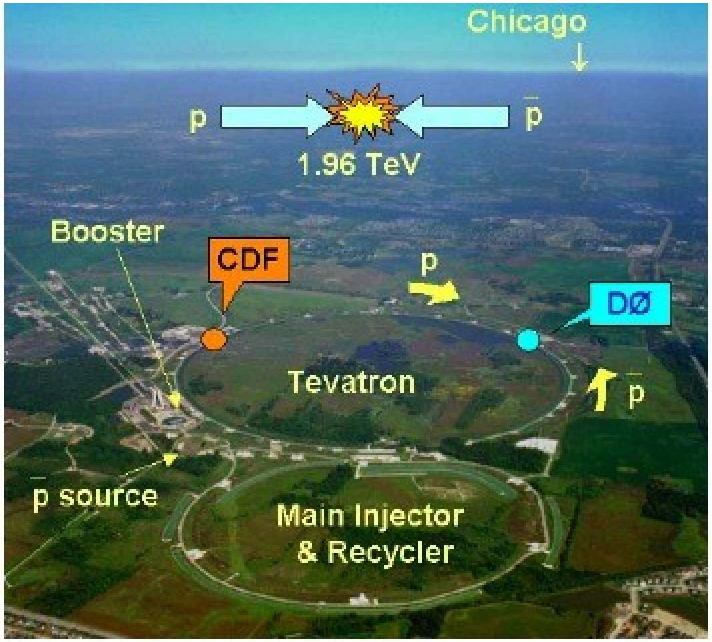
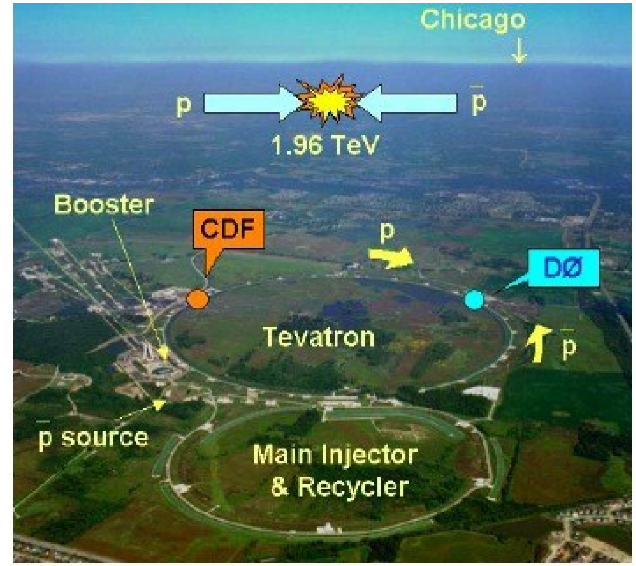
Top Quark Mass and Cross Section Results from the Tevatron

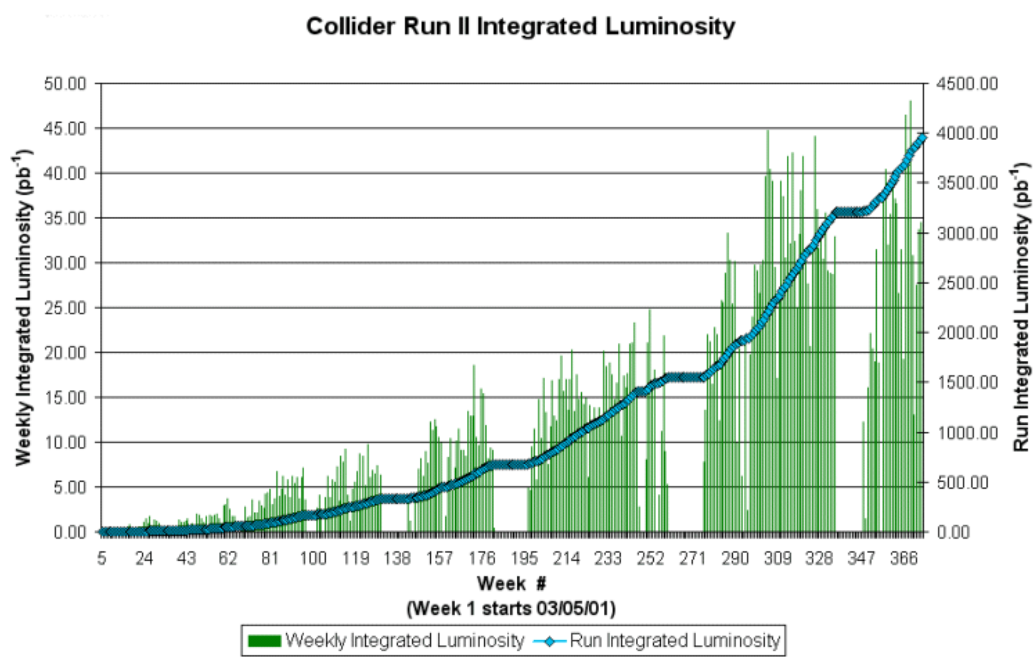
Ford Garberson, UCSB
On Behalf of the CDF and D0 Collaborations



The Tevatron

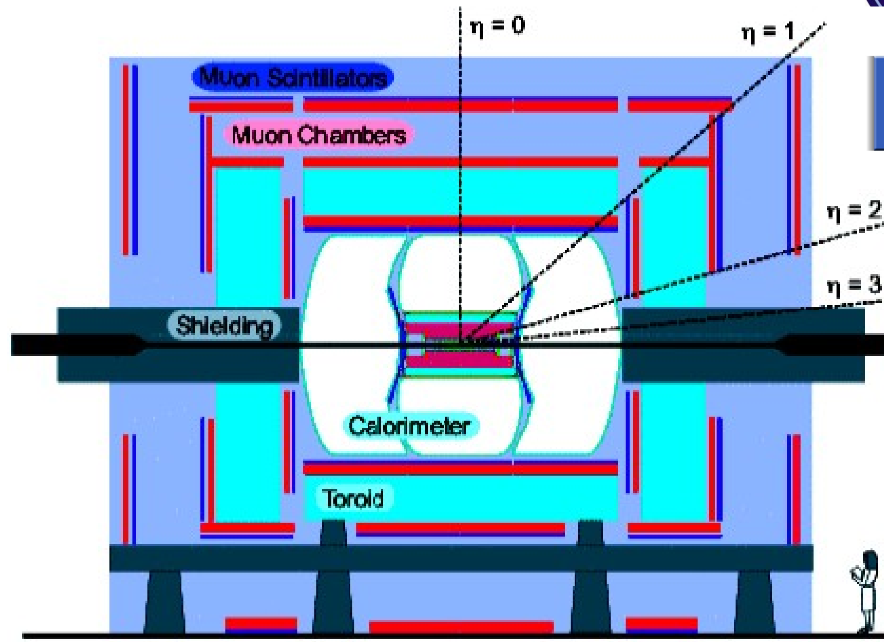
- Collides $p\bar{p}$ at 1.96 TeV
  - Still world's highest energies!
  - Two multipurpose detectors, CDF and D0
- Beam luminosity has been steadily improving
  - Total of ~4 fb^{-1} has been delivered to each detector
    - About 80% data acquisition efficiency
    - Recent analyses use about 2 fb^{-1}
  - Recently accumulated more than 50 pb^{-1} in one week!



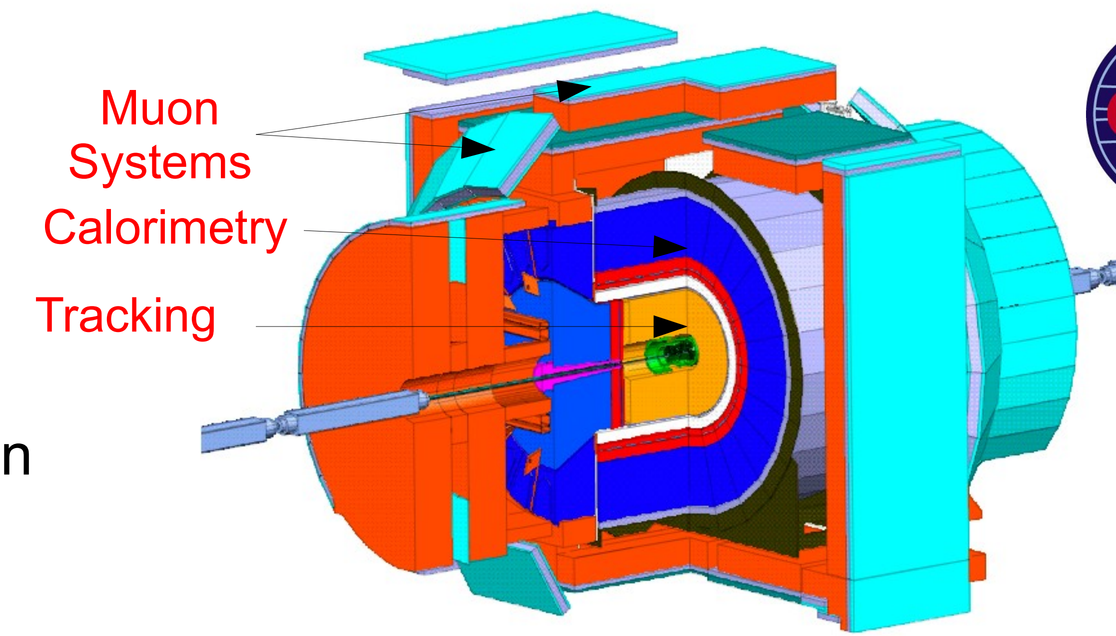


The Detectors

- Both detectors have a similar design
  - Geared to study and search for all kinds of different phenomena
  - Tracking inside of calorimetry inside of muon systems



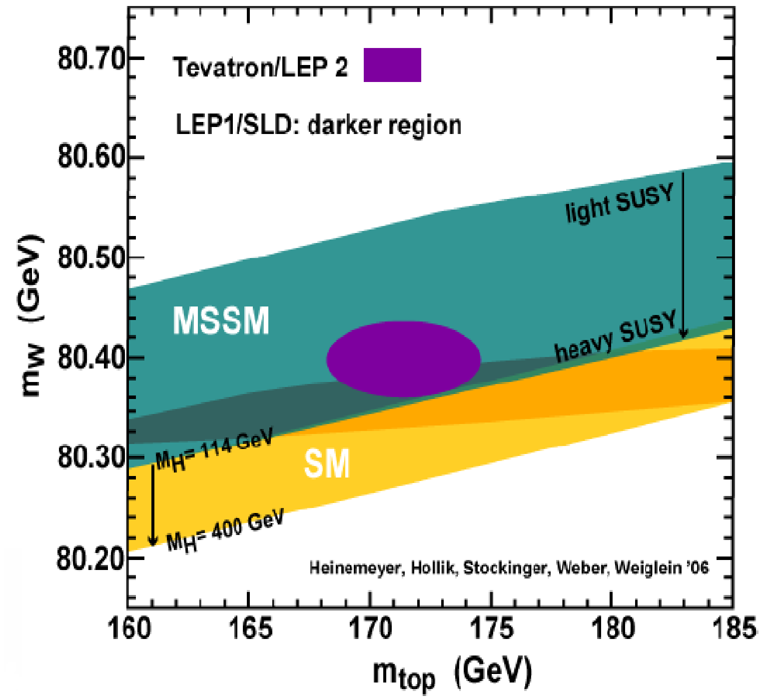
- Specialties
  - CDF has very good central tracking
  - D0 has very good muon coverage



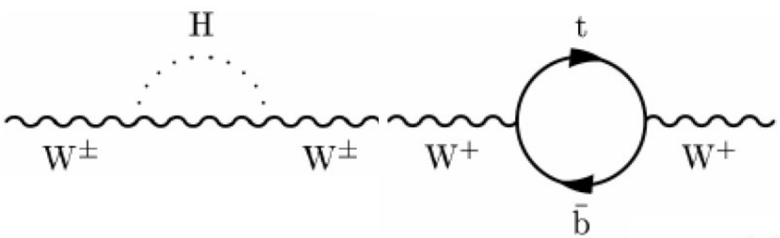
The Top Quark

- Have produced thousands of $t\bar{t}$ events at the Tevatron
  - Are they all Standard Model top?
  - Measure cross section: check for consistency & SM deviations

- The top quark mass can teach us about the Higgs
  - The top quark and the Higgs both couple to the W boson
  - Top mass and W mass determine SM Higgs mass
    - Measure to constrain Higgs mass
    - Test of standard model

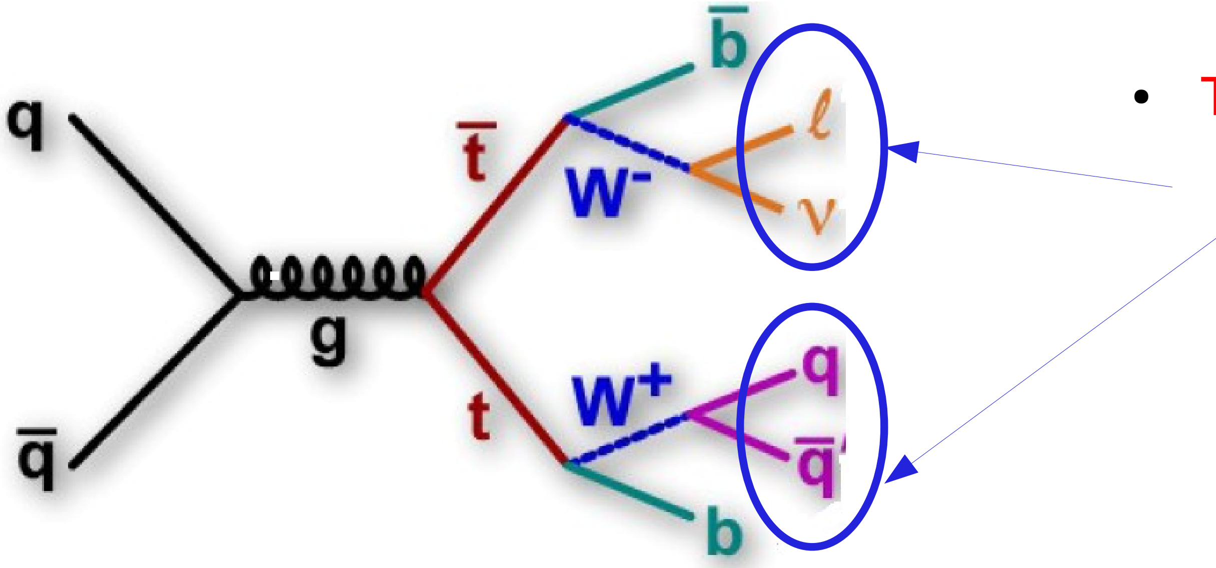


1-Sigma Constraint on Higgs mass (2006)



Higgs and top quark couplings to W boson

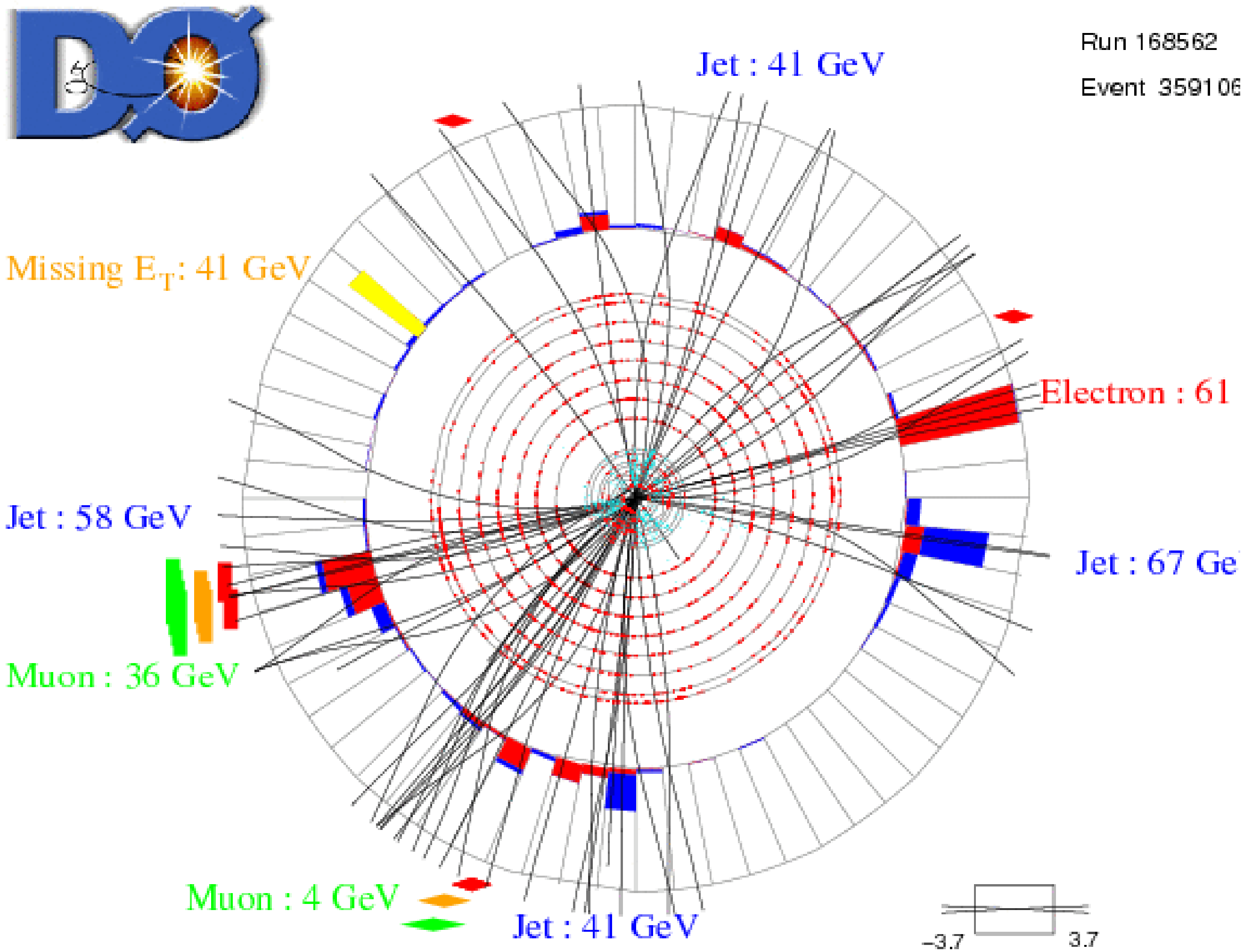
$t\bar{t}$ Production



- The top ~always decays to Wb
  - W can decay leptonically or hadronically
  - Usually focus on electron or muon lepton decays

- Signature:
  - Dilepton Channel: two leptons, two neutrinos, two b-quarks (5 %)
  - Lepton+Jets Channel: one lepton, one neutrino, four quarks (two b's) (29 %)
  - All Hadronic Channel: six quarks (two b's) (44 %)
  - Look for the appropriate particles to find ttbar events

Identifying $t\bar{t}$

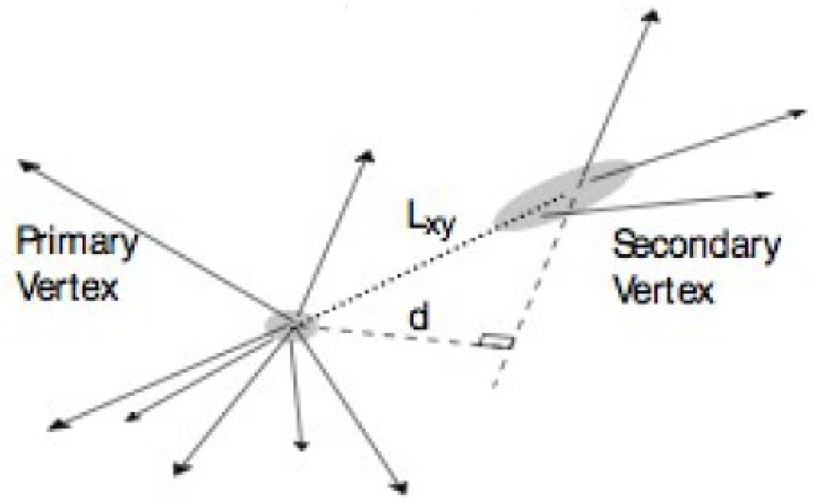


- In practice we might see something like this
  - Is it $t\bar{t}$?

b-Identification (Tagging)

- Identify b's to understand events

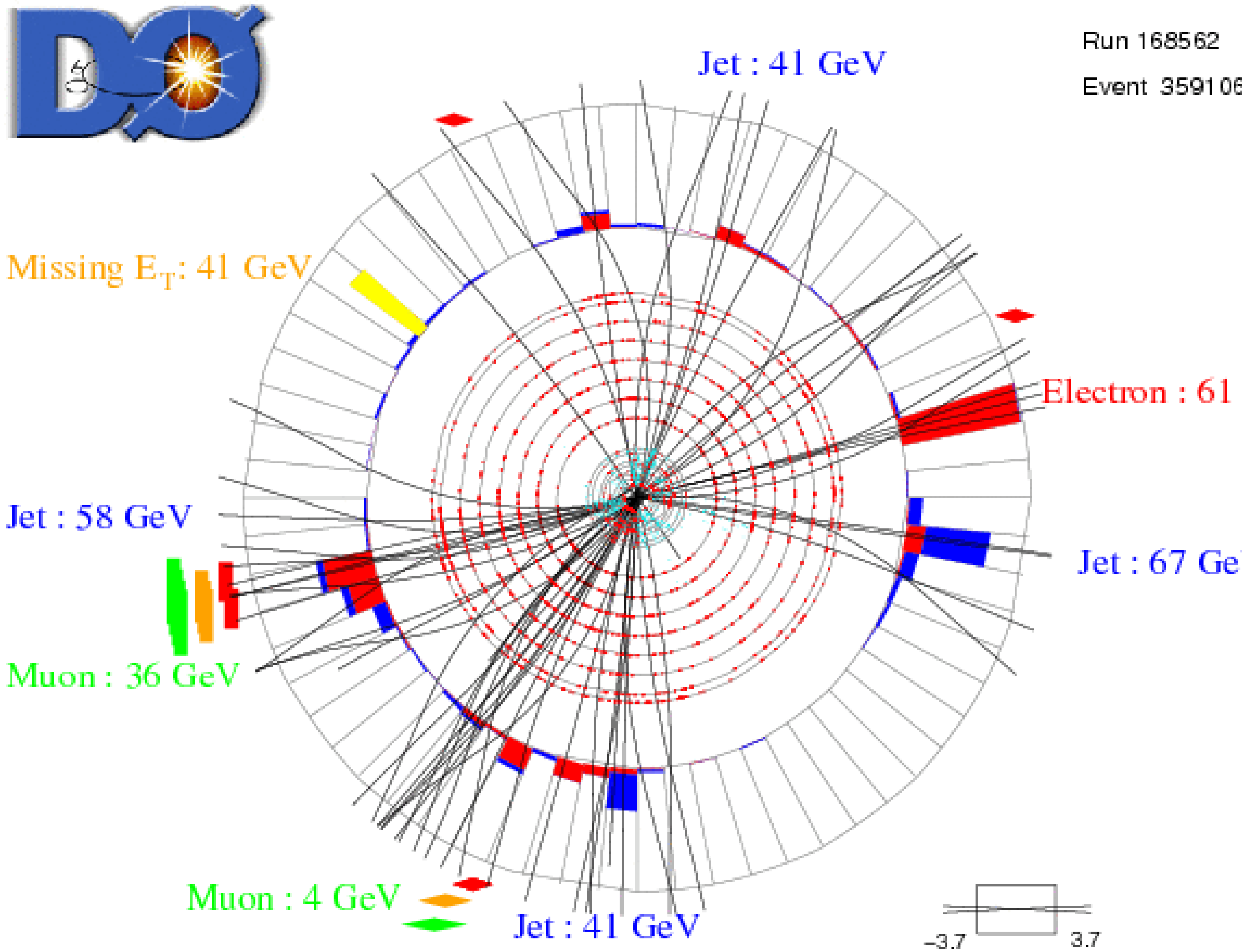
- Many possible approaches
  - Displaced vertices (use long lifetime of b's) (favored by CDF)
  - Neural Network (favored by D0)
    - Uses displaced vertex and other track and jet information
  - Look for “soft” leptons
    - Electrons or muons often in b-decay chain
    - Less efficient, but complementary information



Can identify b's from displaced secondary vertex

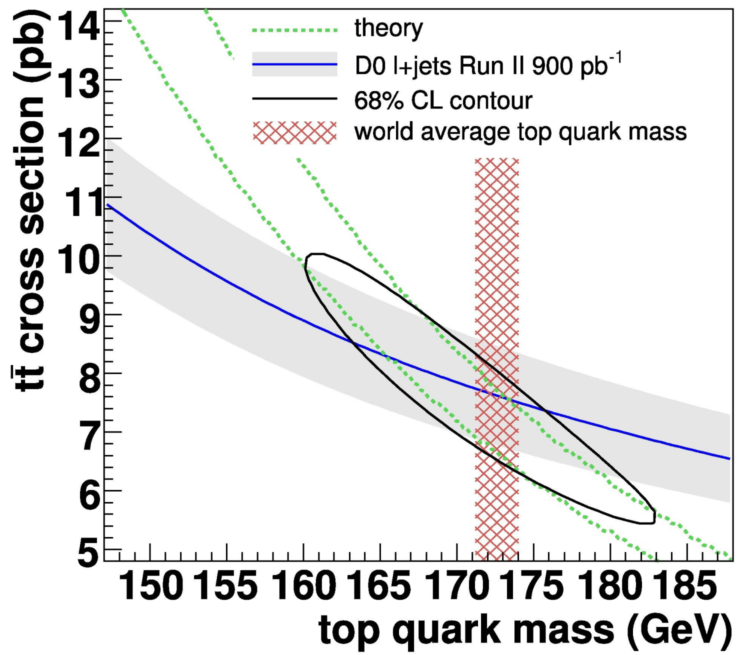
Identifying $t\bar{t}$

- This event can be b-tagged by eye (soft muon tagging)
  - So this is probably an electron+jets $t\bar{t}$ event



Cross Section/Mass Connection

- Measure cross section from excess of events in data
  - Normalize by efficiency, acceptance, luminosity
- A more massive top quark is harder to produce
  - Expect cross section of ~6.7 pb for top mass of 175 GeV/c^2
- Can indirectly determine mass from a cross section measurement
  - And vice versa
  - D0 results with 0.9 fb^{-1} of data



D0 With world average top mass (172.6 GeV/c^2)

$$\sigma_T = 7.62 \pm 0.85\ pb$$

D0 Measured vs theoretical cross sections:

$$M_T = 170 \pm 7\ GeV/c^2$$

Cross Section in Dilepton Channel

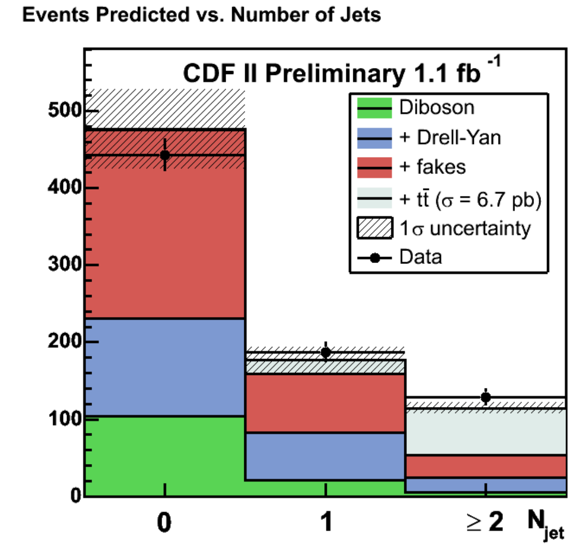
- Dileptons channel statistically limited so can loosen cuts
  - Loosen cuts on one lepton: “lepton plus track analysis”
  - Can choose not to b-tag
- Have to contend with Drell Yan and W+fake lepton backgrounds
  - For no b-tag with lepton+tracks cuts signal fraction ~60-70%
  - With b-tagging and dilepton cuts background fraction can drop to ~10% with loss of half of statistics

CDF lepton+tracks results (1.1 fb^{-1})

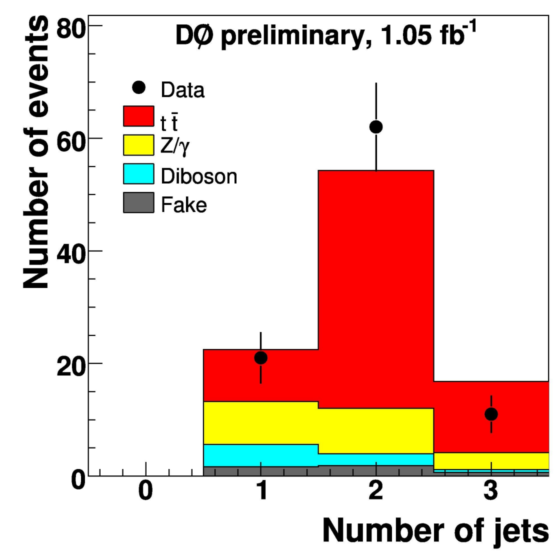
$$\sigma = 8.3 \pm 1.3(stat) \pm 0.7(syst) \pm 0.5(lumi)\ pb$$

D0 lepton+tracks and dilepton combination (1.0 fb^{-1})

$$\sigma = 6.2 \pm 0.9(stat)^{+0.8}_{-0.7}(syst) \pm 0.4(lumi)\ pb$$



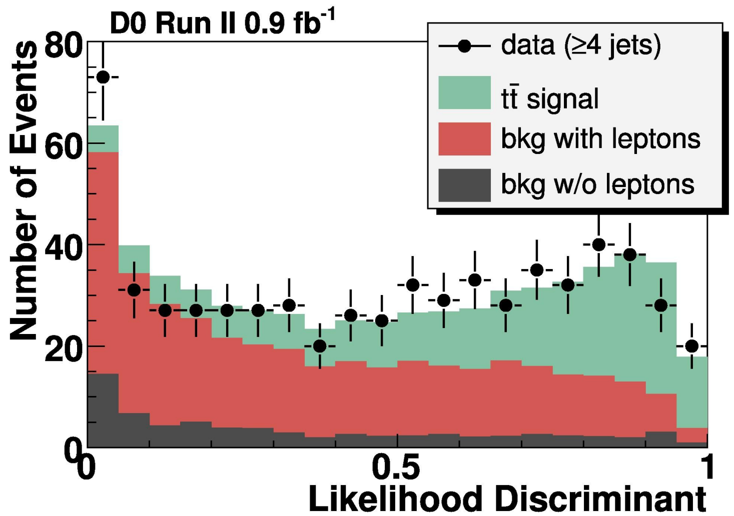
CDF Lepton + Track Results



D0 Dilepton Results

Using Alternate/No b-tagging in LJ Channel

- Using no b-tagging:
  - D0: kinematic likelihood fit using angles, momentum sums, and event shapes
    - Better systematic, worse statistical error than for b-tagging
  - CDF: neural network based on similar kinematic variables
- Using soft lepton tagging
  - Electrons or muons inside of jet
  - Veto if consistent with dilepton decay from Z, J/Psi, or double semileptonic decay



D0 Likelihood Discriminant (0.9 fb^{-1})

$$\sigma = 6.6 \pm 0.8(stat) \pm 0.4(syst) \pm 0.4(lumi)\ pb$$

D0 Likelihood+b-tag Combination (0.9 fb^{-1})

$$\sigma = 7.4 \pm 0.5(stat) \pm 0.5(syst) \pm 0.5(lumi)\ pb$$

CDF Neural Network (no b-tagging) (0.8 fb^{-1})

$$\sigma = 6.0 \pm 0.6(stat) \pm 0.9(syst)\ pb$$

CDF Soft muon tagging (2.0 fb^{-1})

$$\sigma = 8.7 \pm 1.1(stat)^{+0.9}_{-0.8}(syst) \pm 0.6(lumi)\ pb$$

CDF Soft electron tagging (2.0 fb^{-1})

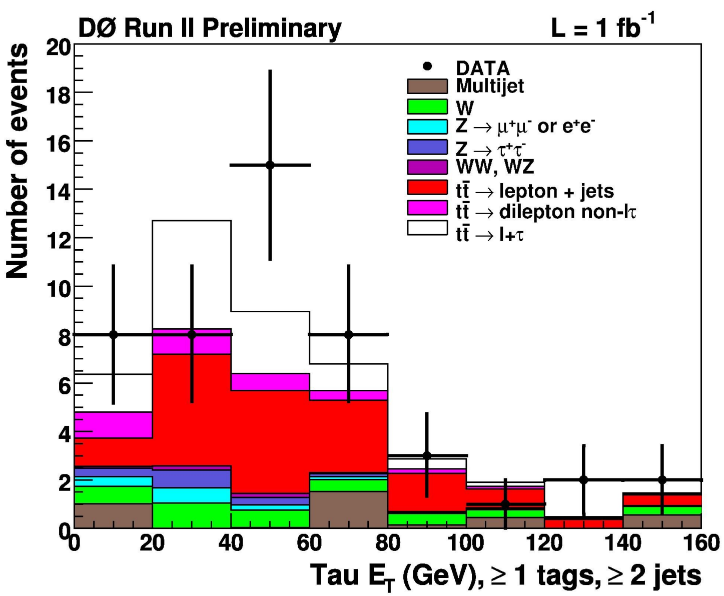
$$\sigma = 7.8 \pm 2.4(stat) \pm 1.5(syst) \pm 0.5(lumi)\ pb$$

Tauonic Cross Sections

- Can also study tauonically decay channels
  - Much larger backgrounds
  - Cross section excess: possibly a sign of charged Higgs decays
  - Consider all hadronically decaying tau types
  - Analyses with 1.0 and 1.2 fb^{-1} performed and combined

D0 Lepton+Tau Channel: (2.2 fb^{-1})

$$\sigma_T = 7.37^{+1.37}_{-1.27}(stat) +^{+1.21}_{-1.07}(syst) \pm 0.45(lumi)\ pb$$



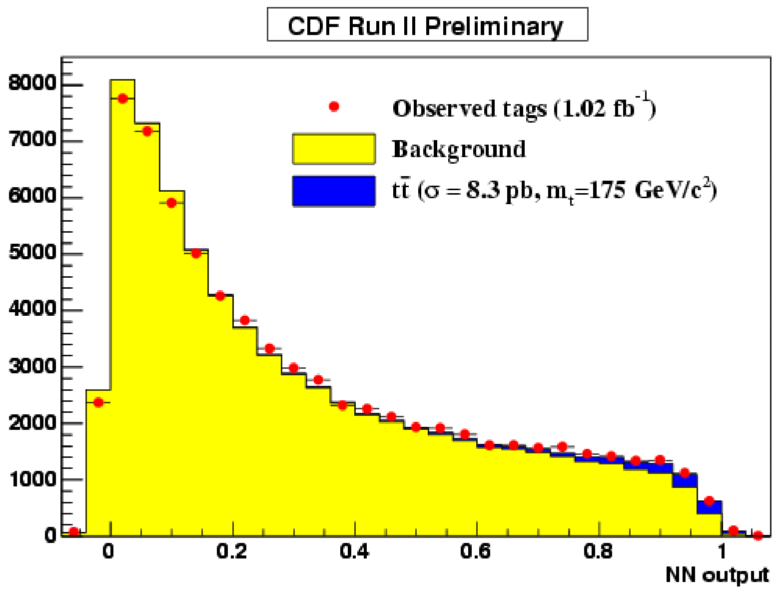
- Taus separated from jets and electrons with neural networks depending on ...
  - Shower shape, cluster energies, track-calorimeter agreement

D0 Tau plus Jet channel: (0.4 fb^{-1})

$$\sigma = 5.1^{+4.3}_{-3.5}(stat) \pm 0.7(syst) \pm 0.3(lumi)\ pb$$

All Hadronic Cross Section

- Have to contend with enormous QCD background
  - B-tagging essential
- Also use Neural Network event selection to reduce background
  - sum ET, event shape information, parton angles
  - Measure angles based on center of mass frame of all jets
  - Extract backgrounds based on b-tag and mistag rate parameterization from 4-jet control region



CDF Neural Network Output

CDF Results, 1.0 fb^{-1}

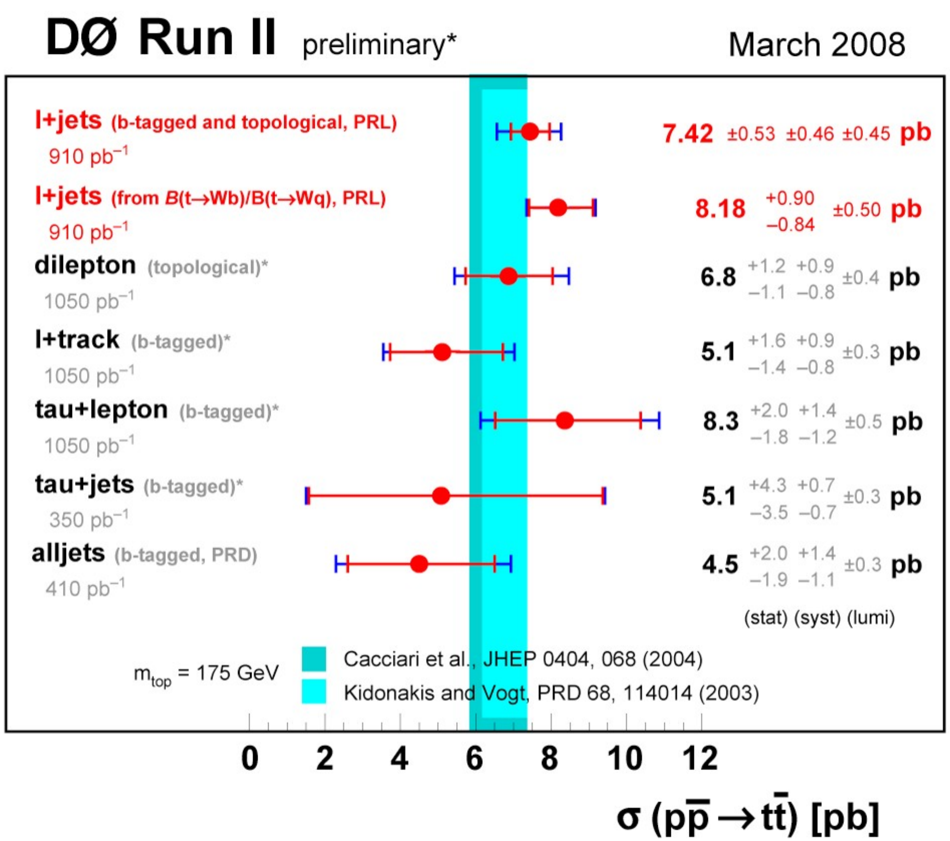
$$\sigma = 8.3 \pm 1.0(stat)^{+2.0}_{-1.5}(syst) \pm 0.5(lumi)\ pb$$

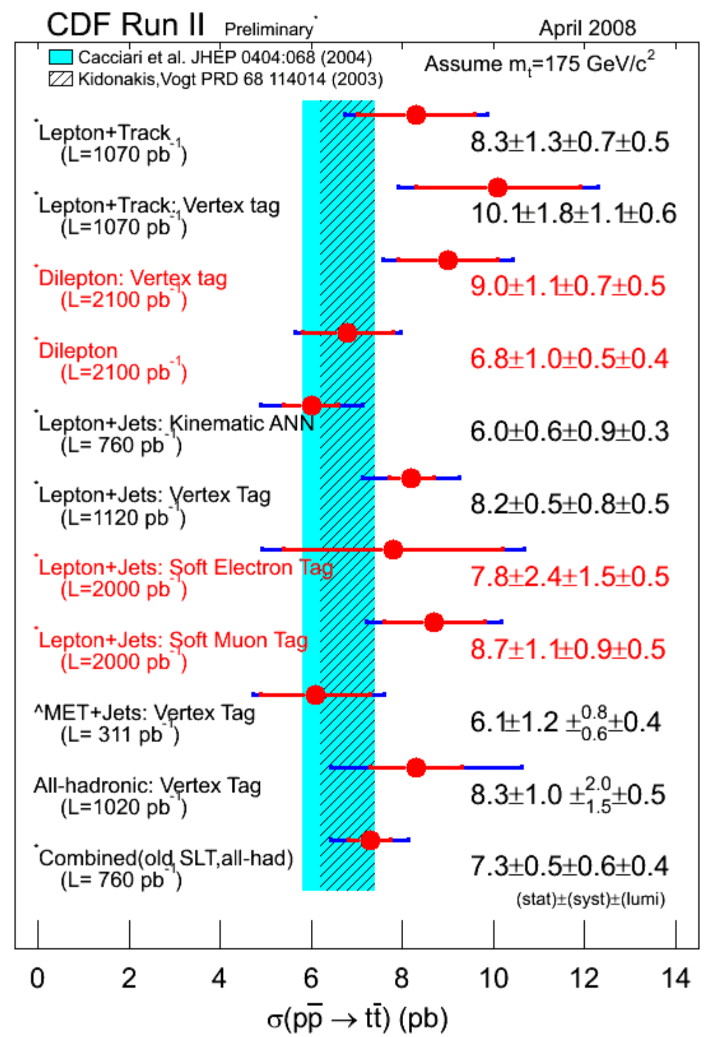
D0 Results, lifetime b-tagging, 0.4 fb^{-1}

$$\sigma = 4.5^{+2.0}_{-1.9}(stat)^{+1.4}_{-1.1}(syst) \pm 0.3(lumi)\ pb$$

Cross Section Summary

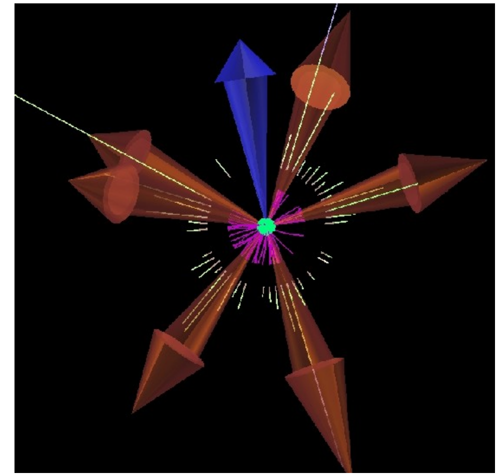
- Both collaborations find results consistent with standard Model expectations



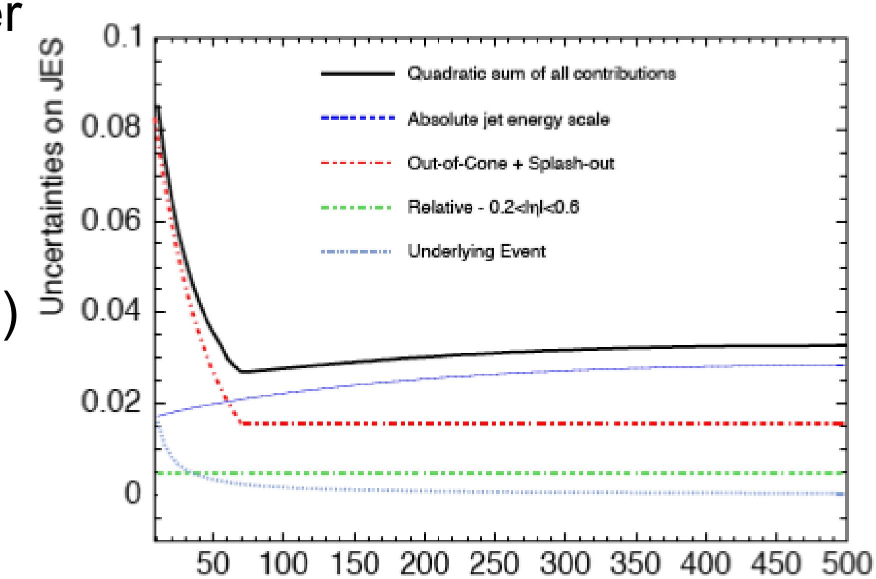


Determining the Mass

- Event reconstruction challenges:
  - Which partons came from which top and which W?
- Jet reconstruction challenges:
  - Are you reconstructing the complicated data in your calorimeter towers correctly?
  - Does your Monte Carlo reconstruct jets consistently?
  - Left with the Jet Energy Scale (JES) uncertainty of ~3-4 GeV on top mass
    - Largest uncertainty on world average top mass



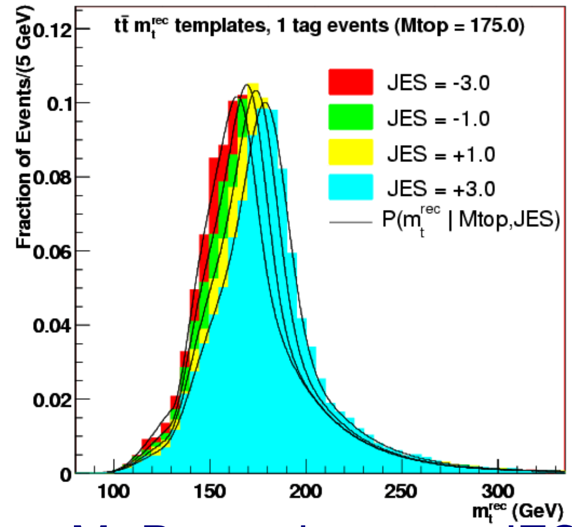
Which jets belong to which invariant mass?



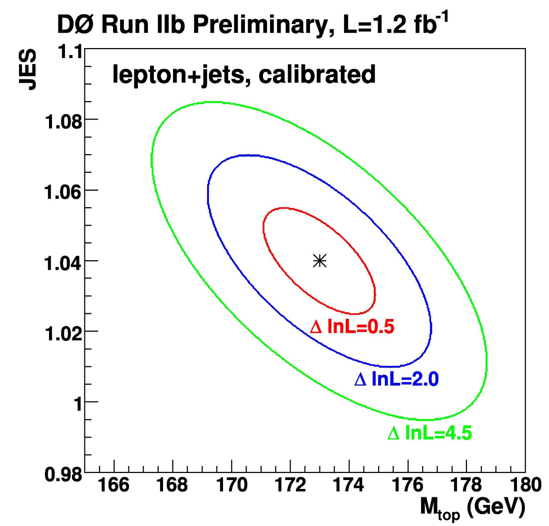
Calibrated JES Uncertainties

Controlling the JES Uncertainty

- Option 1: Perform "in-situ" JES calibration
  - Require the W mass to reconstruct correctly
  - Assume all other jets have same Jet Energy scale uncertainty
  - Do simultaneous fit to top mass and JES
    - Uncertainty becomes statistical
- Residual systematics remain (~0.8 GeV)
  - JES for b-jets vs light flavor jets
  - JES variation based on jet properties



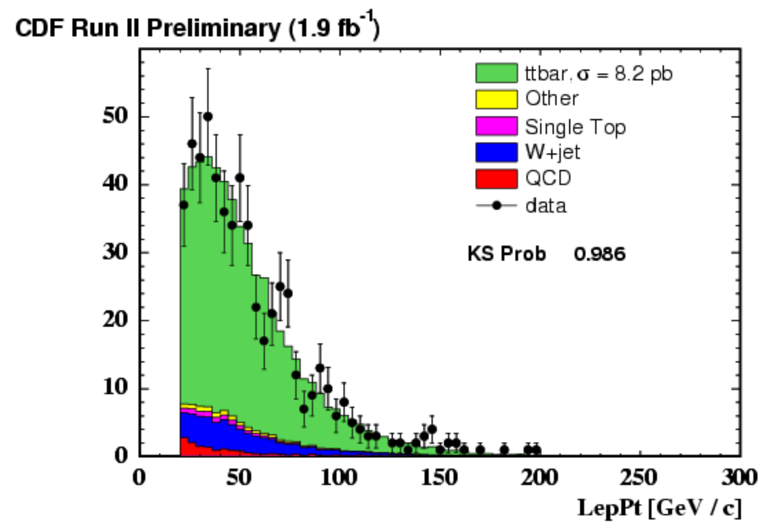
M_T Dependence on JES



Example of a Simultaneous Fit

Controlling the JES Uncertainty

- Option 2: directly measure top mass using quantities unrelated to jet energy
  - Decay length of b-tagged jets
  - Transverse momentum of leptons
  - These measurements should have minimal correlation to other mass analyses
  - Statistical limitations will be no problem at the LHC
    - Systematic uncertainties should also improve with statistics
- Only JES dependence is through jet energy event selection cuts
  - Methods could easily be applied to dilepton channel



CDF Lepton Transverse Momentum Results

Results with 1.9 fb^{-1} in Lepton+Jets Channel:

CDF Decay Length

$$M_T = 176.7^{+10.0}_{-8.9}(stat) \pm 3.4(syst)\ GeV/c^2$$

CDF Lepton Transverse Momentum

$$M_T = 173.5^{+8.9}_{-9.1}(stat) \pm 4.2(syst)\ GeV/c^2$$

Combined

$$M_T = 175.3 \pm 6.2(stat) \pm 3.0(syst)\ GeV/c^2$$

Template Based m_T

- Template Method
  - Make probability distribution functions (templates) for signal and backgrounds
    - Fit data, integrating over all allowed jet and lepton combinations

Signal chisquare for CDF Lepton+Jets analysis

Measurement Constraints

Unclustered Energy Constraints

$$\chi^2 = \Sigma_{i=\ell,4jets} \frac{(p_T^{i,fit} - p_T^{i,meas})^2}{\sigma_i^2} + \Sigma_{j=x,y} \frac{(U_j^{fit} - U_j^{meas})^2}{\sigma_j^2}$$

$$+ \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(M_{\ell\nu} - M_W)^2}{\Gamma_W^2} + \frac{(M_{bjj} - m_t^{\mathrm{reco}})^2}{\Gamma_t^2} + \frac{(M_{b\ell\nu} - m_t^{\mathrm{reco}})^2}{\Gamma_t^2}$$

m_W Constraints

m_T Constraints

CDF Template Method Results

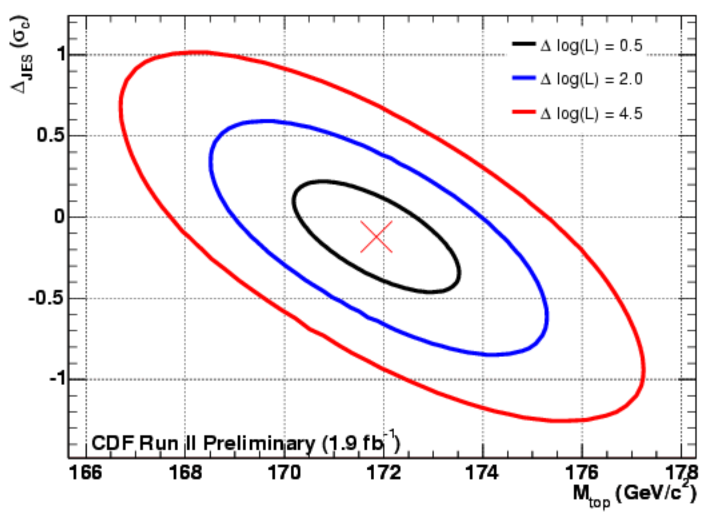
- In-situ JES calibrations performed
- All-hadronic channel: CDF uses same neural network as for cross section measurement
  - Parameterize templates with Gaussian+Lorentzian fits

CDF Combined Dilepton and L+J Results (1.9 fb^{-1})

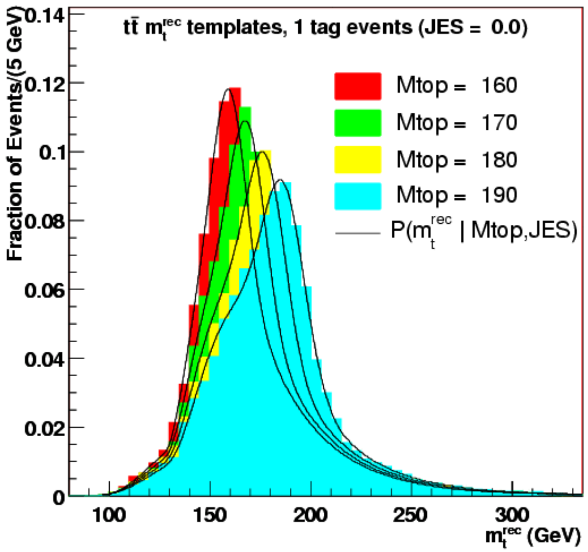
$$M_T = 171.9 \pm 1.7(stat + JES) \pm 1.0(syst) GeV/c^2$$

CDF All Hadronic Results (1.9 fb^{-1})

$$M_T = 177.0 \pm 3.7(stat + JES) \pm 1.6(syst)\ GeV/c^2$$



CDF Combined Dilepton L+J Likelihood Results



CDF All Hadronic Mass Templates

Dilepton Template Mass

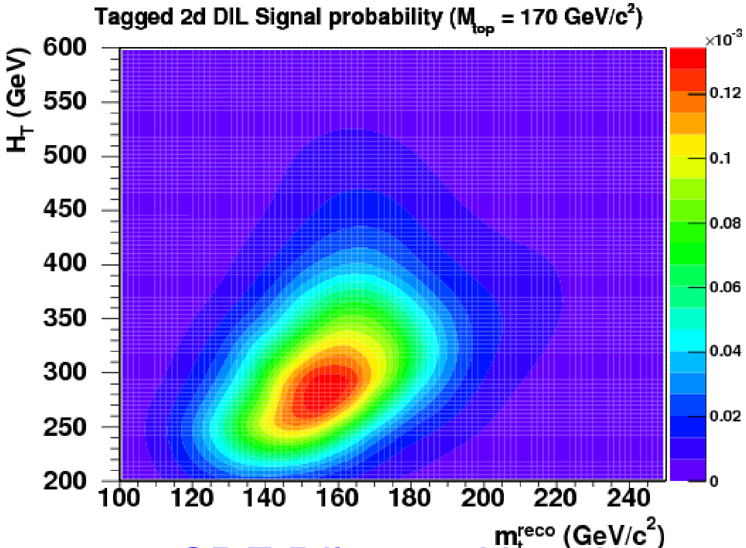
- Template Method (Neutrino Weighting)
  - Integrate over unknown pseudorapidities of neutrinos
  - Weight solutions by agreement with Missing ET
- Template Method (Matrix Weighting):
  - Weight solutions by consistency with lepton energies and PDF
    - Evaluate mass event by event
  - D0: Smear momenta within detector resolution

D0 Matrix and Neutrino Weighting Combined (1.0 fb^{-1})

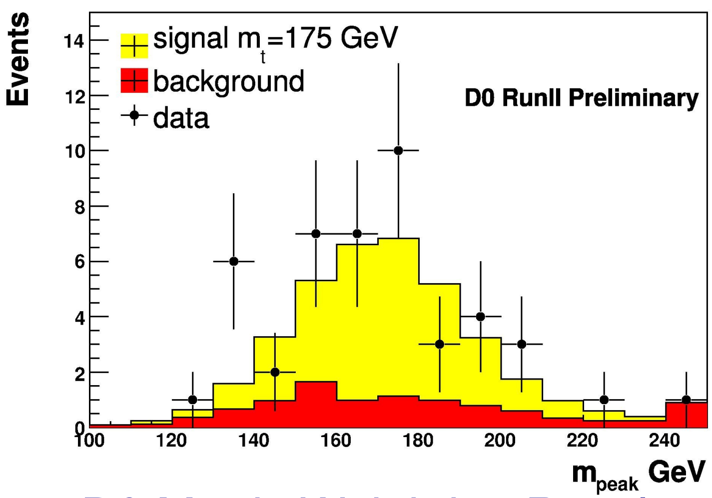
$$M_T = 173.7 \pm 5.4(stat) \pm 3.4(syst)\ GeV$$

CDF Neutrino Weighting (1.9 fb^{-1})

$$M_T = 171.6^{+3.4}_{-3.2}(stat) \pm 3.8(syst)\ GeV/c^2$$



CDF Dilepton Neutrino Weighting



D0 Matrix Weighting Results

Matrix Element m_T

- Attempt to extract more information from each event
  - Find mass likelihood event by event based on signal probability from theoretical Matrix Element calculation and background probability
  - Integrate over all unknowns with probabilistic weighting
  - Example: D0 Lepton plus jets measurement

Signal Probability Proportional to ...

$$\sum_{\text{perm}} w_i \int_{q_1,q_2,y} \sum_{\text{flavors}} dq_1 dq_2 f(q_1) f(q_2) \frac{(2\pi)^4 \left|\mathcal{M}(q\bar{q}\to t\bar{t}\to y)\right|^2}{2q_1 q_2 s} d\Phi_6 W(x,y;JES)$$

b-tagging probability

Parton Distribution Functions

Transfer Functions: Probability of observing momenta x given real momenta y and JES

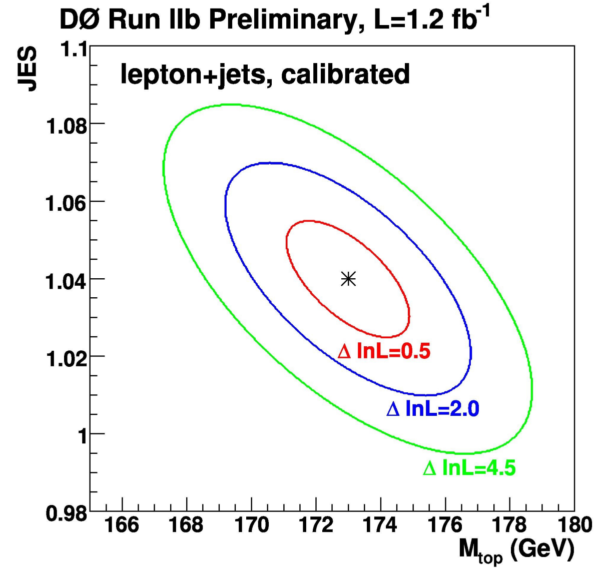
Sum over jet and flavor combinations

Matrix Element from theory

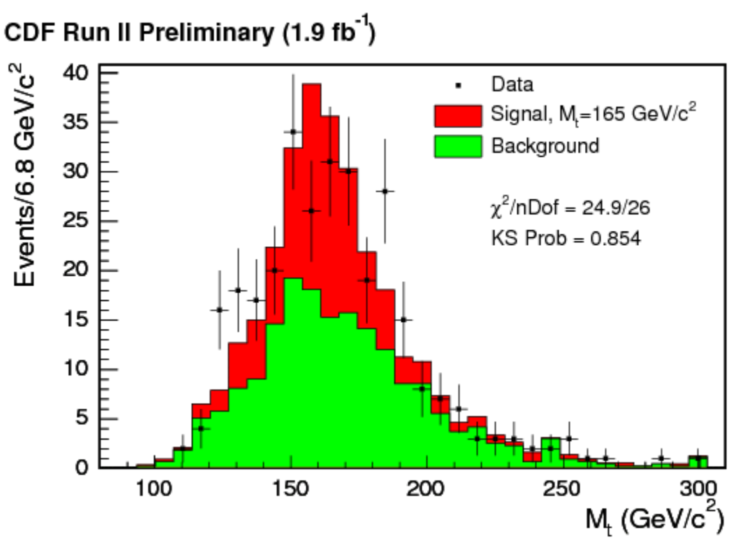
Matrix Element m_T

- Evaluate total mass probability simultaneously with JES and signal fraction
  - In-situ JES calibration performed where possible
  - Expression for background probability uses different Matrix Element (no mass dependence)

$$P_{\mathrm{evt}}(x; m_{\mathrm{top}}, JES, f_{\mathrm{top}}) = f_{\mathrm{top}} \cdot P_{\mathrm{sig}}(x; m_{\mathrm{top}}, JES) + (1 - f_{\mathrm{top}}) \cdot P_{\mathrm{bkg}}(x; JES)$$



D0 Lepton+Jet Results



CDF All Hadronic Results

CDF Dilepton (1.9 fb^{-1})

$$M_T = 171.2 \pm 2.7(stat) \pm 2.9(syst)\ GeV/c^2$$

D0 Lepton+Jets (2.1 fb^{-1})

$$M_T = 172.2 \pm 1.1(stat) \pm 1.6(syst) GeV/c^2$$

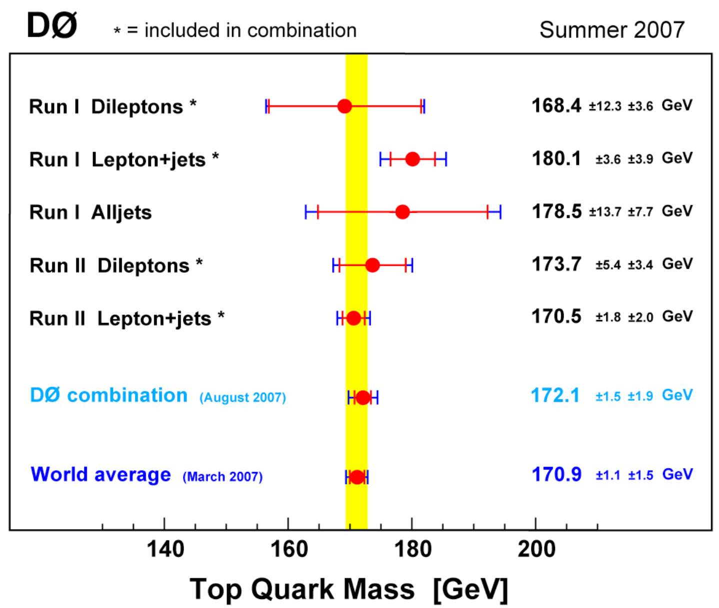
CDF Lepton+Jets (1.9 fb^{-1})

$$M_T = 171.4 \pm 1.5(stat + JES) \pm 1.0(syst) GeV/c^2$$

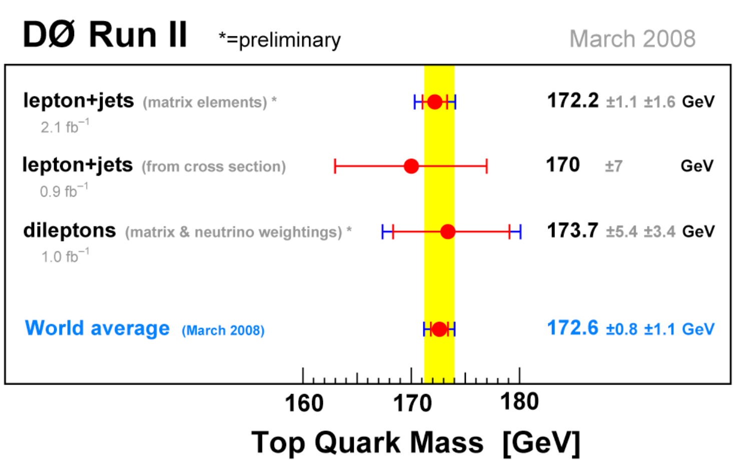
CDF All Hadronic (1.9 fb^{-1})

$$M_T = 165.2 \pm 4.4(stat + JES) \pm 1.9(syst)\ GeV/c^2$$

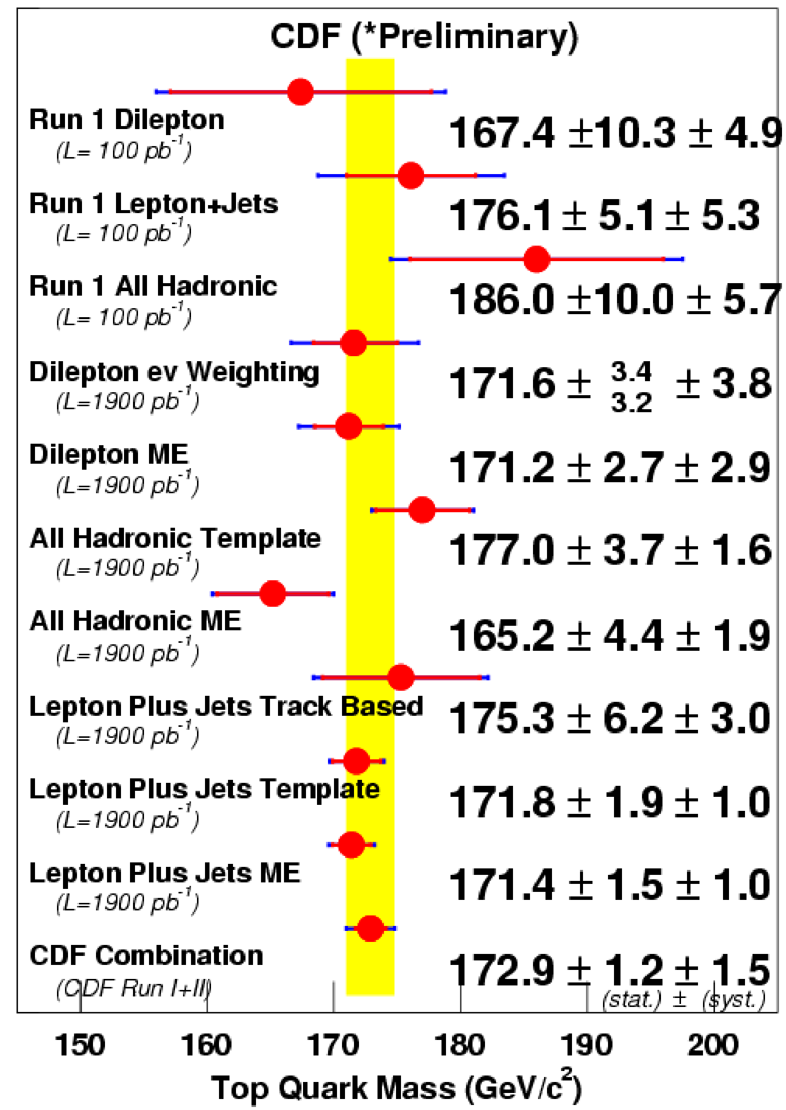
Mass Combinations



D0 Mass Combination



D0 Results since Combination



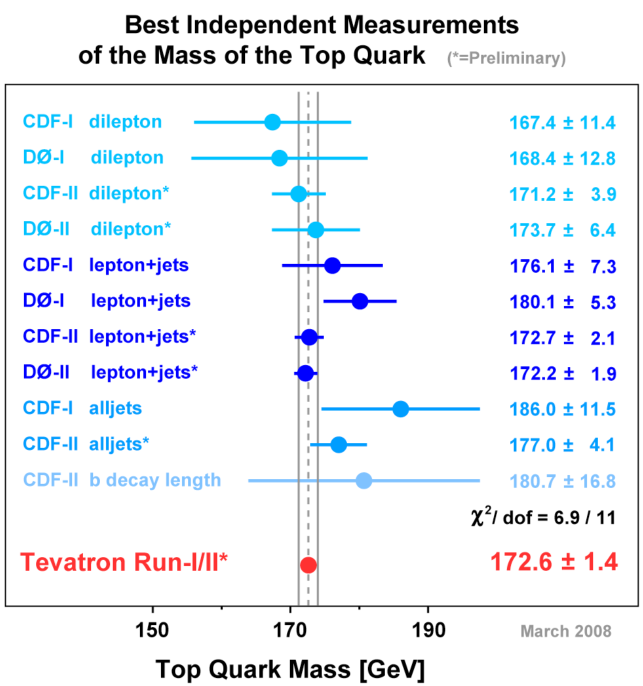
CDF Mass Results

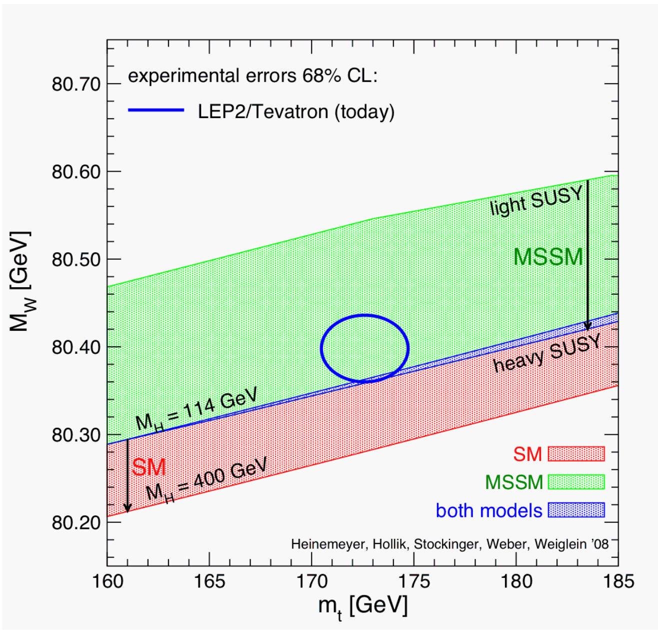
D0+CDF Combination

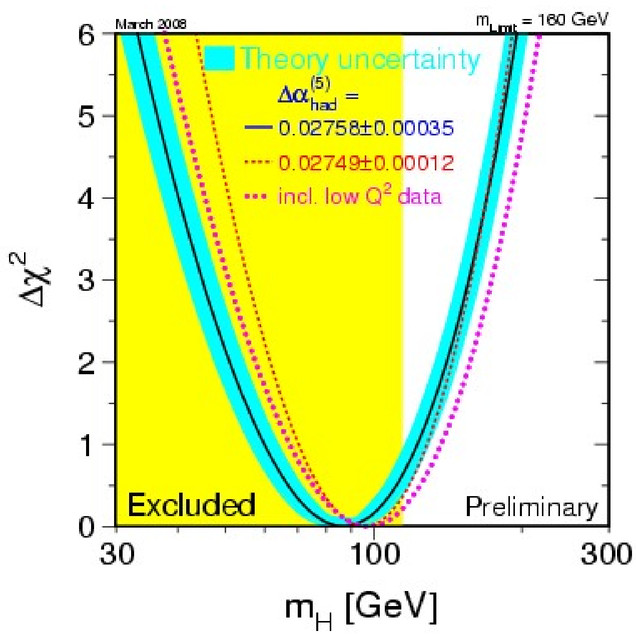
- Using Best Linear Unbiased Estimator technique
  - Correlations estimated between 12 types of uncertainties

$$M_T = 172.6 \pm 0.8(stat) \pm 1.1(syst)\ GeV/c^2$$

- Electroweak fits: SM Higgs mass now < 160 GeV/c^2 at 95% confidence level!
  - With LEP lower limit of M_H>114 GeV/c^2: upper limit rises to 190 GeV/c^2

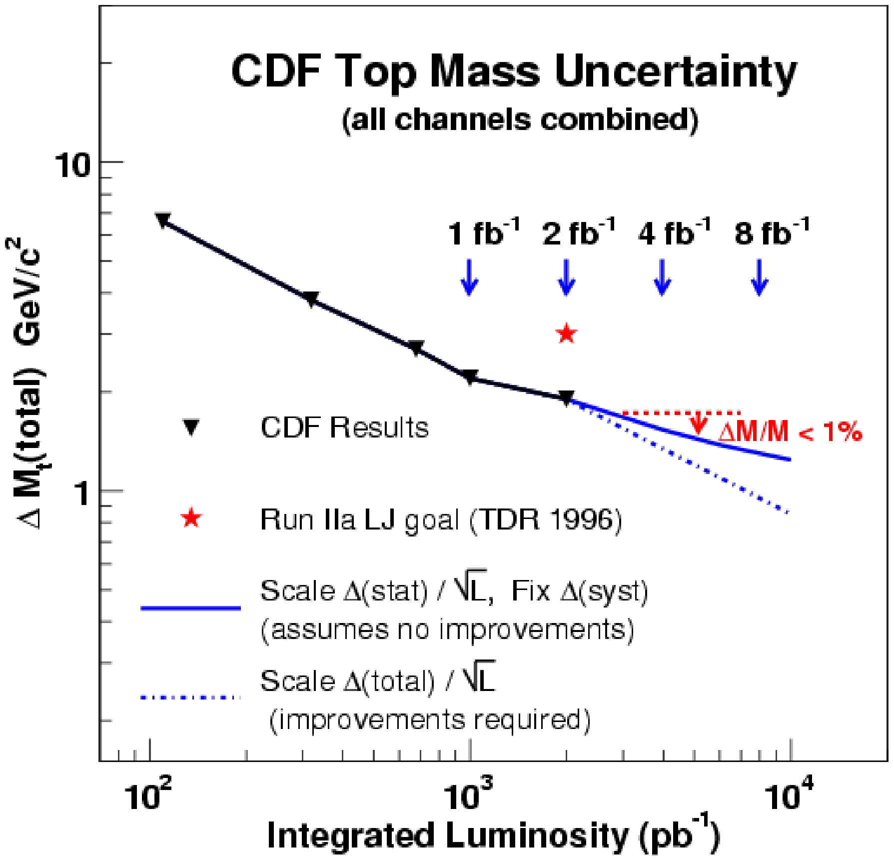






Future Improvements

- Cross section results will continue to improve with statistics
  - All channels stand to benefit
- Mass results are now more systematically limited
  - But even without systematic improvements will have better than 1% precision at both experiments
  - Work on improving systematics still ongoing
    - Have a good track record of success: already far ahead of where we projected we would be at this luminosity!



Past Expectations and Future M_T Projections at CDF

Summary and Outlook

- Cross section results are precise in some channels
  - But others could still be hiding non $t\bar{t}$ physics
  - Can push these uncertainties down with higher statistics

- Top mass known to high precision, but work remains
  - Understanding the Higgs will take further improvements
  - With higher statistics can greatly reduce the jet energy scale uncertainty in all channels
    - Using in-situ calibration and alternate variables
  - QCD radiation uncertainties will play a larger role
  - New, subtle uncertainties will have to be understood
  - Are we really measuring the pole mass?