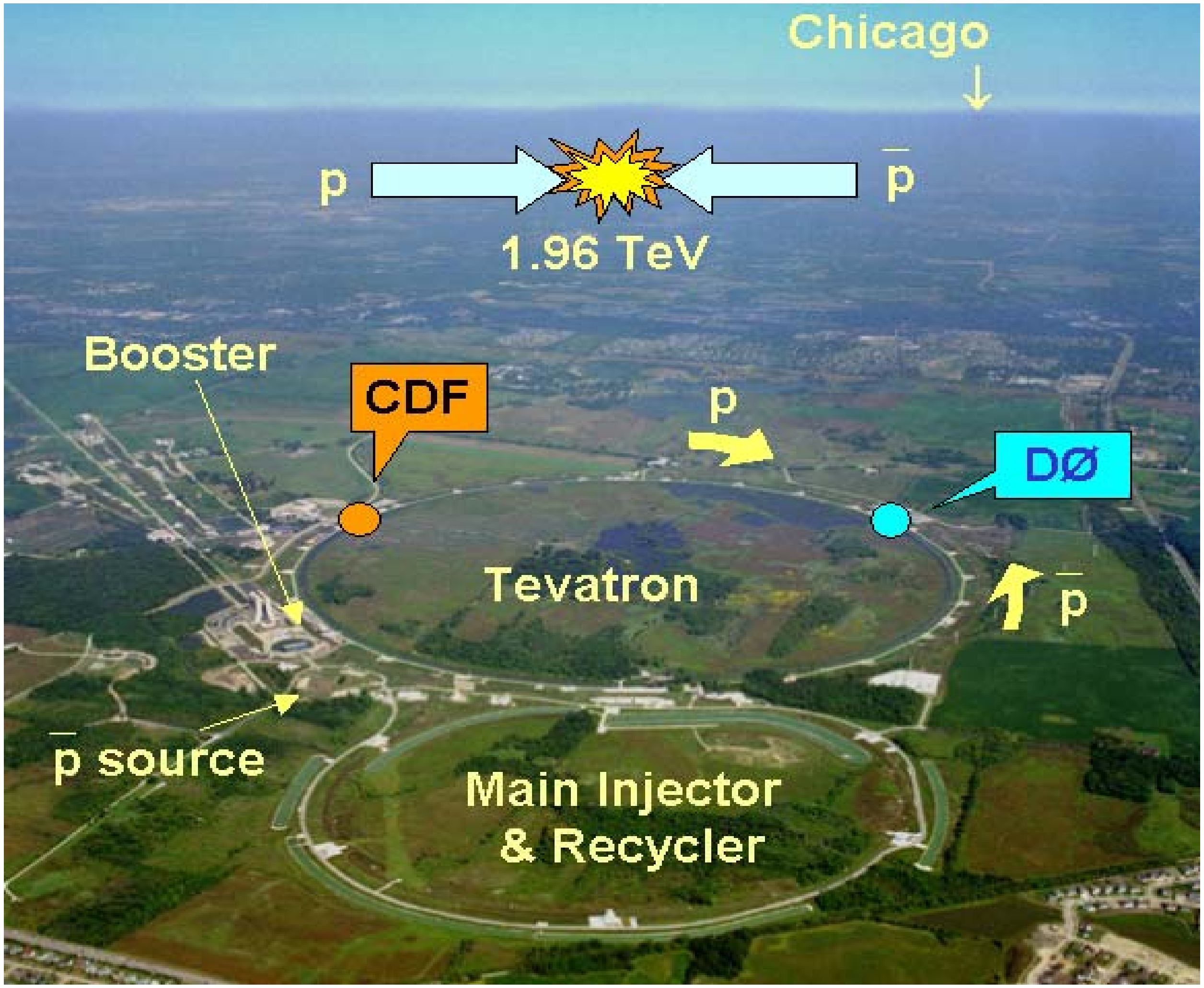
Tevatron Program - Status and Future Prospects

Outline

- Tevatron program goals
- The Tevatron
- Detectors and data
- Highlights of the recent Tevatron results
- Standard Model Higgs
- Future Tevatron experimental program
- Summary



Accelerator Division Seminar

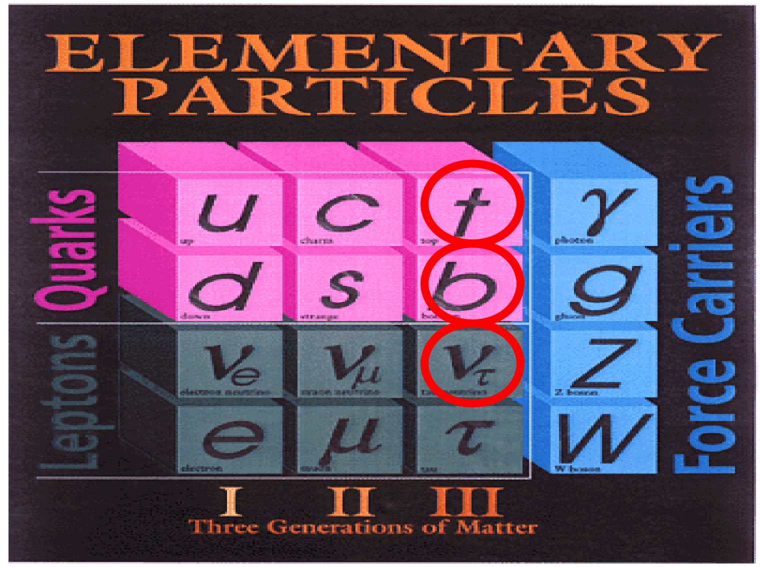
February 2, 2010

Dmitri Denisov, Fermilab

Disclaimer: DØ is used for majority of the examples, CDF in most cases has similar results

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

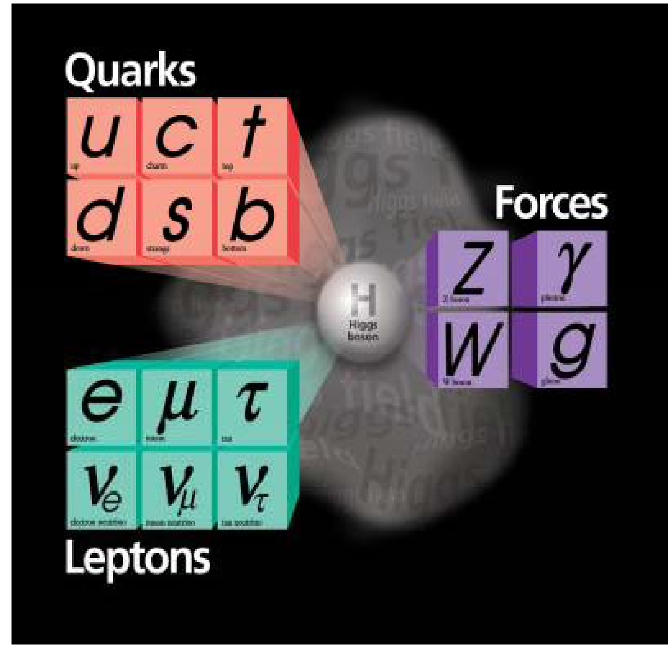
Tevatron Physics Goals

Precision tests of the Standard Model

- **Weak bosons, top quark, QCD, B-physics…**

Search for particles and forces beyond those known

- **Higgs, supersymmetry, extra dimensions….**



Fundamental Questions

Quark sub-structure?

Origin of mass?

Matter-antimatter asymmetry?

What is cosmic dark matter? SUSY?

What is space-time structure? Extra dimensions?…

Experimental Tools - Accelerators

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

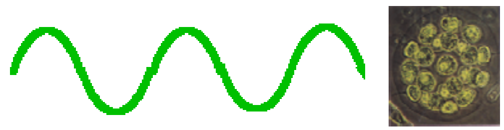
Wavelength = h/E

Electron microscope is better than optical!

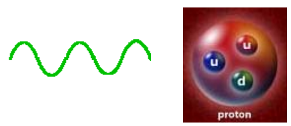
- **Accelerators are "converters" of energy into mass**

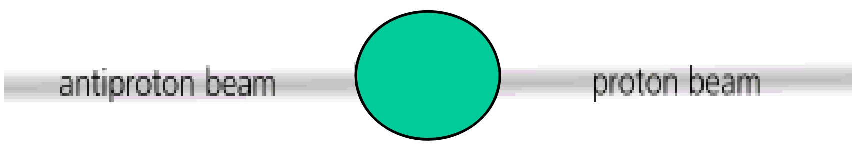
$E = mc^2$

Objects with masses up to
Mass = $2E_{beam}/c^2$ could be created



Cell





E_{beam} Mass E_{beam}

Tevatron collisions energy is 2000 GeV
or ~2000 proton masses
1 GeV = 1 proton mass

Tevatron: Proton-antiproton Collider

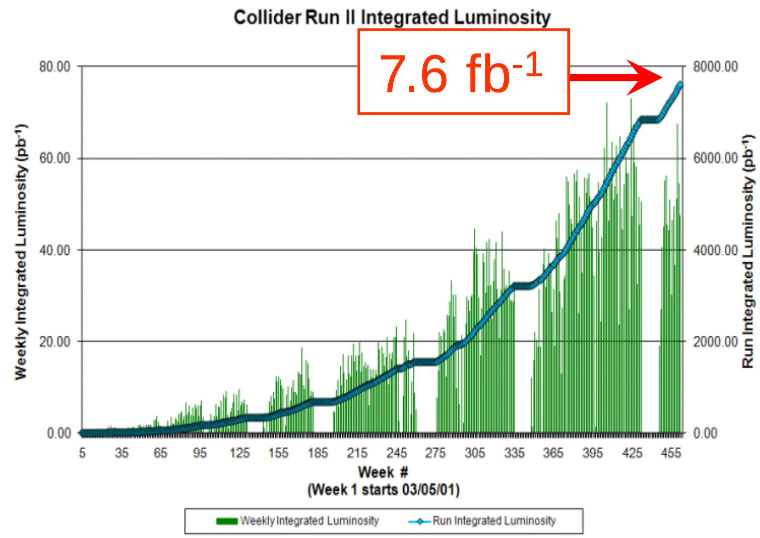
Colliding protons and antiprotons with 1.96 TeV center of mass energy

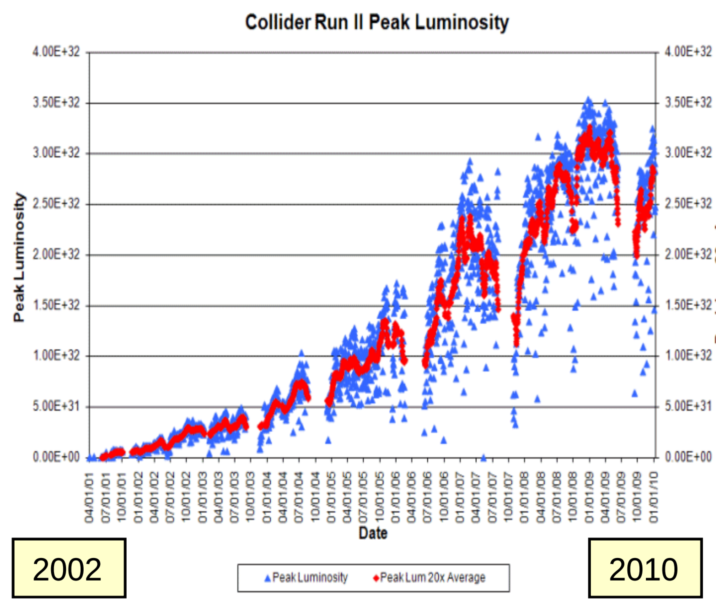
Energy and luminosity

$$N_{events}\,(sec^{-1}) = \sigma(E) \times L$$

	Run I	Run IIa	Run IIb
Bunches in Turn	6 × 6	36 × 36	36 ×36
√s (TeV)	1.8	1.96	1.96
Typical L ($cm^{-2}s^{-1}$)	1.6×10^{30}	9×10^{31}	3×10^{32}
∫ Ldt (pb^{-1}/week)	3	17	50
Bunch crossing (ns)	3500	396	396
Interactions/ crossing	2.5	2.3	8

Run I → Run IIa → Run IIb
$0.1\ fb^{-1}$ $\sim 1 fb^{-1}$ $\sim 12\ fb^{-1}$

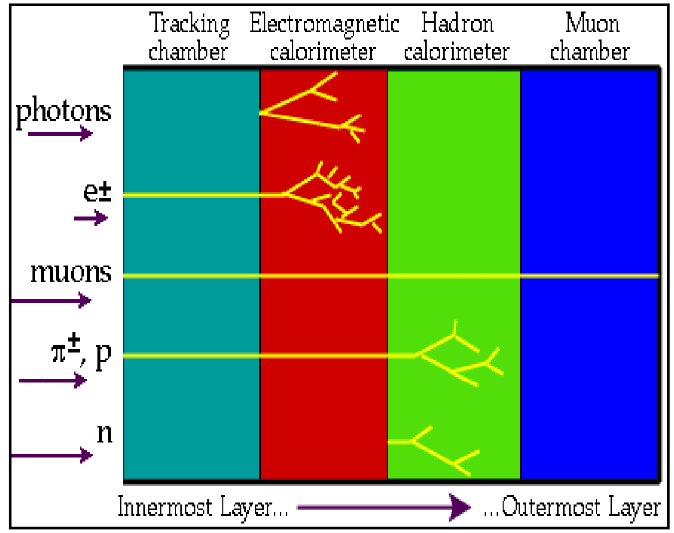




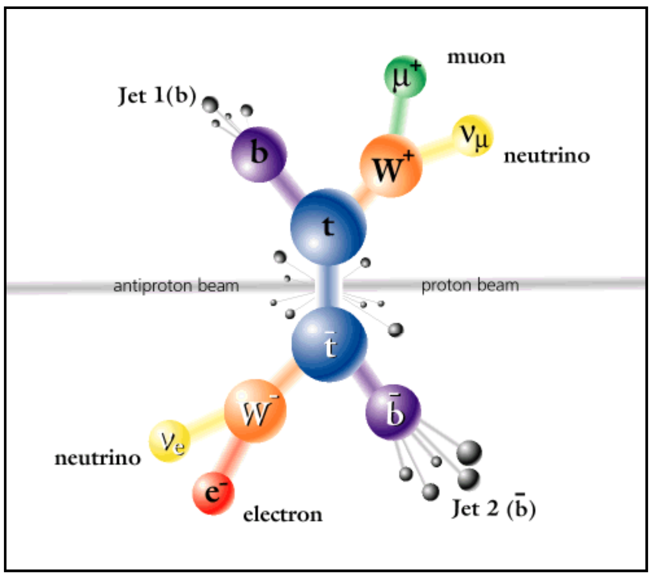
Thank you, AD!

How Physicists Detect Particles

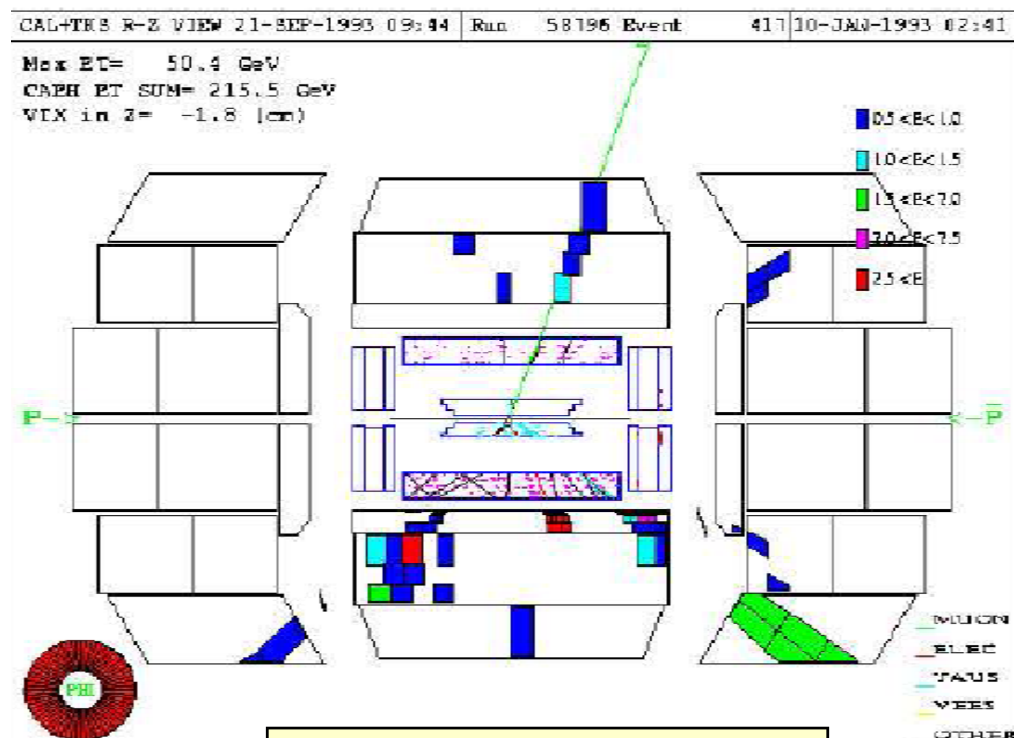
- Majority of produced particles decay into other particles almost immediately
  - Detectors surround interaction region
  - Many layers to detect different species
- Particles we study have very high energies large detectors are needed to absorb them
- We are taking millions of "pictures" per second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



Top quark pair production



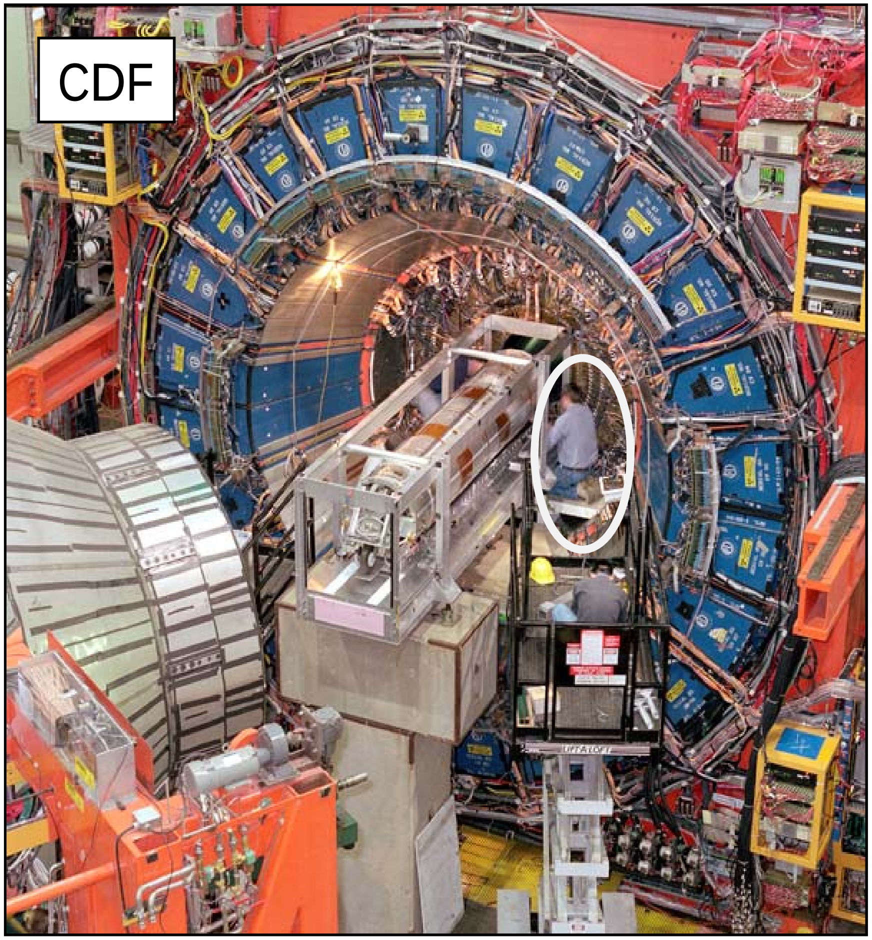
Mass of parent object could be reconstructed from decay products

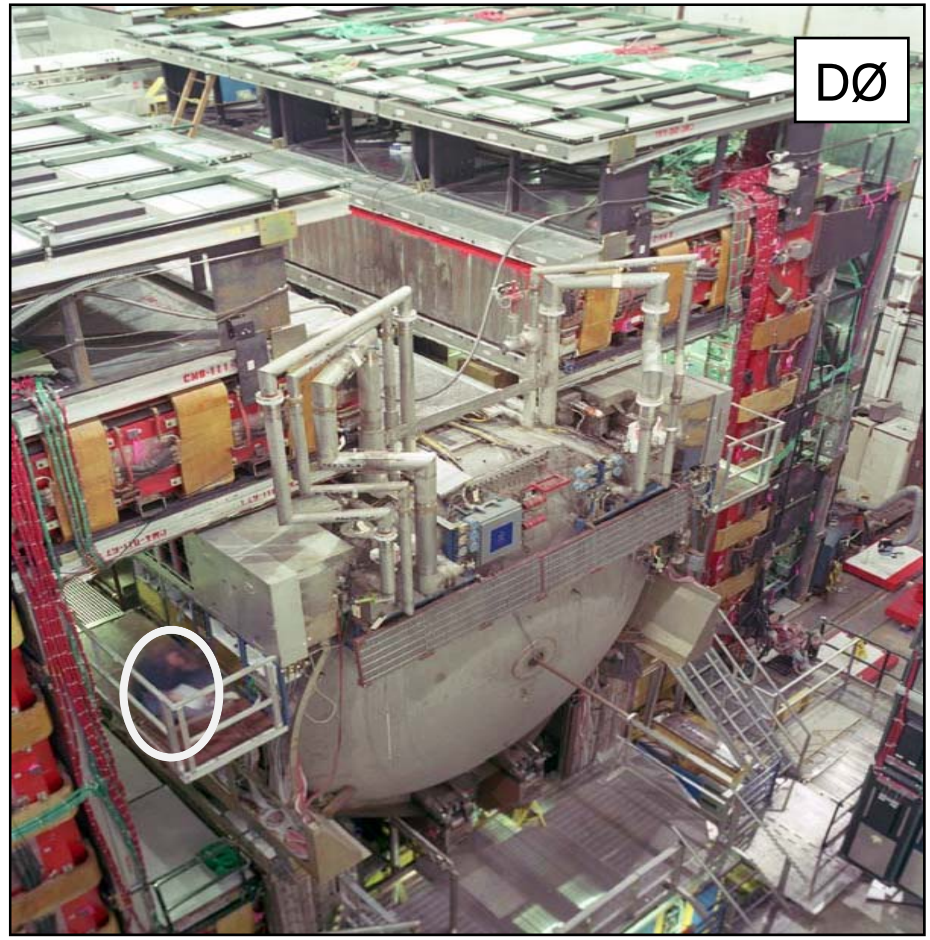


Top quark pair production event display

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

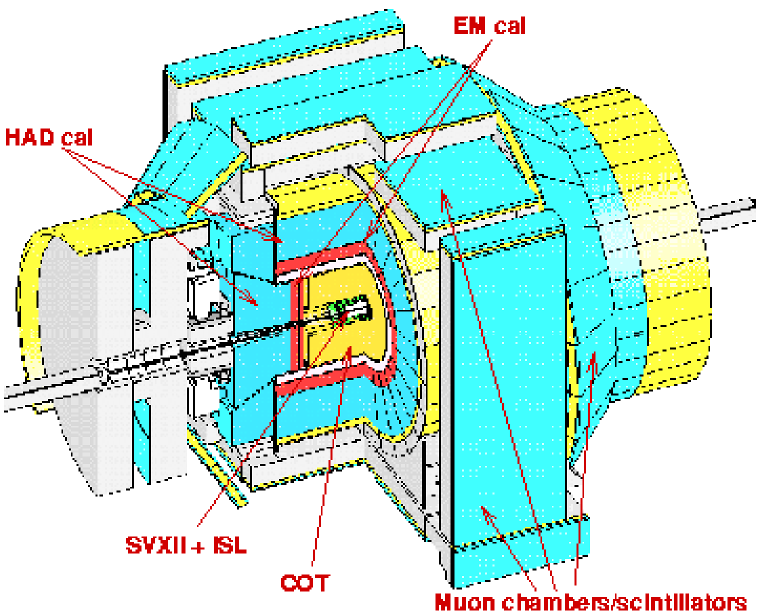




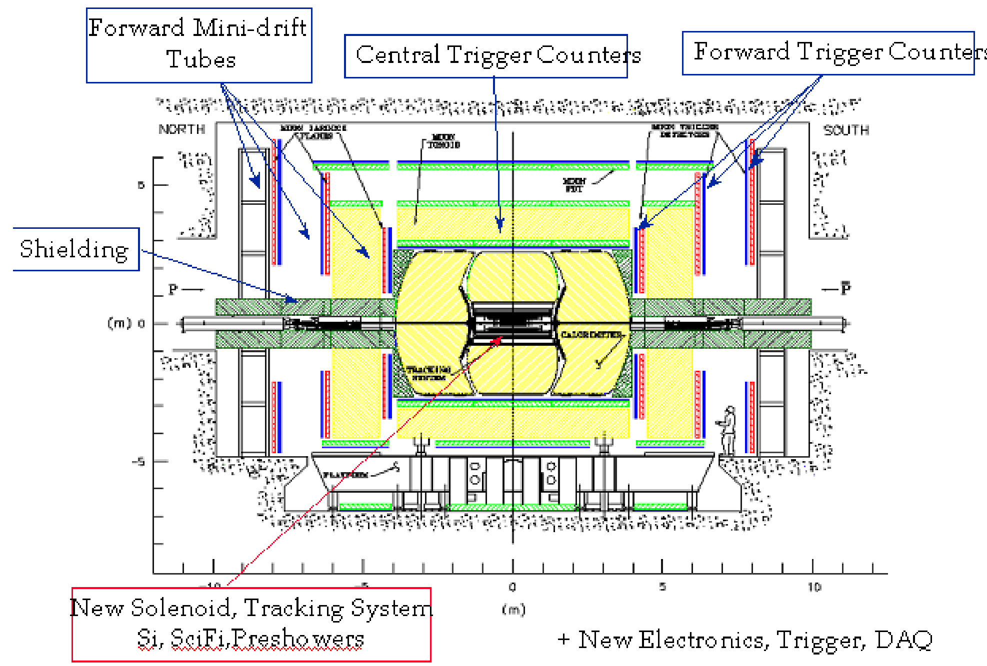
Why two detectors?
To verify results, to increase accuracy and chances to discover new phenomena, and to create healthy competition

CDF and DØ Experiments

CDF



DØ

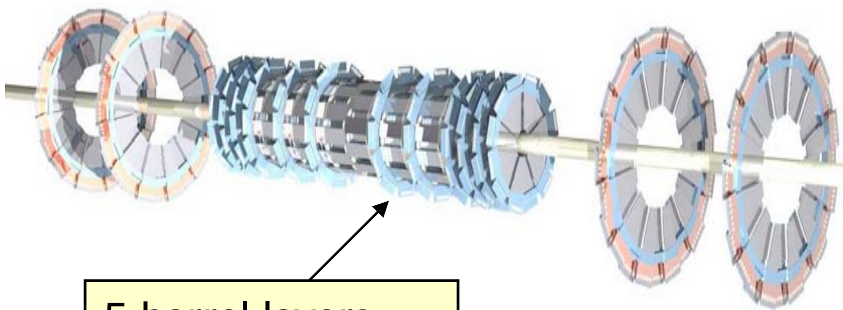


Silicon Detector
Central Drift Chamber
Calorimetry
Extended muon coverage
Fast electronics

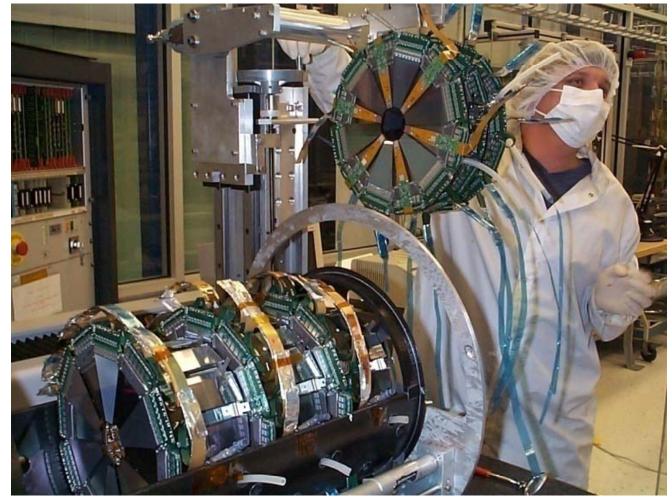
Silicon Detector
2 T solenoid and central fiber tracker
Large coverage muon system
Fast electronics

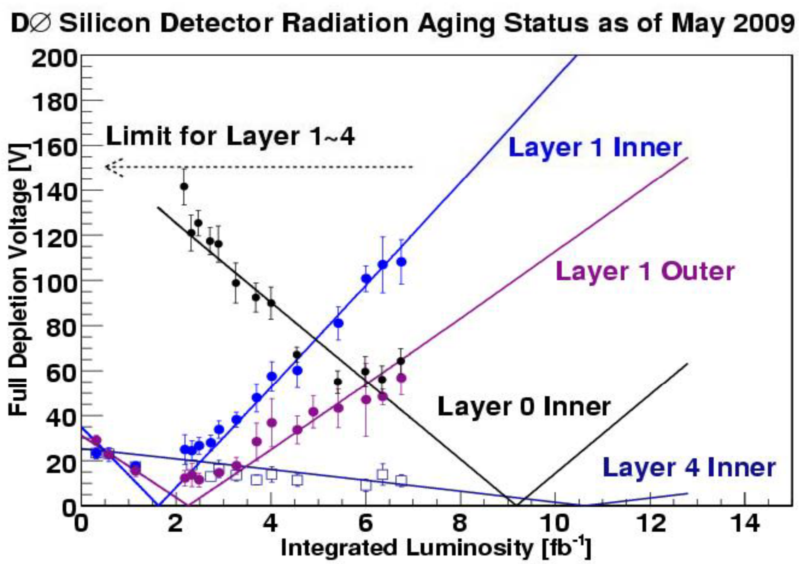
Driven by physics goals detectors are becoming “similar”:
silicon, central magnetic field, hermetic calorimetry and muon systems

Silicon Microstrip Tracker



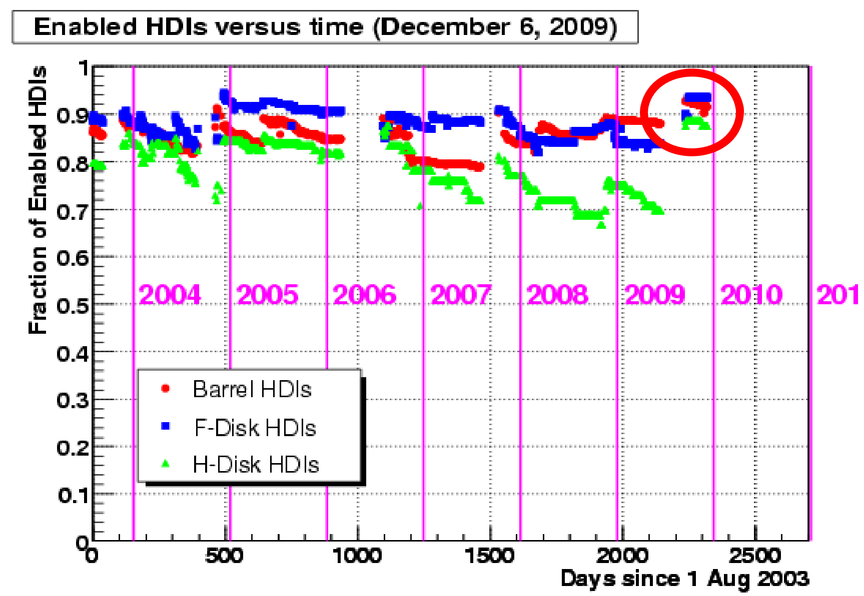
5 barrel layers
800k channels
~10 μm precision





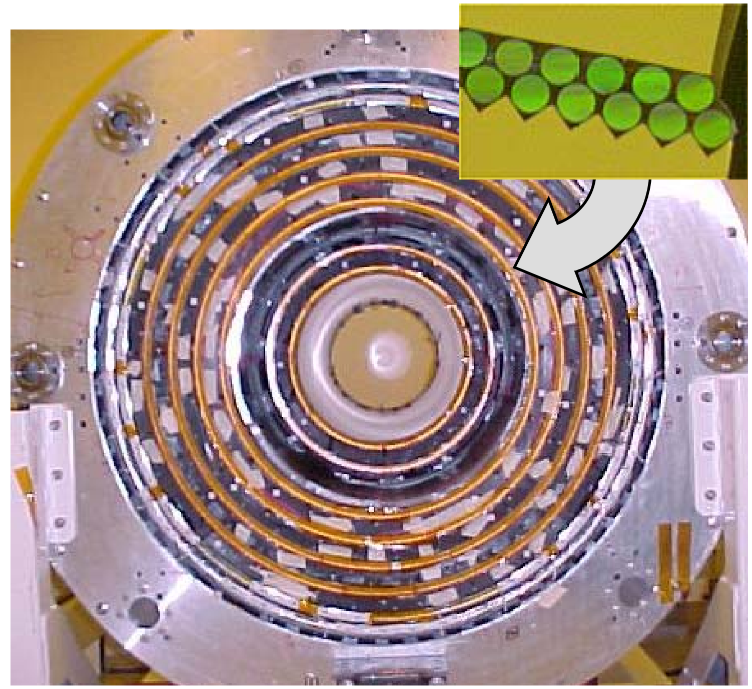
Radiation dose → no issues for running up to 12 fb^{-1} of delivered luminosity

Detector is working well
Stable number of operating sensors

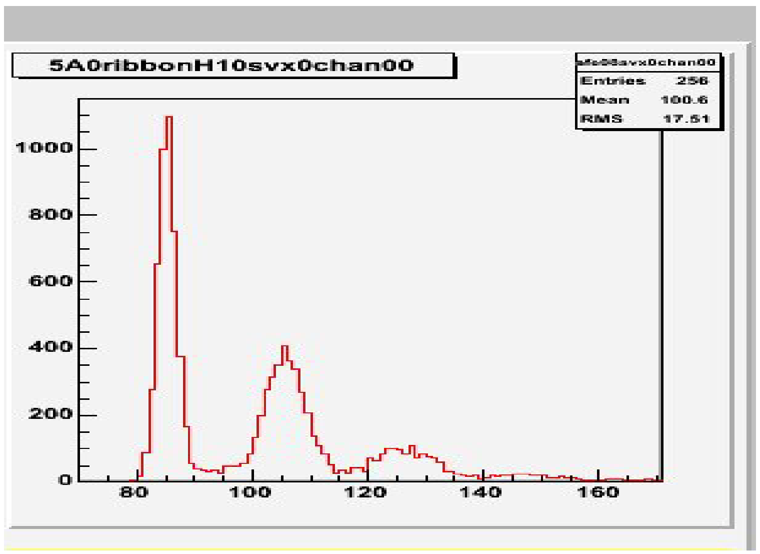


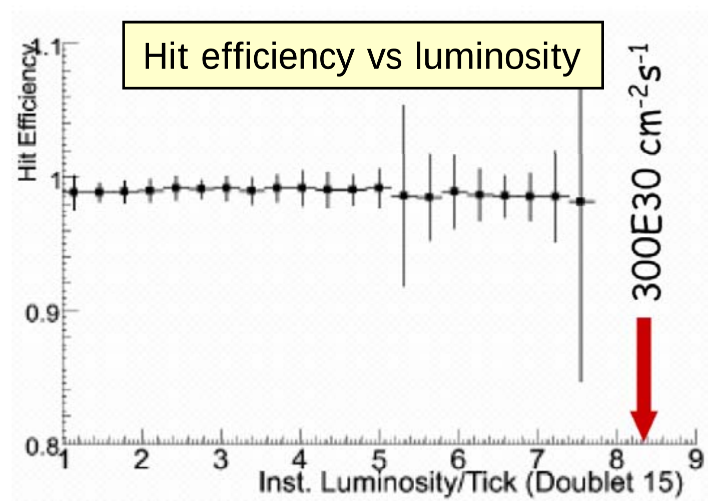
Scintillating Fiber Tracker

- 8 fibers double layers, 1mm in diameter
- Visible Light Photon Counters (VLPC) readout
  - Light yield of ~7 photo electrons/charged particle
- ~77,000 channels



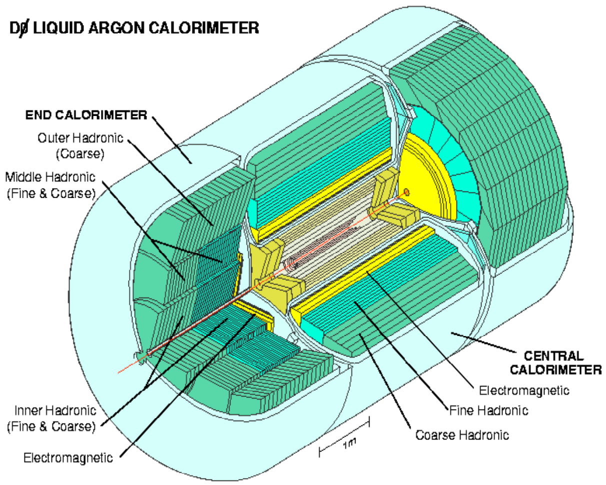
Single photo-electron peaks





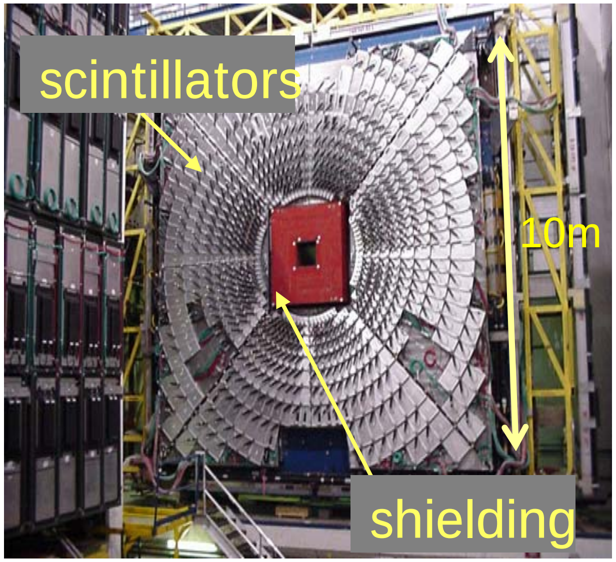
Fiber tracker and silicon detector are running in 1.9T magnetic field created by superconducting solenoid

Calorimeter and Muon System

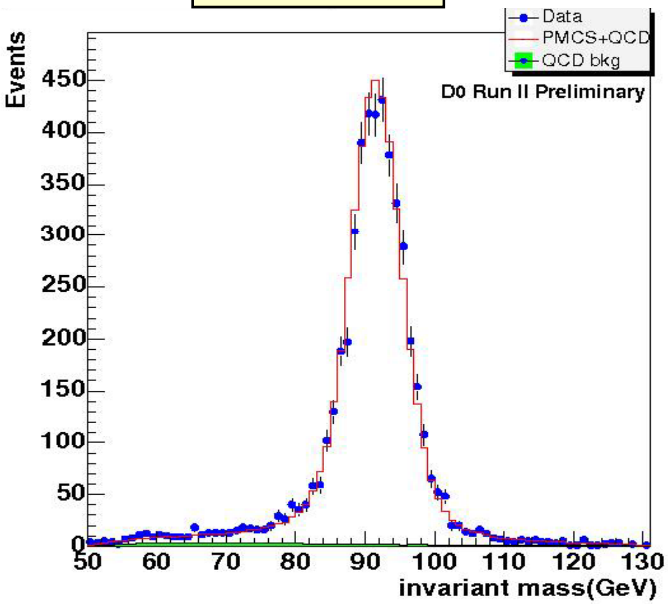


Uranium Liquid Argon calorimeter
Drift tubes and scintillation counters based muon system

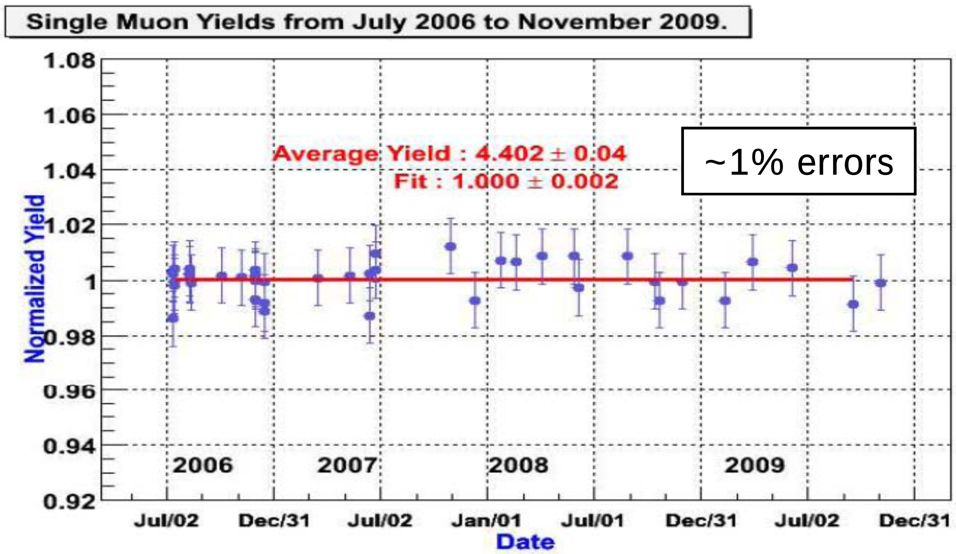
~50,000 channels in each system



$Z \rightarrow e^+e^-$



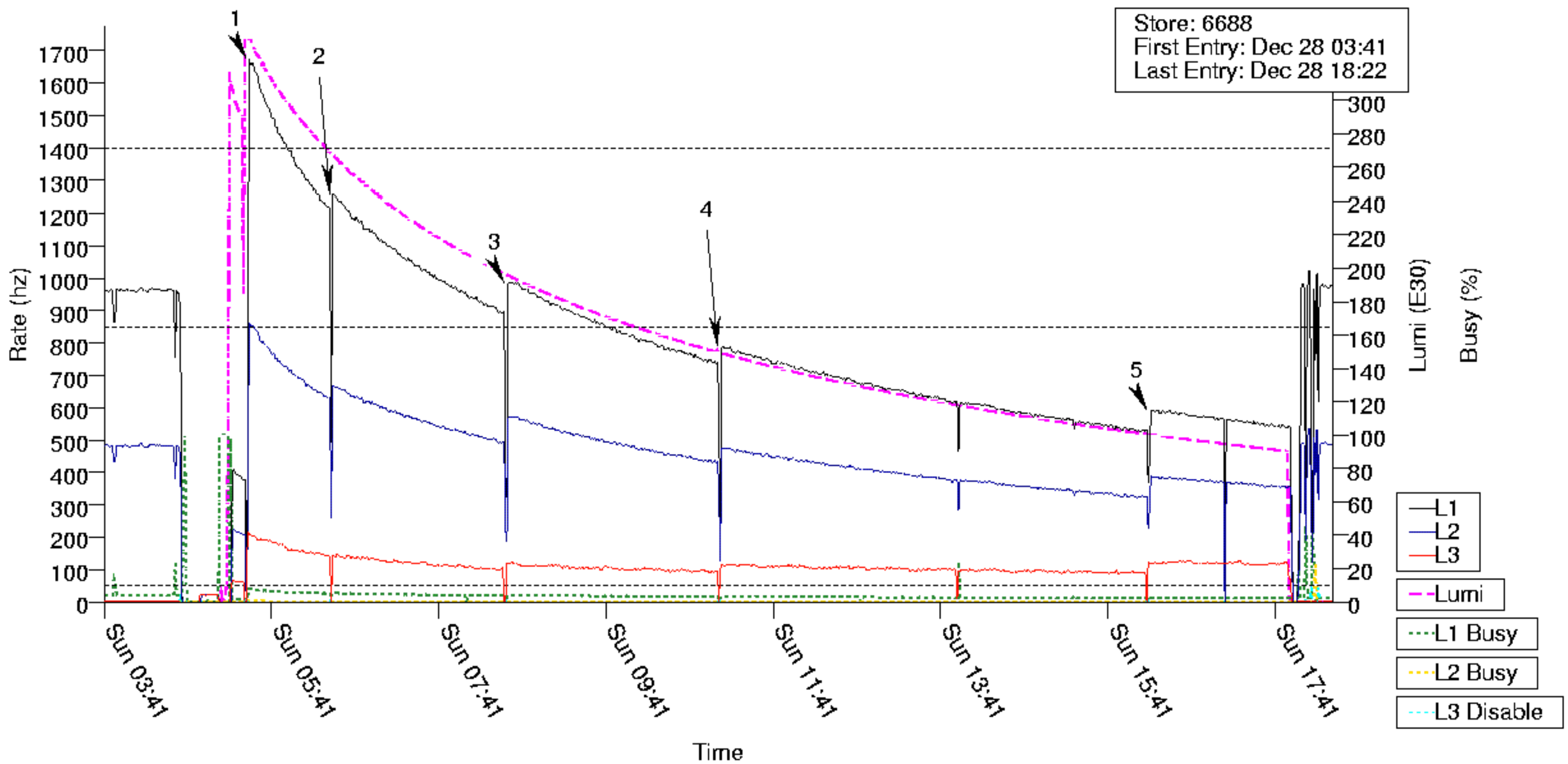
Monitoring of muon system stability using inclusive muon production



Triggering

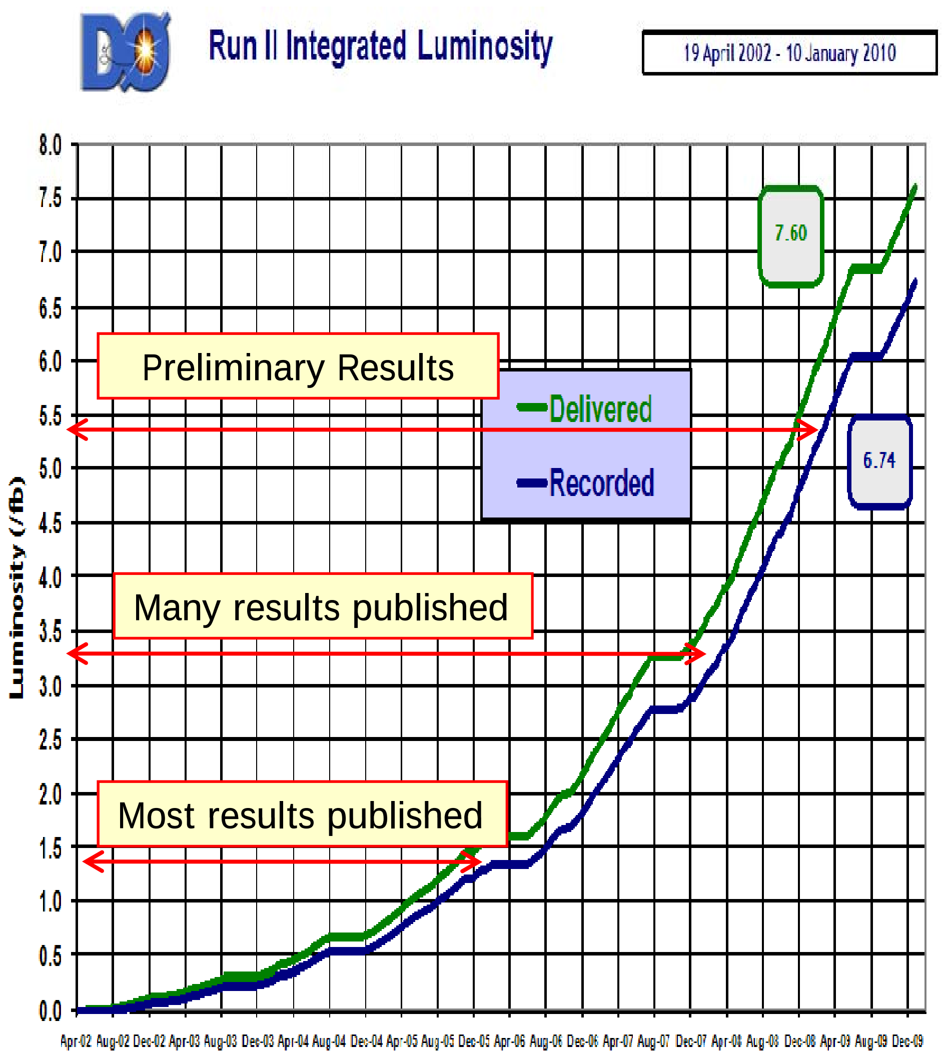
Rate of interactions between protons and antiprotons is ~10 MHz

Only ~100 events per second could be written to tapes – select them with 3 level "trigger system" very quickly marking interesting events such as with possible Higgs production and decay



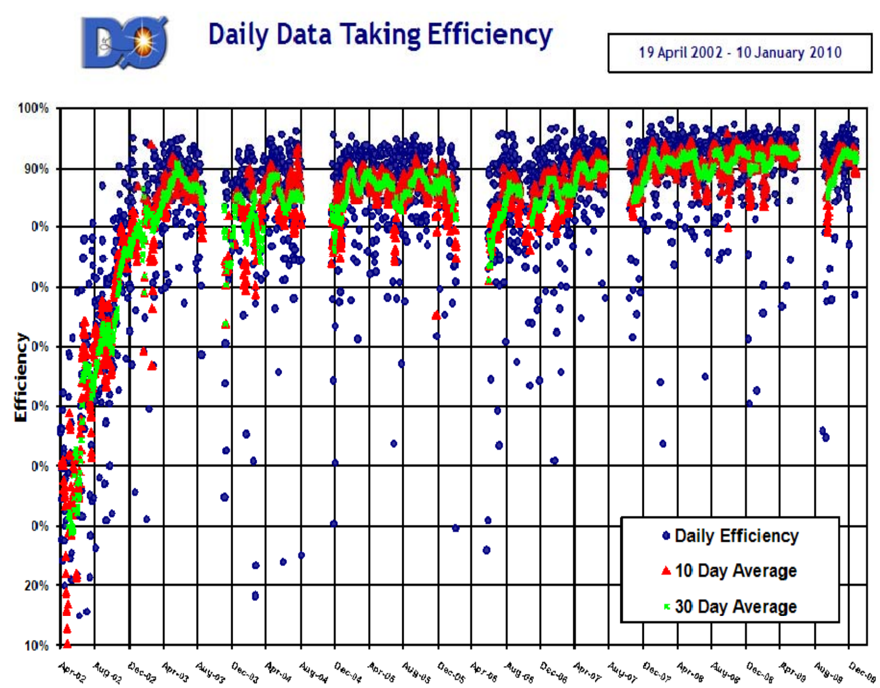
Typical store with starting luminosity of $3.5 \cdot 10^{32}$ cm^{-2}sec^{-1}

Data Collection



2002 **January 2010**

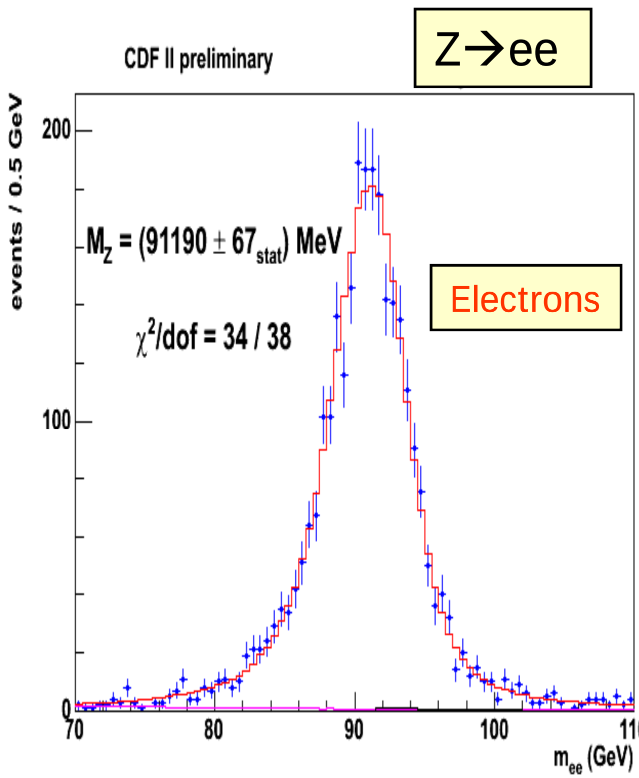
- **Smoothly recording physics data**
  - **Typical week ~50 pb^{-1}**
- **On average 92% data taking efficiency**
- **As of today DØ has ~6.7 fb^{-1} on tapes**

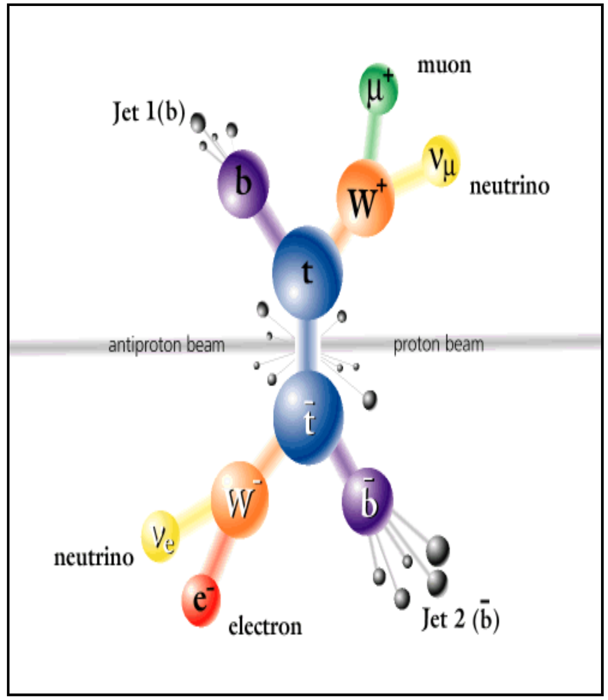


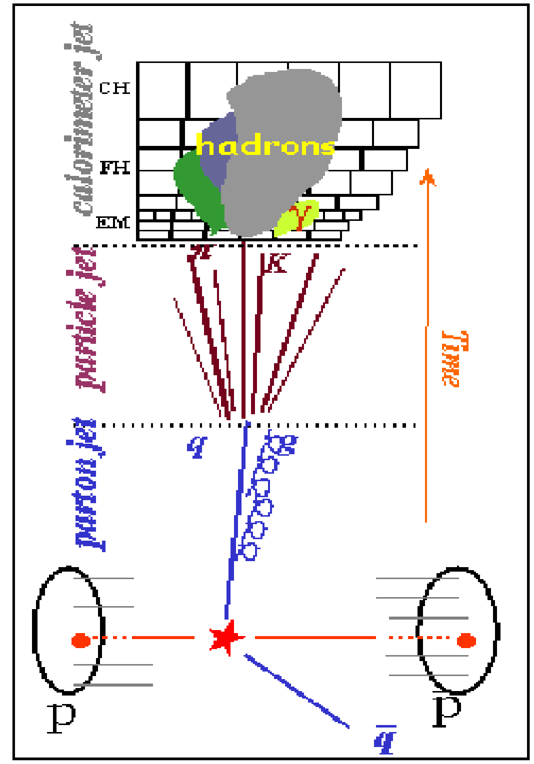
2002 **January 2010**

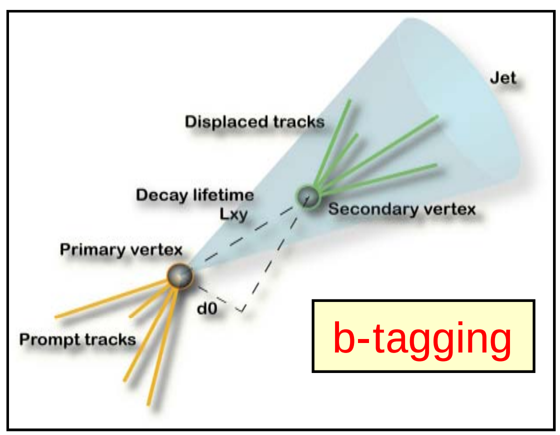
Detectable Objects – Particle Identification

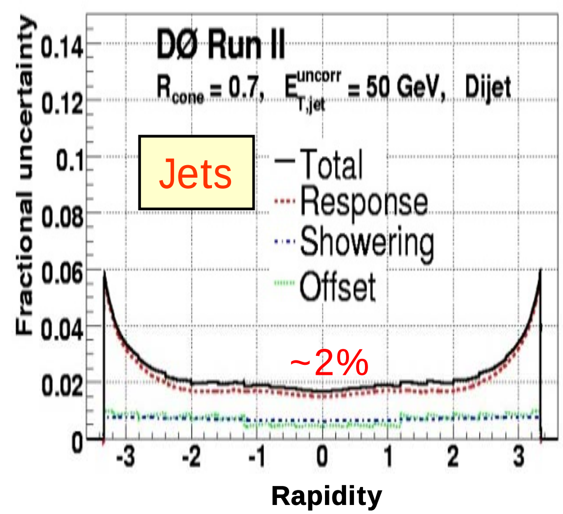
Final decay products
→ electrons
→ muons
→ charged tracks
→ jets (b)
→ missing E_t (ν)
Detection and MC optimization using well known objects





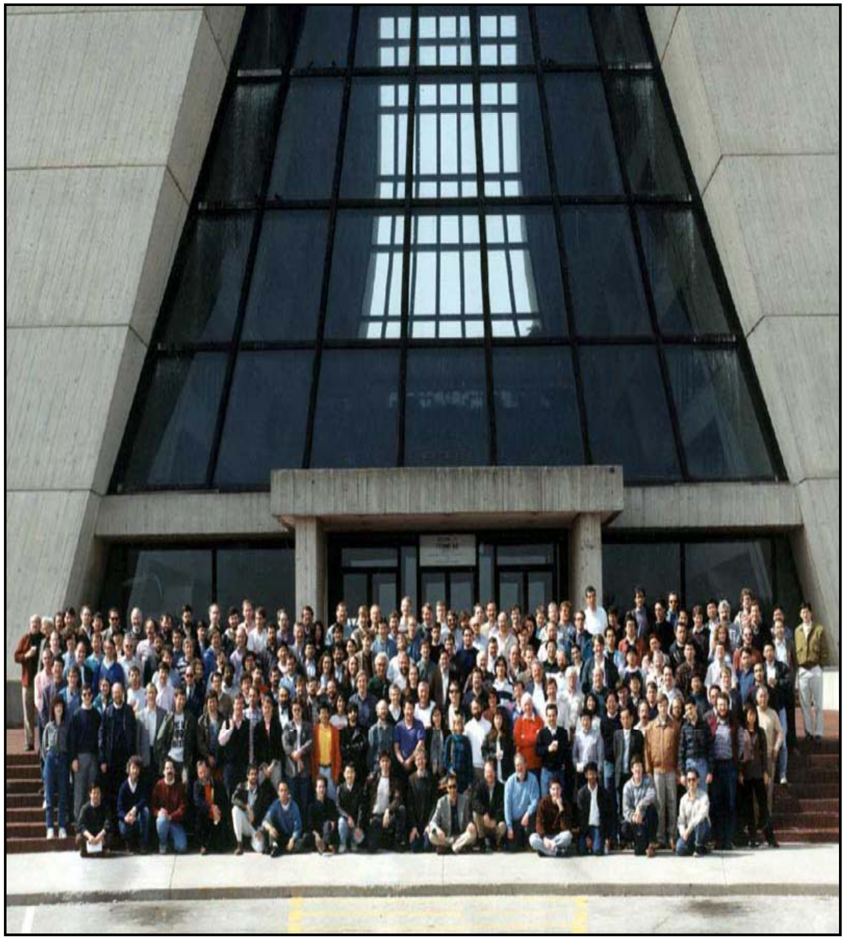






CDF and DØ Collaborations

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 : ~600 physicists, 15 countries, 63 institutions

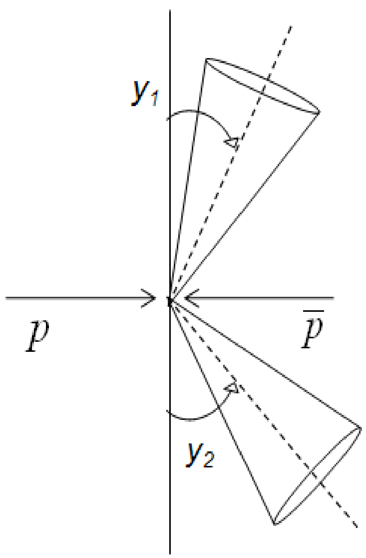
DØ : ~510 physicists, 18 countries, 90 institutions

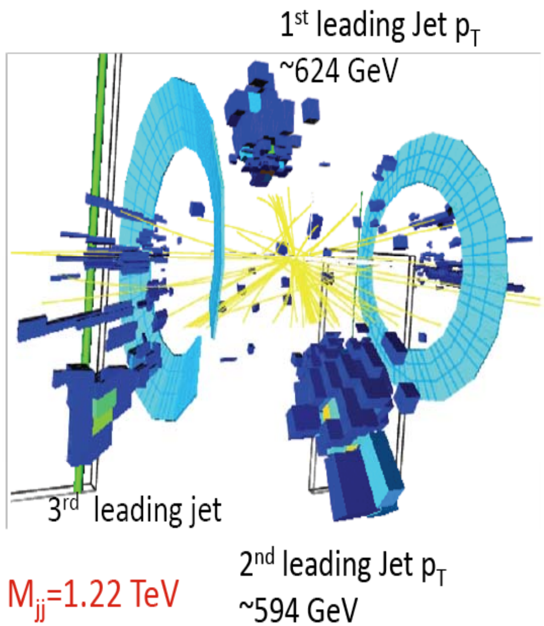
QCD Studies

Inclusive jet cross sections

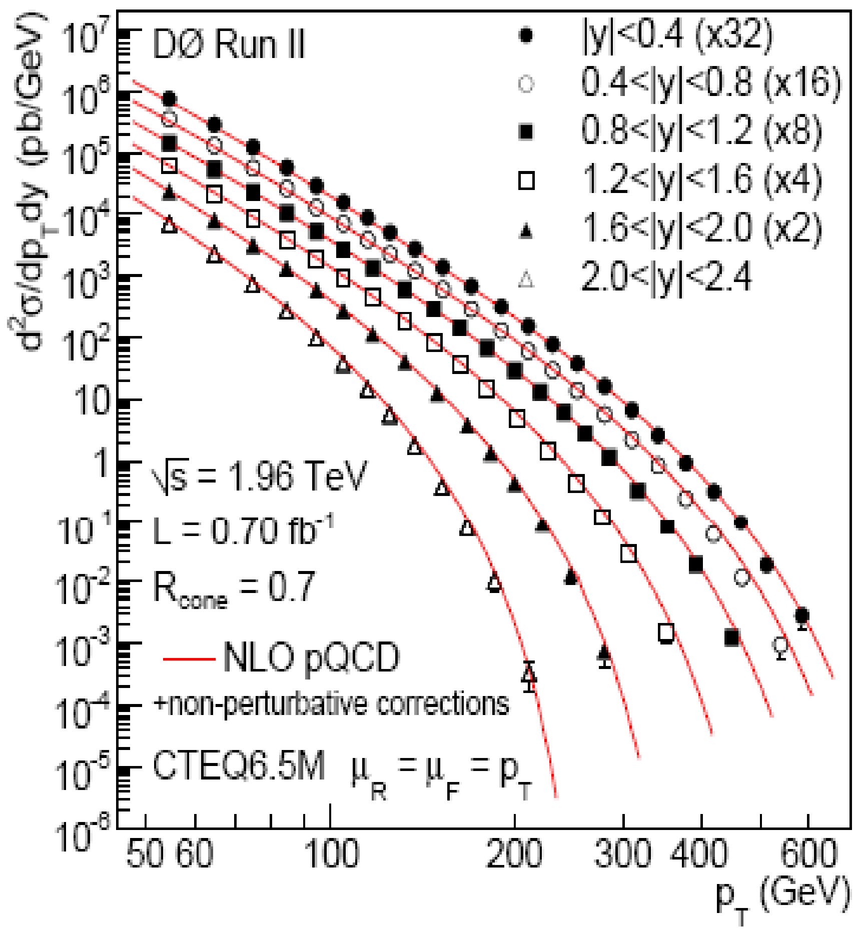
Use partons scattering to study proton structure
- Quarks sub-structure? Rutherford style experiment

- Measured in the widest kinematic region
  - In rapidity and transverse momentum
- 8+ orders of magnitude σ changes
- In agreement with theory predictions



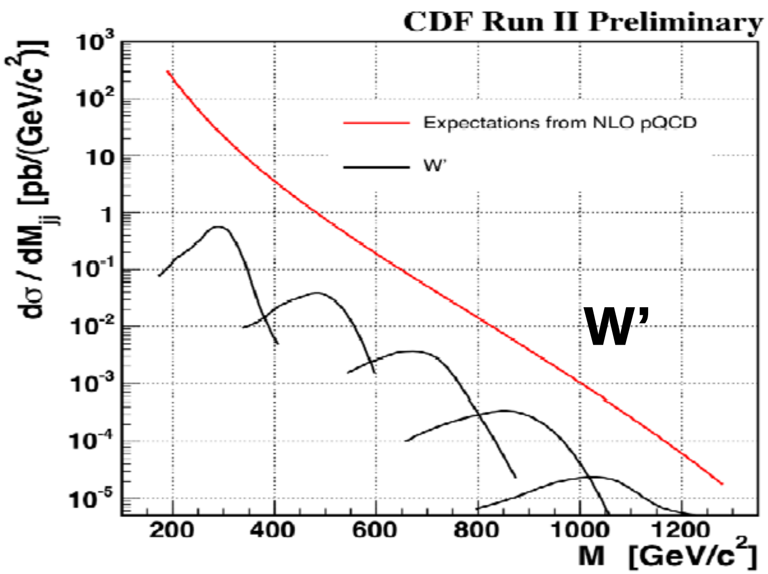


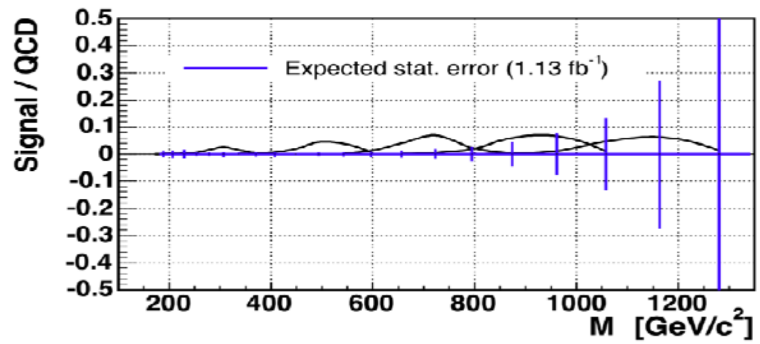
1TeV energy deposition!

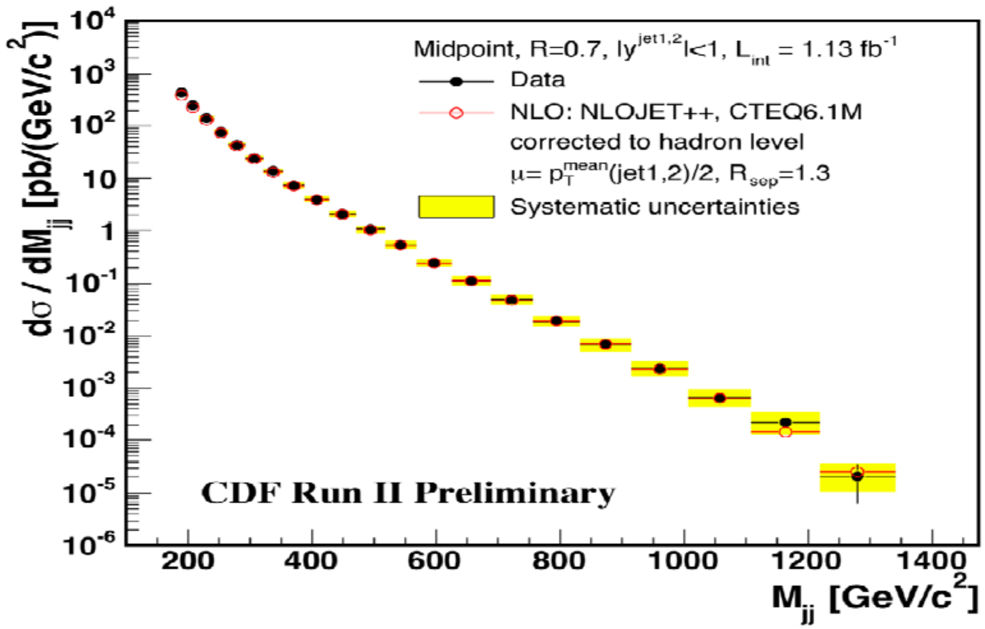


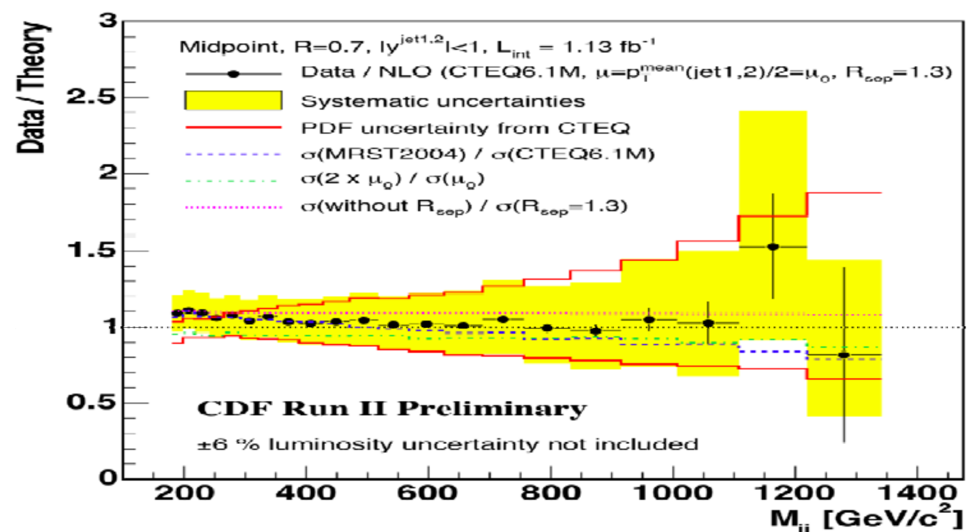
Di-jet Resonances

- Di-jet resonances predicted in beyond Standard Model theories
- Masses up to 1.2 TeV studied









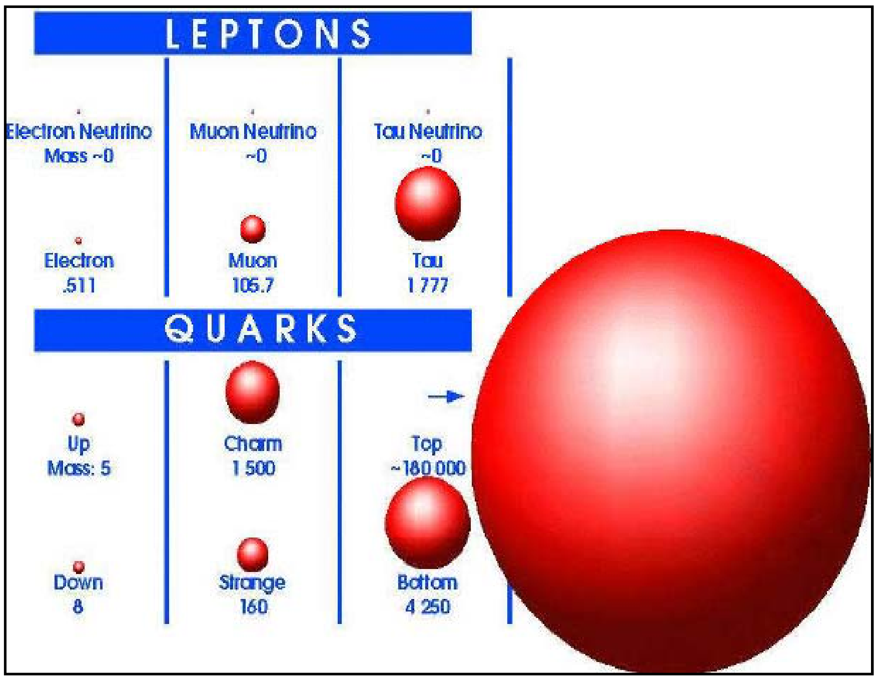
No W' observed for now…

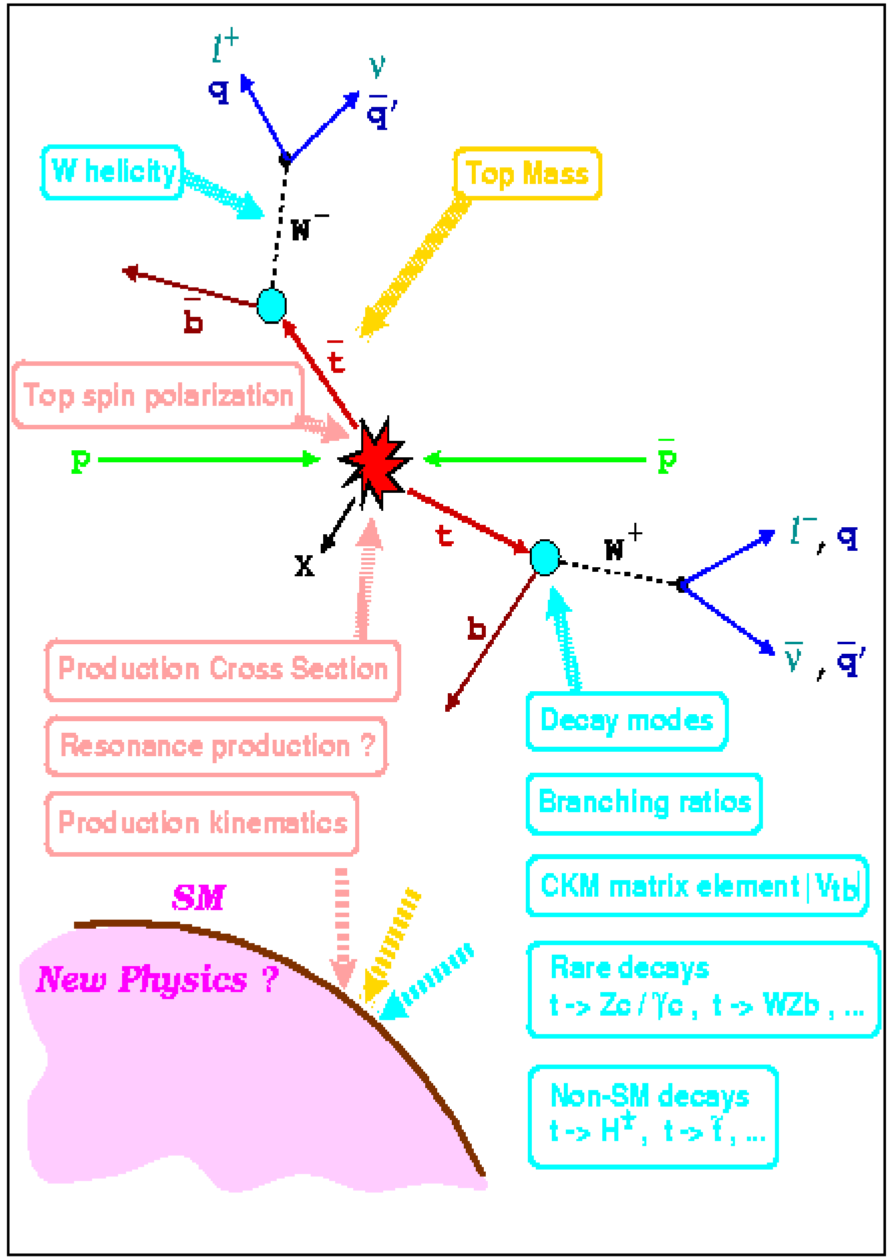
Top Quark Studies

Heaviest known elementary particle: 173 GeV

→Measure properties of the least known quark
- mass, charge, decay modes, etc.
- data sets of 1000's of top quarks exist

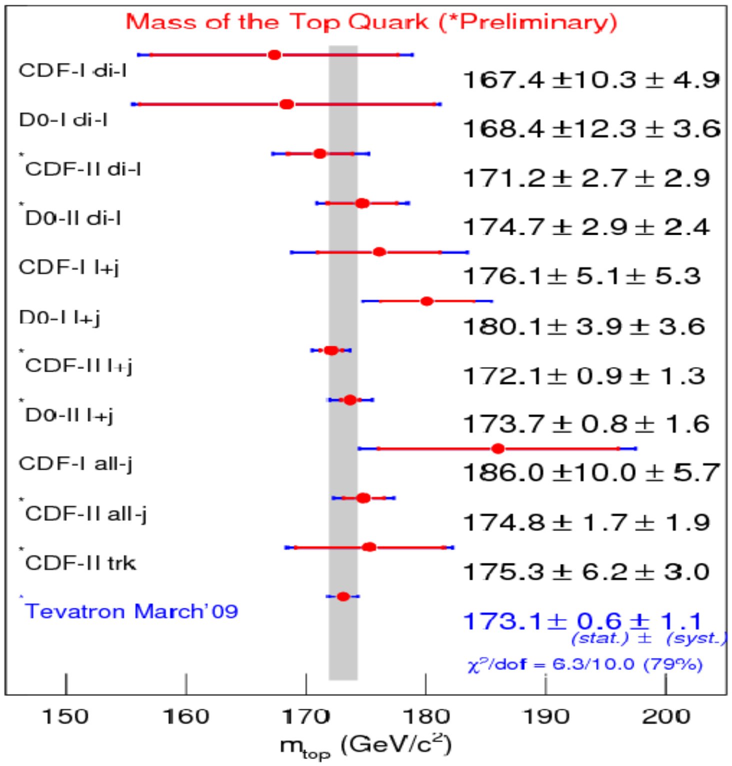
→ Short life time: probe bare quark



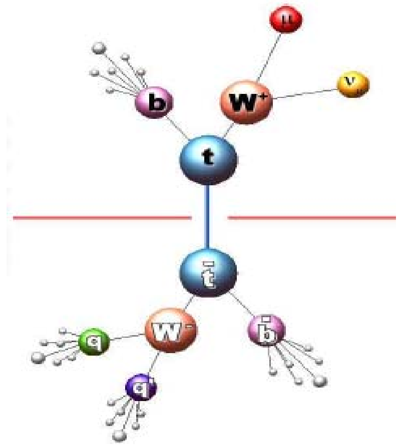


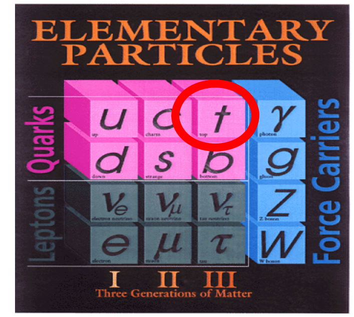
Top Quark Mass Measurement

- Top mass is measured using decay products in many different channels
- Lepton+jets channel with two jets coming from W boson is the most precise

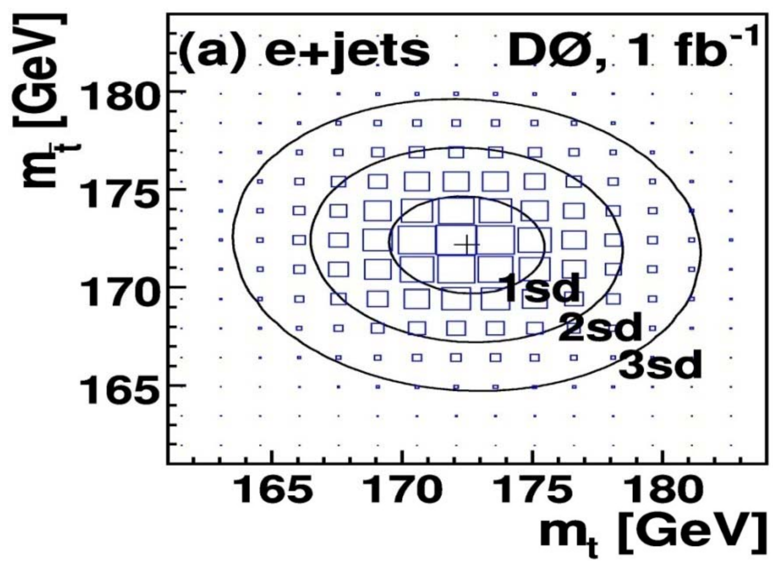


DØ and CDF combined top mass result
m_t = 173.1±1.2 GeV
0.7 % accuracy
Best (of any) quark mass measurement!





First measurement of quark-anti quark mass difference: CPT test in quark sector

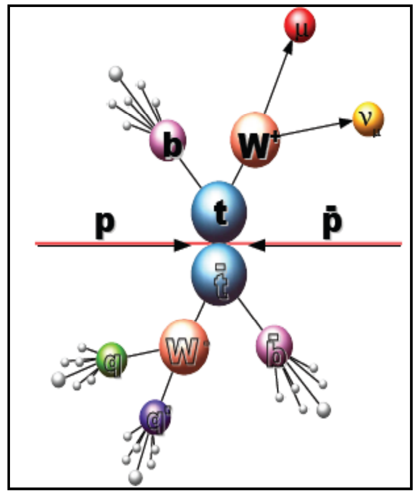


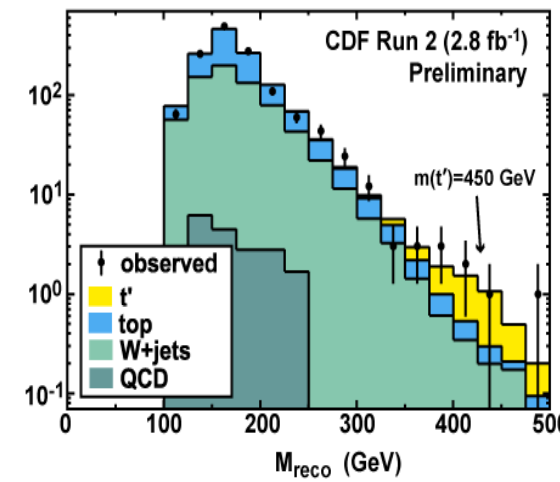
$$m_t - m_{\bar{t}} = 3.8 \pm 3.7\,\mathrm{GeV}$$

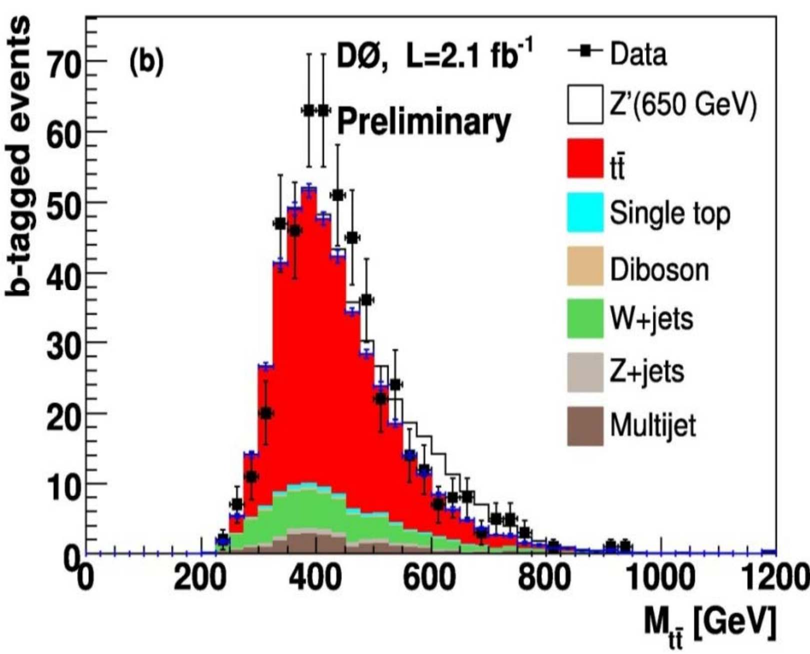
Search for New Physics in Top Quark Sector

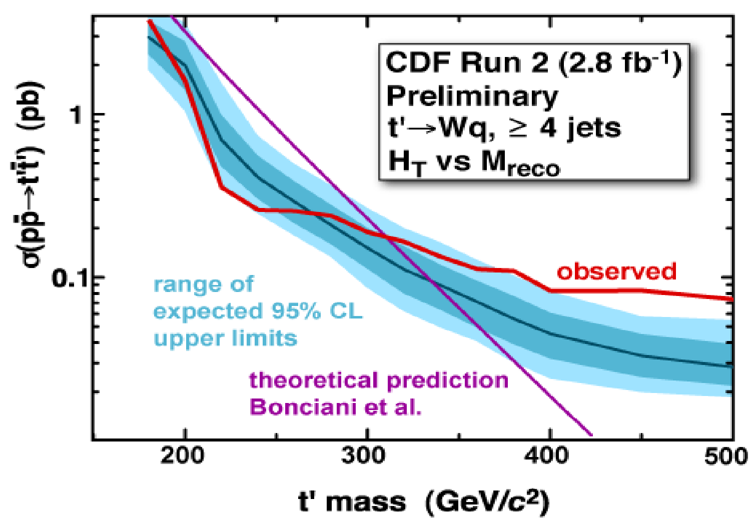
- In the Standard Model top decays before hadronization
- Theories beyond Standard Model predict existence of resonances
- Search for narrow resonance optimised at high masses
  - Using reconstructed 4-momenta of two top quarks

Heavy t' quark search in the top samples in t't'→WqWq









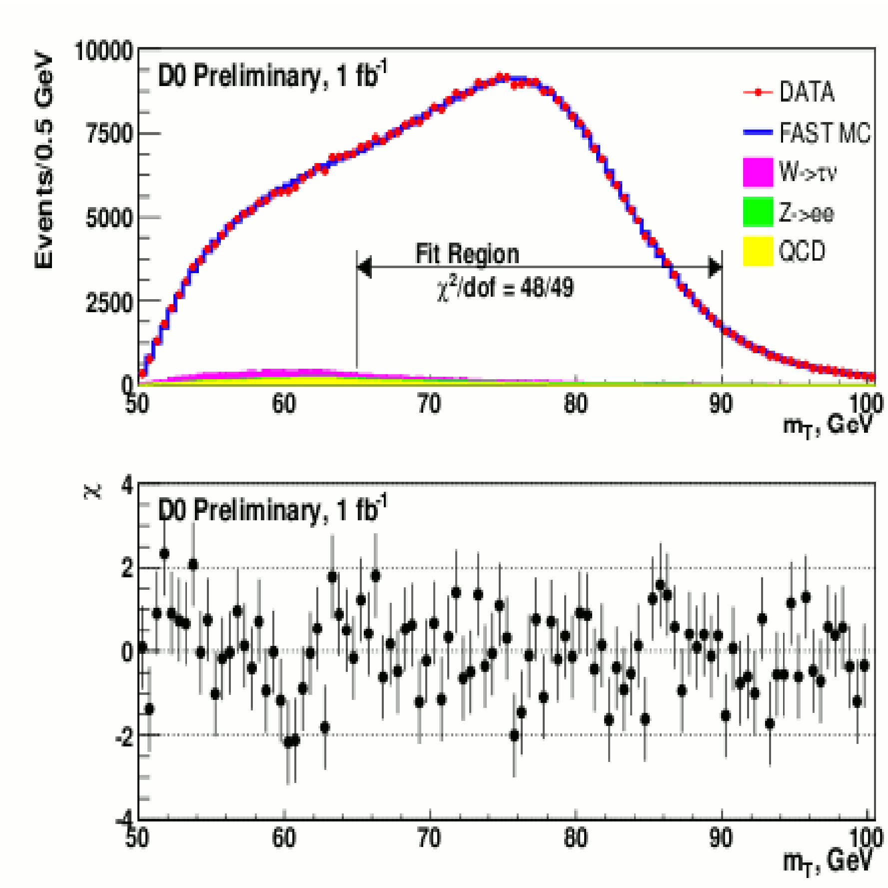
Excess?!

$$m_{t'} > 311\,GeV\ @\ 95\%\ CL$$

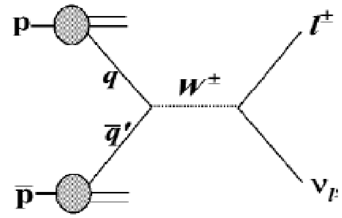
Electroweak Physics

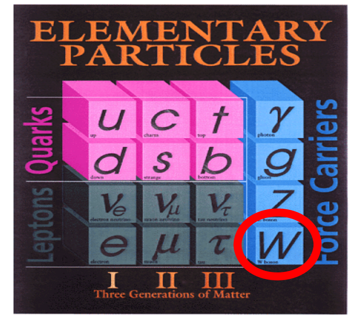
Indirectly constrain new physics through precision measurements of electroweak parameters
Measure single and multi-boson production, W mass, W production asymmetry,...

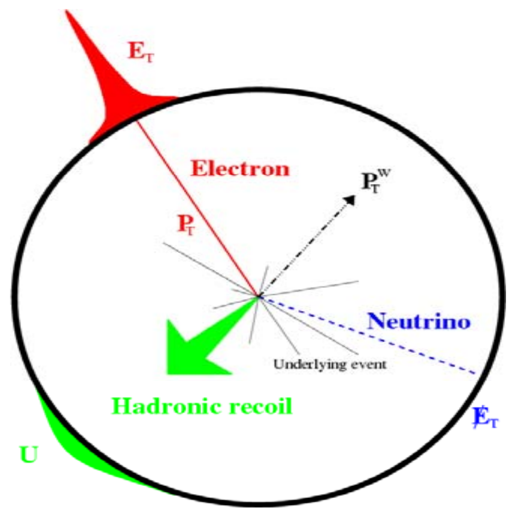
World most precise W mass measurement



80.401 ± 0.021(stat.) ± 0.038(syst.) GeV



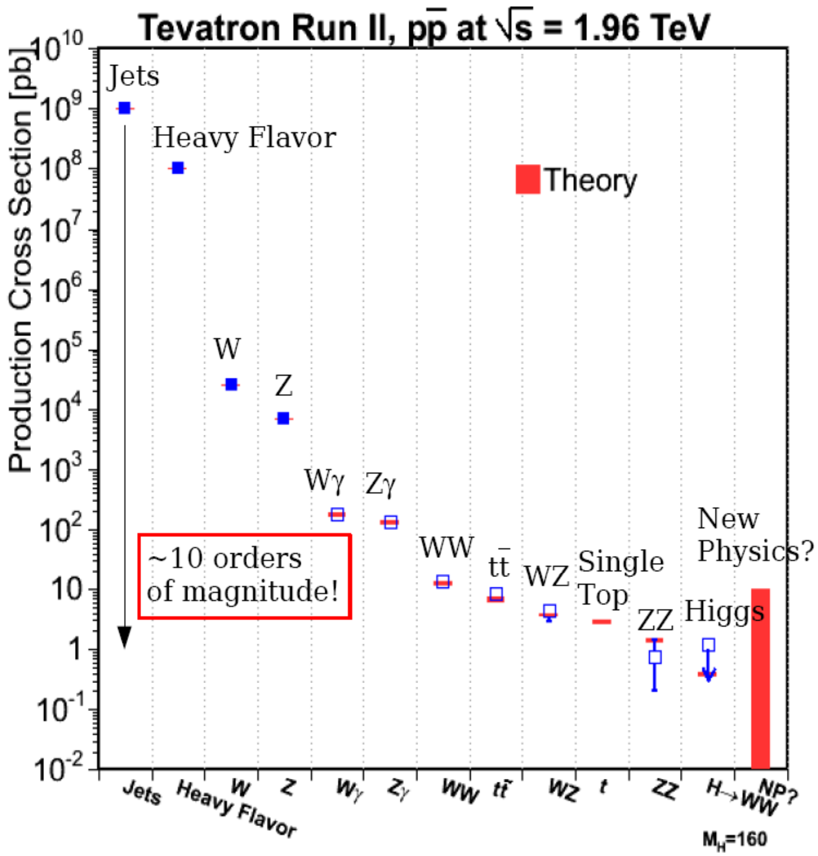


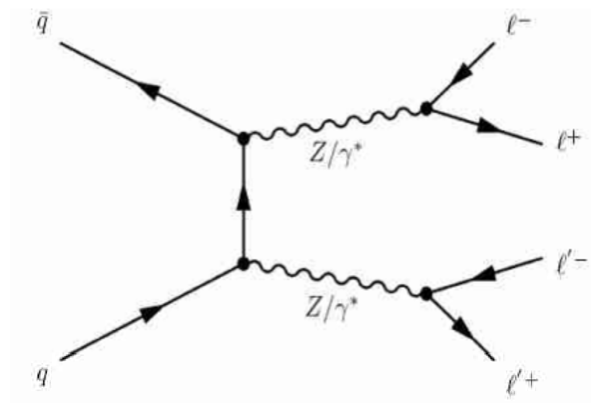


World average is now
80.399 ± 0.023 GeV (0.025%)
Helps to predict Higgs mass

Studies of di-boson Production

Detect very rare processes, search for anomalous vector boson couplings and develop experimental methods for Higgs hunting

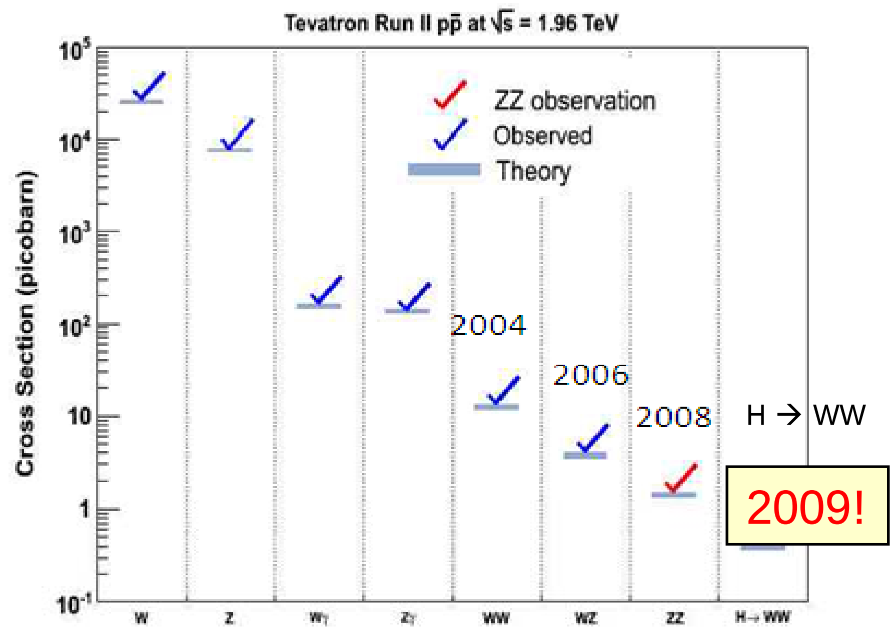




ZZ has the smallest di-boson cross section

$\sigma(ZZ) = 1.6 \pm 0.1$ pb

... next lower is the Higgs



Dmitri Denisov, AD Seminar, 02/02/10

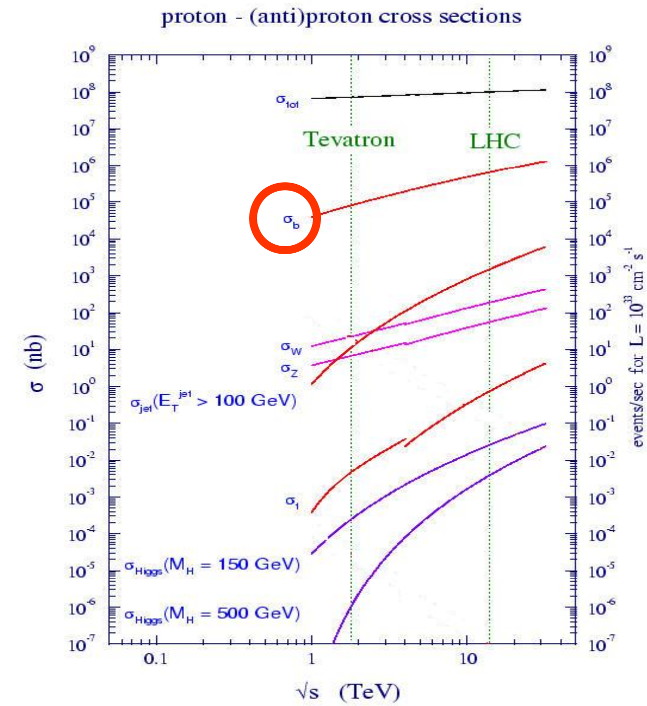
b Quark Studies

High b quark cross section: ~10^{-3} σ_{tot}

~10^4 b's per second produced!

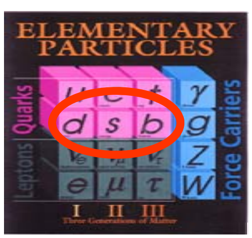
All b containing species are produced

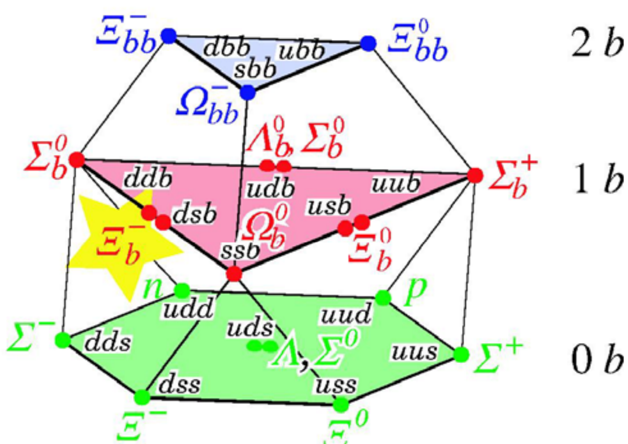
$B^{\pm}$, B^0, B_s, B_c, Λ_b…

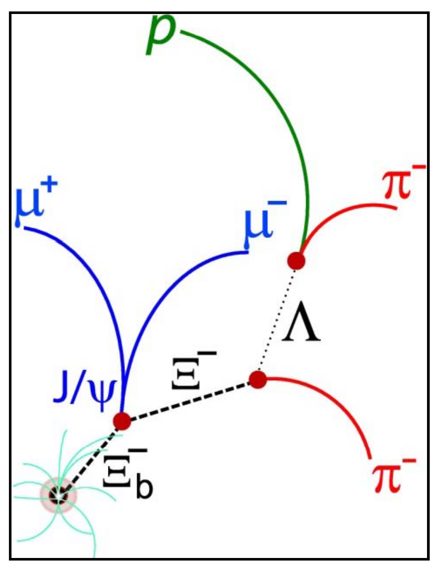


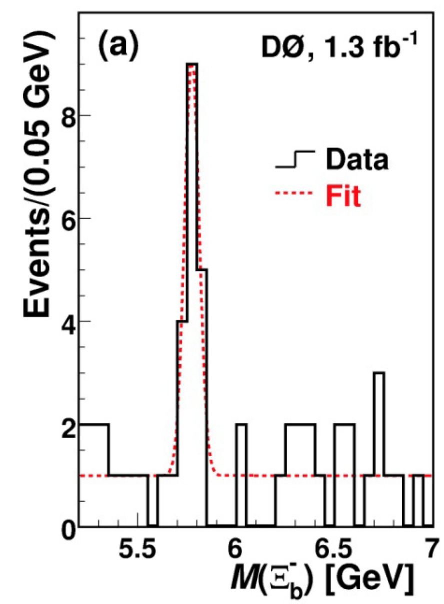
Large b quark data samples provide

- B mesons lifetime studies
- Mass spectroscopy (B_c, etc.)
- Studies of B_s oscillations
- CP violation studies
- Search for new b hadrons
- Search for rear decays









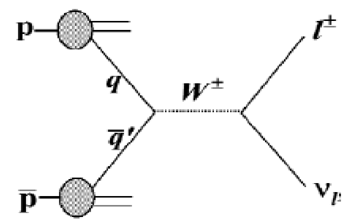
First particle with quarks from all three generations observed!

Search for New Phenomena

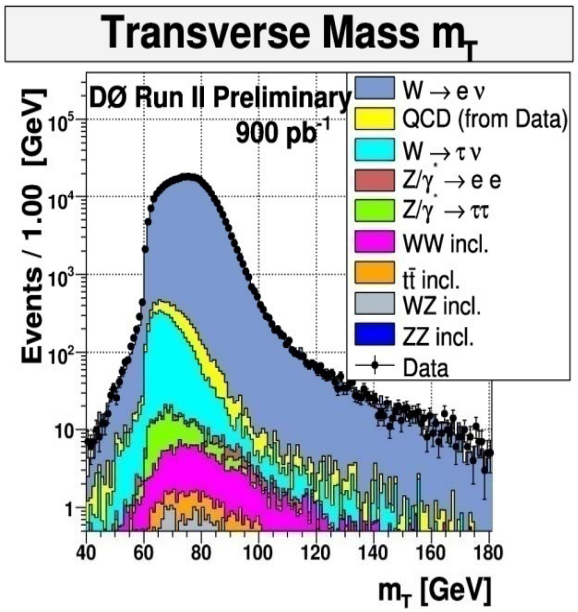
One of the most natural studies is to look for New Phenomena at the high energy collider ($E=mc^2$): SUSY, leptoquarks, Technicolor, new exotic particles, extra dimensions…

Recipe: search for irregularities in effective mass spectra or other kinematic parameters to study events not described by the Standard Model

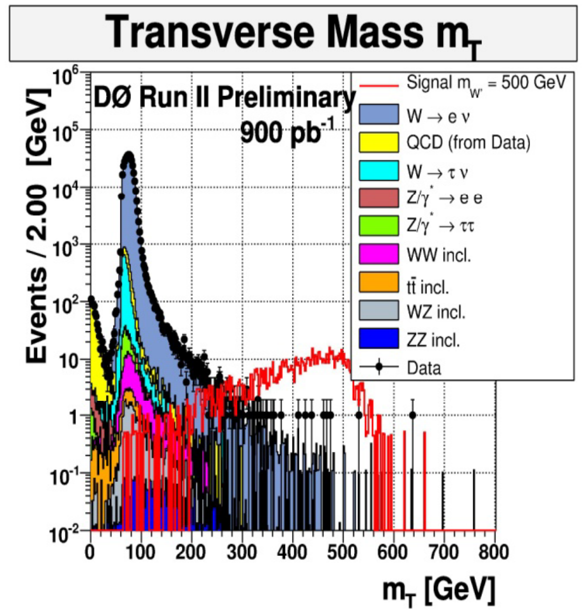
Example: Search for heavy W' boson decaying to electron and neutrino



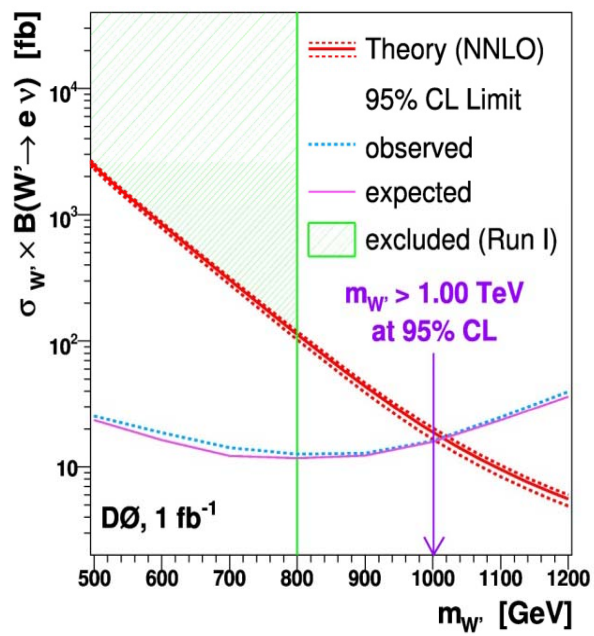
First check prediction of SM processes in low mass region



Then look into high mass region



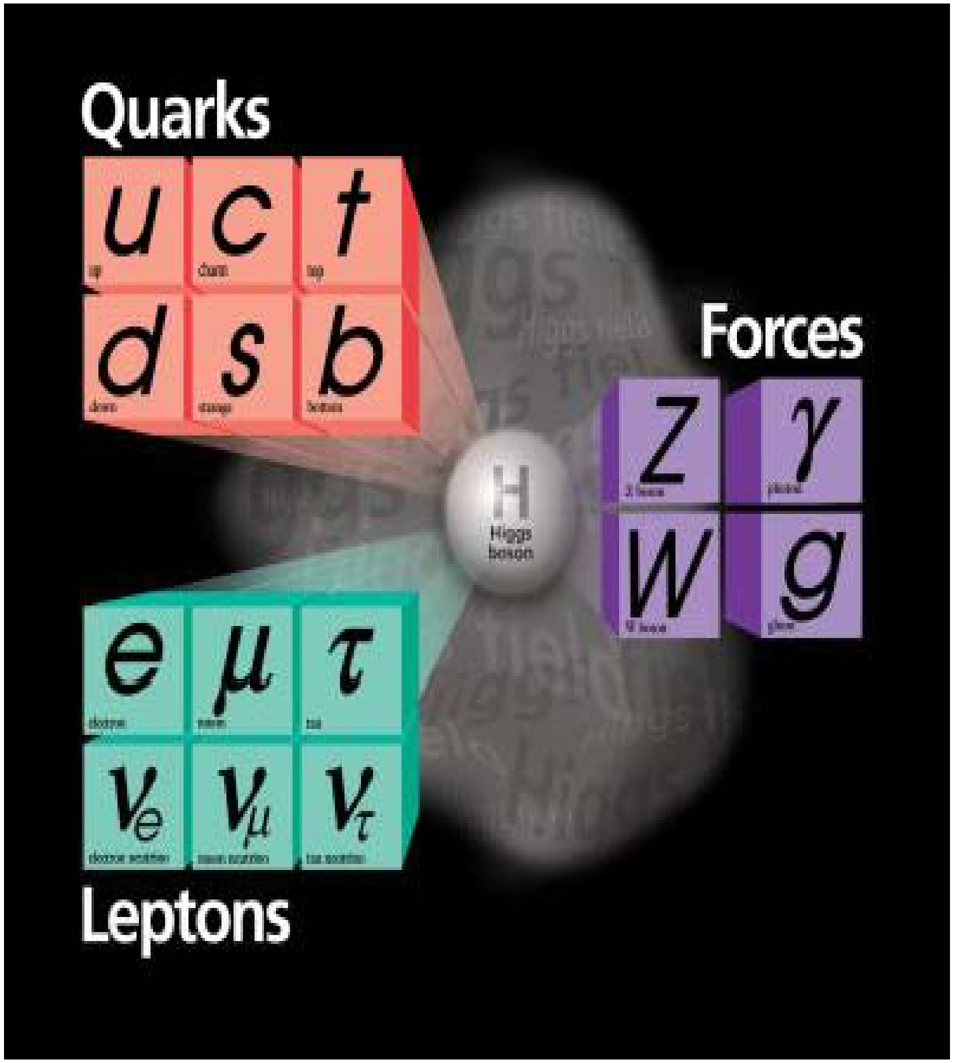
If no excess found, set limits



Reaching masses of ~1TeV – ½ of the Tevatron center of mass energy!

Introducing the Higgs Particle

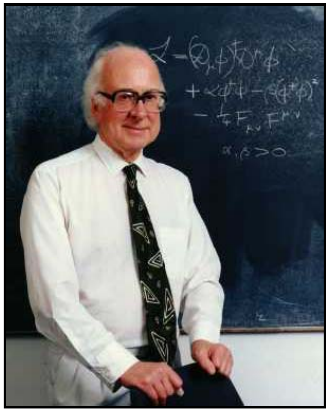
- Mass is a fundamental parameter of any object
  - Inertia, gravitational force, energy
- The fundamental forces of the Standard Model are symmetric (do not depend) upon mass
  - In order to provide particles with masses the symmetry breaking mechanism has been developed
- The “Higgs mechanism” provides 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!

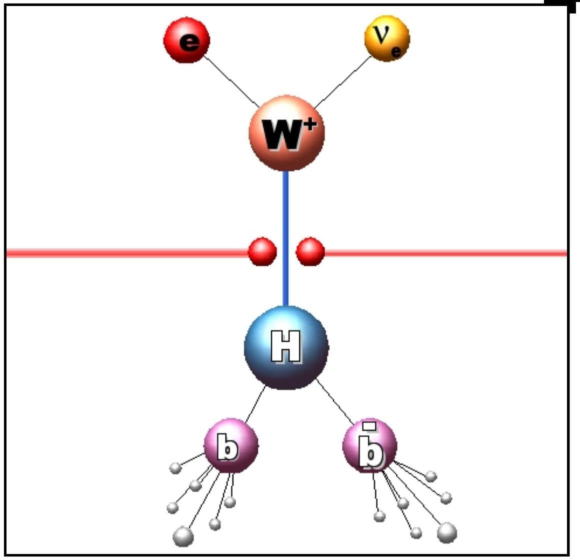


It is now challenge for experimental physicists to find this particle – the last undiscovered particle of the Standard Model

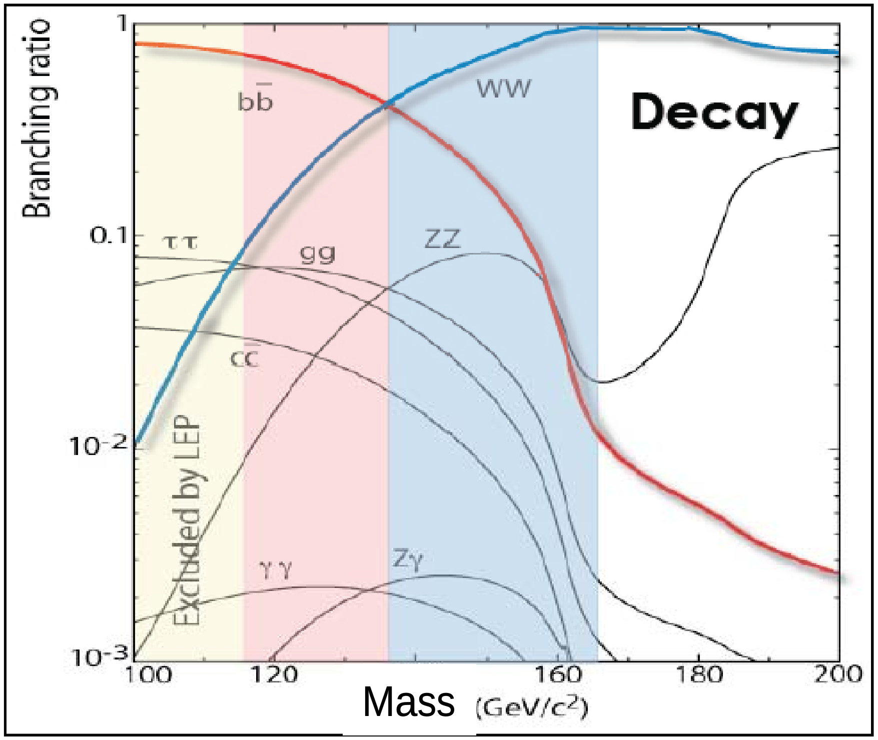
What Will the Higgs Particle Look Like?

- **Not exactly like Peter Higgs…**
- **Theory predicts Higgs particle properties**
- **Higgs will decay very quickly in 10^{-24} second 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**

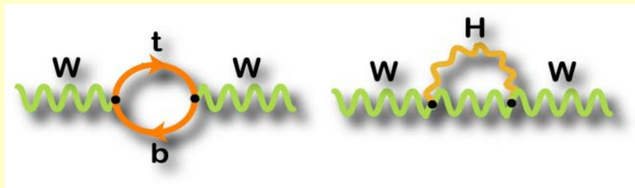


What is Higgs Mass?

Available experimental limits

→ Direct searches at LEP: M_H >114 GeV at 95% C.L.

→ Precision theory fits

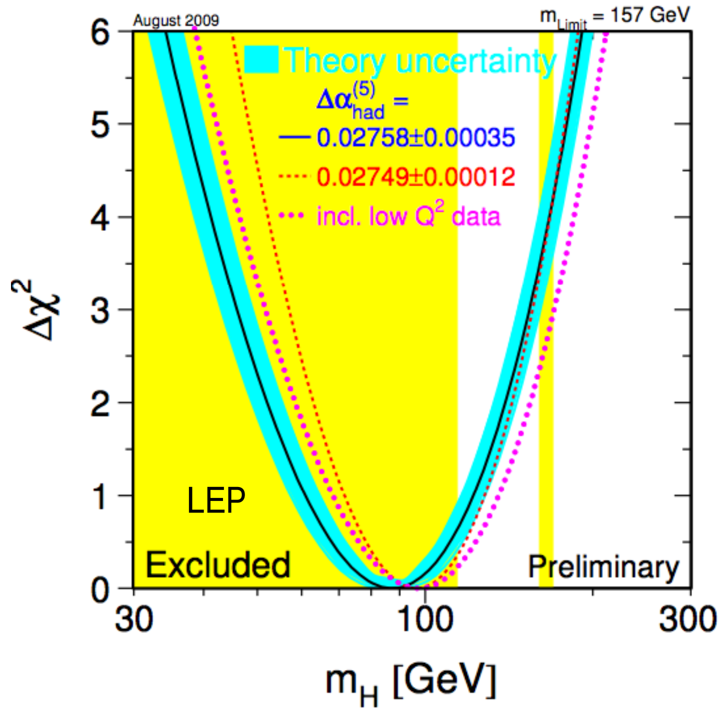


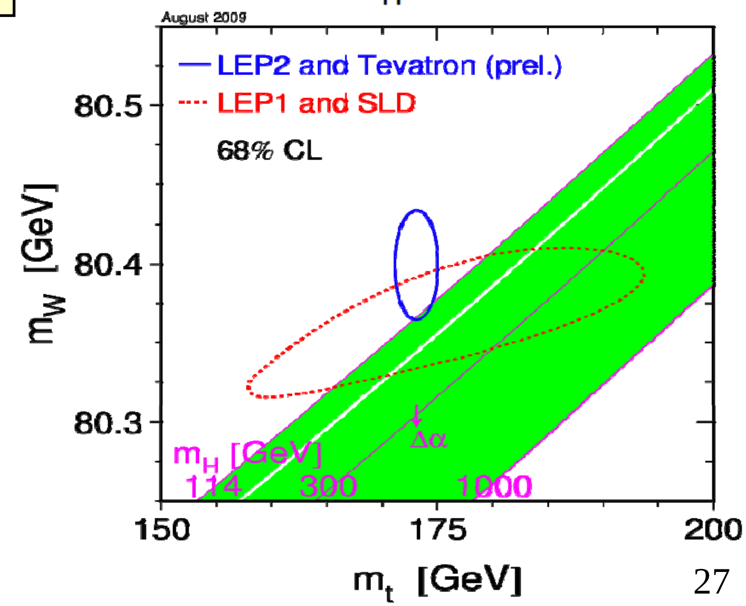
M_H< 157 GeV (95%) or <185 GeV with direct LEP limit

Light Higgs favored – in the Tevatron energy range!

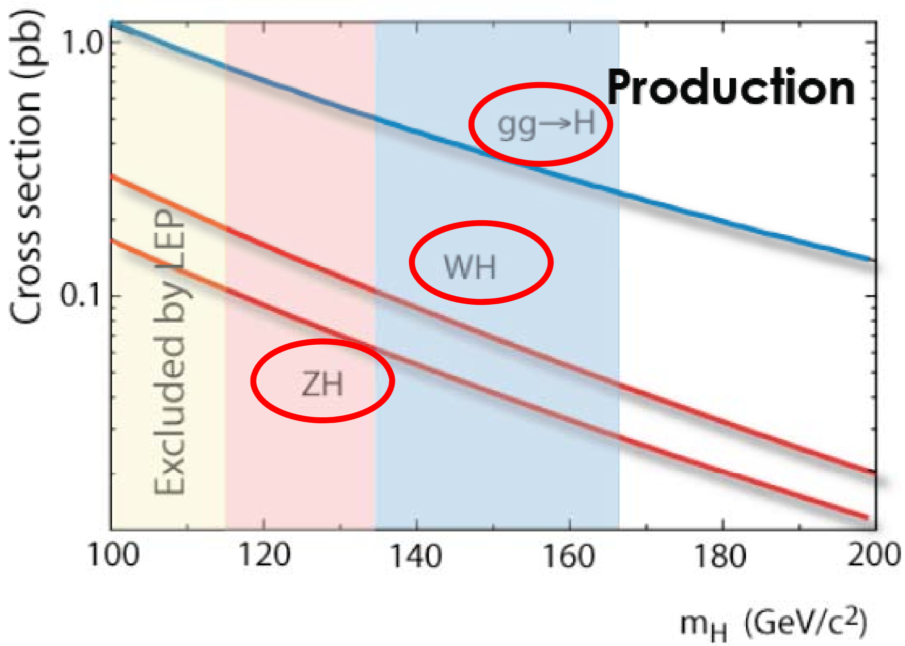
Tevatron provides:

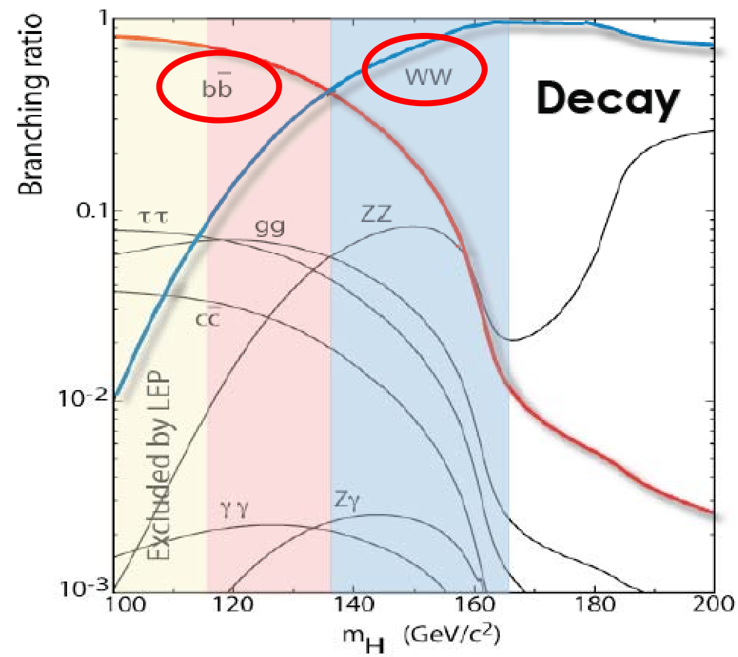
Precision m_{top} and M_w measurements





Higgs Production and Decays at the Tevatron





Production cross sections
→ in the 1 pb range for gg → H
→ in the 0.1 pb range for associated vector boson production

Decays
→ bb for M_H < 130 GeV
→ WW for M_H > 130 GeV

Search strategy:
M_H <130 GeV associated production and bb decay W(Z)H → lν(ll/νν) bb
Backgrounds: top, Wbb, Zbb…
M_H >130 GeV gg → H production with decay to WW
Backgrounds: electroweak WW production…

Experimental Challenges

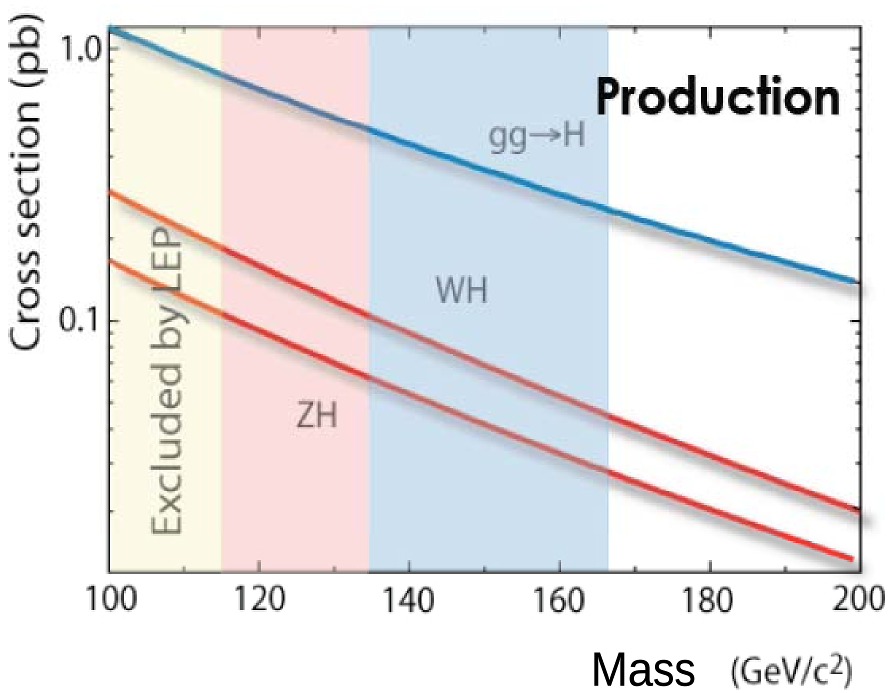
- Probability of producing Higgs particle is low

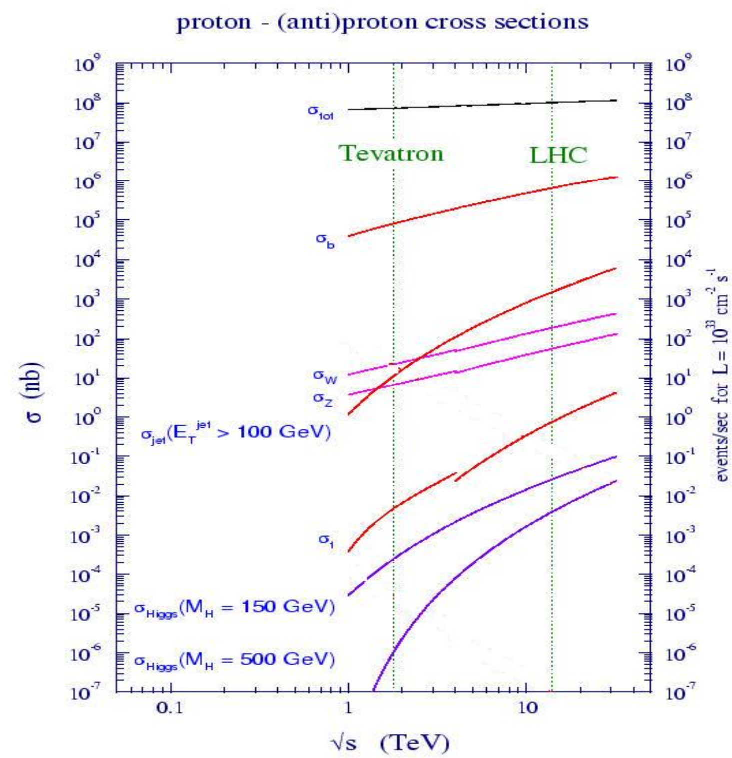
$$N_{events} = L \times \sigma$$

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 10^{12} collisions might contain Higgs particle
- Separation of backgrounds is one of the main challenges in hunt for the Higgs



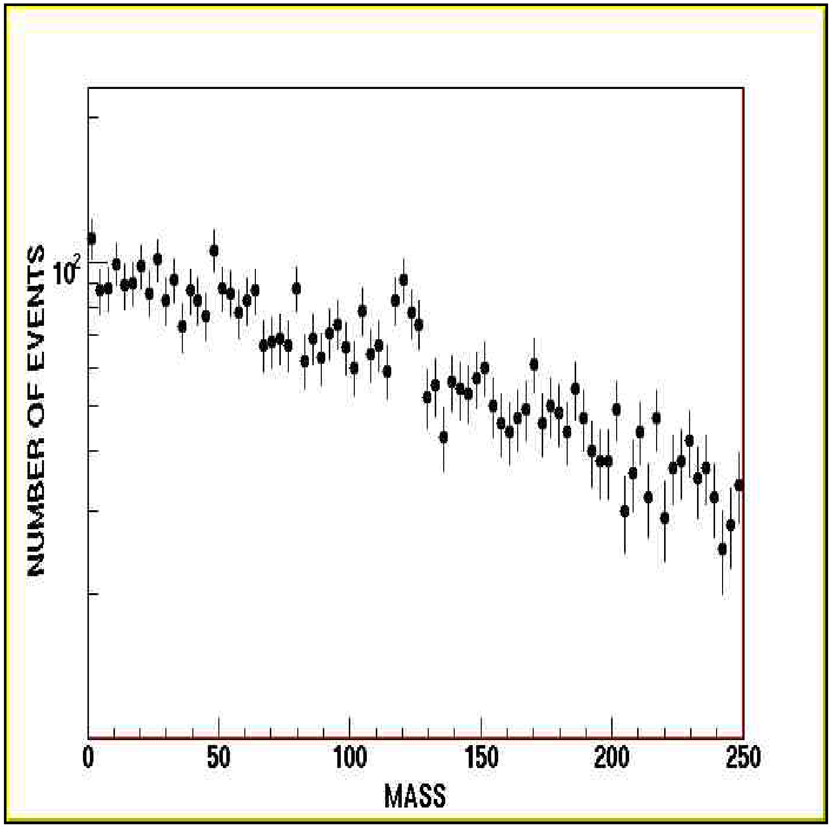


Statistical Power of Large Data Set

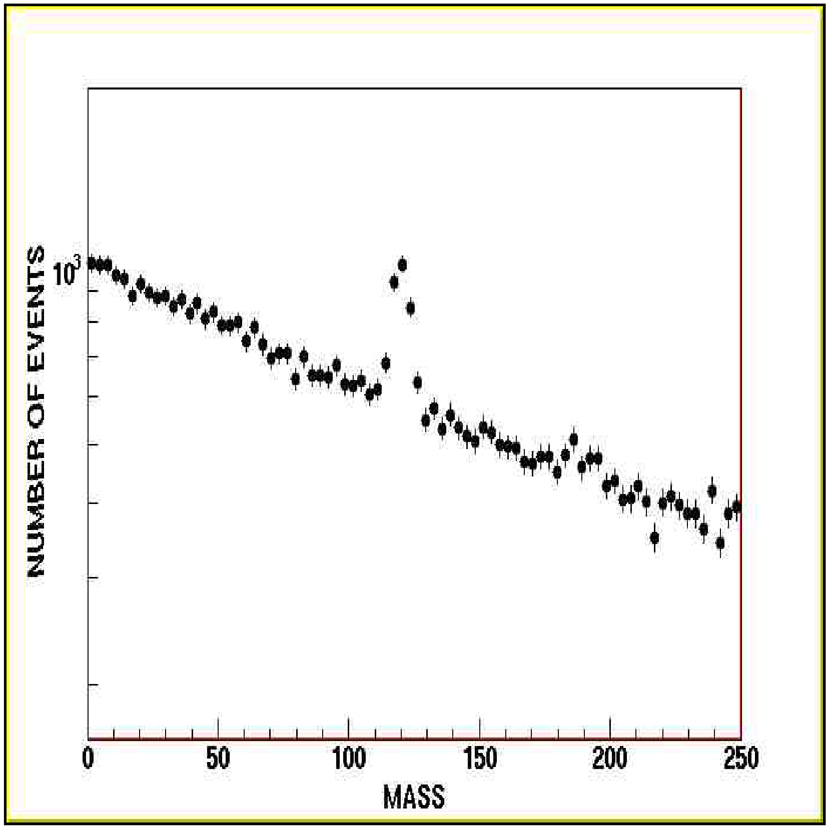
All studies in particle physics are subject to statistical fluctuations

Probabilistic nature of results with small number of events

Simulation Example



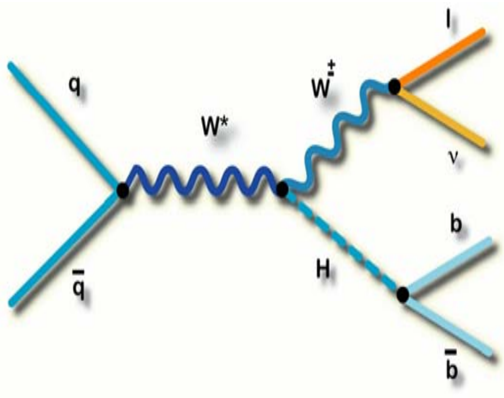
x10 data →

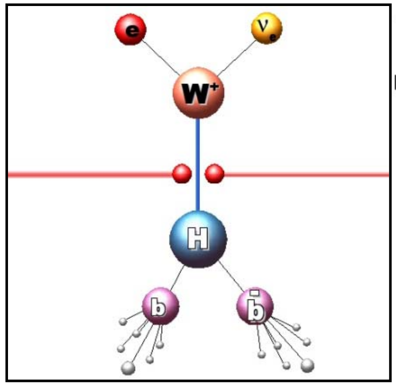


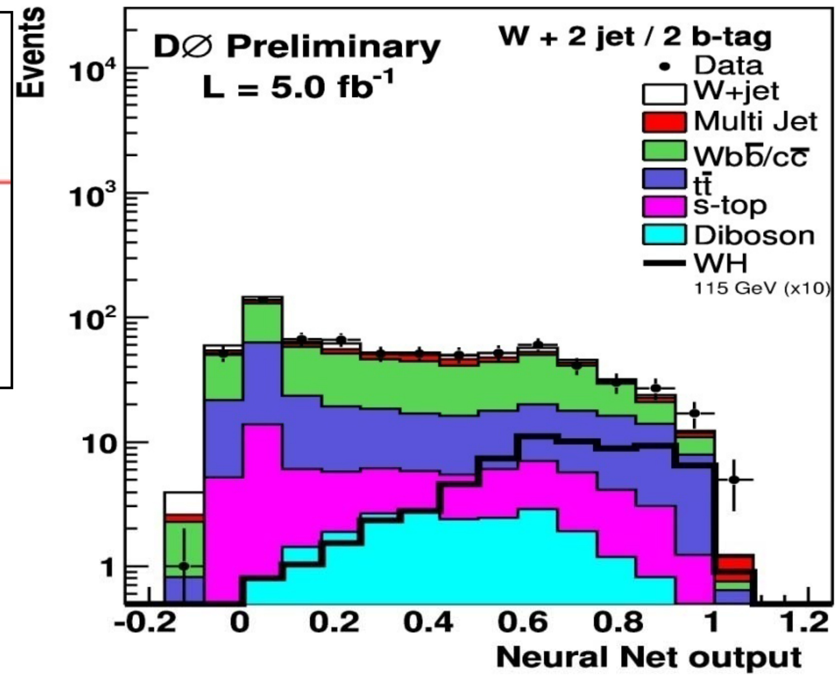
Increase in the data set could make “hints of a signal” obvious and statistically significant

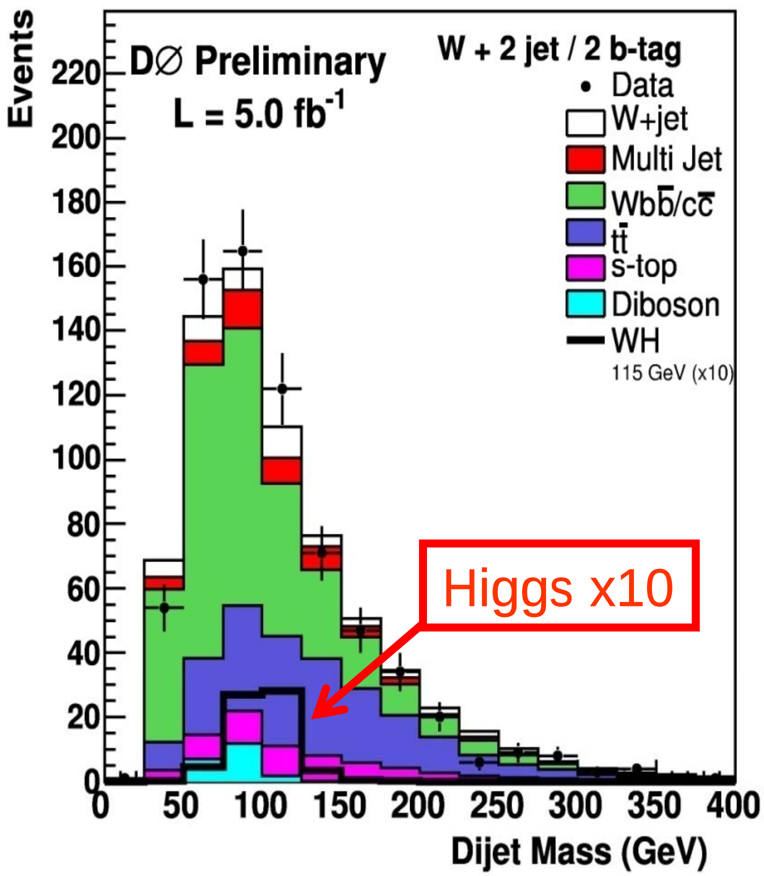
Continuing operation of the Tevatron is absolutely critical component of the Higgs search

Higgs Search: WH → $l\nu bb$ (M_H<130 GeV)



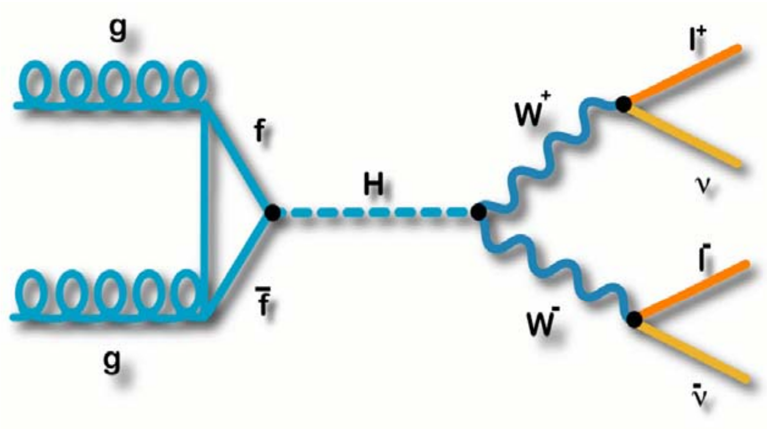




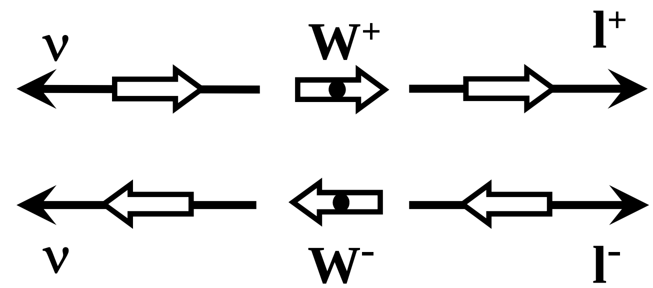


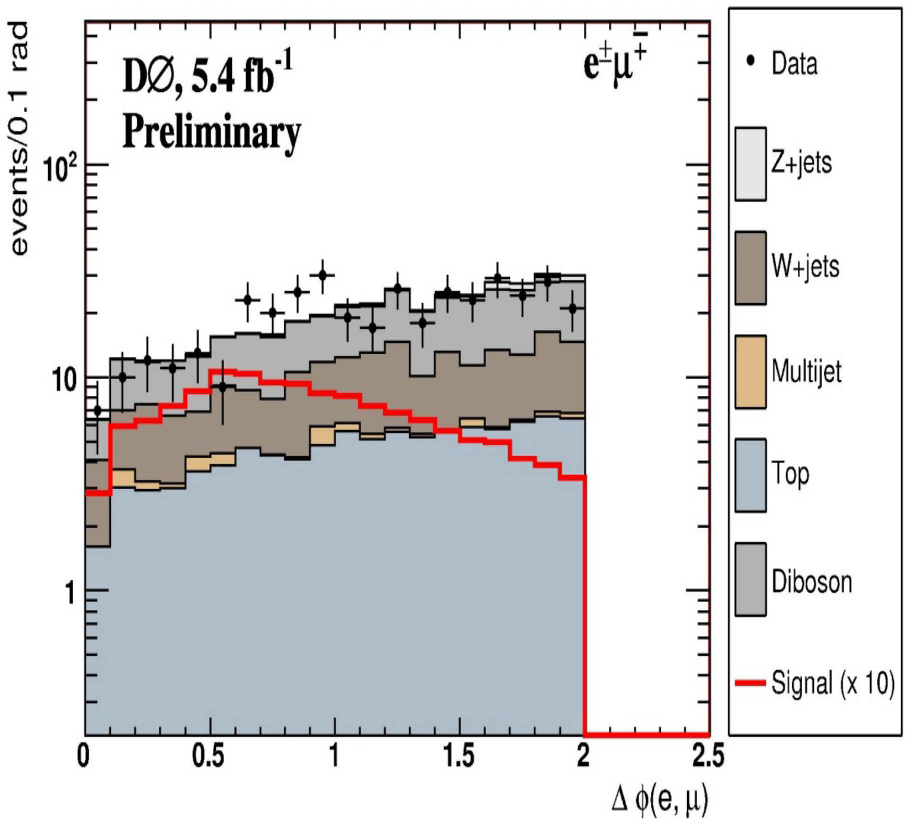
- One of the most sensitive channels in the ~110-130 GeV mass range
- Select events with lepton (muon or electron), neutrino (missing energy) and pair of jets from b-quarks
- Dijet mass → any peaks?
- For more sensitivity and to use all information about particles in an event
  - Dijet mass ➔ multivariate discriminant

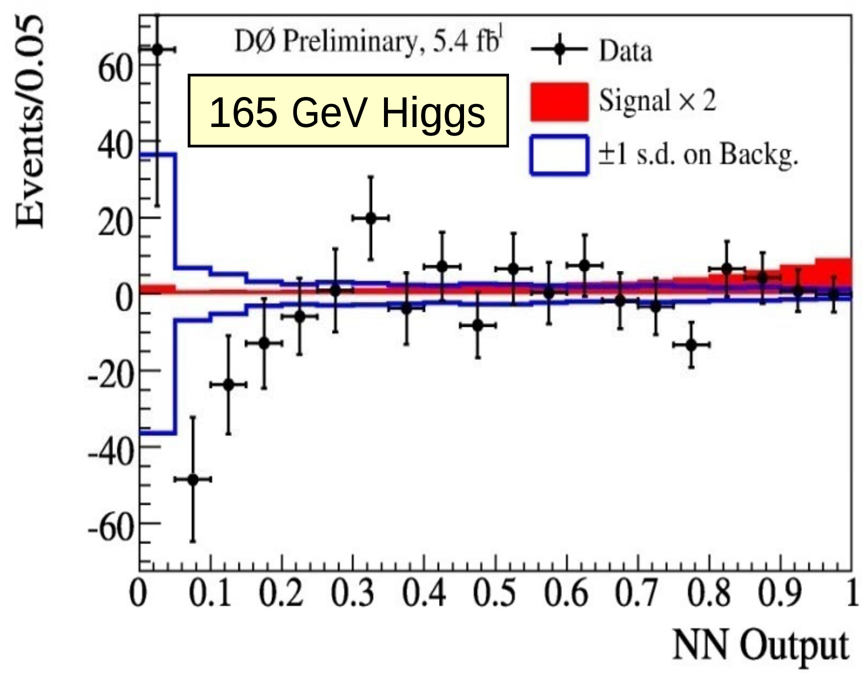
Higgs Search: H → WW → lνlν (M_H >130 GeV)



Search strategy:
→ 2 high P_t leptons and missing E_t
→ WW pair comes from spin 0 Higgs: leptons prefer to point in the same direction

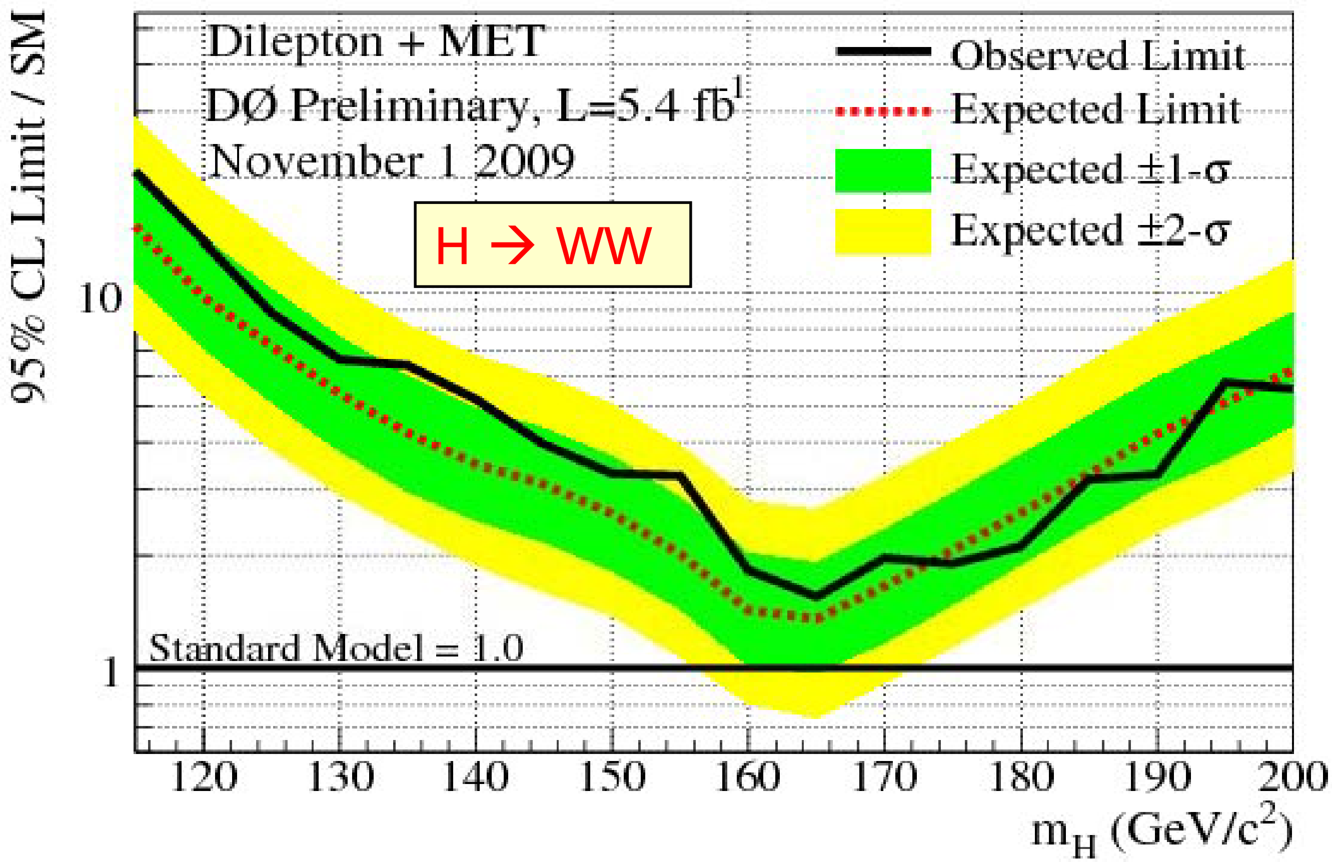






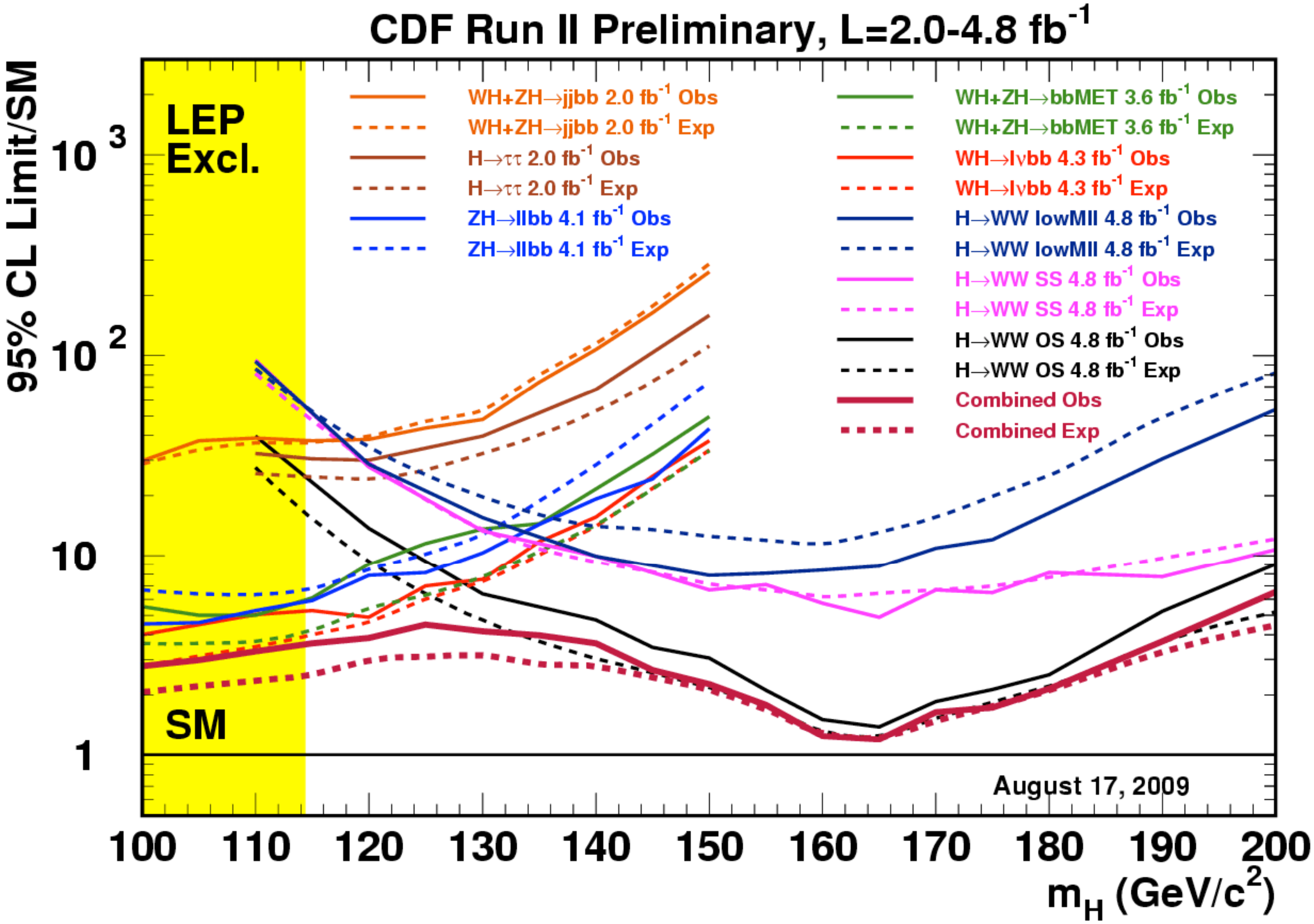
Setting Limits on Standard Model Higgs

Limits on Higgs cross section set in each individual channel and normalized to Standard Model Higgs cross section at a given mass



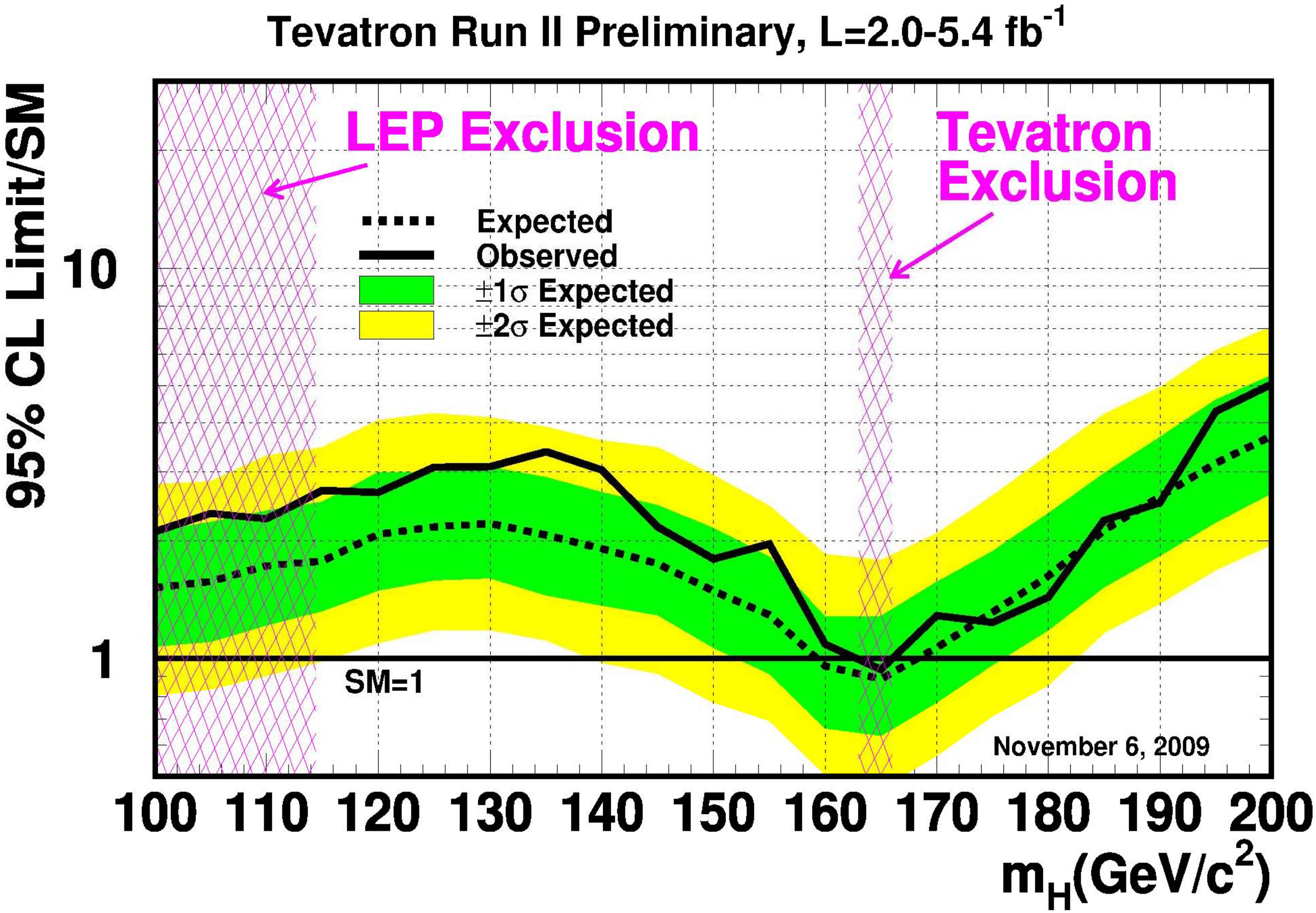
Limit at 165 GeV : 1.36 (expected) and 1.55(observed)
When line equal to 1.0 is crossed – Higgs is excluded at that mass

Combining Multiple Channels

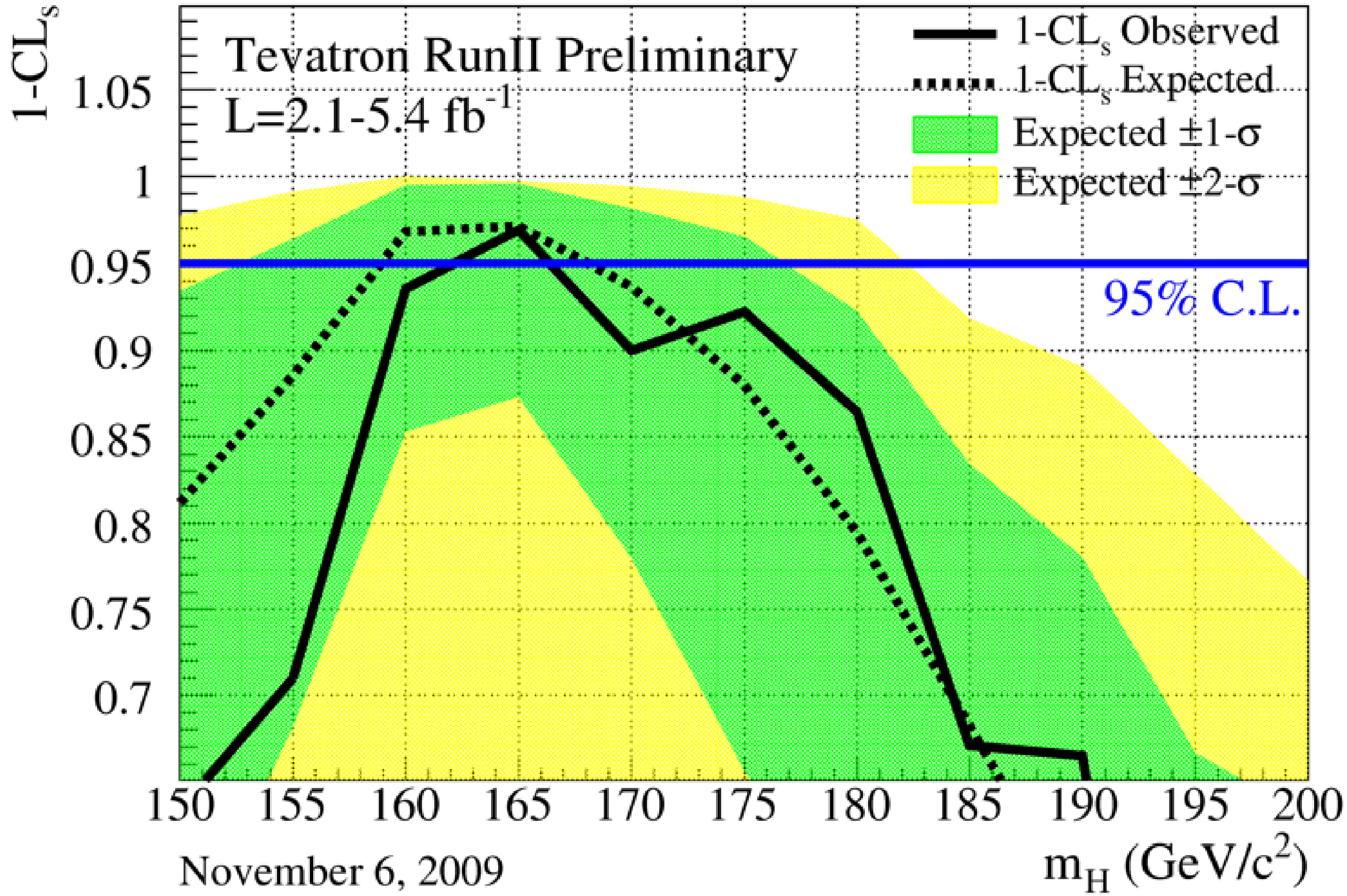


Similarly, DØ uses 58 sub-channels

Combining Two Experiments… exclusion!



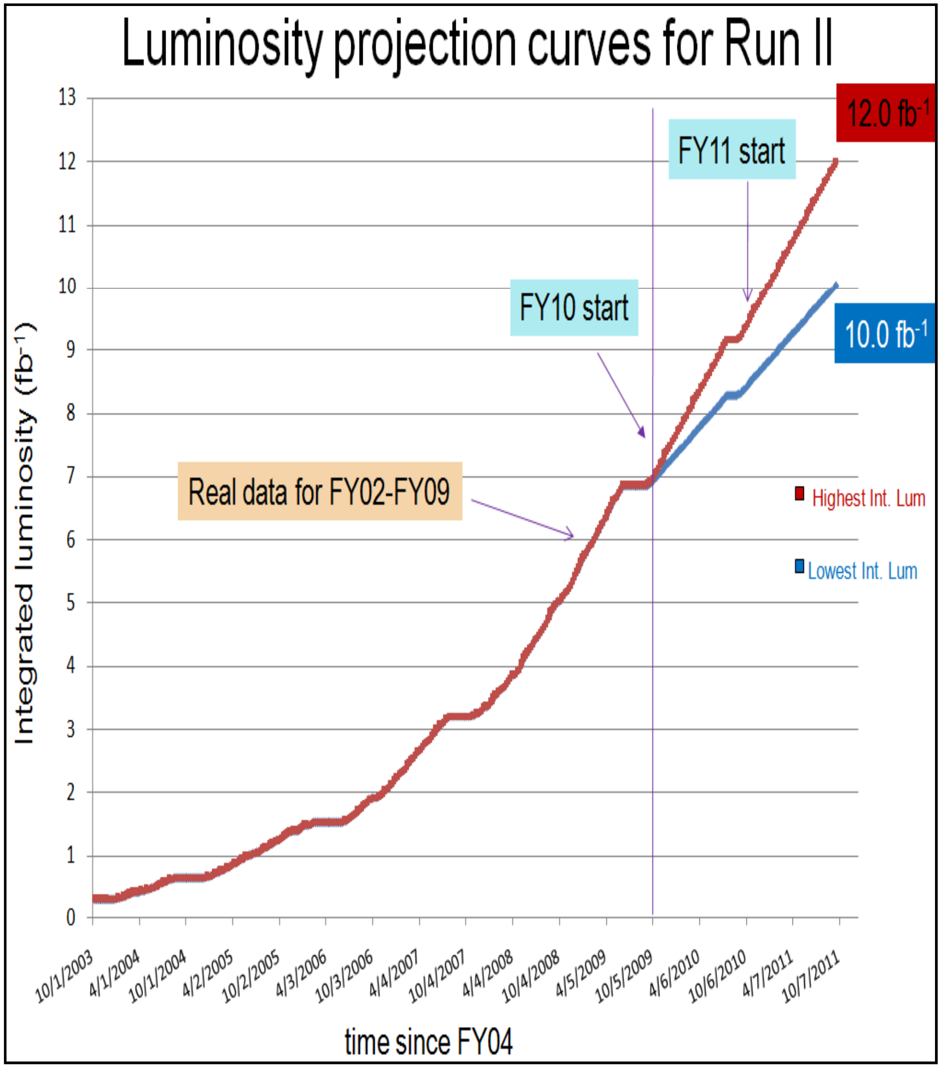
Confidence Level Combined Plot



Higgs excluded in the range 163-166 GeV at 95% confidence level

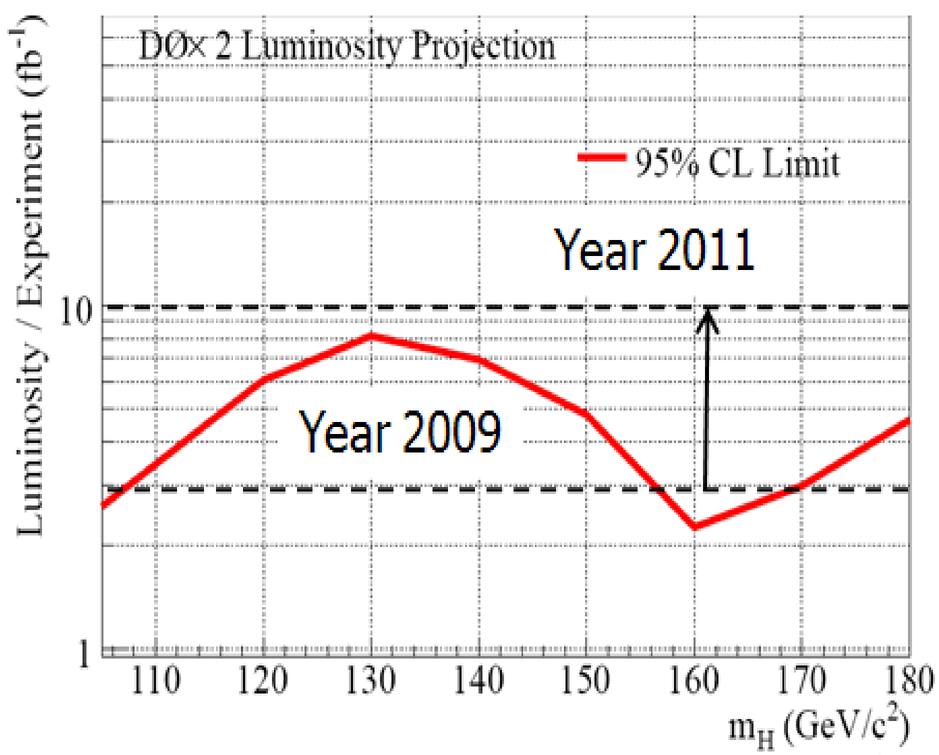
Tevatron demonstrated sensitivity to Higgs and will continue to increase exclusion region or... find the Higgs

Tevatron Luminosity Projections



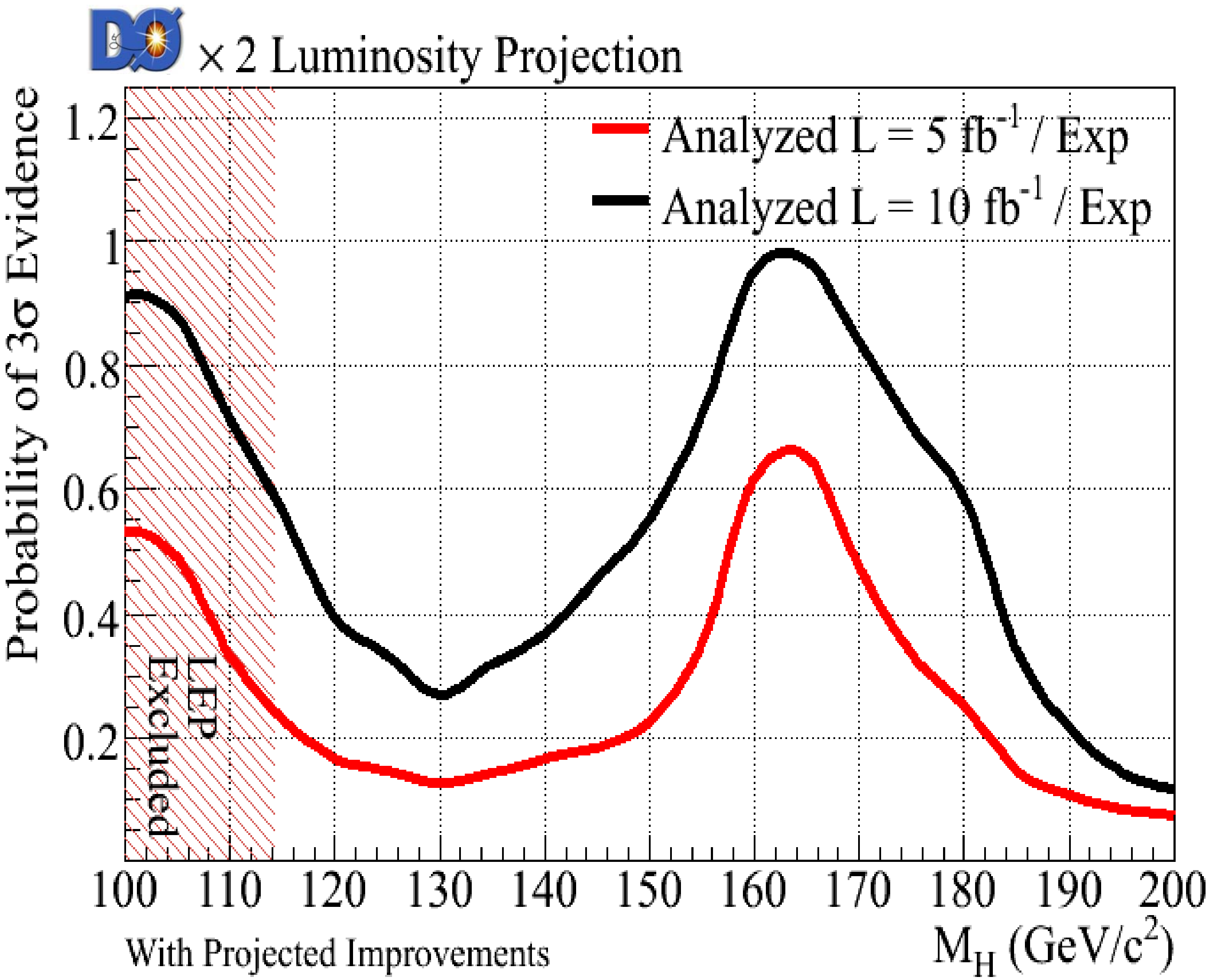
- Projections are based on extrapolations of the current performance
  - Improvements are still coming
- We expect 12 fb^{-1} delivered by 2011

Tevatron Higgs Exclusion Expectation



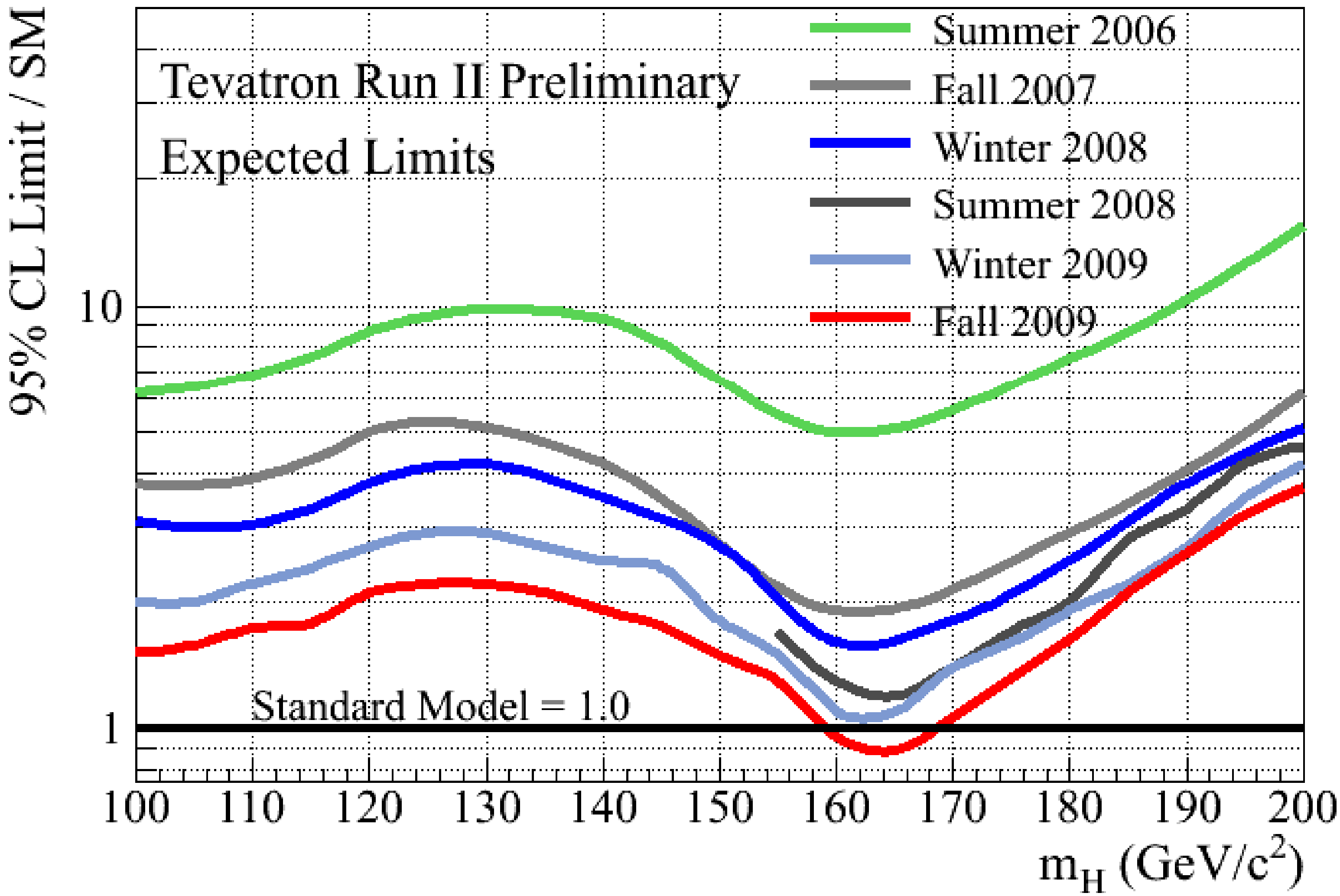
With data accumulated by the end of 2011 will achieve 95% probability of Higgs exclusion over entire allowed mass range

Tevatron Standard Model Higgs Projections



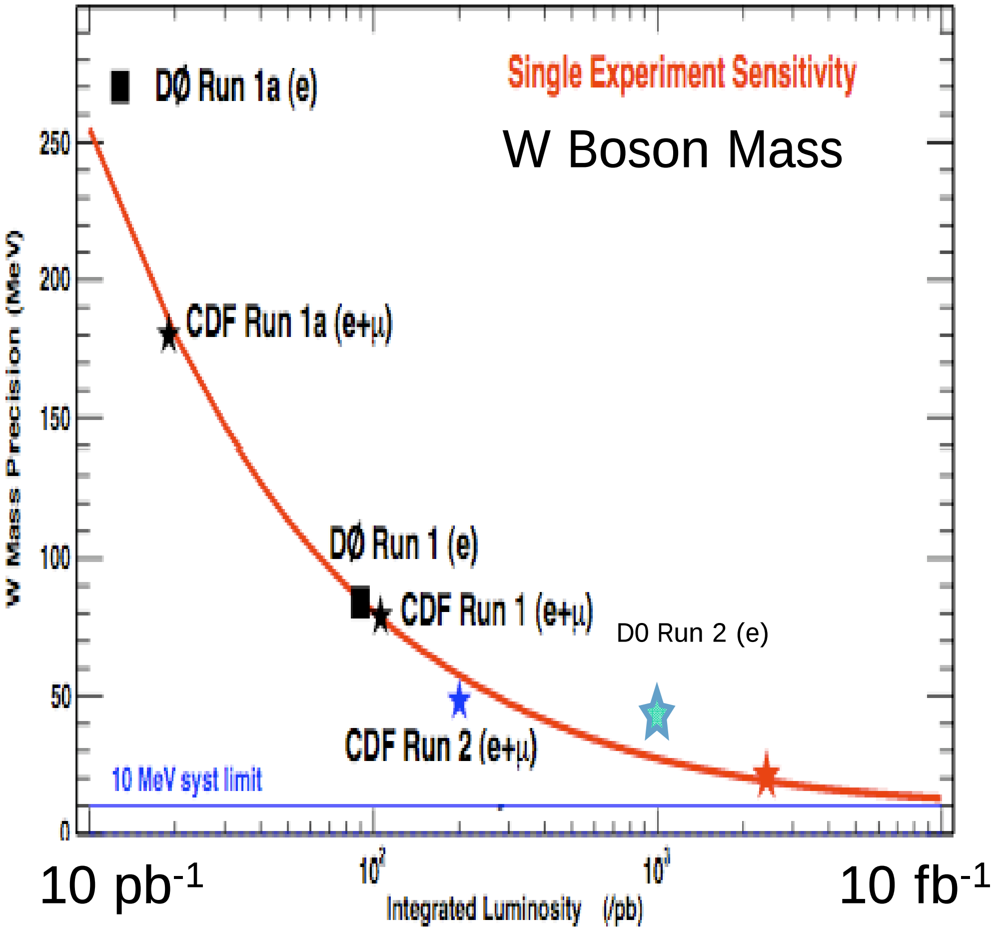
Good chance with 2011 data to see Hints of the Higgs boson!

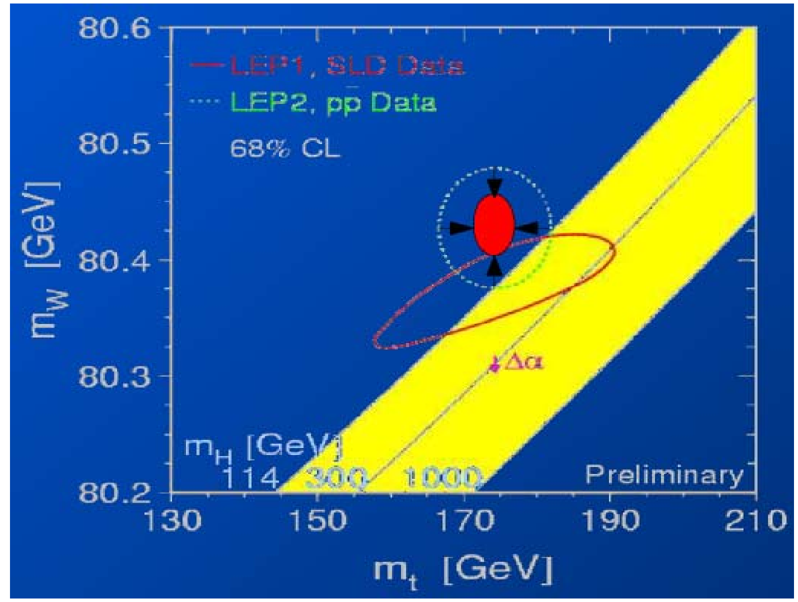
Progress with Higgs limits at the Tevatron



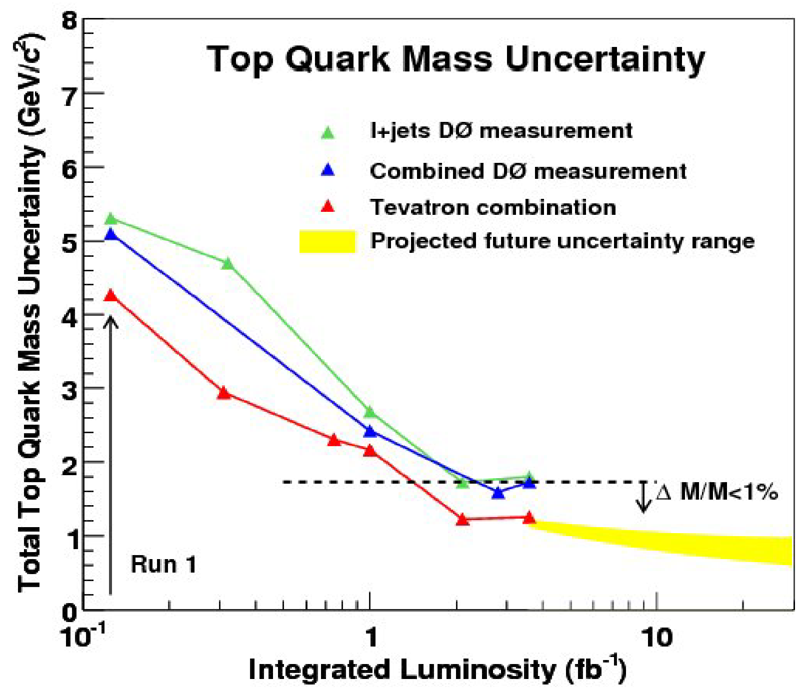
Steady progress with increase in data set and analysis experience
Factor of 1.78 from prediction at Higgs mass 115 GeV

Tevatron Projections





15 MeV error on W boson mass and no changes in the mean value means Higgs exclusion with M_H <117 GeV!

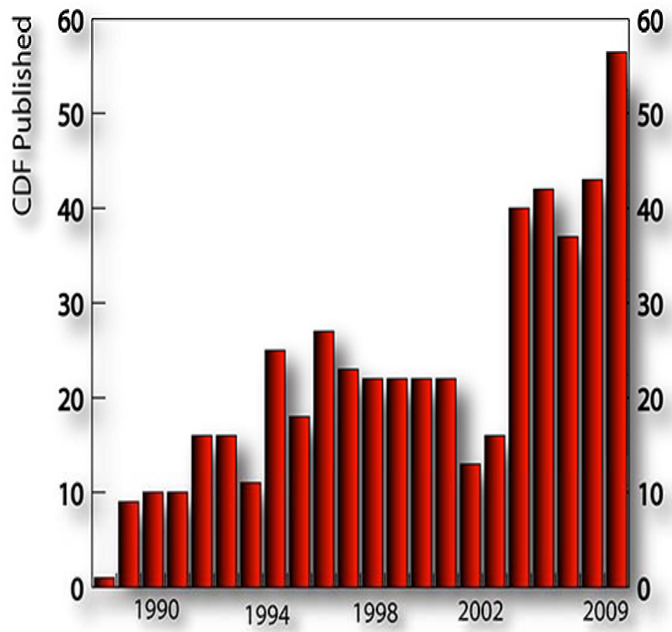


Many other exciting studies progressing

Tevatron Program Success

- **Around 100 publications in referenced papers per year**
  - **Most precise measurements of the Nature fundamental parameters**
  - **Discoveries of particles and processes**
  - **Search for new particles and interactions**
- **Over 400 invited talks at the conferences per year**
  - **Tevatron results dominate all particle physics conferences**
- **About 60 PhDs defended per year on two Tevatron experiments**
  - **Excellent training for young scientists**
- **Development of productive international cooperation between many countries**

CDF Publications per year



Tevatron Highlights: Summary

Tevatron is performing extremely well: expect 12 fb^{-1} by 2011

Experiments are collecting and analyzing data smoothly
→ Many discoveries and precision measurements
→~200+ studies in progress publishing ~2 papers a week

No significant deviations from the Standard Model observed... yet
→ Although there are a few "~2 sigma" discrepancies...
→ Data samples analyzed are to increase by 2-10 times

Many legacy measurements in progress
→ Will be in the textbooks for a while!
→ Some results from ppbar collider are unique

Higgs boson search is in a very active stage
→ Excluded at 95% CL Higgs with mass around 165 GeV
→ Proceeding to exclude wider mass range or...
to see evidence of the Higgs!

Looking forward for continuing exciting physics results from the Tevatron and would like to thank Accelerator Division for the luminosity!