Top Quark Properties

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Overview

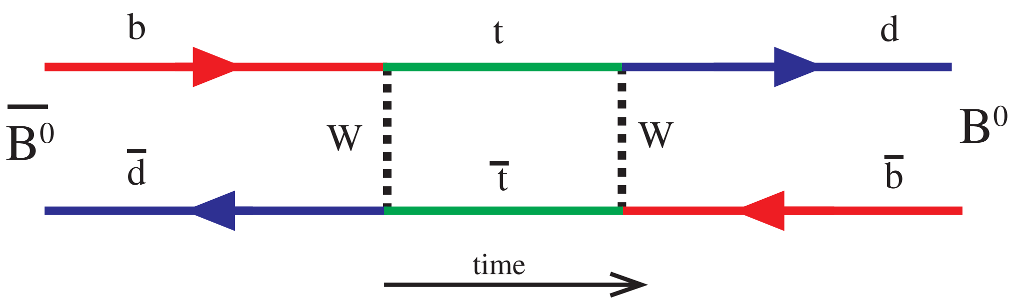
- What We Learn From the Top Quark
- Overview of Experiments
- Top quark mass and cross section
- Single top production
- Top quark P_T distribution
- On to Run II

Work done in collaboration with Pierre Savard and Andrew Robinson

The Top Quark in the Standard Model

The SM "needs" a massive top quark

- b quark requires an SU(2) partner
  - suppression of FCNC decays
  - $e^+e^- \to b\bar{b}$ scattering
- Many loop effects in SM driven by M_{top}
  - W/Z boson mass ratio
  - $b - \bar{b}$ mixing
  - Rare K decays



Direct observation of top in 1995

- Confirmed all these predictions
- Gave us a "free quark" system to study

$\Rightarrow$ New frontier in particle physics

Recent History of Top

CDF and DØ collected ~ 100 pb^{-1} of data in 92-96

- 1.8 TeV $p\bar{p}$ collisions
- Collected events with
  - High P_T leptons ($P_T \gtrsim 10$ GeV/c)
  - $\not{E}_T > 25$ GeV
  - High P_T jets ($P_T \gtrsim 100$ GeV/c)
- In 1995, presented evidence for $t\bar{t}$ production

Subsequent studies have strengthened this

- Different techniques used to look at the same data
  - Kinematic distributions
  - Neural network approaches
- Have verified consistency in all channels
  - See reasonable signals in τ lepton final states
  - All hadronic modes are also understood

SM Top Quark Phenomenology

Top quarks decay via the weak force

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

Can be viewed as a "pure" charged current

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

- Toponium doesn't have time to form
- T mesons $\sim$ degenerate (if there was time...)

Decay dominated by "longitudinal W^+"

- Means the W^+ prefers helicity 0
- Result of large top and W^+ mass

What Do Top Decays Tell Us?

SM predicts "pure" $V - A$ decay

- clear test of polarisation at decay vertex

$$\frac{W_{\mathrm{long}}}{W_{\mathrm{T}}} \sim \frac{1}{2}\left(\frac{M_t}{M_W}\right)^2 \sim 2.2$$

- V_{ts} CKM matrix elements
- Constraints on other SM parameters (eg. A_{LR})
- Effectively another consistency check of SM

Sensitive to some classes of "new physics"

- Higgs couples strongly to top
- Could decay into a SUSY H^+

$$t \to H^+ b$$
$$\qquad\quad \hookrightarrow \tau^+ \nu_\tau$$

- Top quark might be "special" in unexpected way
  - New physics that couples to $t\bar{t}$ system
  - Low Scale Gravity a good recent example

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)

Used these samples for top quark measurements

What are the Interesting Top Properties?

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

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

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

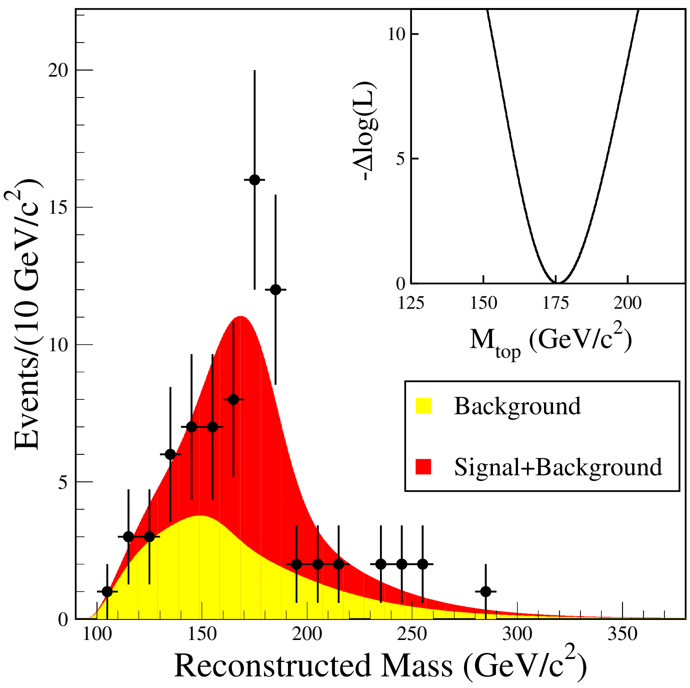
- Top Quark Decay Kinematics
  - SM expects decay to be polarized
  - Have made first measurement of polarization

Top Quark Mass

Measurements now limited by systematic uncertainties

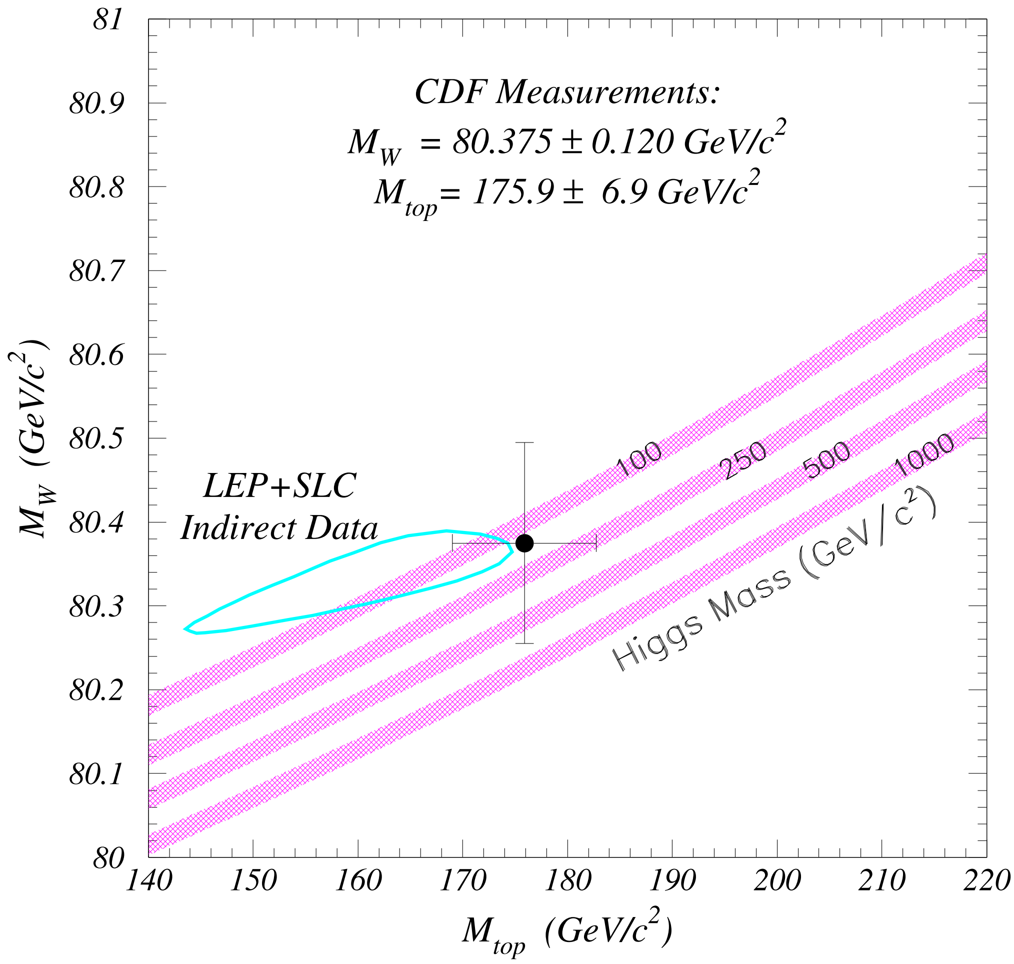
- Overall systematic uncertainty is ~ 5 GeV/c^2
  - Dominated by uncertainties in soft gluon contributions and energy scale

- Statistical uncertainty limit our ability to constrain this



The final Run I values are

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


CDF Measurements:
$M_W = 80.375 \pm 0.120$ GeV/c^2
$M_{top} = 175.9 \pm 6.9$ GeV/c^2
LEP+SLC
Indirect Data
100
250
500
1000
Higgs Mass (GeV/c^2)
M_W (GeV/c^2)
M_{top} (GeV/c^2)
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

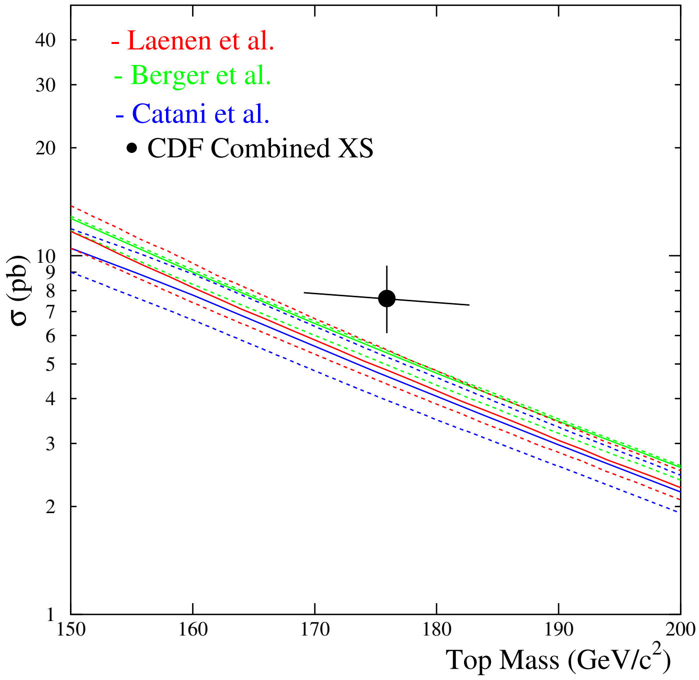
Top Quark Production Cross Section

The cross section obtained by a fit to

- Lepton + jets rate
- Dileptons rate
- All hadronic event rate

Depends on M_{top} because of acceptance

$$\sigma_{t\bar{t}} \quad = \quad 7.6^{+1.8}_{-1.5} \text{ pb}$$

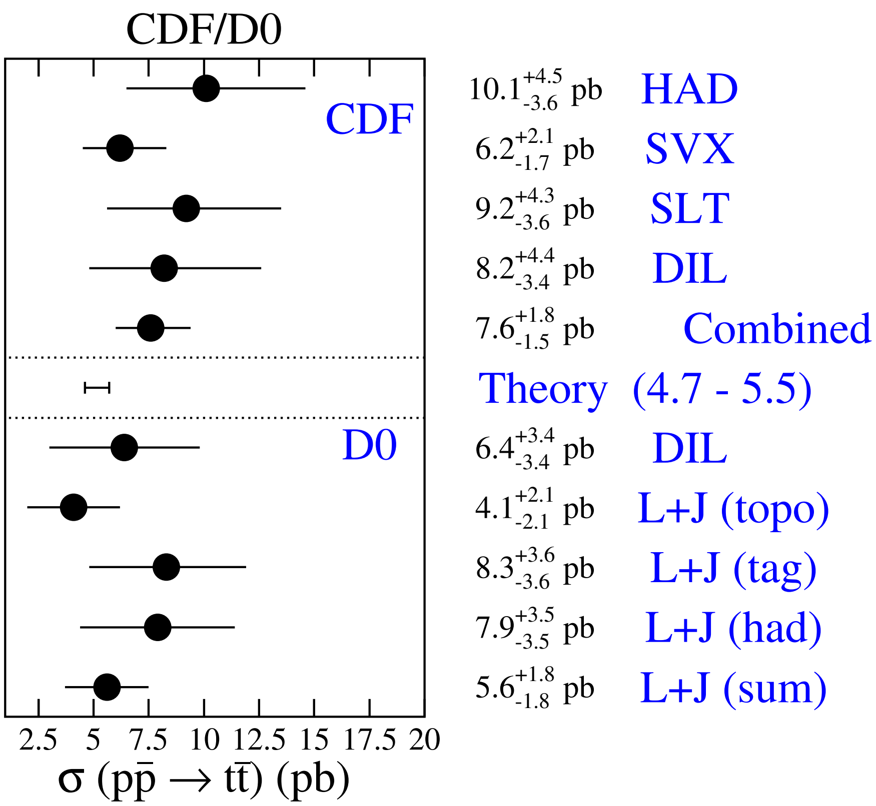


Rarest process ever measured in hadron collider!

- Theory predictions range from 4.7 to 5.5 pb

Comparison with DØ

Measurements by DØ also quite consistent



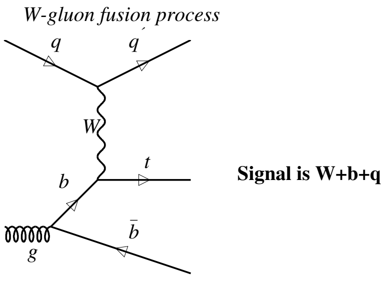
Single Top Production

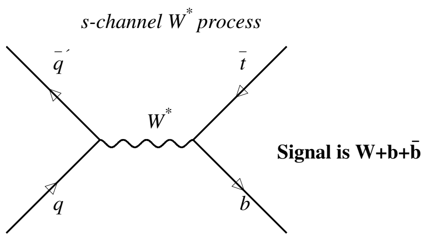
Single top production is a much lower rate process

- Sensitive to Γ_t
- Also could have contributions from non-SM sources

There are two primary SM production processes

1. t-channel $W-g$ fusion $\Rightarrow W^+bq$ final state
2. s-channel W^* process $\Rightarrow W^+b\bar{b}$ final state





- Predicted cross sections are 1.7 ± 0.3 and 0.7 ± 0.1 pb

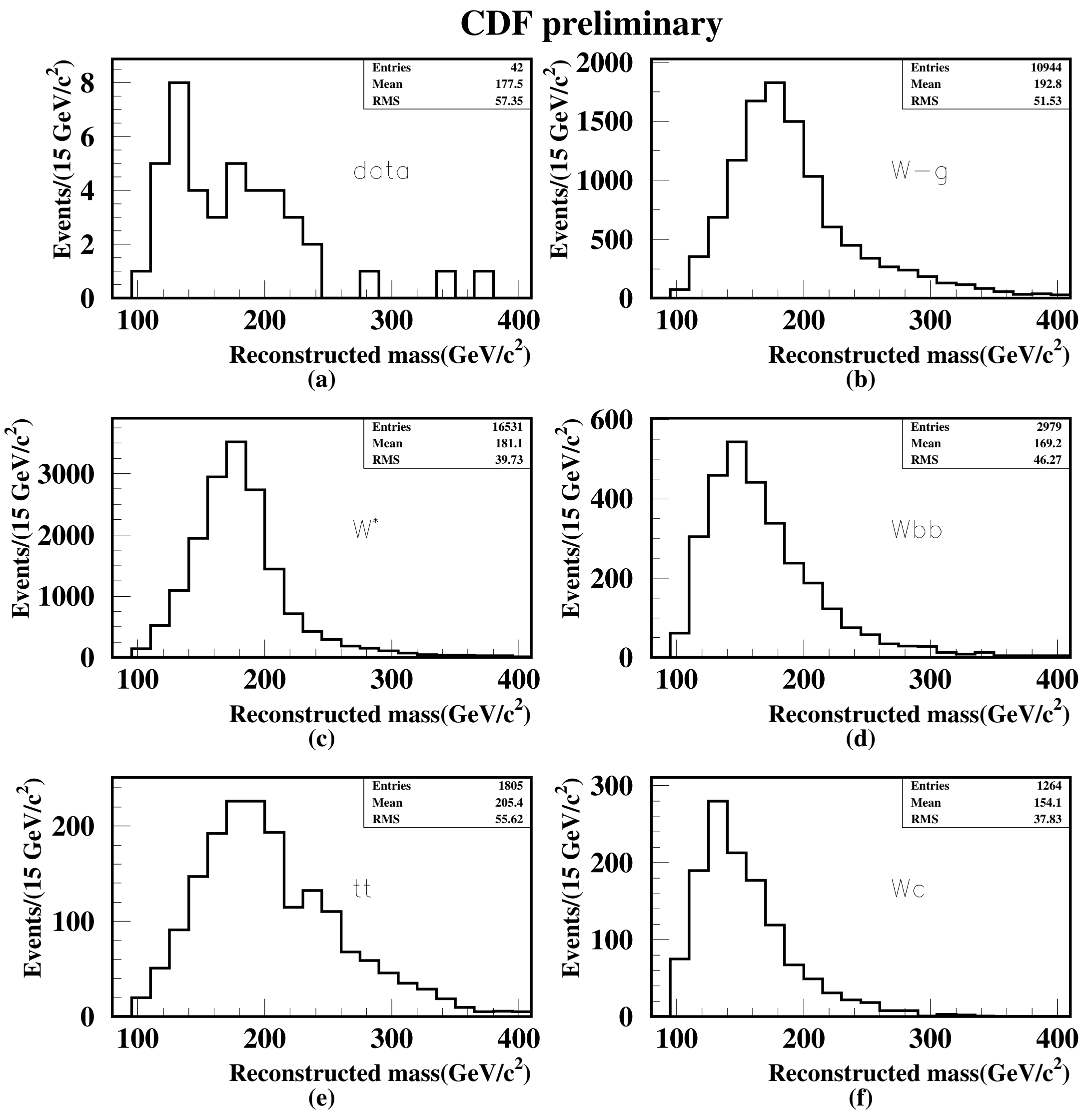
Search Technique

Kinematics of processes somewhat different

- Use almost the same selection for both processes
  - Exactly 2 jets with $E_T > 15$ Gev and $|\eta| < 2.0$
  - At least one b-tagged jet
  - Require $145 \leq M_{top} \leq 205$ GeV/c^2
- Differences are
  - For W-gluon fusion, require exactly one b-tag
  - Have different acceptance

	W^*	W-gluon
σ_{theory} (pb)	0.73 ± 0.10	1.7 ± 0.3
Integrated luminosity (pb^{-1})	106 ± 4	106 ± 4
$W + 2$ jet acceptance (%)	3.4 ± 0.7	3.3 ± 0.6
SVX b-tag efficiency (%)	37.5 ± 3.1	24.8 ± 2.0
Number of expected events	1.0 ± 0.2	1.5 ± 0.3

Top Mass Reconstruction



Results of Search

Observed 42 events in this sample

- Largest single background are mis-tags
  - $t\bar{t}$ itself is a problem now

Process	Event Yield
$Wb\bar{b} + Wc\bar{c}$	9.0 ± 2.5
Mistags	6.3 ± 2.6
Wc	4.3 ± 1.5
Non-W	2.3 ± 1.0
Miscellaneous	2.1 ± 0.6
$t\bar{t}$	5.7 ± 1.3
W-gluon	1.5 ± 0.3
W^*	1.0 ± 0.3
Total expected	32 ± 5
Observed	42

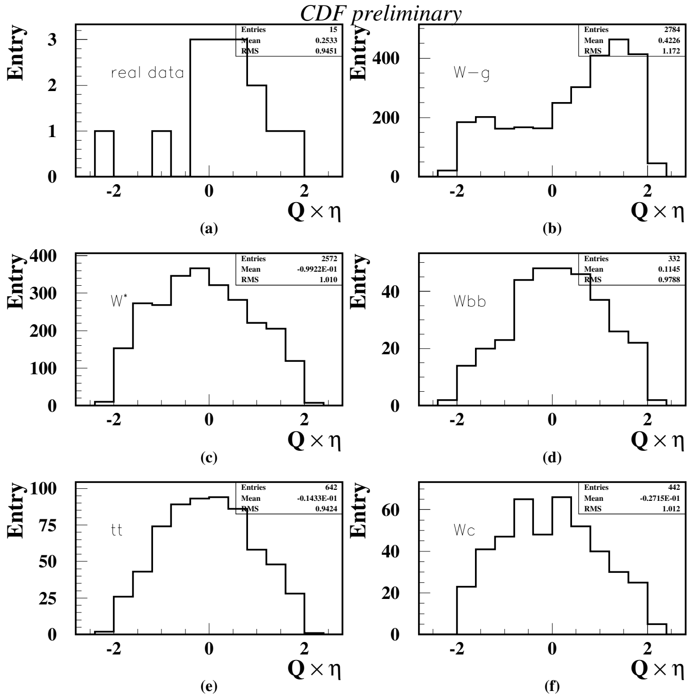
Not yet sensitive to SM single top rate

- Can set limits separately on different processes

Single Top Production from W-gluon Fusion

Can exploit a rapidity correlation

- Top quark and light quark are in same hemisphere
- We fit the $Q \times \eta_{jet}$ distributions where $Q = Q_{jet} \times Q_{lepton}$



Perform maximum likelihood fit to signal + backgrounds

- Constrains single top rate from this process
- Fit gives $N_{W-\text{gluon}} = 1.4^{+4.2}_{-3.4}$ events

$$\Rightarrow \sigma_{W-\text{gluon}} \quad < \quad 15.4 \text{ pb}$$

Single Top Production from W^* Production

Essentially all the information is in the observed yield

- Some discrimination in top mass distribution
- Set upper limit in similar manner to W-gluon fusion case

Perform maximum likelihood fit to signal + backgrounds

- Use likelihood function to constrain single top rate
- Fit gives $N_{W^*} = 7.3^{+7.4}_{-6.7}$

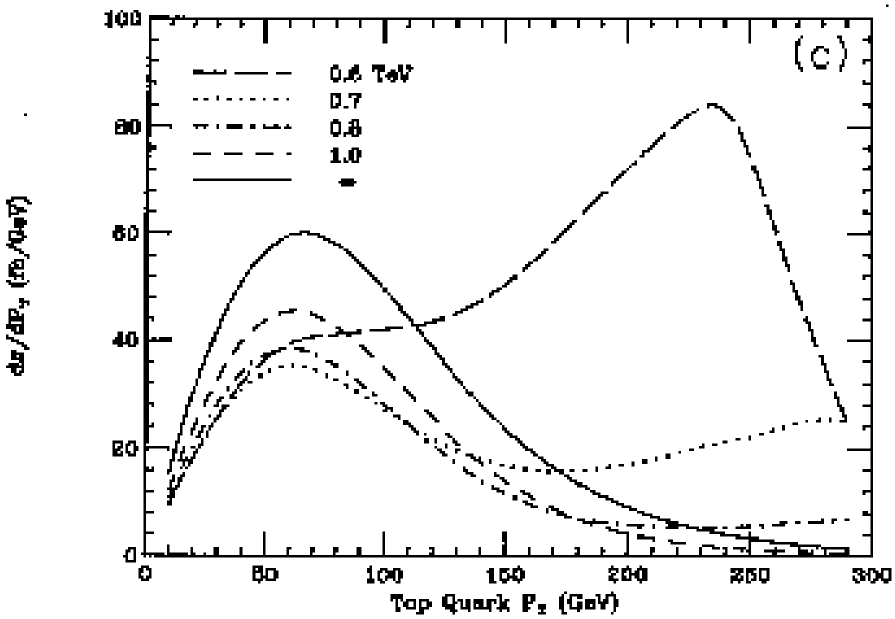
$$\sigma_{W^*} \quad < \quad 15.8 \text{ pb}$$

So still well away from SM rate

- Can conclude that there is no huge anomaly
- It is a feasable measurement for Run II

Top Quark Transverse Momentum Distribution

- Goal is to produce model-independent constraints on the top quark P_T distribution
  - Produce a set of confidence limits on $\frac{d\sigma_t}{dP_T}$
  - Limited to large bins ($\Delta P_T = 75$ GeV/c)
- Properly correct for resolution smearing and acceptance
- Can test models (such as ADD) in which the P_T spectrum is more sensitive to new physics then the total cross section



Event Selection

Use the "standard" lepton + jets event selection:

- Single isolated $e(\mu)$ having $P_T > 20$ GeV/c and $|\eta| < 1.0$
- $\not{E}_T > 20$ GeV
- ≥ 4 jets, 3 with $E_T > 15$ GeV and $|\eta| < 2.0$
  - fourth with $E_T > 8$ GeV, $|\eta| < 2.4$

To increase the signal significance, require that

$$N_{\text{jet15}} \geq 4 \text{ or } N_{tag} \geq 1 \ .$$

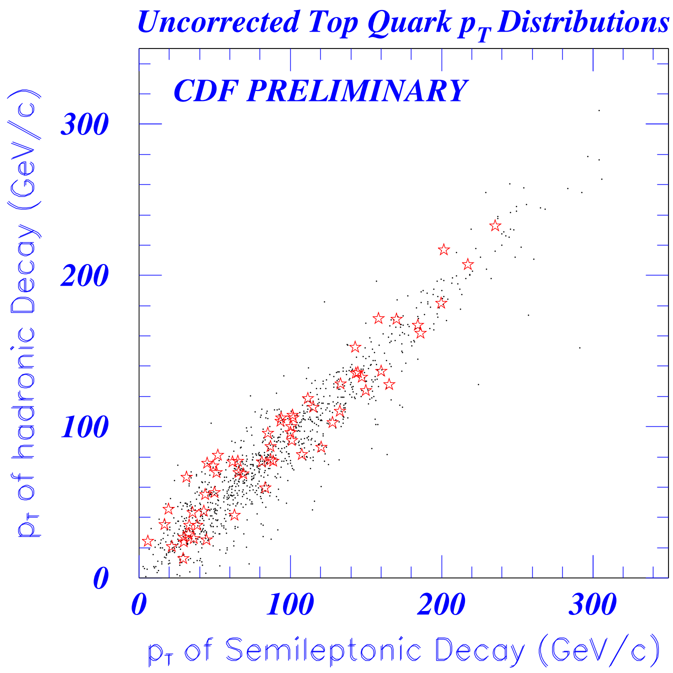
Kinematically fit event, constraining $M_{top} = 175$ GeV/c^2

- Require $\chi^2 < 10$

$\Rightarrow$ Left with 61 events

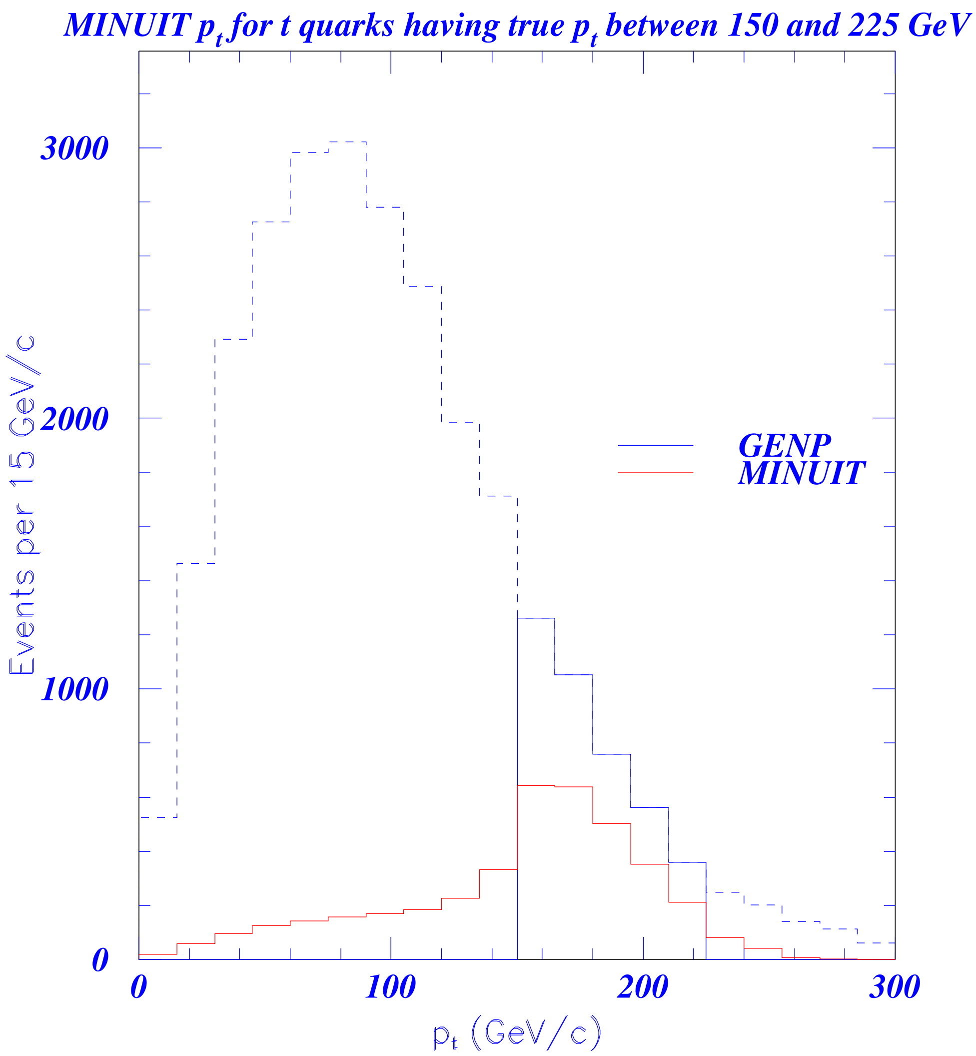
Measurement of P_T

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



- Make measurement using only jet-side top quarks

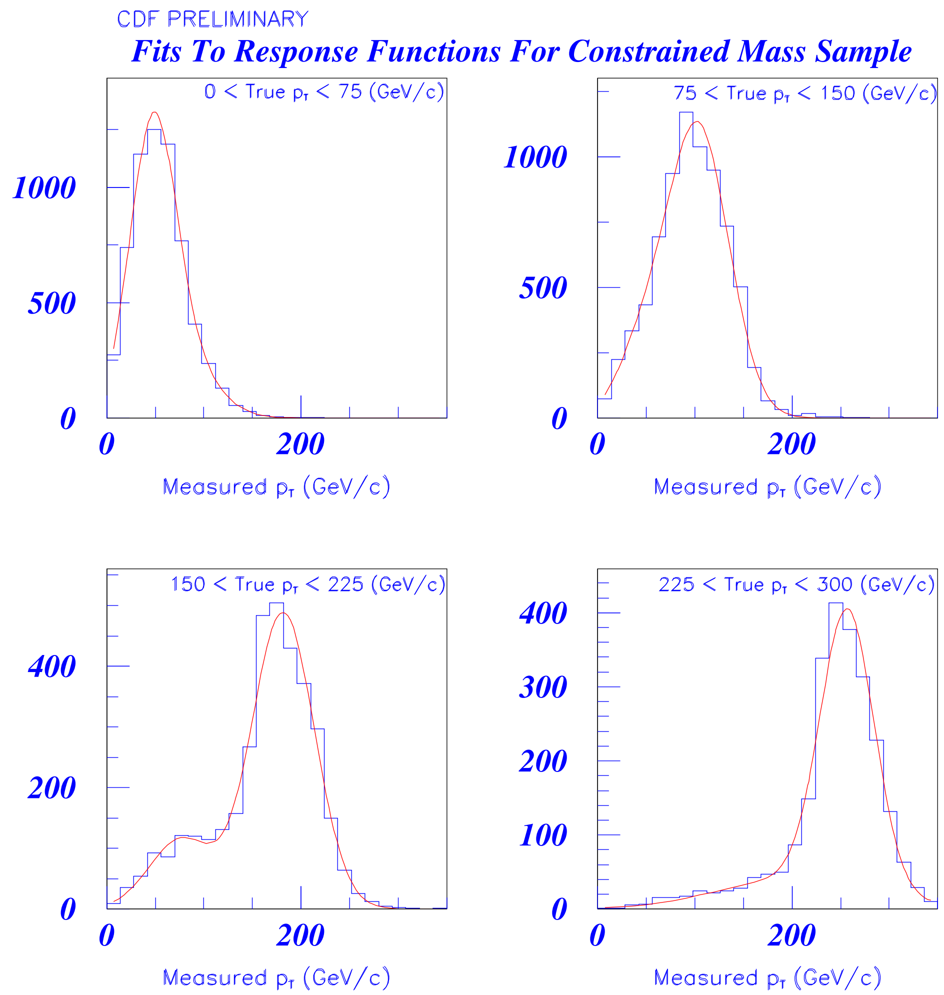
Output of the Fitter



Only $\sim 50\%$ of top quarks in mass sample with true P_T in the range $150 \leq P_T \leq 225$ GeV, have reconstructed P_T in the correct bin!

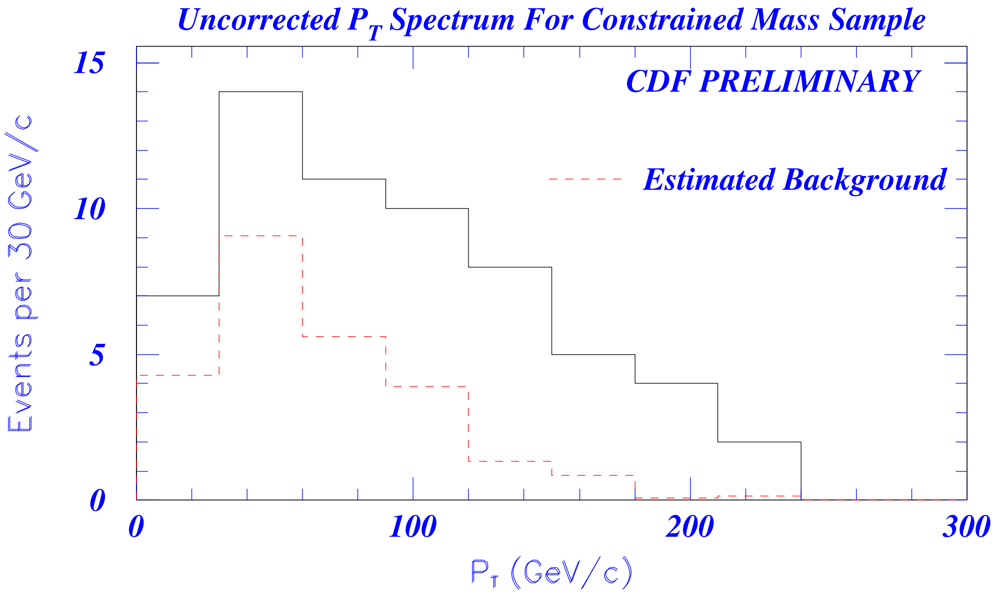
P_T Response Functions

Have measured P_T smearing using MC and detector simulation



- Use standard HERWIG MC calculations
- Most smearing arises from incorrect jet assignments

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 unbinned likelihood fit to response functions and bkg shapes

- 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 with P_T

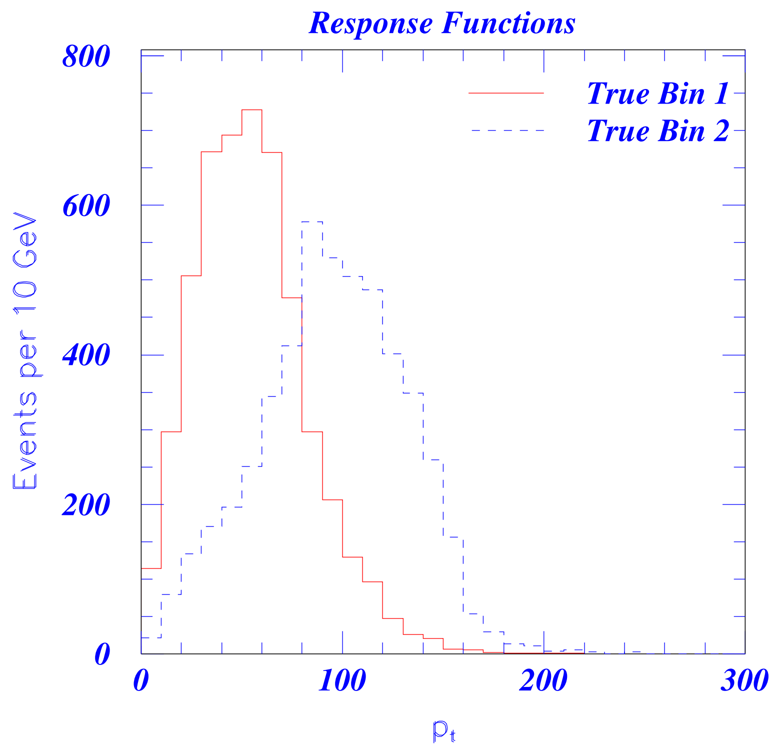
Acceptance Corrected Results:

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

Combining R_1 and R_2

R_1 and R_2 have strong negative correlation

- large uncertainties from fit
- Makes sense to combine these into single measurement



Resulting combined fraction of low P_T top quarks is

$$R_1 + R_2 = 0.68 \pm 0.13$$

Verification of Methodology

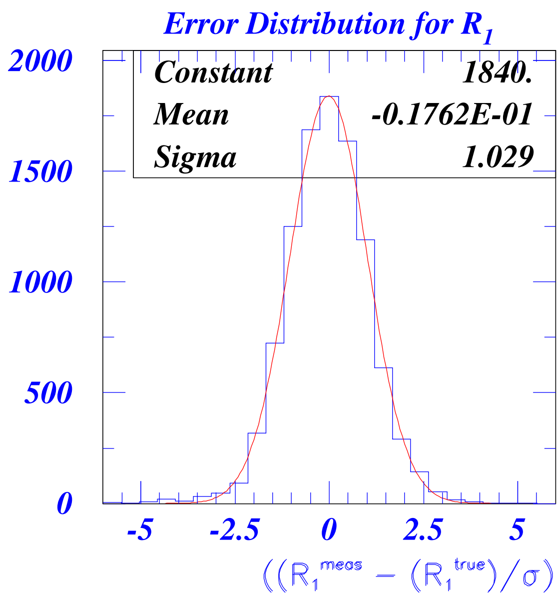
Use MC technique to verify robustness of technique

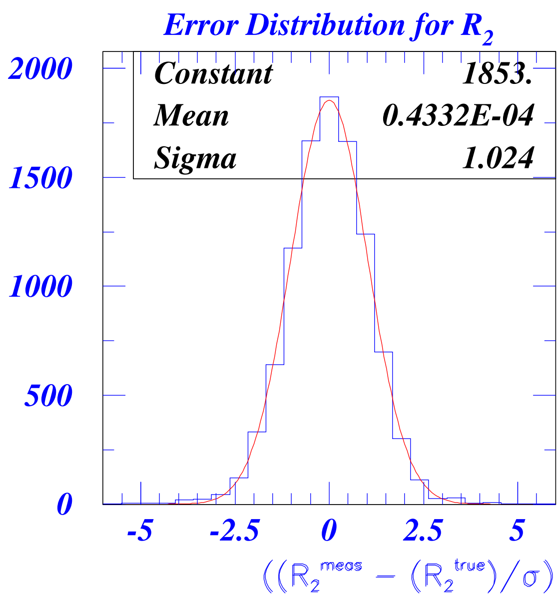
Sample	N_{ev}	$N_{bgd} \pm \sigma_{bgd}$
No Tag	32	18.9 ± 5.6
Tagged	29	6.4 ± 1.3

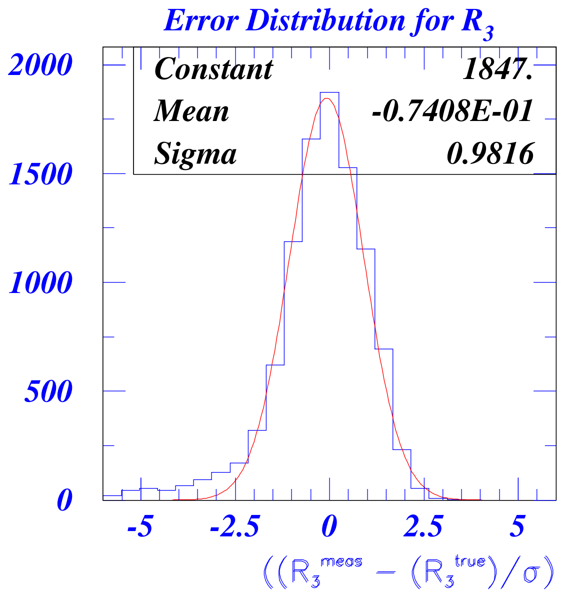
Perform MC Carlo experiments on random samples of 32 untagged and 29 tagged events:

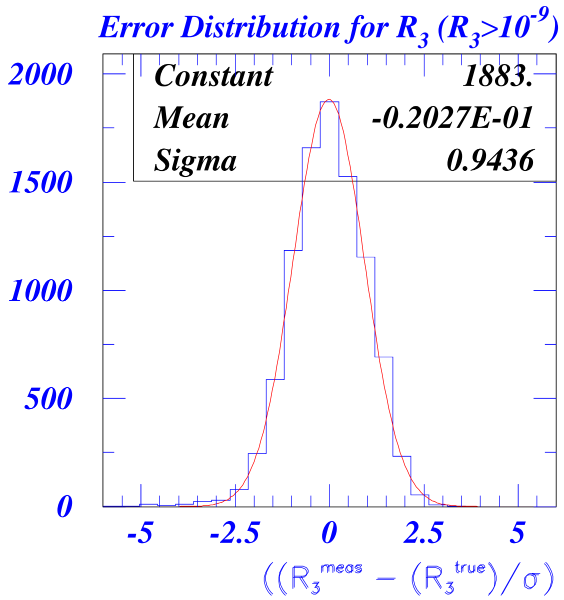
- Assume background in each tagging subsample distributed as $N(N_{bgd}, \sigma_{bgd})$
- Draw the appropriate numbers of background and signal events and run analysis
- Compare means of distributions to the expected SM P_T distribution

So. . . Does all this work?



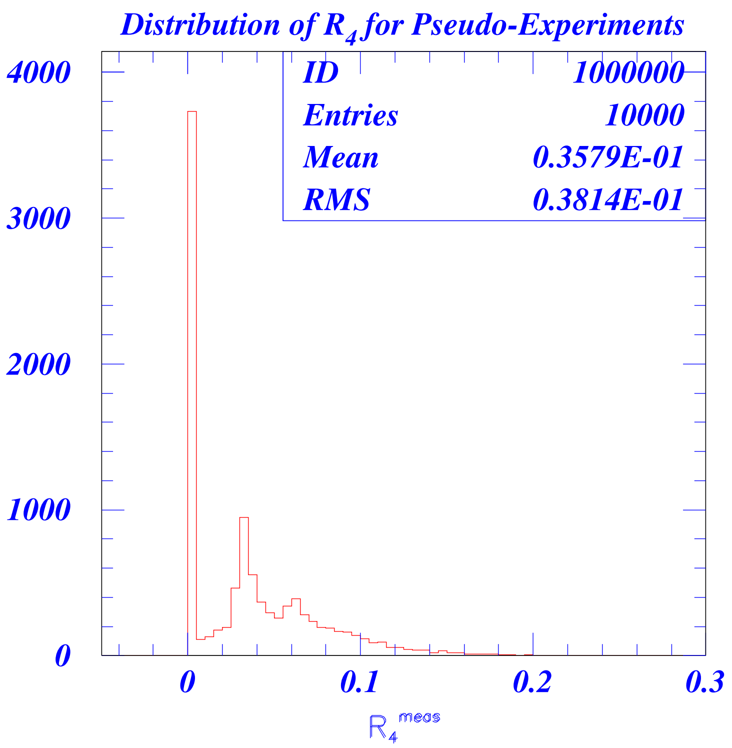






Problems in small fraction(4%) of the pseudo-experiments, flagged by a very small value of R_3.

Upper Limit in Highest P_T Bin



Examine the one-sided upper limit:

$$P = \frac{R_4^{\text{true}} - R_4^{\text{meas}}}{\sigma^+}, \qquad (1)$$

- Expect that $P > 1$ will occur 16% of the time
- Observe 17.5%

Confidence Level Interval on R_4

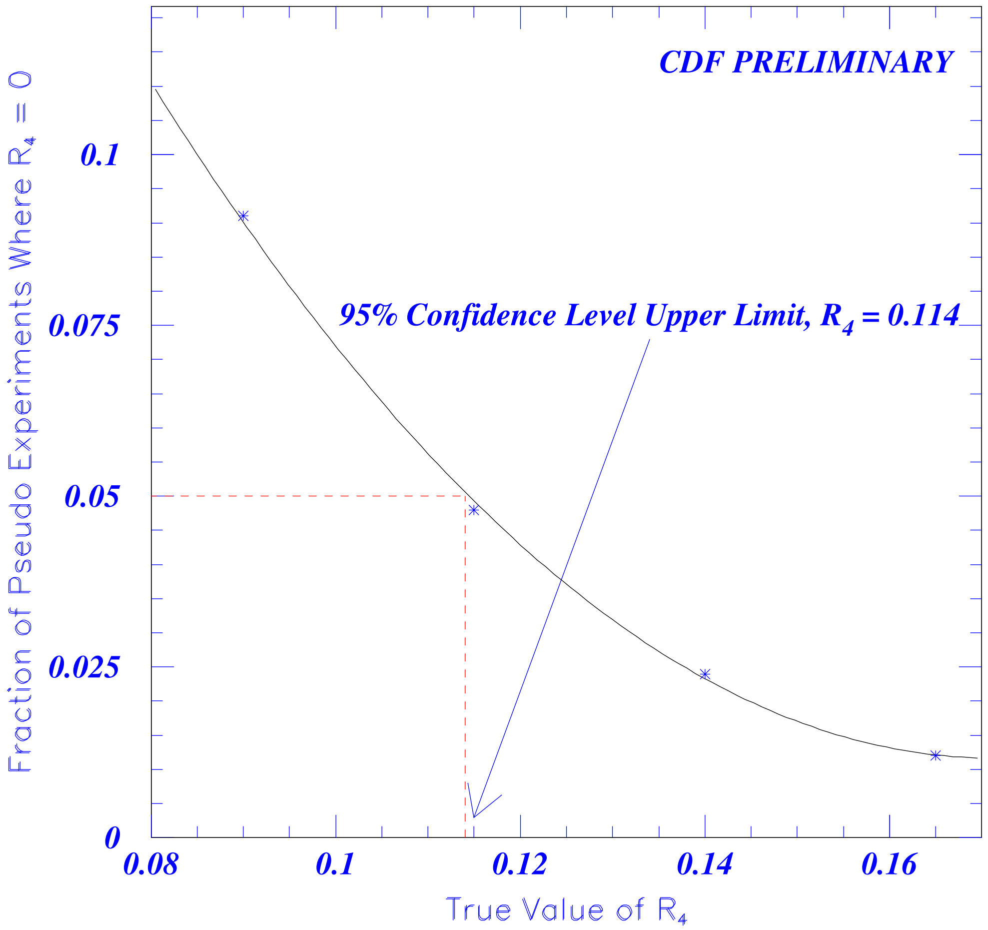
Obtain $R_4^{\text{fit}} = 0$ (fraction of top with $P_T > 225$ GeV/c)

- Set a 95% CL limit using a MC technique
  - Analyze samples of MC events with varying R_4^{true}.
  - Smear R_4^{true} in each with Gaussian distribution with a width equal to systematic uncertainty
  - Determine value of R_4^{true} where only 5% of the pseudo experiments have $R_4^{\text{fit}} = 0$

CDF PRELIMINARY

Systematic Effect	$\delta(R_4)$
Background Model	± 0.0028
Jet Energy Scale	$^{+0.0007}_{-0.0042}$
No Initial State Radiation	± 0.0045
Final State Radiation	± 0.0095
Flat P_T Spectrum	± 0.0157
$m_t = 180$ GeV	-0.0160

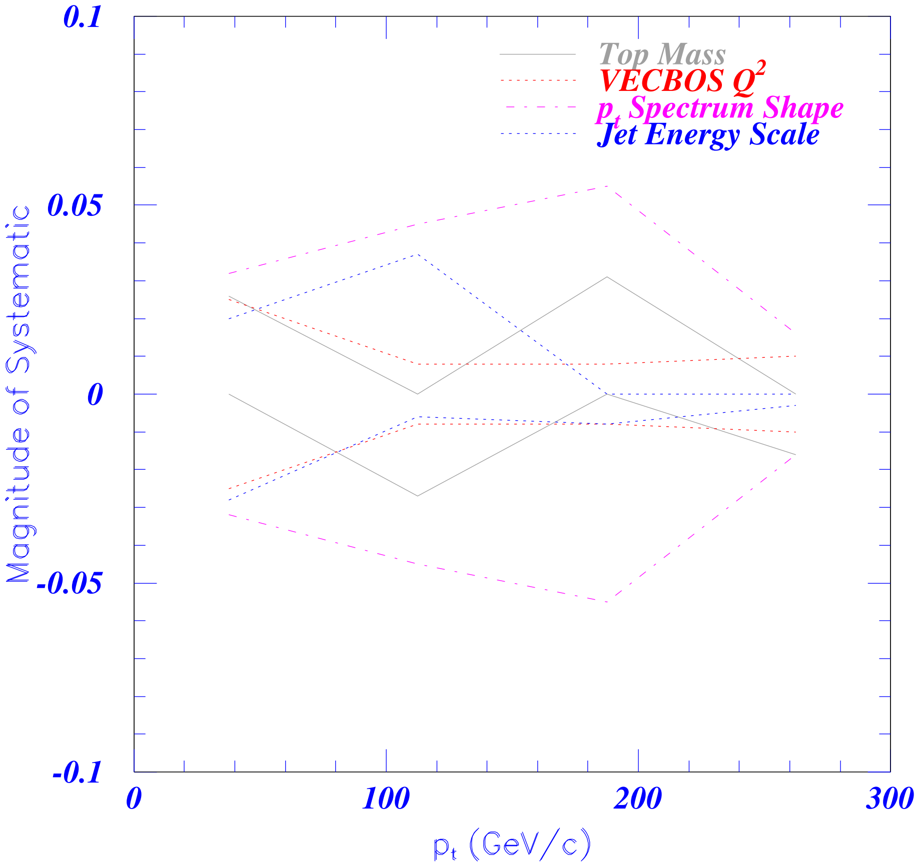
95% Confidence Level Upper Limit



In agreement with result obtained by integrating under the likelihood function.

Without systematics, $R_4 < 0.109$ at 95% CL

Magnitude of Various Systematics

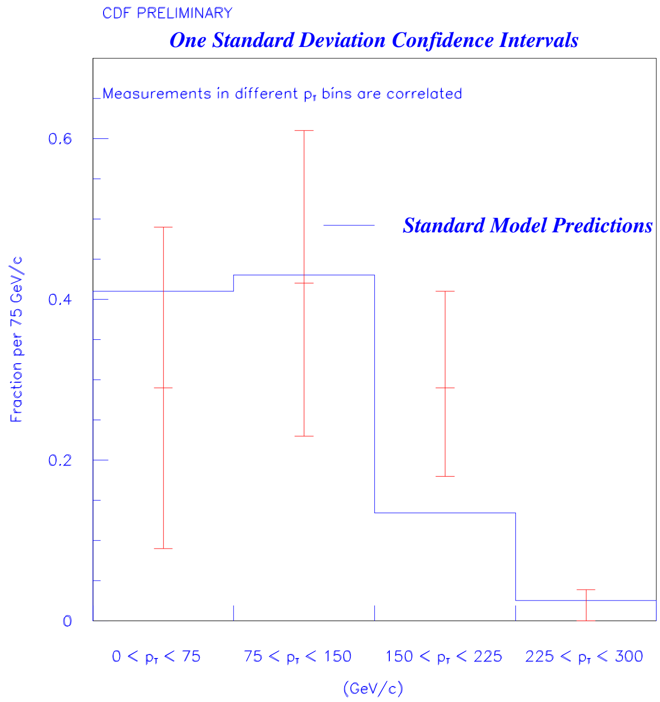


CDF PRELIMINARY

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	±0.016	±0.011	±0.005	±0.005	±0.007
FSR	±0.038	±0.023	±0.010	±0.005	±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	±0.025	±0.008	±0.008	±0.010	±0.016
P_T	±0.032	±0.045	±0.055	±0.016	±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

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

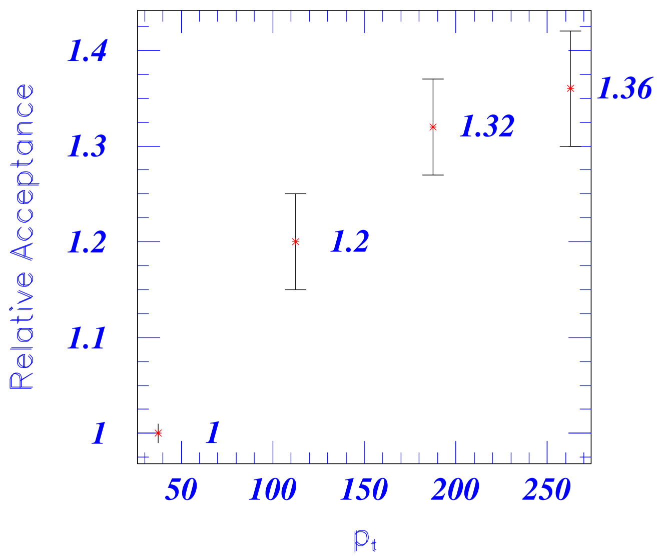


P_T Bin	Measured Fraction of Top Quarks
$0 < P_T < 75$ GeV/c	$R_1 = 0.29^{+0.18}_{-0.18}(\text{stat})^{+0.08}_{-0.08}(\text{syst})$
$75 < P_T < 150$ GeV/c	$R_2 = 0.42^{+0.18}_{-0.18}(\text{stat})^{+0.05}_{-0.07}(\text{syst})$
$150 < P_T < 225$ GeV/c	$R_3 = 0.29^{+0.12}_{-0.10}(\text{stat})^{+0.06}_{-0.05}(\text{syst})$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

Acceptance Calculations

Question: Are selection criteria/triggers biased in P_T?

- Generate large HERWIG+QFL$'$ samples, each constrained to have top quarks coming from one P_T bins, and count the fraction of events that pass cuts
- Only interested in Relative acceptance for each bin
- Estimate systematic uncertainty by recomputing results for most important systematic errors



Unsmearing Methodology

Break the data sample up into two subsamples and perform an unbinned likelihood fit to the data

- No Tag Hadronic (k=1)
- Tagged Hadronic (k=2)

Then perform simultaneous maximization of the following likelihood function in each of the tagging subsamples:

$$-\ln[\mathcal{L}_k] = \sum_{i=1}^{n_{data}} -\ln\left[(1 - B_k)\sum_{j=1}^{n_{bin}} R_j T_{jk}(P_T^i) + B_k V(P_T^i)\right] \qquad (2)$$

- R_i is the fraction of top quarks produced in true bin i
- B_1 is the background fraction in the untagged events.
- B_2 is the background fraction in the tagged events.
- The T_k, V are the response functions for the signal and background, respectively.

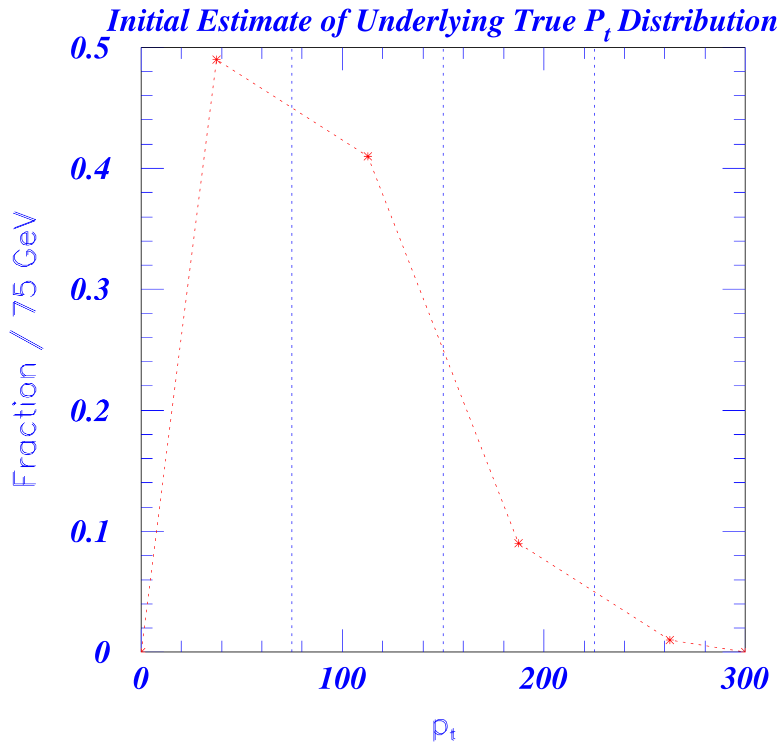
The signal ($T_{jk}(P_T)$) and background ($V(P_T)$) response functions are normalized to unity.

The B_i are constrained via Gaussian probability distributions about the background estimates.

The Bootstrap

- Methodology appears to be reasonably successful
- However, have overlooked one potential problem
- A given set of response functions is only valid for a particular assumption about how the P_T distribution varies within each true P_T bin!

Thus, we bootstrap:



After each iteration, perform rejection against new true P_T distribution to generate next set of response functions

Summary

Our work on top using Run I data coming to close

- Will complete P_T measurements
- Have $W' \to t\bar{b}$ analysis underway
- Would like to complete branching fraction study

All this sets the stage for Run II

- Will start data taking sometime in 2000 (April-Sep?)
- Run for 2-4 years, with goal to collect ~ 2 fb^{-1}
- Increase top quark sample $\times 50$

By the time ATLAS turns on,

- Top will be well-studied
  - Understood as a background
- We will be able to focus on those properties that are most crucial to extending our understanding of elementary particles