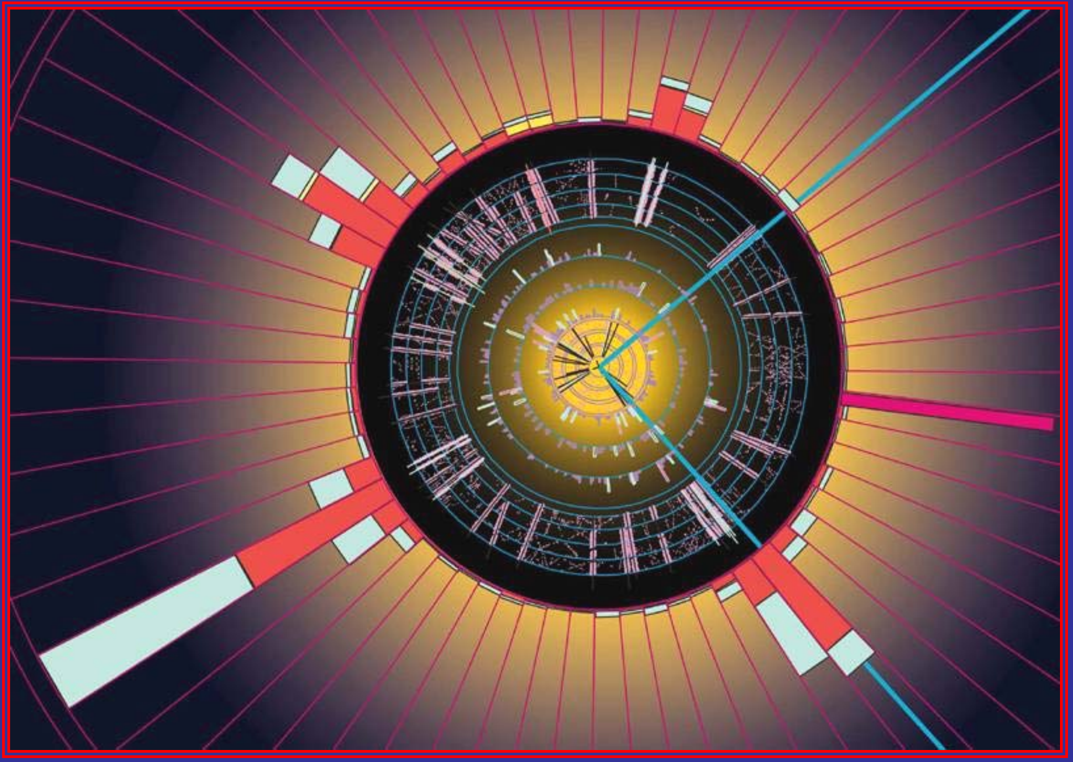
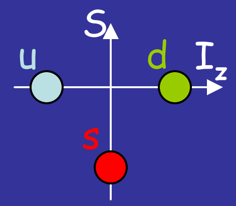
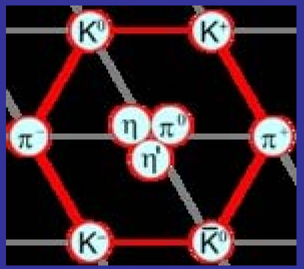
The Discovery of the Top Quark



P. Grannis
Saclay, May 27, 2011

Prehistory





❖ In 1964, Gell-Mann and Zweig proposed B = 1/3 quarks to explain hadron spectroscopy, using an isodoublet (u, d) with Q = (+2/3, -1/3), S = 0 and the isosinglet s-quark (Q=-1/3, S=-1).

All combinations of 3 quarks and 3 antiquarks give the observed 9 pseudoscalar mesons.

❖Cabibbo's 1963 postulate, put into quark terms, said that the weak interaction d and s flavor quarks are 'rotated' to different eigenstates $d_W = d \cos\theta + s \sin\theta$ for the weak interactions, to account for discrepant n and μ decay rates.

❖ Pauli principle requires anti-symmetric wave functions for states composed of identical fermions. But, for example, the Ω^- (sss), with spin = 3/2, isospin = 0, the overall wavefunction is symmetric under exchange of any two quarks! In 1964, Greenberg postulated that all quarks come in three 'colors', and that the Ω^- is antisymmetric under exchanges in the color wave function. The $e^+ e^-$ cross section and π^0 decay rate support the color hypothesis. Ultimately, color charge is the basis for QCD.

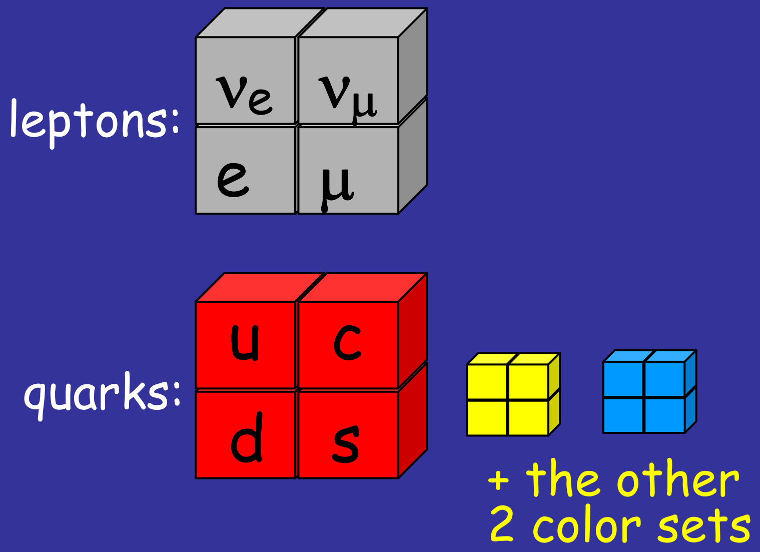
Prehistory

❖ The absence of flavor-changing neutral currents (e.g. $s \to d\,\gamma$) led Glashow, Iliopoulous & Maiani (1970) to propose a 4th (charm) quark to form an analogous iso-doublet to the (u,d_W). If the charm quark mass were small enough, the contributions from the two doublets cancel FCNCs. Starting in 1974, hadrons containing charm were discovered.

Now the lepton and quark sectors were again symmetric, as is needed to avoid anomalous contributions to weak interaction proceses

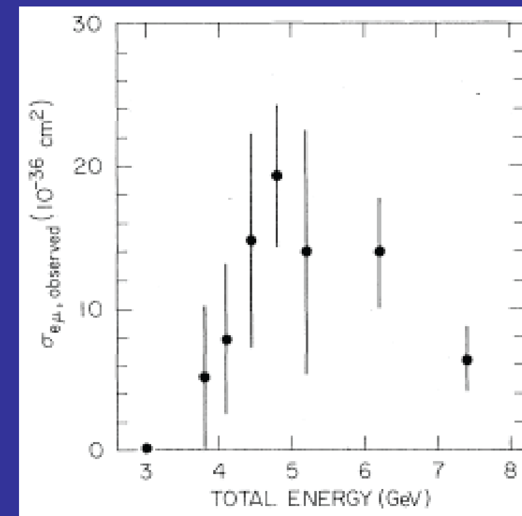
$$\underbrace{\begin{pmatrix}\nu_e\\ e^-\end{pmatrix}_L \quad \begin{pmatrix}\nu_\mu\\ \mu^-\end{pmatrix}_L}_{\text{doublets}} \qquad \underbrace{e^-_R \quad \mu^-_R}_{\text{singlets}}$$

$$\underbrace{\begin{pmatrix}u\\ d'\end{pmatrix}_L \quad \begin{pmatrix}c\\ s'\end{pmatrix}_L}_{\text{doublets}} \qquad \underbrace{u_R \quad d_R \quad c_R \quad s_R}_{\text{singlets}}$$



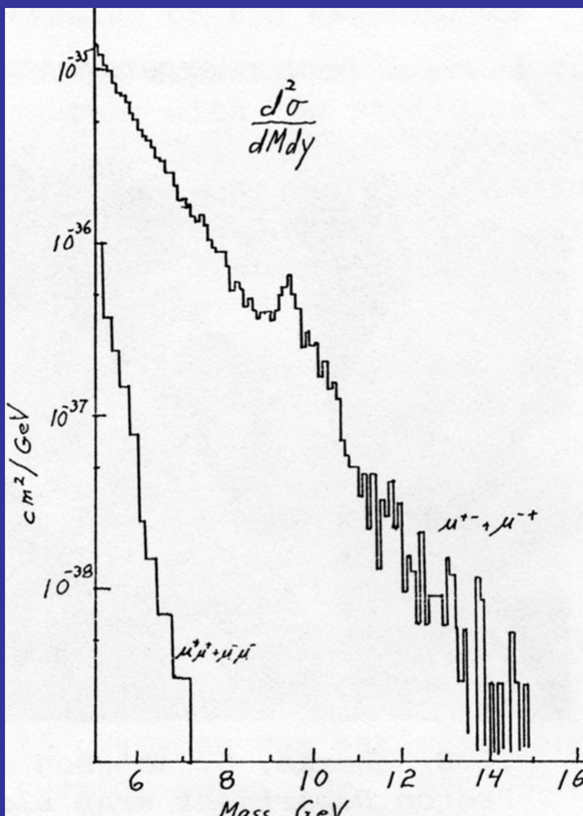
Prehistory

- In 1975, a new lepton, τ, was found at SLAC and its neutrino partner ν_τ, was inferred.



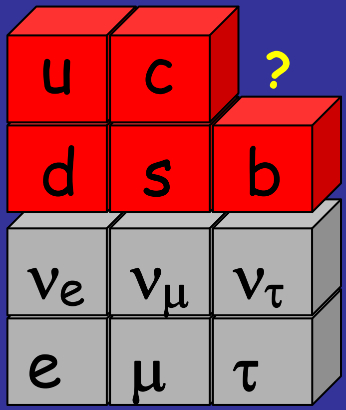
τ **lepton, SLAC (1975)**

$(m_\tau \sim 1.8$ **GeV)**



- In 1976, the Upsilon at 9.5 GeV was discovered at Fermilab and was understood to contain a new 5th quark, bottom, and its anti-quark.

Prehistory



It does not take a genius to sense that something is missing!

The absence of FCNC reactions like $b \rightarrow s\, e^+e^-$ again implied that b was a member of an isodoublet and needed a 'top' partner.

Since $M_b \approx 3 \times M_c \approx 9 \times M_s$, it seemed 'natural' to guess that the new Top quark would have $M_t \approx 3 \times M_b \approx 15$ GeV, so a bound state of $t\bar{t}$ might then be expected at $M_{tt} \approx 30$ GeV.

By 1984, the PETRA e^+e^- collider ruled out top quarks with $M_t > 23.3$ GeV.

So a new e^+e^- collider Tristan, with energy up to 60 GeV, was built in Japan to find it. Alas, there was no discovery, and by late 80's, a limit $M_t > 30.2$ GeV was set.

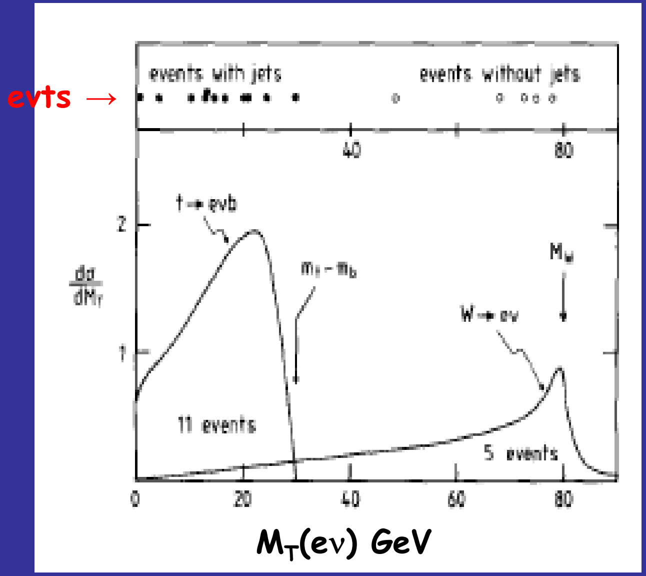
Prehistory

❖ Starting in 1981, the energy frontier had passed to the CERN SppS proton-antiproton collider, which in 1983, discovered the carriers of the unified EW force, the W and Z at masses of ~80 and ~90 GeV.

❖ One would expect to see a top quark in W decay if M_t < ~75 GeV. A good channel for the search is $W \rightarrow tb \rightarrow (e\nu b)\, b$. The main background is QCD production of $W(e\nu)$+jets.

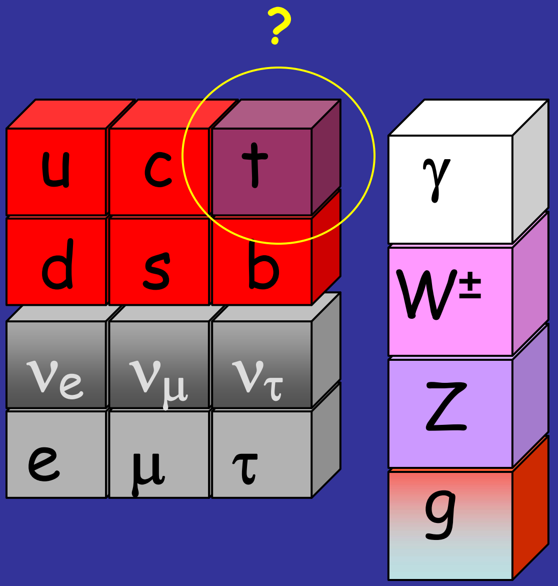
In 1984, UA1 reported preliminary evidence for an excess of events at low $M_T(e\nu)$ when jets were present, characteristic of a 40 GeV top. They saw 12 events with 3.5 expected background! In retrospect we understand that the W+jets background was underestimated.

By 1988, this had turned into a limit (> 44 GeV)



Prehistory

So where is (isn't) the top?



- ~1990: LEP experiments set limits M_t > 45.8 GeV

- 1990: UA2 set a limit ($W \rightarrow t\bar{b}$) at 69 GeV, effectively closing the search channel W → top. (At the time there was a fear that the top and W or Z masses might be very similar, making it hard to find the top.)

- 1992: CDF at the Tevatron, now searching for $t\bar{t}$ pairs with top mass above the W mass, set limit M_t > 91 GeV

- 1994: DØ joined the party and set the last top quark <u>limit</u> M_t > 131 GeV.

The central players – the accelerators

400 MeV Linac

8 GeV Booster

150 GeV Main Ring

$\bar{p}$ target

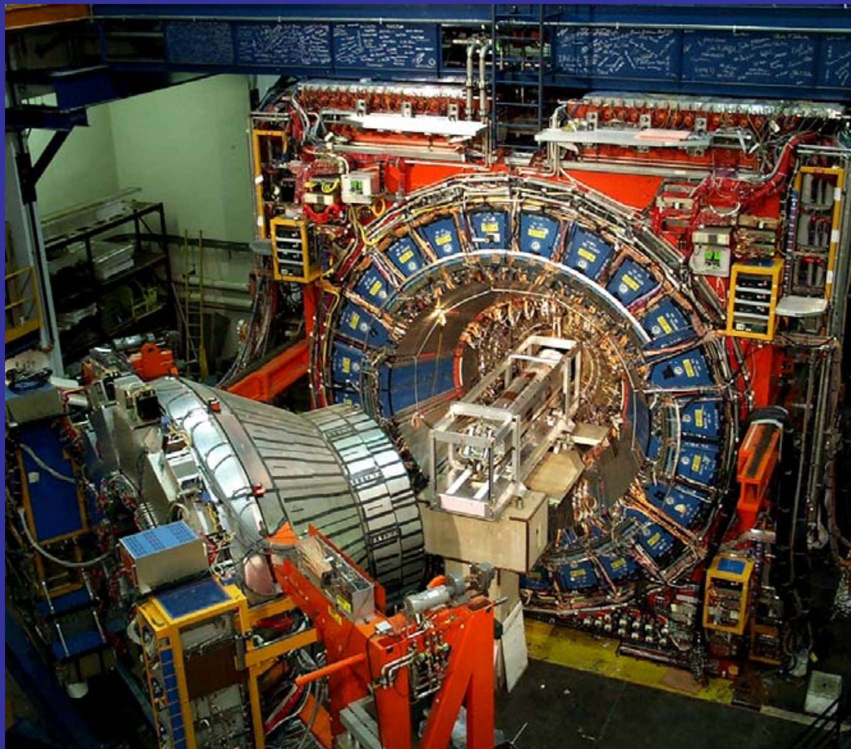
8 GeV Debuncher

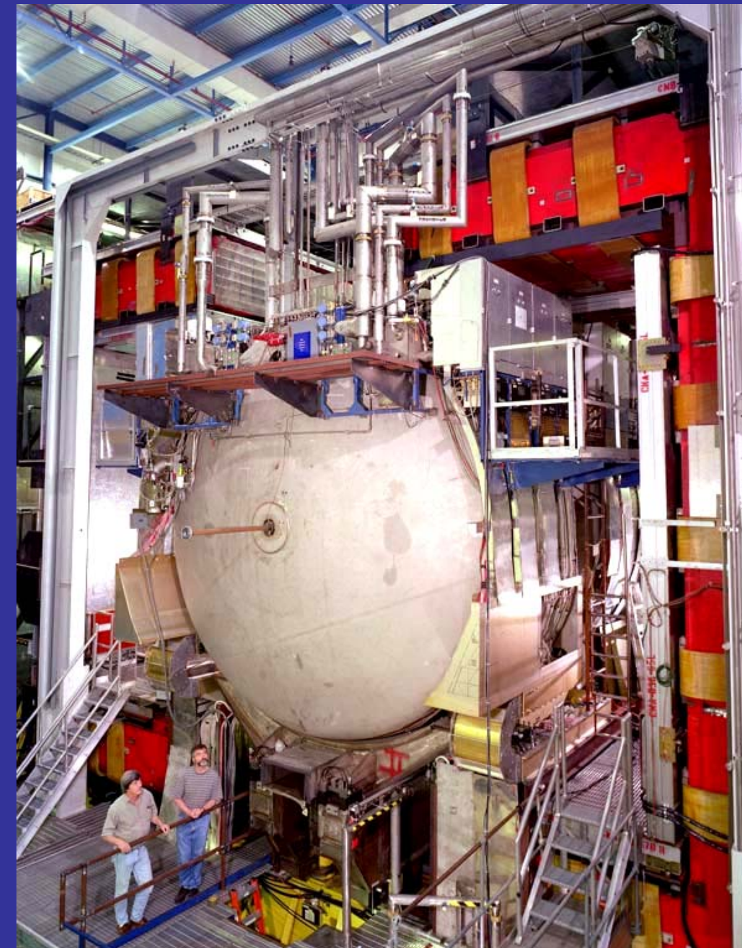
8 GeV Accumulator

1800 GeV Tevatron with counter-rotating protons and anti-protons

The Tevatron complex steadily increased the luminosity, which in 1995 rose to about 2×10^{31} cm^{-2}s^{-1}. The exceptional performance of the accelerators and collider was critical to enabling the top quark discovery.

The central players – the detectors



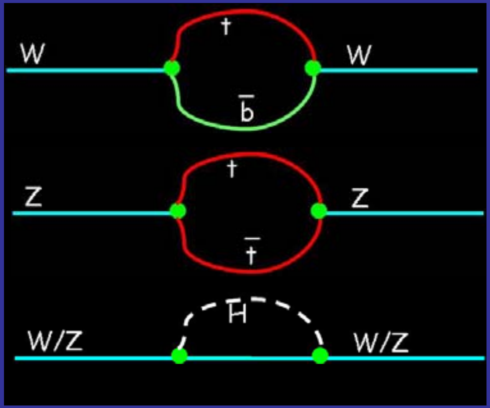


CDF and DØ in Run I (1992 – 1996) were both 4π detectors with central tracking, calorimeters, muon detectors and multi-level triggering systems. They had complementary strengths:

CDF had a solenoidal magnet surrounding tracking and a silicon microstrip vertex detector.

DØ had no magnet but high resolution, hermetic, finely segmented Uranium - LAr calorimetry and an extended muon system.

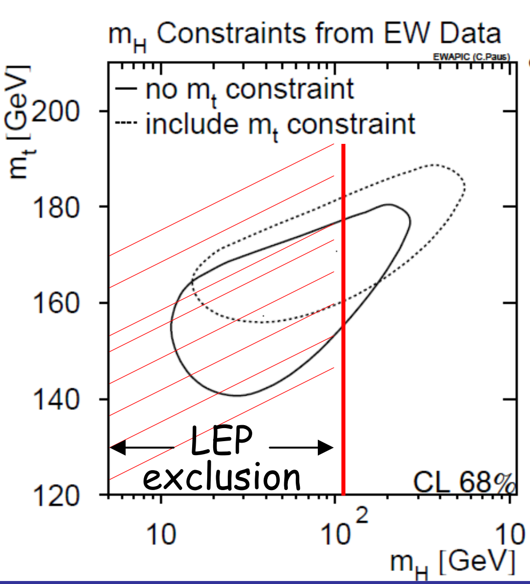
Toward discovery

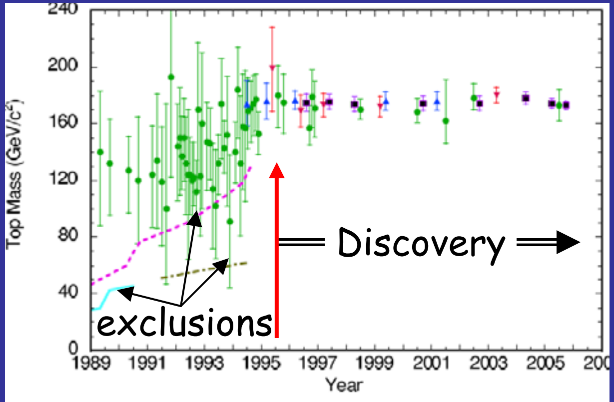


The top and Higgs are present in virtual loops which affect the Z decay properties (F-B asymmetries, rates to different fermion species, Z width etc), and the W mass. Thus precision studies of the observed Z and W place constraints on the allowed top and Higgs masses <u>in the context of the SM.</u>

The Higgs constraint is rather weak, but the top constraint is strong. The two dimensional contours of 1σ allowed values is shown in the dotted (solid) ellipse when using (not using) existing Tevatron bounds on top mass. The combination of LEP/SLC/ Tevatron data predicts M_t in the (155 – 185) GeV range, in the SM context.

(Red shading shows subsequent LEP SM Higgs limit ~2001)





The indirect estimates of top mass stayed just above the excluded regions up to 1995.

So: The SM says a top partner to b should exist, and precision measurements tell us where to look.

Toward discovery

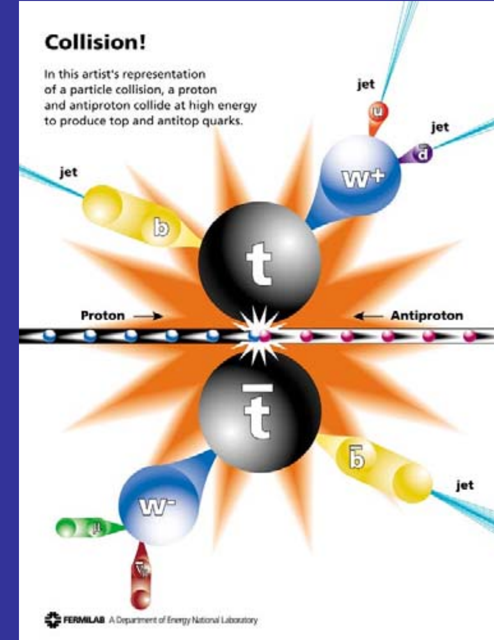
$t\bar{t}$ search channels:

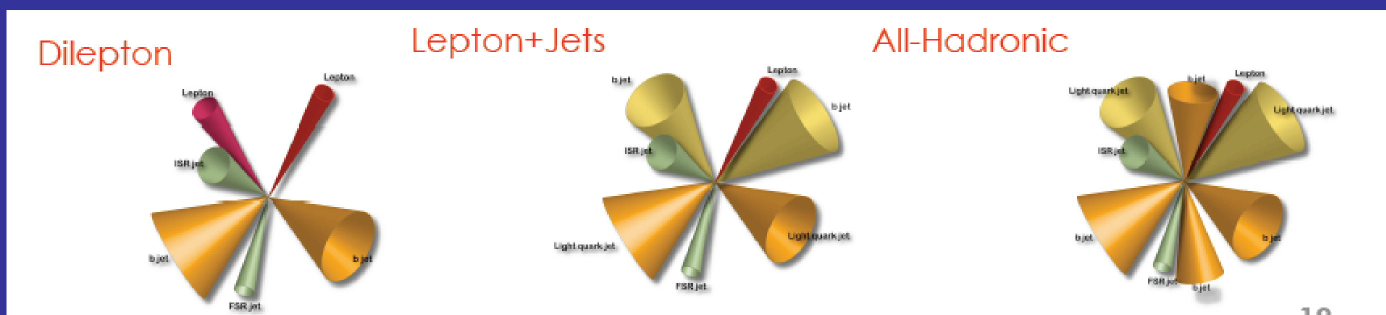
In SM, heavy top decays ~100% of time to W b

W decays: 33% ($e\nu$, $\mu\nu$, $\tau\nu$) or 67% ($u\bar{d}_W$, $c\bar{s}_W$)

Final states reached from $t\bar{t}$ then characterized by

a) Neither W decays leptonically (Alljets)
b) One W leptonic and one hadronic (Lepton + jets)
c) Both W's decay leptonically (Dilepton)





Low background, low rate

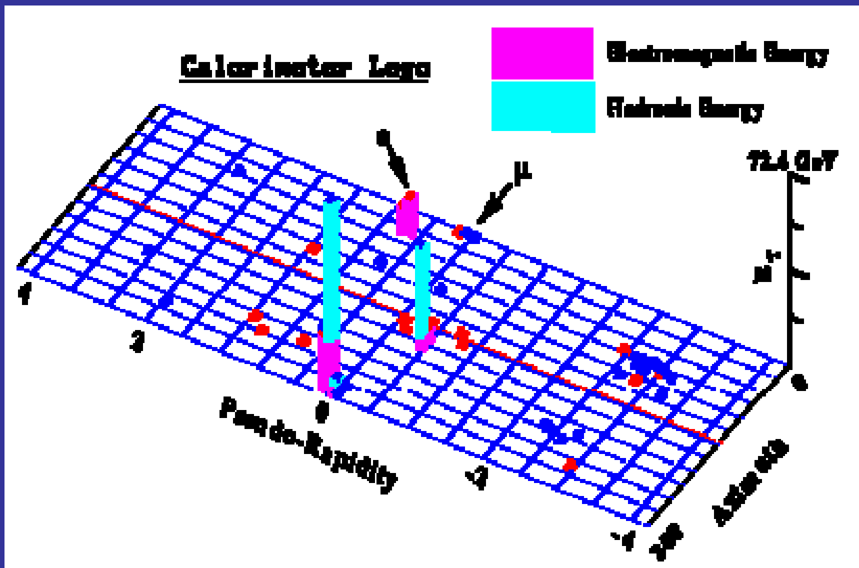
modest background, higher rate

large background, highest rate

For the original top measurements, use only e and μ (τ is difficult), and do not attempt the high background Alljets channel. (By today, all final states have been used.)

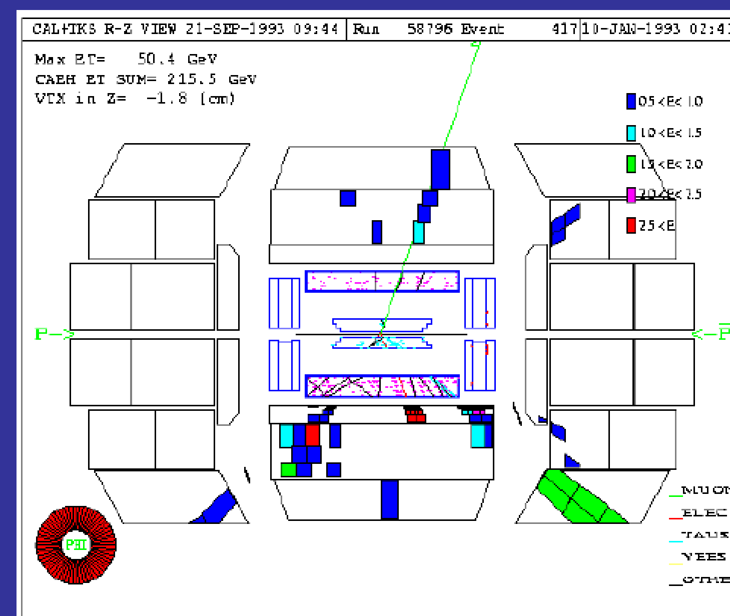
Toward discovery

By 1993, CDF and DØ were seeing interesting individual events, but at low statistical sensitivity.



1992 CDF dilepton event: event with 2 energetic jets (one is b-tagged), isolated moderate p_T e and μ, and substantial MET.

A striking DØ dilepton event seen in its final limit paper [e (p_T=99 GeV), μ (p_T=198 GeV), MET (102 GeV), 2 jets, (E_T=25, 22 GeV)] was in a very low background region.
If hypothesize to be from top pair production ($t\bar{t} \rightarrow (e\nu j)(\mu\nu j)$), mass was consistent with M_t=(145-200) GeV.

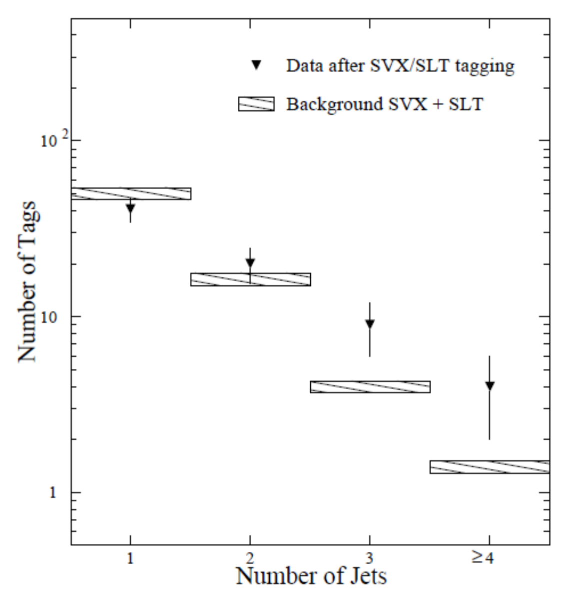


Toward discovery

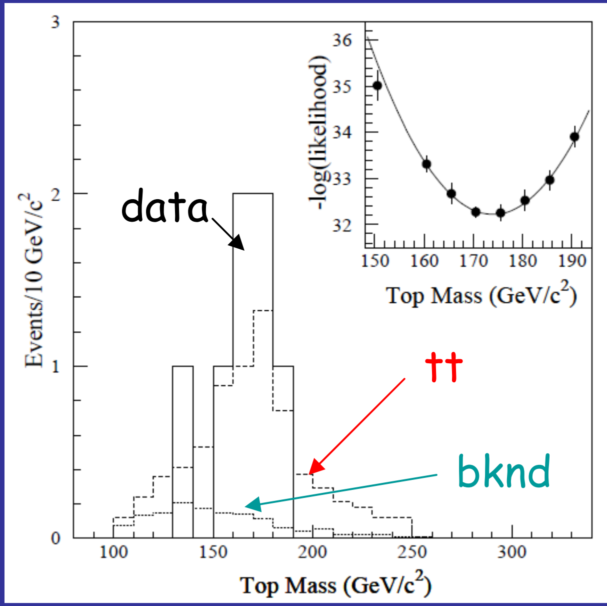
In early 1994, CDF published an analysis based on 19 pb^{-1} in which they found 2 events with eμ + 2jets and MET, and 10 events with e or μ + ≥3 jets and MET, in which at least one of the jets is b-tagged by the silicon vertex detector or a by semileptonic decay. The estimated background (W+jets, QCD multijets) was 6.0 ± 0.5 events, giving a probability for the background-only hypothesis of 0.26% (2.8σ Gaussian equivalent).

F. Abe et al, PRL, 73, 225 (1994), "Evidence for Top Quark Production …"

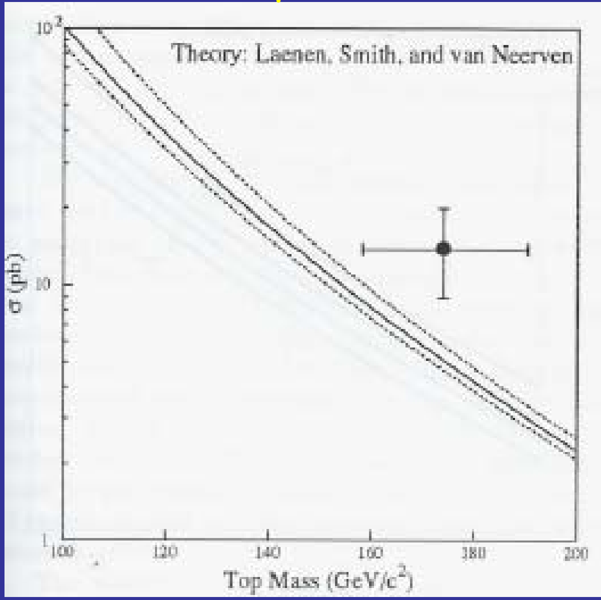
Excess over expectation appears for ≥3 jets



Mass fit from MC templates yields 174 ± 16 GeV

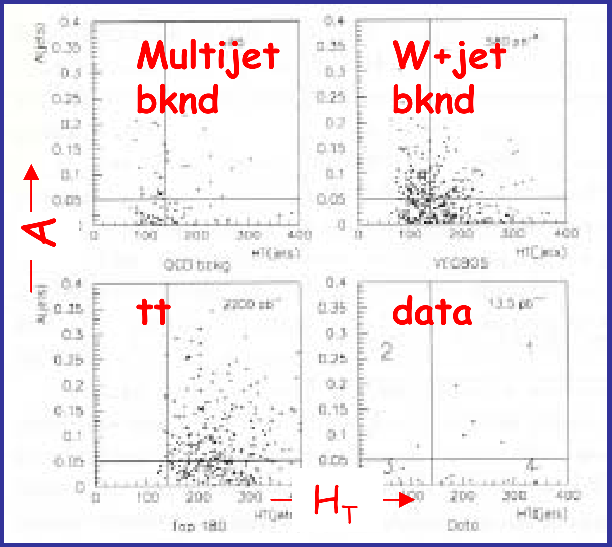


Cross section, $\sigma = 13.0^{+6.1}_{-4.8}$ pb, larger than the theoretical value of ~6 pb.



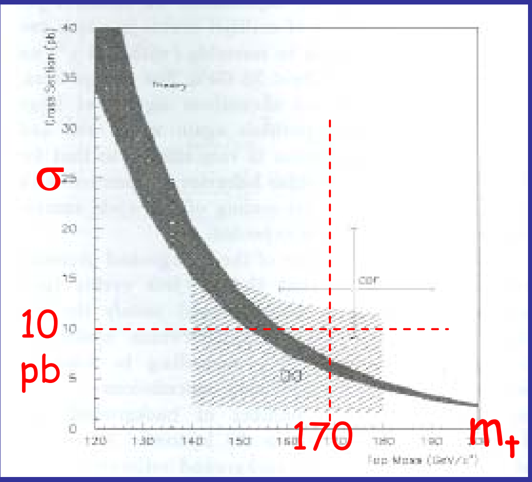
Toward discovery

On the basis of its earlier 131 GeV limit, and the understanding that CDF was preparing its 'evidence' paper, DØ had optimized its selection for higher mass top. Unlike CDF, DØ had limited b-tagging capability, so developed a selection based on event topology variables, *A* (aplanarity = smallest eigenvalue of momentum tensor) and H_T (scalar sum of jet E_T's).



DØ preliminary result (Proceedings of ICHEP XXVII, 1994) with 13.5 pb^{-1} had 7 events (1 eμ, 4 ℓ+jets topological tag and 2 ℓ+jets events μ-tag) where Bknd = 3.2±1.1 events (7.2% probability for background only hypothesis).

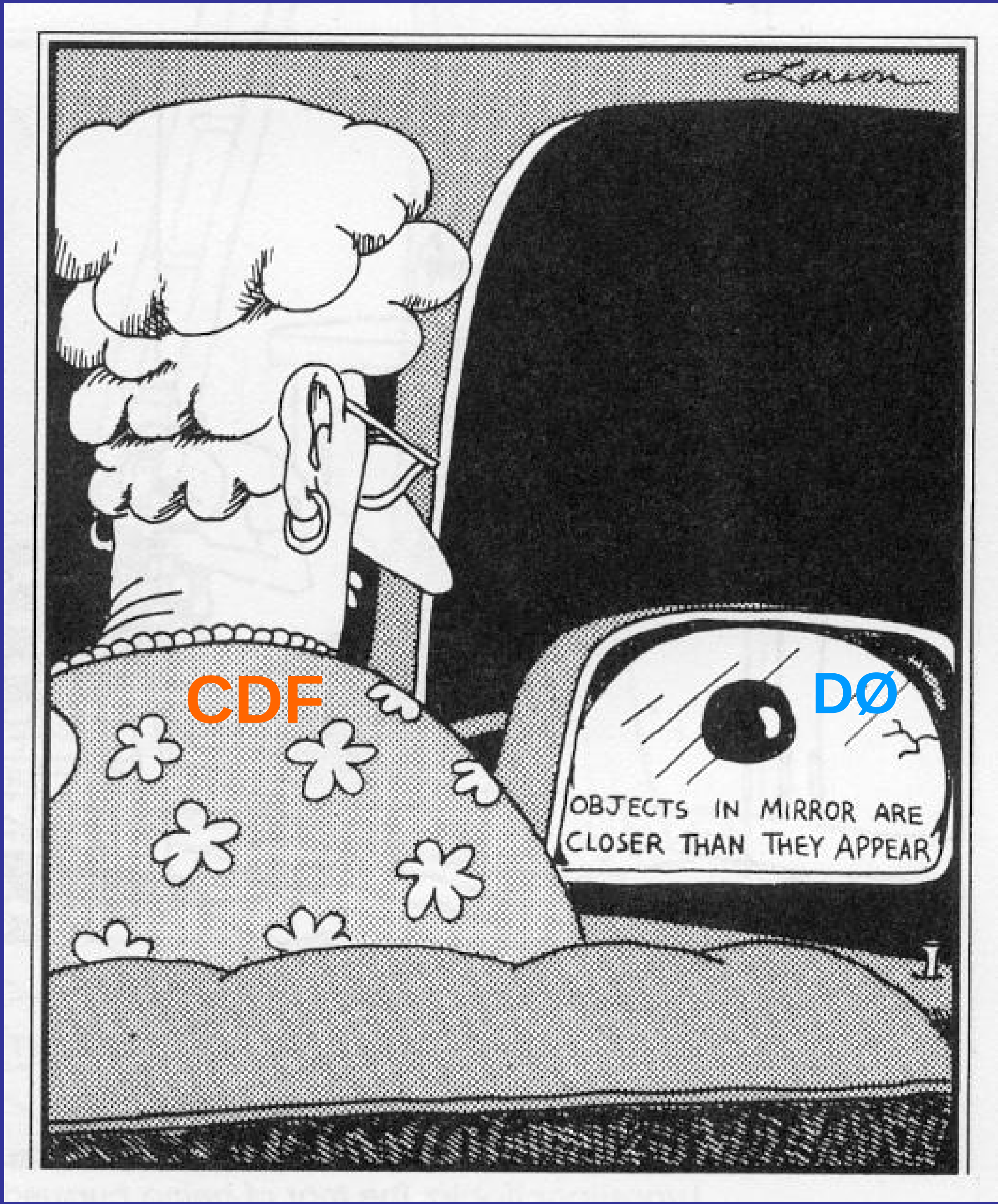
Sensitivity (expected signal/√bknd) of DØ and CDF was the same.



With no significant excess, DØ did not estimate a mass, but showed a cross section for its excess for a range of possible masses, in agreement with theory.

Toward discovery

The race toward discovery was heating up!



from "Top Turns 10" symposium talk by CDF physicist, D. Glenzinski.

Top quark discovery

By January 1995, after a significant improvement in the Tevatron (fixing a rotated magnet) both collaborations had collected >50 pb^{-1}. In the January Aspen Conference, DØ reported on 25 pb^{-1}, from which it could be understood that with double the data set analyzed, either collaboration could achieve the ~5σ level needed for discovery.

The February discovery data sets were 67 pb^{-1} for CDF and 50 pb^{-1} for DØ.

In both CDF and DØ, activities ramped up to fever pitch to analyze the remaining data, and to finalize selection cuts, mass measurement techniques, cross checks and systematic uncertainties. To large extent the two collaborations proceeded independently with no formal communications.

The prior phase of 'evidence' in 1994 had given both collaborations valuable experience in understanding the data and refining their analyses, and this time around the convergence was much faster. (~Six weeks from start to paper submission.)

Top quark discovery

An agreement had earlier been reached with Director John Peoples that for the top discovery, either collaboration could trigger the end game by submitting a discovery paper to him. On receipt, a one week holding period would commence, during which the other collaboration could finalize its result if desired, after which publication submission would proceed.

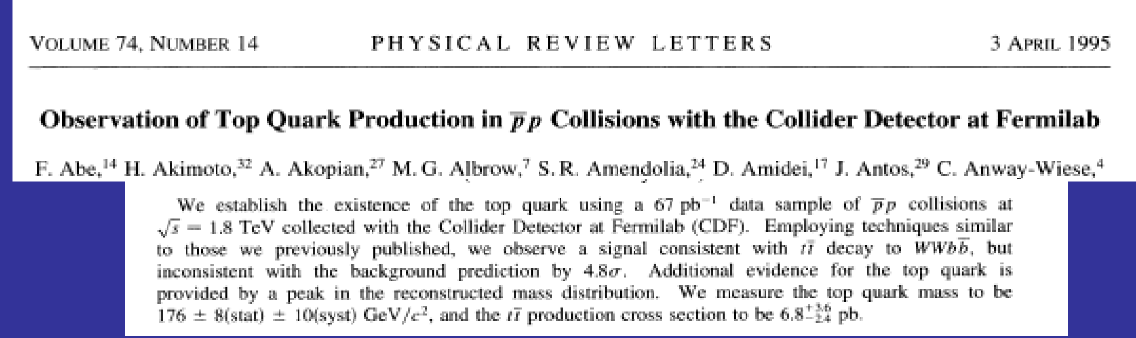
This agreement introduced 'sanity' into the process, as neither collaboration had to worry about being scooped while conducting final tests.

On Feb. 17, CDF delivered its paper to Peoples. DØ chose to wait for several days to do more cross-checks.

On Feb. 24, CDF and DØ submitted papers to Phys. Rev. Letters simultaneously. The results were embargoed until the public seminar at Fermilab on March 2 (but several newspapers got wind of the discovery and tried to make a scoop).

paper submissions

CDF Top quark discovery



VOLUME 74, NUMBER 14 PHYSICAL REVIEW LETTERS 3 APRIL 1995

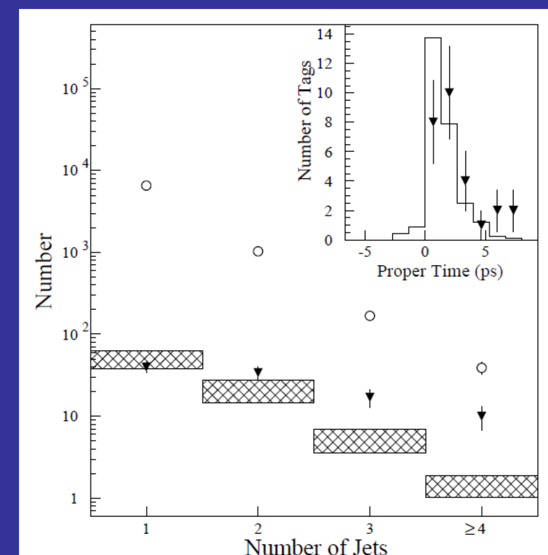
Observation of Top Quark Production in $\bar{p}p$ Collisions with the Collider Detector at Fermilab

F. Abe,[14] H. Akimoto,[32] A. Akopian,[27] M. G. Albrow,[7] S. R. Amendolia,[24] D. Amidei,[17] J. Antos,[29] C. Anway-Wiese,[4]

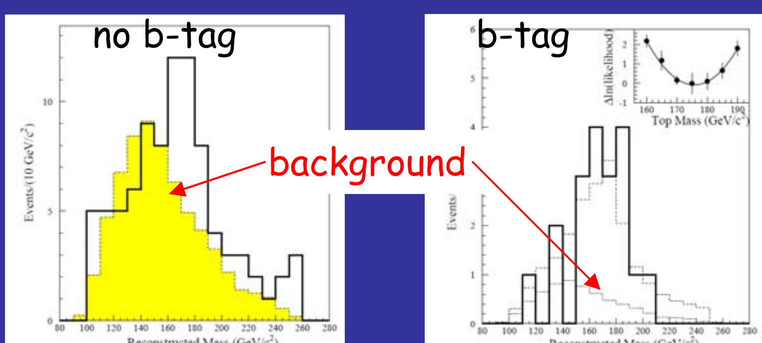
We establish the existence of the top quark using a 67 pb^{-1} data sample of $\bar{p}p$ collisions at $\sqrt{s}$ = 1.8 TeV collected with the Collider Detector at Fermilab (CDF). Employing techniques similar to those we previously published, we observe a signal consistent with $t\bar{t}$ decay to $WWb\bar{b}$, but inconsistent with the background prediction by 4.8σ. Additional evidence for the top quark is provided by a peak in the reconstructed mass distribution. We measure the top quark mass to be 176 ± 8(stat) ± 10(syst) GeV/c^2, and the $t\bar{t}$ production cross section to be $6.8^{+3.6}_{-2.4}$ pb.

CDF's selection followed the 'evidence' paper strategy with an improved b-tagging algorithm. They found 6 dilepton events and 43 lepton+jets events (50 b-tags), with estimated background of 22.1±2.9 tags.

- M_t = 176 ± 13 GeV
- $\sigma_{tt} = 6.8^{+3.6}_{-2.4}$ pb
- Background-only hypothesis excluded at 4.8σ



Reconstructed mass distribution before and after b-tagging.



Number of single lepton events vs. Njets. Inset shows proper time of ≥3 jets for silicon vertex tags, consistent with expectation for b-quarks

DØ Top quark discovery

VOLUME 74, NUMBER 14 PHYSICAL REVIEW LETTERS 3 APRIL 1995

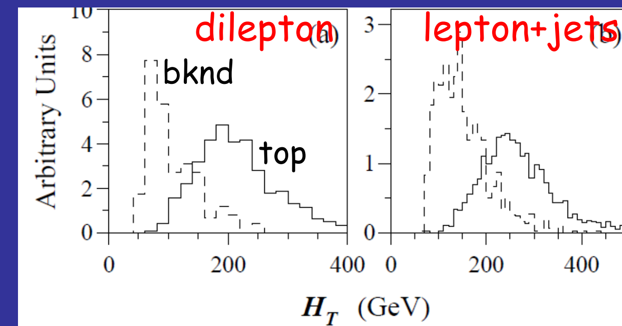
Observation of the Top Quark

S. Abachi,[12] B. Abbott,[33] M. Abolins,[23] B. S. Acharya,[40] I. Adam,[10] D. L. Adams,[34] M. Adams,[15] S. Ahn,[12] H. Aihara,[20]

The D0 Collaboration reports on a search for the standard model top quark in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV at the Fermilab Tevatron with an integrated luminosity of approximately 50 pb^{-1}. We have searched for $t\bar{t}$ production in the dilepton and single-lepton decay channels with and without tagging of b-quark jets. We observed 17 events with an expected background of 3.8 ± 0.6 events. The probability for an upward fluctuation of the background to produce the observed signal is 2×10^{-6} (equivalent to 4.6 standard deviations). The kinematic properties of the excess events are consistent with top quark decay. We conclude that we have observed the top quark and measured its mass to be 199^{+19}_{-21} (stat) ±22 (syst) GeV/c^2 and its production cross section to be 6.4 ± 2.2 pb.

DØ's selection refined the topological ($\mathcal{A}$,H_T) selection to improve signal/bknd by x2.6. With tight cuts, found 3 dilepton events, 8 lepton+jets events (topological selection) and 6 lepton+jets events (μ tag). Estimated background to these 17 events was 3.8±0.6 events.

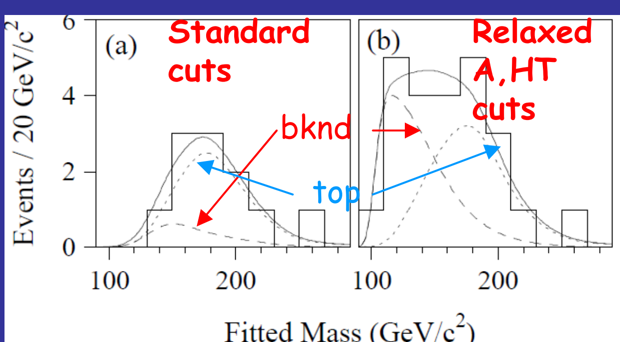
- M_t = 199±30 GeV
- σ_{tt} = 6.4±2.2 pb
- Bknd-only hypothesis rejected at 4.6σ

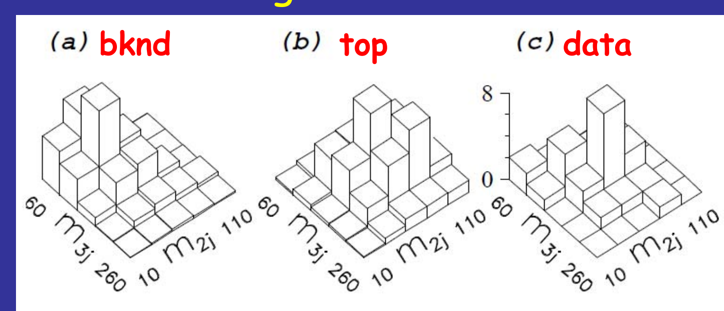


H_T distributions for signal and background

For l+4jets events, plot the 2 jet and 3 jet masses for the top decaying hadronically. Top signal and backgrounds differ.

Reconstructed mass distribution





Top quark discovery

DØ author list – Abachi to Zylberstejn

S. Abachi,[12] B. Abbott,[33] M. Abolins,[23] B.S. Acharya,[40] I. Adam,[10] D.L. Adams,[34] M. Adams,[15] S. Ahn,[12] H. Aihara,[20] J. Alitti,[36] G. Álvarez,[16] G.A. Alves,[8] E. Amidi,[27] N. Amos,[22] E.W. Anderson,[17] S.H. Aronson,[3] R. Astur,[38] R.E. Avery,[29] A. Baden,[21] V. Balamurali,[30] J. Balderston,[14] B. Baldin,[12] J. Bantly,[4] J.F. Bartlett,[12] K. Bazizi,[7] J. Bendich,[20] S.B. Beri,[31] I. Bertram,[34] V.A. Bezzubov,[32] P.C. Bhat,[12] V. Bhatnagar,[31] M. Bhattacharjee,[11] A. Bischoff,[7] N. Biswas,[30] G. Blazey,[12] S. Blessing,[13] A. Boehnlein,[12] N.I. Bojko,[32] F. Borcherding,[12] J. Borders,[35] C. Boswell,[7] A. Brandt,[12] R. Brock,[23] A. Bross,[12] D. Buchholz,[29] V.S. Burtovoi,[32] J.M. Butler,[12] D. C[illegible] H. Castilla-Valdez,[9] D. Chakraborty,[38] S.-M. Chang,[27] S.V. Chekulaev,[32] L.-P. Chen,[20] W. Chen,[38] L. Chevalier,[36] S. Chopra,[31] B.C. Choudhary,[7] J.H. Christenson,[12] M. Chung,[15] D. Claes,[38] A.R. Clark,[20] W.G. 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404 Authors

A note on 'Discovery':

In today's usage, 'Evidence' for something new requires 3σ significance and 'Discovery' requires 5σ significance. (see CERN Bulletin, May 23, 2011)

These rules largely derived from the Tevatron top quark discovery process.

Strictly speaking then, the 1994 results were not Evidence, and neither CDF or DØ made a Discovery on their own (jointly, they did).

If P_1 and P_2 are probabilities of discovery in two experiments, then $P_{tot} = P_1 P_2 (1 - \ln P_1 P_2)$

Top quark discovery

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

Top quark discovery

The public is interested in physics discoveries!

1995 Spokesmen du jour: Bellettini (CDF) , Grannis (DØ), FNAL Director Peoples, Montgomery (DØ), Carithers (CDF)

But far more important were those who did the hard work in the trenches. Here are some of the DØ PhD students in 1995.

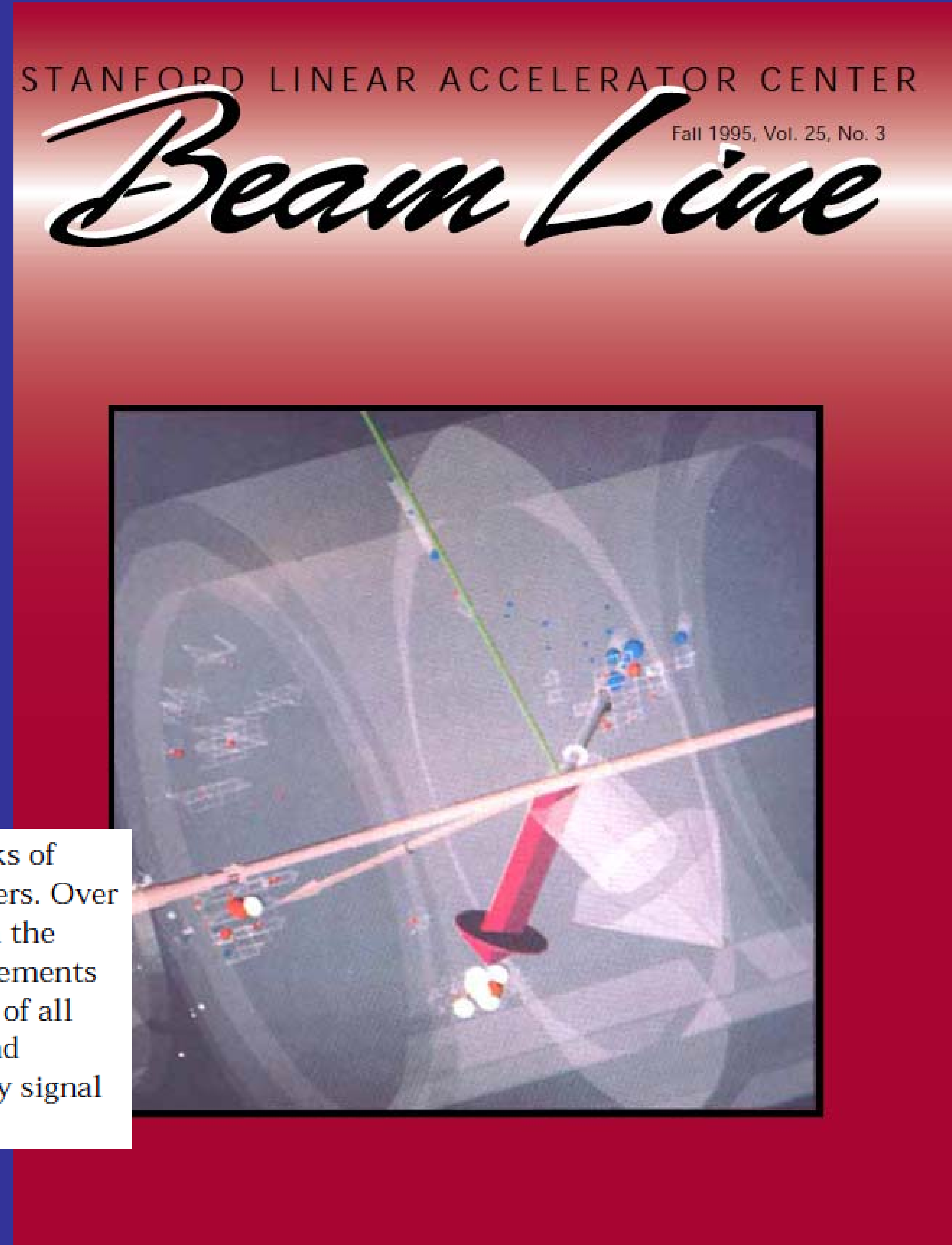
Top quark discovery

There was a great sense of accomplishment, and a sense of shared responsibility for the discovery across the collaborations.

Indeed, all of the ~400 people in CDF and DØ were key contributors to building and operating the detectors, creating the software infrastructure and event reconstruction programs, and devising the analysis techniques on which the top quark discovery depended.

Top quark discovery

The events leading up to the observation of the top quark, and the discovery itself were recorded in the Fall 1995 issue of the SLAC *Beam Line*, shortly after the CDF and DØ discoveries.



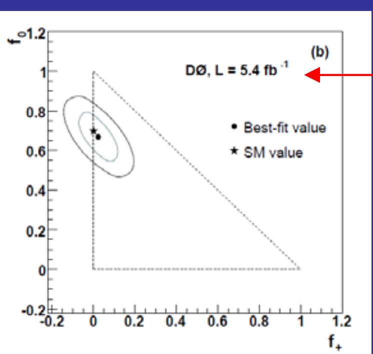
MANKIND has sought the elementary building blocks of matter ever since the days of the Greek philosophers. Over time, the quest has been successively refined from the original notion of indivisible "atoms" as the fundamental elements to the present idea that objects called quarks lie at the heart of all matter. So the recent news from Fermilab that the sixth—and possibly the last—of these quarks has finally been found may signal the end of one of our longest searches.

http://www.slac.stanford.edu/pubs/beamline/pdf/95iii.pdf

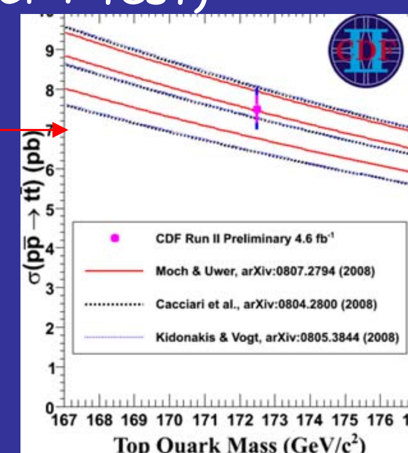
What followed discovery?

CDF and DØ discovered something new, but was the SM top? Cross section and decays were right. Subsequently:

- 'Top' charge could be 2/3 ($t \rightarrow W^+ b$) or 4/3 ($t \rightarrow W^- b$). Measurements sensitive to the charge of b associated with W^+ indicate Q=2/3e at >95% CL.
- 'Top' is consistent with being the isospin doublet partner of the b: No flavor changing neutral currents ($t \rightarrow Zq$) are seen (GIM suppression again).
- CKM matrix element now measured to be V_{tb} > 0.77 (95% CL) consistent with ~1 as expected for a 3 generation quark sector.



- 'Top' has expected couplings: W boson helicity fractions agree with SM and no anomalous axial vector or tensor couplings are seen.
- Top and anti-top masses equal to within ~1% (CPT test)
- 'Top' quark pair production agrees with SM QCD color charge coupling prediction (6%).
- Data favors color singlet 'W' in 'Top' decay

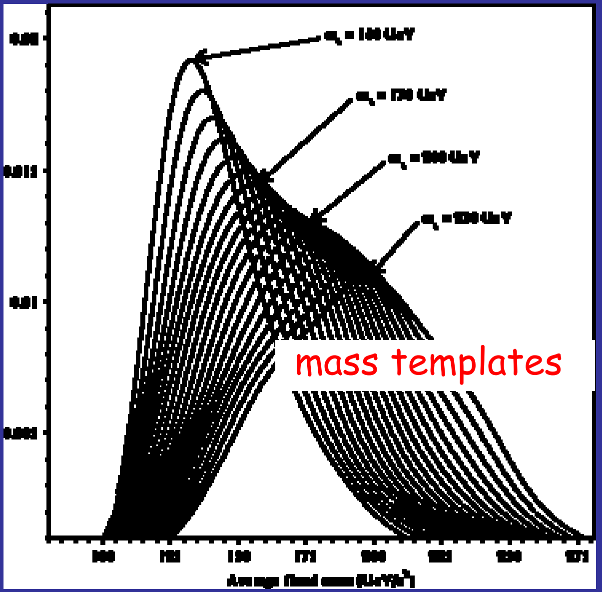


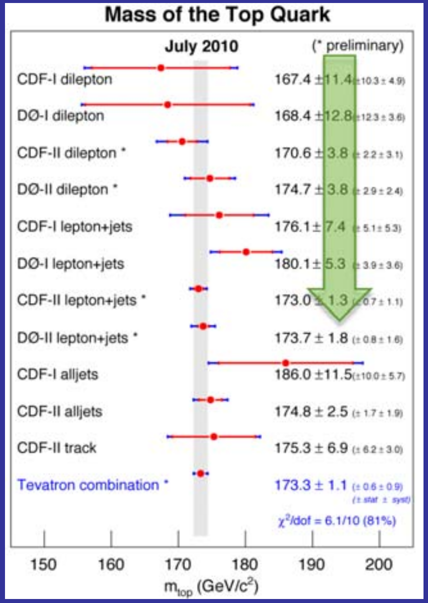
It walks like a quark, quacks like a quark, so …

Top quark mass

Construct 'fitted mass' from the best χ^2 solution to a 2C fit to single lepton + jets events.

Original methods for measuring the top quark mass used templates based on MC prediction for the fitted top mass. These have now been supplemented by methods incorporating leading order matrix elements and integration of probabilities over full phase space.





Many measurements now exist for Dileptons (including tau's), Lepton+jets and All Jets final states, with excellent agreement.

M_t = 173.1 ± 1.1 GeV (0.6%) (Tevatron avg summer 2010)

The top quark now has the most precisely known mass of all the quarks

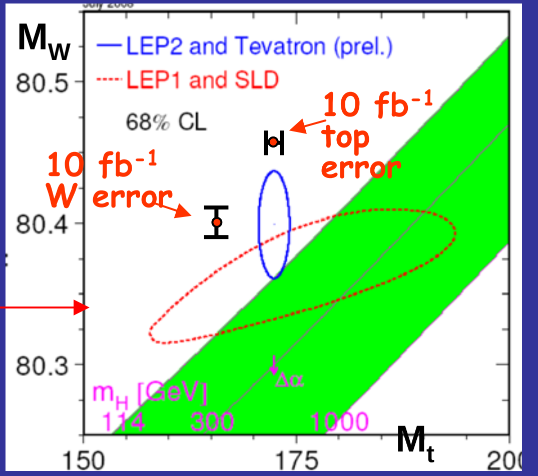
Top quark mass

There is uncertainty in what 'mass' is being measured: The experimental answer is "*whatever mass is in the Monte Carlos*". Recent measurement, using the mass obtained from comparing the measured cross section to theory, suggests that it is closer to being the 'pole mass' than the '$\overline{MS}$ mass'.

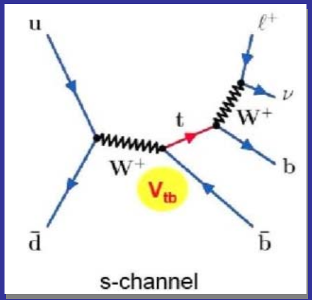
Further improvements to the mass will be modest as the measurements are systematics limited. But it will be some time before LHC overtakes the Tevatron.

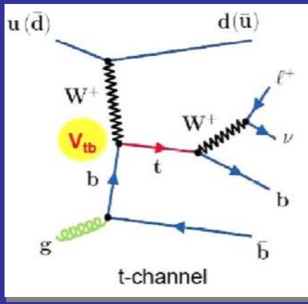
With precise knowledge of top (and W) mass, the same virtual loop processes that helped predict the top mass in 1990's can now be turned to predicting the final element of the SM, the the Higgs boson.

Blue ellipse shows the current top and W mass values, constraining Higgs boson to values below ~150 GeV. With the full Tevatron data set, it would be possible to exclude the SM Higgs at 95% if the current top and W masses stay at current values.

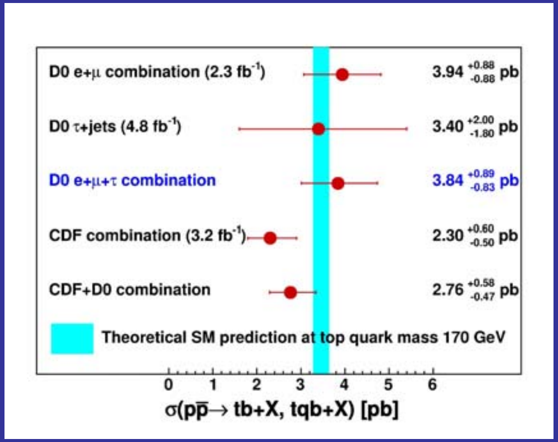


Single Top by EW production

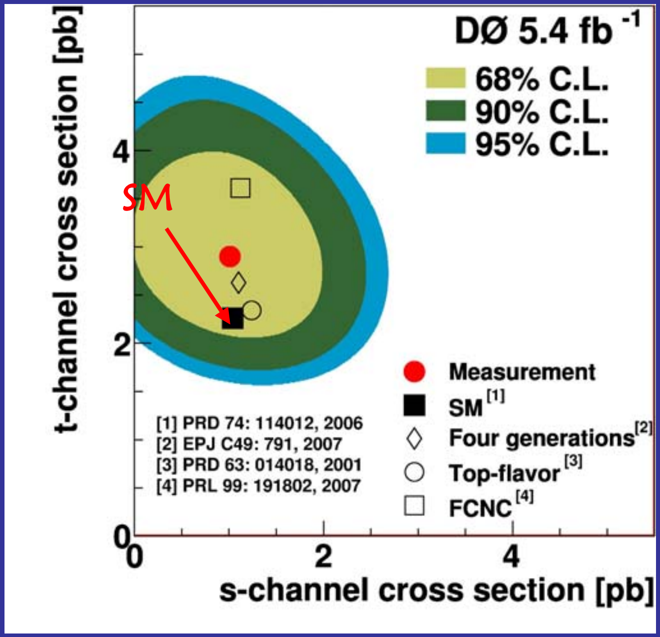




Top quarks were discovered in strong interaction pair-production (preserving flavor symmetry), but single top quarks can also be produced by EW interaction via s-channel or t-channel W exchange). SM predicts $\sigma \approx 3.2$ pb. DØ and CDF made first observations in 2009.



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

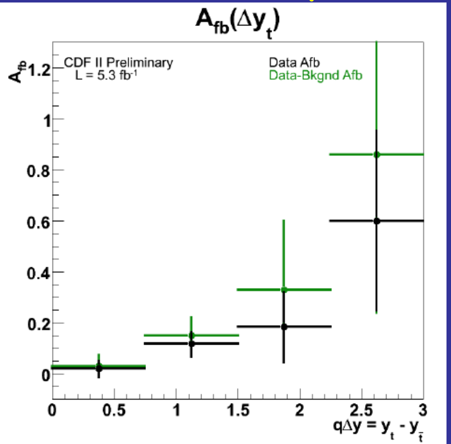


Now we are obtaining separate t- and s-channel cross sections, with t-channel XS significance ~5.5σ. (These measurements can rule out some models for new physics.)

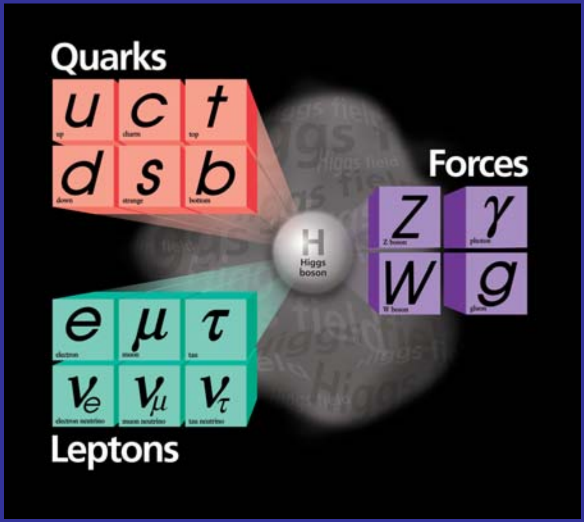
The Top gives a window for new discovery

The top quark is unique in that its Yukawa coupling (g_{ttH}) is near unity because of its large mass. This opens the possibility that new physics could be seen in its properties.

- Top decays before 'hadronizing'. Its lifetime would be affected if new particles are involved. The measured $\tau = 3.3\,^{+1.3}_{-0.9} \times 10^{-25}$ s agrees with the SM (1/3 of a yoctosecond!).
- Due the short lifetime, correlations between t and $\bar{t}$ spins are preserved in decay and are measured. Modifications from non-SM effects are not seen.
- A 4th generation t' quark could decay into the same final state (W+q) as Top. None seen below ~300 GeV.
- If a charged Higgs boson (supersymmetry inspired) exists with $M_{H\pm} < M_t$, it would alter the Top branching ratios. No such effect is seen.
- If new physics couples to the heavy Top, $t\bar{t}$ resonances would be expected. None seen < 800 GeV.
- In $\bar{p}p$ collisions, there can be a forward-backward asymmetry in top (antitop) production. In the SM, this is small. An intriguing hint of non-SM behavior is now seen in A_{FB}. The asymmetry may grow with top and anti-top rapidity separation.



Does the Top quark matter?



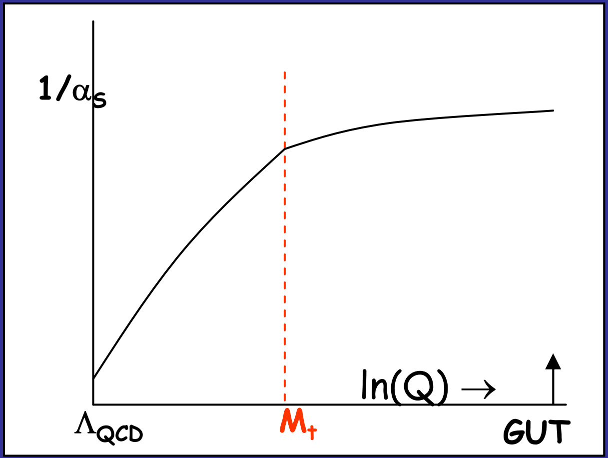
The discovery of the top quark completes the list of fundamental constituents of matter in the SM (fermions) and helps point the way to the Higgs.

Its large mass (~40x that of the b-quark, comparable to Au nucleus) is a puzzle. Does this signify that top plays a special role in generating Electroweak symmetry breaking. Is the Top the only 'normal' quark, or is it the cowbird in the quark nest?

Are there practical consequences? (C. Quigg) Assume ≈unified SU(3), SU(2) and U(1) couplings at the GUT scale and evolve α_s down to $Q=M_t$ (6 active flavors). From the QCD scale Λ_{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:

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

(Factor 40 change in M_t gives ~100% change in M_p! If M_t were at the scale of the other quarks, protons would be much lighter and our world would be quite different!)



Conclusion

- The discovery of the top quark by the CDF and DØ collaborations in 1995 completed the table of expected constituents of matter.
- That accomplishment will remain a primary legacy of the Tevatron.
- The use of the top quark to seek new physics has begun, and will continue as we enter the LHC era.