Top Quark Mass and Other Properties

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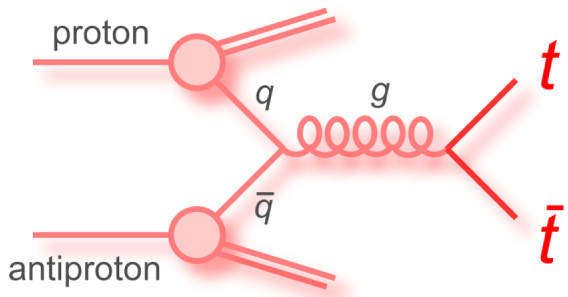
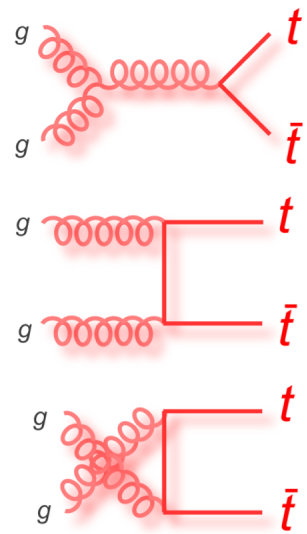
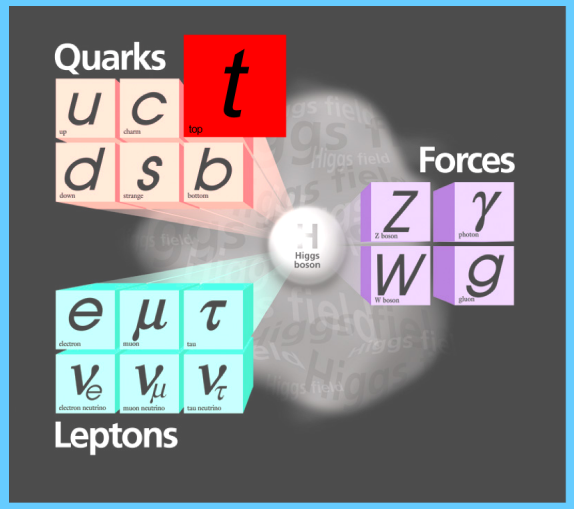
Top Quarks

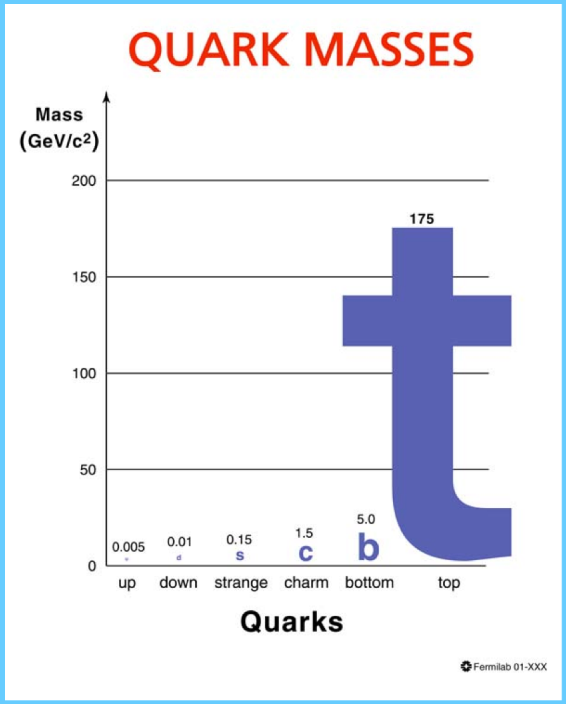
- Spin 1/2 fermion, charge +2/3
- Isospin partner of the bottom quark
- ~40x heavier than its partner





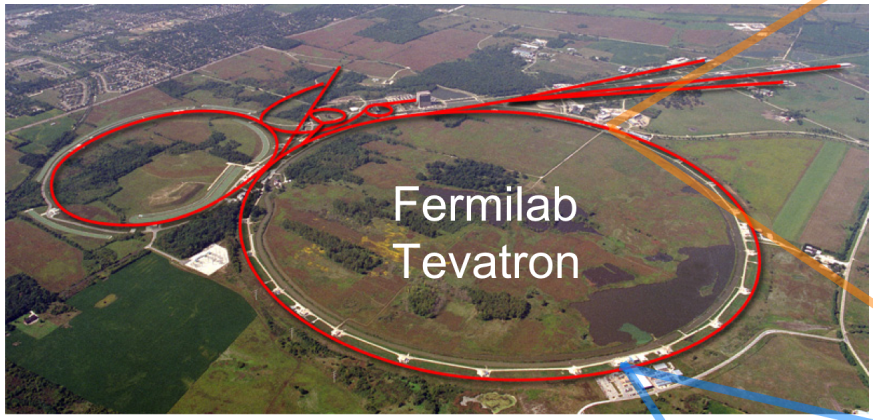
- Produced mostly in top-antitop pairs at the Tevatron
  - 85% $q\bar{q}$, 15% gg
  - Cross section = 6.8 ± 0.6 pb at NNLO

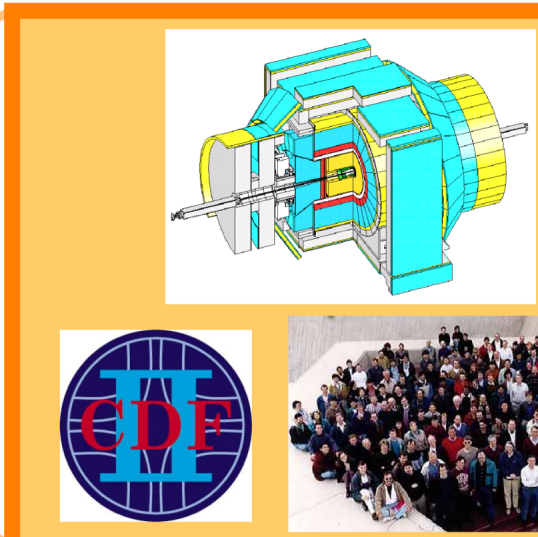


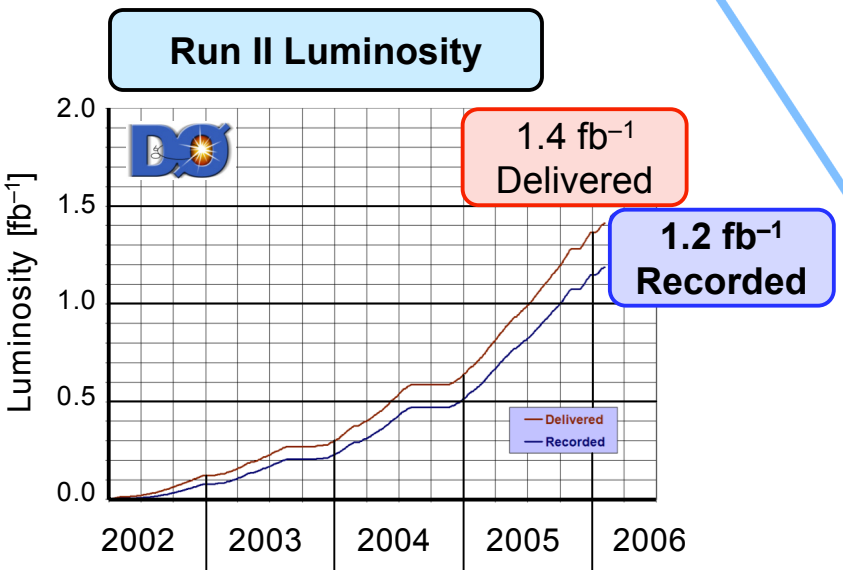


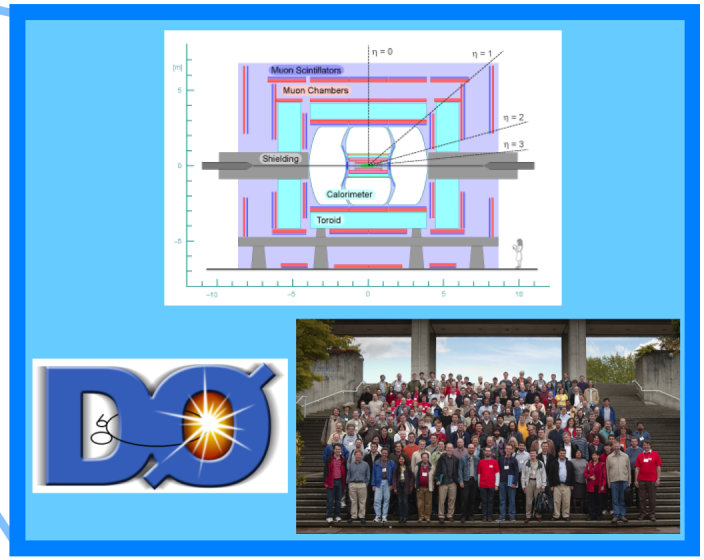
The CDF and DØ Experiments

- Top quarks observed by CDF and DØ in 1995 with ~50 pb^{-1} of data
- These experiments are still the only place to see top
- Now have 20x more data → precision measurements







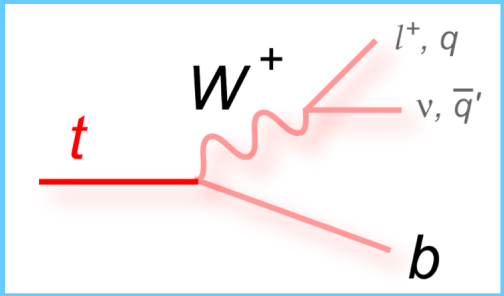


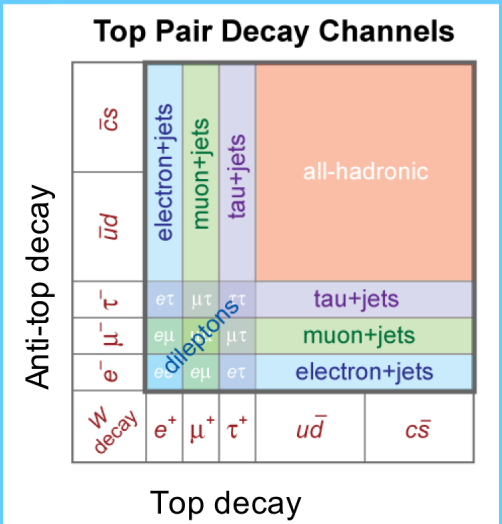
Top Quark Decay

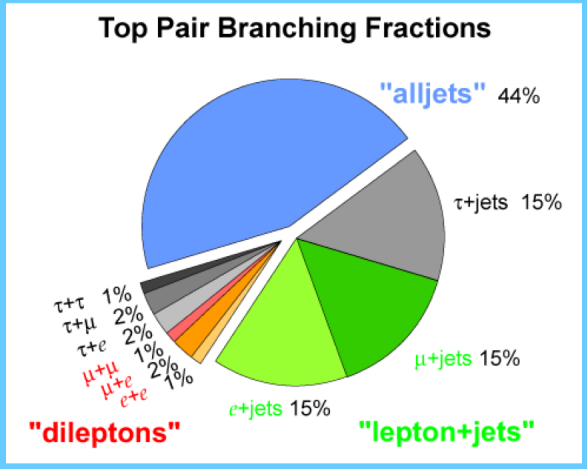
- Top decays before it can hadronize
  - Lifetime Γ_{top}^{-1} = (1.5 GeV)$^{-1}$ << Scale Λ_{QCD}^{-1} = (200 MeV)$^{-1}$
- Top decays to W^+b 99.9% of the time

- Classify $t\bar{t}$ events by the decays of the W's
  - Dileptons
    - $e^+e^- + b\bar{b} + \not{E}_T$
    - $e\,\mu + b\bar{b} + \not{E}_T$
    - $\mu^+\mu^- + b\bar{b} + \not{E}_T$
  - Lepton+jets
    - $e + jj + b\bar{b} + \not{E}_T$
    - $\mu + jj + b\bar{b} + \not{E}_T$
  - Alljets
    - $jj + jj + b\bar{b}$

- Need to reconstruct and identify:
  - Electrons, muons, light jets, b jets, and missing transverse energy

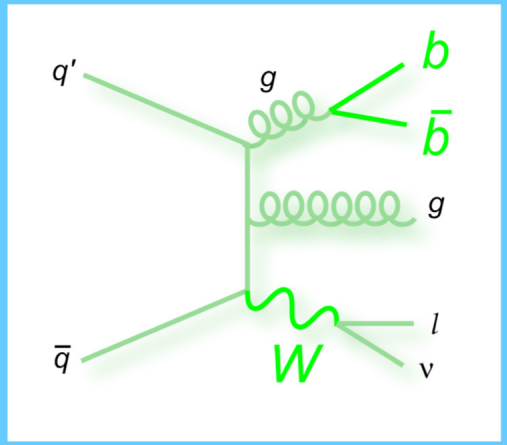




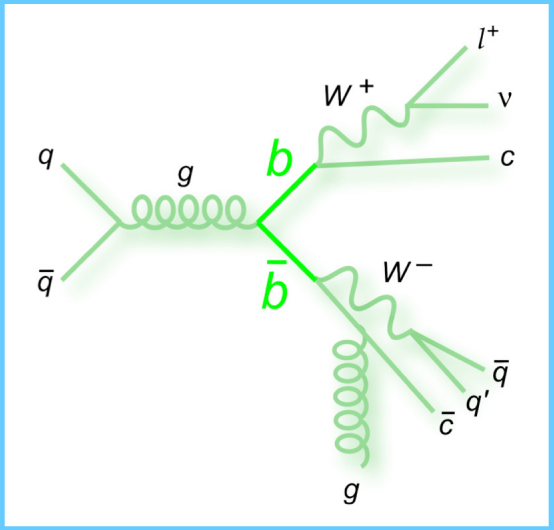


Backgrounds

- Events with real *W* or *Z* bosons
  - *W*+jets (Xsec is ~1000x higher than top)
  - *Z*+jets
  - *WW, WZ, ZZ*
- Events with misidentified leptons
  - Multijet events with a jet misidentified as an electron
  - $b\bar{b}$+jets with a misidentified electron or muon from a *b* decay
- Miscellaneous sources
  - Cosmic rays, multiple $p\bar{p}$ interactions, pattern recognition mistakes, etc.
- For most $t\bar{t}$ decay channels, processes with a real *W* boson and real *b* jets are the most difficult to remove



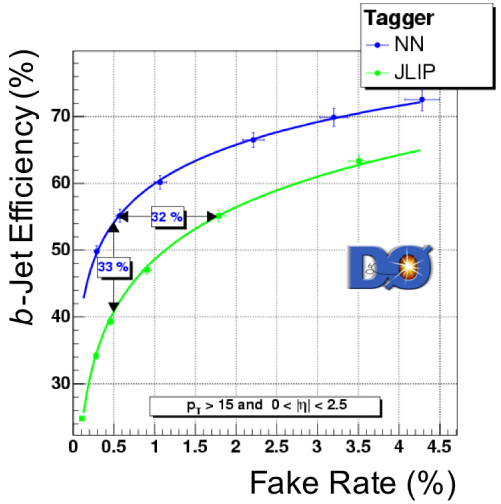
W+jets

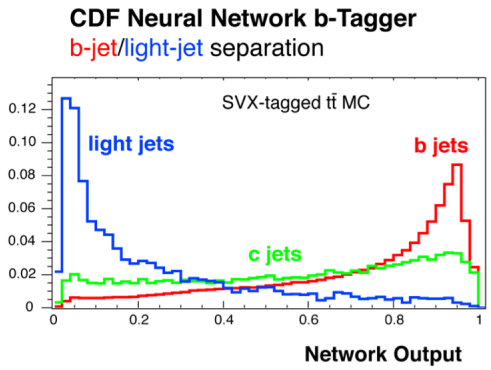


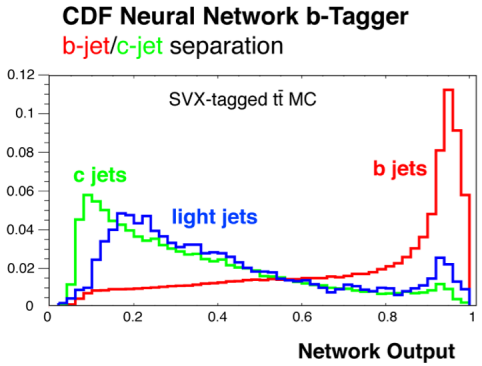
$b\bar{b}$+jet

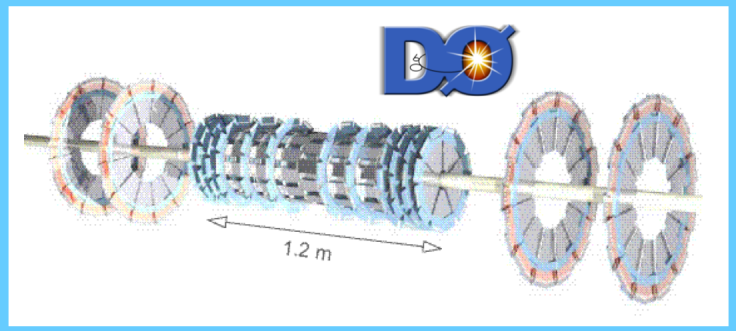
b-Jet Identification

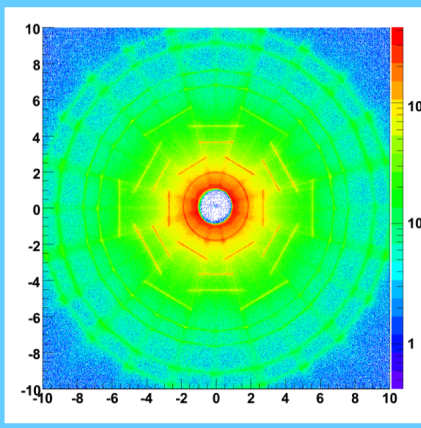
- Separate *b*-jets from light-quark and gluon jets to reject *W*+jets background
- DØ and CDF have each developed several algorithms. Newest use neural networks



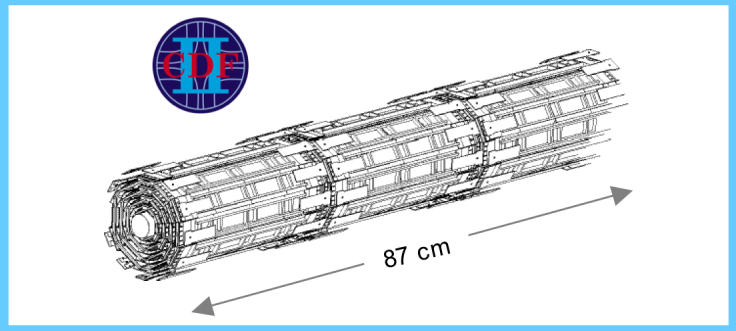








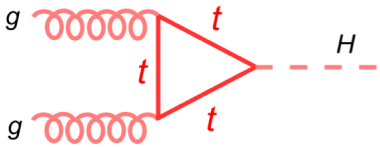
Photon-conversion image of DØ's tracker using 1 fb^{-1} of data



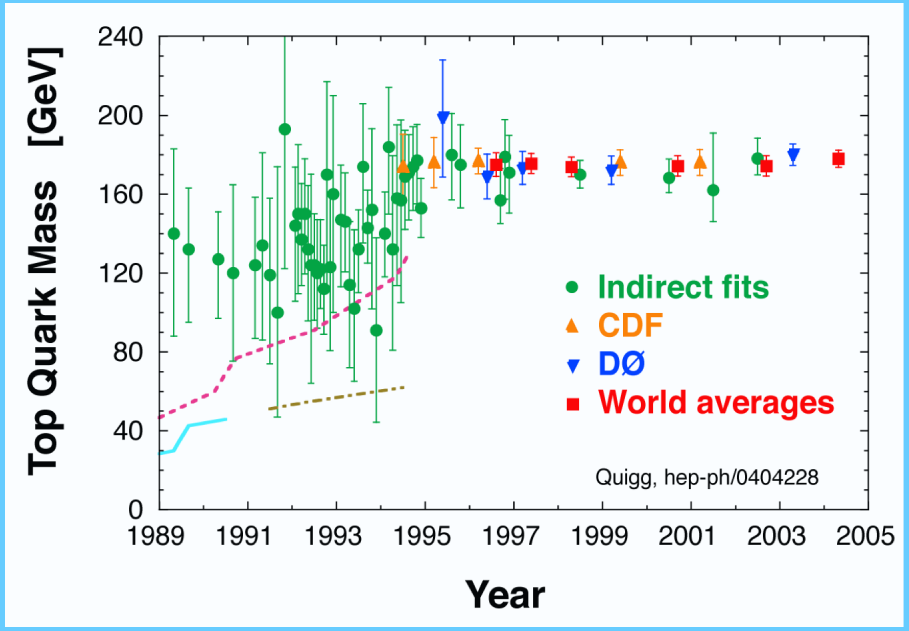
Top Mass Overview

- Fundamental parameter of the Standard Model
  - Precision measurement helps calculations of other SM physics

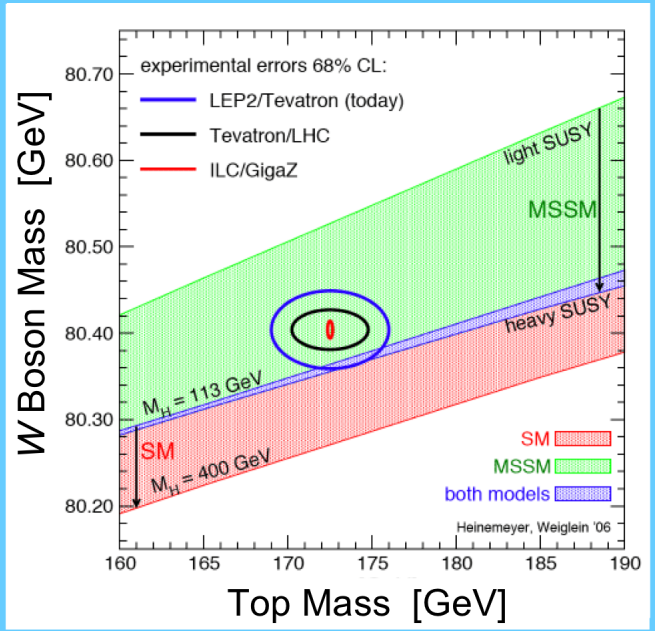
- Yukawa coupling of top to Higgs is unity, makes the top mass high
  - Use the mass to learn about electroweak symmetry breaking



History of the Top Quark Mass



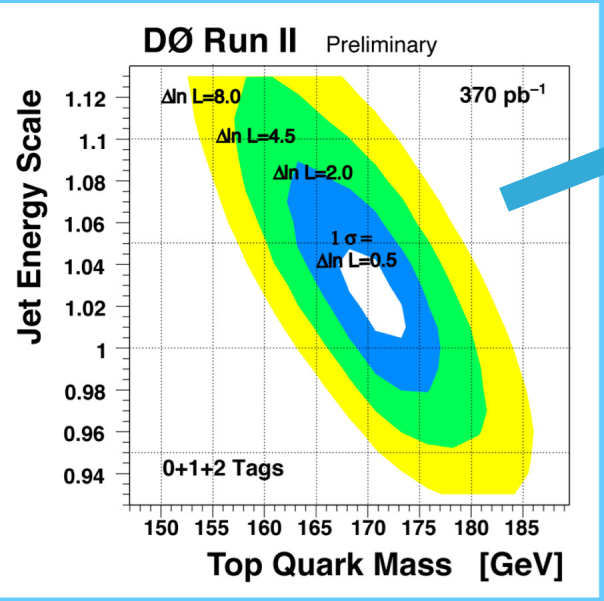
Limiting the Higgs Boson Mass



DØ's Top Mass Measurements

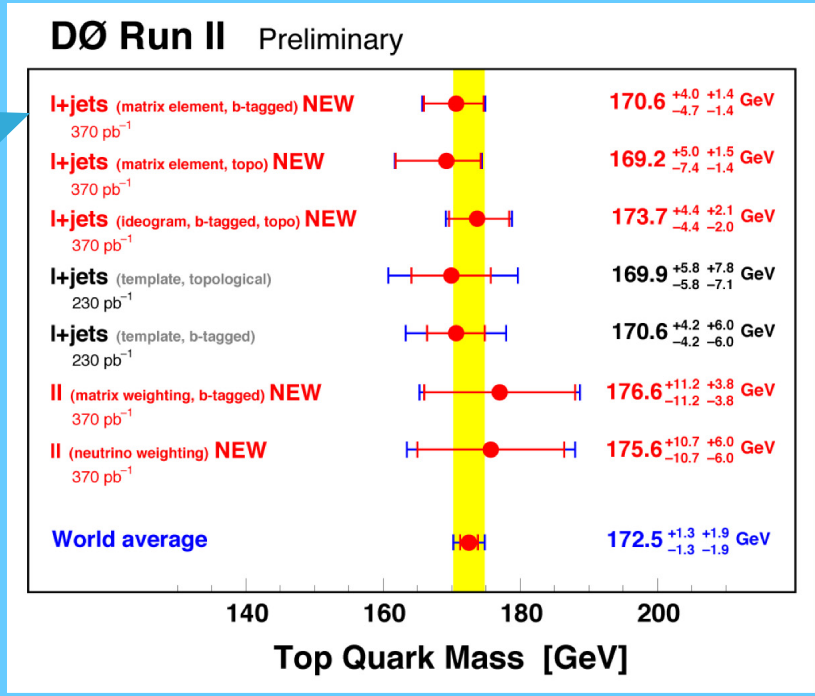
- Several techniques used to measure the top quark mass
  - Developed by DØ:
    - Matrix-weighting
    - Neutrino-weighting
    - Matrix- element
  - Also applied by DØ:
    - Ideogram
    - Templates
- Each uses varying amounts of information from the signal and background events
- Matrix element method is most sensitive (published in *Nature*, June 2004)
- Method improvements since then include simultaneous fit to JES to calibrate it in situ and use of the information of which jets are *b*-tagged

Matrix Element Method – Best Result



$M_{top} = 170.6^{+4.0}_{-4.7} \pm 1.4$ GeV

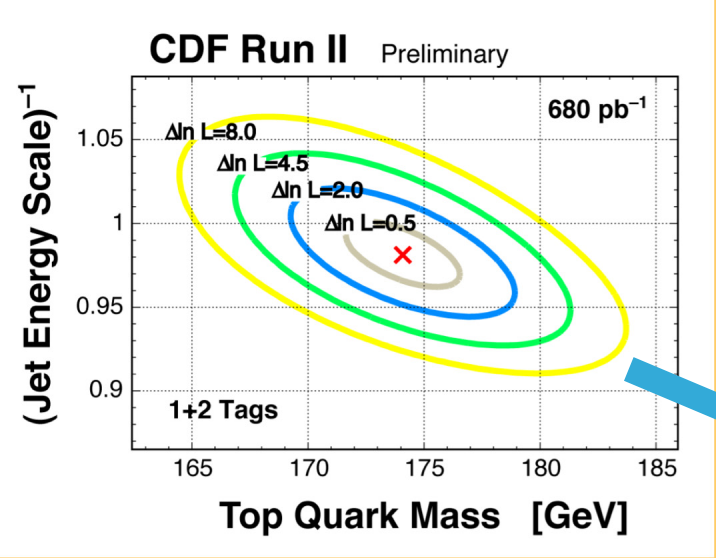
All DØ's Top Mass Measurements



CDF's Top Mass Measurements

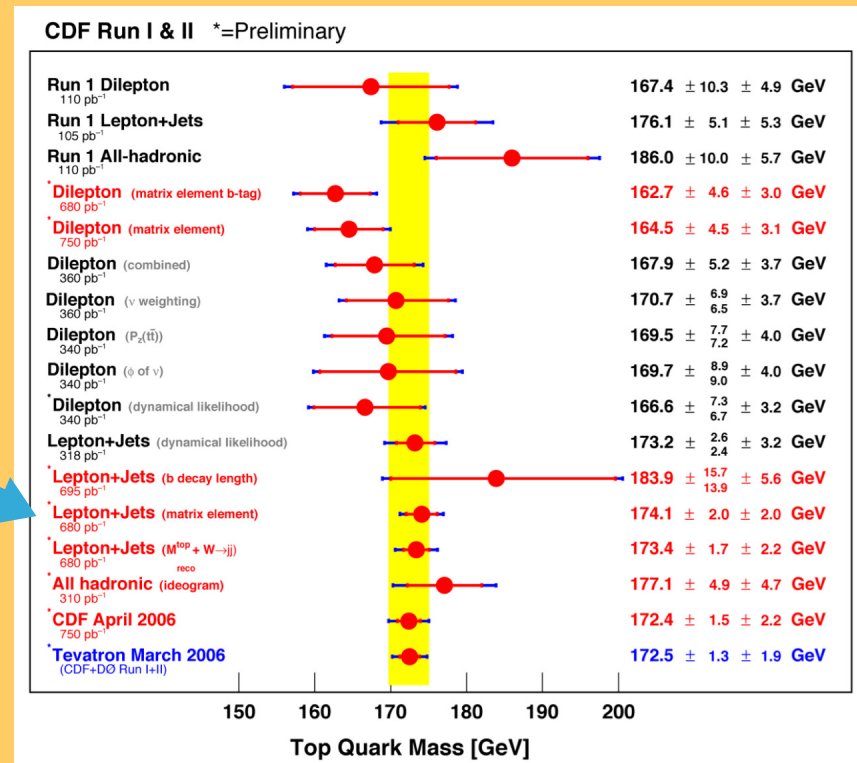
- Many techniques used to measure the top quark mass
  - Developed by CDF:
  - Also applied by CDF:
  - b-jet likelihood
  - Templates
  - Matrix element
  - Multivariate
  - Ideogram
  - Dynamic likelihood
  - Neutrino-weighting
- Best CDF result uses DØ's matrix element method with in situ jet energy scale calibration on lepton+jets events, using the b-tagged jet information

Matrix Element Method – Best Result



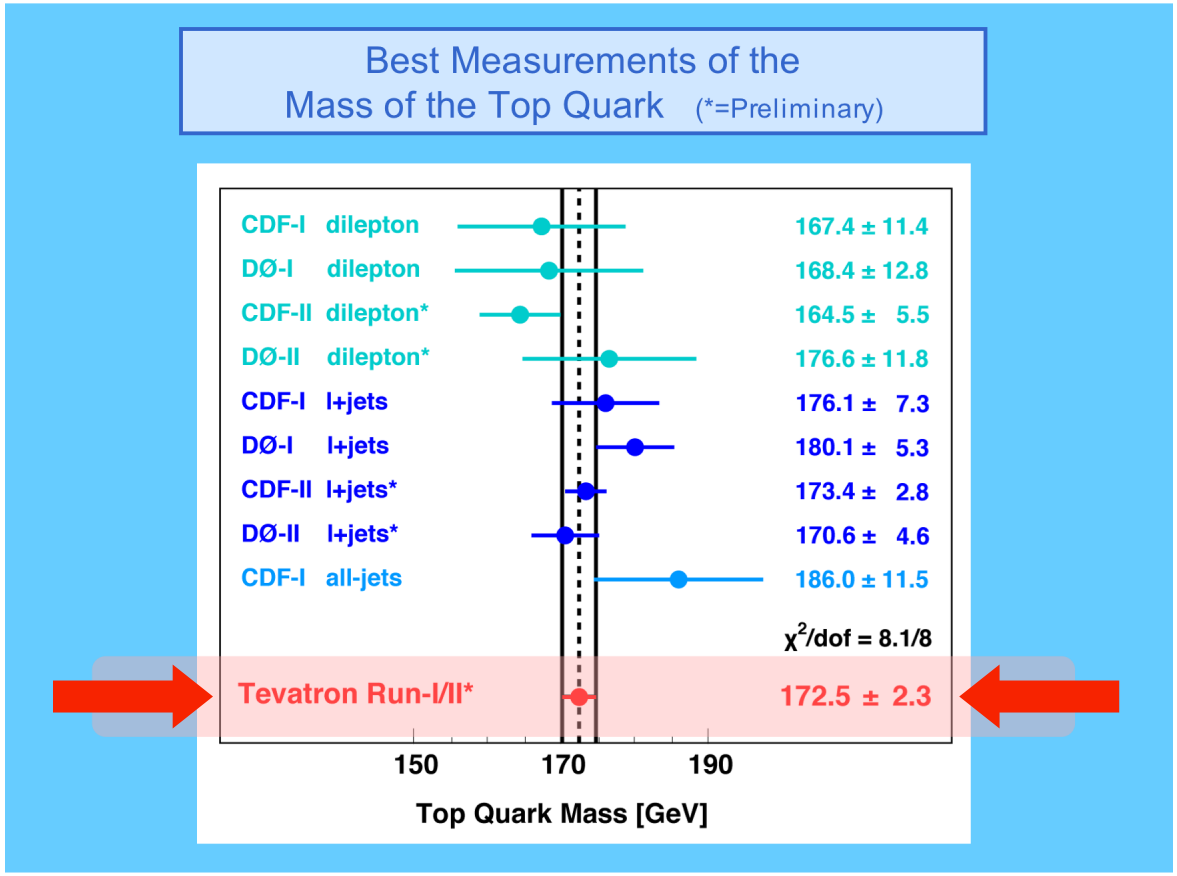
M_{top} = 174.1 ± 2.5 ± 1.4 GeV

All CDF's Top Mass Measurements

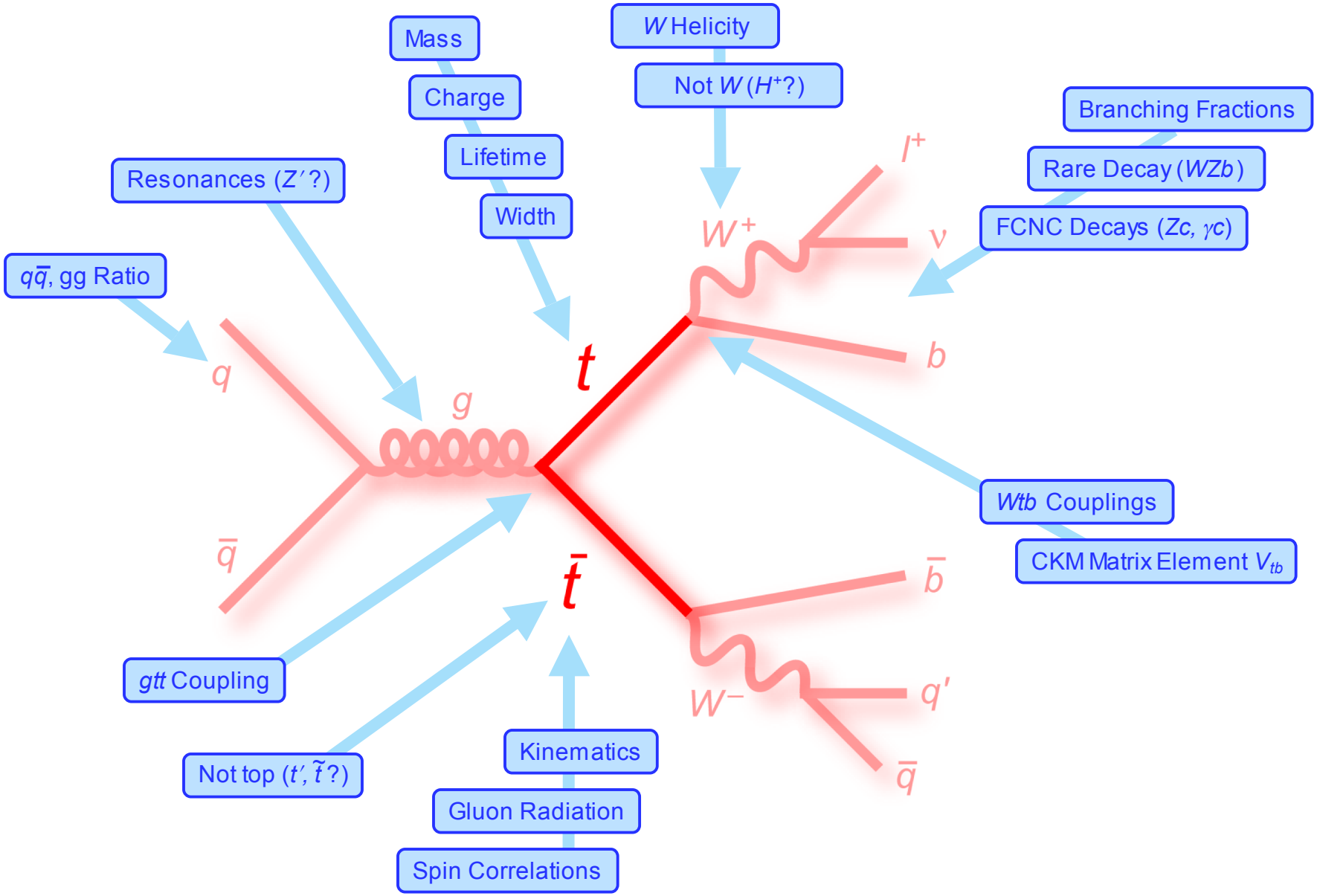


Combined Top Mass Measurements

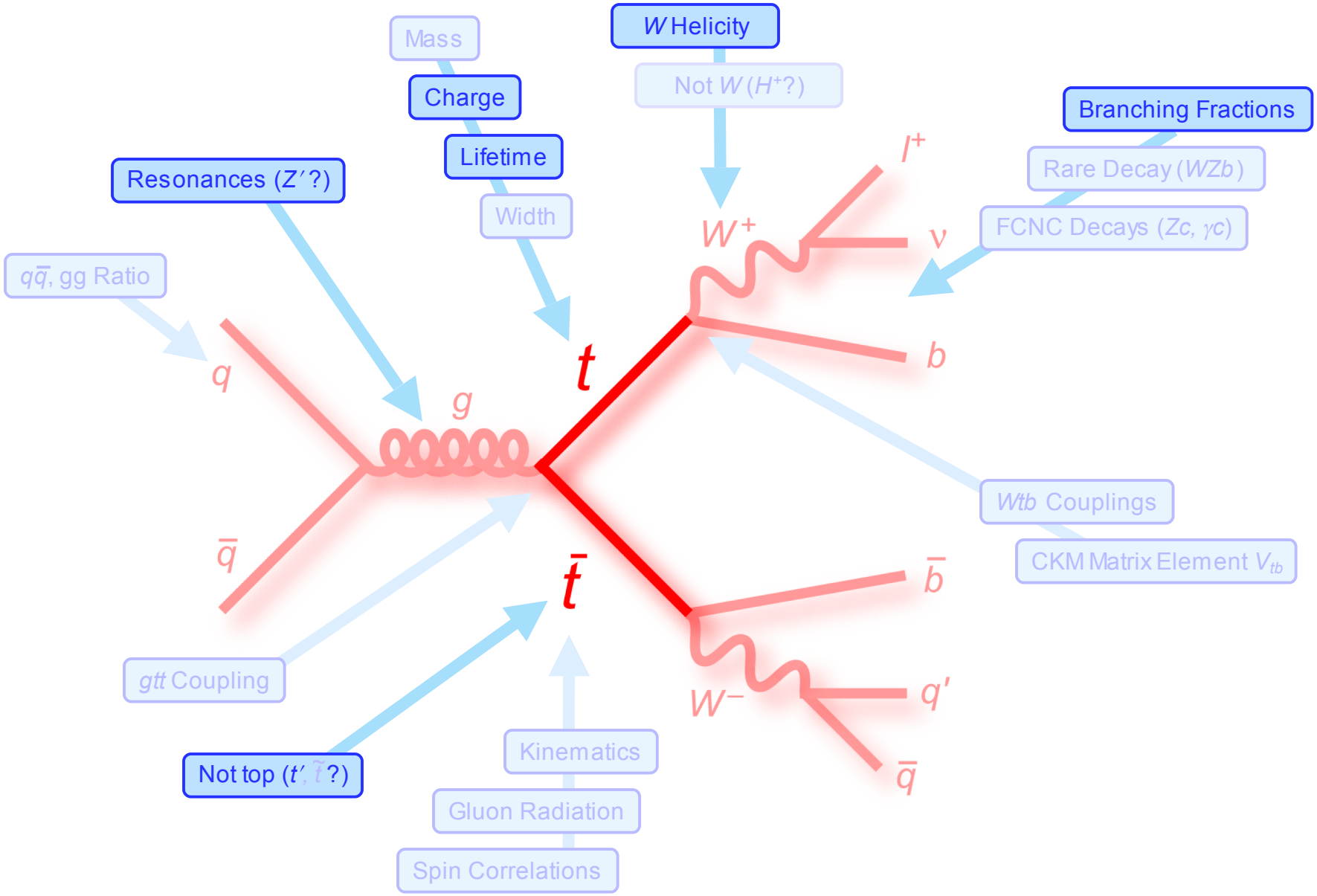
- In March 2006, the Tevatron Electroweak Working Group combined nine measurements of the top quark mass to get a world average value: hep-ex/0603039
  - Dilepton measurements from CDF and DØ in Run I and Run II
  - Lepton+jets measurements from CDF and DØ in Run I and Run II
  - Alljets measurement from CDF in Run I (DØ's measurement published too recently)
- **Measurement has a ±1.3% uncertainty!**



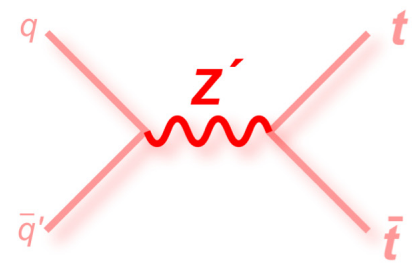
Top Quark Properties



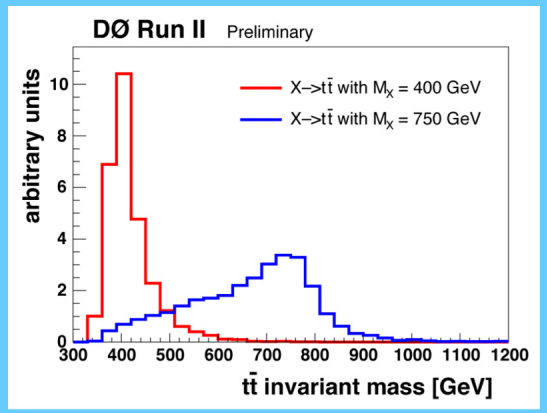
Top Quark Properties

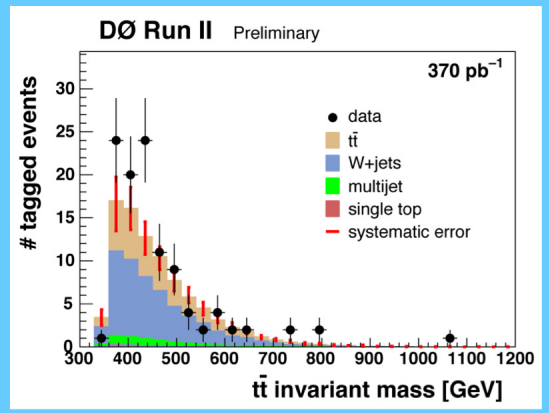


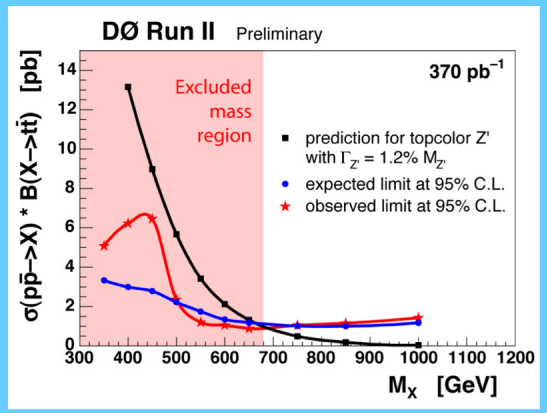
Resonance Production



- Search for a bump in the $t\bar{t}$ invariant mass spectrum
- Compare with theory models to limit mass of new particles
- e.g., a narrow leptophobic topcolor Z'

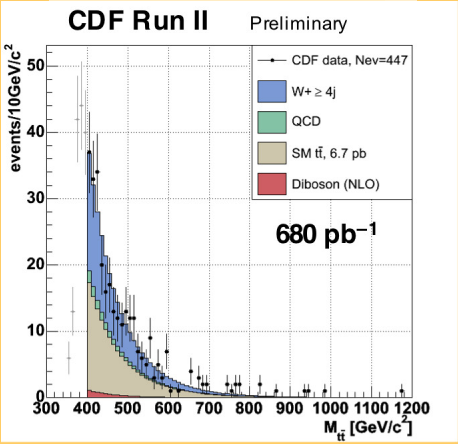


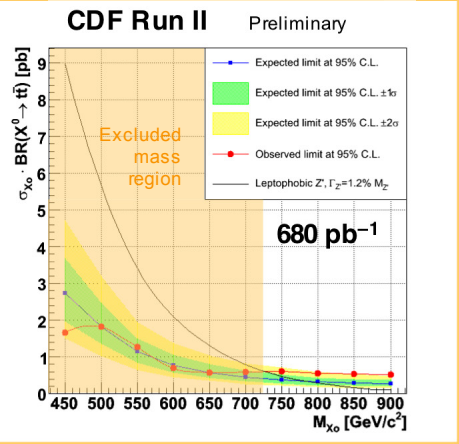




$M_{Z'} > 680$ GeV (DØ)
95% confidence level

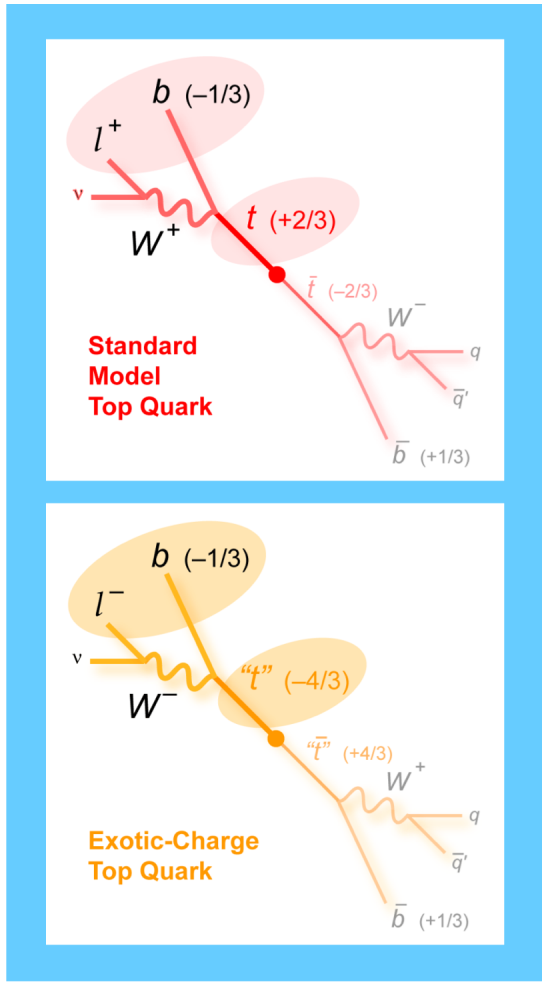
$M_{Z'} > 725$ GeV (CDF)
95% confidence level

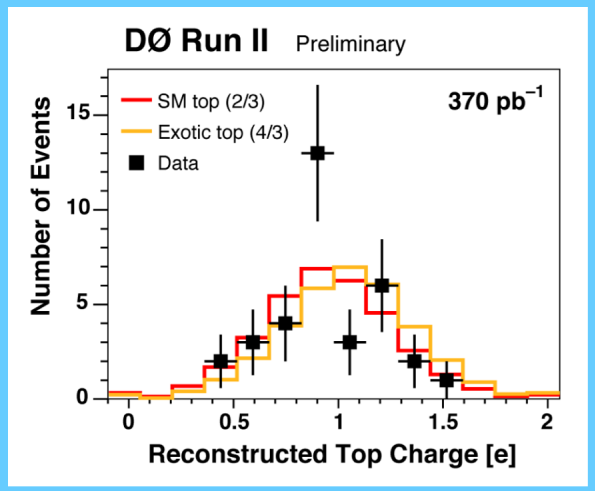


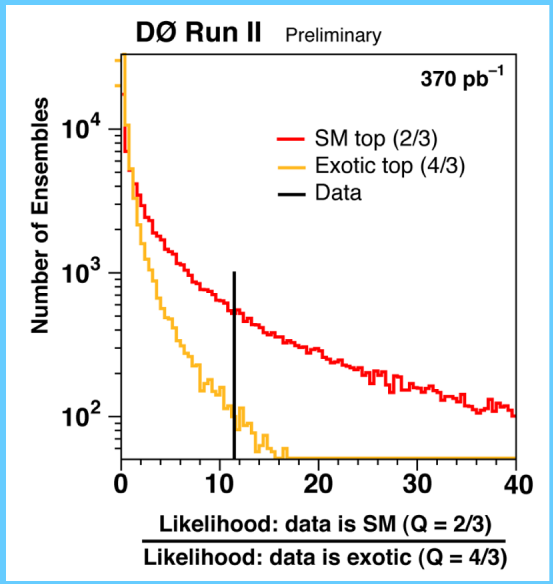


Top Quark Charge

- Top quark could have exotic charge –4/3 instead of SM value +2/3
  - (Chang, Chang, and Ma, PRD 59, 091503 (1999))
- Analysis
  - Use 17 double-tagged lepton+4jet top-pair candidate events
  - Reconstruct them matching *b*-jets to *W*'s to form top mass
  - Find charge of *b* from p_T-weighted average of track momenta
  - Compare sum of lepton and *b* charge to templates for 2/3 and 4/3 top charge







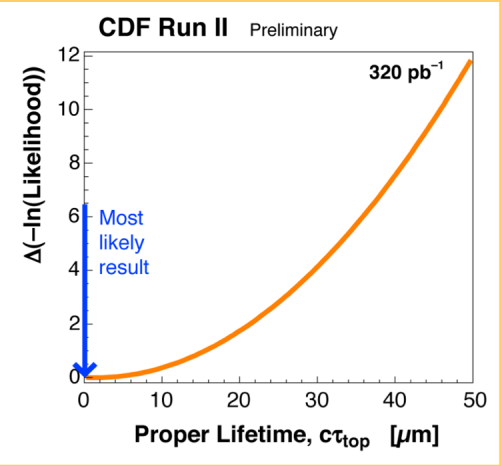
Q(top) = –4/3 excluded at 94% confidence level

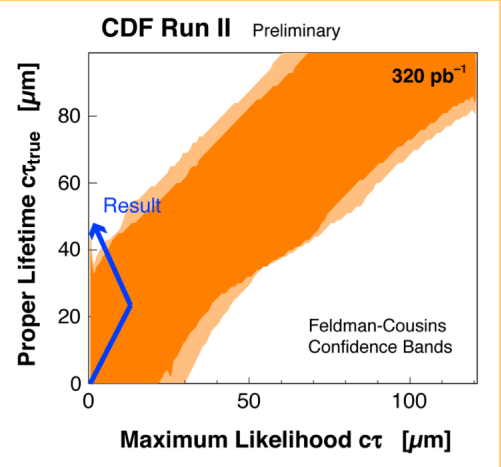
Top Quark Lifetime

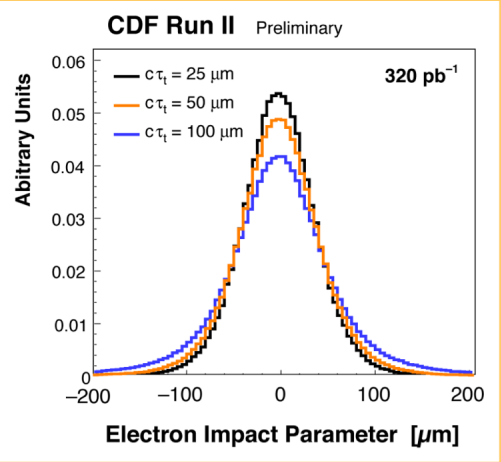
- Lifetime calculated to be

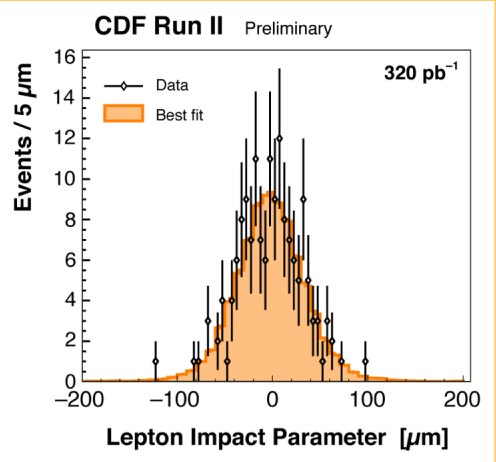
  $\tau = 0.5 \times 10^{-24}$ s $\Rightarrow$ Proper lifetime = $c\tau = 1.5 \times 10^{-10}$ μm
- No experimental measurement, but first limit now set
  - Use 157 *b*-tagged lepton+≥3jet top-pair candidate events
  - Constrain primary vertex position using the jets
  - Measure the lepton impact parameter, compare to templates

Proper lifetime, $c\tau < 52.5$ μs
95% confidence level



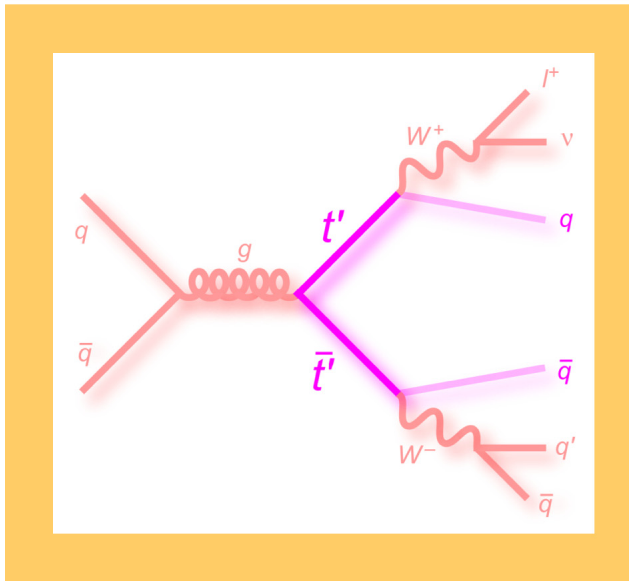


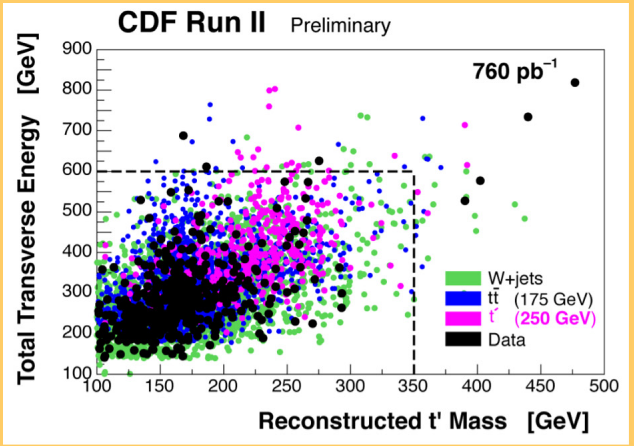


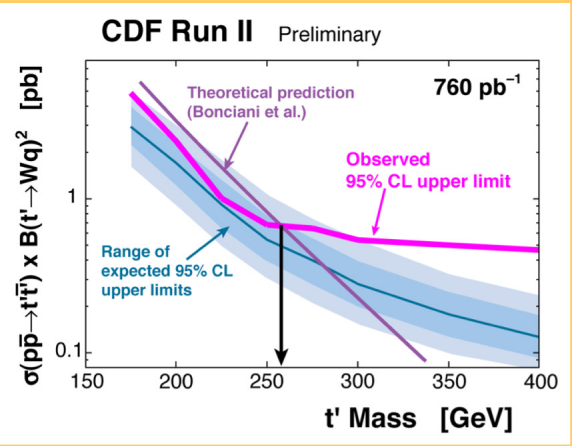


Is it a Fourth Generation Quark?

- Many models allow (or need) a new quark
  - SM-like fourth-generation quark, Q = +2/3
  - Two-Higgs-doublet models
  - N=2 SUSY models
  - "Beautiful mirrors" model
  - Non-minimal "little Higgs" models
- Consistent with data (He, Polonsky, Su, PRD 64, 053004 (2001))
- Decays to Wq if $M(t') > M(b') + M(W)$
- Perform a binned likelihood fit in the (H_T, M_{reco}) plane to find upper limit on $t'\bar{t}'$ production as a function of t' mass







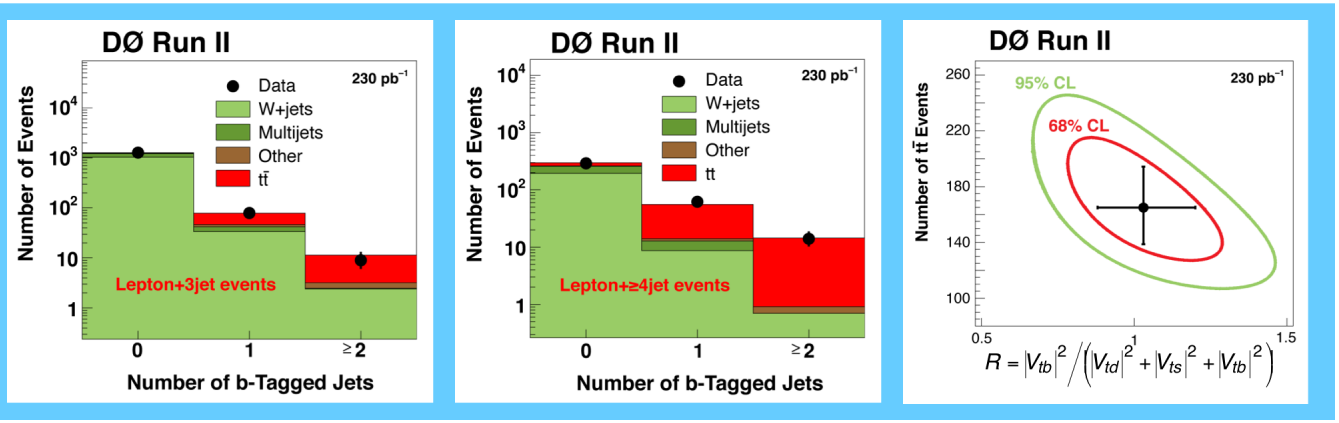
$M(t') > 258$ GeV
95% confidence level

Branching Fractions in Top Decay

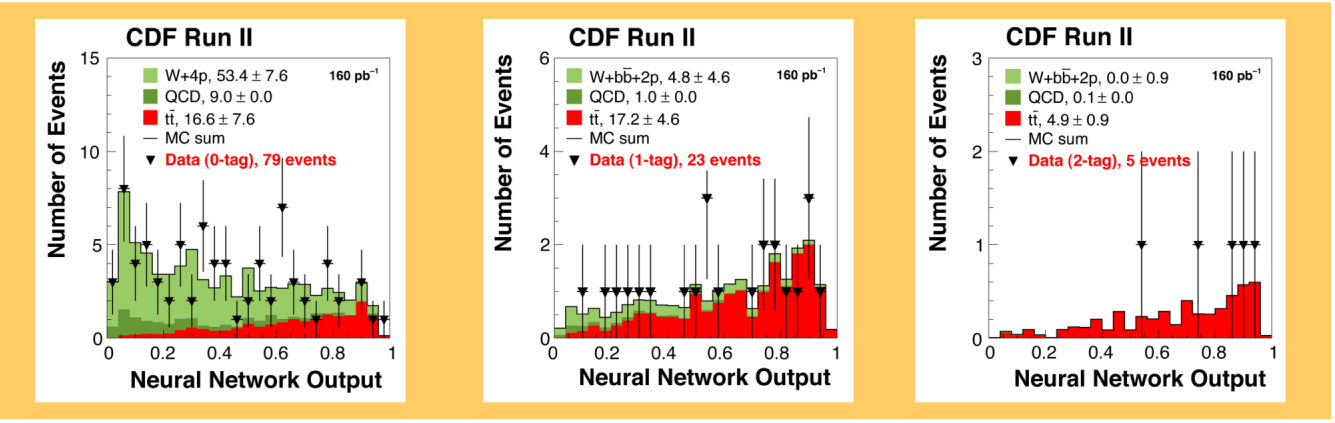
- Standard Model says that top decays 99.9% of the time to *Wb*

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ \boldsymbol{V_{td}} & \boldsymbol{V_{ts}} & \boldsymbol{V_{tb}} \end{pmatrix} = \begin{pmatrix} 0.9739-0.9751 & 0.221-0.227 & 0.0029\pm0.0045 \\ 0.221-0.227 & 0.9730-0.9744 & 0.039-0.044 \\ \mathbf{0.0048-0.014} & \mathbf{0.037-0.043} & \mathbf{0.9990-0.9992} \end{pmatrix}$$

- These values assume exactly three quark generations
- Check by measuring the fraction of *b*-tagged jets in top events



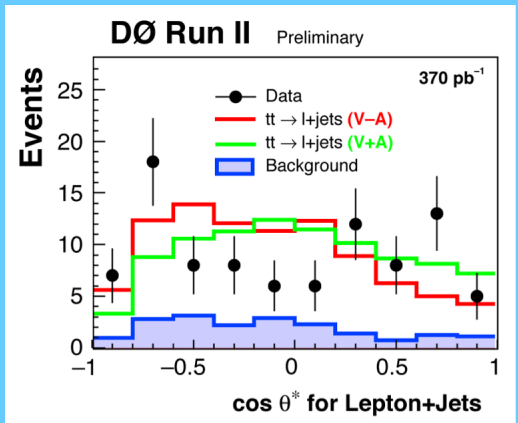
$|V_{tb}| > 0.78$ (DØ)
95% confidence level

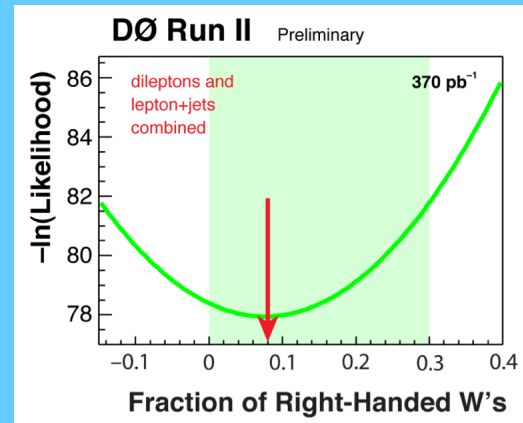


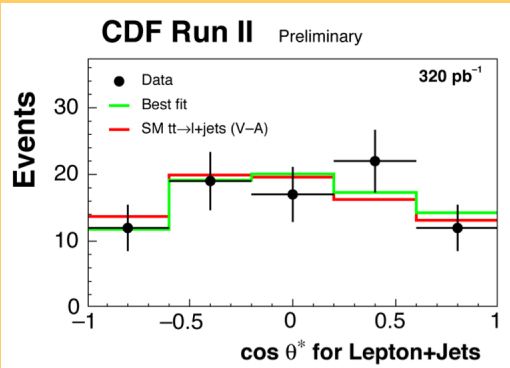
$|V_{tb}| > 0.78$ (CDF)
95% confidence level

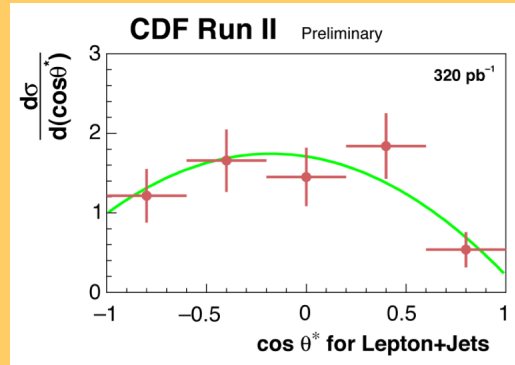
W Helicity in Top Decay

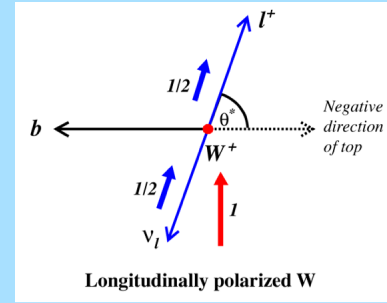
- Standard Model predicts top decays to
  - Longitudinally polarized *W* 70% of the time
  - Left-handed *W* 30%
  - Right-handed *W* 0.036%
- Select $t\bar{t}$ events and fit distributions of sensitive variables to *V–A* and *V+A* expectations

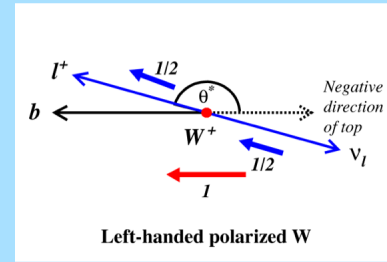


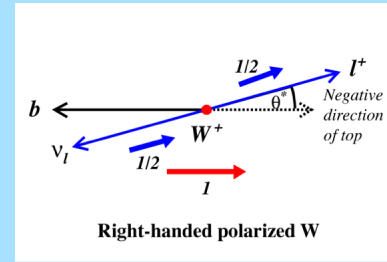










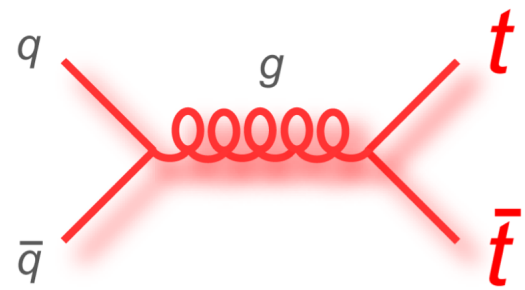
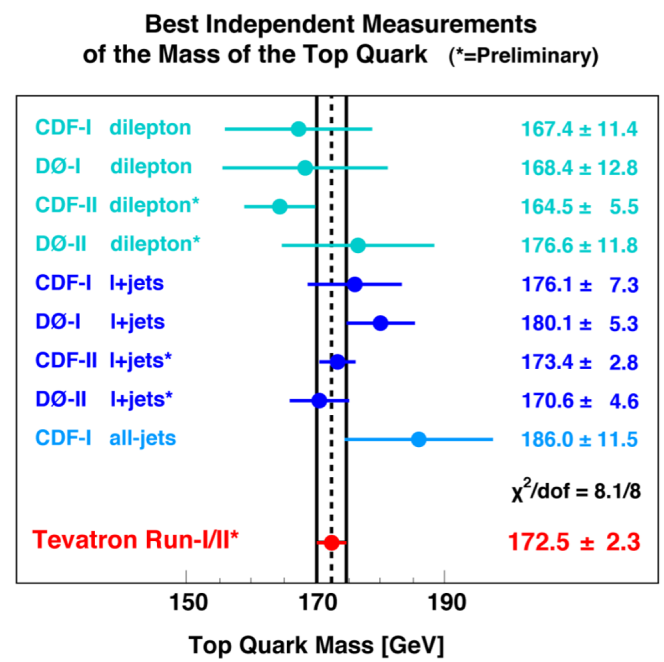


Right-handed *W* fraction
= 0.08 ± 0.08 ± 0.05 (DØ)

Right-handed *W* fraction
$= 0.05 \pm^{0.11}_{0.05} \pm 0.03$ (CDF)

Summary of Top Quark Measurements

- The CDF and DØ experiments at the Fermilab Tevatron have a wide-reaching program of precision measurements and new phenomena searches using the top quark
- Expect results from 10–20x more data in the future than shown here
- Top quark mass measurement is one of the most significant things to come from the Tevatron collider program (1.3% precision to date):

$$M_{top} = 172.5 \pm 2.3 \text{ GeV}$$

- We now have the data to
  - Look for beyond-the-standard-model production mechanisms
  - Test fundamental top quark properties like mass, charge, and width
  - Study the top quark's color and electroweak couplings
  - Look for beyond-the-standard-model decay modes
  - Decide whether what see is only top or something else as well or instead
- A very exciting program of top quark physics measurements is underway, stay tuned for many more new results in the near future