Fermilab

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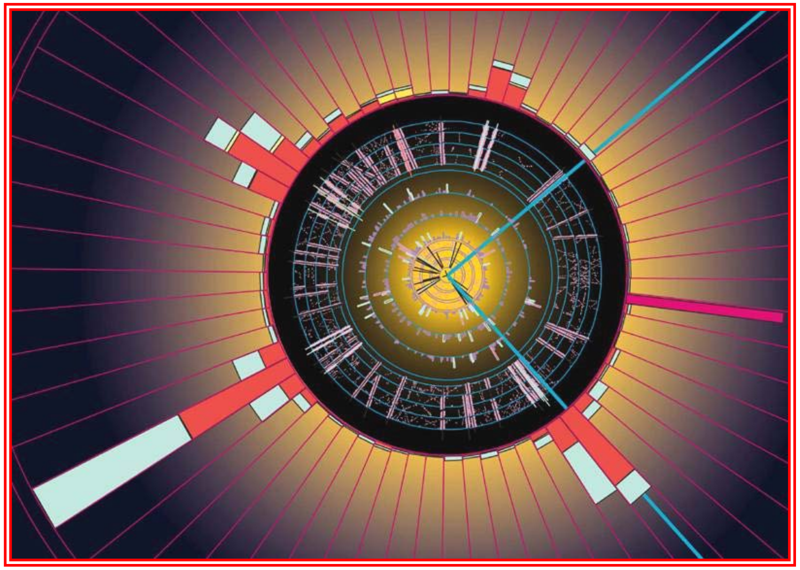
Overview and History



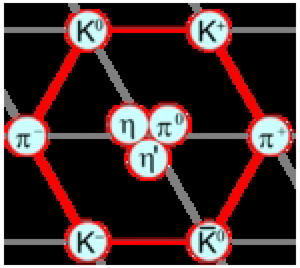
Nigel Lockyer

Top at Twenty Workshop

April 9, 2015

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.

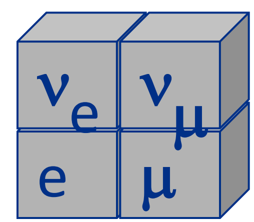
Prehistory

❖ The absence of flavor-changing neutral currents (e.g. s → d γ) 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 processes.

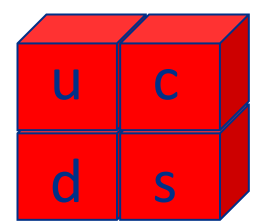
$$\underbrace{\begin{pmatrix}\nu_e\\ e^-\end{pmatrix}_L \quad \begin{pmatrix}\nu_\mu\\ \mu^-\end{pmatrix}_L}_{\text{doublets}} \qquad \underbrace{e^-_R \quad \mu^-_R}_{\text{singlets}}$$

leptons:

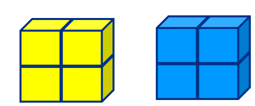


$$\underbrace{\begin{pmatrix}u\\ d'\end{pmatrix}_L \quad \begin{pmatrix}c\\ s'\end{pmatrix}_L}_{\text{doublets}} \qquad \underbrace{u_R \quad d_R \quad c_R \quad s_R}_{\text{singlets}}$$

quarks:

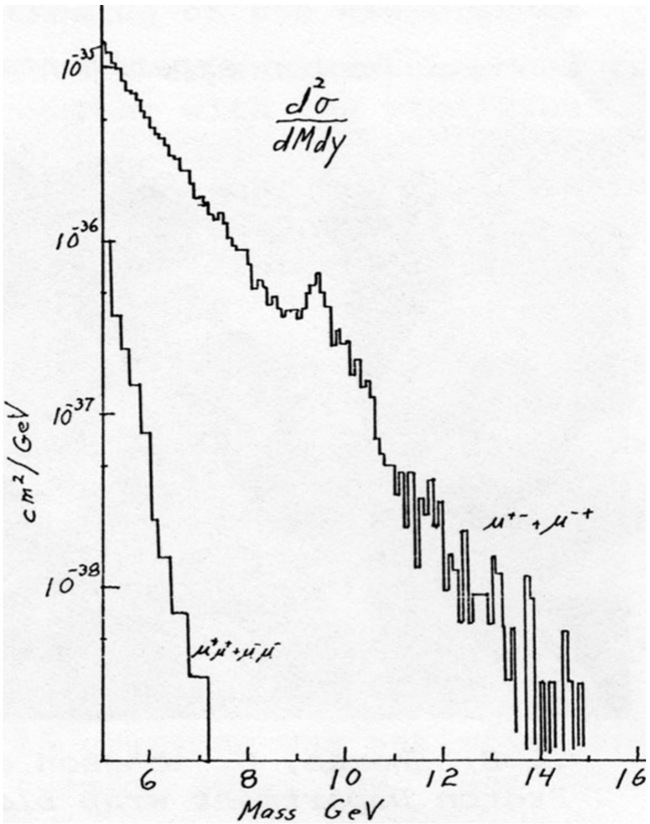


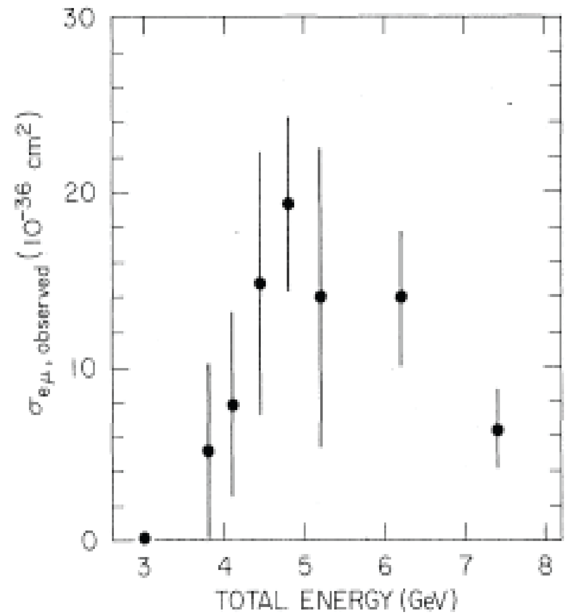
+ the other 2 color sets



Prehistory

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

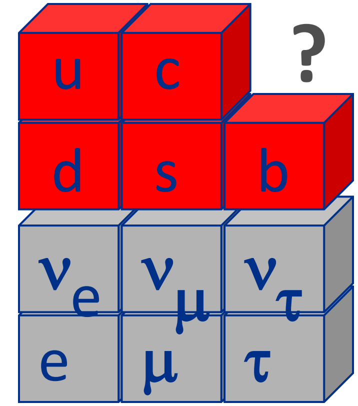




τ lepton, SLAC (1975)
($m_\tau \sim 1.8$ GeV)

❖ 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→s e^+e^- again implied that b was a member of an isodoublet and needed a 'top' partner.

Since $M_b \approx 3\text{x}M_c \approx 9\text{x}M_s$, it seemed 'natural' to guess that the new Top quark would have $M_t \approx 3\text{x}M_b \approx 15$ GeV, so a bound state of tt 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.

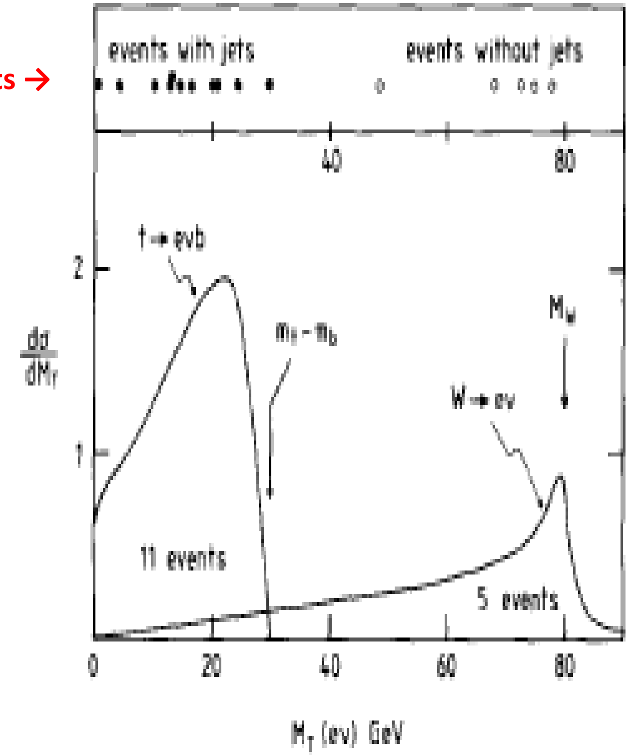
So a new e^+e^- collider Tristan, with energy up to 60 GeV, was built in Japan to find it. Alas, there was no discovery, and by late 80's, a limit $M_t > 30.2$ GeV was set.

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 $W \to tb \to (e\nu b)\, b$. The main background is QCD production of $W(e\nu)$+jets.

evts →



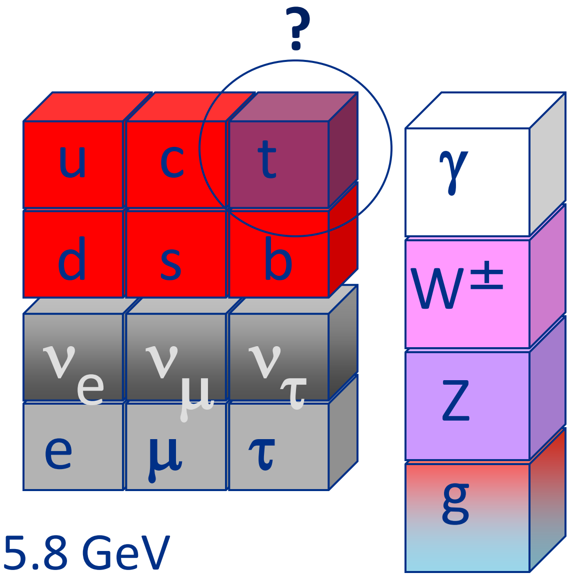
In 1984, UA1 reported evidence for an excess of events at low $M_T(e\nu)$ when jets were present, characteristic of a 40 GeV top (Arnison et al., PL B147 (1984) 493). They saw 12 events with 3.5 expected background! In retrospect we understand that the W+jets background was underestimated.

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

Fermilab

Prehistory

So where is (isn't) the top?



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

- 1990: UA2 set a limit ($W \rightarrow tb$) at 69 GeV, effectively closing the search channel $W \longrightarrow$ 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

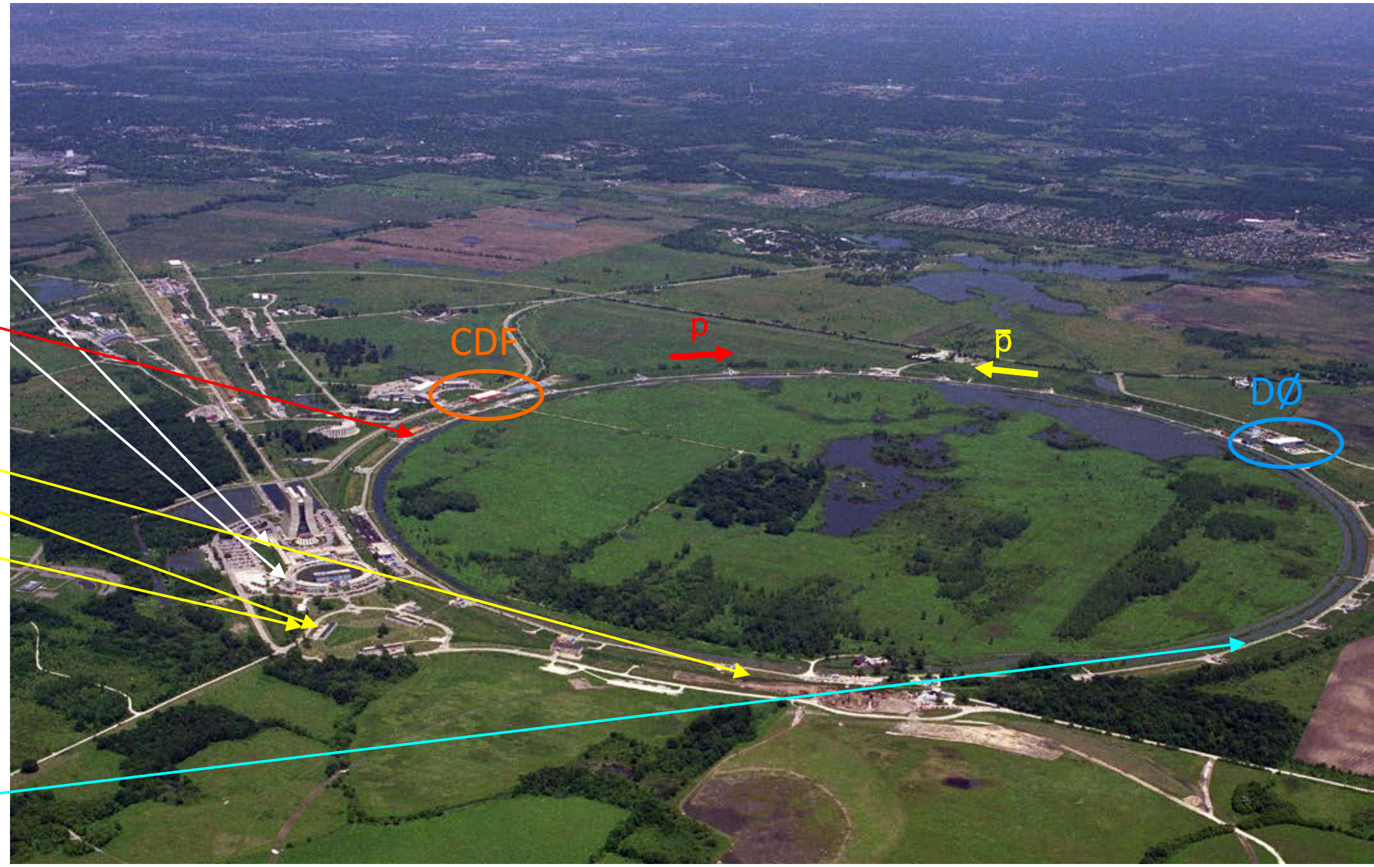
150 GeV Main Ring

p target

8 GeV Debuncher

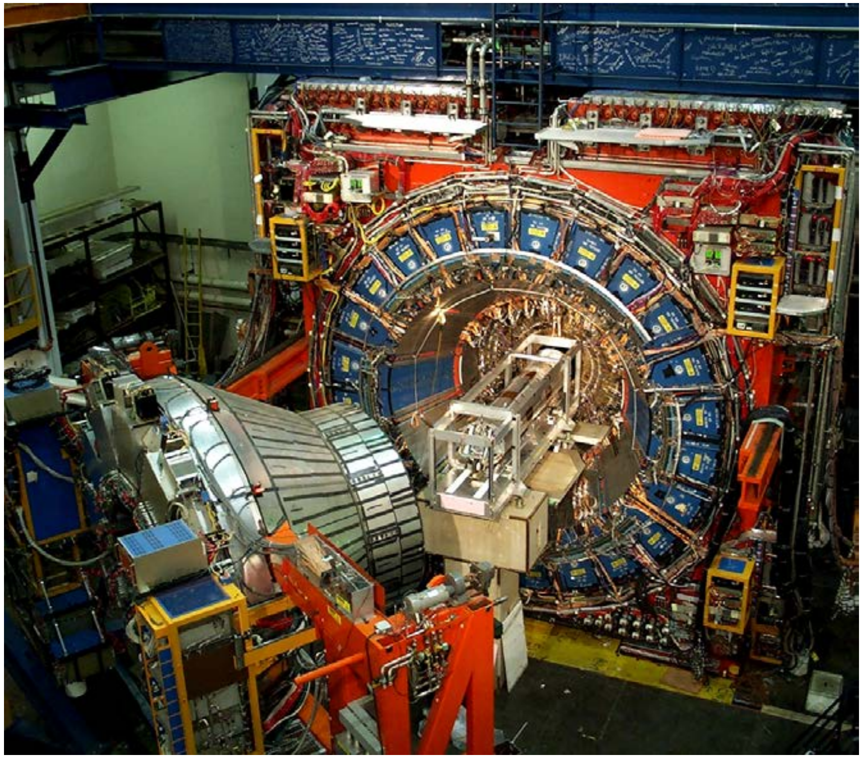
8 GeV Accumulator

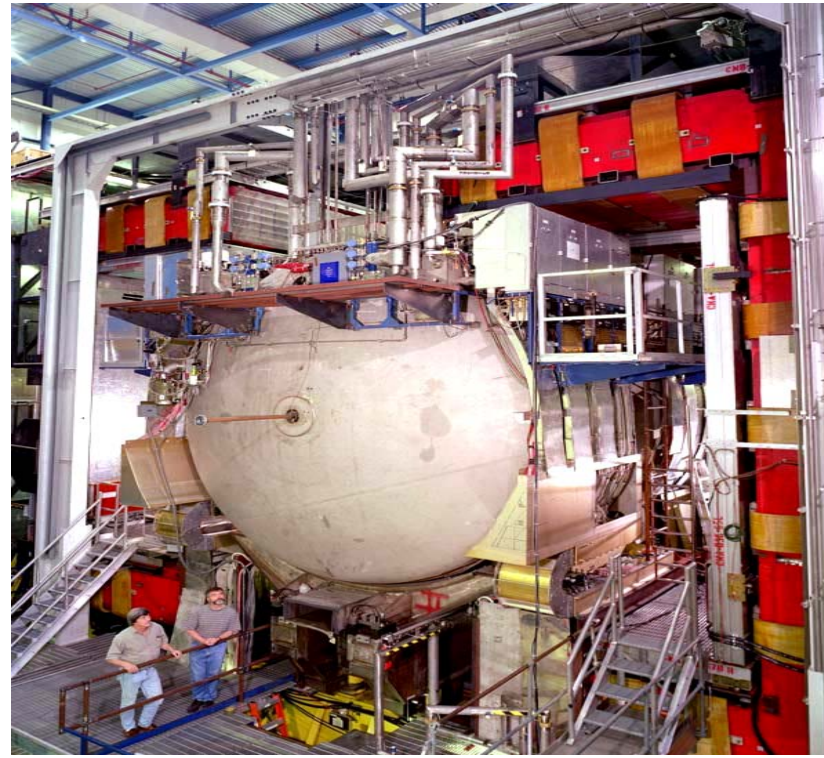
1800 GeV Tevatron with counter-rotating protons and anti-protons



The Tevatron complex steadily increased the luminosity, which in 1995 rose to about $2\text{x}10^{31}$ $\text{cm}^{-2}\text{s}^{-1}$. 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 solenoid 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.

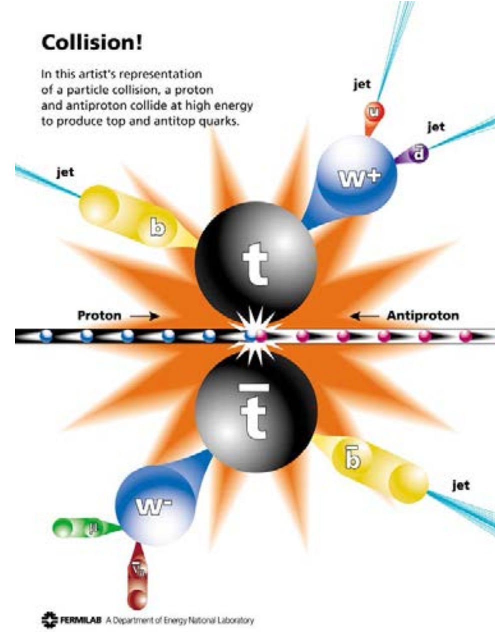
Toward discovery

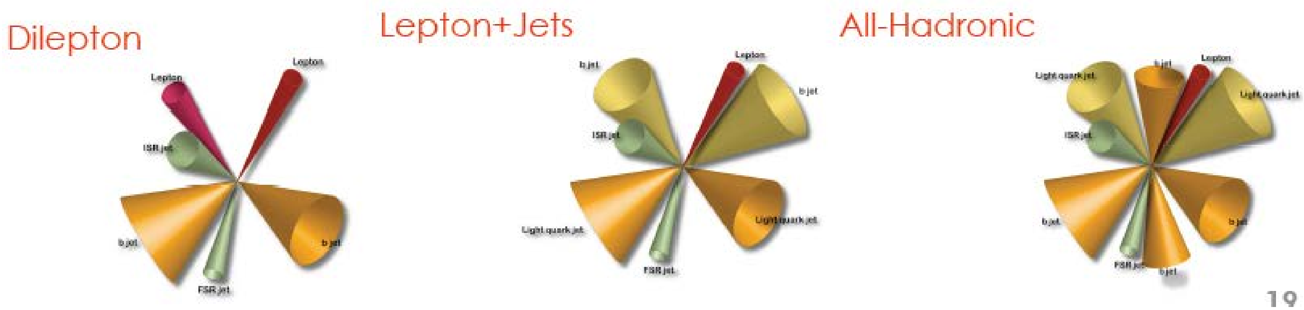
$t\bar{t}$ search channels:

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

decays: 33% (eν, μν, τν) or 67% ($u\bar{d}_W$, $c\bar{s}_W$)

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





Low background, low rate

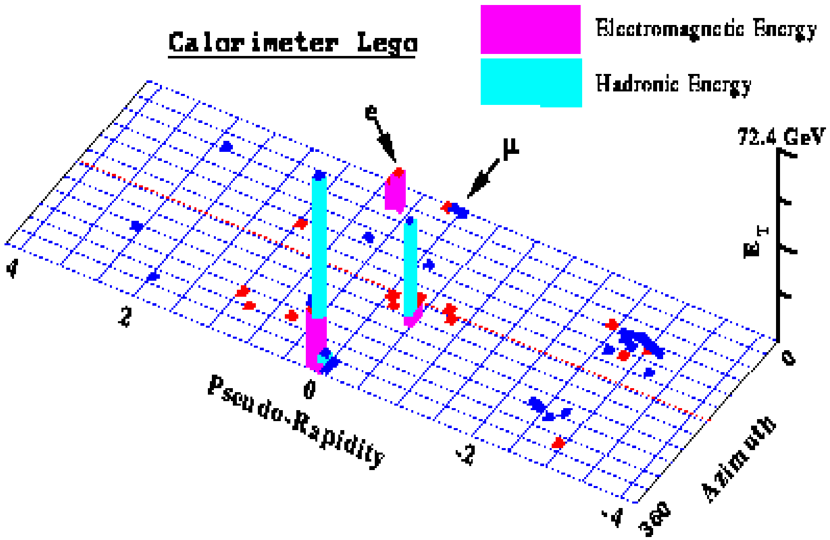
modest background, higher rate

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.)

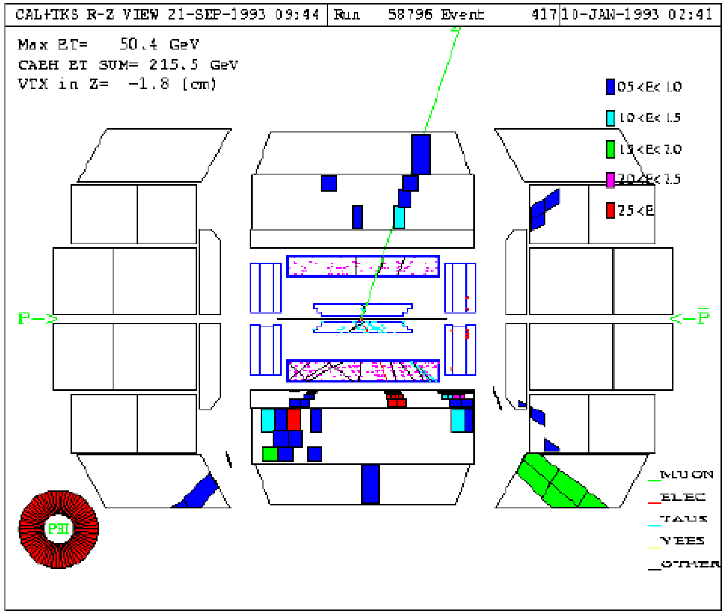
Toward discovery

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 (tt→(eνj) (μνj), mass was consistent with M_t=(145-200) GeV.

Toward discovery

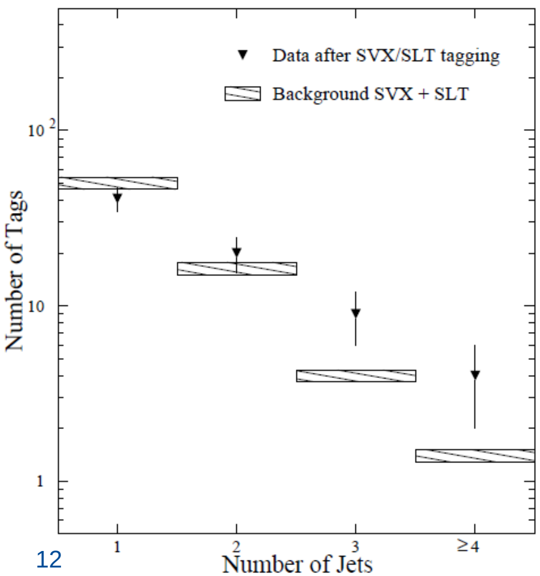
In early 1994, CDF published an analysis based on 19 pb^{-1} in which they found 2 events with $e\mu$ + 2jets and MET, and 10 events with e or μ + ≥3 jets and MET, in which at least one of the jets is b-tagged by the silicon vertex detector or a by semileptonic decay. The estimated background (W+jets,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

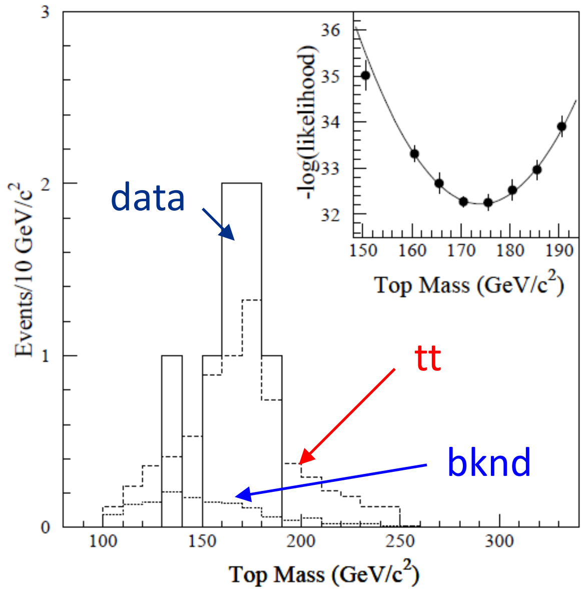
F. Abe et al, PRL, 73, 225 (1994), "Evidence for Top Quark Production …"

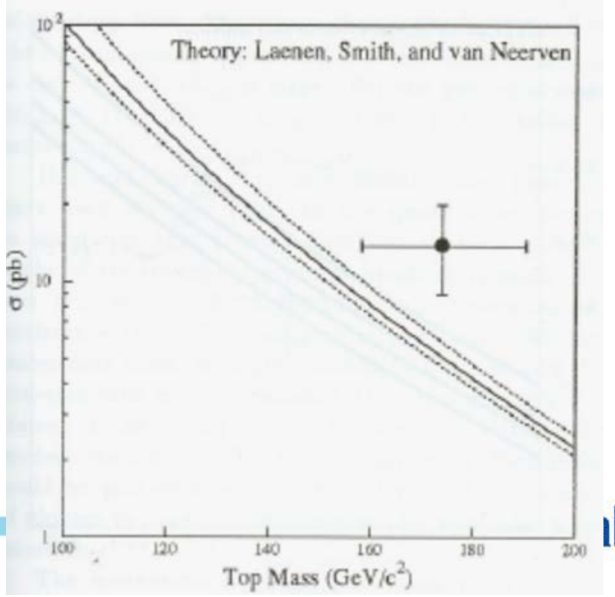
Excess over expectation appears for ≥3 jets

Mass fit from MC templates yields 174 ± 16 GeV

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







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).

Papers submissions

CDF Top quark discovery

VOLUME 74, NUMBER 14 PHYSICAL REVIEW LETTERS 3 APRIL 1995

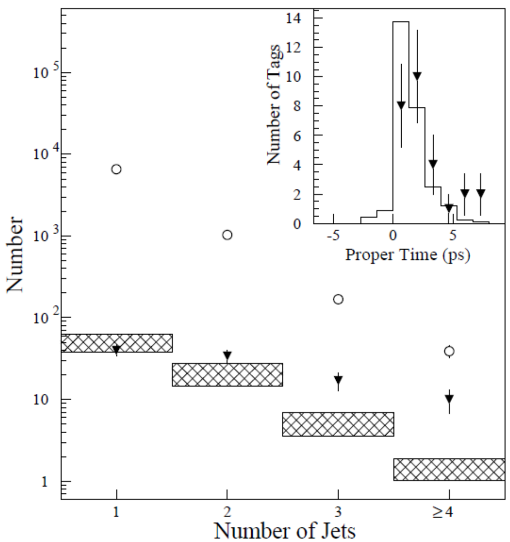
Observation of Top Quark Production in $\bar{p}p$ Collisions with the Collider Detector at Fermilab

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]

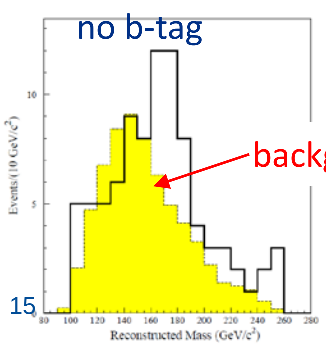
We establish the existence of the top quark using a 67 pb^{-1} data sample of $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV collected with the Collider Detector at Fermilab (CDF). Employing techniques similar to those we previously published, we observe a signal consistent with $t\bar{t}$ decay to $WWb\bar{b}$, 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 $176 \pm 8(\text{stat}) \pm 10(\text{syst})$ GeV/c^2, and the $t\bar{t}$ production cross section to be $6.8^{+3.6}_{-2.4}$ pb.

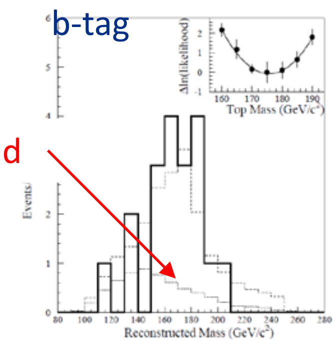
CDF's selection followed the 'evidence' paper strategy with an improved b-tagging algorithm. They found 6 dilepton events and 43 lepton+jets events (50 b-tags), with estimated background of 22.1±2.9 tags.

- $M_t = 176 \pm 13$ 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

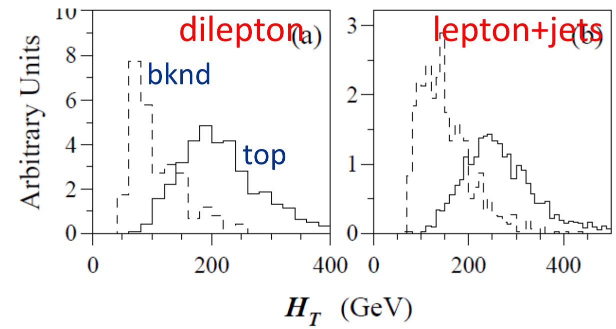
Observation of the Top Quark

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.

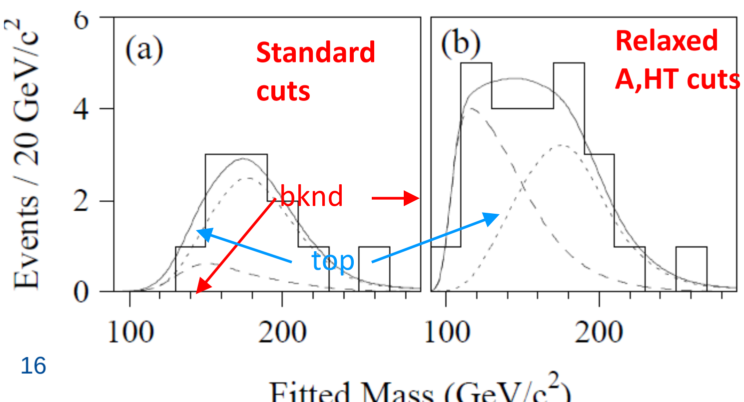
DØ's selection refined the topological (A,H_T) selection to improve signal/bknd by x2.6. With tight cuts, found 3 dilepton events, 8 lepton+jets events (topological selection) and 6 lepton+jets events (μ tag). Estimated background to these 17 events was 3.8 ± 0.6 events.

- $M_t = 199 \pm 30$ GeV
- $\sigma_{tt} = 6.4 \pm 2.2$ pb
- Bknd-only hypothesis rejected at 4.6σ

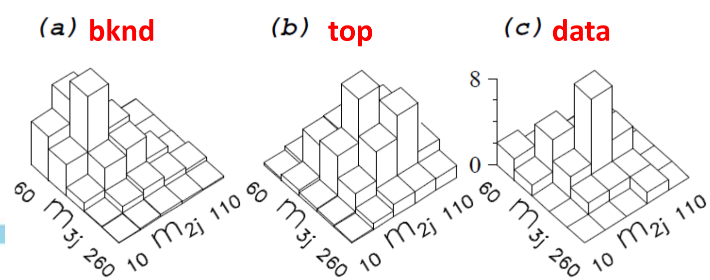


H_T distributions for signal and background

Reconstructed mass distribution



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



Top quark discovery

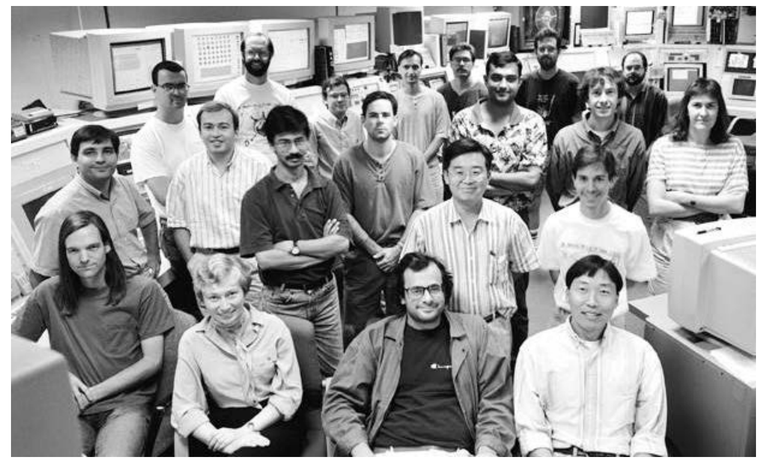
March 2, 1995: Joint CDF/DØ seminar announcing the top quark discovery

Fermilab

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)



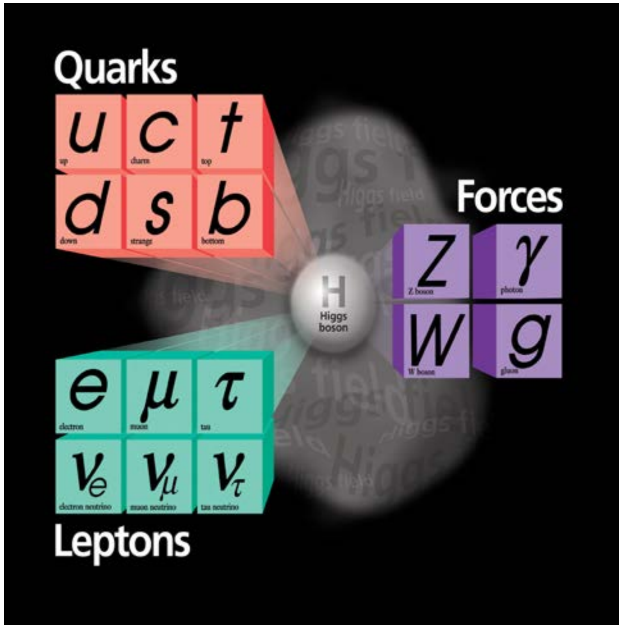
But far more important were those who did the hard work in the trenches. Here are some of the DØ PhD students in 1995.

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.

Does the Top quark matter?



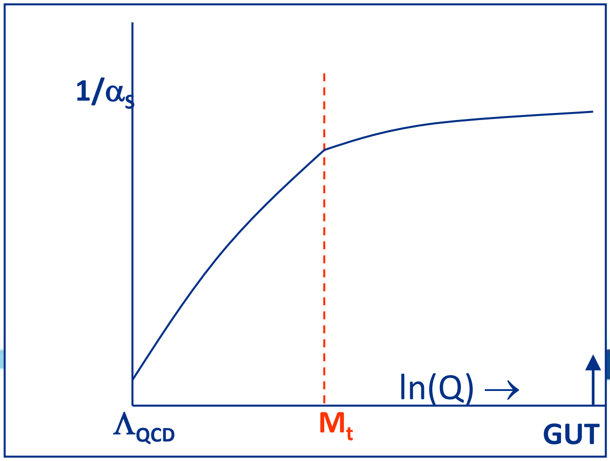
The discovery of the top quark completes the list of fundamental constituents of matter in the SM (fermions) and helps point the way to the Higgs.

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?

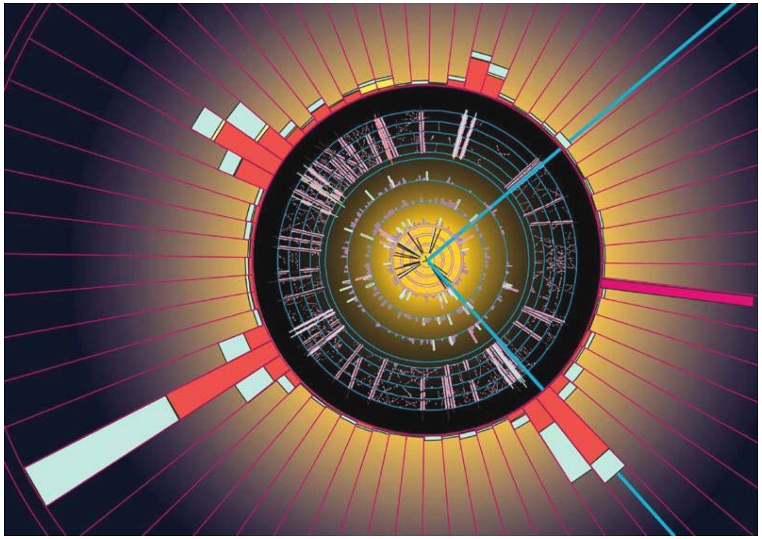
Are there practical consequences? (C. Quigg) Assume ≈unified SU(3), SU(2) and U(1) couplings at the GUT scale and evolve α_s down to $Q=M_t$ (6 active flavors). From the QCD scale Λ_{QCD}, which sets the mass of the proton, we can evolve up to $Q=M_t$ (3, 4, 5 flavors). Matching $1/a_s$ at $Q=M_t$, one 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!)



Conclusions



- 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 Tevatron and the LHC data are analyzed.