The Role of Calorimetry in Top Physics

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Overview

- The Standard Model Top Quark
- Detecting and Reconstructing Top
- Intrinsic Limitations – Top mass and p_T
- Limitations and Expected Improvements

Work done in collaboration with Pierre Savard
and Andrew Robinson

Standard Model Top Quark Phenomenology

Produced in collider environment

- Produced through annihilation $f\bar{f} \to t\bar{t}$
- In $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV, $\sigma \sim 5$ pb

Top quarks decay via the weak force

- Predict $\sim 100\%$ $t \to W^+ b$
- For heavy top ($M_{top} \gtrsim 100 - 120$ GeV/c^2), decays before it hadronises

Can be viewed as "pure" β decay

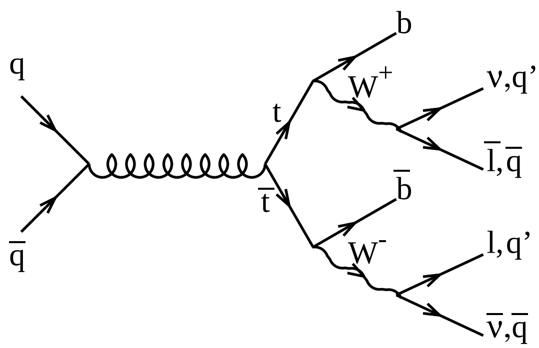
$$\Gamma_{\text{top}} = \frac{G_F M_t^3}{8\sqrt{2}\pi}\left(1 - \frac{M_W^2}{M_t^2}\right)^2 \left(1 + 2\frac{M_W^2}{M_t^2}\right)$$
$$\sim 175 \text{ MeV} \left(\frac{M_t}{M_W}\right)^3 \sim 2 \text{ GeV}$$

- Toponium doesn't have time to form
- T mesons $\sim$ degenerate (if there was time...)
- Decay dominated by "longitudinal W^+"

Reconstructing Top

Since top is pair-produced and β decays

- Expect to see 6 final state particles



- $t\bar{t} \to l\nu_l +$ jets (24/81 for $l = e^-/\mu^-$)
- $t\bar{t} \to l\nu_l l'\nu_{l'}$ (2/81 for $l = e^-/\mu^-$)
- $t\bar{t} \to$ n jets (36/81)

Backgrounds are large:

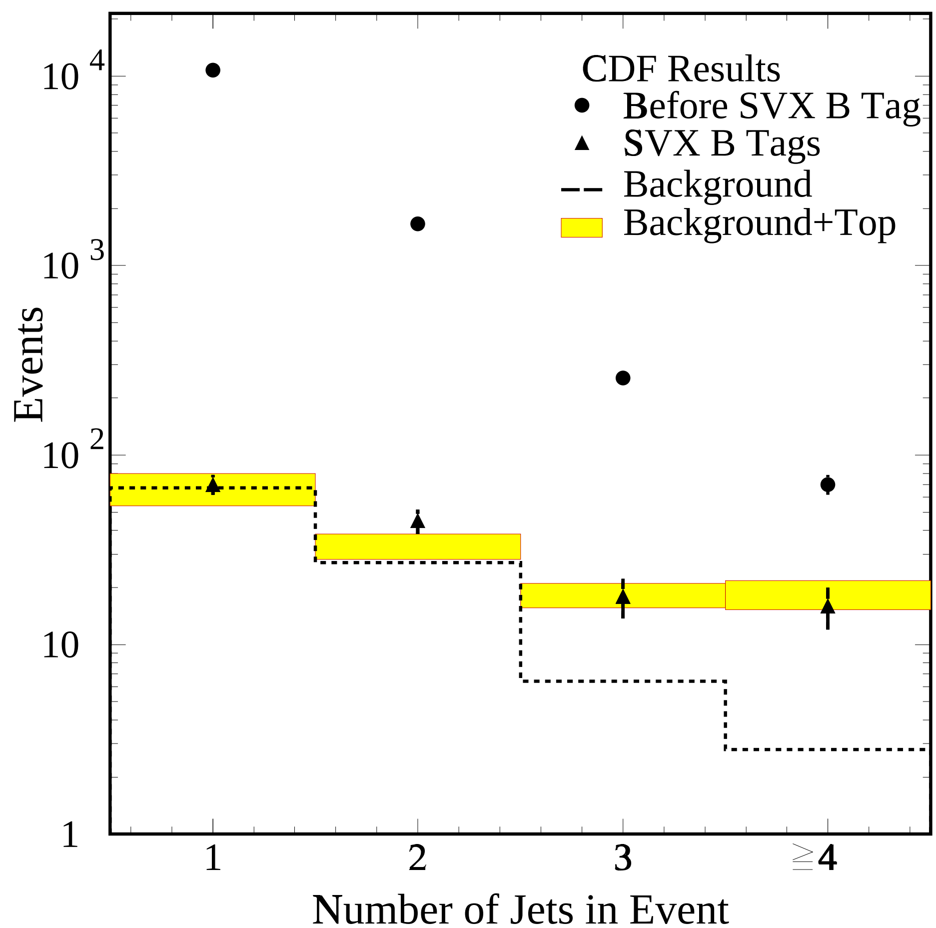
- Fake lepton candidates from QCD multijet events
- $W+$ jets production

$\Rightarrow$ Controlled by requiring ≥ 1 b-tagged jet

Effect of b-Tagging

Require b-tag in $W+ \geq 3$ jet sample

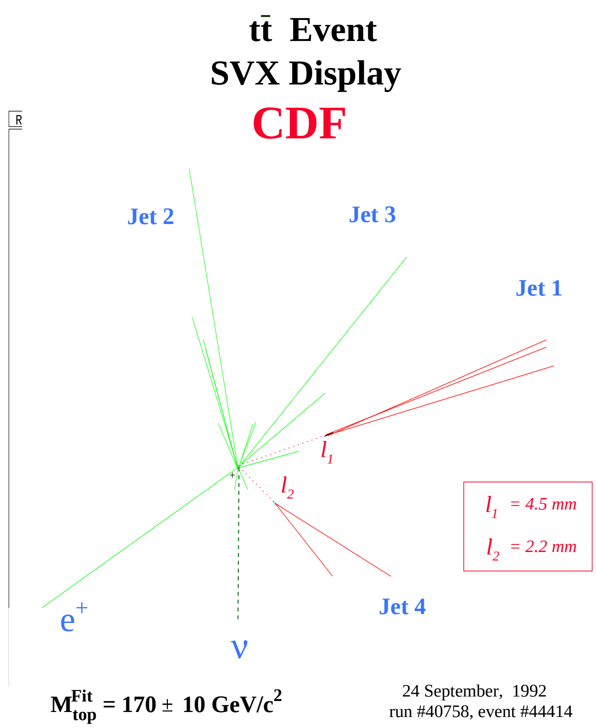
- Expect $S/B \sim 7$



Identifying Top Decays in $p\bar{p}$ Collisions

In order to identify lepton + jets top candidates

- Search for $W \to l\nu_l$ candidate
  - Electron or muon with $p_T > 20$ GeV/c
  - Missing transverse energy $\not{E}_T > 20$ GeV
- Search for at least one b jet
  - Most effective tool is to find a secondary vertex
- Some evidence of other W in event
  - Either two more jets or another lepton



Today's Technology

Both CDF and DØ detector employ 1980's calorimetry

- CDF has a Pb-scintillator/Fe-scintillator sandwich
  - For $|\eta| > 1.2$, employs PWC wire/pad readout
  - $\sigma_E \sim 0.15\sqrt{E}$ for EM
  - $\sigma_E \sim 1.1\sqrt{E}$ for jets

- DØ has a more uniform U-liquid Ar calorimeter
  - $\sigma_E \sim 0.07\sqrt{E} + 0.016E_0.66$ for EM
  - $\sigma_E \sim 1.15\sqrt{E}$ for jets

Calorimetry extends to $|\eta| \sim 4$

- Region $|\eta| \lesssim 2.5$ most important for top

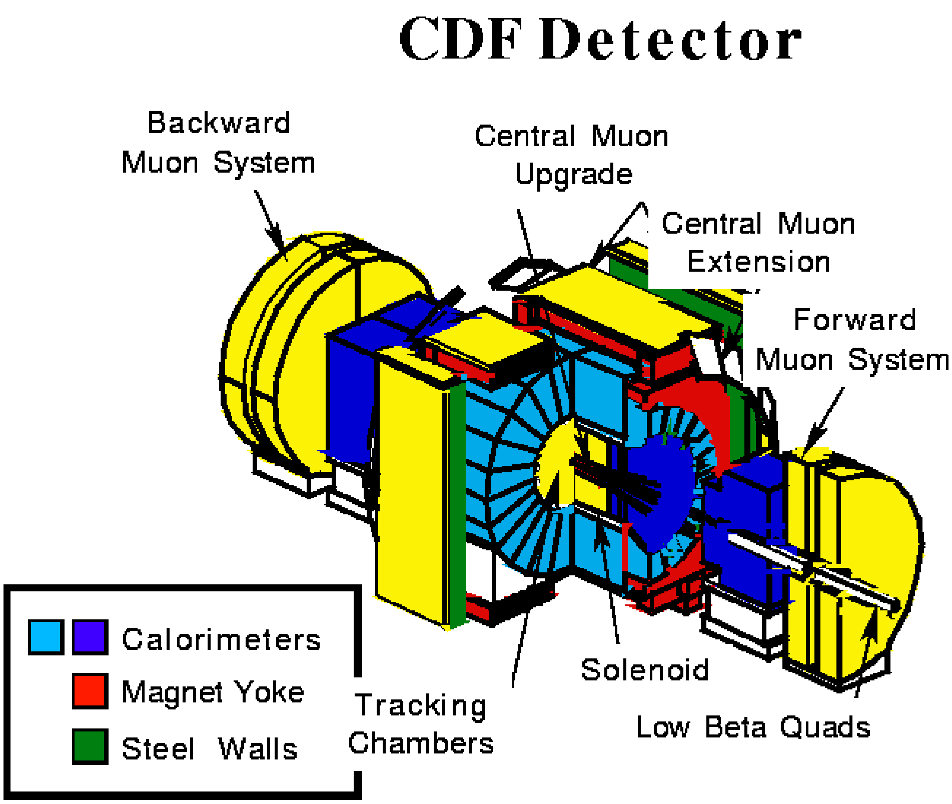
- Missing E_T calculated over region $|\eta| < 3.6$

Will be using CDF as example in this talk

- b-tagging is more effective

- Has most complete set of top kinematic results

CDF Run I Detector



- Pb/Fe-scintillator for $|\eta| < 1.1$
- Pb/Fe-PWC for $1.1 < |\eta| < 4.2$

The Status of Top Today

CDF has now detected top in virtually all decay modes

- Lepton + Jets mode (for mass analysis)
  - lepton $p_T > 20$ GeV/c and $\not{E}_T > 20$ GeV
  - ≥ 3 jets, $E_T > 15$ GeV and $|\eta| < 2$
  - Require 1 b-tagged jet OR a 4th jet with $E_T > 15$

  $\Rightarrow$ 76 candidates (expect 31 ± 7 bkg)

- Dileptons
  - 2 leptons with $p_T > 20$ GeV/c
  - Remove Drell-Yan and Z° background

  $\Rightarrow$ 9 candidates (2.4 ± 0.5 events bkg)

- All hadronic decays
  - between 5 and 8 jets ($E_T > 15$ GeV and $|\eta| < 2.0$)
  - $\sum E_T > 300$ GeV + additional kinematic cuts

  $\Rightarrow$ Observe 187 b-tagged jets (142 ± 11 expected bkg)

These are purest samples for top quark measurements

What are the Interesting Top Properties?

- Top Quark Production Cross Section
  - Discovery technique
  - Predicted by QCD with less uncertainties than σ_b
  - Look for single top production

- Top Quark Mass
  - SM constrains it to M_W/M_Z
  - Important consistency check of theory

- Top Quark Production and Decay Kinematics
  - p_T distribution sensitive to "new" physics
  - SM expects decay to be polarized

- Top Quark Decay Rates
  - Measured $t \to W^+b/t \to W^+q$
  - Searched for FCNC such as $t \to Z^\circ c$

Role of Calorimetry in Top Physics

Calorimetry plays crucial role in top quark studies

- Lepton identification
  - Principle tool for electron ID
- Neutrino detection
  - Use technique of "missing transverse energy"
- Quark $\rightarrow$ jet reconstruction
  - Need to reconstruct b quark jets for tagging
  - Have to efficiently reconstruct $W \rightarrow q\bar{q}'$
- Energy flow in event
  - Have to understand recoil system

Charged Lepton ID

Electron ID places stringent criteria

- E_T measurement
- Shower shape discrimination (lateral and longitudinal)
- Charged track $\leftrightarrow$ cluster match
- Can achieve efficiencies $\sim 85\%$
  - Rejection of $\sim 10^3$ for QCD-induced backgrounds

Criteria on calorimetry fairly stringent

- Fine tower segmentation - $\Delta\eta \times \Delta\phi \lesssim 0.1 \times 0.05$
  - Finer transverse segmentation for shower shape
  - Longitudinal segmentation necessary
    - $\gtrsim 2$ samples
- Good resolution for energy - charged track matching
  - typically $\sigma_E \sim 0.1 - 0.15\sqrt{E}$ is sufficient

Used for muon ID

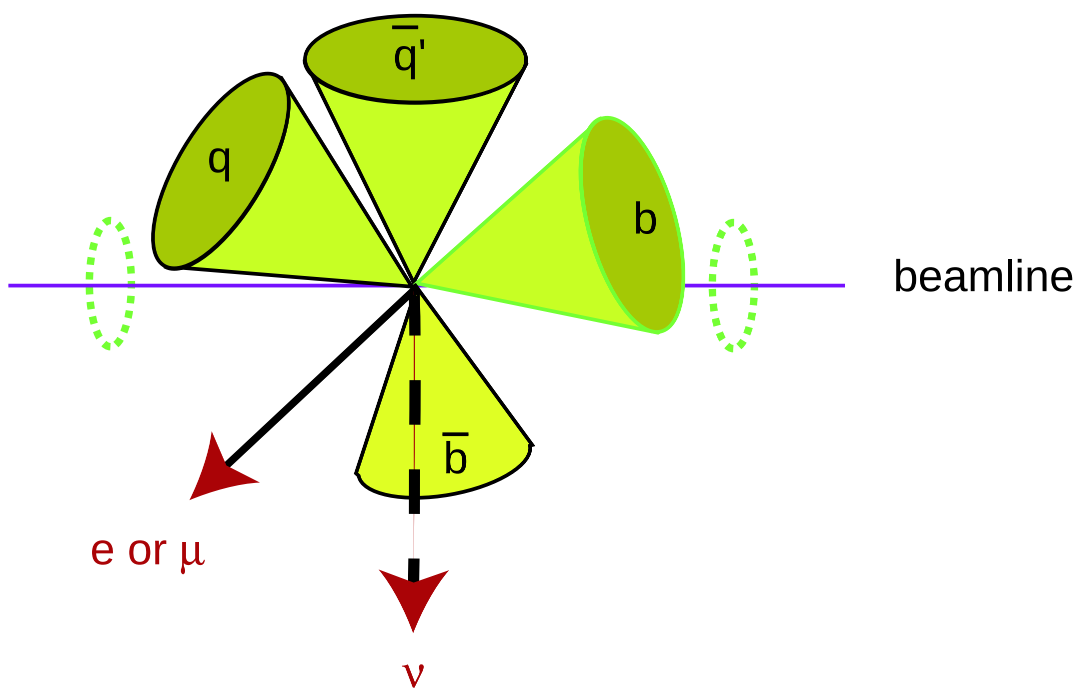
- Look for minimum-ionizing tracks

Neutrino Identification

Use standard definition of "missing E_T"

$$\begin{aligned} \not{E}_T &= -\sum E_i \hat{n}_i \\ &= p_T^{\vec{\nu}} \\ &= -\sum_{i=1}^{n_l} p_T^{\vec{l}} - \sum_{i=1}^{n_j} p_T^{\vec{j}} - \vec{X} - U\vec{E} \end{aligned}$$

- Non-linear calorimetry response for jets
- Fluctuations in underlying event(s) (UE)
- Response to recoil system (X)
- Cracks and holes in detector



Calorimeter Response to Jets

Jets are messy objects

- High-energy parton fragments and hadronizes
  - "Core" of jet contains most energy
  - Calorimetry non-linearities, e/h, ...
- Have to use "clustering" algorithm
  - Use narrow cone $R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$
  - Fluctuations due to "out-of-cone" losses
  - Overlapping showers
- Fluctuations coming from UE contributions
  - Mean is $\sim 1 GeV$ per steradian

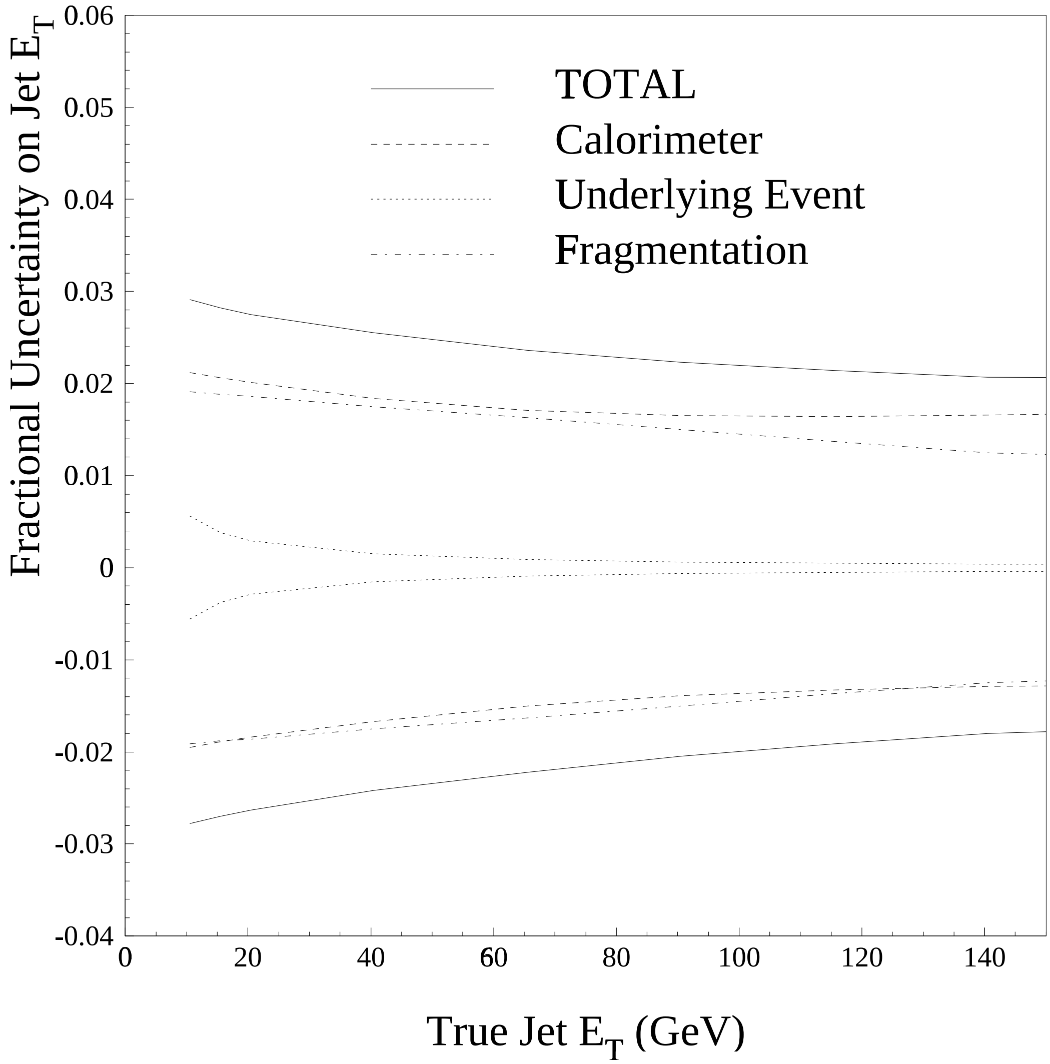
Lots of extra (and missing) jets

Jets	Data	$t\bar{t}$ MC
3	35%	33%
4	50%	50%
5	11%	14%
> 5	0%	2.5%

Jet Systematics

Can measure the response *in situ*

- Systematics are complex mix of effects
- Use dijet-balancing, $Z+$ jet events and MC



Putting $t\bar{t}$ Event Together

First correct for jet response

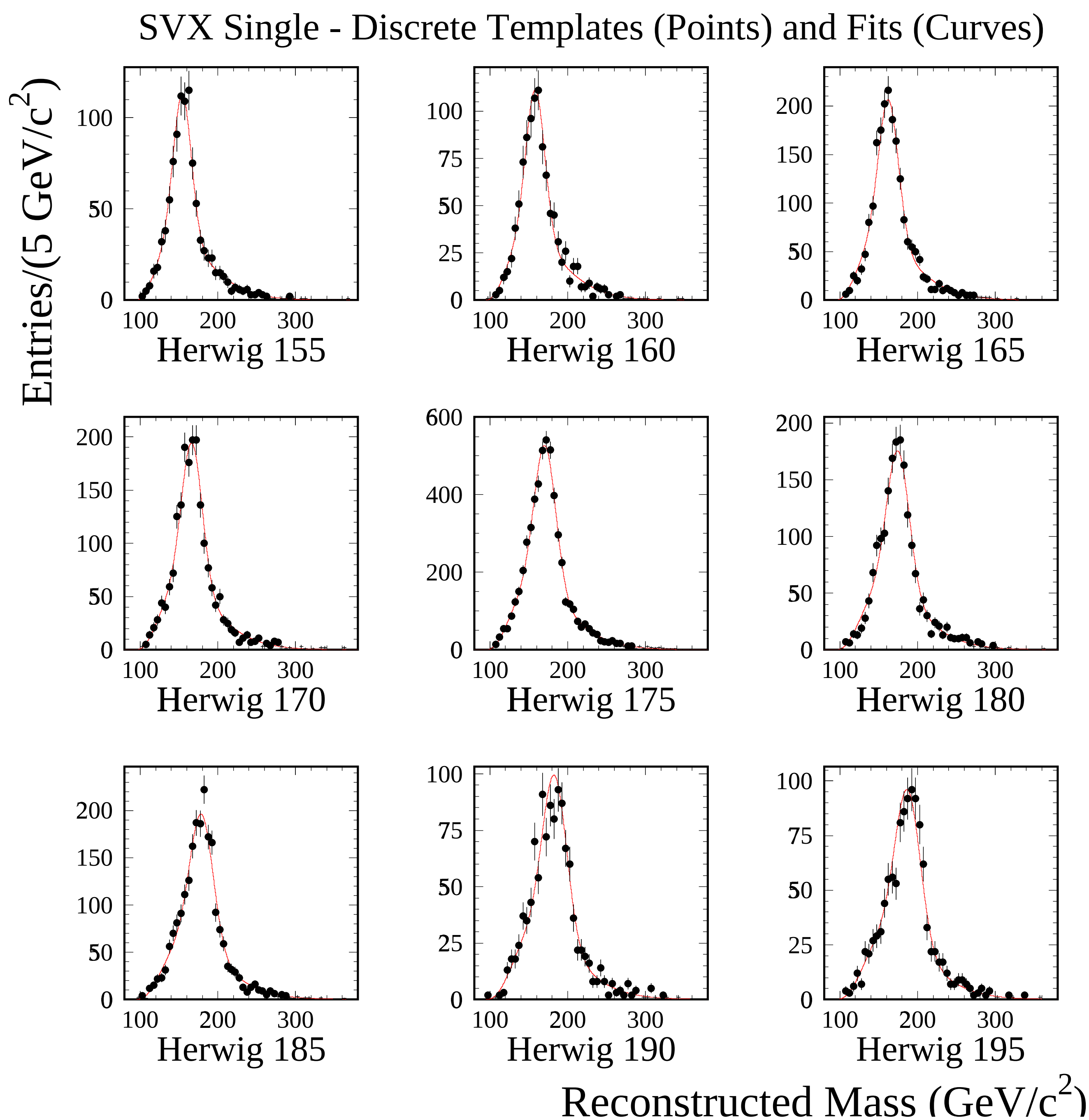
- Correct $\not{E}_T$ using known jet corrections

$$\not{E}_T{}^{(cor)} \quad = \quad -\sum_{i=1}^{n_l} p_T^{\vec{l}} - \sum_{i=1}^{n_j} p_T^{\vec{j}}{}^{(cor)} - X^{(cor)}$$

Put events together in following way

- Choose 4 leading jets
- Identify any b-jets
- Fit kinematics (masses equal, W boson mass constraint)
- Select parton-jet assignment with smallest χ^2
  - This works about 40% of the time

Overall works reasonably well for single-tagged events

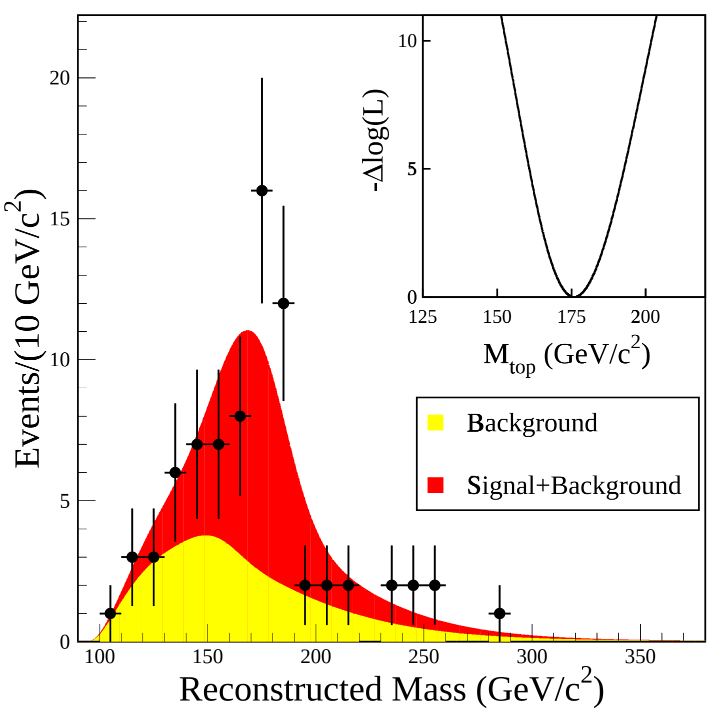


Top Quark Mass

Measurements now limited by systematic uncertainties

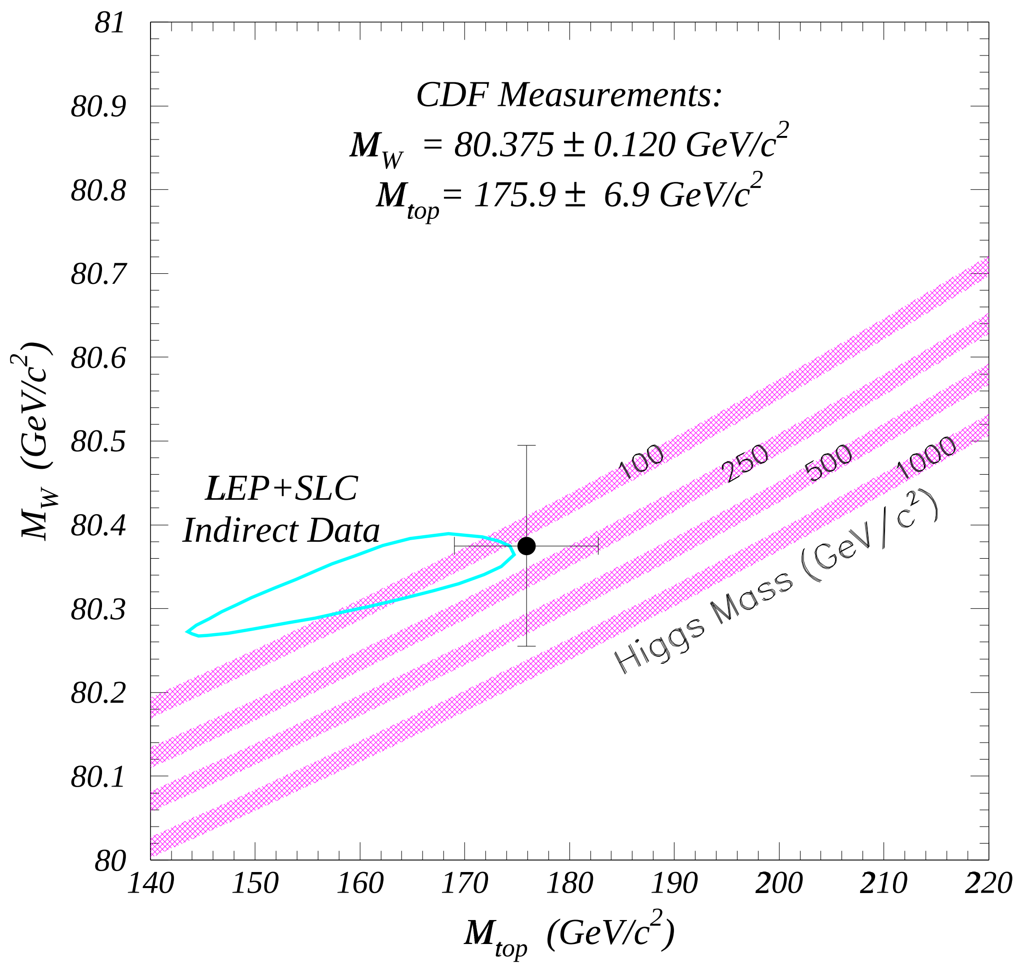
- Overall systematic uncertainty is ~ 5 GeV/c^2
  - Dominated by uncertainties in soft gluon contributions and energy scale

- Run I statistics limit systematic uncertainty



The final Run I values are

$$M_{top} = 176.0 \pm 6.5 \text{ GeV c}^2 \text{ (CDF)}$$
$$M_{top} = 172.1 \pm 7.1 \text{ GeV c}^2 \text{ (DØ)}$$
$$M_{top} = 174.3 \pm 5.1 \text{ GeV c}^2 \text{ (RunI)}$$


CDF Measurements:
M_W = 80.375 ± 0.120 GeV/c²
M_{top} = 175.9 ± 6.9 GeV/c²
LEP+SLC
Indirect Data
100
250
500
1000
Higgs Mass (GeV/c²)
81
80.9
80.8
80.7
80.6
80.5
80.4
80.3
80.2
80.1
80
140
150
160
170
180
190
200
210
220
M_W (GeV/c²)
M_{top} (GeV/c²)

Top Quark p_T Distribution

SM predicts top quarks produced "back-to-back"

- Broad p_T distribution – $< p_T >\sim M_{top}/2$
- p_T of $t\bar{t}$ system expected to be low

Statistics limit any measurement

- Use data to set confidence limits on $\frac{d\sigma_t}{dp_T}$
- Limited to large bins ($\Delta p_T = 75$ GeV/c)

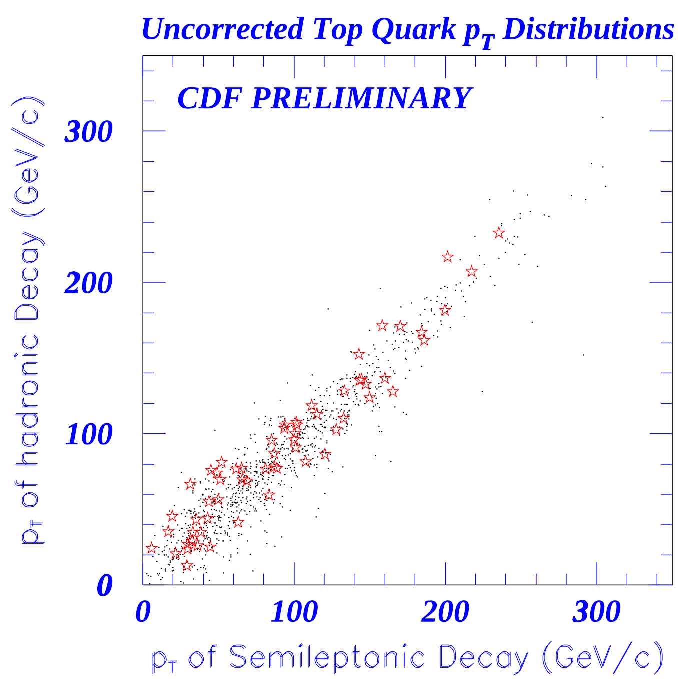
Kinematically fit event, constraining $M_{top} = 175$ GeV/c^2

- Require $\chi^2 < 10$

⇒ Left with 61 events

Measurement of p_T

Measurements on lepton-side and jet-side are strongly correlated!



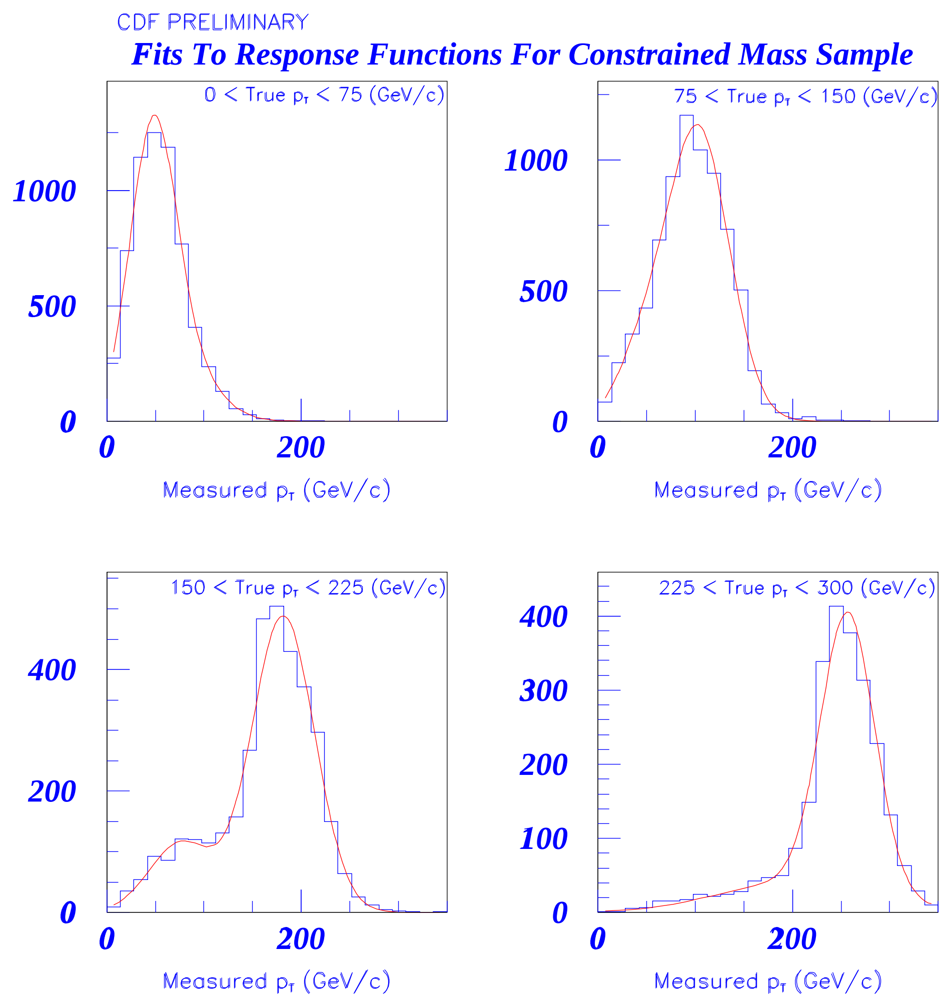
Make measurement using only jet-side top quarks

- In principle can measure $p_T(t\bar{t})$ system
- Simply no resolution to do so with statistics

p_T Response Functions

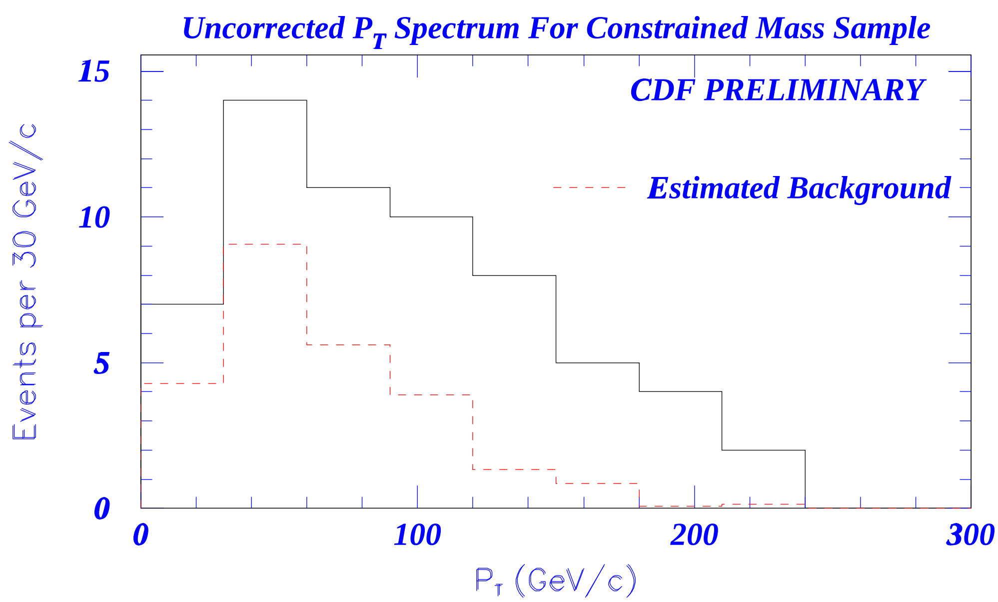
Measured p_T smearing using MC/detector simulation

- Use HERWIG MC and full detector model



- Most smearing arises from incorrect jet assignments
- Blame it mostly on "stupid" algorithm

Uncorrected p_T Distribution



- 61 events pass selection criteria
- Background distribution normalized to estimated rate
  - We estimate $N_{bgd} = 24.6 \pm 5.8$ events

Resulting Fitted p_T Distribution

Perform likelihood fit to response functions and bkg shape

- Fit tagged and untagged events with different templates
- Use "bootstrap" technique to minimize assumptions about shape of p_T spectrum within each true bin
- Define

$$R_i \equiv \frac{\text{fraction in } i\text{th bin}}{\sigma_{t\bar{t}}}$$

Apply p_T-dependent acceptance correction

- Acceptance increases $\sim 35\%$ with p_T

$$\begin{aligned} R_1 &= 0.29^{+0.18}_{-0.18} \\ R_2 &= 0.42^{+0.18}_{-0.18} \\ R_3 &= 0.29^{+0.12}_{-0.10} \\ R_4 &= 0.000^{+0.035}_{-0.000} \end{aligned}$$

Magnitude of Systematic Uncertainties in p_T

Used combination of MC and data to estimate systematic uncertainties

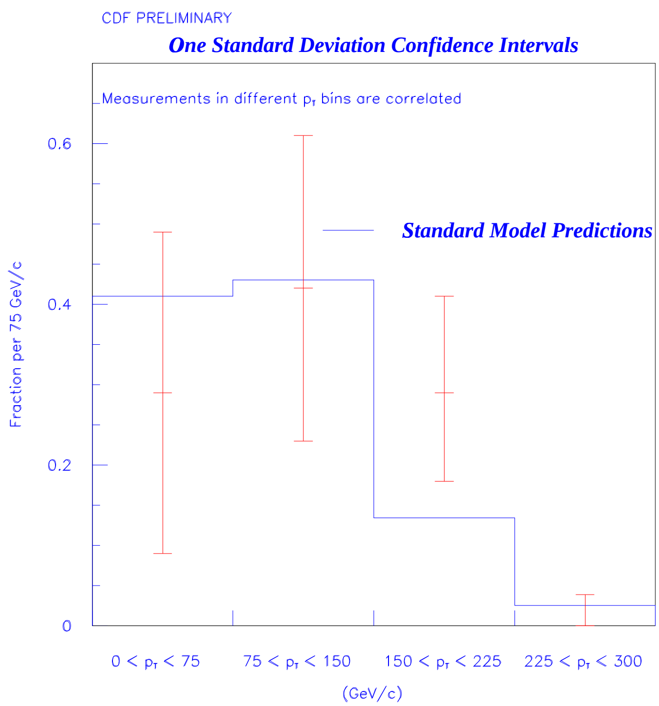
- Largest relates to how well we "unfold" data
  - Assume standard model distribution within bin
  - "Bootstrap" removes most of the bias
- Worst case δR_i is $\sim$ 0.06
- Uncertainties are dominated by small sample size

CDF PRELIMINARY

Syst.	δR_1	δR_2	δR_3	δR_4	$\delta(R_1 + R_2)$
m_t	$^{+0.026}_{-0.000}$	$^{+0.00}_{-0.027}$	$^{+0.023}_{-0.000}$	$^{+0.000}_{-0.018}$	$^{+0.006}_{-0.012}$
ISR	$\pm$0.016	$\pm$0.011	$\pm$0.005	$\pm$0.005	$\pm$0.007
FSR	$\pm$0.038	$\pm$0.023	$\pm$0.010	$\pm$0.005	$\pm$0.015
JES	$^{+0.020}_{-0.028}$	$^{+0.037}_{-0.006}$	$^{+0.000}_{-0.008}$	$^{+0.000}_{-0.003}$	$^{+0.014}_{-0.000}$
Q^2	$\pm$0.025	$\pm$0.008	$\pm$0.008	$\pm$0.010	$\pm$0.016
p_T	$\pm$0.032	$\pm$0.045	$\pm$0.055	$\pm$0.016	$\pm$0.036
Acceptance	$^{+0.010}_{-0.023}$	$^{+0.013}_{-0.012}$	$^{+0.016}_{-0.014}$	$^{+0.000}_{-0.000}$	$^{+0.025}_{-0.011}$

Top Quark Differential Cross Section

$$R_1 + R_2 = 0.72^{+0.13}_{-0.13}(\text{stat})^{+0.06}_{-0.06}(\text{syst})$$
$$R_4 < 0.114 \text{ at } 95\% \text{ C.L.}$$



p_T Bin	Measured Fraction of Top Quarks
$0 < p_T < 75$ GeV/c	$R_1 = 0.29^{+0.18}_{-0.18}(\text{stat})^{+0.08}_{-0.08}(\text{syst})$
$75 < p_T < 150$ GeV/c	$R_2 = 0.42^{+0.18}_{-0.18}(\text{stat})^{+0.05}_{-0.07}(\text{syst})$
$150 < p_T < 225$ GeV/c	$R_3 = 0.29^{+0.12}_{-0.10}(\text{stat})^{+0.06}_{-0.05}(\text{syst})$
$225 < p_T < 300$ GeV/c	$R_4 = 0.000^{+0.035}_{-0.000}(\text{stat})^{+0.019}_{-0.000}(\text{syst})$

Limitations from Calorimetry

Have "stepped back" and considered limitations

1. Have difficulty reconstructing jet "objects"
2. Not able to properly reconstruct events
3. Intrinsic calorimeter resolution plays little role

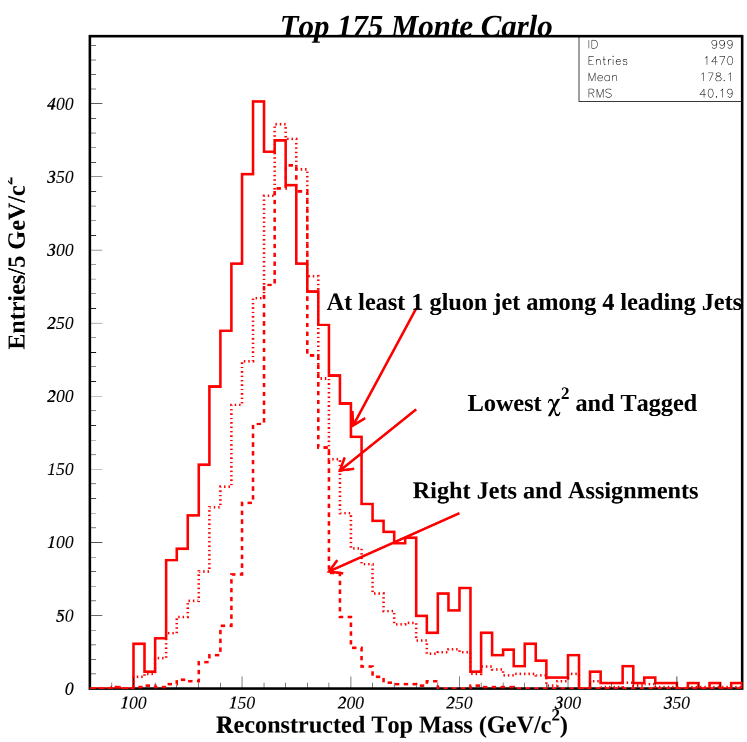
Can demonstrate using "standard" CDF simulation

- Reconstruct and identify correct partons
- Vary calorimeter response
  - Back-of-the-envelope implies $\sigma_M \sim 6 - 8$ GeV/c^2
  - Reality is $\sigma_M \sim 25 - 30$ GeV/c^2

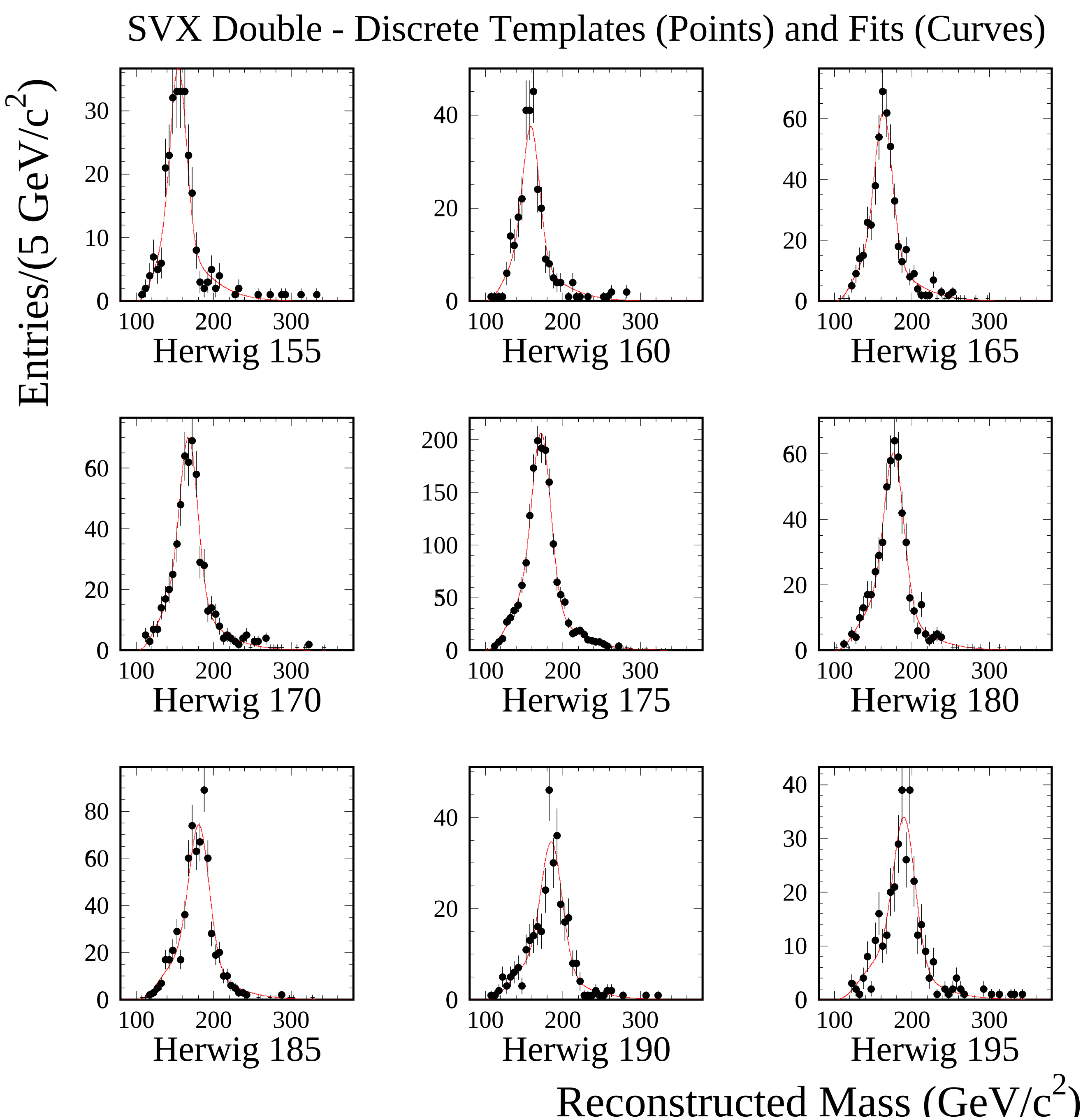
Effects on Top Mass

Have investigated source of these resolution effects

- "Hard gluon radiation" plays pivotal role
  - Also create dominate systematic uncertainty
- Getting parton-jet assignments right next
- Intrinsic calorimeter resolution comes third

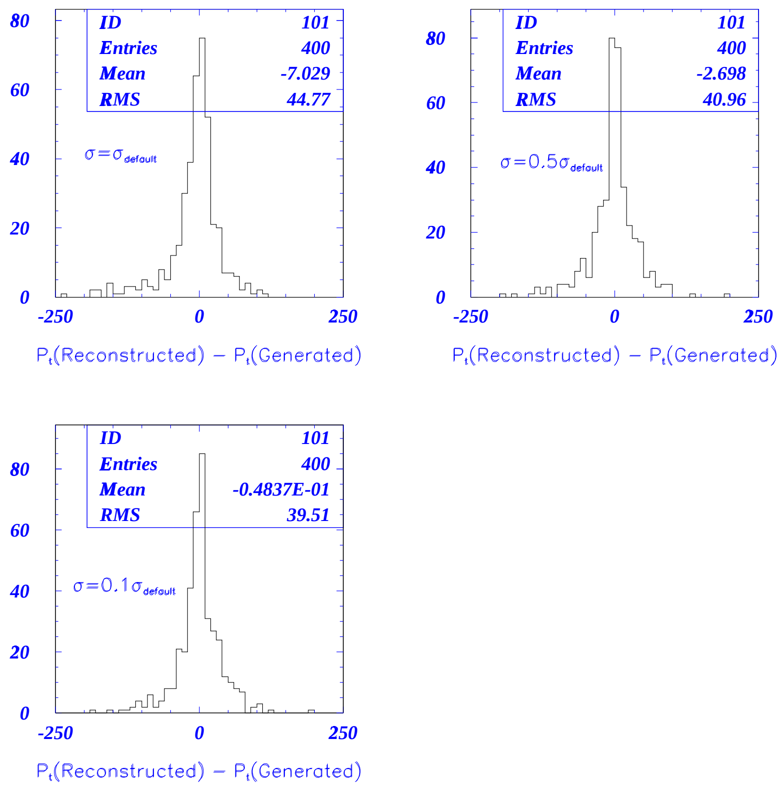


Mass Resolution of Double Tagged Events



Contributions to p_T Resolution

Top quark p_T resolution insensitive to intrinsic response



Jet resolution dominated by "hard" gluon radiation/hadronizati

- Can get p_T RMS to 7 GeV/c when turned off
- Increases rate of "correct" combinations by $\sim$ 50%

Summary of Kinematic Limitations

Gains have to come from improved jet/event reconstruction

- Tagging both b-jets makes significant difference
  - Loose $40 - 50\%$ of data
  - OK if lots of events to begin with

- Improvements in jet algorithms
  - $R = 0.4$ fixed cone algorithm not perfect
    * Need sophisticated "pattern recognition"
    * Reduce out-of-cone corrections
    * Reduce UE contribution?
  - Hard to make big improvements

- Use improved resolution to enhance kinematic constraints
  - Makes χ^2 technique more effective at selecting right combination
  - Allows one to sort out 5 and 6-jet combinations

Expected Improvements for Run II

For Run II at Tevatron

- Will have the same fundamental calorimetry
- Advantage will be in larger statistics
  - Biggest gain will come from improving reconstruction algorithm

Also can control systematics better

- Systematics in M_{top} limited by gluon radiation
- Calorimetery response will continue to challenge
  - Use $W \to q\bar{q}'$ shape

Most favourable estimates give

- Jet-parton energy scales $1 - 2$ GeV
- Event modelling 1 GeV

Top at the Large Hadron Collider

Top physics at the LHC looks a lot easier

- Trick is that the σL is $\times 10^4 - 10^5$
- Can now literally throw away $t\bar{t}$ events
  - Concentrate on events with high top p_T
  - Avoid combinatorial problems
  - High E_T jets that are more collimated

Have essentially the same problems

- Limited by large jet multiplicities
- Effects of overlapping jets, UE events

Summary

Calorimetry plays crucial role in top quark physics

- Charged lepton ID
- Neutrino measurement
- Jet reconstruction

Biggest effects have to do with sorting out the physics

- Real gains will come from using data more intelligently
  - Improve jet clustering algorithms
  - Deal with combinatorial problems more effectively
  - Employ b-tagging more creatively
- Better intrinsic resolution helps (but slowly)

Certainly much to do for Run II

- Expect $\times 50$ more data
- Much opportunity to optimize