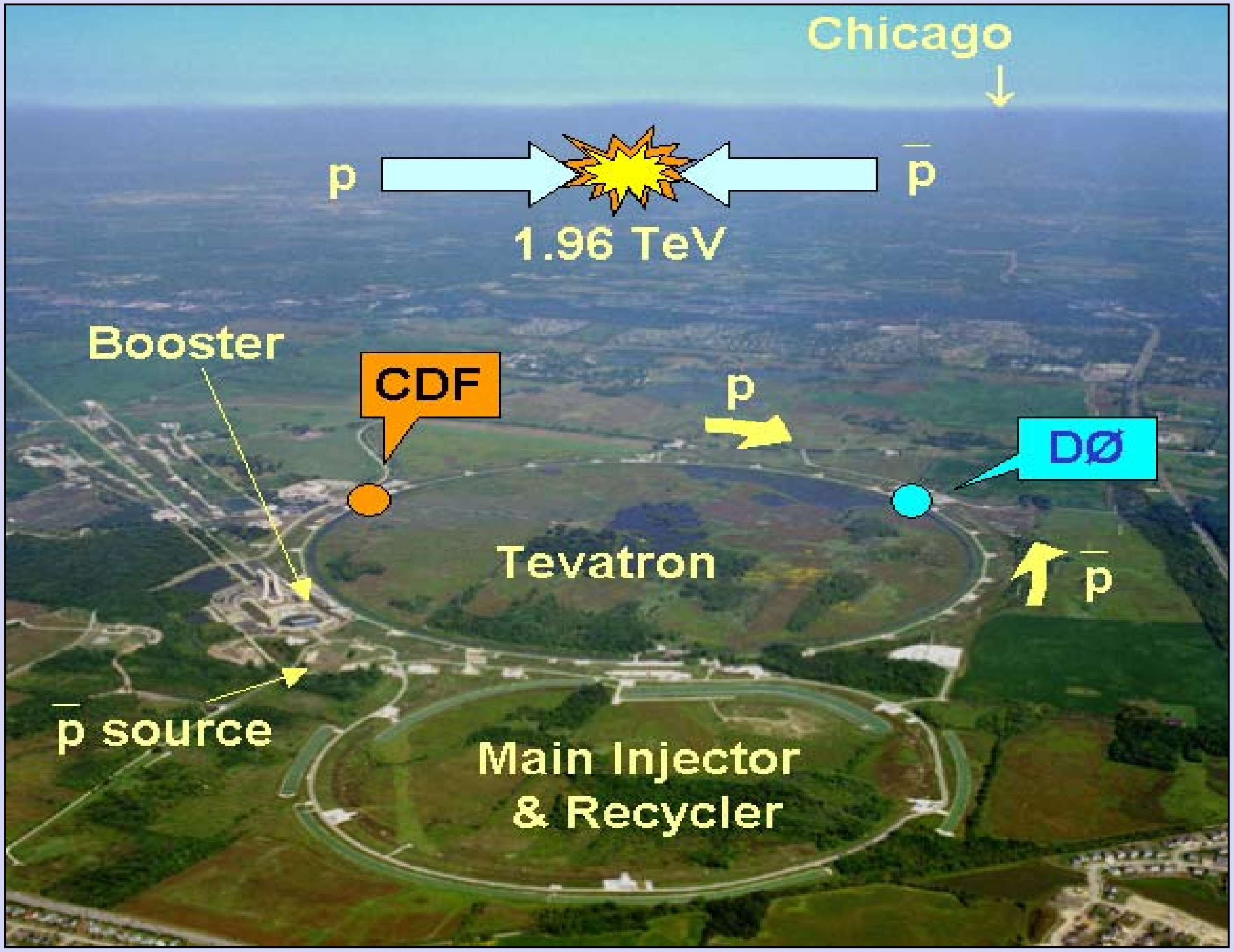
Experiments at the Tevatron from the Discovery of the Top Quark to Search for the Higgs Boson

Outline

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



Jefferson Lab Seminar

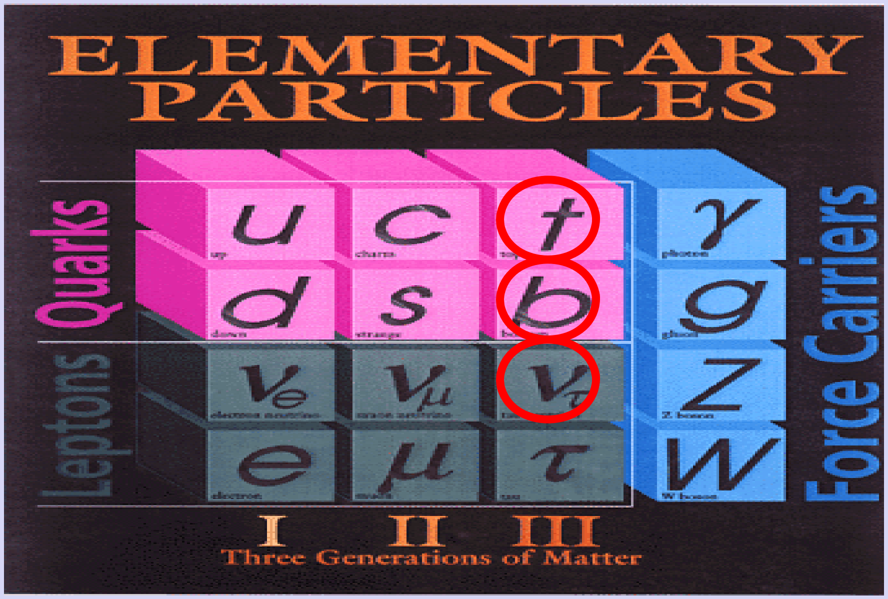
March 25, 2011

Dmitri Denisov, Fermilab

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

Standard Model

- **The Standard Model is the modern theory of particles and interactions**
  - **Describes 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 is "wrong" with the Standard Model**
  - **The goal is to define limits of applicability and find what lies beyond**

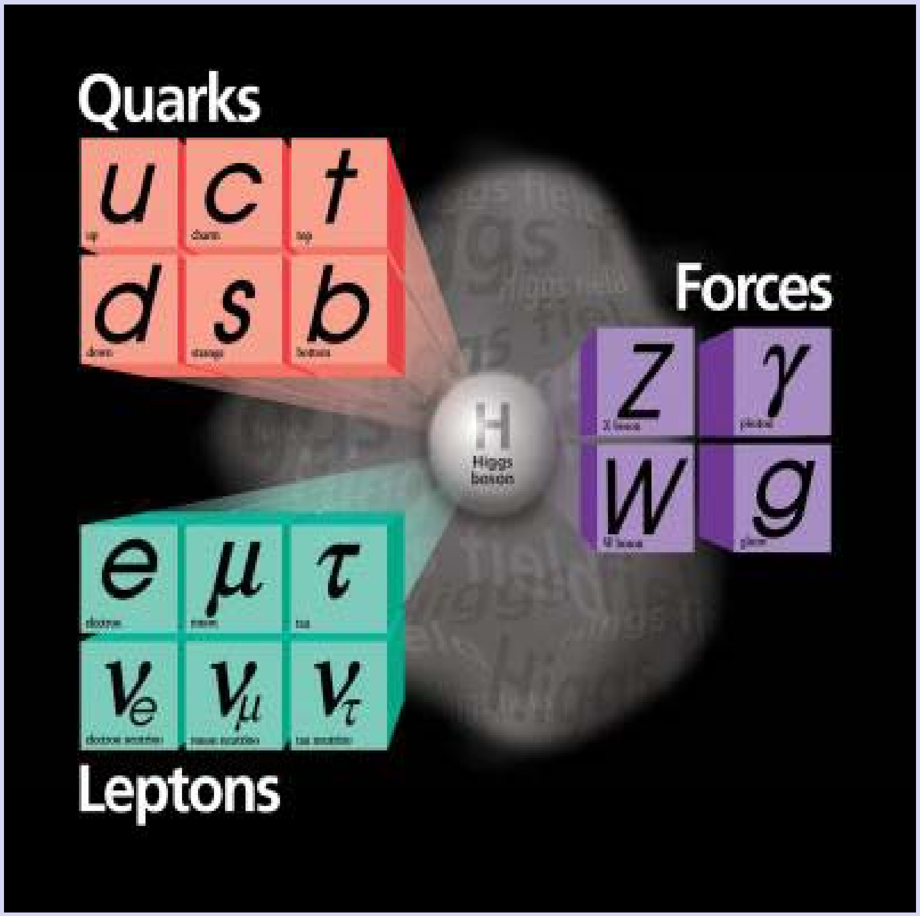
Tevatron Physics Goals

Precision tests of the Standard Model

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

Search for particles and forces beyond those known

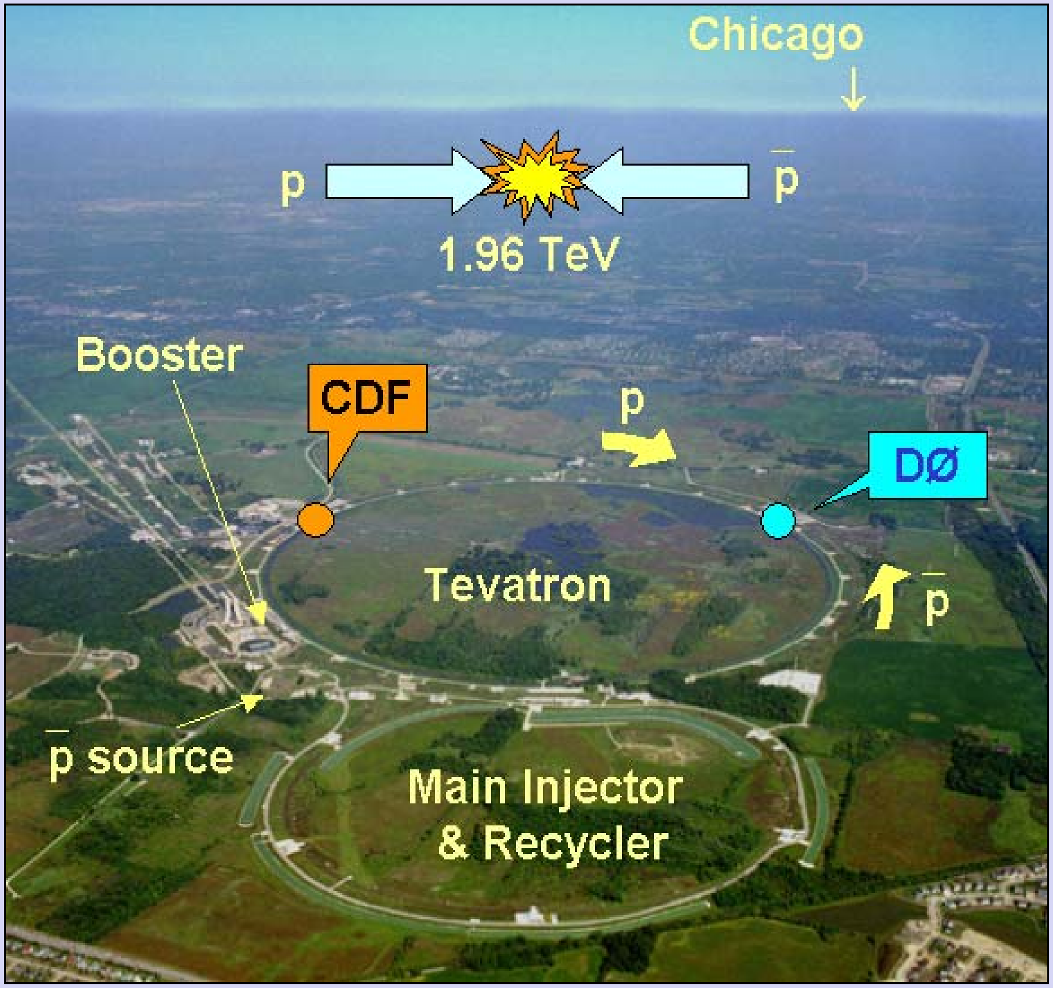
- **Higgs, supersymmetry, extra dimensions…**

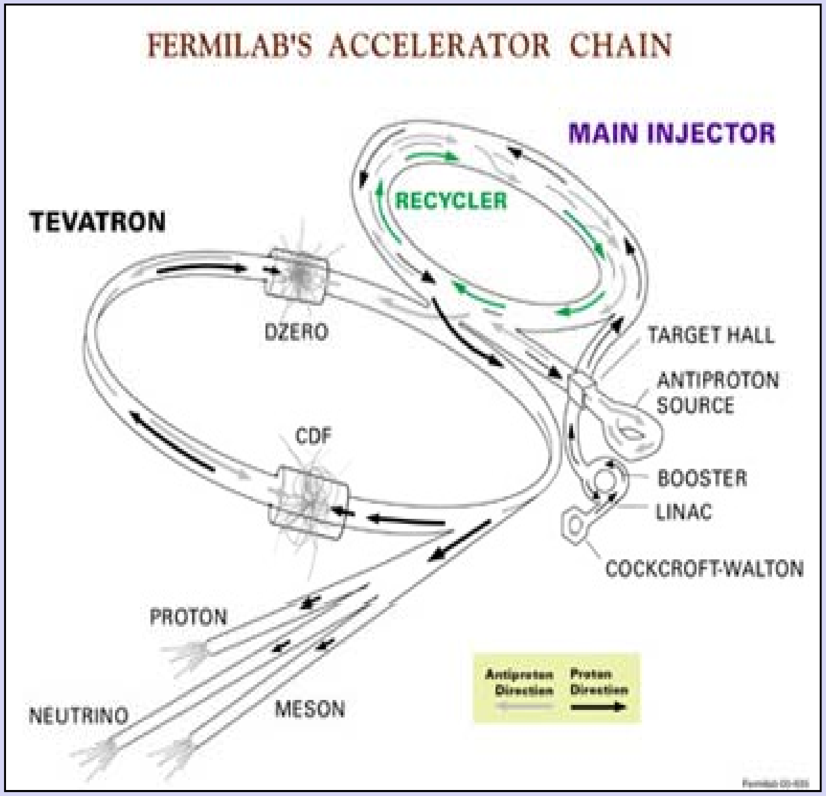


Fundamental Questions

- ✓ **Quark sub-structure?**
- ✓ **Origin of mass?**
- ✓ **Matter-antimatter asymmetry?**
- ✓ **What is cosmic dark matter?**
  SUSY?
- ✓ **What is space-time structure?**
  Extra dimensions?…

Tevatron: Proton-antiproton Collider





- **Chain of six accelerators to get to 1 TeV per beam energy**
- **Single magnet ring – protons and antiprotons circulate in the opposite directions**
- **Beam particles wavelength of ~10^{-16} cm**
- **Objects with mass up to ~2 TeV could be created**

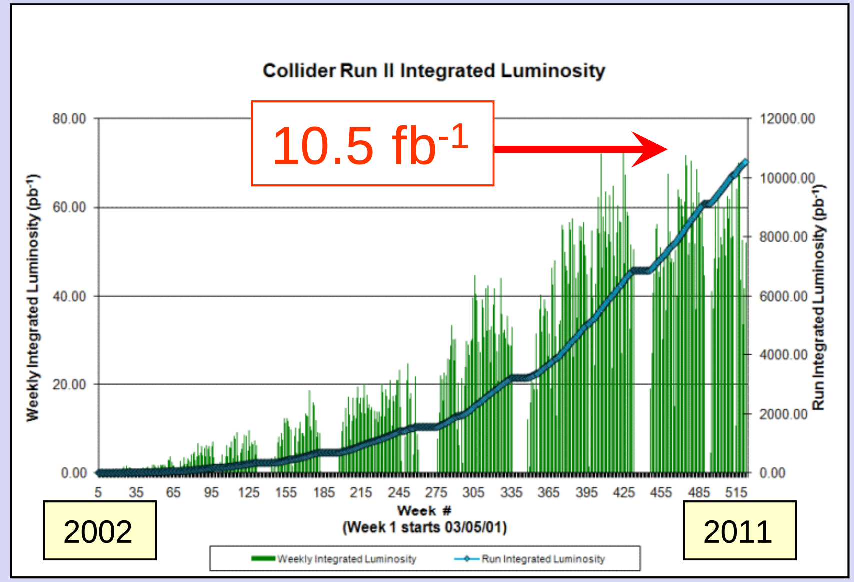
Tevatron Performance

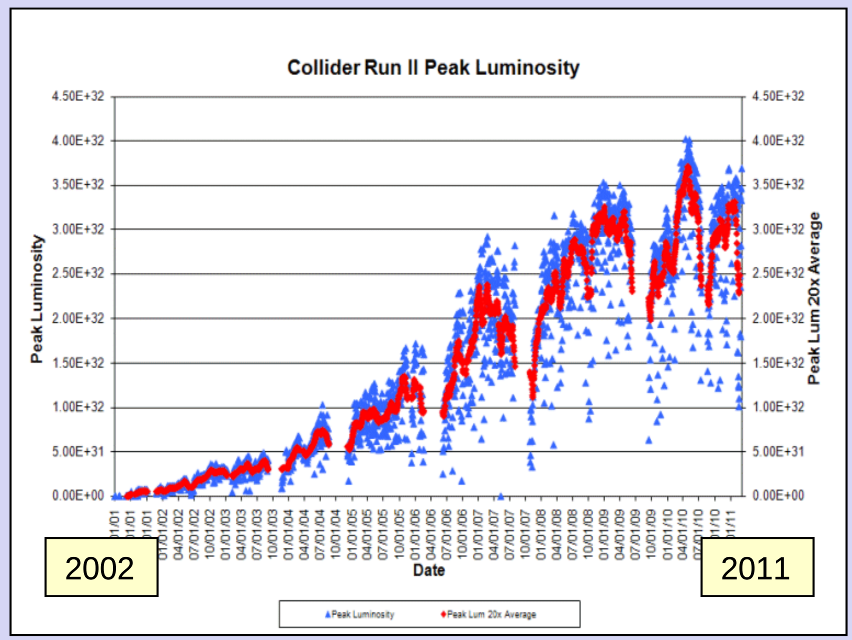
Colliding protons and anti-protons with 1.96 TeV center of mass energy

Energy and luminosity

$$N_{events} = \sigma(E) \times L$$

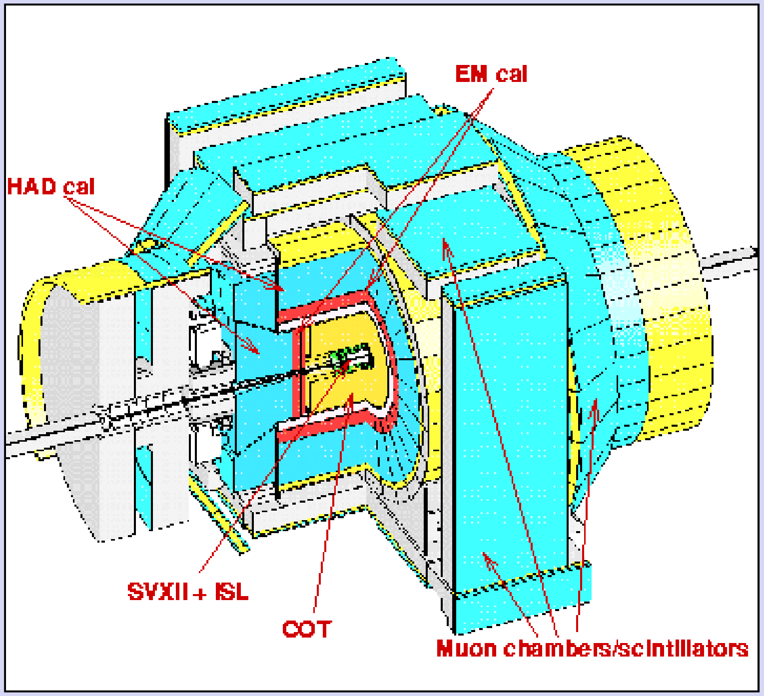
	Run I 1992-1996	Run IIa 2001-2006	Run IIb 2006-2011
Bunches in Turn	6×6	36×36	36×36
$\sqrt{s}$ (TeV)	1.8	1.96	1.96
Typical L ($cm^{-2}s^{-1}$)	1.6×10^{30}	9×10^{31}	3×10^{32}
$\int Ldt$ (pb^{-1}/week)	3	17	50
Bunch crossing (ns)	3500	396	396
Interactions/crossing	2.5	2.3	8
	Run I → 0.1 fb^{-1}	Run IIa → ~1fb^{-1}	Run IIb ~12 fb^{-1}





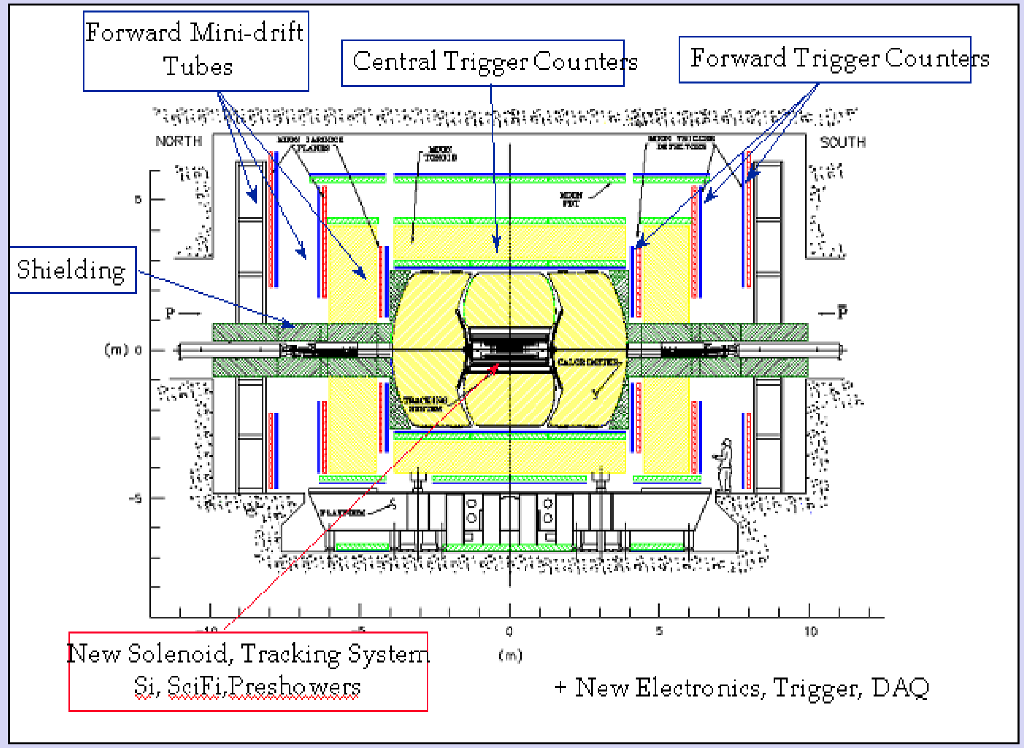
CDF and DØ Detectors

CDF



- **Silicon Detector**
- **Central Drift Chamber**
- **Calorimetry**
- **Extended muon coverage**
- **Fast electronics**

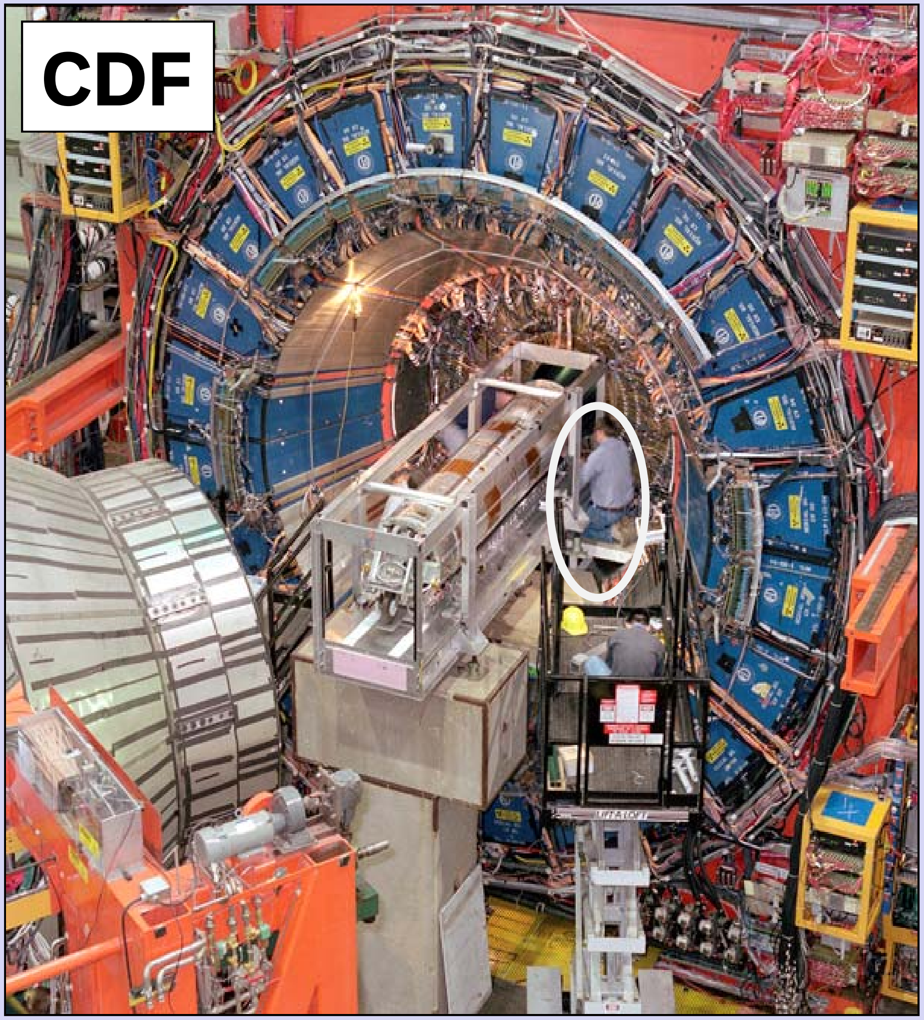
DØ

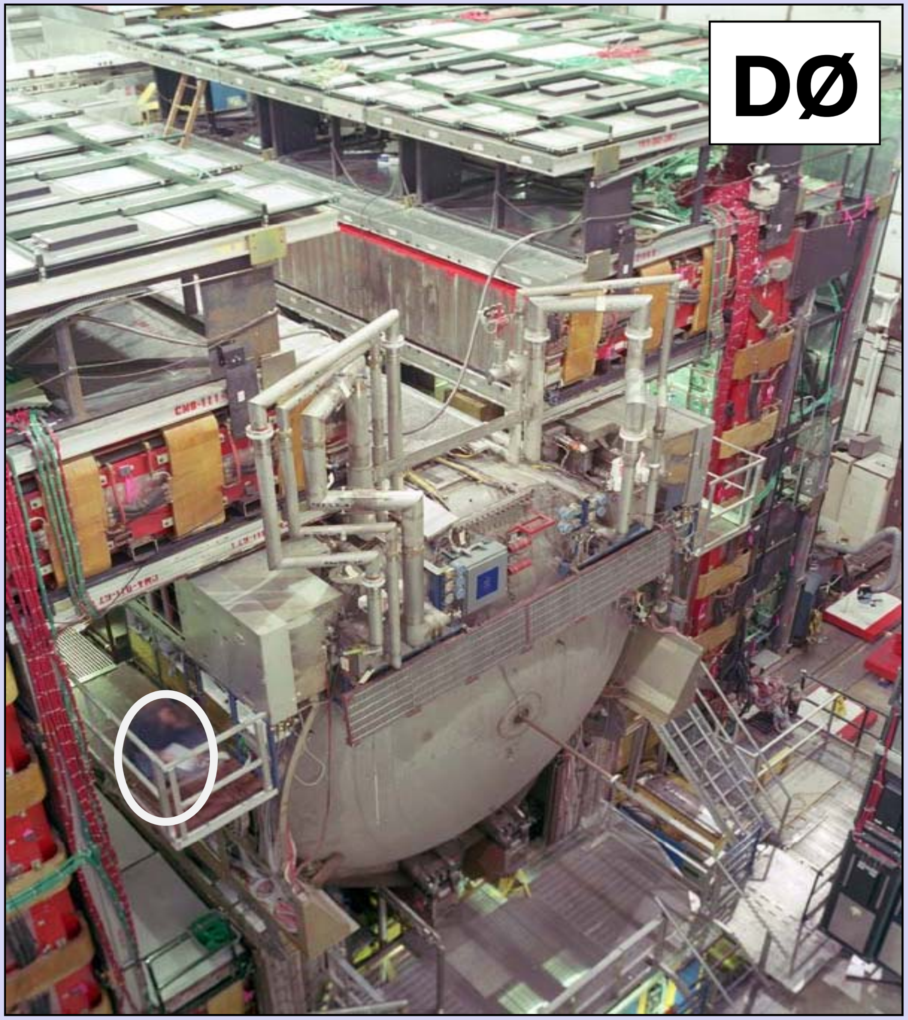


- **Silicon Detector**
- **2 T solenoid and central fiber tracker**
- **Large coverage muon system**
- **Fast electronics**

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

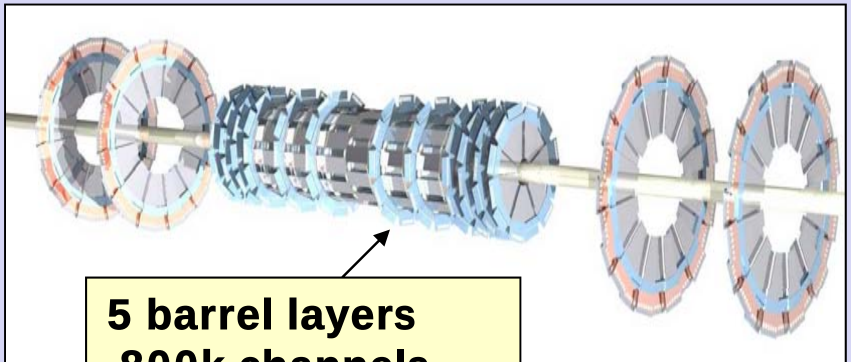
CDF and DØ Detectors



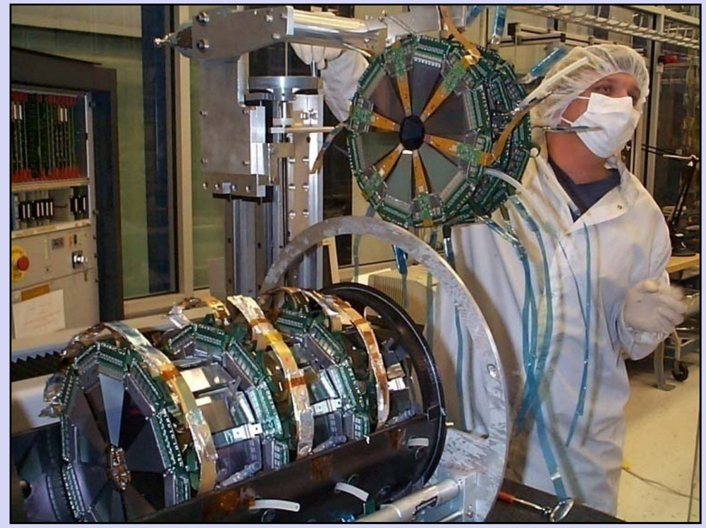


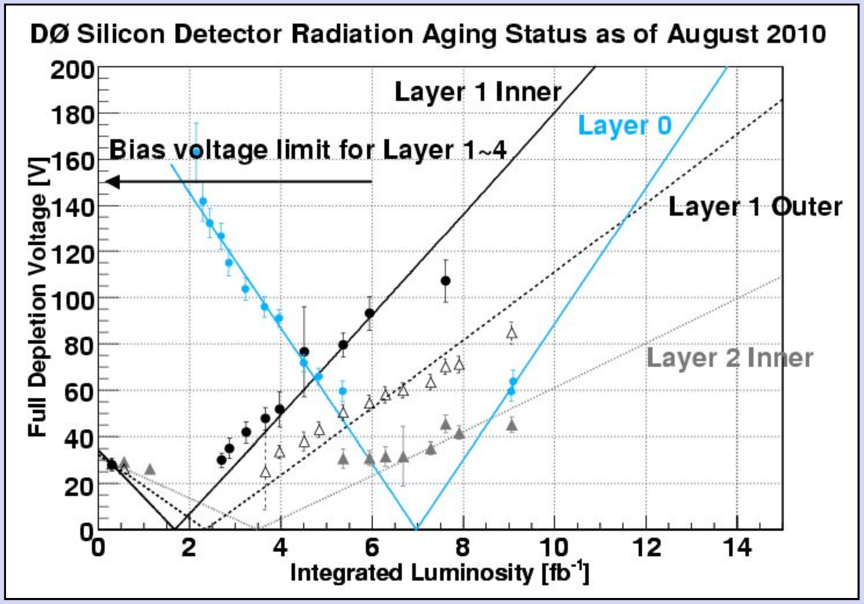
Why two detectors?
To verify results, to increase accuracy and chances to discover new phenomena, and to create healthy competition

Silicon Microstrip Tracker



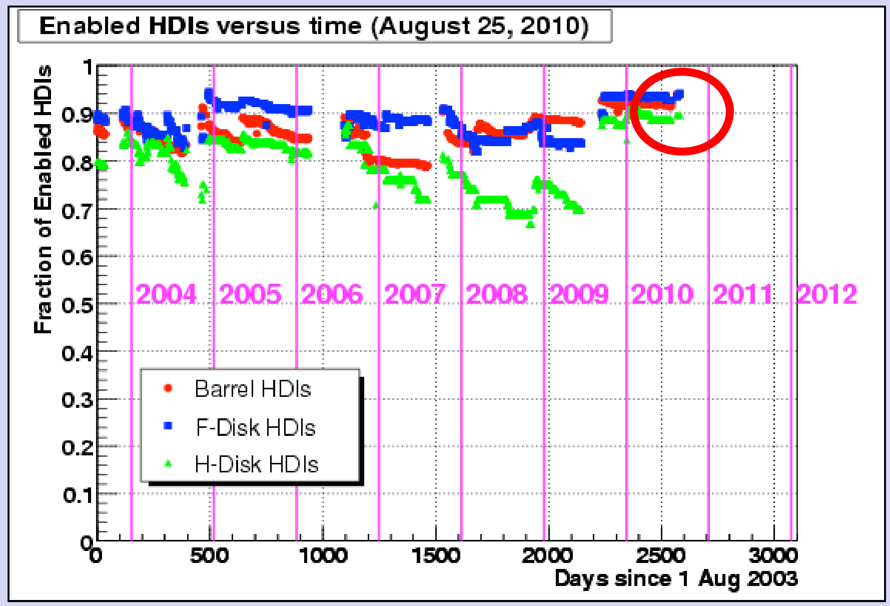
5 barrel layers
800k channels
~10 μm precision





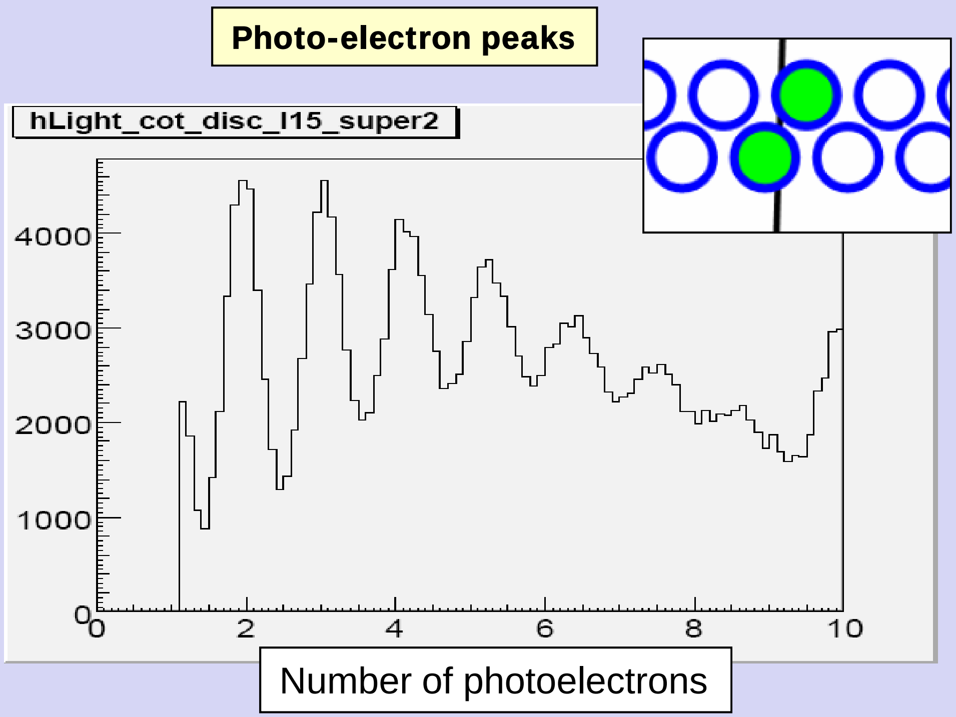
~10 years of radiation aging monitoring provides in depth understanding of complex radiation damage processes

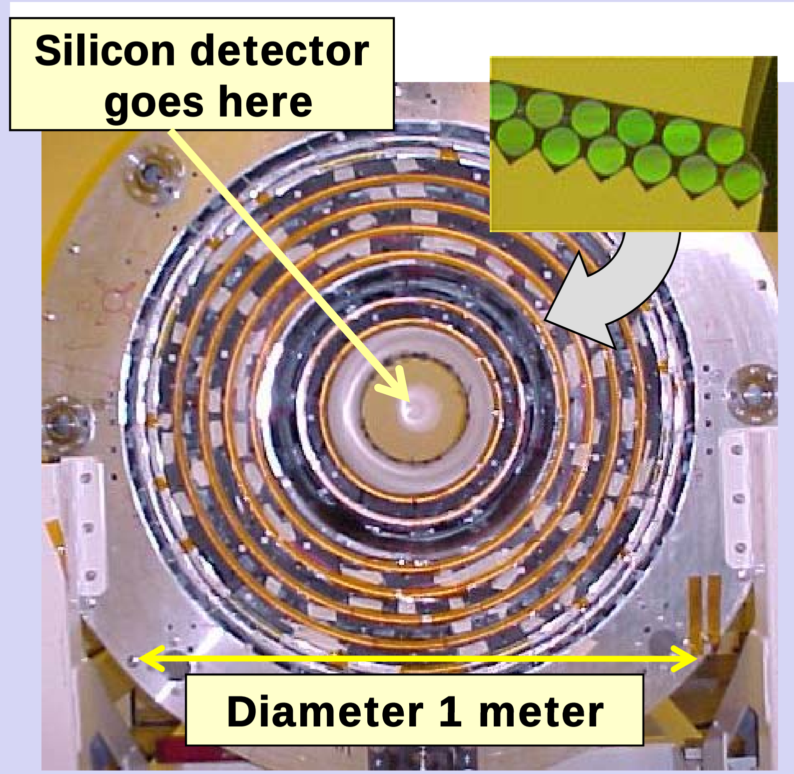
Detector is working well
Stable number of operating sensors



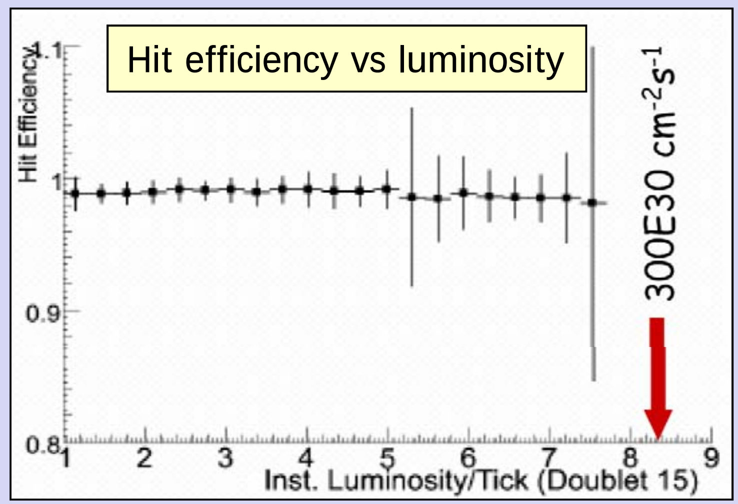
Scintillating Fiber Tracker

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

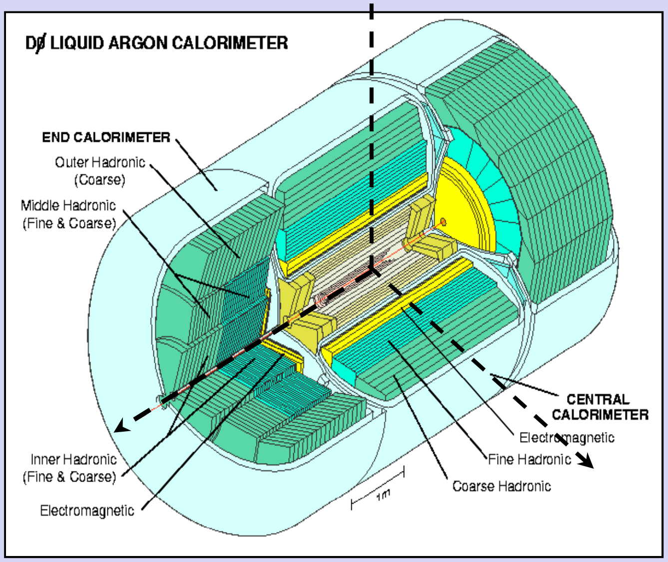




Fiber tracker and silicon detector are in 1.9T magnetic field created by superconducting solenoid



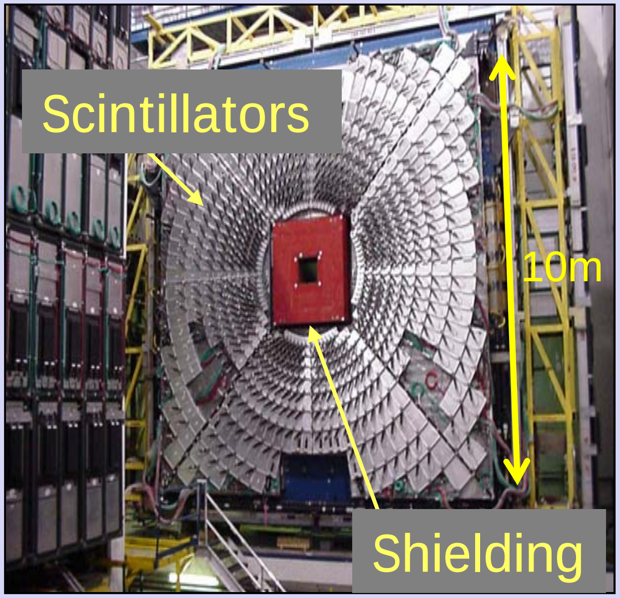
Calorimeter and Muon System



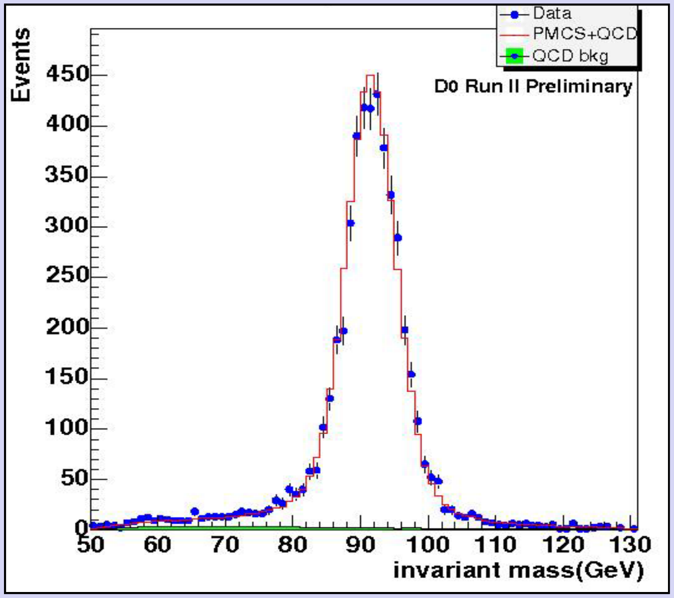
Uranium Liquid Argon calorimeter

Drift tubes and scintillation counters based muon system

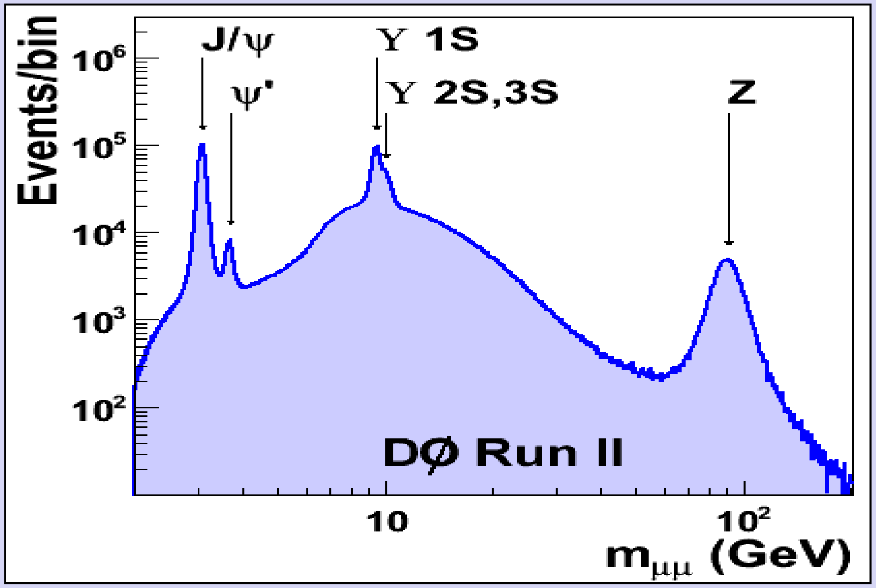
~50,000 channels in each system



Z → e^+e^-



Muons are excellent for studies of resonances production

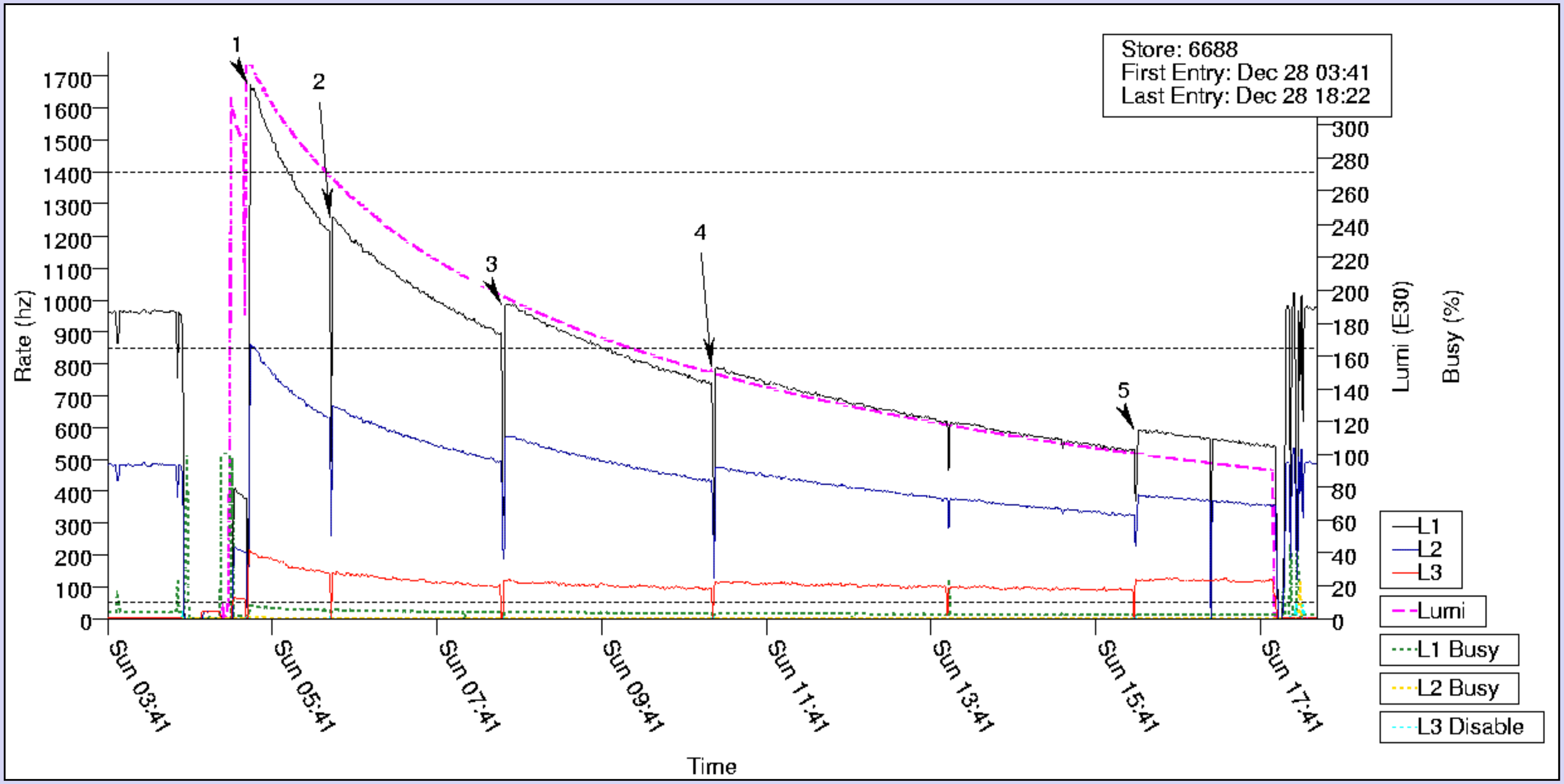


Triggering

Rate of interactions between protons and anti-protons is ~10 MHz

Only ~200 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

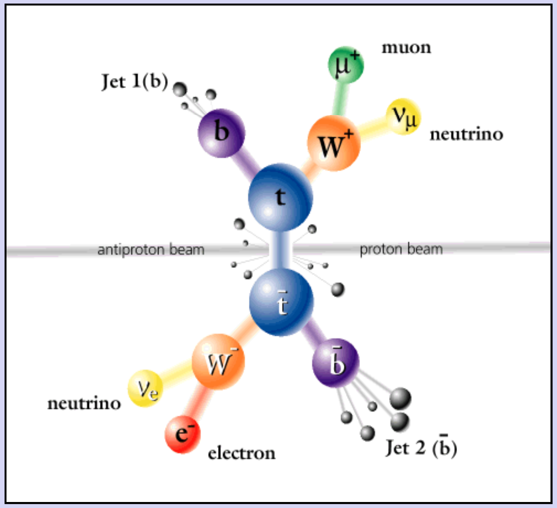


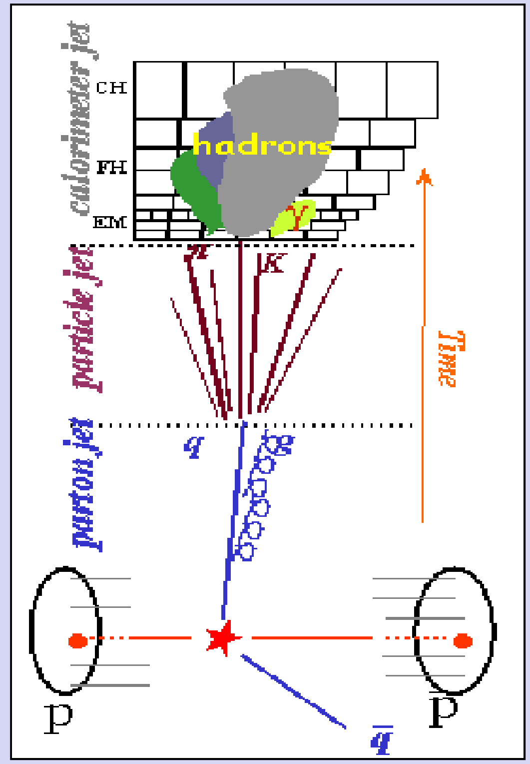
Typical Tevatron store with starting luminosity of $3.5 \cdot 10^{32}$ cm^{-2}sec^{-1}

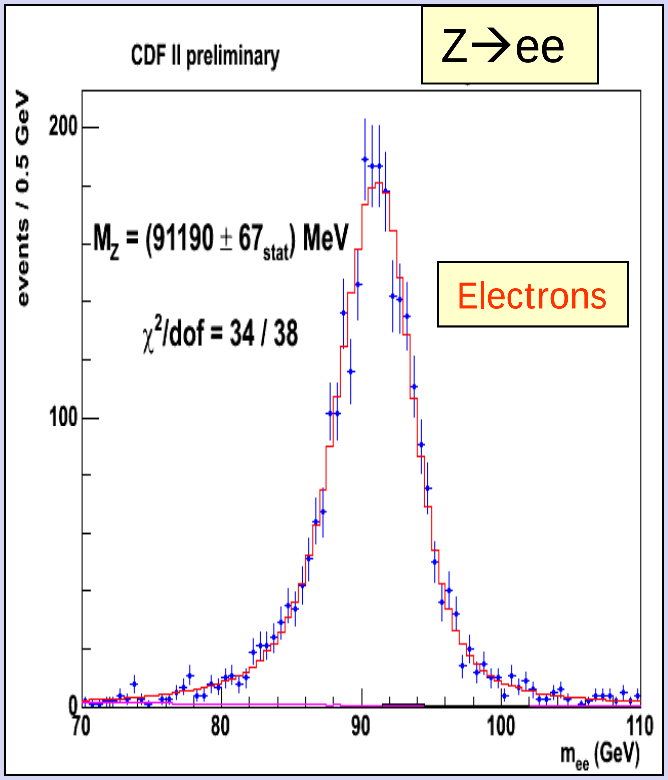
Detectable Objects – Particle Identification

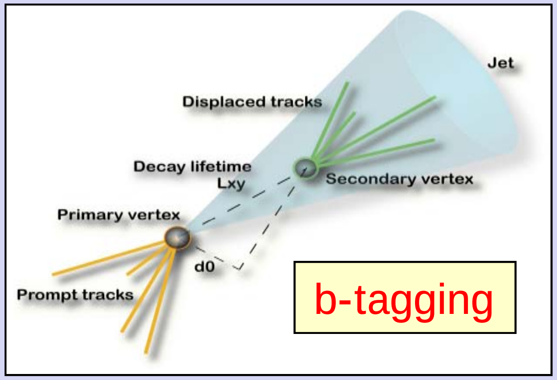
Final decay products
→ electrons
→ muons
→ charged tracks
→ jets (and b-jets)
→missing E_t (ν)

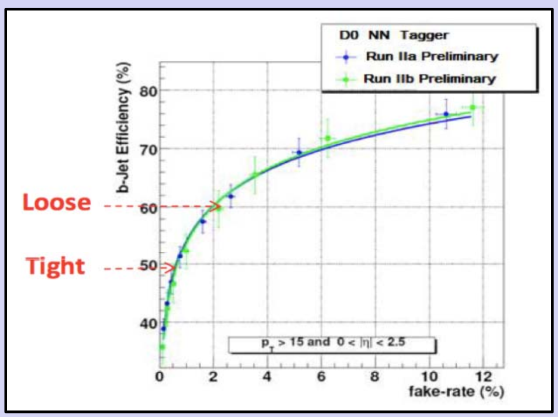
Excellent understanding of particles detection

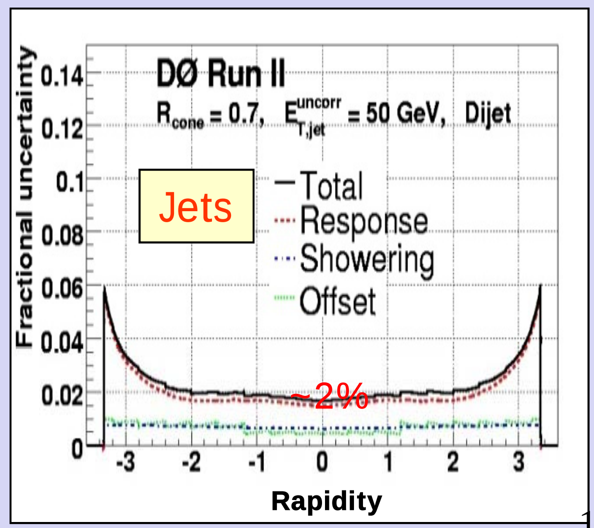




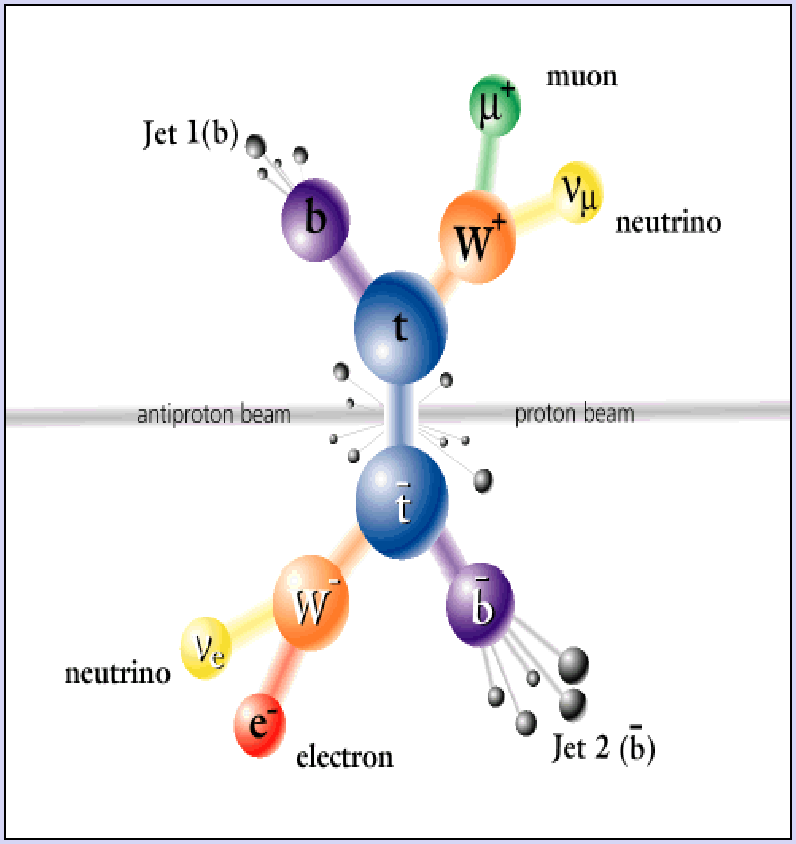


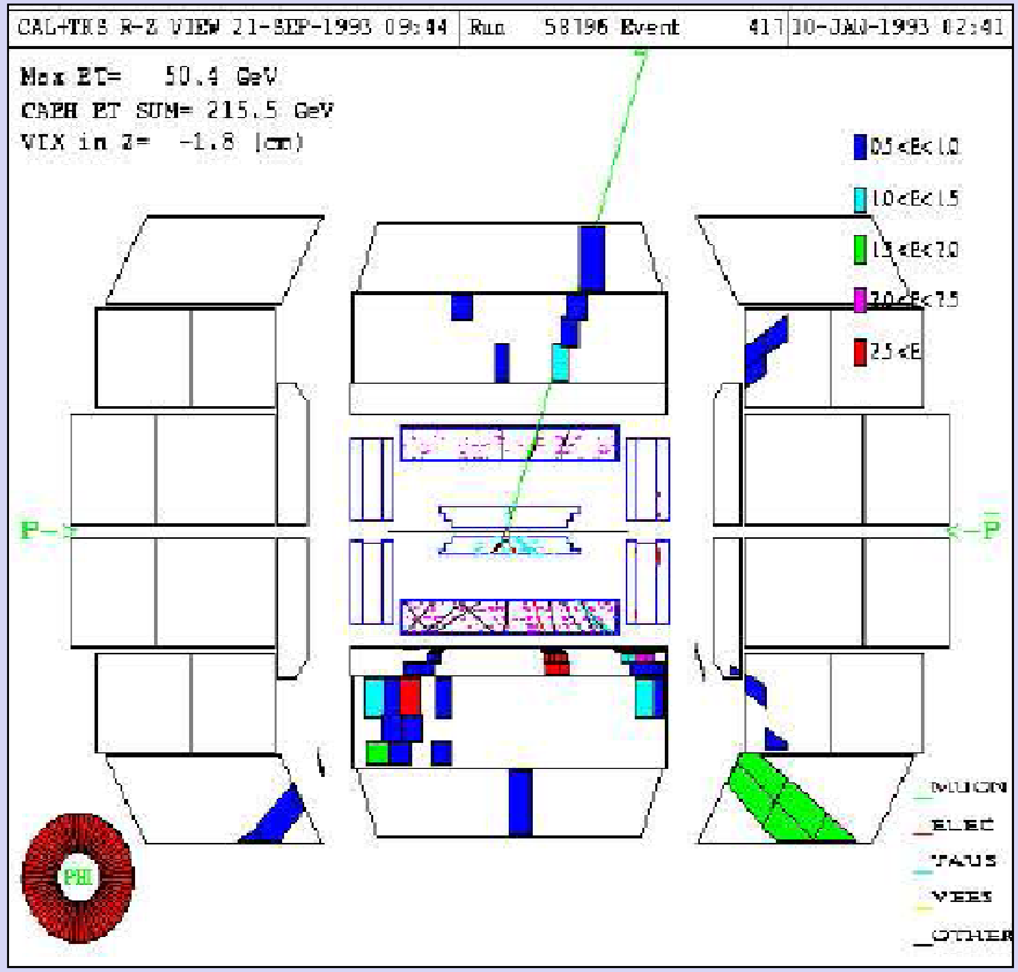






Example: Discovery of the Top Quark

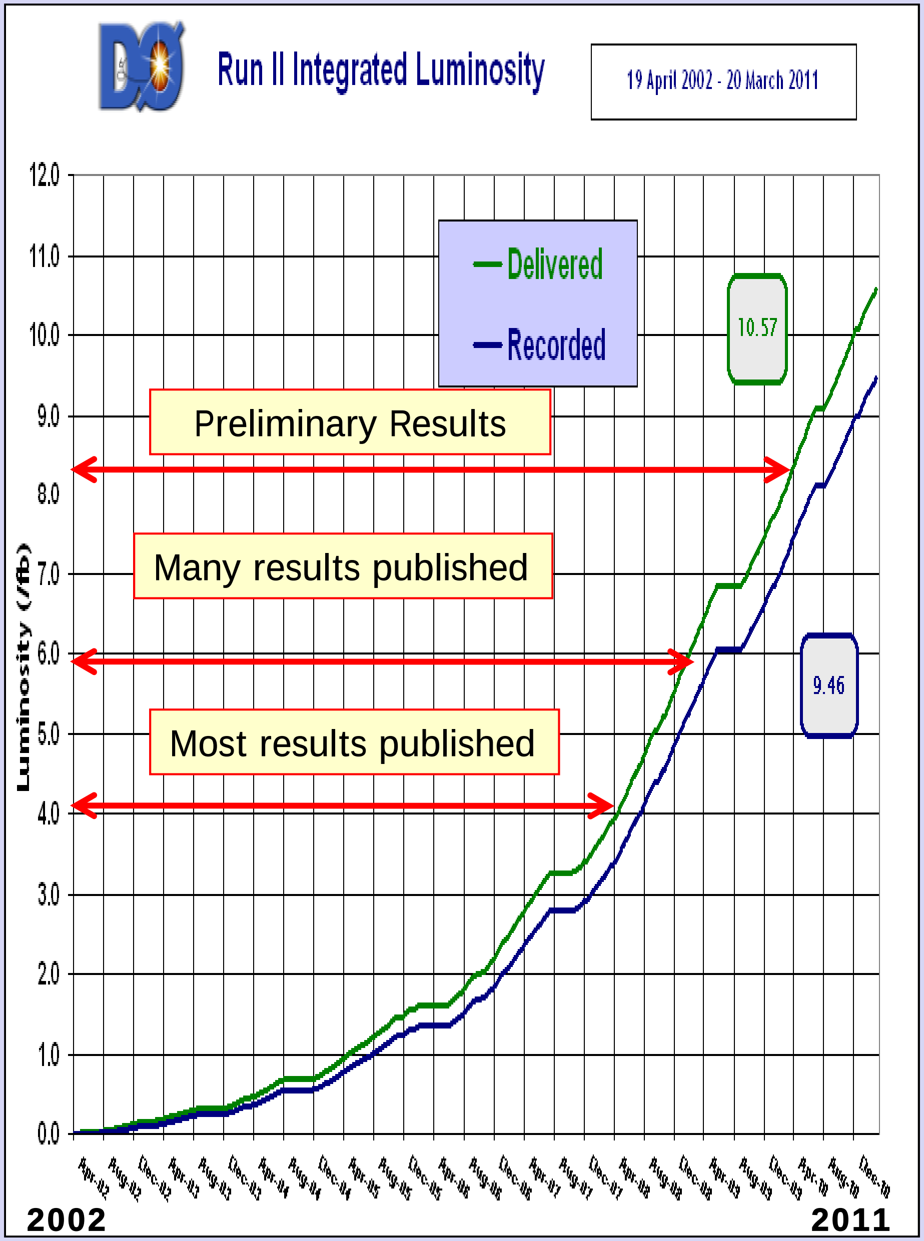




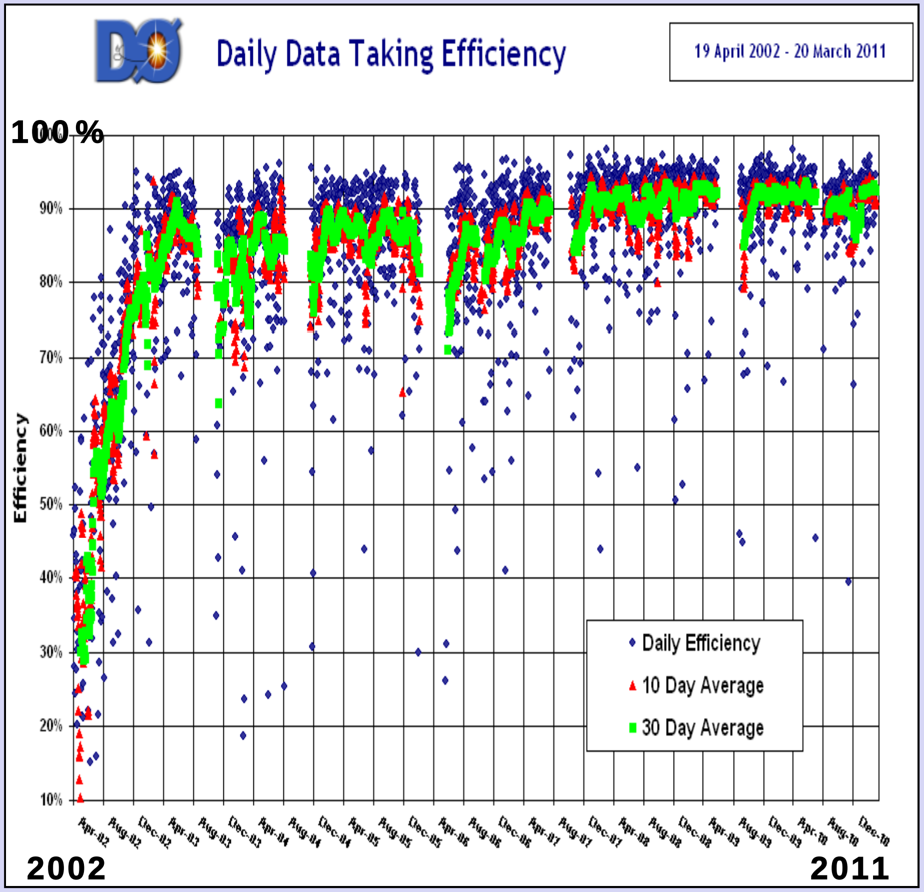
Mass of a parent object reconstructed from the decay products

Candidate top quark pair production event display

Data Collection

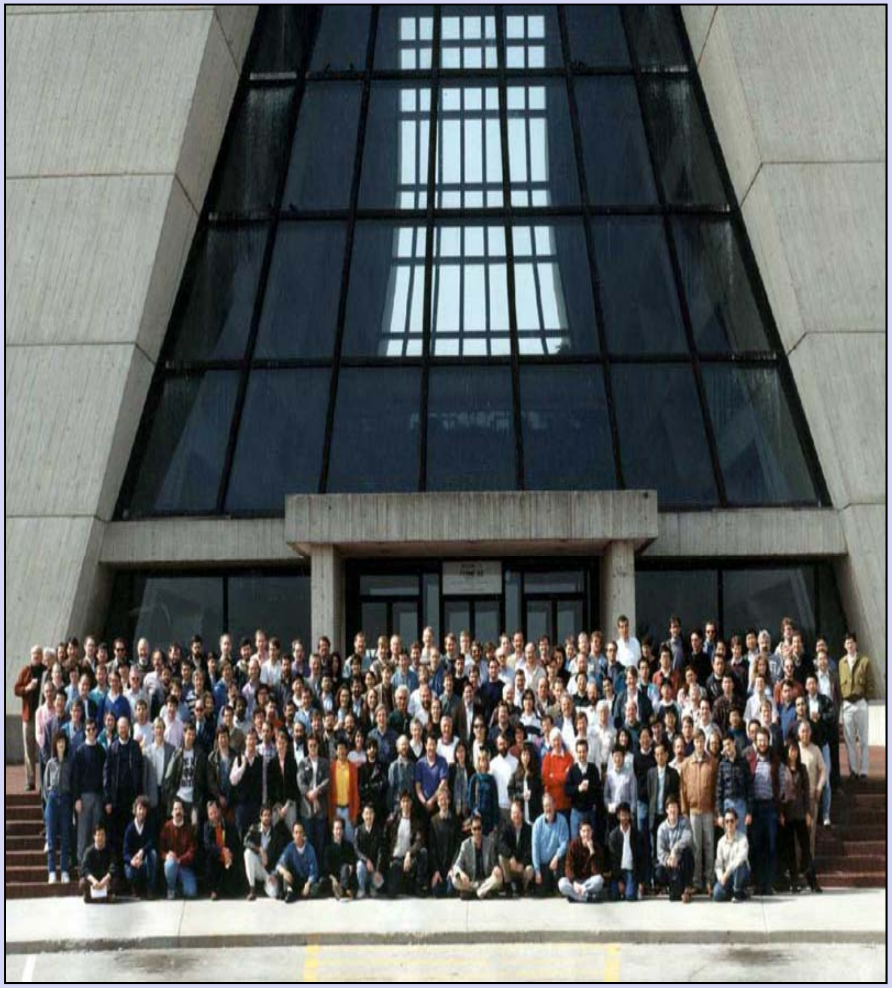


- **Smoothly recording physics data**
  - **Typical week ~55 pb^{-1}**
- **On average 92% data taking efficiency**
- **As of today DØ has ~9.5 fb^{-1} on tapes**



CDF and DØ Collaborations

Behind all technical complexity there are 100's scientists from all over the world working closely together



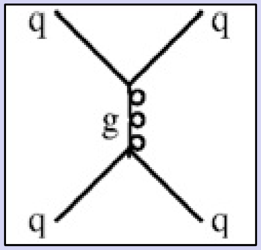
CDF : ~540 physicists, 15 countries, 63 institutions

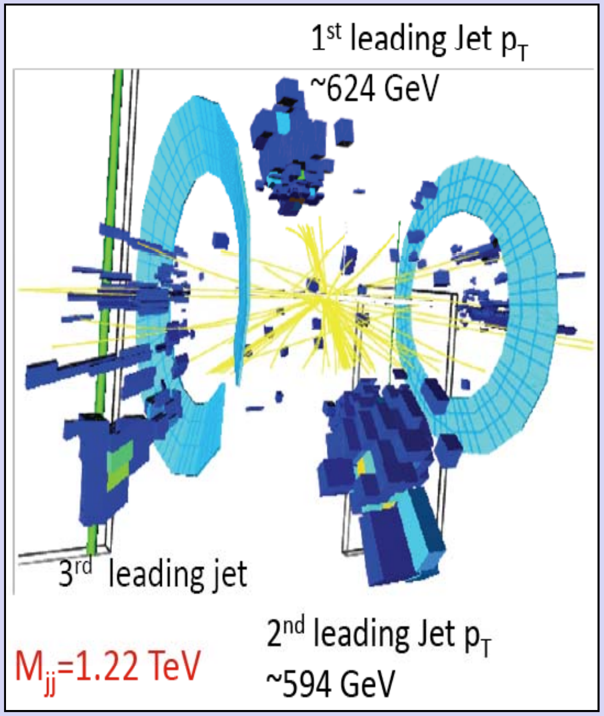
DØ : ~500 physicists, 20 countries, 87 institutions

QCD Studies: Jets

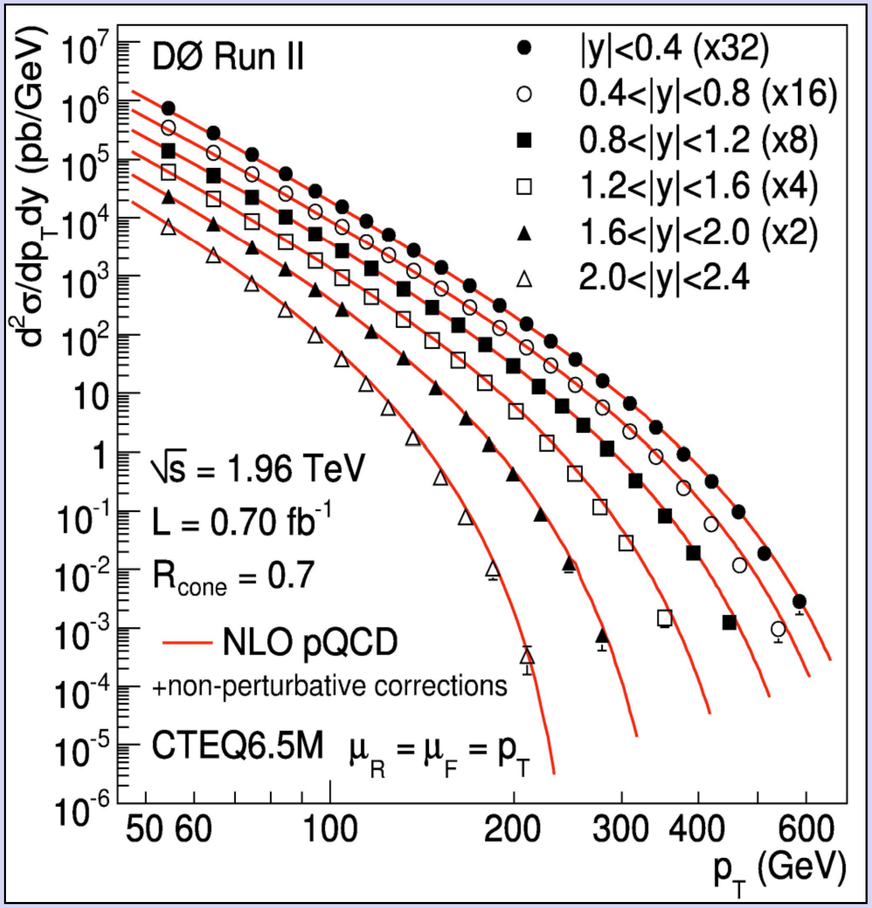
Use quarks and gluons scattering to study strong interaction

- **Rutherford style experiment**
- **Quarks sub-structure?**





Inclusive jet cross sections

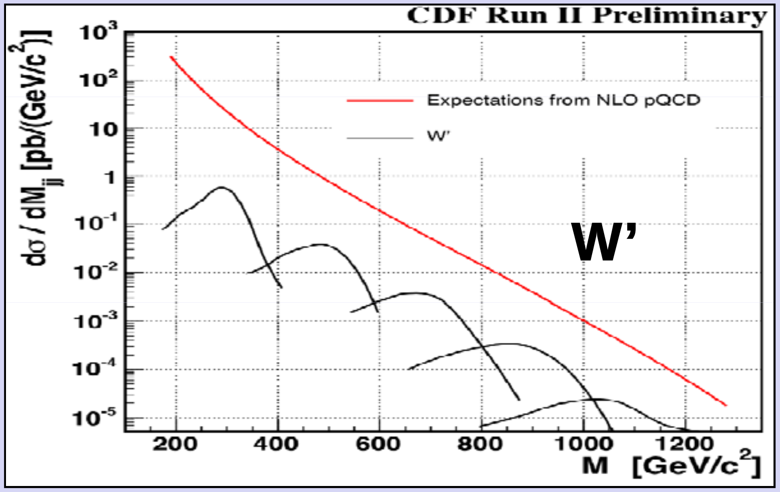


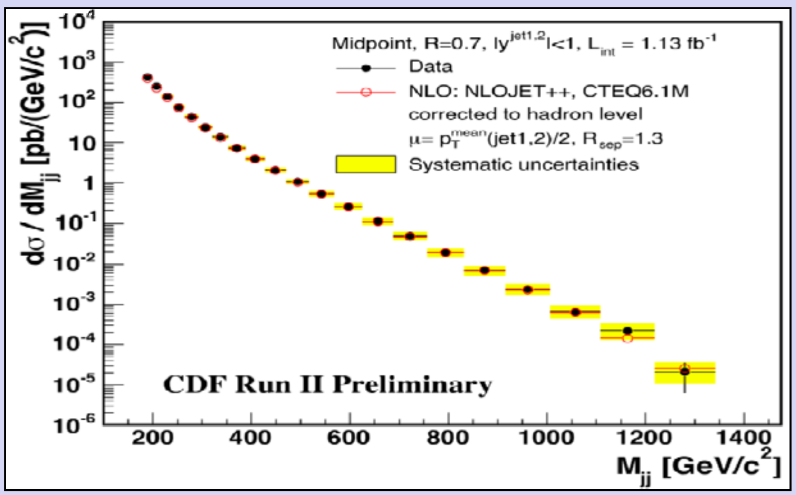
1 TeV energy deposition!
Half of the total beams energy

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

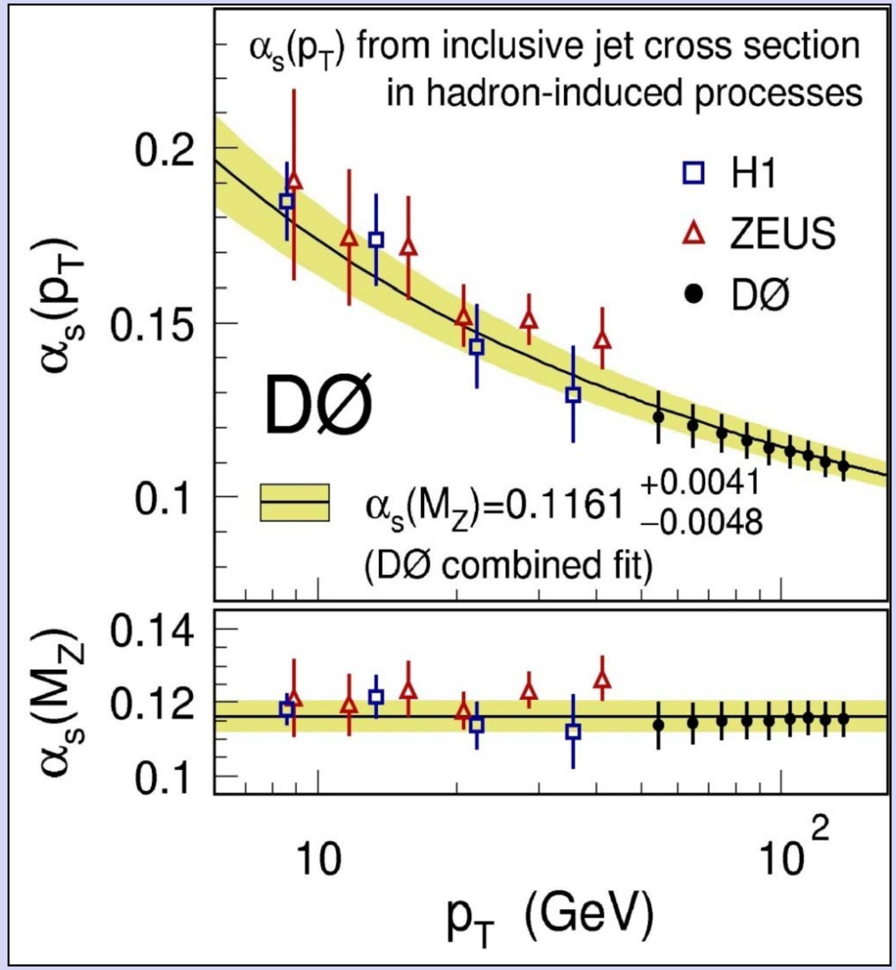
And More Jets

- **High mass di-jet resonances predicted in beyond SM theories**
- **Masses up to 1.2 TeV studied**





No W' observed for now…



- **Determination of the strong coupling constant from the inclusive jet cross sections**
- **High accuracy α_s measurement and running of α_s vs energy studied**

Top Quark Studies

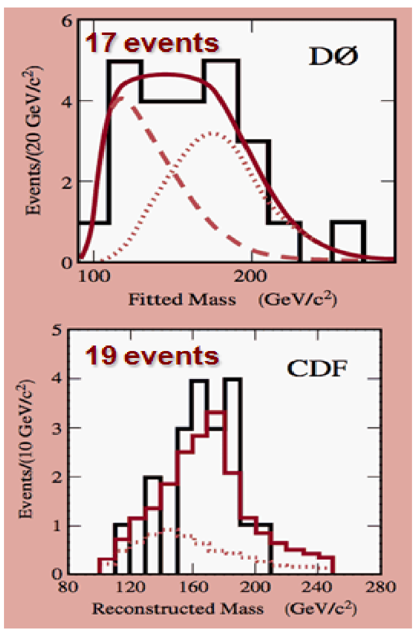
Heaviest known elementary particle: ~173 GeV

→Measure properties of the least known quark

- **mass, charge, decay modes, etc.**
- **data sets of 1000's of top quarks exist**

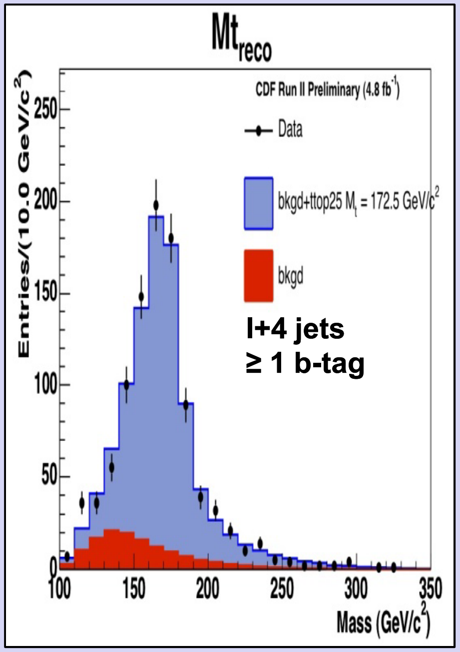
→ Short life time: probe bare quark

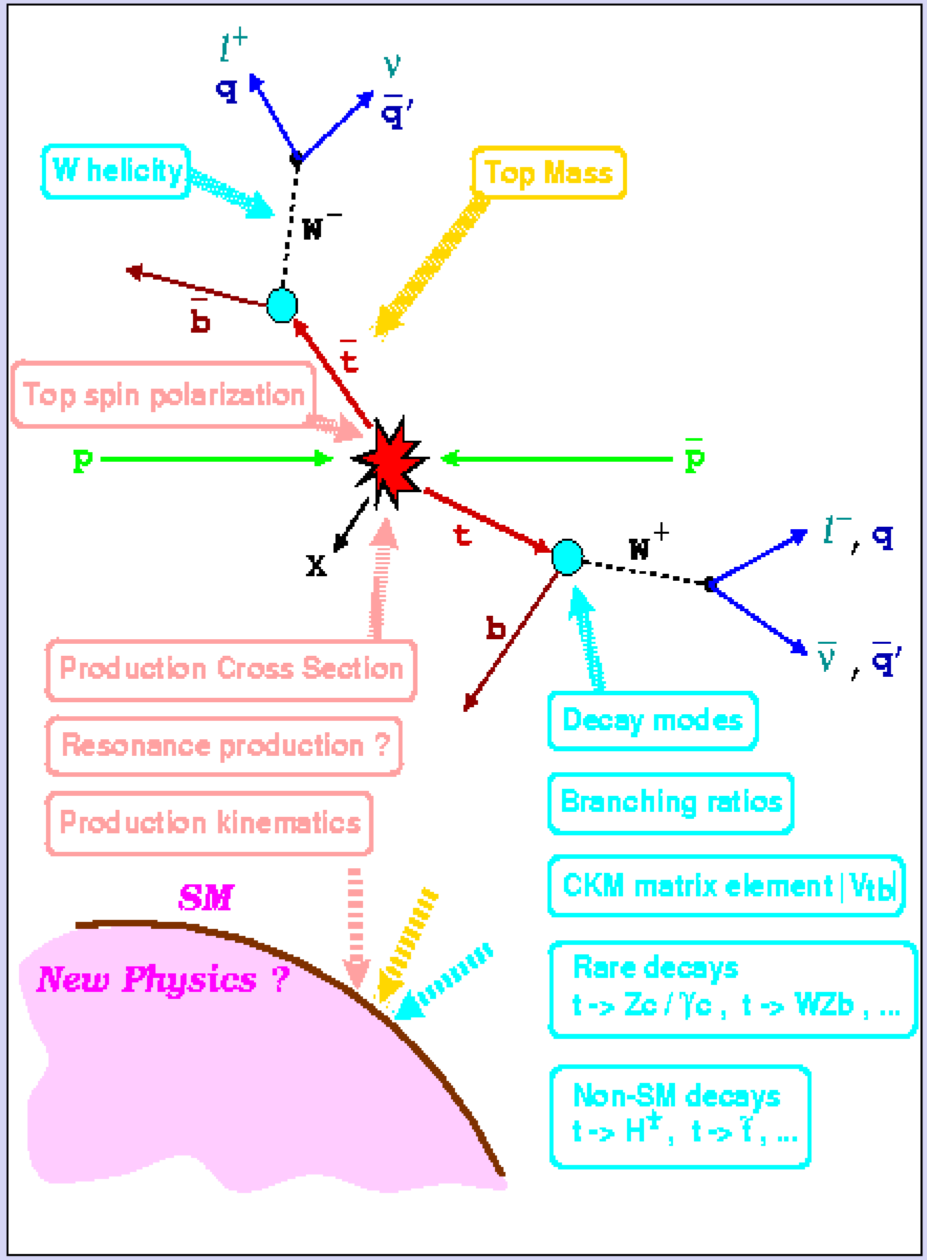
Discovery in 1995



1995, CDF and DØ experiments, Fermilab

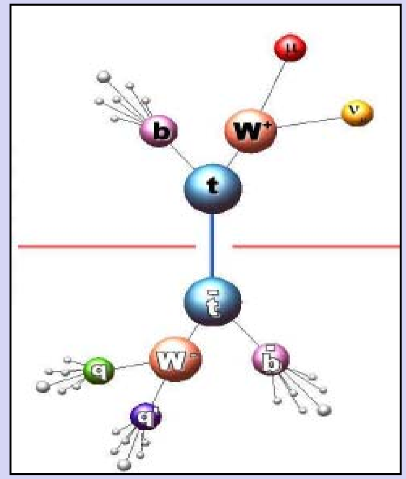
Today

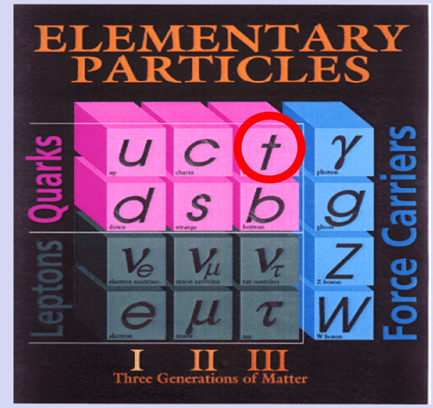


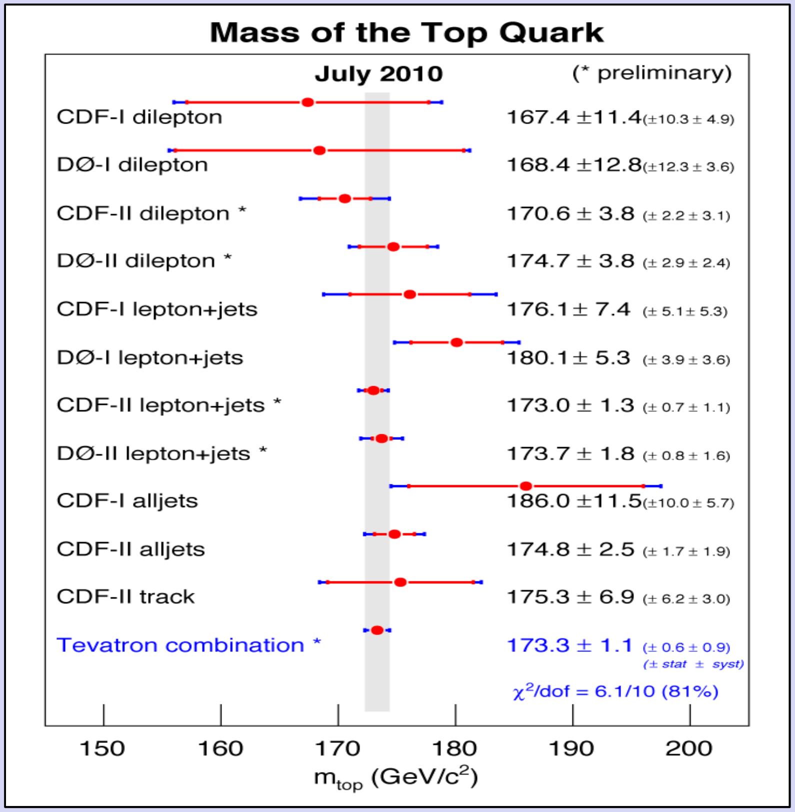


Top Quark Mass Measurement

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

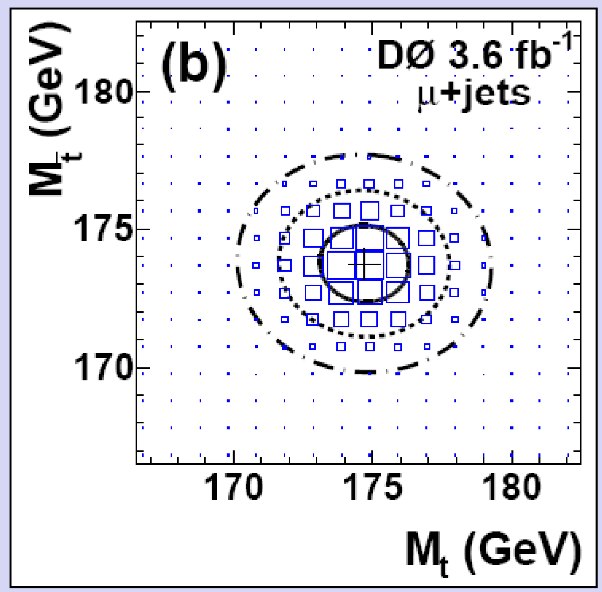






DØ and CDF combined top mass result
m_t = 173.3±1.1 GeV
0.6 % accuracy
Best (of any) quark mass measurement!

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



$$\Delta M = 0.8 \pm 1.8\ (\text{stat.}) \pm 0.8\ (\text{syst.})\ \text{GeV}$$

Main Top Quark Properties Measured at the Tevatron

- Top quark mass: m_t = 173.3±1.1 GeV (0.6% accuracy)
- Are top and antitop masses the same? Test of CPT
  - Δm=0.8± 1.9 GeV (equal to 1%)
- Top quark lifetime
  - Γ_t=1.99(+0.69/-0.55) GeV agrees with SM
- Top charge |q|=2/3e to 95% C.L.
- W helicity in top decay expect 70% longitudinal, 30% left-handed
  SM looks good
- Asymmetry of top quark in p vs pbar direction expected to be ~1%
  DZero 8±4%; CDF high mass anomaly?
- Correlations of spins of top and anti-top are consistent with SM
- No flavor changing neutral currents
  $<2\times10^{-4}$ ($t \to gu$); $<4\times10^{-3}$ ($t \to gc$)
- No evidence for SUSY $H^{\pm}$ in top decays
- Anomalous top vector/tensor couplings?
  Combination of W helicity & single top is in good agreement with SM V-A
- 4th generation t'? None below ~358 GeV
- tt resonances? None below ~700 GeV
- Is W in t decay color singlet? Singlet preferred
- Electroweak single top quark production observed: $|V_{tb}|$ > 0.77 @ 95% C.L.

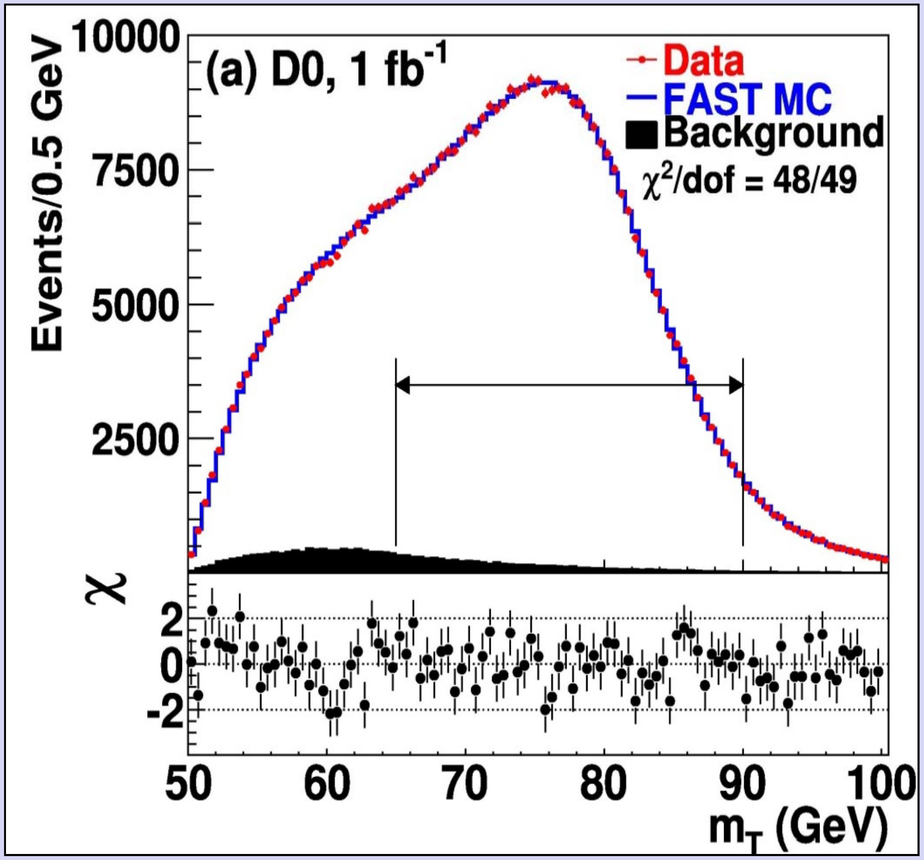
Very well know quark by now!

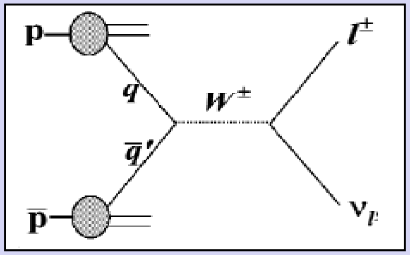
Electroweak Physics

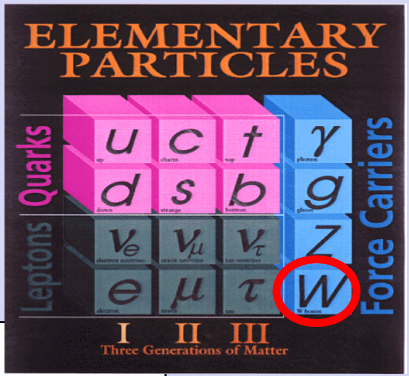
Precision measurements of electroweak parameters

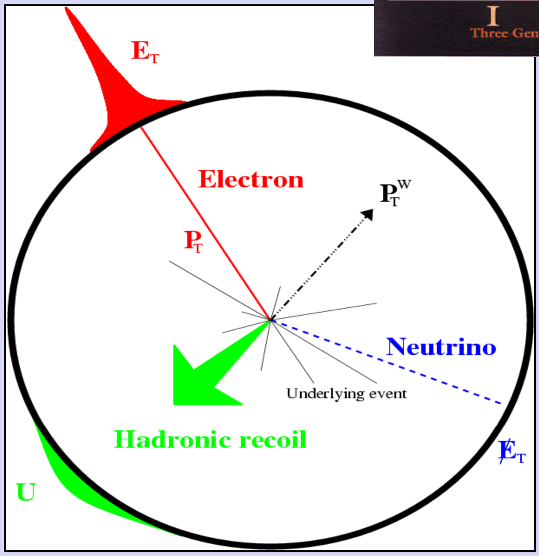
Measure single and multi-boson production, W mass, W production asymmetry,...

World most precise W mass measurement







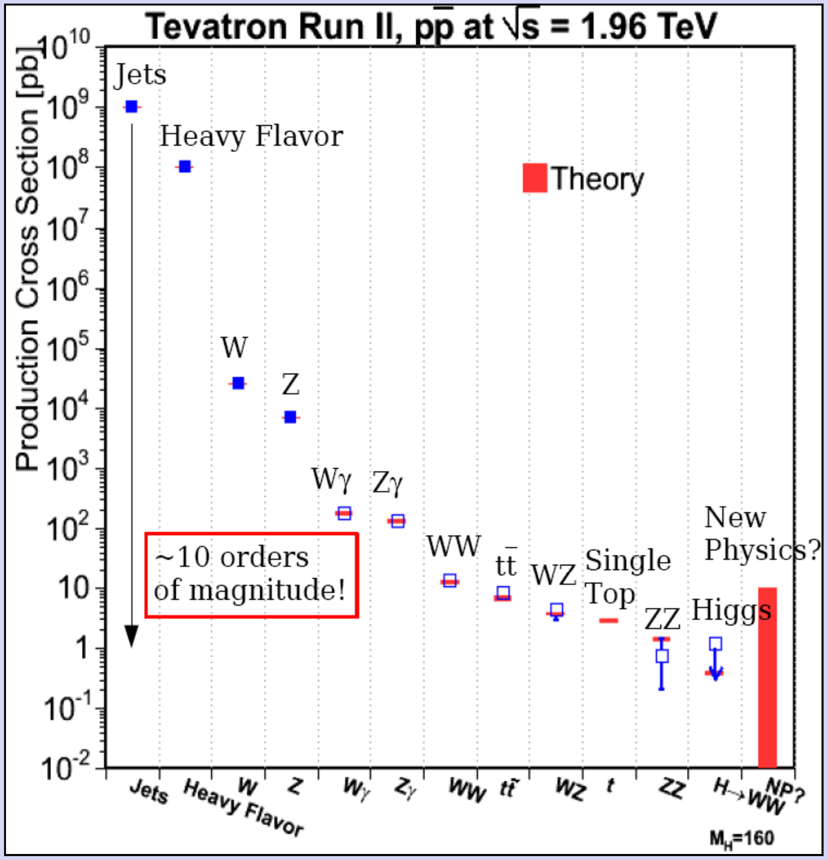


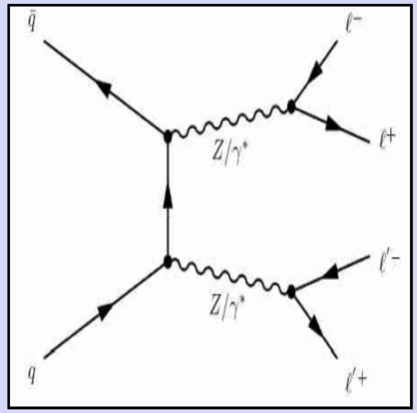
80,401 ± 21(stat.) ± 38(syst.) MeV
0.05 %

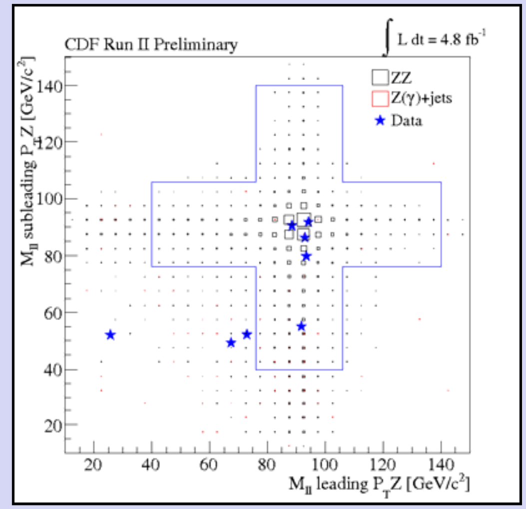
W mass world average is now
80,399 ± 23 MeV (0.025 %)
Helps to predict Higgs mass

Studies of di-boson Production

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



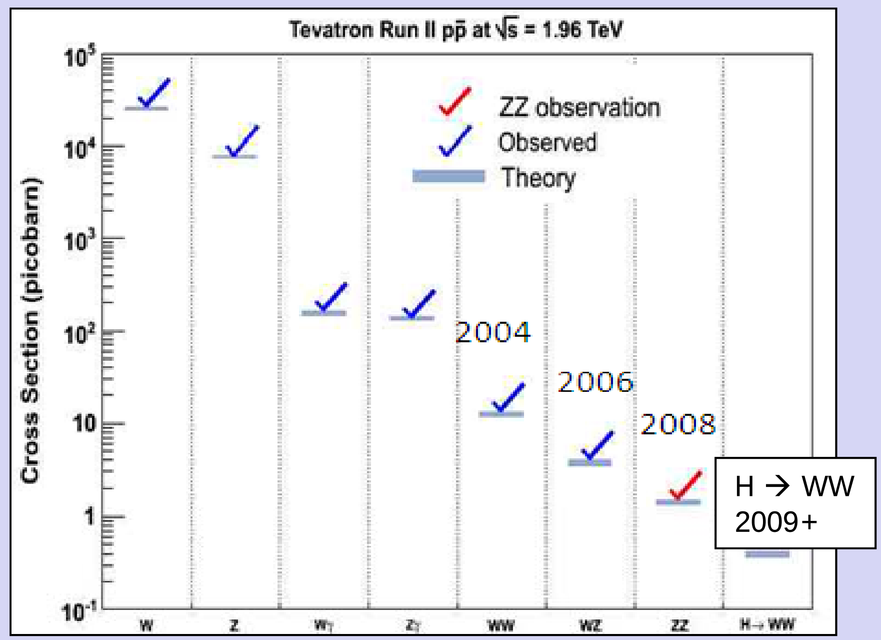




ZZ has the smallest di-boson cross section

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

... next lower is the Higgs



b-quark Studies

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

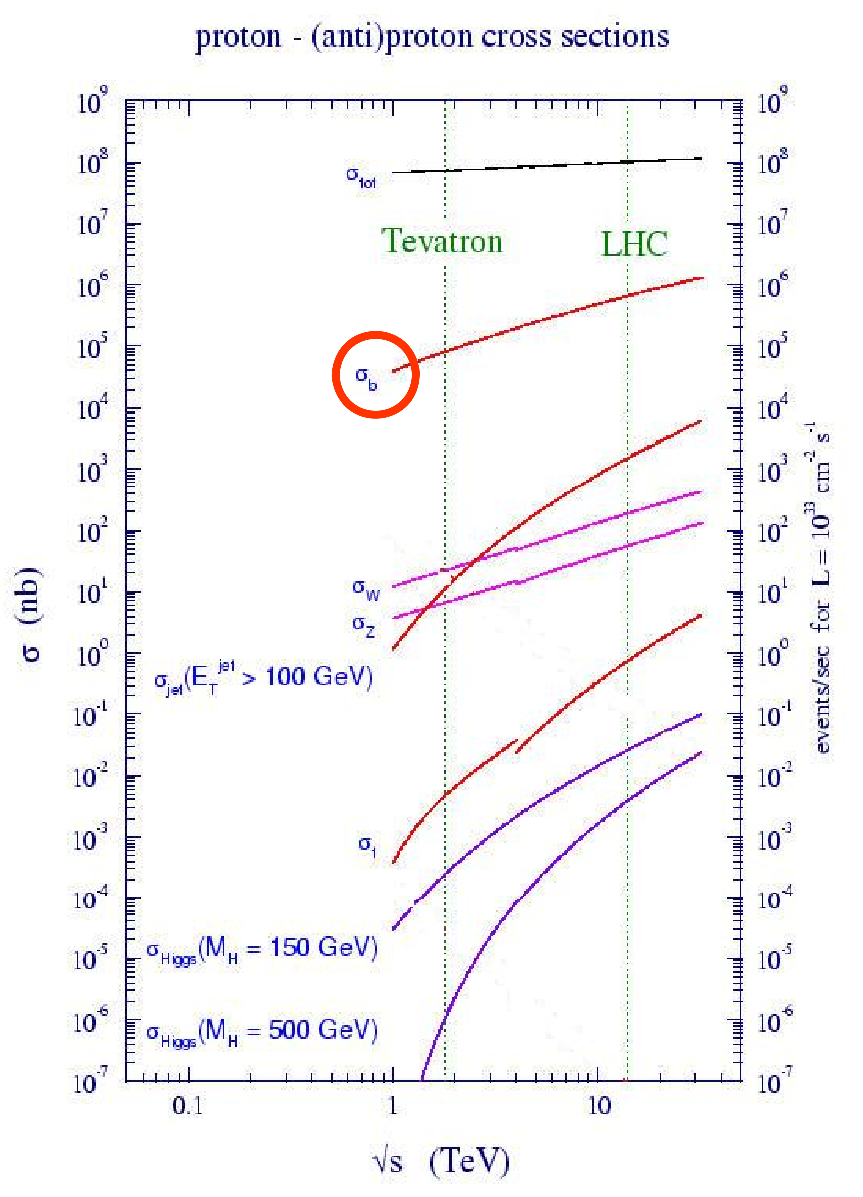
~10^4 b's per second produced!

All b containing species are produced

$B^{\pm}$, B^0, B_s, B_c, Λ_b…

Large b quark data samples provide

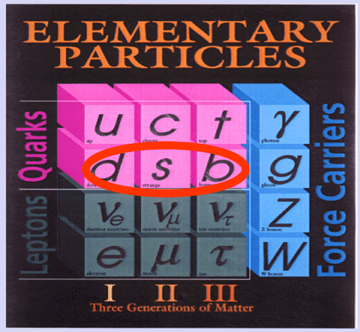
- **B mesons lifetime studies**
- **Mass spectroscopy (B_c, etc.)**
- **Studies of B_s oscillations**
- **CP violation studies**
- **Search for new b hadrons**
- **Search for rear decays**

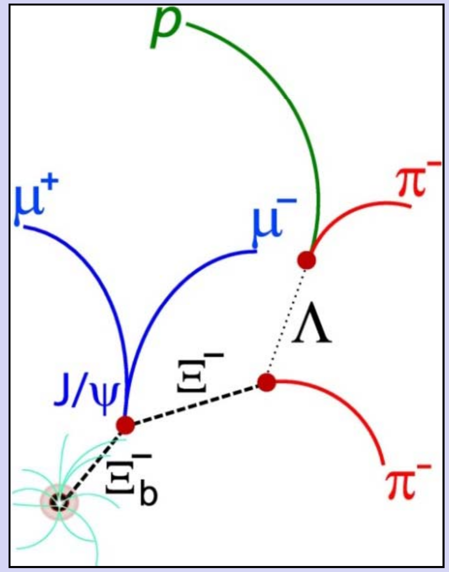


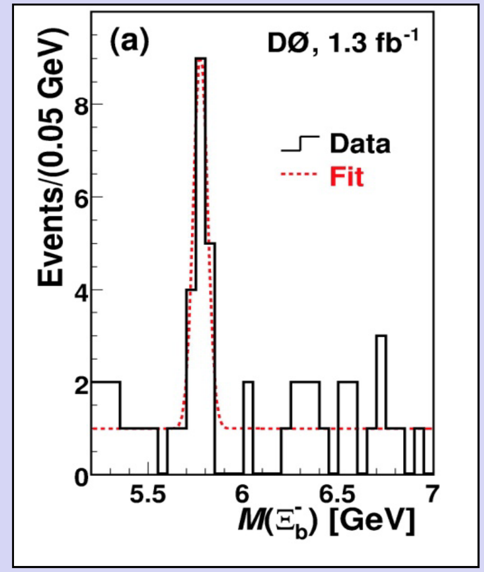
New Particles with b-quarks

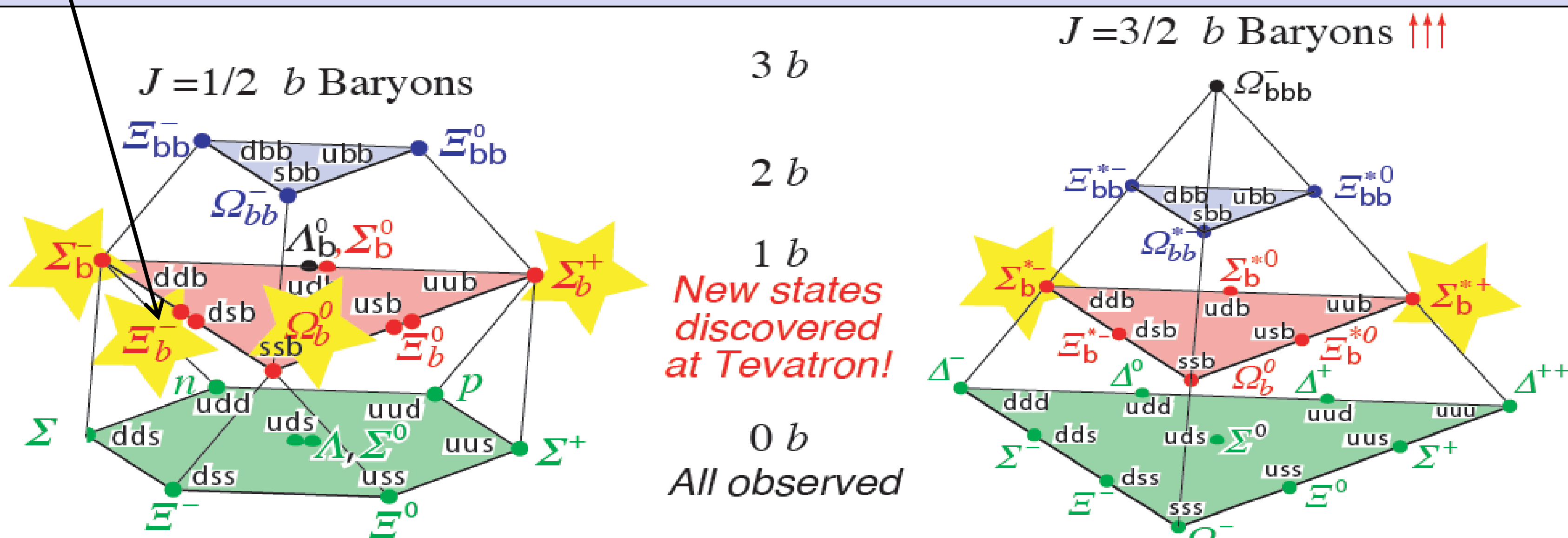
All b quark containing species are produced: $B^{\pm}$, B^0, B_s, B_c, Λ_b…

First baryon with quarks from all three generations observed!





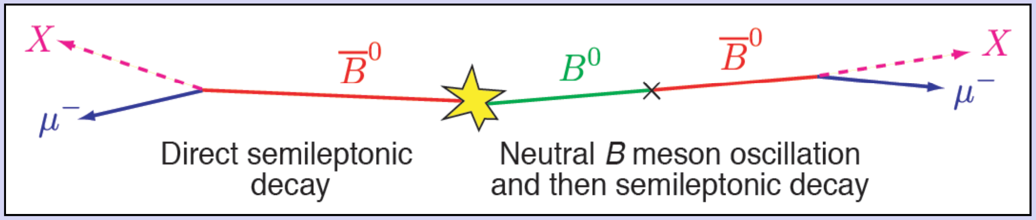


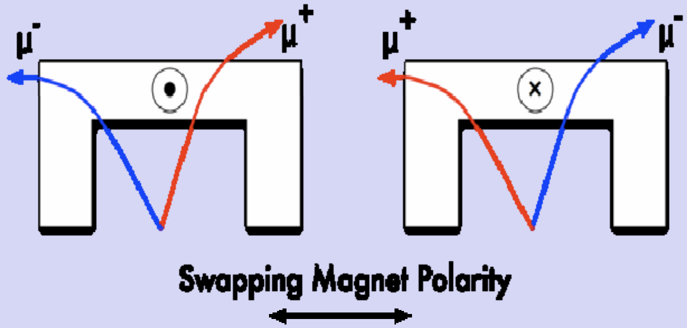


- Until Tevatron, ground state Λ_b was the only directly observed b baryon

$\Lambda_b^0 = |bud\rangle$ LEP, DØ, CDF

DØ di-muon Charge Asymmetry Puzzle





- **Di-muon charge asymmetry**

$$A_{sl}^{b} \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$

for events coming from decays of mesons containing b quarks undergoing mixing

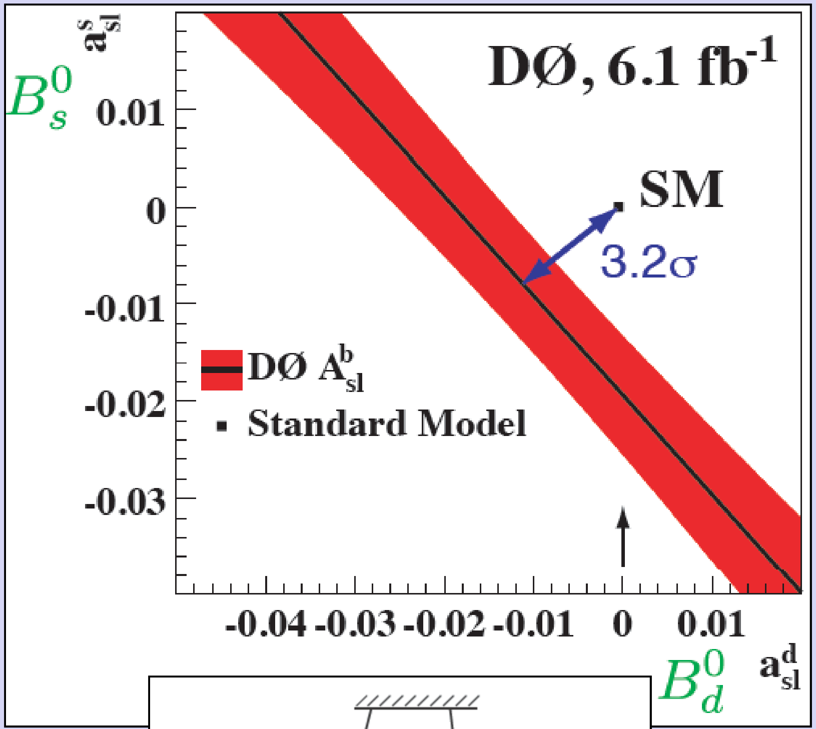
- **Standard Model predicts this asymmetry to be very small**

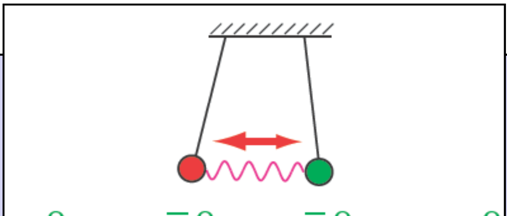
$$A_{sl}^{b} = (-2.3^{+0.5}_{-0.6}) \times 10^{-4}$$

- **Any substantial deviation of this asymmetry from zero will be indication of new source of CP violation**
- **Measured value is 3.2σ from prediction**

$$A_{sl}^{b} = (-0.957 \pm 0.251\,(\text{stat}) \pm 0.146\,(\text{syst}))\%$$

This result might help to understand matter-antimatter asymmetry of the Universe



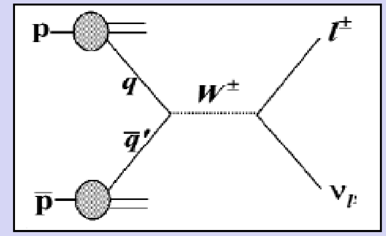


$B^0 \to \bar{B}^0 \neq \bar{B}^0 \to B^0$

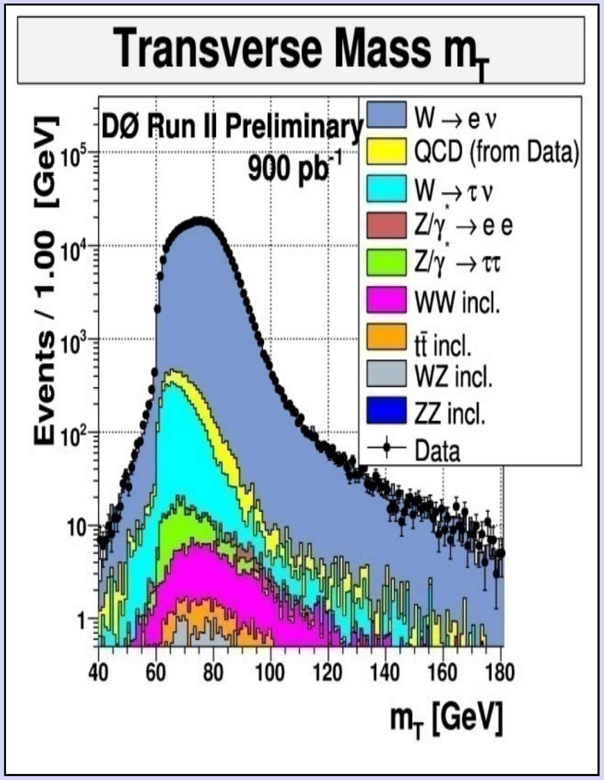
Search for New Phenomena

One of the most exciting studies is to look for new phenomena at the high energy collider
SUSY, leptoquarks, technicolor, new exotic particles, extra dimensions...

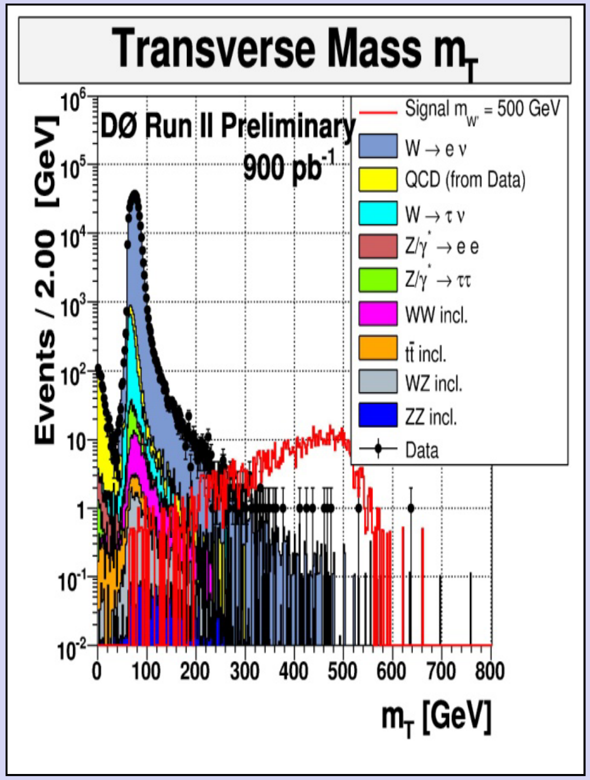
Example: heavy W' boson search



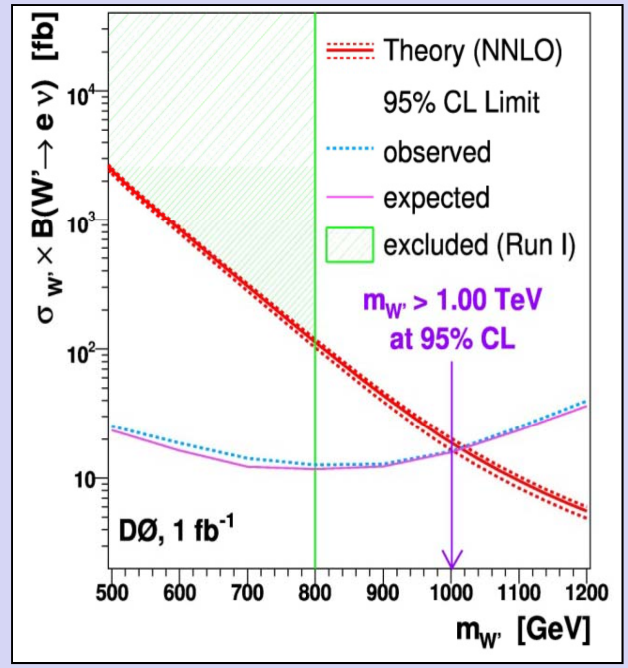
Check prediction of SM processes in low mass region



Then look into high mass region

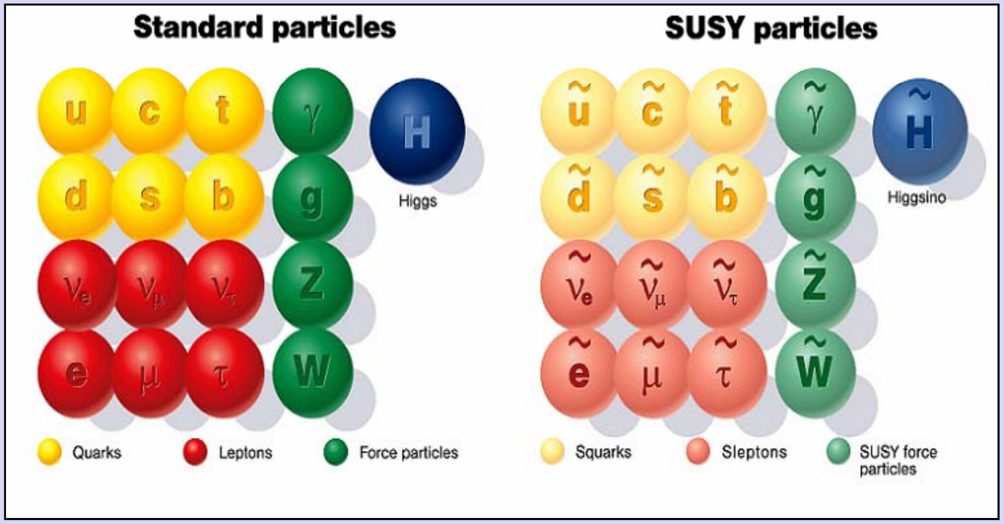


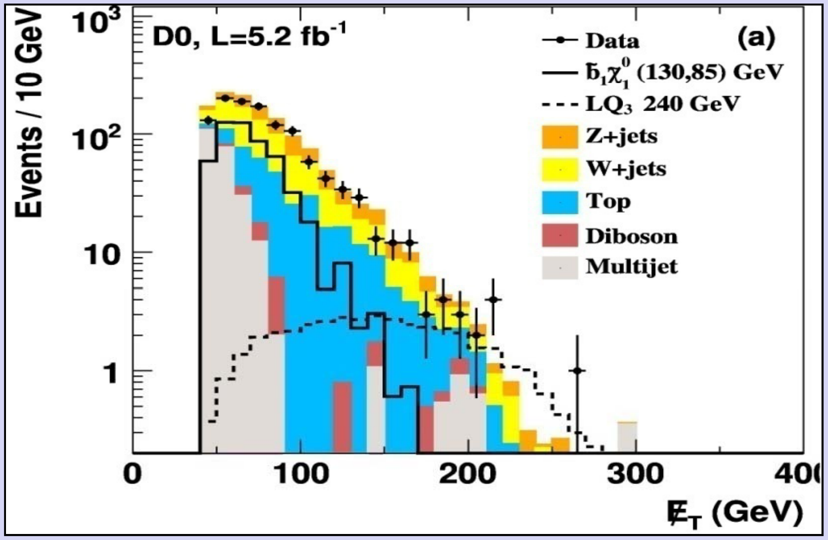
If no excess found, set limits



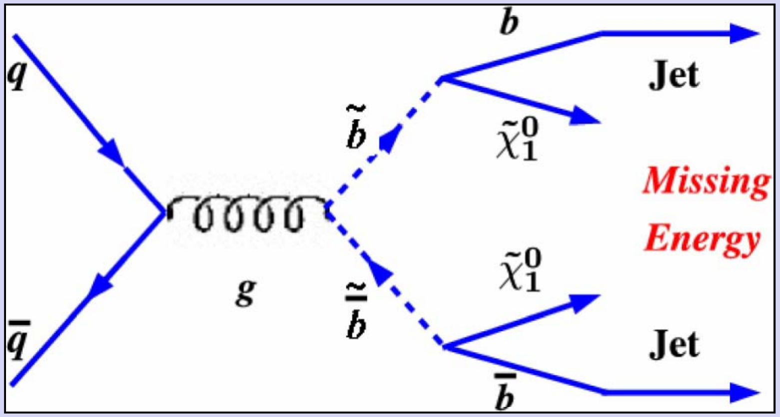
Reaching masses of ~1TeV – ½ of the Tevatron center of mass energy

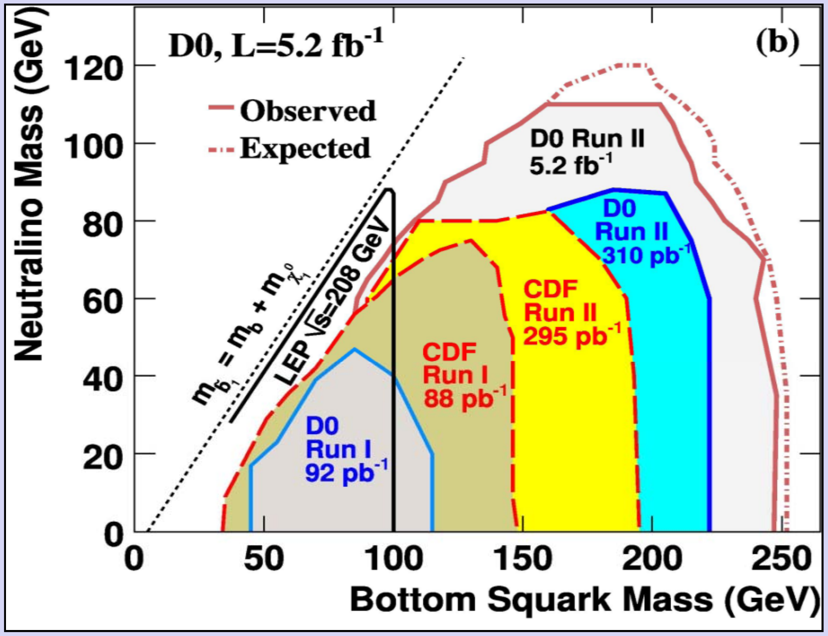
SUSY Searches





Search for sbottom quarks

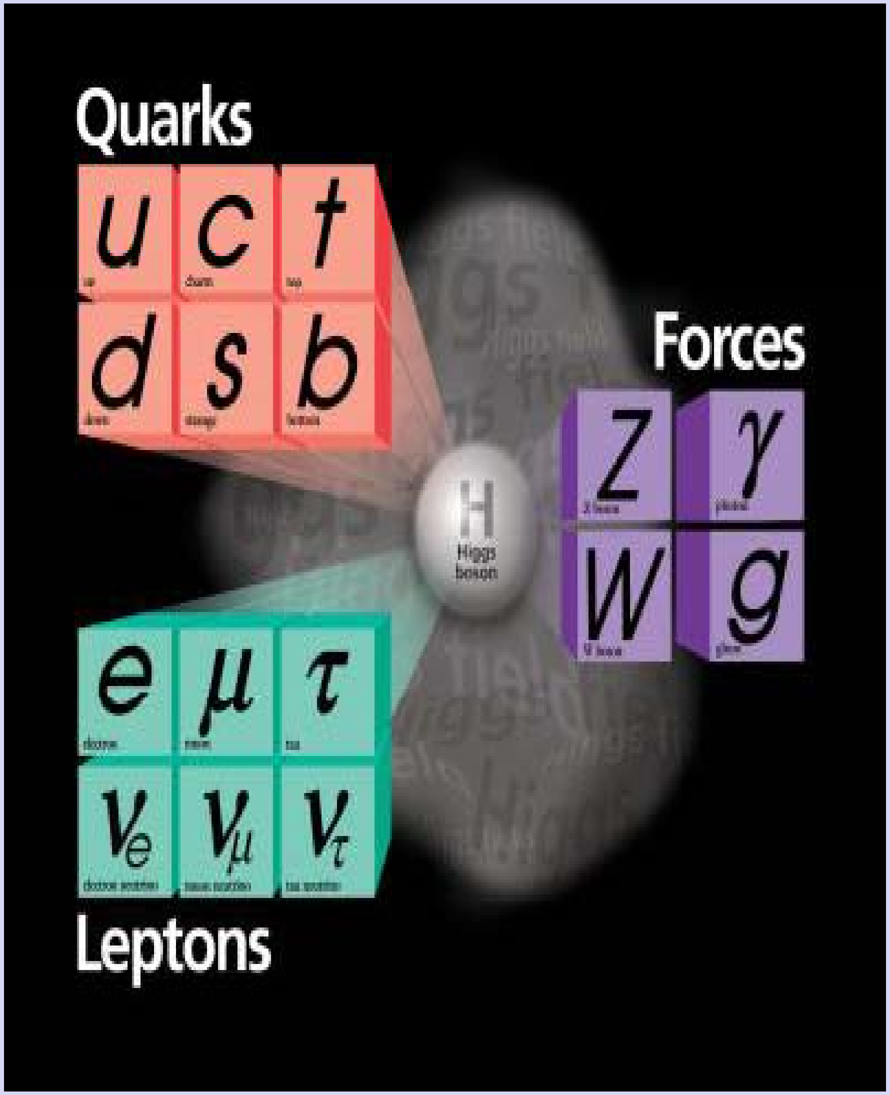




No indication of SUSY with particles masses below ~250-400 GeV

Introducing the Higgs

- 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



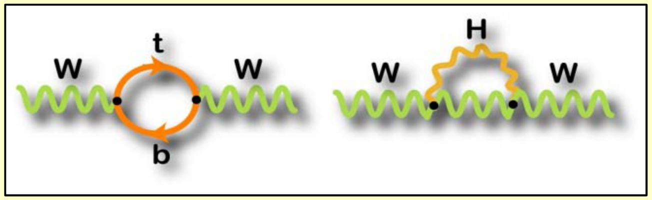
It is challenge for experimental physicists to find Higgs particle – the last undiscovered particle of the Standard Model

What is Higgs Mass?

Available experimental limits

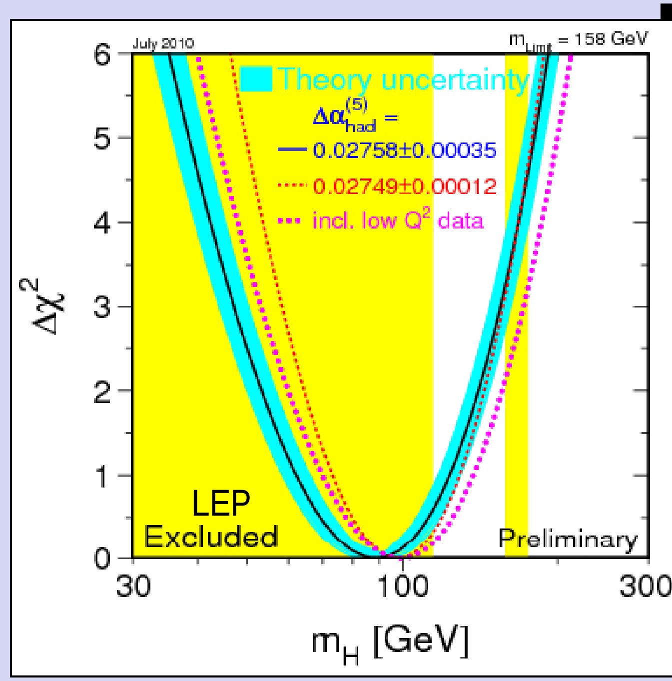
→ Direct searches at LEP: M_H >114 GeV at 95% C.L.

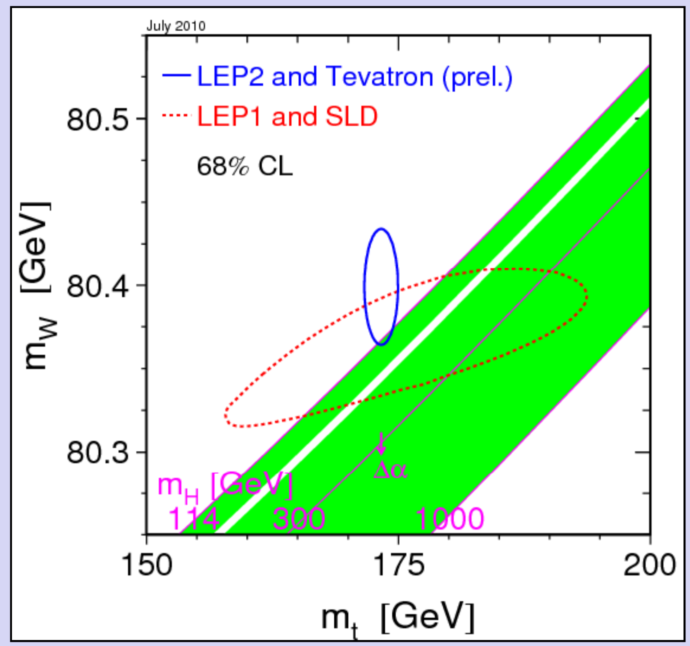
→ Precision theory fits



M_H<185 GeV with direct LEP limit

Light Higgs favored –> in the Tevatron energy range!

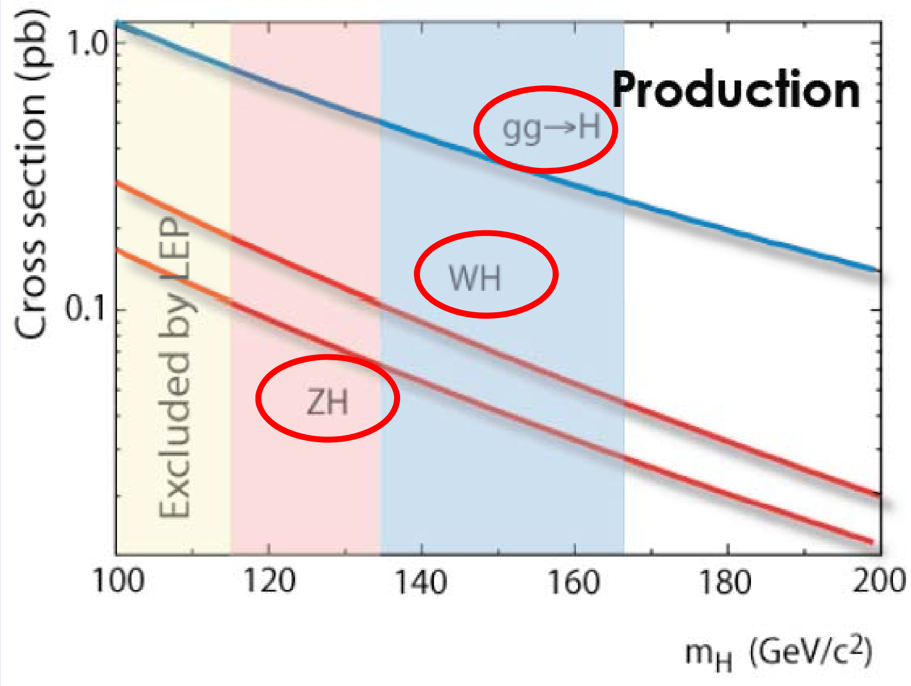


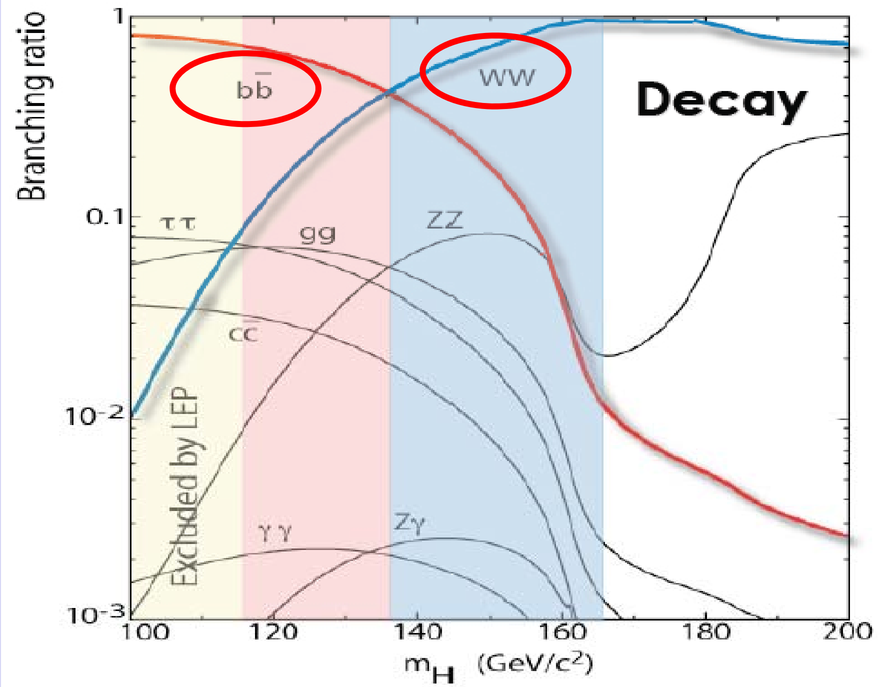


Tevatron provides:

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

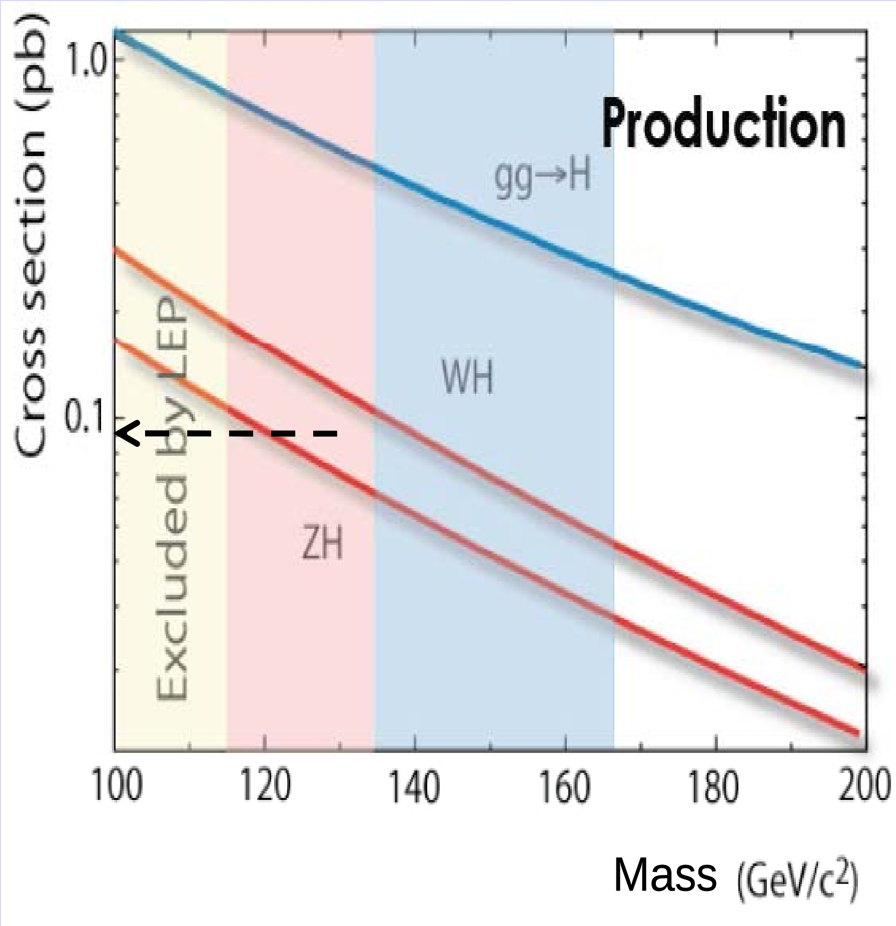
- Probability of producing Higgs is low

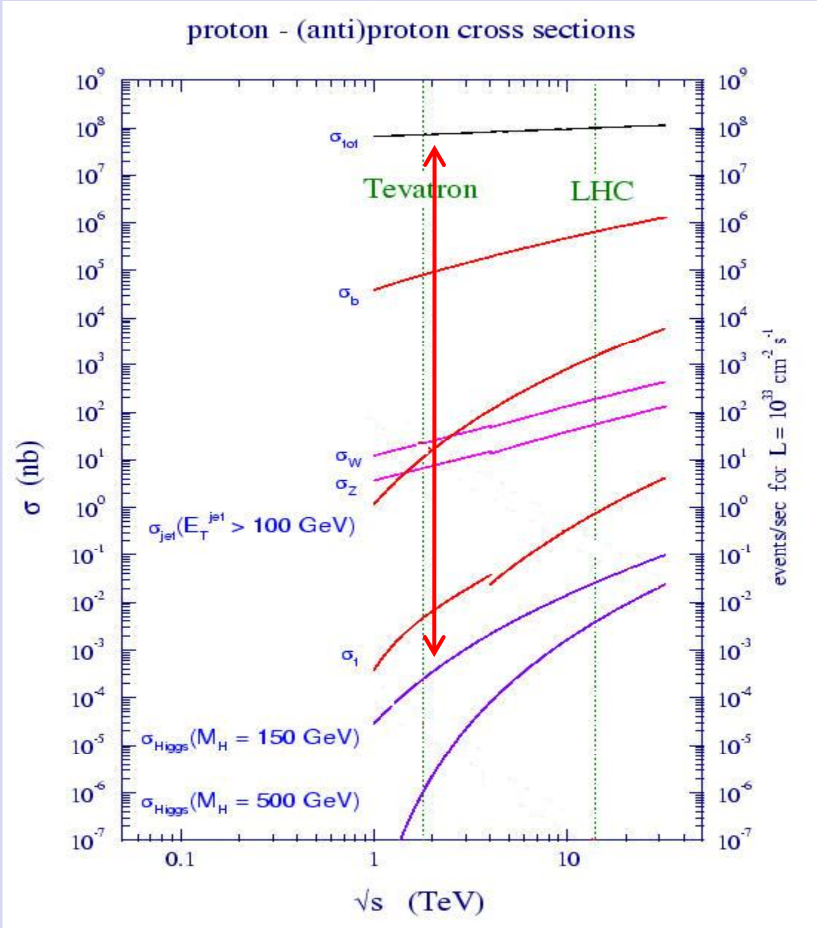
$$N_{events} = L \times \sigma$$

L is "Tevatron luminosity", σ is "cross section"

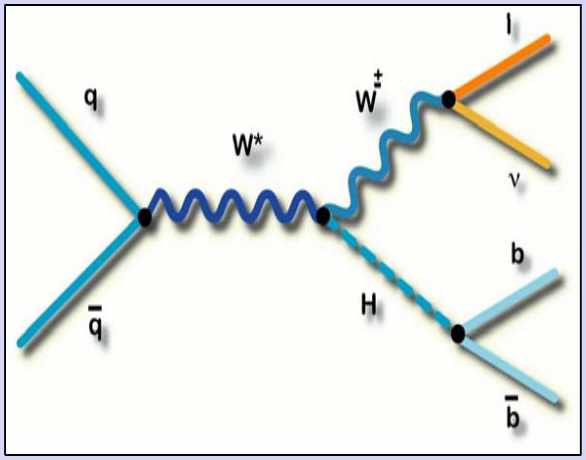
- To increase number of produced Higgs bosons we need luminosity

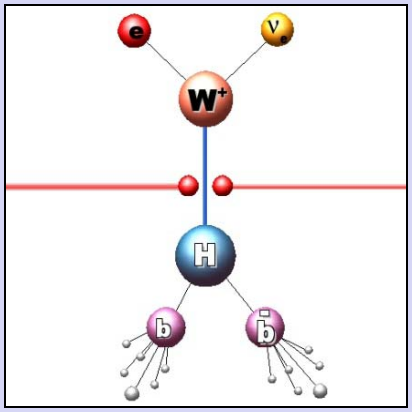
- Backgrounds from Standard Model processes are high
  - Only one out of 10^{12} collisions might contain Higgs particle
- Separation of backgrounds is one of the main challenges in hunt for the Higgs

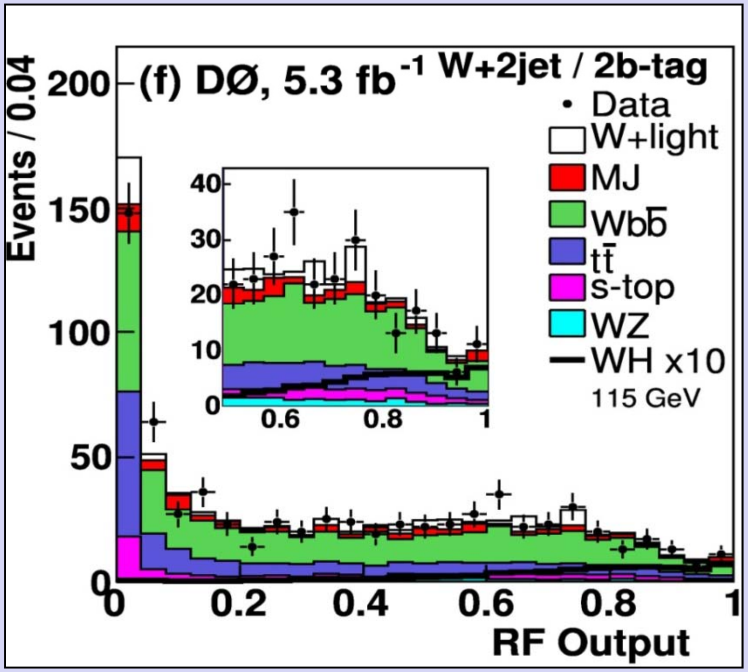




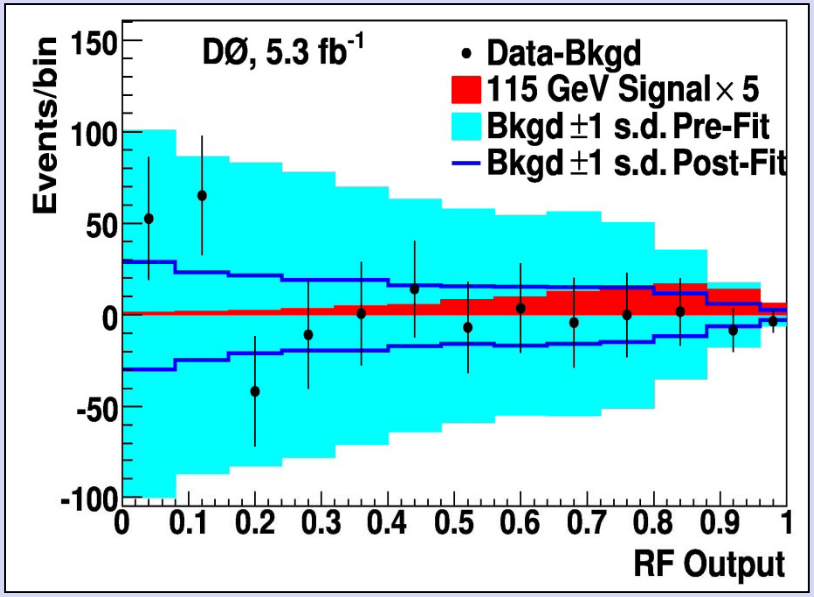
Higgs Search: WH → lνbb (M_H<130 GeV)



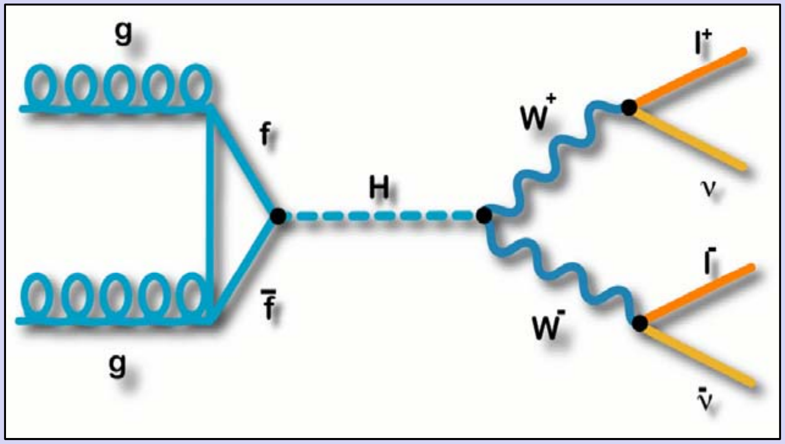




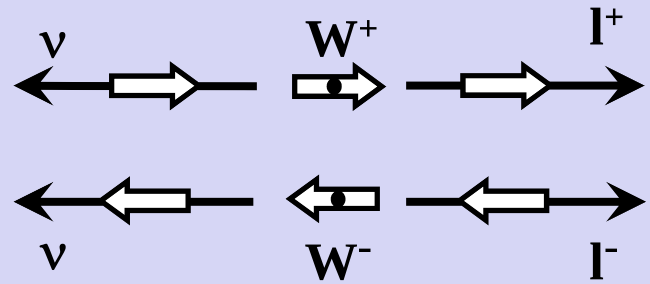
- One of the most sensitive channels in the ~110-130 GeV mass range
- Select events with lepton (muon or electron), neutrino (missing energy) and pair of jets from b-quarks
- Dijet mass → any peaks?
- For more sensitivity and to use all information about particles in an event
  - Dijet mass → multivariate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

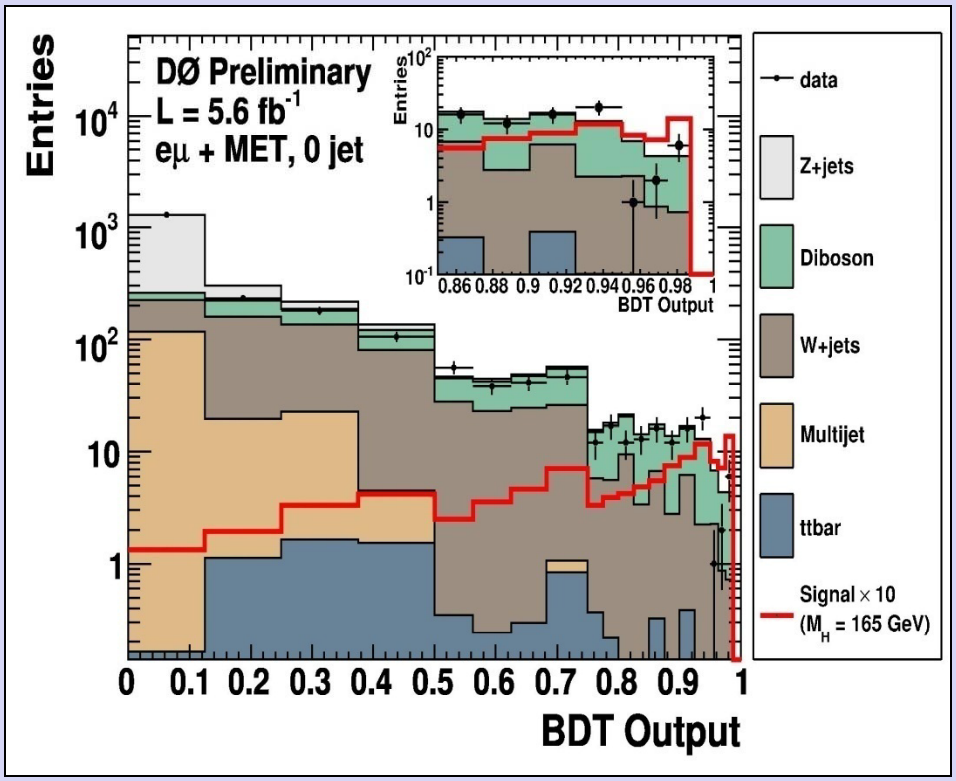


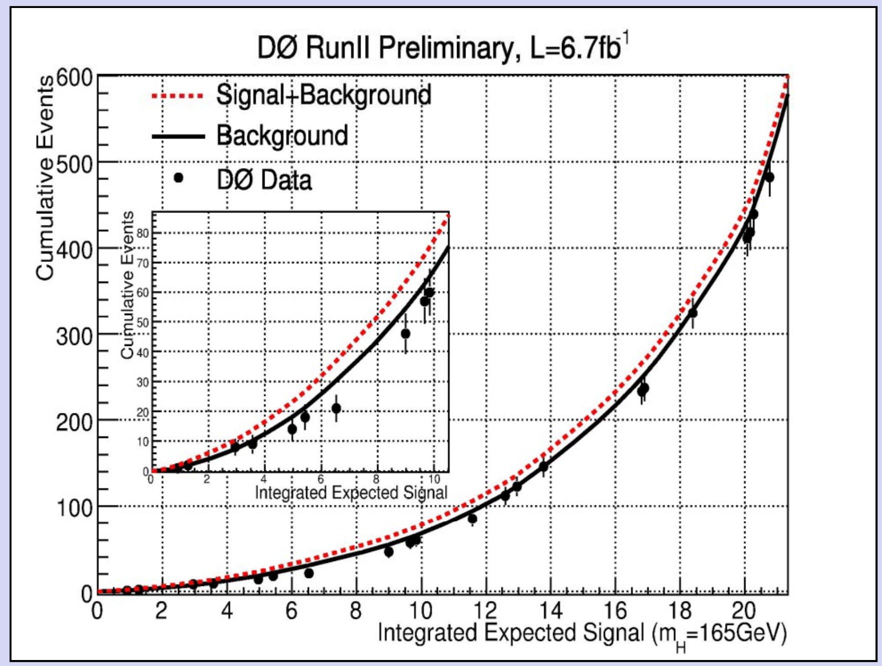
Higgs Search: H → WW → lνlν (M_H >130 GeV)



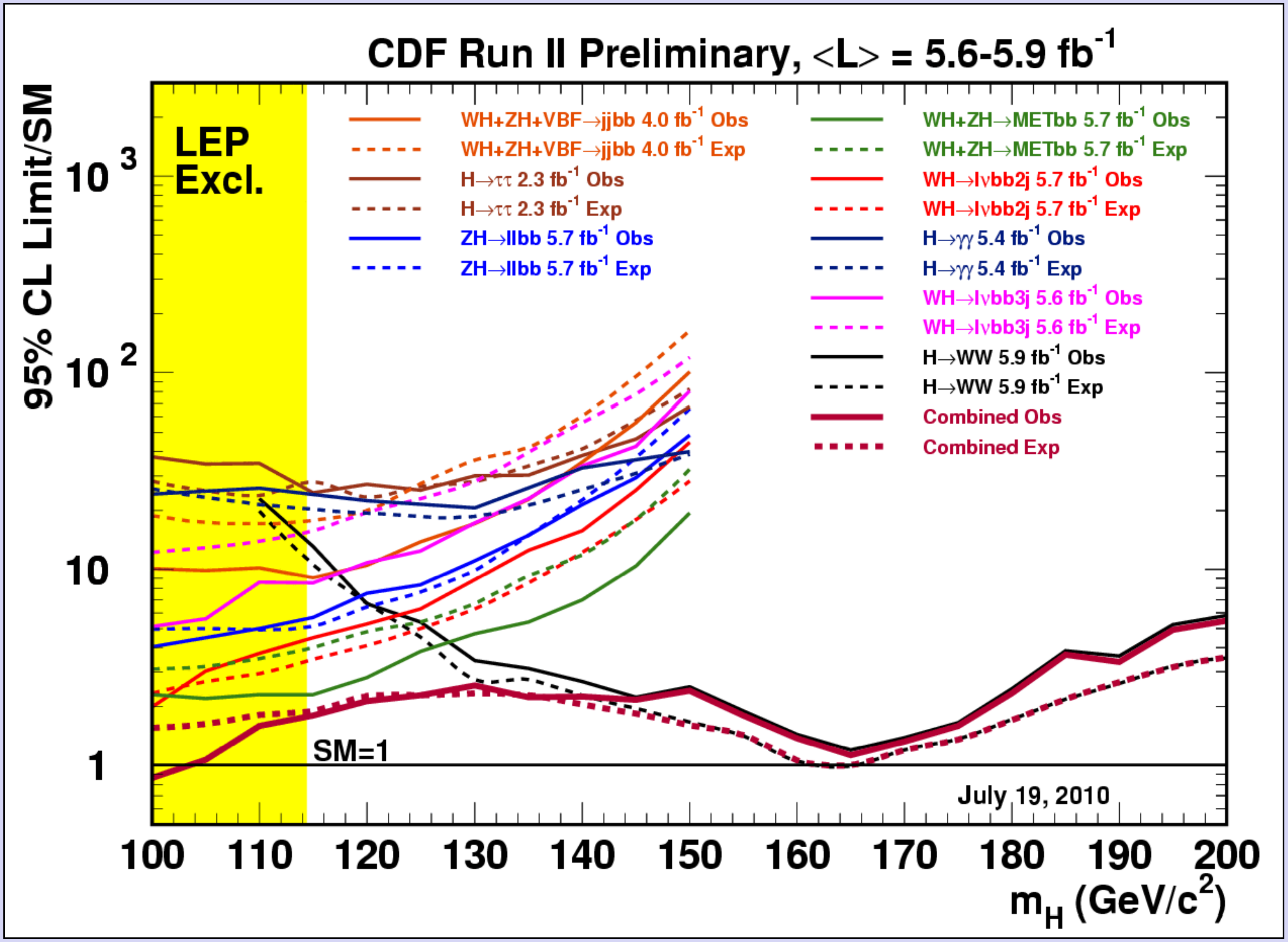
Search strategy:
→ 2 high P_t leptons and missing E_t
→ WW pair comes from spin 0 Higgs: leptons prefer to point in the same direction





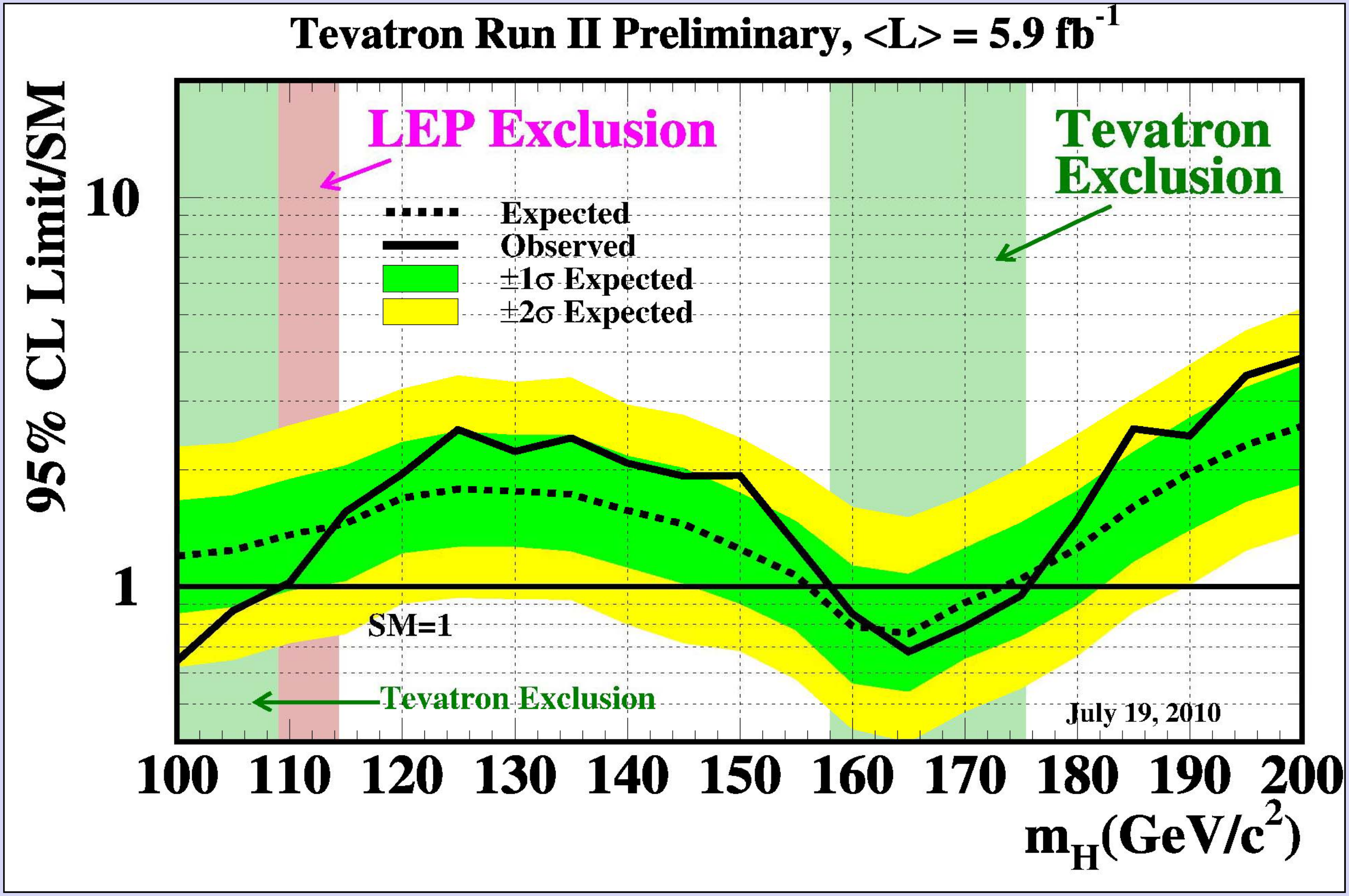


Combining Multiple Channels



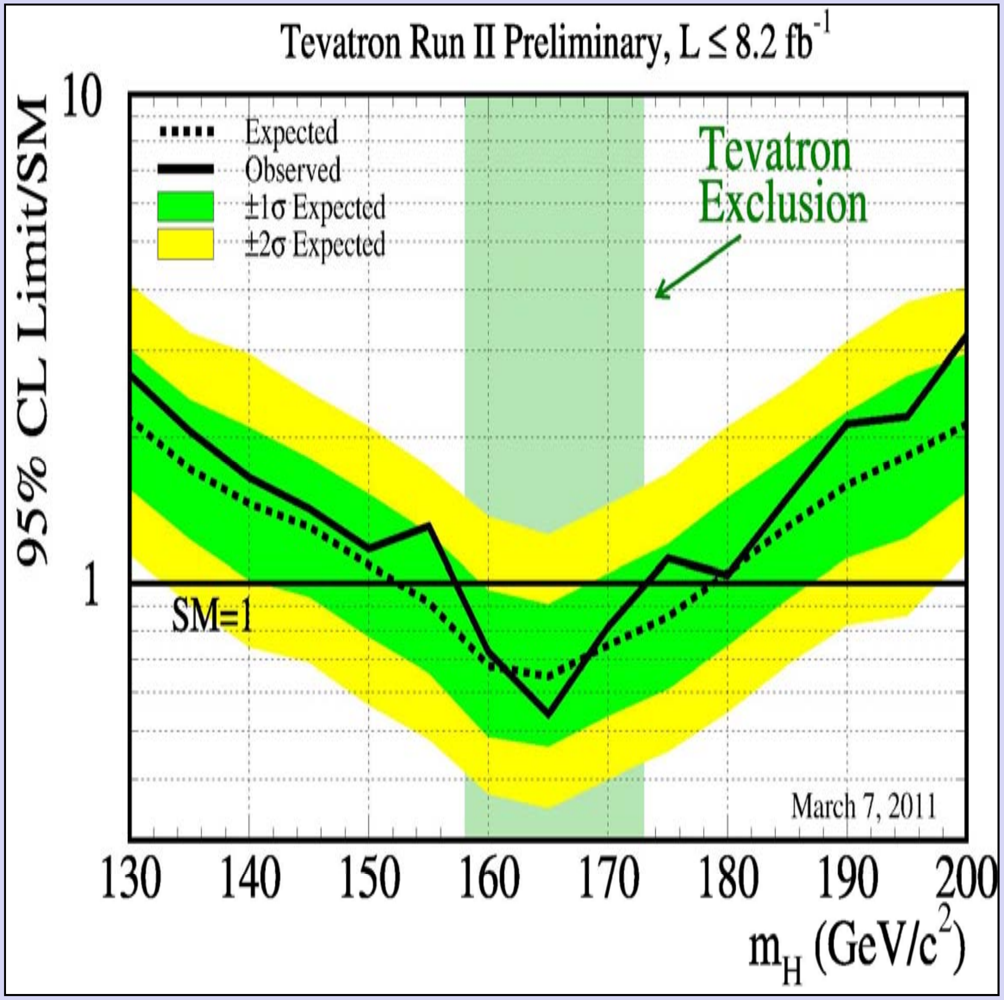
Similarly, DØ uses 58 sub-channels

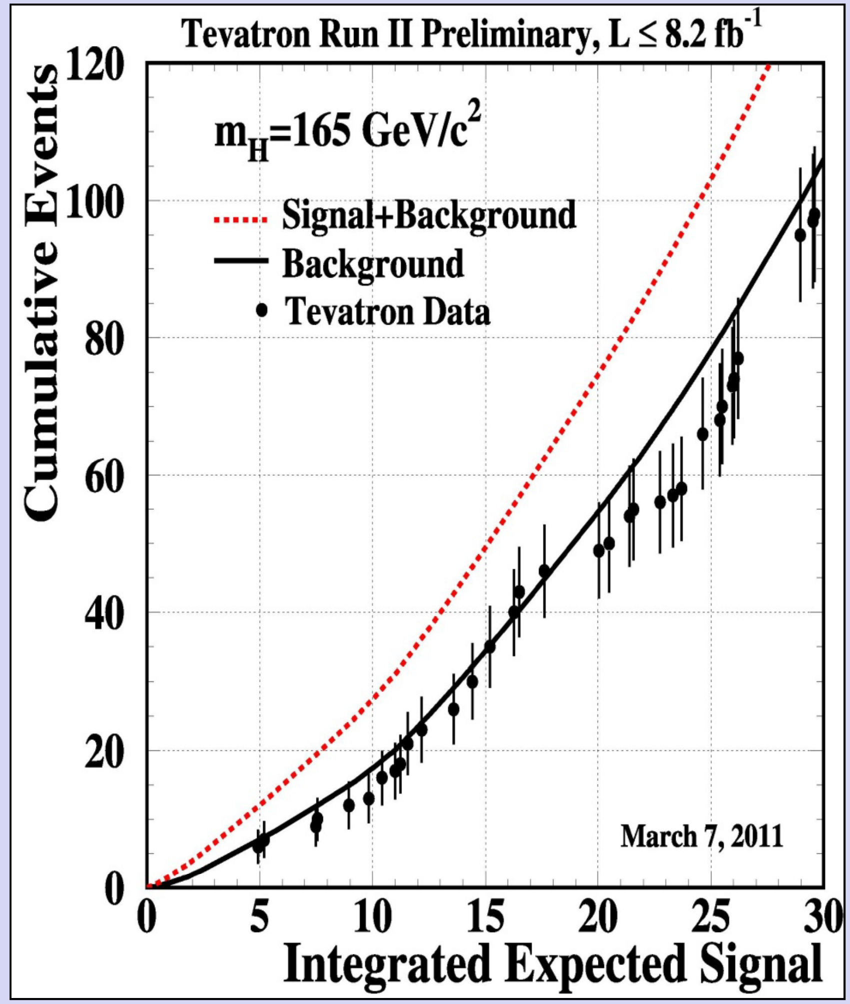
Combining Two Experiments… exclusion!



158-175 Higgs mass region is excluded at 95% CL

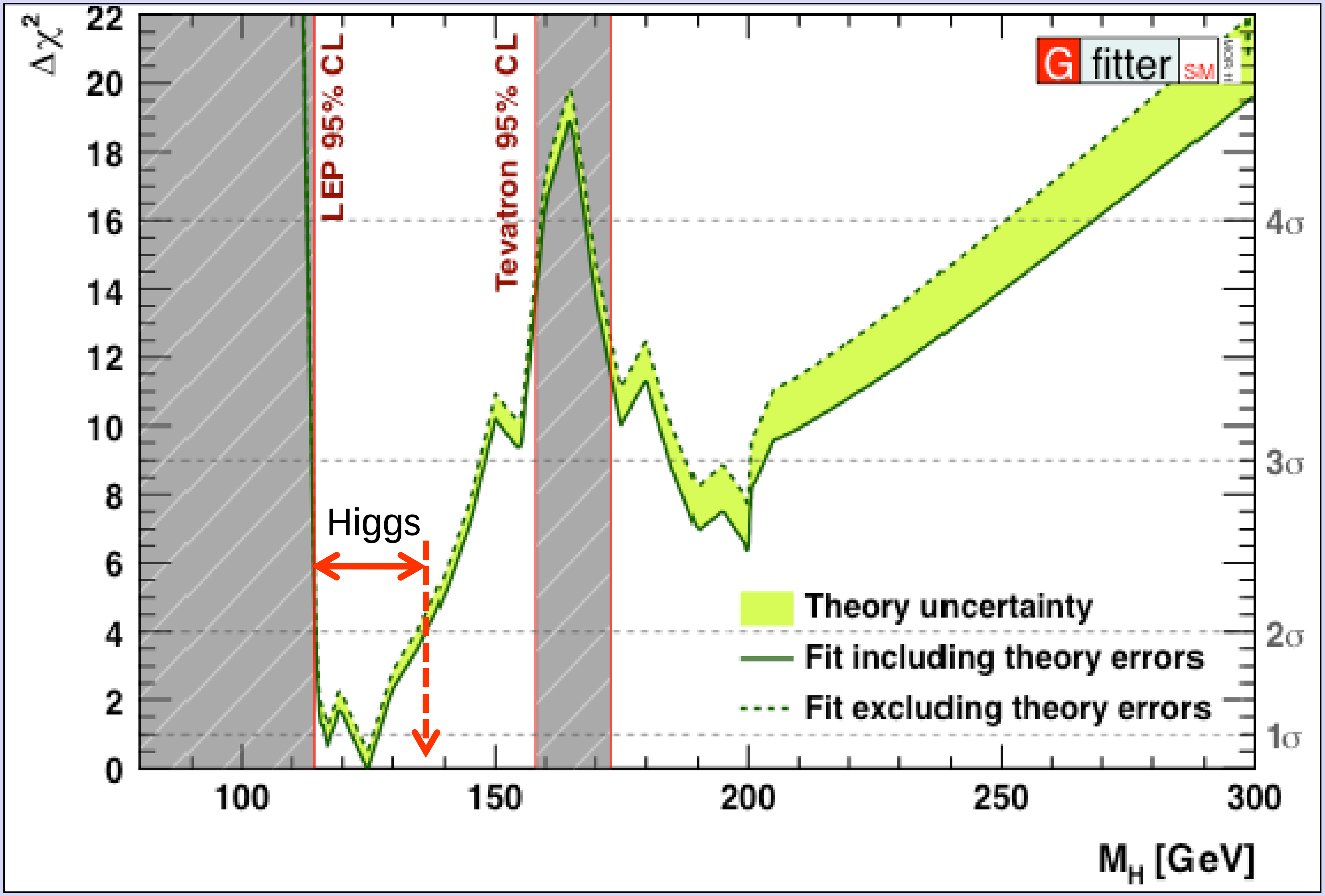
High Mass Higgs Update March 2011





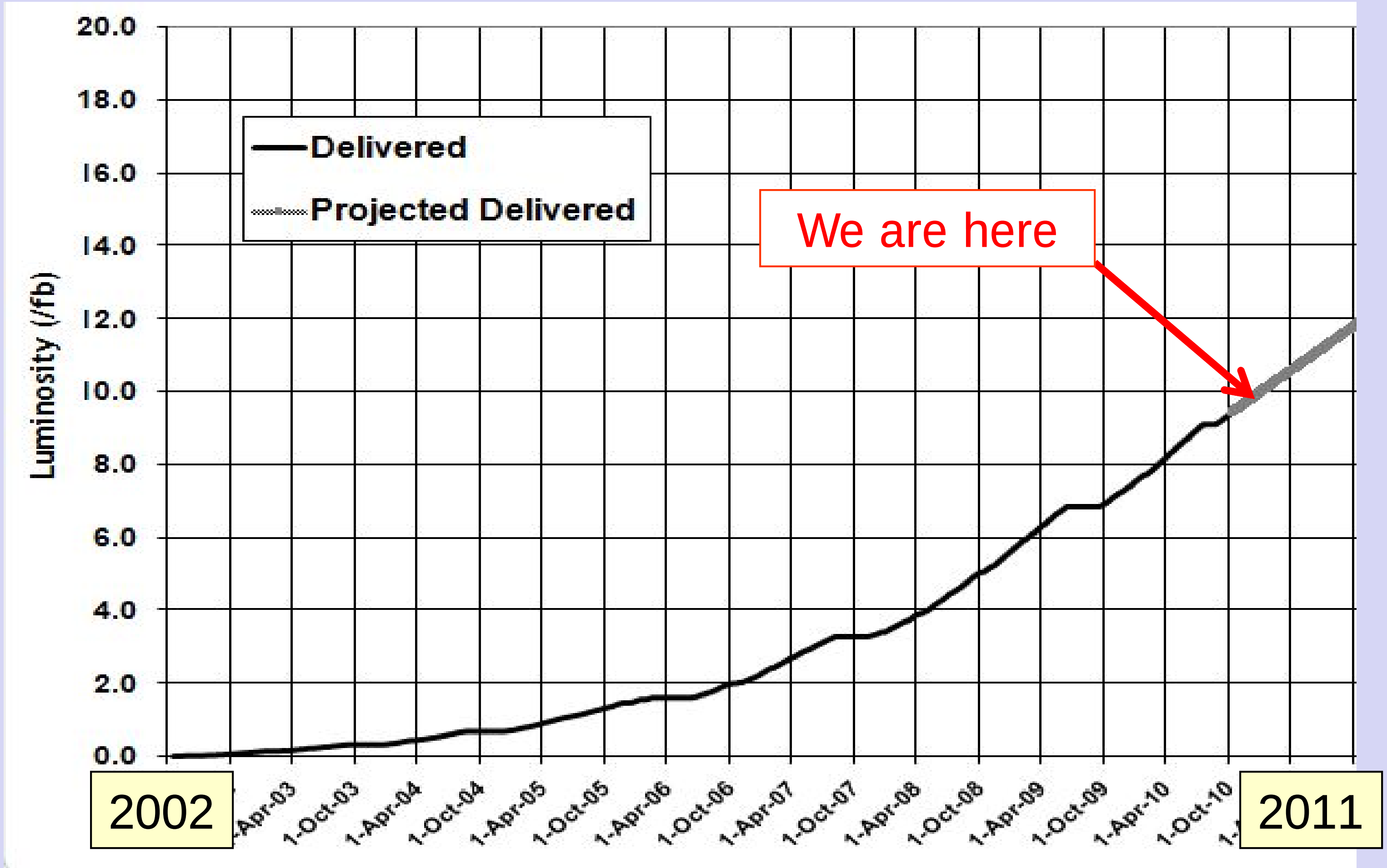
Higgs cross section twice below SM prediction at 165 GeV is excluded

Combining Direct and Indirect Searches



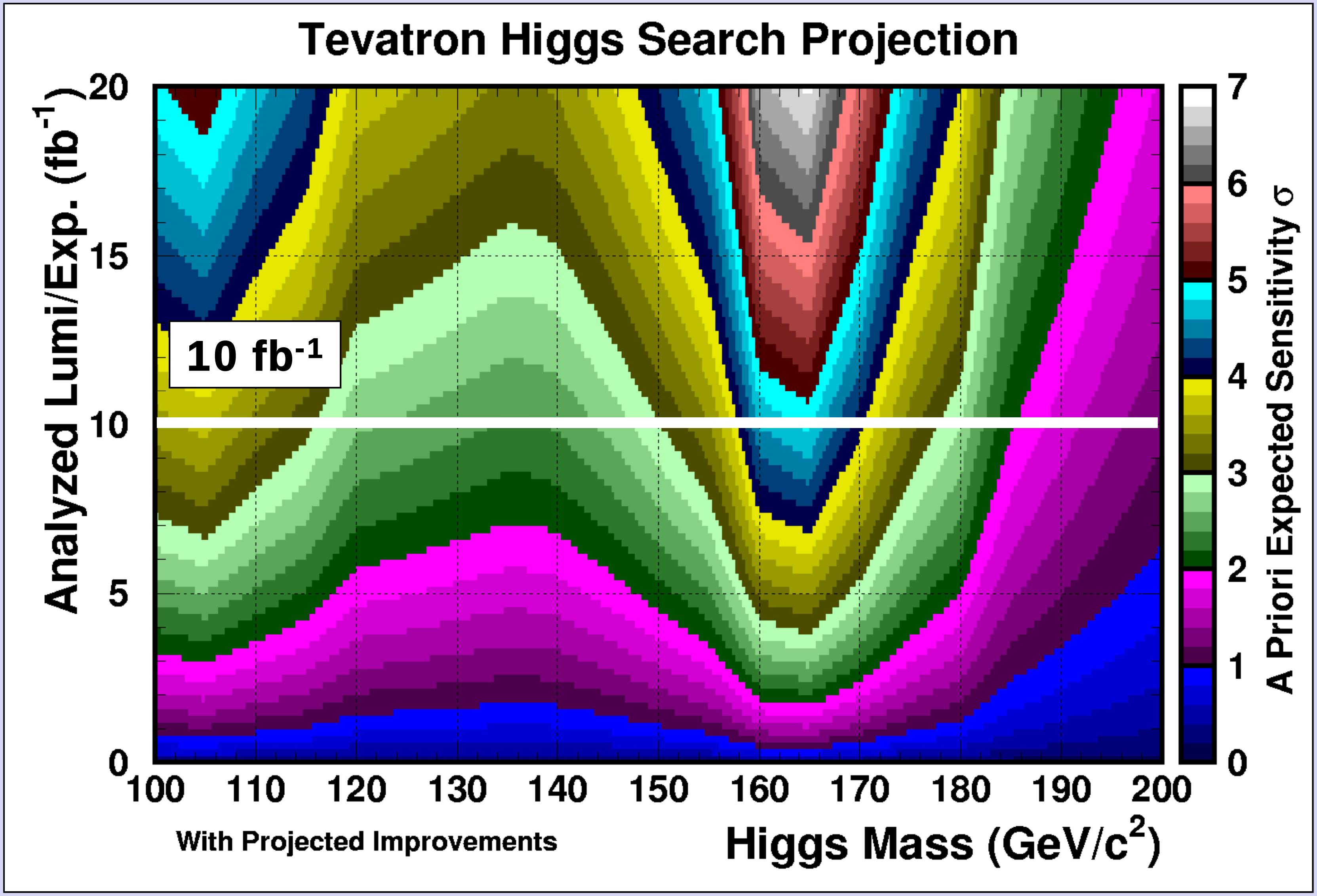
March 2011 update: Higgs mass is 114-137 GeV – excellent match for the Tevatron!

Tevatron Luminosity Projections



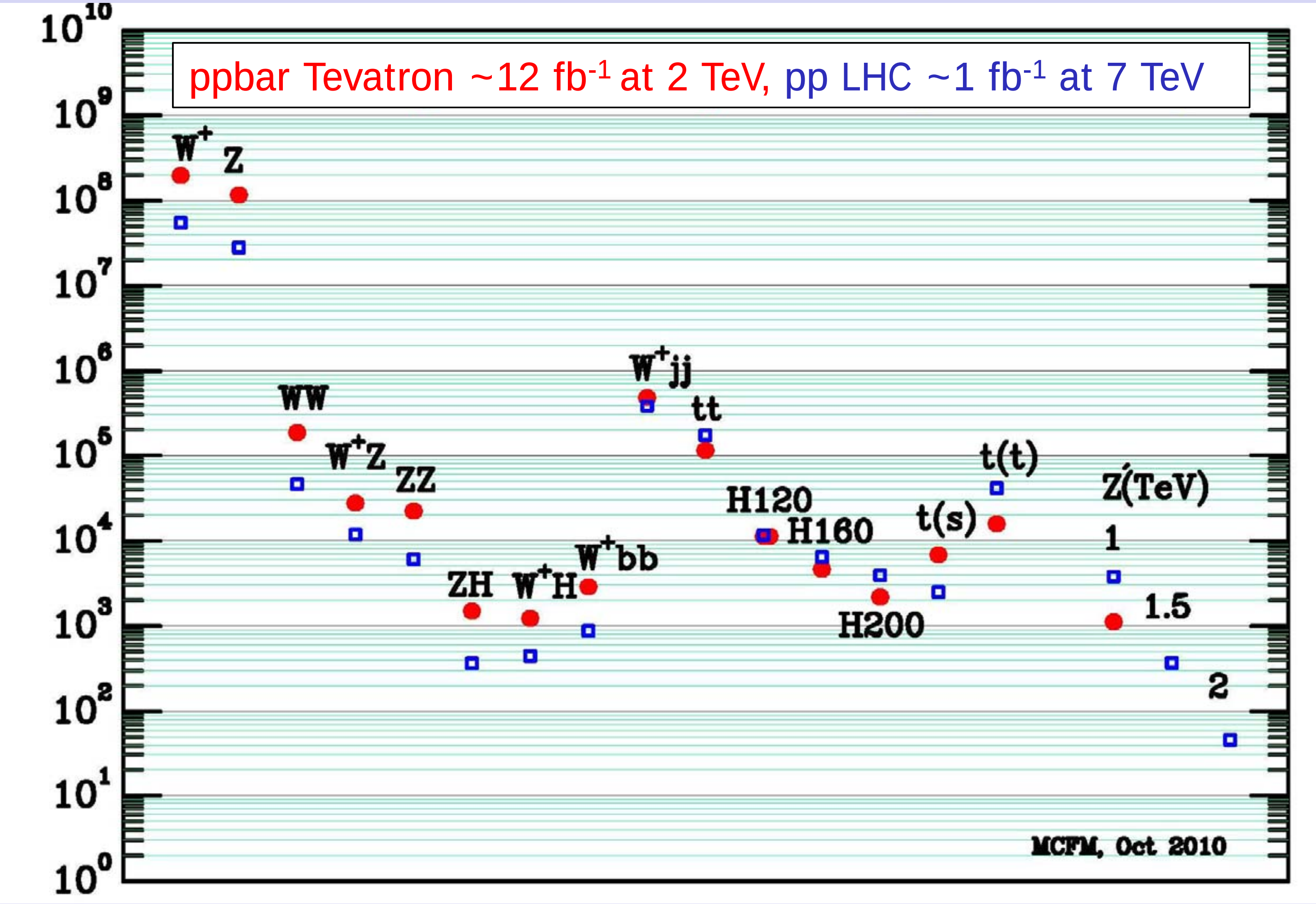
- **Projections are based on extrapolations of the current performance**
  - **Expected end of Tevatron data collection is October 2011**
- **We expect ~12 fb^{-1} delivered by late 2011, with ~10 fb^{-1} available for analysis**

Tevatron Standard Model Higgs Projections



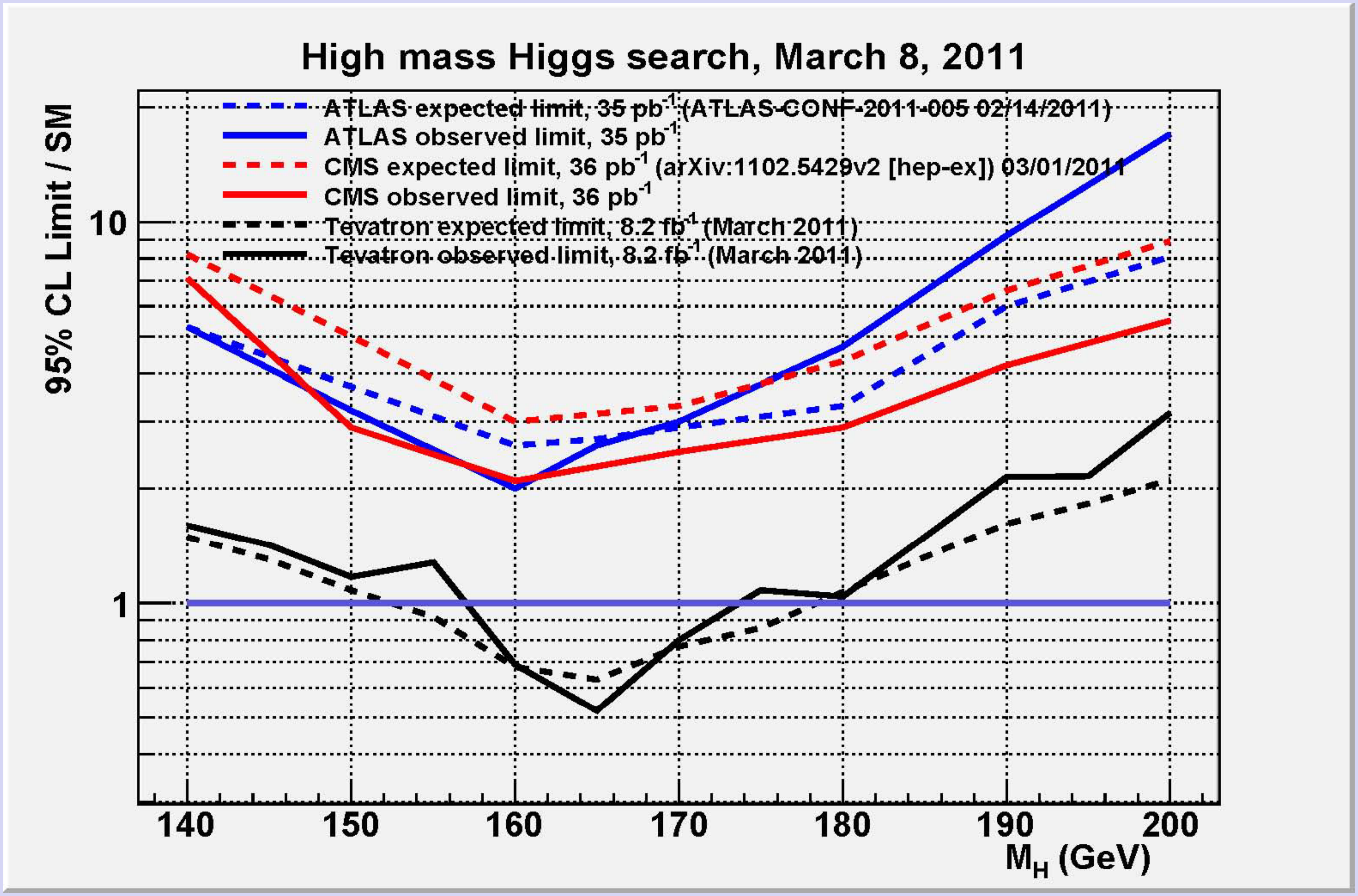
With 10 fb^{-1} can reach 95% CL exclusion Higgs in full allowed mass range and 3σ sensitivity at low masses

Tevatron and LHC - Complementarity



High yields of low mass states, including Higgs, at the Tevatron complement large cross sections of heavy objects at the LHC

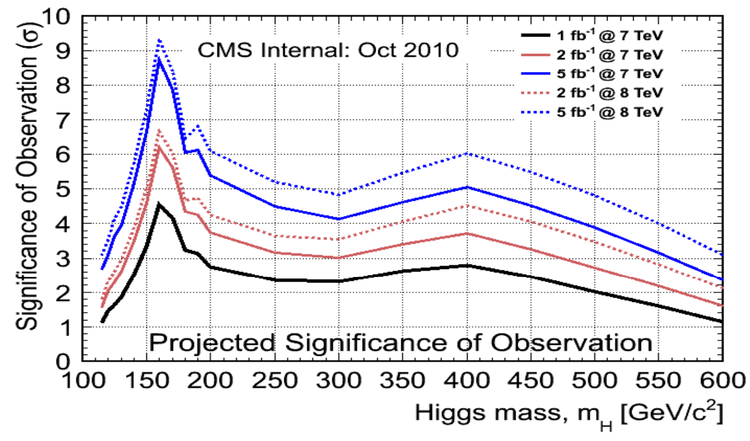
Direct Higgs Searches, March 2011

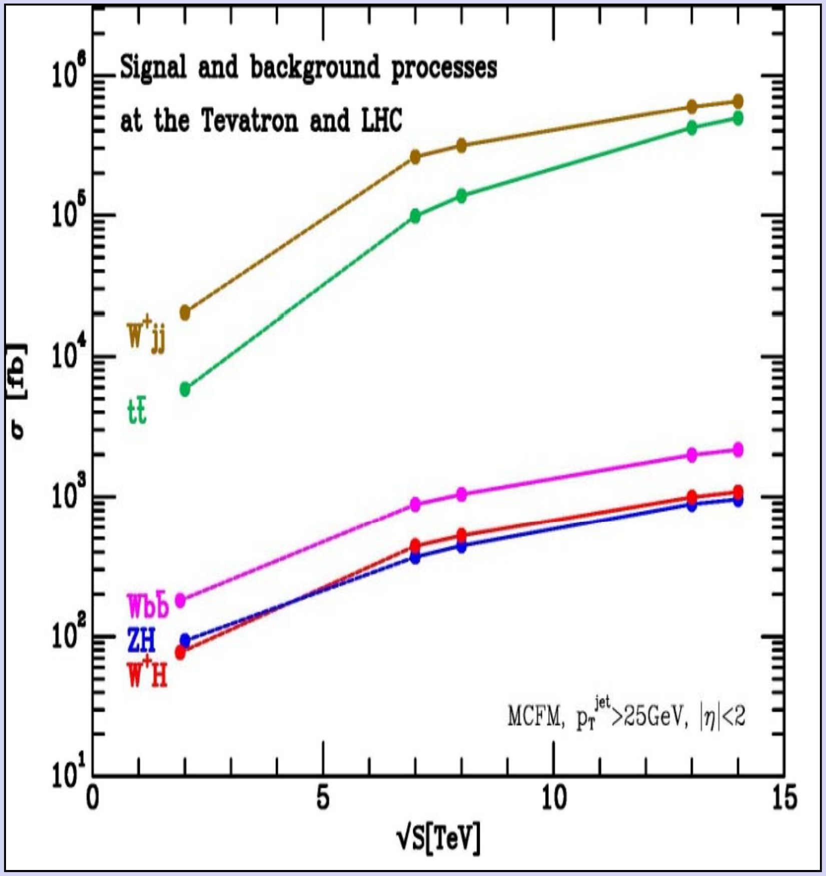


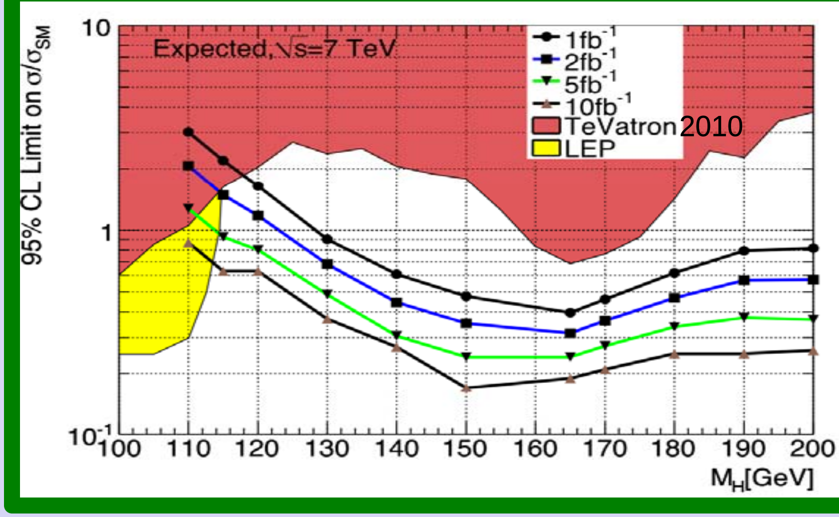
Becoming very exciting!

Tevatron, LHC and Higgs - Complementarity

- **Challenging search at the LHC at low mass and especially in bb decay mode**
- **Main backgrounds cross sections are increasing faster, than signal**

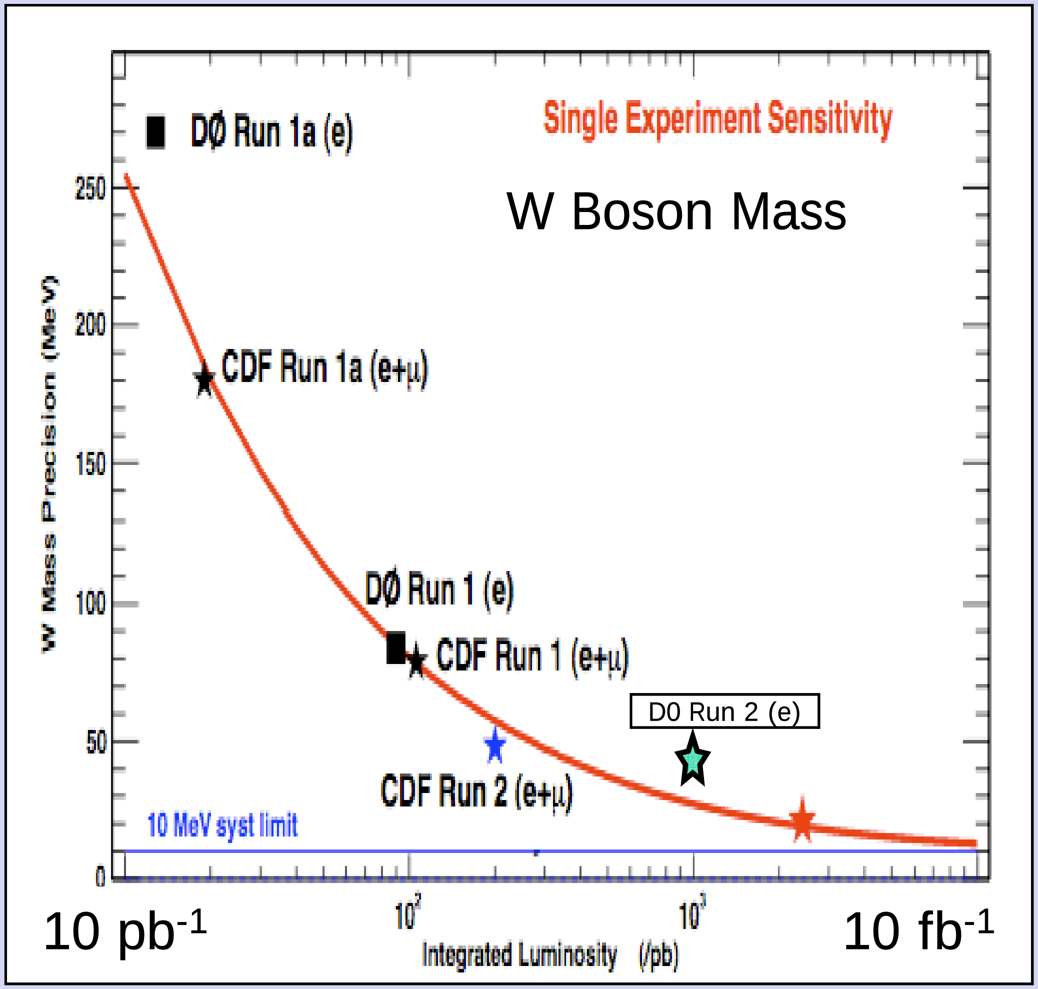


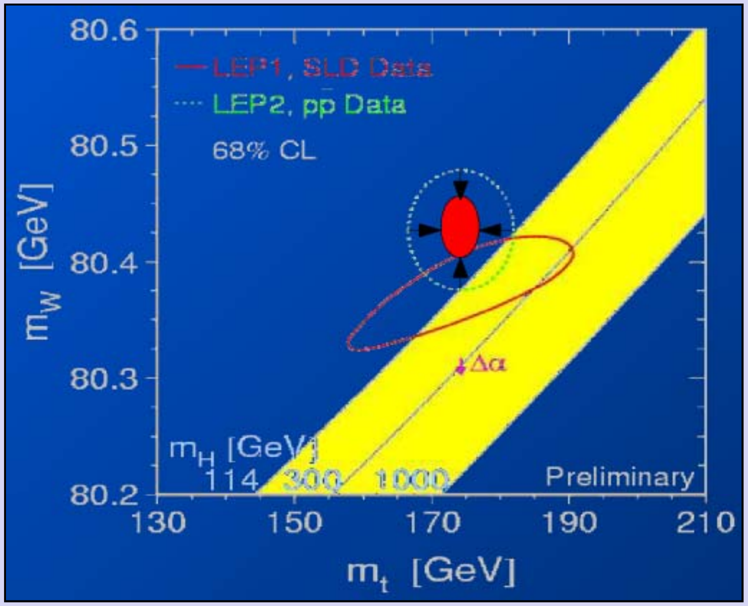


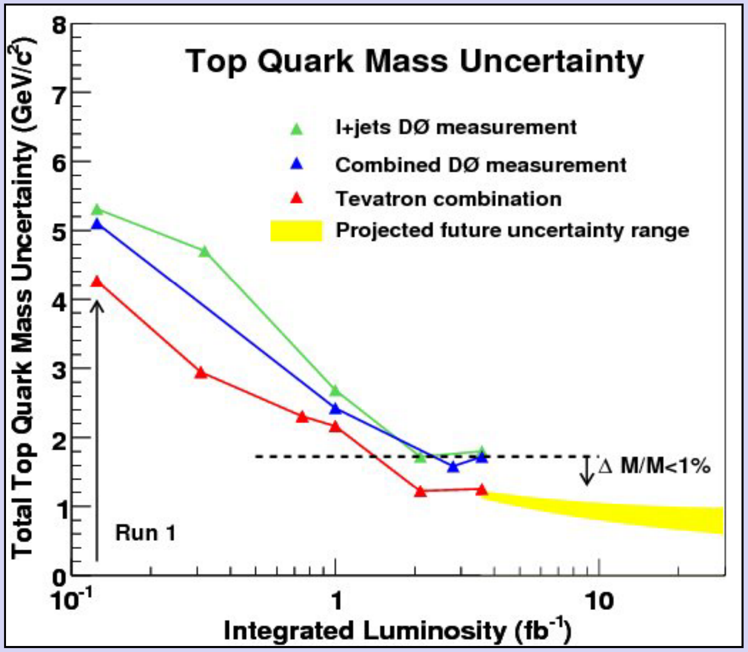


- **~30 fb^{-1} needed at the LHC to probe main Higgs bb decay mode at low mass**
- **5-10 fb^{-1} needed for H→ $\gamma\gamma$**
- **~45 pb^{-1} accumulated in 2010**

Tevatron Projections – 10 fb^{-1}



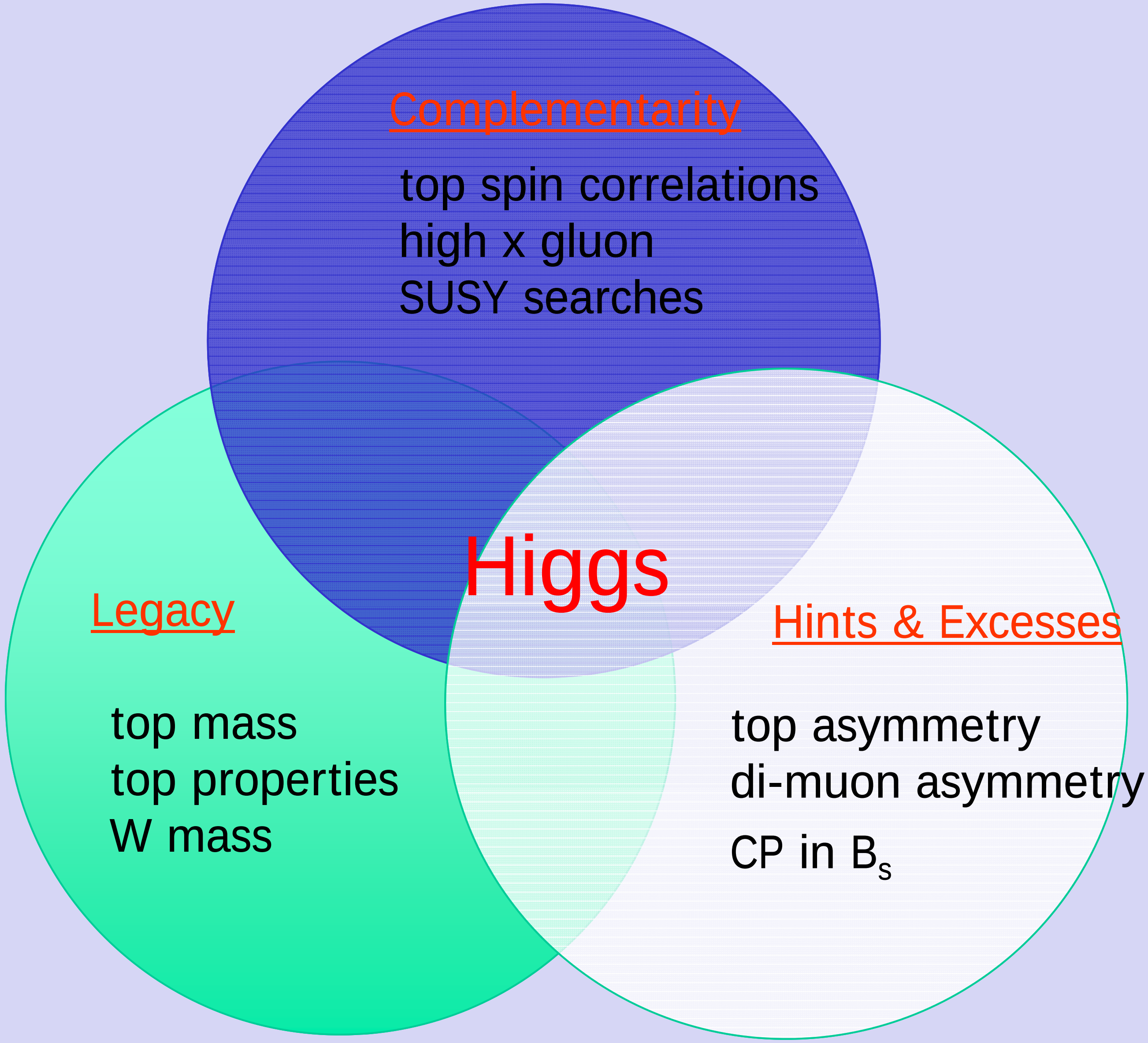




15 MeV error on W boson mass with no changes in the mean value means SM Higgs exclusion with M_H <117 GeV

Many other exciting studies progressing

Tevatron Potential

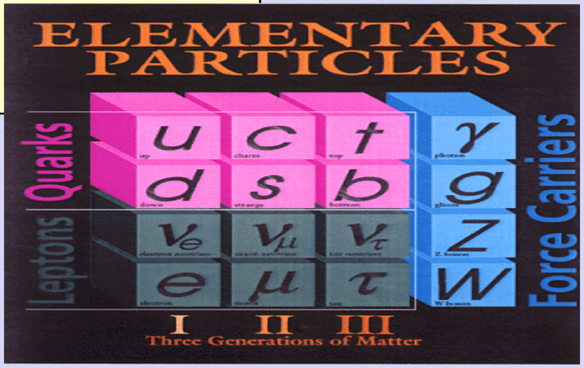


Tevatron Highlights: Summary

Tevatron is performing extremely well
→expect ~12 fb^{-1} by late 2011

Experiments are collecting and analyzing data smoothly
→ Many discoveries and precision measurements
→~100+ studies in progress publishing ~6 papers per month

Interesting hints of deviations from the Standard Model observed
→ di-muon asymmetry in B meson oscillations
→ Data samples analyzed are to increase by 2-5 times



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

Higgs boson search is in a very active stage
→ Excluded at 95% CL Higgs with mass 158-175 GeV
→ Proceeding to exclude wider mass range or…
to see the evidence of the Higgs!

Thank you for the invitation and an opportunity to share with you exciting results and future plans of the Tevatron