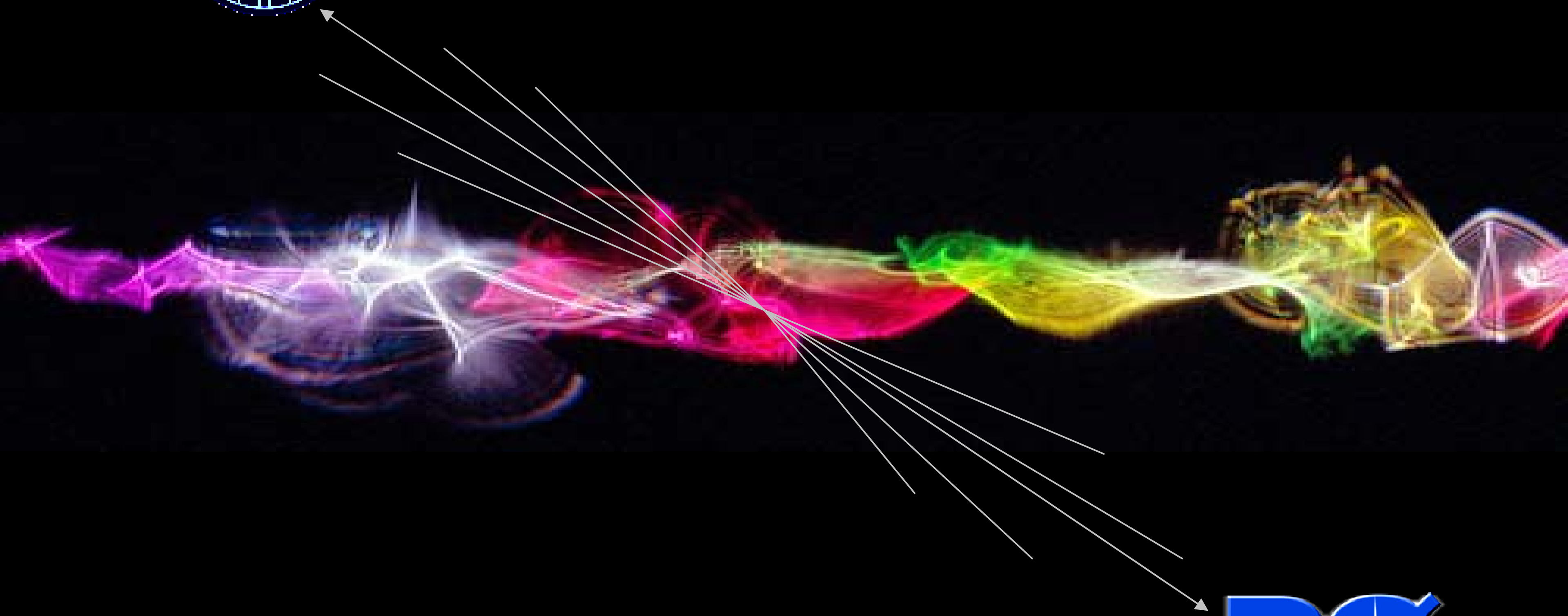
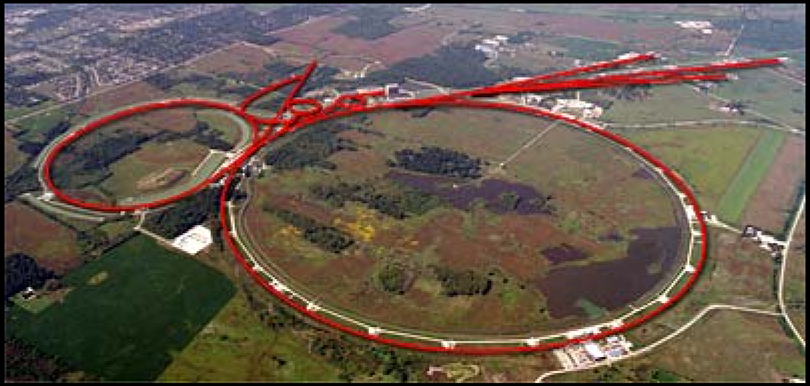
The Tevatron Legacy

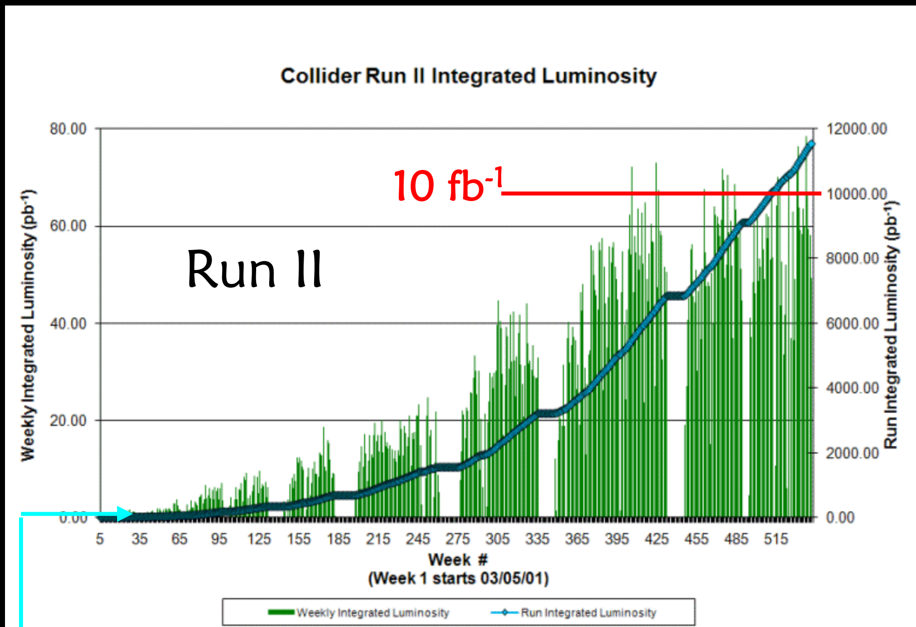
25 years of Physics at the Tevatron
(in 25 minutes)



DPF Meeting, Brown University
P. Grannis, Aug. 13, 2011

The Tevatron



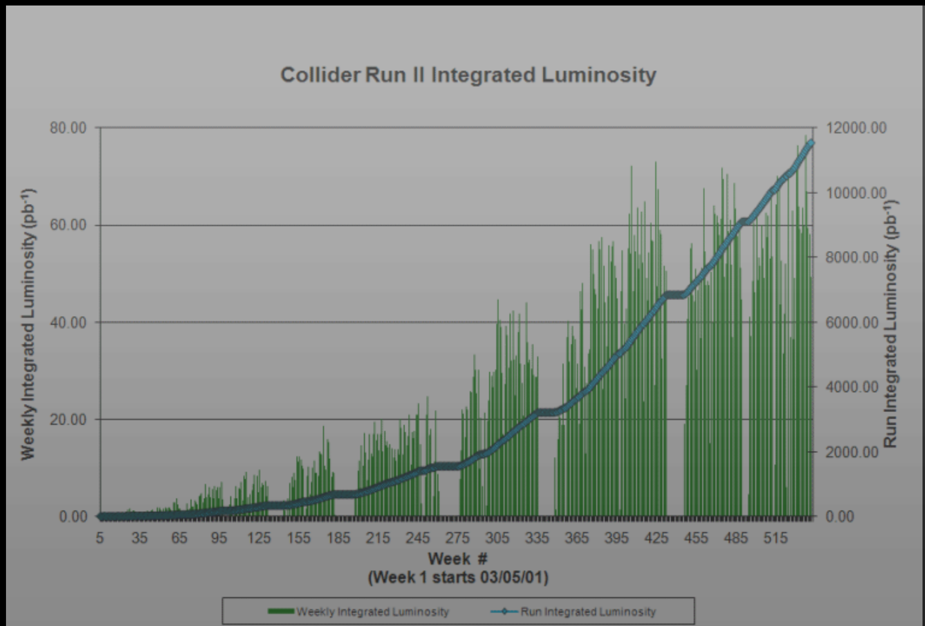


Total Run I accumulation
(120 pb^{-1})

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

(on target for $\int \mathcal{L}dt$ >12 fb^{-1} delivered by Sept. 30)

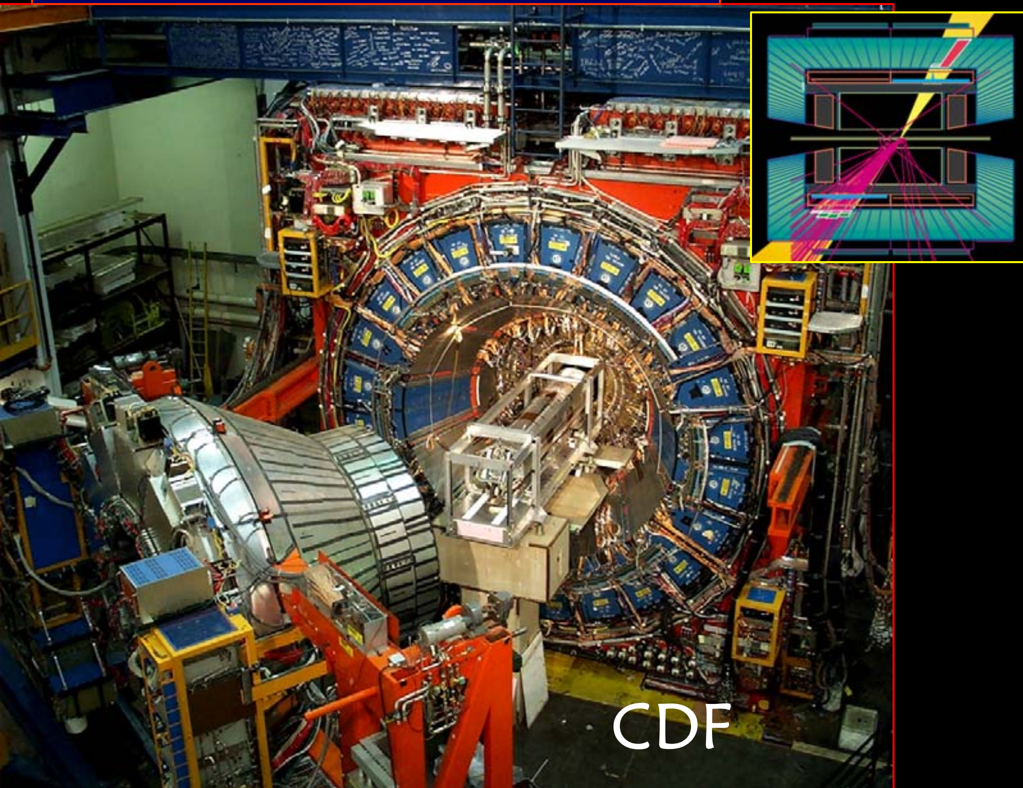
The Tevatron



I leave the Tevatron story to Steve Holmes, but note that despite the Accelerator Division's best effort, they never did see the white flag fluttering from CDF and DØ. (But we got it out several times !)

Thanks to the Accelerator folks!

The Experiments



Major detector upgrades for Run II:

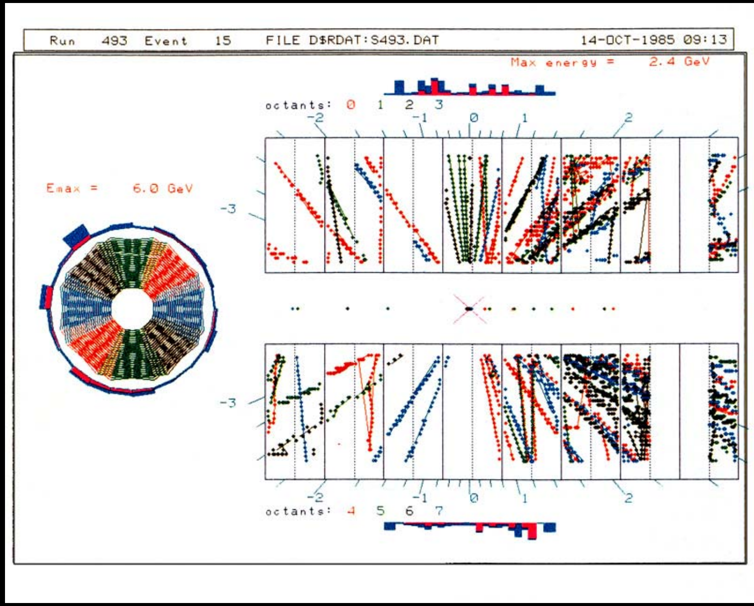
CDF: new tracker, new Si vertex det, upgraded forward cal and muons

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

The upgraded experiments looked more like each other!
But have complementary strengths and the
cross checks with >1 experiment are crucial!

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})

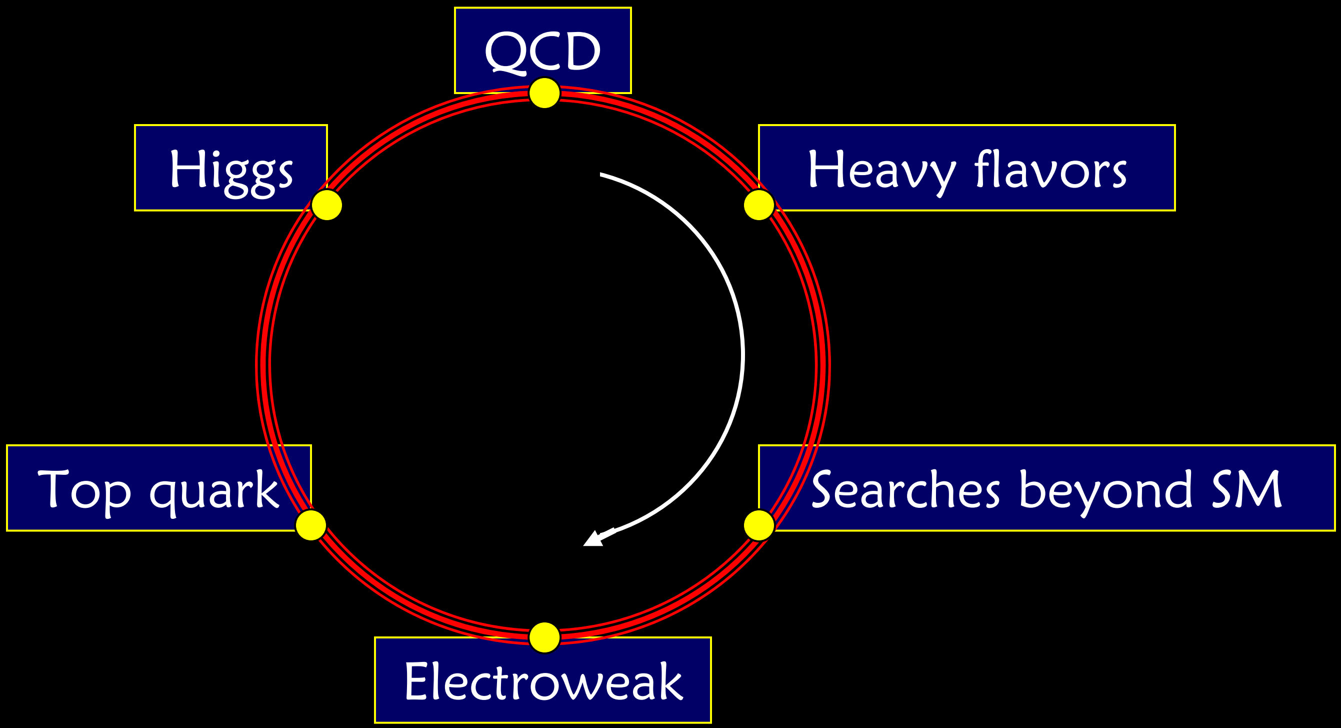
1992 – 1996: Run 1 with both CDF and DØ (120 pb^{-1}) 1.8 TeV

2001 – 2011: Run 2 (~12,000 pb^{-1}) 100x Run 1 1.96 TeV

The Tevatron Program

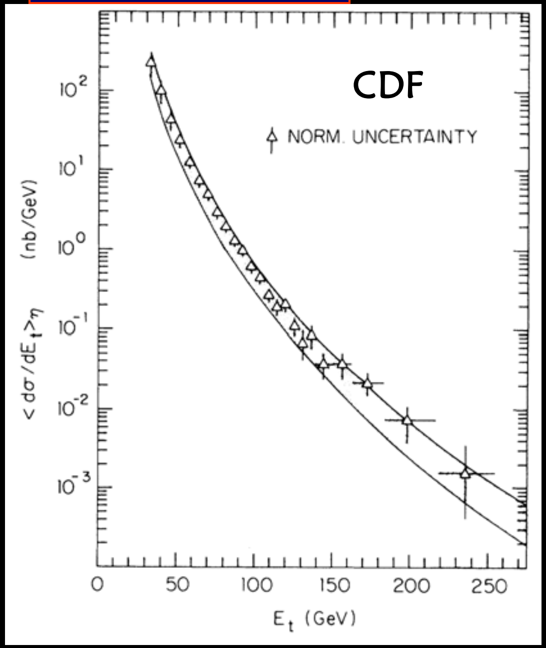
CDF and DØ organize their physics programs within six Physics Groups.

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



QCD

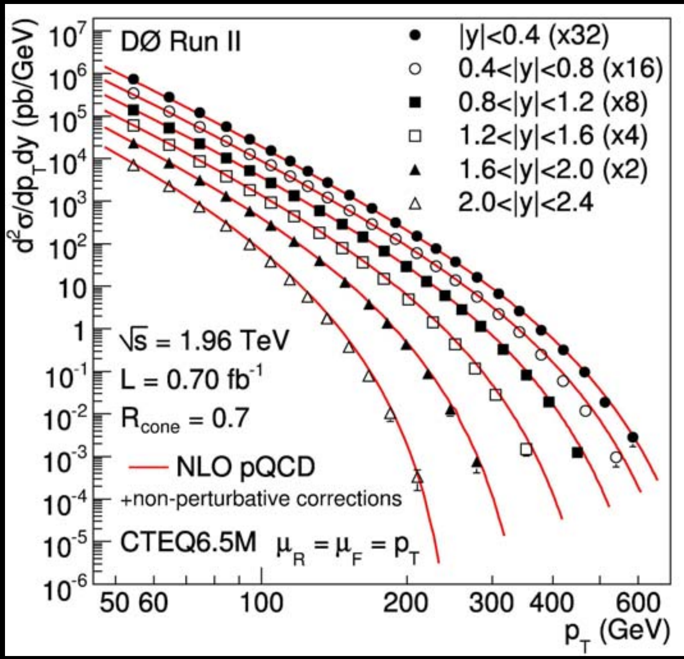
Inclusive jet production



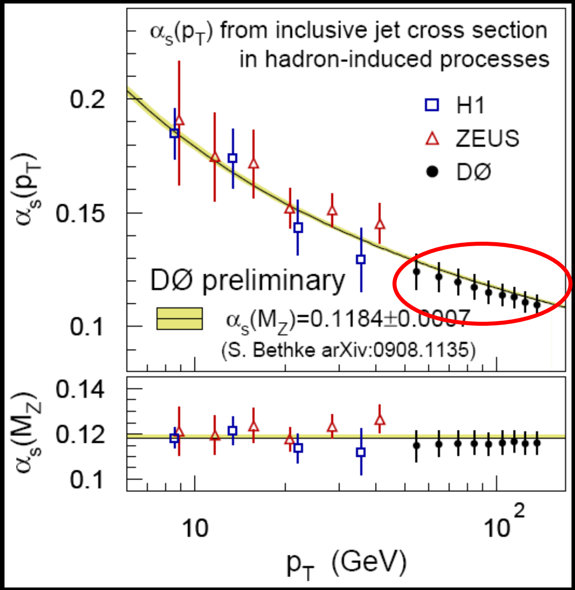
1989
7 nb^{-1}

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.



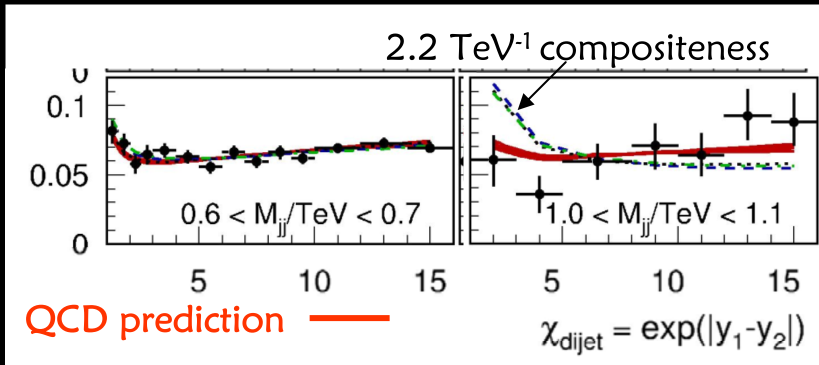
Extract $\alpha_s(Q^2)$ to extend knowledge of running coupling to high Q^2



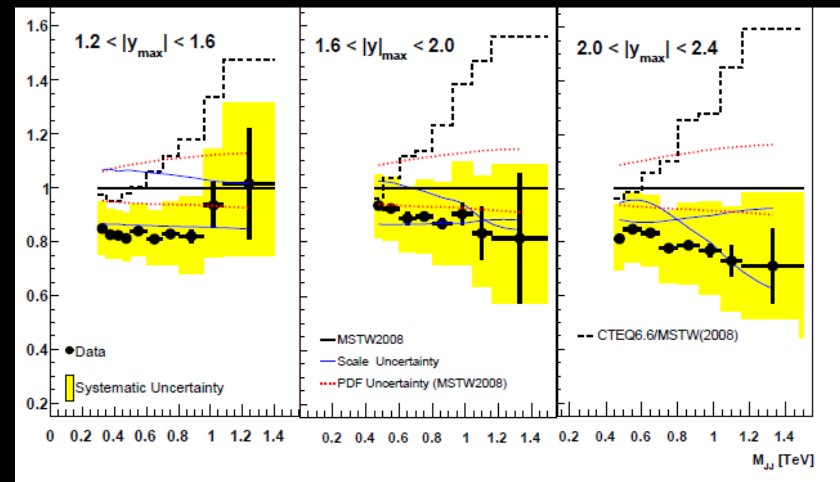
Q=700 GeV → probing proton to 0.3 am (attometer) scale, showing excellent agreement with pQCD.

QCD

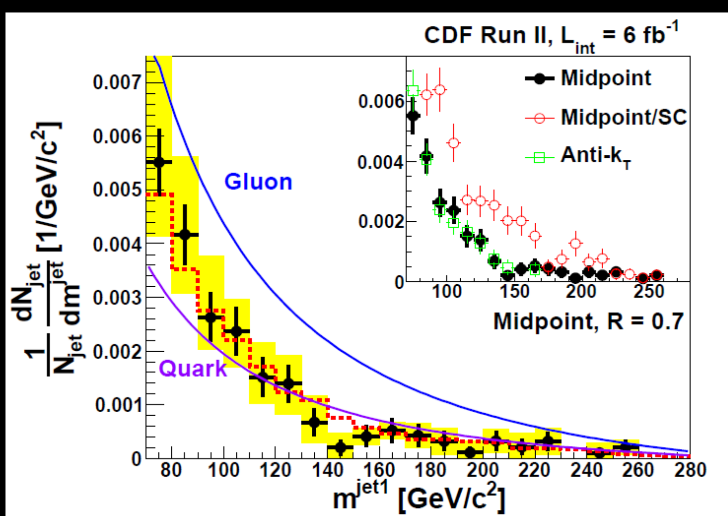
Jet properties



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



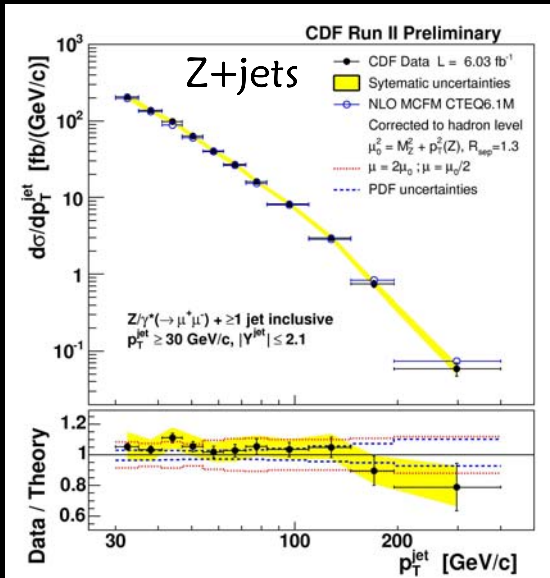
Dijet invariant mass and rapidity distributions offer another constraint on PDFs, and will modify the next generation of fits.



Jet mass distributions: Can distinguish quark and gluon jets, data agree with models for parton showering.

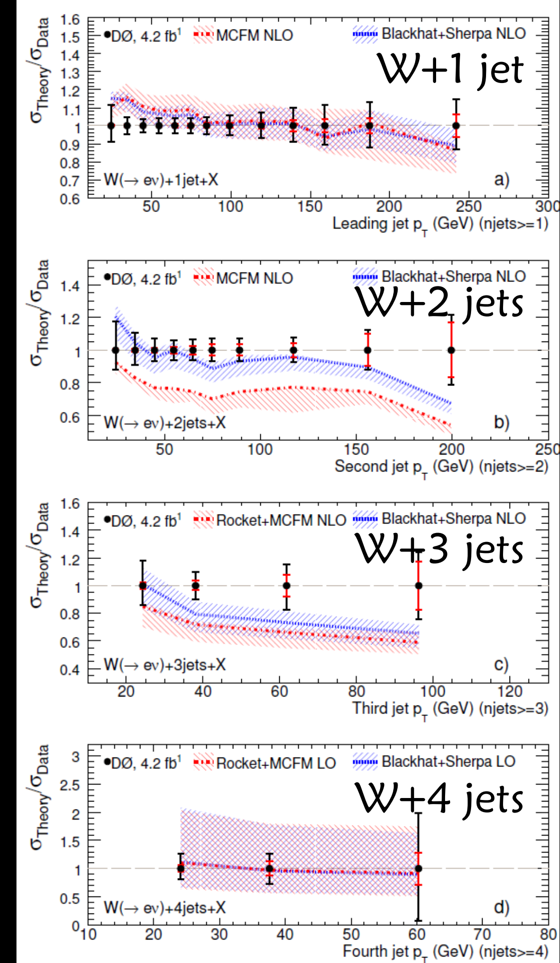
QCD

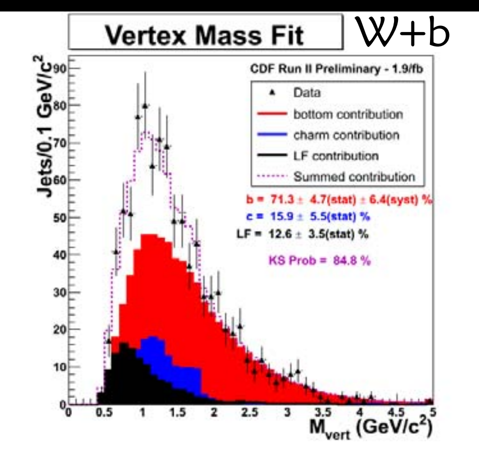
W/Z + jets



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.



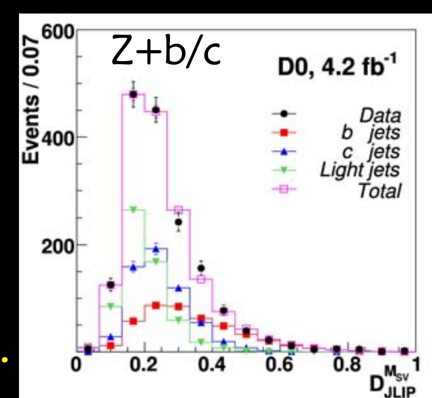


Separate jet flavors using vertex mass

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

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

Separate jet flavors using impact param.

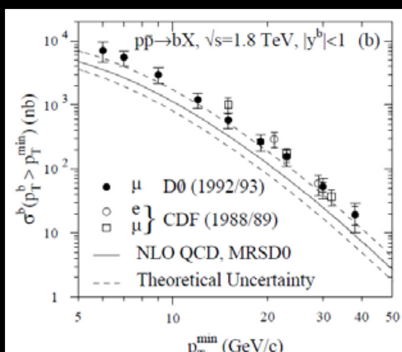


Heavy Flavor Physics

(See talks: Sheldon Stone & Hasan Jawahery)

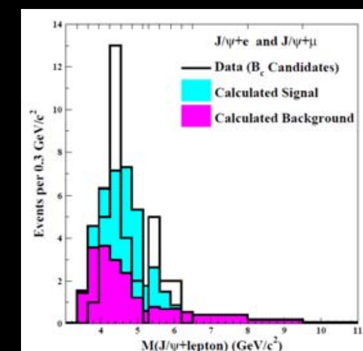
Conventional wisdom held that the Tevatron could not compete with e^+e^- colliders for b-physics.

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)



<u>First observation of</u>:

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

Now, first CDF hint of $B_s \to \mu^+\mu^-$ (BR >SM)

<u>and world leading measurements</u>:

Precision B_d mixing

b hadron masses, BRs, lifetimes, and production dynamics

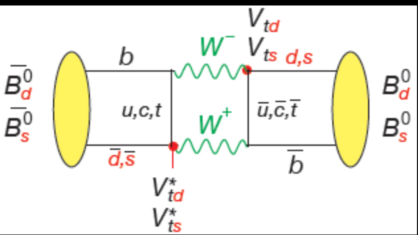
Rare B decays

Diffractive J/ψ production

charmless B_s decays

Heavy Flavor Physics

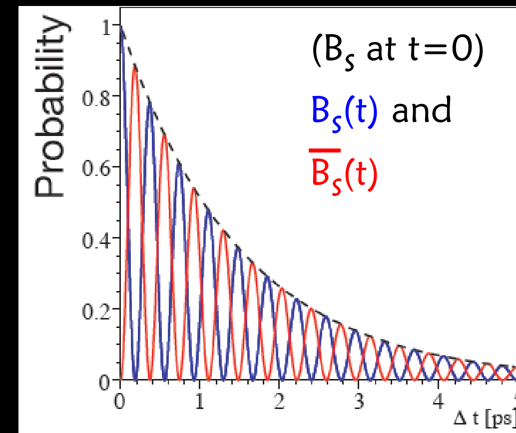
B_s mixing



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

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

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

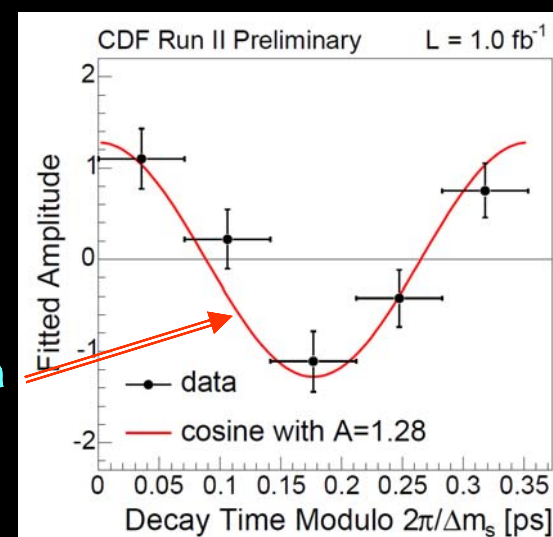


Large Δm_s means B_s mixing is very rapid (T_{osc}~0.3ps) – a large experimental challenge.

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.



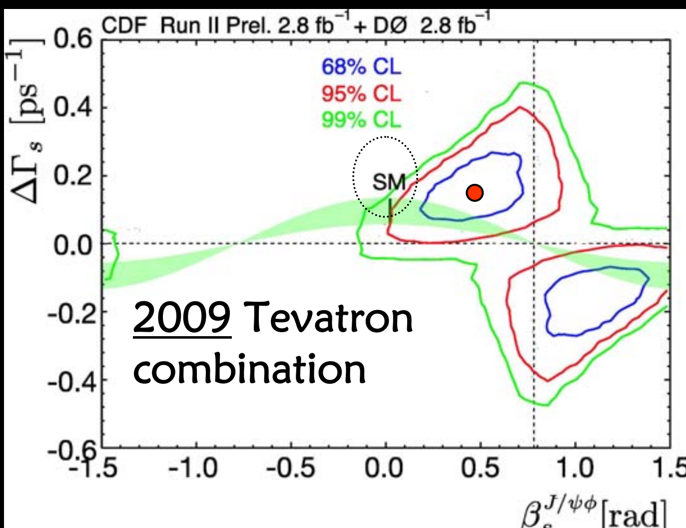
Heavy Flavor Physics

CP violation in B_s decay

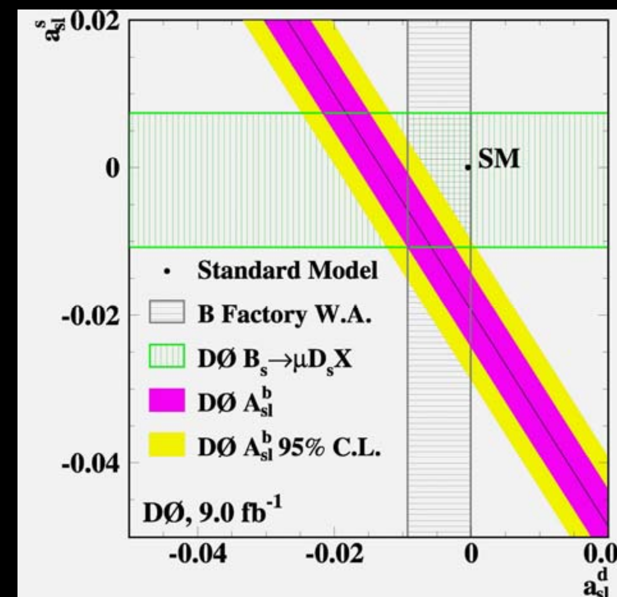
In the SM, CP violation is due to CKM phase, which is consistent for the CP violation seen in the K^0 and B_d^0 systems. DØ and CDF did measurements in the B_s^0 ($\bar{b}s$) and $\bar{B}_s^0$ systems ($\rightarrow J/\Psi\ \phi$) that are inaccessible in the B factories.

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 observed β_s large, inconsistent with SM at 2σ. More data from both expts decreases the significance.



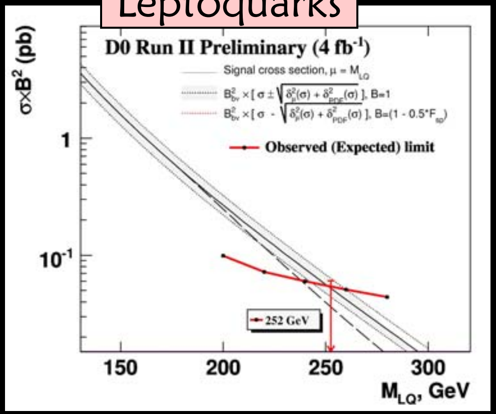
Asymmetry $N(\mu^+\mu^+)-N(\mu^-\mu^-)\ /N(\mu^+\mu^+)+N(\mu^-\mu^-)$ differs by 3.9σ from SM prediction. Here, more data increased the significance.

Searches for New Physics

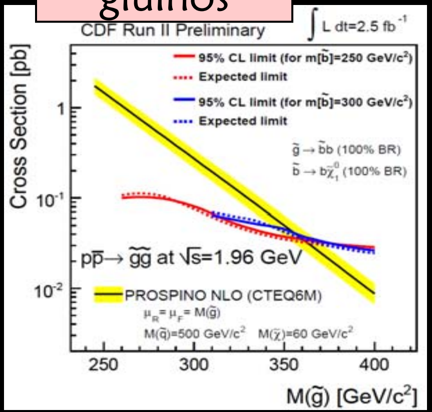
"400 Physicists Fail to Find Supersymmetry" **(NYTimes, ca 1992)**

As well as …

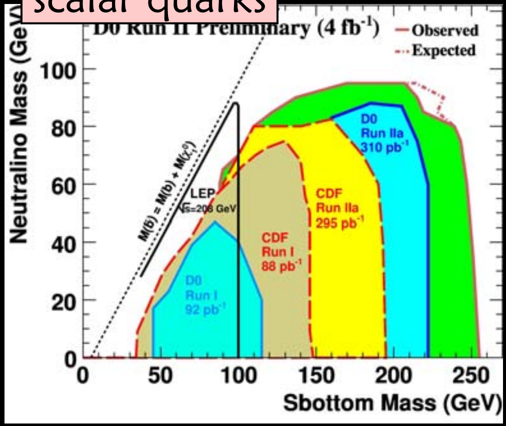
Leptoquarks



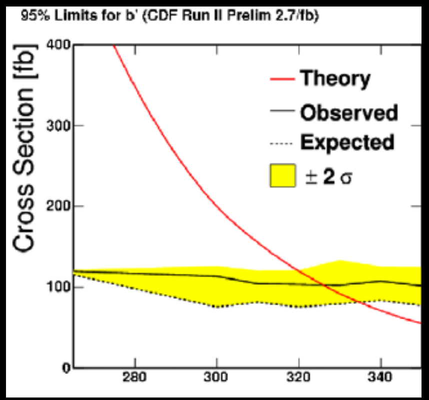
gluinos



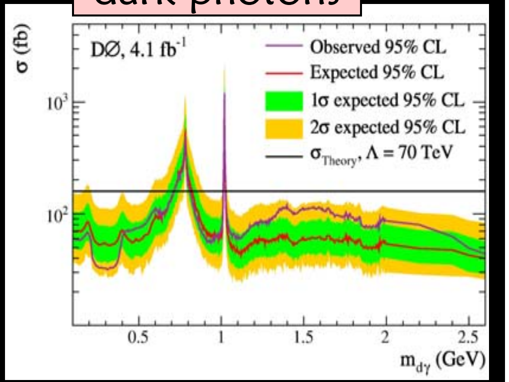
scalar quarks



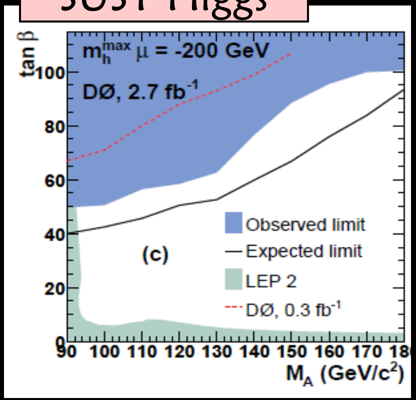
4^{th} generation quarks



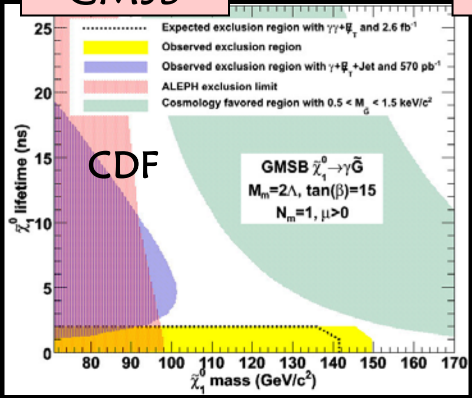
dark photons



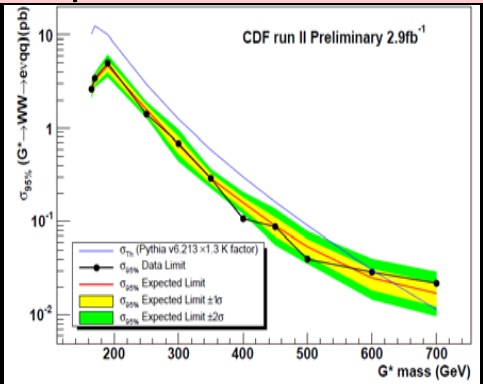
SUSY Higgs



GMSB



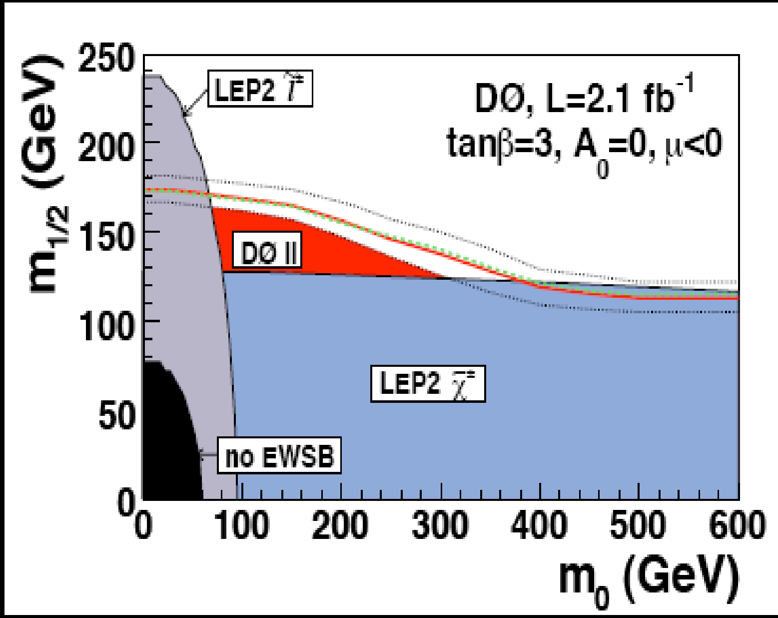
Warped extra dimensions



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.

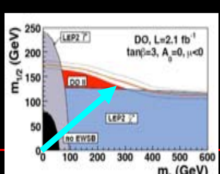


Supersymmetry (MSugra) squark/
gluino search in jets+MET

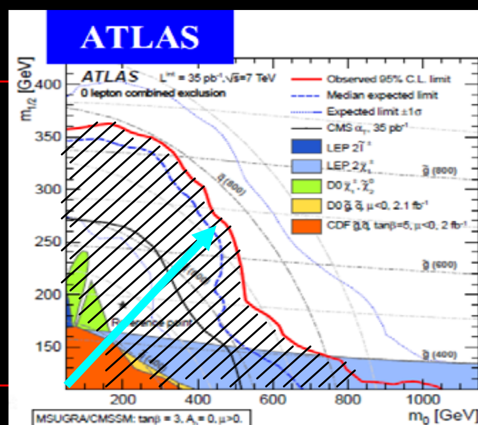
But …

Searches for New Physics

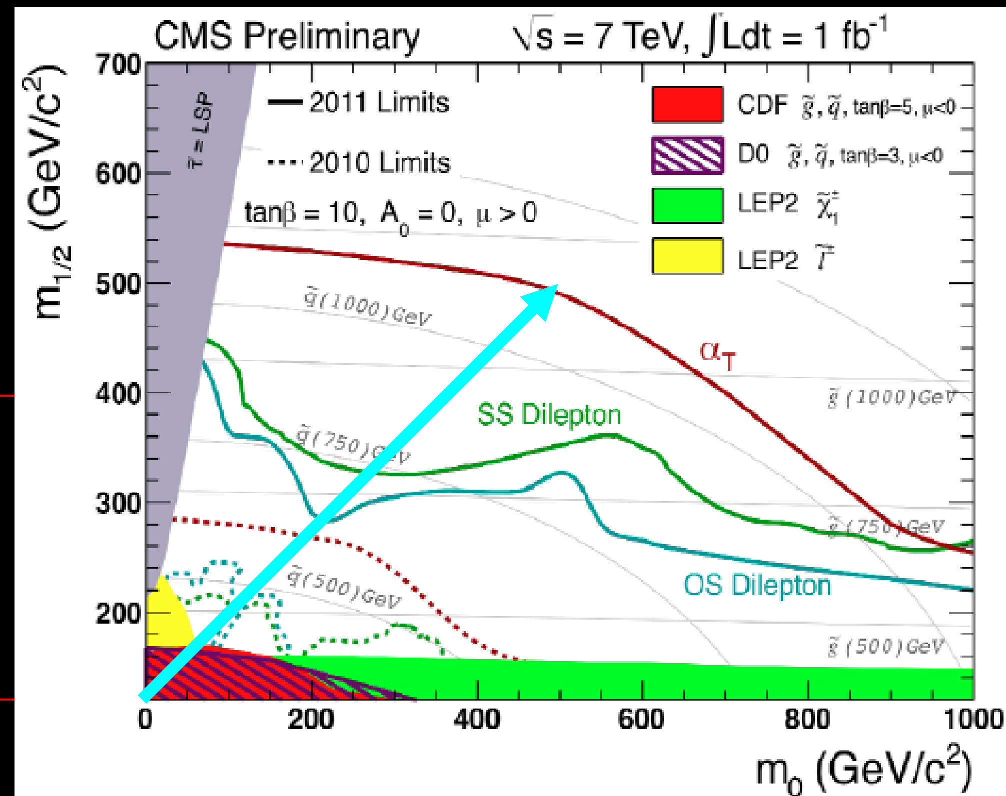
We need to put these limits in perspective – plotting on the same scale shows the power of LHC for high mass searches.



Tevatron



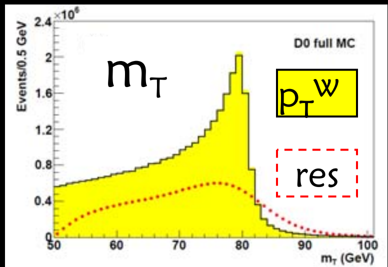
LHC 36 pb^{-1}

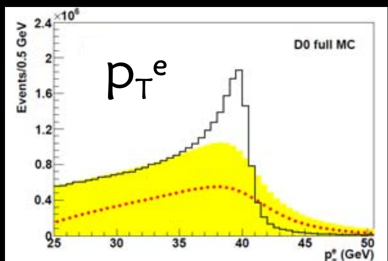


LHC 1000 pb^{-1}

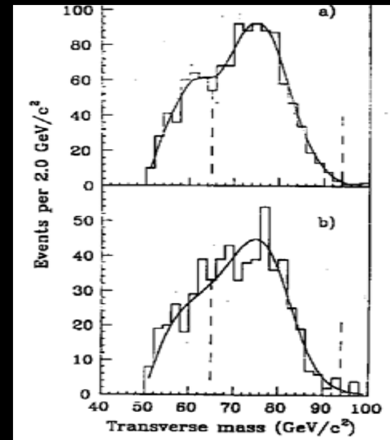
Electroweak

W mass





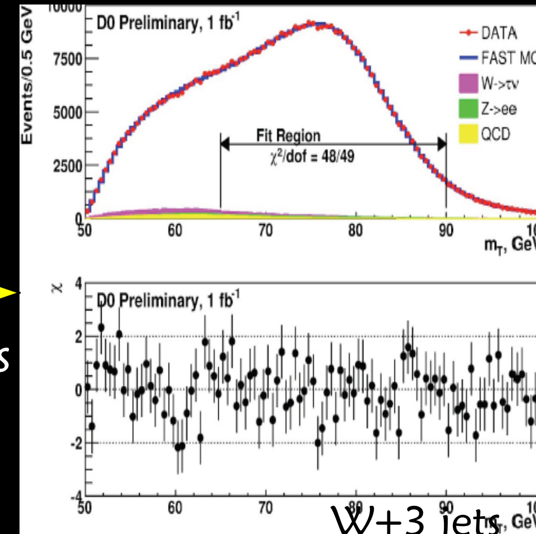
Transverse mass and p_T^e: different sensitivity to p_T^W and resolution



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%)

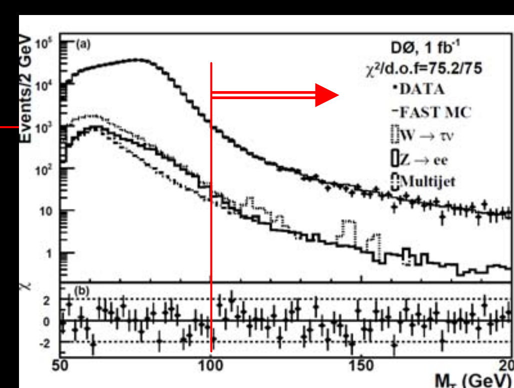
With 10 fb^{-1}, aim for δm_W=15 MeV. Current 1 fb^{-1} per expt uncertainties are:

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

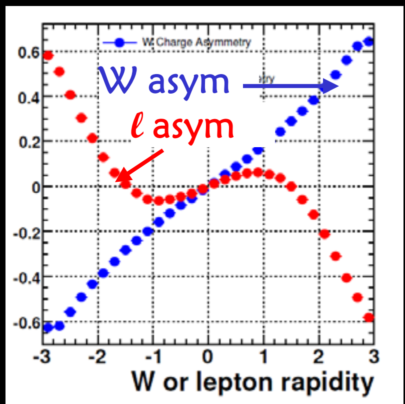
The W decay width measured from high m_T Breit Wigner tail. Γ_W measurement (± 3.5%) agrees with SM.



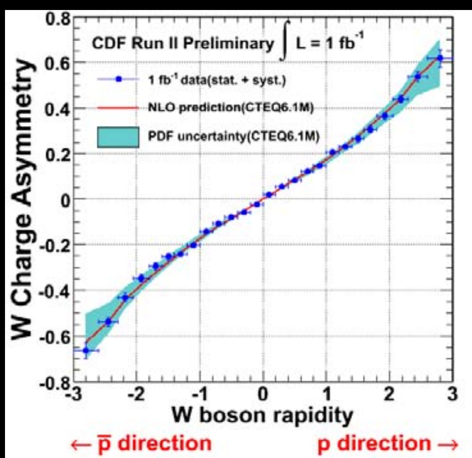
Electroweak

W production

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

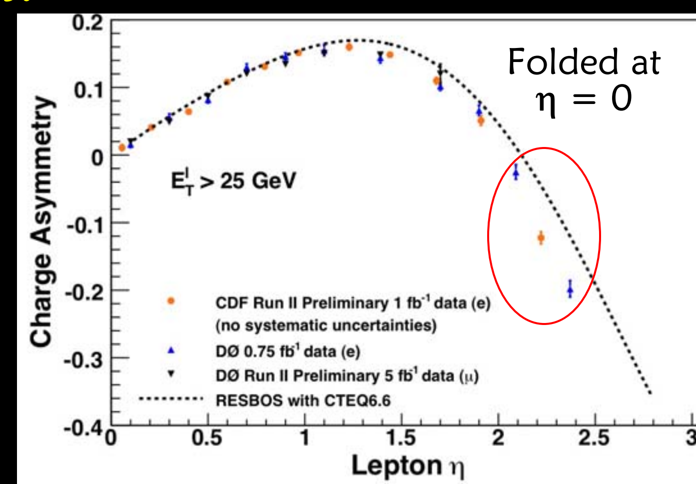


Owing to the initial $p\bar{p}$ state, the W^+ and W^- are produced mostly in opposite hemispheres. The V–A decay gives a decay lepton asymmetry of opposite sign to the W asymmetry.



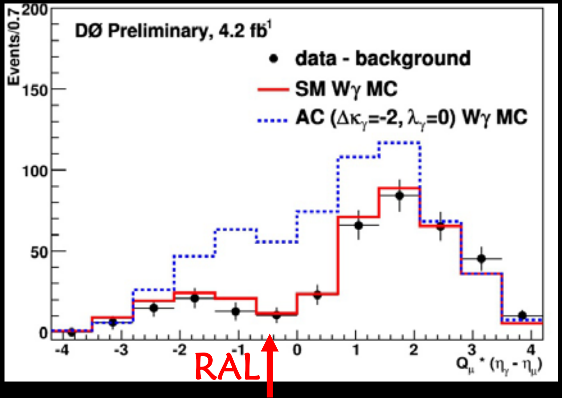
The asymmetry constrains the PDFs for u and d quarks – needed to model the W mass measurements. CDF has performed the difficult unfolding to get the W asymmetry which agrees with current PDFs.

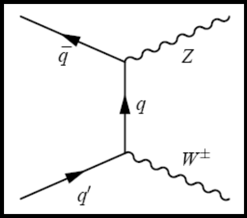
Both experiments measure the lepton asymmetry. Though they agree with each other, they did not agree with the PDF predictions at large η.

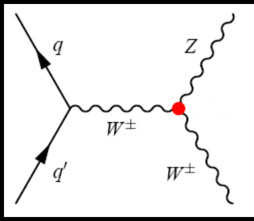


Electroweak

Diboson production



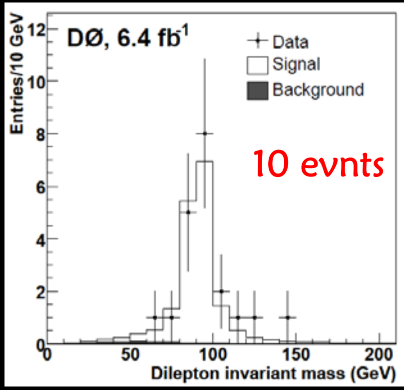




Largest diboson cross section for Wγ production (WWγ coupling)

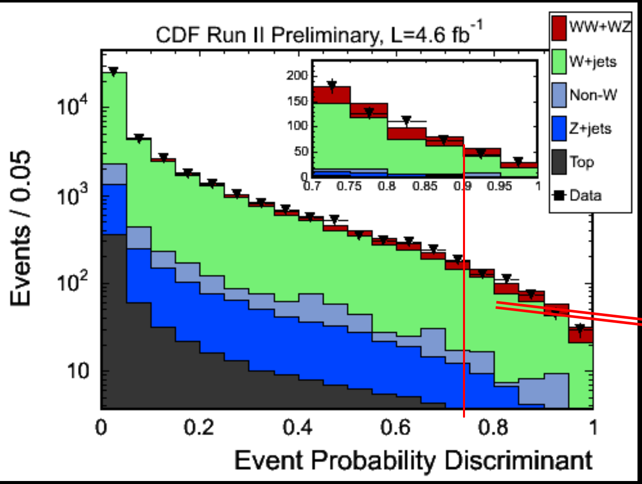
Observe SM radiation amplitude zero in (interference of s & t channel diagrams).

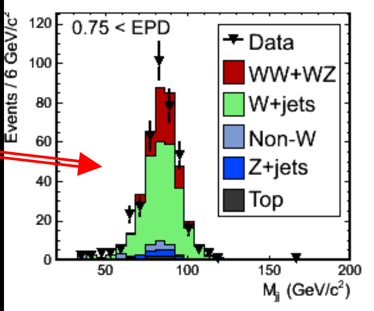
Smallest diboson XS for ZZ production also now observed (both 4ℓ and $\ell\ell\nu\nu$).



Anomalous coupling limits now better than LEP; XS's agree with SM. LHC is overtaking Tevatron owing to higher √s.

Now observing WW/WZ in the challenging $\ell\nu jj$ final state.





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)

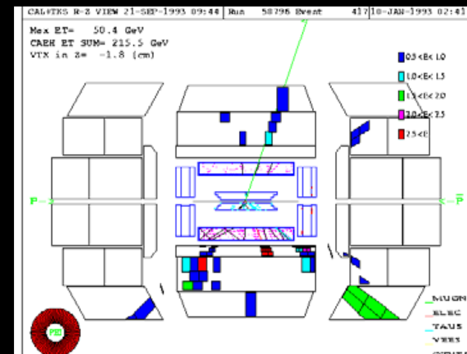
1990: CDF sets limit $m_t > 91$ GeV ruling out W decay to top

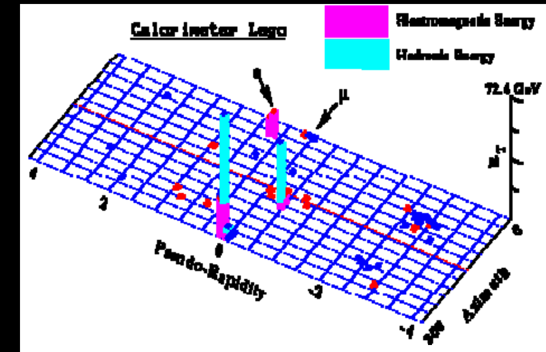
'90's: LEP/SLC: $m_t \sim 150\text{-}200$ GeV

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~2σ





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 J. 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

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

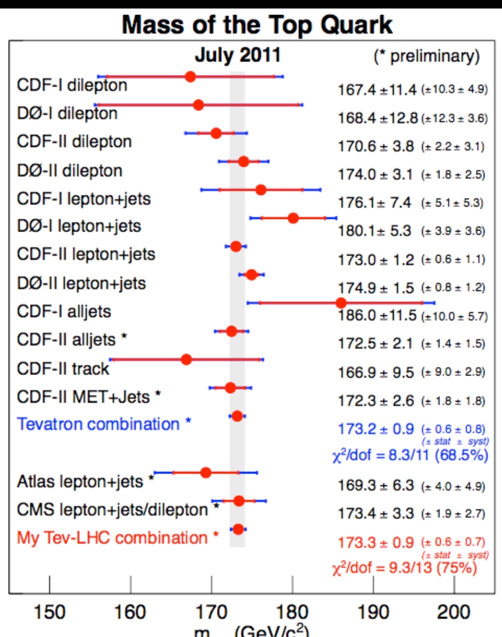
In an editorial, Bjorken wrote of the race to discovery and the need for 2 collaborations, He commented on the oft-corrosive relations between groups making simultaneous discoveries and wrote: "… the ensuing CDF/DØ competition has been a class act."

(Again confirming the need for more than one experiment)

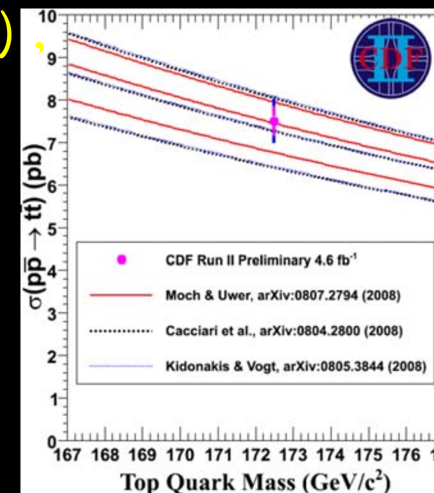
Top quark

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.



$\sigma(t\bar{t}) = 7.50 \pm 0.48$ pb (6%) (CDF 4.6 fb^{-1}) 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.

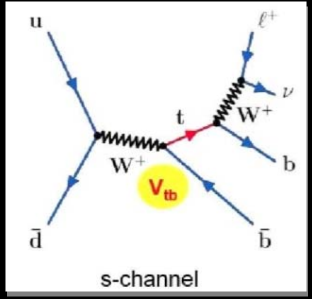
m_t (WA) = 172.9 ± 0.9 GeV (0.5%)

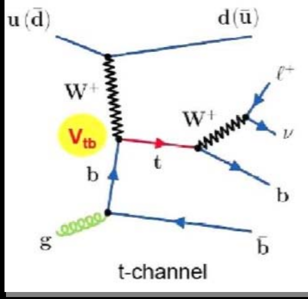
Recent DØ measurement of mass from comparison of expt/theory XS suggests that the measured mass is closer to being the pole mass than the $\overline{MS}$ mass.

Further improvements will be modest (limiting systematic is knowledge of jet energy scale). The LHC is making rapid progress on the mass.

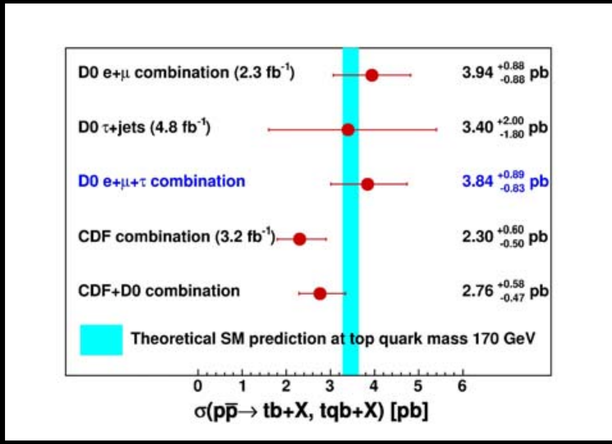
Top quark

Single top EW production

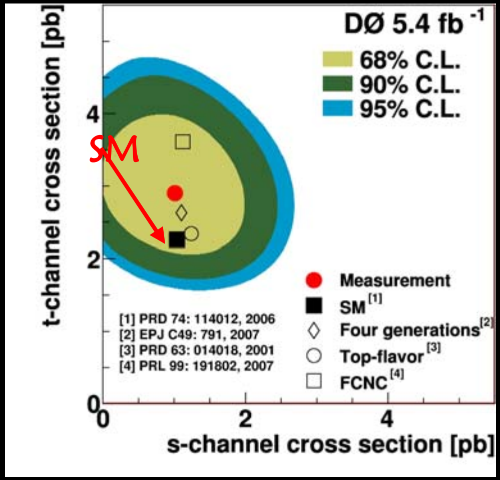




Top quarks are pair-produced by the strong interaction (preserving flavor symmetry). Single top quarks can be produced by EW interaction via s-channel or t-channel W exchange). SM predicts $\sigma \approx 3.2$ pb. DØ and CDF made first observation in 2009.



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.

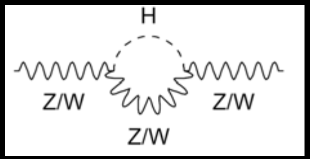
Can also measure the tbW coupling directly: $|V_{tb}|=0.95\pm0.02$ (SM =1)

Top quark

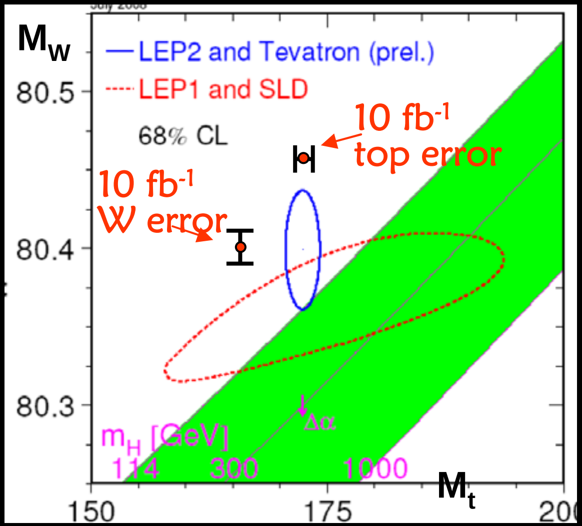
With samples of 1000's of $t\bar{t}$, many properties of the top have been studied, and limits on New Physics set. (See talk of Kirsten Tollefson)

- Top and antitop masses are consistent (CPT test)
- Top quark lifetime as in SM (0.3 yoctosec) (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 ($M_{t'}$ > 358 GeV)
- No $t\bar{t}$ resonances seen below ~800 GeV (some DØ excess ~950 GeV ?)
- SM angular & p_T distributions
- Prefer 'W' in t decay to be color singlet

Top and W: messengers to the Higgs and beyond



etc.

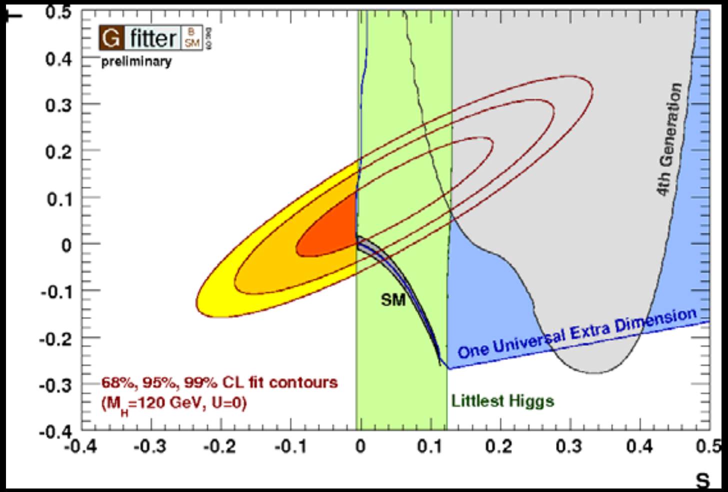


The top and W masses are modified by loop corrections involving the SM Higgs, and thus constrain the Higgs mass.

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 (errors 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 could invalidate the SM, even without further Higgs exclusion.

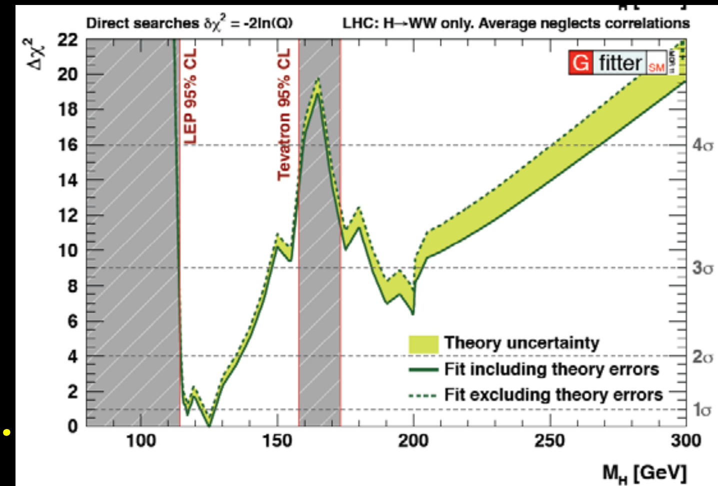
Allowed S-T parameters (vacuum polarization oblique corrections)

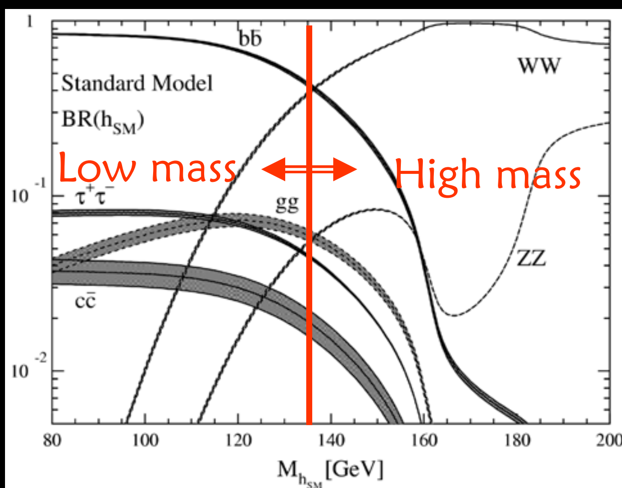


The precision measurements (LEP/SLC Z, Tevatron W,t) also severely constrain potential models of Physics beyond SM.

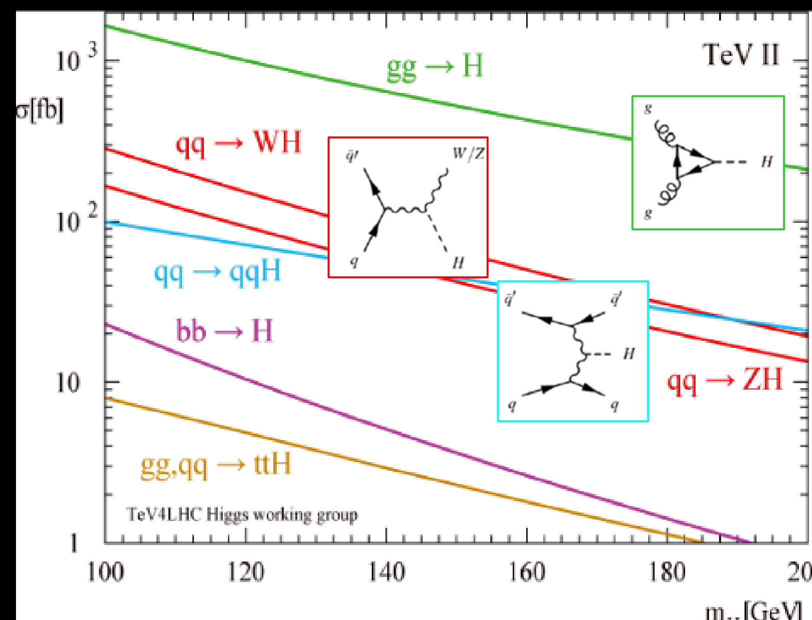
The Higgs Boson

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.





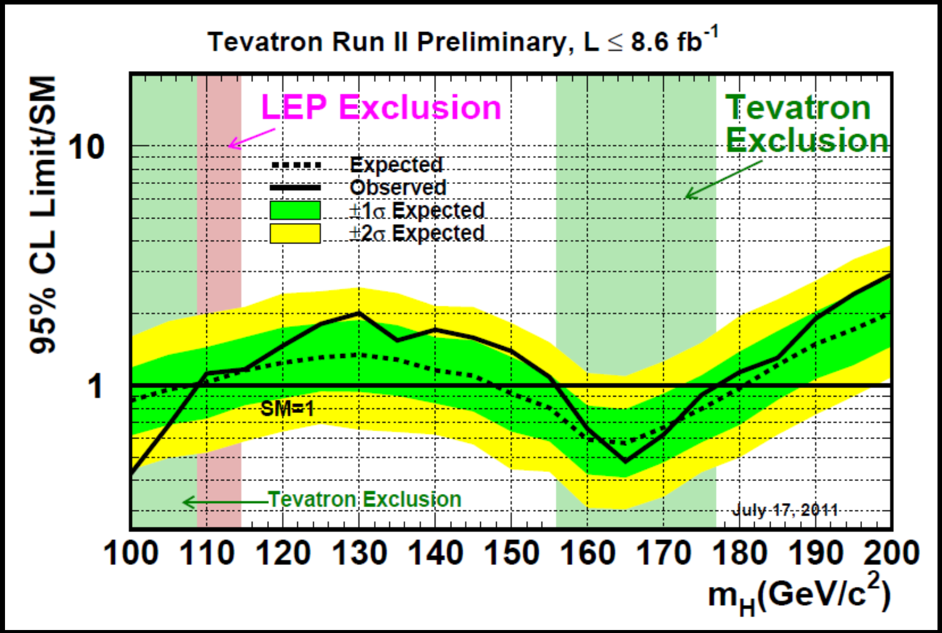
Decays:
$b\bar{b}, \tau\tau$ ($m_H < 135$);
WW, ZZ ($m_H > 135$)



Tevatron searches seek production by gluon gluon fusion, associated VH production and vector boson fusion, and ttH, with many decays (bb, ττ, WW, ZZ, γγ)

The Higgs Boson

Current status (see talk of Aurelio Juste)

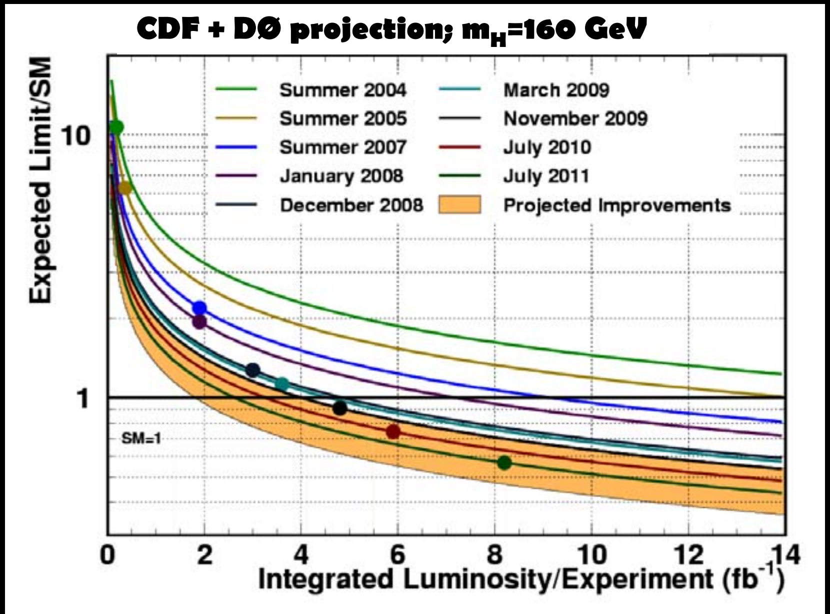


Summer 2011: Analyses with up to 8.6 fb^{-1} of data. Combination of CDF & DØ exclude (at 95% C.L.)

$156 < m_H < 177$ GeV and

$100 < m_H < 108$ GeV,

approaching the LEP exclusion limit, (<114.4 GeV)



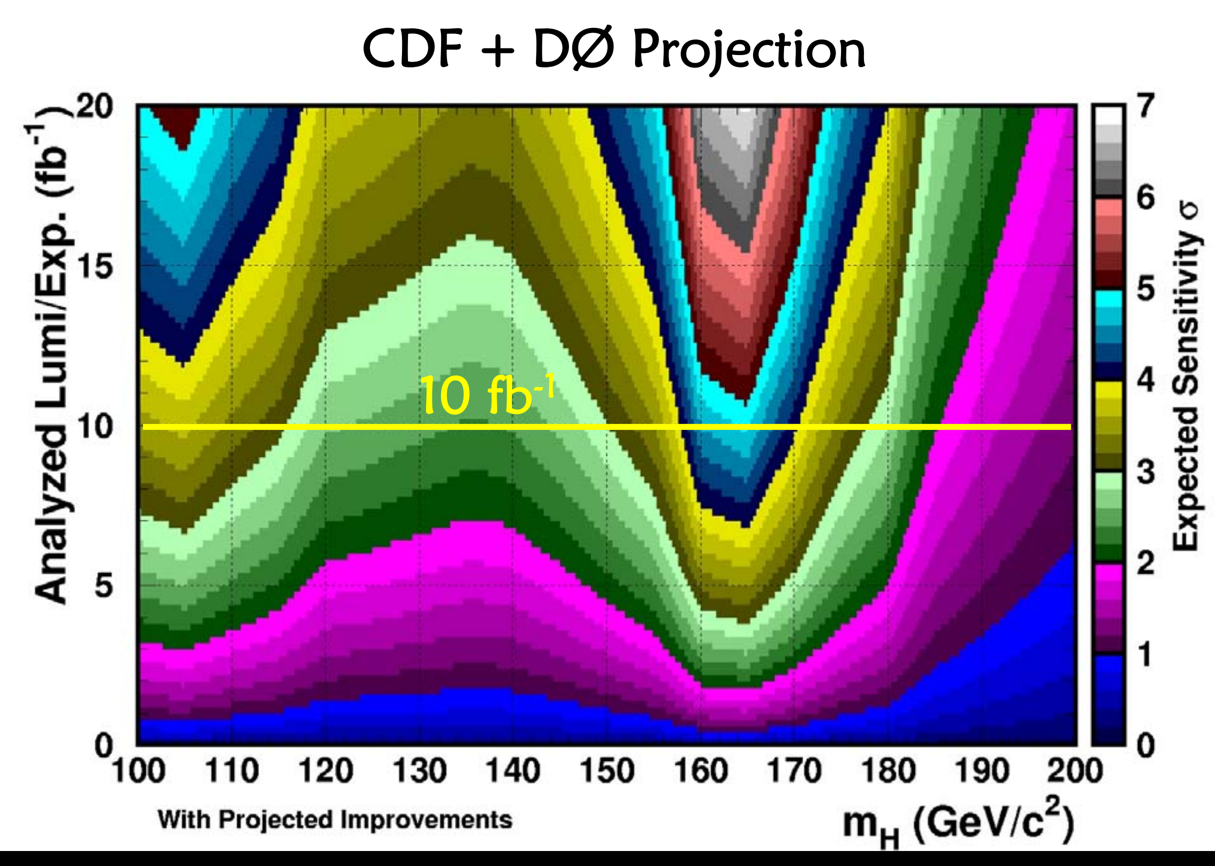
Over time, limits have improved faster than $\mathcal{L}^{-1/2}$, due to addition of new channels, improved b-tagging, lepton efficiency, jet mass resolutions, etc.

The Higgs Boson

Projection

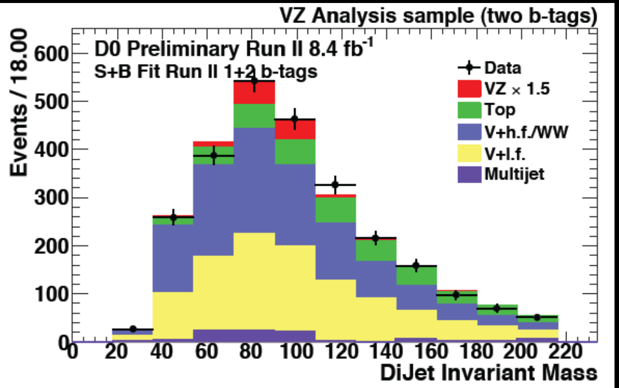
Plot is projection for both experiments, with some improvements, many of which are accomplished.

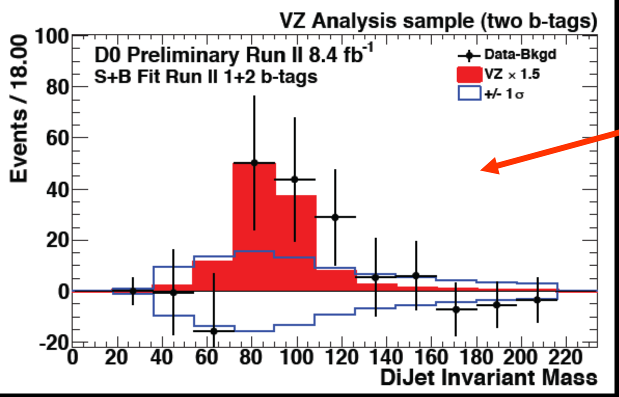
- 95% C.L. exclusion if no SM Higgs to ~185 GeV.
- 3σ evidence up to ~120 GeV (where LHC has most trouble), and in the region 150 – 175 GeV.
- If see evidence in favored low mass region, Tevatron provides measurement of dominant coupling to $b\bar{b}$ to complement LHC.



Higgs boson

We need a sanity check – analyses are complex!

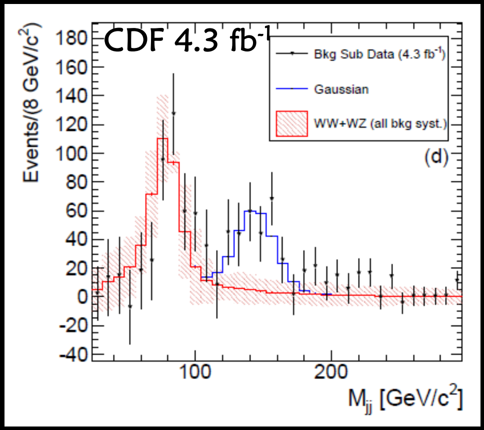




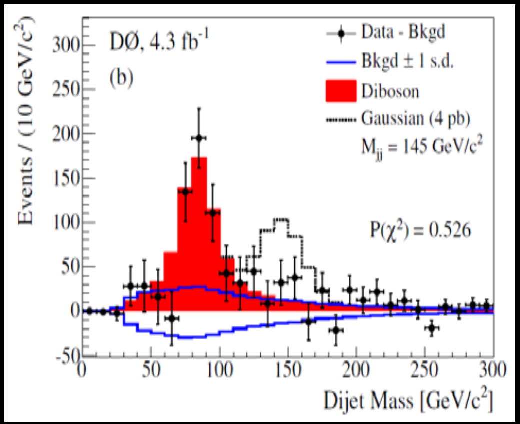
Search for the diboson production processes, seen previously in all lepton final states, now with one boson decaying to jets (e.g. $\ell\nu$ +2 jets) using the Higgs multivariate and limit setting machinery. Measured cross sections agree with SM.

A recent example: use the ννbb Higgs, including the b-tagging and identical multivariate chains, to obtain $\sigma(VZ) = 6.9\pm2.2$ pb in good agreement with $\sigma_{SM} = 4.6$ pb.

We have also seen that these sanity checks of measuring WW/WZ cross sections could even bring surprises! But again demonstrate the necessity of having more than one exp't.



3.2σ excess; "~4pb" (EPS2011: added data: 3.0±0.7pb)



95% upper limit 1.9 pb (for 3pb, p-value=5×10^{-4})

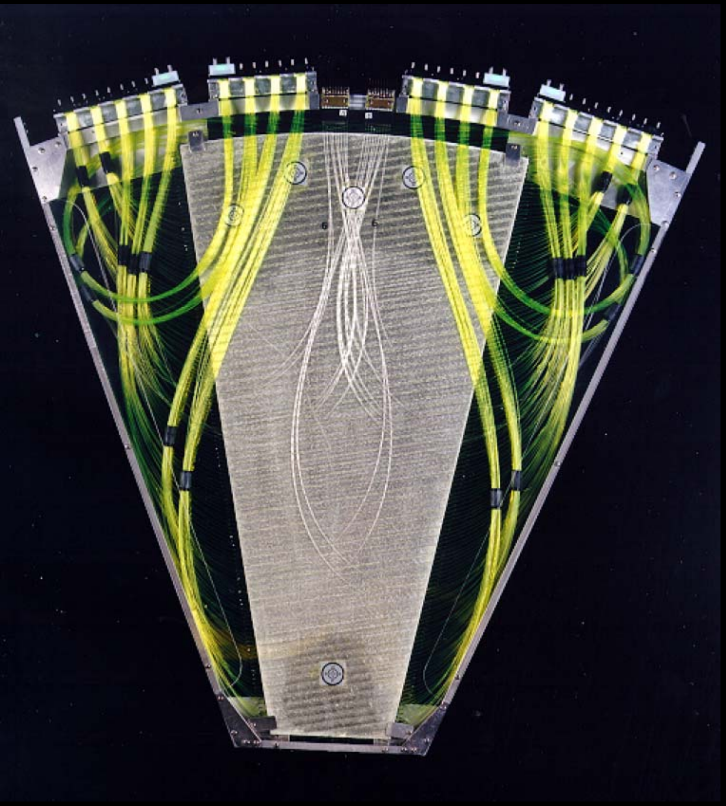
Innovations at the Tevatron

Without the Tevatron's superb operation, the physics I have described would not have been possible.

- CDF pioneered the first 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 are 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

People make the difference

The collaborations are large (~500 people) and it is tempting to view them as monolithic entities.

Seen from the inside, individual contributions are at the heart of building the detectors, developing the software and doing the physics – typically in groups of 2 to 4. Every great achievement bears the footprints of a few inventive and dedicated people.

Over time, the loyalty to the collaboration comes to rival that to the institutes that pay us.

The Tevatron Legacy

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

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 ($\not{C}\!P$ in b hadrons, $t\bar{t}$ F-B asymmetry …)

We eagerly await the next steps on the journey by the LHC …