Cross Section for Top Production

Can use counting experiments to estimate $\sigma_{t\bar{t}}$

- Subtract the expected backgrounds
- Perform a maximum likelihood fit to estimate $\sigma_{t\bar{t}}$
- A number of issues have to be addressed
  - Make consistent background calculation
    - CDF backgrounds assume all pre-tagged events are background
    - Bootstrap to get correct estimate
  - Does one count b-tags or events?
    - relatively low tagging efficiency
    - have two b quarks for signal events
    - slightly more information in tags
  - Mass dependence of acceptance
  - Correlations between channels

Uncertainties are dominated by Poisson fluctuations

- Not a Gaussian statistic
- Systematic uncertainties have to be included
- Correlations are potentially important

Methodology

The expected number of events observed in each channel given by

$$\begin{aligned} N^i &= B^i + \int \mathcal{L}\,\mathrm{dt}\,\epsilon^i\,\sigma_{t\,\bar{t}} \\ \Rightarrow \sigma_{t\,\bar{t}} &= \frac{N^i - B^i}{\int \mathcal{L}\,\mathrm{dt}\,\epsilon^i} \end{aligned}$$

where

- B^i is expected background in ith channel
- ϵ^i is efficiency in ith channel

Maximum likelihood solution for n channels is

$$\sigma_{t\,\bar{t}} = \frac{\sum_i \left(N^i - B^i\right)}{\int \mathcal{L}\,\mathrm{dt}\,\sum_i \epsilon^i}$$

In practice, have to account for uncertainties

Source	Uncertainty % (CDF)
Integrated luminosity	3.6
Lepton detection	5
Jet energy scale (depends on M_{top})	$10 \rightarrow 3$
Initial state radiation	7
B tagging efficiency	12
Total	16%

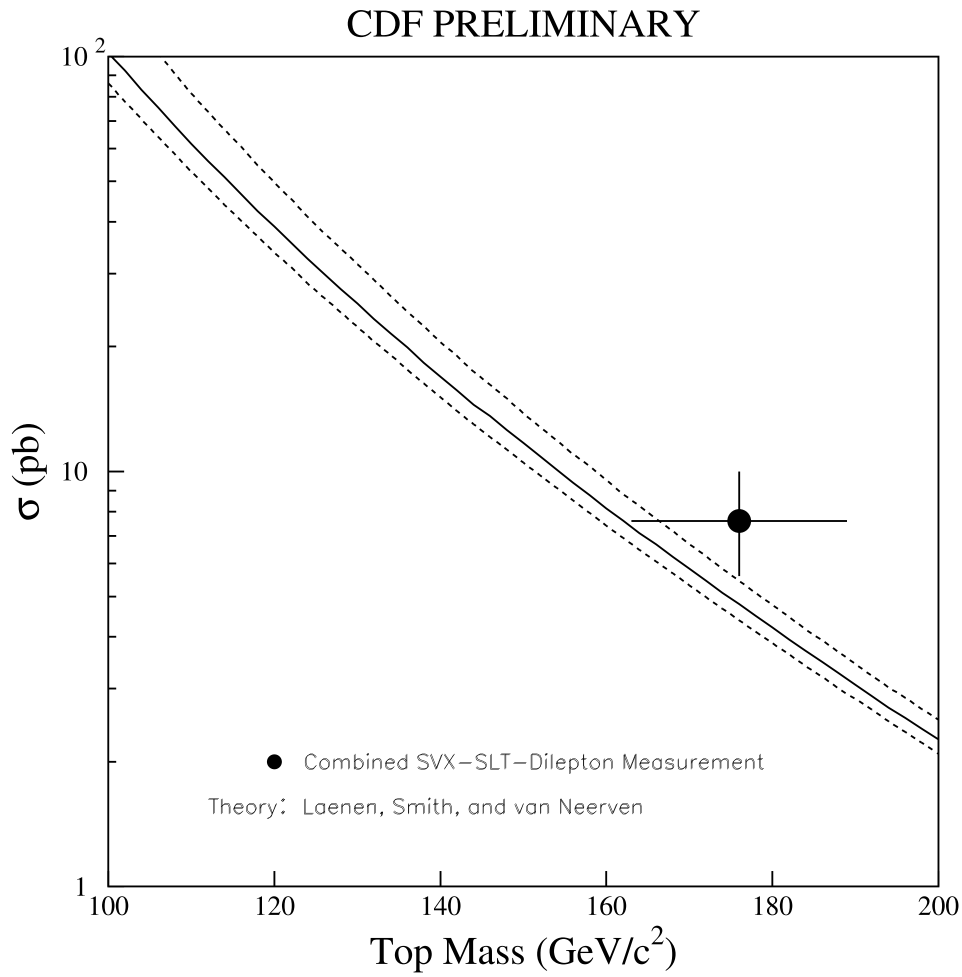
CDF Cross Section Result

CDF uses the results from the three channels

- SVX tags have the most information
- SLT and DIL channels have $\times 2$ larger uncertainty

Result of fit (quoted at $M_{\rm top} = 176$ GeV/c^2)

$$\sigma_{t\bar{t}} = 7.6^{+2.4}_{-2.0} \text{ pb}$$



$$\sigma(t\bar{t}) = 7.6\ ^{+2.4}_{-2.0}\ pb$$

$\boxed{\text{The Top Quark Mass}}$

"Best" M_{top} measure comes from $t\,\bar{t}$ reconstruction
Alternatives are:

- b jet spectrum
- correlation with H_T
  - Recent CDF result gets to $\sim \pm 20$ GeV/c^2
- Can use cross section
  - CDF $\sigma_{t\,\bar{t}} \Rightarrow \pm 12$ GeV/c^2
  - But assumes standard model, BR, etc.
- Direct measurement preferable

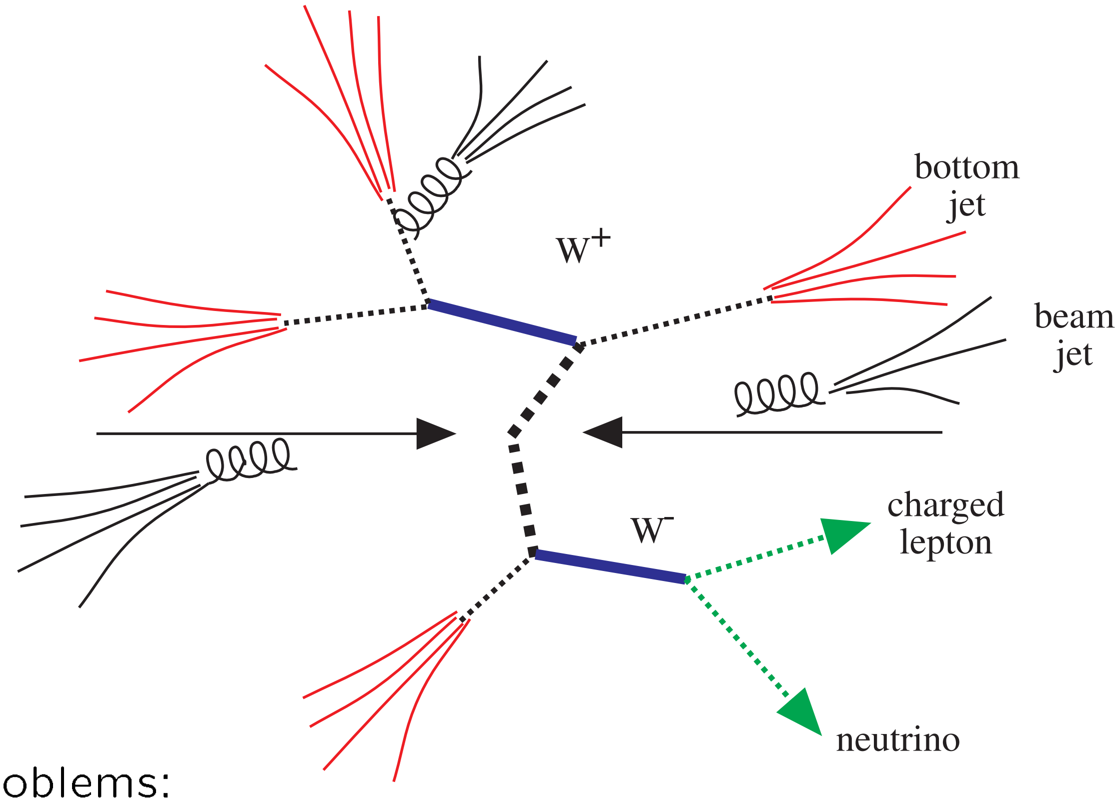
However, has lots of problems

- ≥ 6 partons need to be identified
  - 2 ν's in dilepton mode problematic
  - Have fewest constraints and fewest events
- Focus has been on lepton + jets channels

Lepton + Jets Reconstruction

In this mode, have measured almost all $t\,\bar{t}$ daughters

- Lepton 4-momentum solid and ν_l is missing only p_z
- $W \rightarrow q\bar{q}'$ observed as 2 jets
- bottom quarks observed as jets (perhaps tagged)



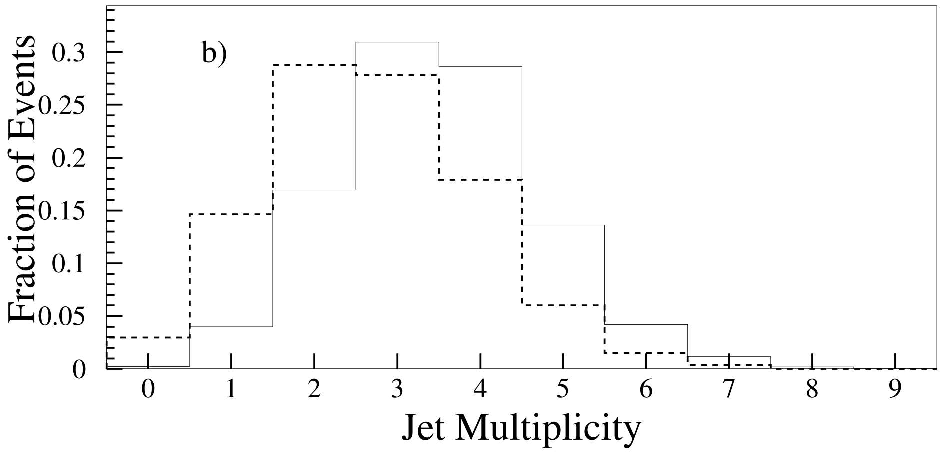
Problems:

- QCD radiation generates additional jets
- Combinatorics in identifying jets $\leftrightarrow$ partons
- Background events

Biggest Problem is Jet Assignments

Jets in real $t\bar{t}$ events arise from

- $W \to q\bar{q}'$ and b quarks
- Initial state radiation and "beam" jets
- Final state radiation



Has to be overcome by looking at likely combinations

- Fortunately highest p_T jets are most likely from $t\bar{t}$
- Can use tagging information...
- Take into account biases due to mis-identification
  - Yet another source of MC dependency

CDF Measurement of Top Mass

Select a subsample of events with ≥ 4 jets

- Place loose cuts on 4rth jet
  - Require $E_T > 8$ and $|\eta| < 2.4$
  - High efficiency ($\sim 85\%$ for $t\bar{t}$)

- Combine all jet pairs to form $W \to q\bar{q}$
  - 12 jet-parton assignments
  - Correct jets depending on assignments
  - 2 unique solutions for neutrino p_z
- Fit each assignment:
  1. W daughters invariant mass constrained to M_W
  2. t and $\bar{t}$ have same mass
  3. Allow for $p\bar{p} \to t\bar{t}X$
  4. Gives 2C fit
  - Choose one with best χ^2
  - Require $\chi^2 < 10$
- Use b-tag information to identify b quark jet

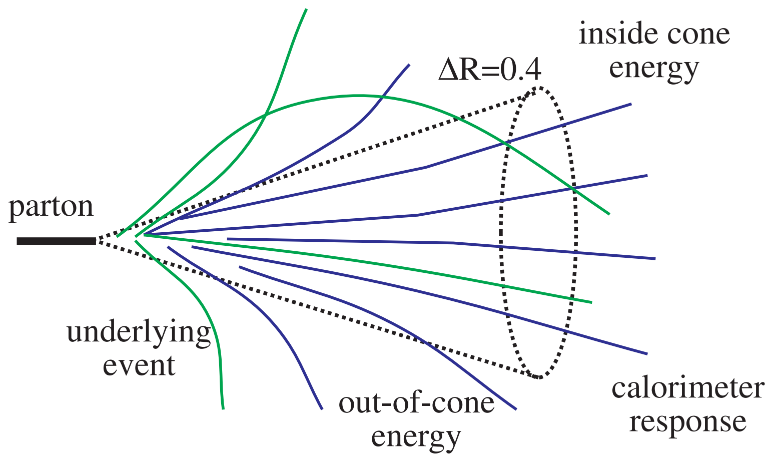
The fourth jet cut leaves 99 events out of 203

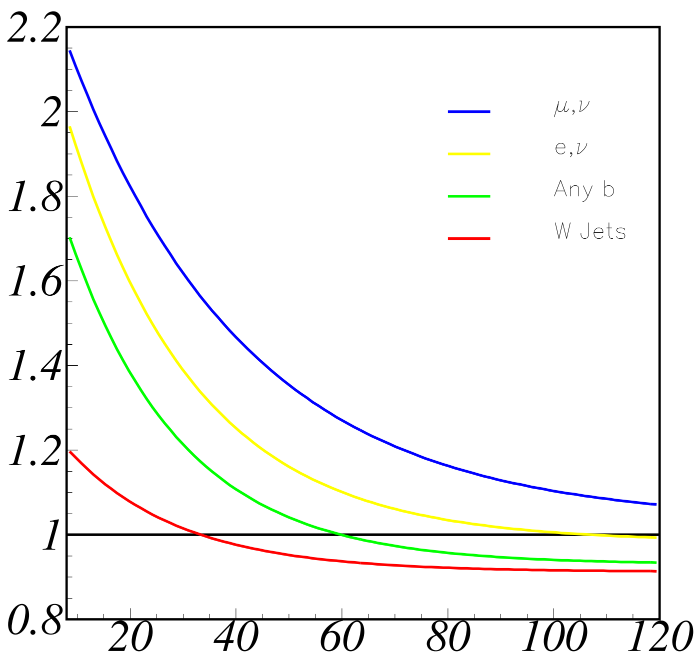
- 88 have at least one good fit
- 19 events have at least one b tag

Jet-Parton Corrections

Have to first correct observed E_T to parton E_T

- Corrections determined by MC and testbeam studies
- Make additional corrections for $t\bar{t}$ topology





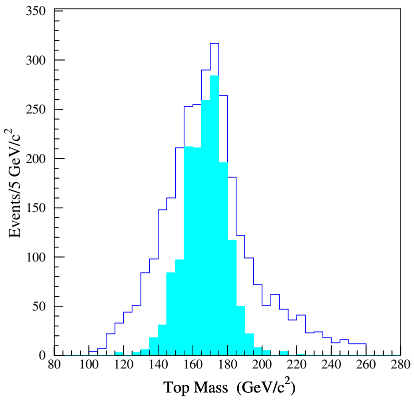
Tests of CDF Reconstruction

Can test how well procedure works with MC events

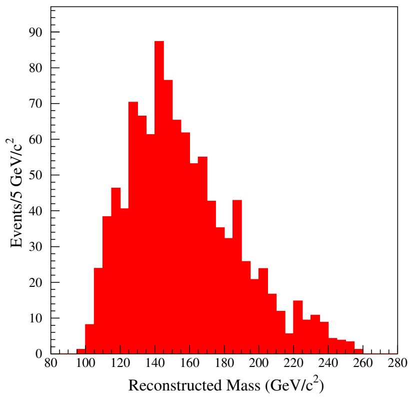
- Look at correct and "best" assignments
- Also look at how background would reconstruct

Mass Reconstruction for Top and W+jets Monte Carlo

Reconstructed mass for HERWIG MonteCarlo, $M_{top} = 170$ GeV



Reconstructed mass for the VECBOS+HERPRT W+3 jets events.

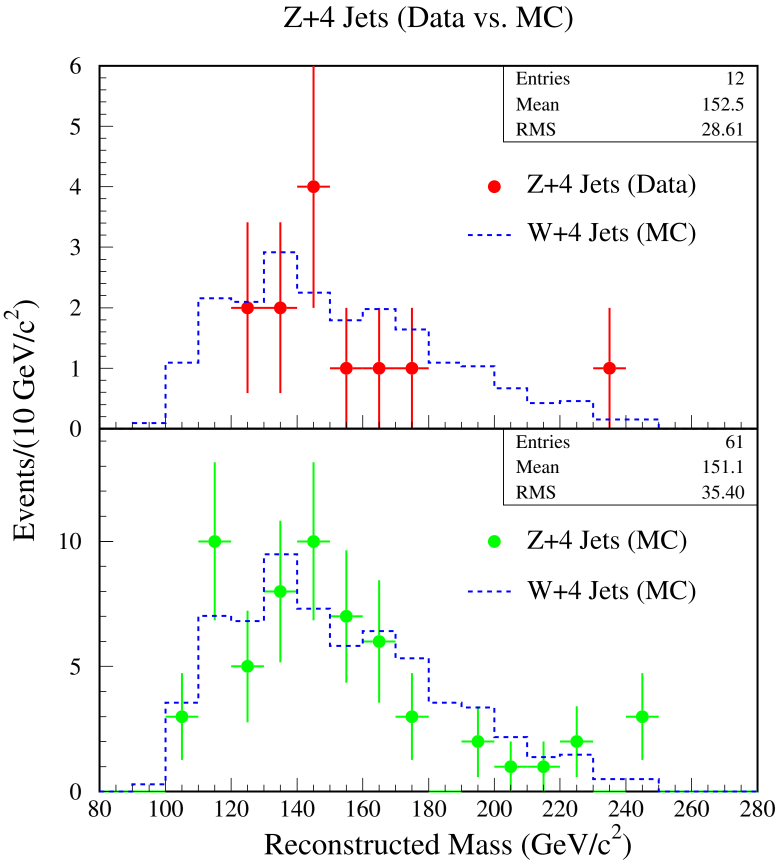


Background Effects

Primary backgrounds are from $Wb\bar{b}$ and fake leptons

- Use background rates from counting experiments
- Can check $Wb\bar{b}$ shape by looking at $Z+$ jets
- Use "non-isolated" lepton + jet sample for fakes
- Look identical to VECBOS $W+$ jets prediction

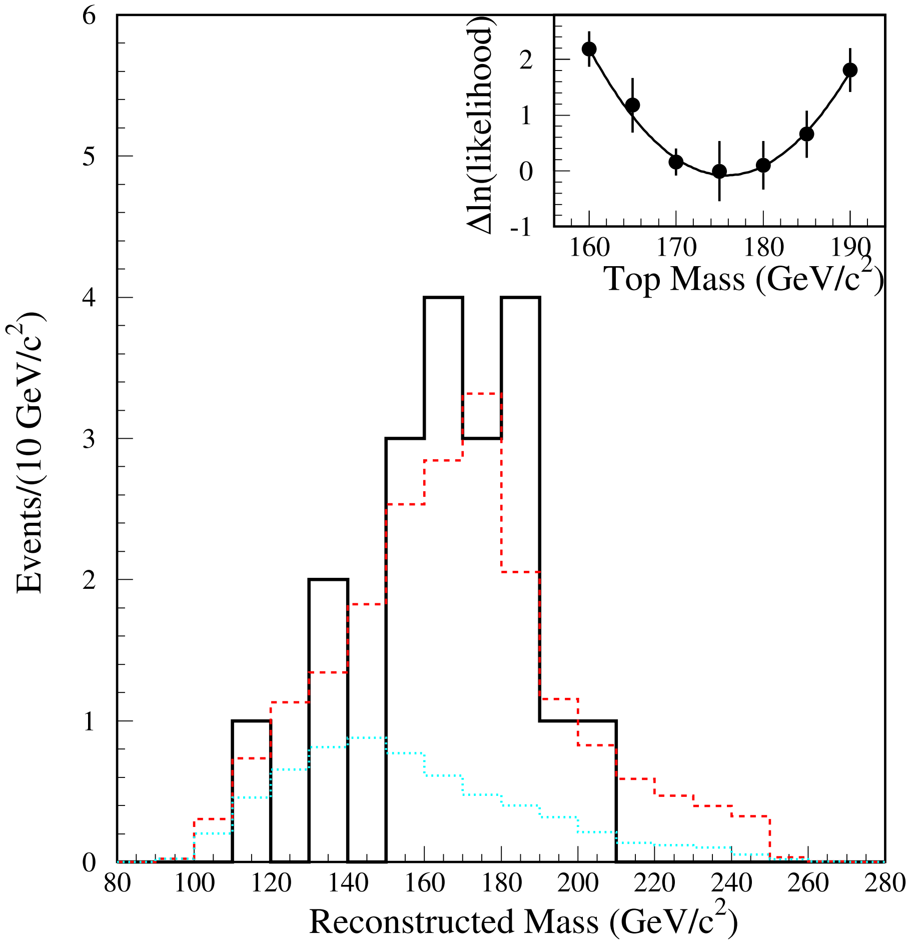
  $\Rightarrow$ Use VECBOS $W+$ jets MC for bkg shape



CDF Mass Results

Estimate background based on W+jet sample

- Use known fake tag rates and $Wb\bar{b}$
- Background shape in M_{top} comes from MC calculation
- Estimate background to be $6.9^{+3.4}_{-2.4}$ events
  - Primarily QCD W+jet



$$M_{\text{top}} = 176 \pm 8 \pm 10 \quad \text{GeV}/c^2$$

Systematic Uncertainties

Systematic error is dominated by energy scale

Systematic	Value (GeV/c^2)	Percentage
Jet E_T scale (ISR)	7.7	4.4
MC Statistics	3.1	1.8
Fit procedures	2.5	1.4
SLT Tagging bias	2.1	1.2
Background shapes	1.6	0.9
Minimisation procedure	1.6	0.9
Fitting likelihood	1.2	0.7
SVX Tagging bias	1.1	0.6
Total	10.0	5.7

Jet enery scale uncertainty comes largely from our lack of knowledge about the physics

- Should come down as we accumulate larger samples
- Currently focus of effort in reducing uncertainty

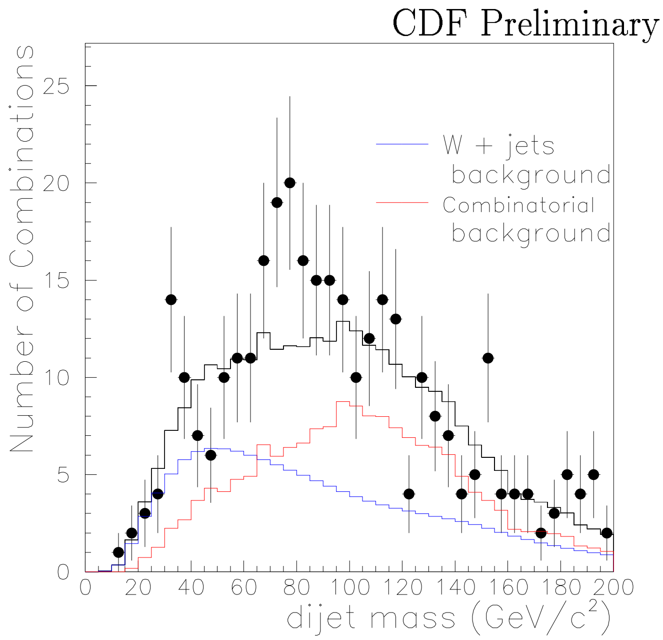
Evidence for W $\rightarrow$ q$\bar{\text{q}}$

Observation of $W \rightarrow q\bar{q}$ is important

- Strong evidence of signal in $W^+W^-b\bar{b}$ channel
- Can calibrate jet energy scale

Have to refit data relaxing W mass constraint

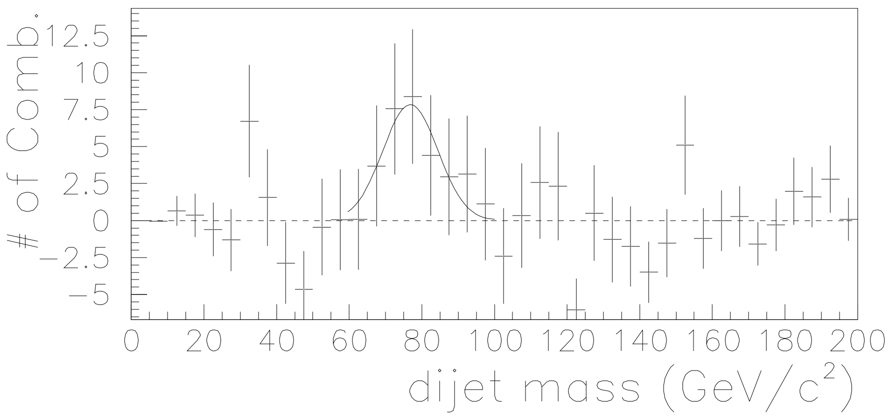
- Look for W signal plotting all mass combinations
  - Makes it tough since 6 combos/event
- Reduce backgrounds by requiring $H > 300$ GeV



Hadronic W Observation (cont.)

Can perform a background subtraction

- Observe signal of 27 ± 12 events
- Expect about 28 events from $t\,\bar{t}$ production



Width of signal is consistent with that expected in $t\,\bar{t}$ decays

- Can eventually calibrate jet energy scale to $1 - 2$ GeV
- Can also extract signal in other ways
  - Relax mass contraint and choose best fit
  - Similar result is obtained

Top Quark Branching Fractions

Indication of new physics would be if $BR(t \to W^{\pm}b) \neq 1$

- SM expects V_{tb} to be unity
  - Unitarity constraints
    * V_{ud} large from nuclear β and μ decay
    * V_{us} constrained by K_{e3} decays
    * V_{cd} comes from $\nu n \to cX$
    * V_{cs} constrained by D_{e3} decays
    * V_{cb} small because large τ_b
    * V_{ub} even smaller ($b \to u$)
  - Expect V_{ts} and V_{td} much smaller than V_{tb}
- $V_{tb} \lesssim 0.9985$ violates (or bends) SM

Experimentally, we can measure

$$\mathcal{R} \equiv \frac{BR(t \to Wb)}{BR(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2}$$

Measure the rate of zero, single and double b-tagged events

- Need to be able to b tag
- Can only use zero tagged events with dileptons where backgrounds small without b tagging

BR Technique

Fraction of zero, single and double-tagged events is

$$\begin{aligned} f_0 &= (1 - \mathcal{R}\epsilon)^2 \\ f_1 &= 2\mathcal{R}\epsilon(1 - \mathcal{R}\epsilon) \\ f_2 &= (\mathcal{R}\epsilon)^2 \end{aligned}$$

- ϵ is tagging efficiency

Rate of single vs double tags gives

$$\mathcal{R} = \frac{2}{\epsilon(f_1/f_2 + 2)}$$

Rate of zero vs single tags gives

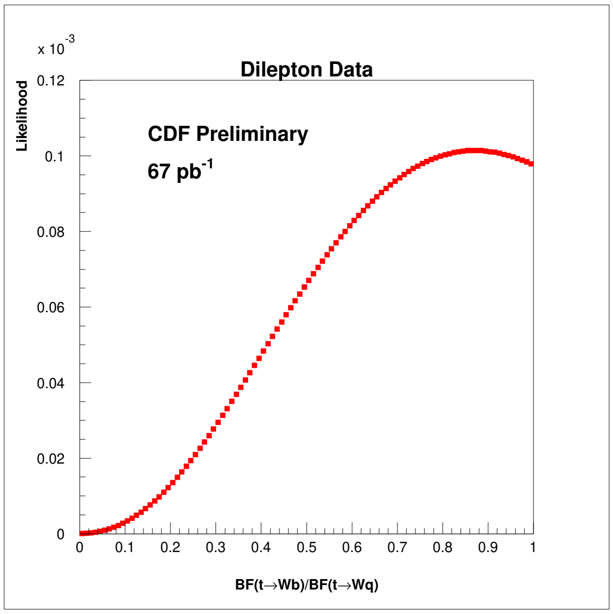
$$\mathcal{R} = \frac{1}{\epsilon(2f_0/f_1 + 1)}$$

"Best" way of estimating $\mathcal{R}$ is to use maximum likelihood technique

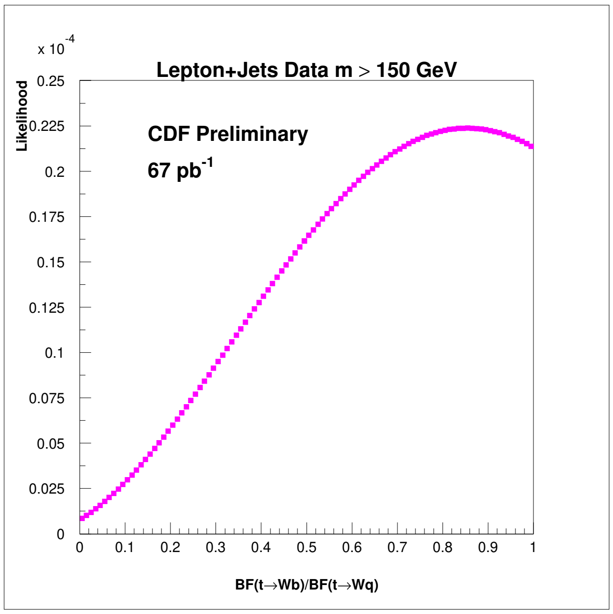
- For a given number of observed events,
  - calculate probability of observing 0, 1 and 2 tags
  - maximize probability by varying $\mathcal{R}$
- Can use probability to constraint $\mathcal{R}$

CDF BR Results

Result from dilepton data is $\mathcal{R} = 0.875 \pm 0.4$



Result from lepton + jets data is $\mathcal{R} = 0.87 \pm 0.3$



BR Conclusions

Largest systematic uncertainty comes from b-tagging efficiency

- introduces 0.08 – 0.10 variation in R
- Overall systematic uncertainty is ${}^{+0.13}_{-0.11}$

$$\mathcal{R} = 0.87^{+0.13}_{-0.30}(\mathrm{stat})^{+0.13}_{-0.11}(\mathrm{syst})$$

Can convert that into a measure of $|V_{td}|$ by assuming

- $0.004 \leq |V_{td}| \leq 0.015$ and $0.030 \leq |V_{ts}| \leq 0.048$
- Take average values of these to obtain

$$|V_{tb}| = 0.11^{+0.89}_{-0.05}$$

This is in good agreement with the SM (note errors)!

- Really saying that $|V_{tb}| \gg |V_{ts}|$ or $|V_{td}|$
- Alternatively, 95% CL is $V_{tb} > 0.016$

New Physics Searches Using Top

Large mass of top has spurred speculation

- Top color model (Hill & Parke)
- Multiscale technicolor (Eichten & Lane)
- Lots of other variations on models

Predict structure in $t\bar{t}$ system

- Can look for "resonant' production

$$p\bar{p} \to V\,X \to t\,\bar{t}\,X$$

- Should see peak in $M_{t\bar{t}}$ distribution
- Stiffer p_T distribution for top
- Possibly larger $\sigma_{t\bar{t}}$

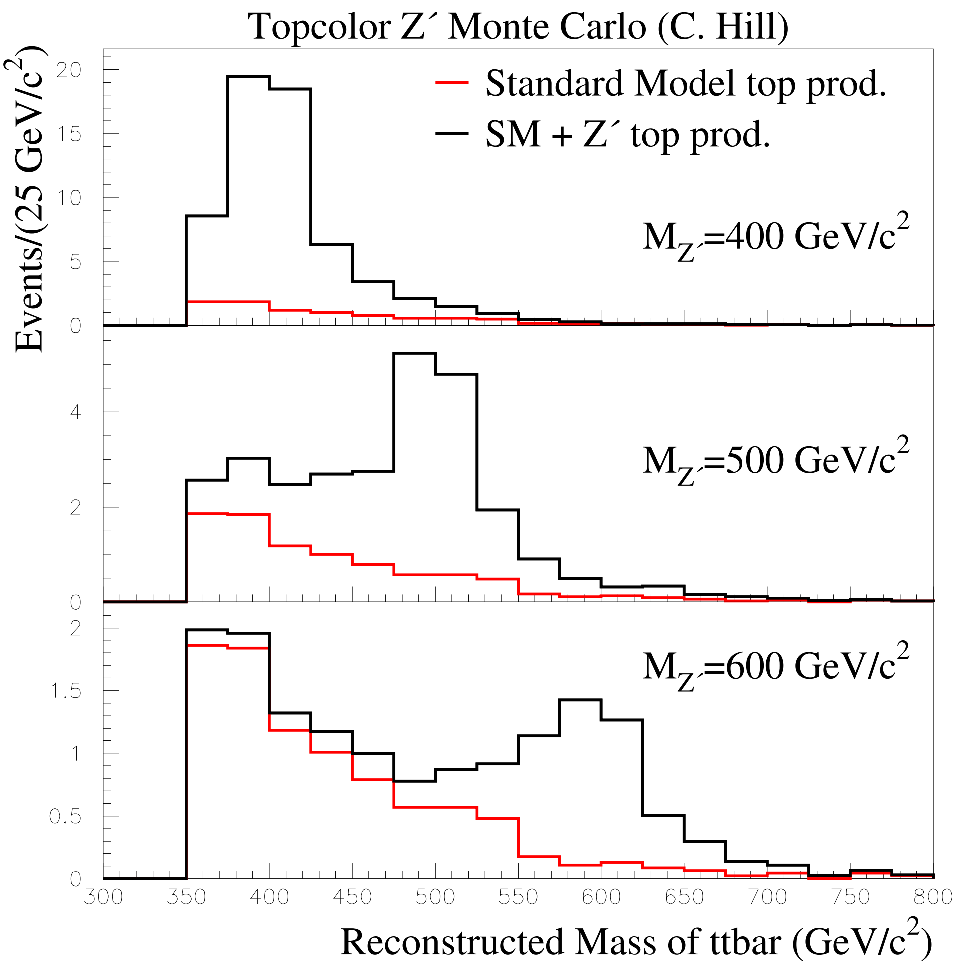
Can look at fully reconstructed $W + 4$ jet events

- Background is small
- Have sorted out (for the most part) jet confusion

Predicted signal for Top Color

Calculations by C.Hill et al. predict clear signature

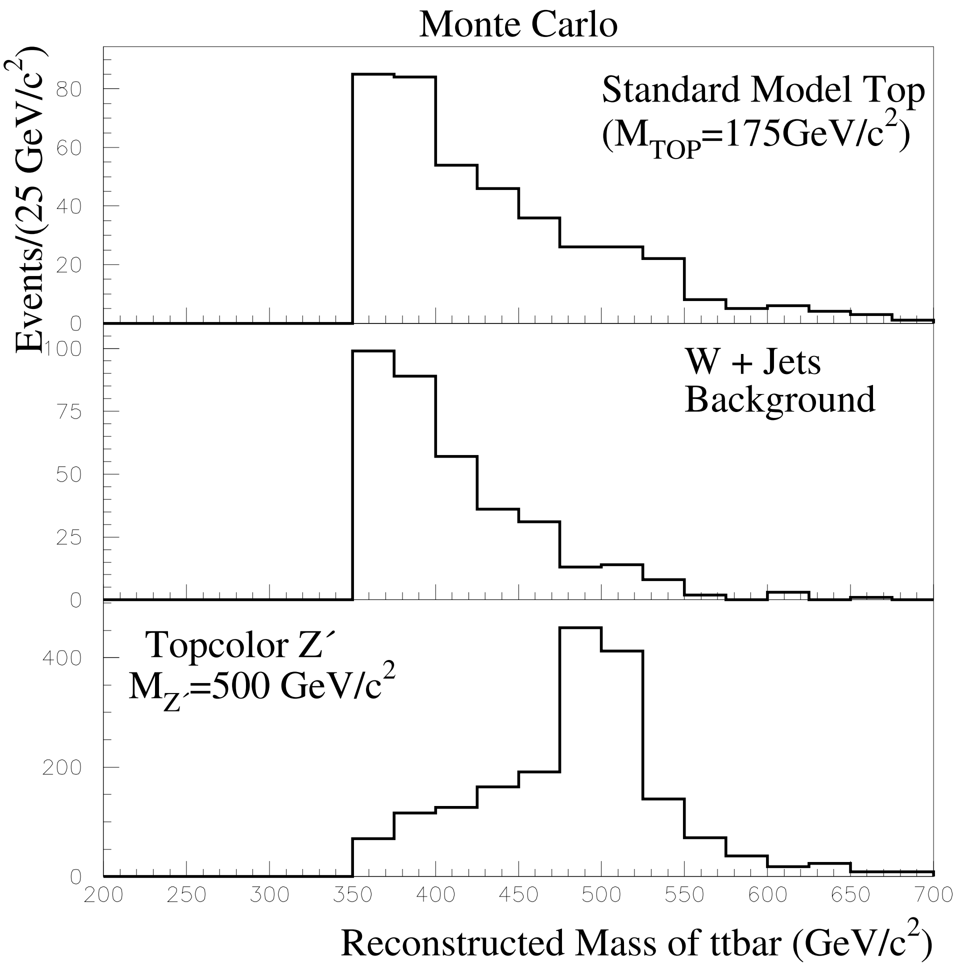
- Coupling to light quarks strong enough to yield appreciable cross section
- Invariant $t\bar{t}$ mass best place to look for effect



Backgrounds to Top Color

Standard model $t\bar{t}$ production most significant background

- Depends on Z' mass
- Can compare shape of backgrounds from $W+$ jets



$t\bar{t}$ Invariant Mass

Data is statistics limited

- There is no apparent enhancement
- An upper limit on Top-Color Z' mass and cross section coming soon