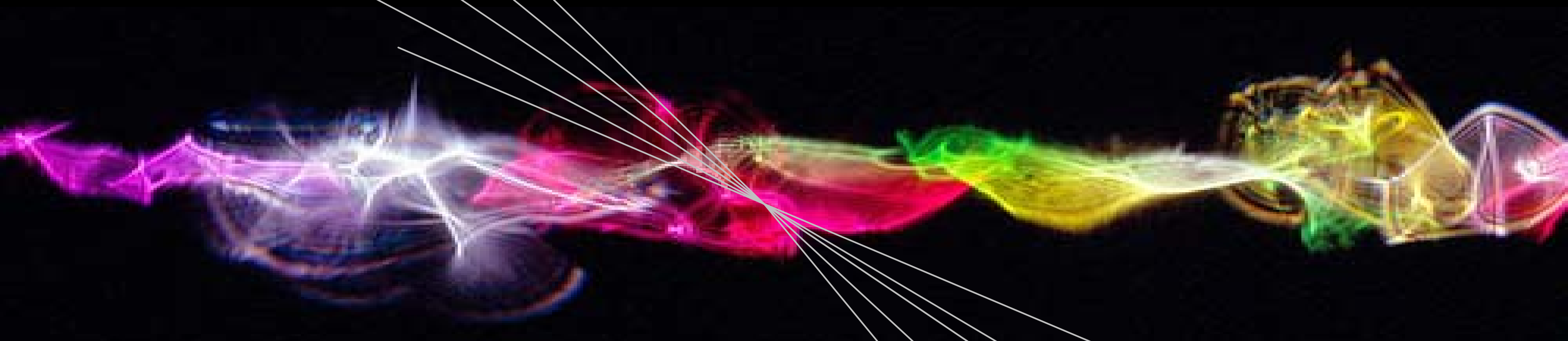
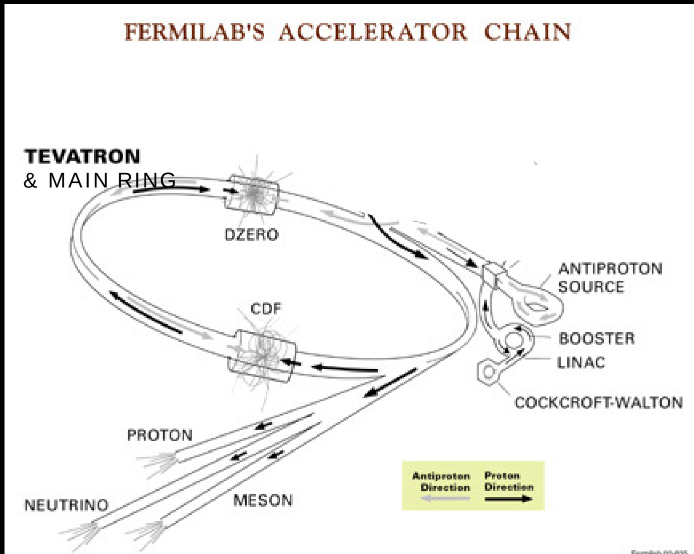
The Tevatron Legacy

25 years of Physics at the Tevatron
(in 25 minutes)



Rencontres de Blois
P. Grannis, 30 May, 2010

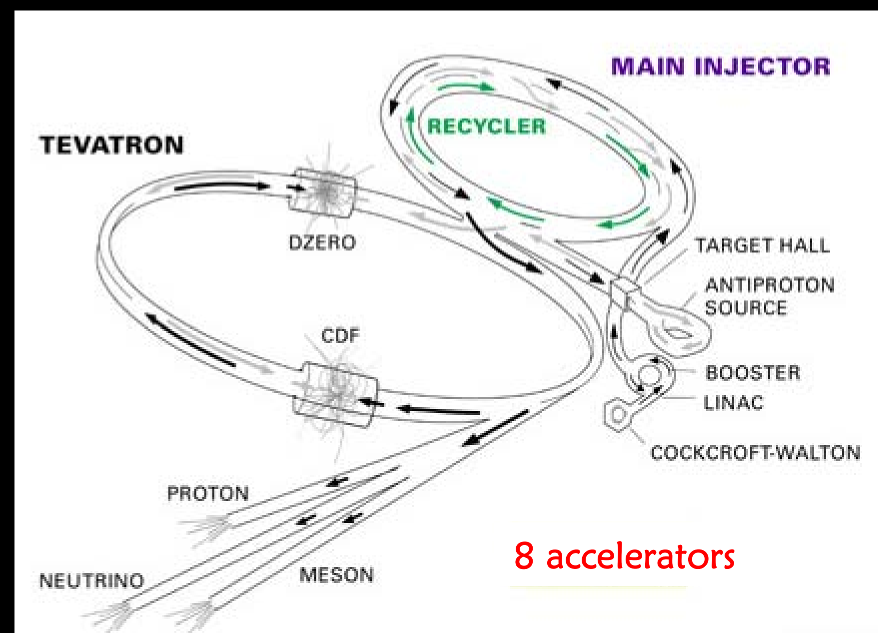
The Tevatron Collider

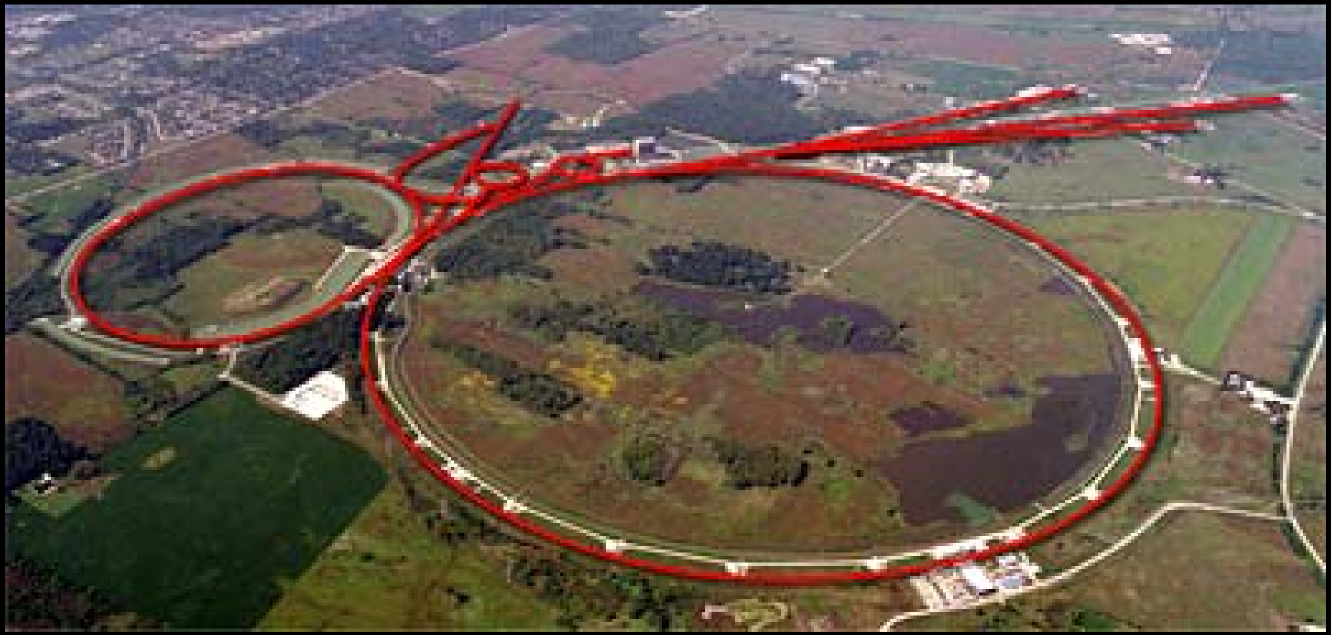


<u>Tevatron Run I: (1987 – 1996)</u> 1.8 TeV collider in same tunnel as 120 GeV Main Ring. MR creates anti-protons and delivers them to Debuncher and Accumulator, then fed back to the MR and Tevatron. 6 bunches with $\mathcal{L}_{max}$ $\sim 2 \times 10^{31}$ cm^{-2} s^{-1}.

(The MR went through the DØ calorimeter and experiment was blanked during MR passage).

<u>Run II: (2001 – 2011)</u> Upgrade energy to 1.96 TeV with 36 bunches per beam. $\mathcal{L}_{max} \sim 4 \times 10^{32}$ cm^{-2}s^{-1}. Add the 150 GeV Main Injector for pbar production (and fixed target beams) and later install Recycler for pbar storage and recovery, and electron cooling.

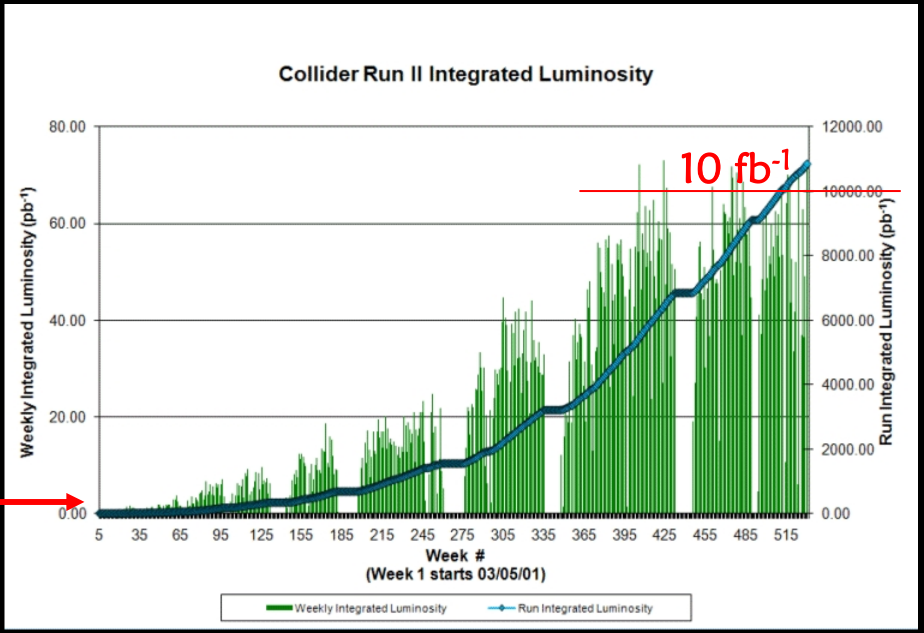


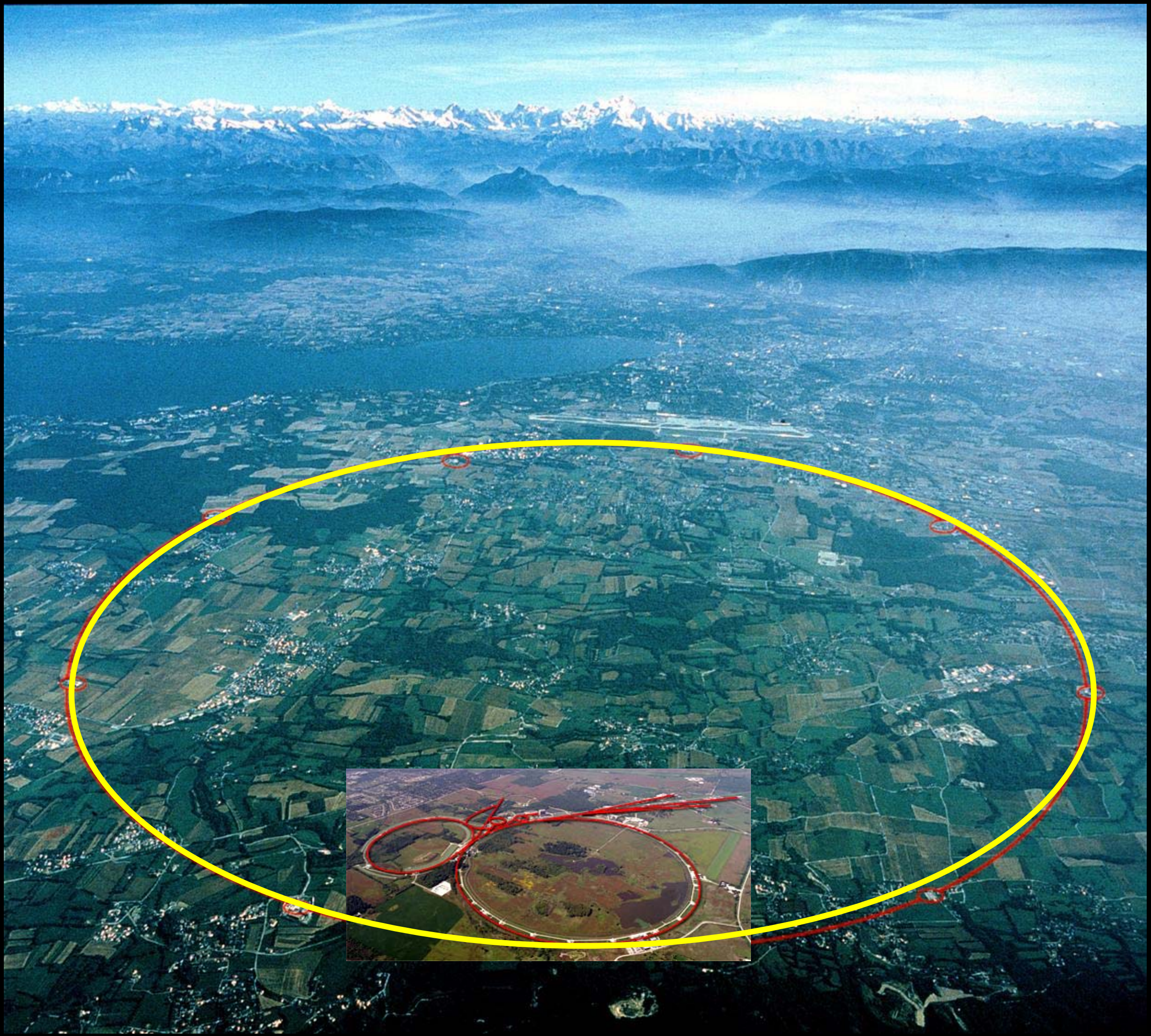


2 km diameter: 1.96 TeV pbar p collisions

Max. Instantaneous
$L \approx 4.3\ 10^{32}\ cm^{-2}\ s^{-1}$
(30M collisions/s)

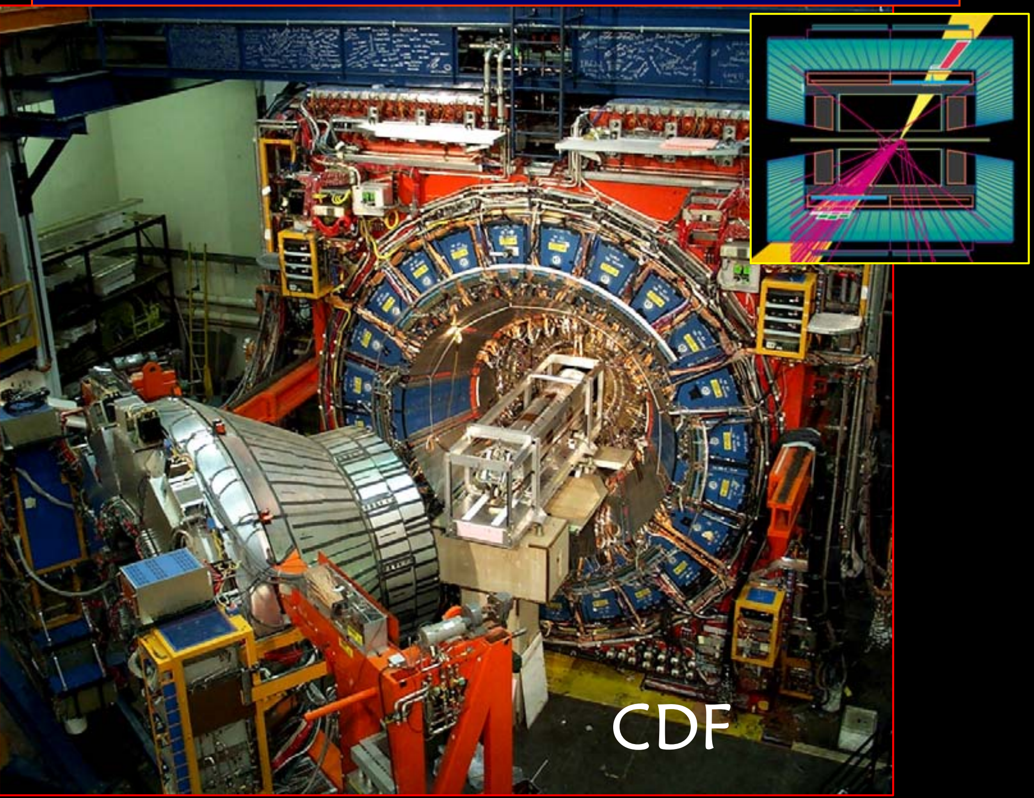
Total Run I accumulation
($120\ pb^{-1}$)





The energy frontier has now passed the LHC: 4x the size and (in future) 7 times the energy. We look forward eagerly to LHC discoveries, but the Tevatron is still producing excellent physics.

The Tevatron Experiments



Major detector upgrades for Run II:

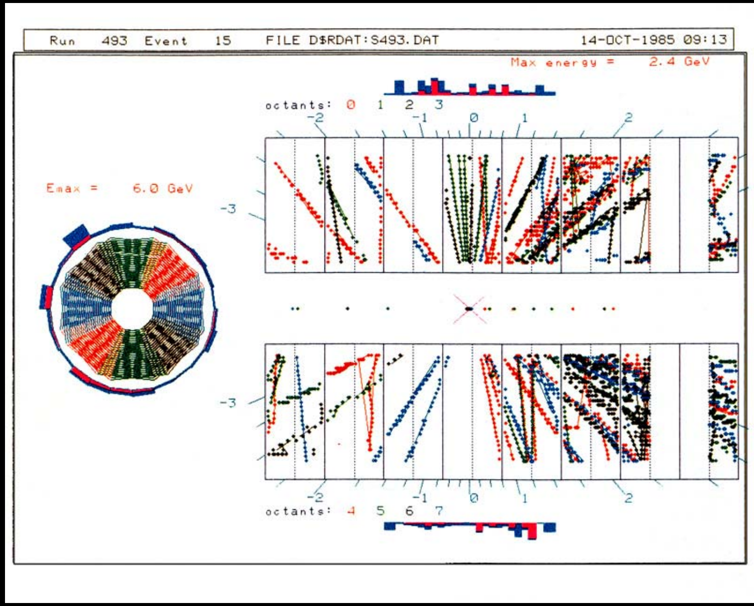
<u>CDF:</u> new tracker, new Si vertex det, upgraded forward cal and muons

<u>DØ:</u> add solenoid, fiber tracker and Si vertex dets, preshower detectors, new forward muon detectors.

(The upgraded experiments look more like each other!
But have complementary strengths)

The Tevatron Program

26years ago, in winter 1984-5, the Tevatron Collider was being commissioned and dedicated.



October 14, 1985: First collisions were recorded in the (partially complete) CDF detector. DØ was still a hole in the ground.

1987: First CDF physics Run 0 (4 pb^{-1})

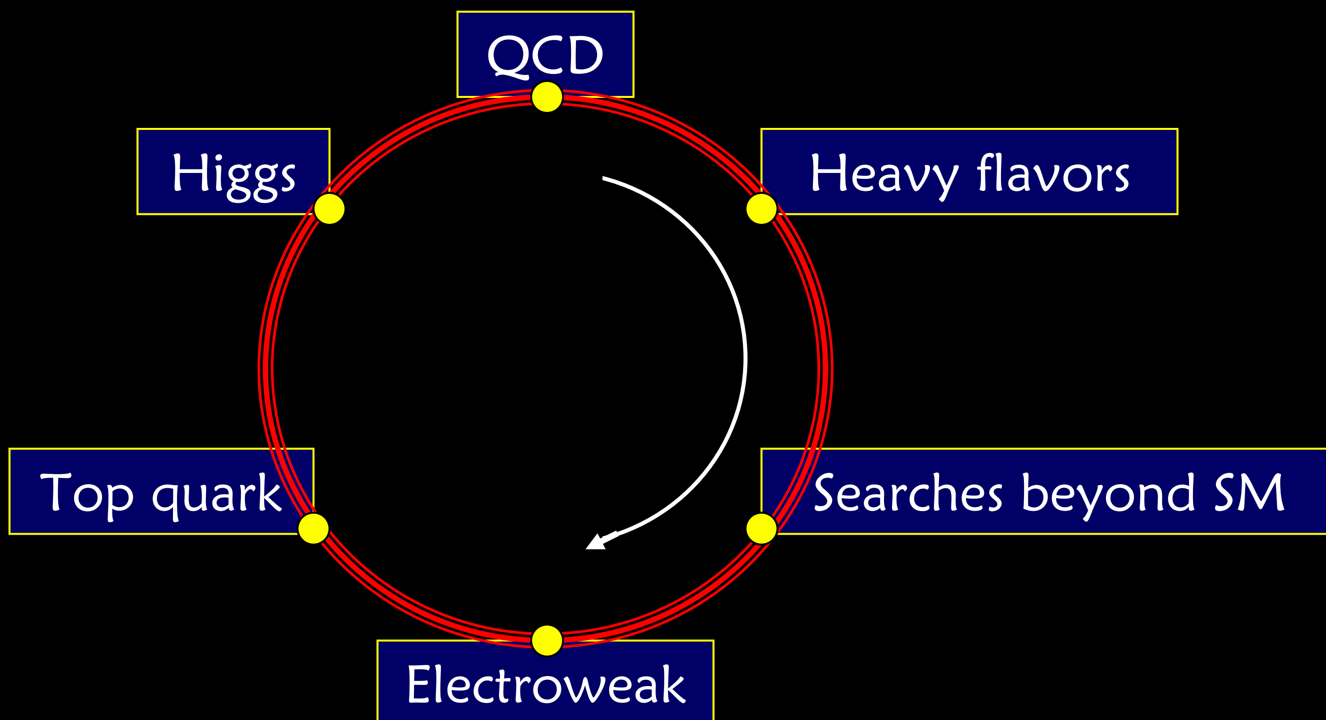
1992 – 1996: Run I with both CDF and DØ

2001 – 2011: Run II

The Tevatron Program

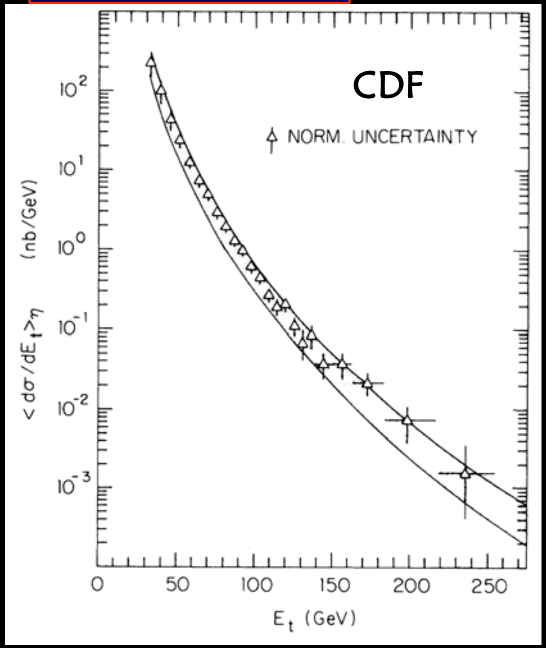
CDF and DØ organize their physics programs within six Physics Groups.

I will visit these with an idiosyncratic selection of results that I think delineate the Tevatron legacy.



QCD

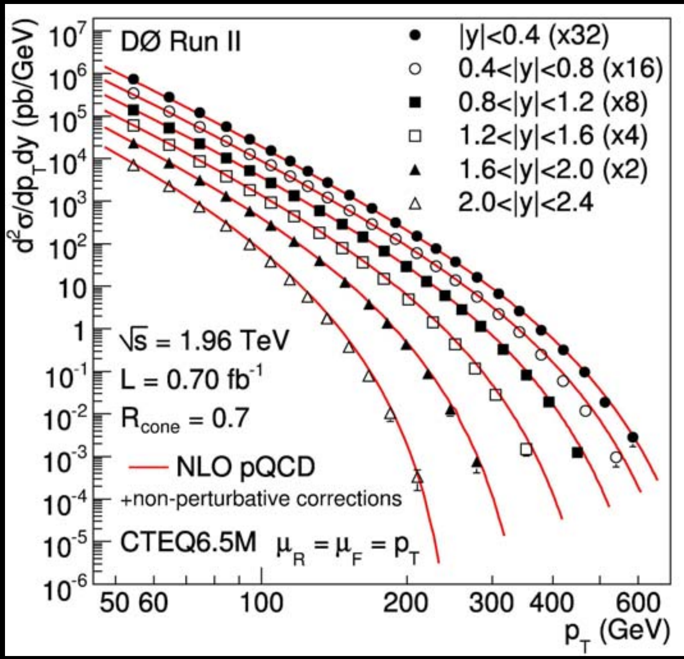
Inclusive jet production



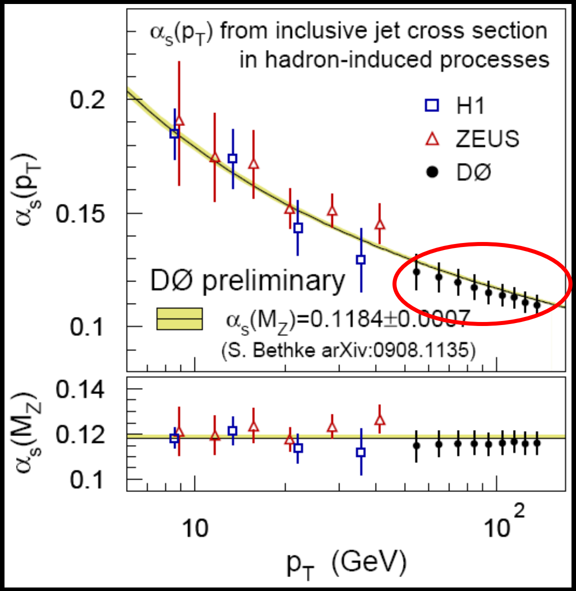
1989
7 nb^{-1}

2008
700,000 nb^{-1}

Extend p_T range from 250 to 700 GeV and probe out to y=2.4. Good agreement with NLO QCD out to 60% of √s. The data constrain PDFs and are forcing reduced gluon content at high x.



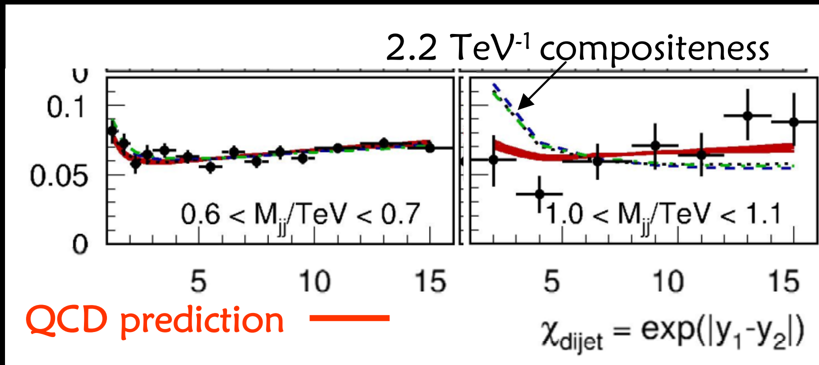
Extract $\alpha_s(Q^2)$ to extend knowledge of running coupling to high Q^2



Q=700 GeV → probing proton to 0.3 am (attometer) scale, showing excellent agreement with pQCD.

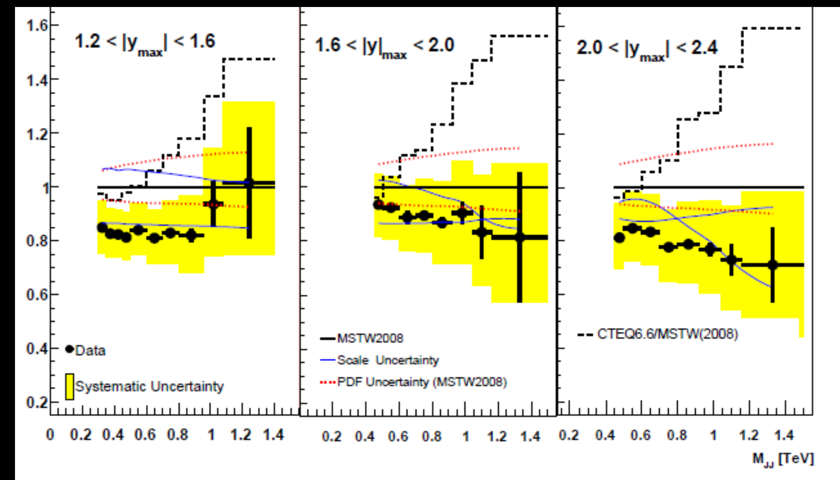
QCD

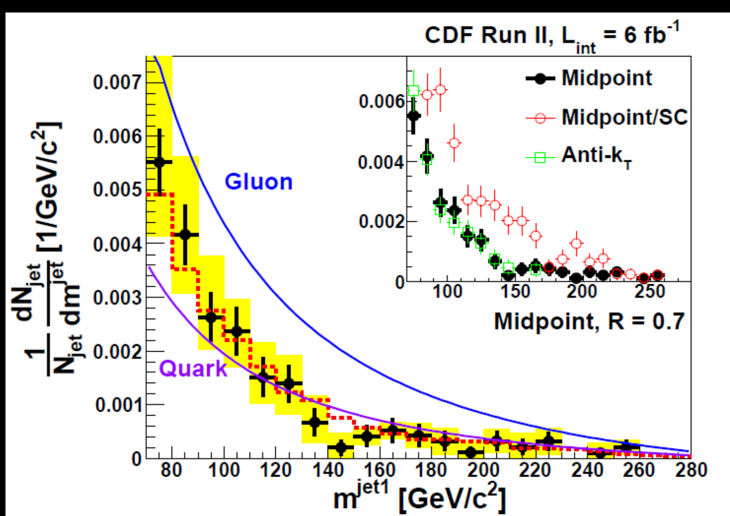
Jet properties



Dijet angular distributions test QCD and probe new physics up to the multiTeV scale.

Dijet invariant mass and rapidity distributions offer another constraint on PDFs, and will modify the next generation of fits.

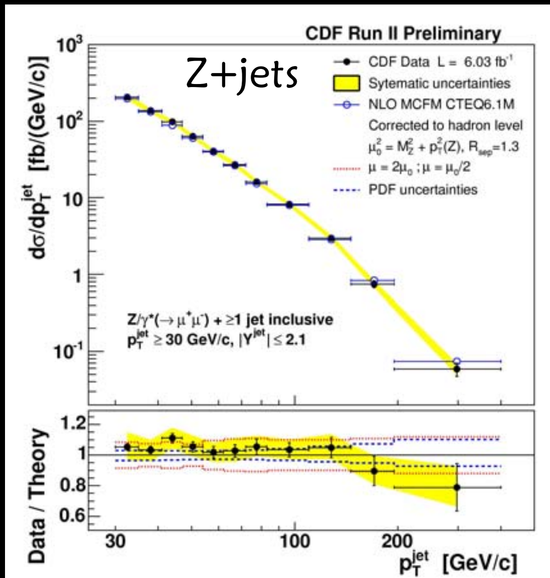




Jet mass distributions: Can distinguish quark and gluon jets, data agree with theory

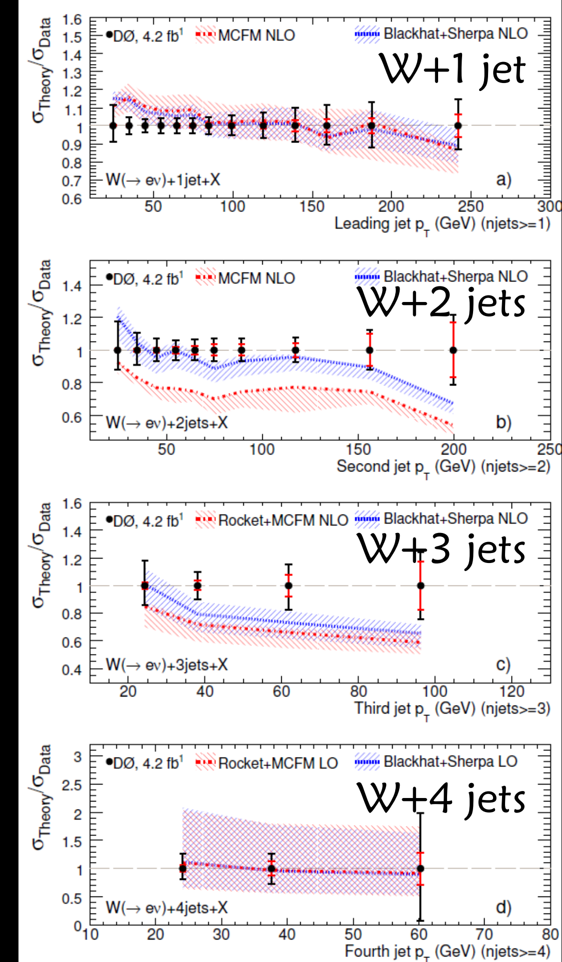
QCD

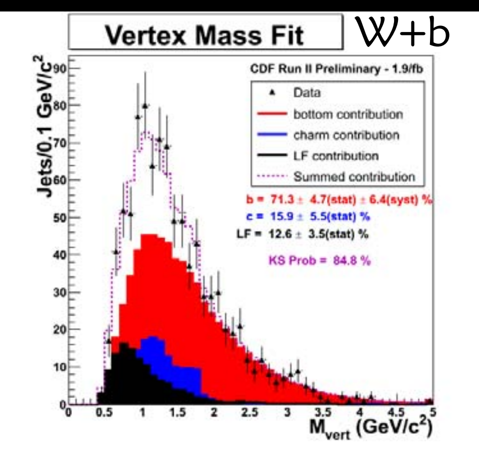
W/Z + jets



W/Z +jets measurements are important to fix backgrounds (e.g. Higgs). QCD predictions are uncertain and we need measurements, particularly for heavy flavor.

W/Z+jets ~agrees with theory for p_T<250 GeV and $n_{jet} \leq 4$. Now guiding MC generators.



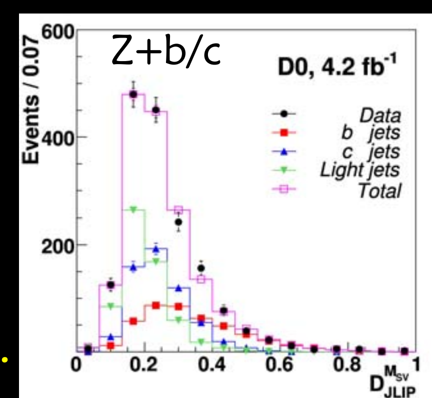


Separate jet flavors using vertex mass

CDF: W+b : data/NLO theory~3

DØ: (Z+b)/(Z+jets) consistent with NLO

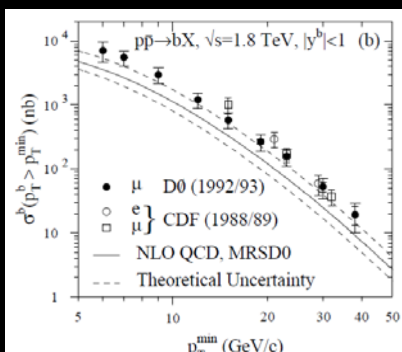
Separate jet flavors using impact param.



Heavy Flavor Physics

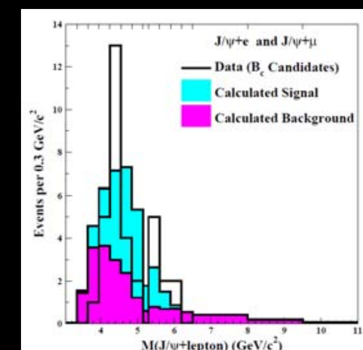
Conventional wisdom held that the Tevatron could not compete with e^+e^- colliders for b-physics.

The advent of silicon vertex detectors and triggers, high luminosity, large production cross sections changed that. CDF and DØ (in Run II) have made a host of heavy flavor measurements including, in particular, exploration of the mesons and baryons containing b quarks and other heavy quarks:



In Run I, measured inclusive b production – not in agreement with theory (later resolved)

CDF Run I observation of B_c (showing power of hadron collider for states inaccessible to B factories)



First observation of:

B_s ($J/\psi\ \phi$), B_C, X(3872) ($J/\psi\ \pi^+\pi$), Σ_b, Ξ_b, Ω_b

B_s mixing

Evidence for $D\overline{D}$ mixing

$J/\psi\ \phi$ resonance near threshold

and world leading measurements:

Precision B_d mixing

Measurements of b hadron masses, BRs, lifetimes, and production dynamics

Limits on rare B decays

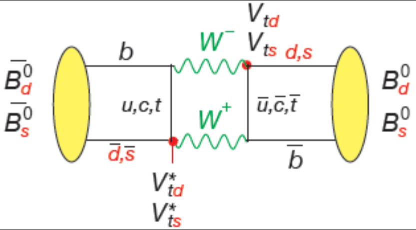
Diffractive J/ψ production

Observation of charmless B_s decays

Heavy Flavor Physics

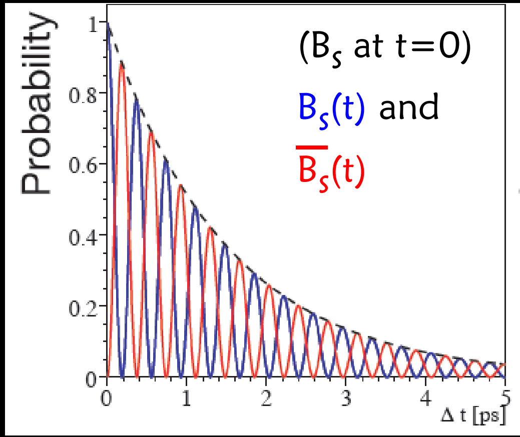
B_s mixing

Quark weak eigenstates are rotated from flavor eigenstates by the CKM matrix. Box diagrams give mixing of neutral B mesons.



$$i\frac{d}{dt}\begin{pmatrix} B^0_s \\ \bar{B}^0_s \end{pmatrix} = \begin{pmatrix} M - \frac{i\Gamma}{2} & M_{12} - \frac{i\Gamma_{12}}{2} \\ M^*_{12} - \frac{i\Gamma^*_{12}}{2} & M - \frac{i\Gamma}{2} \end{pmatrix}\begin{pmatrix} B^0_s \\ \bar{B}^0_s \end{pmatrix}$$

$$\mathrm{Prob}[\bar{B}^0](t) = \frac{1}{4}\left[\exp(-\Gamma_1 t) + \exp(-\Gamma_2 t) - 2\exp(-\Gamma t)\cos(\Delta m t)\right]$$

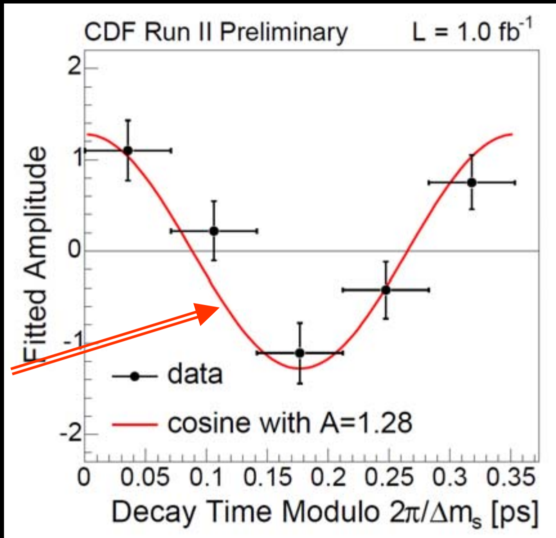


Large Δm means B_s mixing is very rapid (T_{osc}~0.3ps) – a large experimental challenge.

Measuring the ratio of B_s to B_d mixing cancels most of the large theoretical uncertainties and allows accurate determination of CKM matrix element V_{ts}.

Tevatron measured B_s mixing consistent with SM, limiting possible new physics.

Many oscillation periods folded into one.



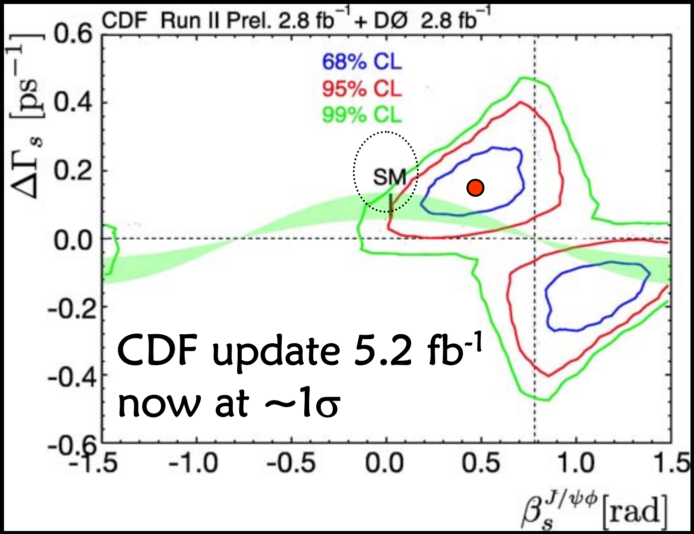
Heavy Flavor Physics

CP violation in B_s decay

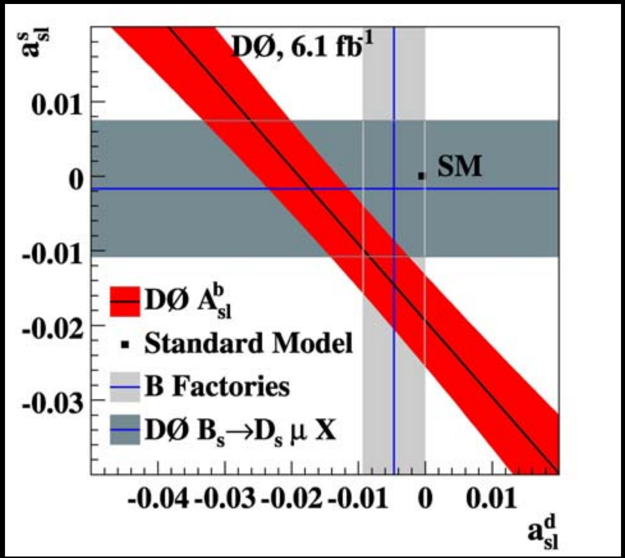
In the SM, CP violation is due to CKM phase, which is consistent for the CP violation seen in the K^0 and B_d^0 systems. DØ and CDF did measurements in the B_s^0 ($\bar{b}s$) and $\bar{B}_s^0$ systems ($\rightarrow J/\Psi\ \phi$) that are inaccessible in the B factories.

In SM, $\Delta\Gamma_s = \Gamma_L - \Gamma_H \approx 2\cos 2\beta_s$ (SM β_s is very small based on other measurements)

β_s is analog of B_d unitarity triangle angle β ,but from 2nd/3rd row of CKM matrix



CDF & DØ observe $\Delta\Gamma$ consistent with SM, but β_s large, inconsistent with SM at 2σ level



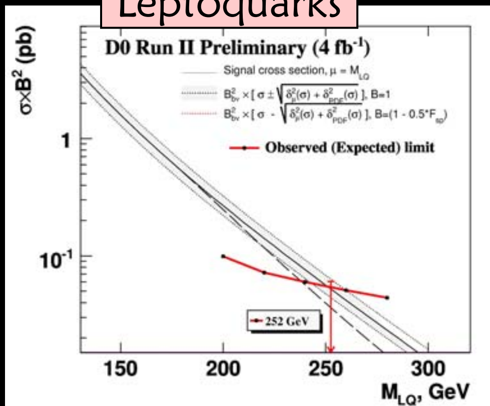
Asymmetry $N(\mu^+\mu^+)-N(\mu^-\mu^-)\ /N(\mu^+\mu^+)+N(\mu^-\mu^-)$ differs by 3.2σ from SM prediction

Searches for New Physics

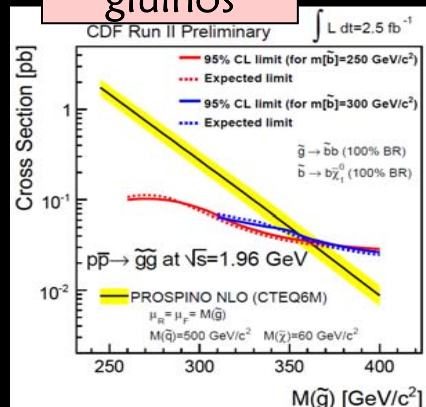
"400 Physicists Fail to Find Supersymmetry" **(NYTimes, ca 1992)**

As well as …

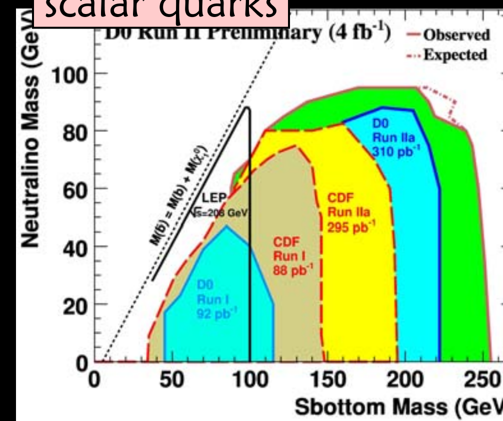
Leptoquarks



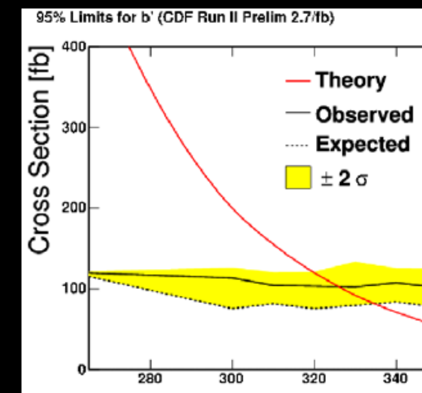
gluinos



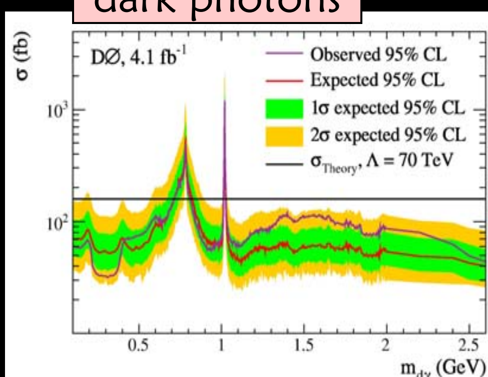
scalar quarks



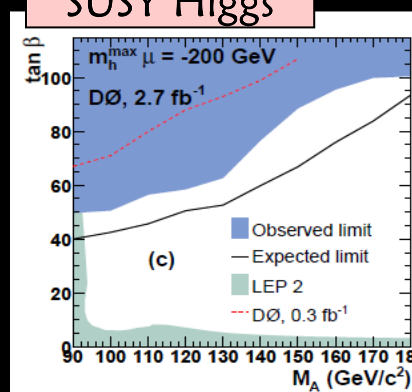
4th generation quarks



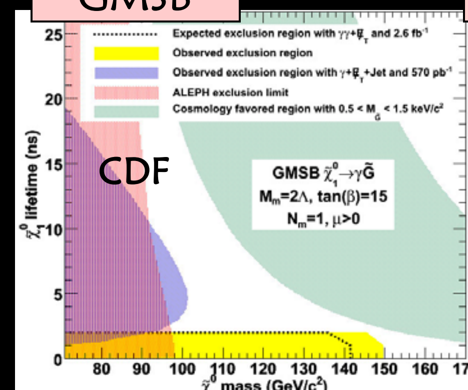
dark photons



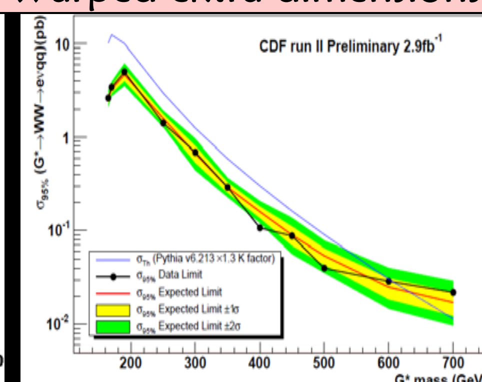
SUSY Higgs



GMSB



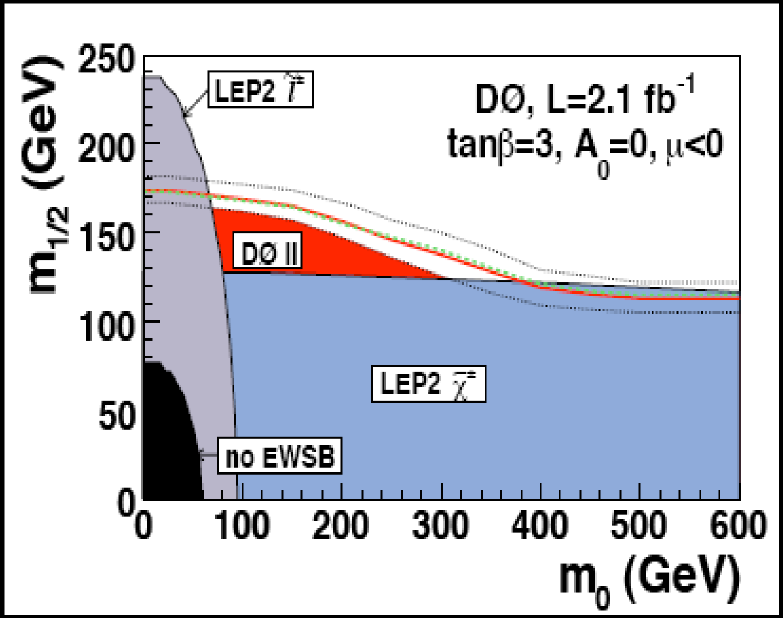
Warped extra dimensions



Plus W'/Z'/ℓ'/q', cannonballs, quirks, monopoles, axigluons, etc etc …

Searches for New Physics

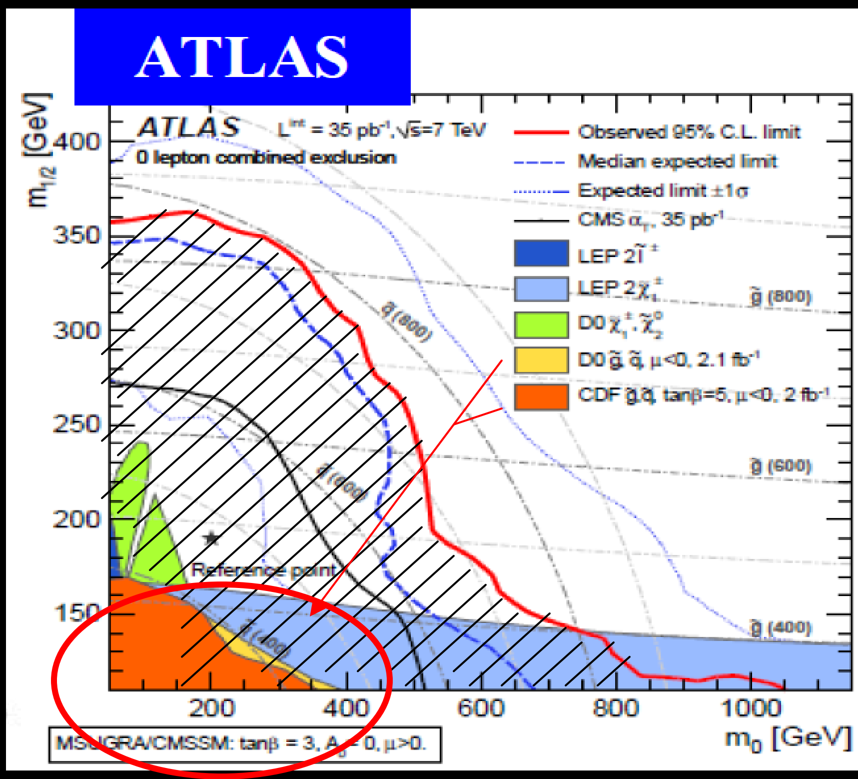
CDF and DØ have invested a huge effort in searching for new phenomena beyond the SM (nearly ½ of the published papers are searches), and can be justifiably proud of this body of work.



Supersymmetry (MSugra) squark/
gluino search in jets+MET

Searches for New Physics

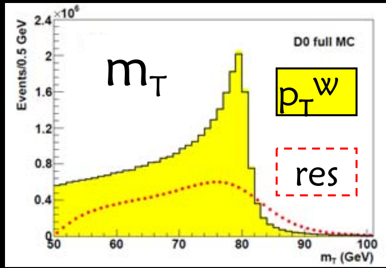
CDF and DØ have invested enormous effort in discovering new phenomena beyond the SM (nearly ½ of the published papers are searches), and can be justifiably proud of this body of work.

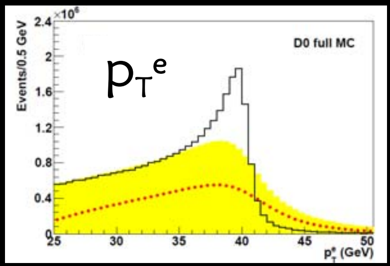


But the LHC is already exceeding the Tevatron limits with just 35 pb^{-1}!

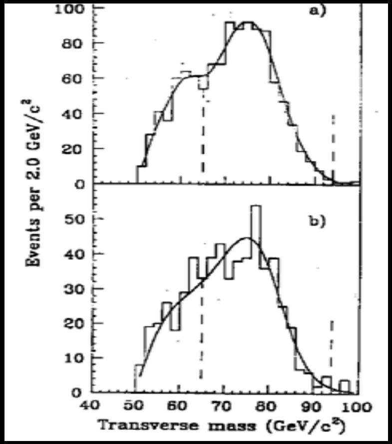
Electroweak

W mass



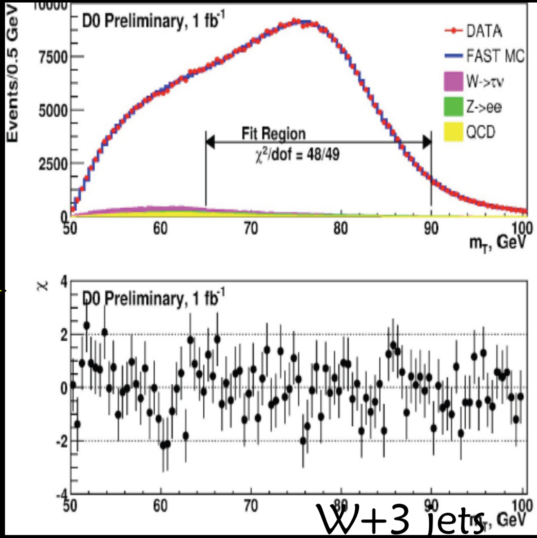


Transverse mass and p_T^e: different sensitivity to p_T^W and resolution



1990 CDF measurement (~1700 events, 4 pb^{-1}):
δm_W=390 MeV

20 years of W studies



2009 DØ measurement (500K events, 1000 pb^{-1})
δm_W=43 MeV

Now m_W=80.420±0.031 (Tevatron); 80.399±0.023 GeV (world) (0.03%)

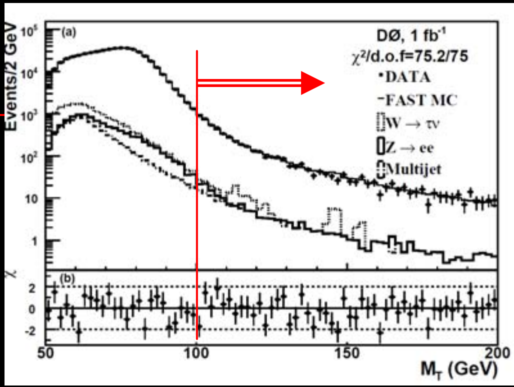
With 10 fb^{-1}, aim for δm_W=15 MeV. Current 1 fb^{-1} per expt uncertainties are:

δm_W = 23 (W stat) ⊕ 35 (Z stat) ⊕ 12 (model, mostly PDFs) (MeV):

To reach 15 MeV, need progress on PDF error.

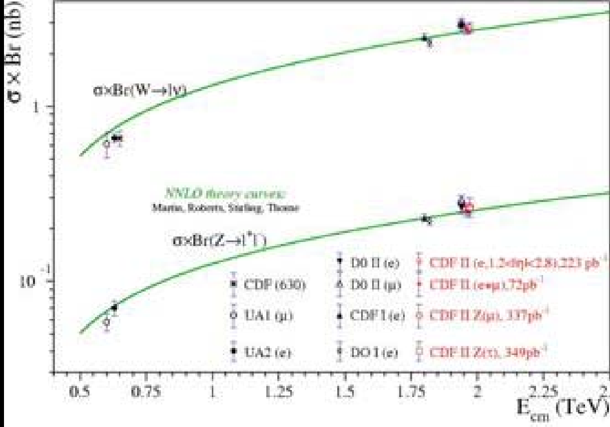
LHC will be long in overtaking Tevatron

The W decay width measured from high m_T Breit Wigner tail. Γ_W measurement (± 3.5%) agrees with SM.

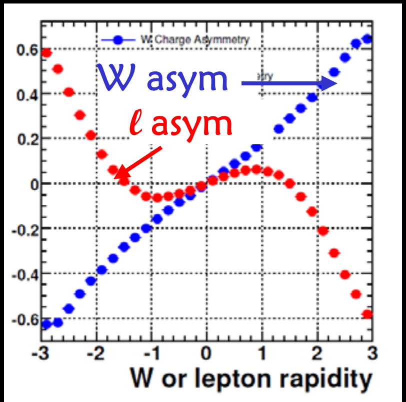


Electroweak

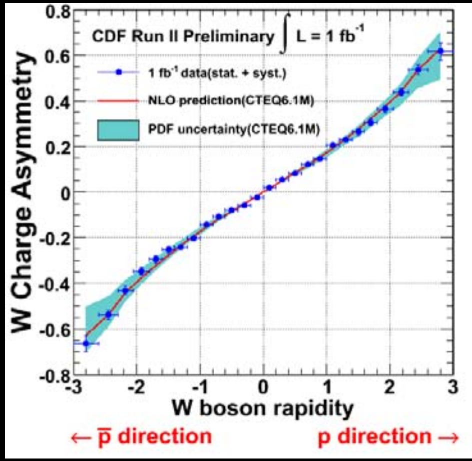
W production



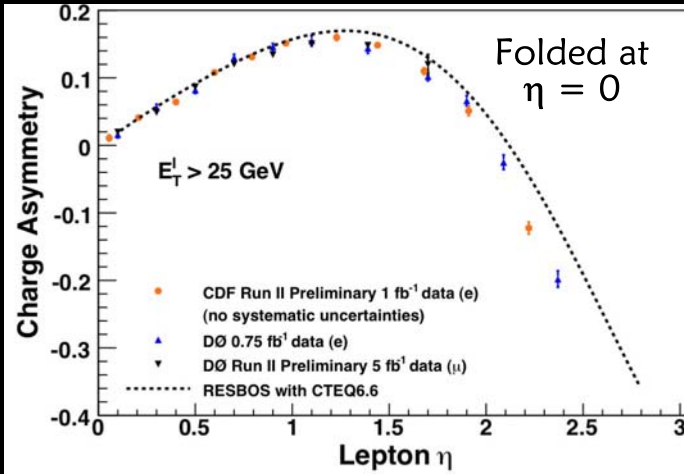
W production: Total cross sections agree well with QCD prediction. See no WW or WZ resonances < ~700 GeV



Owing to the initial $p\bar{p}$ state, the W^+ and W^- are produced mostly in opposite hemispheres. The V–A decay gives a decay lepton asymmetry of opposite sign to the W asymmetry.



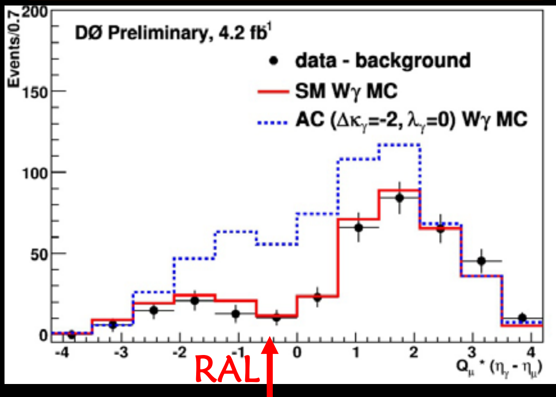
The asymmetry constrains the PDFs for u and d quarks – needed to model the W mass measurements. CDF has performed the difficult unfolding to get the W asymmetry which agrees with current PDFs.

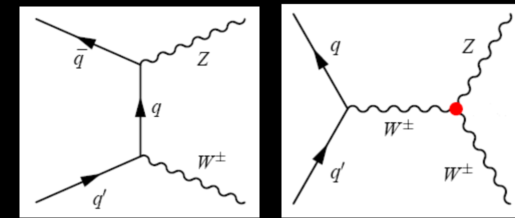


Both experiments measure the lepton asymmetry. Though they agree with each other, they did not agree with the PDF predictions.

Electroweak

Diboson production

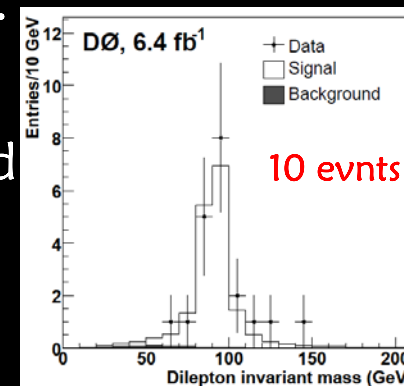




Largest diboson cross section for Wγ production (WWγ coupling)

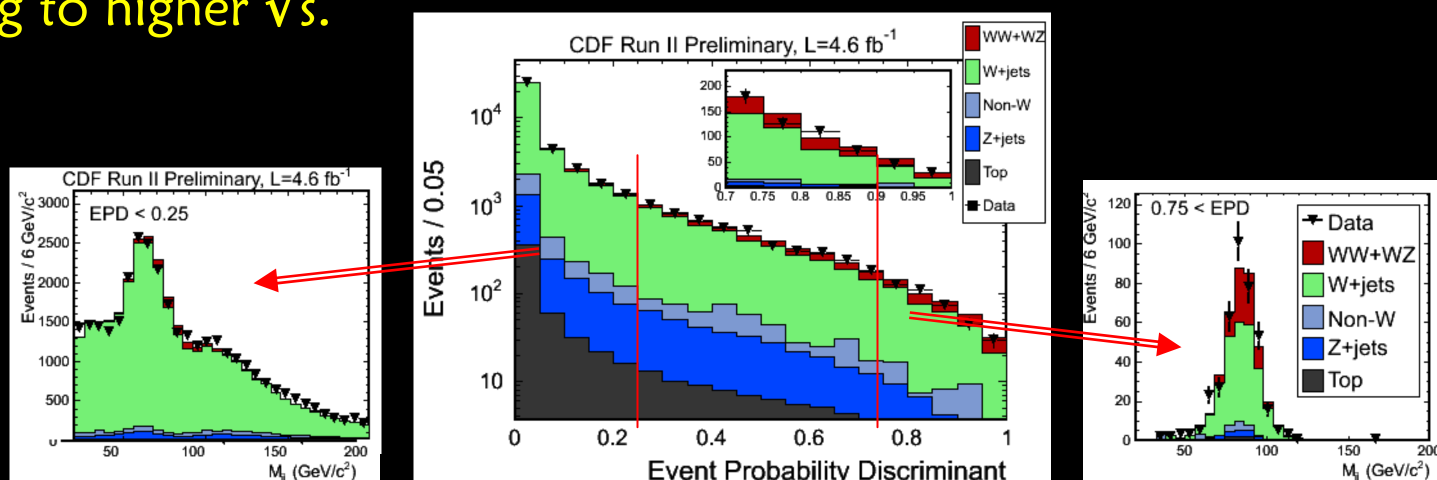
Observe SM radiation amplitude zero in (interference of s & t channel diagrams).

Smallest diboson XS for ZZ production also now observed (both 4ℓ and $\ell\ell\nu\nu$).



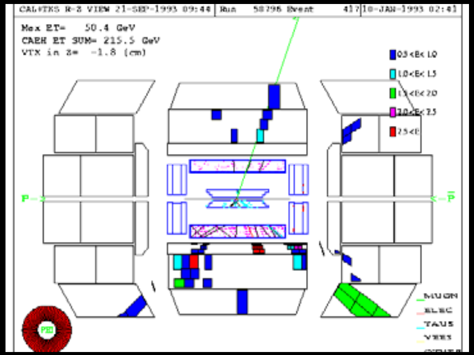
Anomalous coupling limits now comparable to LEP; XS's agree with SM. LHC will overtake Tevatron with comparable sample sizes owing to higher √s.

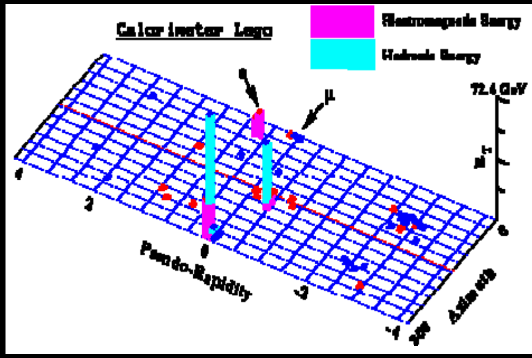
Now observing WW/WZ in the challenging $\ell\nu jj$ final state (similar to Higgs search).



Top quark

Discovery





Chronology

80's: Mass limits 23 GeV (Petra), 30 GeV (Tristan)

1984: UA1 publishes a suggestion of $W \to tb$ ($m_t \sim 40$ GeV)

1990: CDF sets limit $m_t > 91$ GeV ruling out W decay to top

'90's: LEP/SLC: $m_t \sim 150$-200 GeV

1994: DØ limit at $m_t > 131$ GeV

April 1994: Seeing limits not improve with more data, CDF publishes evidence for top at ~ 175 GeV, 2.8σ significance

July 1994: DØ shows similar expected yields, but observed $\sim 2\sigma$

January 1995: Now with 50 pb^{-1}, both collaborations sense a discovery is possible – feverish internal activity but minimal CDF/DØ interactions!

Feb. 17, 1995: CDF delivers a paper to Director Peoples, starting 1 week clock.

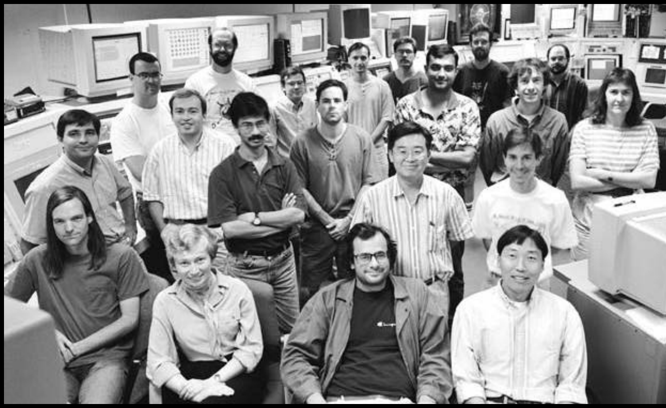
Feb. 24, 1995: Simultaneous CDF and DØ PRL discovery submissions.

Top quark

Discovery

March 2, 1995: Joint seminar announcing the top quark discovery

DØ PhD students



See article SLAC *Beam Line*, 25, #3 (1995) for more on the discovery.

In an editorial, Bjorken wrote of the race to discovery and the need for 2 collaborations, He commented on the oft-corrosive relations between groups making simultaneous discoveries: "… the ensuing CDF/DØ competition has been a class act."

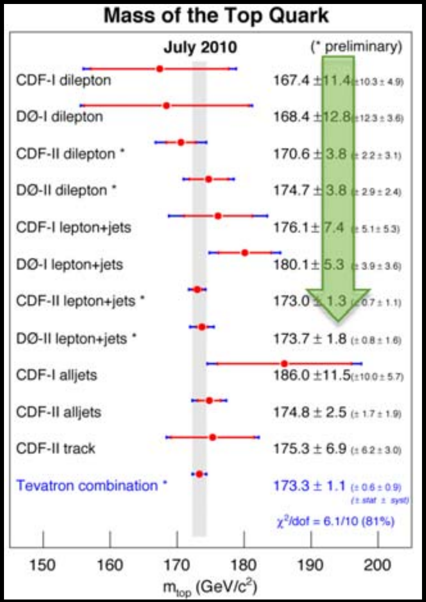
Top quark

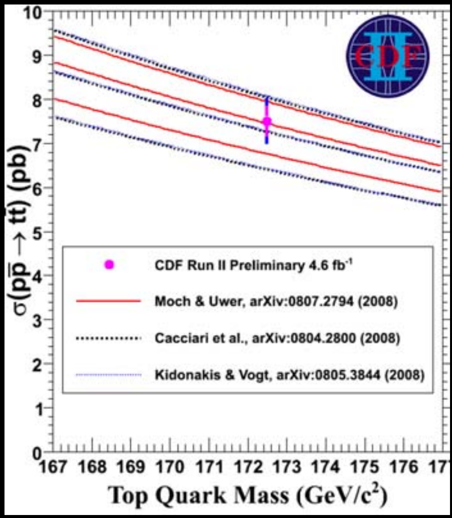
Pair production

In $t\bar{t}$ pair production, both tops decay to Wb, so final states only depend on W decay. By now cross section and top mass have been determined in all possible channels. The single lepton channel ($\ell\nu b$ jjb) is favored for detailed studies of properties, as background is moderate and reconstruction is possible.

(Summer 2010 status)

CDF 4.6 fb^{-1}: $\sigma(t\bar{t})$=7.50±0.48 pb (6%), in agreement with the NNLO theory prediction of comparable precision.





Top quark mass is measured in all channels with several methods to good consistency and high precision.

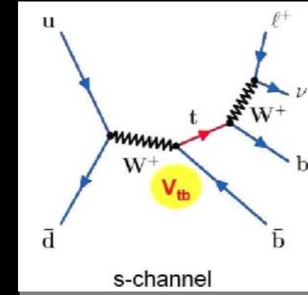
m_t (WA)= 173.1 ± 1.1 GeV (0.6%)

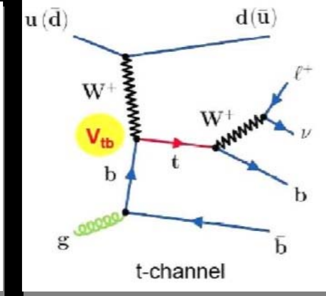
Recent measurement of mass from comparison of expt/theory XS suggests that the measured mass is closer to being the pole mass than the $\overline{\mathrm{MS}}$ mass.

Further improvements will be modest (limiting systematic is knowledge of jet energy scale). But it will be some time before LHC overtakes Tevatron.

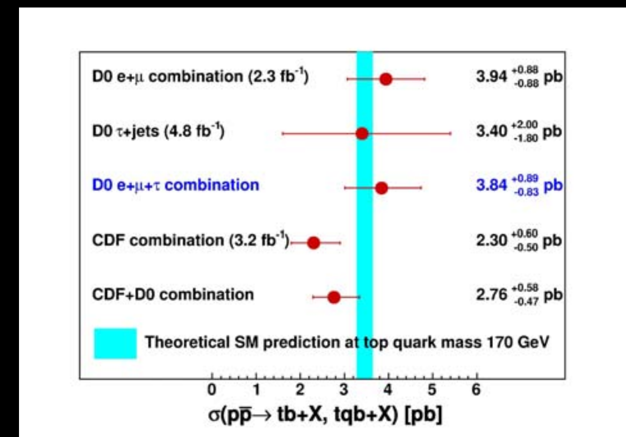
Top quark

Single top EW production

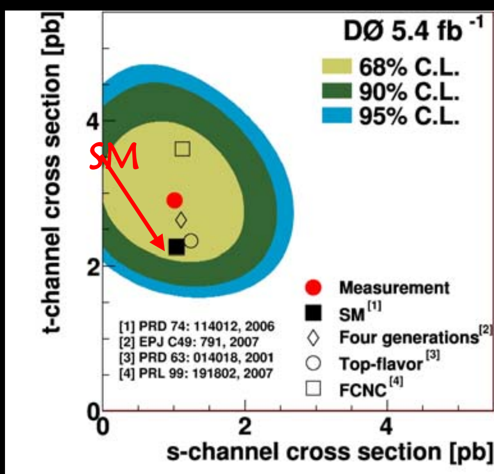




Top quarks are pair-produced by the strong interaction (preserving flavor symmetry). Single top quarks can be produced by EW interaction via s-channel or t-channel W exchange). SM predicts $\sigma \approx 3.2$ pb. DØ and CDF first observation in 2009.



Analyses use sophisticated multivariate methods to dig the signal from large backgrounds. The combined CDF/DØ result is $\sigma = 2.76^{+0.58}_{-0.47}$ pb



DØ has obtained separate t- and s-channel cross sections, with t-channel XS significance =5.5σ. Measurements begin to rule out some models for new physics.

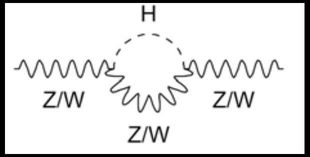
Can also measure the tbW coupling directly (sensitive to 4th quark generation): $|V_{tb}|=0.88\pm0.07$ (SM =1)

Top quark

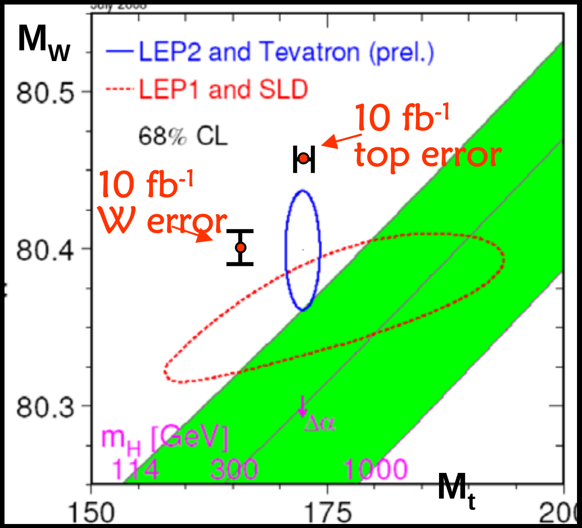
With samples of 1000's of $t\bar{t}$, many properties of the top have been studied, and limits on New Physics set.

- Top and antitop masses are consistent (CPT test)
- Top quark lifetime as in SM (0.3 ys) (decays before hadronizing)
- Top charge is 2/3e
- F-B $t\ \bar{t}$ asymmetry is larger than SM expectation (need NNLO theory!)
- W helicity in top decay as in SM (70% longitudinal, 30% left-handed)
- Correlations of spins of top and anti-top are consistent with SM QCD
- No flavor changing neutral currents observed in decays
- No evidence for Susy charged Higgs in top decays
- No anomalous top axial vector/tensor couplings seen
- No 4th generation t' seen
- No tt resonances seen below ~800 GeV; SM angular & pT distributions
- Prefer W in t decay to be color singlet

Top and W: messengers to the Higgs and beyond



etc.

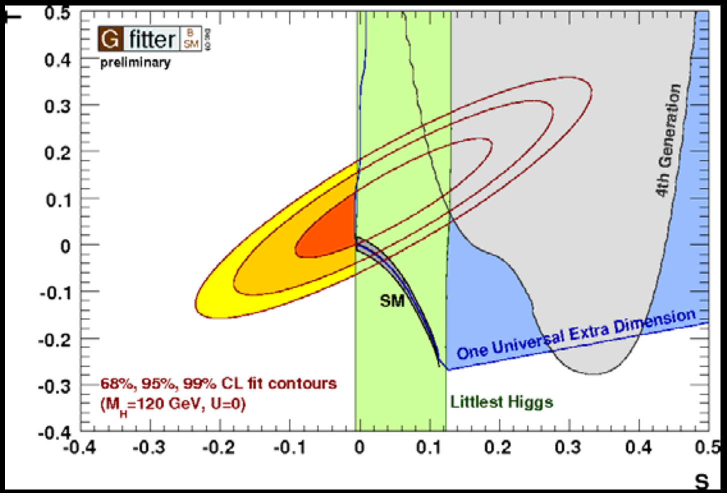


The top and W masses are modified by loop corrections involving the SM Higgs, and thus constraining the Higgs mass.

The $m_W - m_t$ plot scale is adjusted to give the Higgs bands at 45°. The error ellipse shape emphasizes that m_W most needs improvement. Fortunately, the W mass is still statistics dominated, unlike the top mass.

With the expected 10 fb^{-1} precisions (shown on the plot) and assuming the central values stay as they are now, the $m_W - m_t$ measurements and existing Higgs limits, the Tevatron can invalidate the SM, even without further Higgs exclusion.

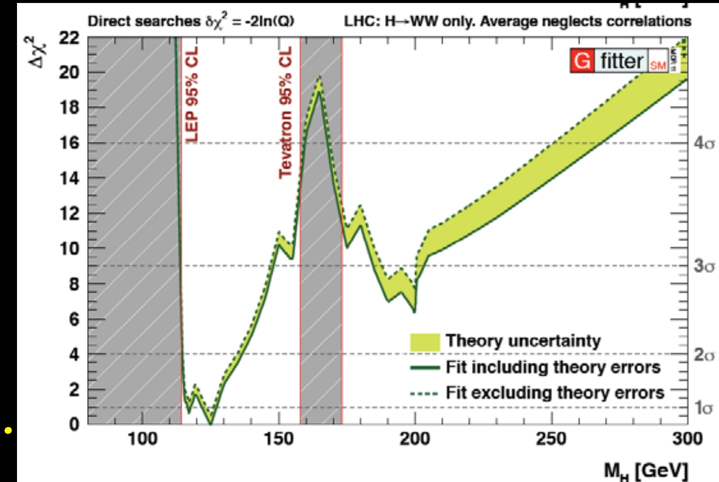
Allowed S-T parameters (vacuum polarization oblique corrections)

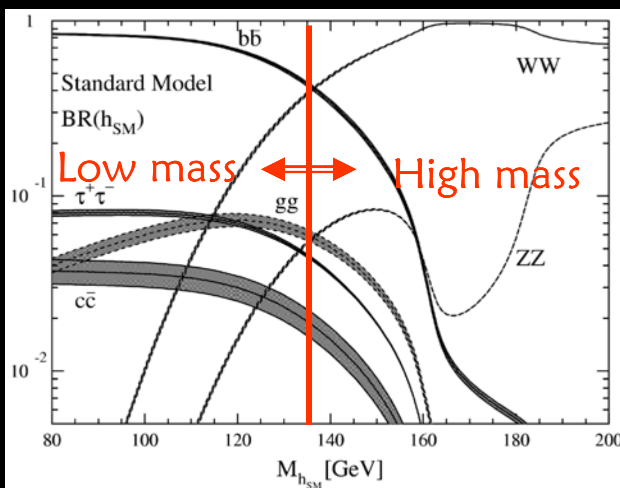


The precision measurements (LEP/SLC Z, Tevatron W,t) also severely constrain potential models of Physics beyond SM.

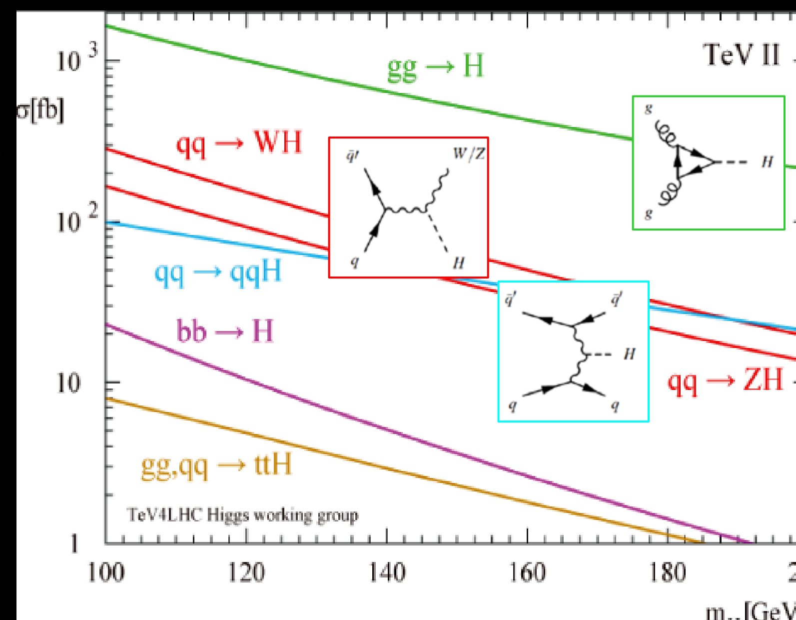
The Higgs Boson

The Brout, Englert, Guralnik, Hagen, Higgs, Kibble boson mass is the single remaining unknown particle in SM. Its mass, as constrained by precision electroweak measurements and direct searches, should lie in the range $115 < m_H < 137$ GeV.





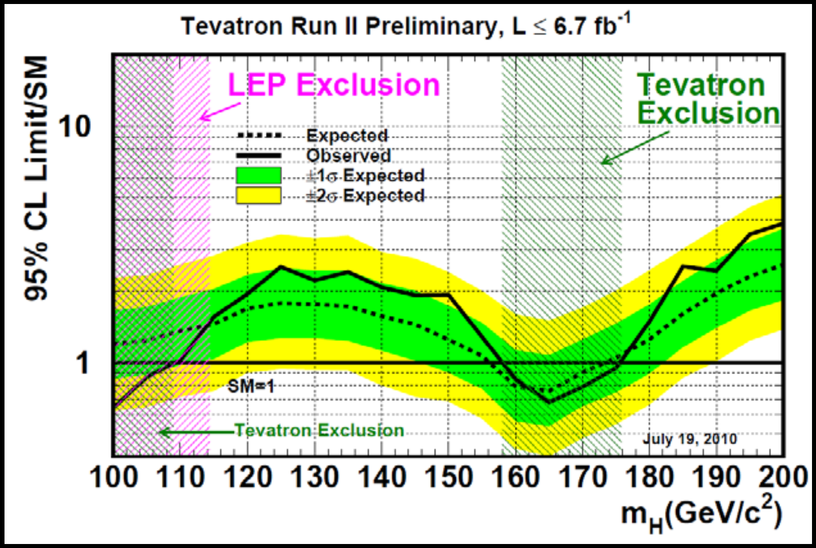
Decays:
$b\bar{b}, \tau\tau$ ($m_H < 135$);
WW, ZZ ($m_H > 135$)



Tevatron searches seek production by gluon gluon fusion, associated VH production and vector boson fusion, many decays (bb, $\tau\tau$, WW, ZZ, $\gamma\gamma$)

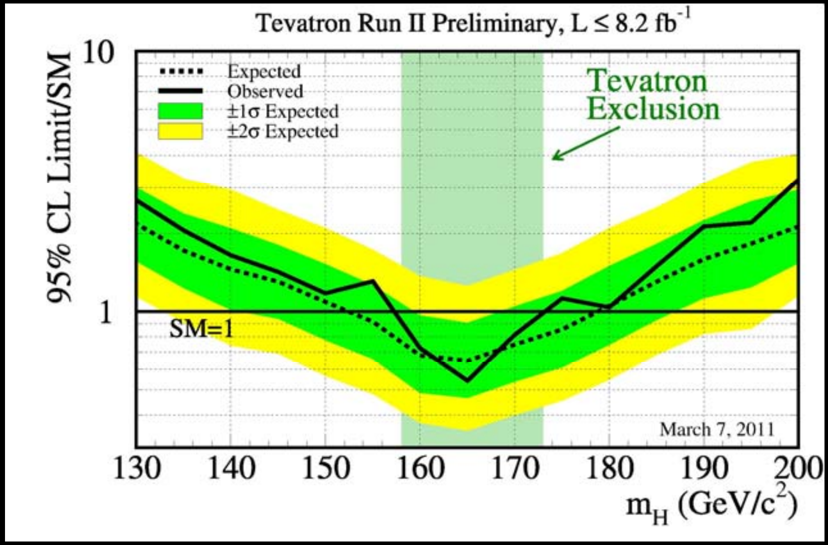
The Higgs Boson

Current status

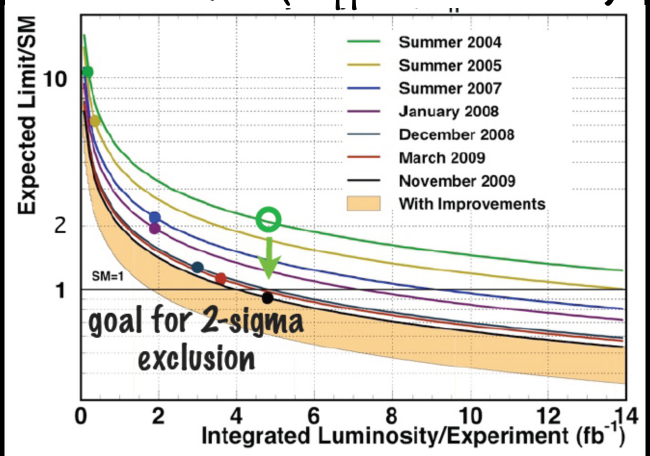


Summer 2010: update full Higgs mass range. Combination of CDF & DØ exclude around 165 GeV at 95% C.L. At low mass, coming close to raising exclusion beyond LEP.

Winter 2011: update high mass Higgs region; now each experiment excludes around 165 GeV separately.



CDF+DØ (m_H = 165 GeV)



Over time, limits have improved faster than $\mathcal{L}^{-1/2}$

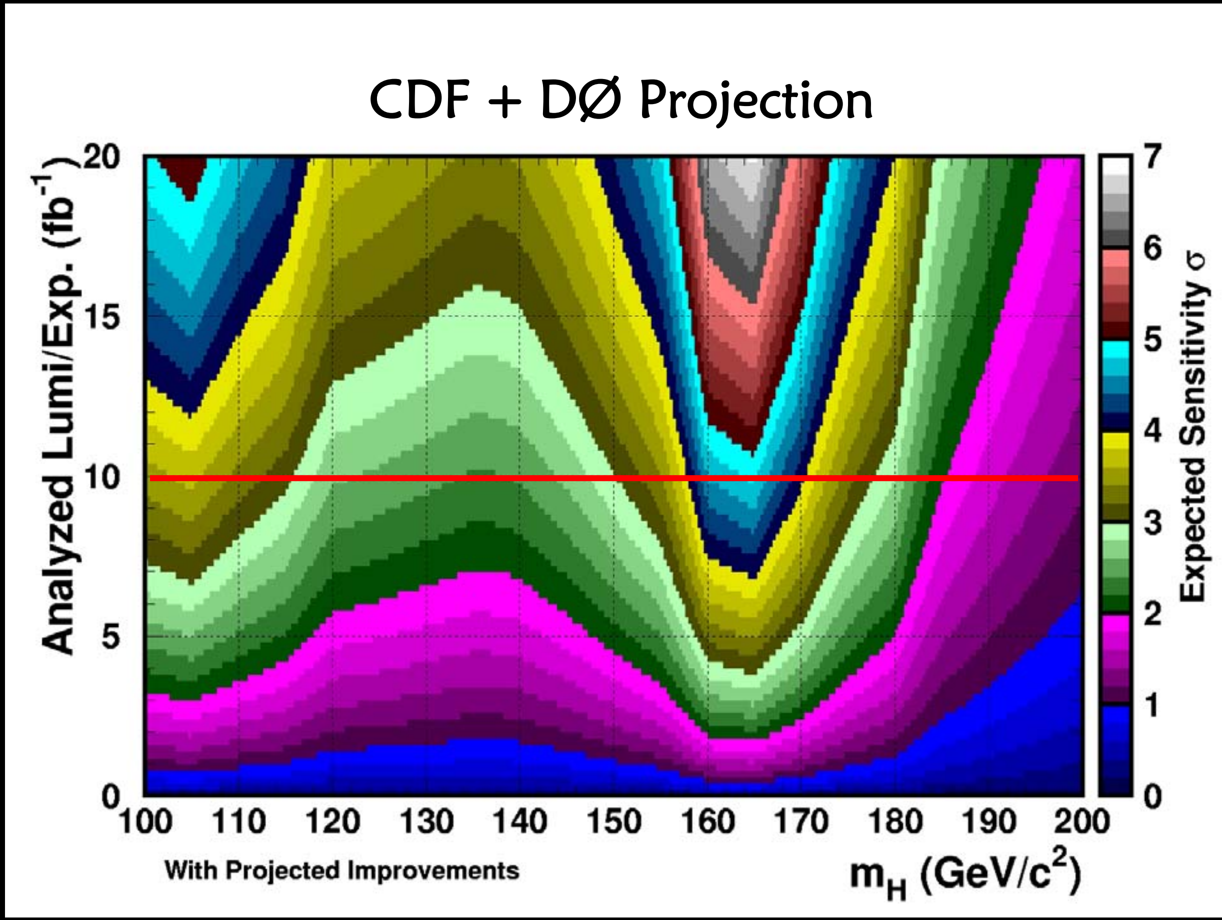
The Higgs Boson

Projection

Expect ~10 fb^{-1} in analysis samples by end of run, Sept. 30, 2011 (~12 fb^{-1} delivered).

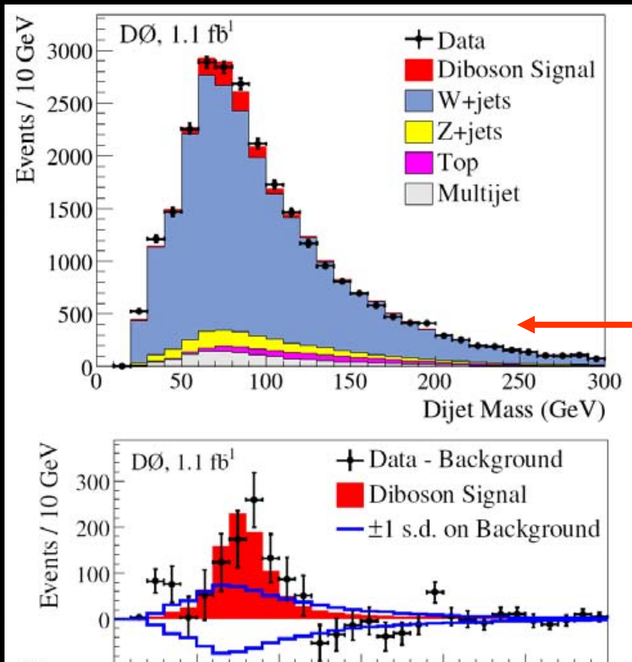
Plot is projection for both experiments, with some improvements, many of which are accomplished.

- 95% C.L. exclusion if no SM Higgs to ~185 GeV.
- 3σ evidence up to ~120 GeV (where LHC has most trouble), and in the region 150 – 175 GeV.
- If see evidence in favored low mass region, Tevatron provides measurement of dominant coupling to $b\bar{b}$ to complement LHC.



Higgs boson

Methodology check

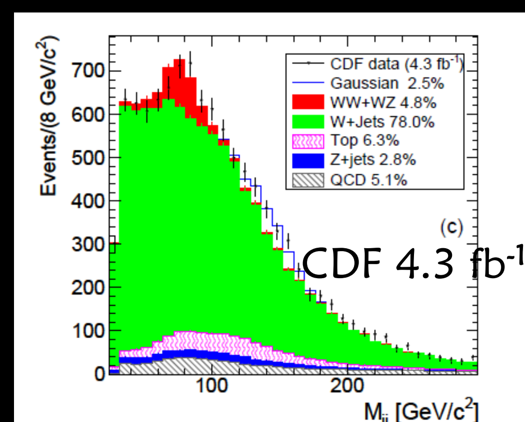


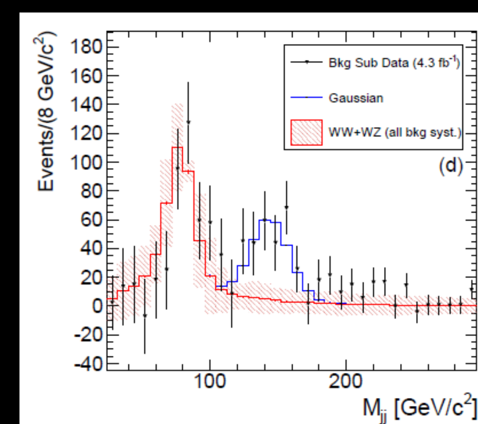
A sanity check: Search for the previously unobserved process, WW/WZ→ℓν +2jets using all the Higgs multivariate and limit setting machinery.

Red portion shows expected signal on top of W+jets or Z+jets background. Bottom shows signal after background subtraction.

Measure XS in agreement with the SM, and previous measurements in the cleaner four lepton final state.

And perhaps these sanity checks of measuring WW/WZ cross sections could even bring surprises!





Innovations at the Tevatron

The Tevatron accelerator complex runs extremely well after a slow start in Run II. It has pioneered such techniques as helical orbits to avoid beam beam interactions and has developed the art of antiproton cooling and storage to new heights. Without the Tevatron's superb operation, the physics I have described would not have been possible.

❖ CDF pioneered the first hadron collider silicon vertex detector and separated vertex trigger

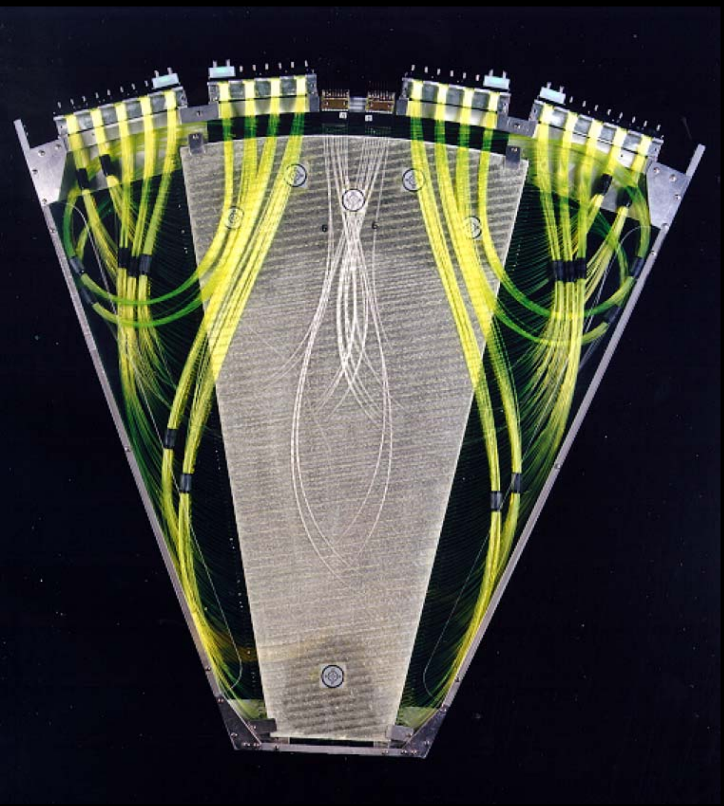
❖ DØ demonstrated that sparse high resolution trackers could stand up to the hadron collider environment. The DØ 4π uranium-liquid argon detector paved the way for the next generation of calorimeters.

❖ CDF and DØ developed multi-level triggering with fast microprocessor farms to give incisive selection of interesting events.

❖ CDF and DØ pioneered multivariate analysis techniques for extracting signals in the face of huge backgrounds: random grid searches, neural networks, decision trees, random forests, and have demonstrated their robustness in measurements of known physics.

❖ These advances now adopted by LHC or future detectors

Detectors as Art



DØ Forward Preshower module at the Museum of Modern Art, New York

CDF Run I Silicon Vertex Detector at the Smithsonian Museum, Washington

The Tevatron Legacy

A great 25 year run at the energy frontier, with a 10 fb^{-1} data set

The baton for the energy frontier has now passed to the LHC, but some important Tevatron legacy measurements will endure:

- Discovery of the top quark and measurements of its properties
- Precision measurements of the W boson mass, and jets, V+jets, diboson cross sections
- Limits on the Higgs boson mass (likely to be continue to be important as complementary to LHC discoveries)
- Remarkable progress on heavy b-quark states and mixing
- Some hints of new physics ($\not{CP}$ in b hadrons, $t\bar{t}$ F-B asymmetry …)