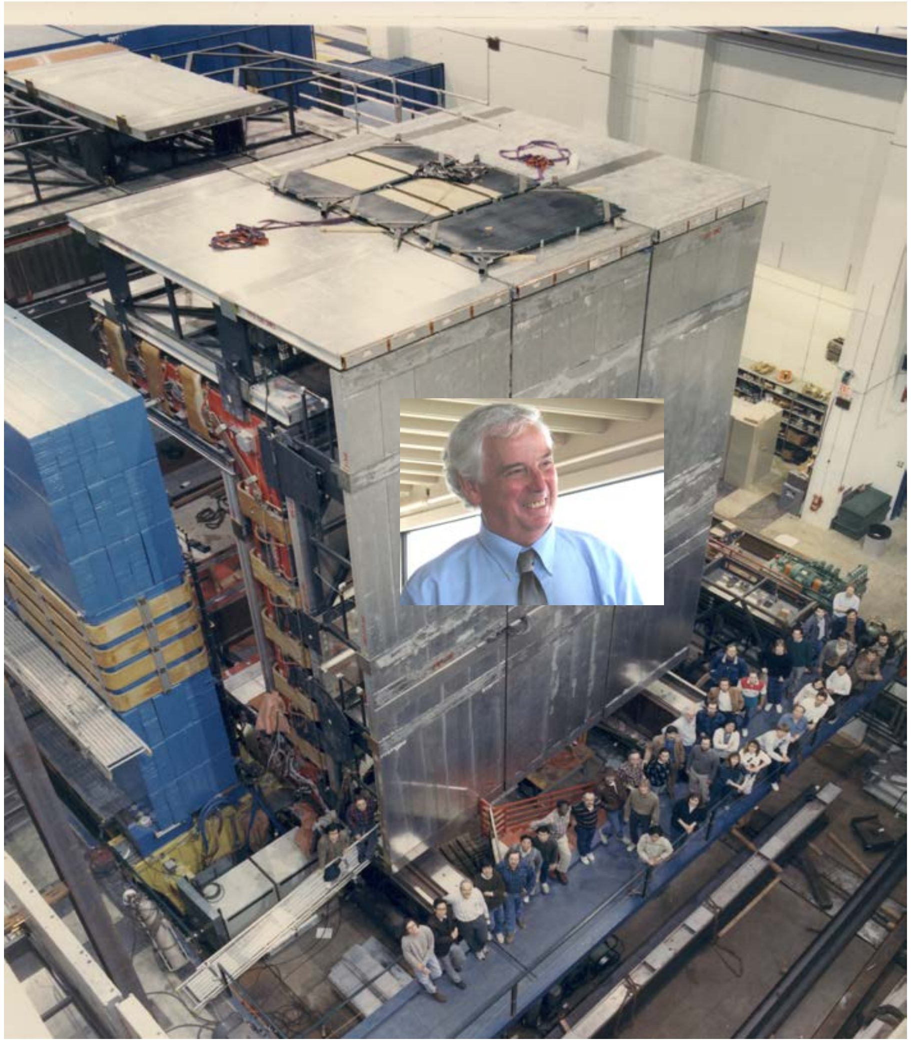
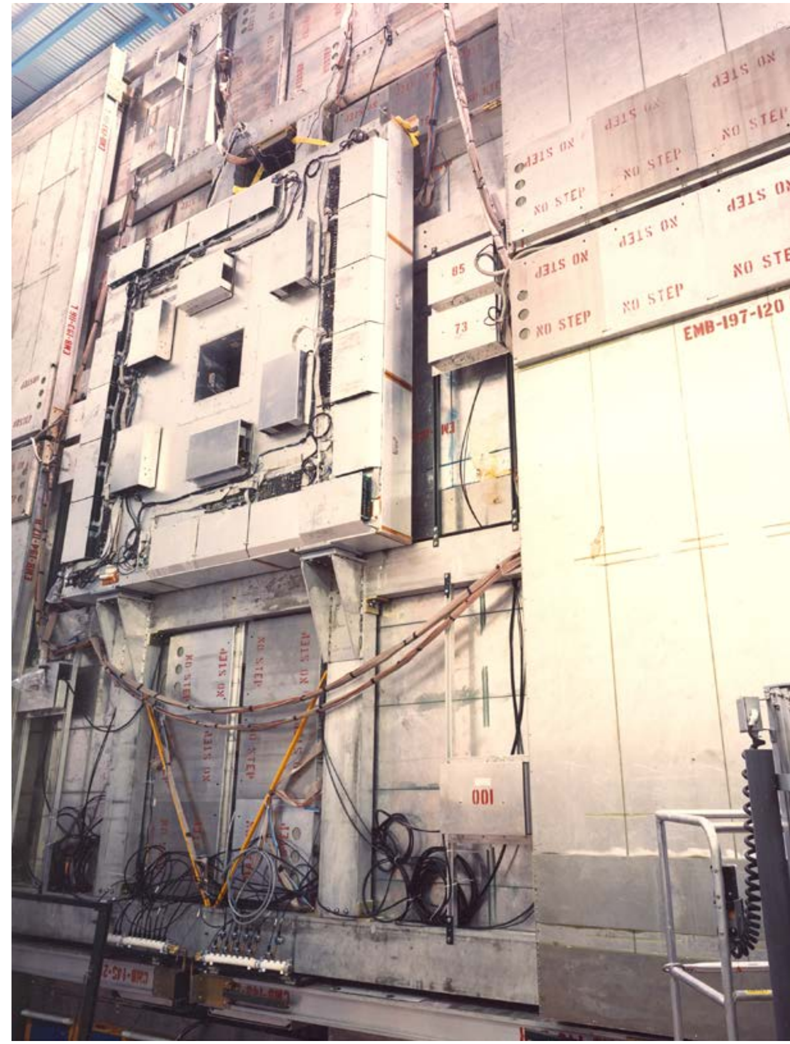
Top Quark Discovery

DanFest, October 19, 2018

Dmitri Denisov, Fermilab
with slides from talk by Paul Grannis
at Saclay on May 27, 2011

D0 Run I Muon System





Dan Green led the design and construction of the D0 Run I muon system

D0 Note # 21, October 1983

GREEN
10/83

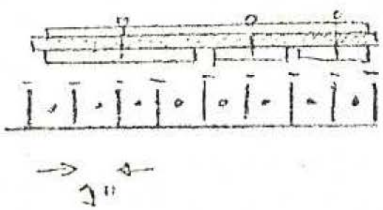
(17)

PAD CHAMBER TESTS

[redacted]

① CONSTRUCTION

THE CONSTRUCTION IS AN ATTEMPT TO APPROXIMATE VERY SIMPLE CONSTRUCTION. AN OLD E594 EXTRUSION (ALUMINUM) WAS USED

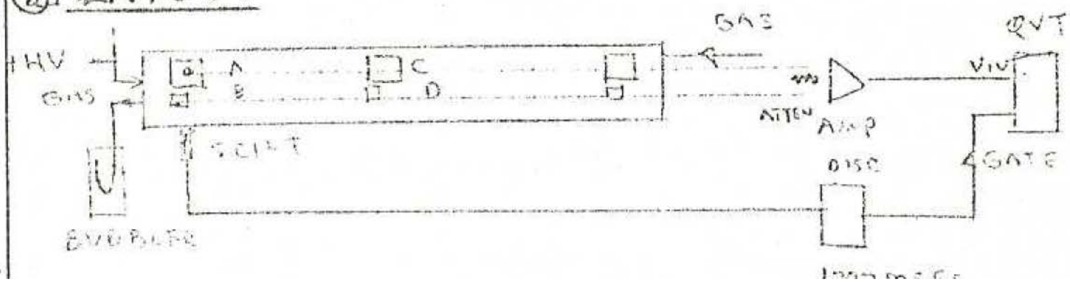


WIRE OVER GROUND READOUT, DRILLED TO PAD AND SOLDERED G-10 Cu CLAD, 4"x4" AND 2"x2" PADS, MILLED KAPTON TAPE

Al EXTRUSION, 50 μm WIRE, Au CLAD W

THE EXTRUSION IS ~12' LONG

② LAYOUT



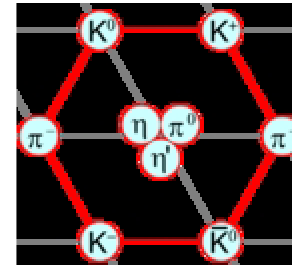
GAS FLOW ~0.8 SCFH

BUBBLES

USE Ar-CO2 (50/50) AND Ar-ETHANE (50/50)

Quarks Model

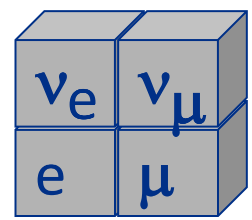
- In 1964, Gell-Mann and Zweig proposed quarks to explain hadron spectroscopy, using an isodoublet (u, d) with Q = (+2/3, -1/3), S = 0 and the isosinglet s-quark (Q=-1/3) S=-1
- The absence of flavor-changing neutral currents (e.g. s → d γ) led Glashow, Iliopoulous & Maiani (1970) to propose a 4th (charm) quark to form an analogous isodoublet. 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



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

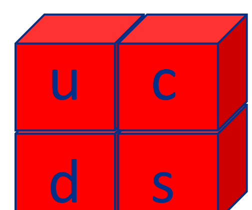
$$\underbrace{\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L}_{\text{doublets}} \qquad \underbrace{e^-_R \quad \mu^-_R}_{\text{singlets}}$$

leptons:

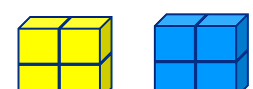


$$\underbrace{\begin{pmatrix} u \\ d' \end{pmatrix}_L \quad \begin{pmatrix} c \\ s' \end{pmatrix}_L}_{\text{doublets}} \qquad \underbrace{u_R \quad d_R \quad c_R \quad s_R}_{\text{singlets}}$$

quarks:

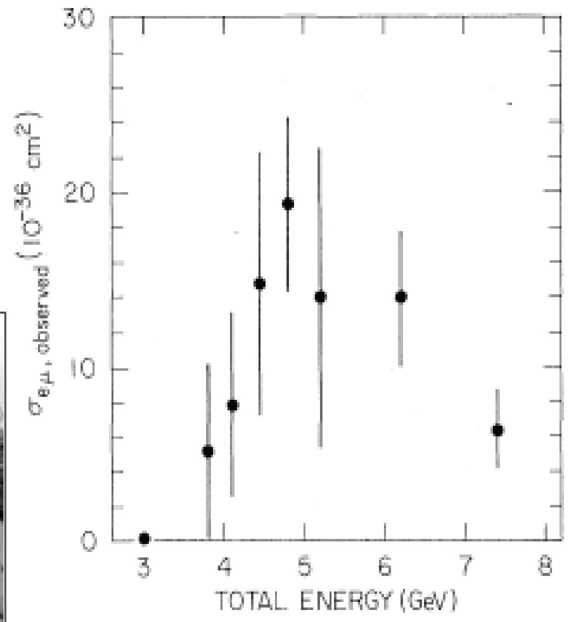


+ the other 2 color sets

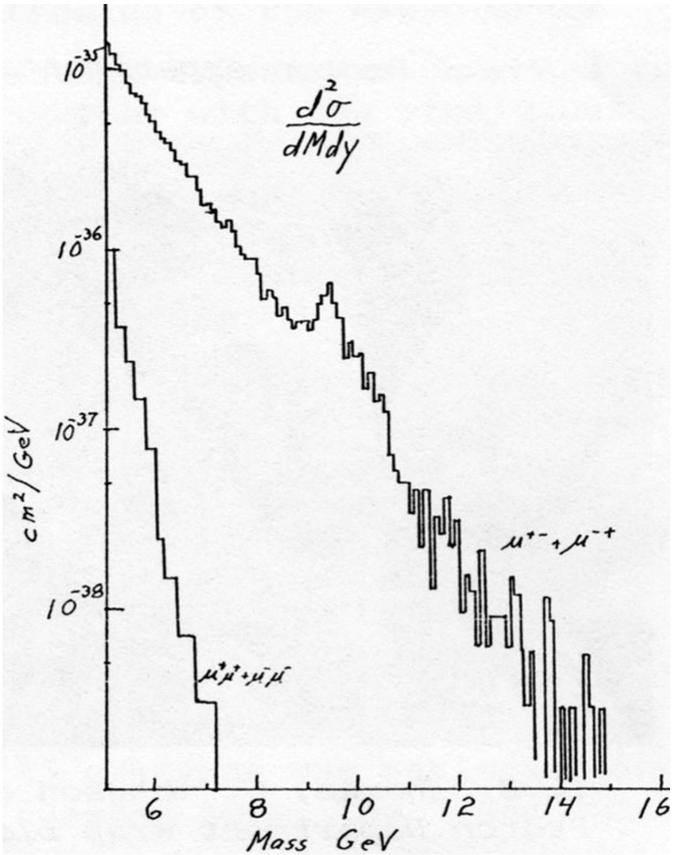


τ Lepton and b-quark

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

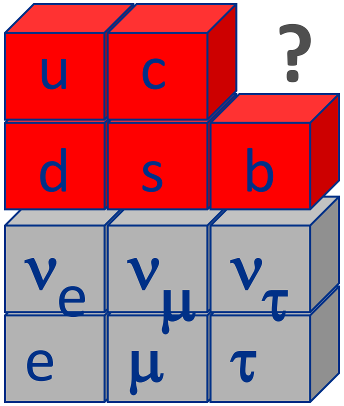


τ lepton, SLAC (1975)
($m_\tau \sim 1.8$ GeV)



- In 1977, the Upsilon at 9.5 GeV was discovered at Fermilab and was understood to contain a new 5th quark, bottom, and its anti-quark

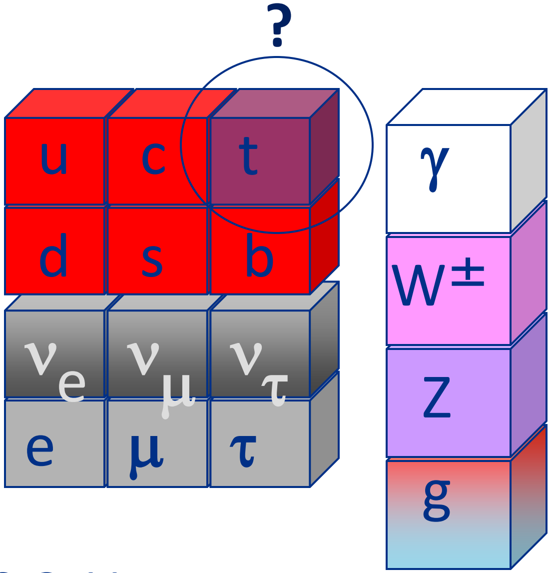
Race to "the top"



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

- The absence of FCNC reactions like $b \to s\ e^+e^-$ again implied that b was a member of an isodoublet and needed a 'top' partner
- Since $M_b \approx 3xM_c \approx 9xM_s$ it seemed 'natural' to guess that the new top quark would have $M_t \approx 3xM_b \approx 15$ 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
- A new e^+e^- collider Tristan, with energy up to 60 GeV, was built in Japan to find the top
  - There was no discovery, and by late 80's, a limit $M_t > 30.2$ GeV was set

Limits, Limits, Limits…

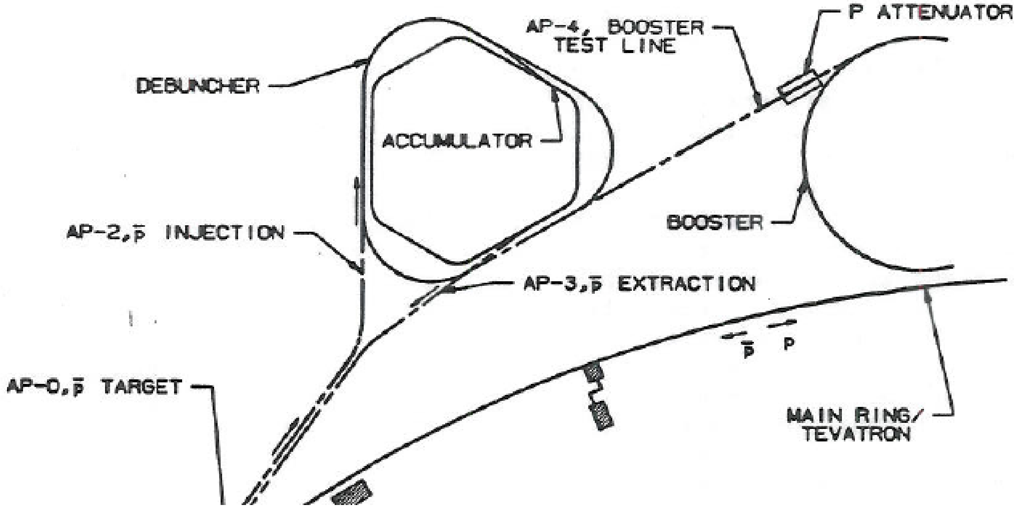


So where is (isn't) the top?

- ~1990: LEP experiments set limits $M_t > 45.8$ GeV
- 1990: UA2 set a limit (W→tb) at 69 GeV, effectively closing the search channel W ⟶ top
- 1992: CDF at the Tevatron, now searching for tt 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 limit $M_t > 131$ GeV

Toward Tevatron

- In 1978 the decision was to first build the doubler – 1 TeV superconducting fixed target accelerator
  - With an option to develop it into collider later
- By 1981 the doubler construction was progressing well and "Tevatron I Project" (colliding beams) got the Department of Energy budget
  - Cost was $80 million without R&D…



The Last Tevatron Magnet Installed March 18, 1983

Helen Edwards signs last magnet installation plaque

Fermilab

Antiproton Accumulator Construction December 1983

- In 1983 Tevatron fixed target run at 800 GeV started
  - While collider program was quickly progressing

The Central Players – the Accelerators

400 MeV Linac

8 GeV Booster

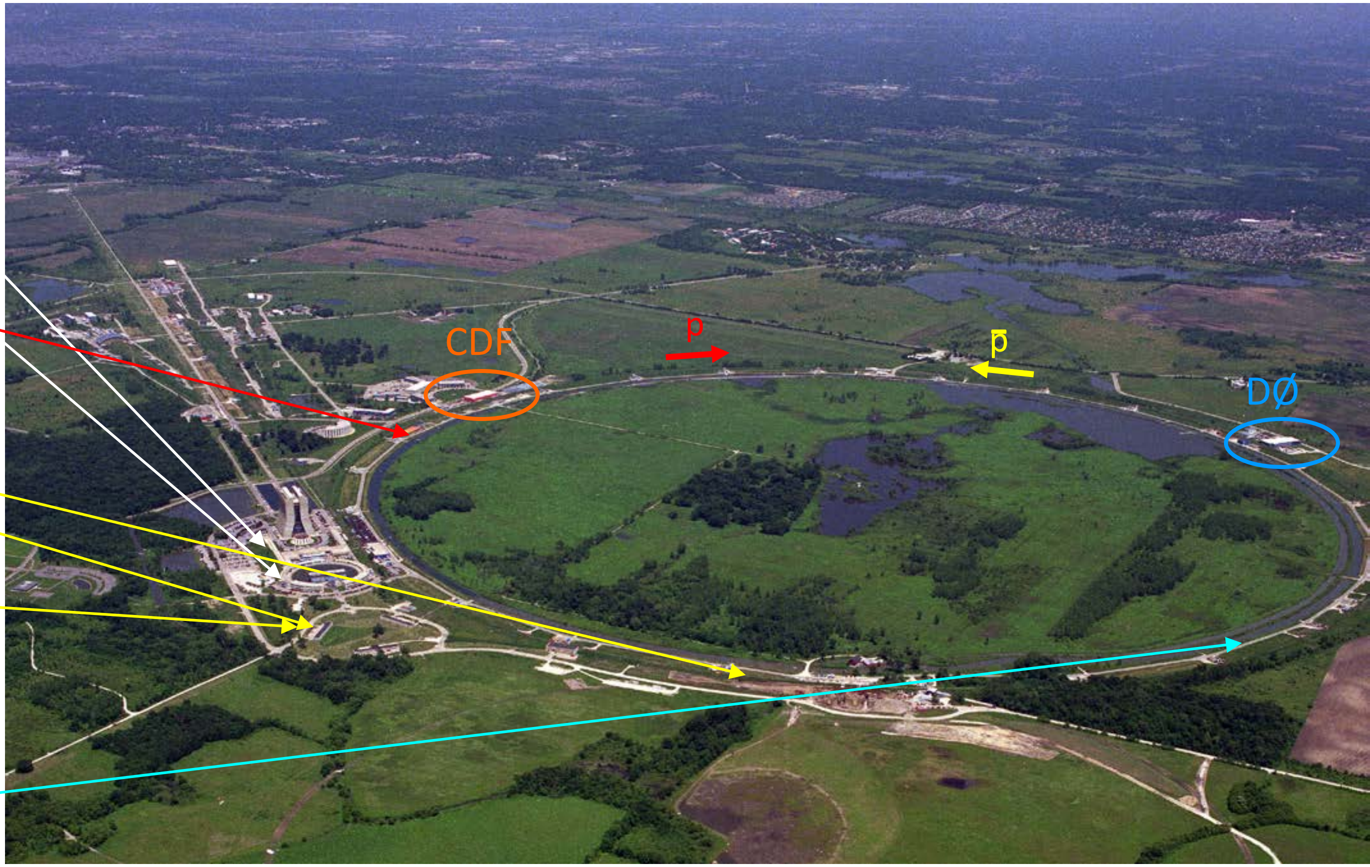
150 GeV Main Ring

p target

8 GeV Debuncher

8 GeV Accumulator

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



The exceptional design and performance of the accelerators and the collider was critical to enabling the top quark discovery

Tevatron Run I Performance

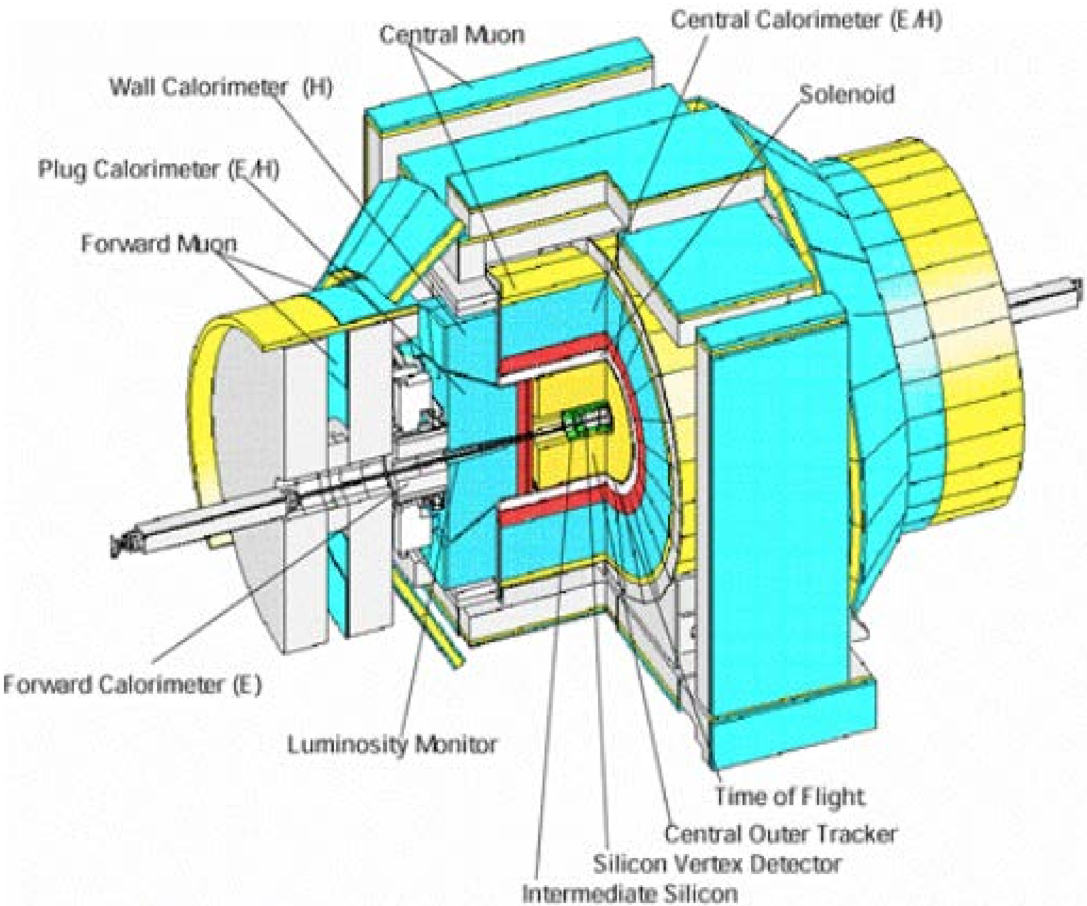
	Run Ia	Run Ib
Duration	August 1992-June 1993	November 1993-February 1996
Peak Luminosity	9.2×10^{30} cm^{-2} sec^{-1}	2.5×10^{31} cm^{-2} sec^{-1}
Typical Luminosity	5×10^{30} cm^{-2} sec^{-1}	1.6×10^{31} cm^{-2} sec^{-1}
Stacking Rate	4.85×10^{10} hr^{-1}	7.02×10^{10} hr^{-1}
Maximum Stack Size	150×10^{10} $\bar{p}$'s	221×10^{10} $\bar{p}$'s
Delivered Integrated Luminosity		147 pb^{-1}

- "Run I" was the first main Run of the Tevatron – 1992-1996
  - Initial Tevatron collider run in 1988-89, ~5 pb^{-1}
- Still well below one interaction per crossing…
  - Even with 3 μs beams crossing time

Tevatron Experiments - CDF

- Designed as general purpose detector in 1980

- Excellent tracker in solenoidal magnetic field
- Extensive calorimetry and muon systems
- Addition for the first time at hadron colliders of silicon vertex detector for 1992 Run



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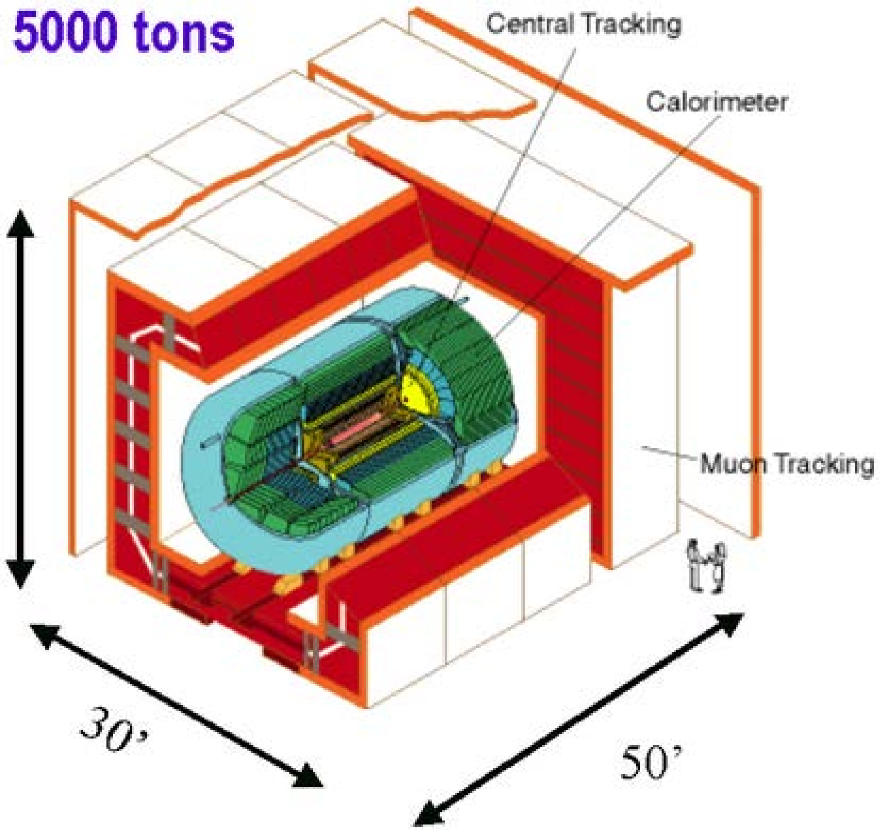
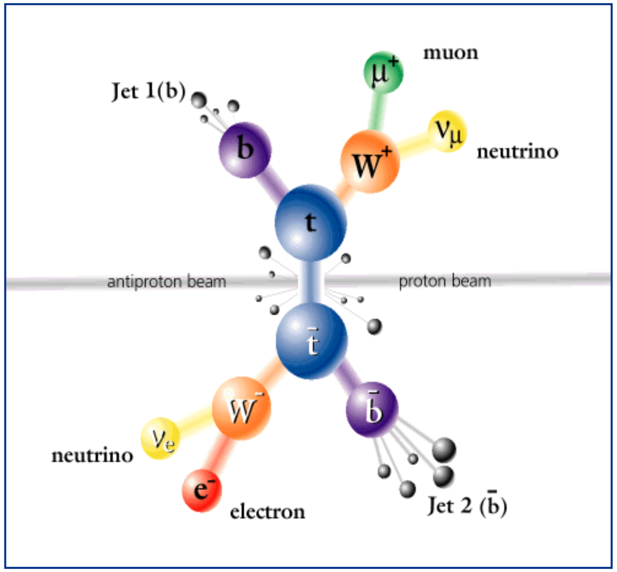
Tevatron Experiments - DØ

- Proposed in 1984 as second large Tevatron collider experiment

- Idea - hermetic calorimetry and muon systems, while no central magnetic field
- Excellent resolution of uranium liquid argon calorimeter helped greatly with many studies
- Elaborate multi-level trigger system



Toward Discovery

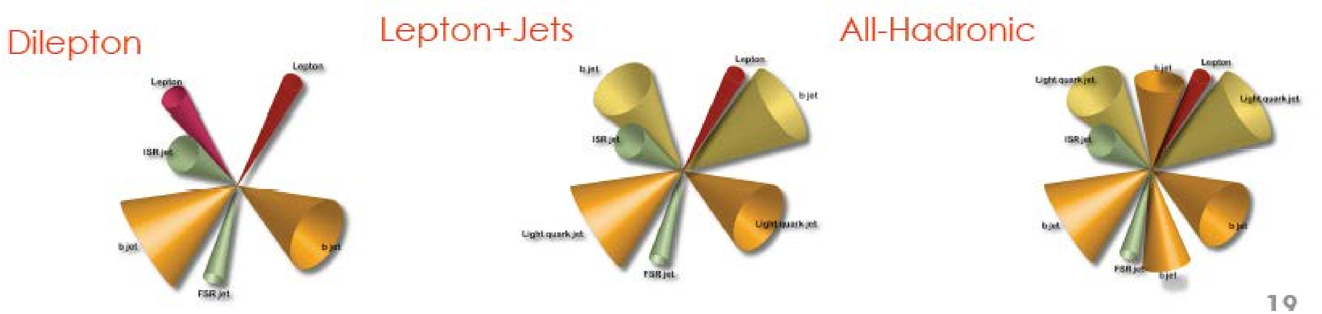


tt pair production search channels:

In SM top quark decays ~100% of time to W+b

W decays: 33% (eν, μν, τν) or 67% (pair of quarks)

Final states reached from tt then characterized by



Low background, low rate

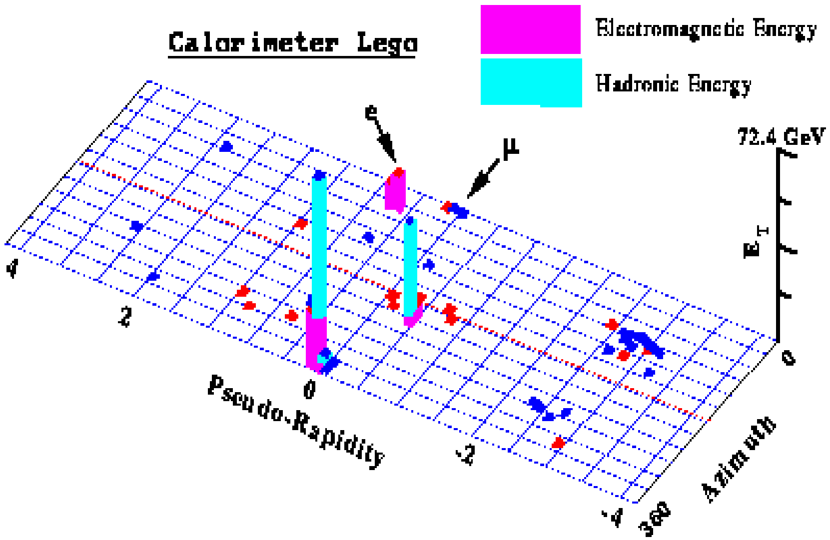
Modest background, higher rate

Large background, highest rate

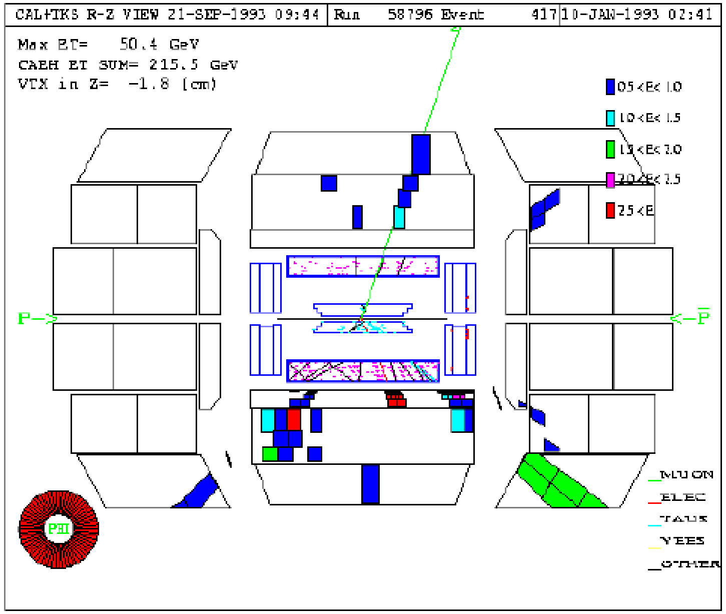
For the top discovery, used only e and μ (τ was difficult), and did not use the high background all-jets channel

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

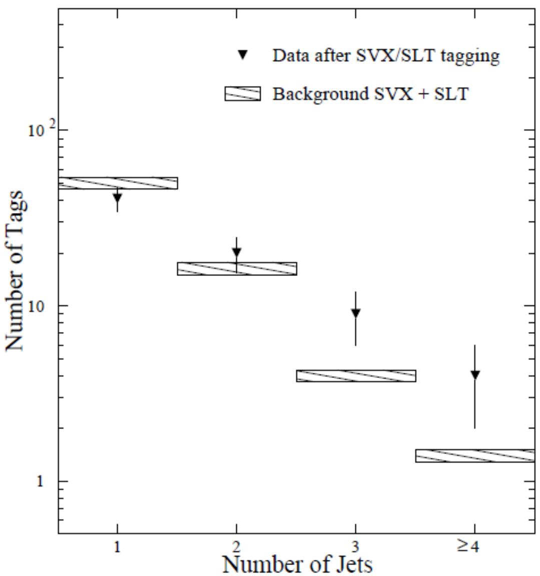
If hypothesize to be from top pair production ($tt \rightarrow (e\nu j)\ (\mu\nu j)$), mass was consistent with M_t=(145-200) GeV

Toward Discovery

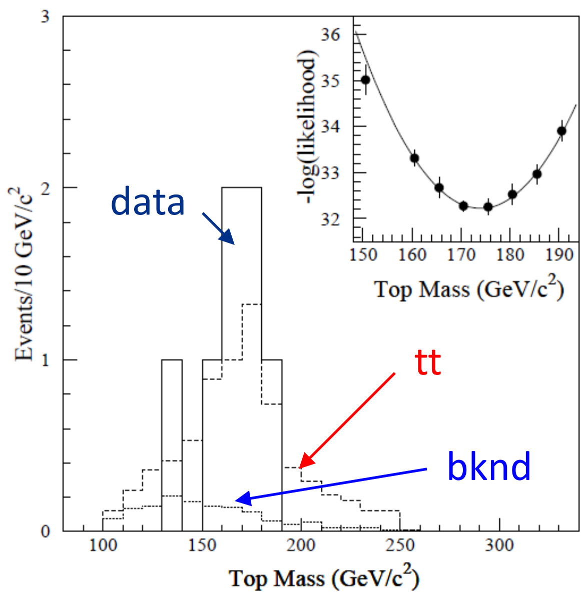
In early 1994, CDF published an analysis based on 19 pb^{-1} in which CDF found 2 events with eμ + 2jets and MET, and 10 events with e or μ + ≥3 jets and MET, in which at least one of the jets is b-tagged by the silicon vertex detector or by semileptonic decay. The estimated background (W+jets, QCD multijets) was 6.0 $\pm$ 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 …"

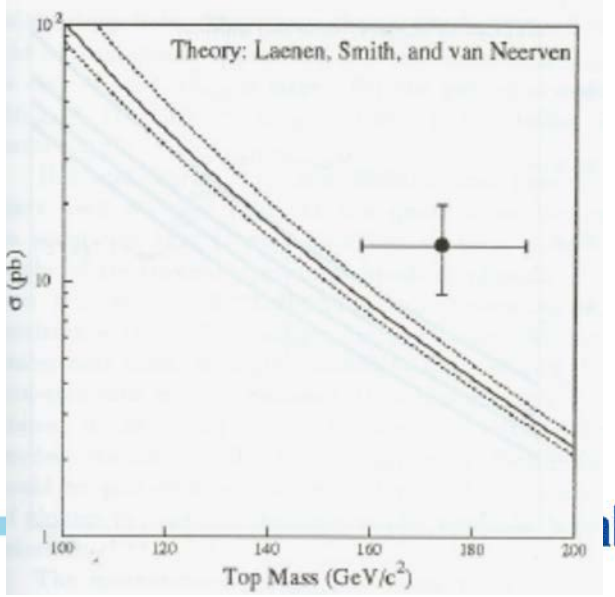
Excess over expectation appears for ≥3 jets



Mass fit from MC templates yields 174 $\pm$ 16 GeV



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



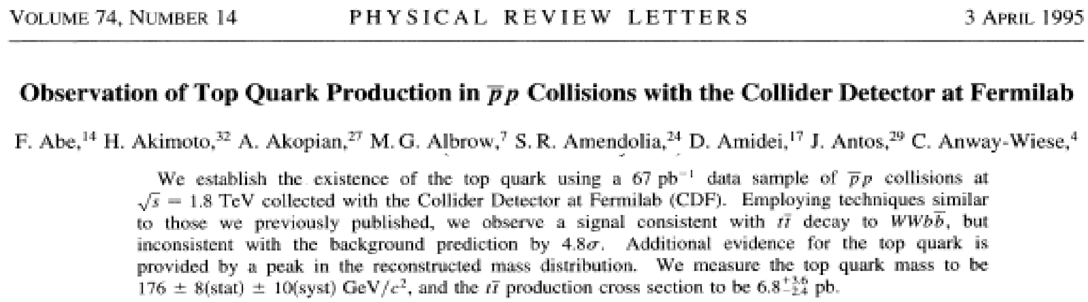
Final Push…

- By January 1995, after a significant improvement in the Tevatron (fixing a rotated magnet) both collaborations had collected >50 pb^{-1} which was needed for ~5σ discovery for a mass of 175 GeV
- 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
- 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 finishing data collection 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.

Papers submissions



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

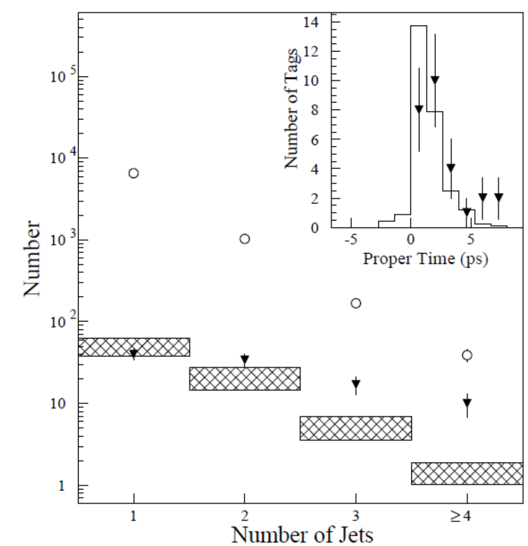
F. Abe,[14] H. Akimoto,[32] A. Akopian,[27] M. G. Albrow,[7] S. R. Amendolia,[24] D. Amidei,[17] J. Antos,[29] C. Anway-Wiese,[4]

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.

Top Quark Discovery

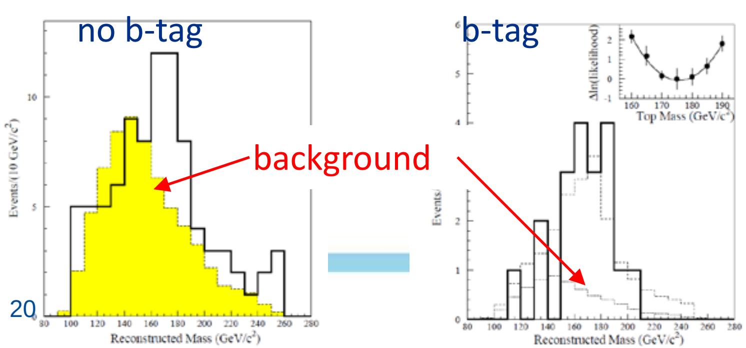
CDF's selection followed the 'evidence' paper strategy with an improved b-tagging algorithm. CDF found 6 dilepton events and 43 lepton+jets events (50 b-tags), with estimated background of 22.1±2.9 tags

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



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

Reconstructed mass distribution before and after b-tagging.



VOLUME 74, NUMBER 14 PHYSICAL REVIEW LETTERS 3 APRIL 1995

Observation of the Top Quark

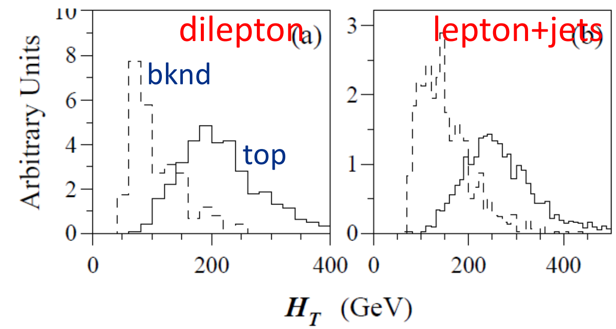
S. Abachi,[12] B. Abbott,[33] M. Abolins,[23] B. S. Acharya,[40] I. Adam,[10] D. L. Adams,[34] M. Adams,[15] S. Ahn,[12] H. Aihara,[20]

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.

Top quark discovery

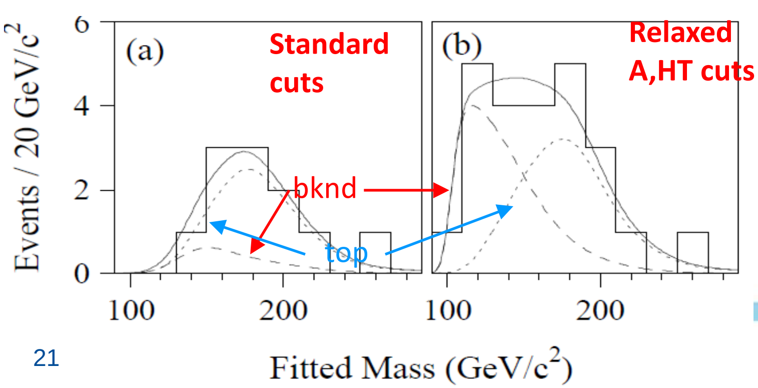
DØ's selection refined the topological (A,H_T) selection to improve signal/bknd by x2.6. With tight cuts, found 3 dilepton events, 8 lepton+jets events (topological selection) and 6 lepton+jets events (μ tag). Estimated background to these 17 events was 3.8±0.6 events.

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

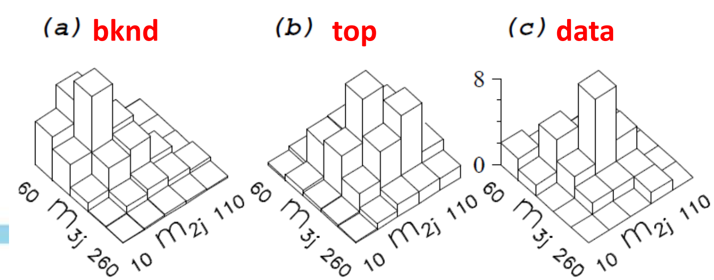


H_T distributions for signal and background

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.

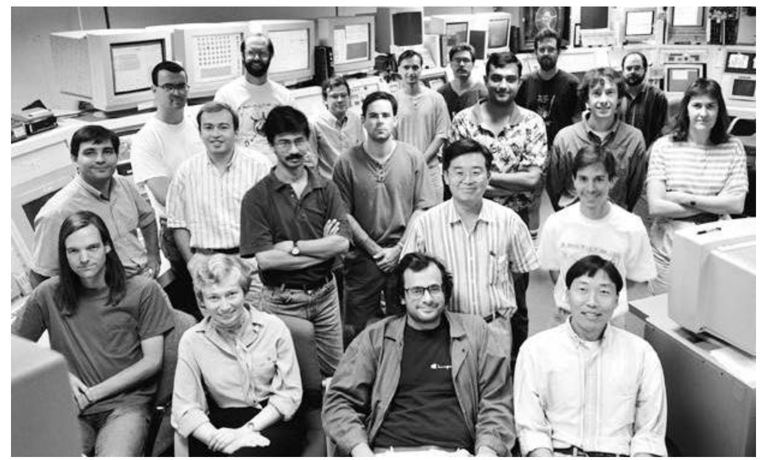


March 2, 1995: Joint CDF/DØ Seminar Announcing the Top Quark Discovery

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 each 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 Properties Measured at the Tevatron

- Top quark mass: m_t = 174.3±0.6 GeV (0.3% accuracy)
- Are top and antitop masses the same? Test of CPT

  Δm=0.8± 1.9 GeV (equal to 1%)
- Top quark lifetime

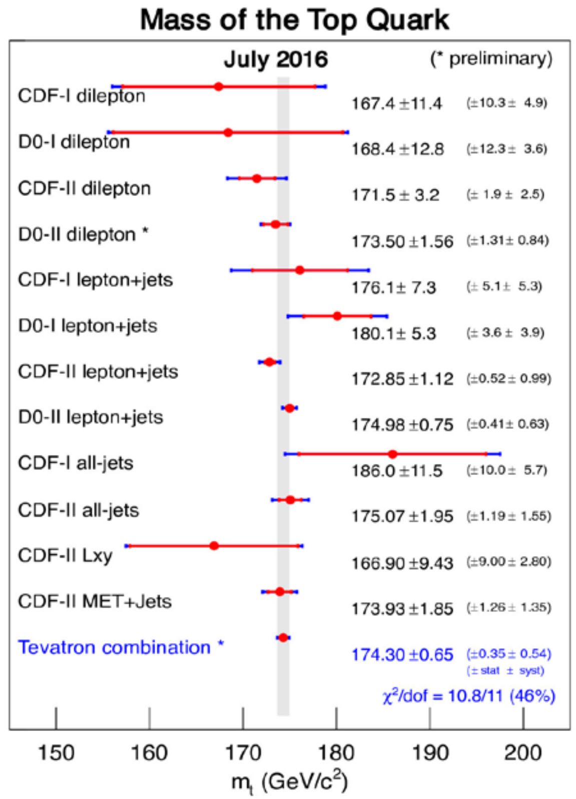
  Γ_t=1.99(+0.69/-0.55) GeV agrees with SM
- Top charge |q|=2/3e to 95% C.L.
- W helicity in top decay expect 70% longitudinal, 30% left-handed

  SM looks good
- Asymmetry of top quark in p vs pbar direction expected to be a few %

  Anomalous asymmetry of ~12% - requires theory improvements?
- Correlations of spins of top and anti-top are consistent with SM
- No flavor changing neutral currents

  <2x10^{-4} (t→ gu); <4x10^{-3} (t → gc)
- No evidence for SUSY $H^{\pm}$ in top decays
- Anomalous top vector/tensor couplings?

  Combination of W helicity & single top is in good agreement with SM V-A
- 4^{th} generation t'? None below ~450 GeV
- tt resonances? None below ~800 GeV
- Is W in top quark decay color singlet? Singlet preferred
- Electroweak single top quark production observed: $|V_{tb}|$ > 0.92 @ 95% C.L.



Very well know quark by now!

Fermilab

Conclusions

- The discovery of the top quark by the CDF and DØ collaborations in 1995 completed the table of expected constituents of matter
- Tevatron accelerator complex, state-of-the-art CDF and DØ detectors, and efficiently functioning large international collaborations were the keys for success
- Thanks to extensive Tevatron and more recently LHC studies, the top quark is by now well known elementary particle and widely used to seek new physics
- Top quark large mass is a puzzle and might play special role in our understanding of the elementary particles world and the Universe