Mass Analysis of Top Quark Candidates in the DØ Experiment

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For the DØ Collaboration

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It's the Mass...

- Discovery of the top quark has been anticipated since the discovery of the τ and b-quark
- Measurement of the weak isospin of the b-quark confirms the need for the top quark in the Standard Model
- What is not known with any great certainty is the mass of the top quark!
- Determination of the top quark mass allows a test of the Standard Model prediction for the top quark production cross section
- Measurement of the top quark mass constrains Standard Model electro-weak radiative corrections
- Precision measurements of the top and W masses constrain the Higgs mass

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One Way to Measure M_t

- DØ has applied traditional kinematic fitting techniques to our sample of lepton + Jet events that pass our top selection criteria
- In principle, kinematic fitting allows one to solve for unmeasured quantities, improve the mass resolution, and help eliminate background by imposing energy, momentum, and mass constraints on an event
- In this talk:
  - » Making jets behave like π mesons
  - » Monte Carlo studies of fitting top events
  - » Monte Carlo and data studies of background processes
  - » Application of the fitting method to DØ data

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Jet Energy Corrections

- A jet is not a π meson!
  - » Partons radiate gluons
  - » Jet energy is sensitive to the clustering algorithm
  - » Jets cover a large detector area
  - » Jets can easily merge or split
  - » Need to calibrate the jet energy scale
- DØ jet energy corrections compensate for a variety of effects
  - » Calorimeter non-linearity for low energy hadrons
  - » Energy from the underlying event
  - » Uranium noise in the calorimeter
  - » Shower spreading in/out of jet cone
- DØ uses "γ" + jet events to determine corrections
  - » "γ" energy is well measured in calorimeter
  - » Require E_T balance along the photon direction
  - » Identical procedure applied to data and Monte Carlo
- Still missing: corrections for out-of-cone radiation

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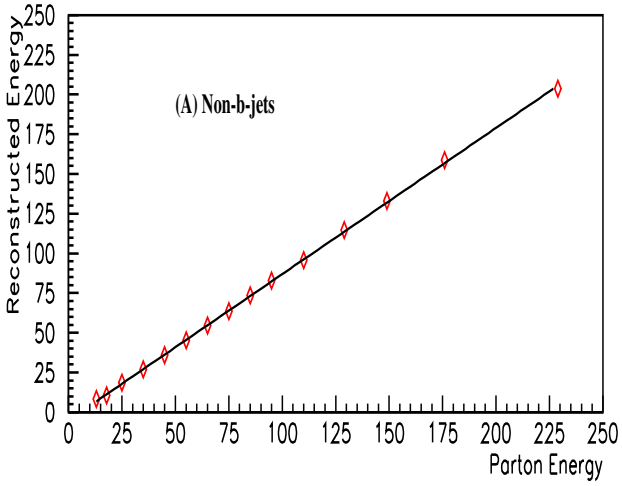
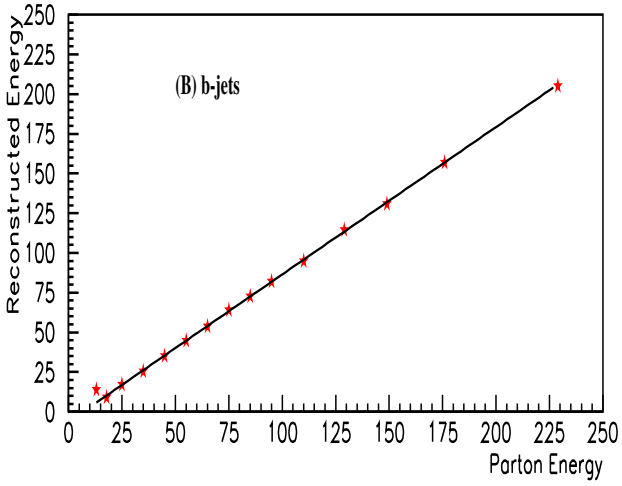
Out-of-Cone Corrections

- Additional jet energy corrections required to compensate for energy outside the jet cone
- Corrections determined by matching the reconstructed jet energy to the parton energy in a GEANT Monte Carlo of top production

- ~8% + 5 GeV correction required
- Corrections for light quarks and non-tagged b quarks are very similar





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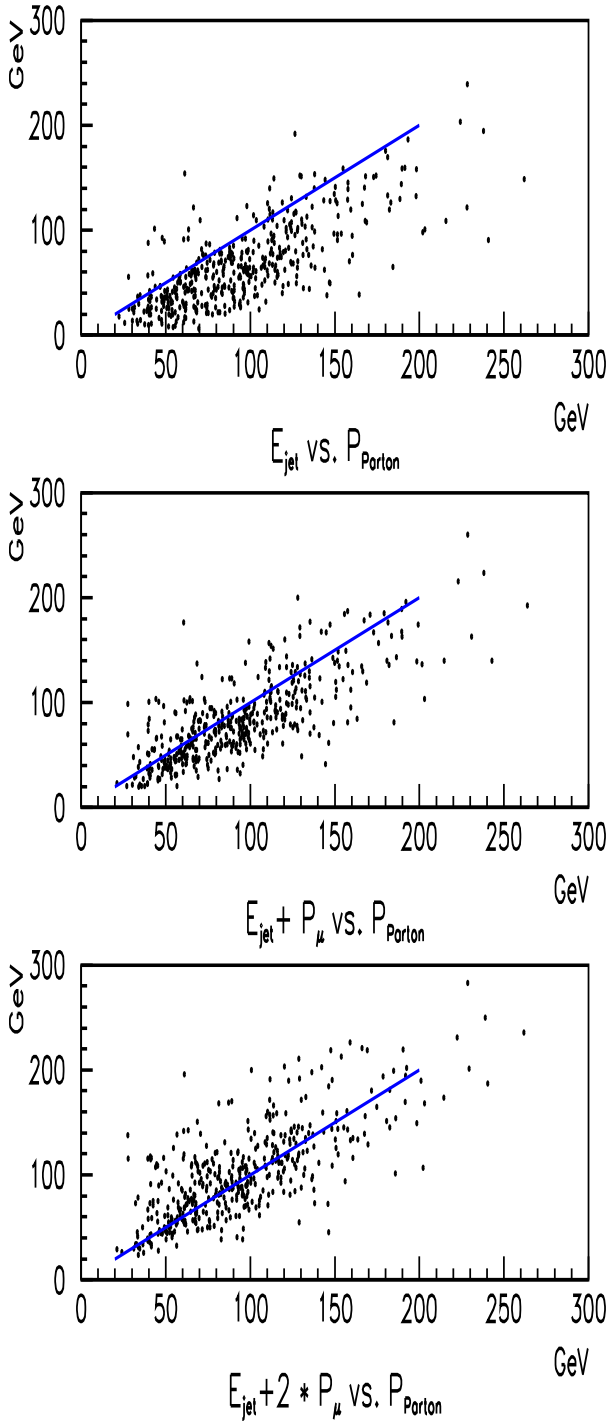
Corrections for Tagged Jets

- b-tagged jets require additional energy corrections to compensate for leptonic energy not measured by the calorimeter
- muon energy compensated for by adding muon p_T to jet E_T
- Additional correction for neutrino energy made by assuming muon and neutrino have similar energies



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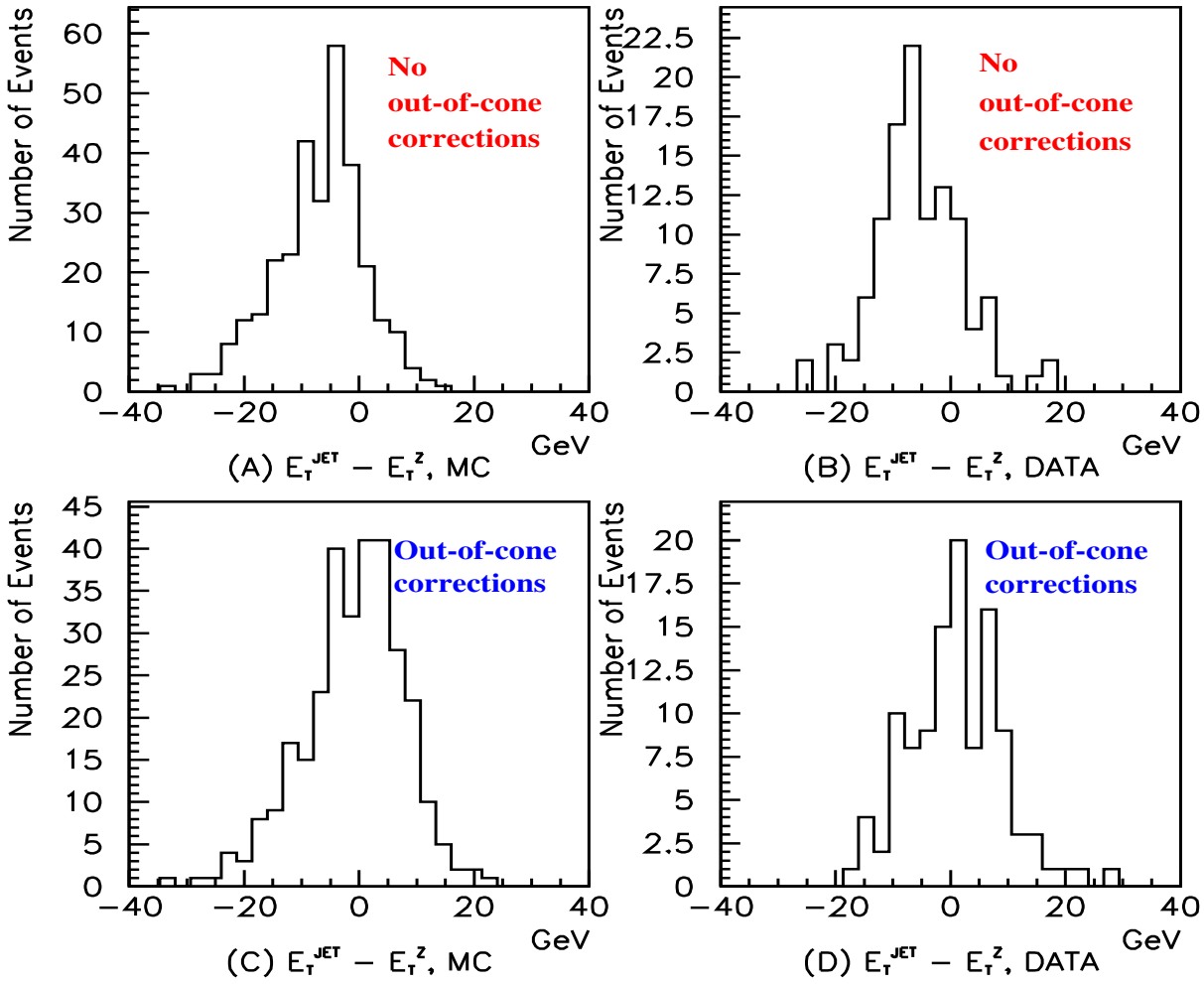
Fitting Z + Jet Events

- Z + Jet events allow test of using kinematic fitting techniques in a lepton + jet topology
- E_T balance achieved by applying out-of-cone corrections derived from top MC
- Pull distributions are well behaved



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Kinematic Fitting Procedure

- 2C Fitting Hypothesis:

$$\left.\begin{aligned} & p\bar{p} \to t + \bar{t} + X, \\ & t \to W^{+} b \to q\bar{q} b \\ & \bar{t} \to W^{-} \bar{b} \to l^{-} \upsilon \bar{b} \end{aligned}\right\} + \ c.c.$$

- Select events with same criteria as in the counting experiment
- Make all jet energy corrections
- Require ≥4 jets with E_T > 15 GeV and $|\eta|$ < 2.5
- Select 4 jets with highest E_T in $|\eta|$ < 2.5
- Perform kinematic fits for each jet combination (SQUAW and custom fitting programs used with similar results)
- Reject fits with χ^2 > 7 (2 DOF)

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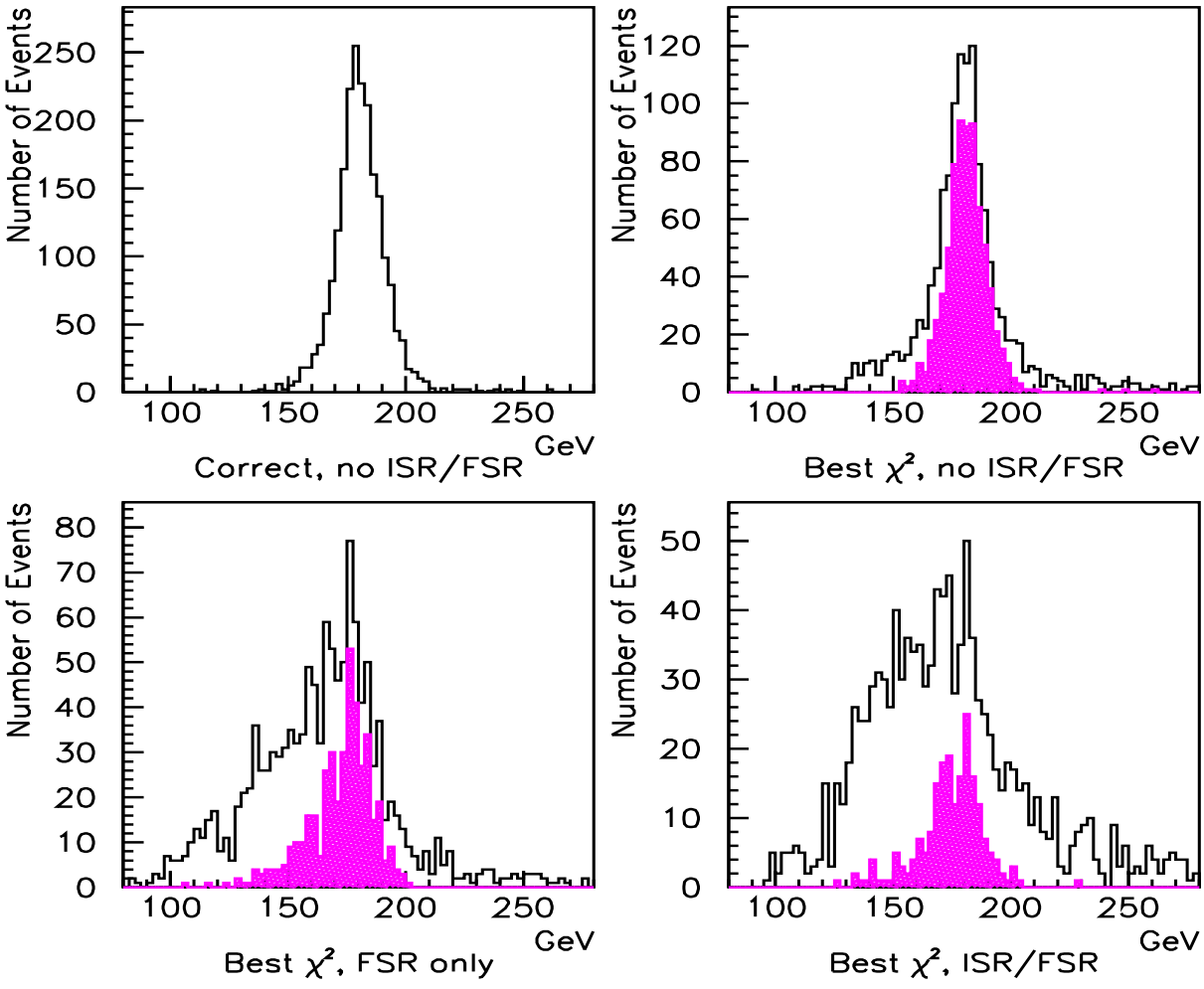
Effect of Jet Combinatorics

- Use smeared ISAJET partons to study effect of jet combinatorics (m_t=180 GeV)
- Initial and Final State Radiation (ISR/FSR) significantly broaden mass resolution
- Wrong combinations bias mass distribution



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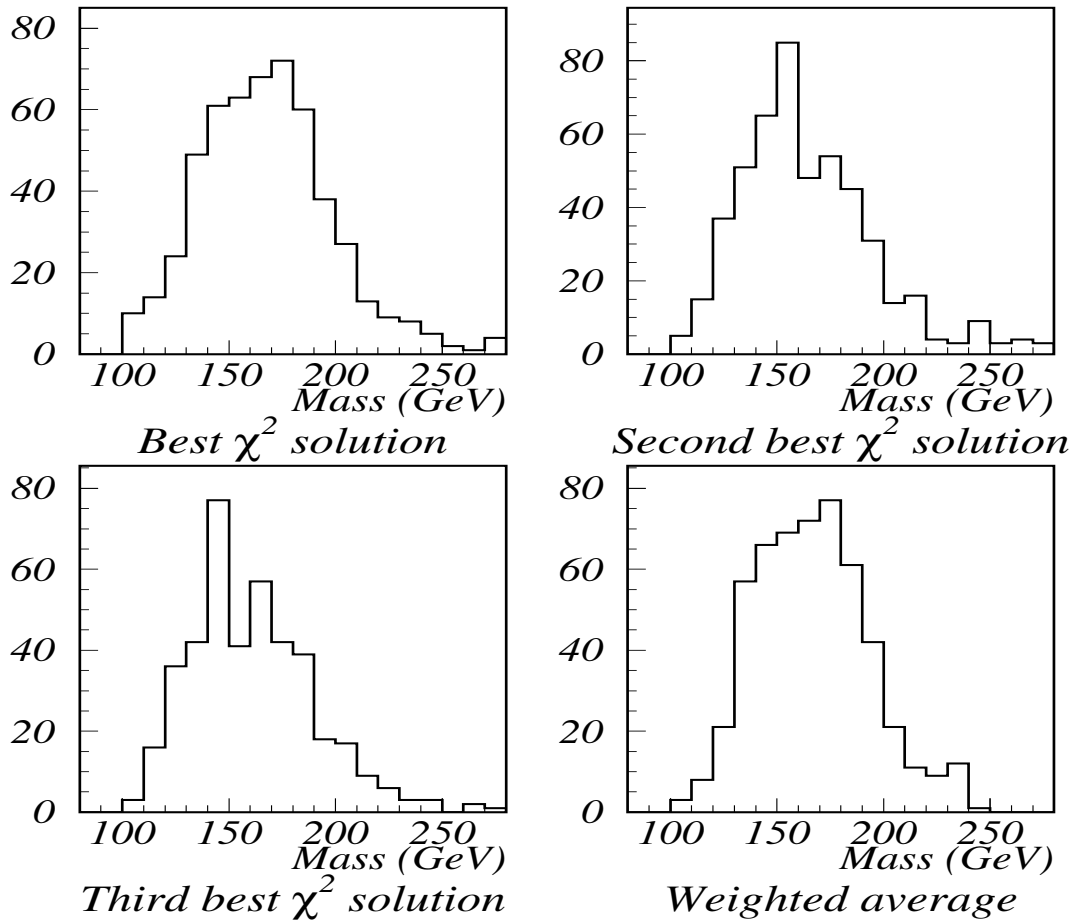
Averaging Fits with Similar χ^2

- Full GEANT detector simulation gives similar resolution to smeared parton model
- Often find multiple solutions with similar χ^2 and equally good mass resolution
- Mass resolution improved by taking χ^2 weighted average of three best fits (χ^2 <7)



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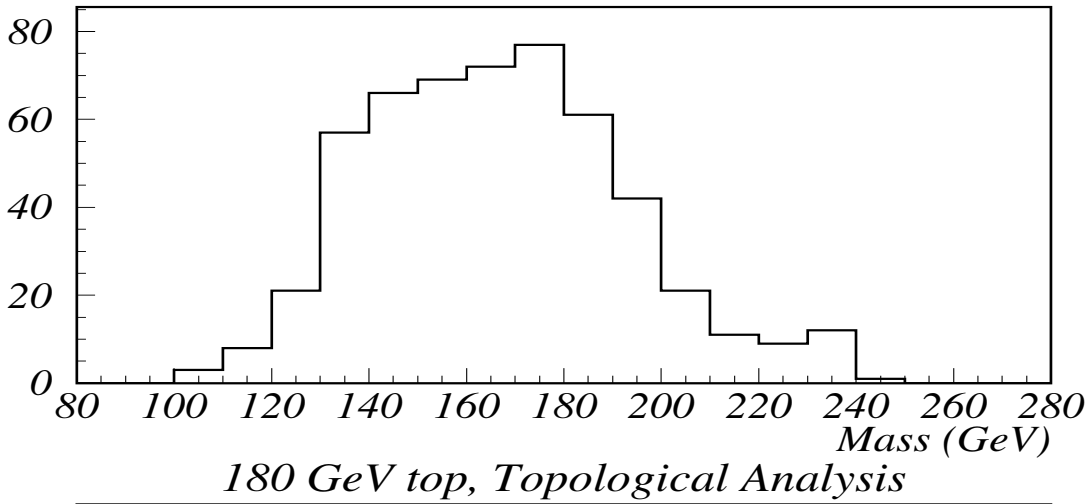
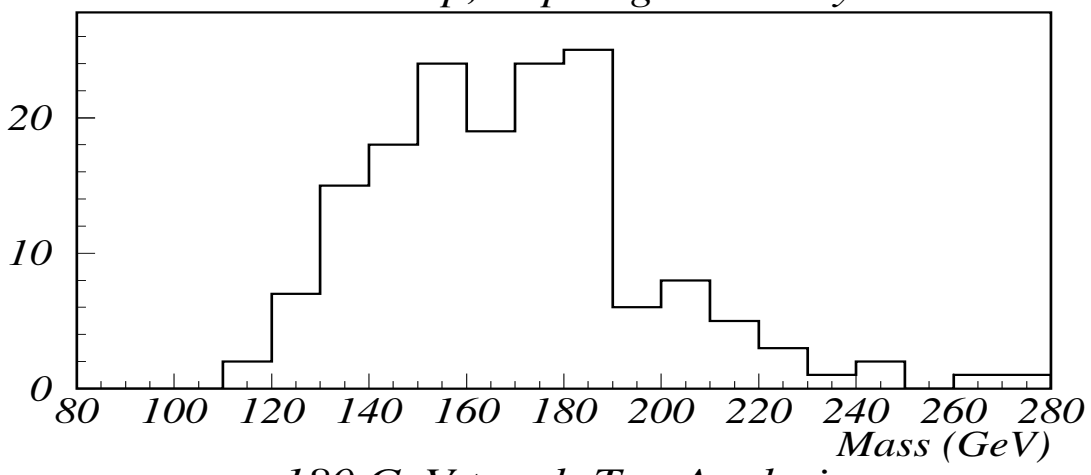
Resolution in b-tag Channels

- If an event has a b-tag, the tagged jet is required to be a b-quark in the kinematic fit
- Similar resolution observed in tagged and non-tagged channels



180 GeV top, Topological Analysis



180 GeV top, b-Tag Analysis

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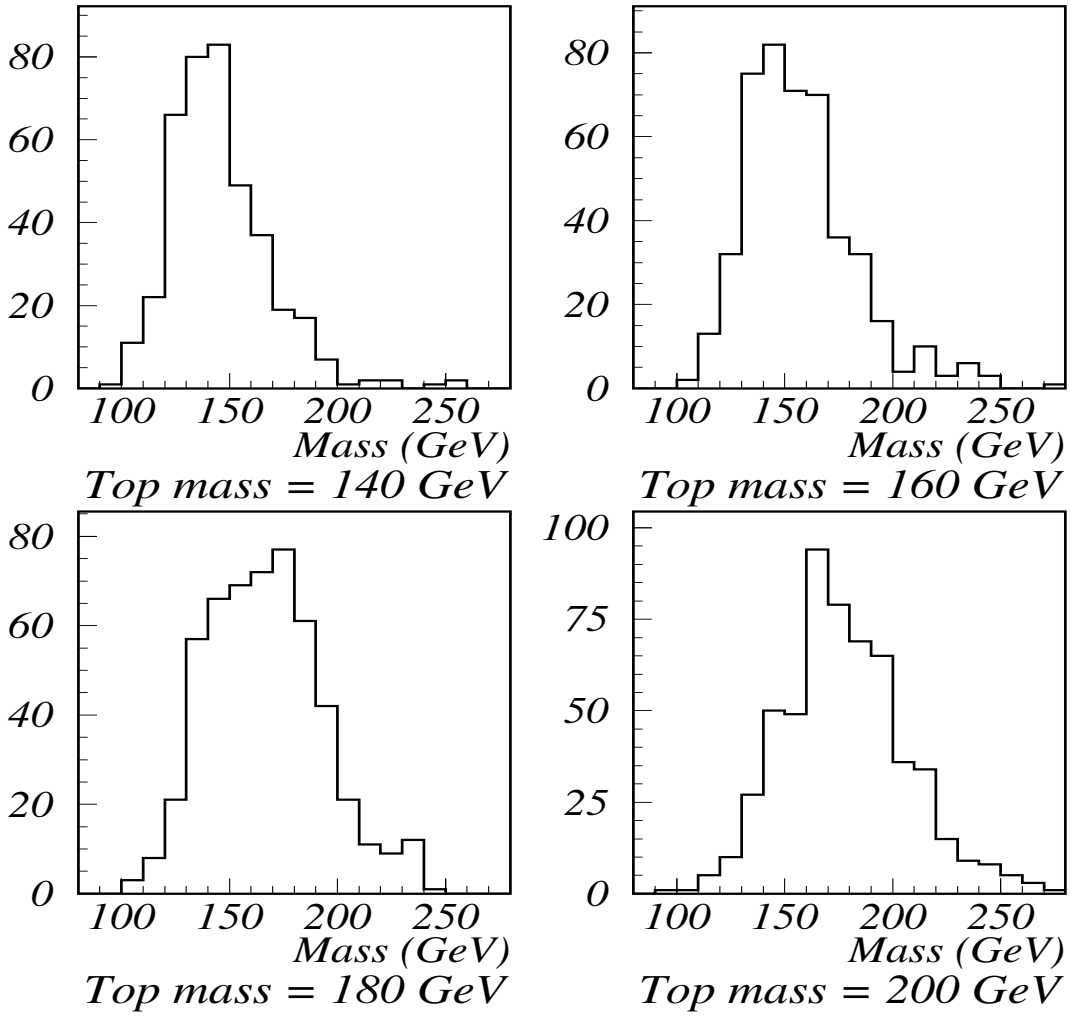
Top Resolution Functions

- Kinematic fitting procedure applied to ISAJET Monte Carlo top events with full GEANT detector simulation
- Smoothing algorithm applied to eliminate statistical fluctuations



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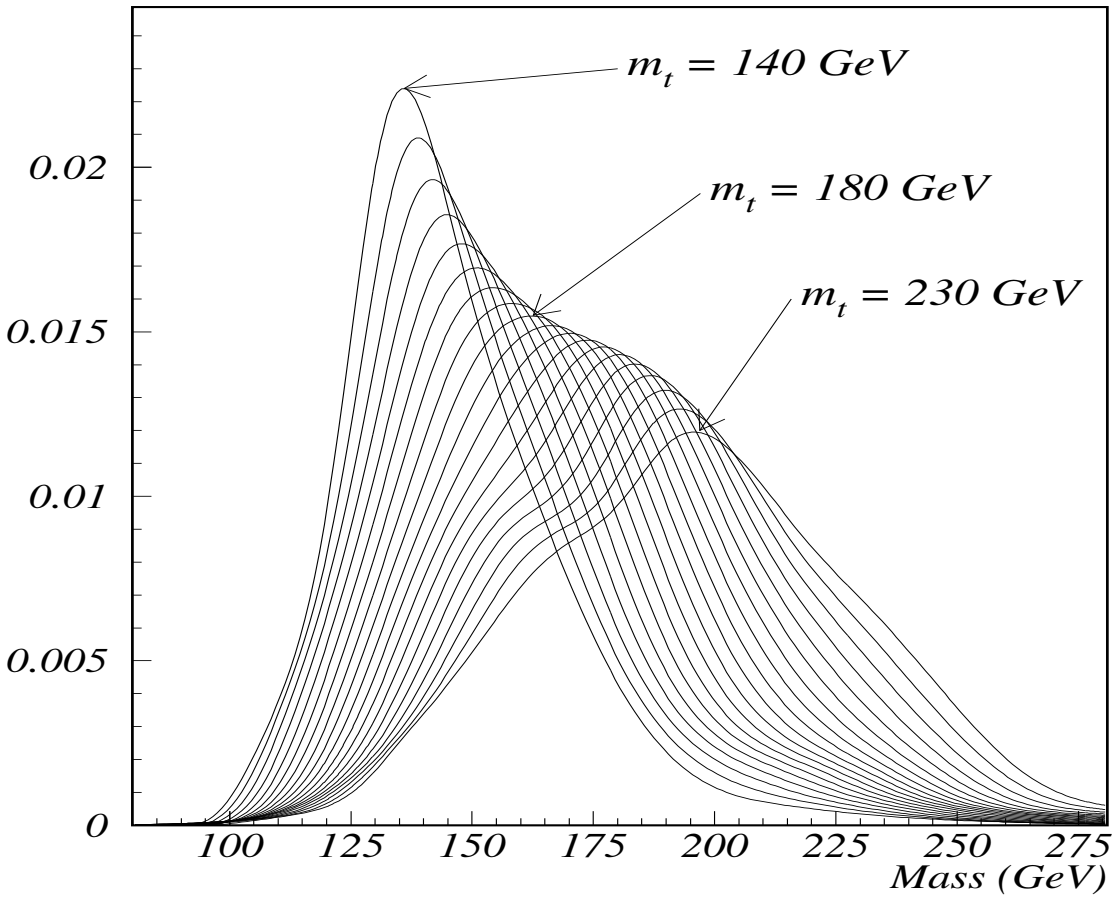
Interpolation Procedure

- Continuous family of resolution curves obtained by interpolating smoothing parameters between MC samples
- Resolution functions obtained for each of the four lepton + jet channels (e + jet shown below)



Interpolated resolution functions for e + jets

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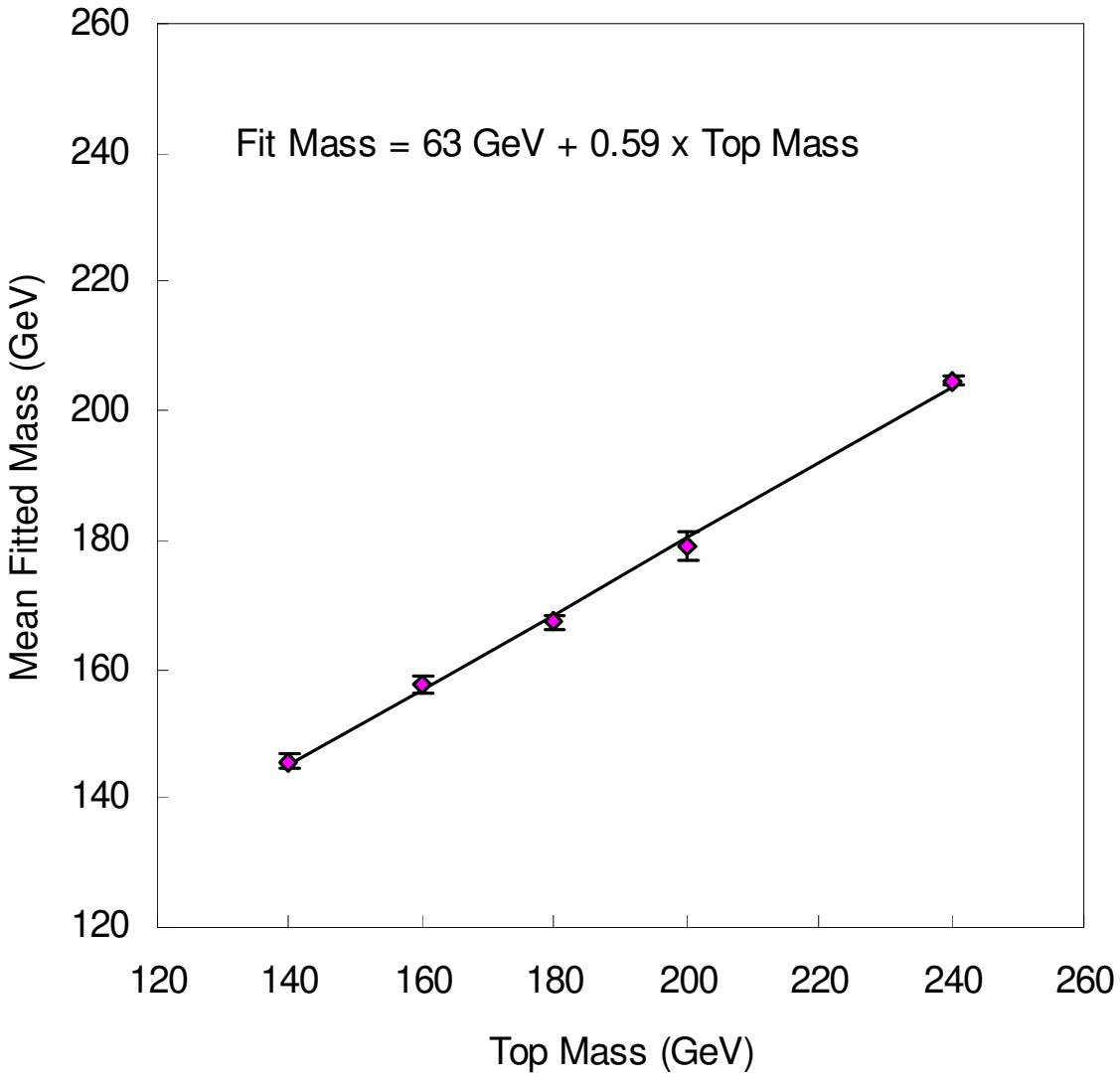
Bias in Reconstructed Mass

- Wrong jet combinations lead to a bias in the mean fitted mass



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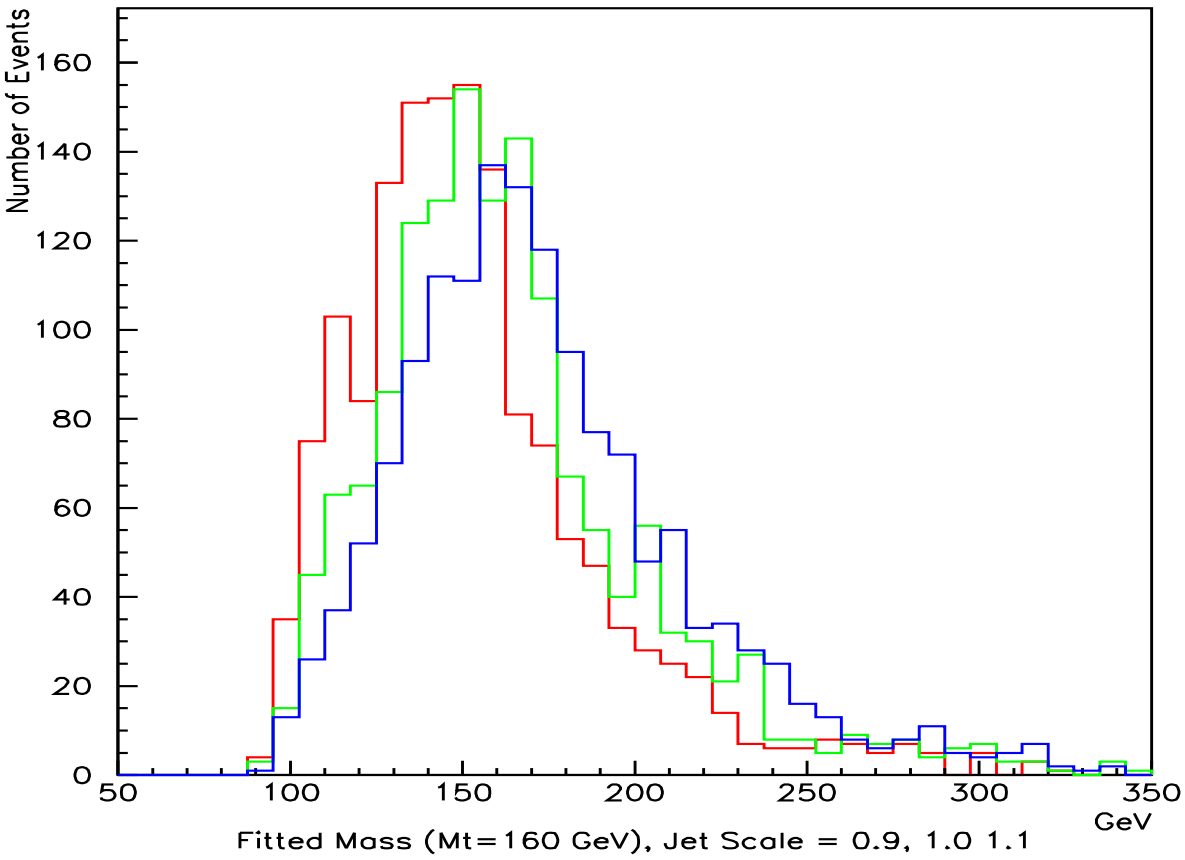
Jet Energy Scale Uncertainty

- Error in energy scale estimated to be less than 10% from consistency of Z + Jet fits in data and Monte Carlo
- Effect on top mass estimated by scaling jet energies by ±10%
- Observed shift in mass peak leads to 11% systematic uncertainty in top mass scale



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What about the Background?

- Understanding the mass distribution of the non-top background is essential if we are to distinguish top from background
- W + Jets and QCD multi-jets with a misidentified lepton are the principle backgrounds in our candidate sample
- DØ uses the VECBOS* Monte Carlo program to generate W + n-Jet partons
  - * W. Giele, E. Glover, and D. Kosower, Nucl. Phys. **B403**, 633 (1993)
- ISAJET is used to further evolve and fragment the VECBOS partons
  - » This procedure reproduces the observed jet multiplicity distribution and b-tagging rate
  - » ISAJET evolution could conceivably impact VECBOS kinematic distributions
- The QCD background is relatively small and is found to have kinematics similar to W + Jets

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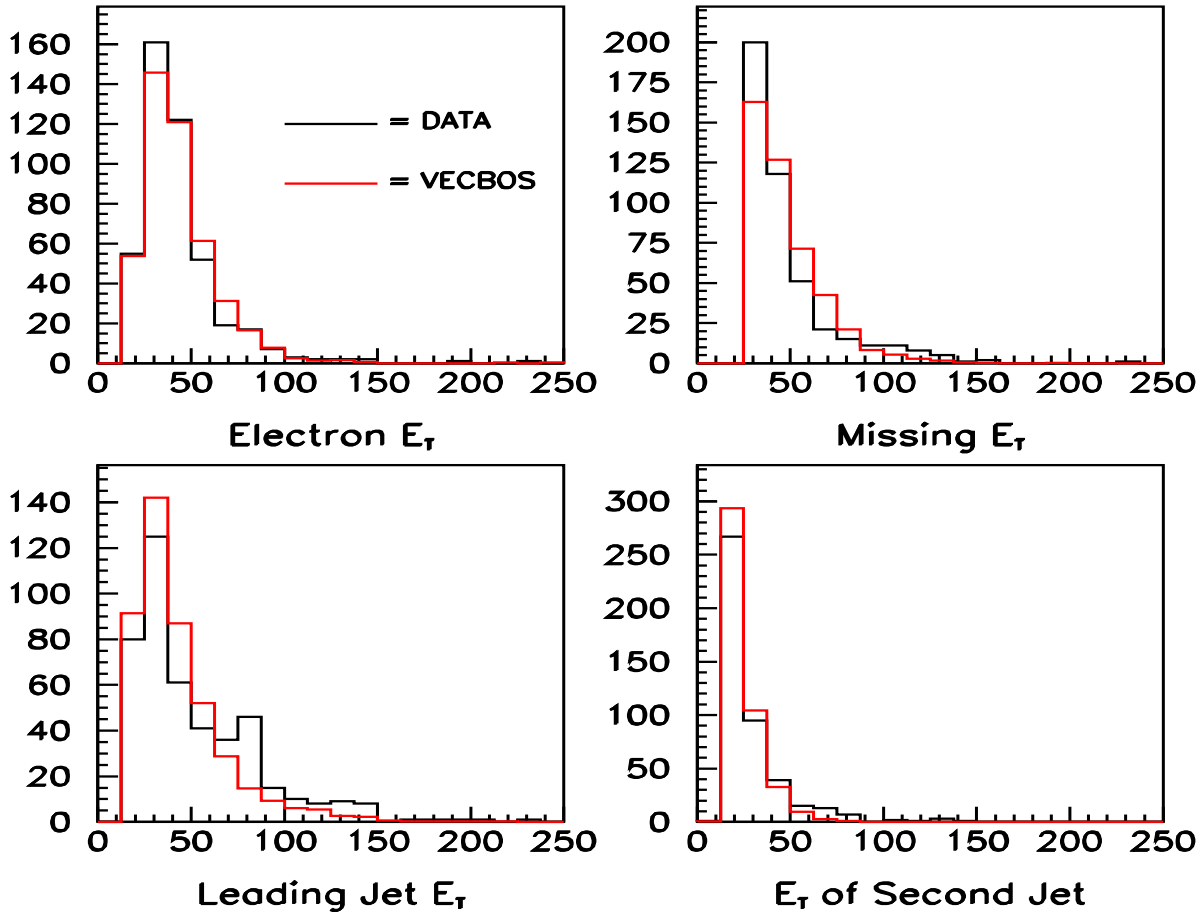
Study of W + ≥2 Jet Events

- Standard DØ e + Jet selection criteria except for topological cuts (A, H_T, N_{jet})
- Lepton kinematics in good agreement with VECBOS predictions
- Jet E_T spectrum is somewhat harder than predicted by VECBOS



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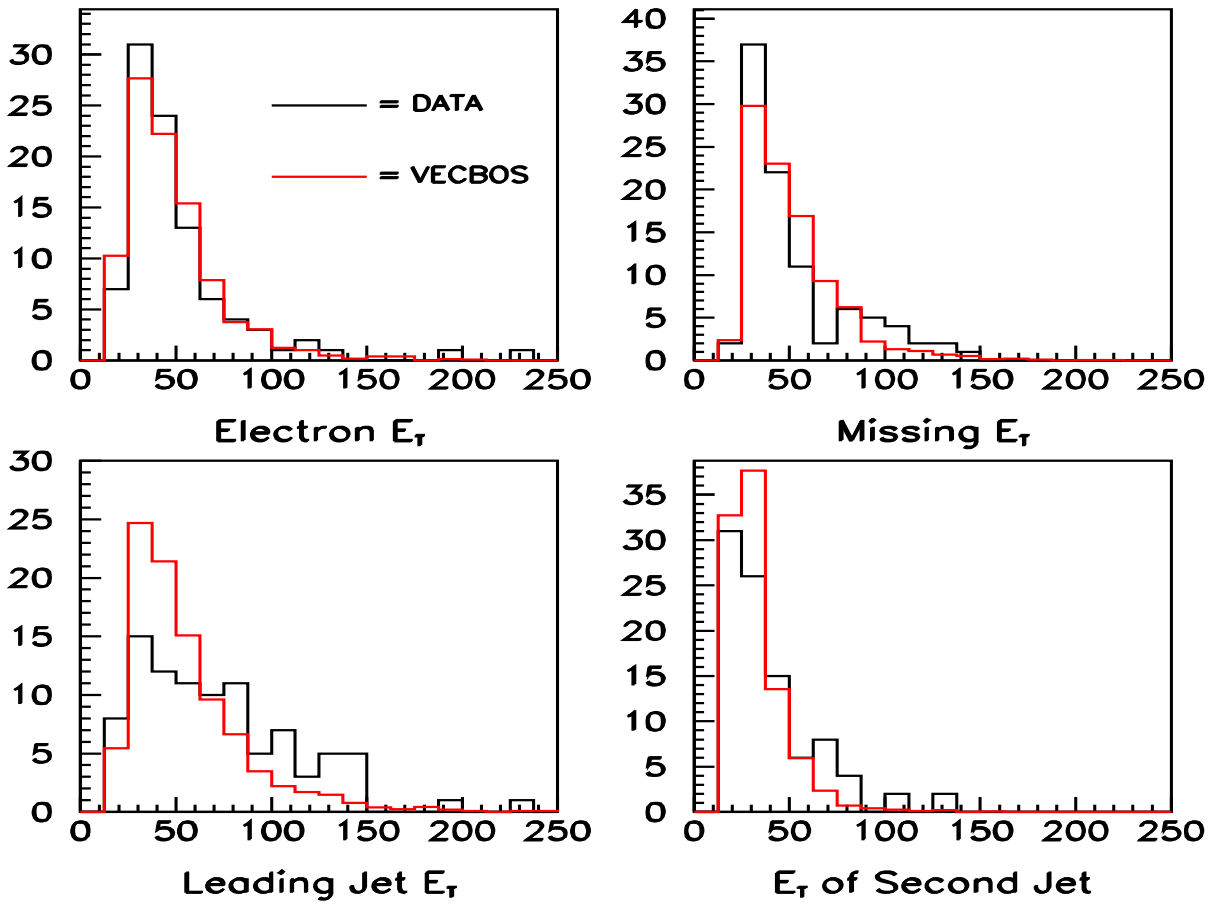
Study of W + ≥3 Jet Events

- Lepton kinematics in good agreement with VECBOS prediction
- Leading jet E_T is substantially harder than VECBOS prediction
- Top contribution is small given DØ's top cross section



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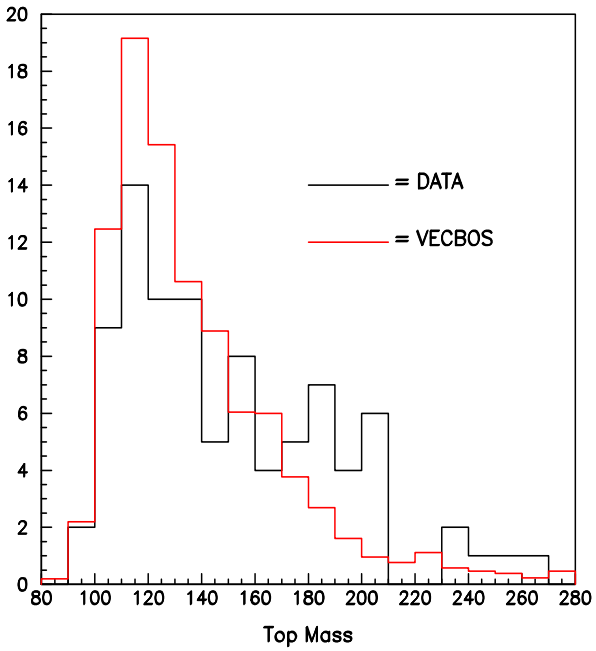
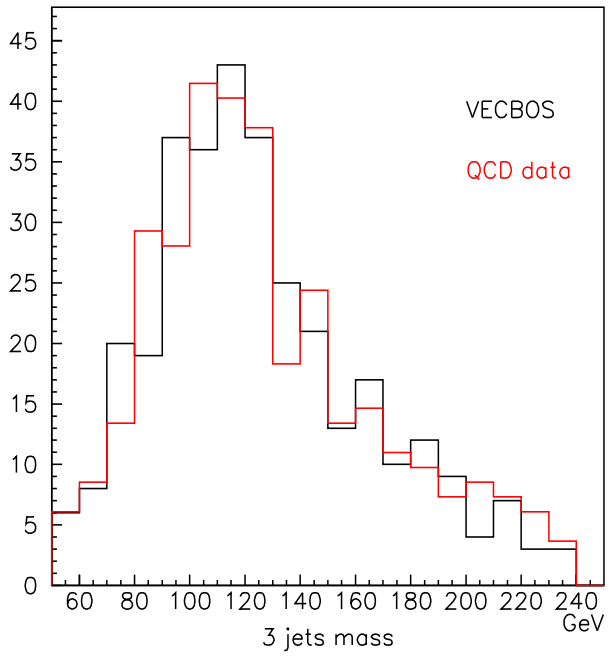
Mass Analysis of Background

- Fit e + ≥3 Jet events to top hypothesis
  - » Use 3 leading jets, assume a jet from W decay is lost
  - » Model p_T of $t\bar{t}$ system to yield 1C "fit" for top mass
  - » Exclude events passing A - H_T cut to reduce top
  - » VECBOS underestimates number of high mass events
- Examine 3 jet mass from QCD events
  - » Select QCD "fake electron" + jet events
  - » Assume highest two E_T jets are b quarks, assign the b quark such that top masses are most nearly equal
  - » Mass distribution of hadronic 3-jet mass in QCD events is generally similar to VECBOS





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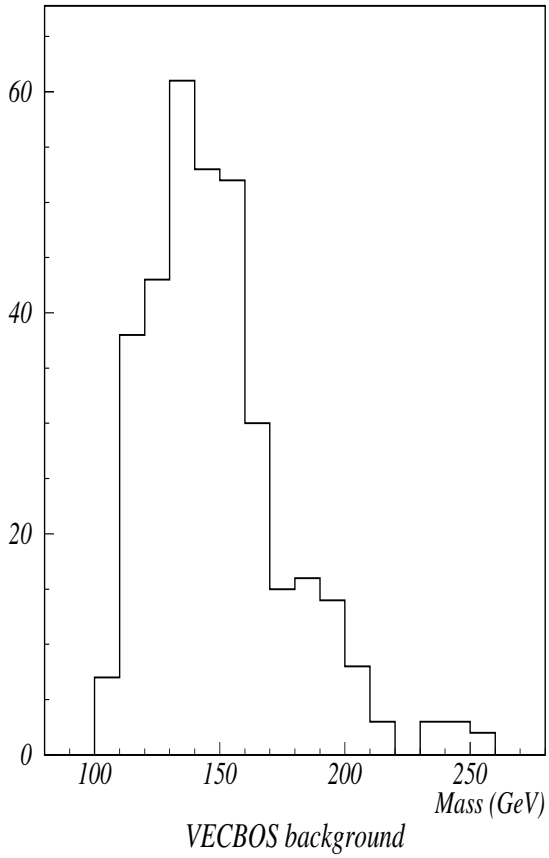
Background Mass Distribution

- Apply all event selection cuts and require at least 4 jets with $E_T > 15$ GeV
- Assume VECBOS models W + Jet and QCD background mass distributions
- Discrepancy between VECBOS and data in the 3-jet mass fits is parameterized by a cubic polynomial correction factor
- Use this correction factor to help evaluate potential systematic errors in background shape



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Extracting the Top Mass

- Use a maximum likelihood fit to extract the top mass from a mass distribution for a mixture of signal and background

$$L = e^{-(n_b - \langle n_b \rangle)^2 / 2\sigma^2} \frac{(n_s + n_b)^N}{N!} e^{-(n_s + n_b)} \prod_i \frac{n_s f_s(m_t, m_i) + n_b f_b(m_i)}{n_s + n_b}$$

- Fit Quantities:
  - » n_s, the expected number of signal events
  - » n_b, the expected number of background events
  - » m_t, the top mass
- f_s is the normalized top resolution function
  - » top resolution function obtained by weighting each channel by its efficiency × Branching Ratio
- f_b is the normalized background shape
  - » background shape function obtained by weighting each channel according to its expected background
- $\langle n_b \rangle$ is the nominal background
  - » background in the counting experiment corrected for the efficiency to pass the kinematic fitting procedure

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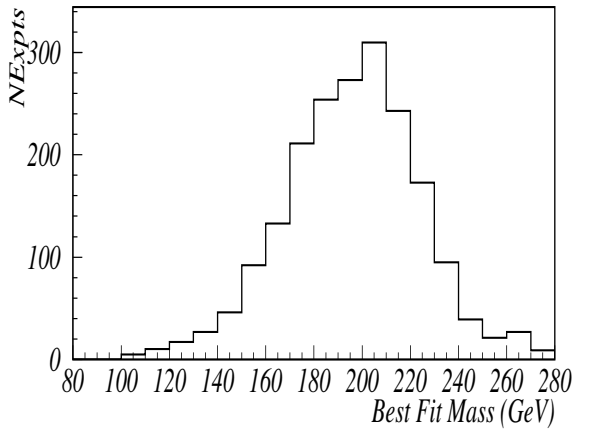
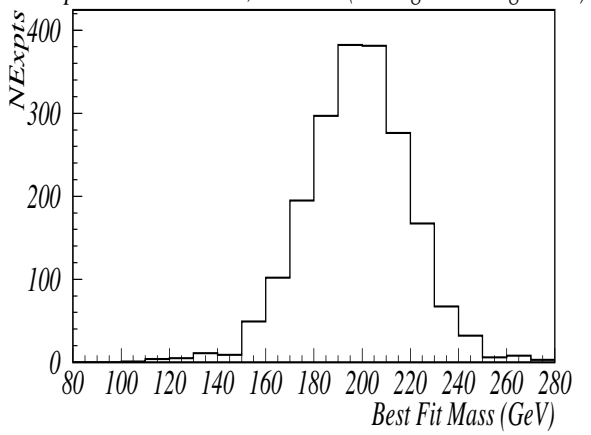
MC Test of Mass Analysis

- Generate an ensemble of Monte Carlo experiments with a fixed sample size and signal:background ratio
- Perform kinematic fits on events in each experiment and apply likelihood fitting technique to determine best fit mass values
- Best fit masses are distributed about generated top mass



Top mass = 200 GeV, N = 10 (1:1 signal:background)



Top mass = 200 GeV, N = 20 (1:1 signal:background)

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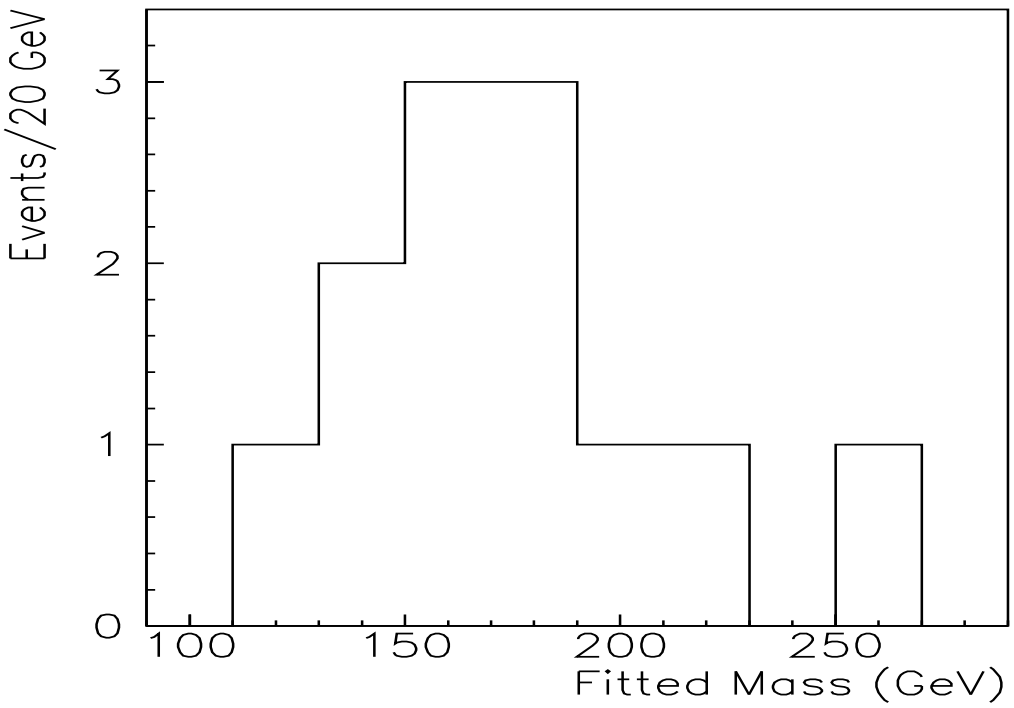
Kinematic Fitting of Data

- Apply kinematic fitting procedure to 16 candidate lepton + jet events in our top candidate sample
- Good fits found for 12 candidates
  - » 3 b-tag events have only 3 jets
  - » 1 b-tag event has no good fits when we require the tagged jet to be a b-quark
  - » Good fits for 4 tagged, 8 un-tagged events
- Candidates are broadly distributed in mass



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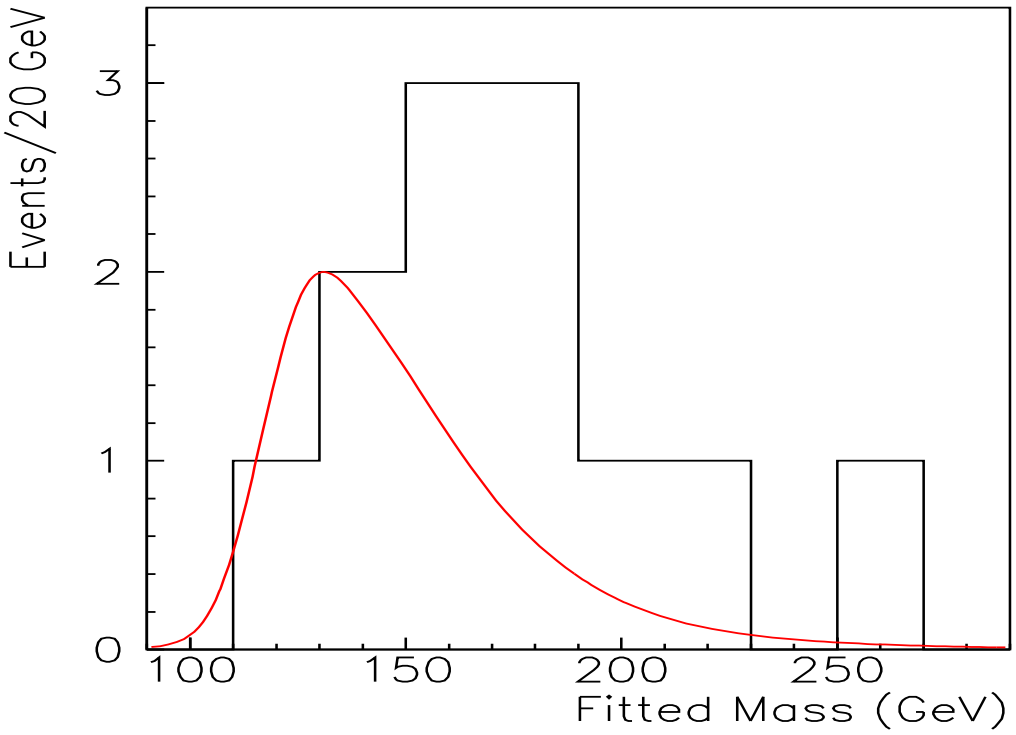
Consistent with Expected BG?

- Fit VECBOS background shape to the data
  - » After correcting for the kinematic fitting efficiency, the expected number of background events is 3.7 ± 1.3
  - » Likelihood fit includes a Gaussian term constraining the fitted value for the expected number of background events
- Small excess of events seen at high mass
- Is excess due to possible discrepancies between VECBOS and our data?



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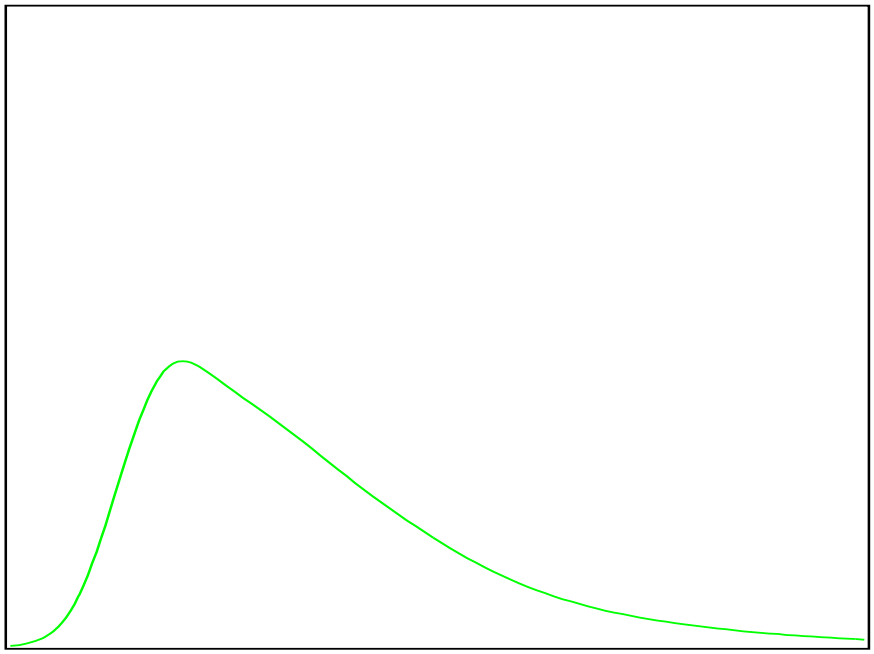
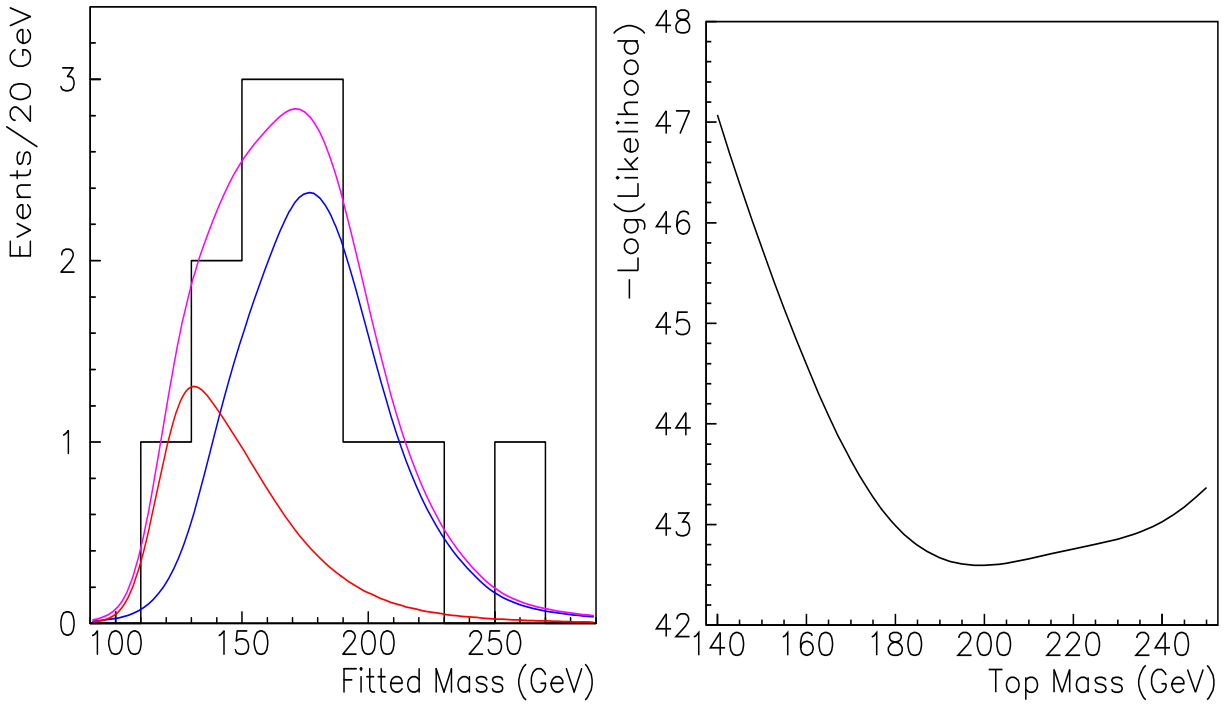
Not entirely



Mass Fit Results



- Assuming a top contribution is present in the data, perform top + background fit
- The likelihood function is asymmetric and non-Gaussian, peaking at $m_t \approx 200$ GeV
- An increase in -Log(Likelihood) by 0.5 from its minimum corresponds to a mass range of ~180 - 240 GeV
- Mass scale has an 11% uncertainty from our uncertainty in the jet energy scale

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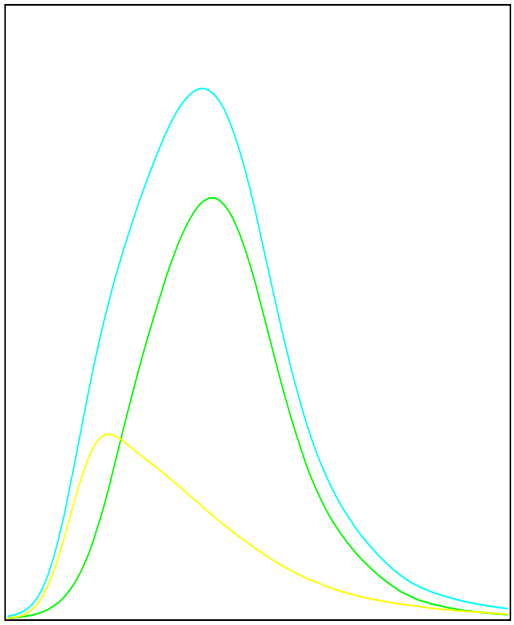

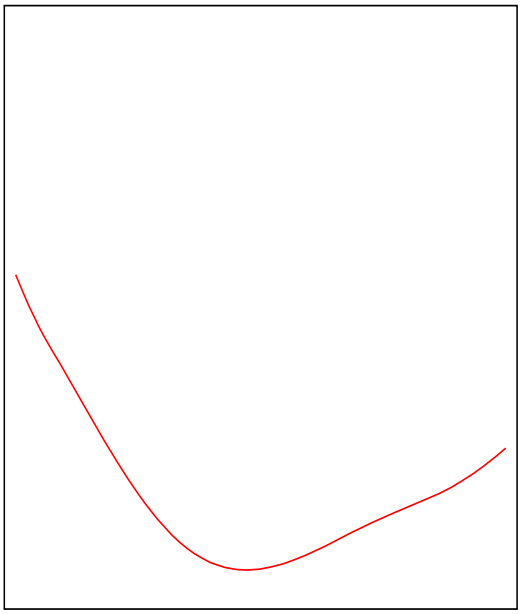

Summary and Conclusions

- Preliminary mass analysis of the DØ top candidate sample from runs 1a and 1b
- Extensive studies have been performed on jet energy corrections, the effect of mis-assignment of jets in the kinematic fit, and the effect of initial and final state radiation
- Possible systematic effects in the mass distribution of background events studied
- 12 events successfully fitted
- Small excess of events over expected background seen at high mass
- Assuming a top contribution, a likelihood analysis of the fitted mass distribution prefers a top mass in the region of 200 GeV, with large statistical and systematic uncertainties
- More data needed!

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