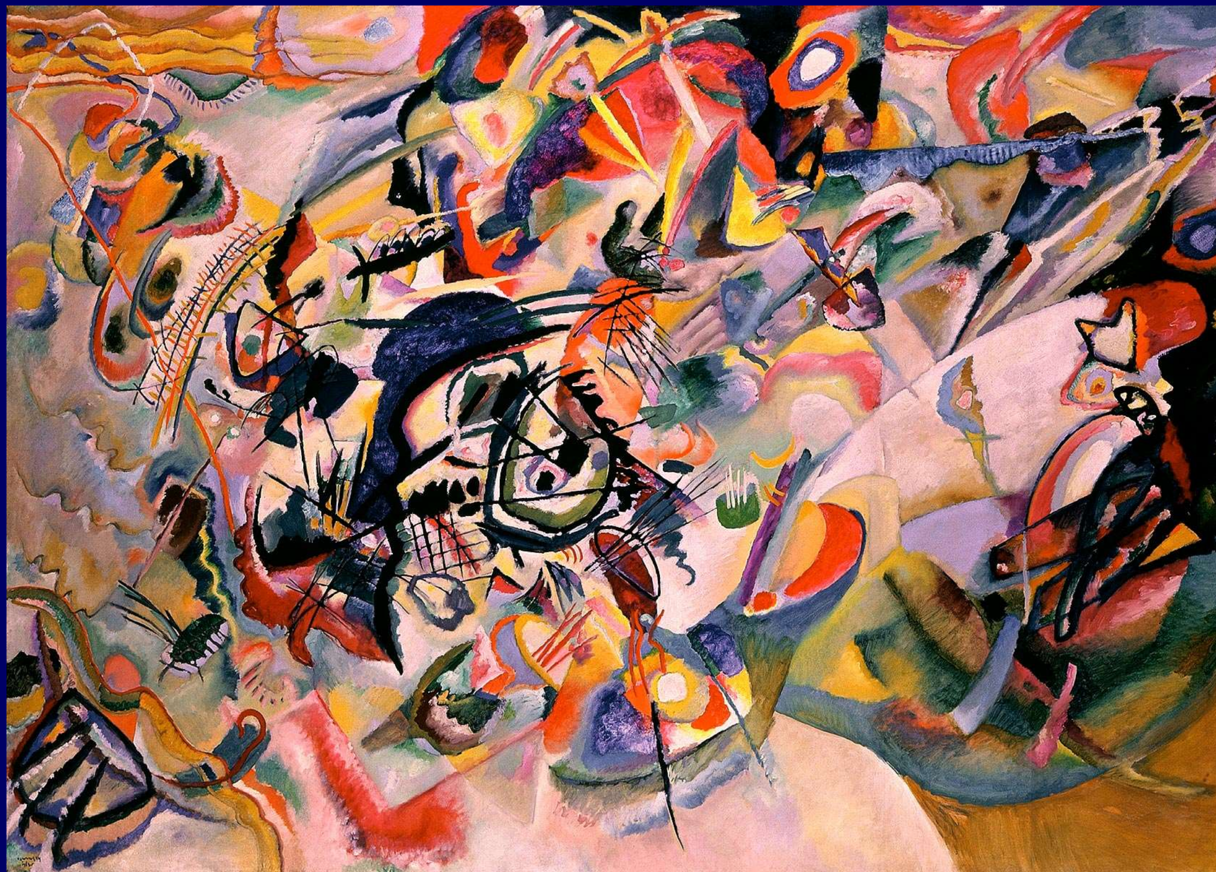
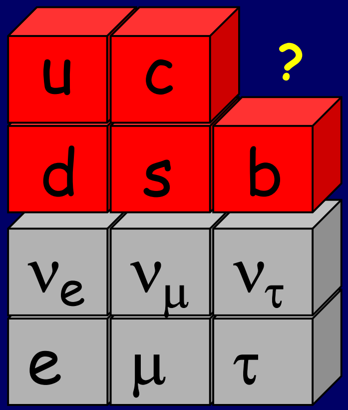


25 Years of the Top Quark

Paul Grannis
Int'l Conference on Particle Physics and Astrophysics
Oct, 2020

Top Quark Prehistory



After the τ lepton (and ν_τ) were discovered , followed by the b-quark that was a member of an isodoublet, it did not take genius to predict the existence of the top quark.

Since $m_b \approx 3 \times m_c \approx 9 \times m_s$, it seemed 'natural' to guess that $m_t \approx 3 \times m_b \approx$ 15 GeV, so a bound state of $t\bar{t}$ might then be expected at $M_{tt} \sim$ 30 GeV.

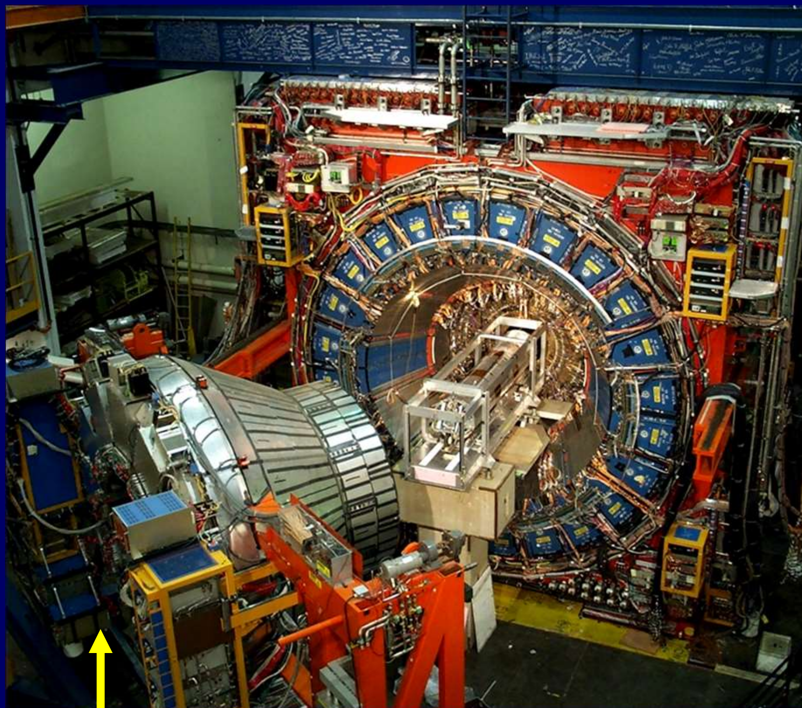
Limits were successively set at e^+e^- colliders PETRA, TRISTAN, LEP.

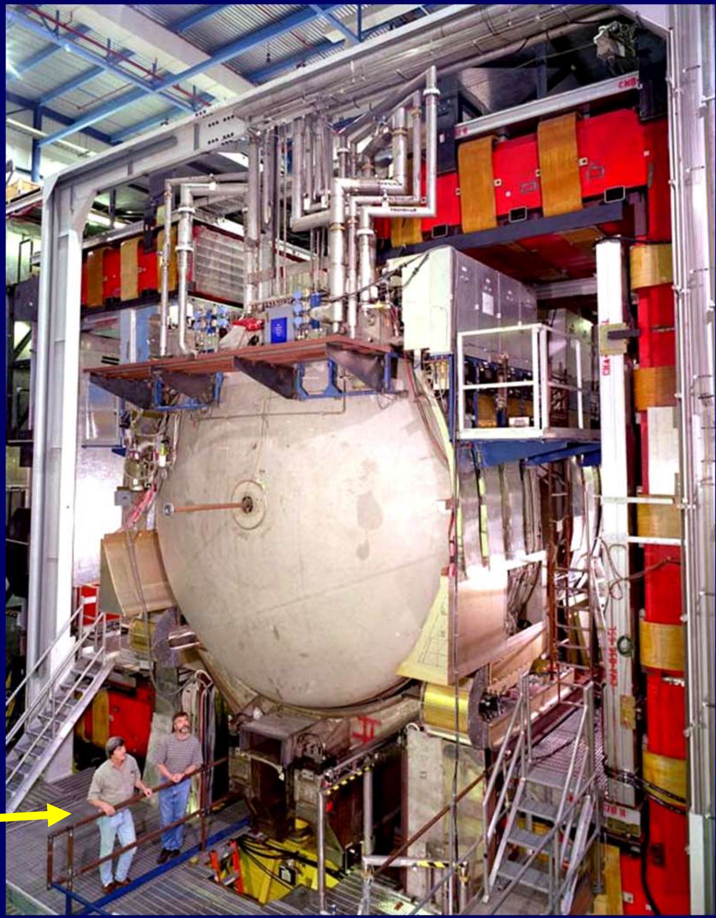
UA1 at CERN SppS reported evidence for $t \rightarrow bW^*$ but this was retracted due to underestimate of W+jets background. UA2 then ruled out top below the W (in $W \rightarrow tb$) .

At the Tevatron, CDF and then D0 searched for top quark pairs with $t \rightarrow Wb$, ultimately raising the limit to 131 GeV.

Tevatron became the only place to seek top

The Tevatron detectors





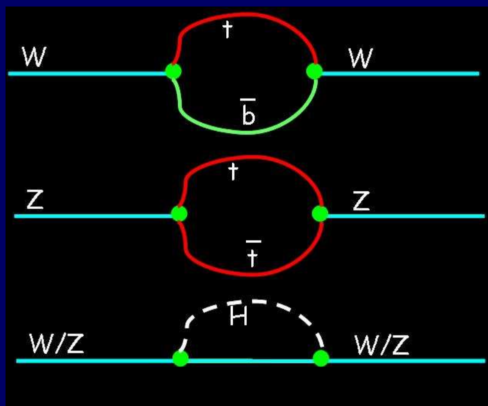
CDF (1987) and DØ (1992) had complementary strengths:

CDF: solenoidal magnet surrounding tracking and a silicon vertex detector for tagging b-quarks via displaced vertex.

DØ : no solenoid, but hermetic, finely segmented Uranium - LAr calorimetry and extensive muon coverage.

Tevatron Run I began in 1992

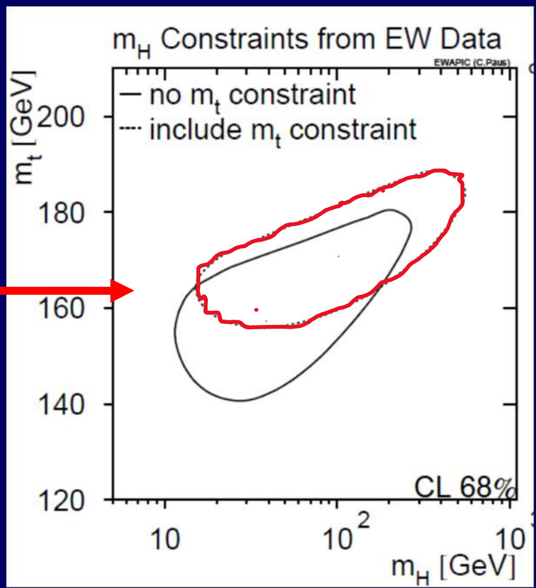
The top mass window



Precision measurements allow indirect constraints on heavy particles

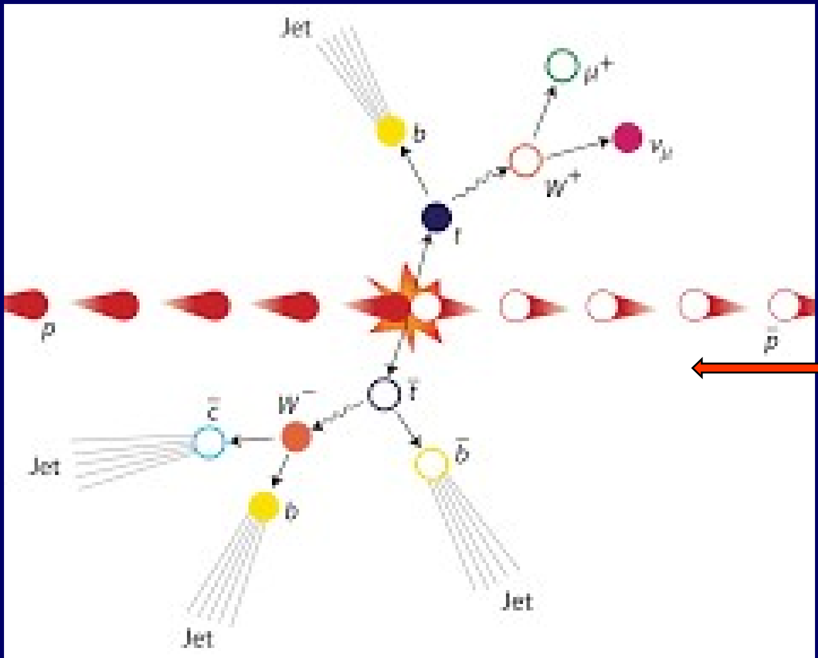
Virtual top and Higgs loops in the Z and W boson propagators give modifications to W/Z properties that depend on m_t. Measurements can thus constrain m_t and M_H (in SM context).

By 1993, precision EW measurements from LEP/SLC + the D0 top mass limit constrained m_t to the (155 – 185) GeV range.



$t\bar{t}$ Final States

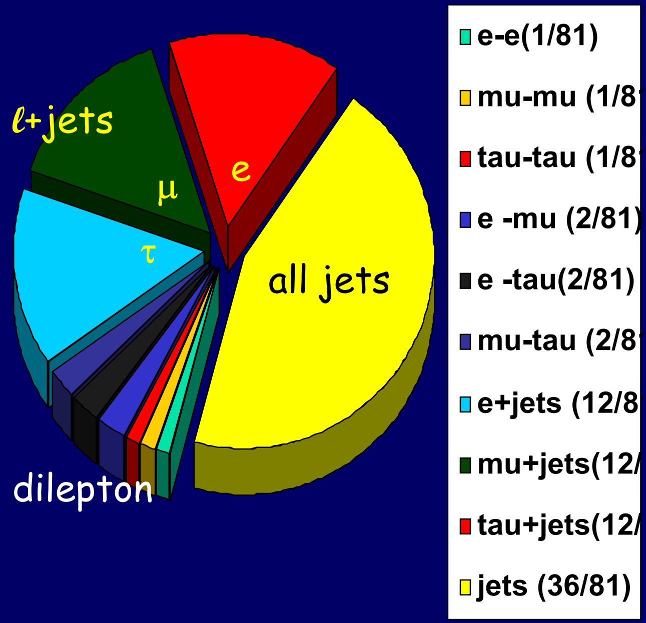
Top decays ~100% to Wb. W decays to $\ell\nu$ or to qq, so final states are determined by the way the two W's decay.



(a) ("All jets"): Both W decay hadronically
-- highest BR but largest background.

(b) ("lepton + jets"): One W decays to leptons & one to hadrons -- moderate BR and bknd

(c) "Dileptons"): Both W's decay leptonically
-- smallest BR and background



Original measurements used only e and μ (τ ID difficult) and did not attempt All Jets (backgrounds high).

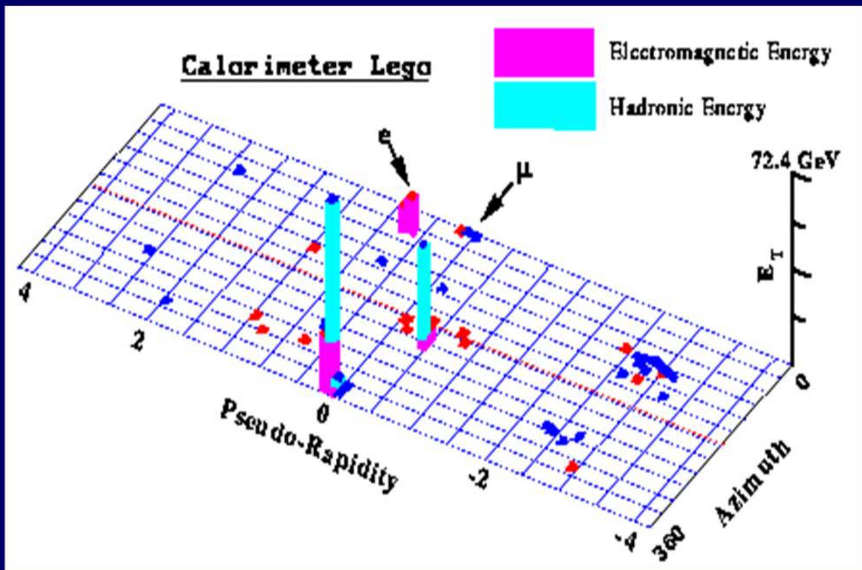
b-jets were identified by displaced vertex or decay muon.

ν's inferred by MET

(Later, all channels were used.)

First signs

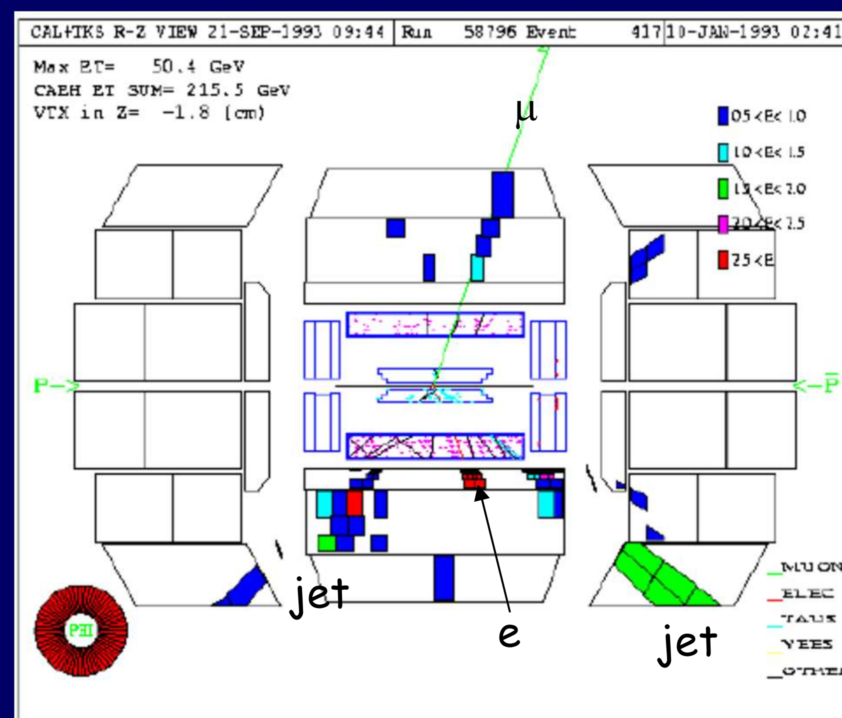
By 1993, CDF and DØ were seeing individual events that looked like top



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

1993 DØ dilepton event : e, μ, MET, all with p_T > 100 GeV, and 2 moderate energy jets. Background probability very small.

If hypothesized to be a top anti-top pair, estimate m_t=(145-200) GeV.



1994 Evidence

In April 1994, CDF published evidence for top with 19 pb^{-1}

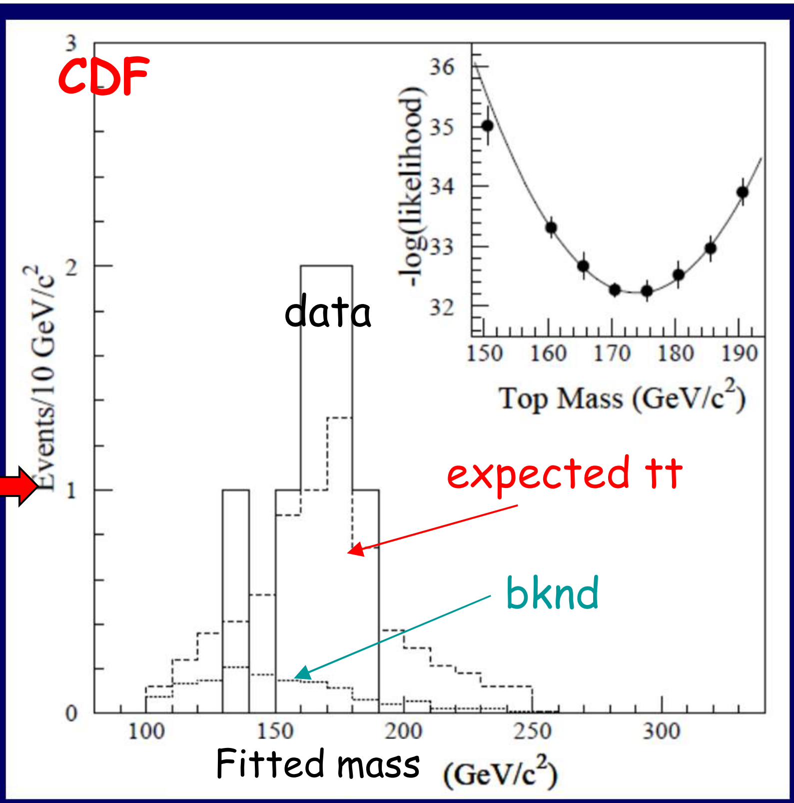
2 dilepton events and 10 ℓ+j evts with ≥ 1 b-tag

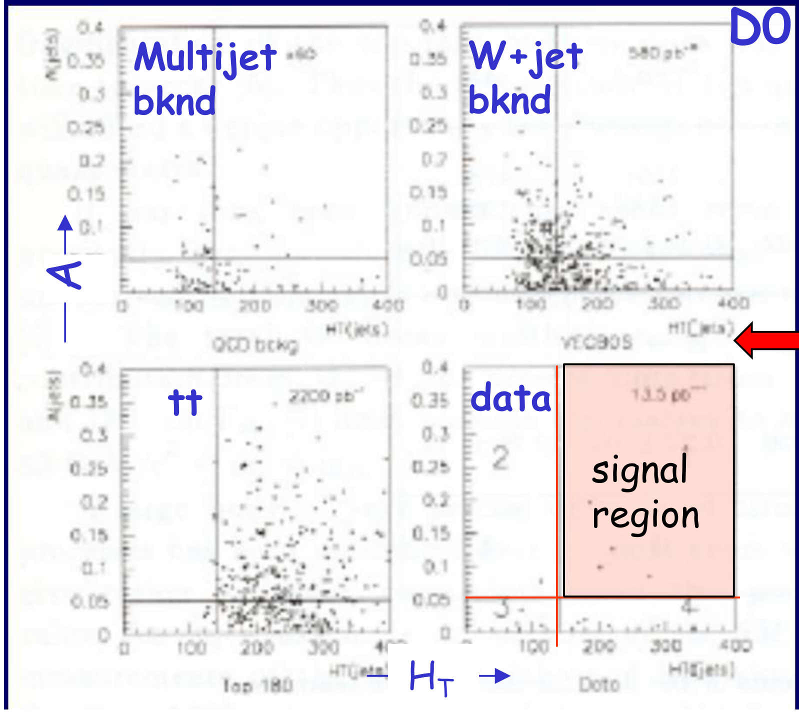
Bkgd = 6.0 ± 0.5 events,

Fitted mass in ℓ+j events 174 ±16 GeV

Observed XS ≈ 2xSM

Null hypothesis p-value = 0.26% (2.8σ).





D0 selection based on topological variables: Aplanarity ***A*** = smallest eigenvalue of momentum tensor and $\mathbf{H_T}$ = Σ E_T(jet).

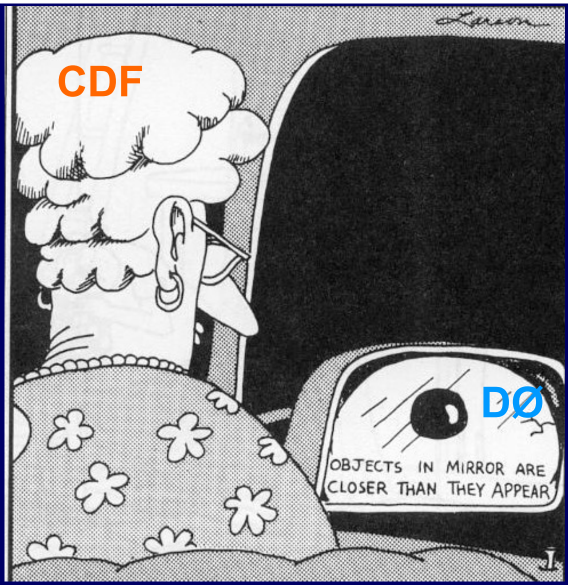
At ICHEP 1994, 7 events, bknd = 3.2±1.1 events

p-value for null hypothesis = 7.2%. Rate compatible with SM top pair production.

(Sensitivity of DØ and CDF very similar)

1995 Race to Discovery

from2005 talk by CDF physicist, D. Glenzinski.



By late 1994, Tevatron performance was much improved. In January 1995 CDF & D0 had >50 pb^{-1} on tape and sensed that this was enough for discovery.

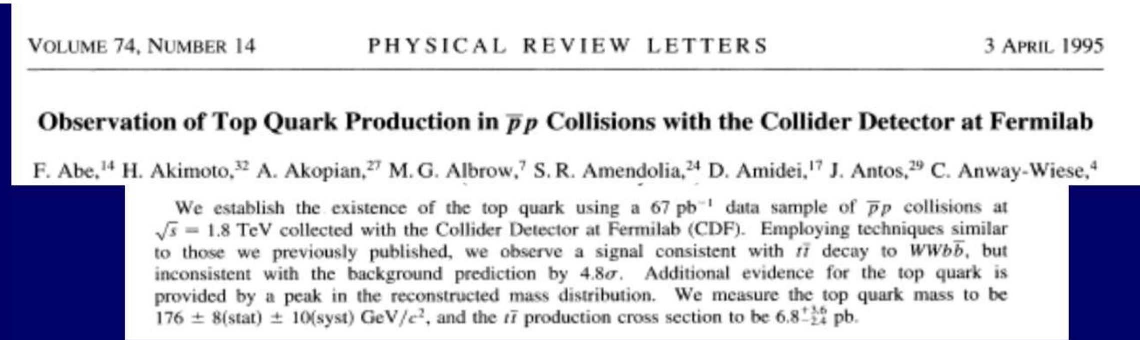
Activities ramped up to fever pitch to finalize the analyses. CDF and D0 proceeded independently with no communications.

FNAL Director John Peoples, CDF and D0 had agreed that either group could start the clock by submitting a discovery paper to Peoples. A 1 week waiting period would start, allowing the other group to complete its work. This introduced sanity into the process, as neither collaboration had to worry about being scooped.

On Feb. 17, CDF delivered its paper. D0 followed, and on **Feb.24, 1995**, CDF and DØ submitted papers simultaneously to Phys. Rev. Letters.

paper submissions

CDF Top quark discovery


VOLUME 74, NUMBER 14 PHYSICAL REVIEW LETTERS 3 APRIL 1995

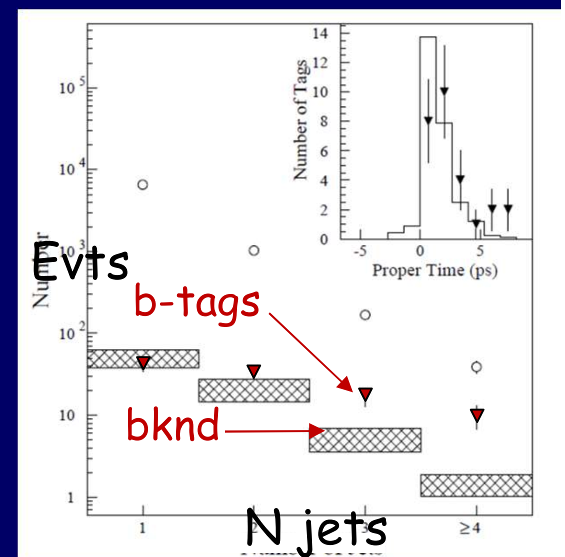
Observation of Top Quark Production in $\bar{p}p$ Collisions with the Collider Detector at Fermilab

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.

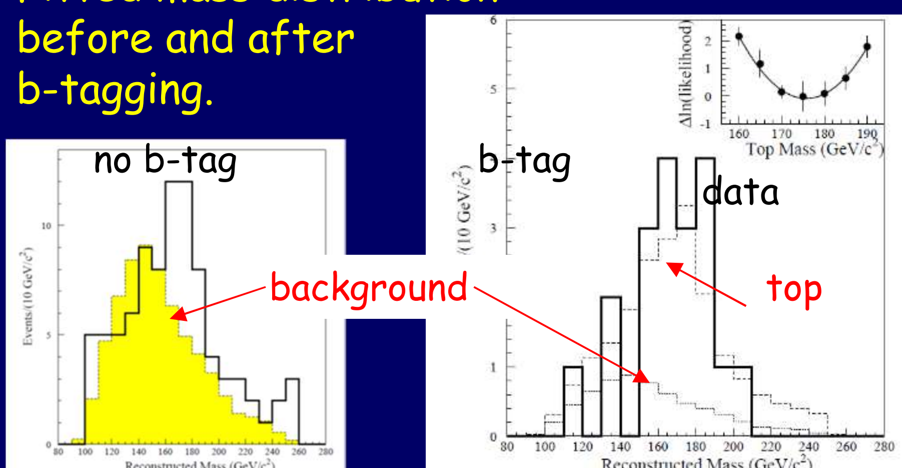
CDF's analysis followed the 'evidence' paper strategy with an improved b-tagging algorithm. With 67 pb^{-1}, 6 dilepton events and 43 lepton+jets events (50 b-tags), with estimated background of 22.1±2.9 tags.

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



Number of single lepton events with b tag vs. Njets; data excess for ≥3 jets. (Inset shows proper time of events with b-tags, consistent with expectation.)

Fitted 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]

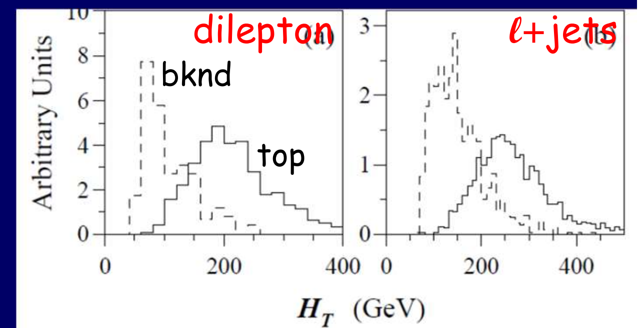
The D0 Collaboration reports on a search for the standard model top quark in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV at the Fermilab Tevatron with an integrated luminosity of approximately 50 pb^{-1}. We have searched for $t\bar{t}$ production in the dilepton and single-lepton decay channels with 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.

D0 refined the topological (A,H_T) cuts to improve signal/bknd by x2.6.

With 50 pb^{-1}, 3 dilepton events, 8 ℓ+jets events (topological selection) and 6 ℓ+jets events (μ tag).

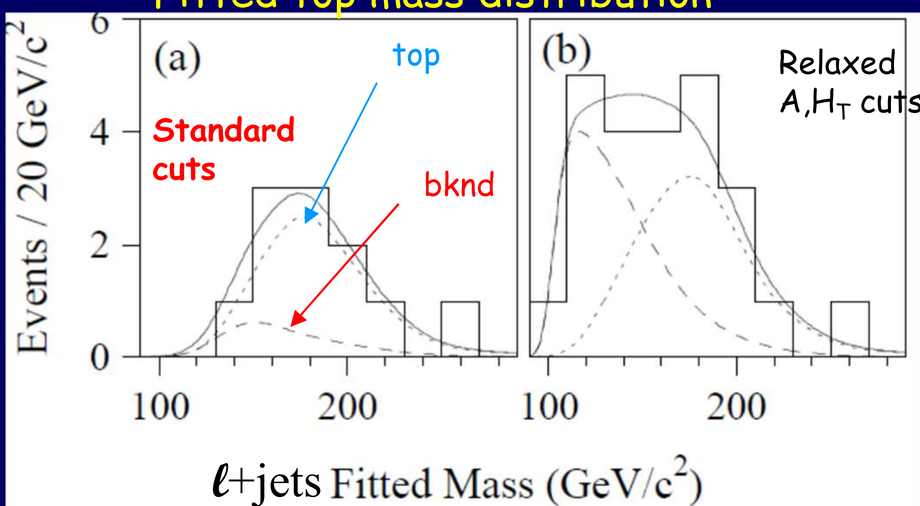
Estimated bkgnd to these 17 events was 3.8±0.6 events.

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

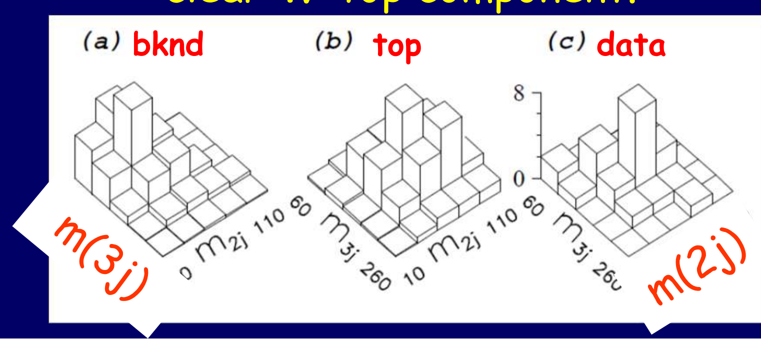


H_T distributions for signal and background

Fitted top mass distribution



2 jet and 3 jet masses for the hadronic top decay. Data shows clear W-top component.



Top quark announcement

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

In-person audience, no social distancing, no masks
No one looking at laptops
Everyone paying attention
Cannot tell if speaker is CDF or D0

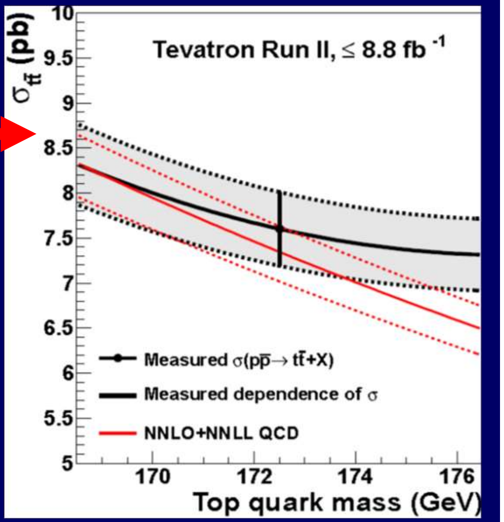
Who gets the credit?

In both CDF and D0 – a great sense of accomplishment and shared responsibility for the discovery

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 SM Top Quark?

The cross section agrees with SM (NNLO QCD + NLO EW) prediction for the observed m_t

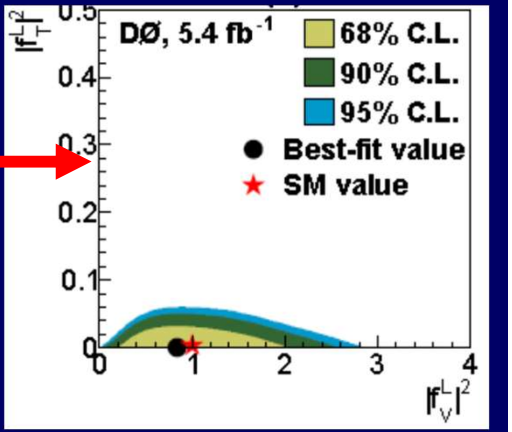


Branching ratios as expected in SM

Charge 2/3 favored

CKM matrix element V_{tb} consistent with 1 as expected for a 3 generation quark sector.

W boson helicity fractions and tbW couplings agree with (V-A) SM



Top polarization and t-tbar spin correlations as in SM

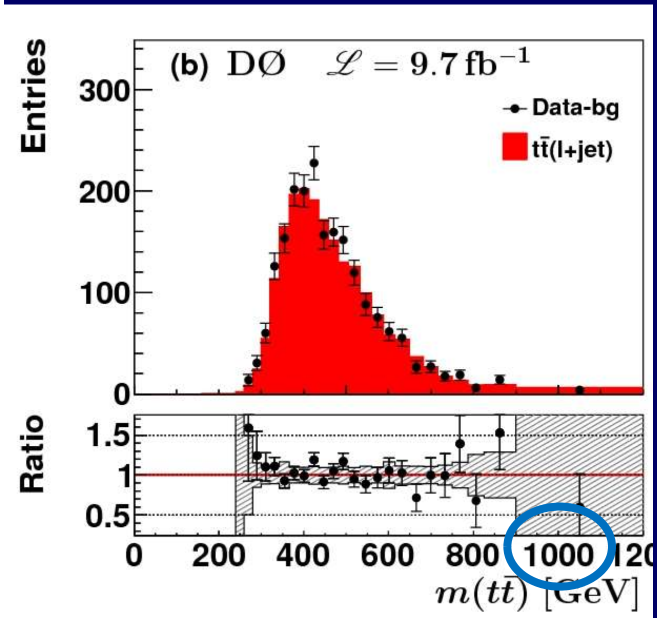
- It looks like top … But is still odd – mass is $40 \times m_b$

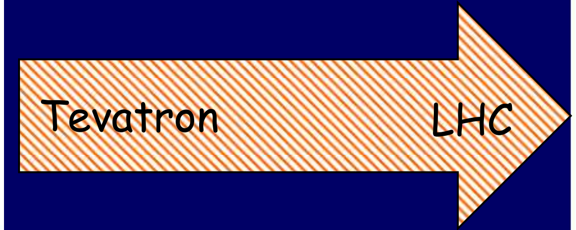
- Very short lifetime (~3×10^{-25} s), decays before hadronization so no $t\bar{t}$ bound state

The top is now approaching middle-age

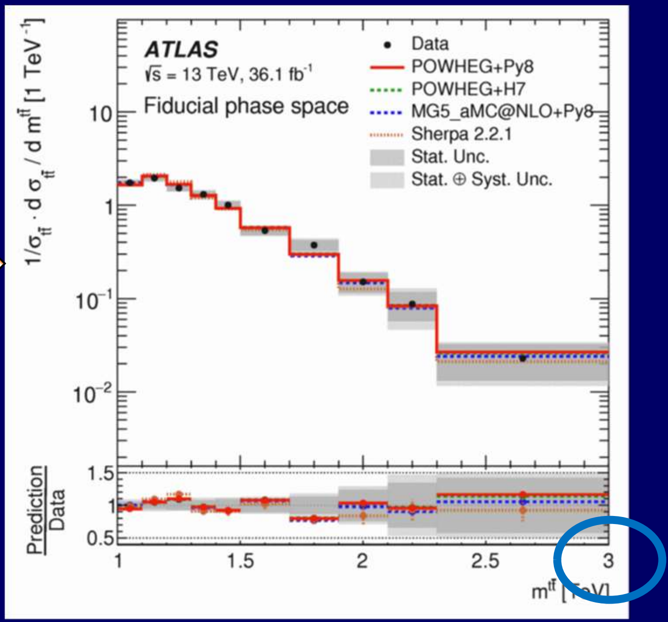
The Tevatron told us much about it but now the LHC has taken over

Top pair production



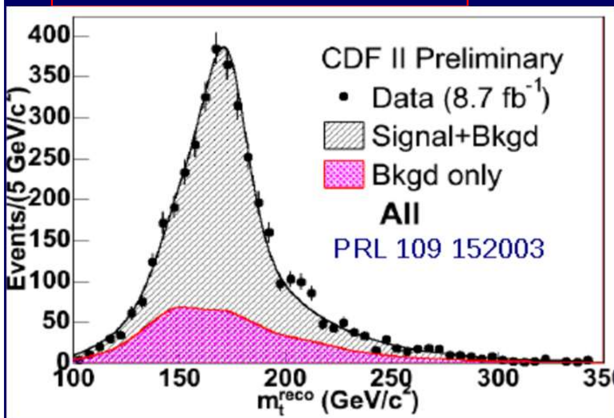


No tt resonances or anomalies

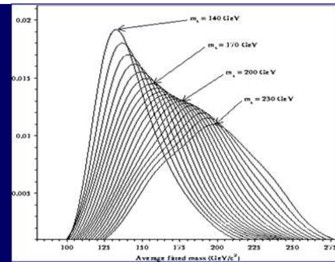


Development of analyses with 'boosted' (merged) jets at LHC is providing significant extension of search window

Mass

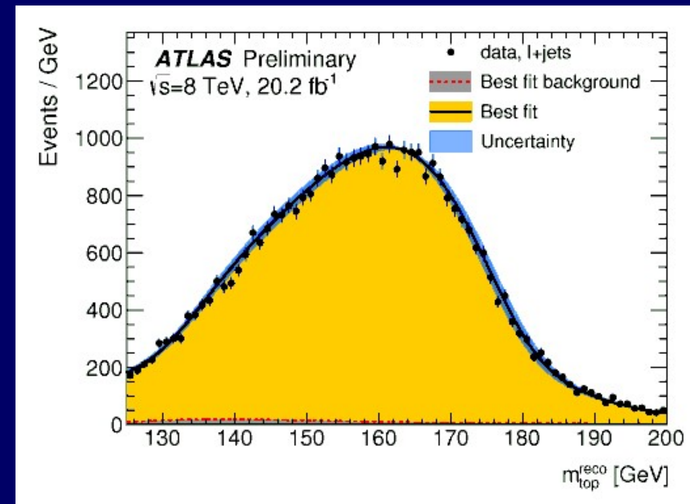


Tevatron combination:
m_t=174.34±0.64 (0.37%)



Compare MC templates different m_t to data

(systematics dominated)



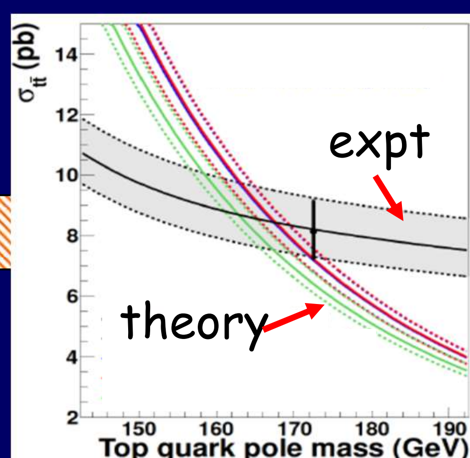
ATLAS combination (2017):
m_t=172.51±0.50 (0.29%)

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

Would like the pole (other well defined) mass

Compare SM theory XS to measured XS as a function of m_{pole}

m_{pole} (D0) =
172.8 ± 3.4GeV

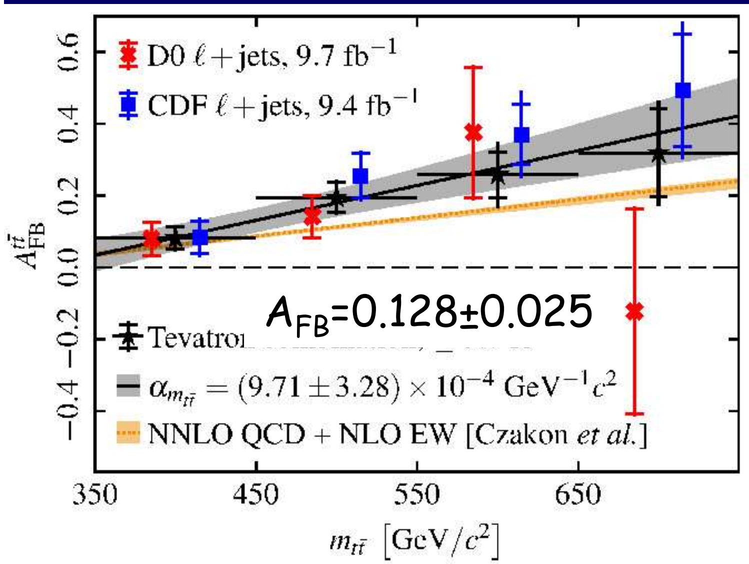


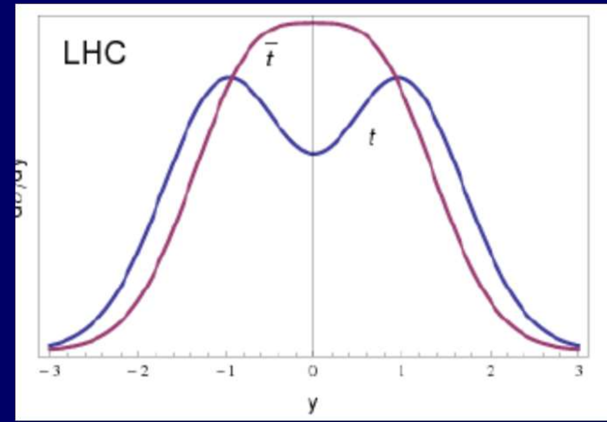
Pole masses limited by systematics and theory unc.

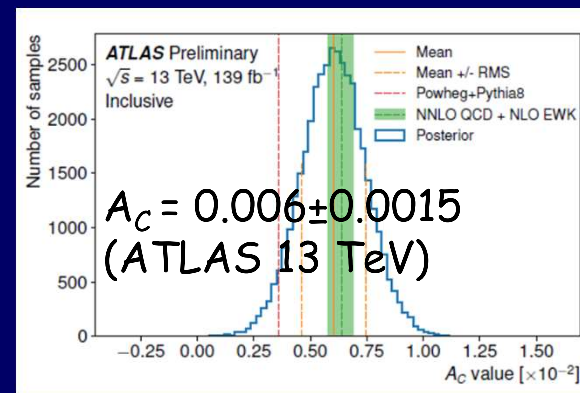
m_{pole} (CMS) =
170.5 ± 0.8GeV

Recent measurement fitting to 3 distributions with much improved precision!

Production asymmetries







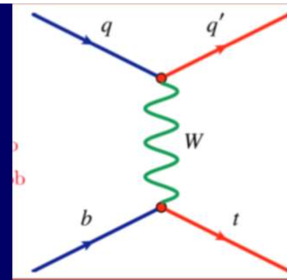
At $p\bar{p}$ Tevatron, forward-backward asymmetry measures tendency for top to be emitted in the proton beam hemisphere. A_{FB} is due to interference of LO and NLO diagrams.

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

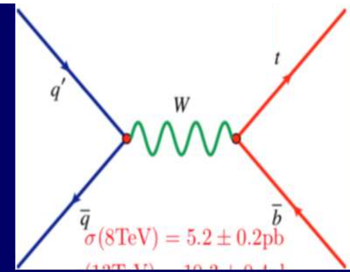
At pp LHC, smaller A_C measures tendency for anti-top to be more central than top. Evidence for asymmetry is consistent with SM.

Single top

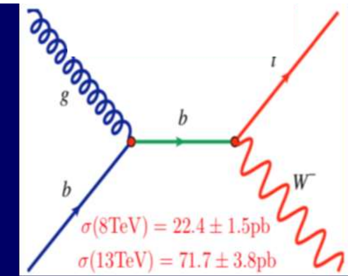
EW production via 3 diagrams:
t-channel W, s-channel W,
t-W (s-channel b)



t-channel



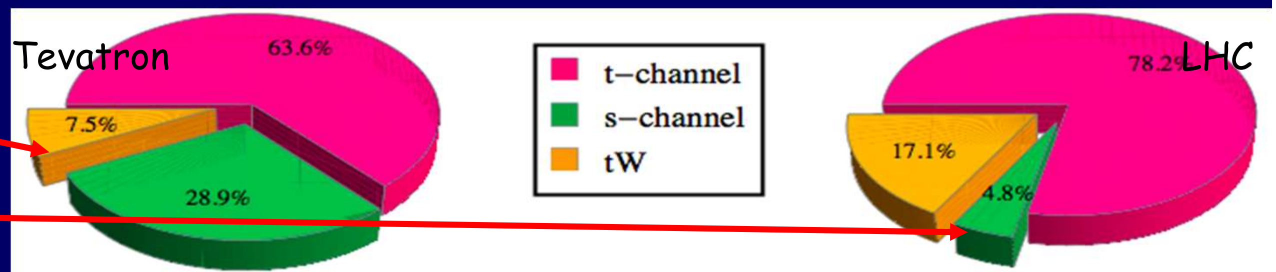
s-channel



t-W prod.

t-W small at Tevatron

s-channel small at LHC



Tevatron combined
σ(t-channel)=2.25 ± 0.30 pb (13%)

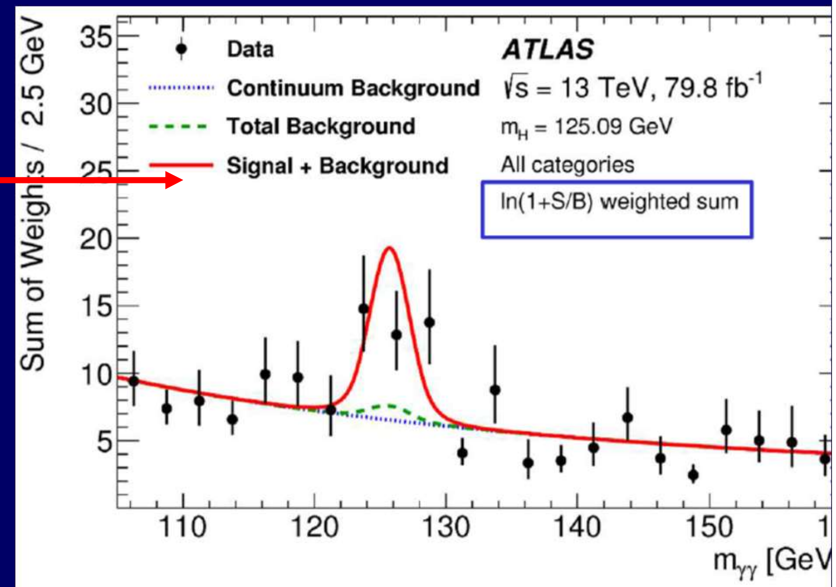
CMS 13 TeV
σ_t(t-channel)=130 ± 19 pb (15%)

Couplings

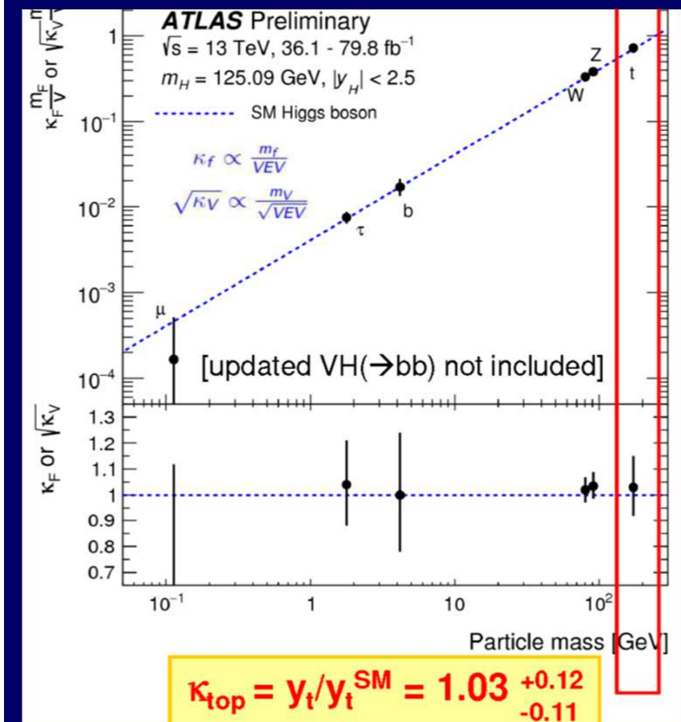
- W in top decay expected to have no right handed component. LHC has improved Tevatron limit on W_R by ≈x4
- tbW (V+A) and tensor couplings are absent in SM. LHC has improved over Tevatron by ≈x2

The LHC is adding much that is new

- Top pair or single top + another object: Z, W, γ, $t\bar{t}$, $b\bar{b}$ to probe non-SM contributions



- Now observe top Yukawa coupling via ttH production with H→bb, $\gamma\gamma$, ZZ* . Comparison with indirect Yukawa from $gg \to H$, $H \to \gamma\gamma$ constrains new physics in loops.



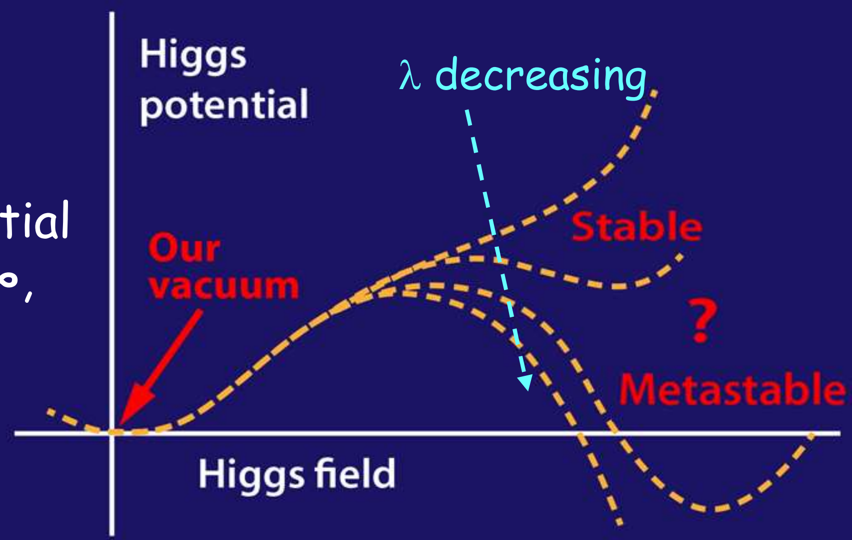
- Higgs couplings; now getting 2nd generation with $H \to \mu\mu$

- Also: HL-LHC will enable searches for new physics: FCNC in $t \to cH$ etc., charged lepton non-universality.

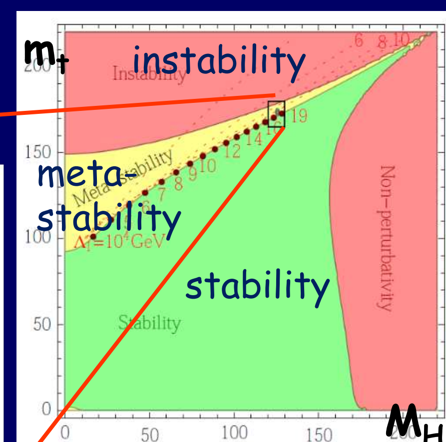
… And yesterday's discovery is tomorrow's calibration (top mass studies help fix jet energy scales and b-tag efficiency)

Precision top mass

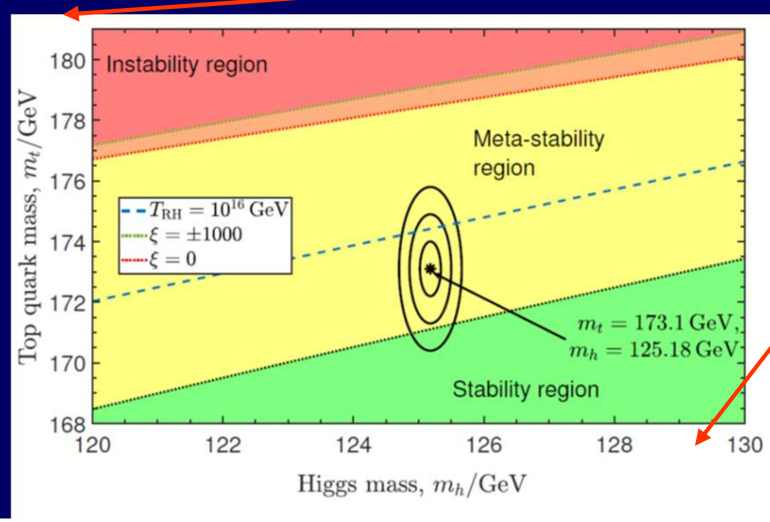
The self coupling term λ in the Higgs potential $V = \mu^2 \phi^2 + \lambda \phi^4$ runs (like α_S etc) . As $Q^2 \rightarrow \infty$, λ decreases and could become negative.



If $\lambda < 0$, the Mexican hat potential turns over, and the absolute minimum is no longer at the usual vacuum expectation location. The universe becomes unstable or metastable



Current values of m_t, M_H indicate we are probably in the metastable region

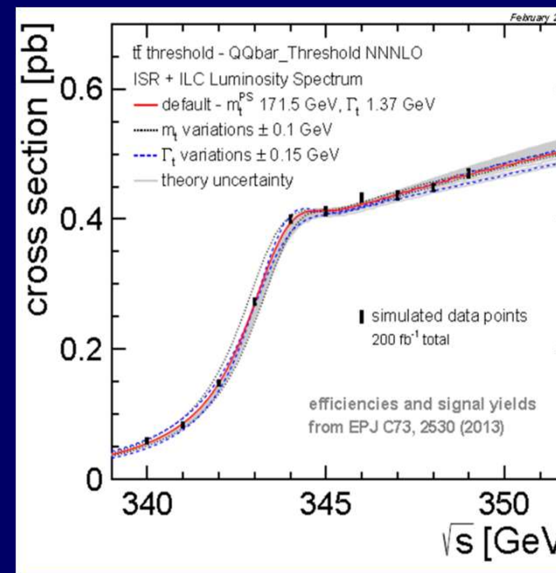


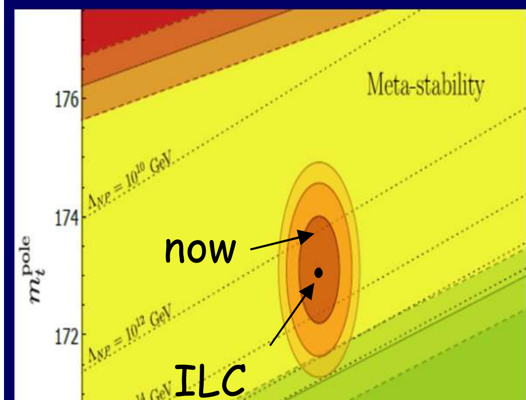
Is the fact we live so close to instability significant or a coincidence?

What to expect in top quark maturity?

With full LHC statistics top pole mass will improve somewhat, but systematics already dominate. (But rare top decays will be much improved.)

Future e^+e^- colliders will go much further. An ILC threshold scan in $e^+e^- \rightarrow t\bar{t}$ will measure a theoretically well defined top mass with δm_t~50 MeV (1/16 current LHC pole mass). (Higgs mass also improved x10)

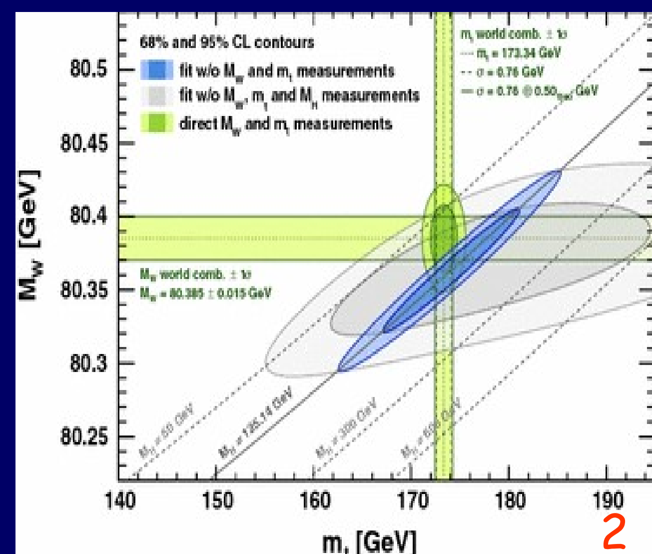




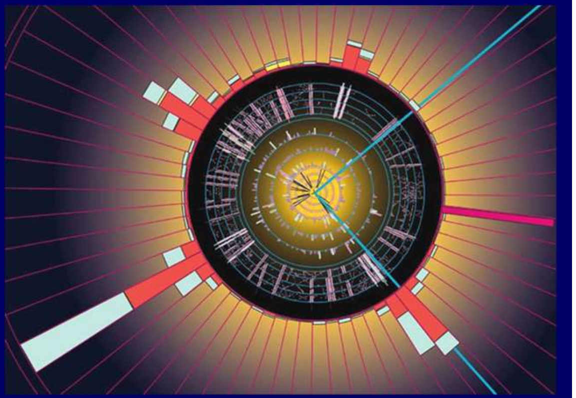
This ILC top mass and high precision Higgs mass will answer the stability question.

50 MeV unc.

With improved precision, the constraints on non-SM physics from comparison of measured M_H and indirect prediction from m_t and M_W should be one of the best available indicators of new physics in loops.



The Biography of Top



infancy ❖ The discovery of the top quark by the CDF and DØ collaborations in 1995 opened the era of top quark studies

youth ❖ The LHC experiments are extending our understanding of the top quark significantly

maturity ❖ Further precision studies at HL-LHC and a future e^+e^- collider will bring qualitatively new insights

Precision top measurements are important as they explore the 3rd generation physics where new physics should be most visible.

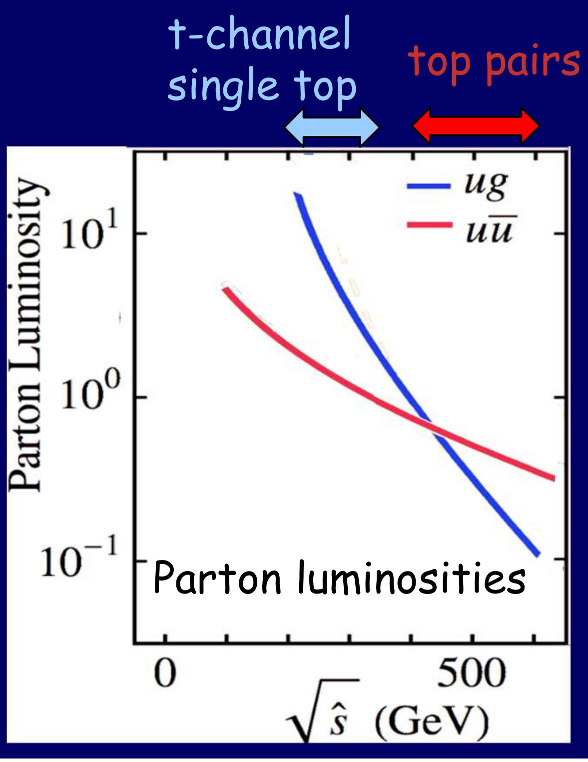
The top Yukawa coupling ≈ 1: Is top the anomaly, or is it the (u,d,s,c,b) that are the peculiar quarks?

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

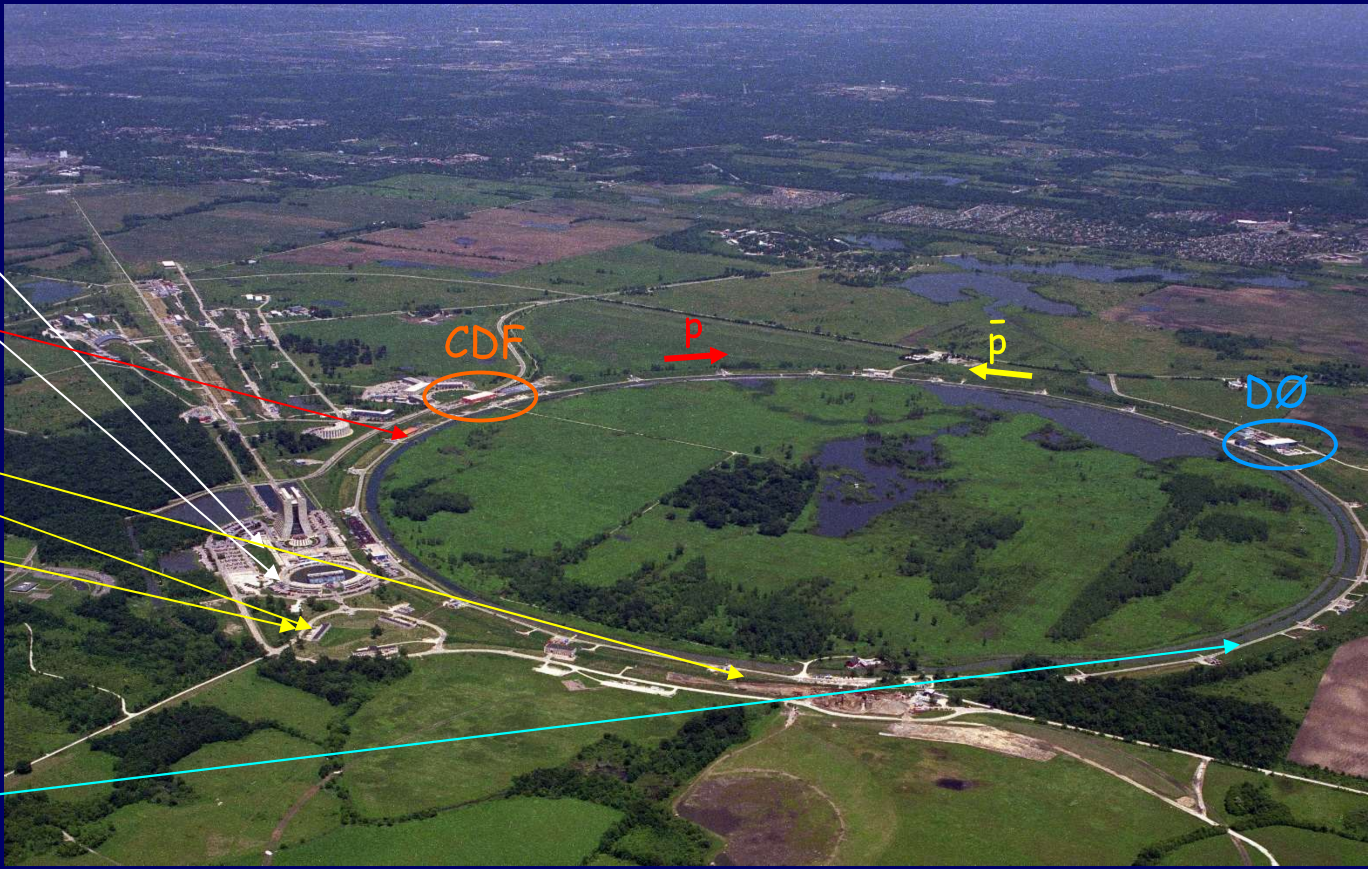
150 GeV Main Ring

$\bar{p}$ 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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404 Authors

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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.

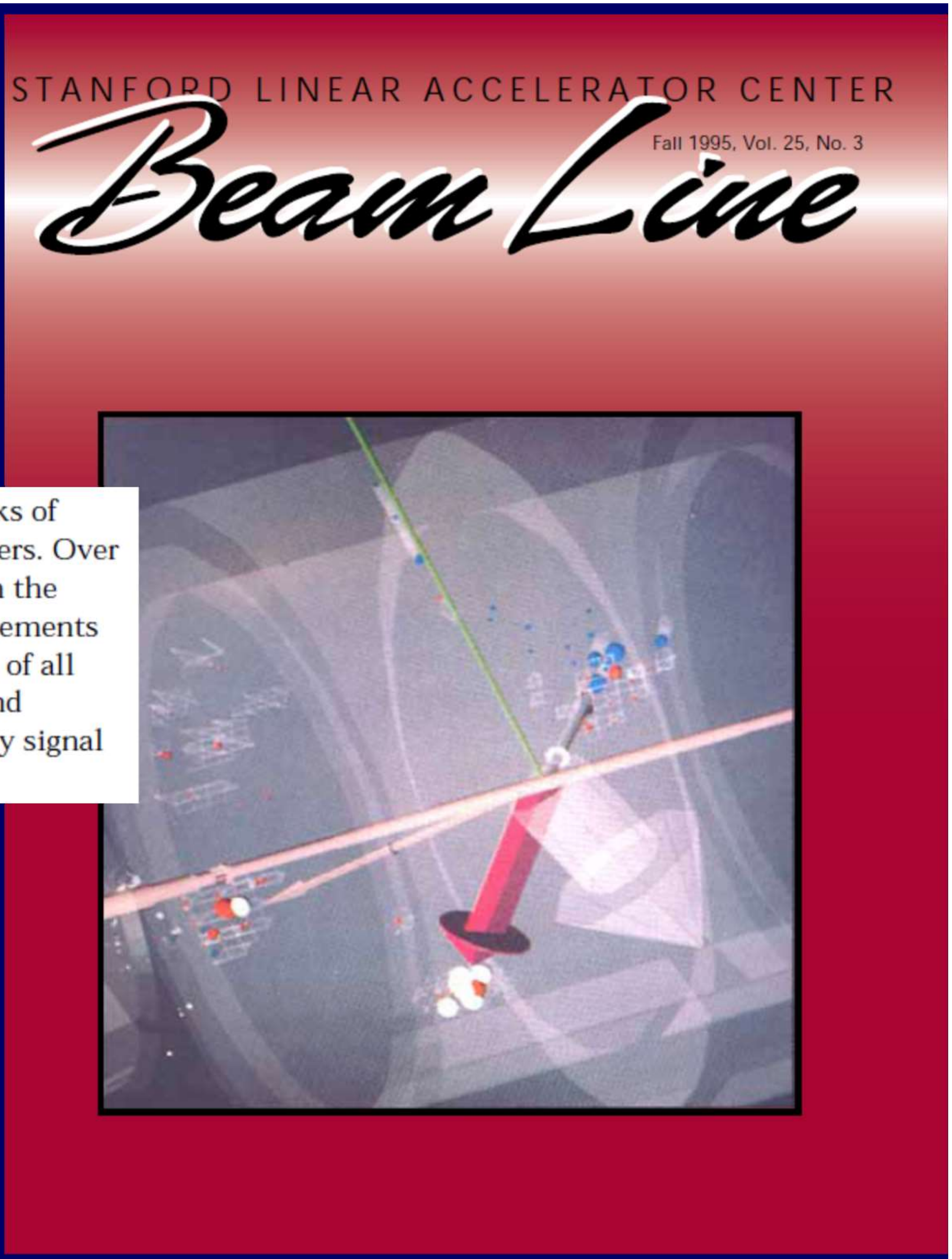
Strictly speaking then, the 1994 results were not Evidence, and neither CDF or DØ made a Discovery on their own (jointly, they did).

If P_1 and P_2 are probabilities of discovery in two experiments, then $P_{tot} = P_1P_2(1-\ln P_1P_2)$

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

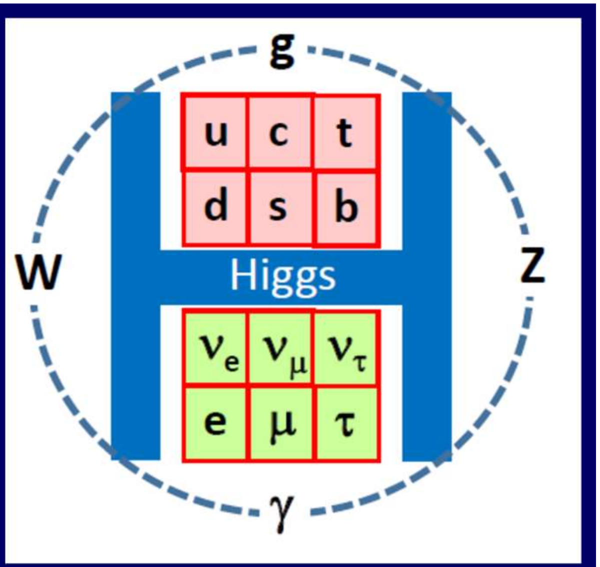
Beam Line editorial by James Bjorken

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?



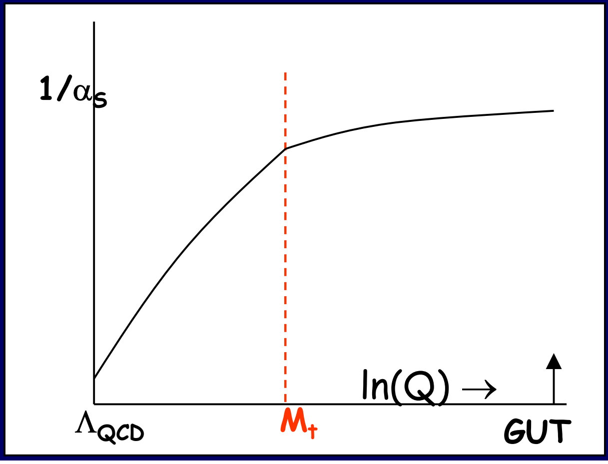
The discovery of the top quark completes the list of fundamental constituents of matter in the SM (fermions) and helps point the way to the Higgs.

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 very different!)



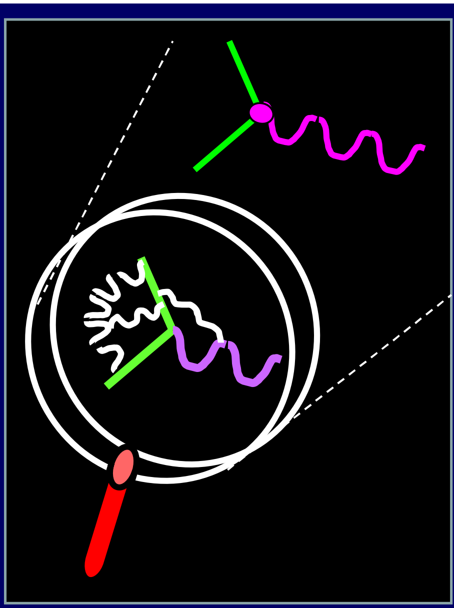
Top quark discovery

The public is interested in physics discoveries!

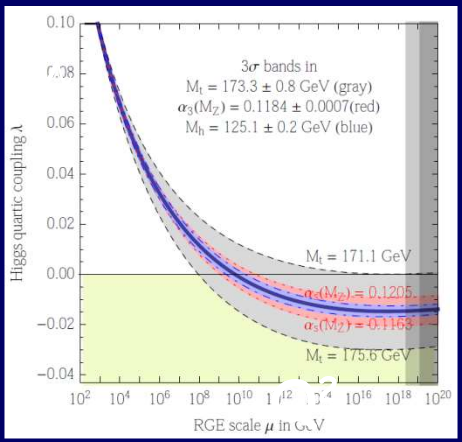
1995 Spokesmen du jour: Bellettini (CDF) , Grannis (DØ), FNAL Director Peoples, Montgomery (DØ), Carithers (CDF)

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.