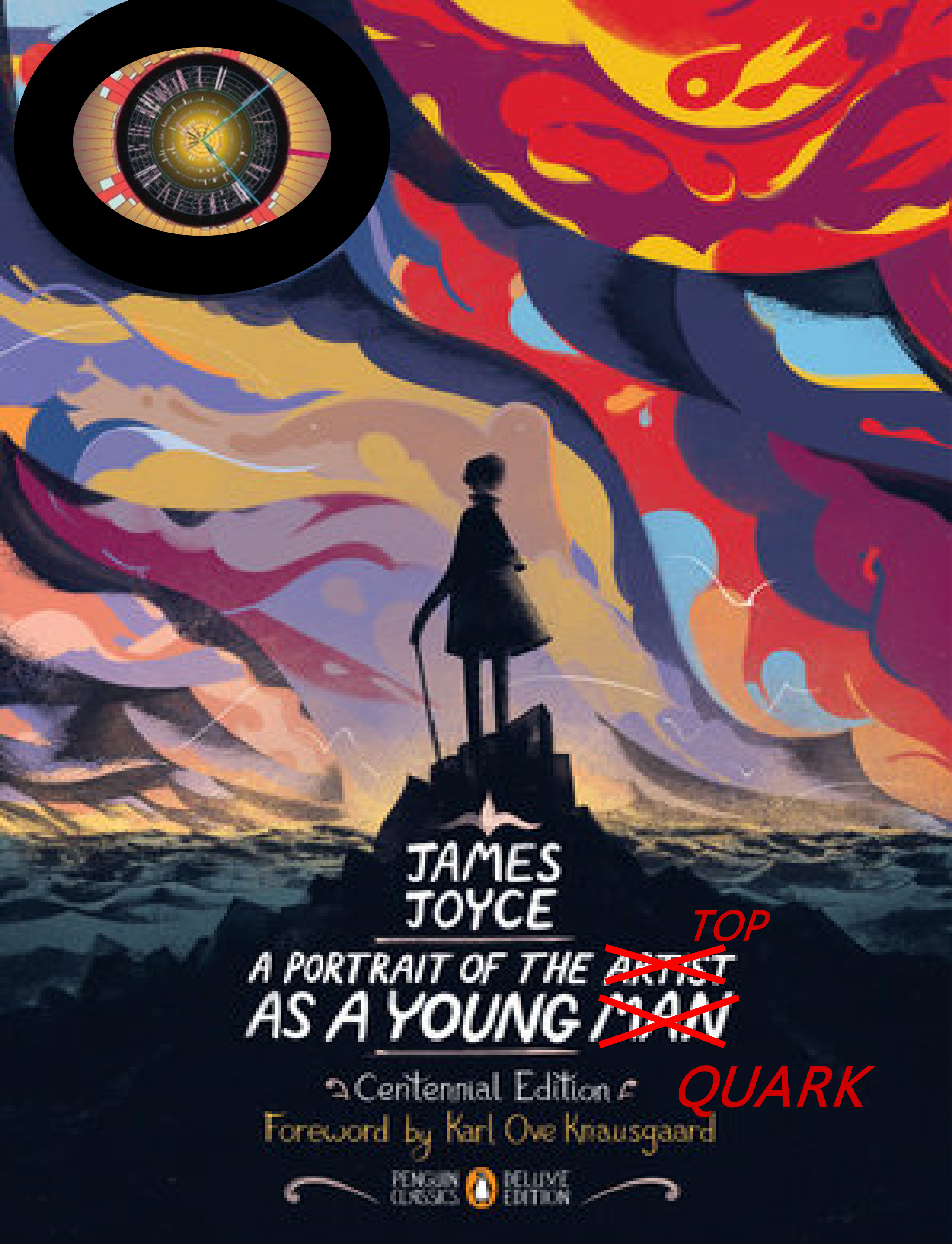
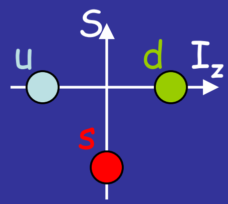
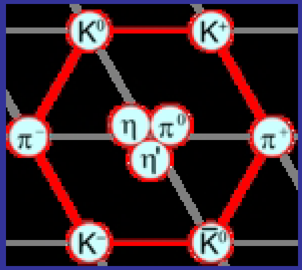


The Coming of Age of the Top Quark

P. Grannis May 15, 2019

Prehistory





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

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

❖ 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 identical 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.

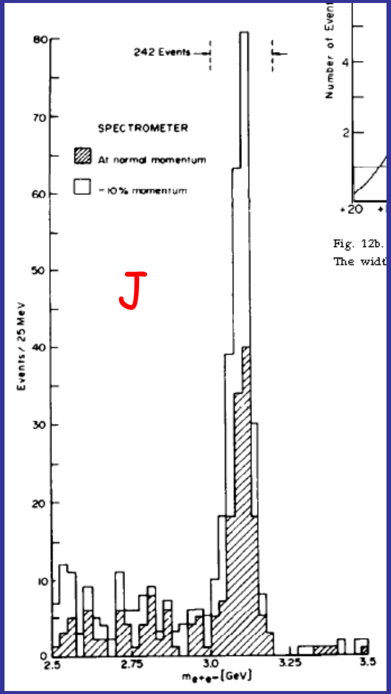
❖ In 1968 deep inelastic scattering experiments at SLAC showed the presence of constituents of the proton, consistent with the hypothesized fractionally charged quarks.

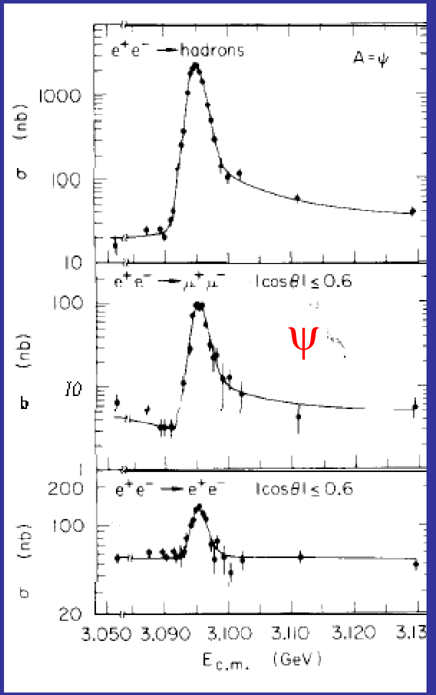
❖ in 1963 Cabibbo proposed (translating to quark language) that the weak quark eigenstates are rotated from the strong quark states:

$$d_W = d_S \cos\theta + s_S \sin\theta; \qquad s_W = -d_S \sin\theta + s_S \cos\theta$$

The second generation

❖ 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). If the charm quark mass were small enough, the contributions from the two doublets would suppress FCNCs. In 1974, the J/ψ charm/anti-charm bound state was discovered at Brookhaven and SLAC.





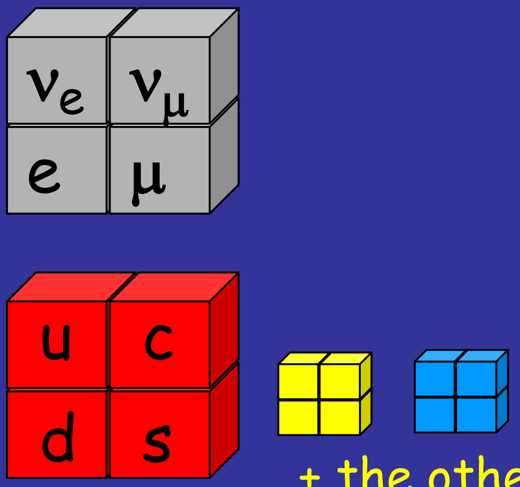
Now the lepton and quark sectors were again symmetric, as is needed to avoid anomalous contributions to weak interaction proceses

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

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

leptons:

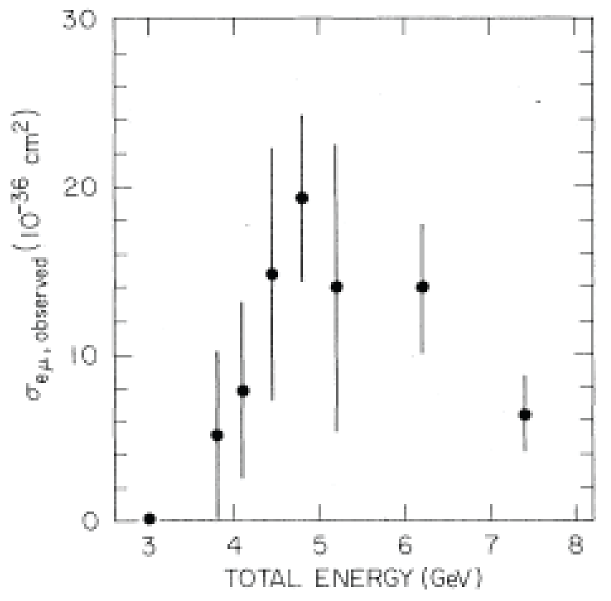
quarks:



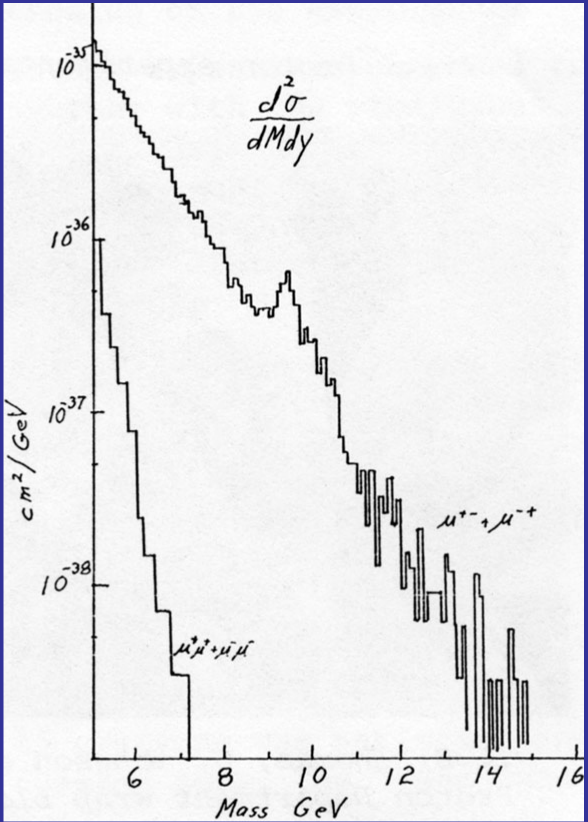
+ the other 2 color sets

The third generation opens

❖ In 1975, a new lepton, τ, was found at SLAC as an enhancement in e or μ production. Its neutrino partner ν_τ, was inferred from missing energy in the decay.



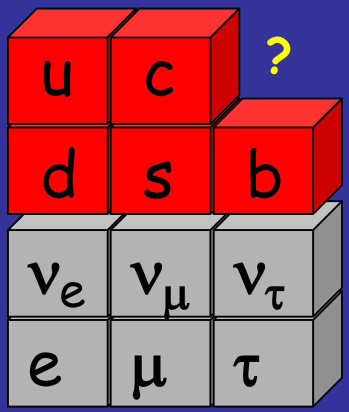
τ lepton, SLAC (1975)
($m_\tau \sim 1.8$ GeV)



❖ In 1976, the Upsilon at 9.5 GeV decaying to $\mu^+\mu^-$ was discovered at Fermilab and was understood to contain a new 5th quark, bottom, and its anti-quark.

Attempts to complete 3rd generation

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.



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

Since $m_b \approx 3xm_c \approx 9xm_s$, it seemed 'natural' to guess that the new top quark would have $m_t \sim 3xm_b \approx 15$ GeV, so a bound state of $t\bar{t}$ might then be expected at $M_{tt} \sim 30$ 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 the late 80's, a limit $m_t > 30.2$ GeV was set.

Top sighting false alarm

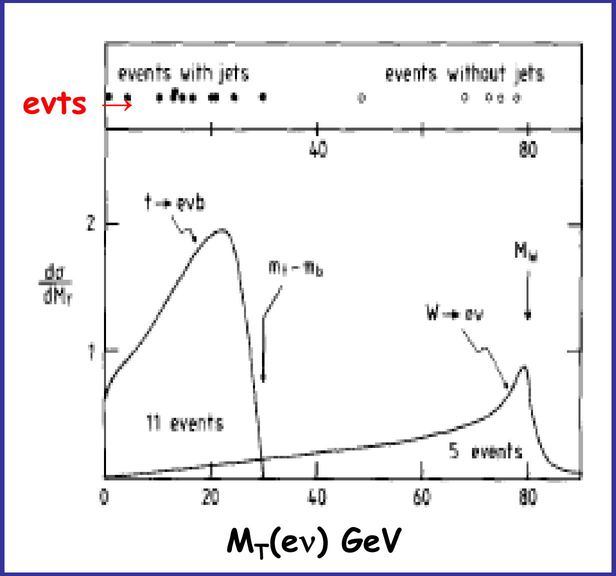
- Starting in 1981, the energy frontier had passed to the CERN SppS proton-antiproton collider, which in 1983, discovered the carriers of the unified EW force, the W and Z at masses of ~80 and ~90 GeV.

- One would expect to see a top quark in W decay if $m_t < \sim 75$ 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 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.

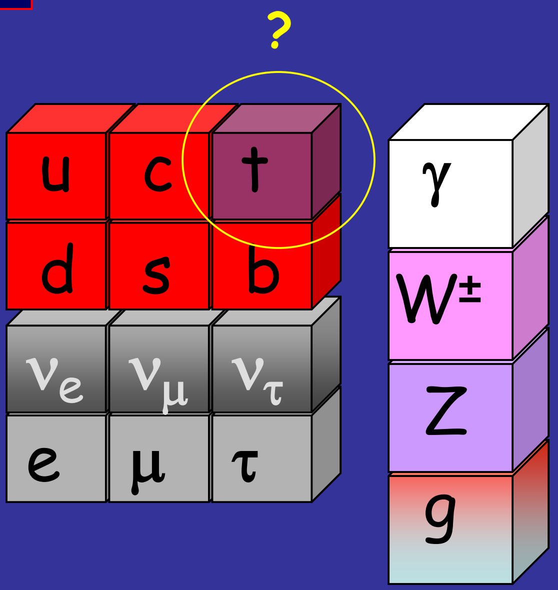
In retrospect we understand that the W+jets background was underestimated.

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



The top quark remains elusive

So where is (isn't) the top?



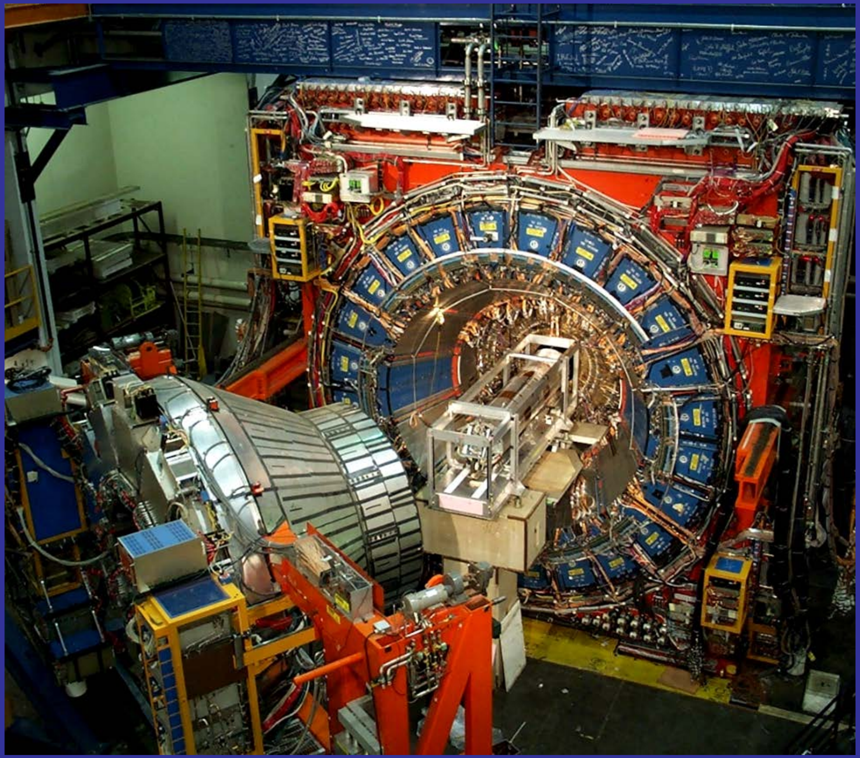
- ~1990: LEP experiments set limits $m_t > 45.8$ GeV (no Z decays to $t\bar{t}$)

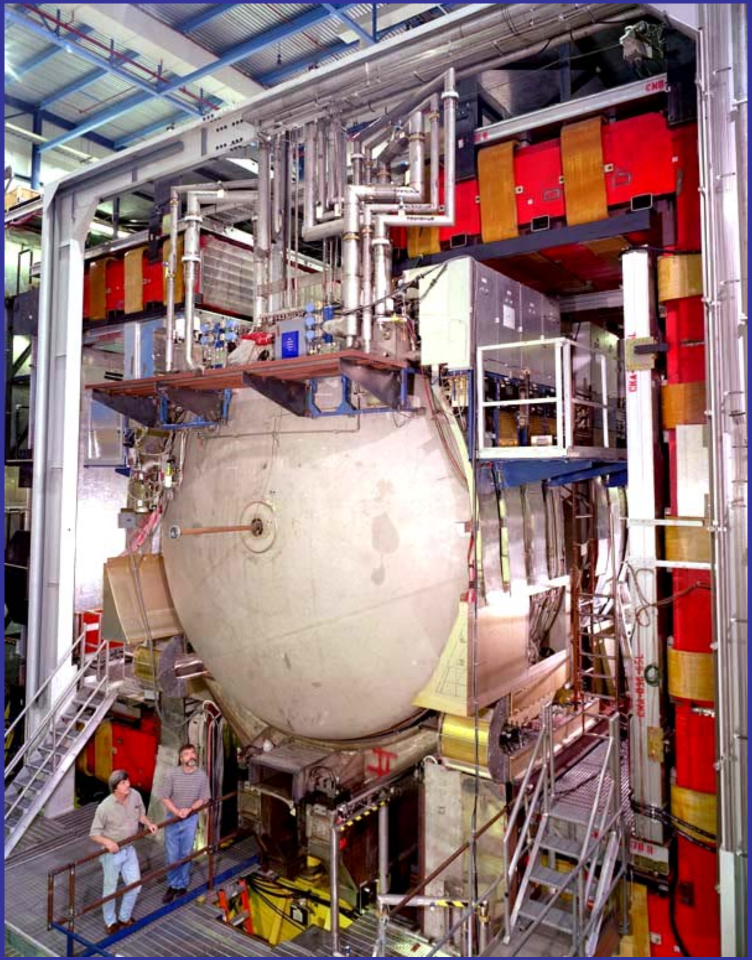
- 1990: UA2 set a limit ($W \rightarrow t\bar{b}$) at $m_t > 69$ GeV, effectively closing the search channel W → top. (At the time there was a fear that the top and W or Z masses might be very similar, making it hard to find the top.)

- 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 using $t \rightarrow bW$

- 1994: DØ joined the party and set the last top quark limit $m_t > 131$ GeV.

The Tevatron detectors



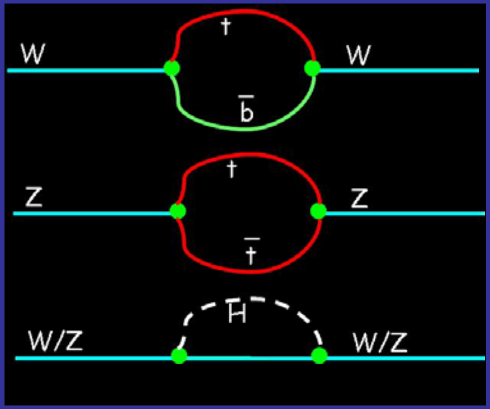


CDF and DØ in Run I (1992 – 1996) were both 4π detectors with central tracking, calorimeters, muon detectors and multi-level triggering systems. They had complementary strengths:

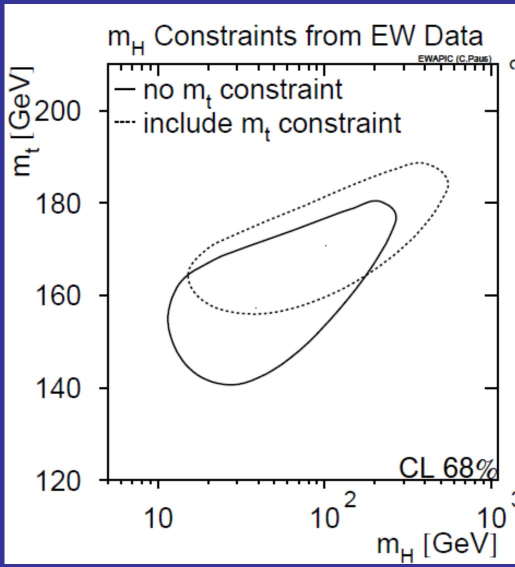
CDF had a solenoidal magnet surrounding tracking and a silicon microstrip vertex detector.

DØ had no magnet but, hermetic, finely segmented Uranium - LAr calorimetry and an extensive muon detector.

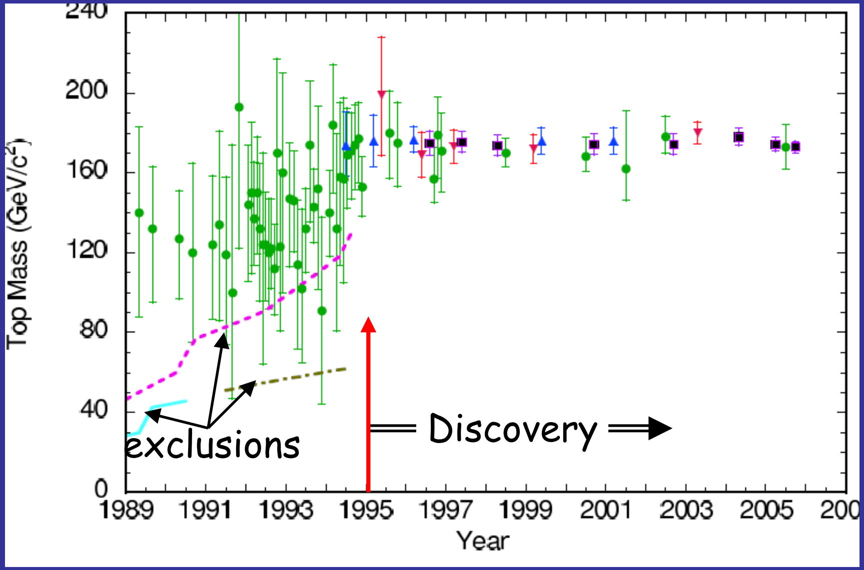
Toward discovery



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 in the context of the SM.

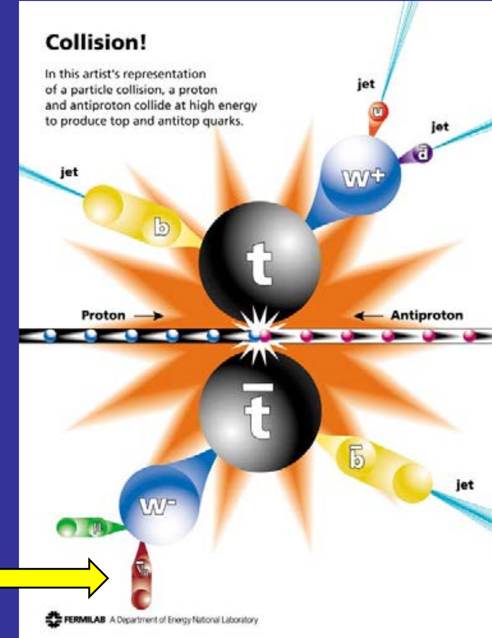


Precision EW measurements allowed constraints on top and Higgs masses. In the SM context, the combination of LEP/SLC/Tevatron data predicts m_t in the (155 – 185) GeV range.



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

Toward discovery



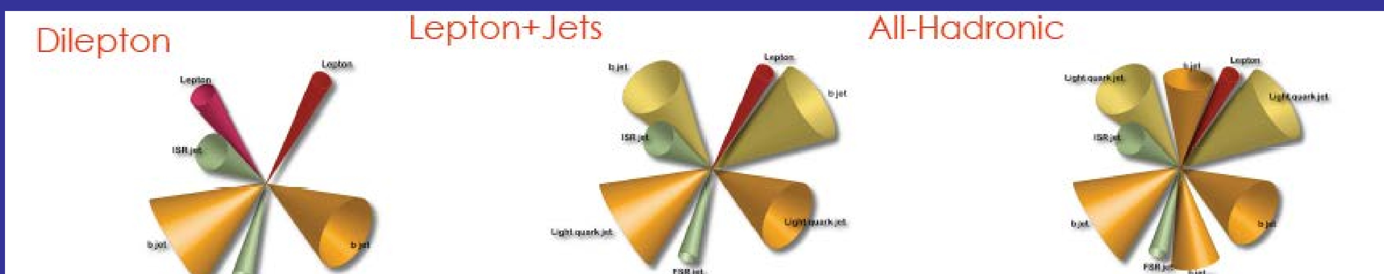
$t\bar{t}$ search channels:

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 $t\bar{t}$ are then characterized by

a) Neither W decays leptonically ("All jets")
b) One W leptonic & one hadronic ("lepton + jets")
c) Both W's decay leptonically ("Dileptons")

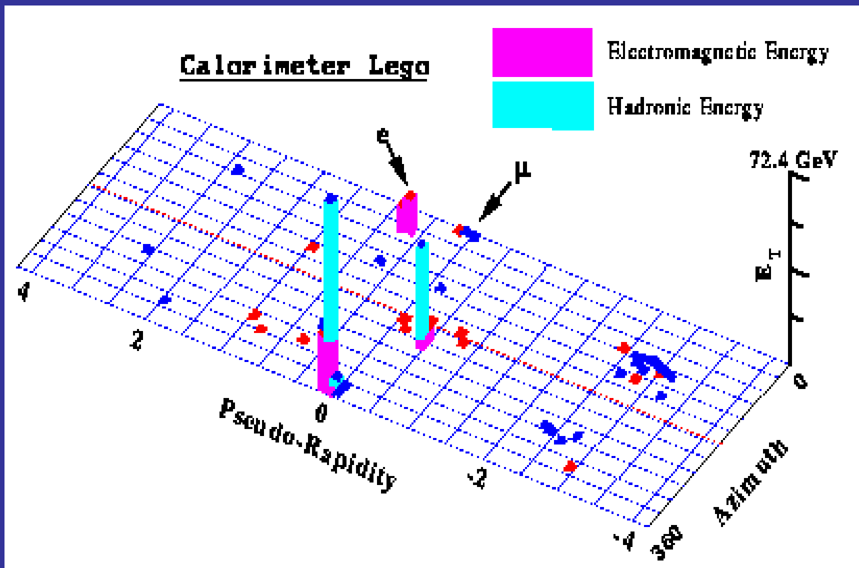


Dilepton	Lepton+Jets	All-Hadronic
2 bjets, 2 ℓ s, 2 νs	2 bjets+2jets, 1 ℓ, 1 ν	2 bjets, 4 light jets
Low background, low rate:	modest background, higher rate	large background, highest rate

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

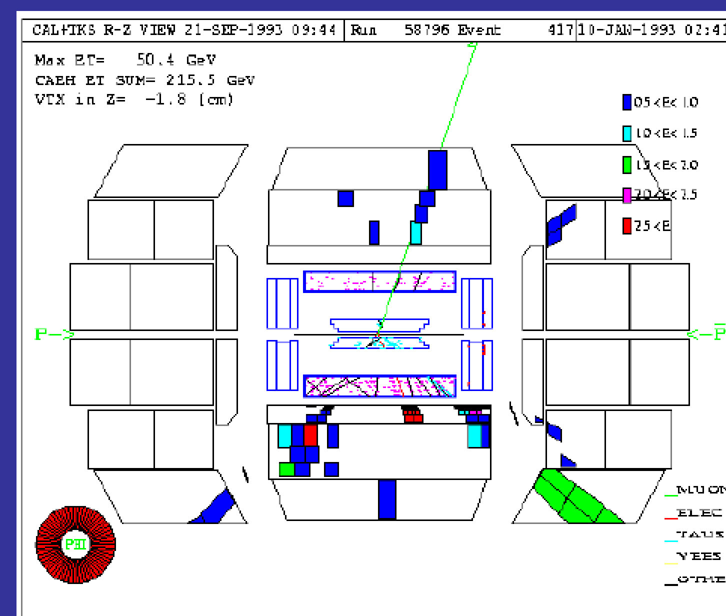
First signs

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



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

A striking DØ dilepton event shown 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 hypothesized to be from top pair production (tt→(eνj) (μνj), mass was consistent with m_t=(145-200) GeV.

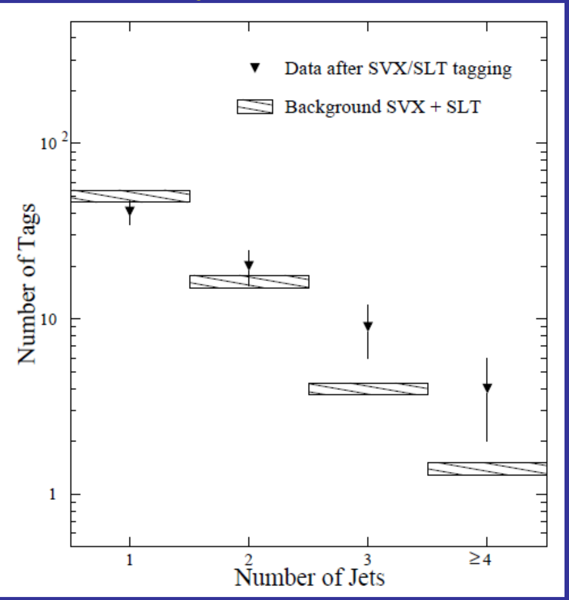


Evidence

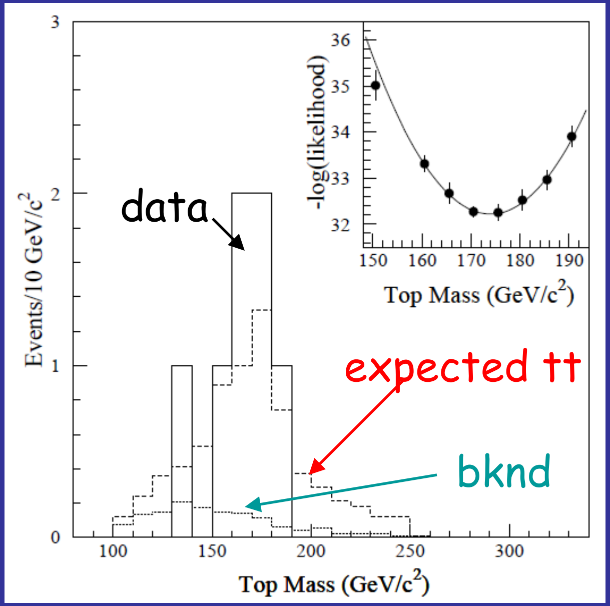
In early 1994, CDF published an analysis based on 19 pb^{-1} in which they found 2 events with eμ + 2jets and MET, and 10 events with e or μ + ≥3 jets and MET, in which at least one of the jets was b-tagged by the silicon vertex detector or a by semileptonic decay. The estimated background (W+jets, QCD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

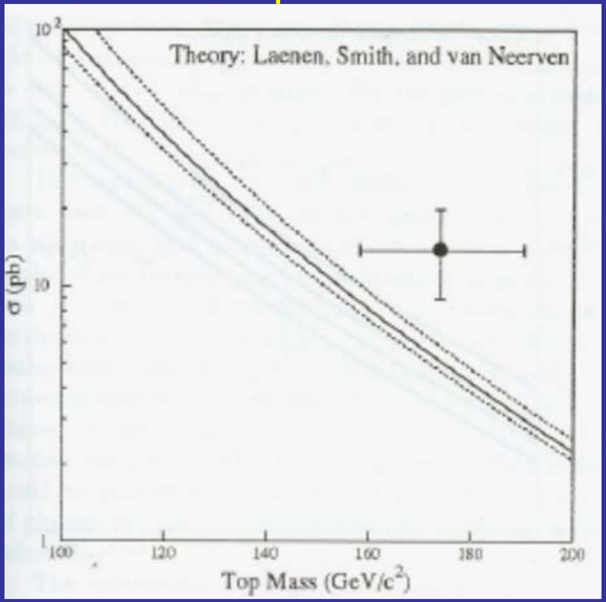
Excess over expectation appears for ≥3 jets



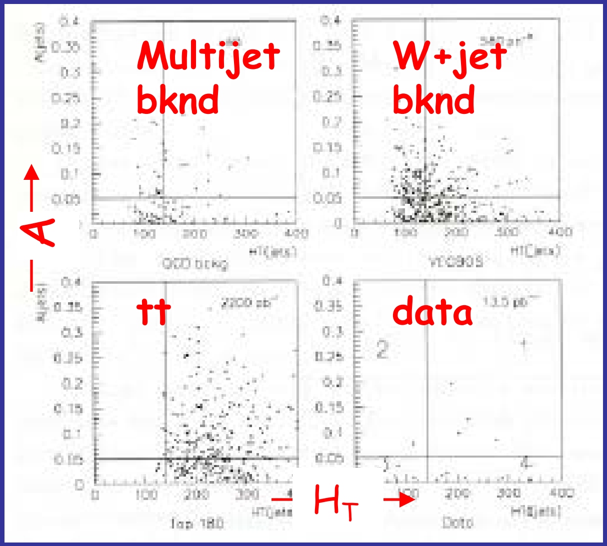
Mass fit from MC templates yields 174 ± 16 GeV



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



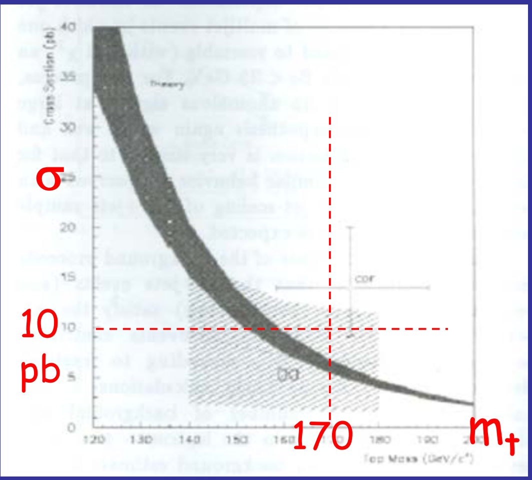
Evidence



On the basis of its earlier 131 GeV limit, and the understanding that CDF was preparing its 'evidence' paper, DØ re-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).

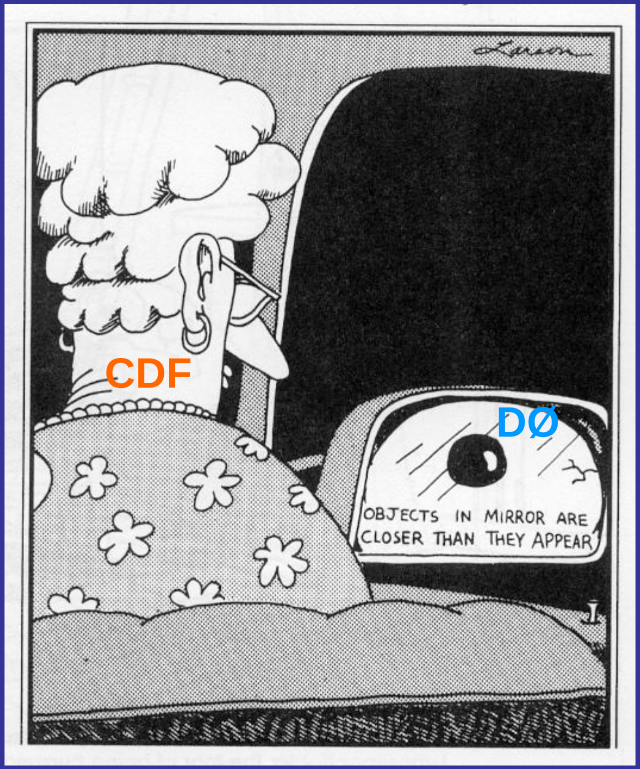
Sensitivity (expected signal/√bknd) of DØ and CDF was very similar.



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.

Closer than it appears

By January 1995, after a significant improvement in the Tevatron (fixing a rotated magnet) both collaborations had >50 pb^{-1}.   In January, DØ reported on 25 pb^{-1}, and implied that with twice the data, could achieve the ~5σ level needed for discovery.



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

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 very arge 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, refining analyses, and managing the discovery process, so this time around the convergence was much faster. (~ 6 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 1 week holding period would commence, during which the other collaboration could finalize its result if desired, after which the publication submission would proceed.

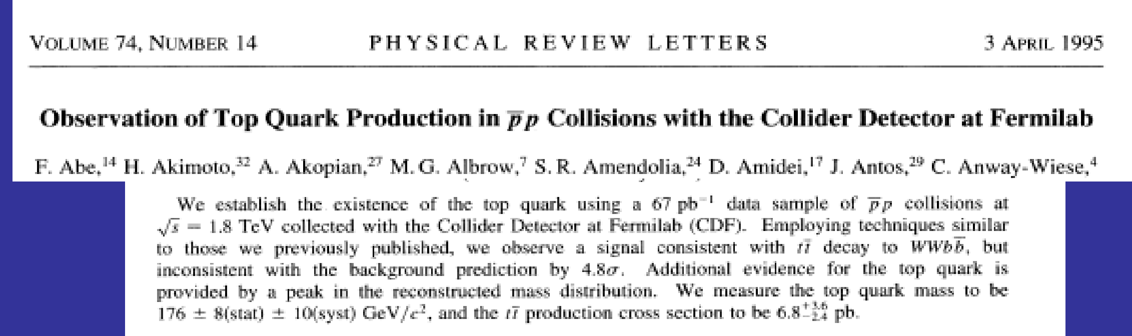
This agreement introduced sanity into the process, as neither collaboration had to worry about being scooped while conducting final tests.

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 simultaneously submitted papers to Phys. Rev. Letters. PRL was primed to do a very rapid peer review. 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

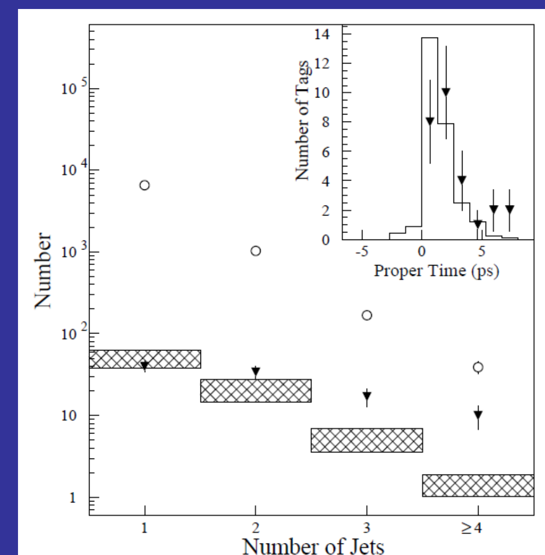
Observation of Top Quark Production in $\bar{p}p$ Collisions with the Collider Detector at Fermilab

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 $176 \pm 8(\mathrm{stat}) \pm 10(\mathrm{syst})$ GeV/c^2, and the $t\bar{t}$ production cross section to be $6.8^{+3.6}_{-2.4}$ pb.

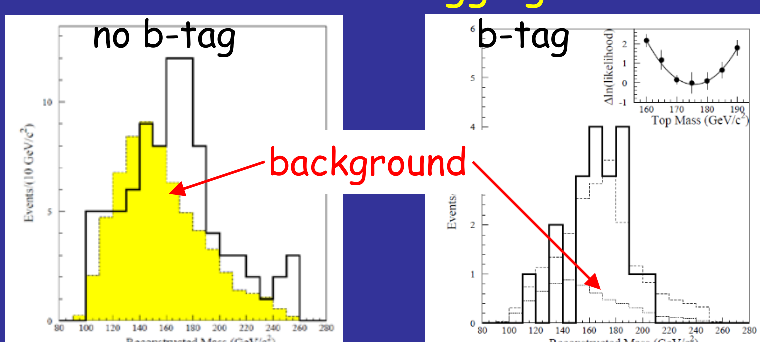
CDF's selection followed the 'evidence' paper strategy with an improved b-tagging algorithm. They found 6 dilepton events and 43 lepton+jets events (50 b-tags), with estimated background of 22.1±2.9 tags.

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

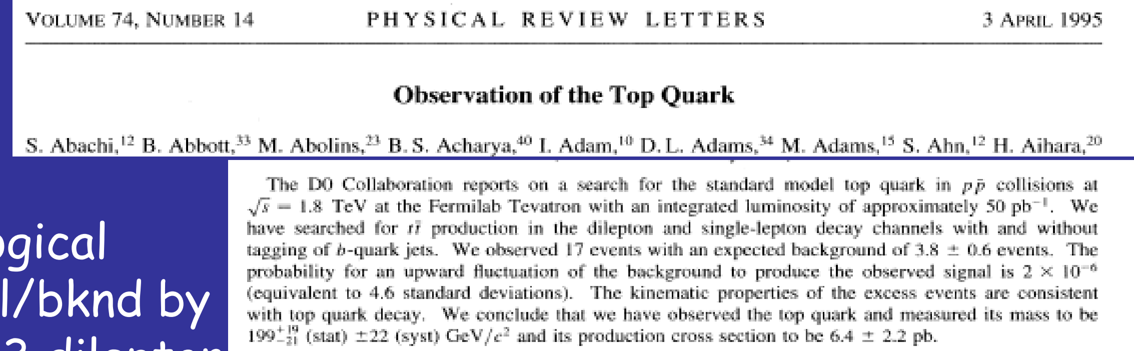


Number of single lepton events vs. Njets. Inset shows proper time of ≥3 jets with silicon vertex tags, consistent with expectation for b-quarks

Reconstructed l+jets mass distribution before and after b-tagging.



DØ Top quark discovery

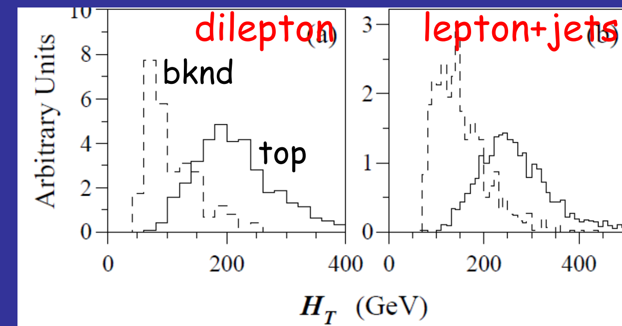

VOLUME 74, NUMBER 14 PHYSICAL REVIEW LETTERS 3 APRIL 1995

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.

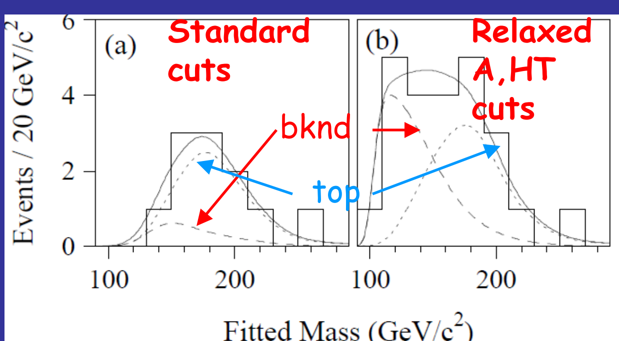
DØ's selection refined the topological (A,H_T) selection to improve signal/bknd by x2.6. With tight cuts, D0 found 3 dilepton events, 8 lepton+jets events (topological selection) and 6 lepton+jets events (μ tag). Although the paper used 'cut and count', alternate multivariate analyses using (A,H_T) were done and subsequently became the standard.



H_T distributions for signal and background

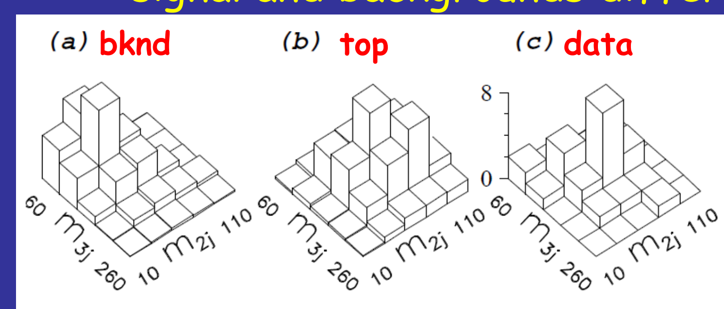
Estimated background to these 17 events was 3.8±0.6 events.

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



Reconstructed l+jets mass distribution

Plot the 2 jet and 3 jet masses for the hadronic top decay. Top signal and backgrounds differ.



Top quark announcement

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

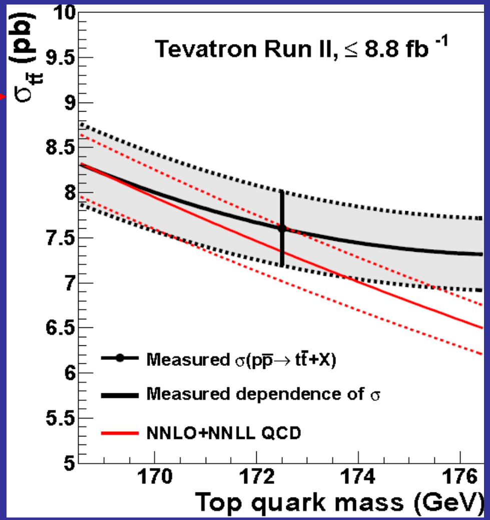
Who gets the credit?

There was a great sense of accomplishment, and a sense of shared responsibility for the discovery in both CDF and D0.

For discoveries such as the top observation, with many separate analyses involving all subdetectors, a set of complex triggers, and an extensive suite of software algorithms, it is impossible to single out a few persons who were responsible. It is intrinsically a team effort.

But was it the top quark?

The cross section (now calculated to NNLO QCD + NLO EW) and branching ratios agree well with the SM prediction for the observed m_t

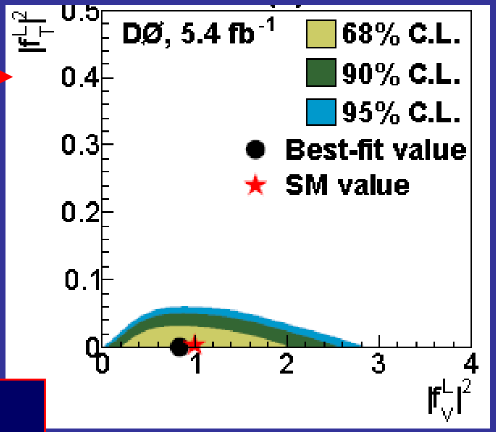


Charge 2/3 favored over -4/3

CKM matrix element V_{tb} > 0.92 (95% CL) consistent with ~1 as expected for a 3 generation quark sector.

W boson helicity fractions agree with SM

Only (V-A) tWb couplings seen.



Top quark polarization consistent with zero (as in SM)

t and tbar spin correlations as predicted in SM

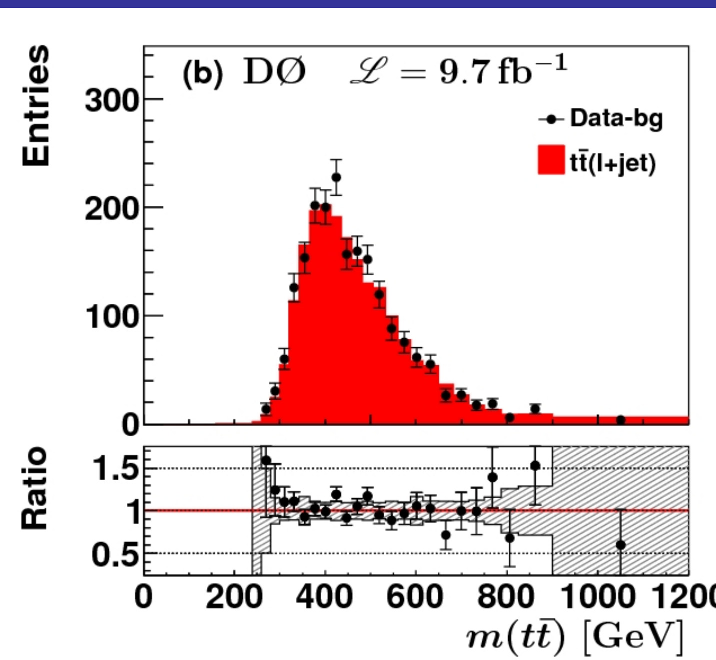
It walks like a quark, quacks like a quark, so …

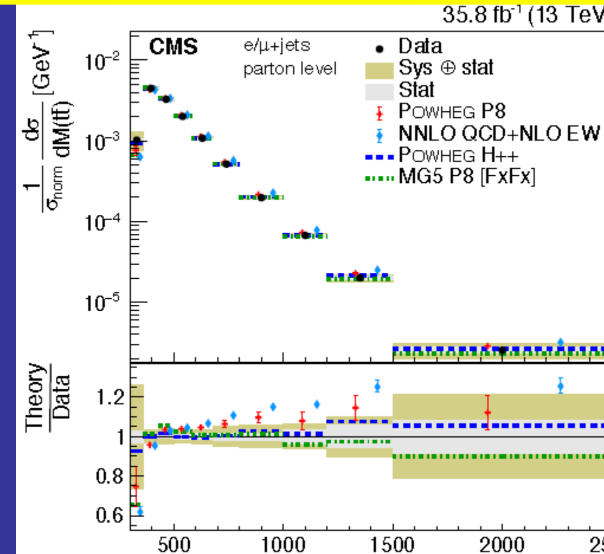
- But it still is odd man out – mass is ~40 times the next heaviest quark
- Top lifetime is small (~3x10^{-25} s) so it decays before forming hadrons

The top is now nearing middle-age. Contrast what we now know from LHC compared with the Tevatron portrait

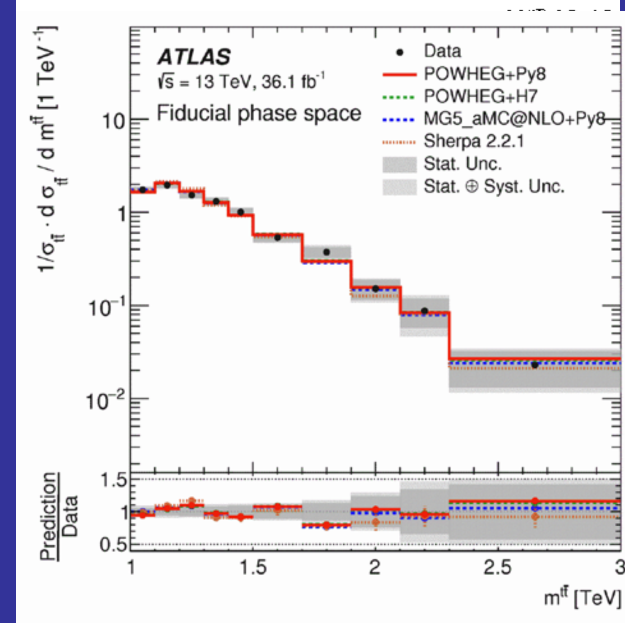
(and bear in mind that the LHC has only 5% of its final data)

Top pair mass distribution



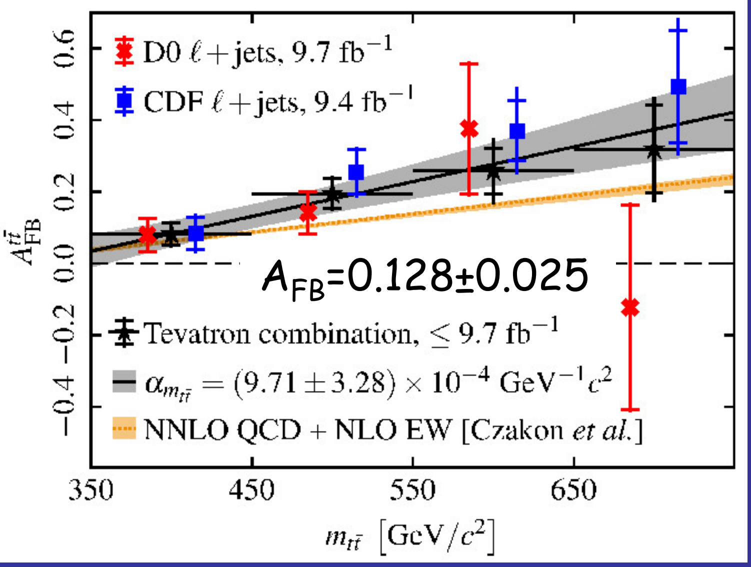


No resonances or anomalies



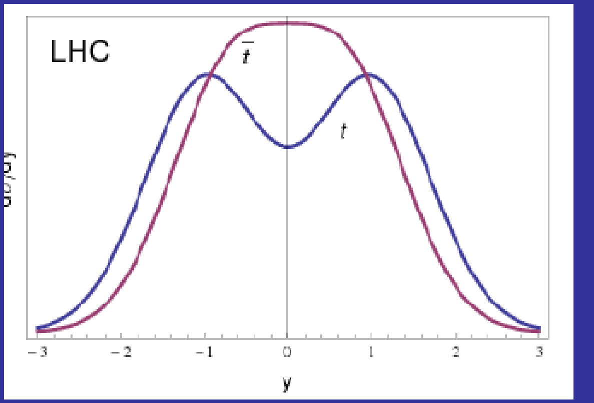
Development of analyses with 'boosted' (merged) jets at LHC is providing significant extension of search window

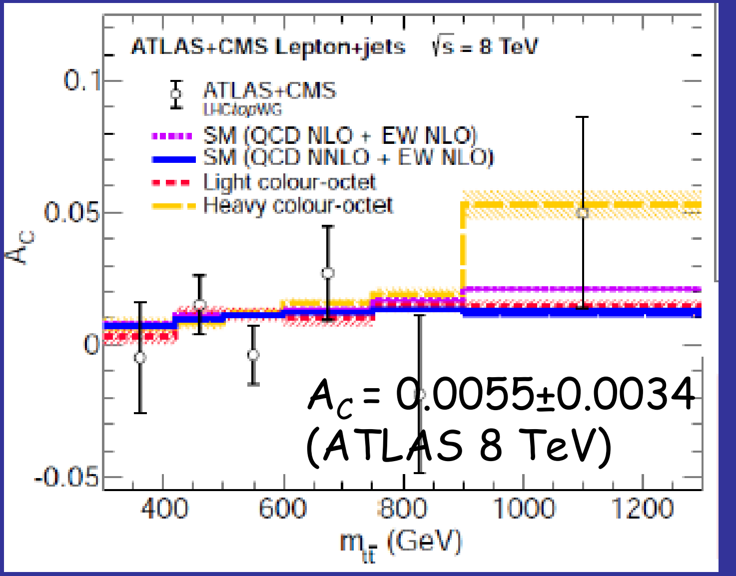
Production asymmetries



At p pbar Tevatron, A_{FB} measures the tendency for the top (anti-top) to be emitted in the proton (anti-proton) beam hemisphere. SM predicts small A_{FB}, growing with m_{tt}.

Early measurements sensed a discrepancy. More precise measurements and improved theory showed SM agreement.



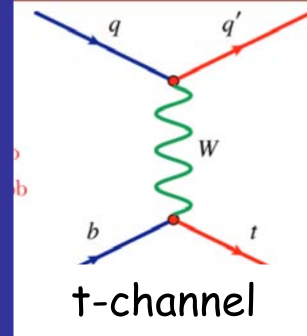


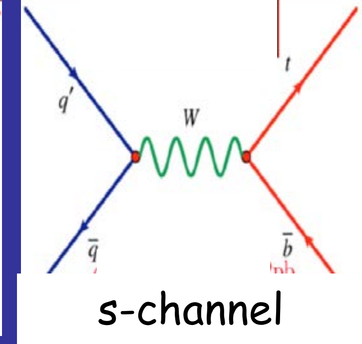
At pp LHC, A_C measures tendency for anti-top to be more centrally than the top.

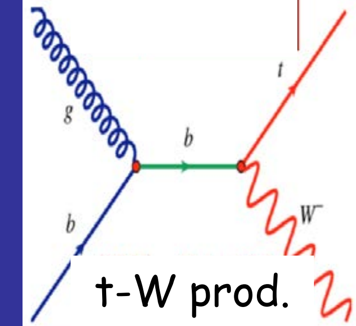
Expect A_C to be small but positive (broader y-distribution for top than anti-top).

Single top

EW production via 3 diagrams:
t-channel W, s-channel W,
t-W (s-channel b)

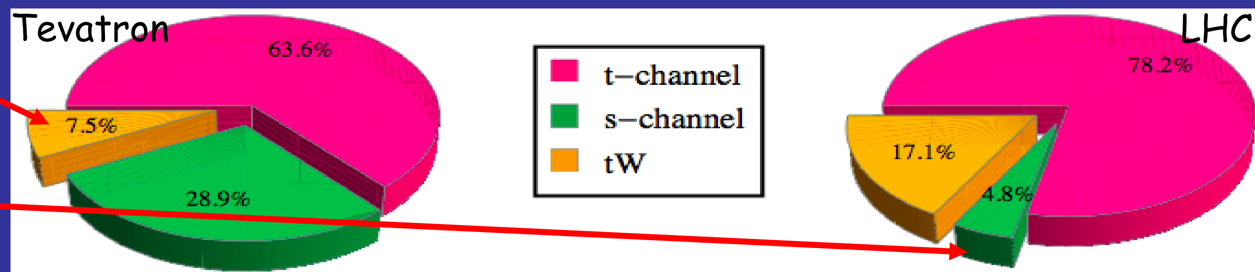






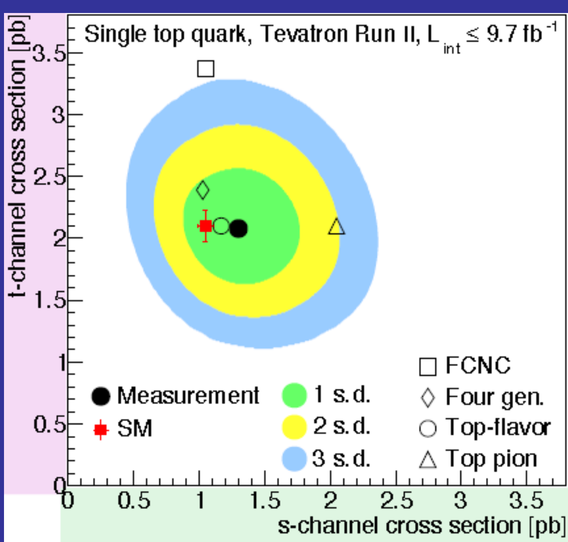
t-W small @ Tevatron

s-channel small @ LHC



Tevatron combined
σ(t-channel)=2.25 ± 0.30 pb (13%)
σ(s-channel)=1.29 ± 0.25 pb (19%)

CMS 13 TeV
σ(t-channel)=136.3 ± 1.1 ± 19.7 pb (15%)
single top (not anti-top) only
σ(t-W)=63.1 ± 6.6 pb (11%)

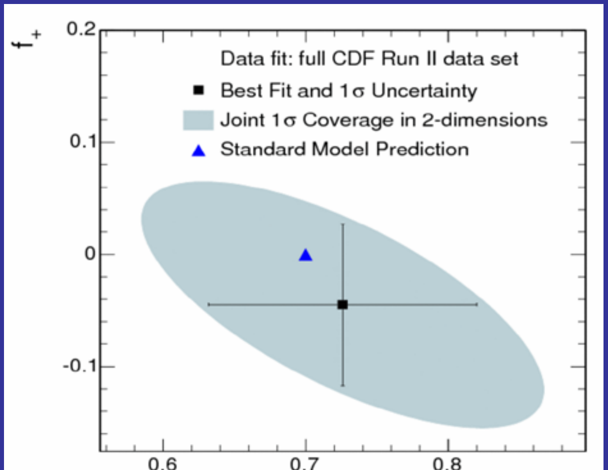


Cross sections are systematics limited (difficult multivariate analyses), but the large LHC samples allow many improvements for couplings, top lifetime, CKM matrix element V_{tb} … and searches for BSM physics

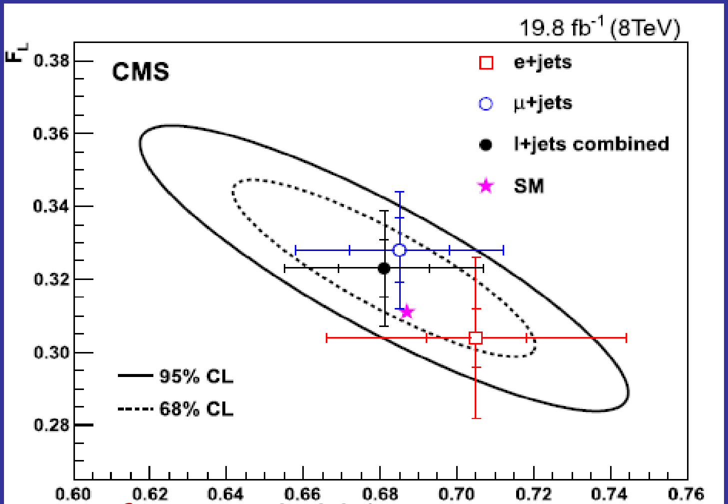
Why is ratio of EW σ(1top) to QCD σ(tt) so large?
(1/2 at Tevatron and 1/3 at LHC)

W helicity and anomalous tWb couplings

W helicity fractions in $t \rightarrow Wb$
(f_{right}, f_{left}, f_{long} = 0.00., 0.31, 0.69 in SM)



f_{right} = -0.045±0.073



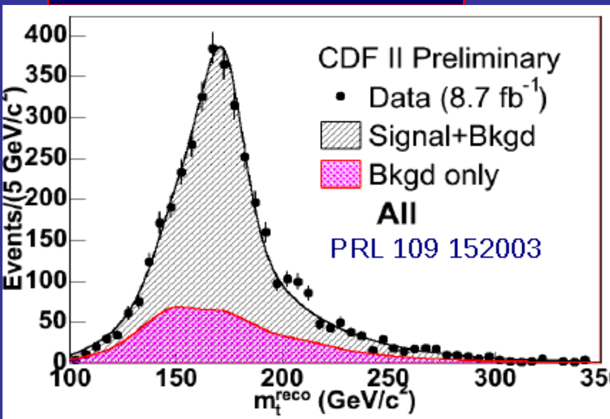
f_{right} = -0.004±0.015

Anomalous tWb couplings (SM has no right-handed vector or tensor couplings)

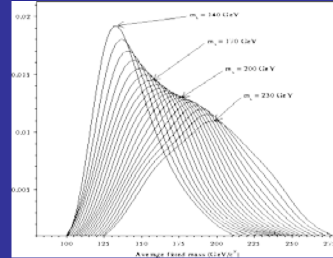
D0 $|V_R/V_L|^2 < 0.30$ (95% CL) using combination of single top and W boson helicity

ATLAS $|V_R/V_L|^2 < 0.14$ (95% CL) (8 TeV) using single top angular distributions

Mass

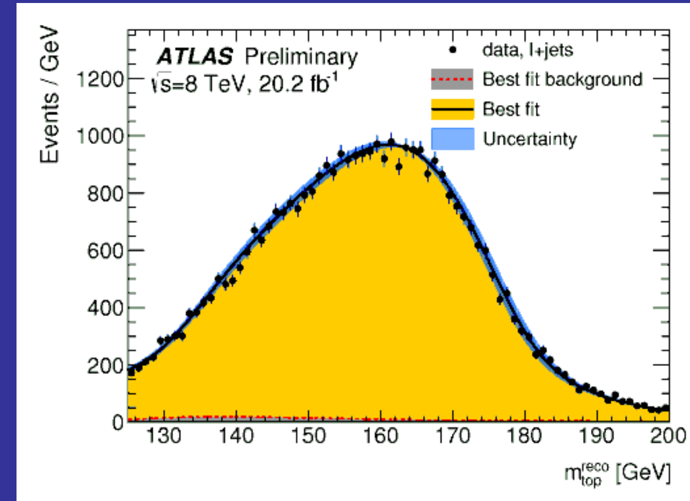


Tevatron combination:
m_t=174.34±0.64 (0.37%)



Compare MC templates to data

(systematics dominated)

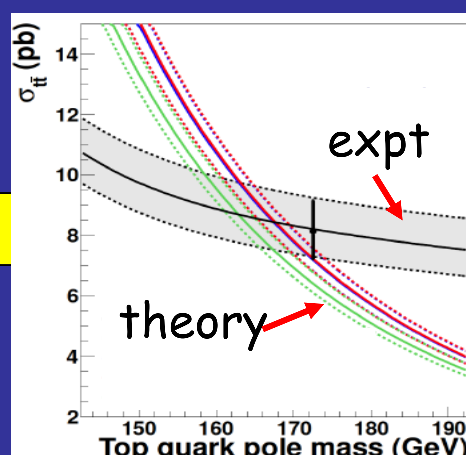


ATLAS combination (2017):
m_t=172.51±0.50 (0.29%)

But Monte Carlo mass has uncertain relation to a theoretically well defined mass.

→ Would like the pole (other well defined) mass

m_{pole} (D0) =
172.8±3.4GeV

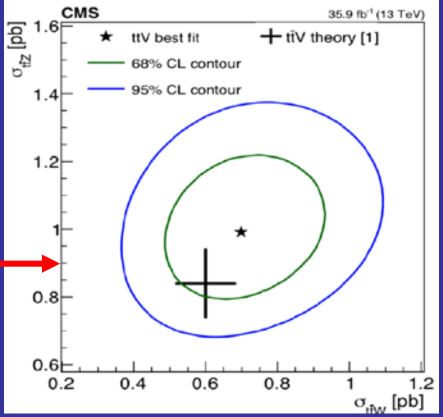


m_{pole} (ATLAS) =
173.2±1.7GeV

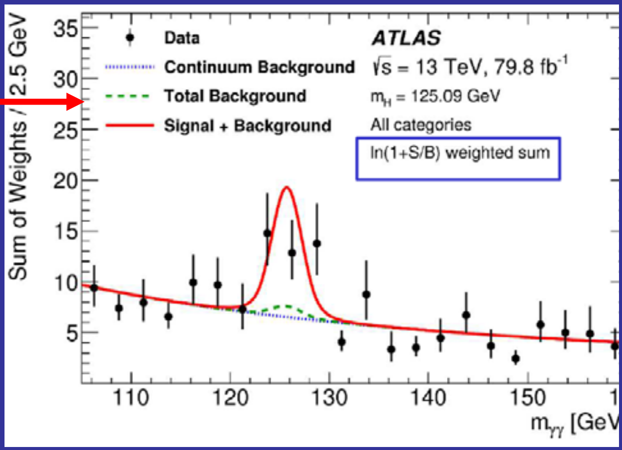
Pole masses limited by systematics and theory unc.

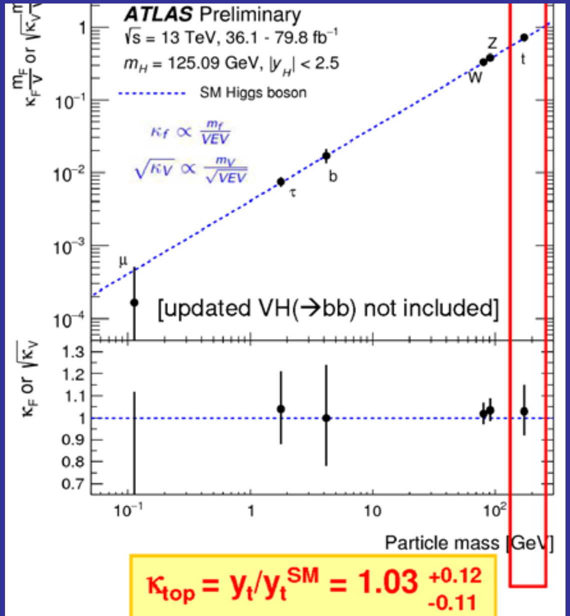
Compare SM theory XS to measured XS

And the LHC is adding much that is new



- Top pairs produced in association with W, Z, γ, as well as tttt, testing top couplings and seeking BSM.
- Single top + boson (Z, γ) is sensitive to anomalous couplings
- ttH production now seen with $H \to bb$, $\gamma\gamma$, ZZ^* (>5σ for both ATLAS and CMS).
- Comparison of direct observation of ttH Yukawa coupling with indirect value from $gg \to H$ and $H \to \gamma\gamma$ constrains new physics in loops.





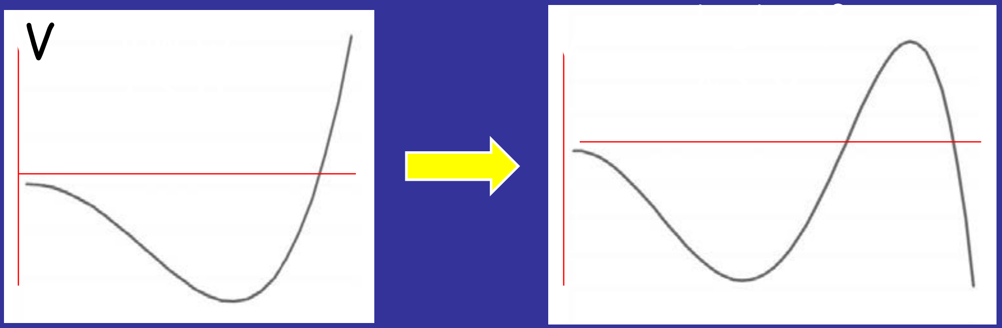
- Also: Searches for new physics giving FCNC in $t \to cH$ etc., and for charged lepton non-universality. These will benefit greatly from the full HL-LHC program.

… And yesterday's discovery is tomorrow's calibration (top mass studies help fix jet energy scales and b-tag efficiency)

Precision top mass

Just as α_{EM}, α_{strong} etc. vary with Q^2, so also does the self-coupling term λ in the Higgs potential $V = \mu^2 \phi^2 + \lambda \phi^4$. As $Q^2 \to \infty$, λ decreases.

If $\lambda < 0$, the Mexican hat potential turns over, and the absolute minimum is no longer at the location that gave us the observed W, Z bosons and the Higgs boson. The universe becomes unstable

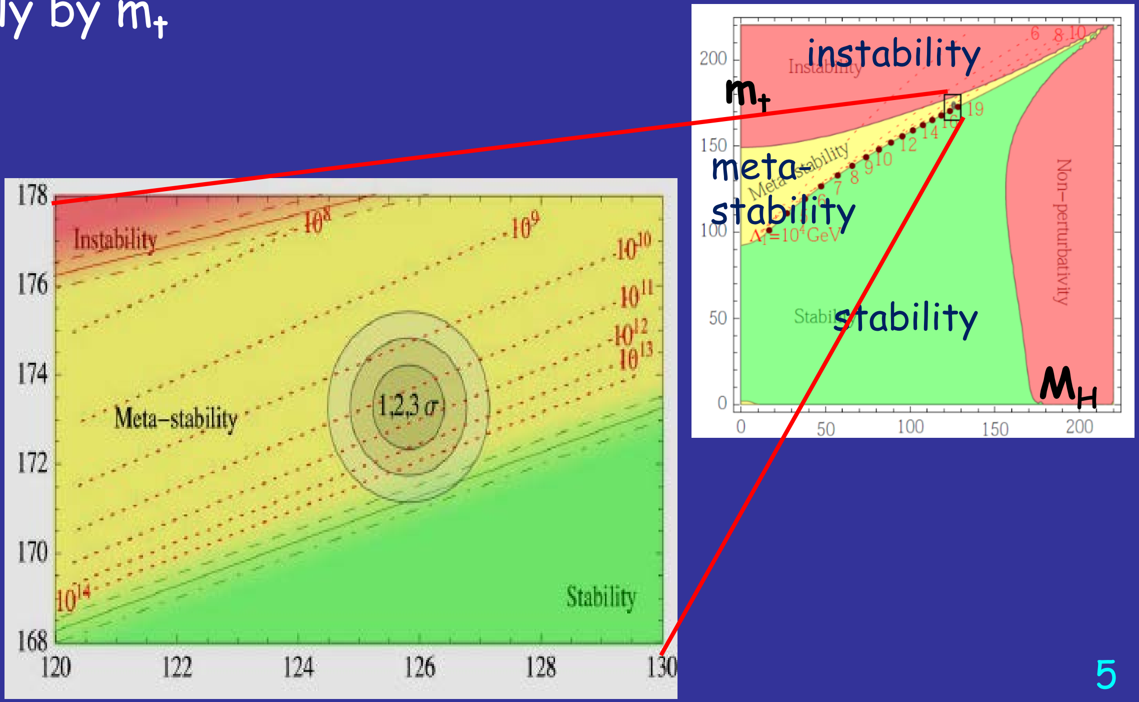


(or metastable if mean time to tunnel to real vacuum is >> age of universe).

The value of λ is controlled mainly by m_t

Current values of m_t, M_H put us in the metastable region, so better precision on m_t is needed (before it is too late !!)

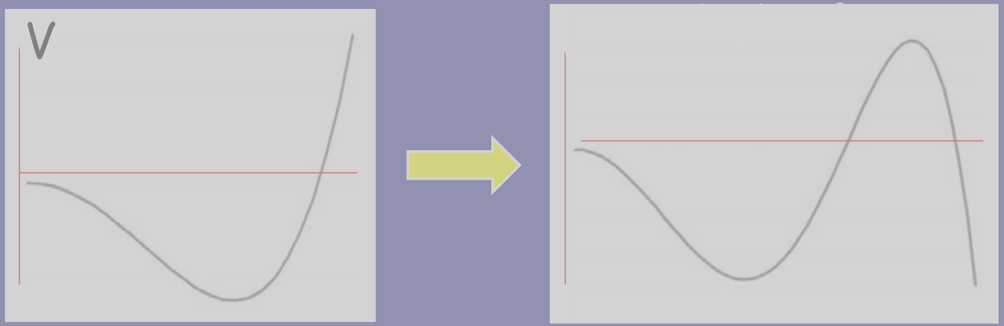
Is the fact that m_t/M_H lie on border of stability/instability a profound coincidence hinting at some deep truth?



Precision top mass

Just as α_{EM}, α_{strong} etc. vary with Q^2, so also does the self-coupling term λ in the Higgs potential $V = \mu^2 \phi^2 + \lambda \phi^4$ and as $Q^2 \rightarrow \infty$, λ decreases.

If $\lambda<0$, the Mexican hat potential turns over, and the absolute minimum is no longer be at the location that gave us the observed W, Z bosons and the Higgs boson, and universe can become unstable or metastable if mean time to tunnel to real vacuum is >> age of universe.

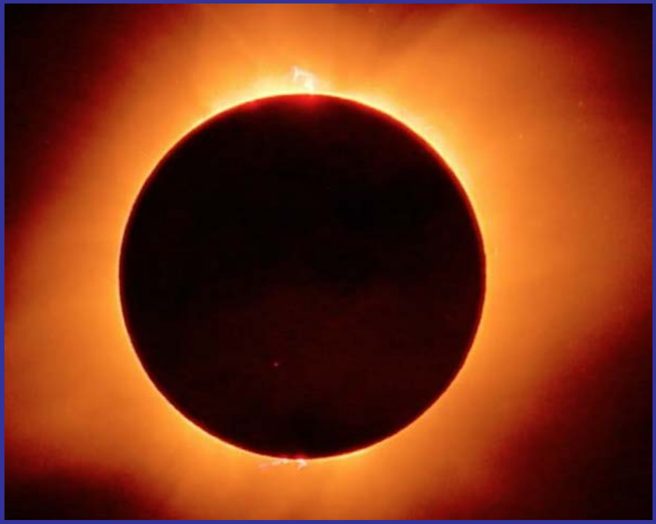


The value of λ is controlled mainly by m_t

Current values of m_t, M_H put us in the metastable region, so better precision on m_t is needed (before it is too late!)

Is the fact that m_t/M_H lie on border of stability/instability a profound coincidence hinting at some deep truth?

The sun and moon subtend same angle as seen from earth!



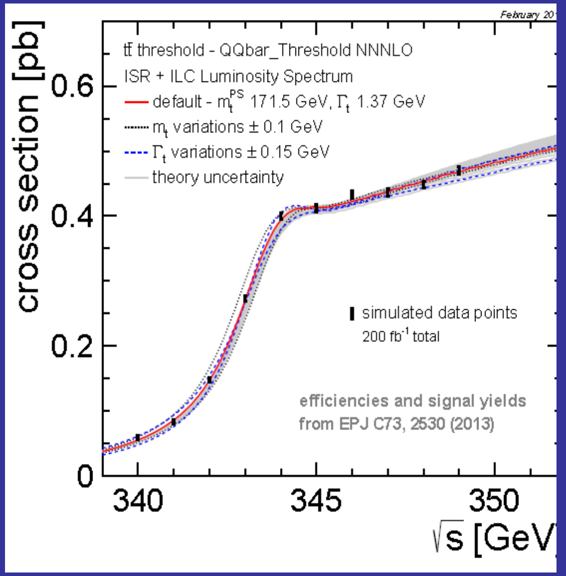
Well maybe … but sometimes a coincidence is just a coincidence

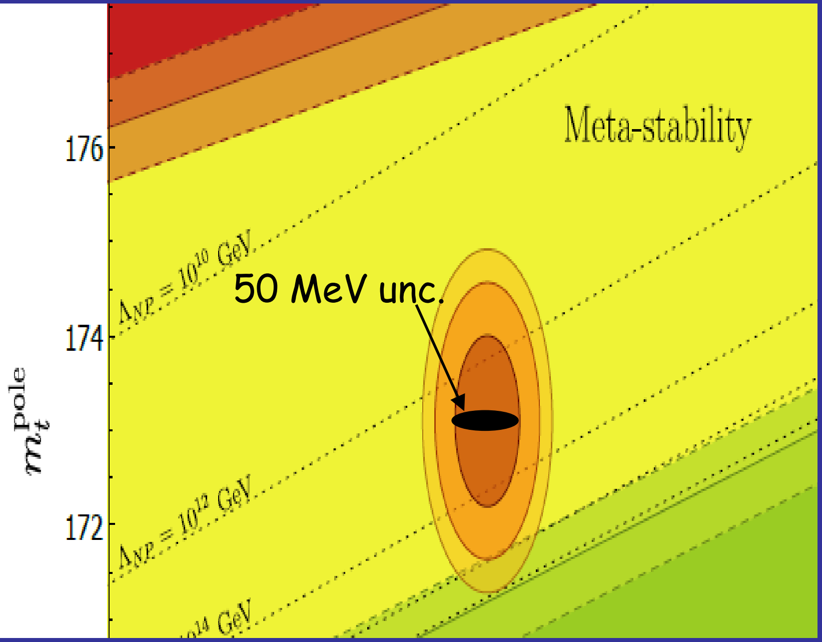
What to expect when the top quark becomes mature?

The full LHC statistics will improve the precision of top pole mass somewhat, but systematics now dominate. Need much hard work by experiment and theory.

High statistics HL-LHC samples will enable big improvements on rare FCNC decays.

Future e^+e^- linear colliders will go much further.
ILC threshold scan in $e^+e^- \rightarrow tt$ will measure a theoretically well defined top mass with δm_t~50 MeV, ~30 times better than the current LHC pole mass precision.



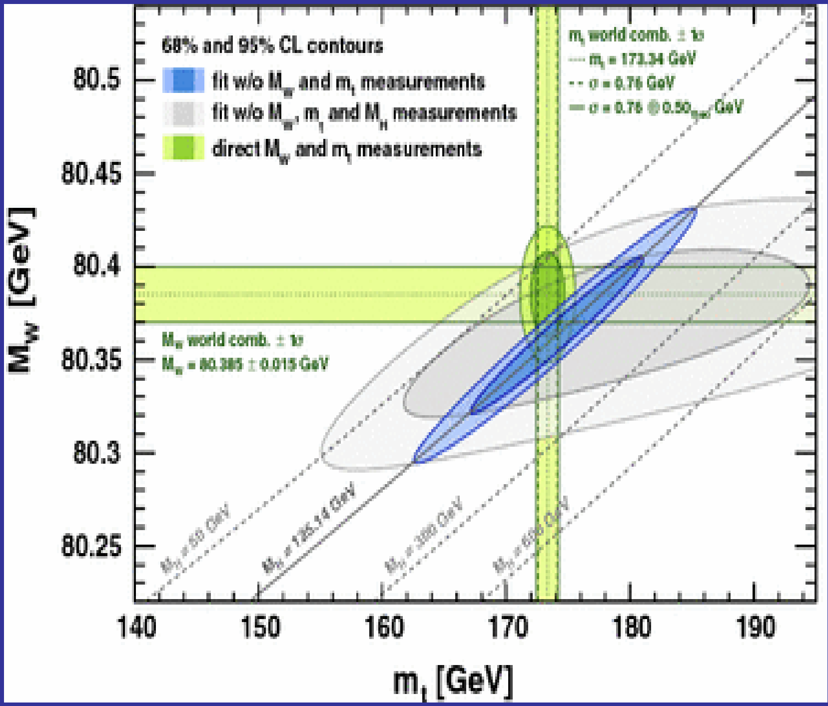


This linear collider top mass will resolve the stability question.

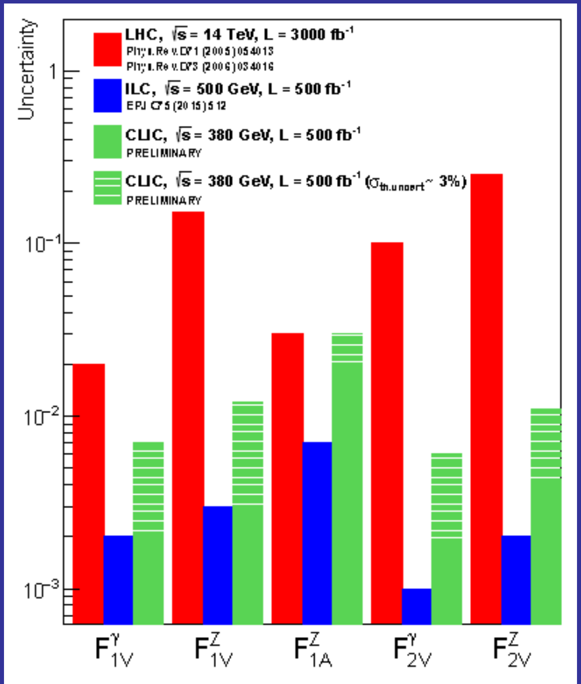
But instability seems a remote possibility – we are pretty sure that the SM is not valid to the GUT scale

What to expect from a mature top quark?

As the precision of the top mass (and W boson mass) gets much better, the constraints on non-SM physics from comparison of direct measurement and indirect prediction of the Higgs mass from m_t and M_W will become very strong.



This should be one of the best available indicators of new physics in loops.



And the precision on anomalous top couplings from the linear colliders will improve upon the HL-LHC by an order of magnitude, again probing for BSM physics.

Conclusion

- The discovery of the top quark by the CDF and DØ collaborations in 1995 was the chief Tevatron legacy
- The LHC experiments are extending our understanding of the top quark significantly
- Further precision studies at HL-LHC and a future e^+e^- collider will bring qualitative improvements in precision

These improvements are important as they explore the 3rd generation physics where new physics should be most visible.

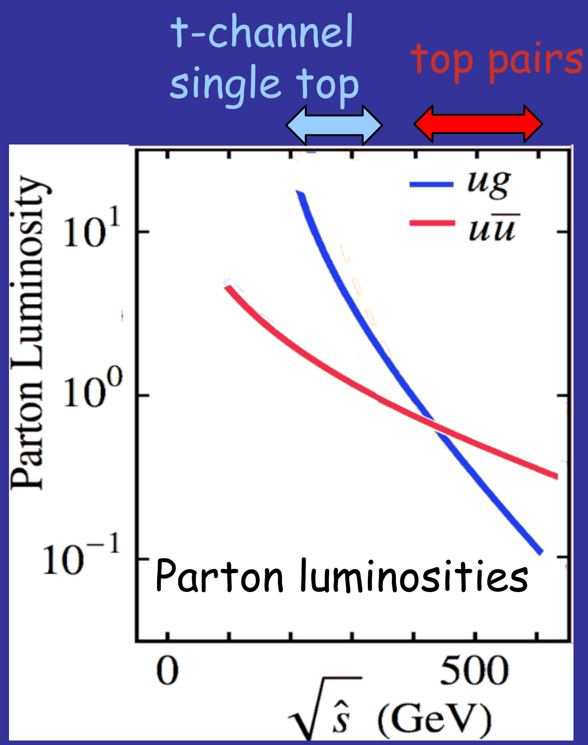
Is the top the odd-quark-out OR, is it the only quark with a reasonable mass and Yukawa coupling?

Backups

Why is ratio of EW σ(1top) to QCD σ(tt) so large?

(0.46 at Tevatron, 0.34 at LHC 13 TeV)

- More phase space for creation of one 175 GeV object than two? (but this effect much diminished at LHC, so it is not dominant)
- Decrease of α_S with Q^2? (not enough)
- Single top is produced by lower x partons than top pair production, so higher parton luminosity.



Reinhard Schweinhorst at "Top Turns 20" (Apr. 2015)

The central players – the accelerators

400 MeV Linac

8 GeV Booster

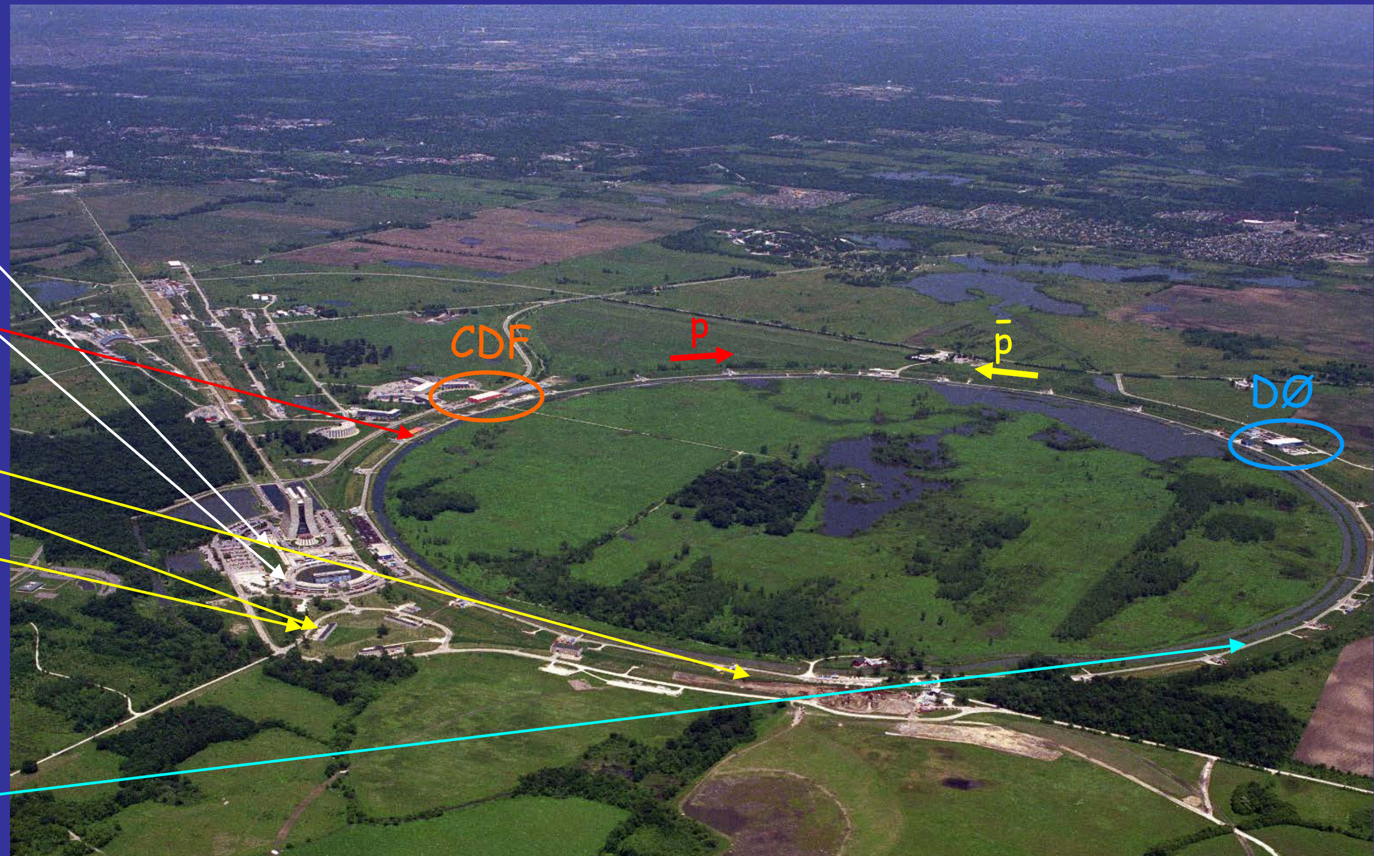
150 GeV Main Ring

$\bar{p}$ 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.

Top quark discovery

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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.

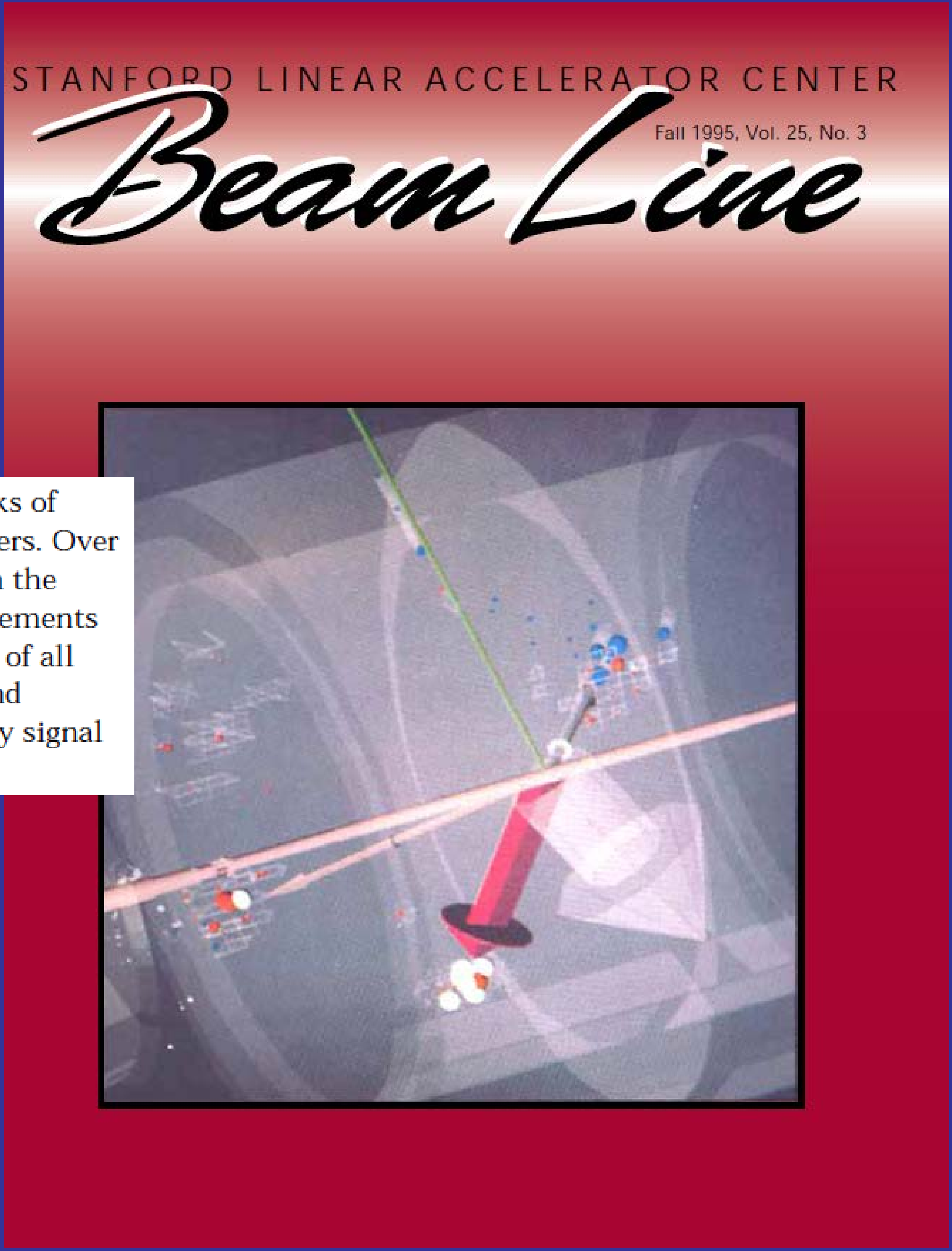
Strictly speaking then, the 1994 results were not Evidence, and neither CDF or DØ made a Discovery on their own (jointly, they did).

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

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

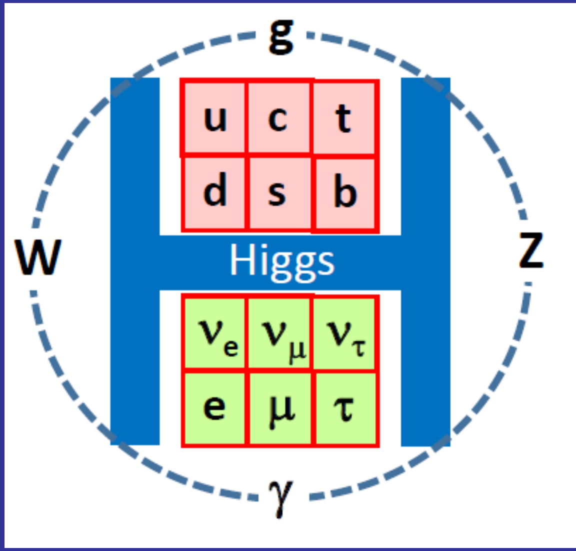
Beam Line editorial by James Bjorken

The history of physics is full of near-simultaneous discoveries by separate individuals or groups, and with that often has come acrimony and controversy, from Newton and Leibnitz to Richter and Ting, and down to the present time. There has been competition between CDF and DØ as well. In fact, it was built in from the beginning by then-director Leon Lederman, who visited CERN's big collaborations, UA1 and UA2, while they were discovering intermediate bosons *W* and *Z* and searching for the top quark. At CERN, it was vital to have two collaborations as checks and balances, and Lederman upon his return strongly encouraged the creation of the present DØ collaboration, something which was not in the works prior to that. And the ensuing CDF/DØ competition has served for constructive purposes; I have never seen this competitiveness to be corrosive. The evidence is in these pages for the reader to see, in the very fact of co-authorship and in the nature of the interactions between the collaborations as described in the article. This piece of competition has been a class act.

Not only has this been true between the collaborations, but it seems also to have been the case within them. This is no mean feat, since harmony within a big group of strong individualistic physicists of great talent and often even greater ego is not easy to maintain. I can do no better than quote here what is found near the end of the article, and I do this without regrets for creating some redundancy:

> In the end, the chief necessity for the convergence on the top discovery was the willingness of a collaboration to abide by a majority view. Securing this willingness requires extensive attention to the process—of being sure that all shades of opinion, reservations, and alternate viewpoints are fully heard and understood. It is more important perhaps that each point of view is carefully listened to than that it be heeded. A fine line in resolving these viewpoints must be drawn between autocracy and grass-roots democracy. The process must have the confidence of the collaboration, or its general effectiveness can diminish rapidly.

Does the Top quark matter?



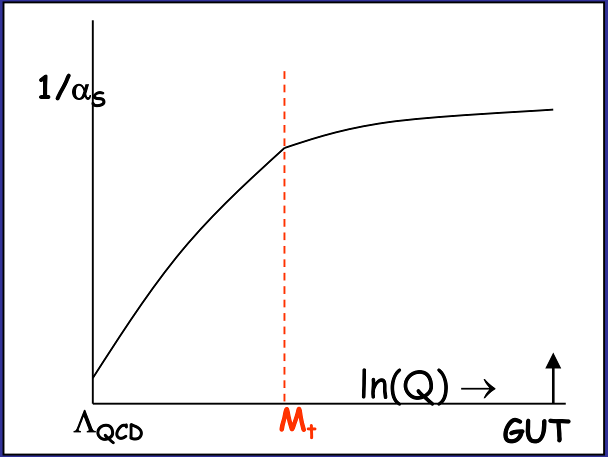
The discovery of the top quark completes the list of fundamental constituents of matter in the SM (fermions) and helps point the way to the Higgs.

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!)



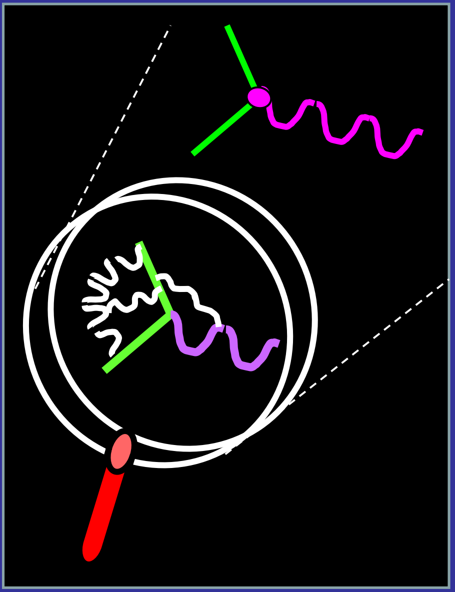
Top quark discovery

The public is interested in physics discoveries!

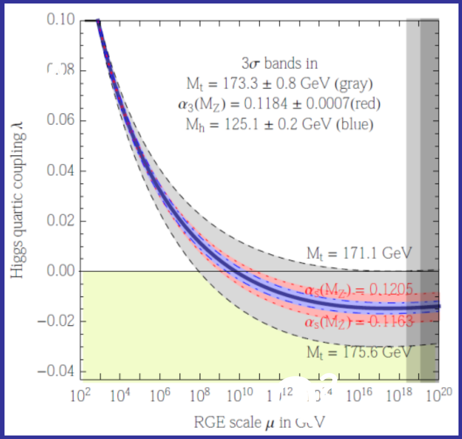
1995 Spokesmen du jour: Bellettini (CDF) , Grannis (DØ), FNAL Director Peoples, Montgomery (DØ), Carithers (CDF)

But far more important were those who did the hard work in the trenches. The postdocs and students (shown here for D0) were the real heros.

Testing the SM at very high energy scales

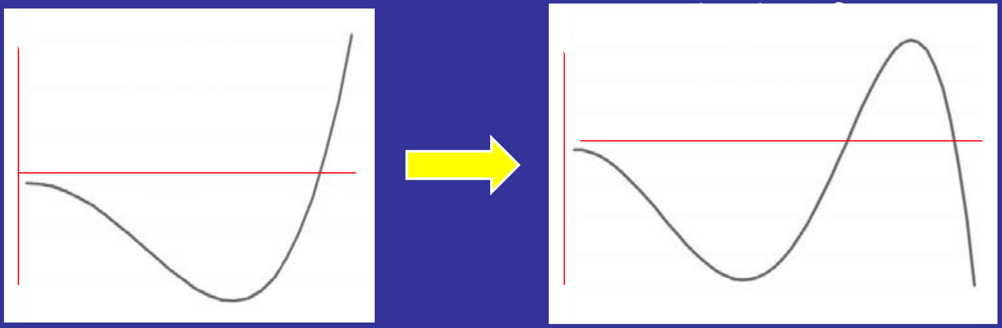


What you see depends on the magnification. A simple process at low resolution becomes more complex at high resolution (high momentum transfer, Q^2).
Thus "constants" like α_{EM}, α_{strong} etc. vary with Q^2. This also occurs for the self-coupling term λ in the Higgs potential $V = \mu^2 \phi^2 + \lambda \phi^4$ and as $Q^2 \rightarrow \infty$, λ decreases.

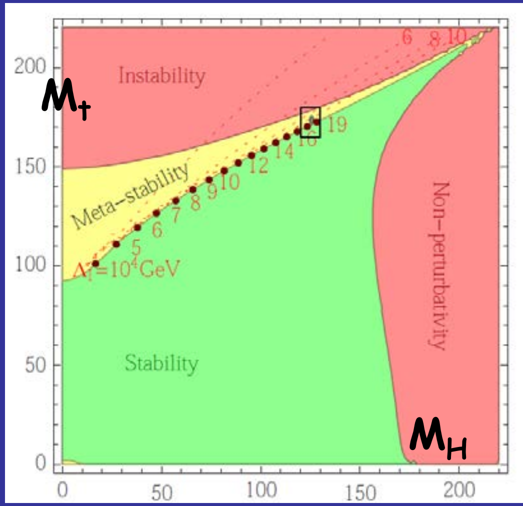


If $\lambda<0$ at high Q^2, the Mexican hat potential turns over, and the absolute minimum in the potential may no longer be at the location that gave us the observed W, Z bosons and the Higgs boson but at very high Q^2.

The variation of λ depends (mainly) on the masses of the top quark and the Higgs boson.



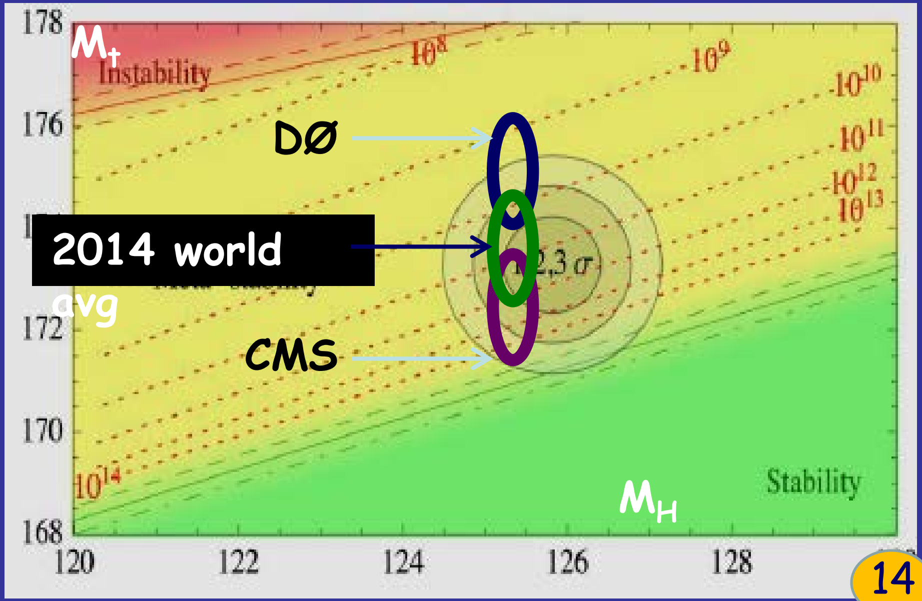
Interplay of top and Higgs masses



For a fixed Higgs mass, raising the top mass leads to a region where no EW vacuum exists (pink). Between that and the stable (green) region where λ stays positive, there is a metastable region (yellow) where a local EW minimum exists but is not the lowest potential at high Q^2. In that region, it is possible to tunnel from the EW state to the new absolute minimum (with disastrous consequences for our known universe).

Current top and Higgs masses put us in the metastable region (but with lifetime << age of universe). Few GeV shift in M_t or M_H makes a big difference.

Caveats: (1) This picture assumes SM is good up to the Planck scale, but NP will modify the picture.
(2) The theoretical meaning of the measured M_t is uncertain to ~1 GeV. Need a more robust method.



But it is odd that we live in a (SM) universe on the edge of stability!