TOP QUARK STUDIES IN RUN II

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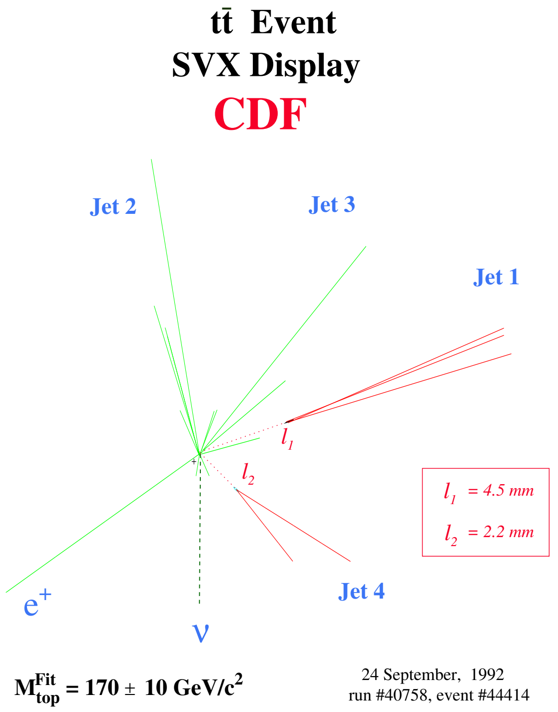
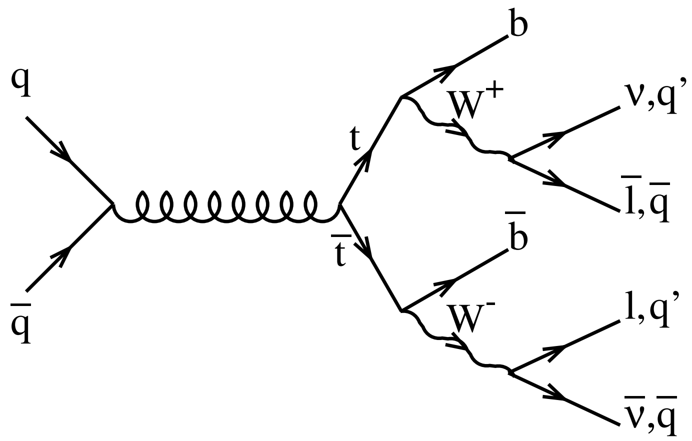


Introduction

Top Quark Production and Decay

Top pairs are produced 90% of the time via a $q\overline{q}$ diagram

$$p\overline{p} \rightarrow t\overline{t}$$



Within the SM top decays into W+b $\sim$ 100% of the time.

$W^+ \rightarrow$	$e^+\nu$	$\mu^+\nu$	$\tau^+\nu$	$u\overline{d}$	$c\overline{s}$
Br	1/9	1/9	1/9	3/9	3/9

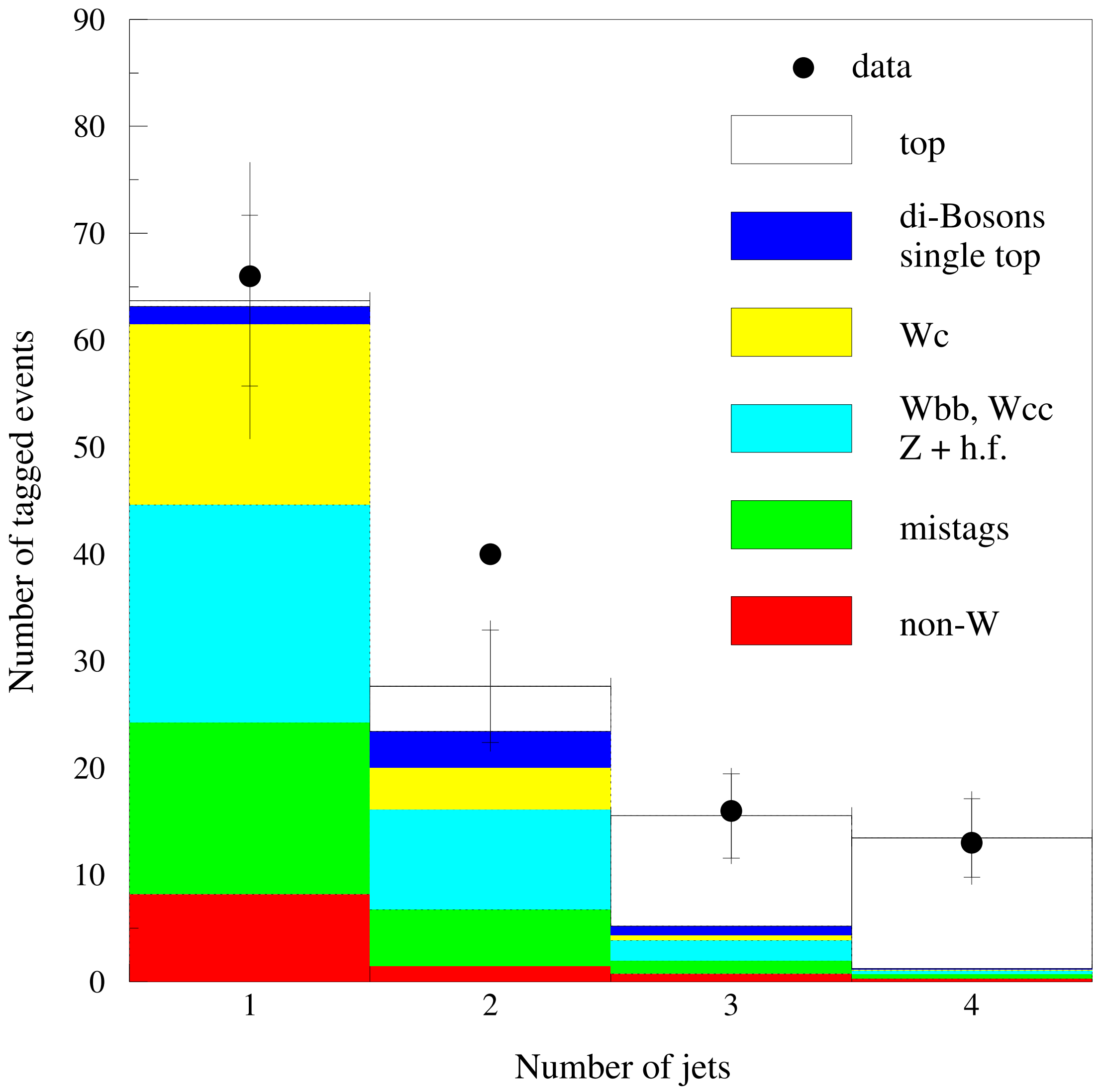
Event topologies are:

- Dilepton Channel ($\ell\nu\ell\nu b\overline{b}$), 5%
  - both W's decay into e *or* μ (τ is separate)
- Lepton+jet Channel ($\ell\nu q\overline{q}b\overline{b}$), 30%
  - one W decays into e *or* μ (τ contamination)
- All-hadronic Channel ($q\overline{q}q\overline{q}b\overline{b}$), 44%
  - both W's decay into quarks pairs

Dilepton: small signal, also small background (2 top signatures).

Lepton+jets: reduce background by requiring $\geq$ 3 jets and $\geq$ 1 b tagged jet.

See distribution of W+njets event with $\geq$ 1 SVX tag



All Hadronic: require 6 jets,reduce background by requiring $\geq$ 1 SVX tag

A few hundred top events have been detected in the D0 and CDF experiments in Run I (106 pb^{-1}).

CDF observed (published results):

Sample	$a \times \epsilon$	Events	Background	
Produced $t\bar{t}$ events	1.	525		obs. $t\bar{t}$
Dileptons	0.74%	9	2.4	6.6
$\ell + \geq$ 3jets	9.2%	324	$\sim$ 274	$\sim$ 50
ℓ+jets (SVX tag)	3.7%	34	9.2	-
ℓ+jets (SLT tag)	1.7%	40	22.6	-
W + 4jets(no-tag)	n.a.	46	25.9	-
W + 4jets(loose jet4)	n.a.	163	115	-
All-Hadr (1 SVX)	4.4%	187	142	45

$a \times \epsilon$ = acceptance $\times$ efficiency = A

E_T(lepton) > 20 GeV $\not{E}_T$ > 20 GeV

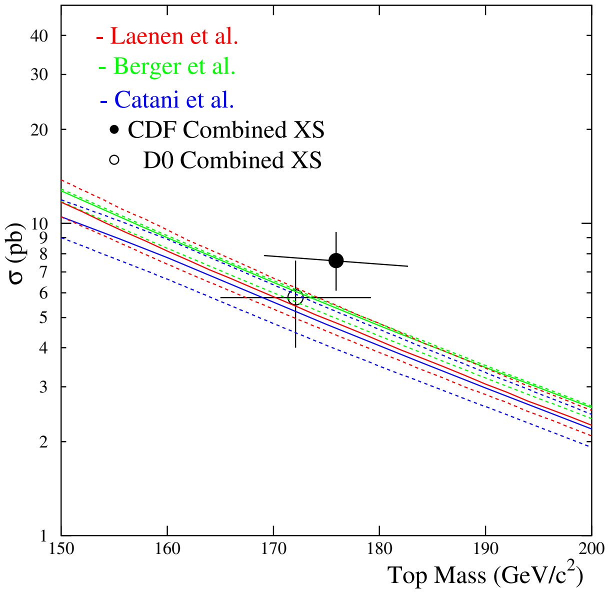
Jets: calor. clusters with E_T > 15 GeV, R(cone)=0.4.

In Run II: 2 fb^{-1} expect (from TDR, done before pubs.)

1. σ to increase by $\sim$ 40% at 2 TeV
2. background to increase by 12%

Sample	A_{Ib}	A_{II}	$(Nev)_I$	$(Nev)_{II}$
Produced $t\bar{t}$ events	1.	1.	525	13600
Dileptons	0.78%	1.1%	6.6	155
$e(\mu) + \tau$	0.12%	0.14%	1.5	19
$\ell + \geq$ 3jets	9.2%	11.2%	$\sim$ 50	1520
ℓ+jets ($\geq$ 1 SVX tag)	3.7%	7.3%	24.8	990
Mass ($\geq$ 1 SVX tag)	3.0%	5.8%	17.4	790
Mass ($\geq$ 2 SVX tag)	0.52%	1.8%	4.8	240

Run I <u>Cross section measurement</u> by both CDF and D0:



The combined cross sections for each experiment are:

$$\sigma_{t\bar{t}} = 6.5^{+1.7}_{-1.4}\ pb \quad @\ M_{top} = 175\ GeV/c^2 \quad CDF \tag{1}$$

$$\sigma_{t\bar{t}} = 5.9^{+1.7}_{-1.7}\ pb \quad @\ M_{top} = 172\ GeV/c^2 \quad D\O \tag{2}$$

<u>Direct Top mass measurements</u> were also made

Channel	CDF	D0
dilepton	167.4 ± 11.4	168.4 ± 12.8
Lepton+jets	176.1 ± 7.4	173.3 ± 7.8
All-hadron	186.0 ± 13.3	n.a.
Combined	176.1 ± 6.6	172.1 ± 7.1

Combined CDF mass is

$$\mathrm{M}_{top} = 176.1 \pm 4.2(\mathrm{stat}) \pm 5.1(\mathrm{syst})\ \mathrm{GeV/c^2}$$

Combined CDF and D0 $\mathrm{M}_{top} = 174.3 \pm 5.1\ \mathrm{GeV/c^2}$

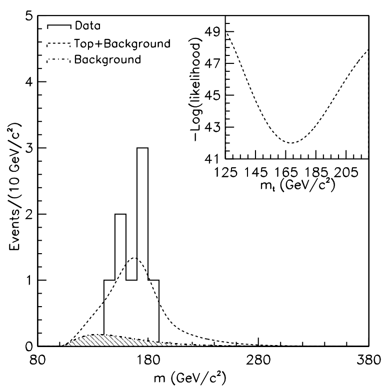
CDF Top Mass Measurement Summary

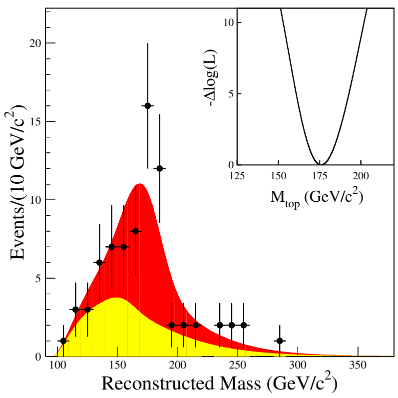
- CDF results on top mass from different channels

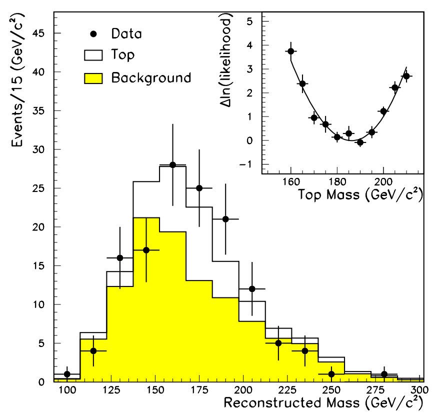
M =	$167.4 \pm 10.3 \pm 4.8$	GeV	dileptons	Submitted to PRL
M =	$175.9 \pm 4.8 \pm 5.3$	GeV	lepton+jets	Publis.+Rev. Sys
M =	$186.0 \pm 10.0 \pm 5.7$	GeV	all hadronic	Publis.+Rev. Sys
M =	$176.0 \pm 4.0 \pm 5.1$	GeV	Combined	

- Systematic errors (in Gev/c^2)

Channel	dilepton	ℓ+jets	all-had.
Jet energy scale	3.8	4.4	5.0
Initial and final state radiation	2.7	2.6	1.8
Monte Carlo modeling	0.6	0.5	0.2
Monte Carlo generator	0.6	0.1	0.8
Background shape	0.3	1.3	1.7
Monte Carlo statistics	0.7	n.a.	0.6
Total	4.8	5.3	5.7





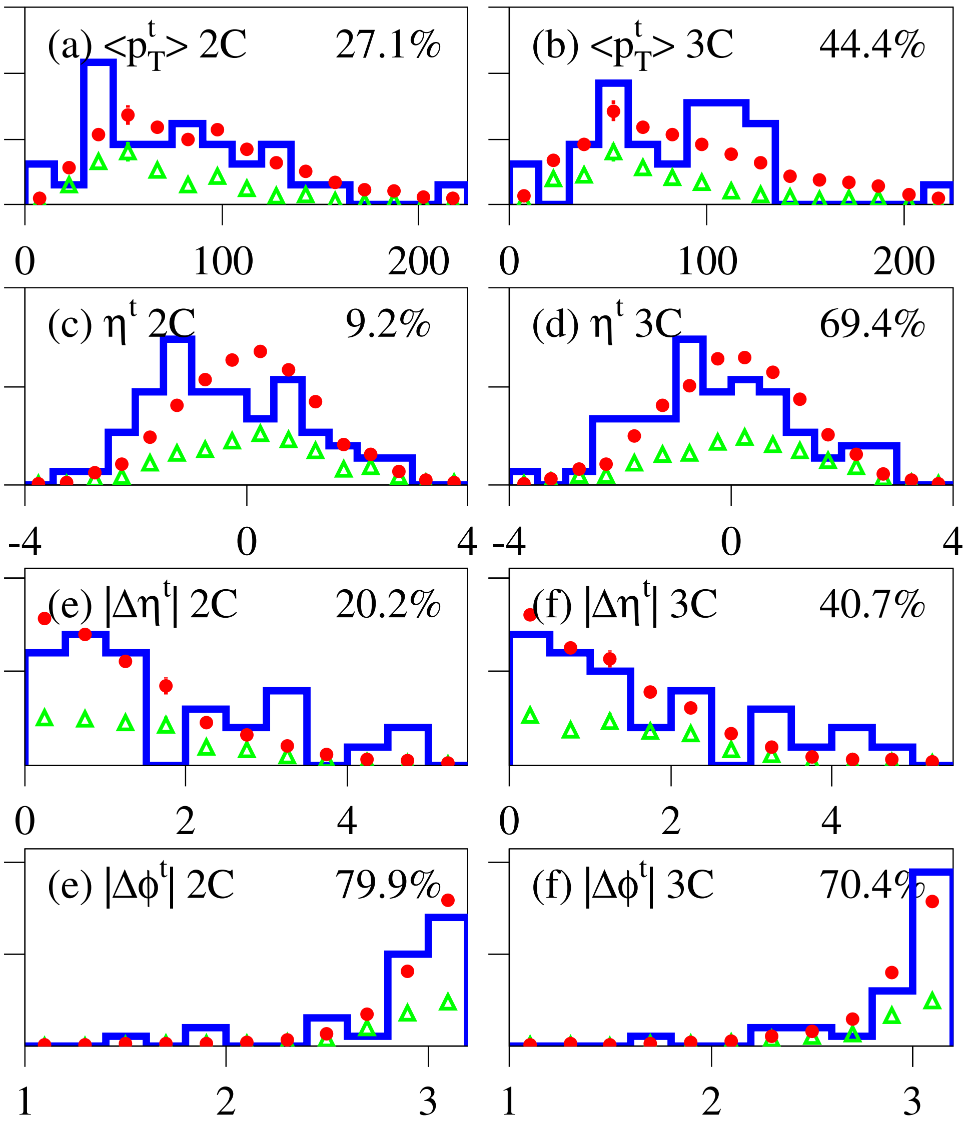


Top Pair Production

$t\bar{t}$ Kinematics (D0)

Constrained fit to events like $p\bar{p} \rightarrow t\bar{t} + X = W + \geq 4$ Jets yield information on top production variables.

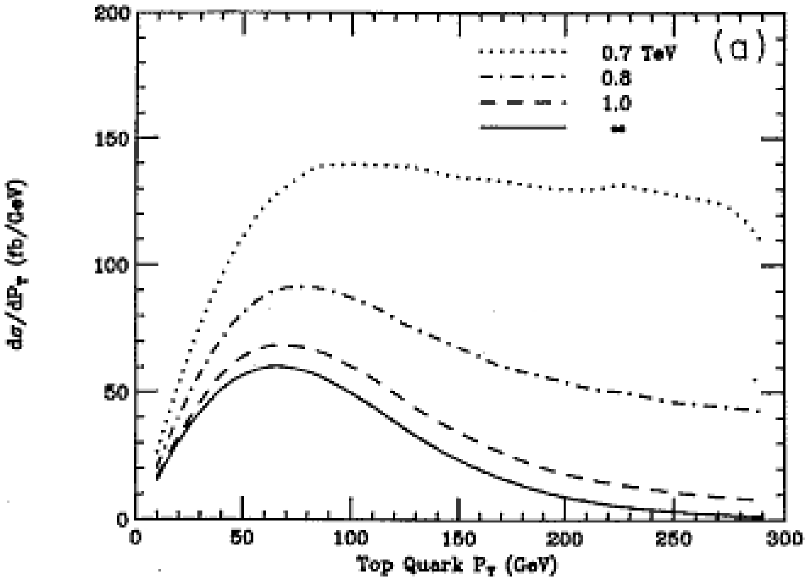
Agreement of data with $t\bar{t}$ HERWIG MC and VECBOS background is good



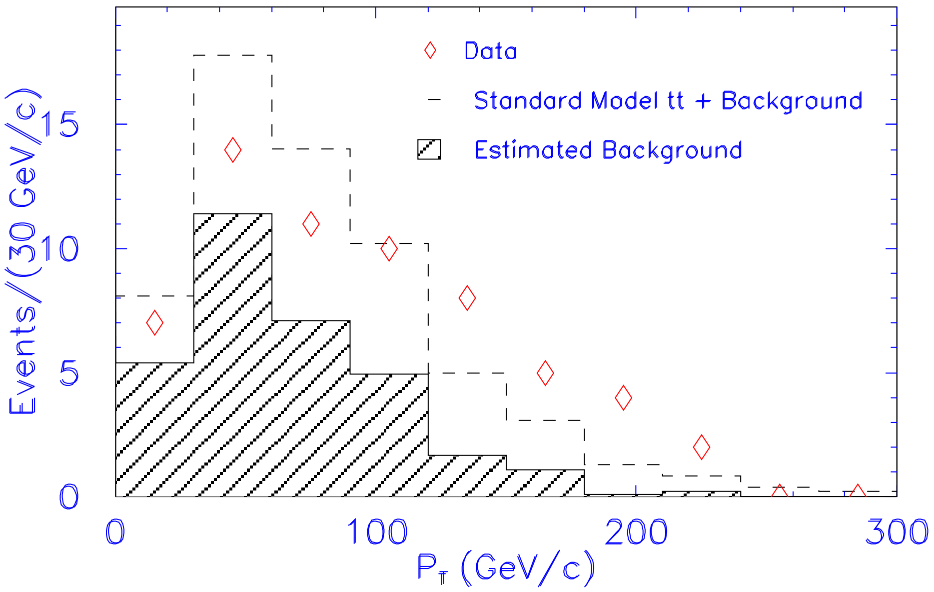
Top P_T in $t\bar{t}$ Production (CDF)

Can we rule out models with large top P_T?

Example: Hill and Park topcolor model with a Z' with strong coupling to top quark. Z' $\rightarrow t\bar{t}$.



Use top mass kinematic fitting with M_{top} = 175 GeV/c^2. After the requirement $\chi^2 > 10$, 61 events (29 tagged, 32 untagged) remain with a background of 31.9 $\pm$ 4.6 events.



To extract P_T spectrum of produced top quark, unfold for resolution smearing and correct for acceptance as a function of P_T. A distribution as a function of "true" top P_T is then obtained.

Unbinned likelihood fit to response functions for $t\bar{t}$ (from HERWIG) and background (from VECBOS) is then performed.

Use iterative technique to minimize assumptions about shape of P_T spectrum within each bin.

Include systematic uncertainties for each bin from different sources: M_{top} value, jet E_T scale, gluon radiation, background shape, acceptance.

p_T Bin	Parameter	Measurement	Standard Model Expectation
$0 \leq p_T < 75$ GeV	R_1	$0.21\,^{+0.22}_{-0.21}(\mathrm{stat})\,^{+0.10}_{-0.08}(\mathrm{syst})$	0.41
$75 \leq p_T < 150$ GeV	R_2	$0.45\,^{+0.23}_{-0.23}(\mathrm{stat})\,^{+0.04}_{-0.07}(\mathrm{syst})$	0.43
$150 \leq p_T < 225$ GeV	R_3	$0.34\,^{+0.14}_{-0.12}(\mathrm{stat})\,^{+0.07}_{-0.05}(\mathrm{syst})$	0.13
$225 \leq p_T < 300$ GeV	R_4	$0.000\,^{+0.031}_{-0.000}(\mathrm{stat})\,^{+0.024}_{-0.000}(\mathrm{syst})$	0.025
$0 \leq p_T < 150$ GeV	$R_1 + R_2$	$0.66\,^{+0.17}_{-0.17}(\mathrm{stat})\,^{+0.07}_{-0.07}(\mathrm{syst})$	0.84

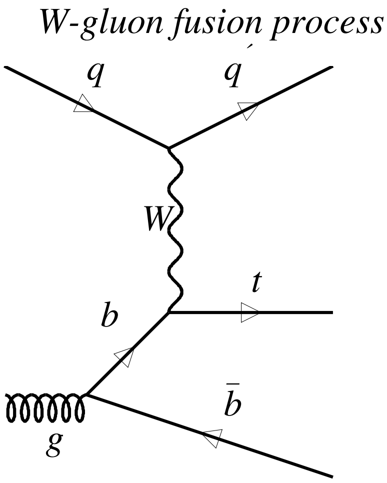
Obtain limit for R_4, i.e., fraction of events in top P_T in the 0-150 and 225-300 GeV/c bins.

$$R_1 + R_2 = 0.66 \pm 0.17(\mathrm{stat}) \pm 0.07(\mathrm{syst})$$
$$R_4 < 0.16 \text{ at } 95\% \text{ CL}$$

The standard model expectation is of 0.84 and 0.025 respectively.
in Run IIa over 1000 events (tagged by SVX) will be available.

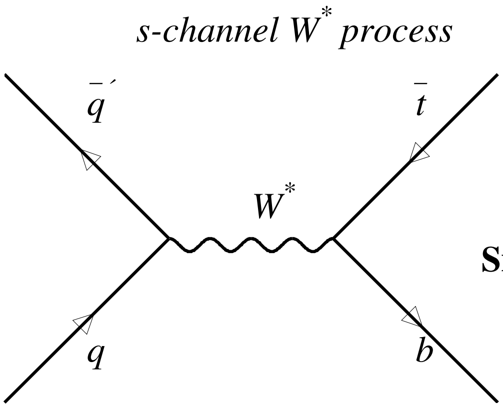
Single top production

Electro-weak Top quark production. Can be used to measure the CKM matrix element V_{tb}.
Sensitive to new physics at the t-W-b vertex, like W' or FCNC.



Signal is W+b+q

$\sigma = 1.7 \pm 0.3$ pb
(Stelter et al. '98)
soft *b* jet from gluon
only one *b* jet



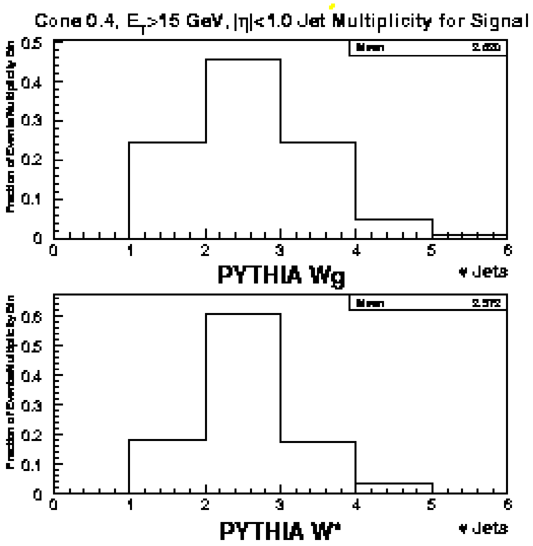
Signal is W+b+$\bar{b}$

$\sigma = 0.73 \pm 0.10$ pb
(Smith et al. '96)
two b jets in event

Background from QCD (Wbb, Wcc, Wc,W+2 jets (mistag) and $t\bar{t}$ production for both processes.

Two analyses have been done in Run I, using different event selections.

The number of jets in the event is somewhat different for the two processes.



Tsukuba-Rockfeller Analysis

W-g sample: lepton + 2jets (1 SVX b-tag).
W* sample: lepton + 2jets ($\geq$ 1 b-tag).

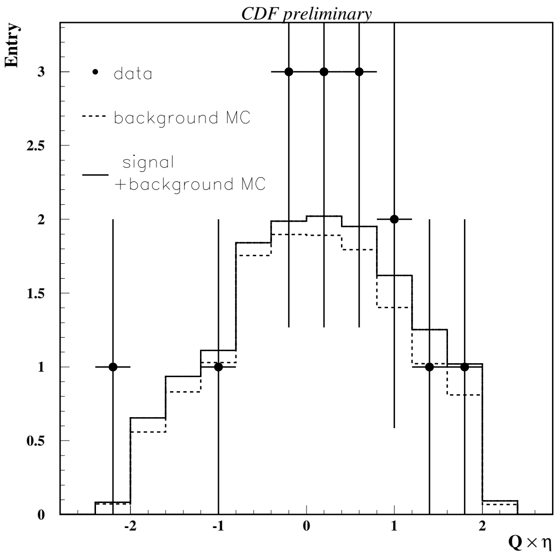
W-gluon fusion process

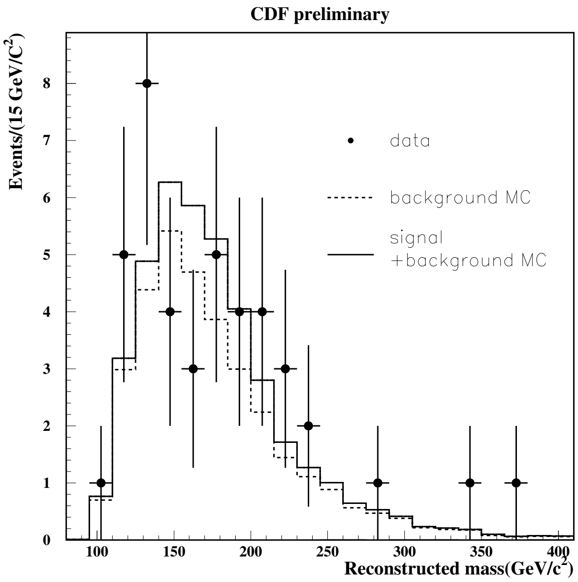
- to reduce $t\bar{t}$ background ($\sigma_{top} = 5.1$ pb), require no b jet at lower vertex (i.e., $E_T < 15$ GeV)
- To reduce QCD background require $145 < M(\ell\nu b) < 205$ GeV/c^2.
- to reduce W* contamination, require only 1 SVX tag.

Expected and observed events are shown below.

Source	QCD	W*	$t\bar{t}$	W-g	Found	$S/\sqrt{B}$
Events	10.2±1.9	0.5±0.3	1.4±0.5	1.3±0.4	15	0.365

Charge of top correlated with pseudorapidity (ℓ^+ has positive η, ℓ^- has negative η). Variable used is Q $\times\eta$. The distribution is shown on the left plot.





Likelihood method used to estimate single top fraction, using templates for $Wb\bar{b}$, W + jets, $t\bar{t}$, etc. Fit results gives N(W-g) = $2.1^{+4.3}_{-3.6}$.
Including systematics uncertainties, it results in a limit:

$$\sigma_{W-g} < 14.8\ pb\ at\ 95\%\ CL$$

W* process

Events with two jets with b-tag are included in this study. Both b jets are expected to be above 15 GeV.
Expected and observed events are shown below.

Source	QCD	$t\bar{t}$	W-glu	W*	Found
Events	24.0±4.5	3.7±1.1	1.7±0.5	1.1±0.3	42

The 42 events include 36 with 1SVX tag and 6 with 2SVX tags. Variable of choice is M($\ell\nu b$), assuming b with larger

η to be associated with ℓ^+ in W^+ production (the opposite for W^-). Choice correct 64% of the time(Monte Carlo).

Maximum likelihood method used to estimate individual contribution to sample. With fixed $t\bar{t}$ and W-g fusion cross sections, the analysis gives $N(W^*) = 7.7^{+7.2}_{-6.5}$. Including systematic uncertainties this gives

$$\sigma_{W^*} < 14.3\ pb\ \ at\ \ 95\%\ \ CL$$

Run IIa can give 40 times the statistics, probably not sufficient. Run IIb necessary for meaningful measurement.

Michigan-Toronto Analysis

This analysis searches for evidence of single top production without distinguishing between the two processes.

- Use N_{jet} = 1,2,3 samples (increase statistics)
- require N(tags) $\geq$ 1 SVX tag
- require the invariant mass $140 < M(\ell\nu b) < 210$ GeV/c^2 to reduce QCD background.

Signal and background events expected are:

Source	QCD	$t\bar{t}$	W*	W-g	Found	$S/\sqrt{B}$
Events	54	8.4	3.0	1.3	65	0.5

Variable used is H_T: top pair production will give a higher value, background will peak at lower H_T.
Including all the systematic errors, they obtain a limit:

$$\sigma_{singletop} < 13.5\ pb\ at\ 95\%\ CL$$

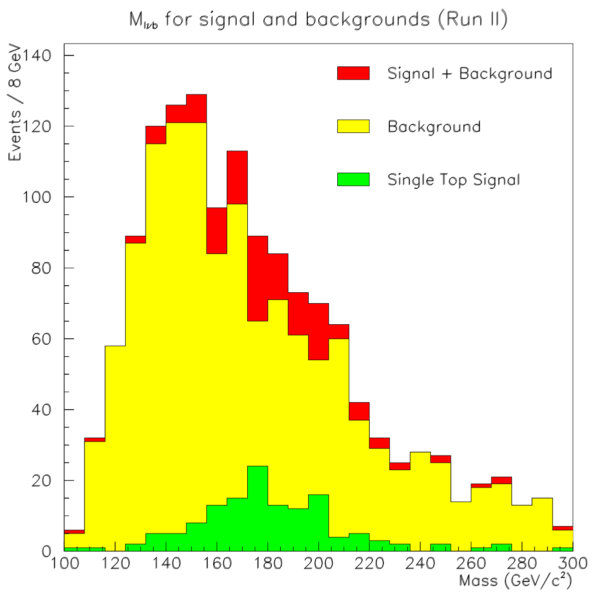
Run II expectation

Limits obtained in Run I are an order of magnitude larger the expected cross section. Is there a chance to obtain a measurement in Run II (2 fb^{-1} of data)? Improvements expected in Run II:

- Factor 20 in luminosity Tevatron Energy up to 2.0 TeV, top cross sections larger by 40%, whereas QCD background increases by 12%.
- Detector improvements expected:
  - ℓ acceptance increases, e by 33%, μ by 12%.
  - SVX $b$tagging efficiencies increases by about 50%

Expected number of events:

Source	QCD	$t\bar{t}$	W-glu	W*
Events	170	80	50	15



Here too, Run IIb will be ecessary.

BF($t \to Wb$) and $|V_{tb}|$

- BF($t \to Wb$) is $\sim$ 100% in the Standard Model. A value significantly different from this could signal new physics.
- Expectation for decays into quarks other then b is very low, $|V_{tb}|$ is constrained by the SM to be $0.9991 < |V_{tb}| < 0.9994$ (PDG).

  We measure the ratio

$$R_b = \frac{BF(t \to Wb)}{BF(t \to Wq)}$$

  In SM (3 generations) R_b is given by:

$$R_b = \frac{V_{tb}^2}{V_{td}^2 + V_{ts}^2 + V_{tb}^2}$$

- Use a few independent data samples. Events with:
  - 0, 1 or 2 b-tagged jets in the Lepton+jets sample
  - 0, 1 or 2 b-tagged jets in the Dilepton sample
- Using a maximum likelihood estimator, we measure R$_b$, hence V$_{tb}$:

$$R_b = 0.99 \pm 0.29 \quad CDF \quad Preliminary$$

  Assuming unitarity CDF obtains:

$$|V_{tb}| = 0.99 \pm 0.15 \quad or \quad |V_{tb}| > 0.76 \ (95\% CL)$$

W Boson Helicity in Top Decays

The Standard Model has an exact prediction (in leading order) of the W helicity states in the top rest frame. Since the top quark decays before it hadronizes the spin information at production is preserved.

$$F_0 = \frac{\frac{1}{2}m_t^2/M_W^2}{1+\frac{1}{2}m_t^2/M_W^2}$$

For $M_{top} = 175$ GeV/c^2 $\quad F_0 = 0.70$

$$F_+ = 0.0$$

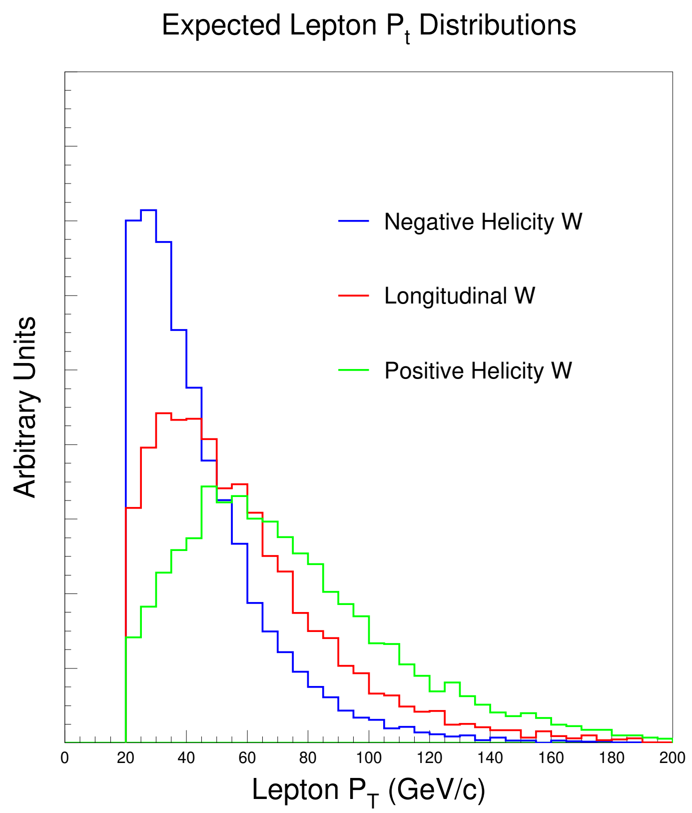
where F_0 = fraction of longitudinal W bosons ($H_W = 0$) and F_+ = fraction of right handed W bosons ($H_W = +1$).

Large deviations from these predictions can be due to :

- Top has non-SM couplings
- What we have observed is not top

Relevant information available from decay angular distributions of leptons in the top rest frame. This requires full reconstruction of the event, with its uncertainties due to combinatorics.

CDF uses the lepton P_T distribution, which also carries this information. More statistics as full reconstruction is not required. Method more sensitive to Monte Carlo model used.



Data used include events from the dilepton and lepton+jets samples.

Sample	SVX tags	SLT tags	No-tag	Dilepton
Events	34	14	46	7
Background	9.2±1.2	6.6±1.2	24.8±6.5	0.76 ±0.21

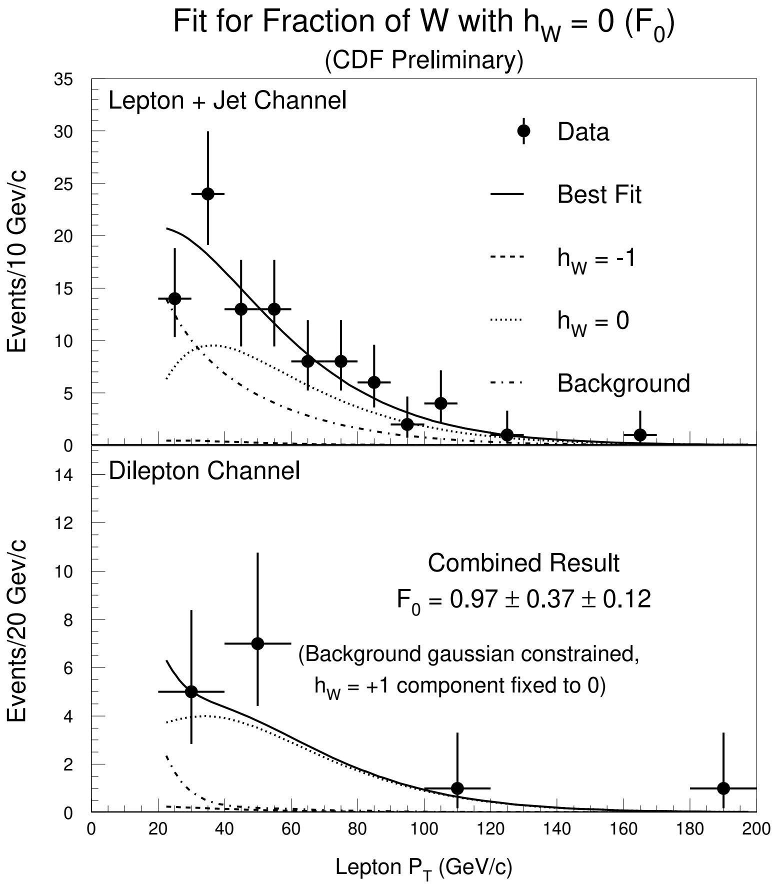
Background in each bin has different composition: b-mistag(QCD) non-W background, W$b\bar{b}$, etc. Background rates and background shapes obtained from data and Monte Carlo.

A maximum likelihood method is used to estimate F_0. The likelihood uses the response functions for the helicity states, the background shapes, and constrains the background rate to the expected value.

CDF obtains:

$$\mathbf{F_0 = 0.97 \pm 0.37(stat) \pm 0.12(syst)}$$

where $F_0 = 0.70$ was expected.



The systematic error includes uncertainties from: m_t, acceptance at low P_T, non-W background shape, gluon radiation in Monte Carlo and other small contributions.

To evaluate a possible F_+ contribution, the F_0 value was fixed in the likelihood to the Standard Modelprediction and a new maximization was performed. The result is

$$\mathbf{F_+ = 0.11 \pm 0.15(stat) \pm 0.06(syst)}$$

Conclusions: with the present statics no deviation from the SM is observed.

D0 spin correlations

The polarization state is transmitted to the angular distributions of the decay products.

$$d\sigma/dcos\theta \sim 1 + \alpha cos\theta$$

where we expect:

particle	α
e^+ or d quark	1
ν or u quark	-0.31
W^+	0.41
b	-0.41

- Charged leptons carry most of the information about the top spin
- For dilepton events, i.e., $t\bar{t} \to \ell^+\ell^- + X$ there is correlations between the two leptons:

$$\frac{d\sigma}{d(cos\theta_+)d(cos\theta_-)} \sim (1 + \kappa cos\theta_+ cos\theta_-)$$

- all the spin correlation information is now in κ.

Analysis carried out using a particular frame defined by Mahon and Parke, where θ is the angle with respect to the so called "off diagonal axis". SM expectation is $\kappa \sim 0.88$, because of gg $\to t\bar{t}$.

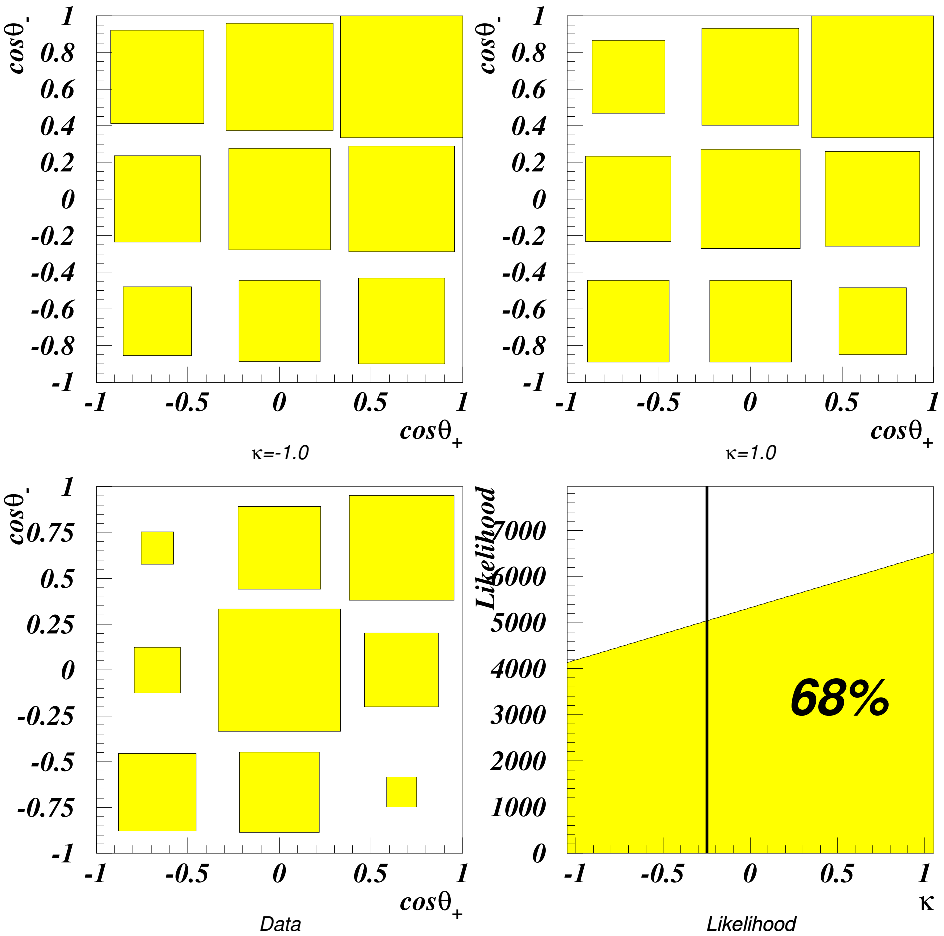
Event reconstruction is needed to allow moving from one reference frame to another. Because of missing constraints in the fitting of dilepton events (two ν are missing, see earlier talk on this), the sensitivity is somewhat diminished.

Combinatorics and backgrounds dilute the effect further. D0 uses the top dilepton sample of Run I to perform this analysis. The sample consists of six events with a background of 1.4 events.

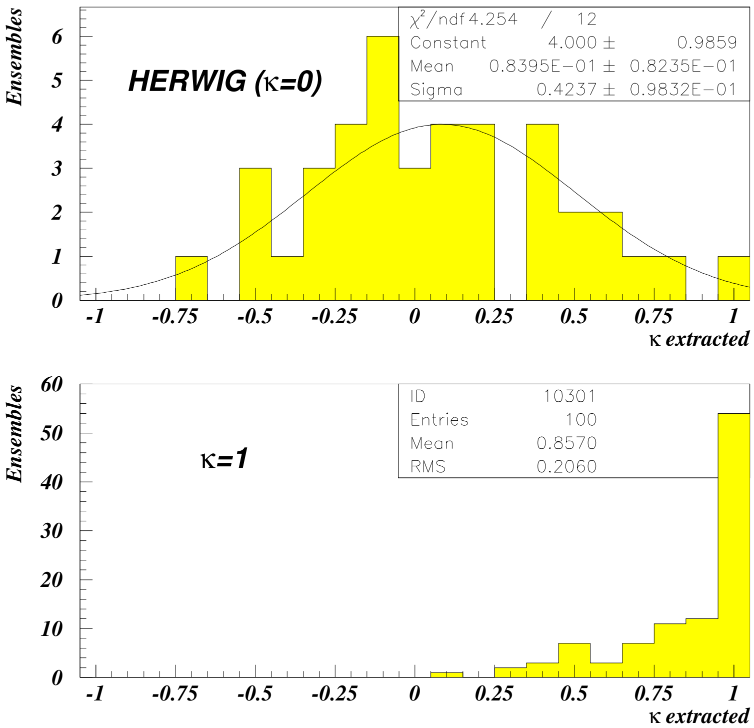
A binned 2 Dimensional likelihood is used to estimate the value of κ. Templates from Monte Carlo are used for the values of κ = -1.0 and 1.0. Also for the background.

D0's preliminary result is:

$$\kappa > -0.25 \text{ at the } 68\% \text{ C.L.}$$



Run II expectation for D0



In Run IIa, CDf will have 155 dilepton events (compared with six events used here).

Beyond the Standard Model

Search for rare Top Decays Two FCNC top decays have been investigated: $t \rightarrow Z + q$ and $t \rightarrow \gamma + q$

Search for t $\rightarrow$ Z q

SM with FCNC predicts BR(t $\rightarrow$ Z q) $\leq$ 0.001 We search in the channels ($\ell = e$ or μ)

$$p\bar{p} \rightarrow t\bar{t} \rightarrow \mathrm{Zq(W/Z)b} \rightarrow \ell^+\ell^- + 4 \text{ jets}$$

with jet $E_T > 20$ GeV. We find one Z $\rightarrow \mu\mu$ event. Background (from WZ, ZZ, ZZ pair production) is expected to be B = 0.6 $\pm$ 0.2 events.

Assuming that it is signal, we set a limit:

$$\mathrm{BR(t \rightarrow Z\ q)} < 0.33 \qquad (95\%\ \mathrm{CL})$$

Search for t $\rightarrow \gamma$ q

We search for t $\rightarrow \gamma$ q (q=u or c).

We use the production channel:

$$q\bar{q} \rightarrow t\bar{t} \rightarrow \mathrm{W\ b}\ \gamma\ \mathrm{q}$$

There are two topologies:

1. for W $\rightarrow \ell\nu$ we search for $\gamma + \ell + \not{E}_T + \geq 2$ jets
2. for W $\rightarrow q\bar{q}\prime$ we search for $\gamma + \geq$4 jets and a b-tag

One event of type 1.) is observed. Background 0.5 ev. (W $\rightarrow \ell\nu$) and 0.5 ev. from W qq'. We can set a limit:

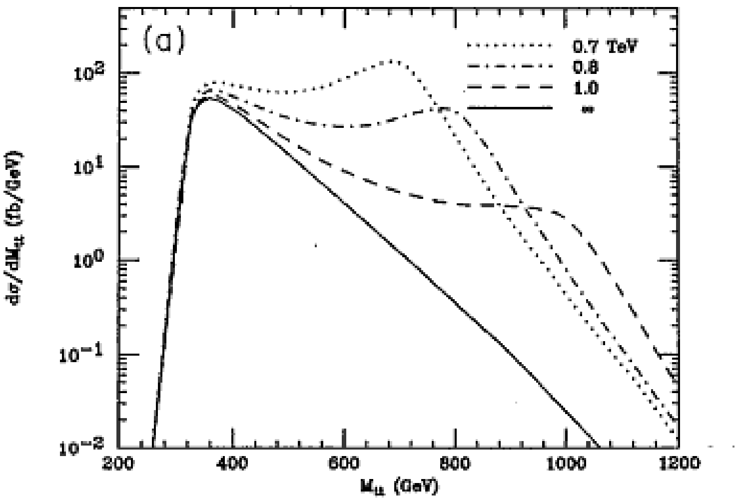
$$\mathrm{Br(t \rightarrow \gamma\ q)} < 0.032 \qquad (95\%\ \mathrm{CL})$$

Study of the $t\bar{t}$ Mass

- New strong dynamics can be at the origin of a $t\bar{t}$ state. A number of models can be found in the letterature on this.
- Topcolor model of Hill and Park predicts a process like:

$$q\bar{q} \rightarrow \ V \ \rightarrow t\bar{t}$$

where V are color octet (and or singlet) Vector bosons



- Technicolor or Topcolor assisted technicolor models of Eichten and Lane, predict the process:

$$g\ g \rightarrow \ \eta_T \ \rightarrow t\bar{t}$$

where the techni-eta is a scalar.

- In some models the $t\bar{t}$ state provides an explanation for the large value of M_{top}, or top itself helps explain the origin of mass.

M($t\bar{t}$),cont.

This is physics to be pursued in Run II and the LHC later on.

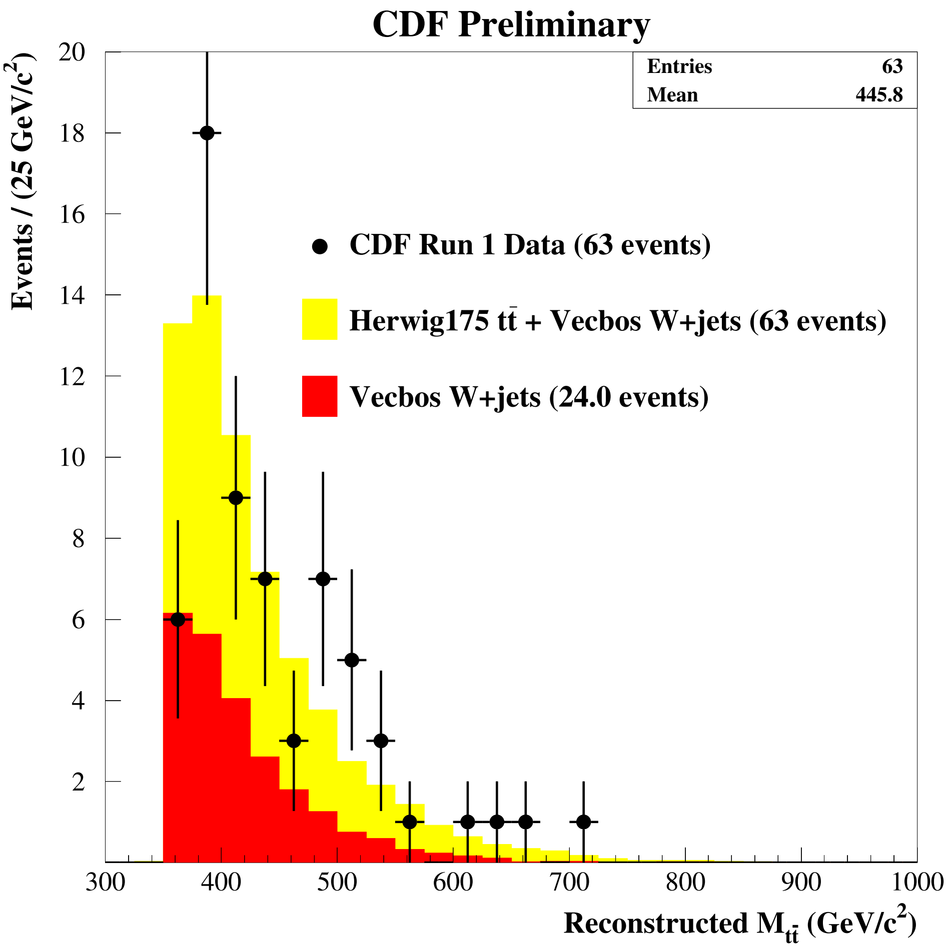
CDF is looking at Run I data for possible hints of a $t\bar{t}$ state and to establish cross sections limits for these models.

Event selection is the same as for the top mass analysis:

E_T(lepton) > 20 GeV $\not{E}_T > 20$ GeV
raw E_T(jet 1-3) > 15 GeV
jet4: tagged as b or $E_T > 15 GeV$

- Apply mass fitting technique with M_{top} fixed at 175 GeV/c^2 (3C fit).
- Loosen χ^2 cut to 50.
- To reduce effect of wrong jet combinations require that the 3-body masses in each event (for the same combination as above, in a fit with no mass constrain) be in the interval 150-200 GeV/c^2.
- A total of 63 events remain with a background of 31 events.

M($t\bar{t}$),cont.



- Using the Technicolor assisted Topcolor model of Chris Hill, and including systematic errors, limits are obtained for production of a lepto-fobic Z':

$$\begin{array}{lll} \mathrm{M(Z')} > 780\ \mathrm{GeV/c^2} & \text{for} & \Gamma(Z')=0.004^*\mathrm{M}_{Z'} \\ \mathrm{M(Z')} > 480\ \mathrm{GeV/c^2} & \text{for} & \Gamma(Z')=0.012^*\mathrm{M}_{Z'} \end{array}$$

- Again Run IIa and IIb can test this hypothesis with much larger statistics.

Summary and Conclusions

- **In RUN I we have observed a few hundred top events.**
- **Analyses of the data have been made to check that both production and decays agree with the standard model.**
- **Production: no surprises**
  - **Kinematic variables agree with SM.**
  - **Production of high P_T top agrees with SM.**
  - **Single top production is out of reach in Run I.**
- **Decays: no surprises**
  - **V_{tb} agrees with the SM assumption.**
  - **W helicity and spin correlations agree with SM.**
- **New phenomena: no surprises**
  - **Rare decays limits well within SM expectations.**
  - **No evidence for a state that decays into a $t\bar{t}$.**

All these analyses will benefit from the increased statistics of Run IIa data (2 fb^{-1}), about a factor 20-40 larger in statistics.

Some of these studies will need the Run IIb data.