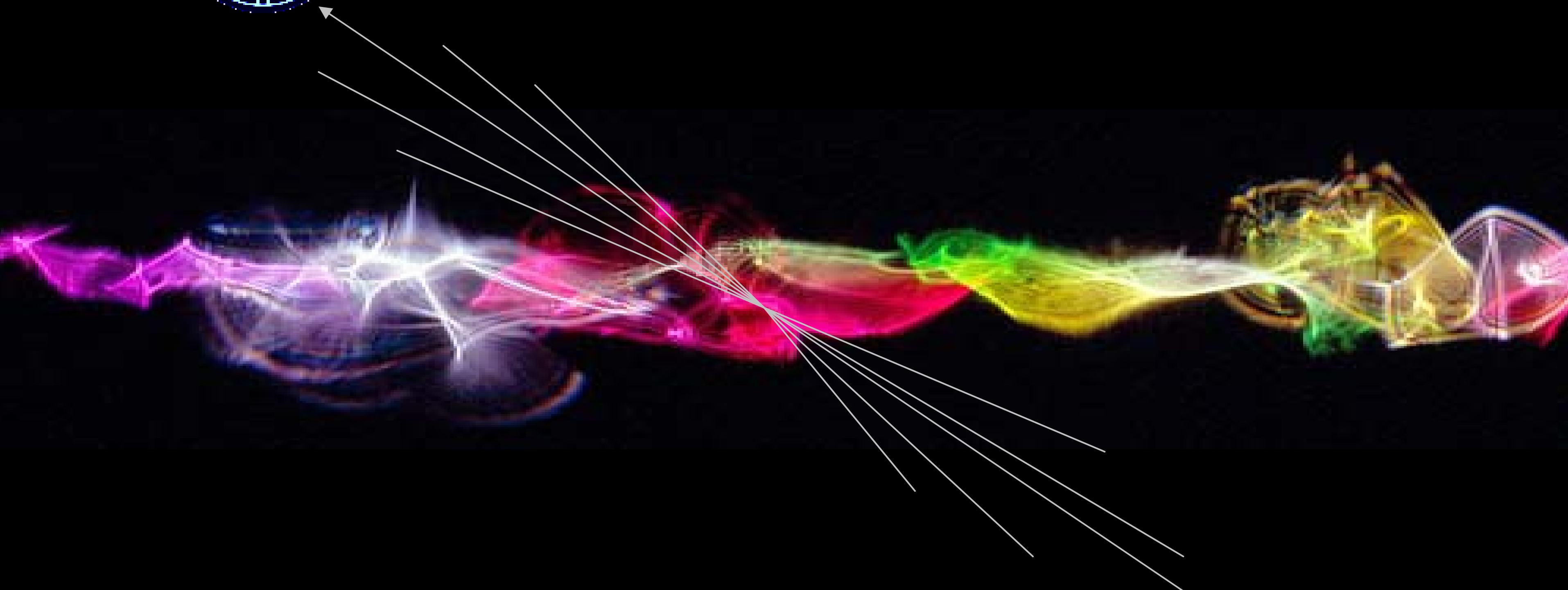
# The Tevatron Legacy



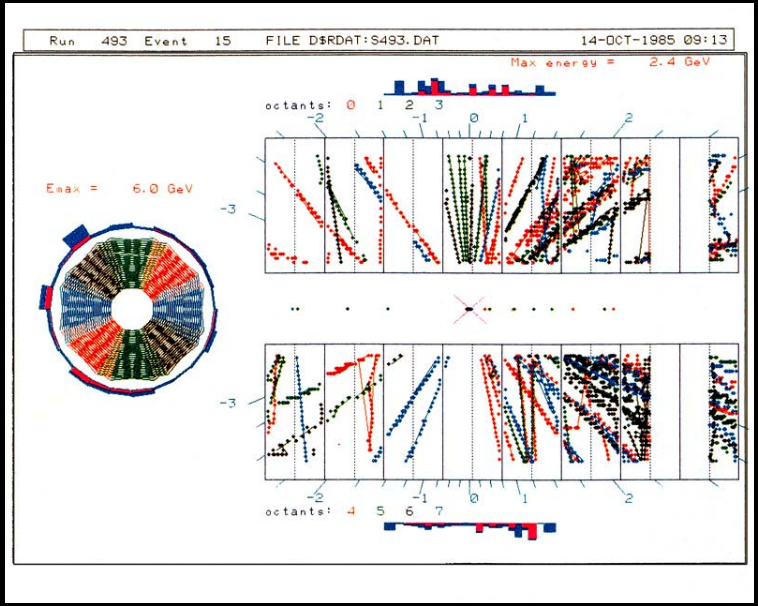
*Minute Particulars and Hidden Symmetries*

Chris Quigg Symposium

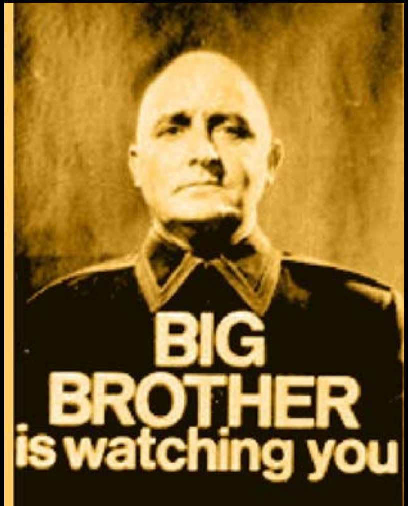
P. Grannis, Dec. 14, 2009

# Start of the Tevatron Era

25years ago, in winter 1984-5, the Tevatron Collider  was being commissioned and dedicated.



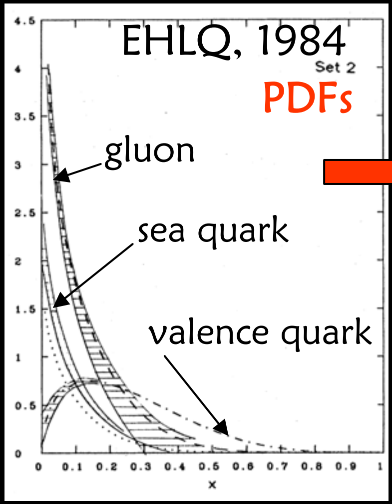

In October 1985, first collisions were recorded in the (partially complete) CDF detector.

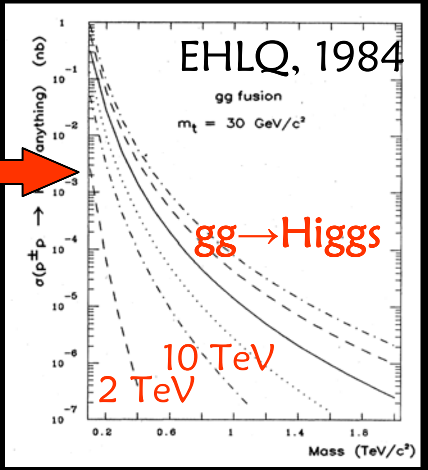



In Nov. 1984, the Temple (Lehman) DOE review of DØ approved the start of construction and detector technical design.

# Defining the Program

In 1984, Eichten, Hinchliffe, Lane & Quigg provided parton distributions from available lepton-proton scattering data to calculate a broad range of hadron collider measurements (jet production, dibosons, Higgs, heavy quarks, and technicolor, Susy, compositeness). RMP 56, 579 (1984.




EHLQ assumed 30 GeV top quark(!); SM Higgs masses up to 1.7 TeV; and colliders √s = 2–100 TeV.

"The most important [conclusion] is that a high-luminosity multi-TeV collider* will meet the objective of exploring the TeV energy scale and illuminating the nature of electroweak symmetry breaking." [* a.k.a. SSC]

For 25 years, the Tevatron has been the only machine at the frontier; nevertheless we have learned much.

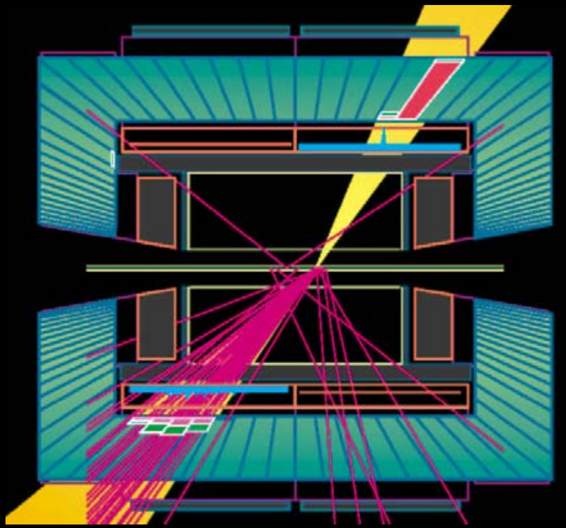
# Tevatron and Detectors

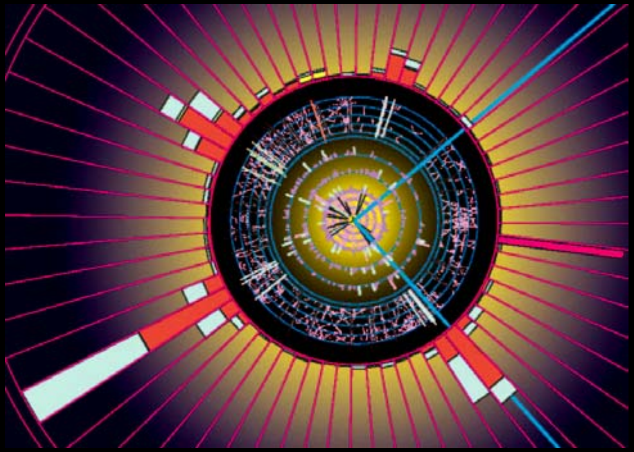
First Tevatron collisions in 1985; CDF Run 0 in 1987. DØ first collisions in 1992. Run 1 (1992 – 1996, 1.8 TeV, 120 $pb^{-1}$) and Run 2 (2001 – 2011?, 1.96 TeV, ~12 $fb^{-1}$). Also, elastic scattering measurements at EØ; studies of processes at large rapidities at CØ.

Tevatron: New antiproton debuncher and accumulator, and for Run 2, Main Injector and recycler rings.

["Tevatron luminosity will not exceed $3\text{x}10^{30}$ $cm^{-2}s^{-1}$" – J. Peoples, then pbar project leader]

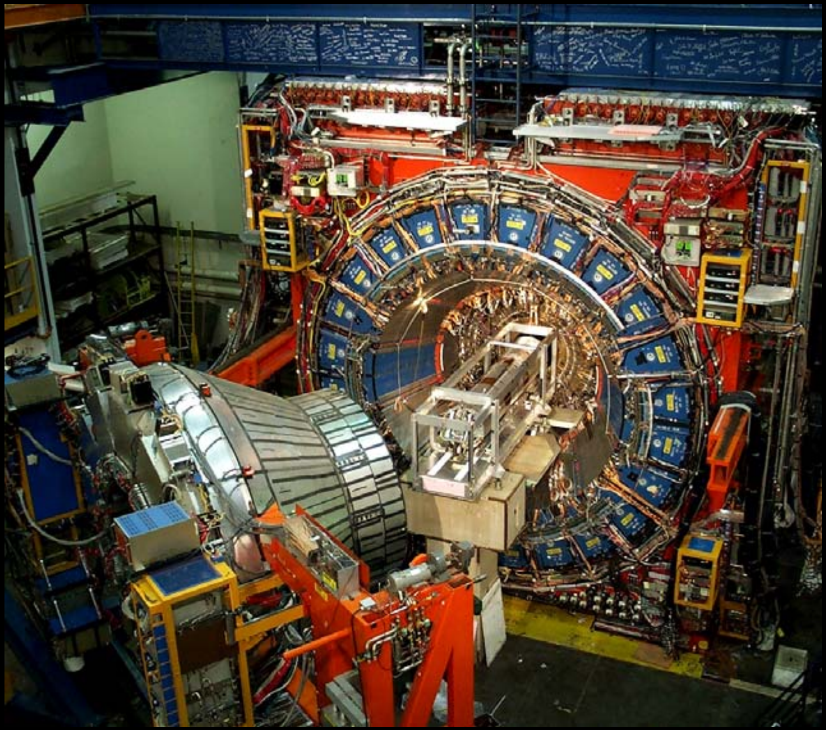
Now running at $3\text{x}10^{32}$ $cm^{-2}s^{-1}$ almost routinely !





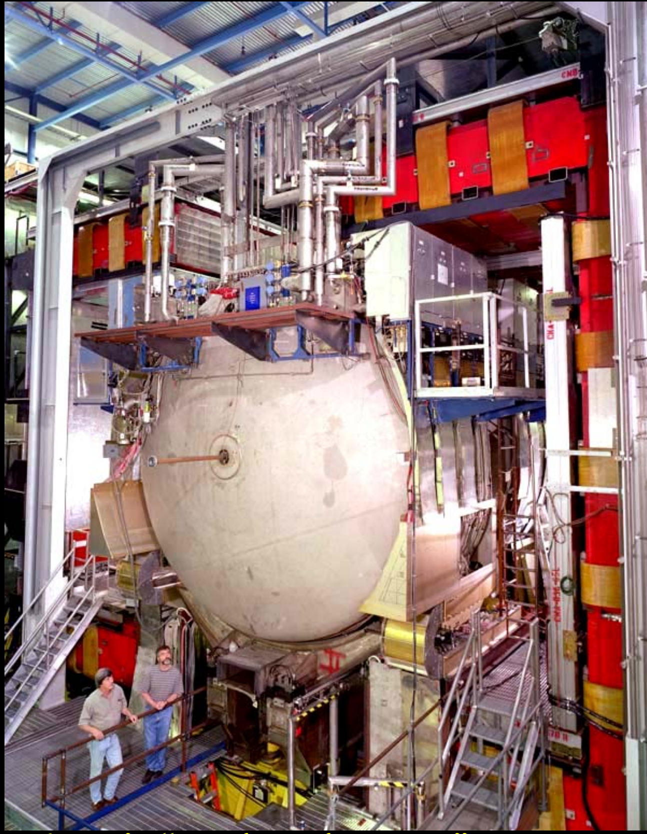
Thanks LQ

# Tevatron and Detectors



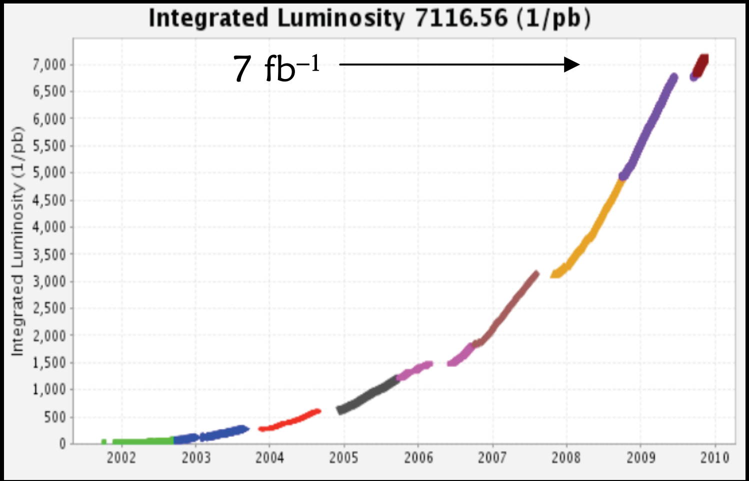
CDF

DØ



Leon's "nook and cranny" experiment to run ~1 – 2 years

The Tevatron has now delivered >7 fb$^{-1}$ of luminosity. Expect ~12 fb$^{-1}$ at end of FY11. About 80% of data delivered goes into physics analyses. Further running will depend on LHC startup and hints of new physics (and $$).

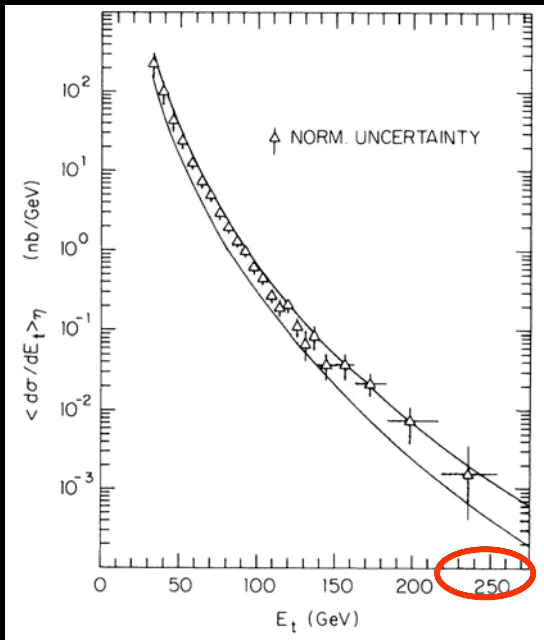


# The Tevatron Legacy

There are ≈600 physics publications from CDF and DØ. In the next 20 slides, I will touch on only some highlights – those that seem to have lasting historical value, or those that simply pleased me.

- Studies of QCD
- Heavy flavor physics
- Electroweak results
- Top quark
- Higgs boson searches
- New phenomena searches

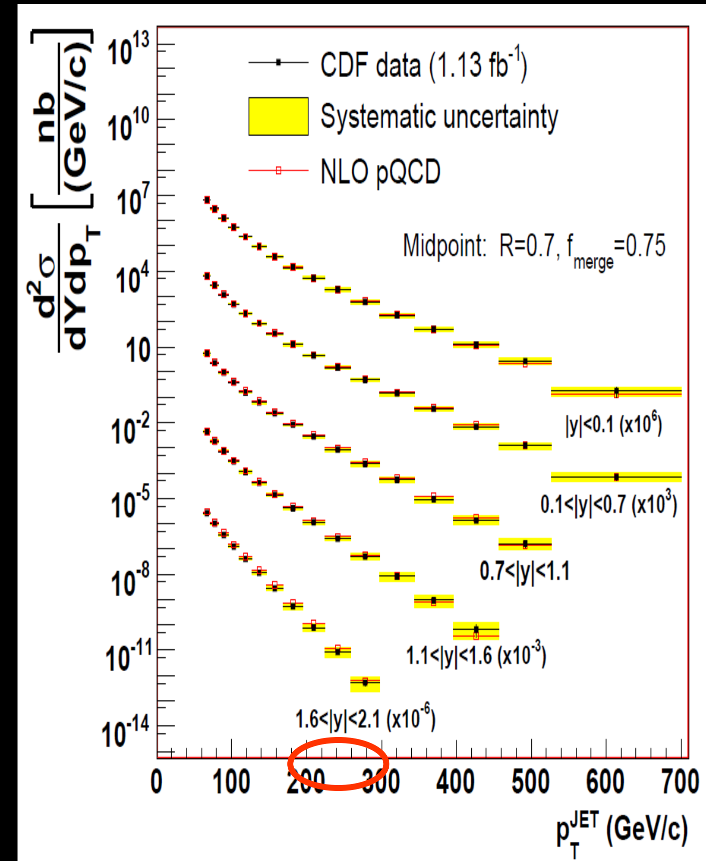
# QCD Inclusive jet production




CDF PRL 62, 612 (1989)

6.9 $nb^{-1}$ → 1,130,000 $nb^{-1}$

$p_T$ range extended from 250 GeV to 700 GeV and displayed as function of rapidity. Systematic errors are reduced by careful determination of jet energy scale.




CDF Phys. Rev. D78, 052006 (2009)

Q=700 GeV → probing proton to 0.3 am (attometer) scale

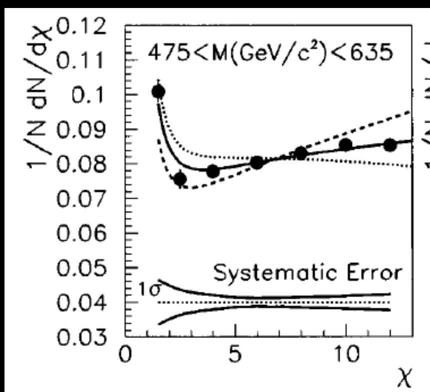
Good agreement with NLO QCD out to 60% of √s. The data constrain PDFs and are forcing reduced gluon content at high x.

Perturbative QCD is extremely well validated by Tevatron data.

# Jet angular distributions

**Define:** $\chi = \exp(|y_1 - y_2|) \approx (1+\cos\theta)/(1-\cos\theta)$ ($\theta$ in di-jet rest frame)

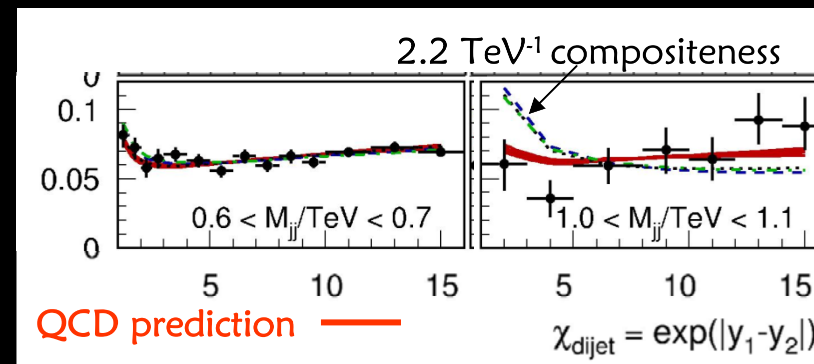
Rutherford $d\sigma/d\cos\theta \sim 1/\sin^4(\theta/2)$, transformed to $d\sigma/d\chi$ = constant. QCD gives some variation due to running $\alpha_S$. New physics (quark compositenesss, extra spatial dimensions) would cause significant modifications.




DØ PRL 80, 666 (1998)

94 $pb^{-1}$ → 700 $pb^{-1}$

Expand dijet mass range from 600 to ~1200 GeV; errors substantially reduced.




DØ (2009)

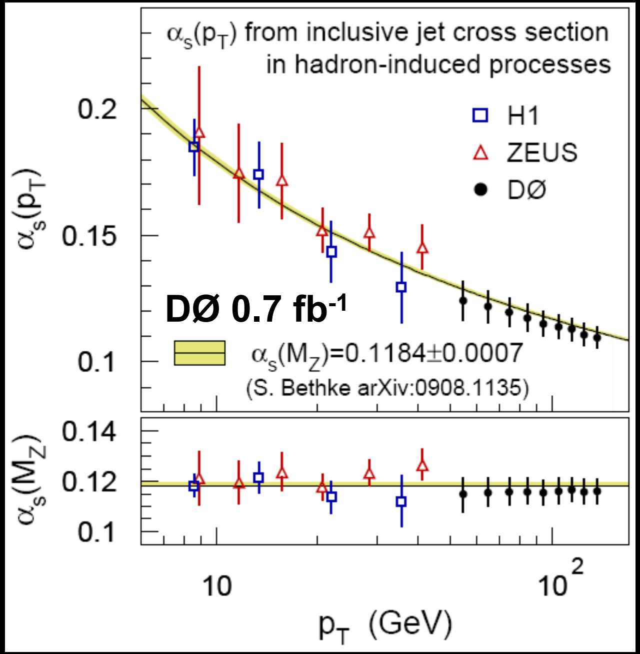
Angular distribution agrees with NLO QCD to ≈ 1 TeV scale. These data provide the best limits on quark compositeness (scale ~2.9 TeV) and $TeV^{-1}$ scale or large ADD extra dimensions (~1.6 TeV).

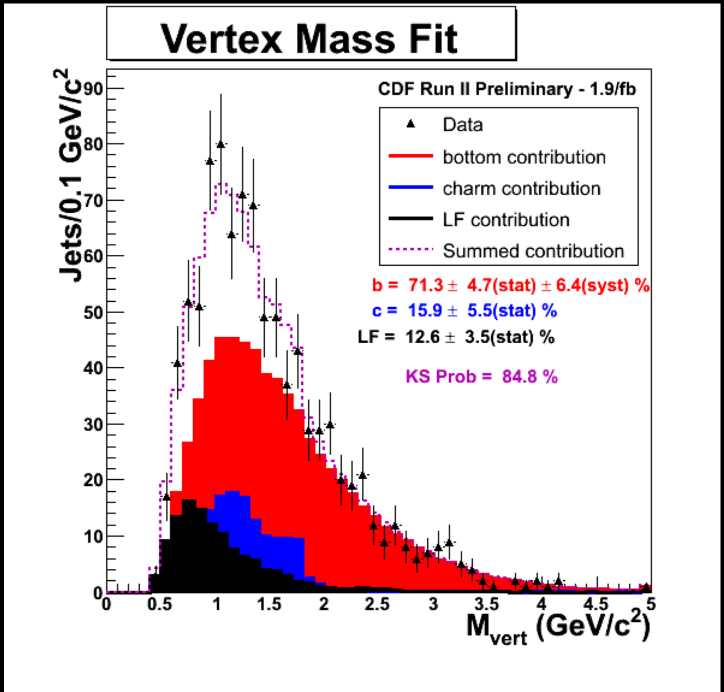
# $\alpha_s(Q^2)$ and W/Z+jets

Tevatron has extended the measurements of **running $\alpha_s$ at high $Q^2$**, beyond the HERA reach.

Good agreement with NLO QCD; $\alpha_s(M_Z)=0.1173\pm0.0045$ (DØ)

(Hadron colliders can do precision physics!)




CDF fit to W+b, W+c and W+q contributions.

W/Z+jets (light and heavy quarks) are important QCD processes and major backgrounds for Higgs, top, new phenomena. They are not currently well modelled. CDF W+b cross section is larger than current theory. Measuring these cross sections will guide theory and event generators, and provide guidance for LHC studies.

# b(c)-quark 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 2) have made a host of heavy flavor measurements including, in particular, exploration of the mesons and baryons containing b quarks and other heavy quarks:

First observation of:

$B_s$ ($J/\psi\ \phi$), $B_c$, X(3872) ($J/\psi\ \pi^+\pi$), $\Sigma_b$, $\Xi_b$, $\Omega_b$

$B_s$ mixing

Evidence for $D\bar{D}$ 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

Best limits on rare B decays

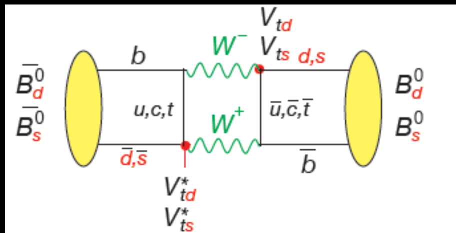
Diffractive $J/\psi$ production

Observation of charmless $B_s$ decays

# $B_s$ mixing

The quark weak eigenstates are rotated from flavor eigenstates: (Cabibbo Kobayashi Maskawa matrix)

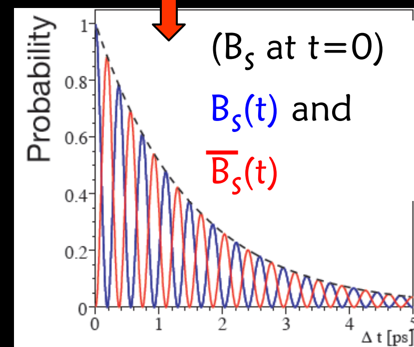
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$




The $B_s^0$ meson evolves (mixes) to $\bar{B}_s^0$ meson through a 2nd order weak process with time dependence dictated by the mass and width matrices.

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

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

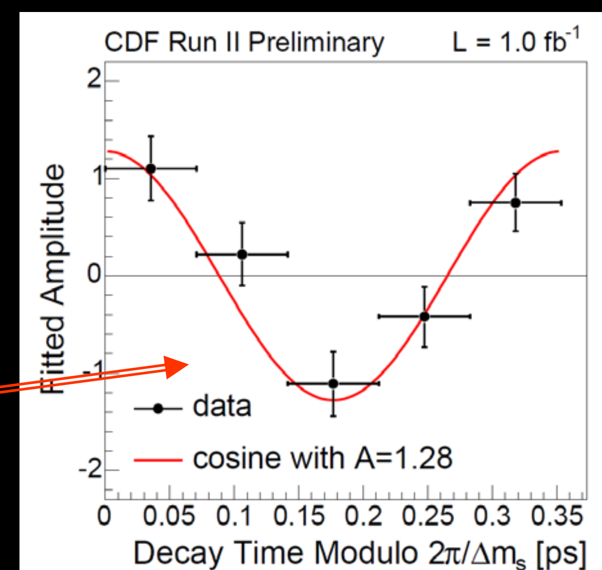



Large Δm means $B_s$ mixing is very rapid ($T_{osc}$~0.3ps), so a large experimental challenge.

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 in 2006 for the first time.

Many oscillation periods folded into one.

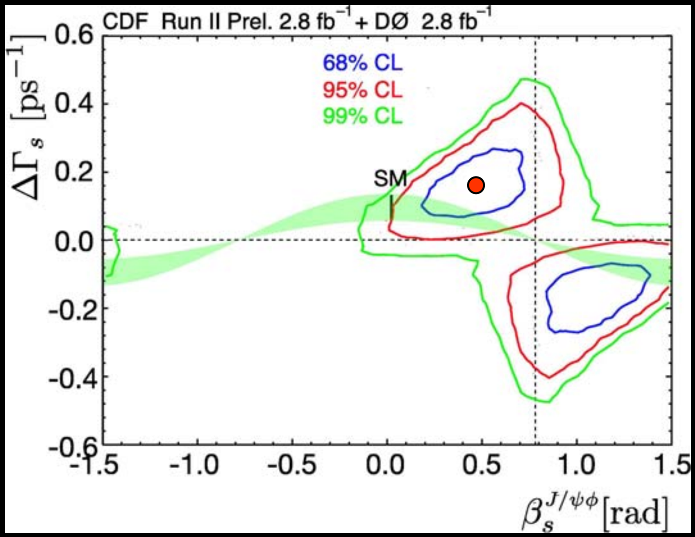


# CP violation in $B_s$ system

In the SM, CP violation is due to a phase in the CKM matrix that relates quark flavor eigenstates to weak eigenstates. This phase is consistent for the CP violation seen in the $K^0$ and $B_d^0$ systems. DØ and CDF studies have been done in the $B_s^0$ ($\bar{b}s$) and $\overline{B_s}^0$ 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 $\beta_S$ is very small based on other measurements)

$\beta_S$ is analog of $B_d$ unitarity triangle angle $\beta$ ,but for $2^{nd}/3^{rd}$ row of CKM matrix

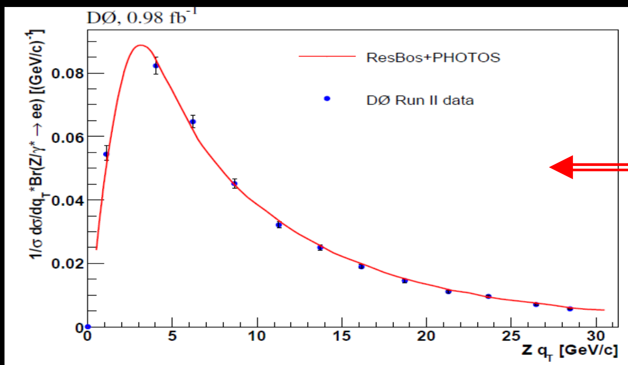



Both CDF and DØ observe $\Delta\Gamma$ consistent with SM, but with angle $\beta_S$ to be large (~0.5 rad), disagreeing with SM ($\beta_S^{SM} = 0.002$) by $2.1\sigma$.

More data will help determine if this is a breakdown of the SM. Further measurements of $B_S \rightarrow J/\psi\ \phi$, $B_S \rightarrow D_S\ \mu^{\pm}\ X$ charge asymmetry and time dependence; dimuon charge asymmetry ($\mu^+\mu^+$ vs. $\mu^-\mu^-$); will all provide further constraints on $\beta_S$.

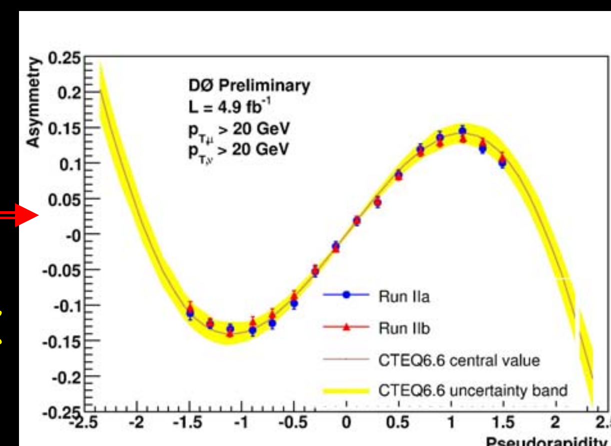
# W and Z bosons

W and Z bosons are copiously produced at Tevatron. In 10 $fb^{-1}$, expect ~10M W's and ~500K Z's. **Production and decay properties** are now well measured:




❖ Production cross sections agree with QCD (and may become the standard candle for measuring luminosity). The $p_T$ dependence for Z measures non-perturbative QCD corrections.

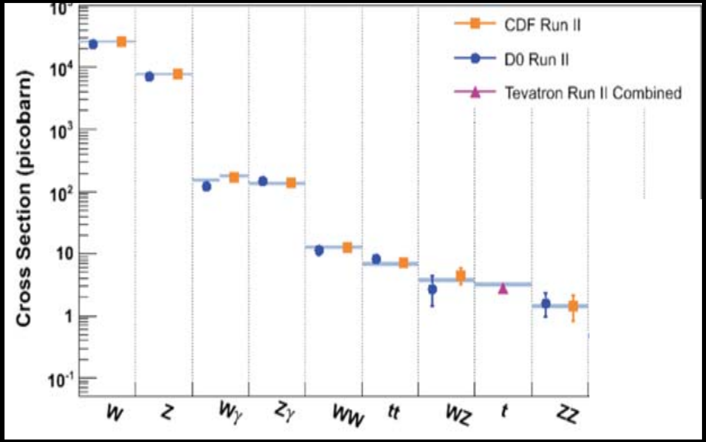
❖ Forward/backward charge asymmetry in W production/decay improves knowledge of proton's up and down quark content (needed as input for all Tevatron/LHC studies). Expt errors now smaller than present theory uncertainty.




Pseudorapidity $\eta = -\ln \tan\theta$ is the natural polar angle variable

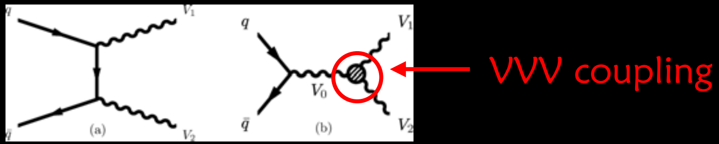
# Diboson Production

**Diboson production** (Wγ, Zγ, WW, WZ, ZZ) processes have low XS. All have been observed at Tevatron, consistent with the SM. These are precursors to Higgs search with even smaller XS.

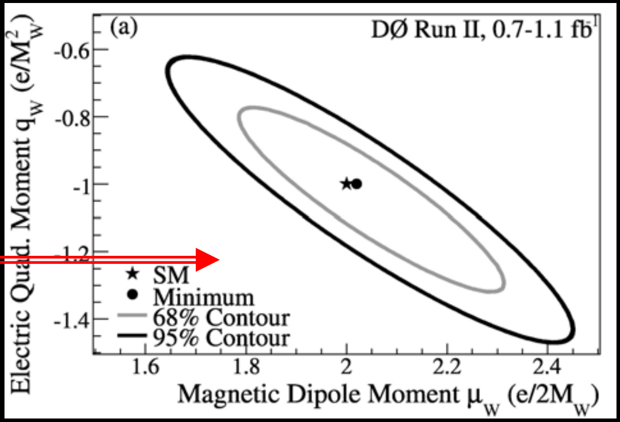


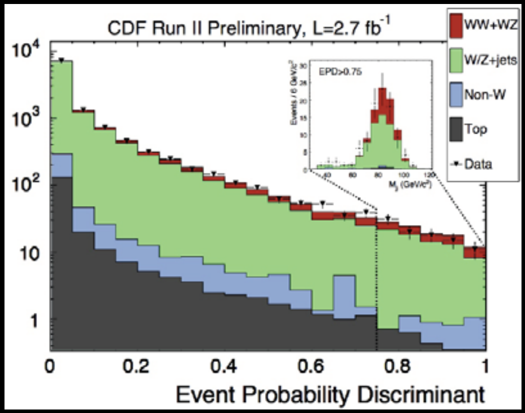

Diboson, tt, t, Higgs XS's

- The rates and angular distributions allow search for non-SM anomalous couplings:




No anomalous couplings are observed. Can translate into anomalous magnetic dipole/electric quadrupole moments of W as predicted in SU(2)xU(1) SM.

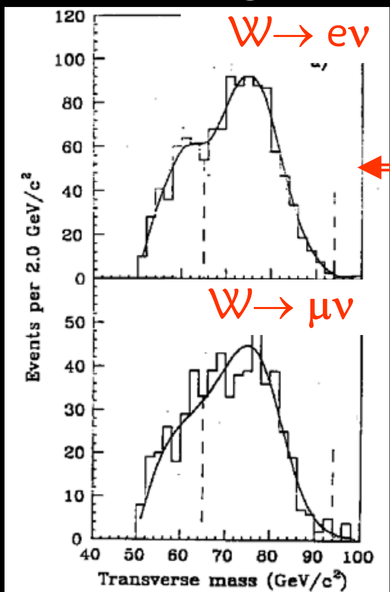



- First observation of WW/WZ production in the challenging jet jet $\ell\nu$ channel. The W/Z mass peak is observed. Allows validation of methods for Higgs search in 'known' processes.

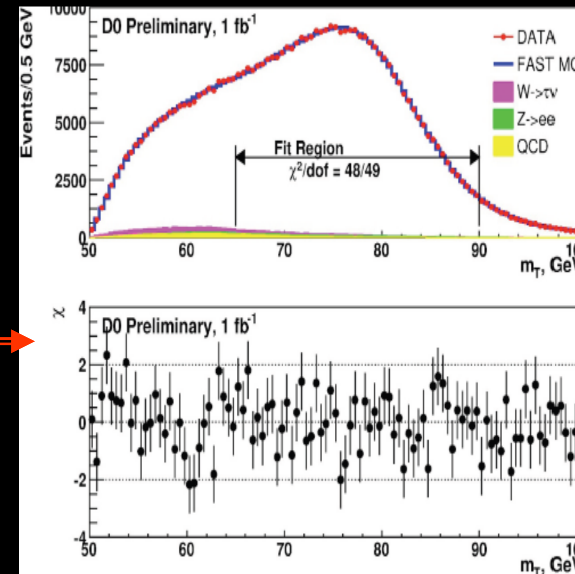
# W boson Mass

W mass is a key parameter in the SM. For $W \rightarrow \ell\nu$ we measure $p_T^\ell$, $p_T^\nu$ (missing energy) or $M_T = \sqrt{[p_T^\ell\, p_T^\nu\, (1-\cos\phi_{\ell\nu})]}$. Compare templates from MC with data to get the best $M_W$. These are exquisitely difficult measurements, requiring control of systematics to $10^{-4}$ level.




1st CDF measurement in 1990 (~1700 events, 4 $pb^{-1}$): $M_W$=79.91±0.39 GeV

2009 DØ measurement (500K events, 1000 $pb^{-1}$) gives $M_W$=80.401±0.043 GeV.

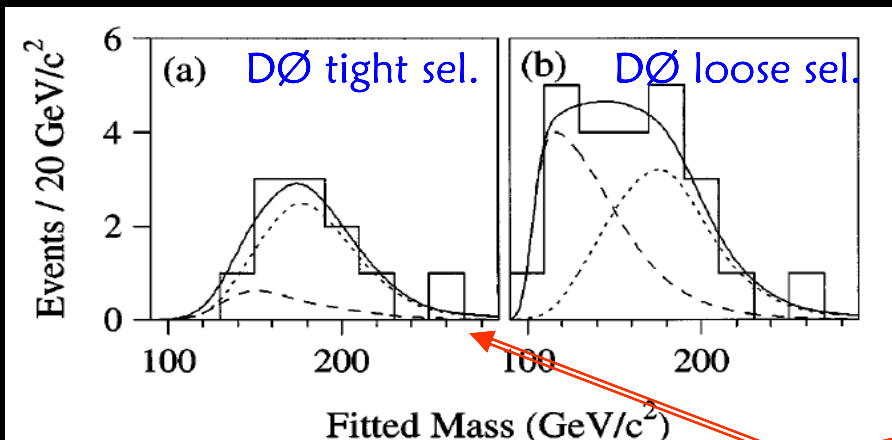


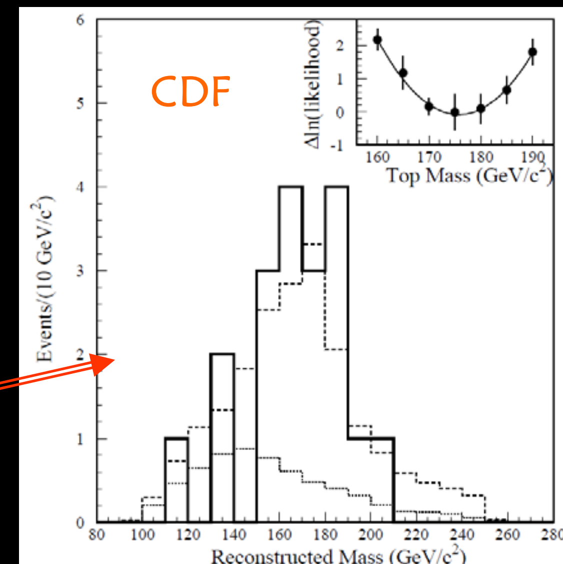

The W mass is a prime constraint on the SM Higgs mass.

Combining all measurements from Tevatron and LEP gives new world average $M_W$=80.399±0.023 GeV (<0.03%). Tevatron is now better than LEP. With 10 $fb^{-1}$, expect $\delta M_W$=12 MeV (Tevatron), 10 MeV (world). It will be a *long* time before LHC matches this – a Tevatron legacy !!

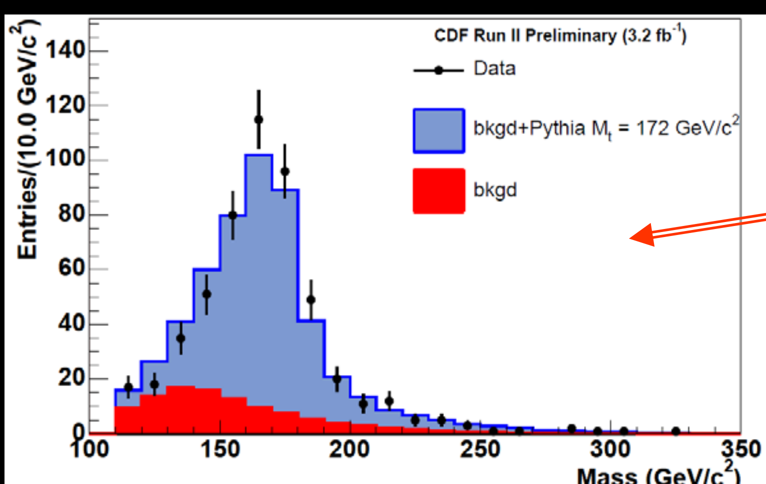
# Top quark

CDF and DØ discovery of top quark in 1995 is perhaps the chief Tevatron legacy. From the original discovery with 0.05 $fb^{-1}$ to current measurements with ~5 $fb^{-1}$, we have come a long way in illuminating the nature of the top.



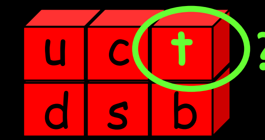




1995 Discovery – handful of events

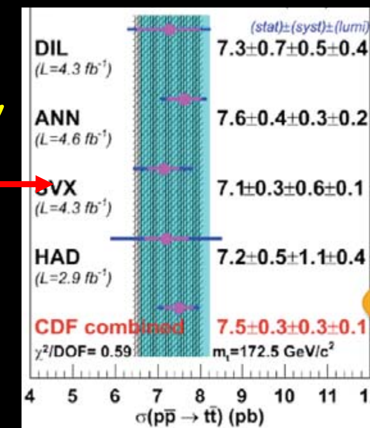



Now hundreds of events with low background.

# Top quark properties




Is the 'top' really the object expected in the SM (the isospin partner to the b-quark)? Note that unlike other quarks, top decays before it hadronizes to ordinary particles, so we can probe its decays directly

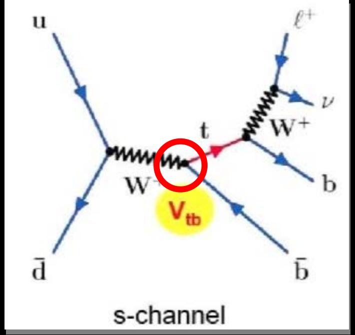


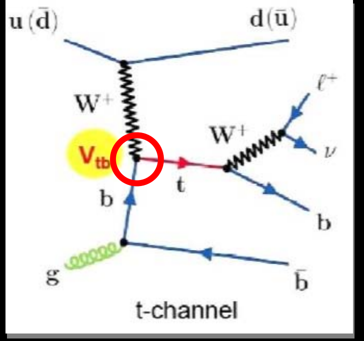

1. $t\bar{t}$ XS (7.5 pb) agrees with QCD NNLO prediction with uncertainty of 6%/expt. Close to systematics limited.
2. Charge Q=4/3e ruled out at 92% C.L. (so t is SM partner to b)
3. top-antitop masses are equal to 3.7% (CPT symmetry confirmed)
4. Decay W boson has L-handed spin projection expected in V-A weak interaction (a hint of discrepency – more data will tell)
5. * Top spin correlations at production are revealed in decay particle momenta; again agrees with QCD prediction but there is a small discrepancy.
6. * See a small preference (2σ) for top to be aligned with $\bar{p}$ beam, not expected in SM
7. No evidence for excited top (but a hint from CDF)
8. No $t\bar{t}$ resonances seen up to mass of 820 GeV. Angle & $p_T$ distributions as in QCD

* Difficult for LHC

It walks like a quark, quacks like a quark, so …

# Single Top Quark Production

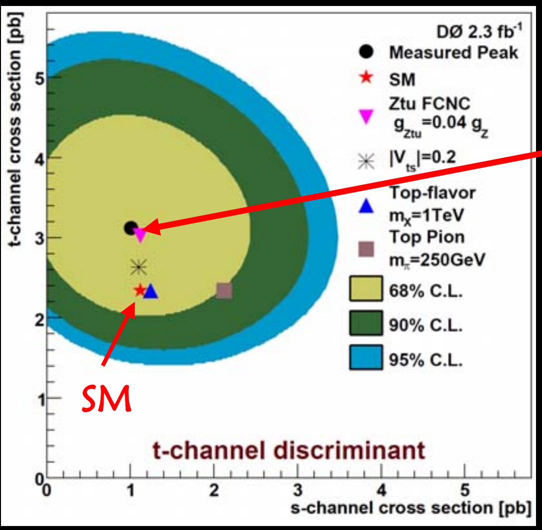



Top quarks pair-produced by the strong interaction (preserving flavor symmetry). Single top quarks can be produced by EW interaction via s-channel or t-channel W exchange). SM predicts $\sigma \approx 3.2$ pb.

Exercise for student: why is this weak process so large? (~ half the strong int. pair production.)

Small signal with large backgrounds! Pull out all the stops -- neural networks, boosted decision trees, matrix element analyses. CDF and DØ recently published observation at $5\sigma$ level, at SM expected level. The increased background will make this a truly challenging measurement at LHC.




The payoff is large; see the recent DØ measurement of t-channel process separately. The comparison of s- and t-channel XS is sensitive to many models of new physics. More data can reveal non-SM physics.

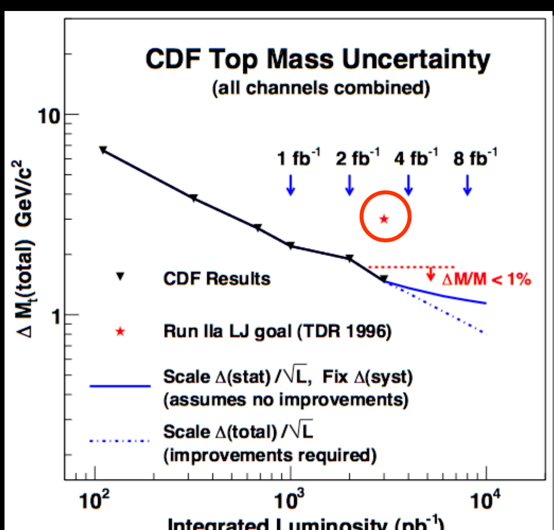
Also can measure the tbW coupling directly (sensitive to 4th quark generation): $|V_{tb}|=0.91\pm0.08$ (SM =1)

# Top Quark Mass


The large top quark mass means its coupling to Higgs is large. The top mass depends on $M_H$ through loop diagrams ($\Delta M_t \sim \log M_H$). Thus a precise top mass measurement is a primary indicator of Higgs mass in SM framework.

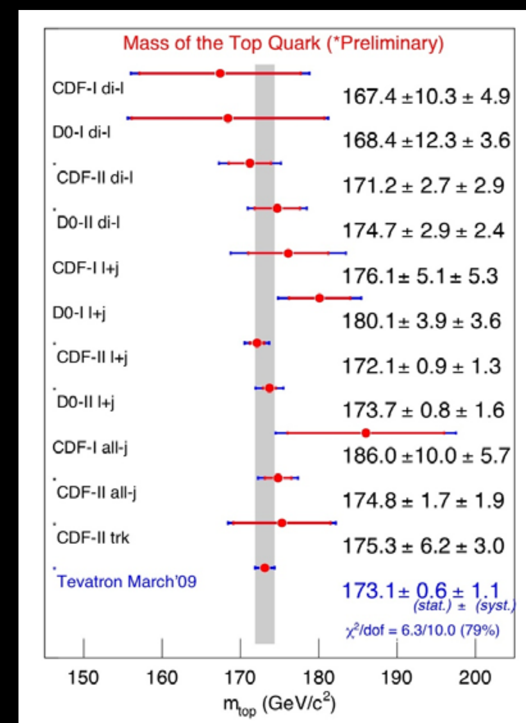
Mass measurements made in dilepton, lepton+jets, all jets channels using a variety of techniques by both CDF and DØ. They are in agreement:

**Tevatron average in Mar. 2009: $M_t$=173.1±1.2 GeV (0.7%)**




Have now exceeded the Tevatron goal δM=2 GeV; expect the final average mass to be below 1 GeV. Now reaching the systematic limit (heavy flavor jet energy scale, signal model, jet resolution).

Reaching this precision will take LHC experiments some time !




# The Top Quark affects the everyday world

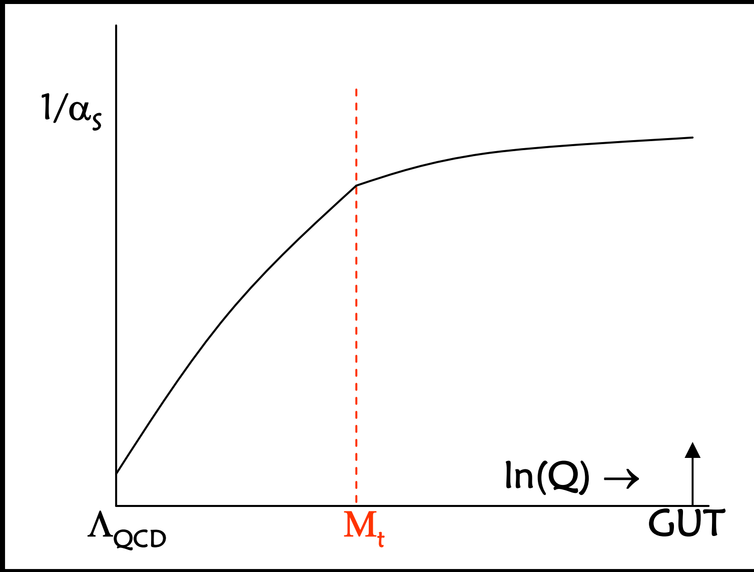
By now we have measured the top quark properties accurately enough to see that it is the object needed in the SM.   But why is its mass so much larger than other quarks?.   The top quark Yukawa coupling is ≈ 1.  Does this make it the only 'normal' fermion?

An argument by Quigg (hep-ph/9507257) points out that the large top mass also has a direct bearing on our everyday world (see other examples in Bob Cahn's Panglossian talk tomorrow):

Assume ≈unified SU(3), SU(2) and U(1) couplings at the GUT scale and evolve $\alpha_s$ down to $Q=M_t$ (6 active flavors).  From the QCD scale $\Lambda_{QCD}$, which sets the mass of the proton, we can evolve up to $Q=M_t$ (3, 4, 5 flavors).   Matching $1/\alpha_s$ at $Q=M_t$, one deduces:

$$M_p \sim M_t^{2/27}$$

(1% change in $M_t$ gives 0.02% change in $M_p$.   If $M_t$ were different, our world would be different!)



# Recognition for large collaboration achievement

Major experimental discoveries often get recognition through awards such as the APS Panofsky Prize, specified as prizes for individuals.

Many would assert that the top quark discovery is prizeworthy.

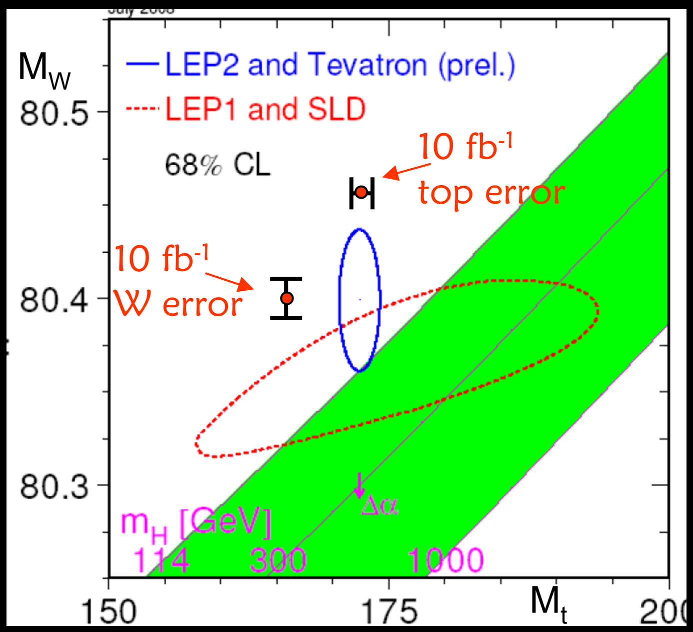
But in a case such as the joint CDF and DØ discovery of the top quark, a very large number of people were critical to the effort. Their contributions in detector building, algorithm development and many physics analyses form almost a continuum. For this reason, nominating just 3 people seems impossible.

**Should these quintessentially group efforts be recognized by awards to collaborations rather than to individuals ?**

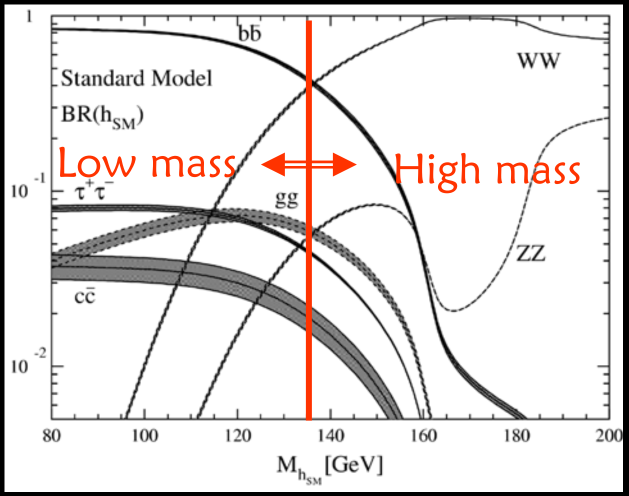
Which raises the question of …

# The Brout, Englert, Guralnik, Hagen, Higgs, Kibble boson

The Higgs mass is the single remaining unknown in the SM. W and top masses constrain it. The blue ellipse shows the current constraint on $M_H$ (114 – 1000 GeV range shown in green band). Already there is tension between measurements and SM. Ultimate Tevatron (10 $fb^{-1}$) mass errors are indicated by the error bars.




If $M_W$ and $M_t$ remain at present values and errors decrease as predicted, the SM Higgs will be ruled out by Tevatron for $M_H$ < 117 GeV. The Tevatron <u>could</u> demonstrate the demise of the SM without discovering anything new !!

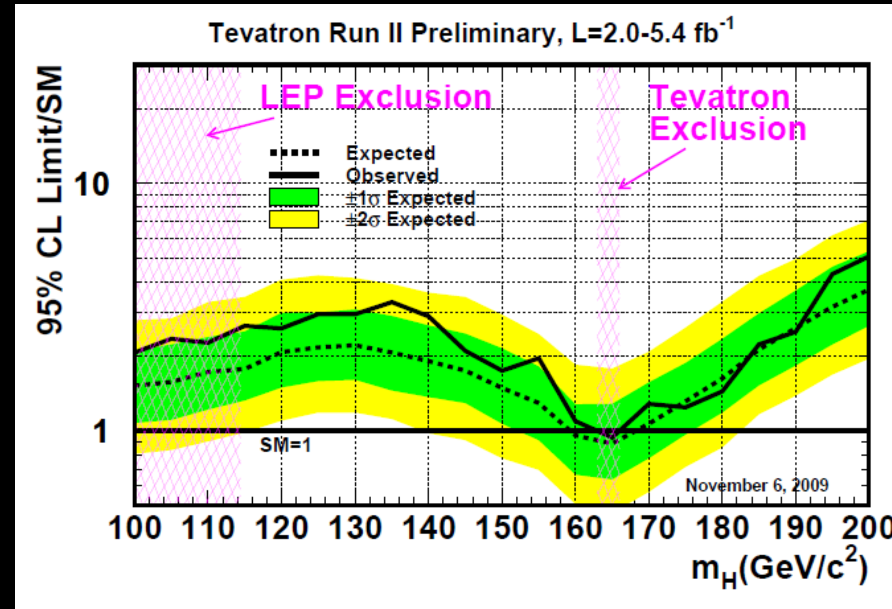


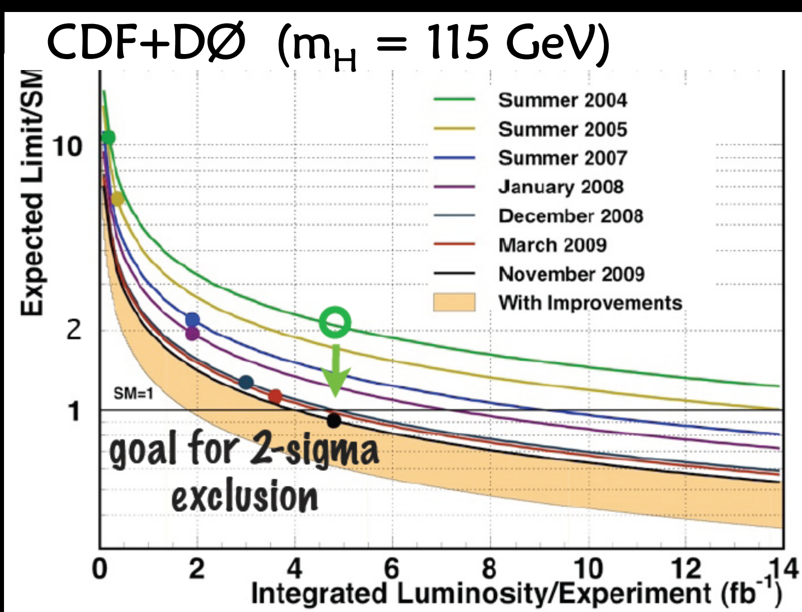

At high mass, Higgs searches use the large(r) gluon fusion production with H→WW*. At low mass, need to use the smaller W/Z+H associated production with W/Z → e, μ τ and H→ bb or ττ.

~100 individual analyses with different final states, selections are searched and combined.

# Higgs boson search

With 2.0 – 5.4 $fb^{-1}$ of data, 95% CL limits on Higgs are now a factor 2–3 above SM prediction for the low mass region.  $163 < M_H < 166$ GeV is ruled out.

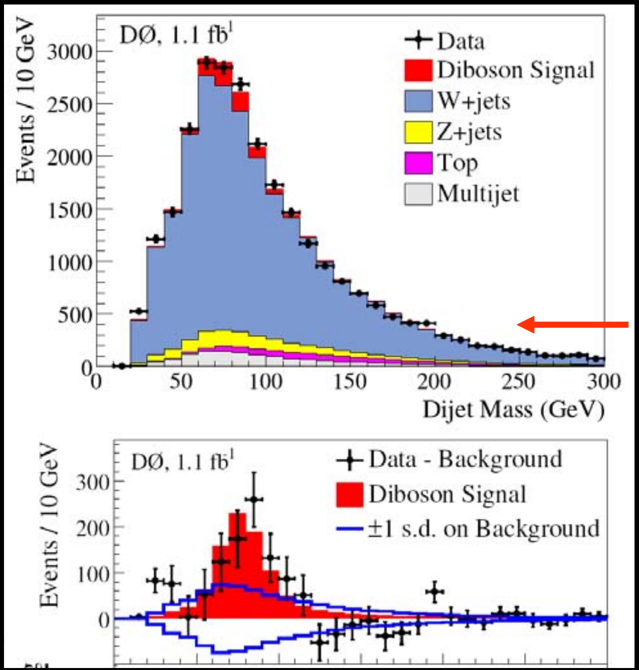



Limits have improved faster than $\mathcal{L}^{-1/2}$. Further improvements should continue this trend:

- Improved b, e, μ, τ object ID
- New search channels (e.g. $H \rightarrow \tau\tau$, ttH, $H \rightarrow \gamma\gamma$ …)
- Improved multivariate techniques to separate signal and background

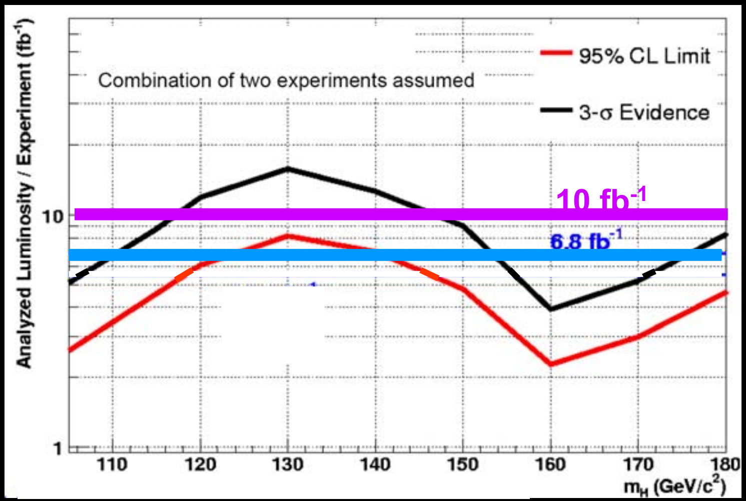
# Higgs boson




A sanity check: Search for the previously unobserved process, $WW/WZ \to \ell\nu$ +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.



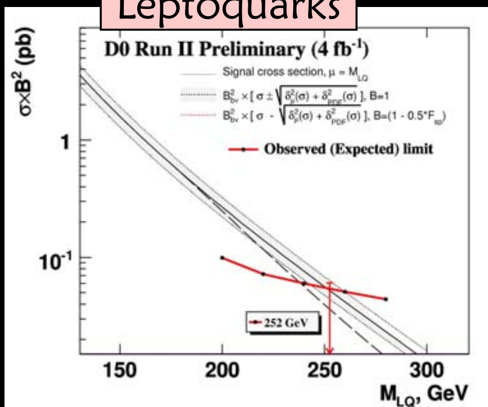

With 10 fb$^{-1}$ analyzed data, expect to rule out Higgs < 200 GeV anywhere it does not exist. CDF and DØ together have the potential to sense Higgs for $M_H$<120 GeV where the LHC is most challenged; the probability for seeing $3\sigma$ evidence at 115 GeV is 60%.

# Searches for New Physics

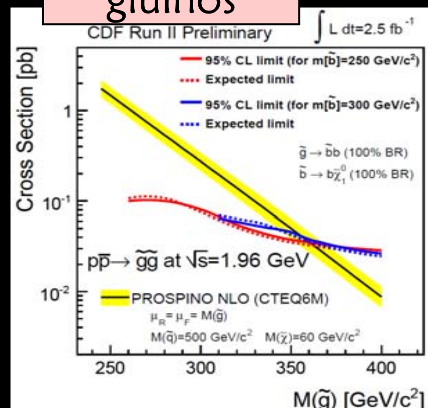
**"400 Physicists Fail to Find Supersymmetry"** (NYTimes, ca 1992)

As well as …

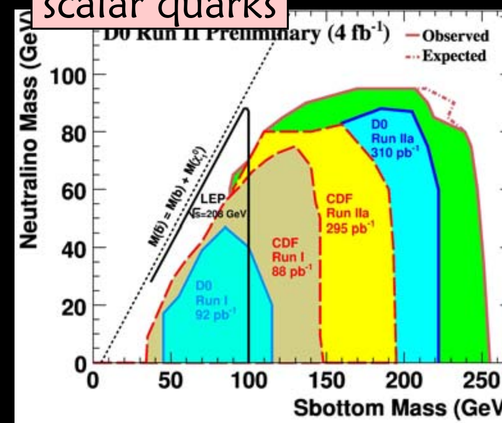
Leptoquarks



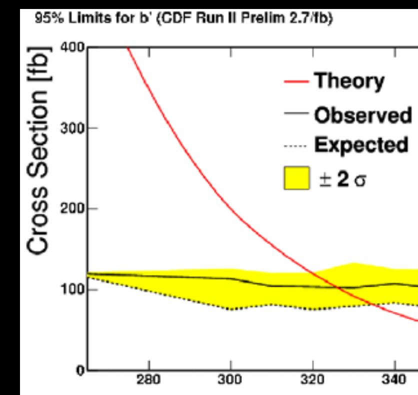

gluinos



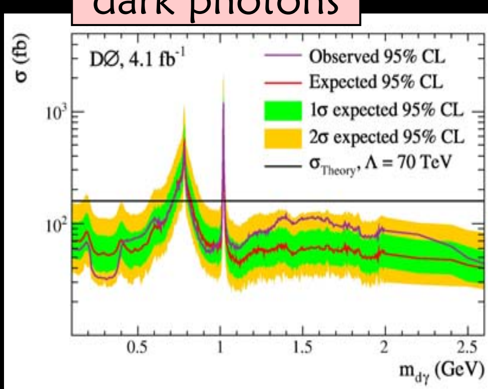

scalar quarks



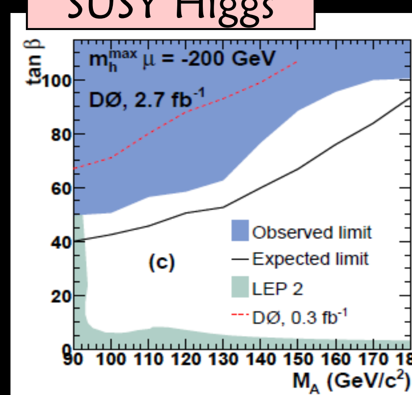

4th generation quarks



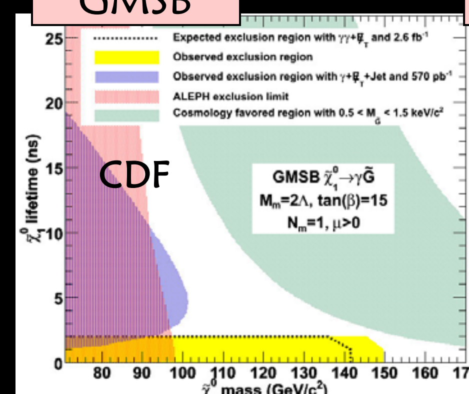

dark photons



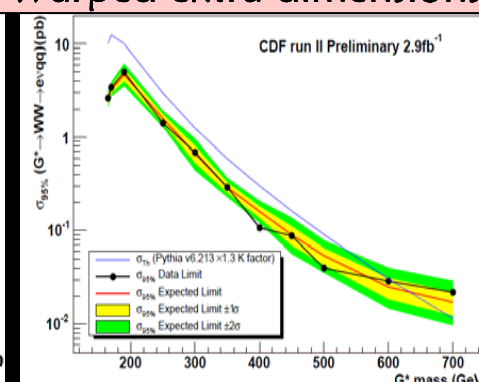

SUSY Higgs




GMSB



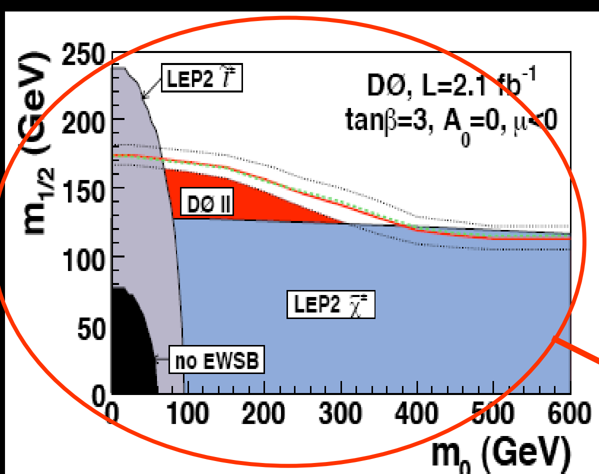

Warped extra dimensions



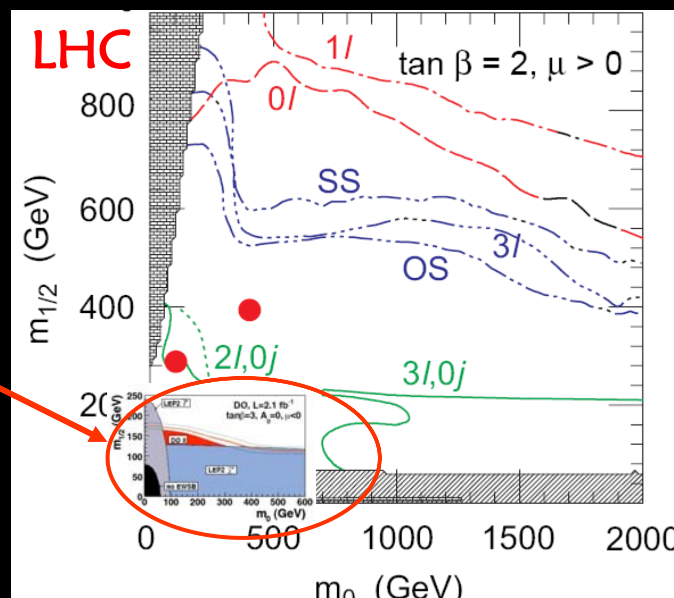

etc etc …

# Searches for New Physics

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




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




But the LHC is coming! There is a vast new territory for discovery.

# In Conclusion …

❖ The Tevatron legacy has been enabled by our colleagues in the Accelerator Division, whose creative work has allowed the Tevatron to surpass our expectations by over two orders of magnitude.

❖ The CDF & DØ collaborations have found ever more sensitive ways to dig new knowledge out of the vast data sets.

❖ Our theoretical colleagues have guided our understanding and invented a steady stream of new ideas for the experiments to explore.

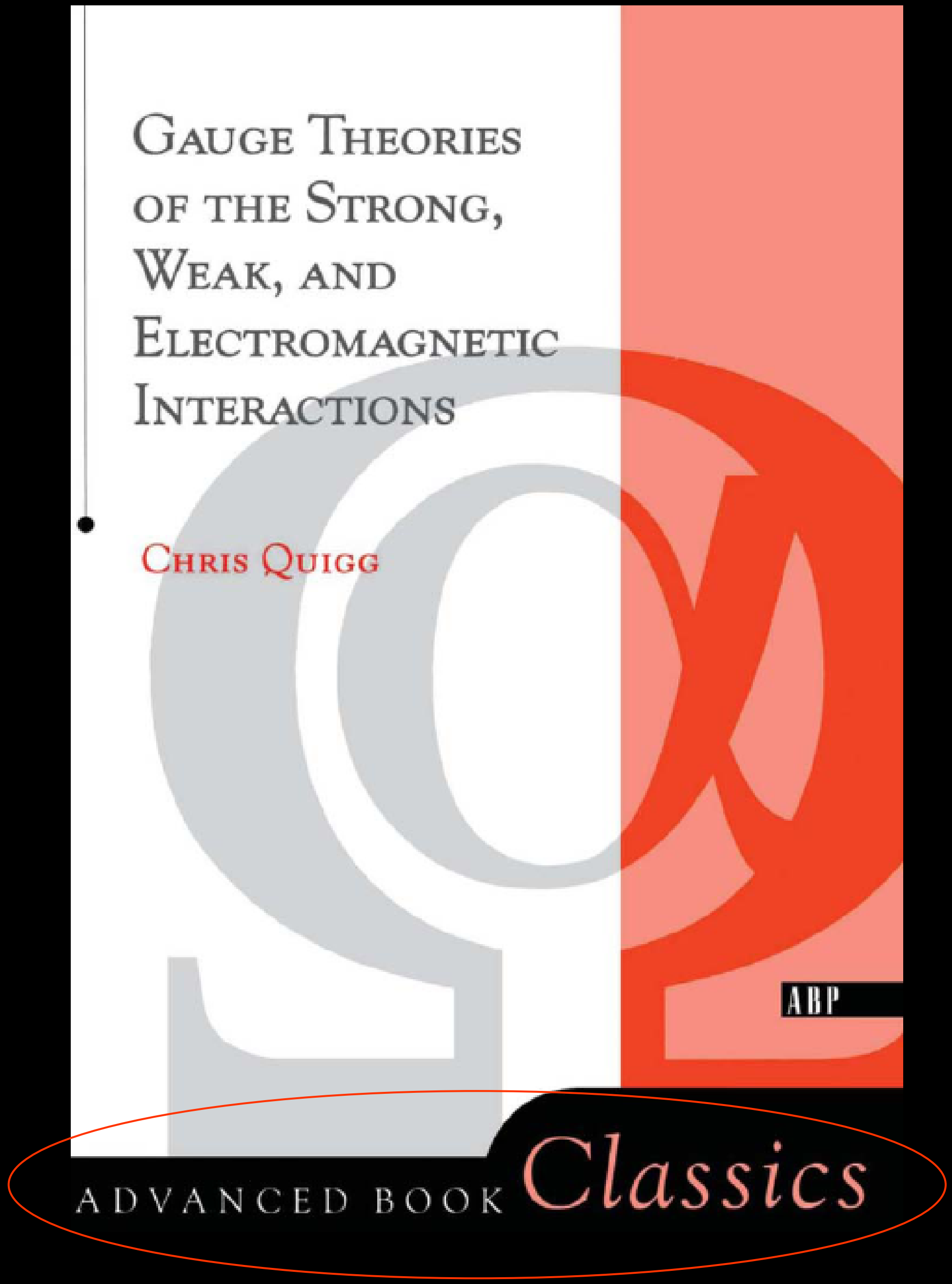
★ We eagerly await the more incisive view of the submicroscopic world from the LHC and wish our colleagues there every success. But the Tevatron has provided the essential springboard for launching the LHC program.

**The Tevatron legacy is still being written!**

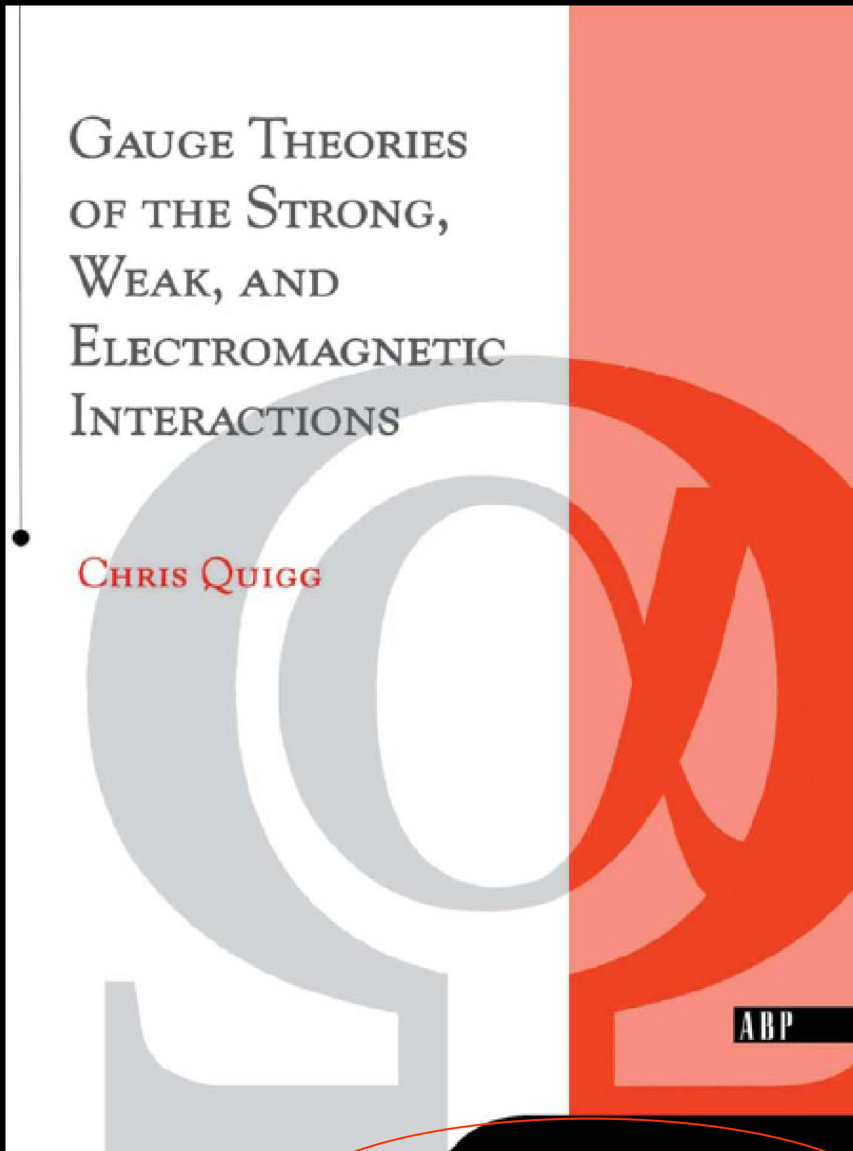
Thank you Chris for your constant and consistent exhortation and guidance over several decades!

"The advances of the past decade have brought us tantalizingly close to a profound new understanding of the fundamental constituents of matter and the interactions among them. While many ideas may precede the definitive experiments, it is likely that theoretical insights will require the impetus of experimental discovery. We may confident that … a multi-TeV hadron collider will supply the means to reveal them." EHLQ, RMP 56, 579 (1984)

"We are on the cusp of a new level of understanding, with the nature of electroweak symmetry breaking virtually certain to be revealed on the 1 TeV scale. At the same time, the incompleteness of the electroweak symmetry argues that we have much more to learn." CQ, Ann. Rev. Nucl. Part. Sci 59, 505 (2009).




The bible guiding us on how to frame the issues of the energy frontier.




A Class Act

I hope we can get off that cusp soon and gain the profound new understanding you have pointed us to!