Weighty Matter:
The Top Quark and Its Mass

Outline

1. What We Know About Fundamental Structure
2. The Top Quark: Discovery & Properties
3. The Role of the Higgs Boson
4. Producing and Detecting Top Quarks
5. Measuring the Top Quark Mass
6. Summary

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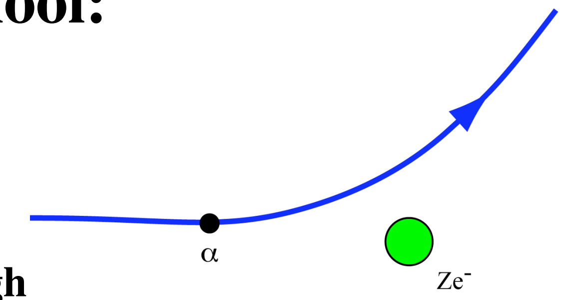
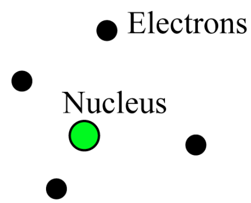
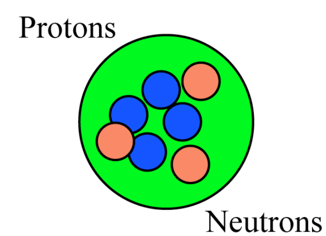
Structure of Matter

- **What we now learn in "high school:"**
  - **Matter is made up of atoms**
    - Electron cloud
    - Hard, small core - nucleus
      - **Discovered by Rutherford through α scattering off gold foil**
      - **Held together by electromagnetic force**



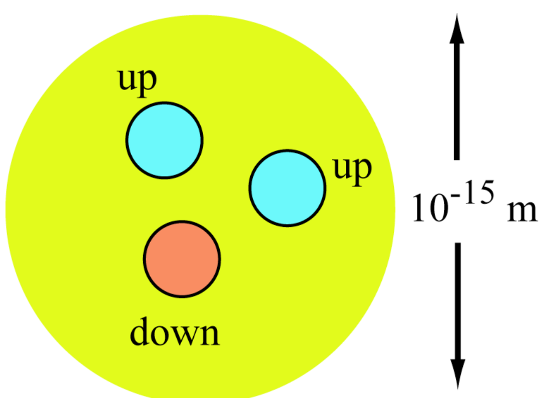
  - **Nucleus itself has structure**
    - Protons
    - Neutrons
    - Can describe all matter
      - **Three types of building blocks**
      - **Electromagnetic force**
      - **"Strong" force**





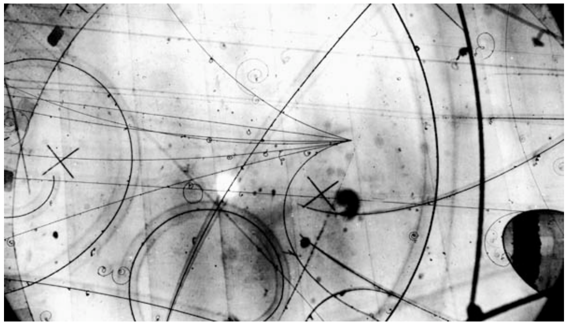
Up and Down Quarks

- **Protons & neutron size about 10^{-15} m**
  - **Use high-energy electrons (10-20 GeV) to "see" into proton**
    - Cf., MeV energies needed to resolve atomic structure
  - **Studies at Stanford in 1960's showed**
    - 3 objects inside proton
    - 2 charge +2/3 - "up" quarks
    - 1 charge -1/3 - "down" quarks

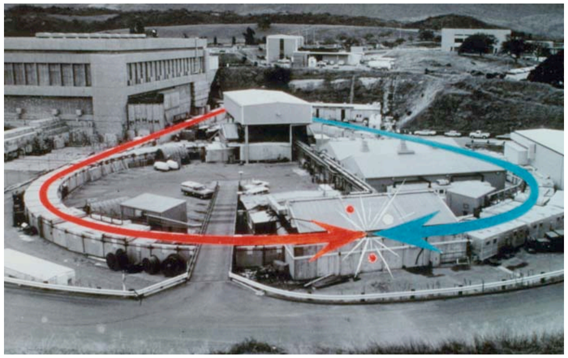


More Quarks!

- By 1977, we had discovered three additional "flavours" of quarks
  - Strange quark -- introduced in 1963
    - Had a mass around 0.3 GeV/c^2
    - Decayed after about 10^{-6} s



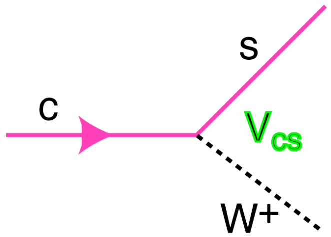
  - Charm quark -- detected in 1974
    - Heavier (about 1.8 GeV/c^2)
    - Lifetime of about 10^{-13} s

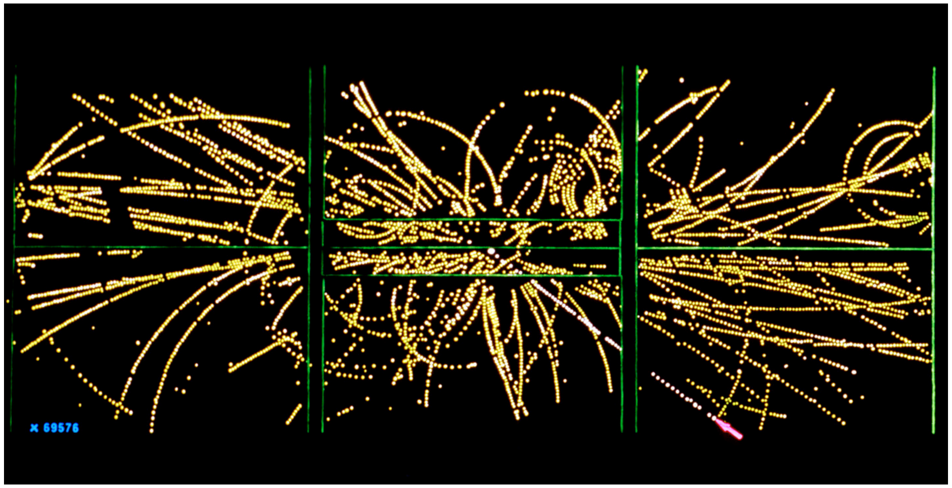


  - Bottom quark -- discovered in 1977
    - Heavier still (about 4.5 GeV/c^2)
    - Lifetime of about 10^{-12} s

And More Forces

- **Heavy quark decays caused by a "weak" force**
  - **"Standard Model" predicted 2 force carriers**
    - W^+ and Z^0 intermediate vector bosons
  - **UA1 and UA2 experiments at CERN discovered them in 1983**



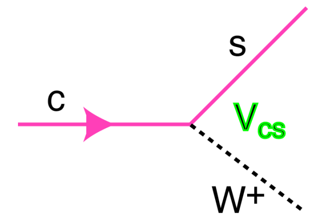


- **Led to partially unified picture:**
  - **Strong force**
    - Bound quarks
  - **Electroweak force**
    - Electromagnetic and weak force
  - **But didn't include gravity**
    - Very weak, no quantum theory

Theory Remained Incomplete

- **Standard Model picture:**
  - **Quarks come in "singlets" or "doublets," and interact via electroweak force**

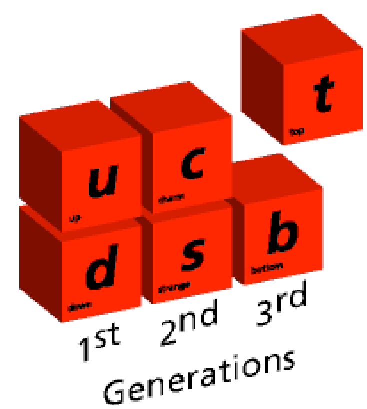
$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix}$$



- **Was b quark a singlet?**
  - **Production of b quarks**

$$e^+e^- \rightarrow b\bar{b}$$

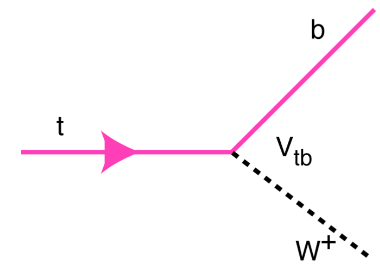
    - Angular distribution depends on # of partners to b quark
    - b quark behaved like a member of a "doublet"
    - Unseen partner defined to be top/truth quark

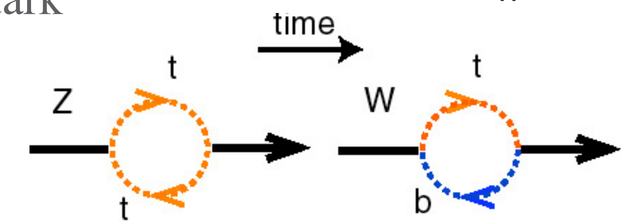


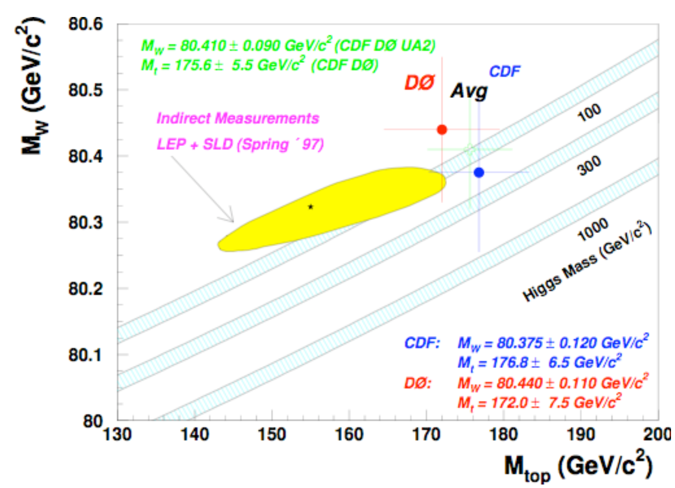
  - **New quark appeared to be heavy**
    - $M_{top} > 28$ GeV/c^2 in 1986
    - $M_{top} > 91$ GeV/c^2 in 1990

Properties of the Top

- **Top quark properties unusual**
  - **Massive fermion**
    - Decays before interacts with other quarks
    - Opportunity to study a "bare" quark
  - **Heaviest object in theory**
    - Most sensitive to "loops"
    - Insight into generation of mass in Standard Model
- **Difficult to observe**
  - **Need high-energy collisions**
  - **Electron colliders limited by energy**
  - **Hadron colliders create huge background rate**
    - Creates "needle in the haystack" problem

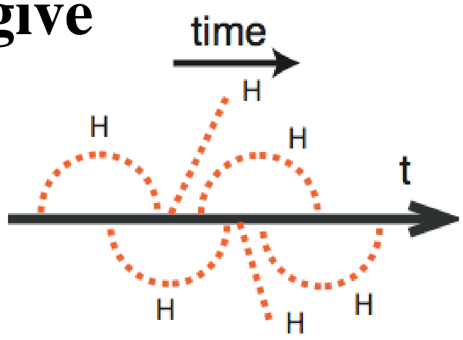






Source of Mass

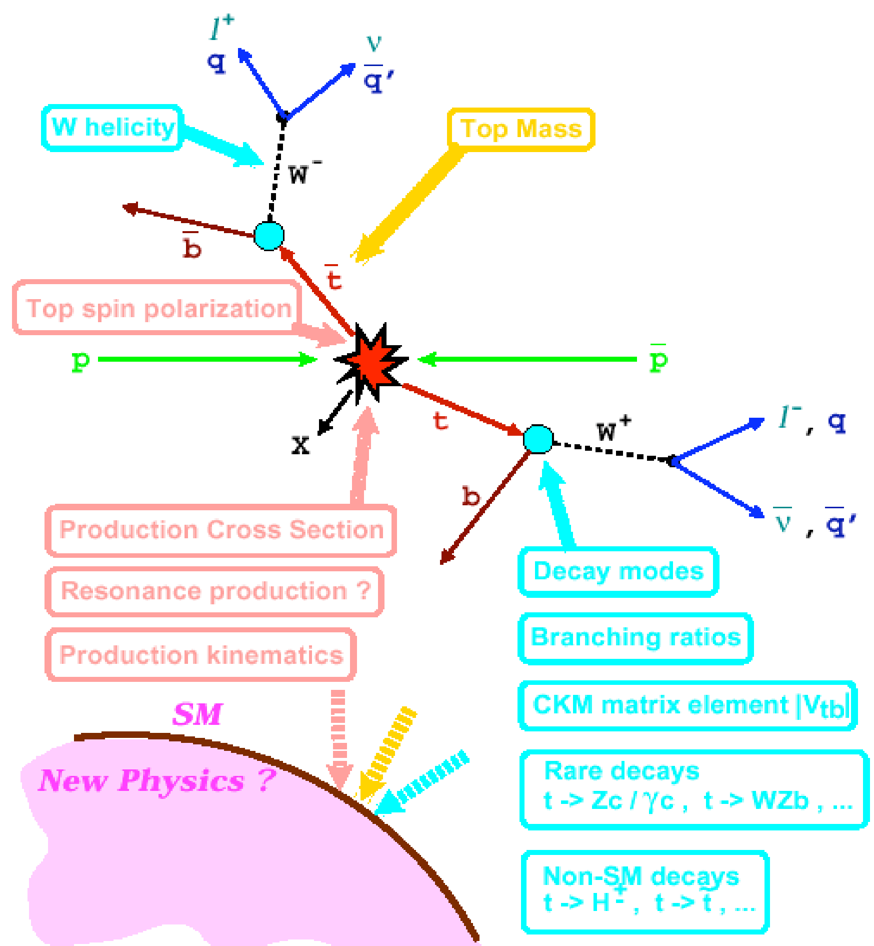
- **Simplest theories predict quarks, leptons and force carriers massless**
  - **Reality is quite different**
    - Masses range from < 0.0005 to > 90 GeV/c^2
  - **Explained theoretically by a "broken symmetry"**
    - EWK interaction mediated by massive W/Z bosons
    - Requires the existence of Higgs boson
- **Higgs provides a crude mechanism to give each particle its own mass**
  - **Higgs interacts with all particles**
  - **Strongest interactions -> heaviest mass**



- **But no direct evidence for Higgs boson**
  - **Searches imply that M_H > 114 GeV/c^2 at 95% CL**

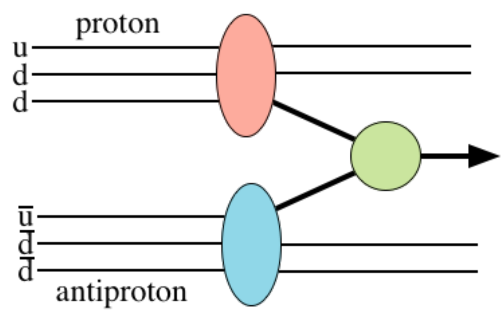
Top Quark Opens Up New Laboratory

- Top provides a broad physics program
  - Production & decay
    - Cross sections
    - Branching ratios
    - Helicity
  - Top quark mass
    - Test of EWK radiative corrections
  - Single top production
    - Top quark width
  - New phenomena
    - Rare decays
    - Unusual events



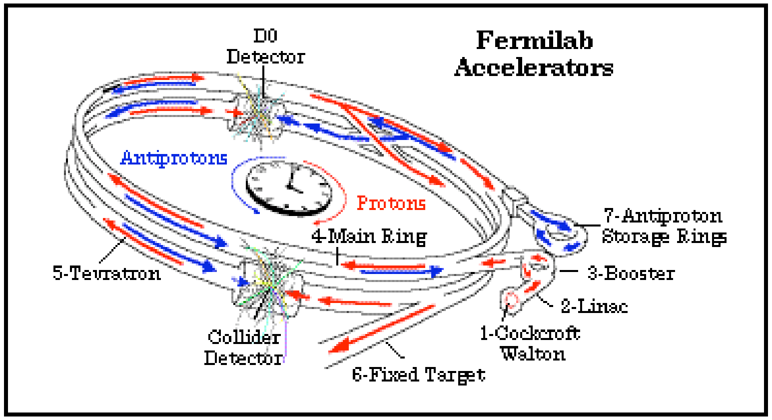
Search and Discovery of Top

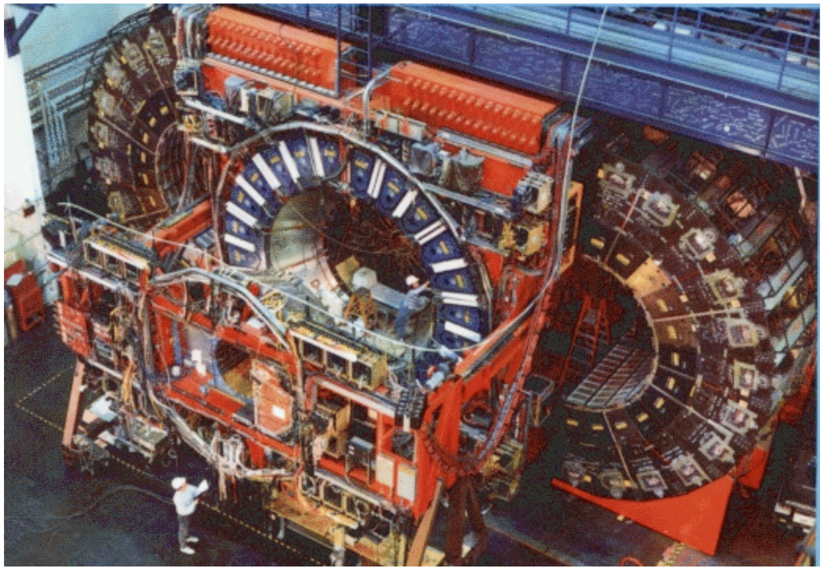
- **Began in 1980's at the Tevatron**
  - **The problem:**
    - Last time we had "lots" of top quarks was within first second of Big Bang
    - We had to recreate those conditions
      - **Very high-energy collisions**
      - **Very dense environment**
  - **The solution:**
    - Collide protons and antiprotons at highest energies possible (1.8 TeV)
      - **Fermilab Tevatron Collider**
    - Record collisions & sift through the data
      - **Collider Detector at Fermilab (CDF)**
      - **DØ Detector**



Fermilab and CDF

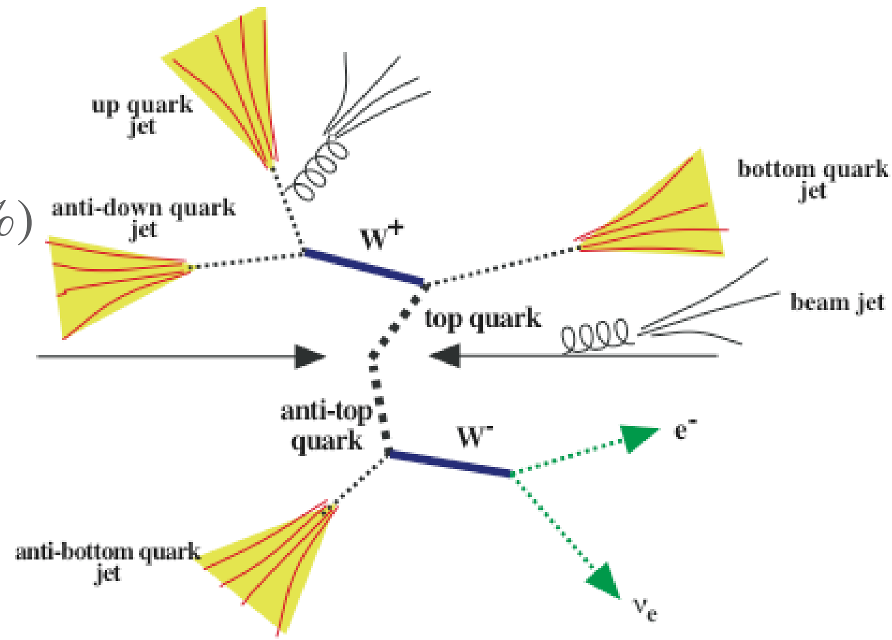
- **Fermilab Tevatron**
  - **Highest energy matter-anti-matter collider**
  - **10^{11} p per bunch**
  - **Collide bunches in 2 places**
  - **Have two detectors**
    - CDF & D∅
- **CDF Detector**
  - **Largest particle detector in 1986**
  - **Image each collision**
    - 50-300 kHz
  - **Keep "interesting ones"**
    - Only 5-10 Hz





Top Quark Production

- **Top is pair-produced in pp collisions**
  - **Decays into W⁺b**
  - **Characterize final states based on W decay**
    - Lepton(e/μ)+jets (35%)
    - Dileptons (5%)
    - All hadronic (60%)



- **Rare: at 1.96 TeV**

$$\sigma_{t\bar{t}} \approx 6 \text{ pb}$$

  - **Created in 1 out of every 10^{10} collisions at Tevatron**
  - **We successfully reconstruct maybe 1 in 20**

Top Quark Search & Discovery

- **Initial CDF search in 1987-88 came up empty**
  - **Look for events with 2 W bosons + ≥1 b quark**
    - W decay into lepton + ν
    - Evidence of second W (2 jets or another lepton+ν)
  - **No significant evidence of a signal**
    - One candidate dilepton event
      - **But expected 0.3 events from background**
  - **If it existed, top quark mass > 77 GeV/c²**

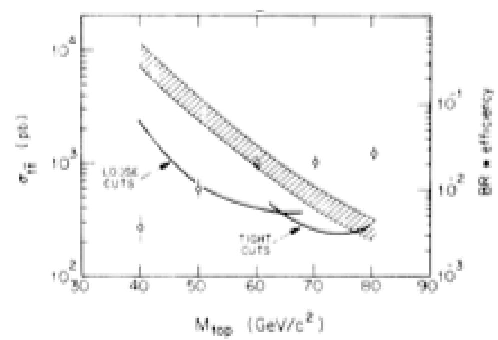
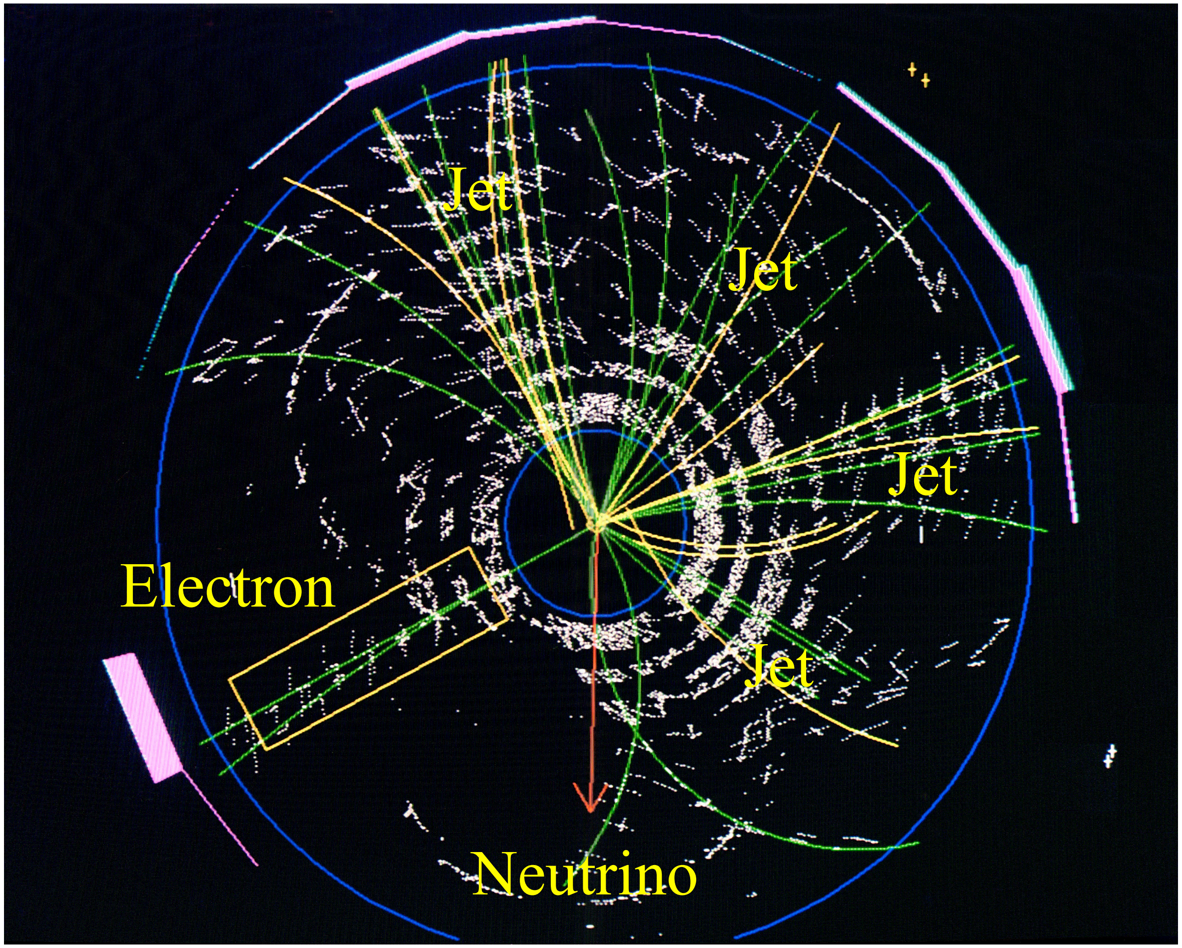


FIG. 3. The 95%-C.L. upper limit for the $t\bar{t}$ production cross section is given by the solid curve, and the predicted cross section (see text) is given by the shaded area. Plotted points show the $t\bar{t}$ branching ratio times efficiency as a function of M_{top} (right-hand scale).

PRL **64**, 142 (1990)

- **Upgraded detector & accelerator in 1990-91**
  - **New search in 1993-95**
  - **By 1994, found "evidence" in data**
    - 12 collisions out of 10^{12}
      - **Equivalent to looking for a coin on the moon!**
    - Expected to see only about 5 from other sources

Typical Event in CDF



Discovery in 1995

- **Discovery came with twice the data**
  - Saw 65 events -- only 23 events from background

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ARTICLES

Evidence for top quark production in $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV

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(Received 25 April 1994)

We present the results of a search for the top quark in 19.3 pb^{-1} of $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV. The data were collected at the Fermilab Tevatron collider using the Collider Detector at Fermilab (CDF). The search includes standard model $t\bar{t}$ decays to final states $ee\nu\bar{\nu}$, $e\mu\nu\bar{\nu}$, and $\mu\mu\nu\bar{\nu}$ as well as $e+\nu+$jets or $\mu+\nu+$jets. In the $(e,\mu)+\nu+$jets channel we search for b quarks from t decays via secondary vertex identification and via semileptonic decays of the b and cascade c quarks. In the dilepton final states we find two events with a background of $0.56^{+0.25}_{-0.13}$ events. In the $e,\mu+\nu+$jets channel with a b identified via a secondary vertex, we find six events with a background of 2.3 ± 0.3. With a b identified via a semileptonic decay, we find seven events with a background of 3.1 ± 0.3. The secondary vertex and semileptonic-decay samples have three events in common. The probability that the observed yield is consistent with the background is estimated to be 0.26%. The statistics are too limited to firmly establish the existence of the top quark; however, a natural interpretation of the excess is that it is due to $t\bar{t}$ production. We present several cross-checks. Some support this hypothesis; others do not. Under the assumption that the excess yield over background is due to $t\bar{t}$, constrained fitting on a subset of the events yields a mass of $174 \pm 10^{+13}_{-12}$ GeV/c^2 for the top quark. The $t\bar{t}$ cross section, using this top quark mass to compute the acceptance, is measured to be $13.9^{+6.1}_{-4.8}$ pb.

PACS number(s): 14.65.Ha, 13.85.Ni, 13.85.Qk

Popular Press Had It's Say

- Newsweek (9 May 94)
  - "How Many Scientists Does it Take to Screw in a Quark?"
- LA Times (10 May 1994)
  - "Ask No More for Whom the Quark Quacks"
- Toronto Star (17 Jul 1994)
  - "Memoirs of a Quark-Hunting Man"

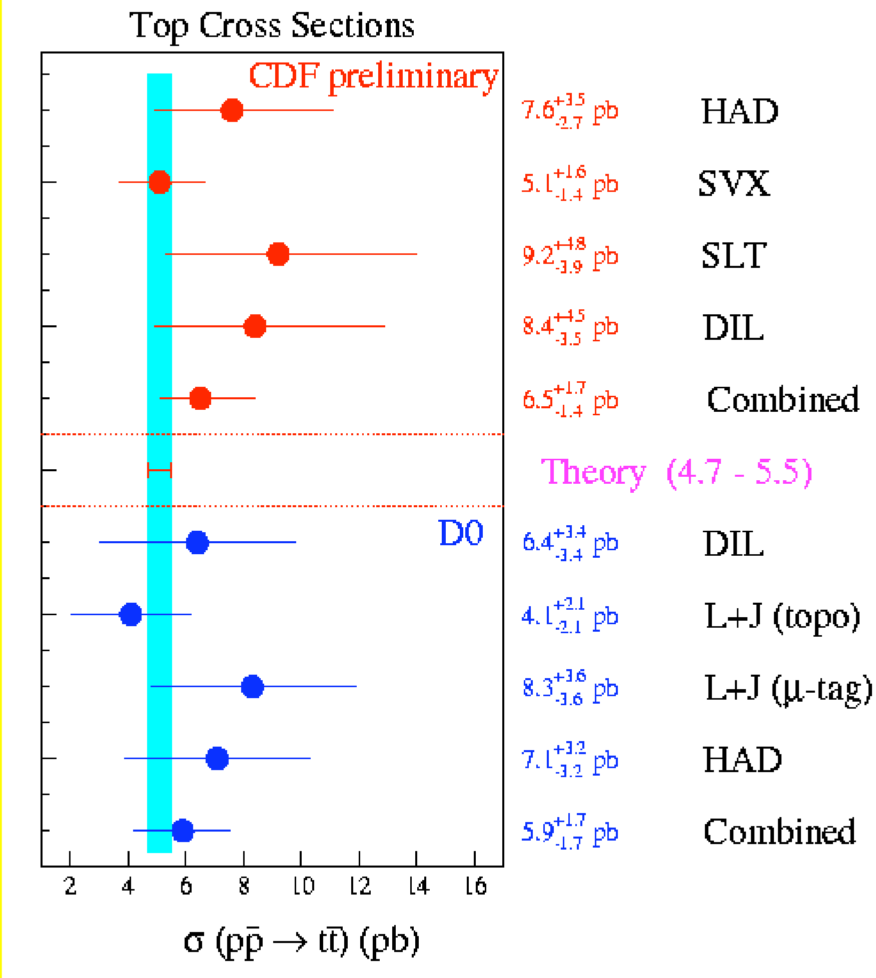
Media loves a good story. Just might not be the one you think!

Run I Top Quark Cross Section

- **Observed top in all expected decay modes**
  - **Combined result had precision of 20-25%**
  - **In good agreement with theoretical prediction**
  - **Also provides a very crude test of the decay rates**

$$t \rightarrow W\,b \quad \text{vs} \quad X\,b$$

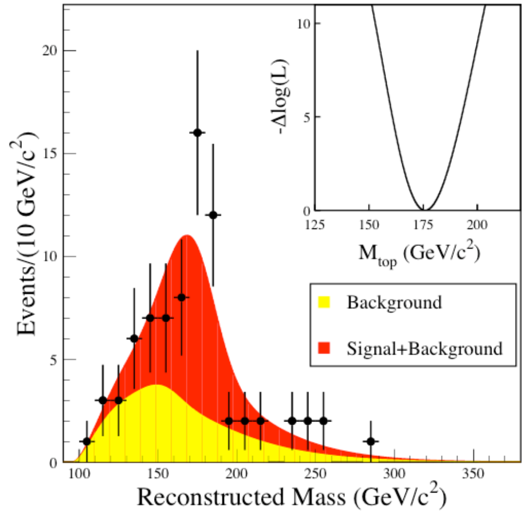
$$t \rightarrow W\,b \quad \text{vs} \quad W\,q$$



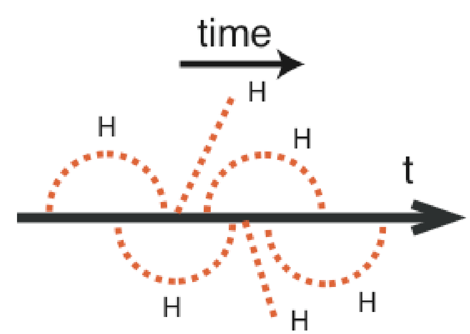
Top Quark Mass

- **Measured the top quark mass by reconstructing final state**
  - **Combined Tevatron result**

$$M_{top} = 174.3 \pm 5.1\,\mathrm{GeV/c^2}$$



- **Why is it so heavy?**
  - **About 40 times heavier than bottom quark**
  - **SM says it has to do with the Higgs boson**
    - The Yukawa coupling of the Higgs field is large
    - Possibly indication of some other phenomenon?

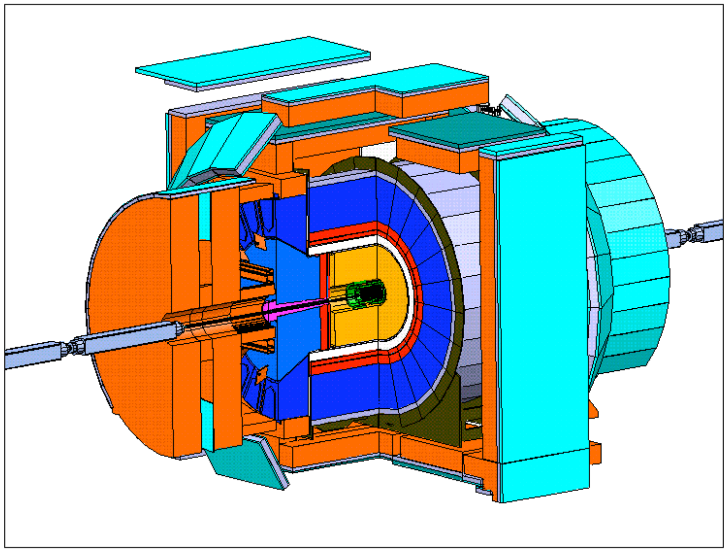


Fermilab Run II Program

- **Fermilab upgraded Tevatron**
  - **Commissioned Main Injector**
    - Improved Tevatron injection
    - Higher pbar production (x10)
    - Increased bunches (6 to 36)
  - **Tevatron Improvements**
    - Energy: 1.8 to 1.96 TeV
    - Design L of 5×10^{31} $cm^{-2}s^{-1}$
  - **Started commissioning in March 2001**
    - Although a slow start
      - **Latest luminosity record of 1.83×10^{32} $cm^{-2}s^{-1}$ (6 Jan 06)**
      - **Have delivered 1.5 fb^{-1}**

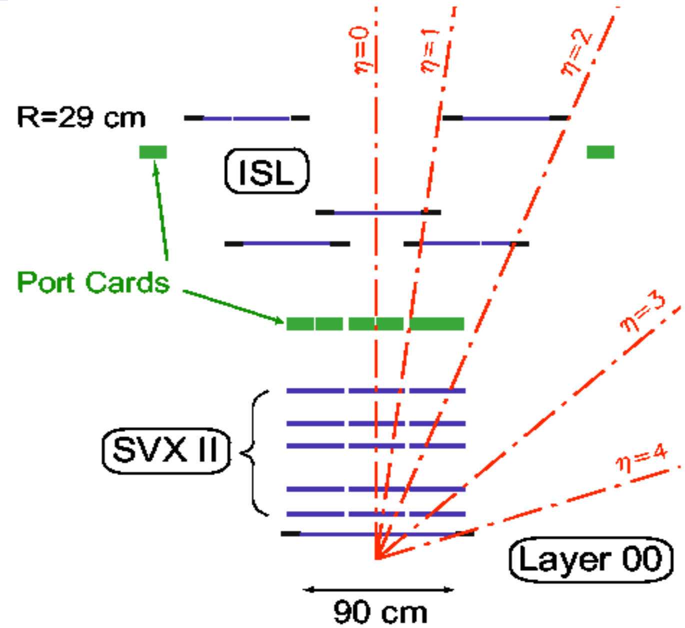
CDF II Detector

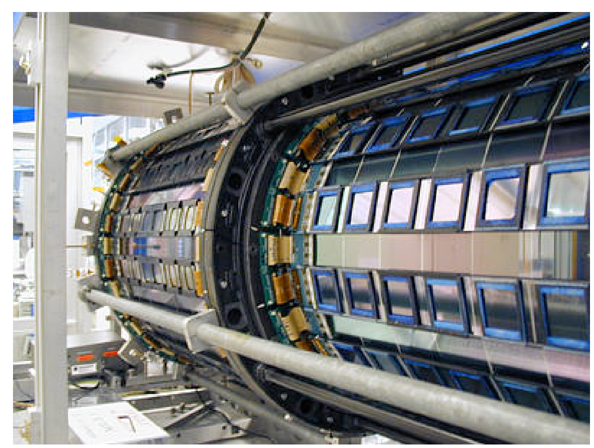
- **Upgraded CDF Detector**
  - **Tracking**
    - New 7-layer SVX system
    - Central Outer Tracker
  - **Calorimetry**
    - New Sci-fi Plug Calorimeter
    - New readout and electronics
  - **Improved muon coverage**
    - Scintillator trigger paddles
    - Completed CMX
  - **New trigger and readout system**
    - SVX impact trigger commissioned
    - Goal is to trigger and readout efficiently at >50 Hz



Silicon Tracking Systems

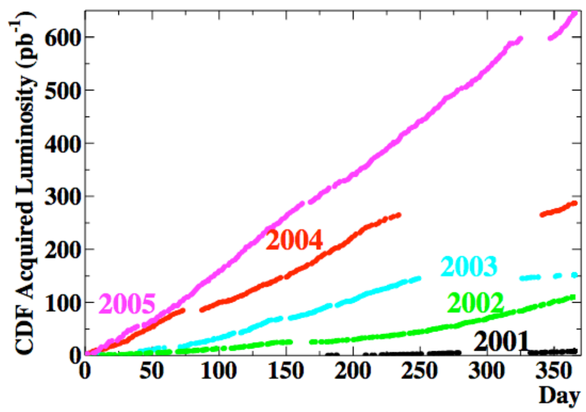
- **7-8 layer tracker**
  - SVX II (5 layers)
  - L00 (on beampipe)
  - ISL (extends η coverage)
- **SVT tracking trigger**
  - L1: charged particle trigger
  - L2: identify secondary vertices
- **System working very well**
  - Challenge is managing radiation environment
  - Original detector expected to survive next two years

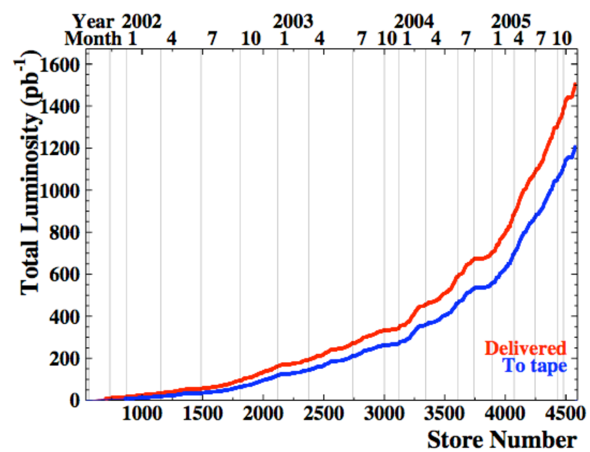




Data Taking Progress

- **Started Run II Officially in July 2002**
  - **Detector/Collider running well**
  - **Challenges have been:**
    - Tevatron start-up
    - Silicon operation
    - Understanding calorimeter energy calibrations
    - Maintaining high data-taking efficiency (>80%)

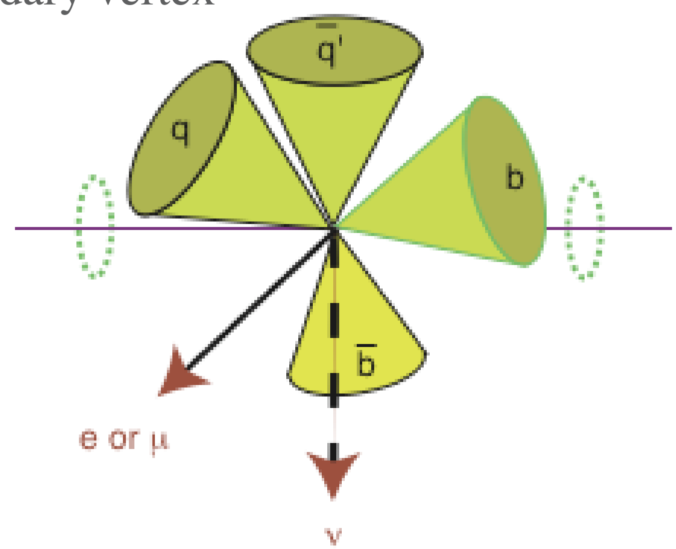




Calendar Year	Collected (fb-1)	Total (fb-1)
2002	**0.12**	**0.12**
2003	**0.17**	**0.29**
2004	**0.35**	**0.64**
2005	**0.65**	**1.29**
2006	0.8	2.1
2007	1	3
2008	>1	>4

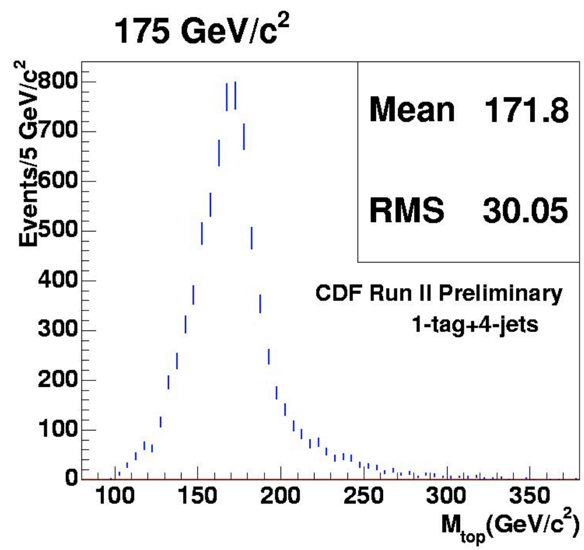
Reconstructing Top Quarks

- **Technique developed in Run I**
  - **Require electron or muon candidate with $E_t > 20$ GeV**
  - **Require neutrino (Missing $E_t > 20$ GeV)**
  - **Require at least 4 jets**
    - At least 3 with $E_t > 15$ GeV & 4th with $E_t > 8$ GeV
    - Identify jets b-tagged with secondary vertex
- **Reconstruct both top quarks**
  - **Identify b quark by "tag"**
    - Find 2 other jets that appear to come from W decay
    - Assume missing energy comes from neutrino
  - **Require combination to conserve energy-momentum**
    - Gives a measured "top mass"

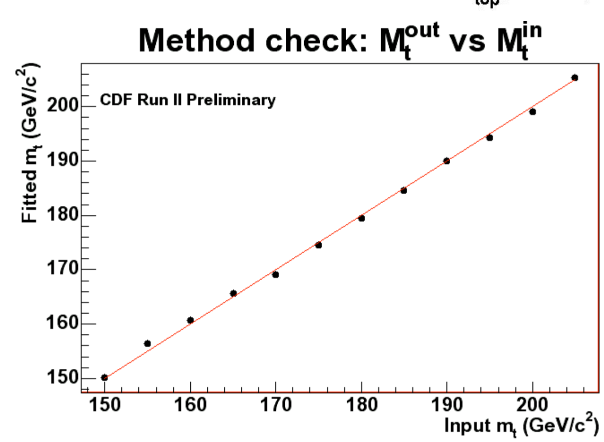


Extracting a Top Mass

- Use "best mass" from each event
  - Sensitive to top mass
  - Interpret data as combination of
    - Signal events
    - Background events
      - Primarily W+jets
  - Perform likelihood fit to sum of two components

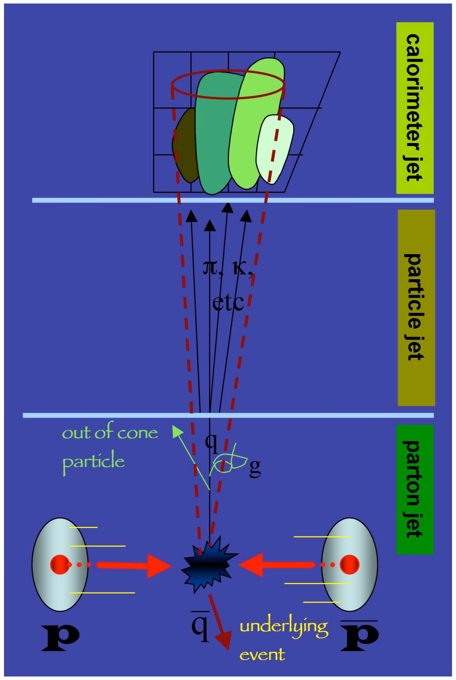


- Check the procedure
  - Use "pseudo-experiments"
    - Vary reconstruction techniques
    - Vary MC assumptions
    - Check for biases



Systematic Uncertainties

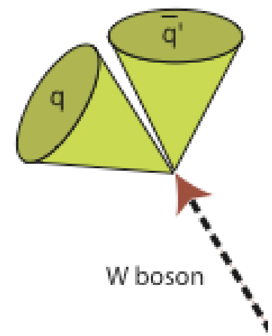
- Largest source is jet energy scale
  - Absolute calibration of calorimeter
  - Jet fragmentation effects
- QCD effects in production & decay
  - Initial state and final state radiation
- MC modeling
  - Modeling of partons in proton
  - Variations in matrix element calculation
  - Non-perturbative effects



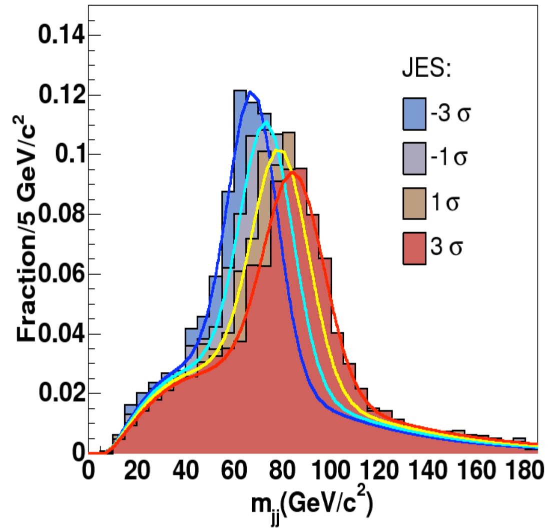
Source	Uncertainty (GeV)
Jet scale	2.5
B jet modelling	0.6
Final state radiation	0.6
Background shape	0.5
Method uncertainties	0.5
Initial state radiation	0.4
MC modelling	0.4
Parton distributions	0.3
Total (w/o JES)	1.3

Taming of Jet Energy Uncertainty

- **To reduce the largest uncertainty**
  - **Use W boson decay to two jets**
    - Expect to see mass of 80.4 GeV/c^2
    - Introduce another variable
      - **JES -- the difference between the observed and assumed jet energy scale**
        - **units are the average uncertainty of 3%**
      - **Fit this to the observed M_{jj} distribution**
  - **Perform simultaneous fit to M_{top} & JES**

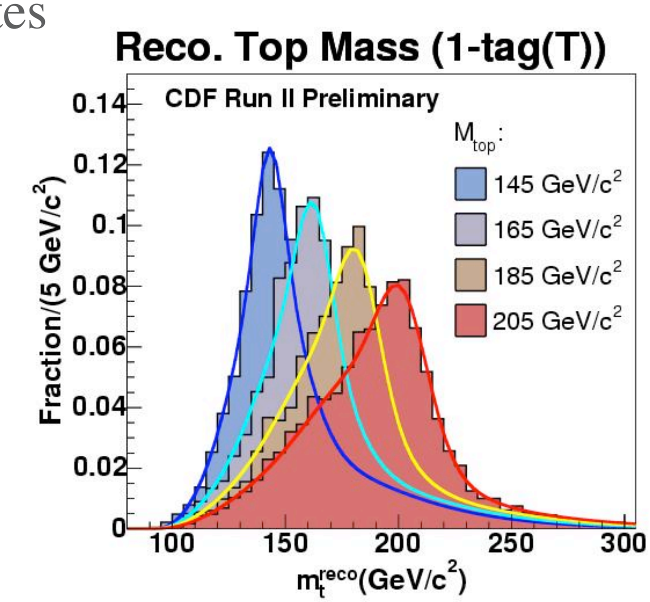


- **Works!**
  - **Reduce top quark mass uncertainty**
  - **Turned largest systematic uncertainty into a statistical uncertainty**



First Run II M_{top} Measurement

- **Have now applied this technique**
  - **Used first 318 pb-1 of data**
    - Collected Sep 2002 to Jun 2004
    - Provides 165 lepton+jet candidates
  - **For dijet calibration study**
    - Divide into 4 subsamples
      - **2 b-tags**
      - **1 b-tag "tight jet" sample**
      - **1 b-tag "loose jet" sample**
      - **No tag sample**
    - Plot all dijet combinations
  - **For top mass reconstruction**
    - Require all candidates to satisfy kinematic fit --> 128 candidates
    - Divide into same 4 subsamples

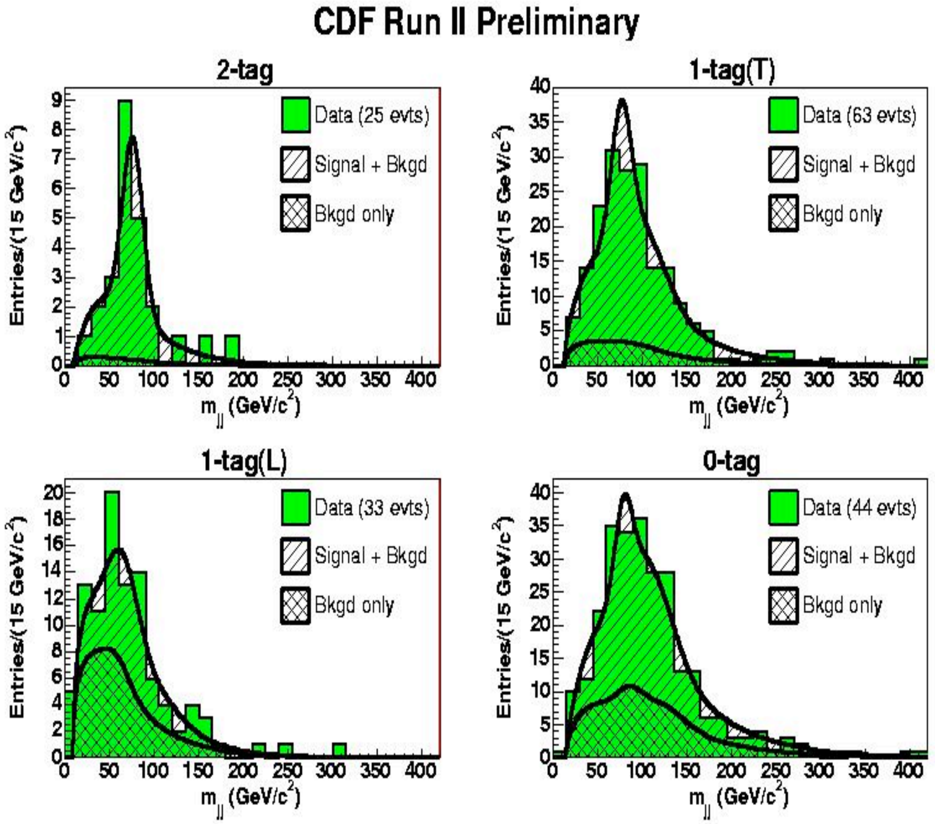


Jet Energy Scale Measurement

- Look at fit to dijet masses first
  - Assume top quark mass is 178 GeV/c^2
  - Provides a "check" of the jet energy scale

$$JES = -0.10^{+0.78}_{-0.80}\ \sigma_c$$

- Conclude that jet energy scale is correctly modelled
  - Uncertainty has been reduced by 20%

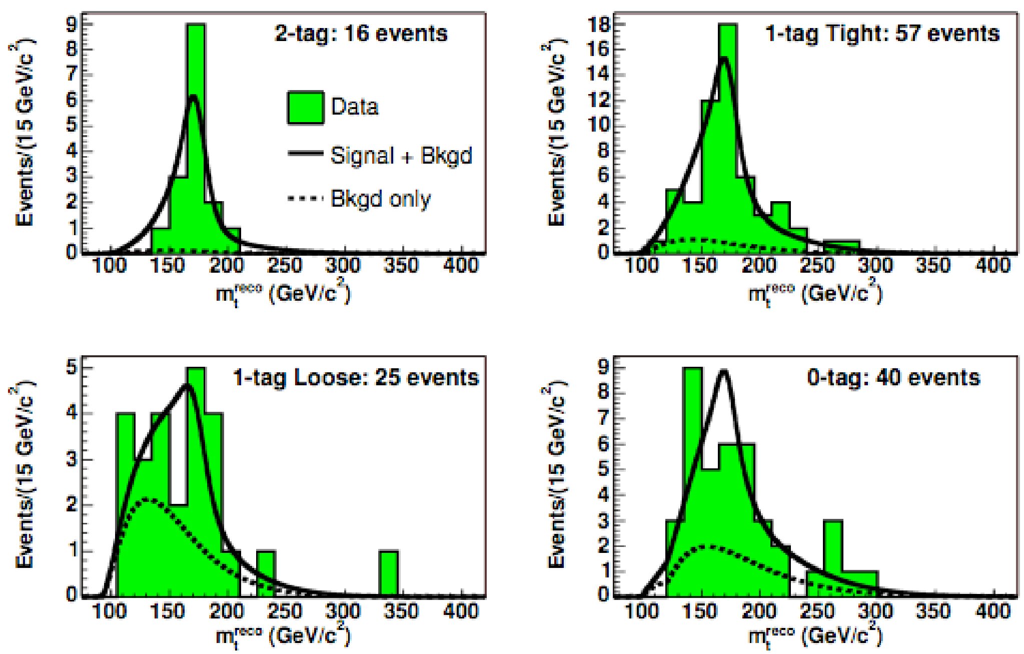


Top Mass Measurement

- **Have 165 events in 318 pb^{-1} sample**
  - **Subdivided into 4 subsamples**
  - **Estimate background of 27±3 events**
- **Likelihood fit:**

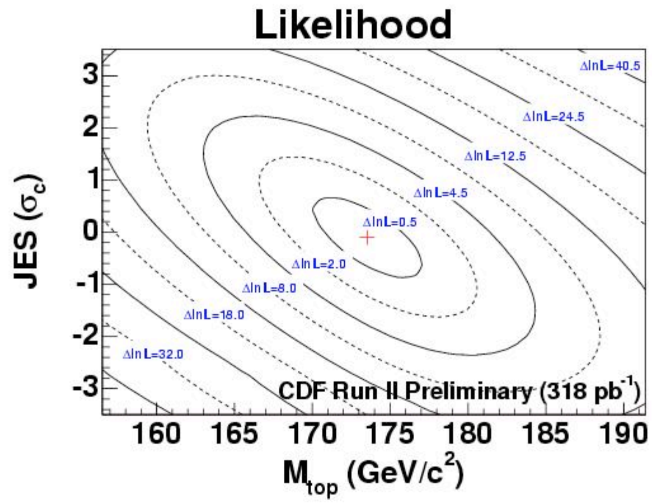
$$M_{top} = 173.5^{+3.7}_{-3.6}(\text{stat}) \pm 1.3\,(syst)\ \text{GeV/c}^2$$

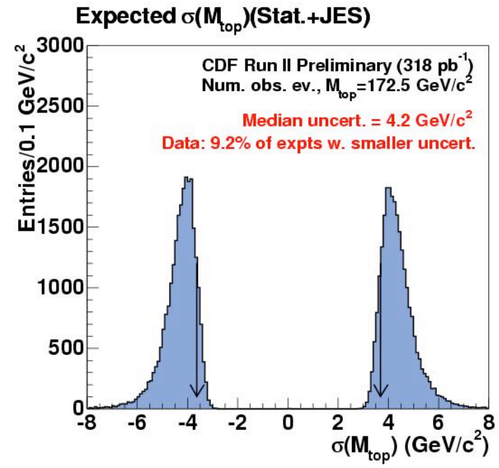
  - **Most precision comes from:**
    - Tight tags
    - Double tags



Statistical Uncertainty

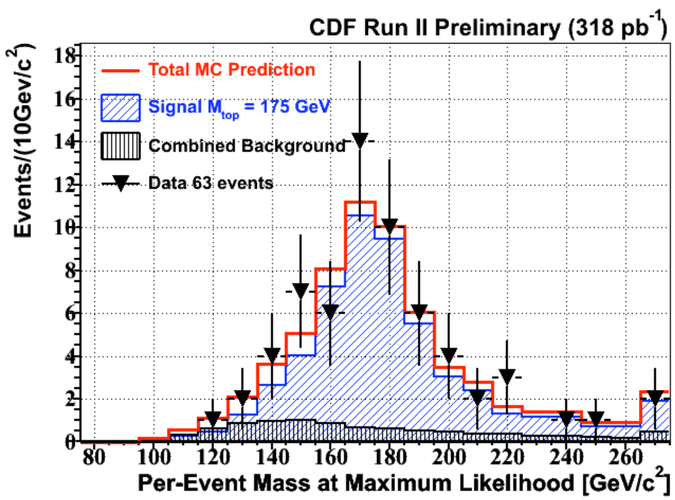
- **Likelihood contours show the expected correlation**
  - **Use delta-likelihood to quote uncertainties**
  - **Scale by 1.04 to obtain 68% confidence intervals**
- **The expected uncertainty is consistent with expectation**
  - **Could suggest we were perhaps "fortunate" in the uncertainty**





Checks on Measurement

- Performed many checks
  - Most of analysis dedicated to this
- Used different technique
  - Matrix element method (DLM)
  - Get similar result, with somewhat larger uncertainty



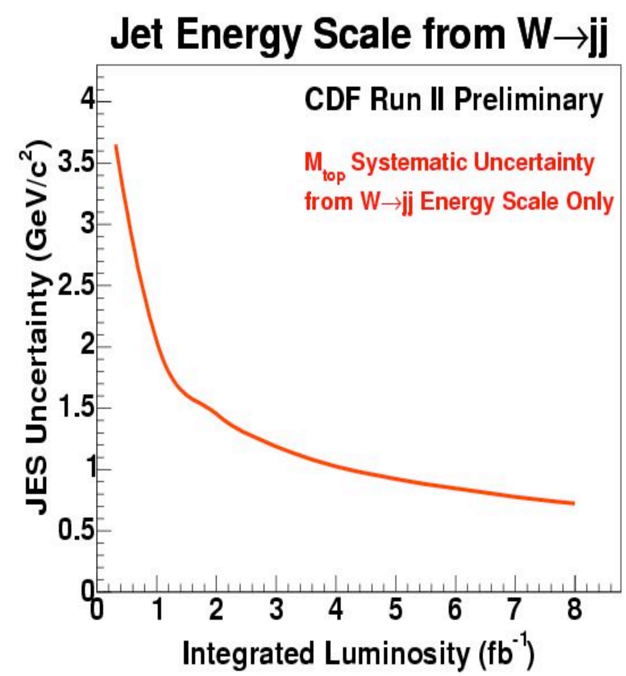
- Checked robustness
  - Varied selection, MC modelling, assumptions used to constrain JES
  - No significant effects
- Checked procedure with "pseudo-experiments"
  - Verified statistical precision
  - Verified that method internally consistent
- Did analysis "blind"
  - Didn't look at data till final systematics estimated
  - Result was very robust

Implications of Measurement

- **Gives us the most precise measurement**

$$M_{top} = 173.5^{+3.9}_{-3.8}\ \text{GeV/c}^2$$

  - **Can combine with all other measurements (CDF & D∅)**
  - **Use information about JES in other analyses**
    - First *in situ* measurement of absolute jet energy scale in hadron collider
    - Validates much of our MC work on calorimeter, jet clustering models, nature of underlying event



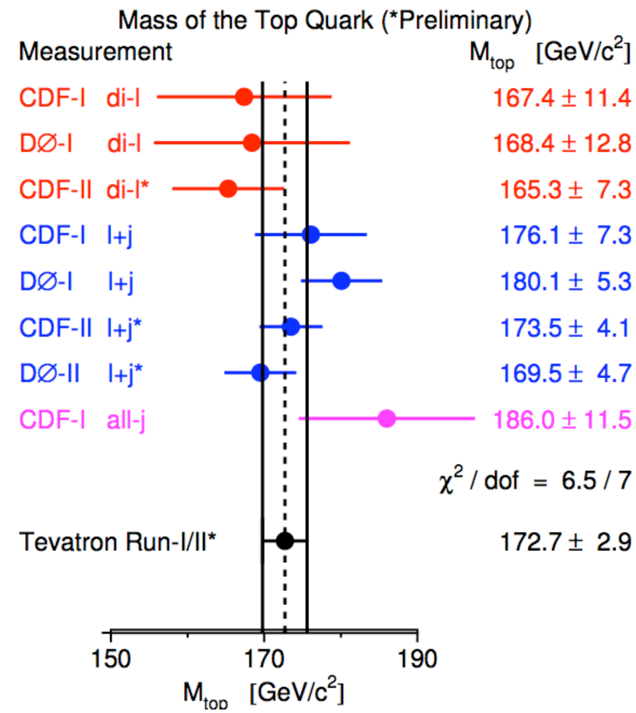
- **Single most important outcome:**
  - **More data will result in greater precision**
  - **Dominant systematic uncertainty now statistical**

Combined M_{top} Measurement

- DØ and CDF have collaborated to produce combined M_{top}
  - DØ preliminary measurement

$$M_{top} = 169.5 \pm 4.7 \text{ GeV/c}^2 \quad \text{(DZero)}$$

  - Combine all 8 different M_{top} measurements
  - Statistically uncorrelated
    - Statistical uncertainty is reduced to 1.7 GeV/c²
    - Systematic uncertainties highly correlated
    - Largest are
      - JES: 2.0 GeV/c²
      - Signal model: 0.9 GeV/c²
      - Bkgd model: 0.9 GeV/c²

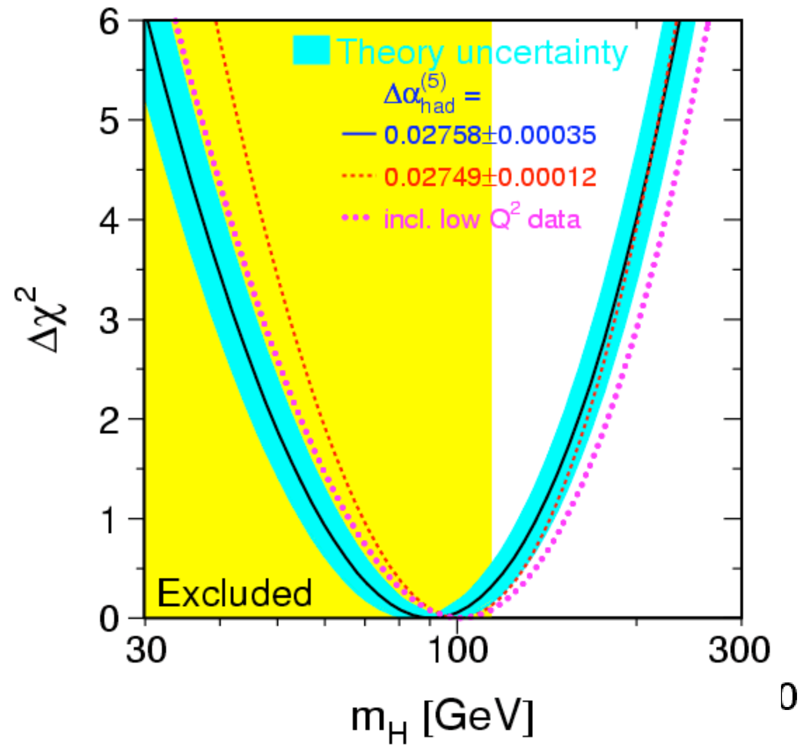


hep-ex/0507091, 21 Jul 05

$$M_{top} = 172.7 \pm 2.9 \text{ GeV/c}^2 \quad \text{(Tevatron)}$$

What About the Higgs?

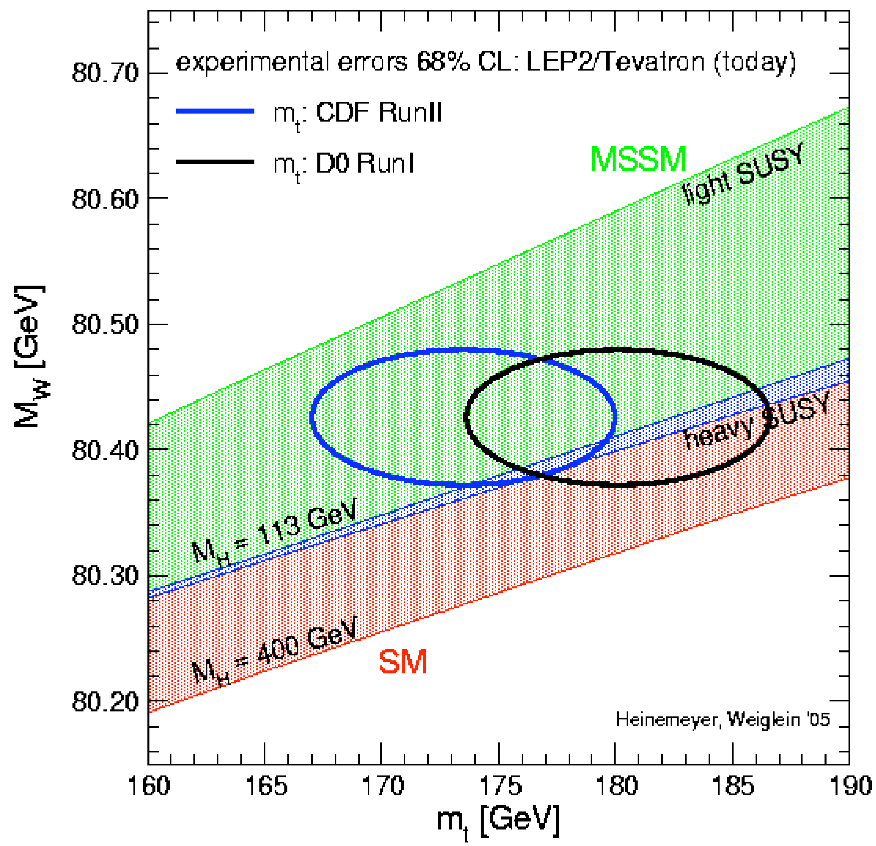
- W and top quark mass constrain Higgs
  - → Can predict the Higgs mass
- Constrain Higgs mass
  - $M_H < 186$ GeV/c² at 95% Conf. Level
  - Know exactly what we should see in higher energy collisions if Standard Model correct



$$M_H = 91^{+45}_{-32}\ \mathrm{GeV}/c^2$$

Implications for non-SM Models

- Supersymmetry is perhaps most popular SM extension
  - Unknown mass scales
  - Particle mass hierarchy not well understood
- Current M_{top} suggests a lower SUSY mass scale
  - But many caveats
  - Don't believe we learn very much because of the SUSY uncertainties
- Take-home message
  - Higher precision measurements are sensitive to non-SM physics



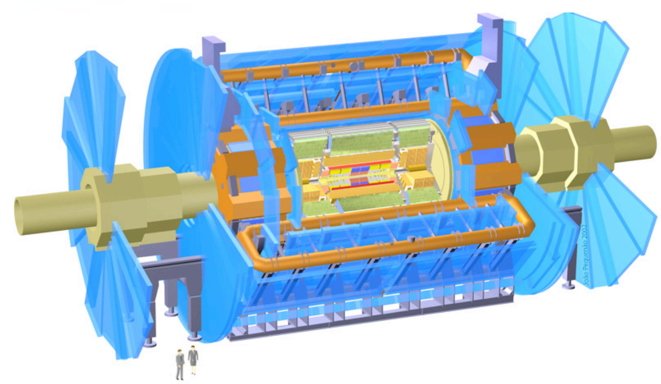
Heinemeyer & Weiglein,
Private Communication, June 2005

What Have We Learned?

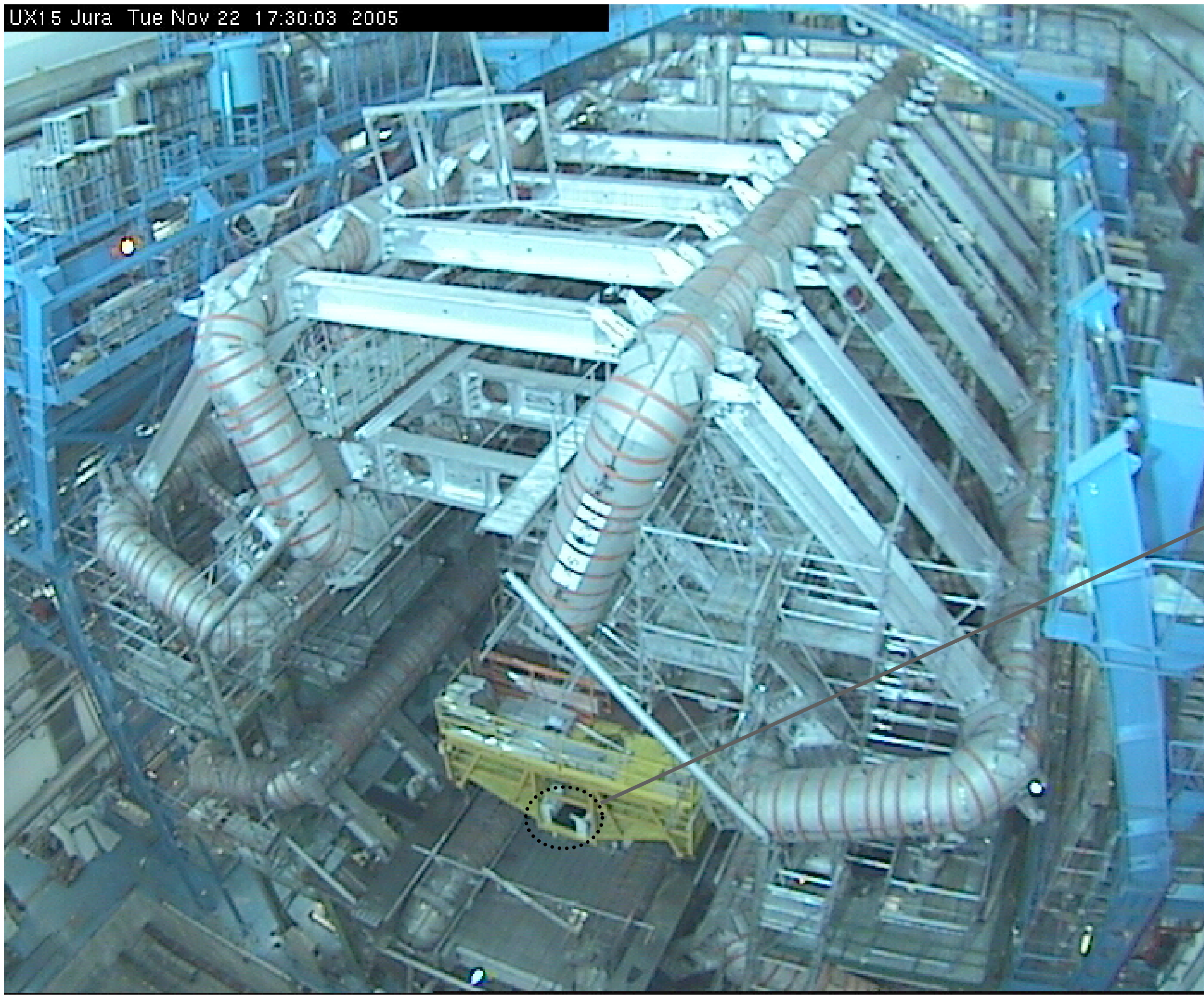
- **Top quark behaves as expected**
  - **Produced at the expected rate**
  - **Decays like expected**
  - **But statistical precision on many properties poor**
    - Have many more measurements to make
      - **Width (or its lifetime)**
      - **What is produced along with it**
- **Top quark mass is HARD to measure**
  - **Difficult to reconstruct events**
  - **Low statistics**
  - **Battle with what we don’t know**
    - Systematic uncertainties can be limiting

Progress at LHC

- **LHC construction still on track for 2007**
  - 14 TeV proton collider
  - Two experiments: ATLAS & CMS
- **Detector construction proceeding well**
  - Now funding and people limited!
  - ATLAS and CMS still scheduled for cosmic ray running in April 2007
  - Detectors starting to take shape



ATLAS Under Construction

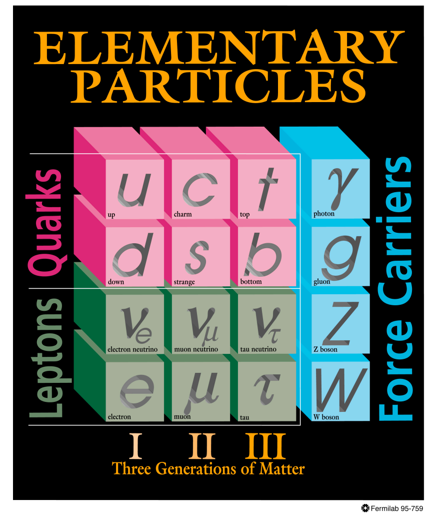


Summary

- **Made progress finding the truth about top**
  - **Fermilab Tevatron has now produced world's largest sample of top quark events**
    - No surprises so far -- looks like Standard Model top quark production
  - **Top mass studies are tough**
    - Making real progress

$$M_{top} = 173.5^{+3.9}_{-3.8}\ \mathrm{GeV/c^2}$$

    - Now analyzing 1 fb^{-1} of data



- **Higgs -- if it exists -- appears to be relatively light**
  - **Might be just around the "corner"**

$$M_H > 114\ \mathrm{GeV/c^2} \quad \text{and} \quad M_H < 186\ \mathrm{GeV/c^2}$$