Science Results from the Fermilab Tevatron

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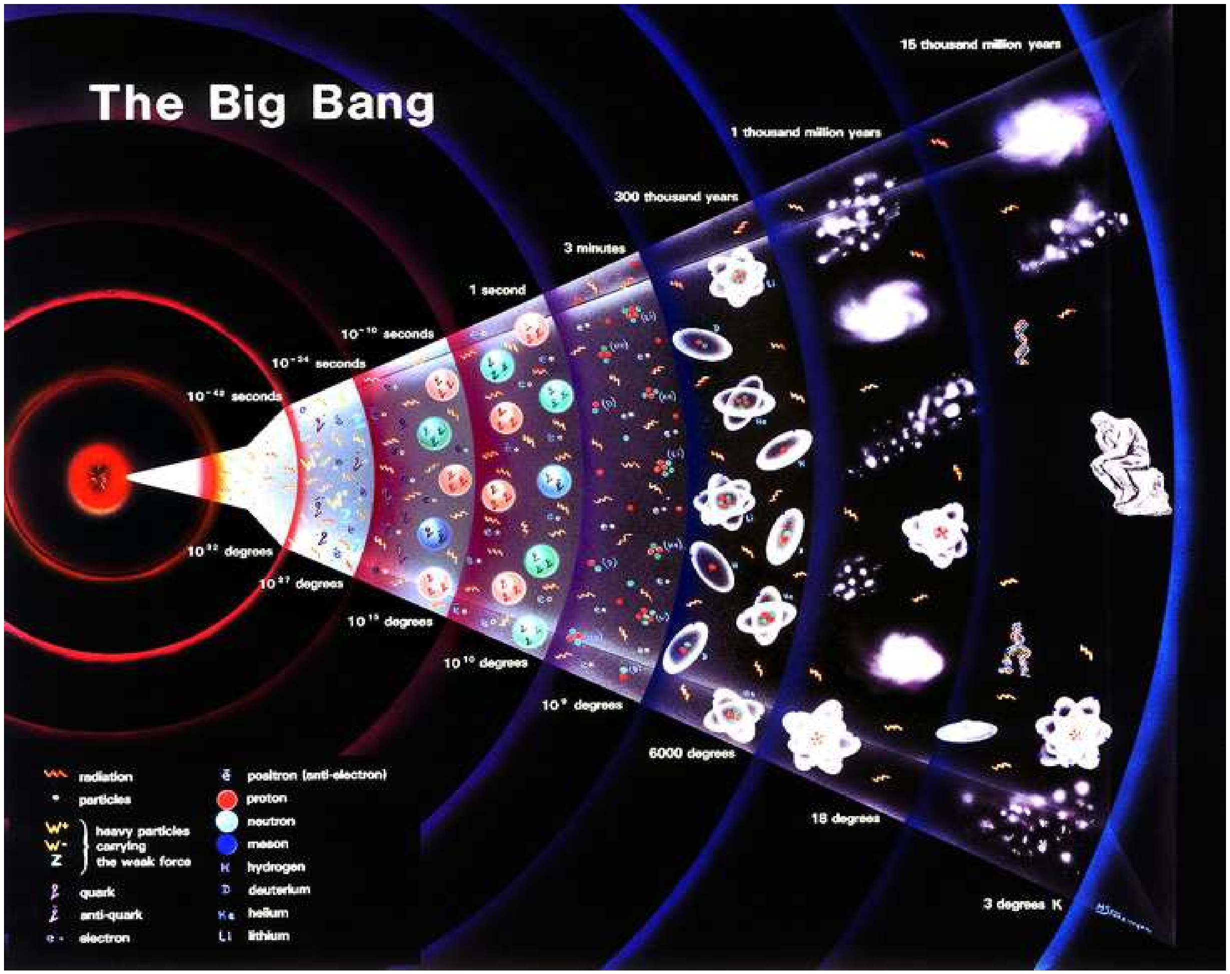
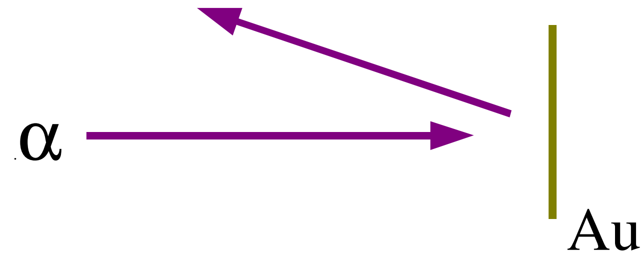


Open Science Grid All-Hands Meeting
UC San Diego, 5 March 2007

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
- 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

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

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

Quarks

u < 1 GeV	c ~ 1.5 GeV	t ~ 175 GeV
d < 1 GeV	s < 1 GeV	b ~ 4.5 GeV

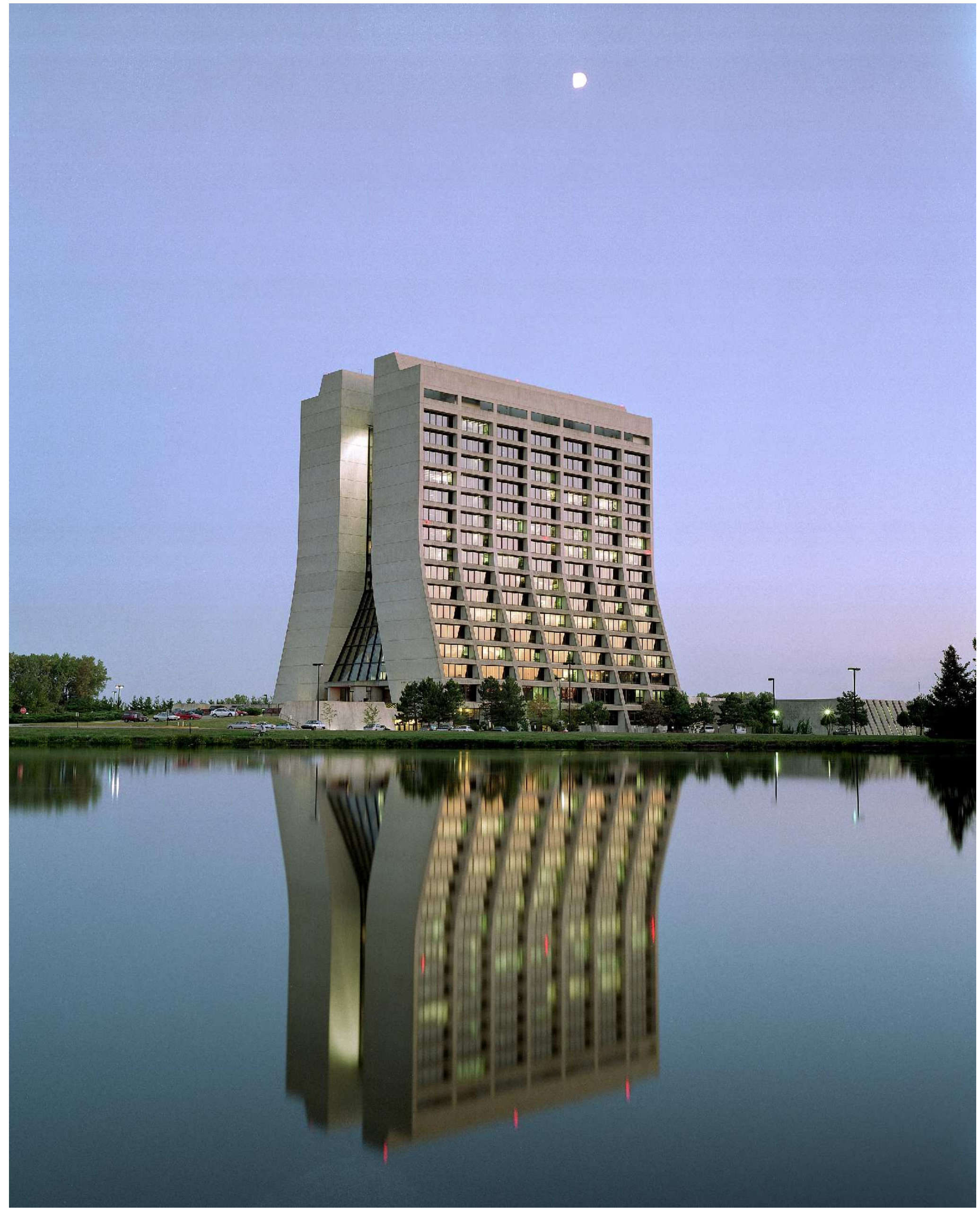
Leptons

$\nu_e < 1$ eV	$\nu_\mu < 0.17$ MeV	$\nu_\tau < 24$ MeV
e 0.5 MeV	μ 106 MeV	τ 1.8 GeV

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
- 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

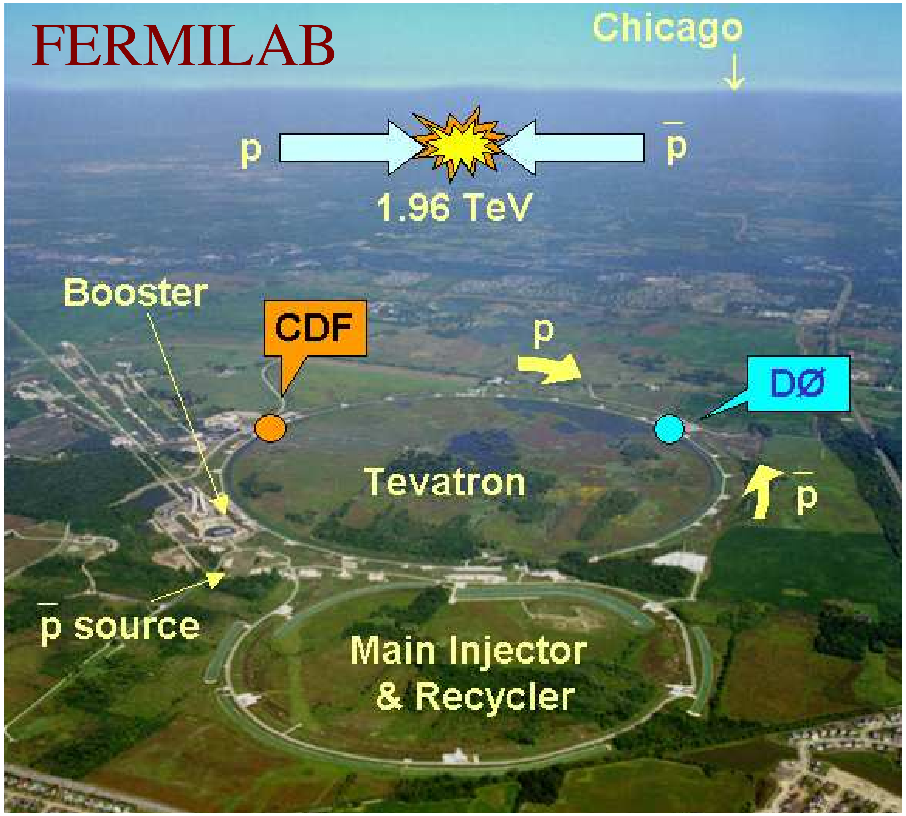
The "Problem", thus Excitement, of Particle Physics

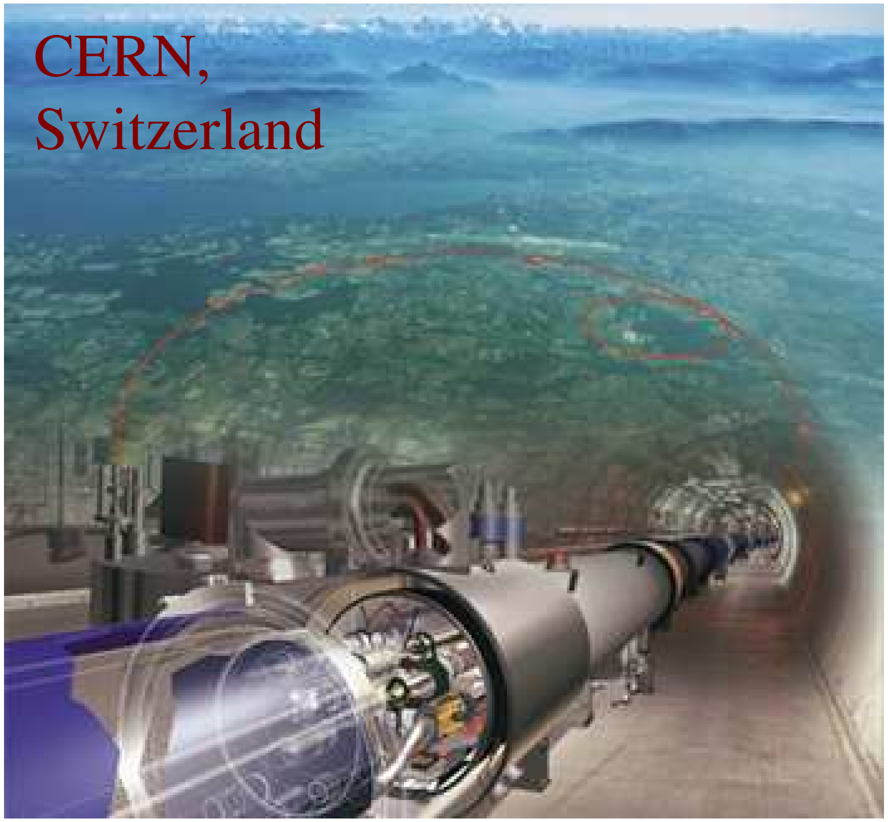
- This highly successful theory predicts that all particles should be massless!
  - Obviously not true in nature
- Theory rescued by postulating a new "Higgs" field, which permeates all space
  - A sticky field, particles moving through space scatter off the Higgs field, thereby *appearing* to be massive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

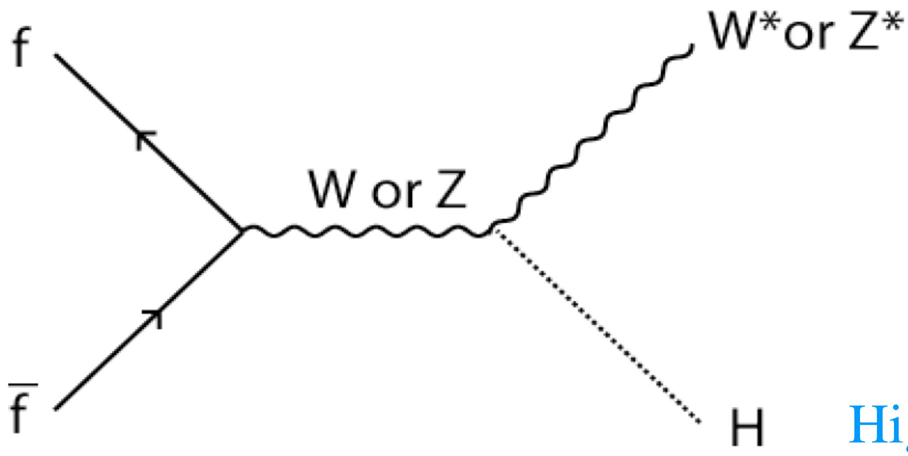
Accelerators at Fermilab (running now with 2 TeV energy) and CERN (start running in 2007 with 14 TeV energy) are at the energy at which the "Higgs Boson" is expected to show up





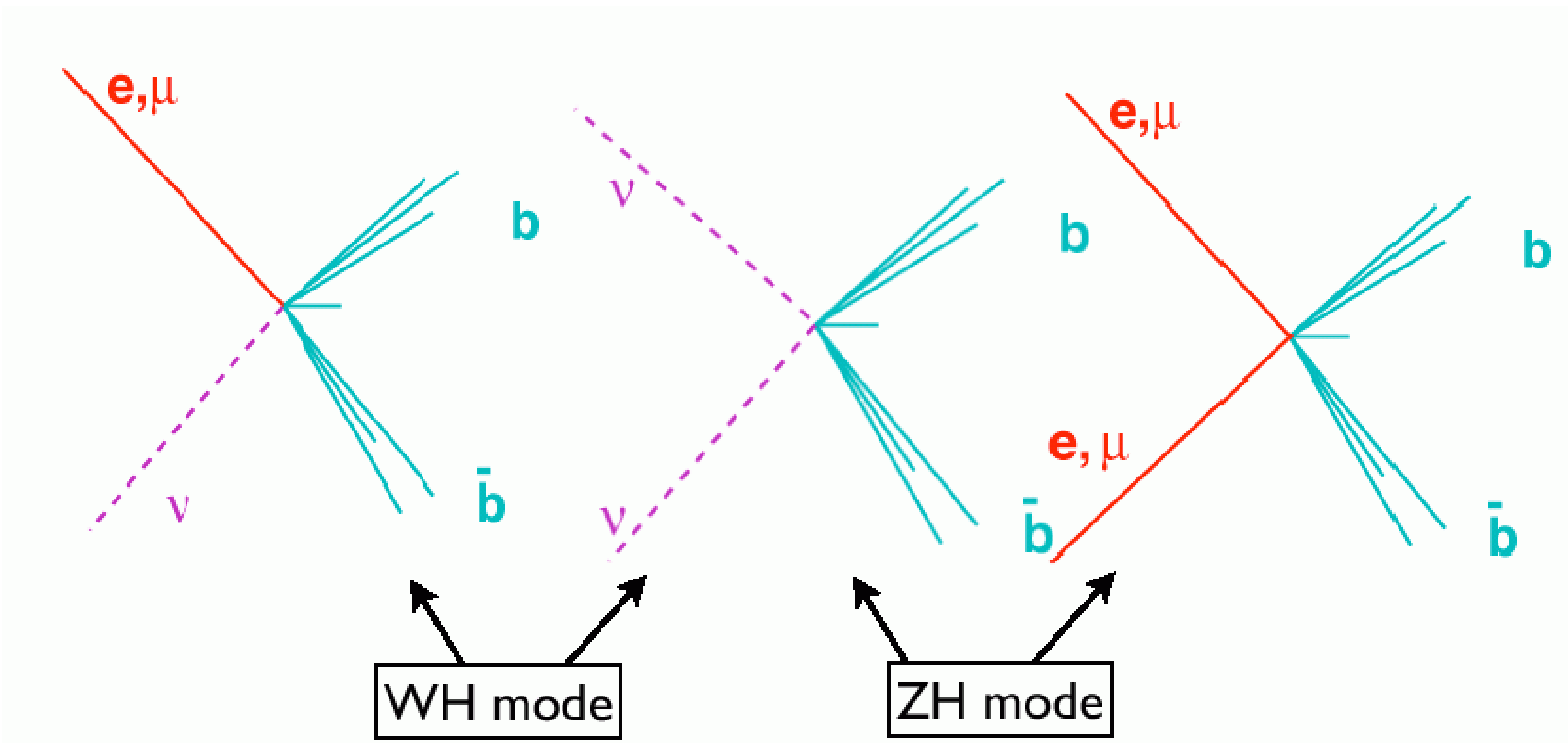
Search for Higgs boson is a key mission of the HEP program

Higgs Boson Production and Decay

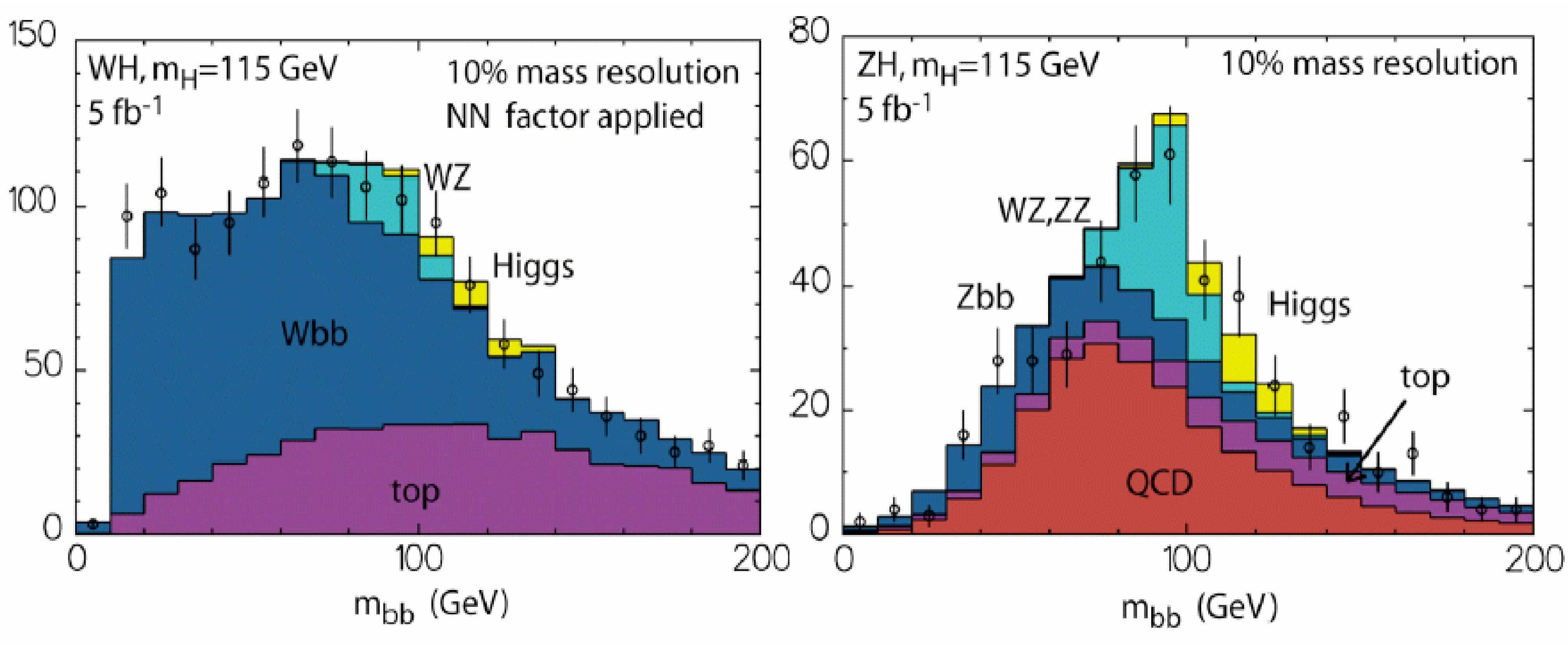


W, Z decay to electrons, muons and/or neutrinos

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

Need for CPU

- Event reconstruction and simulation both require sophisticated programs

- Large amount of CPU required to run these programs over many events

- Each collision event is independent of other events

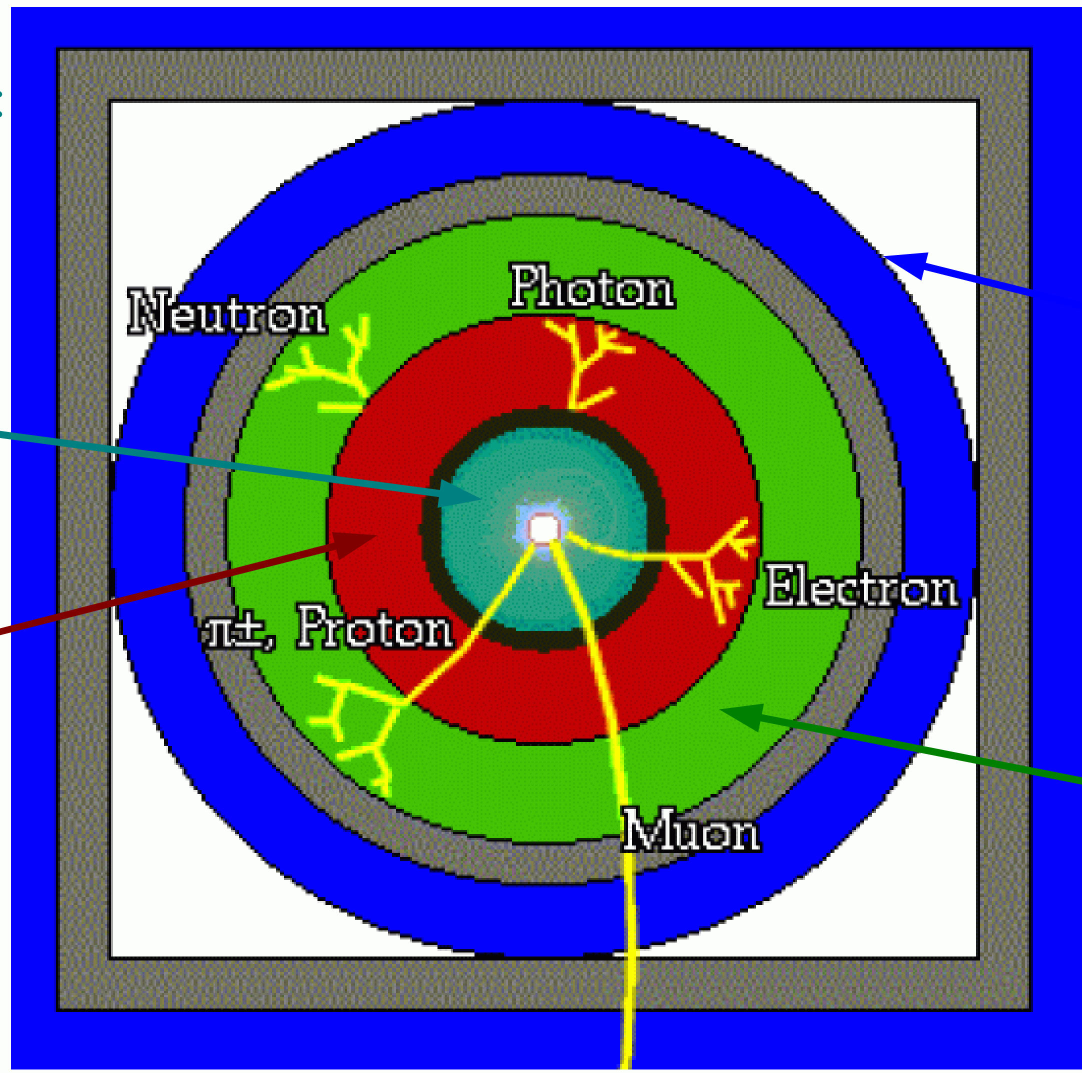
- Therefore events can be reconstructed and simulated in parallel on different computers

- GRID-based CPU clusters *i.e.* OSG is an ideal computing resource for HEP

Particle Detection

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

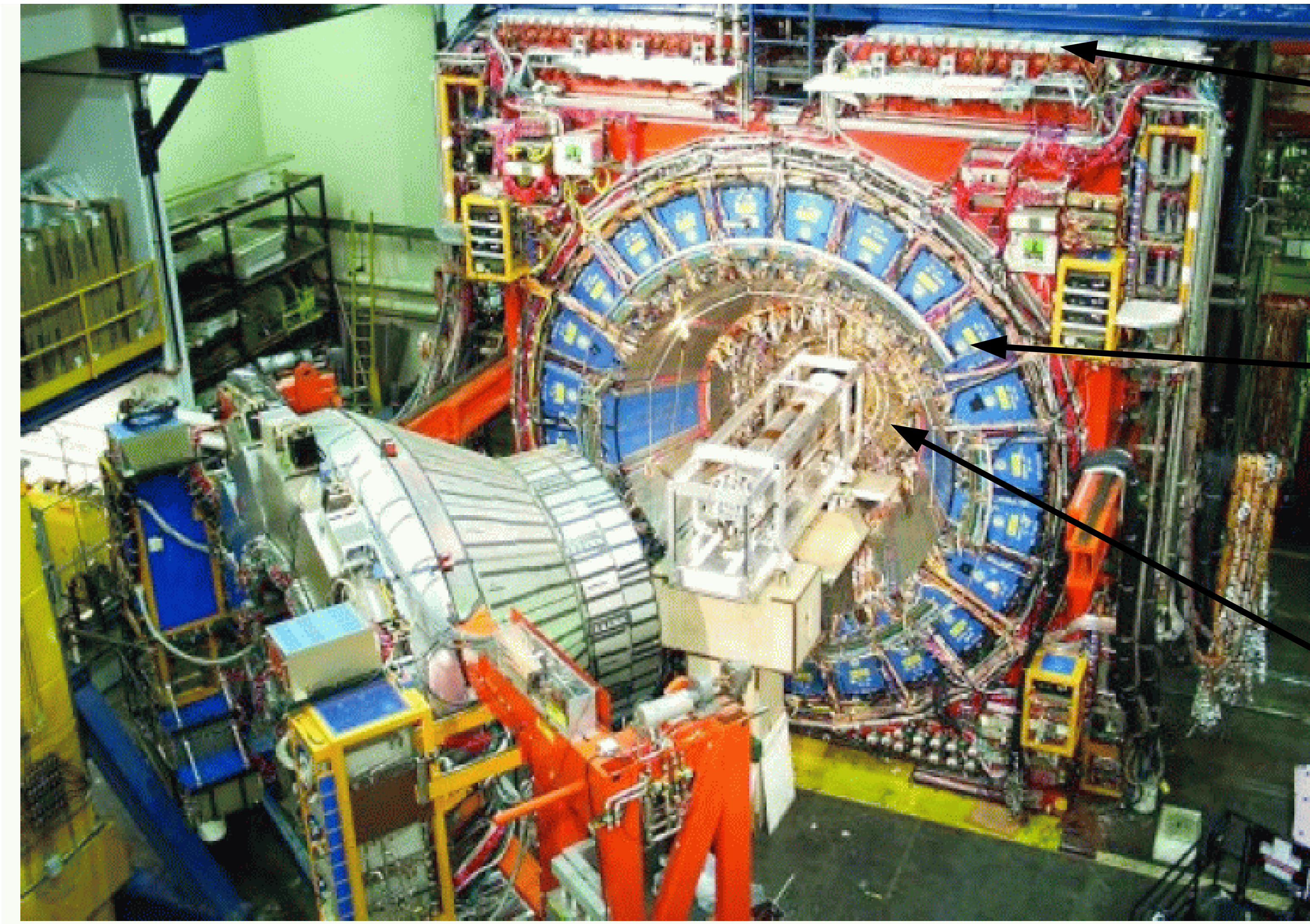
Muon chambers: detect penetrating particles behind shielding



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

Collider Detector at Fermilab (CDF)

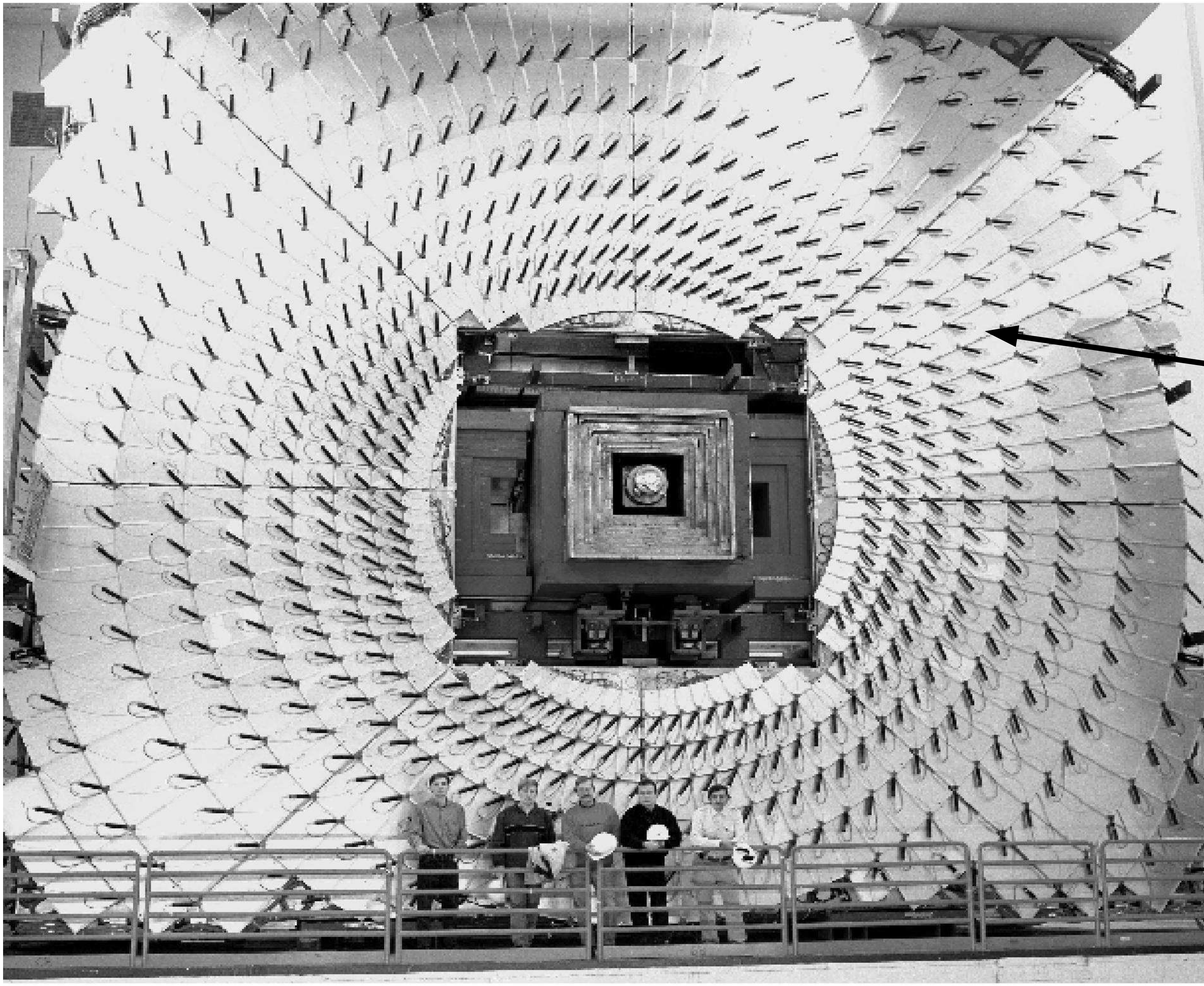


Muon detector

Central hadronic calorimeter

Central outer tracker (COT)

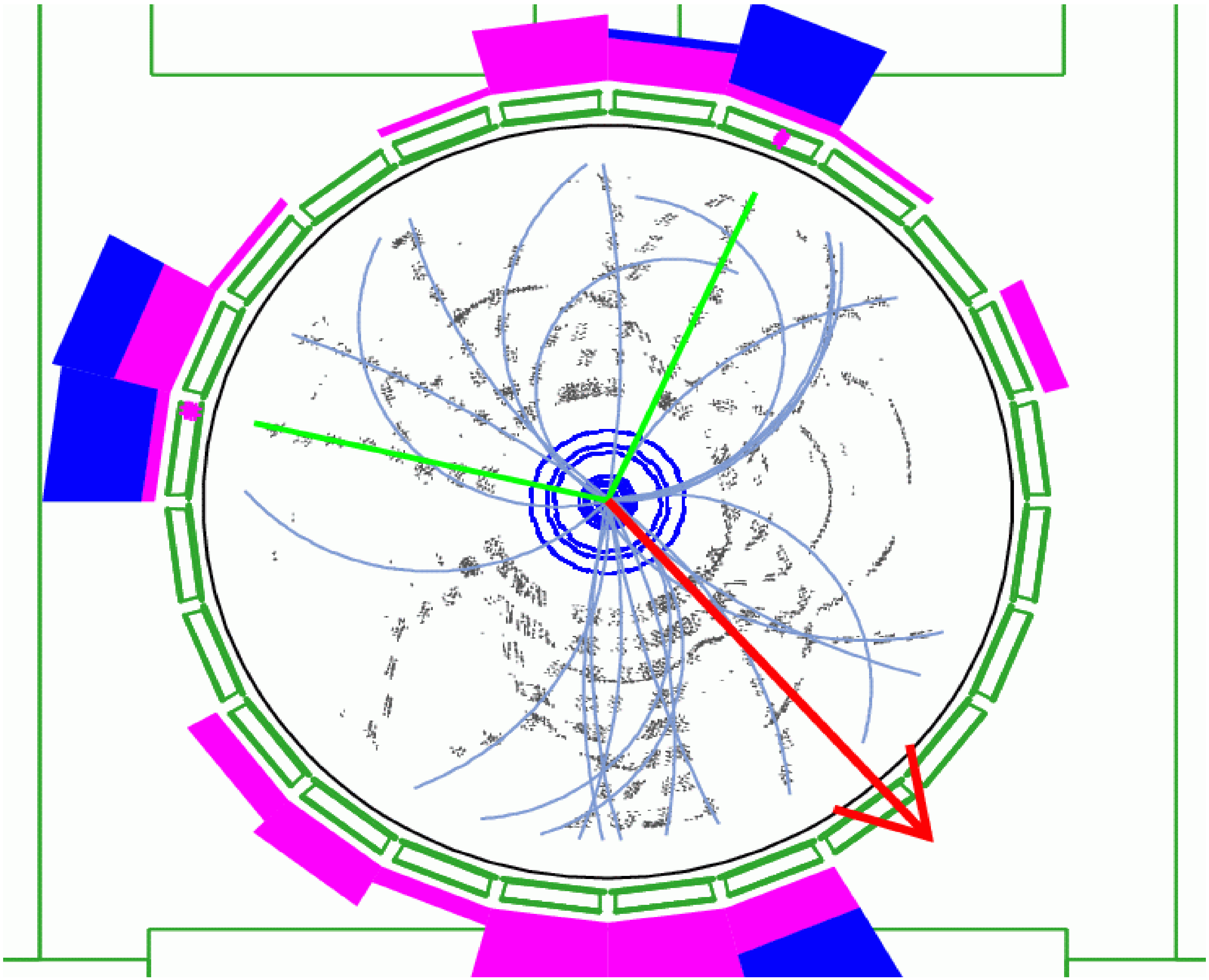
D0 Detector



Forward muon detectors

CDF Tracking Chamber

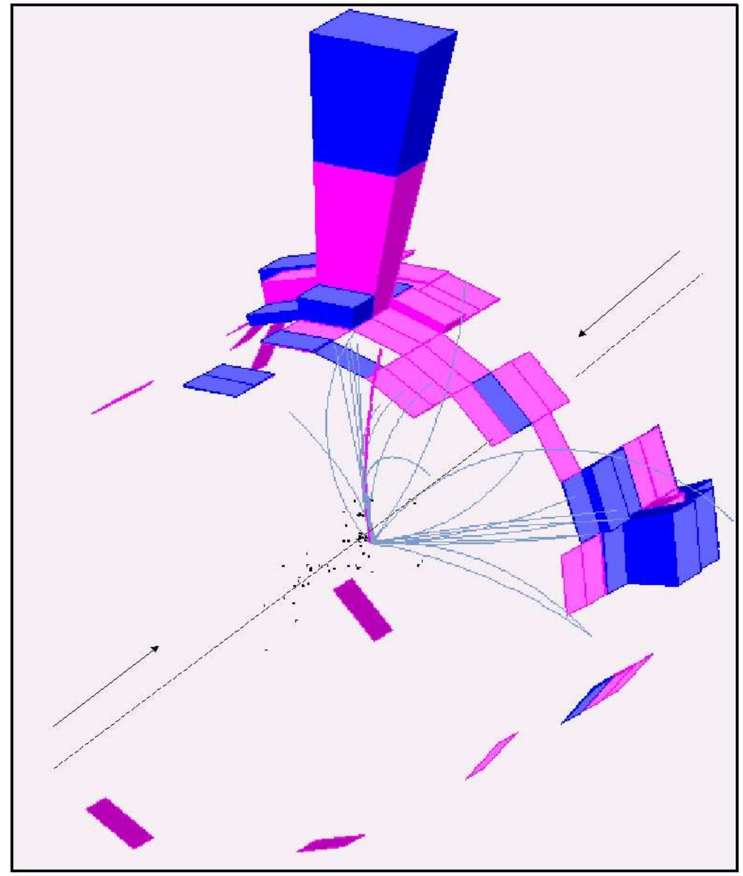
WW Candidate Event in CDF data



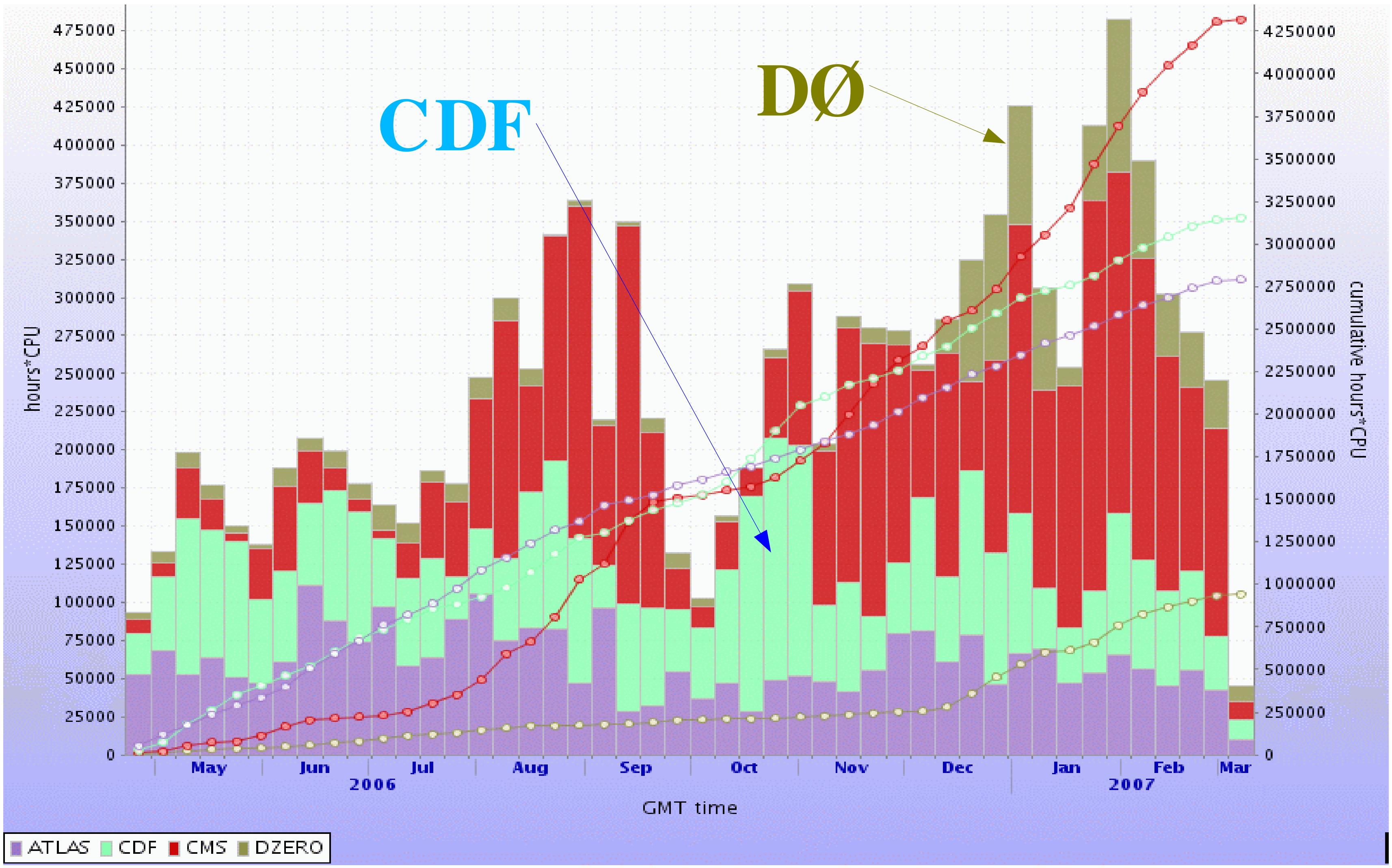
CPU requirements

- CDF:
  - Event reconstruction: 1 Ghz – second
  - Simulation: 10 Ghz – second / event
- D0:
  - simulation & reconstruction: 370 Ghz – second per event
- OSG usage dominated by
  - Simulation events for CDF ~ 1 billion events
  - Data reconstruction for D0 ~ 500 million events

Simulated CDF
ZH -> νν + *bb* event



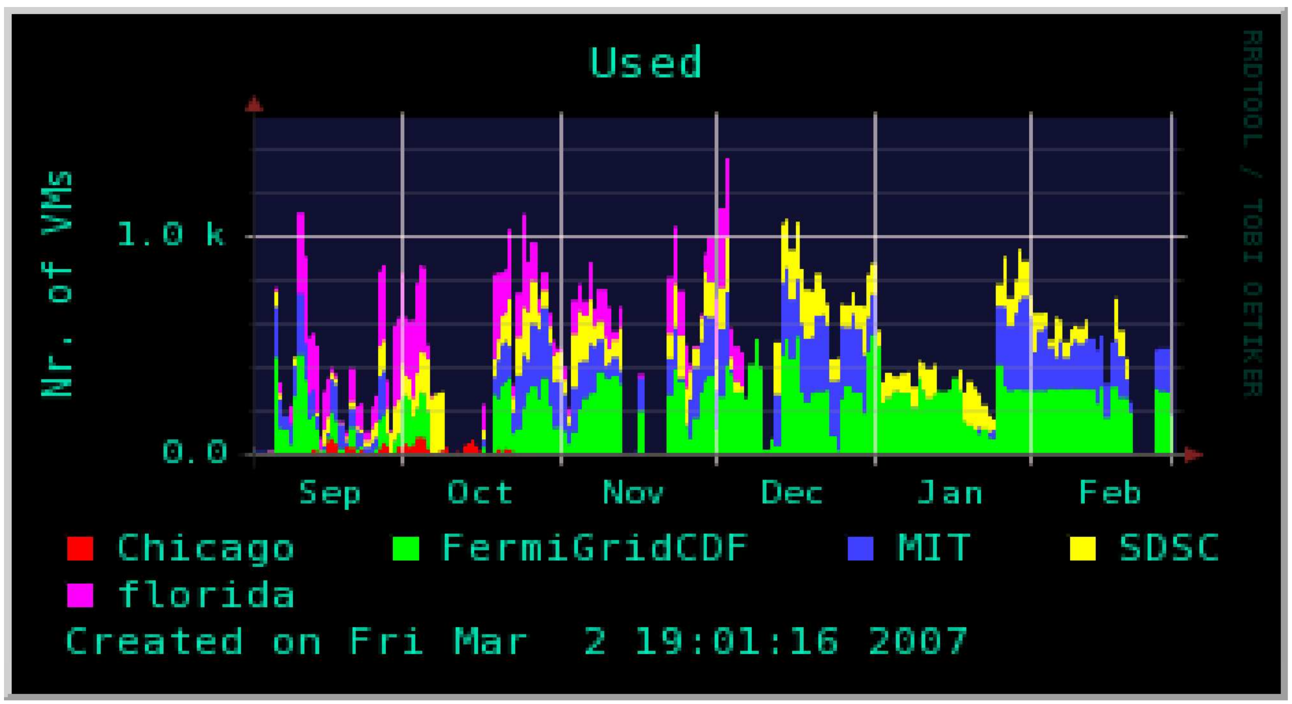
OSG Usage



CDF
DØ
hours*CPU
cumulative hours*CPU
475000
450000
425000
400000
375000
350000
325000
300000
275000
250000
225000
200000
175000
150000
125000
100000
75000
50000
25000
0
4250000
4000000
3750000
3500000
3250000
3000000
2750000
2500000
2250000
2000000
1750000
1500000
1250000
1000000
750000
500000
250000
0
May Jun Jul Aug Sep Oct Nov Dec Jan Feb Mar
2006
2007
GMT time
ATLAS CDF CMS DZERO

CDF Computing on OSG: NAMCAF

- Provides a single point of submission for CDF users, to Open-Science-Grid sites across North America
  - CDF user interface, uses OSG tools underneath
  - no CDF-specific hardware or software at OSG sites
- Accesses OSG sites at MIT, Fermilab, UCSD, Florida & Chicago
- OSG sites at Purdue, Toronto, Wisconsin, McGill to be added



Provides upto 1000 job slots already

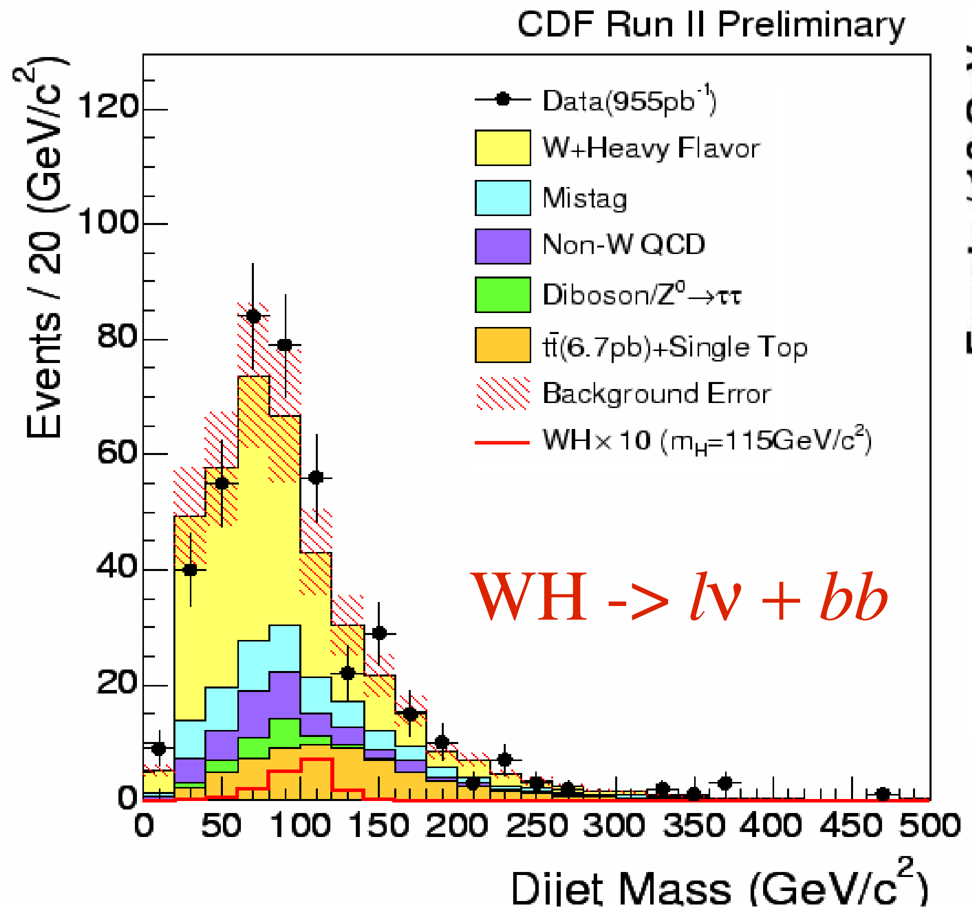
similar entry points to European sites (LCGCAF) and Taiwan, Japan sites (PACCAF)

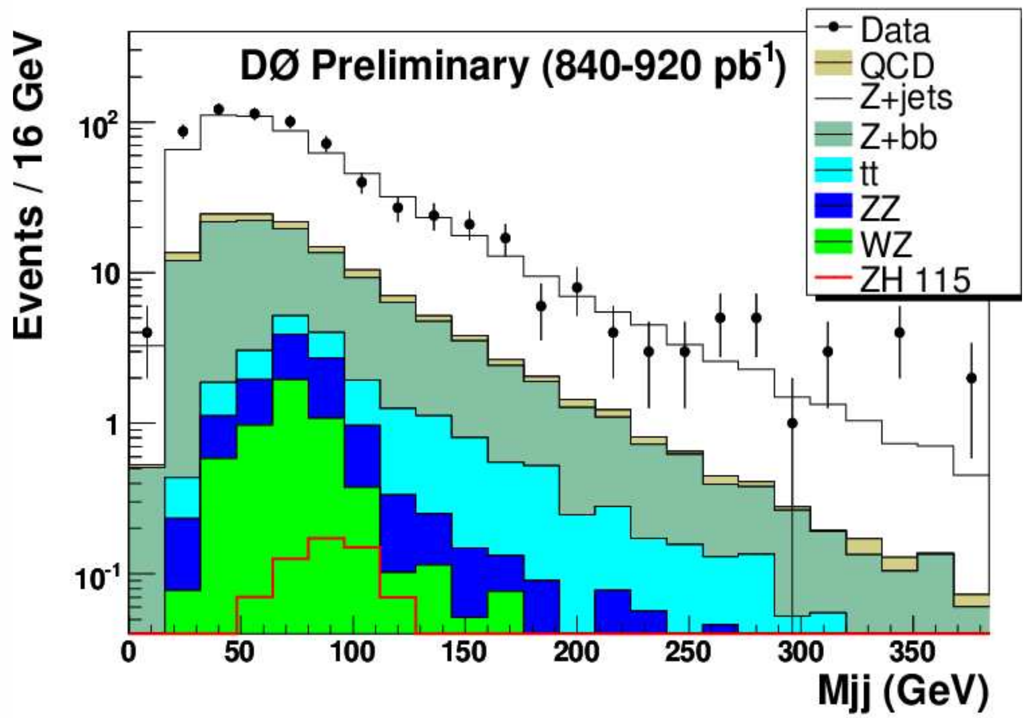
D0 Computing on OSG: SAMGRID

- D0 uses SAMGRID for data reconstruction at the following OSG sites:
  - cmsosgce.fnal.gov
  - grid1.oscer.ou.edu
  - ufloridapg.phys.ufl.edu
  - ufgrid01.phys.ufl.edu
  - spgrid.if.usp.br
  - grid3.avidd.iu.edu
  - ltu.cct.lsu.edu
  - iut2-grid6.iu.edu
  - pdsfgrid2.nersc.gov

SAMGRID also used on LCG sites

Search for the Higgs Boson

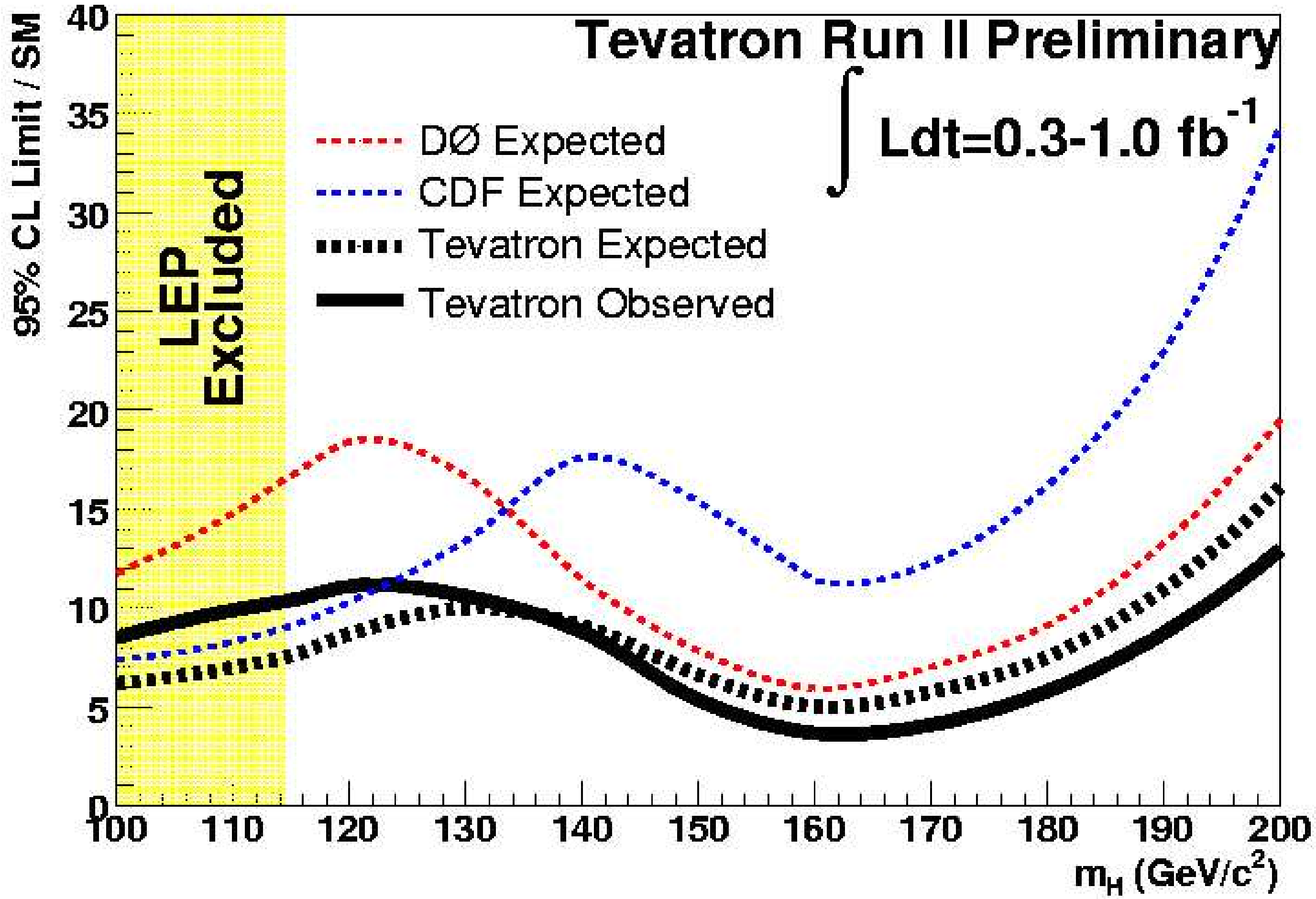




ZH -> *ll* + *bb*

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

Higgs Boson Production Limits

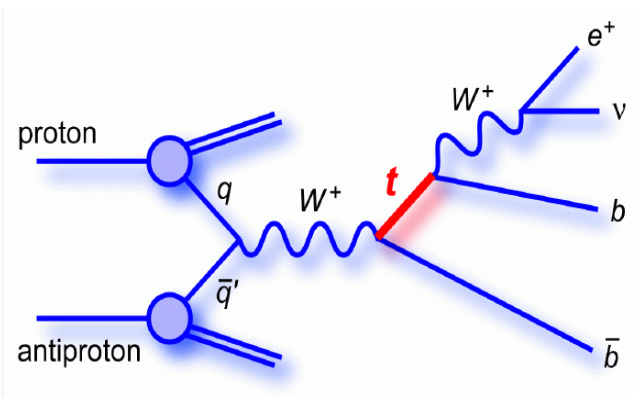


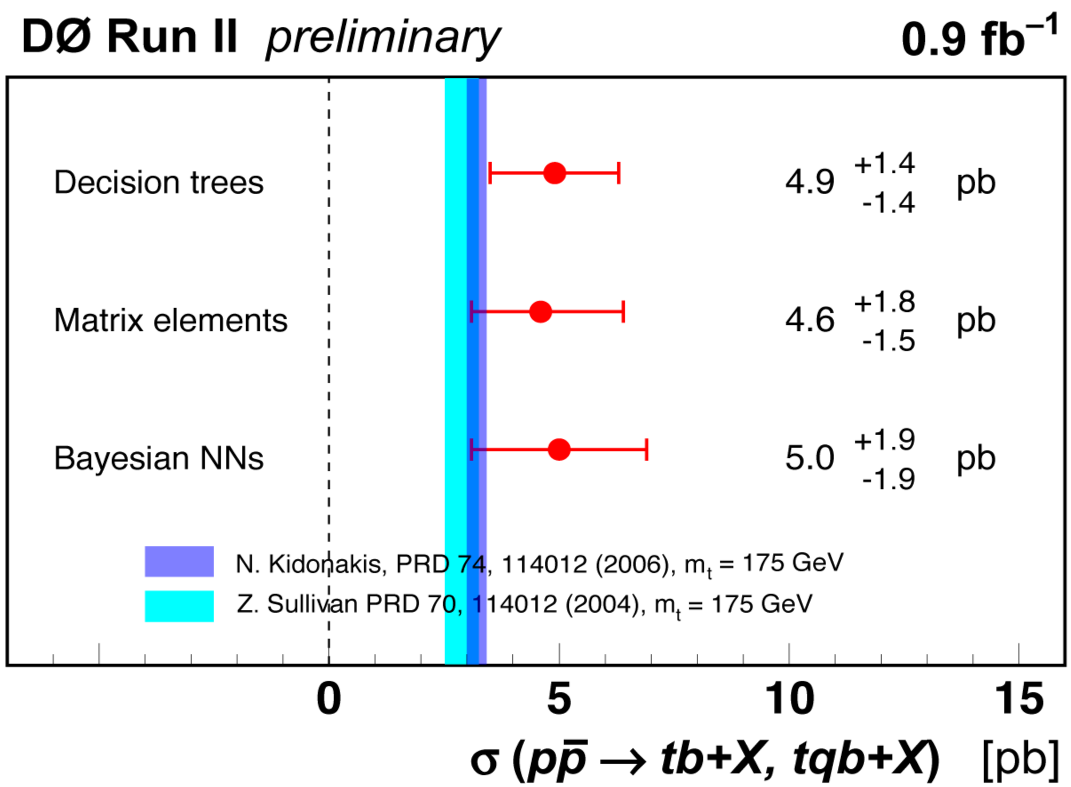
- Comparison of Higgs boson production cross section upper limit to the theoretical expectation shows that analysis of x5 more data at the Tevatron has a good chance of discovering the Higgs boson

- Adequate CPU is an essential resource

Single Top Production

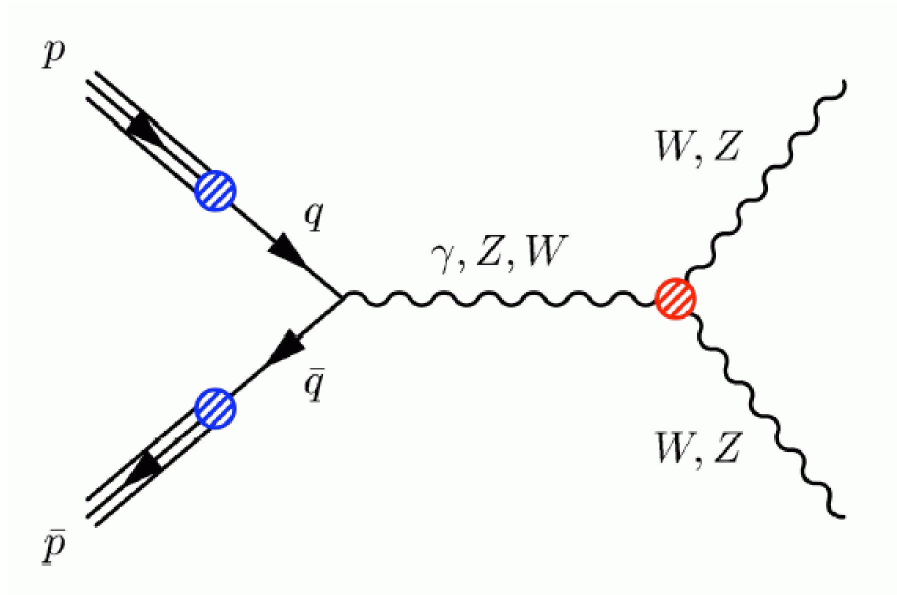
- Top quark discovered in 1995 at the Tevatron using the pair production mode
- Prediction of single top quark has recently been confirmed by the D0 data
- Important measurement of the *t*-*b* coupling
- Similar final state as WH -> *lv* + *bb* search
  - Therefore also a key milestone in the Higgs search





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



WZ analysis: σ(NLO) = 3.7 ± 0.3 pb

Source	Expectation ± Stat ± Syst ± Lumi
Z+jets	1.22 ± 0.27 ± 0.28 ± -
ZZ	0.89 ± 0.01 ± 0.09 ± 0.05
$Z\gamma$	0.48 ± 0.06 ± 0.15 ± 0.03
$t\bar{t}$	0.12 ± 0.01 ± 0.01 ± 0.01
WZ	9.79 ± 0.03 ± 0.31 ± 0.59
Total Background	2.70 ± 0.28 ± 0.33 ± 0.09
Total Expected	12.50 ± 0.28 ± 0.46 ± 0.68
Observed	**16**

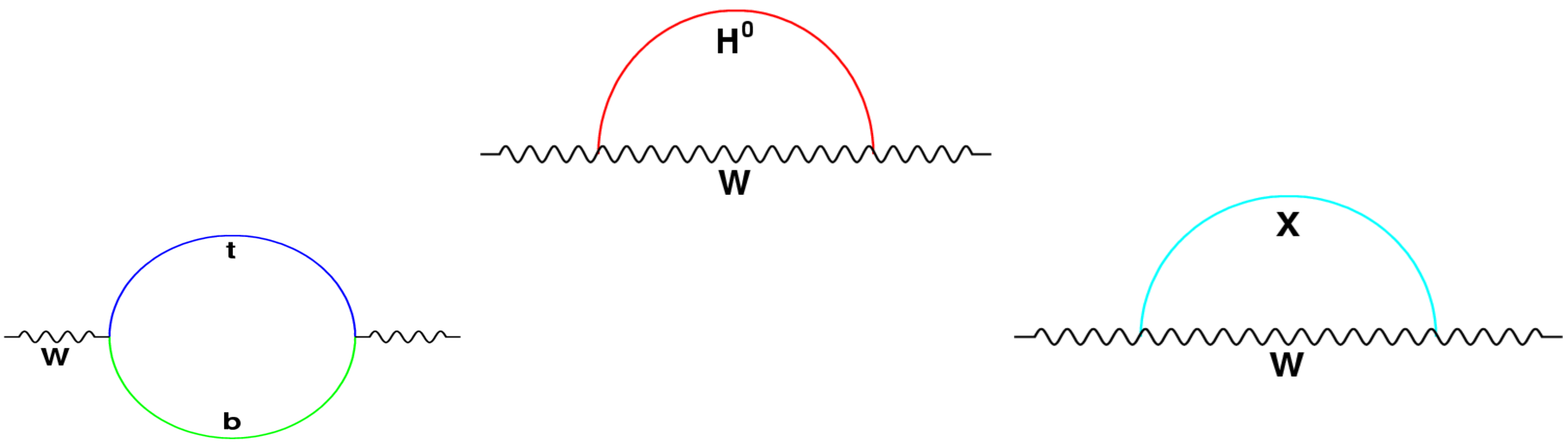
$\sigma(WZ) = 5.0^{+1.8}_{-1.6}$ (stat. + syst.) pb

16 Trilepton events!

=5.9σ Statistical significance

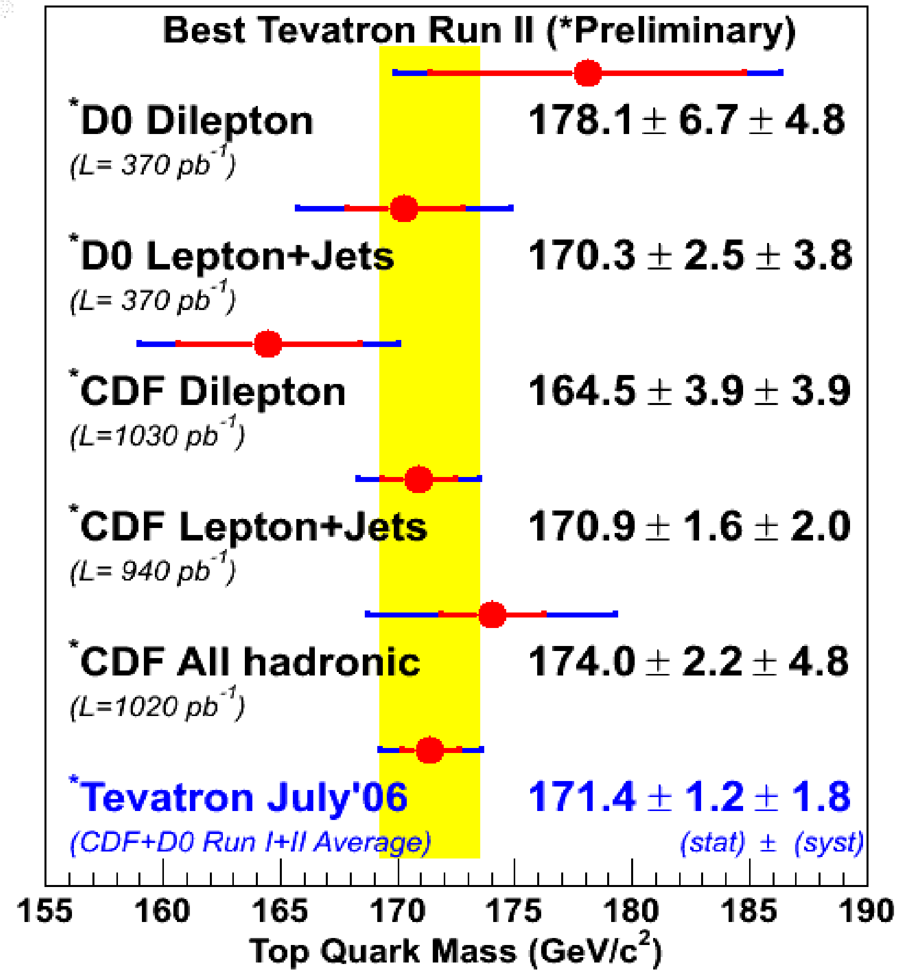
Precision Measurements of W boson and top quark masses

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



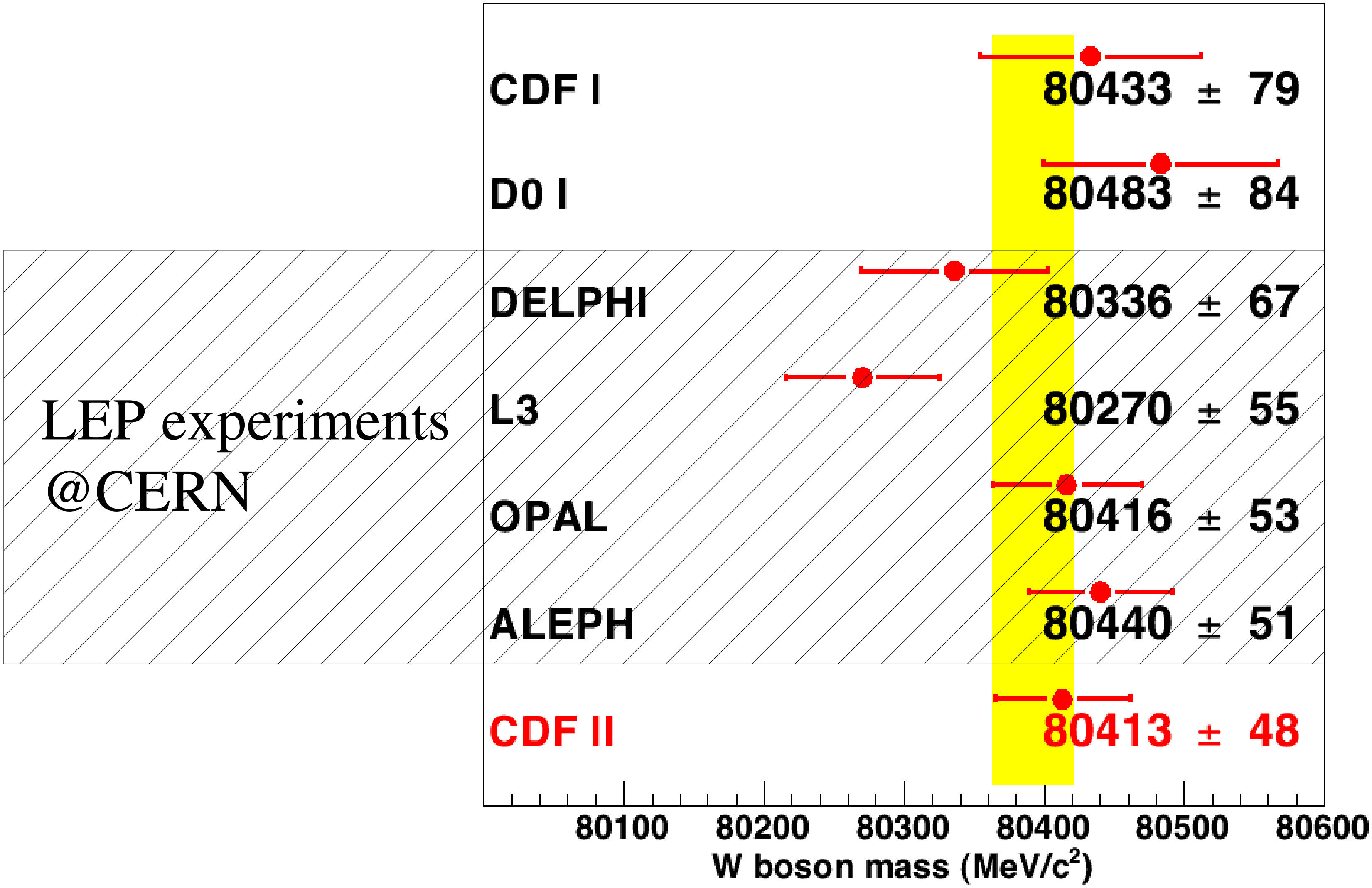
- In conjunction with M_{top}, the W boson mass constrains the mass of the Higgs boson, and possibly new particles beyond the standard model

Progress on M_{top} at the Tevatron



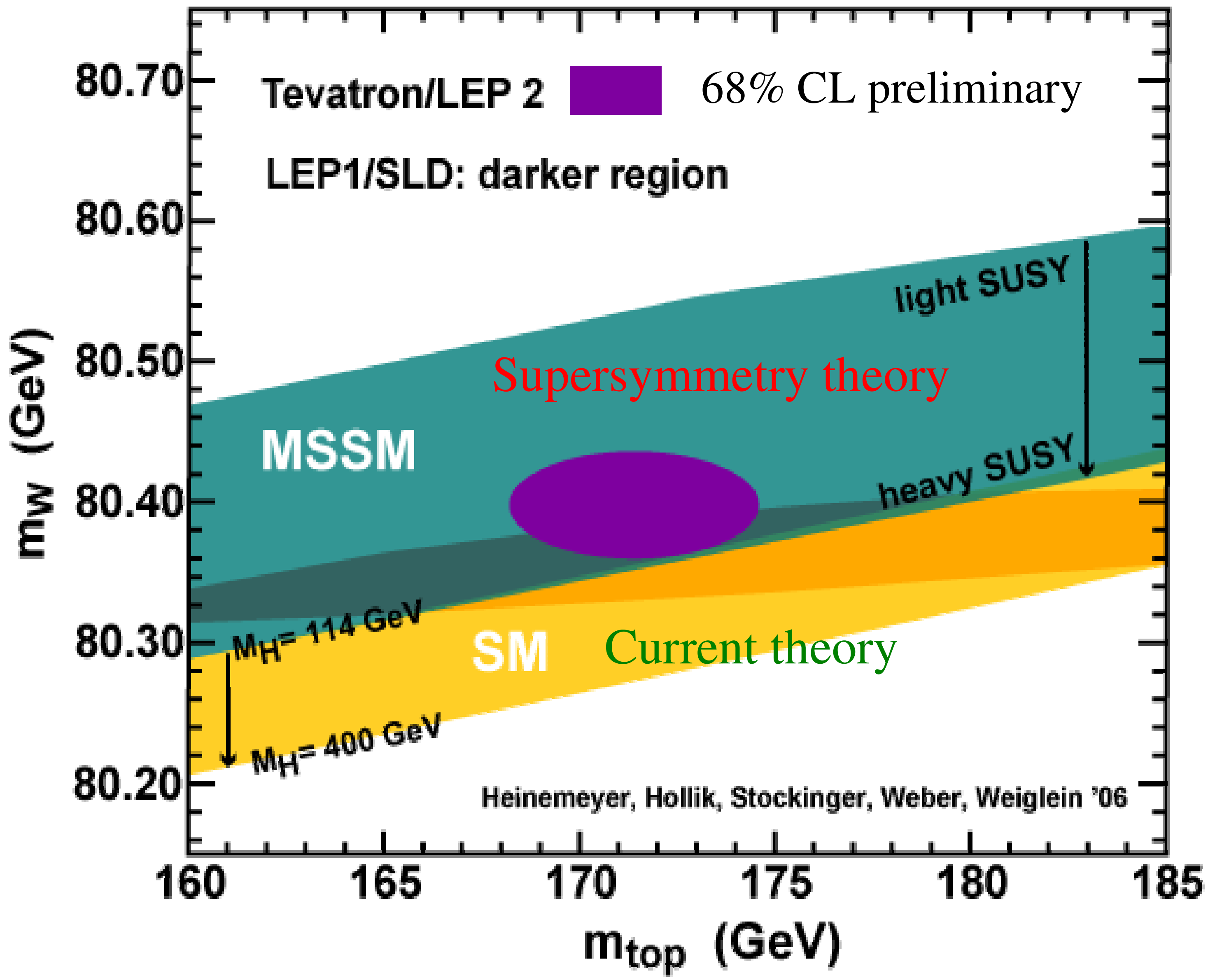
- δM_{top} = 2.1 GeV, the best-measured quark mass (smallest % error)
- In addition to event simulation, top mass-fitting analysis also very CPU intensive
  - e.g. >300,000 CPU hours for top mass fitting in 2007 alone

W boson mass measurement



The CDF Run 2 result is the most precise single measurement of the W mass
(used ~million CPU hours for mass fitting)

M_W *vs* M_{top}



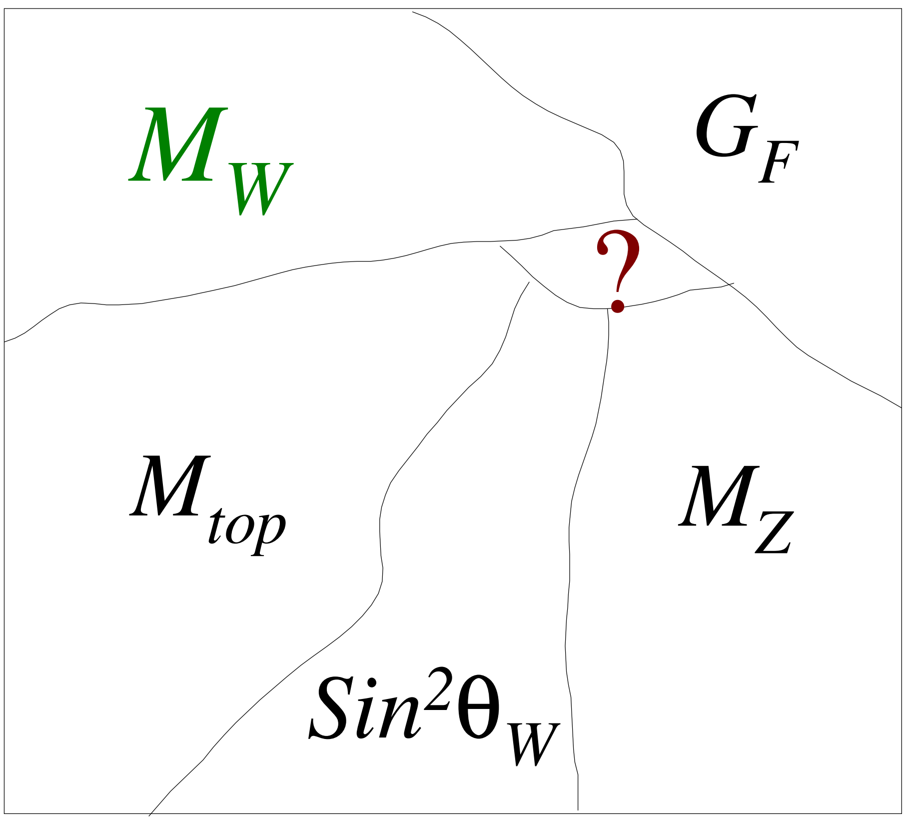
Tevatron/LEP 2
68% CL preliminary
LEP1/SLD: darker region
light SUSY
Supersymmetry theory
MSSM
heavy SUSY
MH= 114 GeV
SM
Current theory
MH= 400 GeV
Heinemeyer, Hollik, Stockinger, Weber, Weiglein '06
80.70
80.60
80.50
80.40
80.30
80.20
mW (GeV)
160
165
170
175
180
185
mtop (GeV)

Summary

- CDF and D0 at the Fermilab Tevatron
  - 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
- Computing resources provided by grids for data reconstruction, simulation and analysis are essential
- CDF and D0 continue to analyze x5 more data in the next few years

Higgs Mass Constraints from Precision Measurements

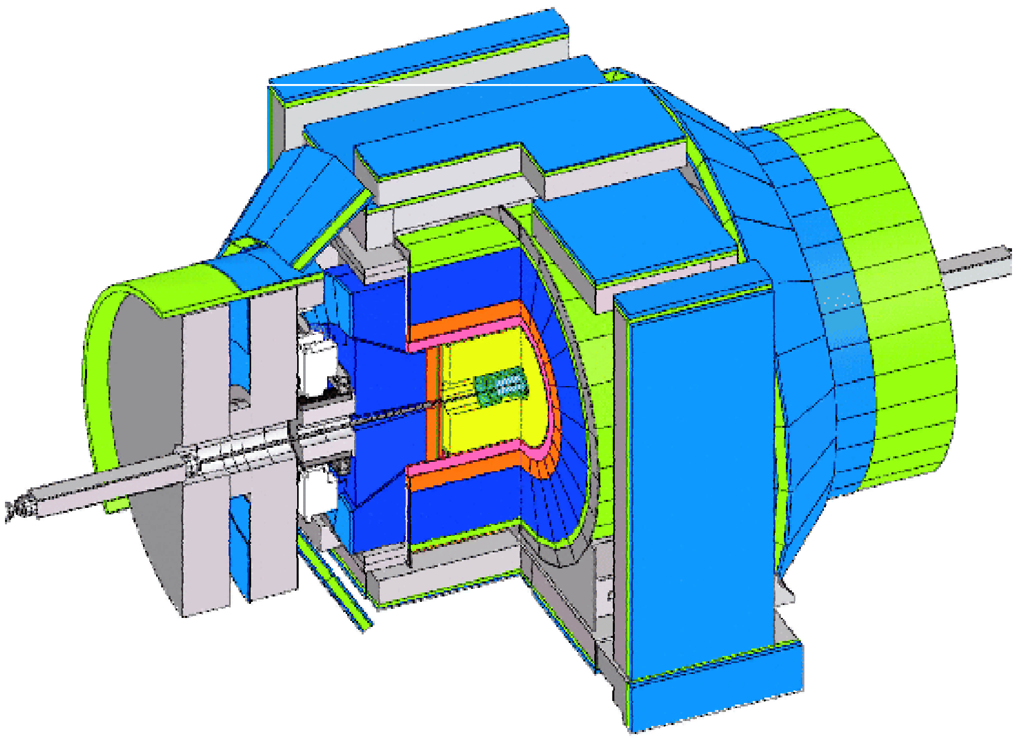
- SM Higgs fit: $M_H = 80^{+36}_{-26}$ GeV (M. Grunewald, private communication)
- LEPII direct searches exclude $M_H < 114.4$ GeV @ 95% CL (PLB 565, 61)



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

Particle Detectors at the Fermilab Tevatron

CDF



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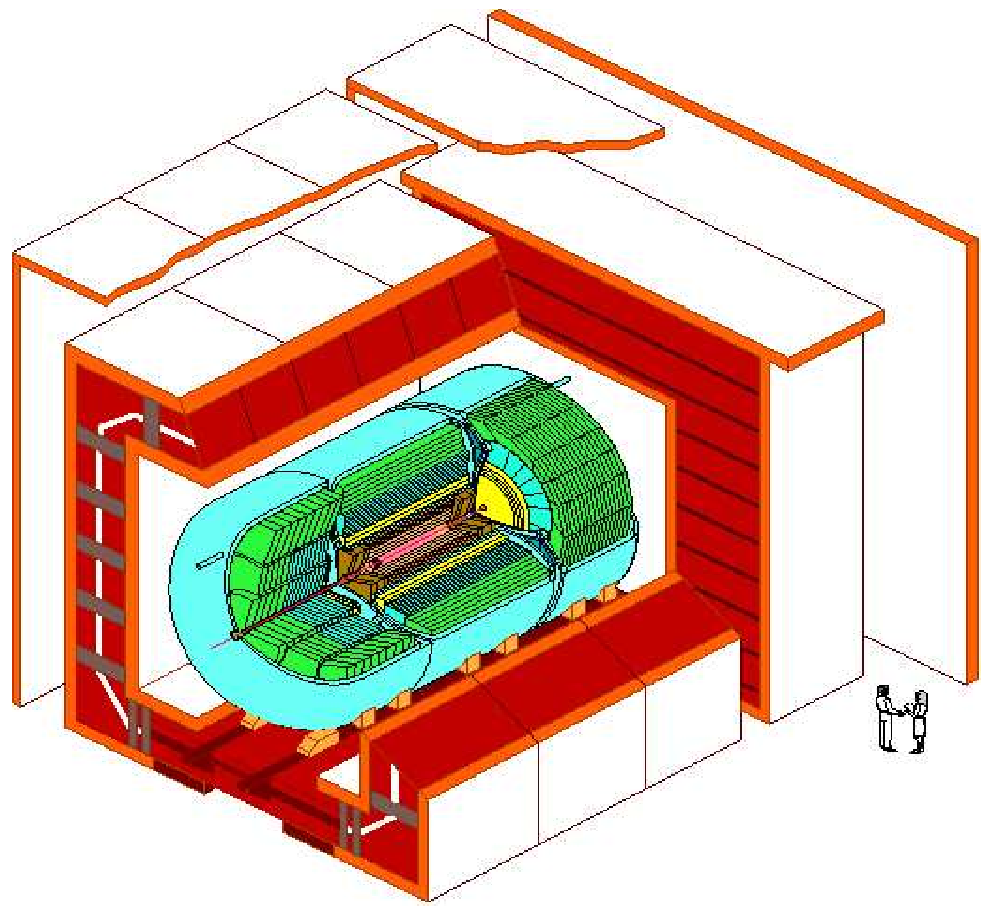
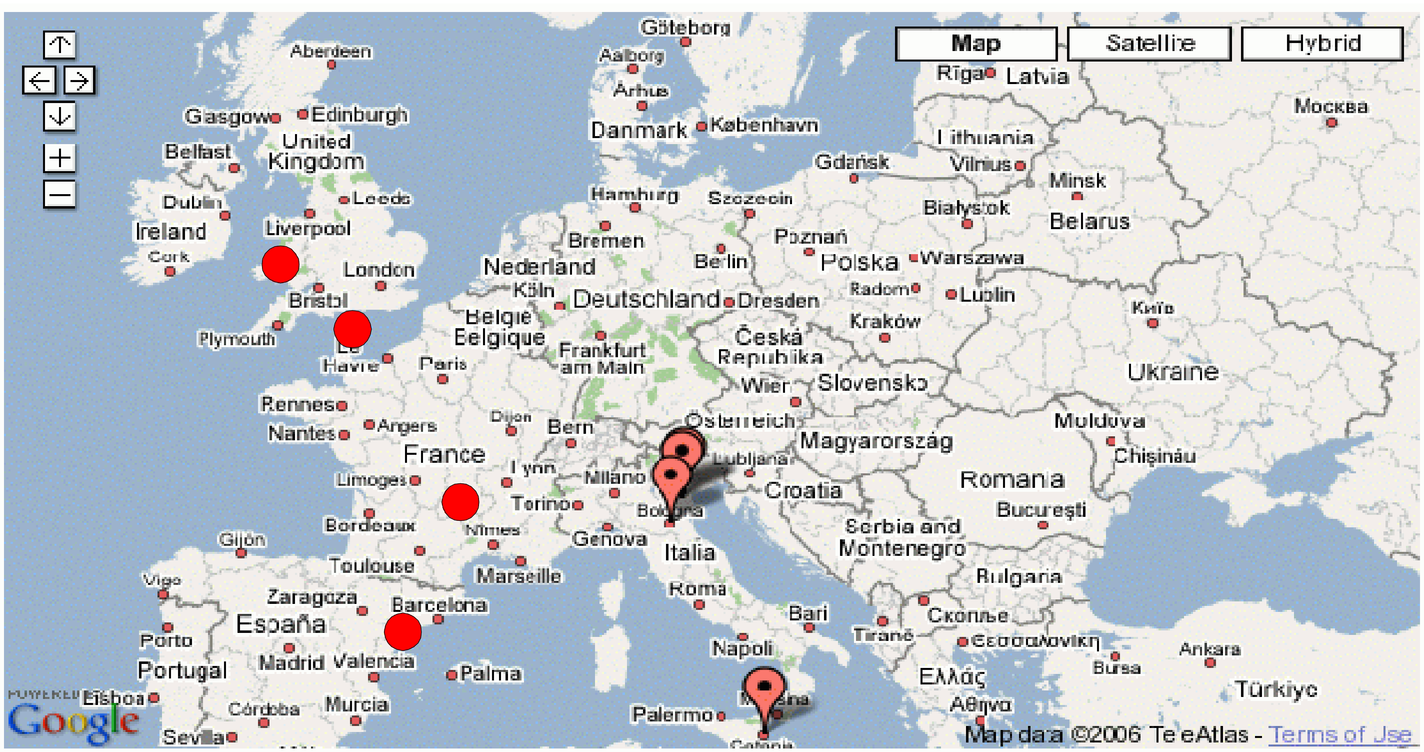


CDF Computing on LCG: LCGCAF

- Provides a single point of submission for CDF users, to LHC-Computing-Grid sites across Europe
  - CDF user interface, uses LCG tools underneath
- Accesses four INFN sites, two in Spain, two in UK & Lyon



Both LCGCAF and NamCAF have large potential expansion

- more sites
- More CPU/site