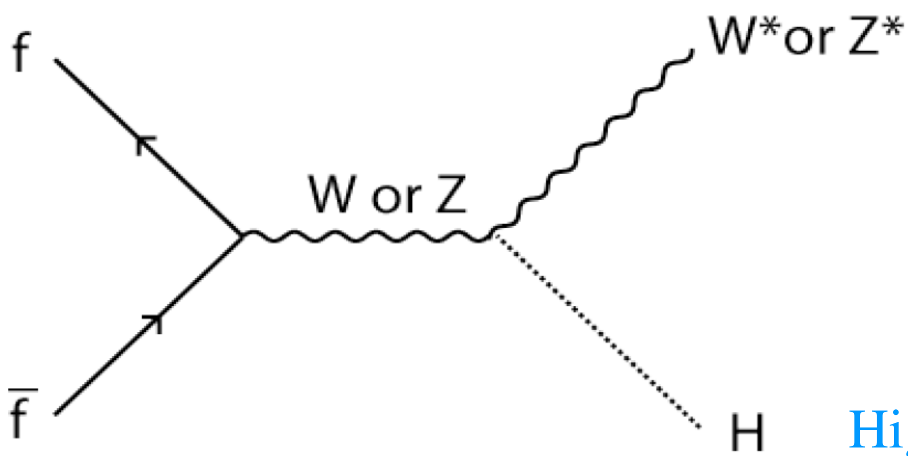




M_H (GeV/c^2)

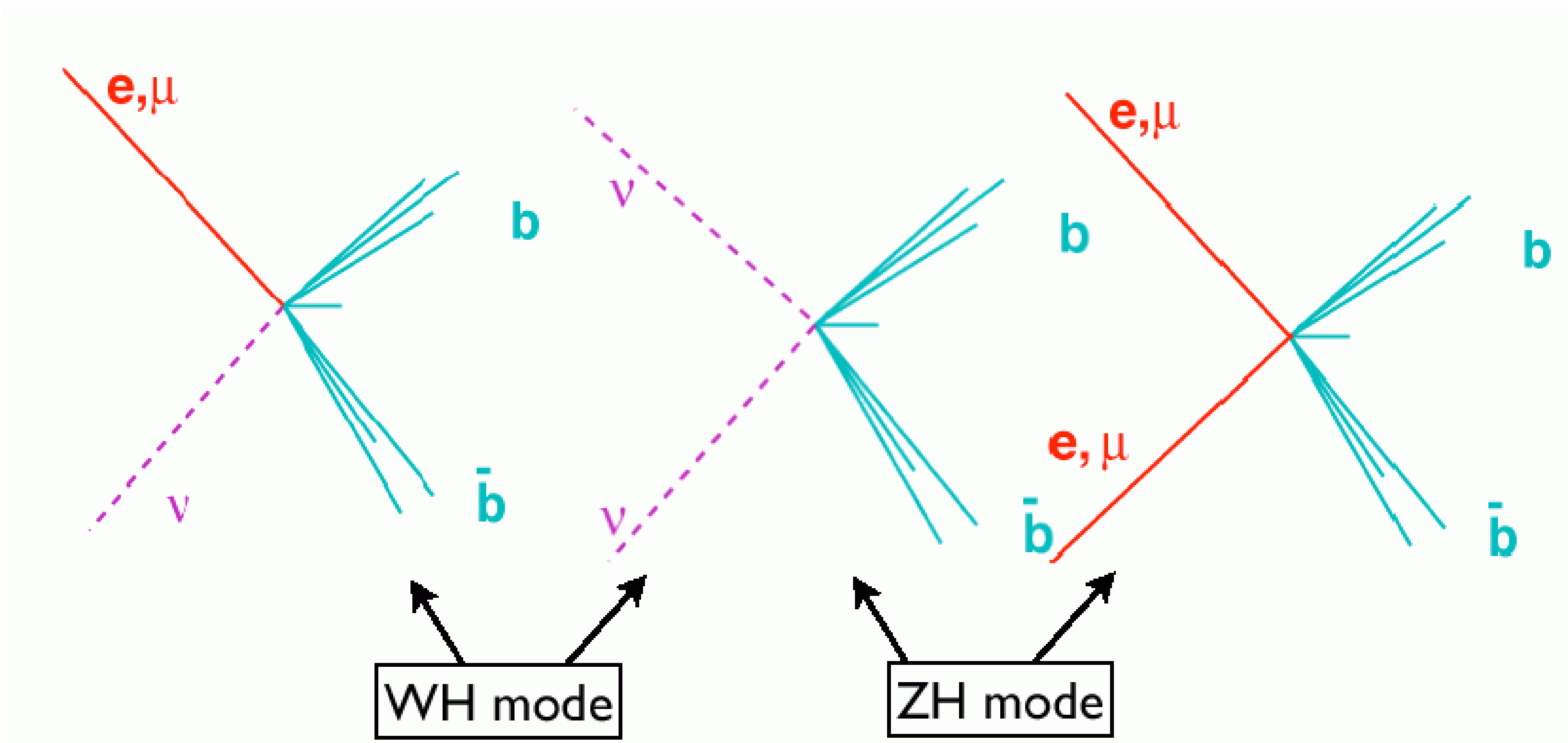
- Different production and decay mechanisms expected for Higgs boson are exploited for its search

Light Higgs Boson Production and Decay

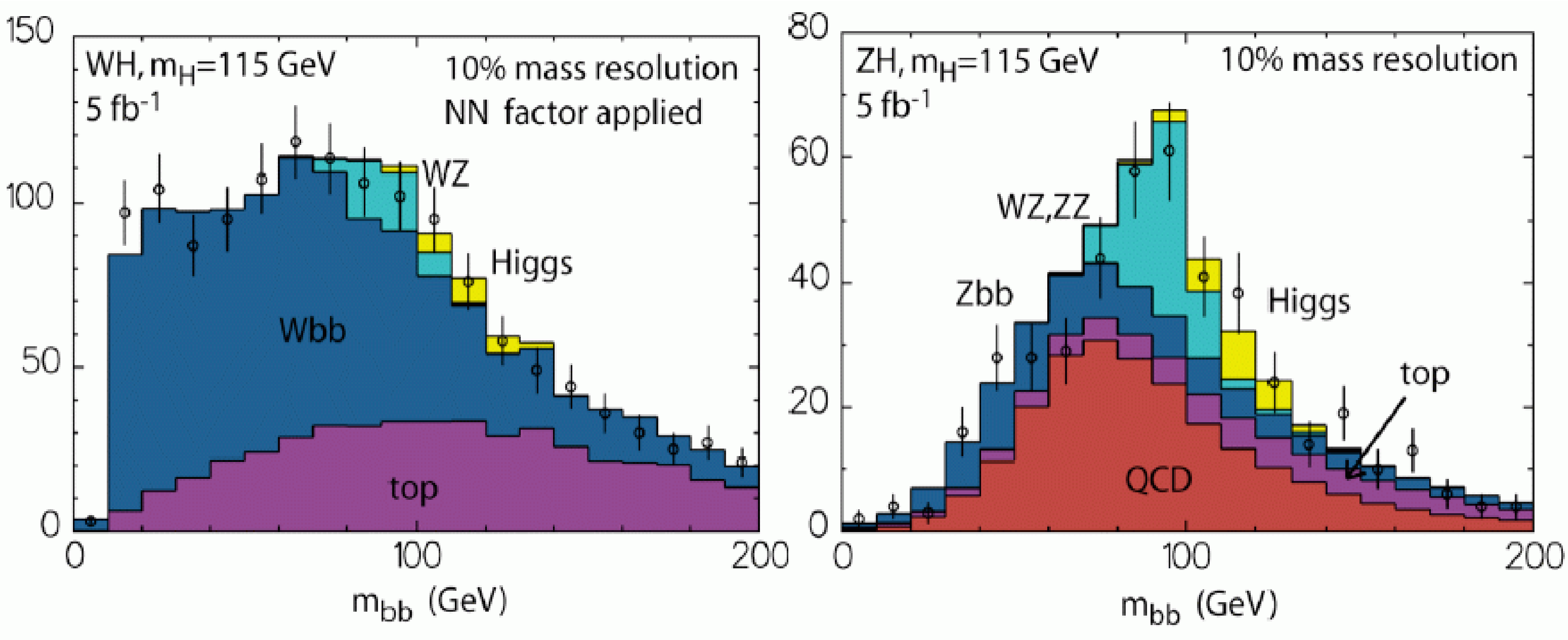


W, Z decay to electrons, muons, τ, and/or neutrinos

Higgs boson decays to bottom quarks



Simulated Higgs Signal on Expected Backgrounds



Key requirements for observing signal:

Excellent lepton identification, good calorimeters for jet and Missing E_T reconstruction, excellent silicon detectors for b jet identification

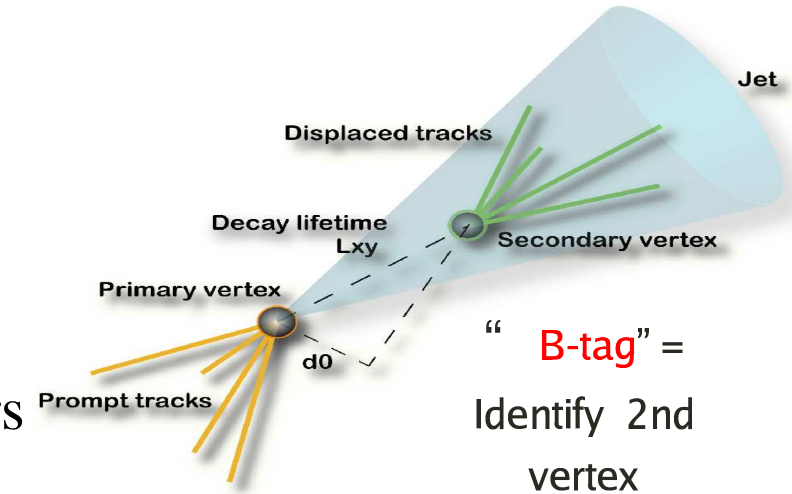
Good reconstruction of decay particle momentum vectors

Good simulation of signal and background events

Tagging of b-quark jets

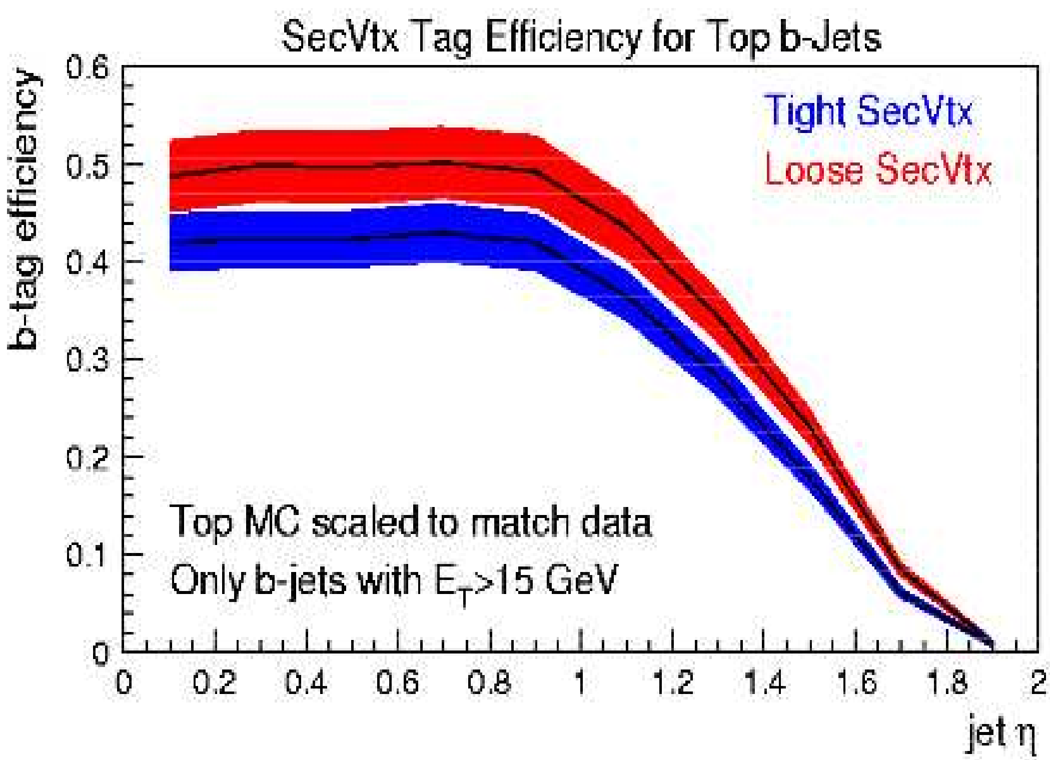
DØ: Neural Network tagger with multiple operating points

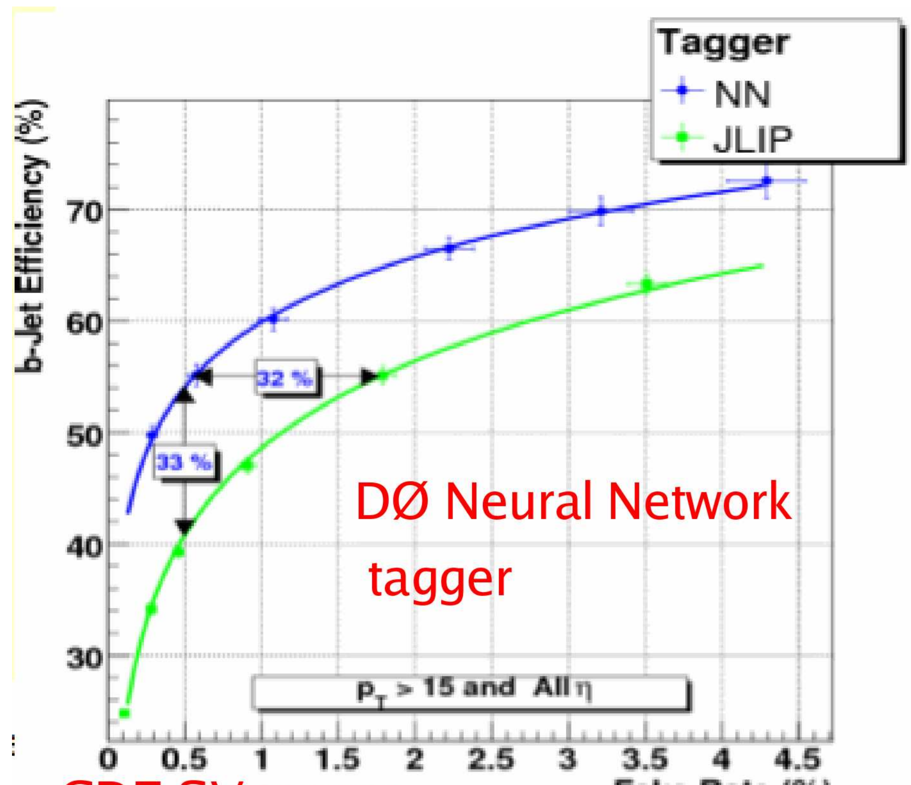
CDF: Secondary Vertex tagger, jet probability tagger, and Neural Network flavor separators



"B-tag" = Identify 2nd vertex

50-70% Efficient with 0.3-5% mistag rate

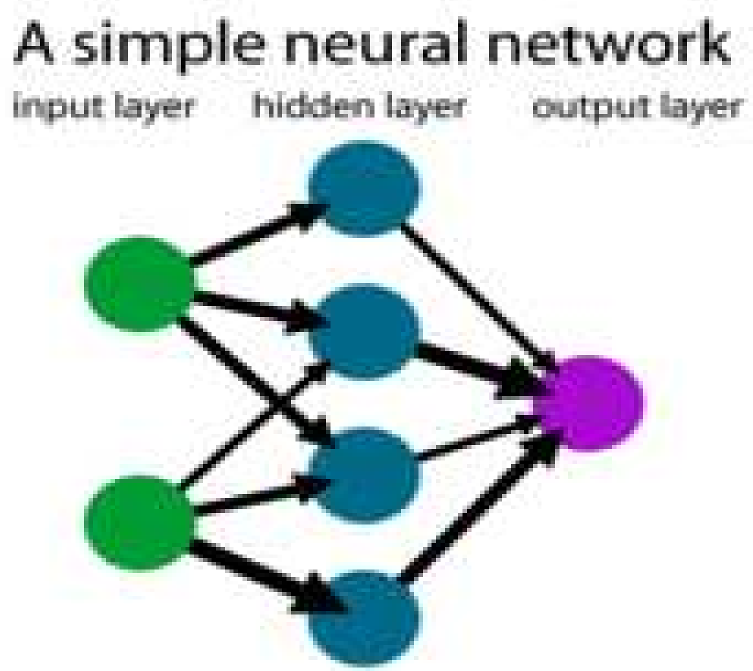




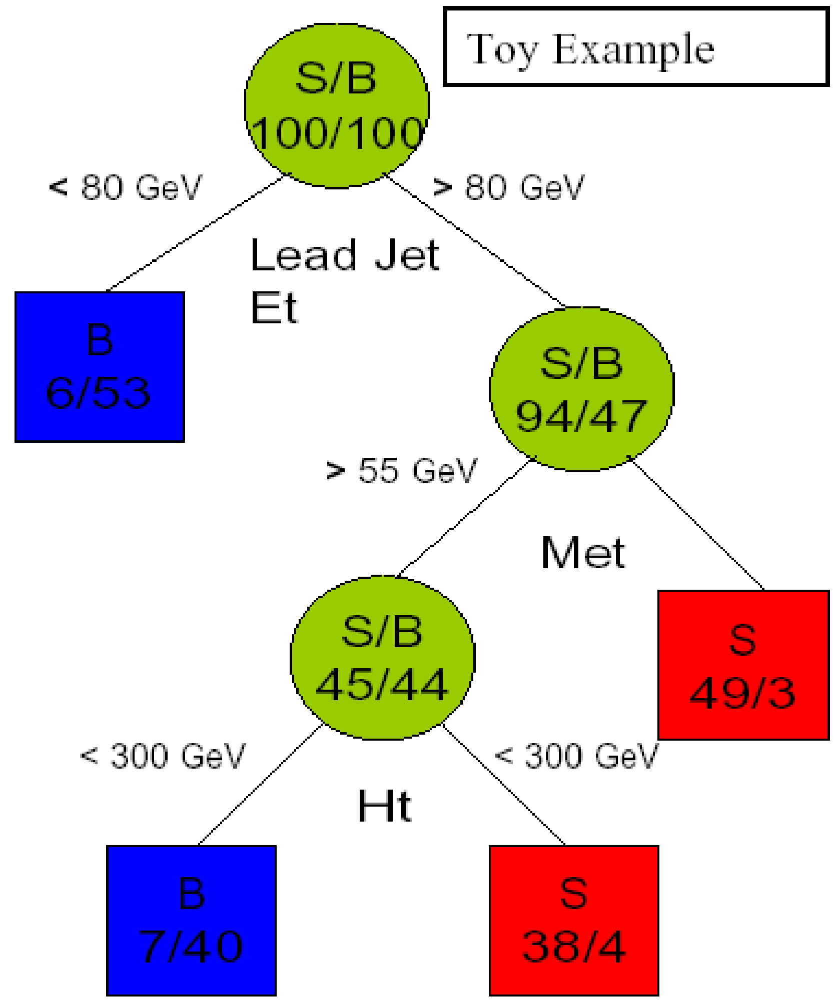
CDF SV tagger

Multivariate Techniques for Signal/Background Discrimination

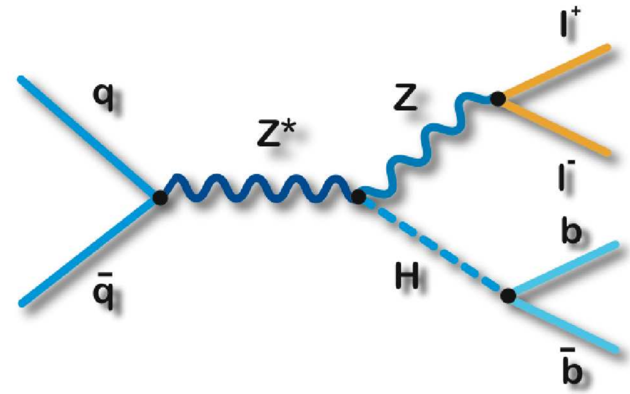
- Likelihood discriminants: Often using Standard Model Matrix Elements to compute differential probability distributions for kinematics
- Artificial Neural Networks: construct nc linear function of kinematics
- Decision trees: event classification using sequential cuts



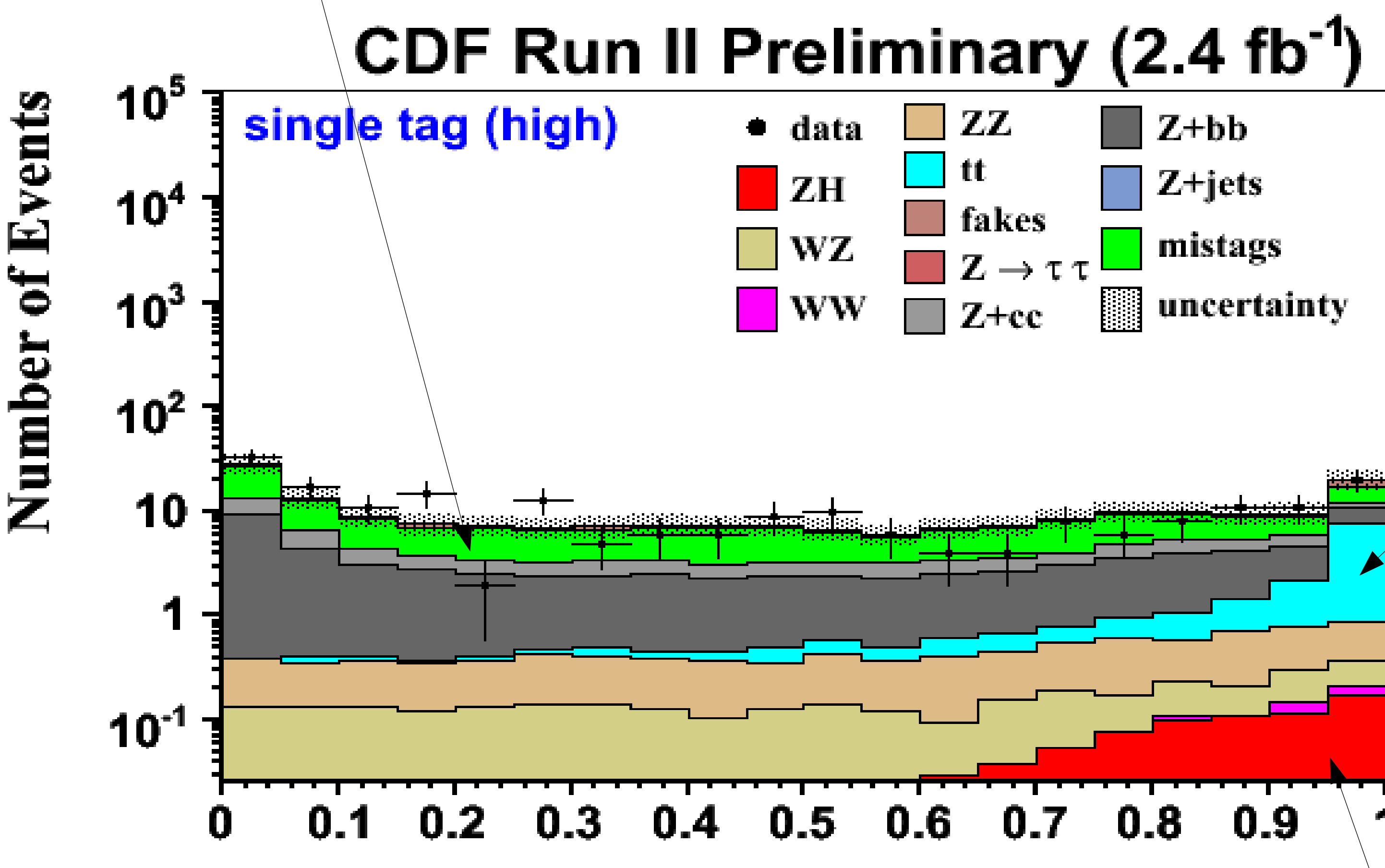
Decision Tree



SM Higgs: ZH→llbb



Z + 2 jets background dominant

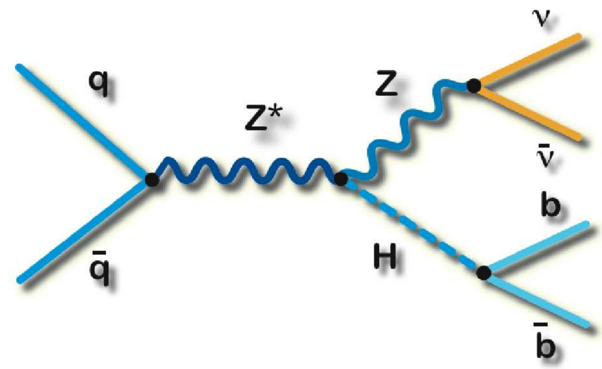


Top quark background suppressed by another neural network

Z+2jets ← Neural Network Output → ZH

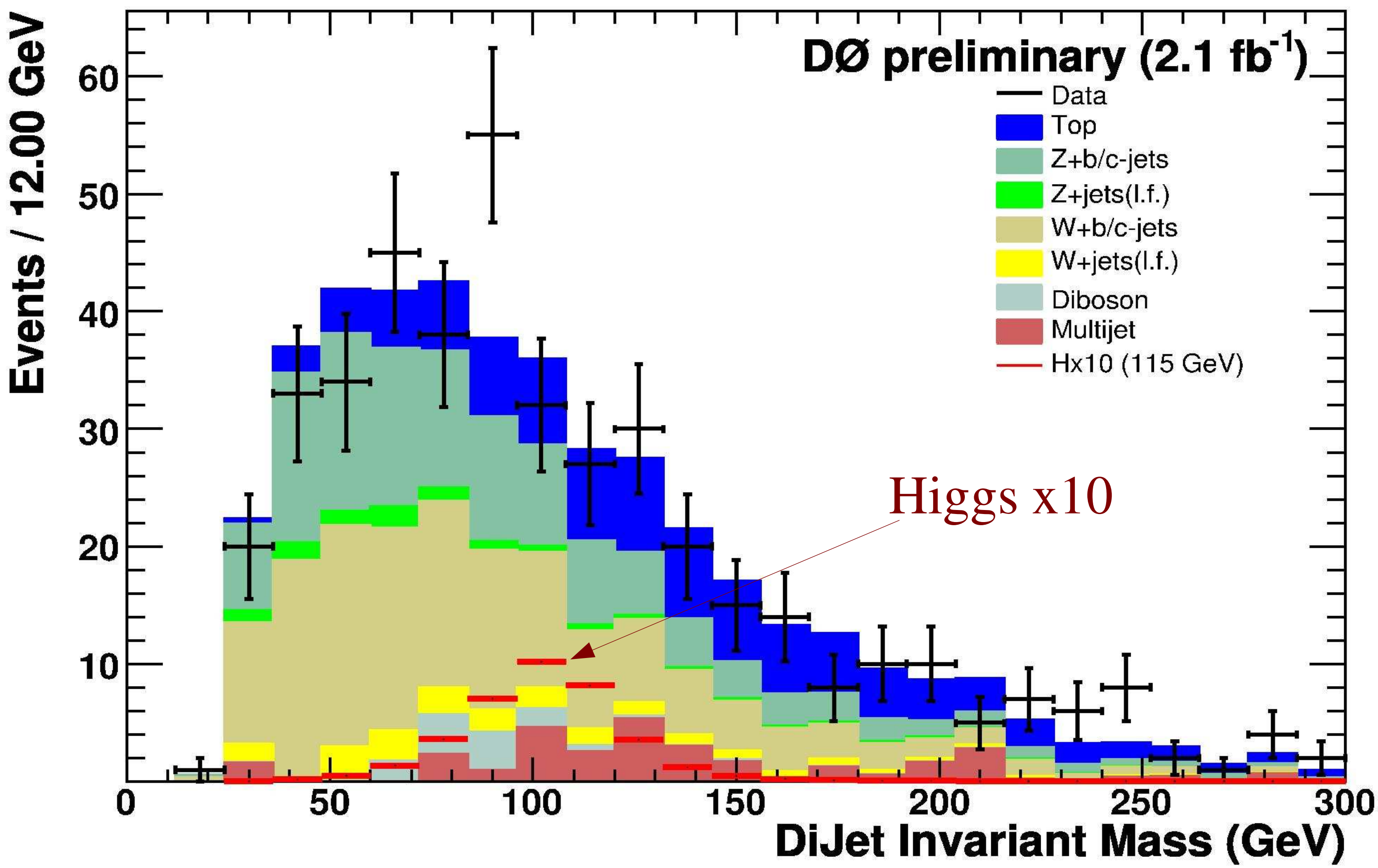
Part of my research group activity

SM Higgs: VH→ννbb

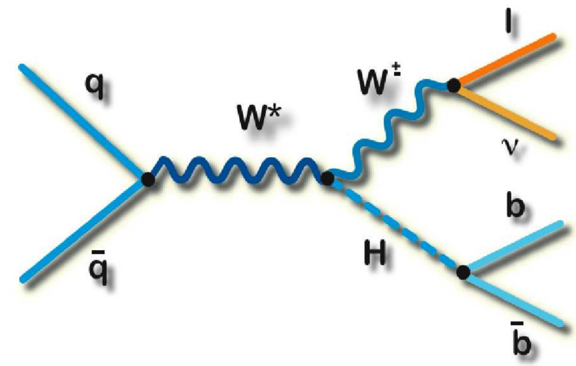


W (-> lν) + Higgs with lepton undetected also included in signal

Key issue: modelling the shape of QCD background



SM Higgs: WH→lνbb



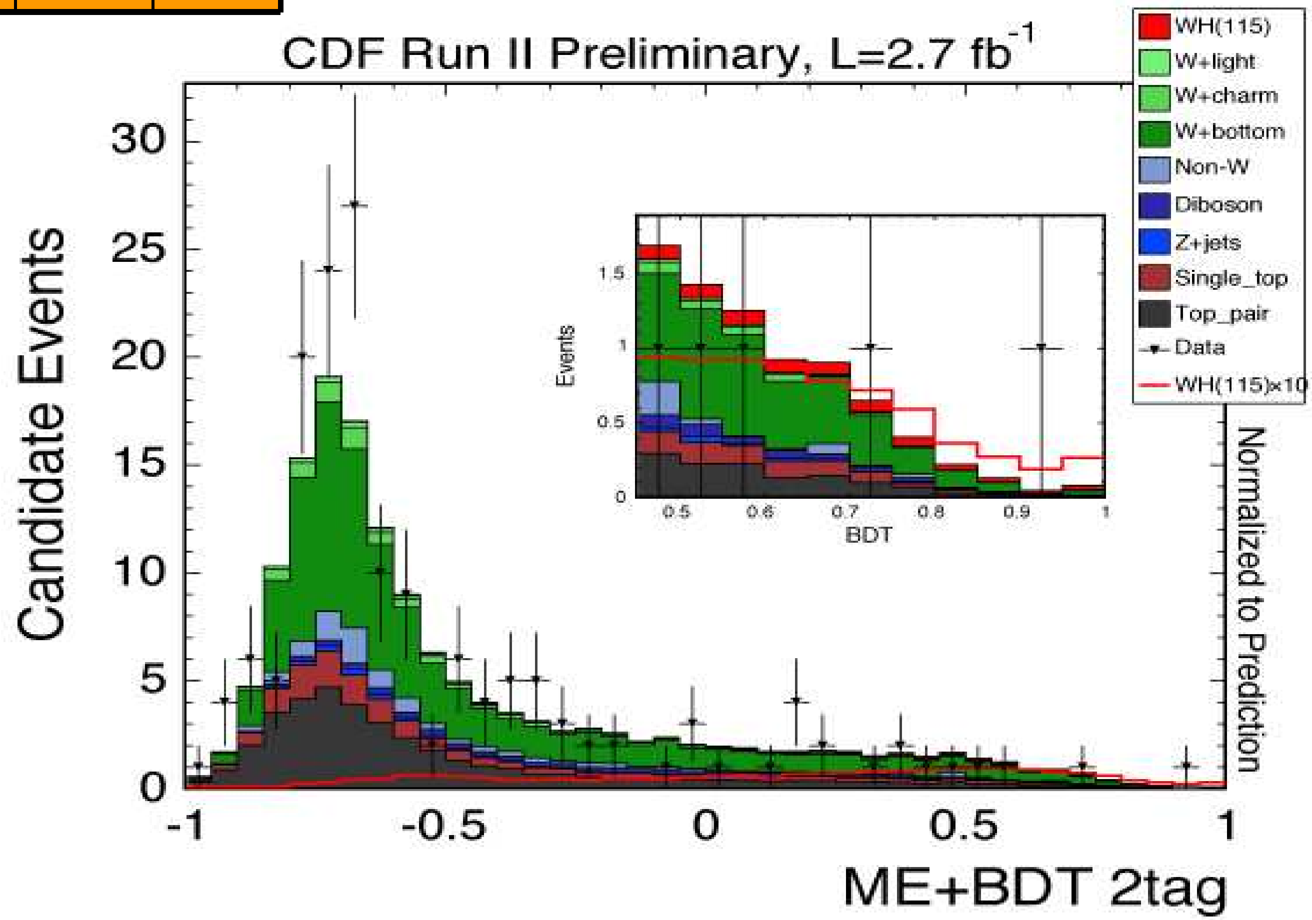
Results at mH = 115GeV: 95%CL Limits/SM

Analysis	Lum (fb^{-1})	Higgs Events	Exp. Limit	Obs. Limit
CDF NN	2.7	8.3	5.8	5.0
CDF ME+BDT	2.7	7.8	5.6	5.7
DØ NN	1.7	7.5	8.5	9.3

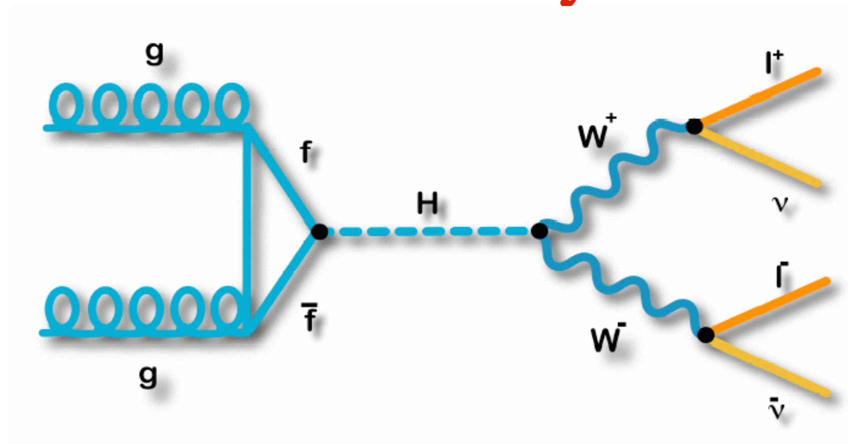
Key issue: shape of W+bb background

obtained from simulation, with normalization from data control regions

most sensitive channel for low-mass Higgs at Tevatron

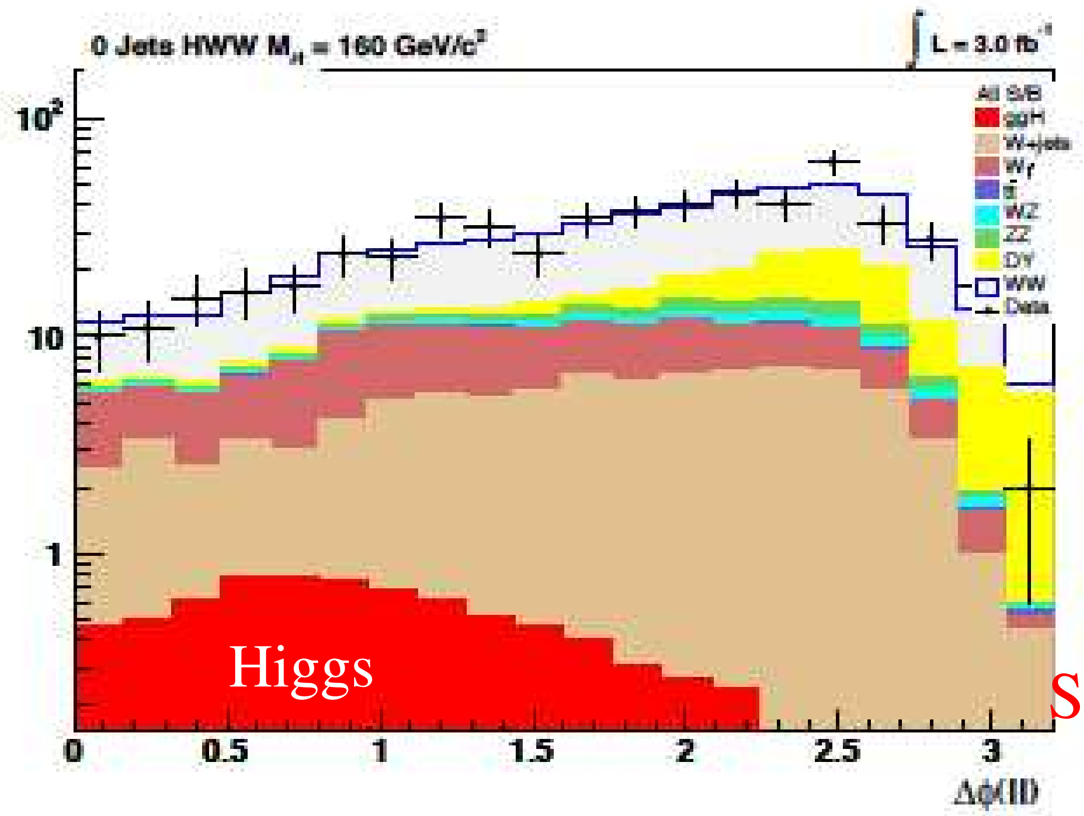


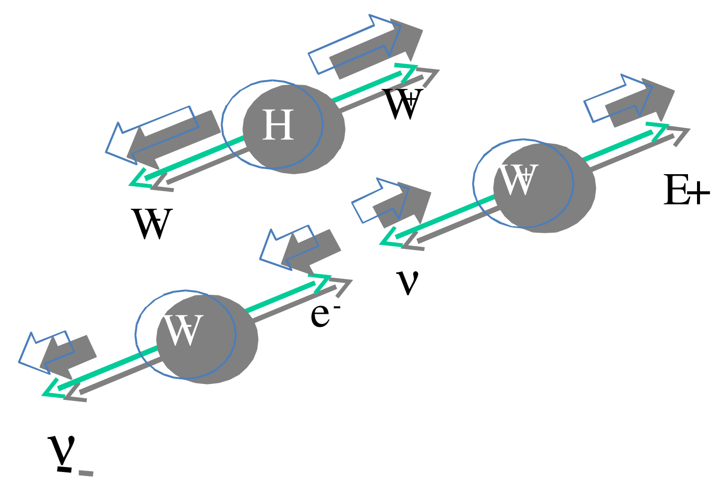
Heavy Higgs Boson Production and Decay



Most sensitive channel at the Tevatron

Key issue: maximizing lepton acceptance





Spin correlation: Charged leptons go in the same direction

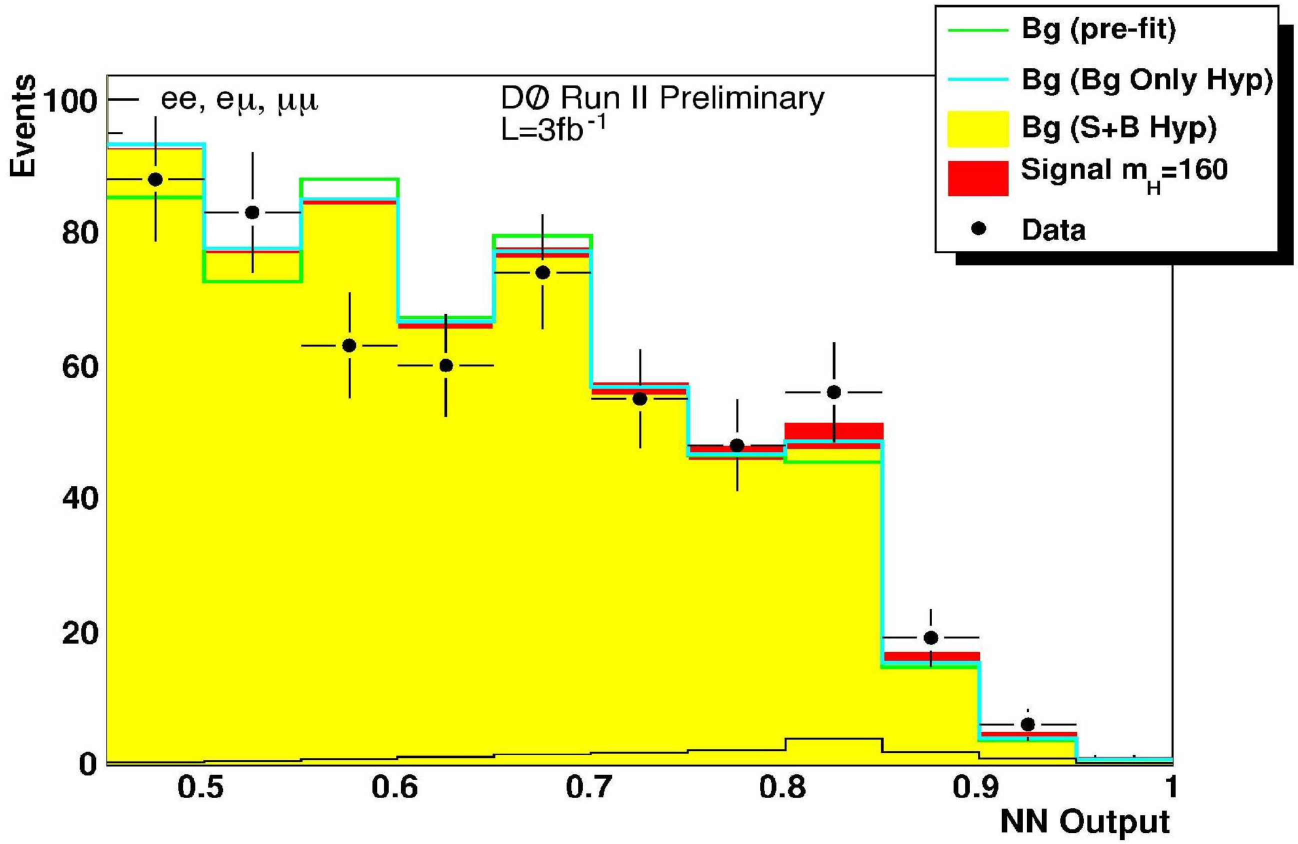
Heavy Higgs Boson Production and Decay

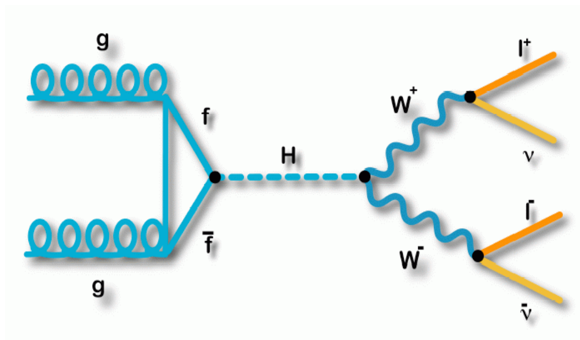
Results at mH = 165GeV : 95%CL Limits/SM

Analysis	Lum (fb^{-1})	Higgs Events	Exp. Limit	Obs. Limit
CDF ME+NN	3.0	17.2	1.6	1.6
DØ NN	3.0	15.6	1.9	2.0

Most sensitive channel at the Tevatron

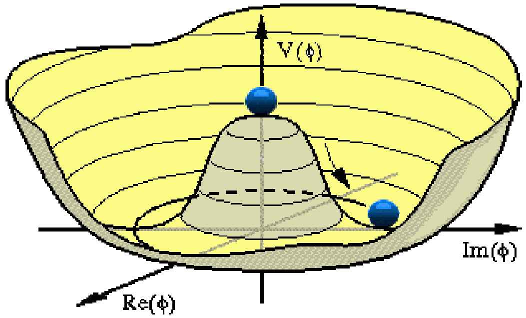
Key issue: maximizing lepton acceptance



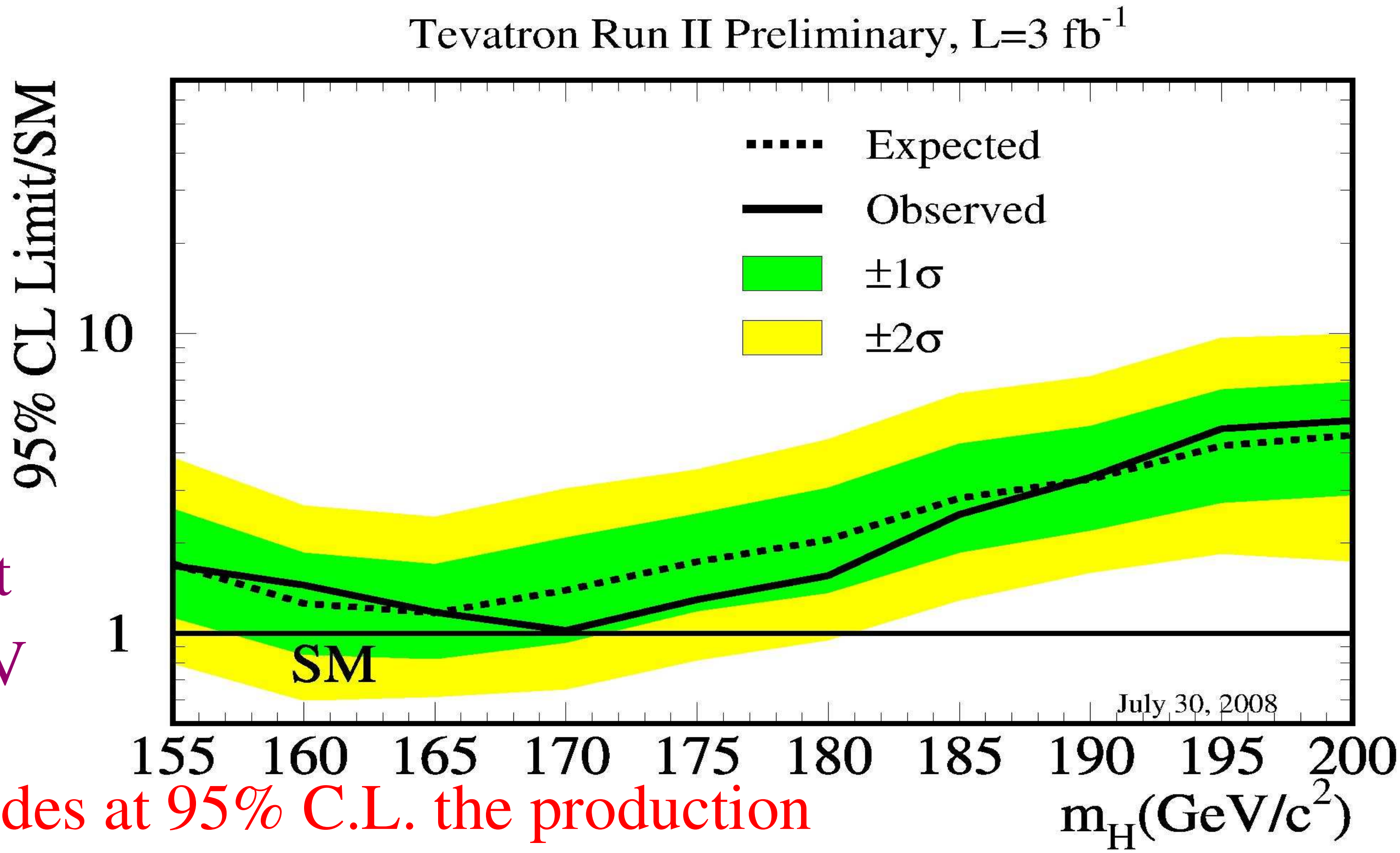


SM Higgs Boson Production Limits

Comparison of Higgs boson production cross section upper limit to the theoretical expectation



Expected Limits on ratio: 1.2 @ 165, 1.4 @ 170 GeV

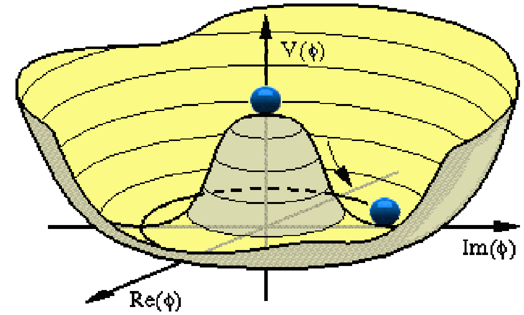


Observed Limit

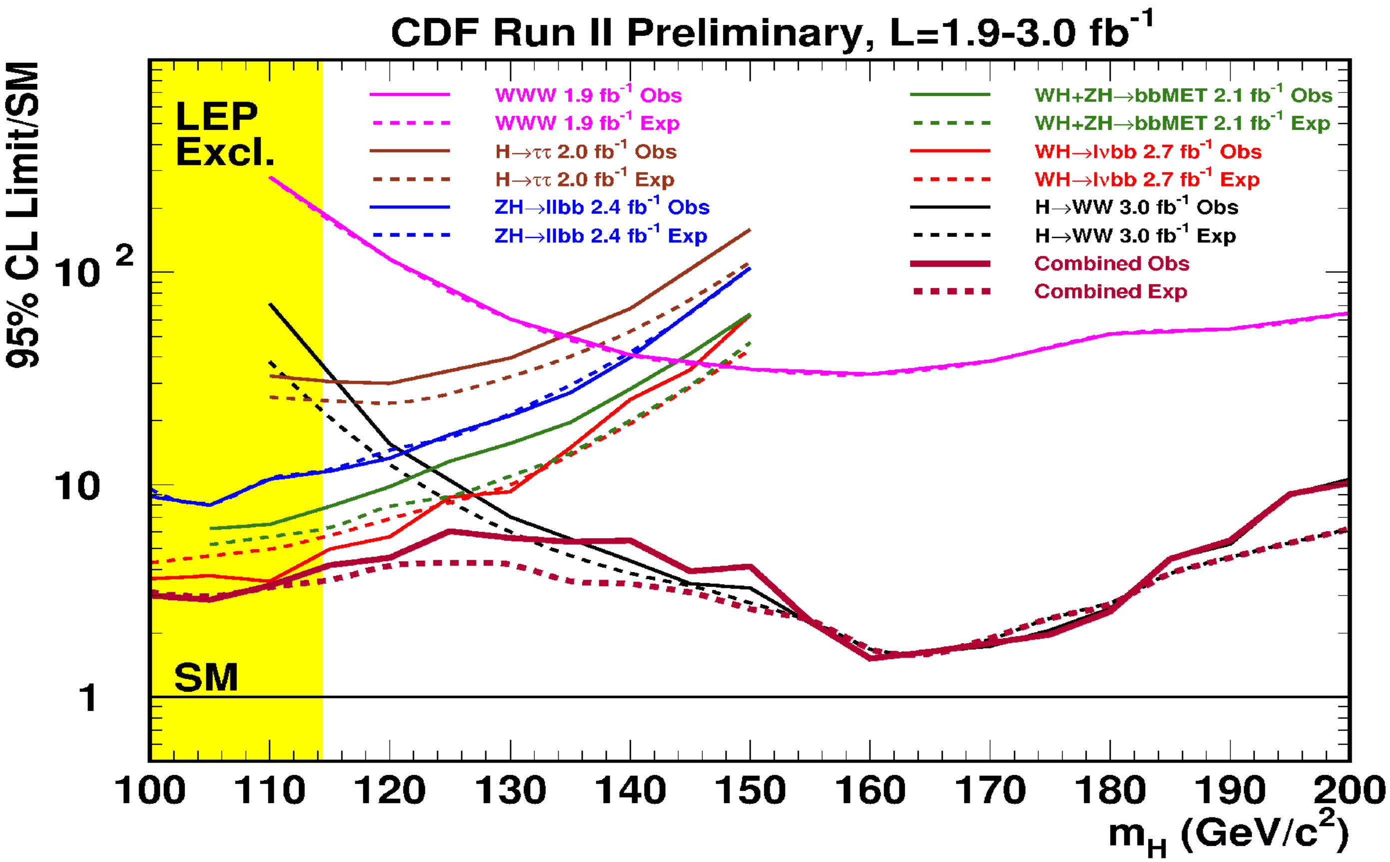
1.0 @ 170 GeV

Tevatron excludes at 95% C.L. the production of a SM Higgs boson of 170 GeV

SM Higgs Boson Production Limits

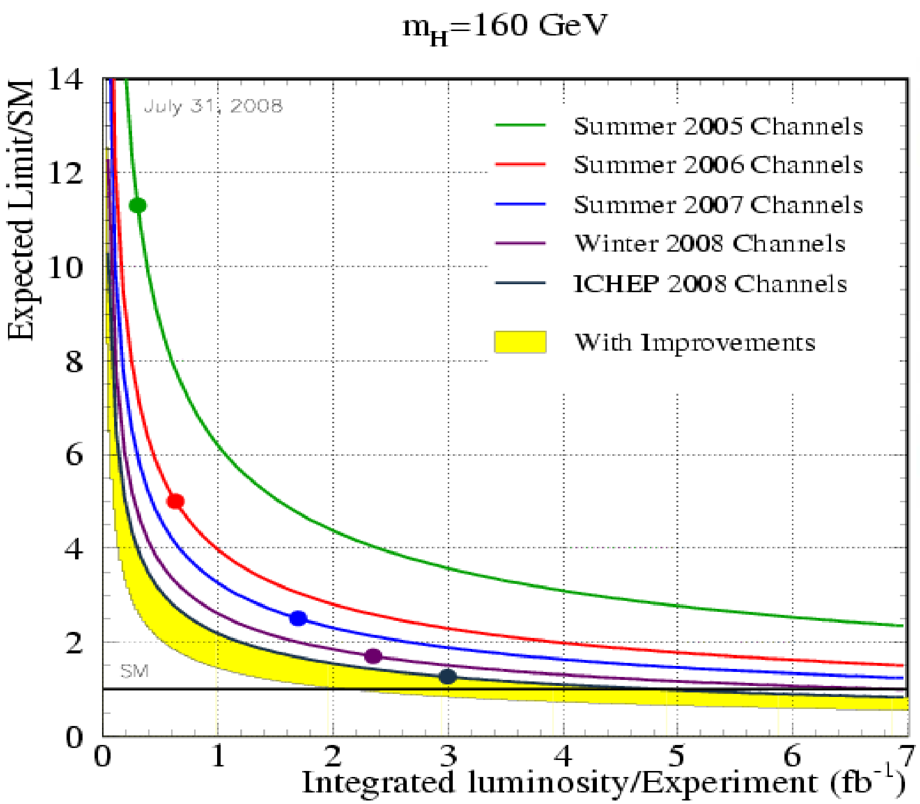


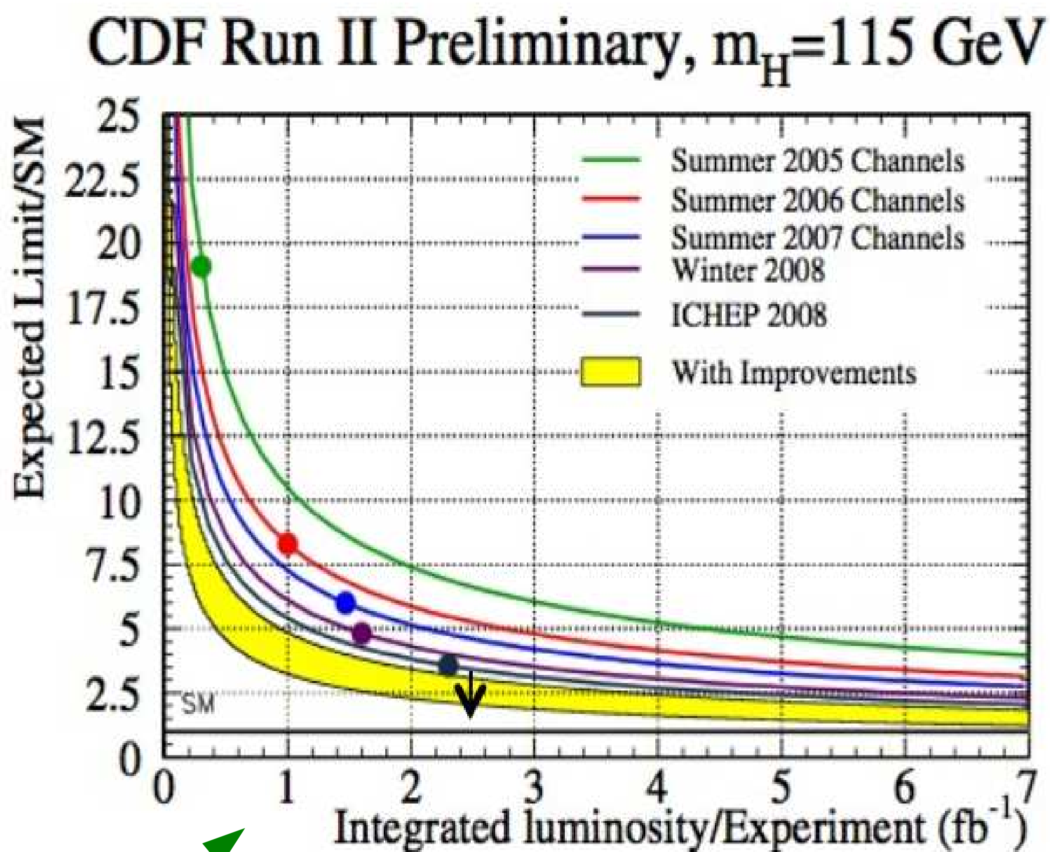
Comparison of Higgs boson production cross section upper limit to the theoretical expectation



- Low mass combination difficult due to ~70 channels
- Expected sensitivity of CDF/DØ combined: <3.0xSM @ 115GeV

Tevatron Higgs Search Projections



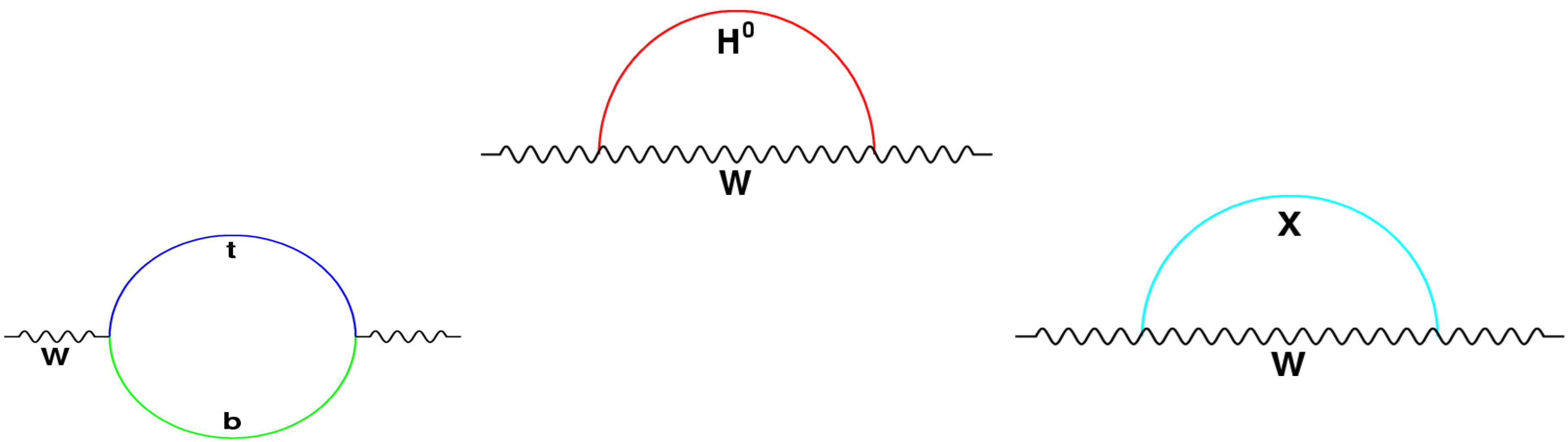


- Improvements for low-mass Higgs in progress
  - Dijet mass resolution, increased lepton acceptance and b-tagging efficiency

Precision Standard Model Measurements
Constraining the Higgs and New Physics

Precision Measurements of W boson and top quark masses

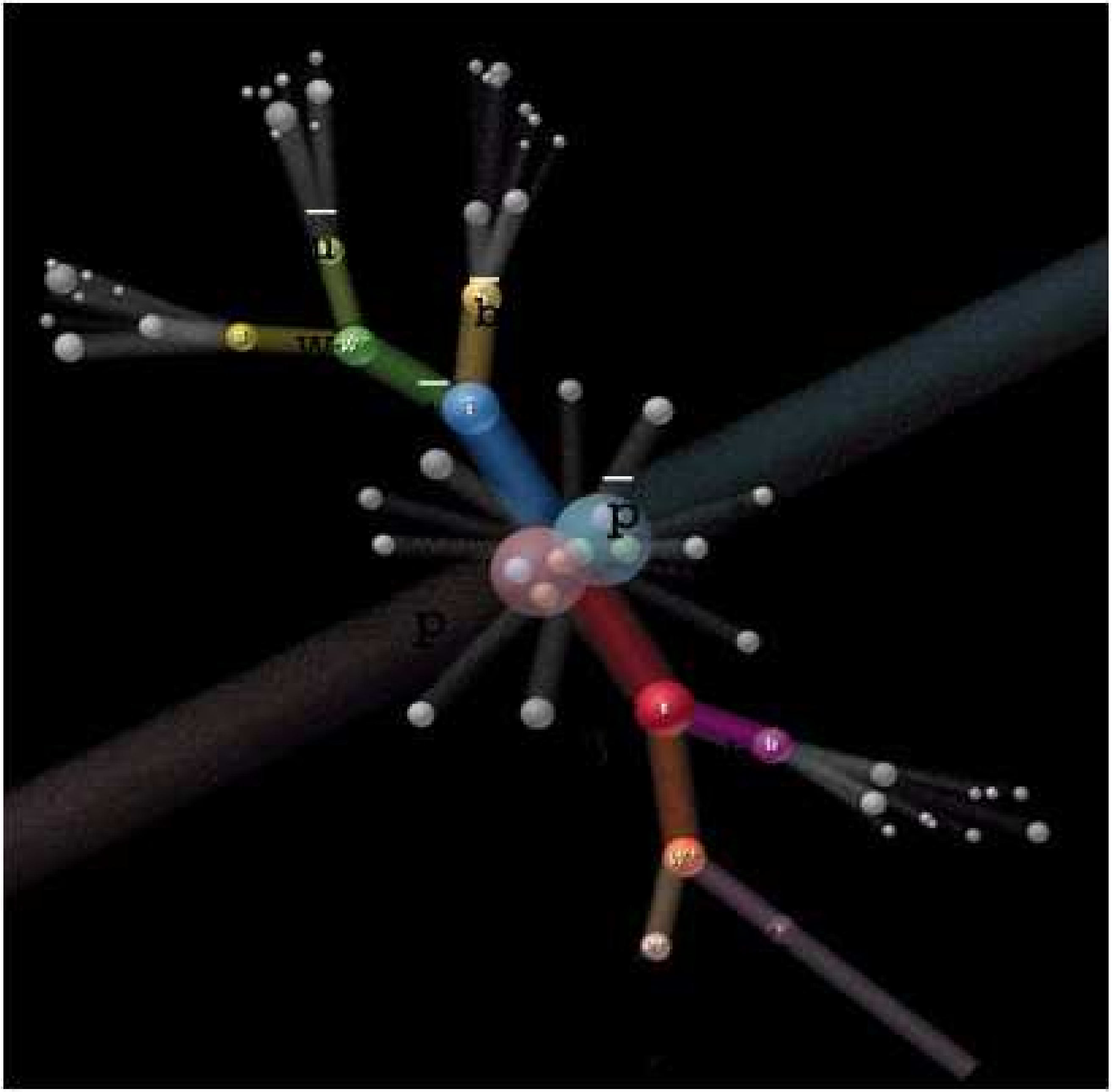
- Radiative corrections due to heavy quark and Higgs loops and exotica



- Top quark mass and W boson mass constrain the mass of the Higgs boson, and possibly new particles beyond the standard model
  - My research focuses on the precise mass measurements of these two particles

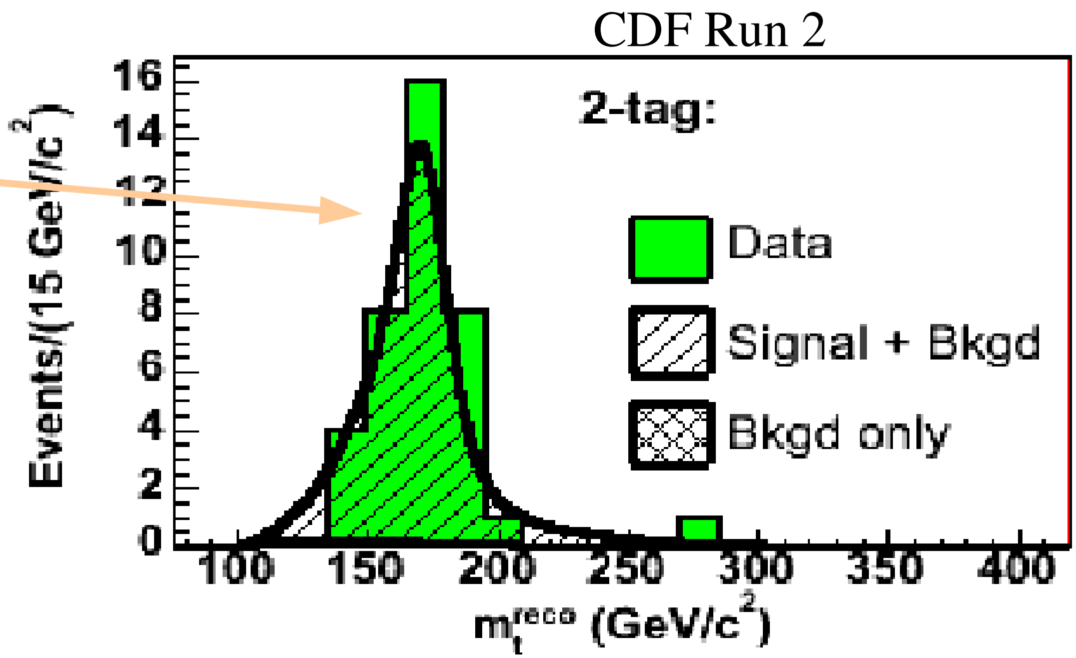
Top Quark Mass Measurement

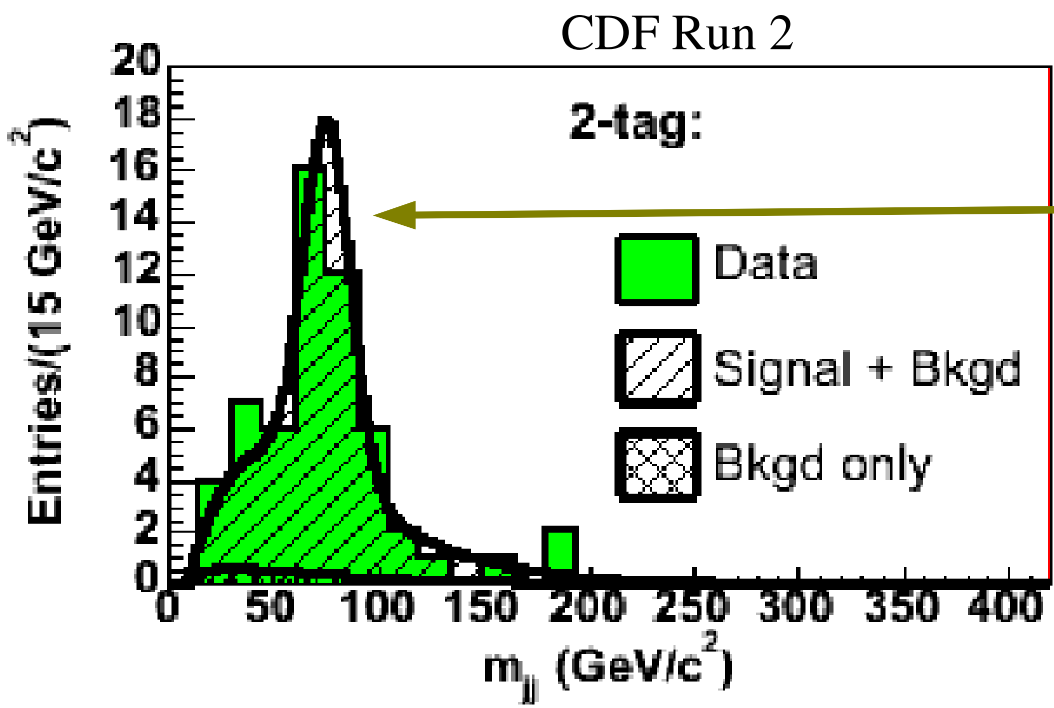
Top Quark Production at the Tevatron



Progress on M_{top} at the Tevatron

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

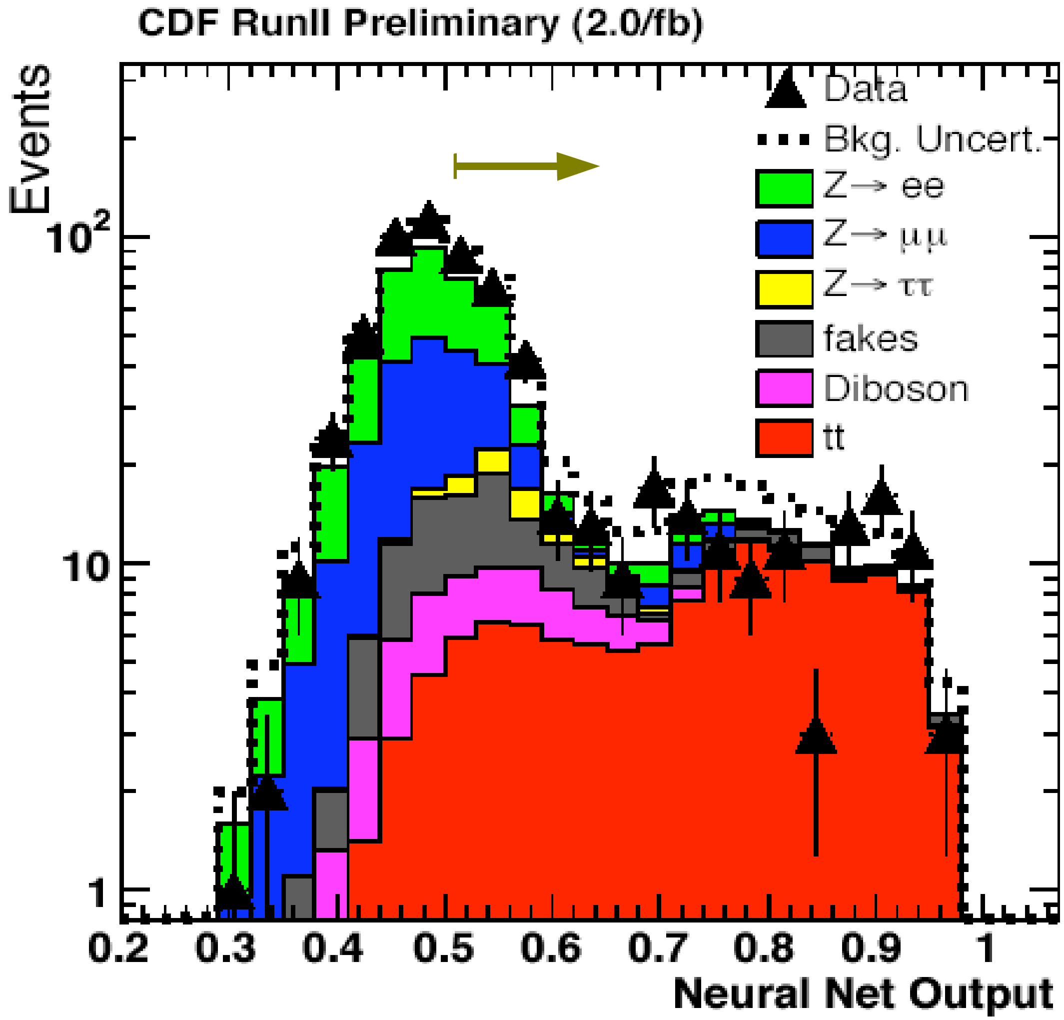




Improved top mass precision due to in-situ calibration of jet energy using W->jj decays in the same events

Measurement of M_{top} in the dilepton channel

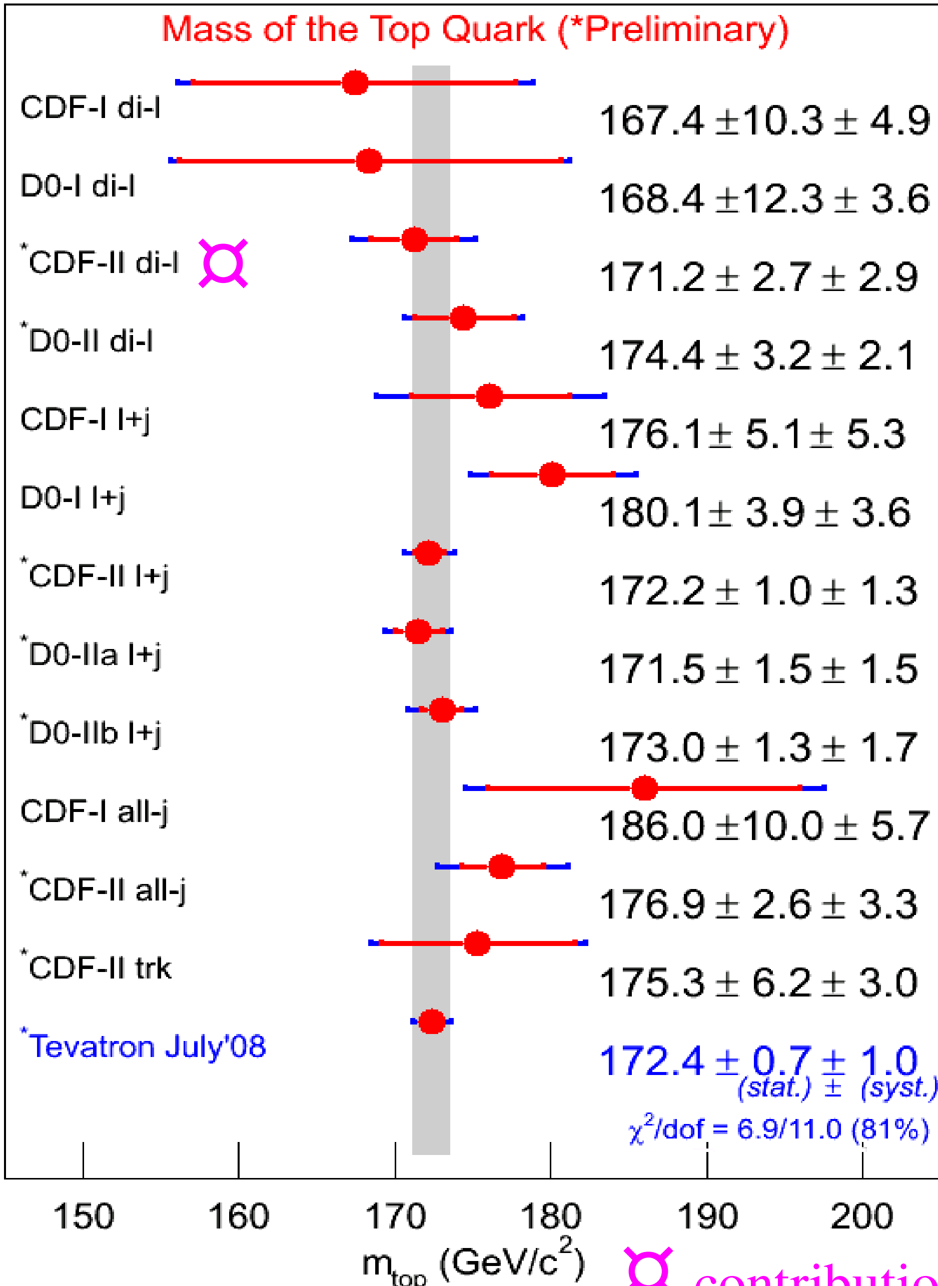
Neural Network for optimized event selection



Part of my research activities

Matrix-element-based likelihood fitting in dilepton channel

Progress on M_{top} at the Tevatron



¤ contribution of my research group

CDF lepton+jets systematics (preliminary)

Systematic source	Systematic uncertainty (GeV/c^2)
Calibration	0.1
MC generator	0.5 ←
ISR and FSR	0.3
Residual JES	0.5 ←
b-JES	0.4 ←
Lepton P_T	0.2
Pileup	0.1
PDFs	0.2
Background	0.4 ←
Total	1.0

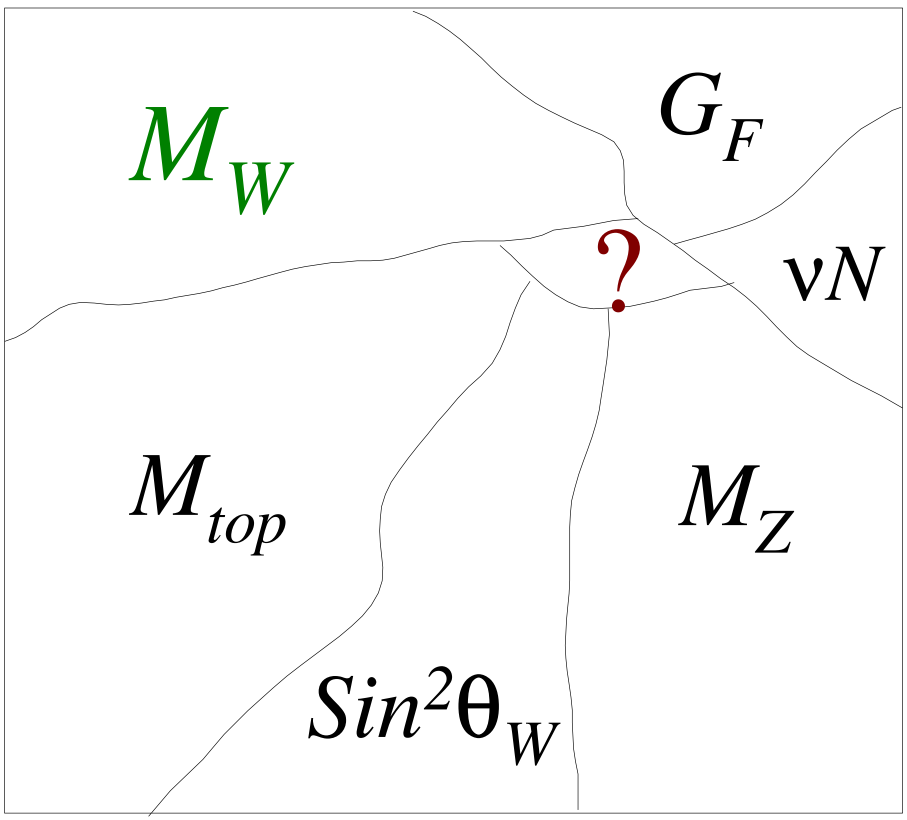
Dominant systematic uncertainties can be reduced with improved understanding of the data and generator models

$\delta M_{top} < 1$ GeV may be possible

W Boson Mass Measurement

Motivation for M_W measurement

- SM Higgs fit: $M_H = 84^{+34}_{-26}$ GeV (LEPEWWG & TeVEWWG)
- LEPII direct searches: $M_H > 114.4$ GeV @ 95% CL (PLB 565, 61)



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

(A_{FB}^{b} *vs* A_{LR}: 3.2σ)

Must continue improving
precision of M_W, M_{top} ...

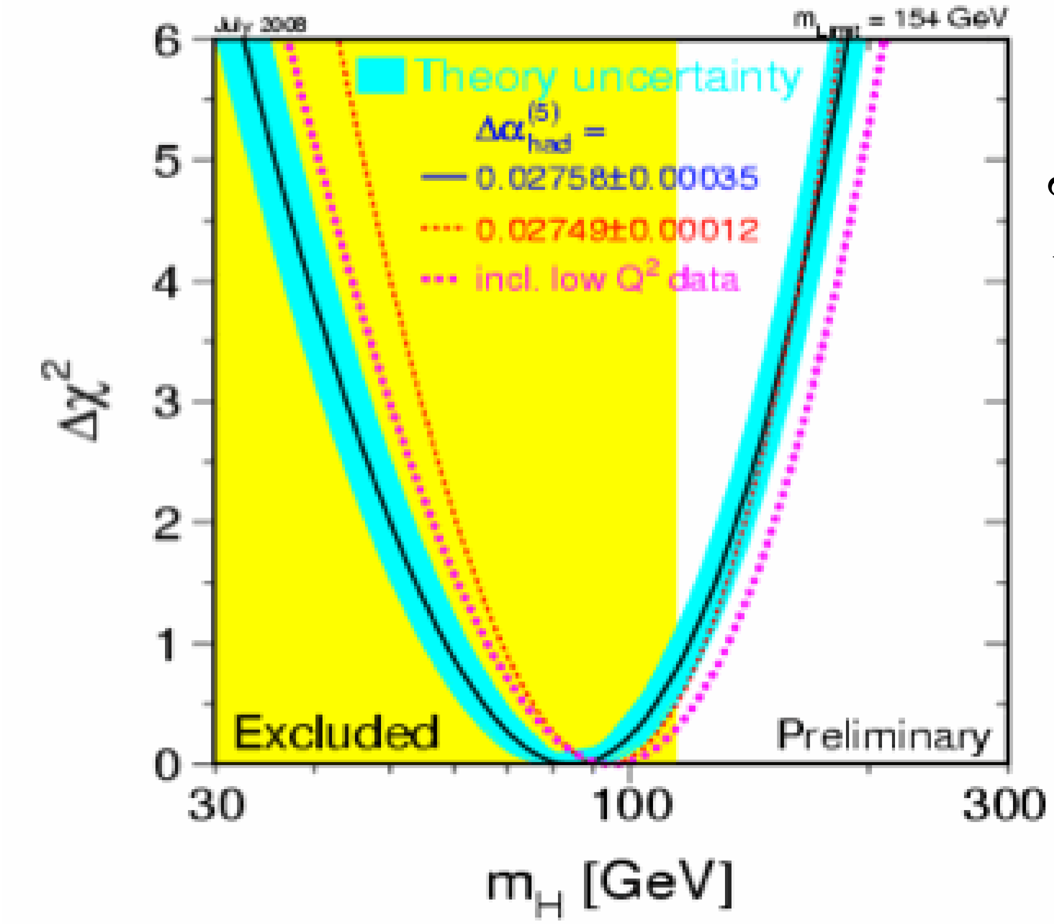
other precision measurements constrain Higgs, equivalent to $\delta M_W \sim 20$ MeV

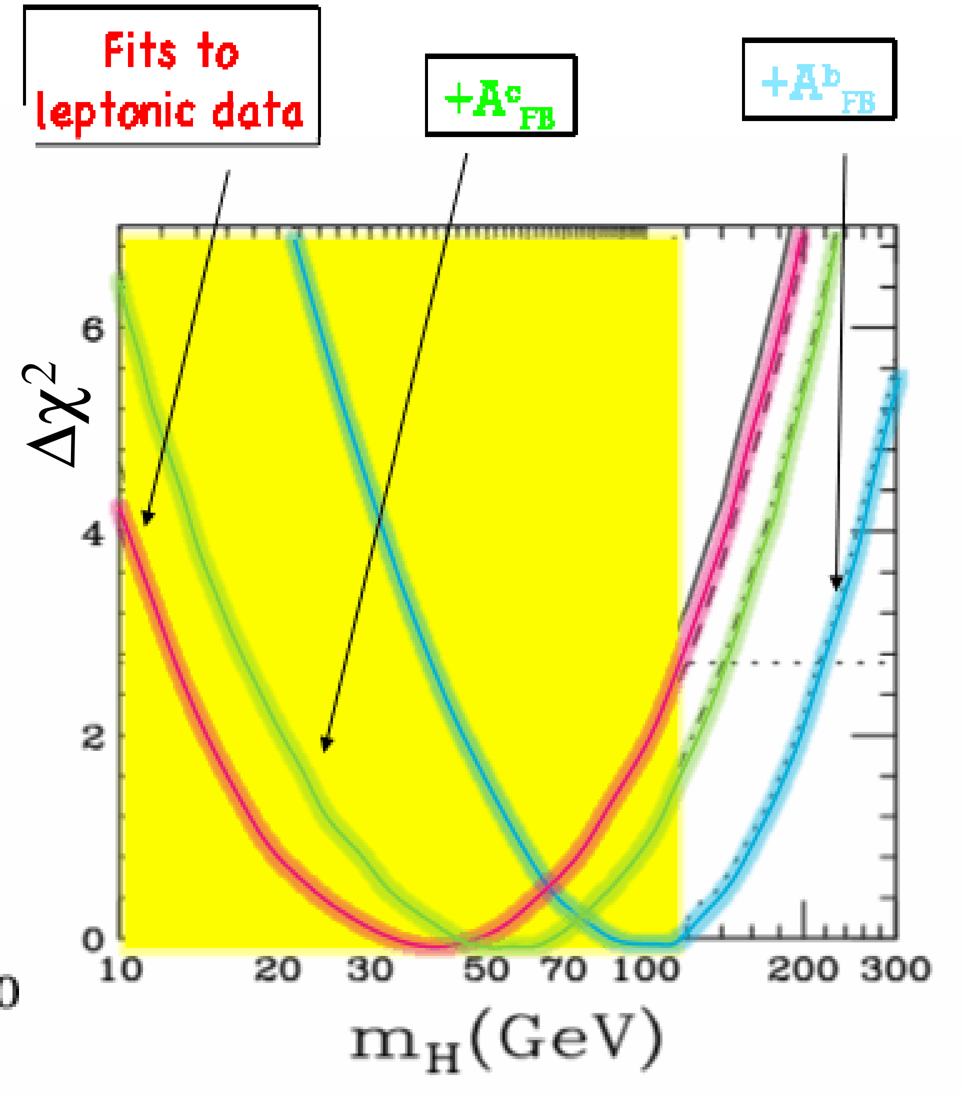
Motivate direct measurement of M_W at the 20 MeV level

Standard Model Higgs Constraint

M_W and leptonic measurements of $\sin^2\theta$ prefer low SM Higgs mass,

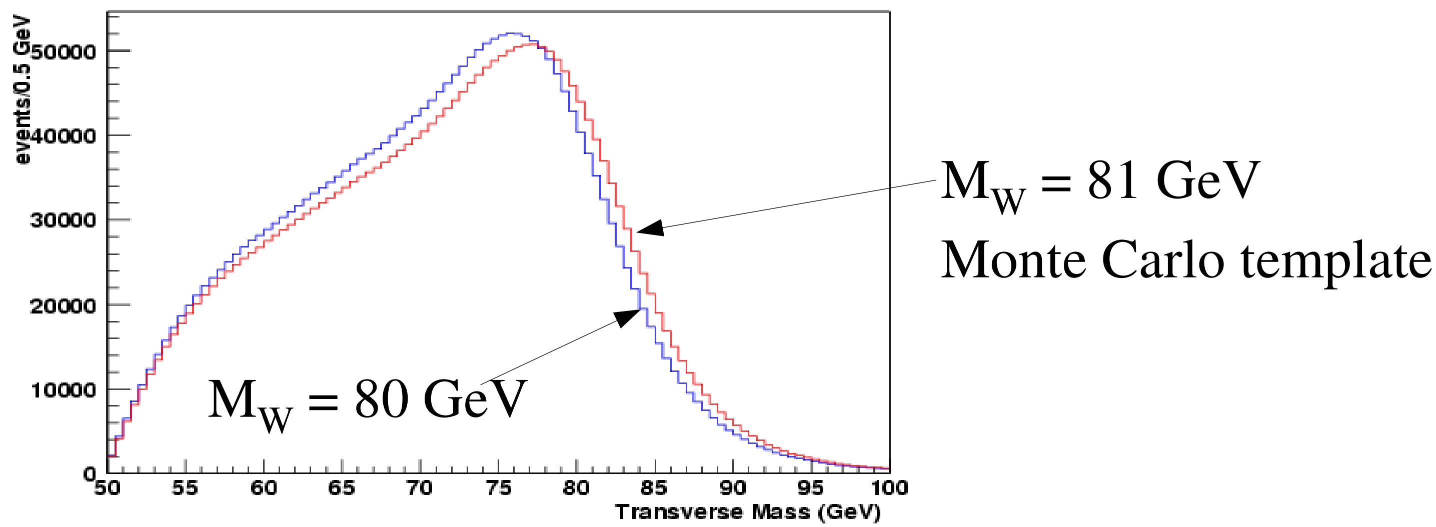
hadronic (heavy flavor) measurements of $\sin^2\theta$ prefer higher SM Higgs mass (A^b_{FB} prefers ~ 500 GeV Higgs)

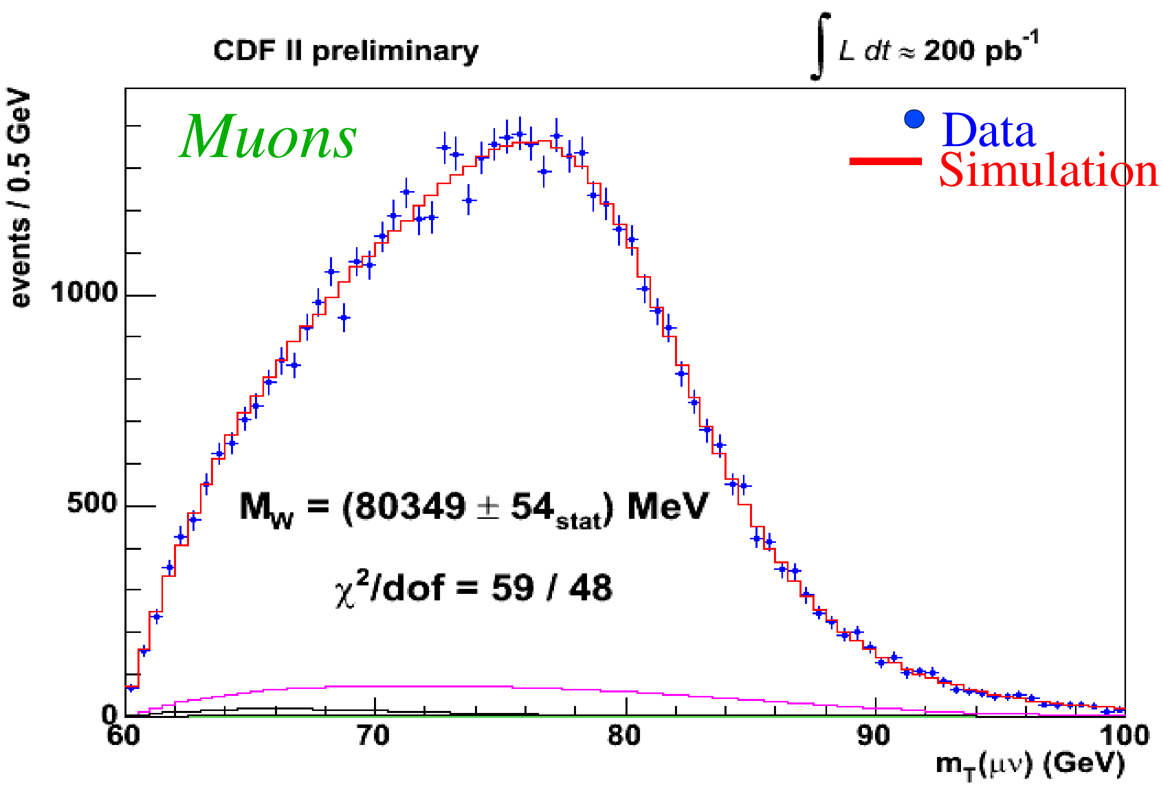




M. Chanowitz, PRL 97 (2001) 231802

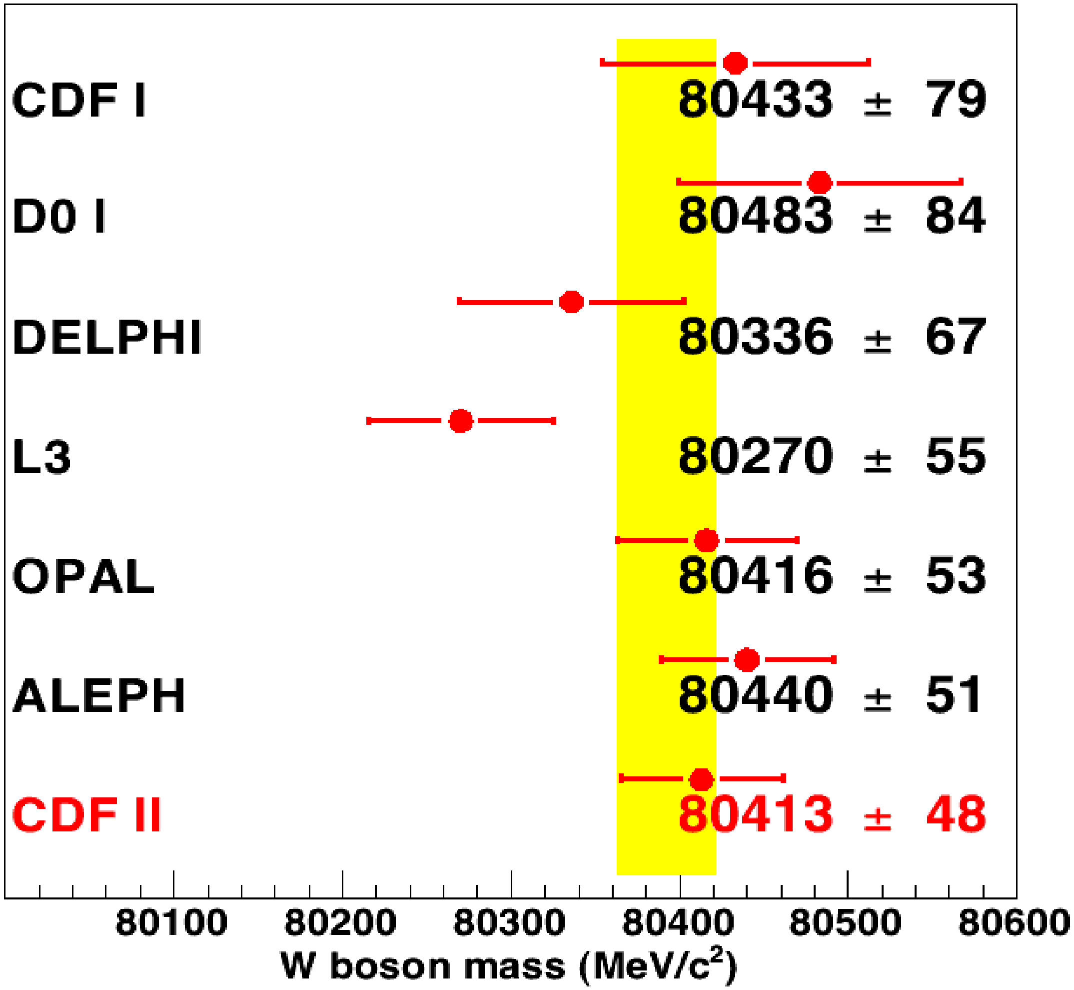
Fitting for the *W* Boson Mass





Perform fits to kinematic distributions sensitive to the W boson mass

Comparisons

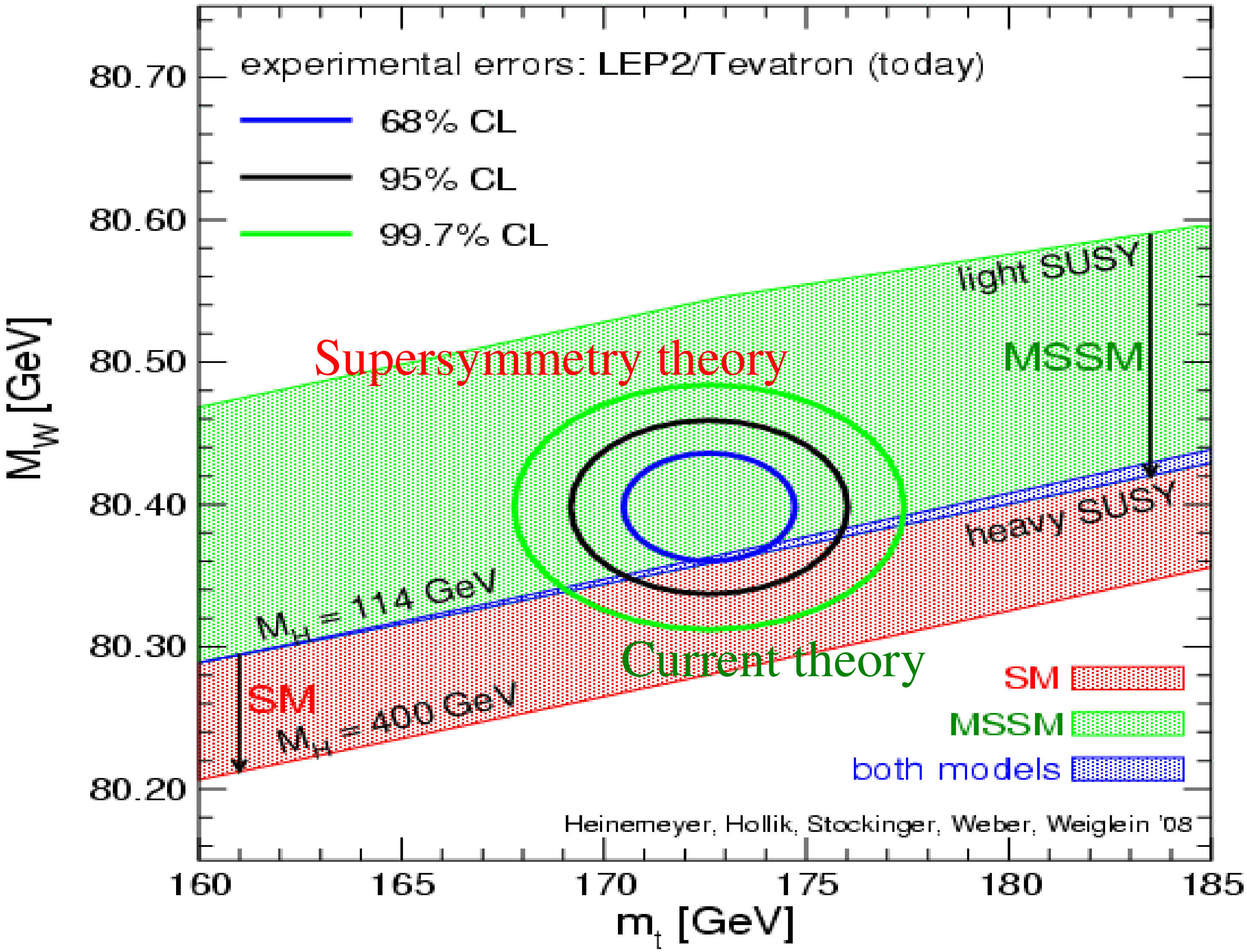


The CDF Run 2 result is the most precise single measurement of the W mass

(PRL 99:151801, 2007; Phys. Rev. D 77:112001, 2008)

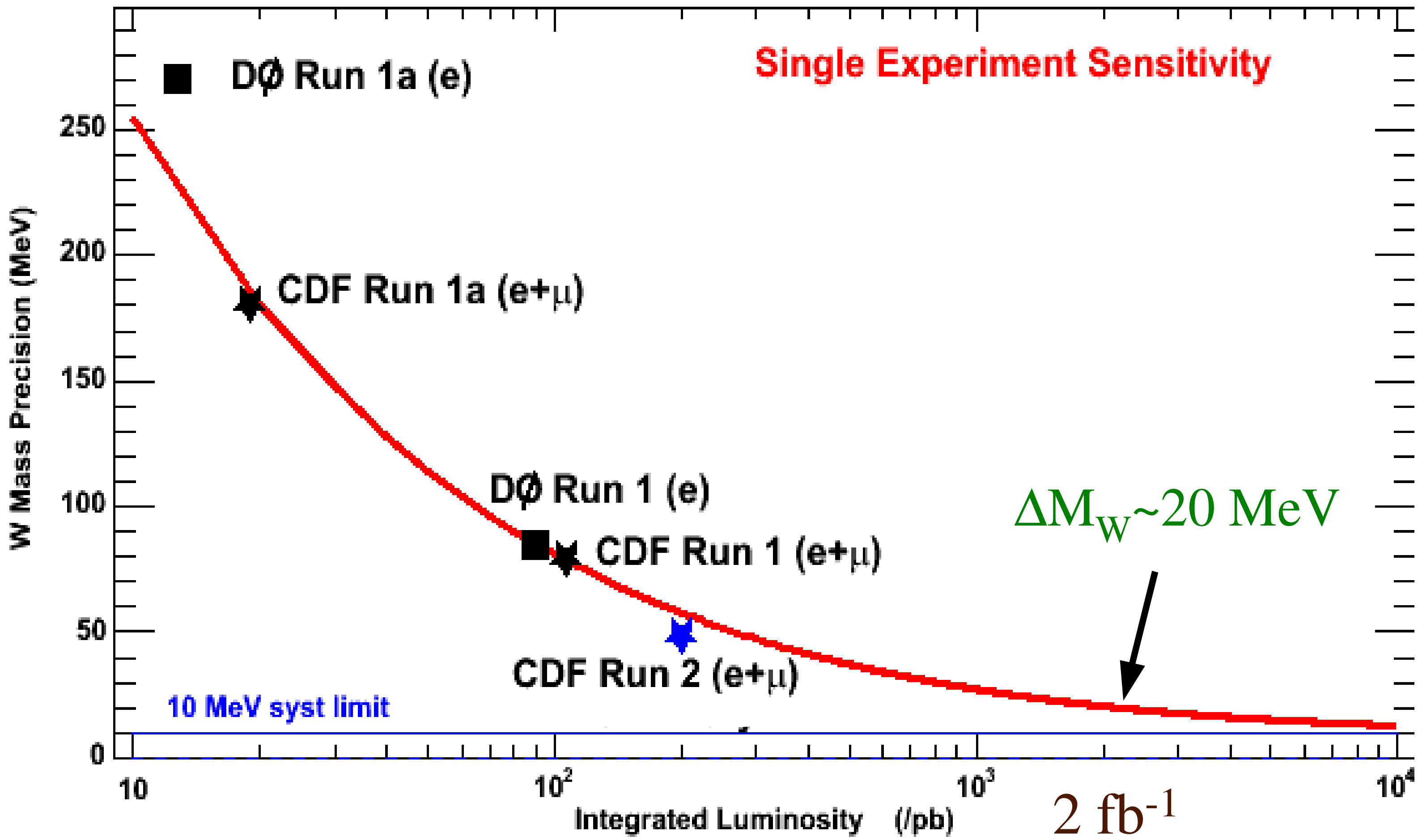
... and factor of 10 more data being analyzed now by my research group

M_W *vs* M_{top}



Lightest neutral supersymmetric particle could be dark matter candidate!

Preliminary M_W Studies of 2.4 fb^{-1} Data from Tevatron

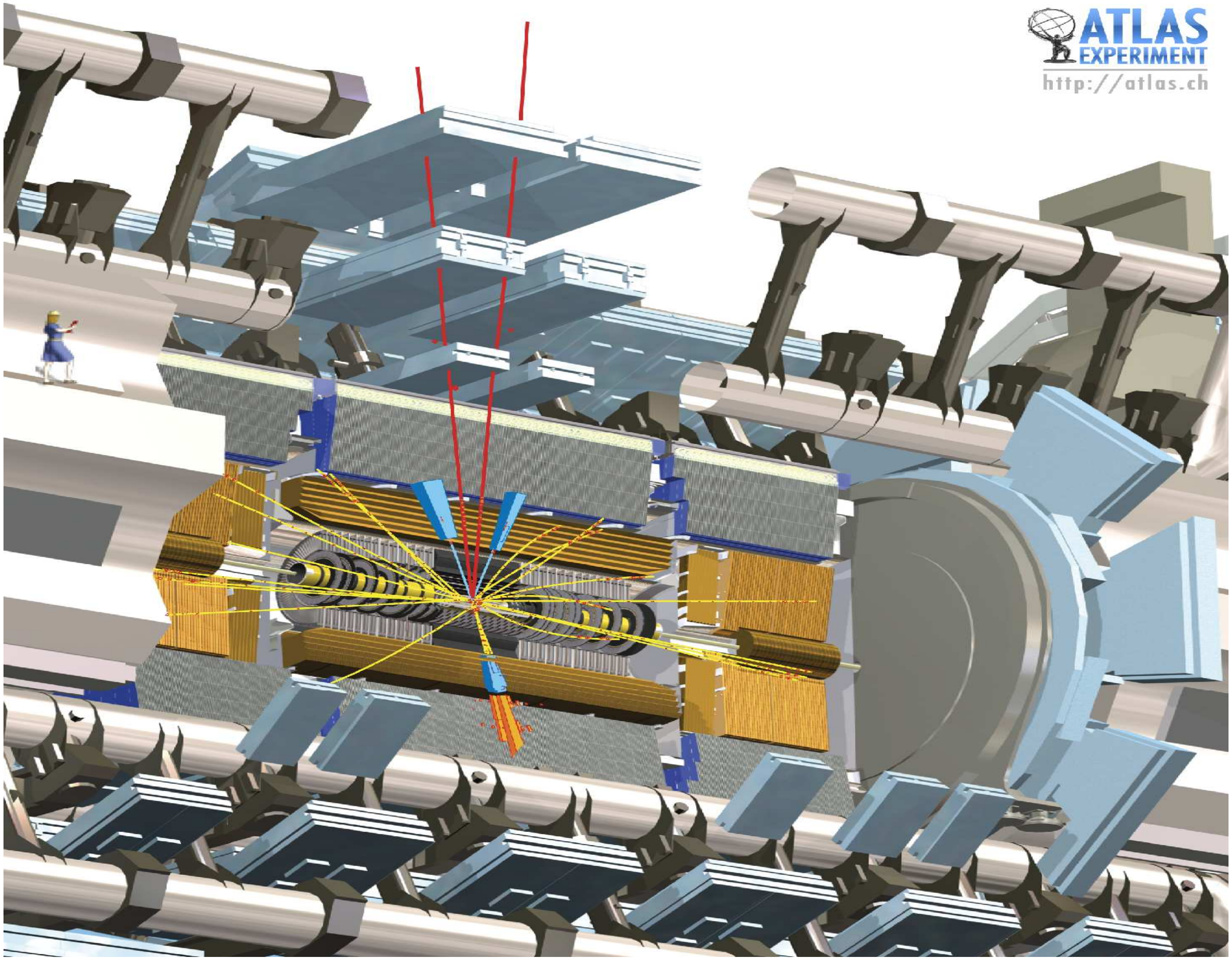


The Future – Large Hadron Collider at CERN

LHC will start collecting data with 14 TeV collisions in 2009

ATLAS Experiment at Large Hadron Collider

A simulated Higgs boson production event, with Higgs decaying to two Z bosons



I am a member of ATLAS Collaboration and will be studying the Higgs boson with ATLAS data

Summary

- CDF and D0 experiments at the Fermilab Tevatron in pursuit of the mass-generating mechanism:
  - Are closing in on the Higgs boson using direct searches
    - Higgs boson excluded at 170 GeV @ 95% CL
  - Are constraining the Higgs boson mass by making the most precise measurements of the top quark and W boson masses
  - Searching for new fundamental symmetries of nature
    - Supersymmetry
    - Substructure of particles
    - New forces
    - Additional spatial dimensions
- Fermilab continues to collect and analyze x3 more data in the next few years – nature may reveal more of its secrets!
- Large Hadron Collider at CERN is likely to reveal additional hidden symmetries