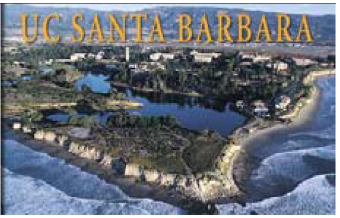
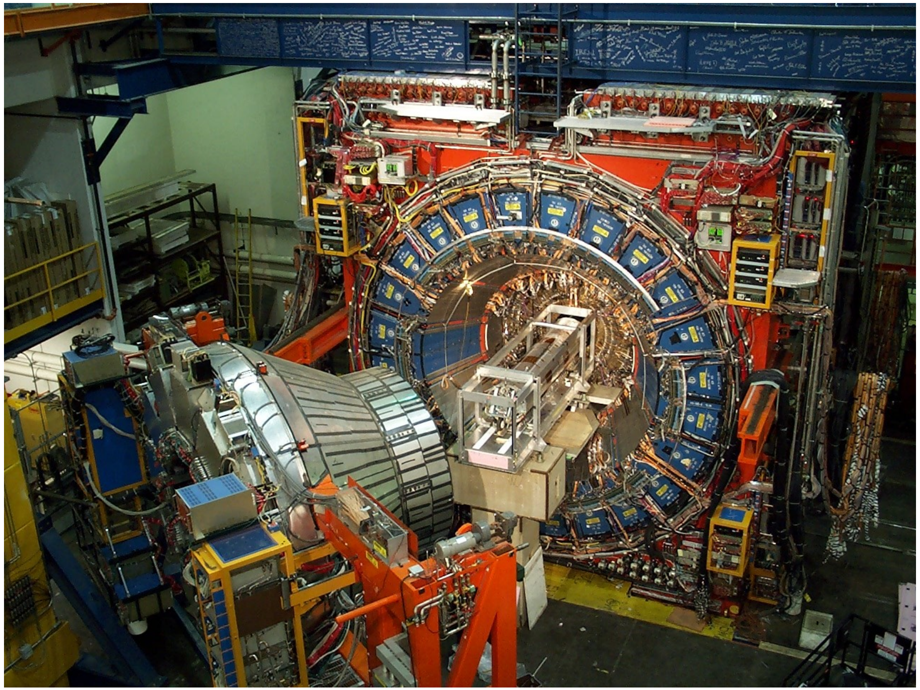


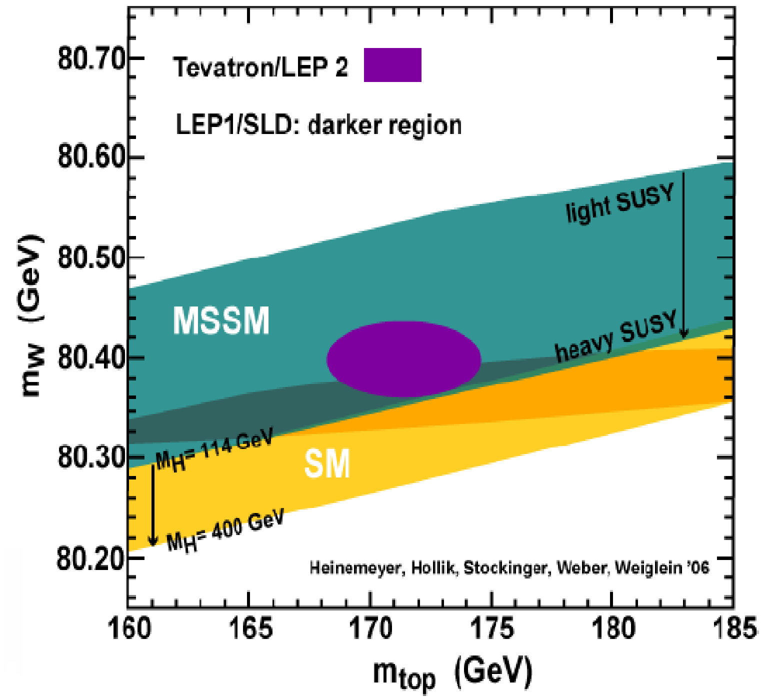
Top Quark Mass Measurements from CDF

Ford Garberson, UCSB
On Behalf of the CDF Collaboration

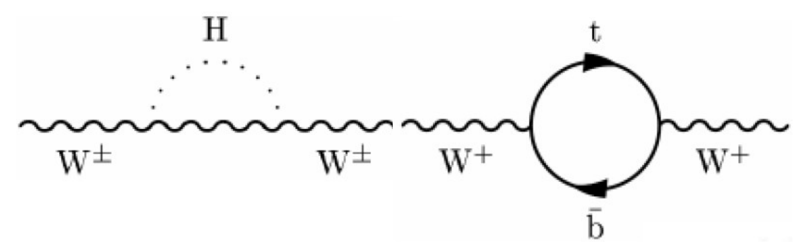


The Top Mass

- The top quark mass is interesting because ...
- Applications at the LHC:
  - Calibrating energies of highly boosted jets
- It 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

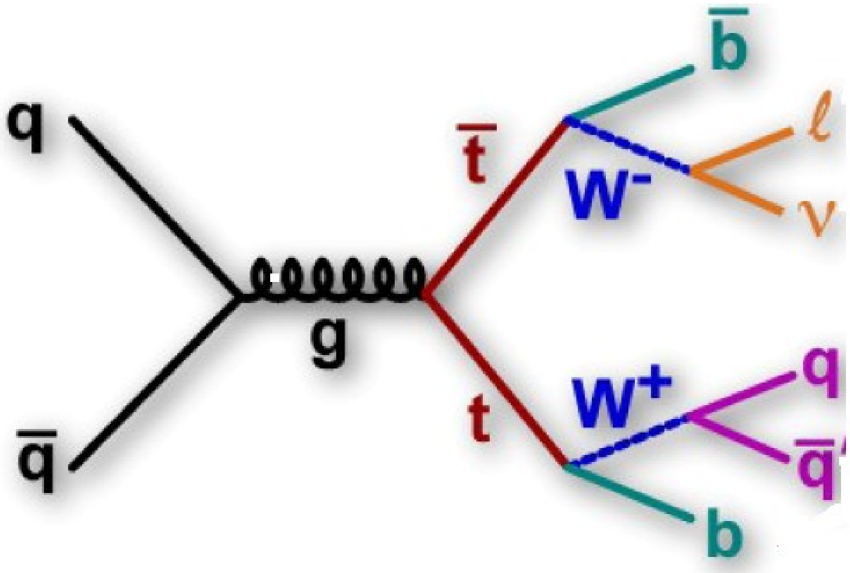


1-Sigma Constraint on Higgs mass (2006)



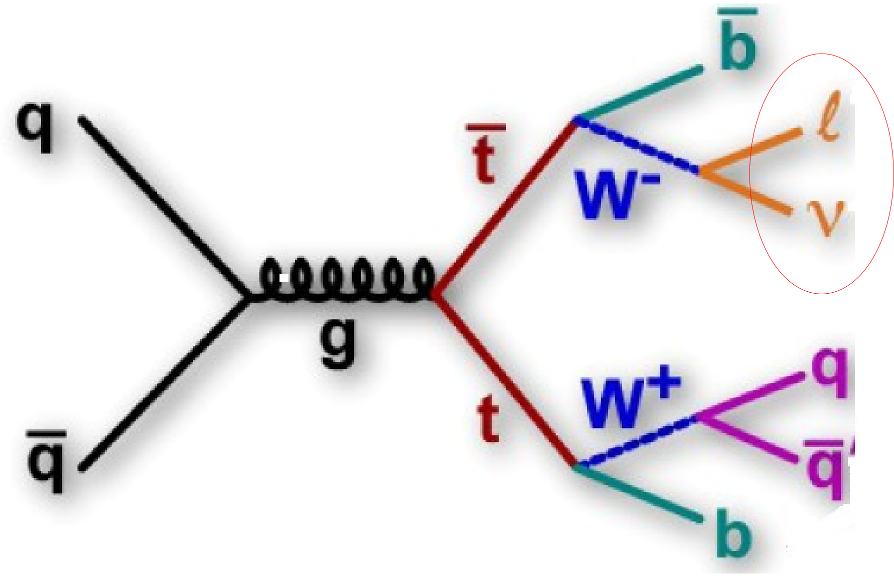
Higgs and top quark couplings to W boson

Identifying $t\bar{t}$



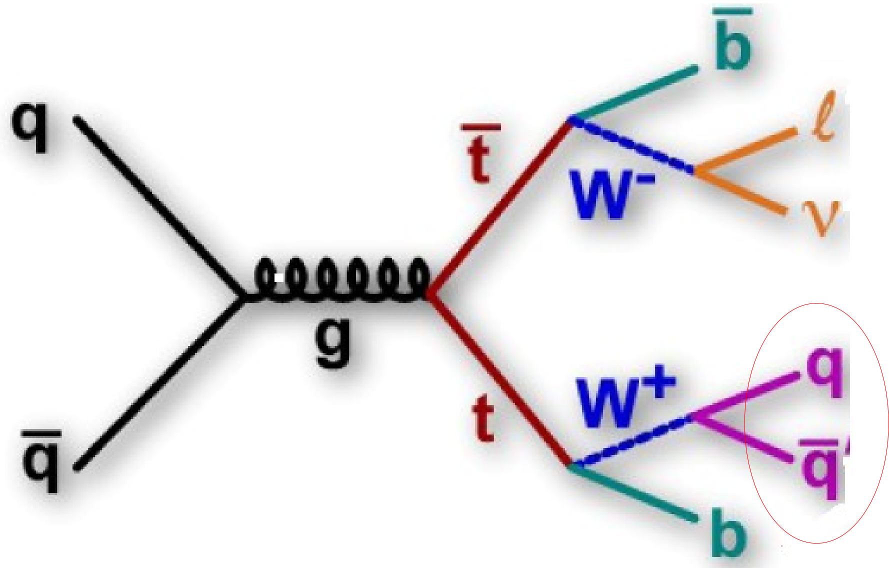
- Tops decay to W's a b's
- Three very different types of mass analyses depending on W decay modes

Identifying $t\bar{t}$



- Tops decay to W's a b's
- Three very different types of mass analyses depending on W decay modes
  - Both W's decay leptonically: “dilepton channel”.
    - Tiny backgrounds, low stats

Identifying $t\bar{t}$



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  - Both W's decay leptonically: “dilepton channel”.
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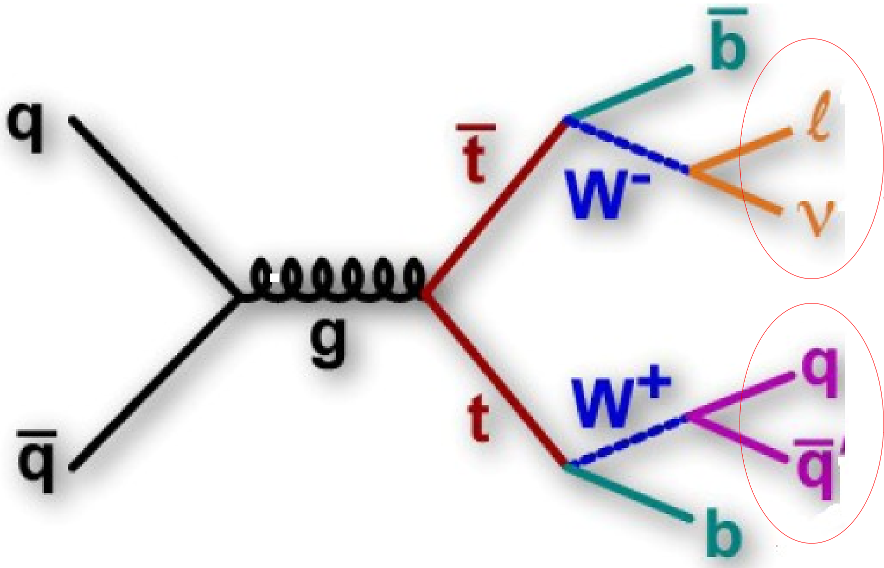
  - Both W's decay hadronically: “all hadronic channel”.
    - Huge backgrounds, high stats

Identifying $t\bar{t}$



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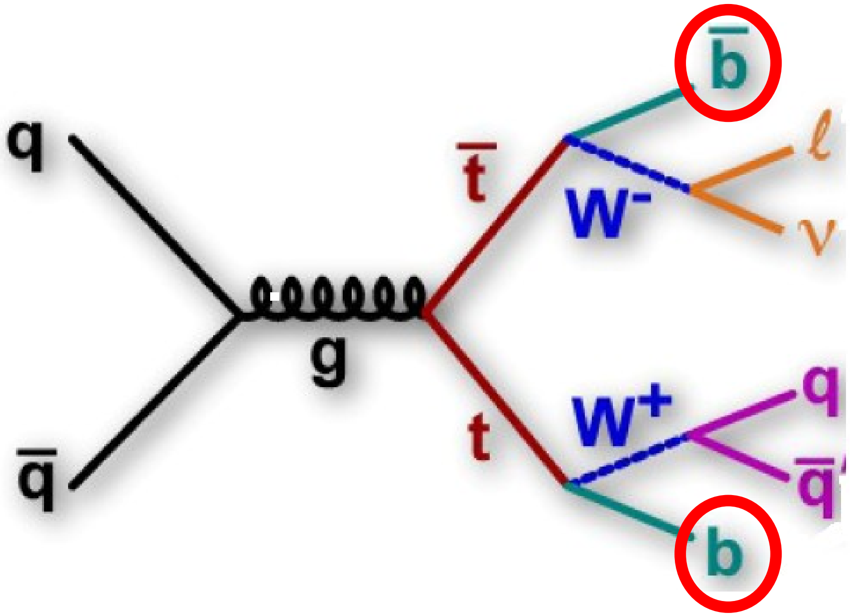
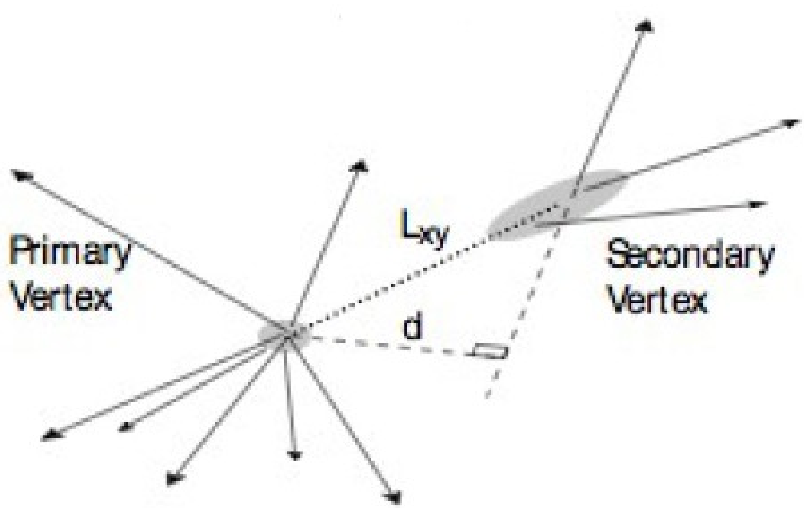
  - One of each: “lepton+jets channel”.
    - Low backgrounds, high stats

Identifying $t\bar{t}$



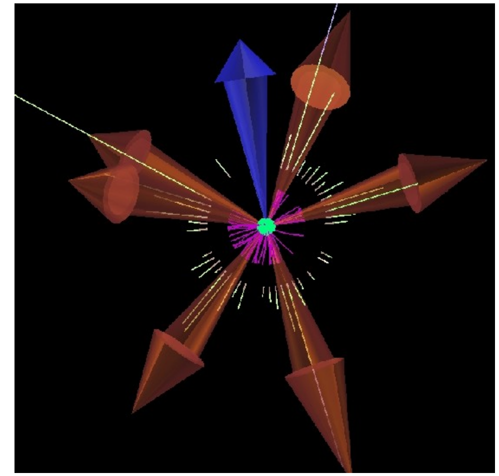


Can identify b's from displaced secondary vertex

- Tops decay to W's a b's
- Three very different types of mass analyses depending on W decay modes
  - Both W's decay leptonically: “dilepton channel”.
    - Tiny backgrounds, low stats
  - Both W's decay hadronically: “all hadronic channel”.
    - Huge backgrounds, high stats
  - One of each: “lepton+jets channel”.
    - Low backgrounds, high stats
- Identify b's (reduces background)
  - Use long b-lifetime: may travel many mm before decay
  - Use tracking to locate displaced vertex

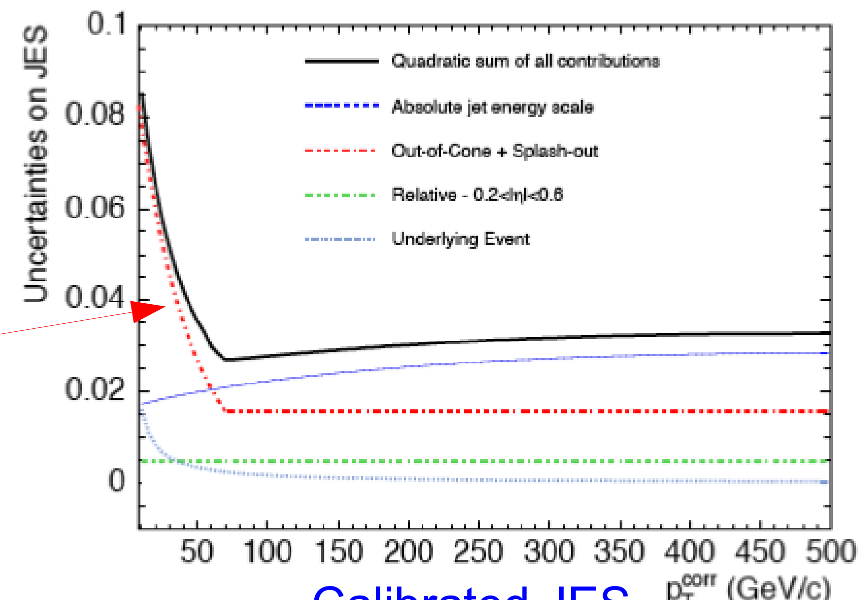
Determining the Mass

- Event reconstruction challenges:
  - Which partons came from which top and which W?



Which jets belong to which invariant mass?

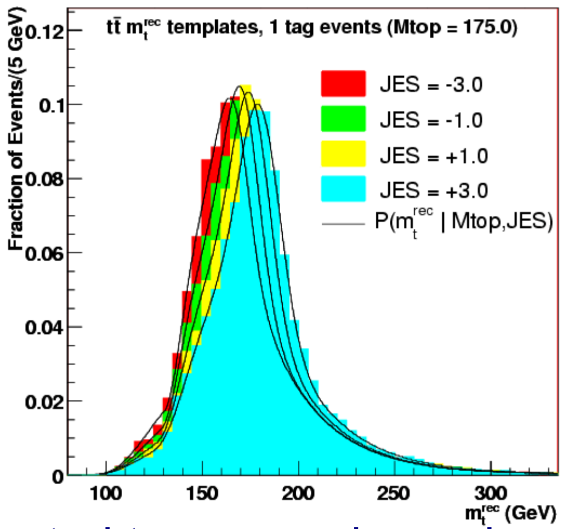
- Jet reconstruction challenges:
  - Have to measure energies of decay quarks to get top mass
    - But can't measure quarks directly, see spray of particles
    - Leads to many “Jet Energy Scale” (JES) uncertainties
      - Black: full uncertainty on quark energy
  - 3-4 GeV uncertainty on top mass



Calibrated JES Uncertainties

Controlling the JES Uncertainty

- Option 1: Use hadronic W decays
  - Assume all jets in event have same JES
    - Constrain JES to reconstruct proper W mass
    - Invariant top mass in simulation increases with JES
  - Obviously impossible in dilepton channel



Expected top mass depends on JES

Controlling the JES Uncertainty

- Option 1: Use hadronic W decays
  - Assume all jets in event have same JES
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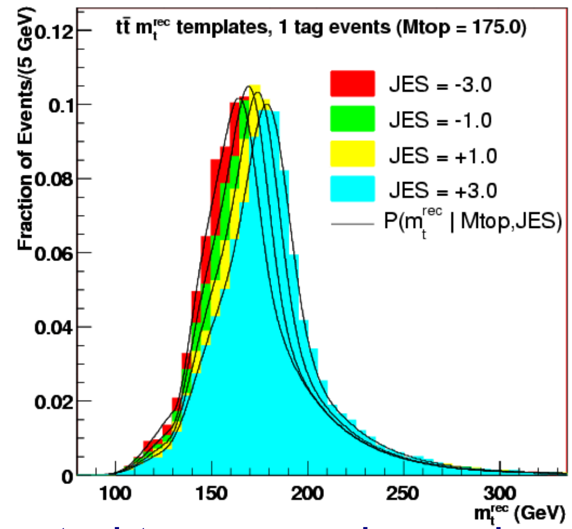
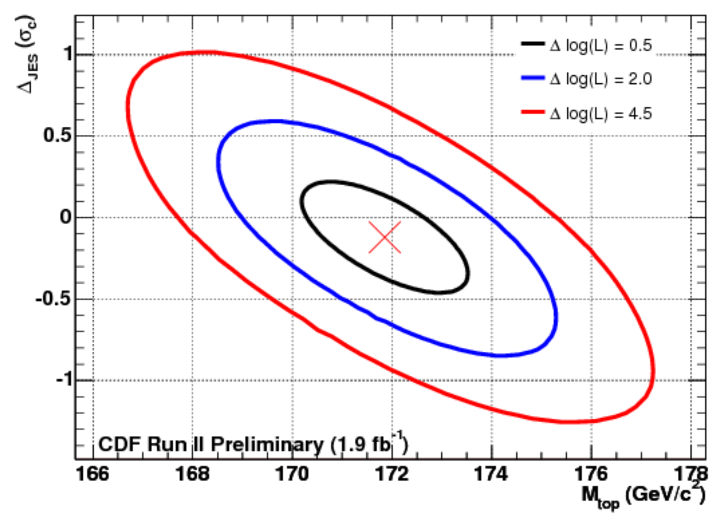


Expected top mass depends on JES

- Fit for JES and top mass simultaneously
  - JES uncertainty becomes statistical!
  - Caveat: left with residual systematics due to assuming same JES for all jets
    - Most top analysis do this, but JES still largest uncertainty on world average top mass



top mass vs JES simultaneous fit

Controlling the JES Uncertainty

- Option 2: don't use jet energy!
  - Decay length of b-tagged jets
  - Transverse momentum of leptons
- Evaluate top mass from mean decay length and mean lepton momentum
  - Plenty of stats at LHC: systematics are what are important
  - Decay length systematics limited by calibration of simulation to data
  - Lepton systematics limited by background modeling, simulation calibration, QCD radiation
    - Actively working on them

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

Decay Length

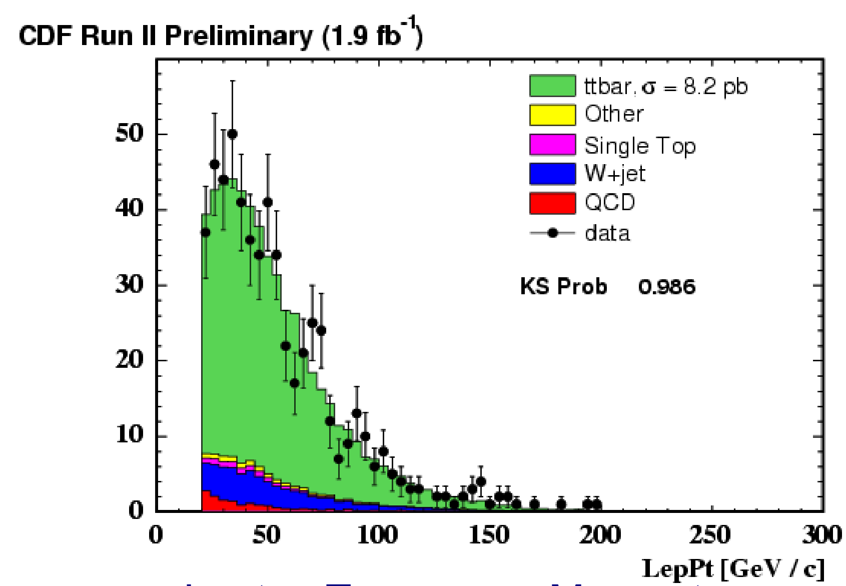
$$m_t = 176.7^{+10.0}_{-8.9}(stat) \pm 3.4(syst) GeV/c^2$$

Lepton Transverse Momentum

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

Combined decay length and lepton transverse momentum

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



Lepton Transverse Momentum

Template Based m_t

- One of two "standard" methods for measuring the top mass
  - Make probability distribution functions (templates) for signal and backgrounds
    - Fit data, integrating over all allowed jet and lepton combinations
  - Straightforward and reliable

Example: Signal chi[2] for CDF Lepton+Jets Template Fit

Measurement Constraints

Unclustered Energy Constraints

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

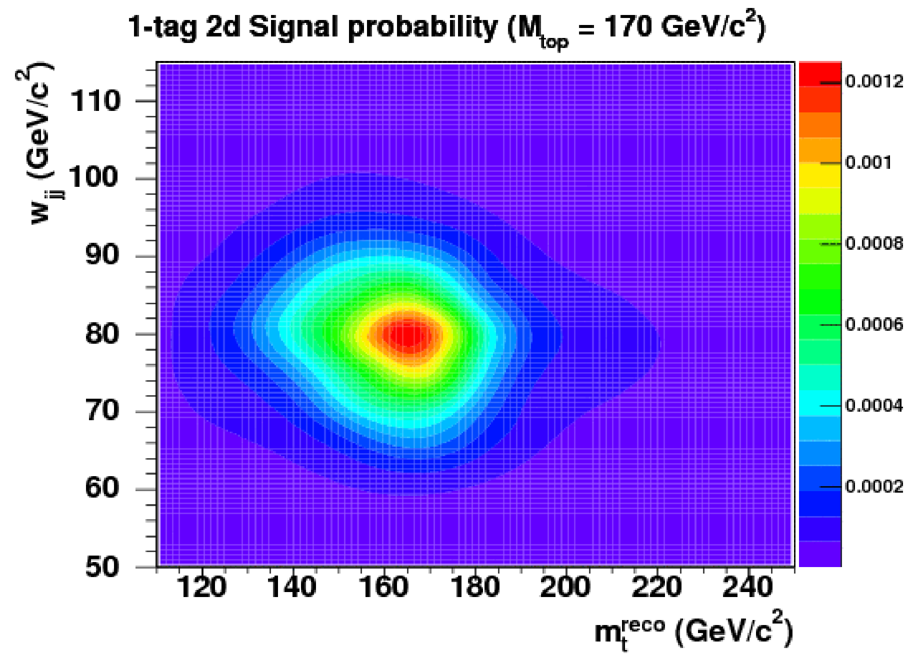
$$+ \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(M_{\ell\nu} - M_W)^2}{\Gamma_W^2} + \frac{(M_{bjj} - m_t^{\mathrm{reco}})^2}{\Gamma_t^2} + \frac{(M_{b\ell\nu} - m_t^{\mathrm{reco}})^2}{\Gamma_t^2}$$

m_W Constraints

m_t Constraints

L+J Template Method Results

- Number of background events extracted from direct fit
  - W+jet, QCD backgrounds largest
  - Constrained within uncertainties determined by cross section measurements
- Assign non b-tagged jets to W decay
  - In manner which best reproduces the W mass
- Dominant systematics:
  - Residual jet energy scale, behavior of *b*-jet (fragmentation, semileptonic fractions, etc)



Example of a template for $t\bar{t}$ signal (in 2D to Constrain JES)

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

$$m_t = 171.8 \pm 1.9(stat + JES) \pm 1.0(syst) GeV/c^2$$

Dilepton Template Method Results

- Dileptons channel differences
  - Much lower statistics and even smaller backgrounds
  - Underconstrained: two neutrinos you can't measure!
    - Integrate over all possible neutrino directions weighted by probability of consistency with observed objects

Dilepton Results (1.9 fb^{-1})

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

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

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

Template Systematics

- Dileptons channel differences
  - Much lower statistics and larger backgrounds
  - Underconstrained: two neutrinos you can't measure!
    - Integrate over all possible neutrino directions weighted by probability of consistency with observed objects
- Examples of systematics shown
  - Note large difference in jet energy scale sensitivity

Systematic	LJ	DIL	Combination
b-JES	0.6	0.5	0.6
Residual JES	0.5	3.5	0.5
ISR	0.3	0.4	0.4
FSR	0.2	0.5	0.2
PDFs	0.3	0.5	0.3
Generator	0.2	0.8	0.2
LJ bkgd shape	0.2	0.0	0.2
DIL bkgd shape	0.0	0.4	0.1
MC statistics	0.1	0.2	0.1
lepton energy scale	0.1	0.4	0.1
pileup	0.1	0.1	0.1
gg fraction	0.0	0.2	0.0
Combined	1.0	3.8	1.0

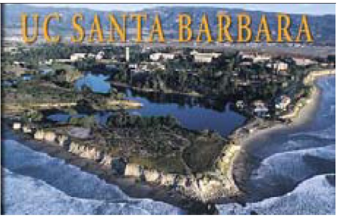
Systematics for these analyses

Dilepton Results (1.9 fb^{-1})

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

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

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



Matrix Element m_t

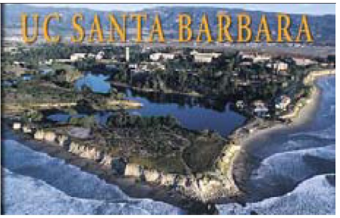
- Extract more information from each event
  - Find mass likelihood event by event based on theoretical Matrix Element calculation for signal/background

Signal Probability Proportional to:

$$L(\vec{y}|m_t, \Delta_{JES}) = \qquad |M(m_t, \vec{x})|^2$$

Top mass and JES Likelihood

"Matrix Element" (Probability Amplitude)



Matrix Element m_t

- Extract more information from each event
  - Find mass likelihood event by event based on theoretical Matrix Element calculation for signal/background
  - Based upon measured kinematics, x (and hypothesized, y)

Signal Probability Proportional to:

Probability of measured momenta, y, given x and JES

$$L(\vec{y}|m_t, \Delta_{JES}) = \qquad TF(\vec{y}|\vec{x}\Delta_{JES})|M(m_t, \vec{x})|^2$$

Top mass and JES Likelihood

“Matrix Element” (Probability Amplitude)

Matrix Element m_t

- Extract more information from each event
  - Find mass likelihood event by event based on theoretical Matrix Element calculation for signal/background
  - Based upon measured kinematics, x (and hypothesized, y)

Signal Probability Proportional to:

Probability of measured momenta, y, given x and JES

$$L(\vec{y}|m_t, \Delta_{JES}) = \frac{f(z_1)f(z_2)}{FF} TF(\vec{y}|\vec{x}\Delta_{JES})|M(m_t, \vec{x})|^2$$

Top mass and JES Likelihood

Probabilities of incoming momenta

"Matrix Element" (Probability Amplitude)

Matrix Element m_t

- Extract more information from each event
  - Find mass likelihood event by event based on theoretical Matrix Element calculation for signal/background
  - Based upon measured kinematics, x (and hypothesized, y)
  - Integrate over unknowns, sum over probability weighted parton associations.

Signal Probability Proportional to:

$$L(\vec{y}|m_t, \Delta_{JES}) = \sum_{i=1}^{24} \int w_i \frac{f(z_1)f(z_2)}{FF} TF(\vec{y}|\vec{x}\Delta_{JES})|M(m_t, \vec{x})|^2 dx$$

Integrate over kinematics

Probability of measured momenta, y, given x and JES

Top mass and JES Likelihood

Sum over parton combinations

Probabilities of incoming momenta

“Matrix Element” (Probability Amplitude)

Matrix Element m_t

- Extract more information from each event
  - Find mass likelihood event by event based on theoretical Matrix Element calculation for signal/background
  - Based upon measured kinematics, x (and hypothesized, y)
  - Integrate over unknowns, sum over probability weighted parton associations. And normalize.

Signal Probability Proportional to:

Normalizations

Integrate over kinematics

Probability of measured momenta, y, given x and JES

$$L(\vec{y}|m_t,\Delta_{JES}) = \frac{1}{N(m_t)}\frac{1}{A(m_t,\Delta_{JES})}\sum_{i=1}^{24}\int w_i \frac{f(z_1)f(z_2)}{FF} TF(\vec{y}|\vec{x}\Delta_{JES})|M(m_t,\vec{x})|^2 dx$$

Top mass and JES Likelihood

Sum over parton combinations

Probabilities of incoming momenta

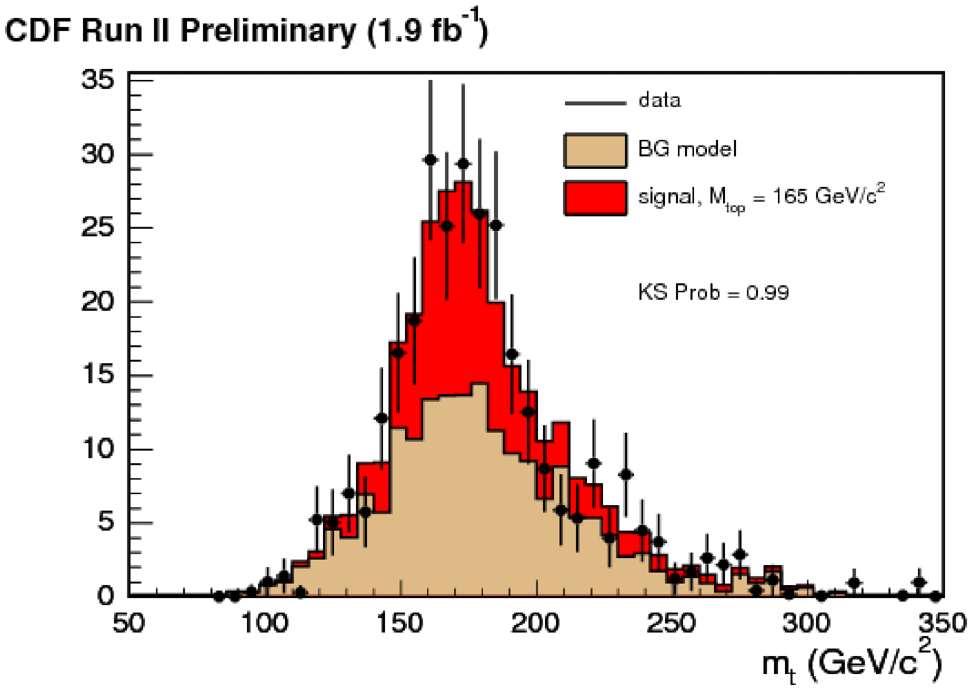
"Matrix Element" (Probability Amplitude)

Leads to very precise results (2.7 fb^{-1}): $m_t = 172.2 \pm 1.0(stat.) \pm 0.9(JES) \pm 1.0(syst) GeV/c^2$

Dominant Systematics: Residual jet energy scale, generator uncertainties

All Hadronic

- Special challenges in this channel
  - 1/400 S/B from base event selection
  - 6 factorial combinations of parton assignments
- Solutions:
  - Require two b-tags in event
  - Use neural network event shape selection (S/B: close to 1/1)
- Fit mass with signal, mismatched signal, background shapes



Final Mass Distribution

Results (1.9 fb^{-1})

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

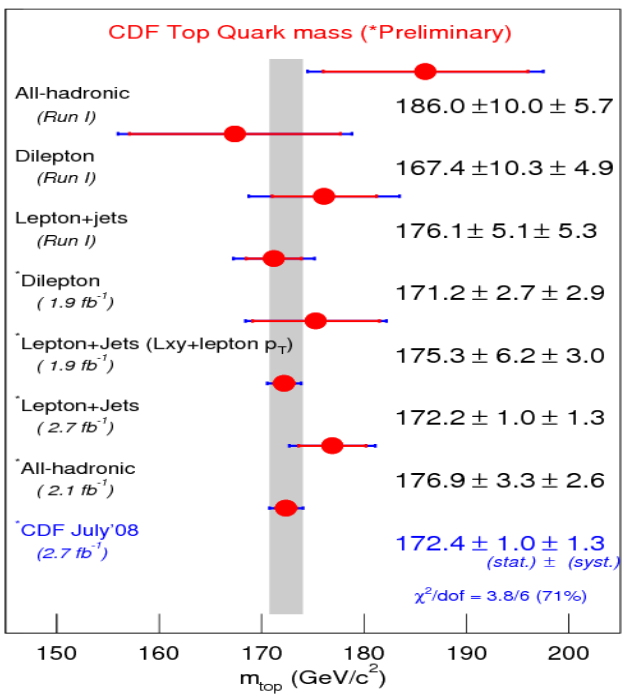
Residual jet energy scale, Pileup, Generator, QCD radiation, Background Modeling systematics all play a modest role

D0+CDF Combination

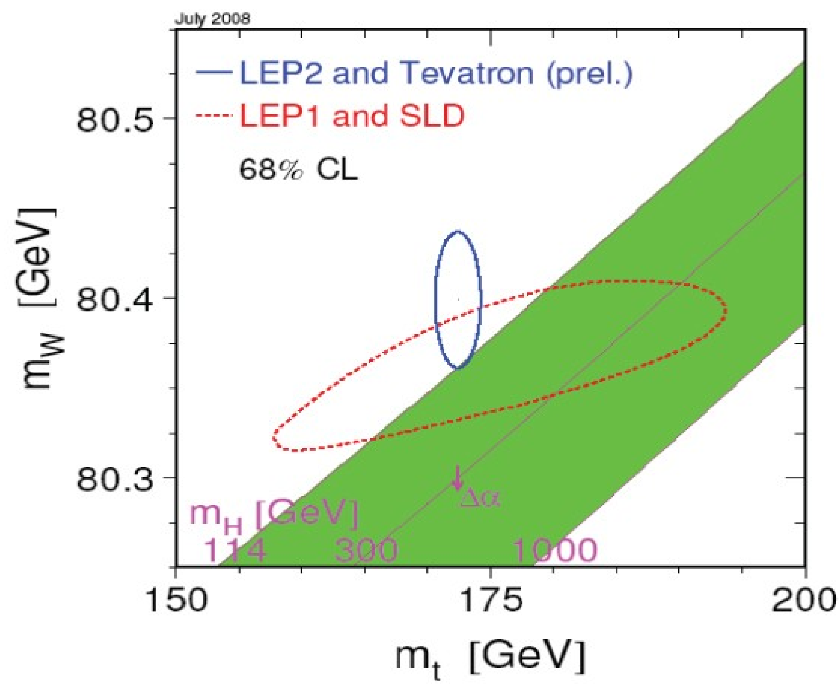
- Using Best Linear Unbiased Estimator technique
  - Correlations estimated between 12 types of uncertainties

$$m_t = 172.4 \pm 0.7(stat) \pm 1.0(syst) GeV/c^2$$

- Electroweak fits: SM Higgs mass now < 154 GeV/c^2 at 95% confidence level!
  - Counting LEP lower limit of M_H>114 GeV/c^2, upper limit rises to 185 GeV/c^2



CDF Mass Results in the Combination



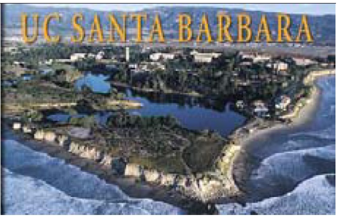
Associated Higgs Fit Results

Summary and Outlook

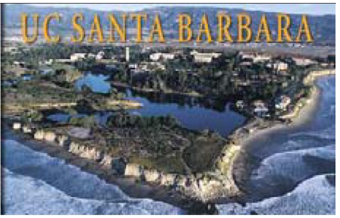
- CDF Top group has performed many high precision top mass measurements
  - Not enough time to talk about all of them
  - Some others in backup slides. For full details, see: http://www-cdf.fnal.gov/physics/new/top/public_mass.html

- Dominant jet energy scale systematic is coming under control
  - Using hadronic W mass calibration
  - Using alternate variables the LHC can ~completely eliminate it

- Work to be done
  - Must be especially careful with systematics in a high precision era
  - More sophisticated combination procedures
  - Limitations of Leading Order simulation must be properly considered

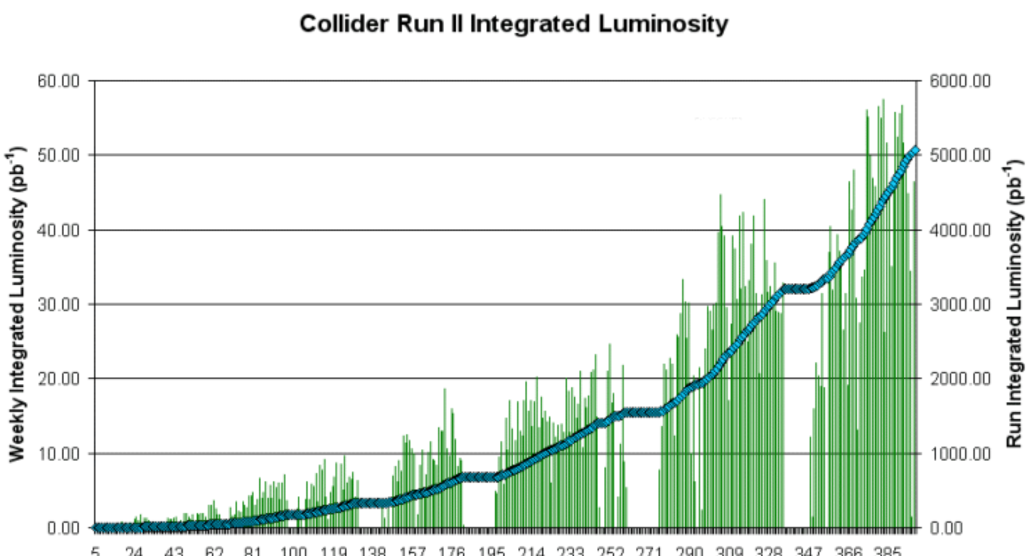


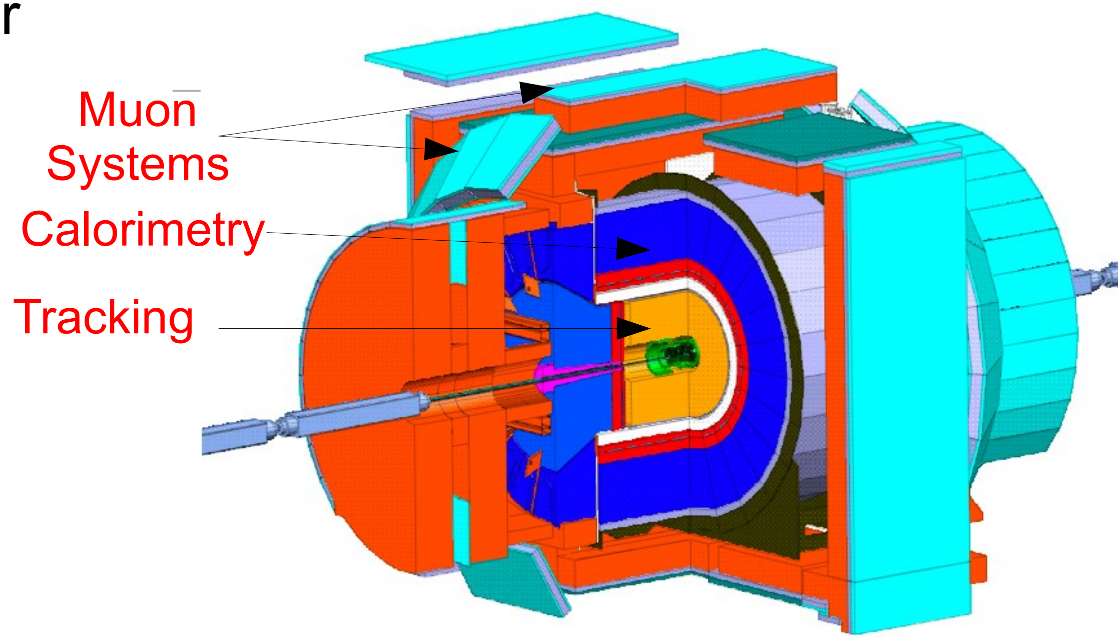
Backups



CDF

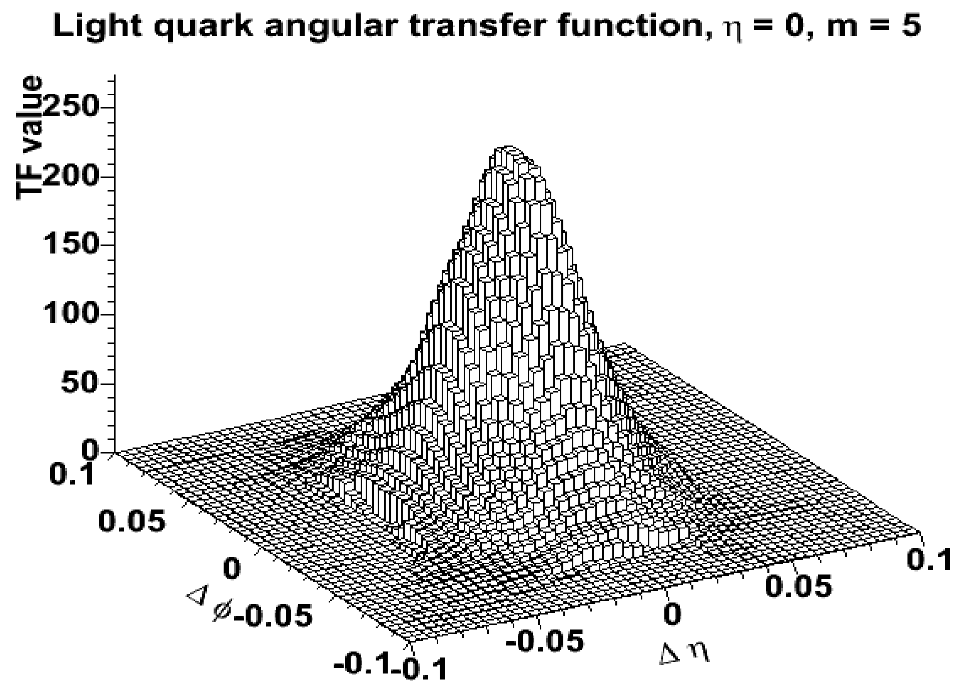
- Tevatron collides $p\bar{p}$ at world's highest energies
- Beam luminosity has been steadily improving
  - Total of ~5 fb^{-1} has been delivered to each detector
    - About 80% data acquisition efficiency
    - Recent analyses use about 3 fb^{-1}





Lepton + Jets Matrix Element

- Makes very few assumptions about kinematics
  - Integrates over 19 parameters representing probabilistic kinematic spreads
    - Top and W masses, boost of system, directions and masses of each jet
  - Specialized integration techniques to make this possible
- Neural network trained to distinguish signal and background
  - Background count determined from this output



Example integration variables: discrepancies in measured jet direction

Results (2.7 fb^{-1})

$$m_t = 172.2 \pm 1.0(stat.) \pm 0.9(JES) \pm 1.0(syst) GeV/c^2$$

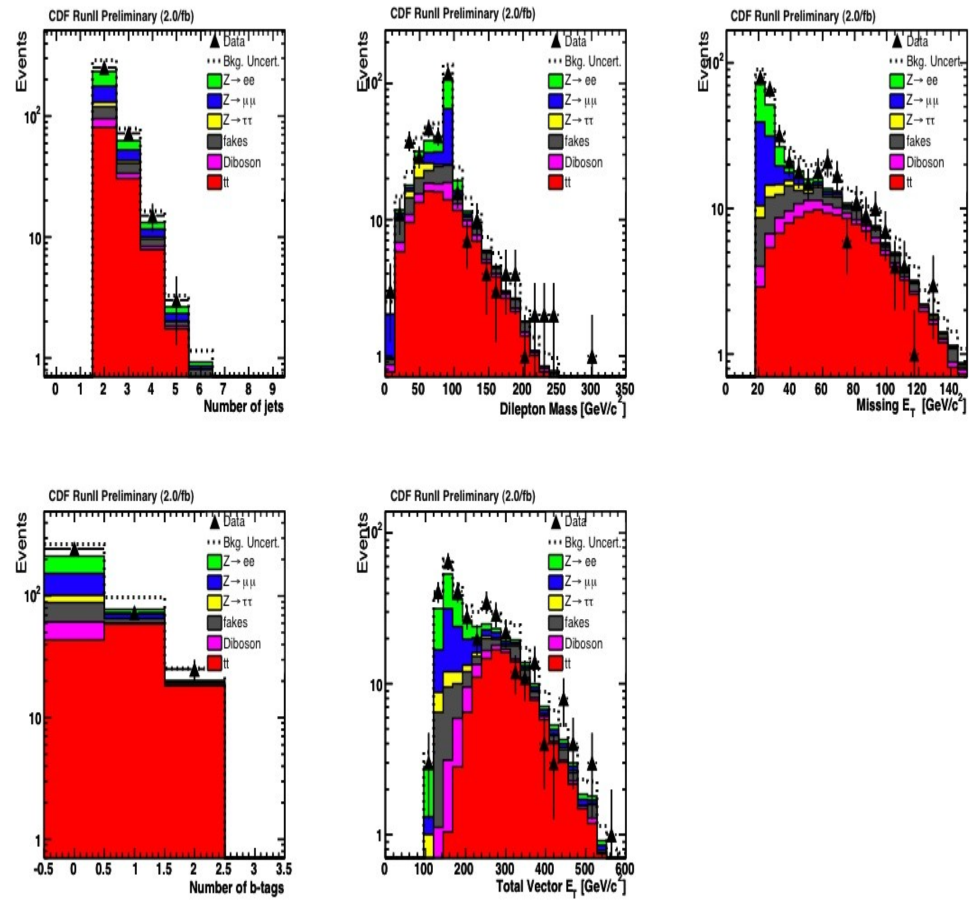
Dominant Systematics: Residual jet energy scale, generator uncertainties

Dilepton Matrix Element

- Mass likelihood evaluated for signal and bkg hypotheses simultaneously
  - Based on tagging information, priors (small p's), kinematic information (x), for signal and backgrounds, k

$$L(\#tag, \vec{x}, m_t) = P_{sig}(\vec{x}, m_t) p_{sig}(\#tag) + \sum_k P^k_{bg}(\vec{x}) p^k_{bg}(\#tag)$$

- Key feature: finds best neural network
  - Optimize NN for mass resolution, *not* signal purity. 20% improvement in statistical uncertainty.
    - First dilepton analysis to be limited by systematics instead of statistics!



NN Performance Validation

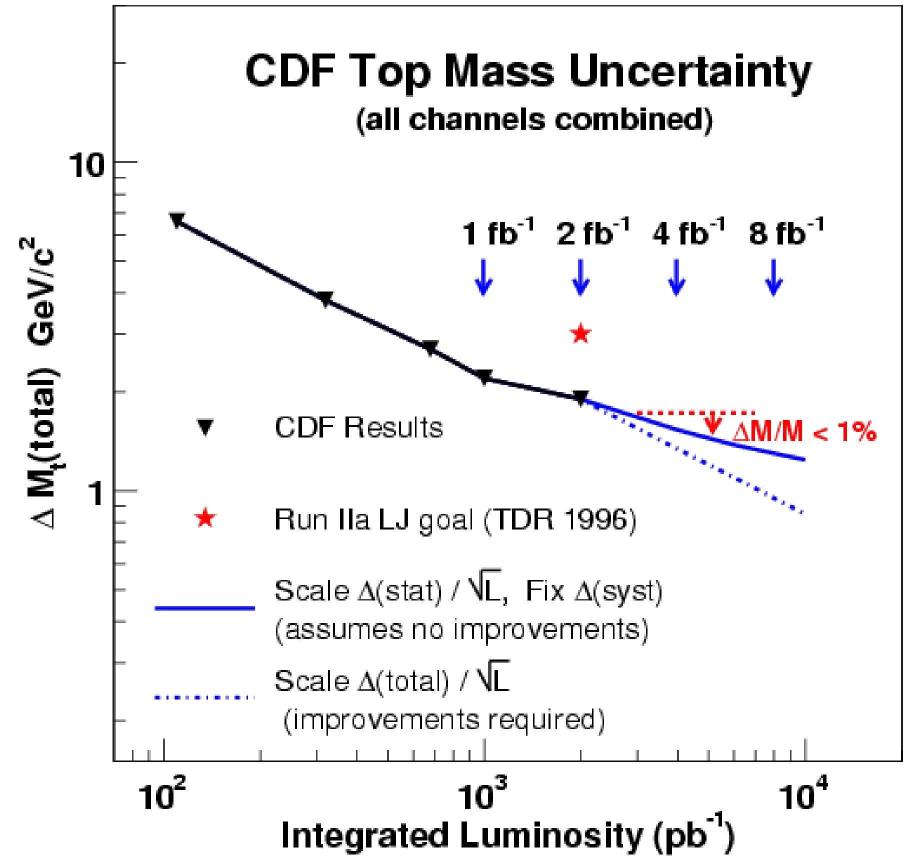
Results (1.9 fb^{-1})

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

Dominant Systematic: Jet energy scale

Future Improvements

- Mass results are now more systematically limited
  - But even without systematic improvements will have better than 1% precision at CDF
  - Work on improving systematics still ongoing
    - Already far ahead of where we projected we would be at this luminosity!



Past Expectations and Future M_T Projections at CDF