INTERNATIONAL ATOMIC ENERGY AGENCY
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INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
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SMR.858 - 46

SUMMER SCHOOL IN HIGH ENERGY PHYSICS AND COSMOLOGY

12 June - 28 July 1995

TOP QUARK SEARCH AT THE TEVATRON

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Observation of the Top Quark at Tevatron

1995. 7. 25 K. Kondo

I. Tevatron Collider and CDF Detector

II. Counting Experiment on $t\bar{t}$ Production

III. Mass Measurement of the Top Quark

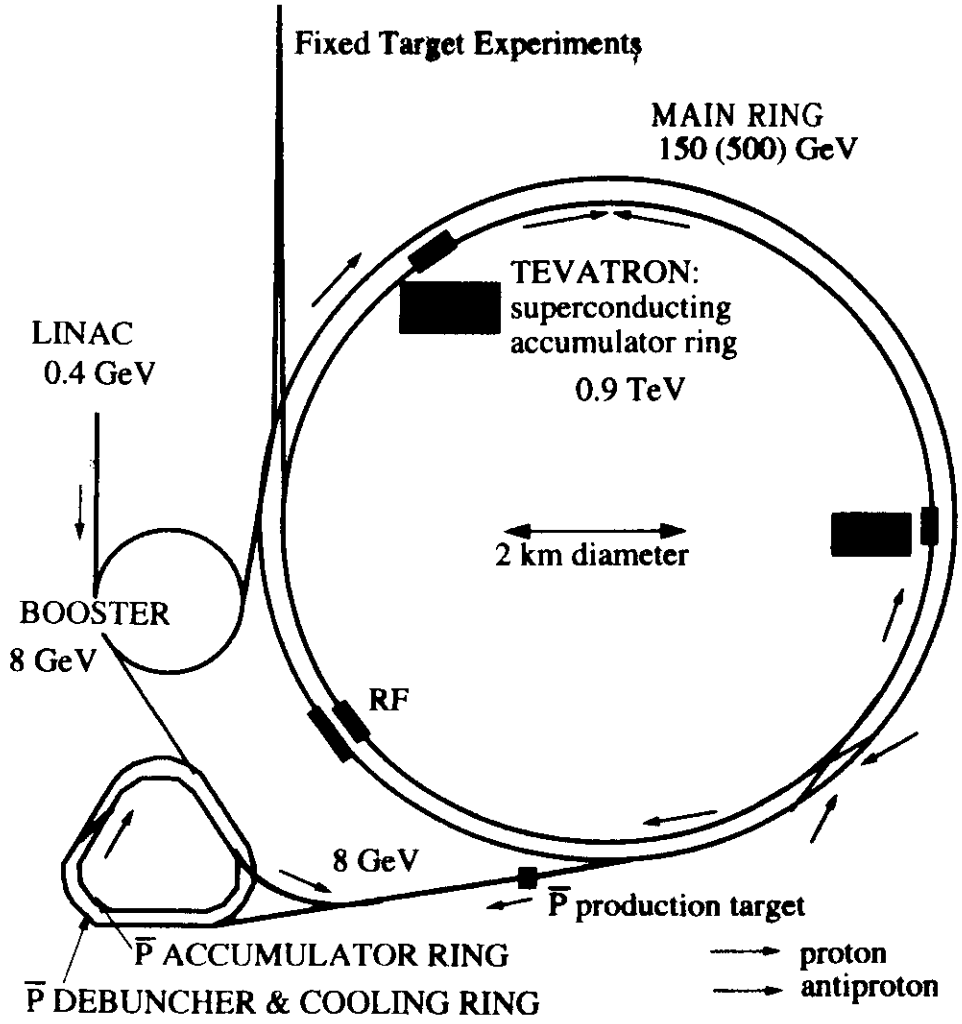
IV. Kinematical Features of $t\bar{t}$ Production

V. Some of Future Subjects on Top Quark at Tevatron

Tevatron Collider and CDF Detector

- Tevatron complex and $p\bar{p}$ luminosity
- CDF detector and Identification of Particles
- Typical processes in $p\bar{p}$ collider
- Precision of Energy/Momentum measurement
- CDF trigger scheme

FERMILAB: THE TEVATRON RING



Accelerator Parameters

$$L = N_B f_0 \frac{N_p N_{\bar{p}}}{4\pi\sigma_V\sigma_H} F$$

- N_B Number of Bunches
- f_0 Revolution frequency
- N_p Protons/Bunch
- $N_{\bar{p}}$ Anti-Protons/Bunch
- F Form Factor

$$\sigma_V^2 = \left(\frac{\epsilon_p^V + \epsilon_{\bar{p}}^V}{2}\right)\frac{\beta_V^\star}{6\pi\beta\gamma}$$

$$\sigma_H^2 = \left(\frac{\epsilon_p^H + \epsilon_{\bar{p}}^H}{2}\right)\frac{\beta_H^\star}{6\pi\beta\gamma}$$

Typical Luminosities at Tevatron (CDF)

Run Ia: ('92-93) $L = 5.4 \times 10^{30}\ cm^{-2}\ s^{-1}$, $\int L dt = 20\ pb^{-1}$

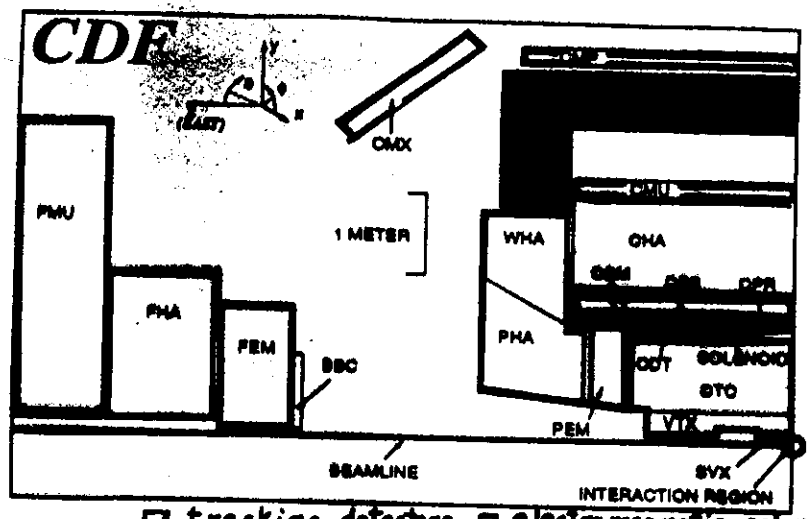
$N_B = 6$, $f_0 = 4.8\times10^4 s^{-1}$, $N_p = 1.2\times10^{11}$, $N_{\bar{p}} = 3.6\times10^{10}$
$F = 0.76$, $\epsilon = 16\pi$ mm-mrad $= 16\pi\times10^{-4}$ cm, $\beta^\star = 50$ cm
$\beta\gamma = p/m = 9.6\times10^2$, $\sigma^2 = 1.4\times10^{-5} cm^2$

Run 1b: ('94-95) $L = 1.4 \times 10^{31} cm^{-2} s^{-1}$, $\int L dt = 100\ pb^{-1}$ } $N_p\ (N_{\bar{p}}) = 22.5\ (6.5)\times10^{10}$, $\beta^\star = 35$ cm

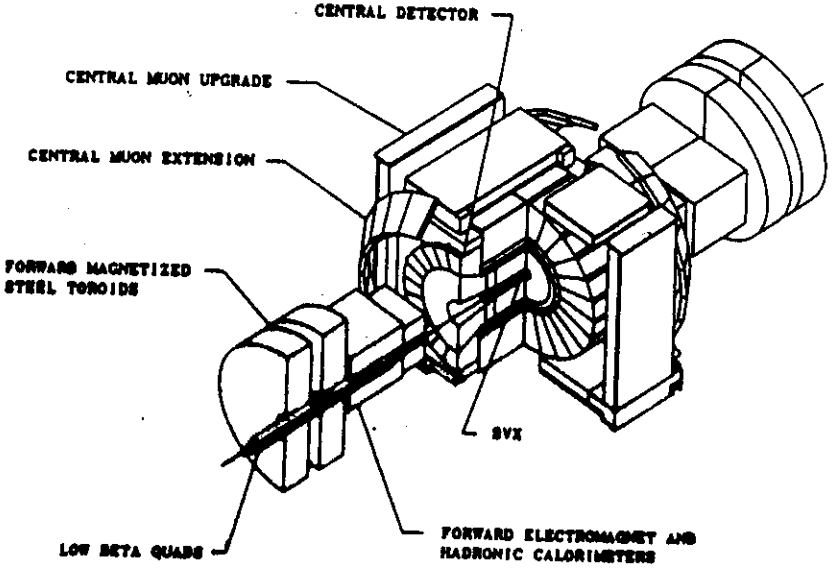
Beam-beam tune shift limits the phase space density to $\lesssim 1.5\times10^{10}$ particles/π mm-mrad.
Present operation: $1.0\ (0.6)\times10^{10}$/π mm-mrad for $p\ (\bar{p})$

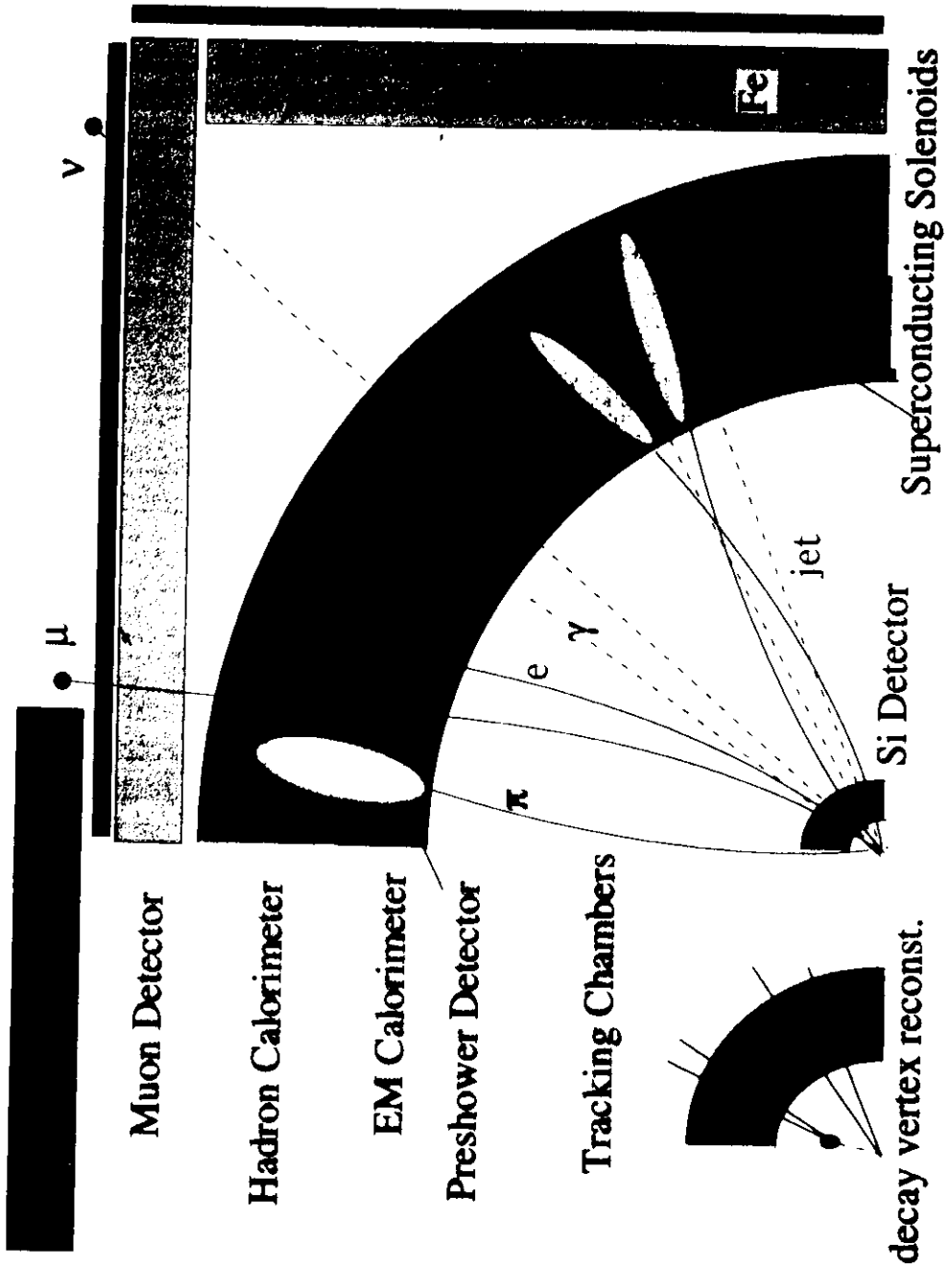
Run 2: ('99~) $N_B = 36$ after Main Injector
$L = 8.3 \times 10^{31} cm^{-2} s^{-1}$
$\int L dt = 2\ fb^{-1}$

High luminosity mode: "TeV33 project"
$L = 1 \times 10^{33} cm^{-2} s^{-1}$
$\int L dt = 10\ fb^{-1}$

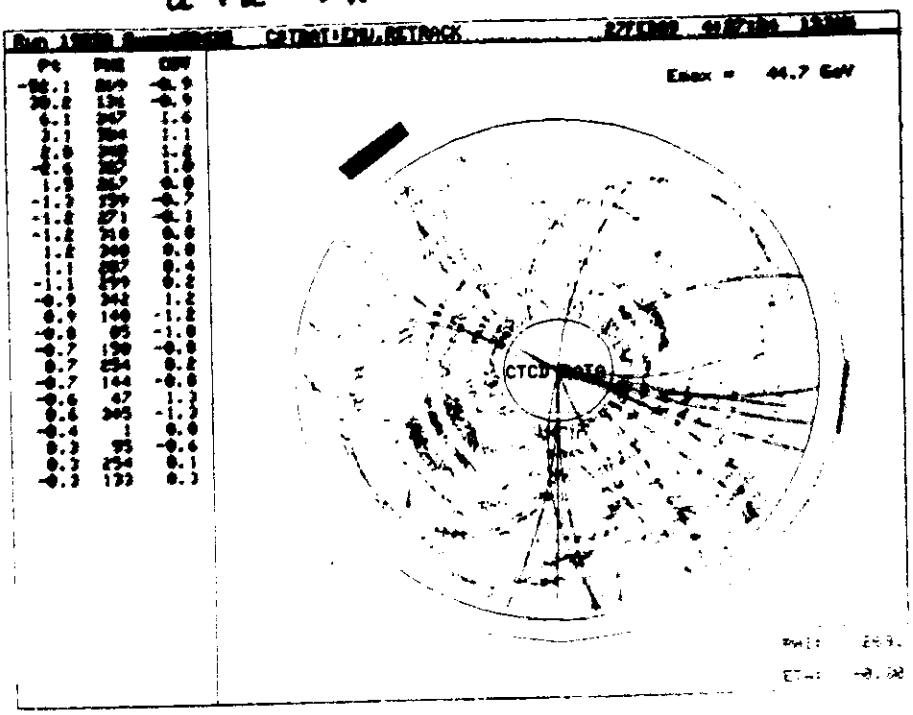


□ tracking detectors □ electromagnetic calorimeters
□ hadron calorimeters □ muon detectors

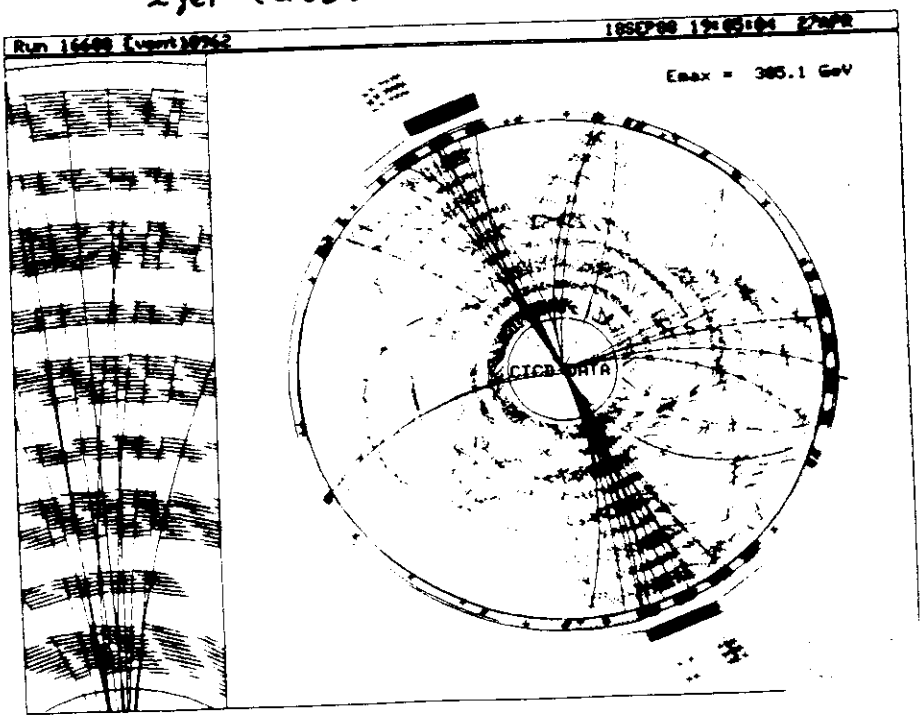




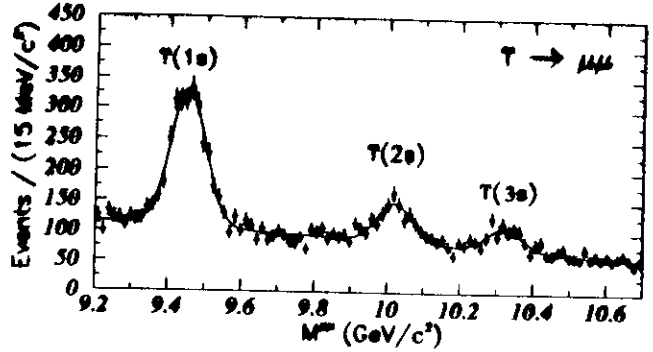
$\bar{u} + d \longrightarrow W^- \longrightarrow e + \bar{\nu}$

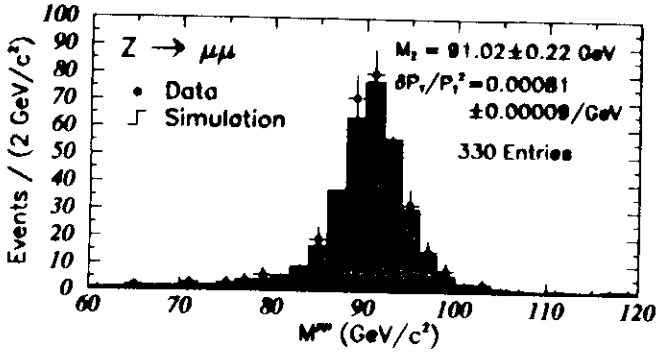


2 jet (QCD) event ($q\bar{q}' \rightarrow q\bar{q}'$ etc.)



Check of Momentum Scale





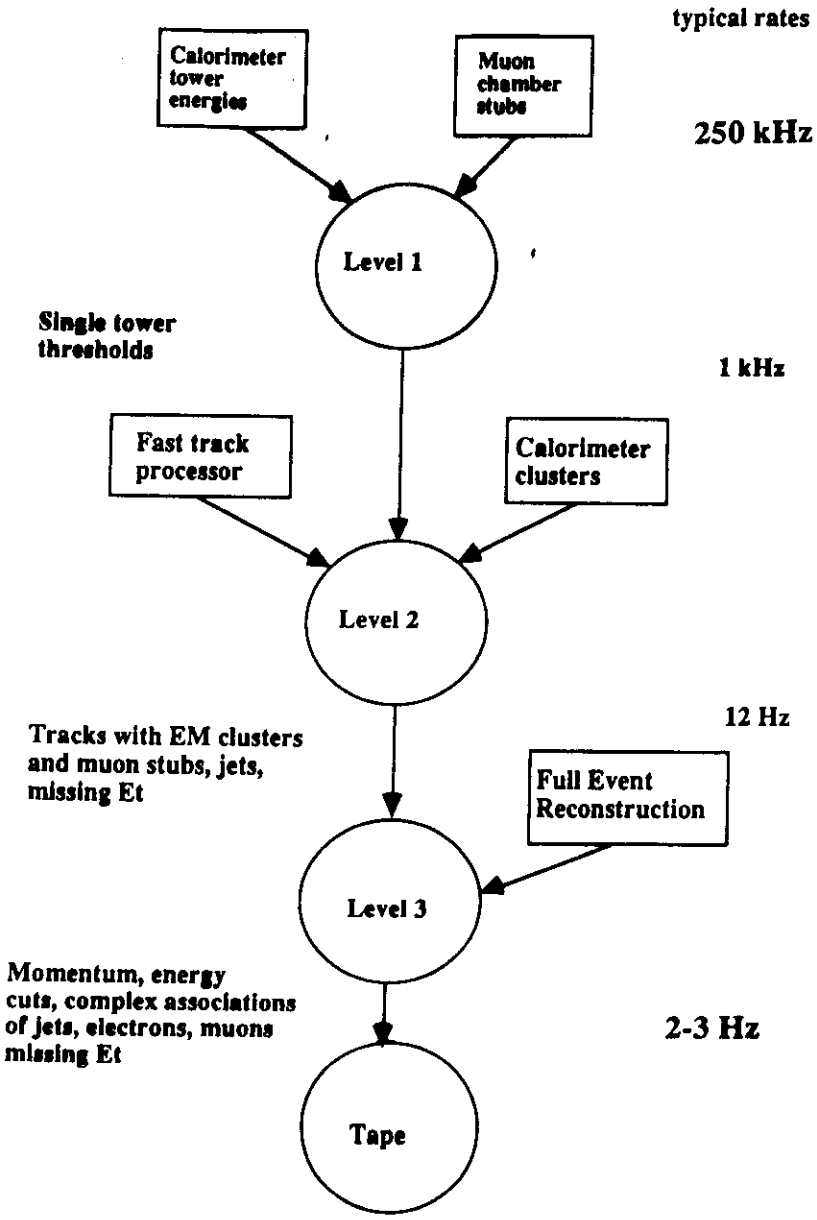
(MeV)

Resonance	Measured Mass	PDG
$\Upsilon(1S) \rightarrow \mu\mu$	$9460 \pm 2 \pm 6$	9460.4 ± 0.2
$\Upsilon(2S) \rightarrow \mu\mu$	$10029 \pm 5 \pm 6$	10023.3 ± 0.3
$\Upsilon(3S) \rightarrow \mu\mu$	$10334 \pm 8 \pm 6$	10355.3 ± 0.5
$Z \rightarrow \mu\mu$	$91020 \pm 210 \pm 55$	91187 ± 7

- P_T resolution from $Z \rightarrow \mu\mu$: $\delta P_T / P_T^2 = 0.00081 \pm 0.00009$ / GeV

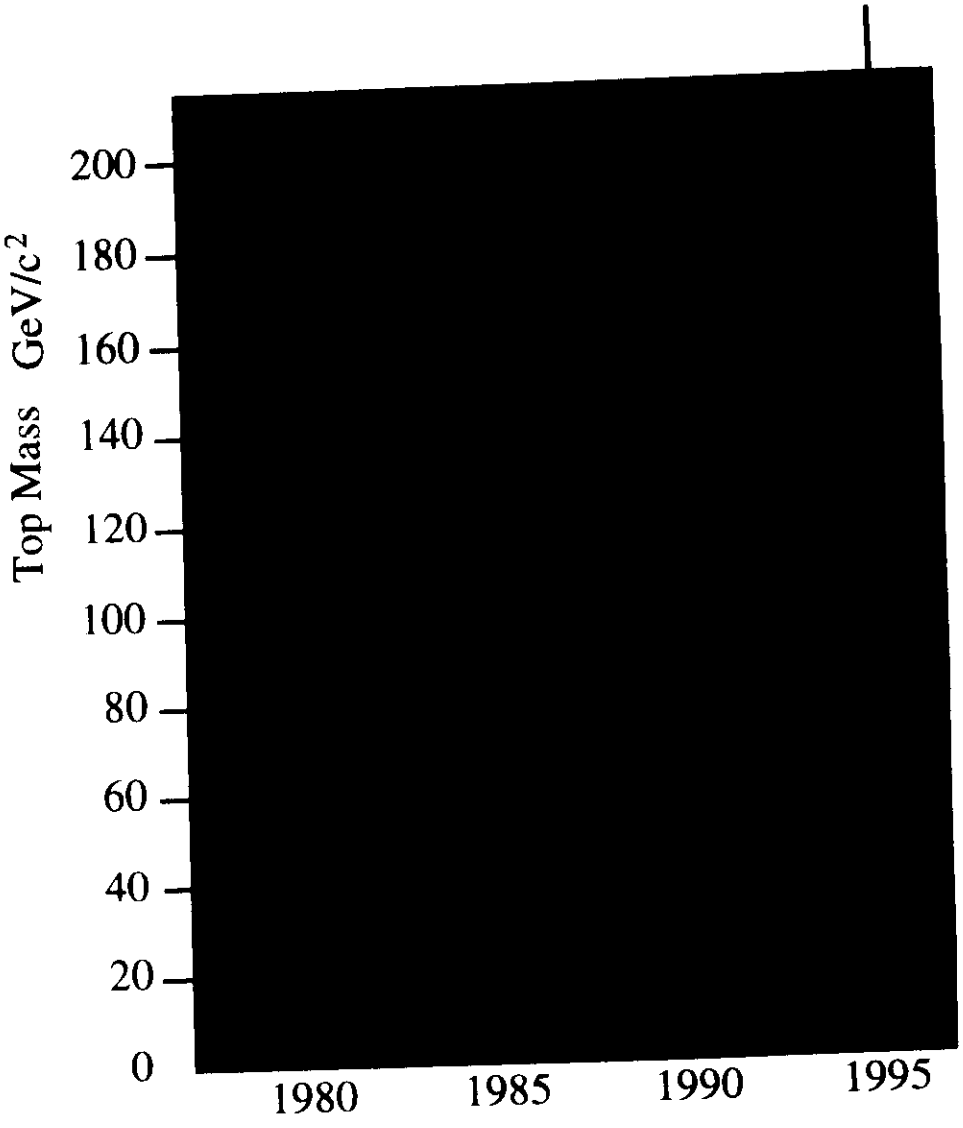
$\delta M_W = 60$ MeV

CDF Trigger



Counting Experiment on $t\bar{t}$ Production

- Brief history of the top quark search
- Basic strategy of the top quark search
- Dilepton channel
- b quark tagging
- Lepton + jets channel
- Results of the counting experiment
- $t\bar{t}$ production cross section



Status of the Top Quark from CDF

Year	L(pb^{-1})	decay mode	Status
1985			Collisions
1987-88	0.025		
1988-89	4.		Limit
Jan-90(L)		e+jets	>77 GeV
Feb-91(A)			
Jan-90(L)		e μ	>72 GeV
Jan-92(L)		e μ +ee+ μ μ	>91 GeV
Jun-92(A)			
1992-93	19.3		Evidence
Jul-94(L)		DL+SLT+SVX	174±11±19GeV
Sep-94(A)			
May-95(A)			Kinematics
1994-95	47.5		Observation
Apr-95(L)	67	DL+SLT+SVX	176 ±8± 10

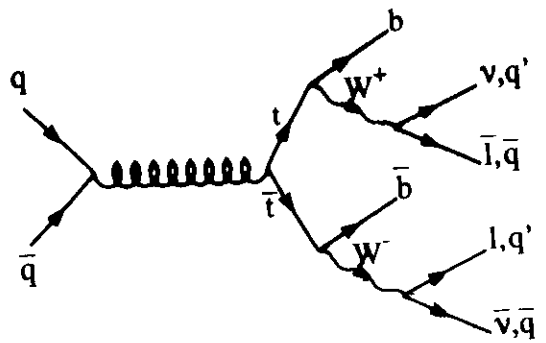
The cross section for the Top is small.

σ (total)= 80.03±2.24 mb
σ (BBC)= 51.2±1.7 mb
σ (Top)= $6.8_{-2.4}^{+3.6}$ pb
Factor of 10^{10}

- Dilepton Branching ratio 5%
- Dilepton Detection Efficiency 20%

Factor of 10^2

- Number of events to Tape (1994-1995)
  - Express Line 2M
  - Production 30 M
  - b-Physics 20 M
- Event Size 0.1 M Bytes
- Luminosity = 1.4 x 10^{31} cm^{-2} s^{-1} (Apr-1995)
- Level 1 = 1.2K$\bar{H}_z$
- Level 2 = 24 H_z
- Level 3 = 6H_z



Process	B.R.	Channel	Signatures
$WW \to l\nu l'\nu'$ ($l,l'=e,\mu$)	4/81	Dilepton	• 2 high-P_T e and/or μ (WW) • missing-E_T(WW) • 2 jets(bb)
$WW \to l_\nu q\bar{q}'$ ($l=e,\mu$)	24/81	L + jets	•1 high-P_T e or μ (W) •missing-E_T(W) •≥ 3 jets(Wbb)
b-tag: $b \to cX$		SVX	•secondary vertex(b)
$b \to c l\nu$		SLT	•soft lepton with jet(b)
$WW \to qq' q^*\bar{q}'$ *	36/81	Multijets	•high E_T jets

• Decay Modes for a $t\bar{t} \to W^+bW^-\bar{b}$

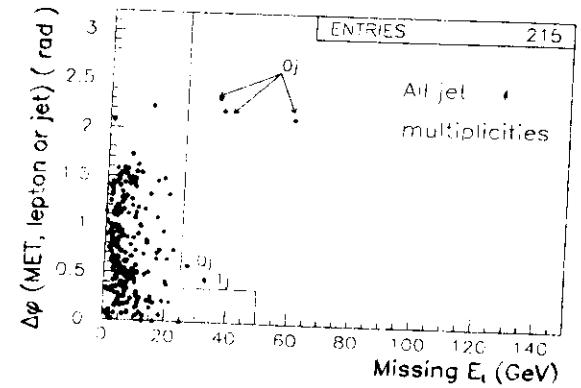
Decay Mode	Branching ratio
All Hadronic	36/81 = 44.4%
6 Jets $qq\bar{b}\,qq\bar{b}$	
Lepton + Jets	36/81 = 44.4%
$qq\bar{b}\,e\nu b$	12/81 = 14.8%
$qq\bar{b}\,\mu\nu b$	12/81 = 14.8%
$qq\bar{b}\,\tau\nu\bar{b}$	12/81 = 14.8%
Lepton + 4 Jets	29.6%
Dilepton	9/81 = 11.1%
$e\nu b\,\mu\nu b$	2/81 = 2.5%
$e\nu b\,\tau\nu\bar{b}$	2/81 = 2.5%
$\mu\nu b\,\tau\nu\bar{b}$	2/81 = 2.5%
$e\nu b\,e\nu b$	1/81 = 1.2%
$\mu\nu b\,\mu\nu b$	1/81 = 1.2%
$\tau\nu b\,\tau\nu b$	1/81 = 1.2%
Dilepton + 2 Jets	4.9%

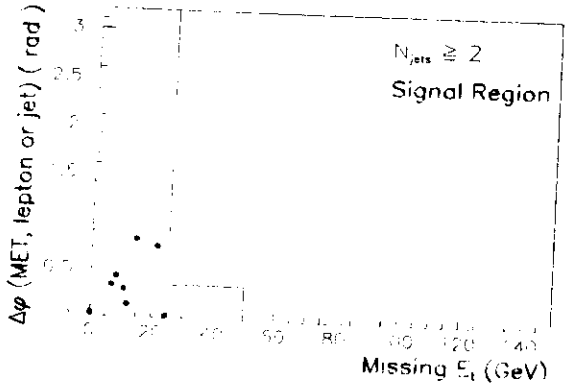
• Delepton Detection Efficiencies

$\varepsilon_{total} = 0.173 \pm 0.015$

$\varepsilon_{geomPT} = 0.74$	$E_T(P_T) \geq$ (20 GeV/c) fiducial volume
$\varepsilon_{ID} = 0.43$	Lepton identification cuts E_{HAD} / E_{EM} E/P L_{shr} Conversion removal ....
$\varepsilon_{isol} = 0.96$	Lepton Isolation
$\varepsilon_{trigger} = 0.97$	Trigger requirements
$\varepsilon_{topology} = 0.66$	Topology cuts Removes Z^0 < 75 M $_{\ell\ell} < 105$ $E_T \geq 25$ GeV ....
$\varepsilon_{twojet} = 0.88$	Two jets required $E_T \geq 10$ GeV and $\lvert\eta\rvert < 2$.

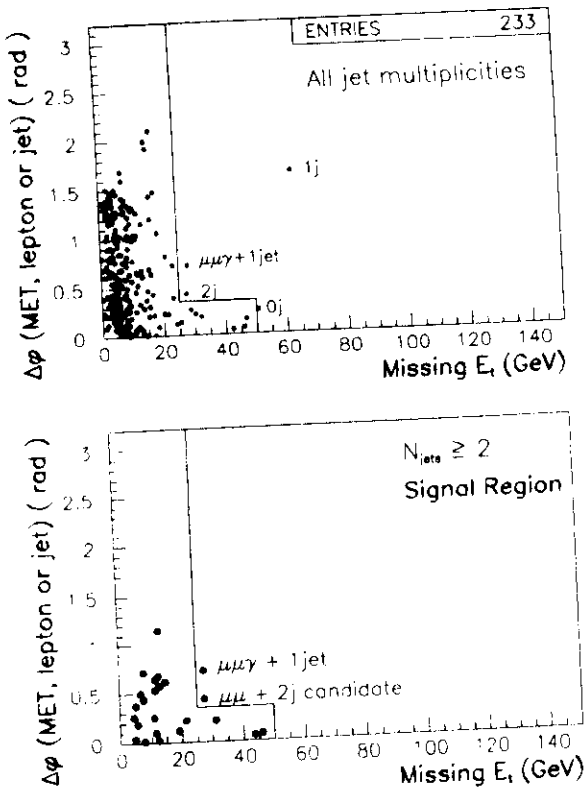
Dilepton Distributions (ee)





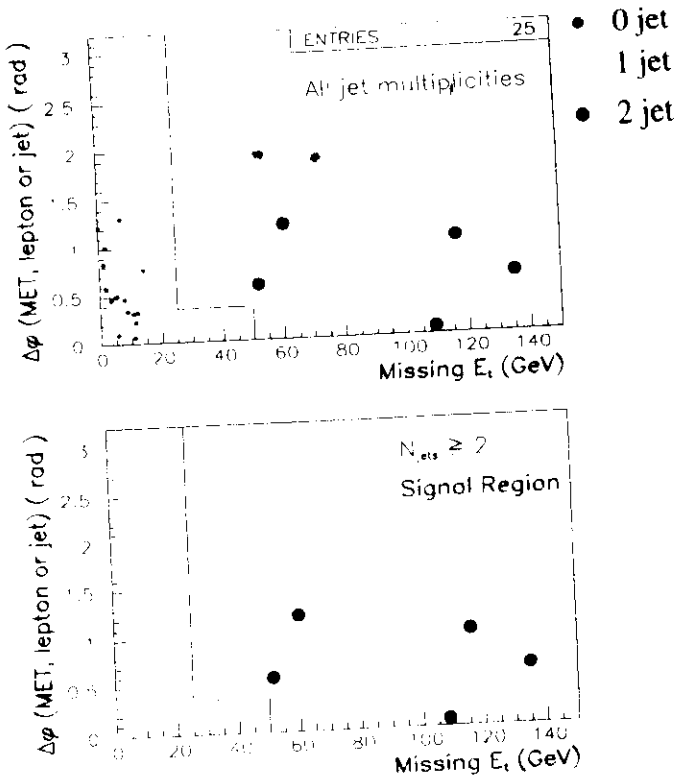
0 Candidates observed

Dilepton Distributions ($\mu\mu$)



2 Candidates observed

Dilepton Distributions ($e\mu$)



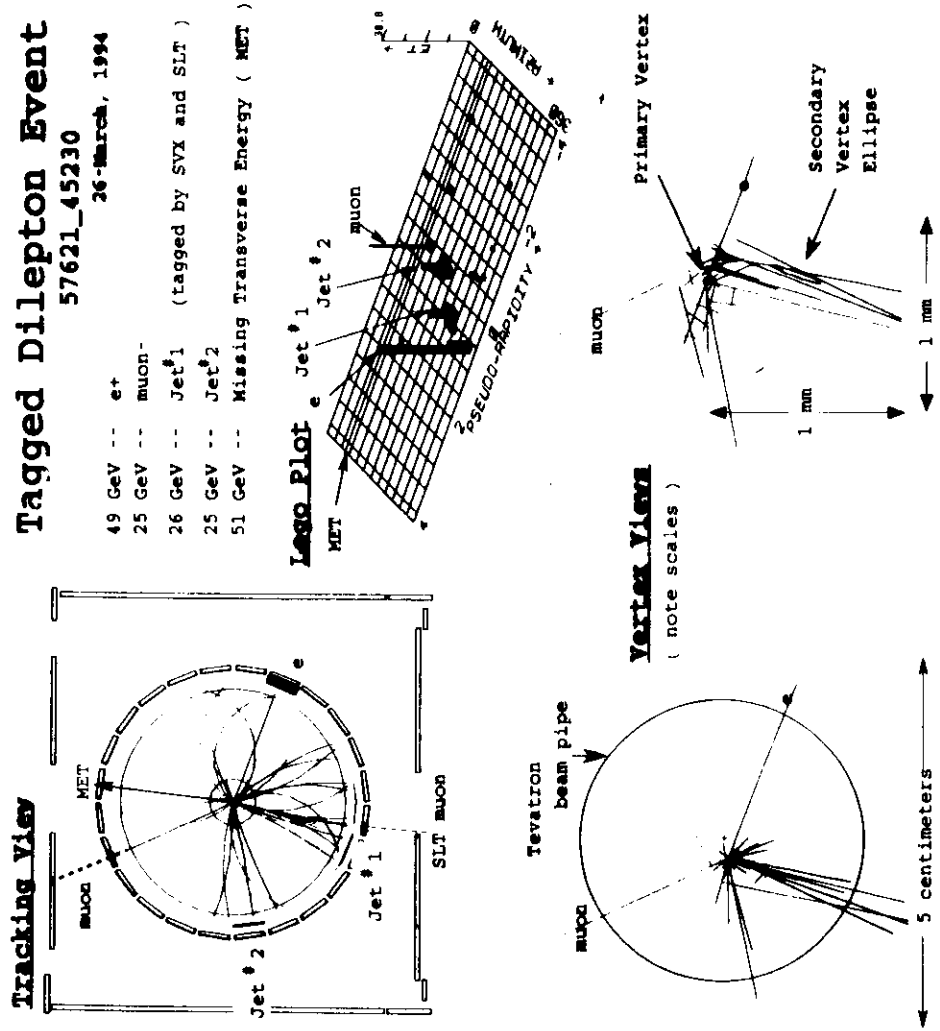
5 Candidates observed

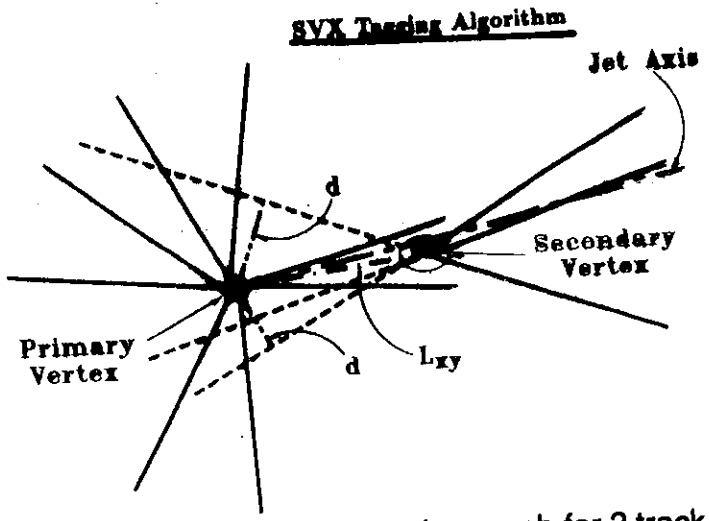
Dilepton Backgrounds

- From data
- From Monte Carlo

• Drell-Yan:	0.44 ± 0.28 events
• $p\bar{p} \rightarrow Z \rightarrow \tau\tau$:	0.38 ± 0.07 events
• Fake leptons:	0.23 ± 0.15 events
• $p\bar{p} \rightarrow WW$:	0.21 ± 0.07 events
• $p\bar{p} \rightarrow b\bar{b}$:	0.03 ± 0.02 events
Total Background	1.3±0.3 events
Observe	6 events

P = 0.33 % (2.7 σ)





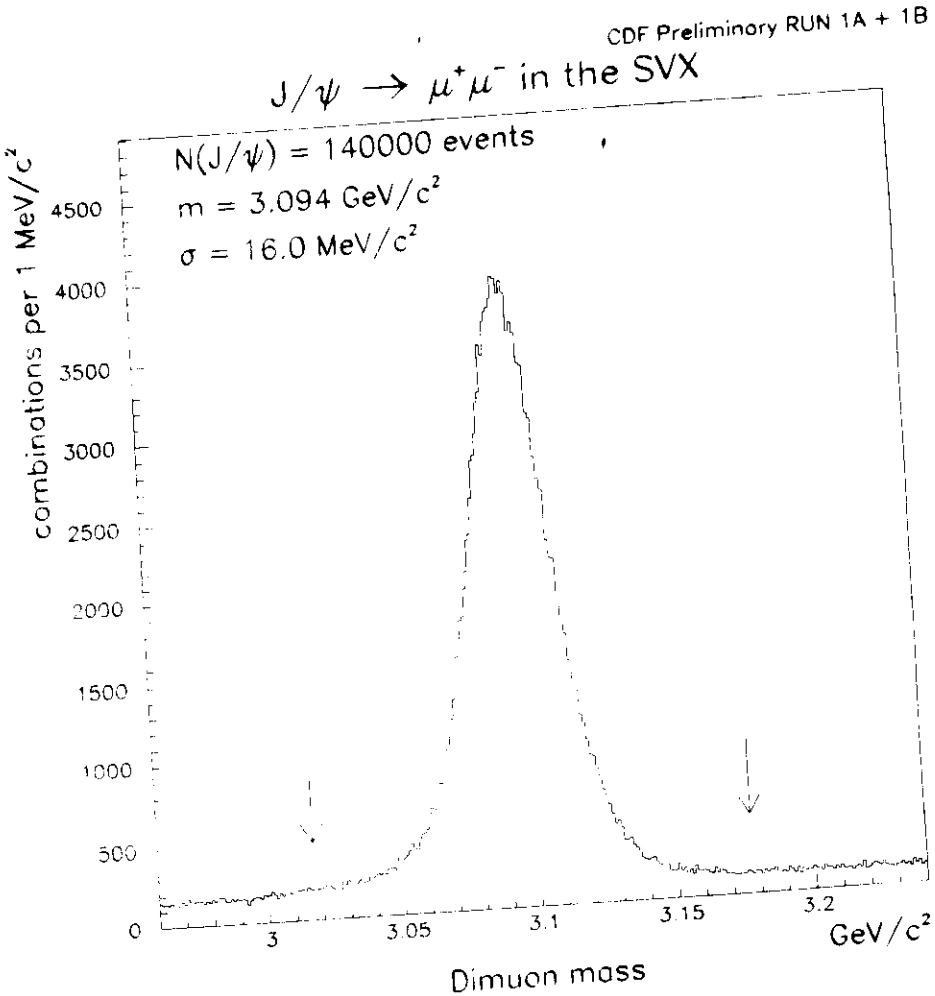
Algorithm makes a first pass to search for 3 track vertices and then a second pass to look for 2 track vertices.
none are found

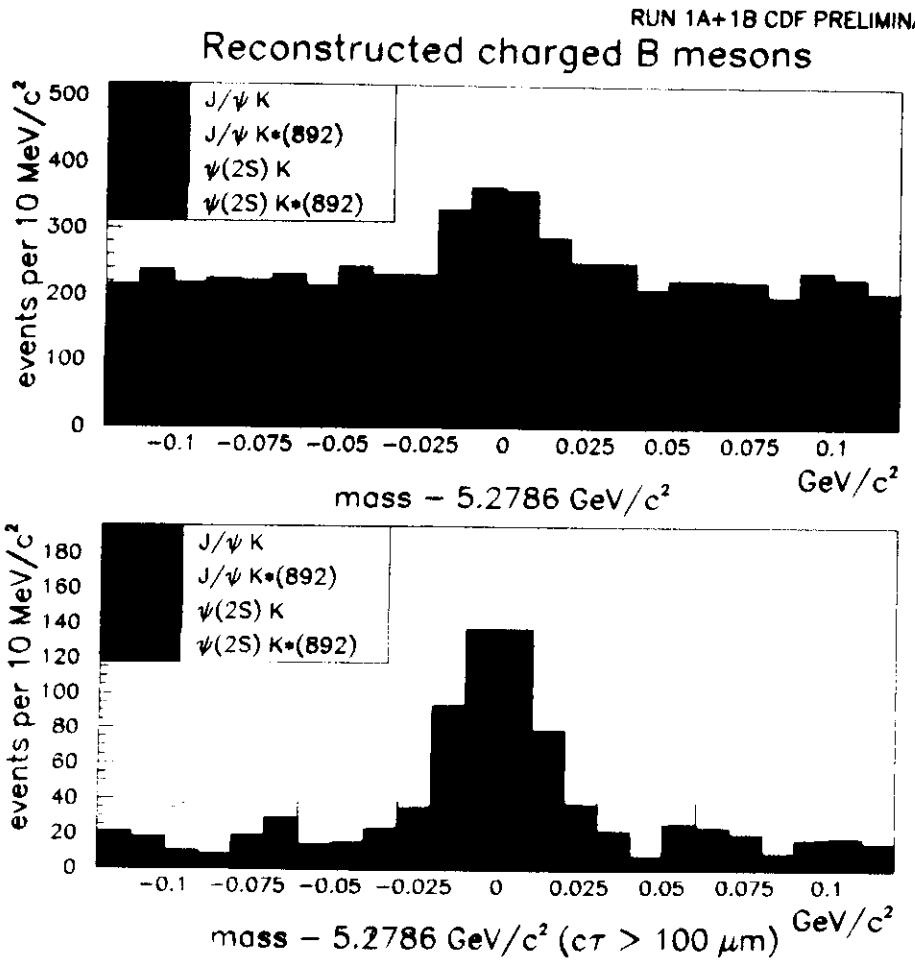
- $L_{xy} / \sigma_{Lxy} > 3.0$

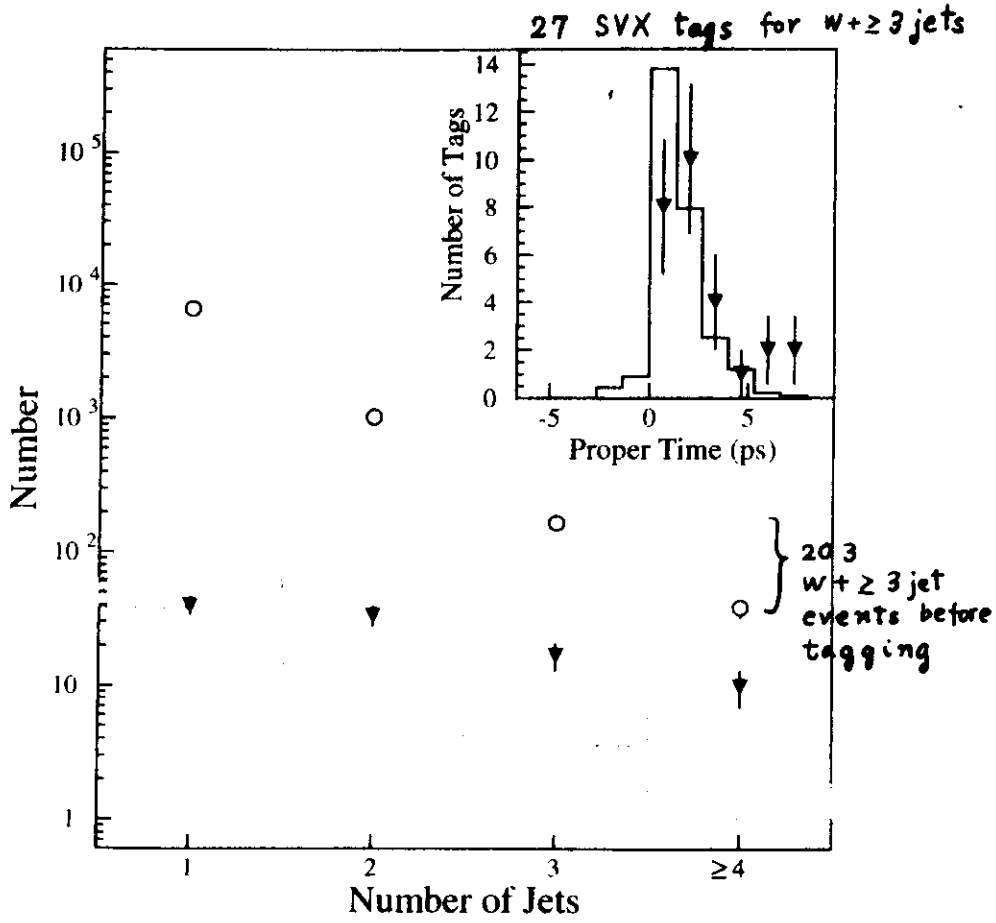
Efficiency for tagging a $t\bar{t}$ event: $42 \pm 5\%$ (Run Ib)
$22 \pm 6\%$ (Run Ia)

Comparison to Run 1A

- Improved Algorithm: Factor 1.25
- Bug Fix in B baryon Lifetime: Factor 1.15
- Statistically more accurate measure of the data/MC scale factor (agree to 1-1.4 σ)







○ Number of events before SVX tagging

▼ Number of tags observed

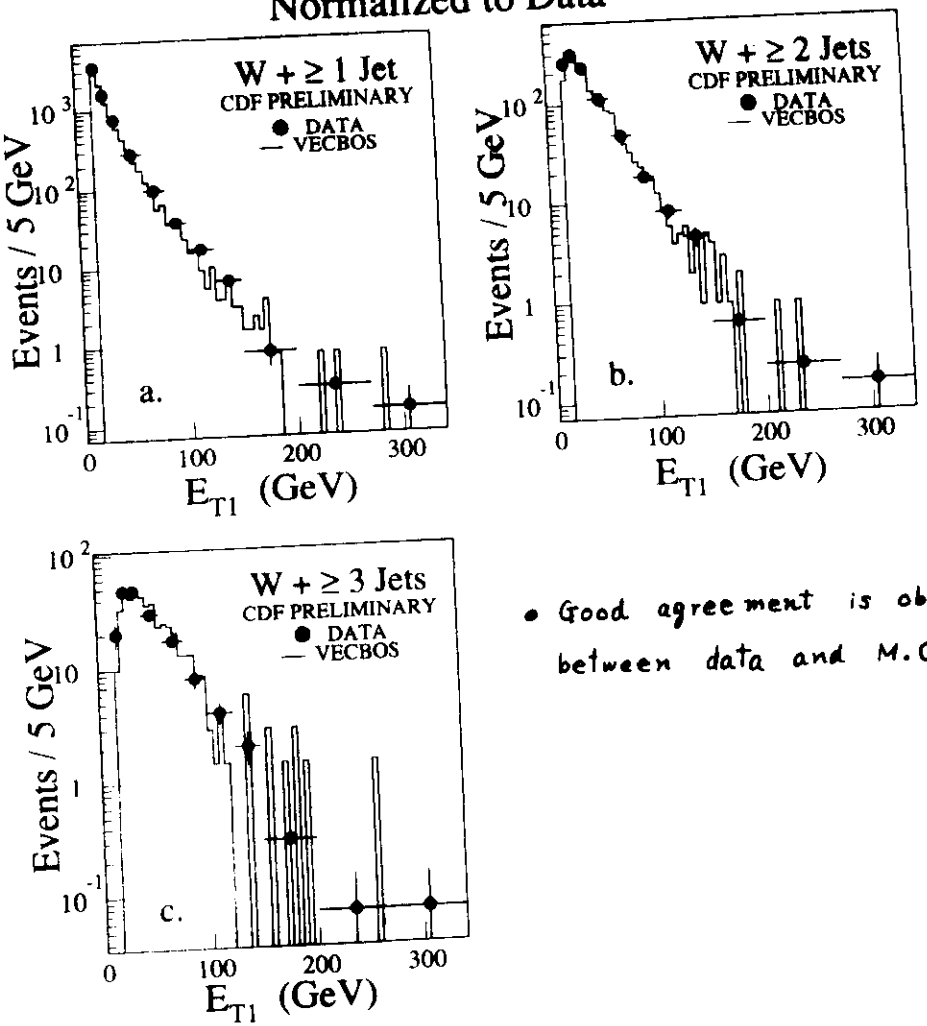
▨ Expected number of background tags

— Expectation for b quark jet from $t\bar{t}$ decay

W + n jet Events before Tagging

CDF data are compared with VECBOS for W+JETS
(48,000 events : $\int \mathcal{L} dt = 73\ pb^{-1}$)

Normalized to Data



- Good agreement is obtained between data and M.C.

Backgrounds for SVX Tagging

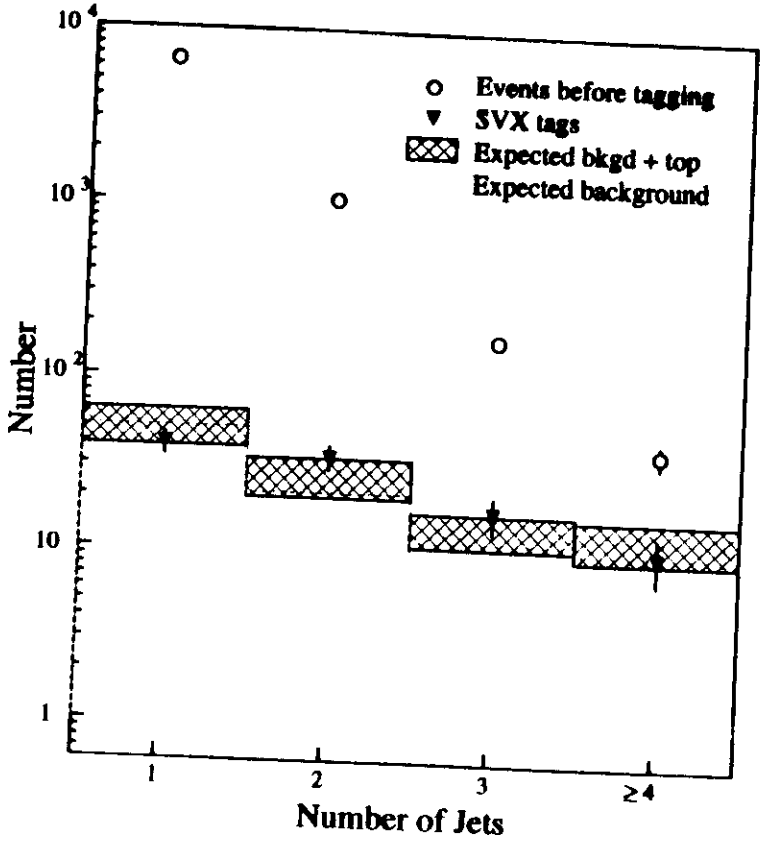
- 1. $Wb\bar{b}$ and $Wc\bar{c}$
  Ghion jet in a W event splits to a heavy flavor pair.
- 2. Mistags
  A non-heavy flavor jet in a W event is tagged as a b-jet due to resolution smearing or errors.
- 3. Wc
  Flavor excitation processes $sg \rightarrow Wc$
- 4. WW (Diboson)
  One high P_T lepton ($W \rightarrow l\,\nu$)
  Heavy flavor ($W \rightarrow c\,\bar{s}$)

  $Z \rightarrow \tau\tau$
- 5. non W $b\bar{b}$

Method 2 Background uses Monte Carlo for all processes except for Mistags.

The Mistags uses the negative decay length tags observed in the generic jet samples

N_{jet} Plot for SVX including Top



SUMMARY OF SVX b-TAG BACKGROUNDS

Source	W + 1 Jet	W + 2 Jets	W + 3 Jets	$W + \geq 4$ Jets
(1) $Wb\bar{b}$, $Wc\bar{c}$ only, Method 2	13.81±11.05	7.79± 6.23	1.96± 1.57	0.50± 0.40
(2) Mistags only, Method 2	14.80± 2.96	5.30± 1.06	1.40± 0.28	0.52± 0.10
(3) Wc	15.34± 4.60	4.24± 1.27	0.92± 0.41	0.22± 0.10
(4) $Z \rightarrow \tau\tau$, WW, WZ	0.77± 0.31	0.78± 0.31	0.19± 0.08	0.04± 0.01
(5) Non-W, including $b\bar{b}$	5.70± 1.44	2.96± 0.76	0.77± 0.19	0.18± 0.04
Total Method 2	50.42±12.42	21.07± 6.50	5.24± 1.66	1.45± 0.43
Events before Tagging	6578	1026	164	39
Observed Tagged Jets	40	34	17	10

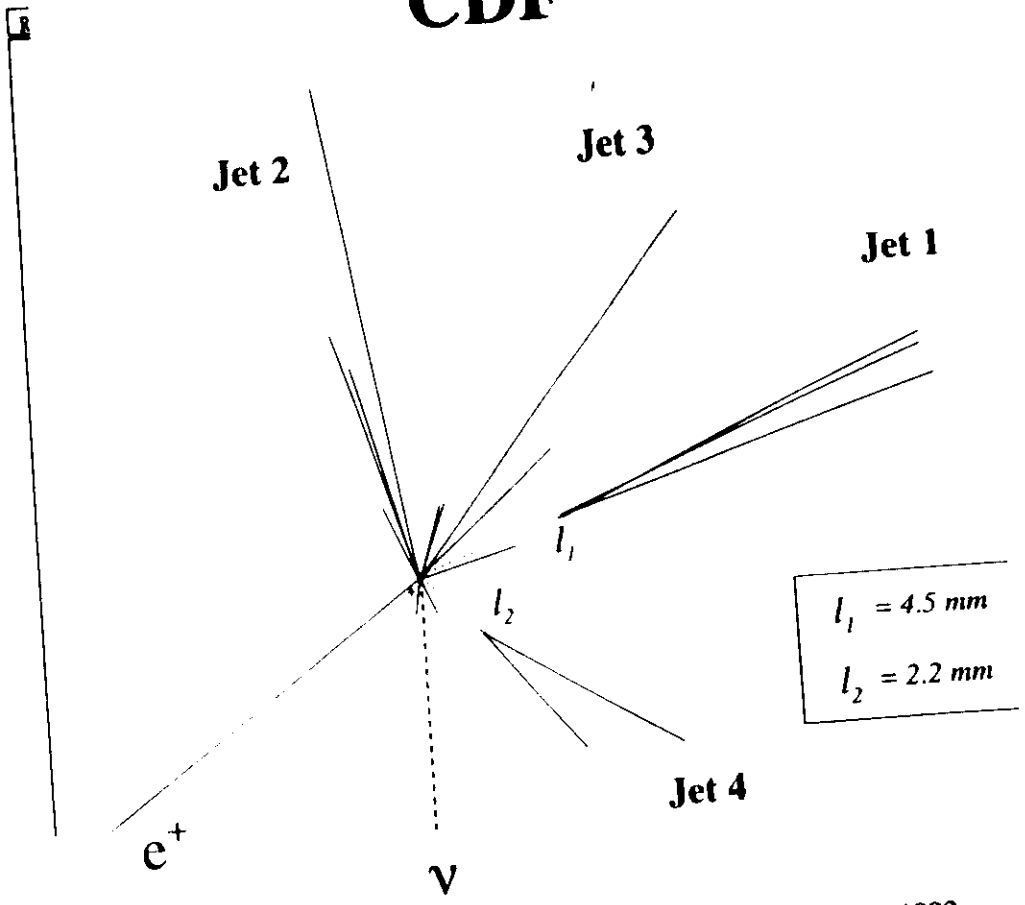
Table 0.1: Summary of background and observed tagged JETS (not events) for SECVTX Run 1A+1B.

Background Method 2: 6.7 ± 2.1 Tags

Observed Tags: 27

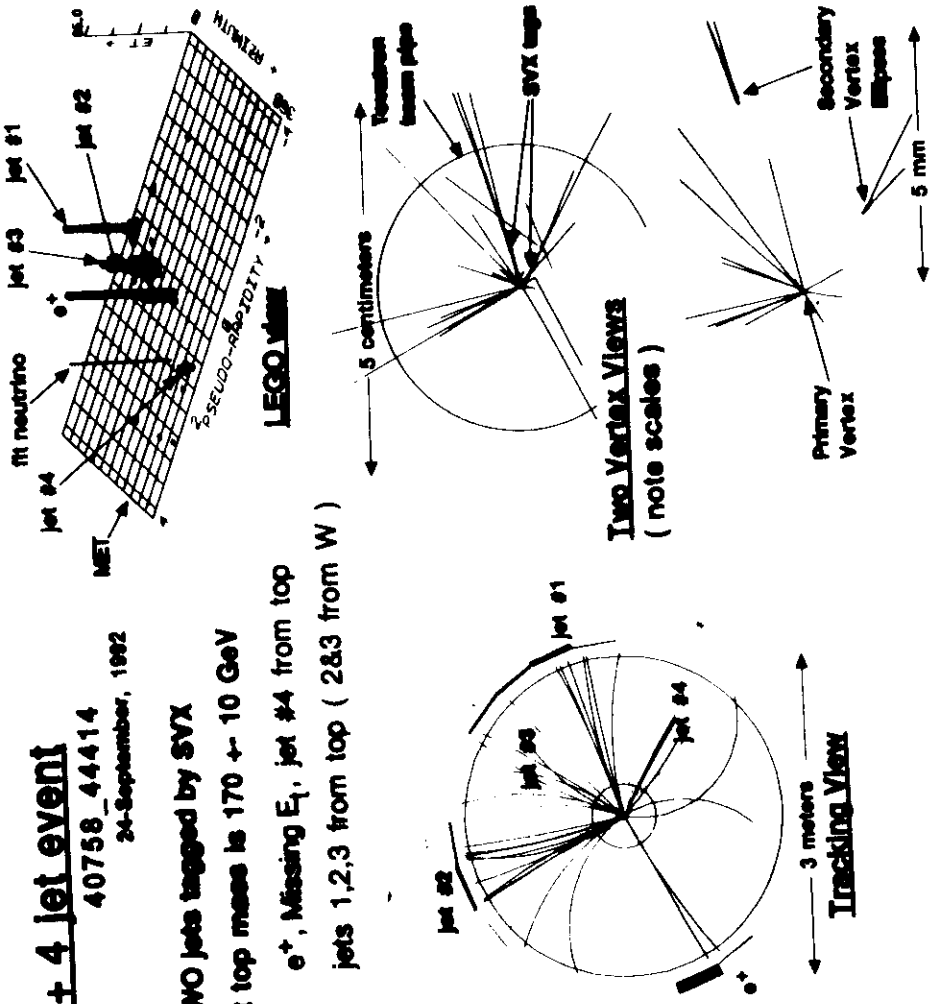
Tagged Events: 21

$t\bar{t}$ Event
SVX Display
CDF



$M_{top}^{Fit} = 170 \pm 10$ GeV/c^2

24 September, 1992
run #40758, event #44414



Counting Experiments

Di-lepton Channel

Lepton + Jets Channel

SLT Soft Lepton b-tagging

SVX Silicon vartex b-tagging

- Run Ia Luminosity = 19.3 pb^{-1}

DL 2 events Backgroud $0.56_{-0.13}^{+0.25}$

SVX 6 tags Backgroud 2.3 ± 0.3

SLT 7 tags Backgroud 3.1 ± 0.3

$P = 0.0026$ (2.8σ)

- Run Ia + 1b Luminosity = 67 pb^{-1}

DL 6events Backgroud 1.3 ± 0.3

SVX 27 tags Backgroud 6.7 ± 2.1

SLT23 tags Backgroud 15.4 ± 2.0

$P = 10^{-6}$ (4.8σ)

Cross Section (Preliminary)

$\sigma = 7.6_{-2.0}^{+2.4}$ pb

DiLepton Channel

Lepton PLus Jets Channel

SVX Silicón vertex b-tagging

SLT Soft Lepton b-tagging

- Run 1a + 1b Luminosity = 67 ± 4.85 pb^{-1}

DL 7 events Backgroud 1.3 ± 0.3

$\varepsilon = 0.78 \pm 0.08\%$

$\sigma = 10.3_{-4.5}^{+5.9}$pb

SVX 21 events Corrected-Backgroud 5.5 ± 1.8

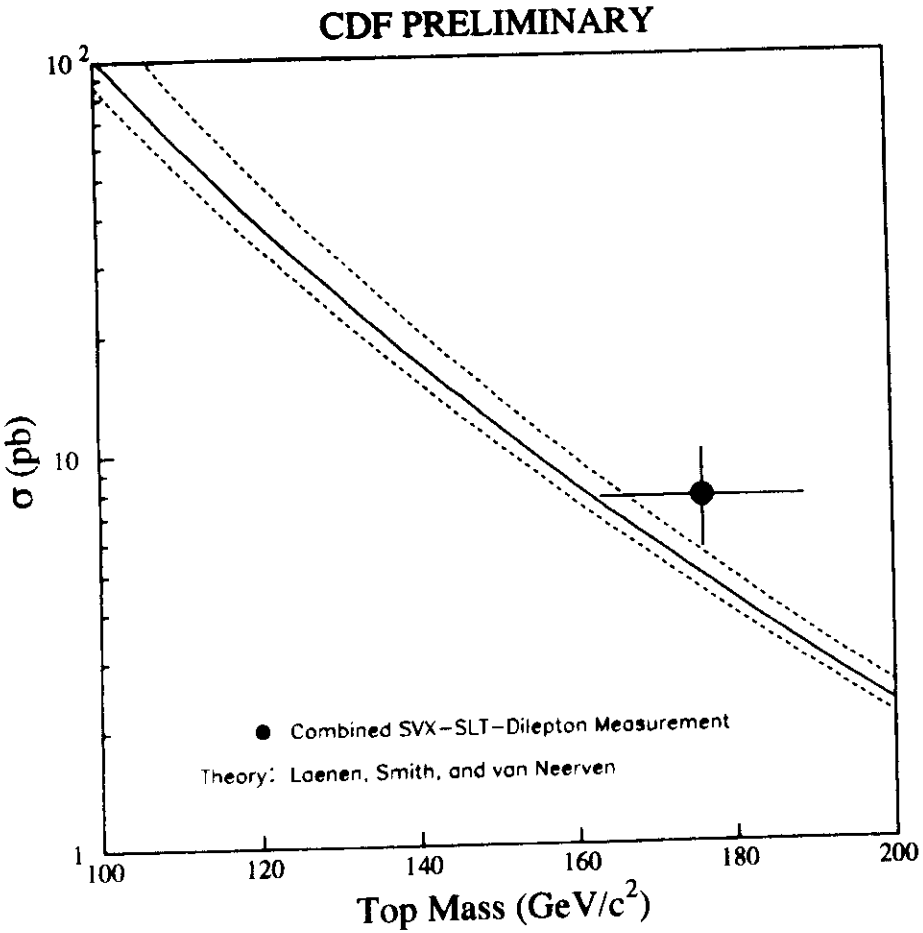
$\varepsilon = 3.38 \pm 0.87\%$

$\sigma = 6.8_{-2.3}^{+2.9}$pb

SLT 21 events Corrected-Backgroud 14.7 ± 2.2

$\varepsilon = 1.73 \pm 0.29\%$

$\sigma = 6.3_{-4.1}^{+5.0}$pb



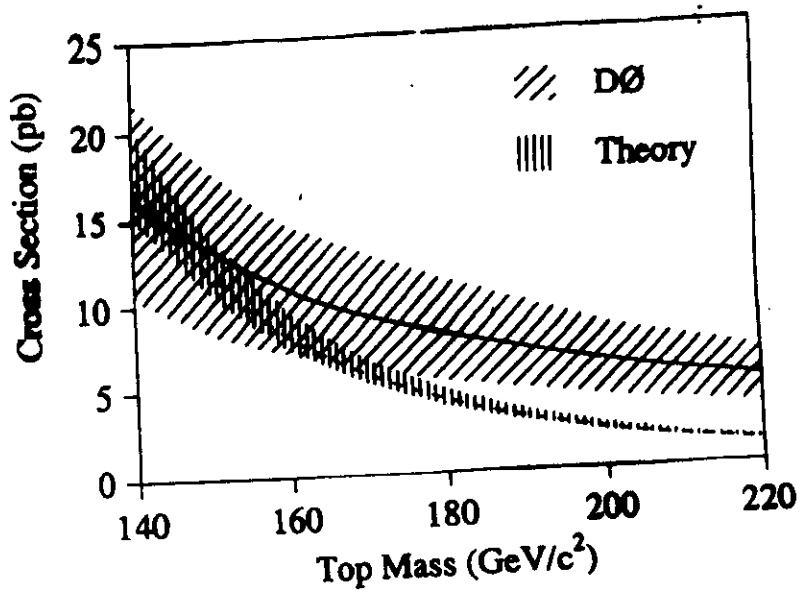


FIG. 3. DØ measured $t\bar{t}$ production cross section (solid line with one standard deviation error band) as a function of assumed top quark mass. Also shown is the theoretical cross section curve (dashed line) [5].

$$\sigma(t\bar{t}) = 7.6\ ^{+2.4}_{-2.0}\ pb\ \ (67\ pb^{-1})$$

$13.9\ ^{+6.1}_{-4.8}$ $(1994.4,\ \int \mathcal{L}dt = 19.3\ pb^{-1})$

$6.8\ ^{+3.6}_{-2.4}$ $(1995.3,\ \int \mathcal{L}dt = 67\ pb^{-1})$

Q: Is there any $t\bar{t}$ production mechanism other than SM?
A: need more statistics

Mass Measurement of the Top Quark

- Method
- Mass spectra with/without b-tagging
- Uncertainties in mass measurement

Kinematical Features of $t\bar{t}$ production

- H variable distribution
- Relative likelihood analysis
- Invariant mass distribution of the $t\bar{t}$ system

Table 0.1: Fitted Top Mass using the MINUIT fitter

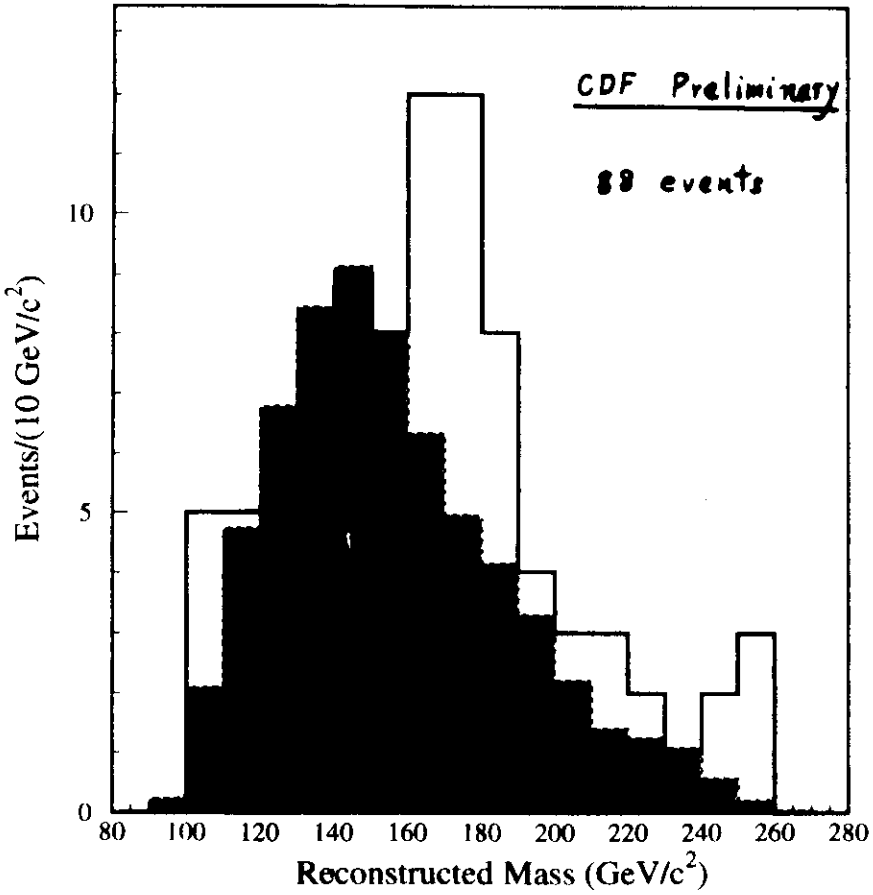
Pretagged Sample	Mass (GeV/c^2)	Fitted BKG (Events)
(1) BKG constrained	176.1 ± 8.6 GeV	$62.6^{+6.1}_{-7.1}$
(2) BKG not contrained	174.6 ± 7.7	$50.5^{+13.7}_{-12.5}$

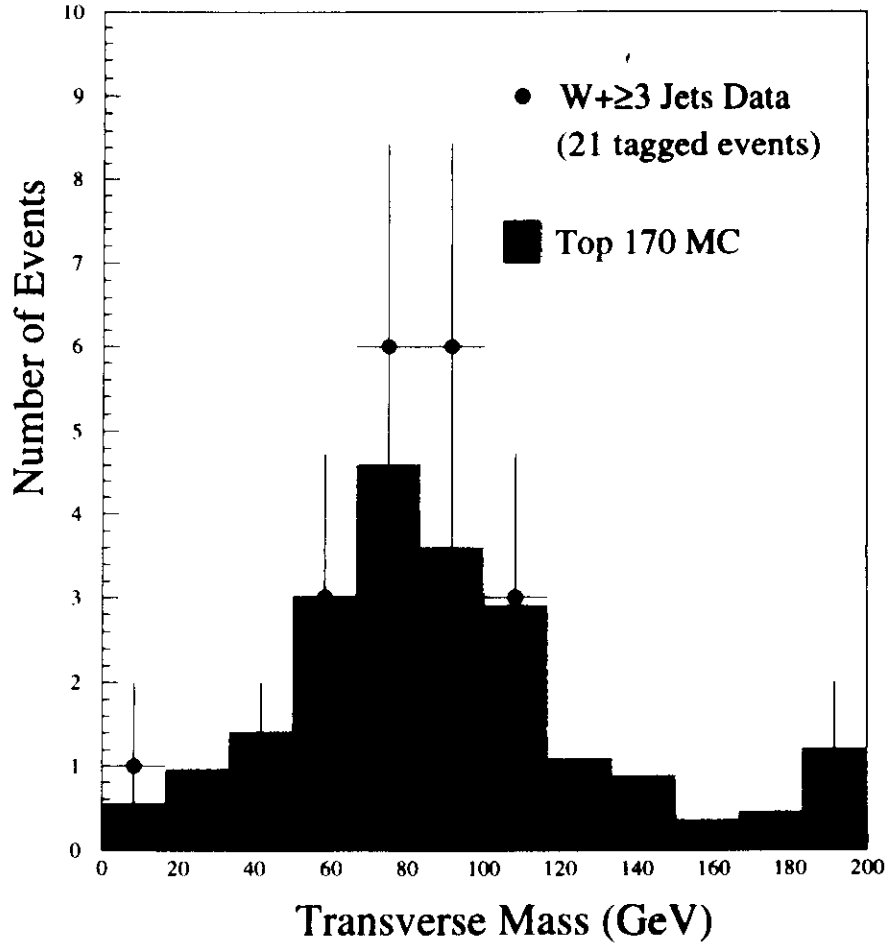
Mass for Pretagged Sample

- 1. $W + \geq 3$ Jets $E_T > 15$ GeV and $|\eta| < 2$.
  Number of events 203
- 2. Fourth Jet $E_T > 8$ GeV and $|\eta| < 2.4$
  Number of events 99
- 3. good events $\chi^2 < 10$
  Number of events 88

Sample is well described as 70% VECBOS and 30% TOP
CDF Preliminary

The mass of the pretagged sample





The background is constrained to 65 events.

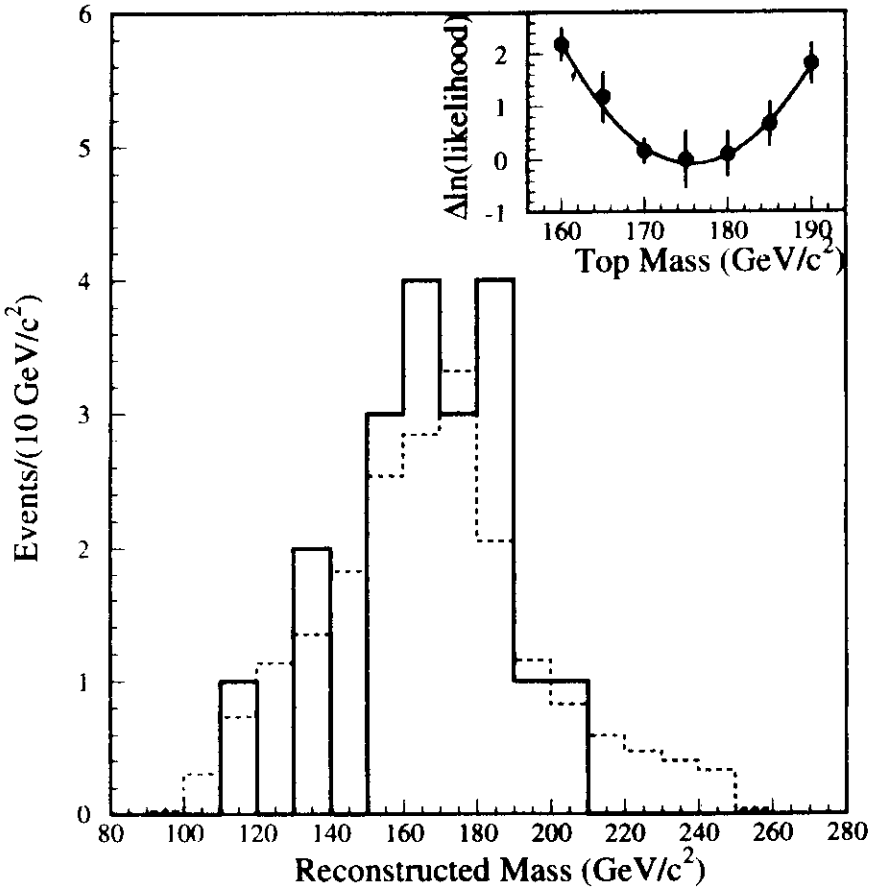
Table 0.1: Fitted Top Mass using the MINUIT fitter

Pretagged Sample	Mass (GeV/c^2	Fitted BKG (Events)
(1) BKG constrained	175.6 $\pm$ 7.8 GeV	$6.3^{+2.1}_{-1.7}$
(2) BKG not contrained	175.0 $\pm$ 6.7	$1.5^{+5.5}_{-1.5}$

Mass for Tagged Sample

- 1. W + $\geq$ 3 Jets $E_T > 15$ GeV and $|\eta| < 2$.
  Number of events 37
- 2. Fourth Jet $E_T > 8$ GeV and $|\eta| < 2.4$
  Number of events 23
- 3. good events $\chi^2 < 10$.
  Number of events 19

Sample is well described as 36% VECBOS and 64% TOP



Review of Run 1A Results from the PRD*

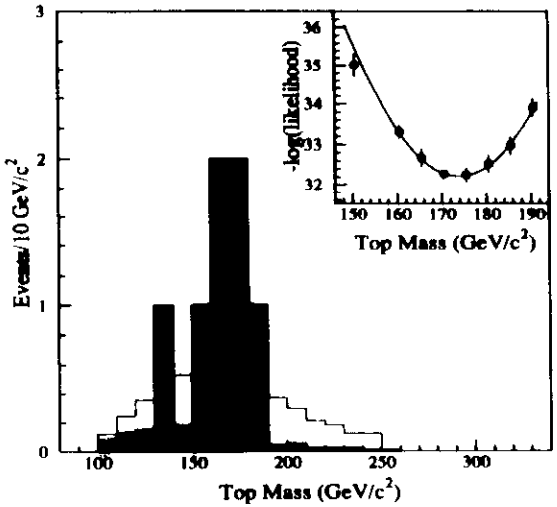
DIL: 2 evts. obs. Back = $0.56^{+0.25}_{-0.13}$

SVX: 6 tags. obs. Back = 2.3 ± 0.3

SLT: 7 tags. obs. Back = 3.1 ± 0.3

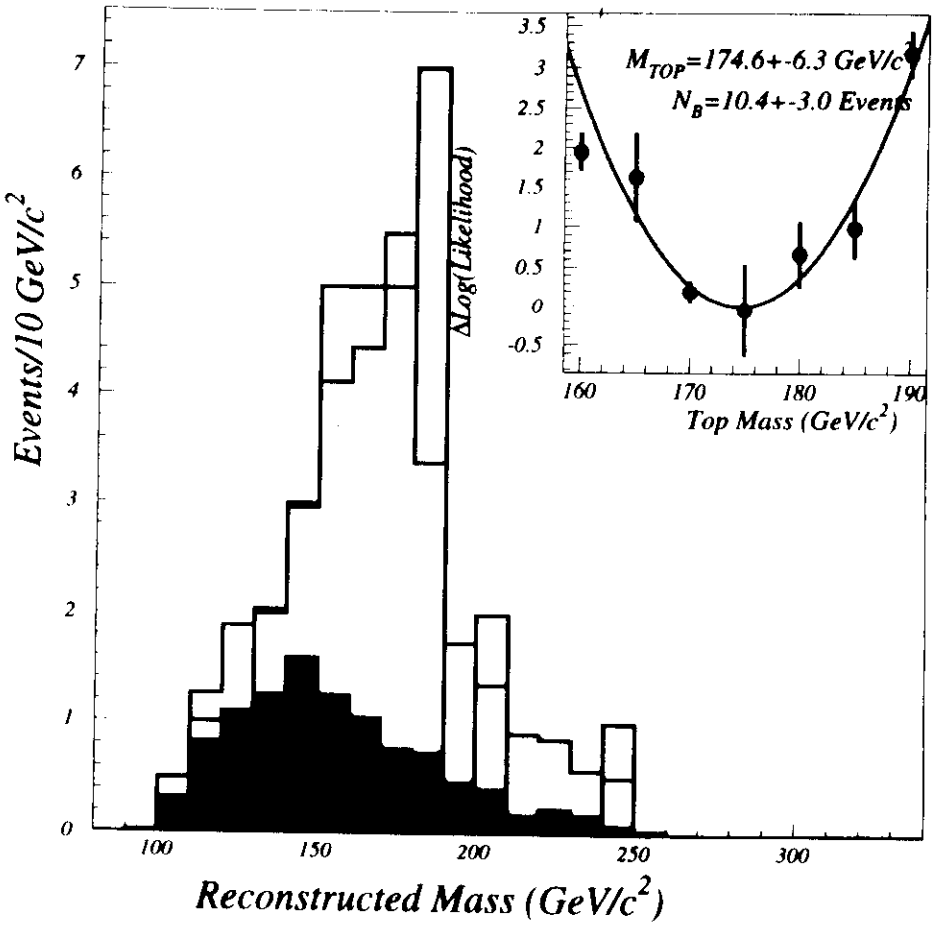
$P = 0.26\%$ (2.8σ)

Mass Plot:



$M_{top} = 174 \pm 10^{+13}_{-12}$ GeV/c^2

$\sigma_{t\bar{t}}\,(M_{top} = 174) = 13.9^{+6.1}_{-4.8}$ pb

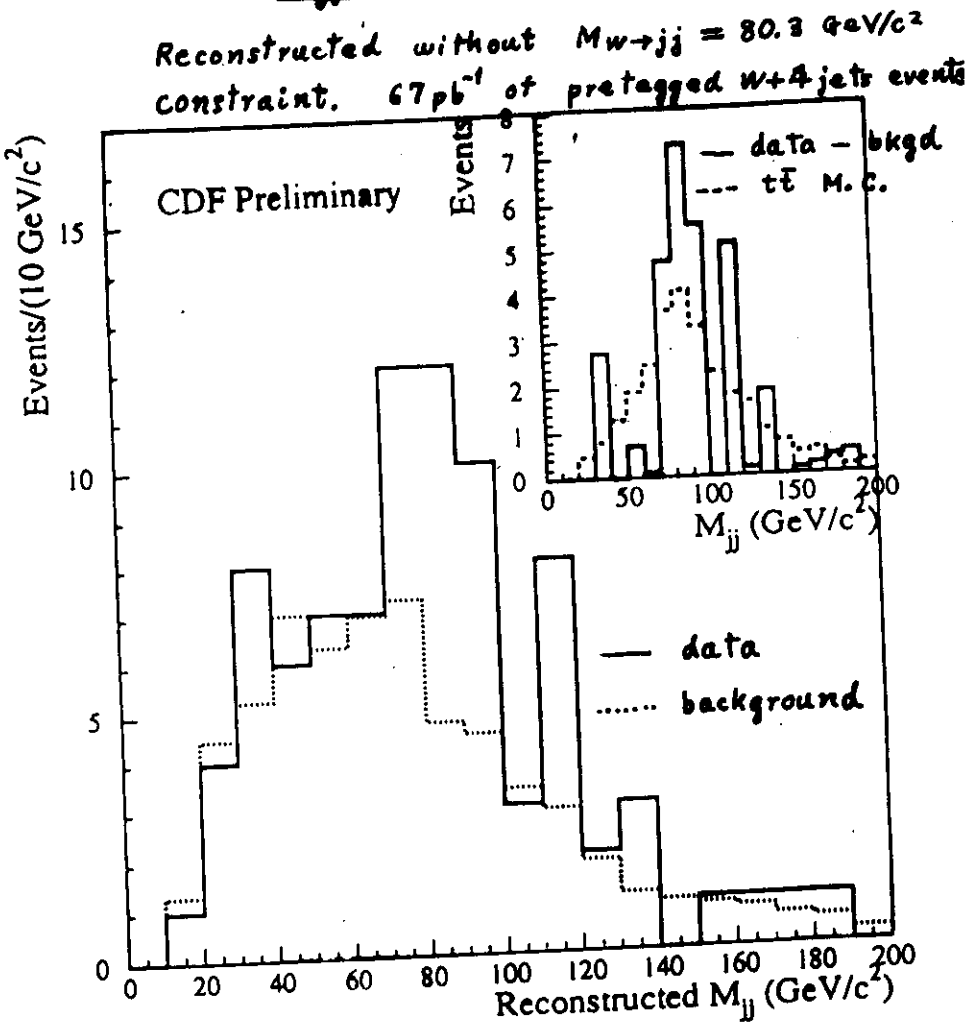


* CDF Collaboration, Phys. Rev. **D50**, 2966 (1994)

Systematic uncertainties in top mass measurement, obtained from Monte Carlo or data.

	Systematics	Value (GeV)	Value (%)
a.	Absolute Jet Energy Scale (detector effects)	3.1	1.8
b.	Relative(Plug-Central) energy scale	0.1	< 0.1
c.	Absolute Energy scale (Gluon Effects)	7.7	4.4
d.	Fit Configuration	2.5	1.4
e.	Signal Shift due to SLT tag	2.1	1.2
f.	Signal shift due to SVX tag	1.1	0.6
g.	Background shifts due to SLT mistag	0.1	< 0.1
h.	Background shifts due to SVX mistag	0.1	< 0.1
i.	Different backgrounds shapes	1.6	0.9
j.	Different type of likelihood fits	1.6	0.9
k.	Different way to fit the points	1.2	0.7
l.	Monte Carlo statistics	3.1	1.8
	Total	9.8	5.6

M_{jj}^{W} distribution



Summary of CDF Experiment from Run Ia and Ib

Counting experiment

$\int Ldt = 67\ pb^{-1}$

Modes	SVX	SLT	D.L.	Total
Num. of Events	21*(6)	22*(7)	6(2)	43(12)
Num. of b-tags	27	23	5	55
Background	6.7±21	15.4±2.0	1.3±0.3	
Non-top Prob.	2×10^{-5}	6×10^{-2}	3×10^{-3}	1×10^{-6}

Conclusions

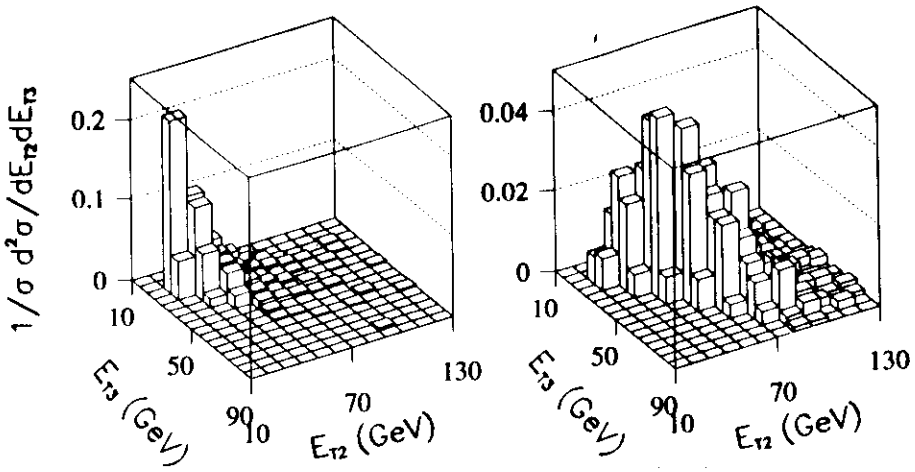
1. The probability that the selected events are explained by the upward fluctuation of known background events is less than 1.0×10^{-6} (2.6×10^{-3} from Run 1a).

2. The top quark mass is measured to be 176± 8(stat.)±10(syst.) GeV/c^2.

3. The $t\bar{t}$ production cross section is measured to be 6.8+3.6/-2.4 pb.

Kinematic Analysis (Fermilab-Pub-94/411-E)

W+3 jets (Vecbos) Top (170 GeV) (Herwig)



E_{T2} and E_{T3} sensitive to difference between $t\bar{t}$ and W+ QCD jets.

Define a relative likelihood:

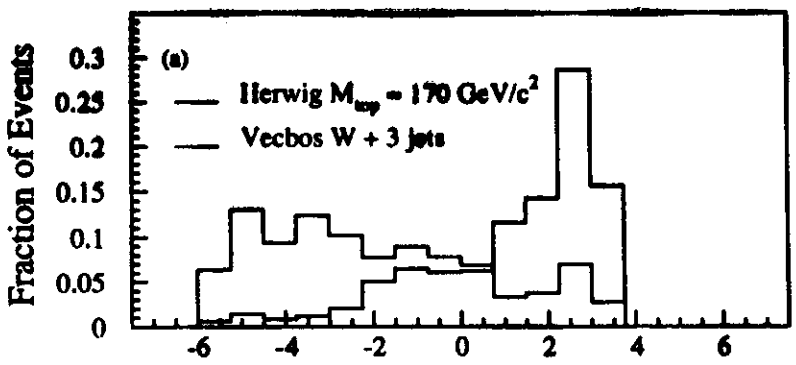
$$L_{rel} = \frac{\left(\frac{1}{\sigma}\frac{d\sigma^{t\bar{t}}}{dE_{T_2}}\right) \times \left(\frac{1}{\sigma}\frac{d\sigma^{t\bar{t}}}{dE_{T_3}}\right)}{\left(\frac{1}{\sigma}\frac{d\sigma^{QCD}}{dE_{T_2}}\right) \times \left(\frac{1}{\sigma}\frac{d\sigma^{QCD}}{dE_{T_3}}\right)}$$

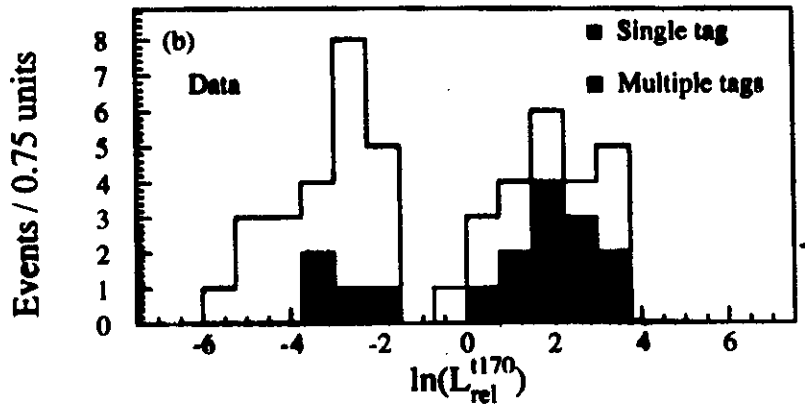
where each cross section term is normalized to 1 (shape analysis)

- $ln(L_{rel}) < 0$ more likely to be QCD
- $ln(L_{rel}) > 0$ more likely to be $t\bar{t}$

Signal Sample

47 events





22 events

$\ln(L) > 0$

$\cos(\theta^*)_{max} < 0.7$

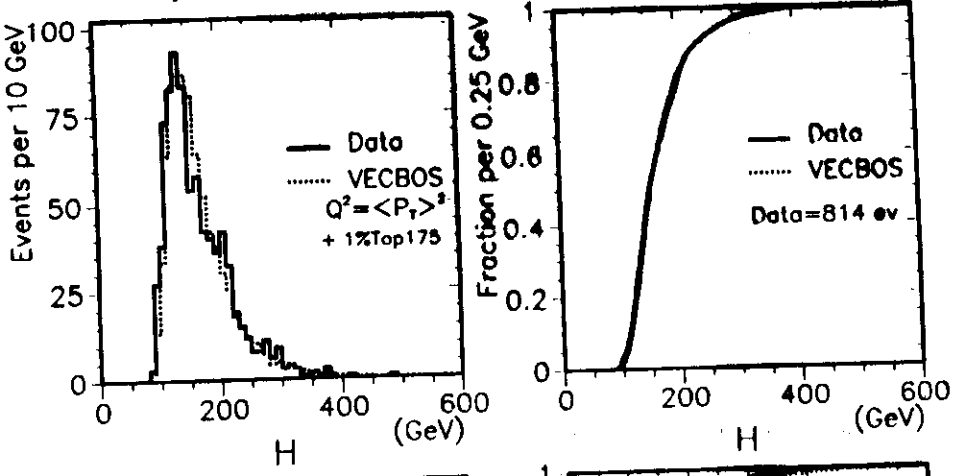
≈ 50% $t\bar{t}$; ≈ 25% VECBOS

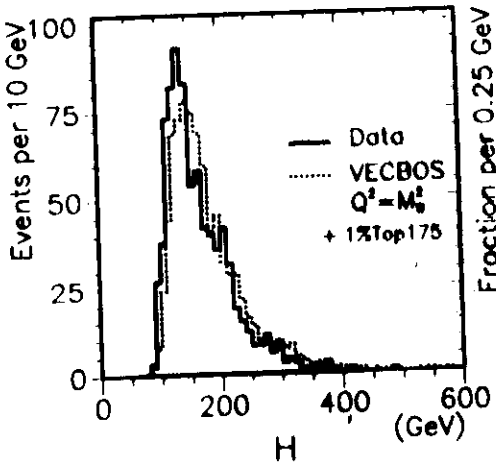
H ANALYSIS

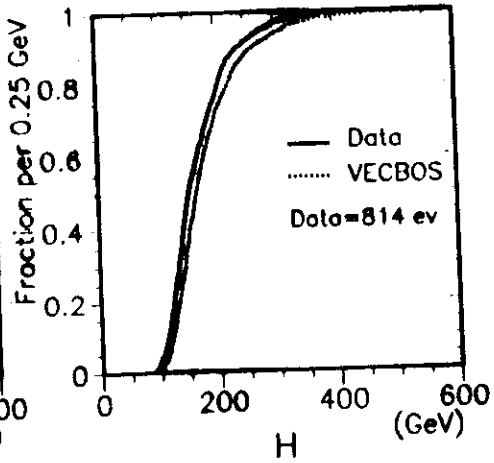
- $H = P_t(lepton) + MET + \Sigma E_t(jets)$
  - A simple, global variable that is ≈ Transverse Mass of the $t\bar{t}$ system.
  - Good correlation with Top Mass. Provides an independent check of Mass and the number of $t\bar{t}$ events.
- Signal Data Sample: Data Set II cuts (mass fitters). Has 99 events, a few more than for the Overview Plots, because an extra trigger path is allowed and there is slightly different background removal.
- Control Data Samples: Veto on 4th Jet with $E_t > 8$ GeV. Low $t\bar{t}$ content.

CDF preliminary. H analysis control sample (3 Jet Low)

j123: Pt≥8 GeV, |η|≤2.4, VETO j4: Pt≥8, |η|≤2.4

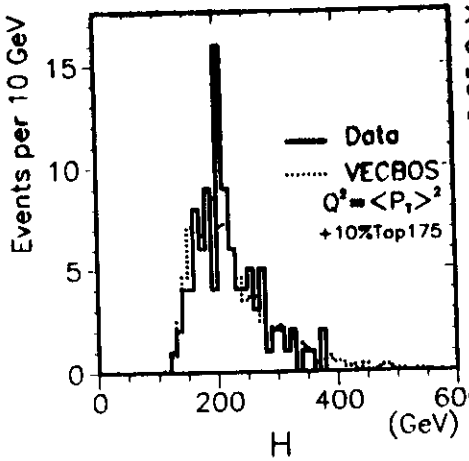


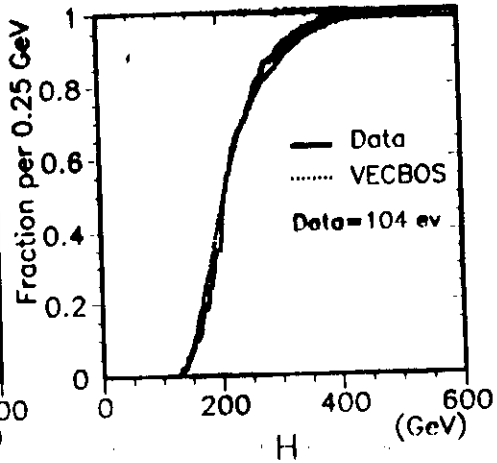


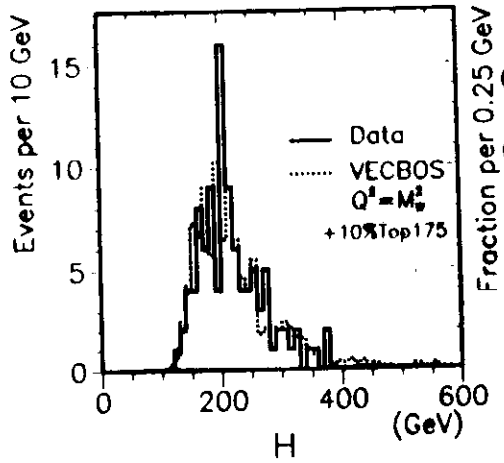


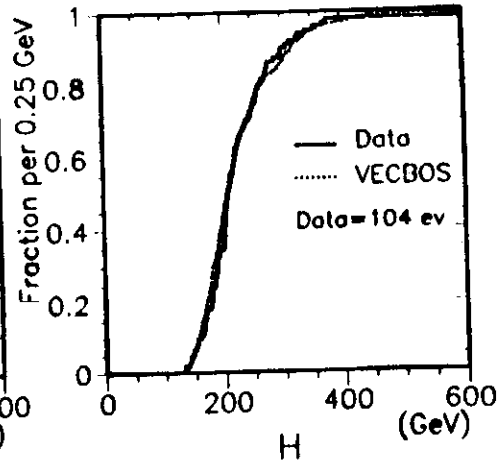
CDF preliminary. H analysis control sample (3 Jet High)

j123: Pt≥15 GeV, |η|≤2.0, veto j4: Pt≥8, |η|≤2.4

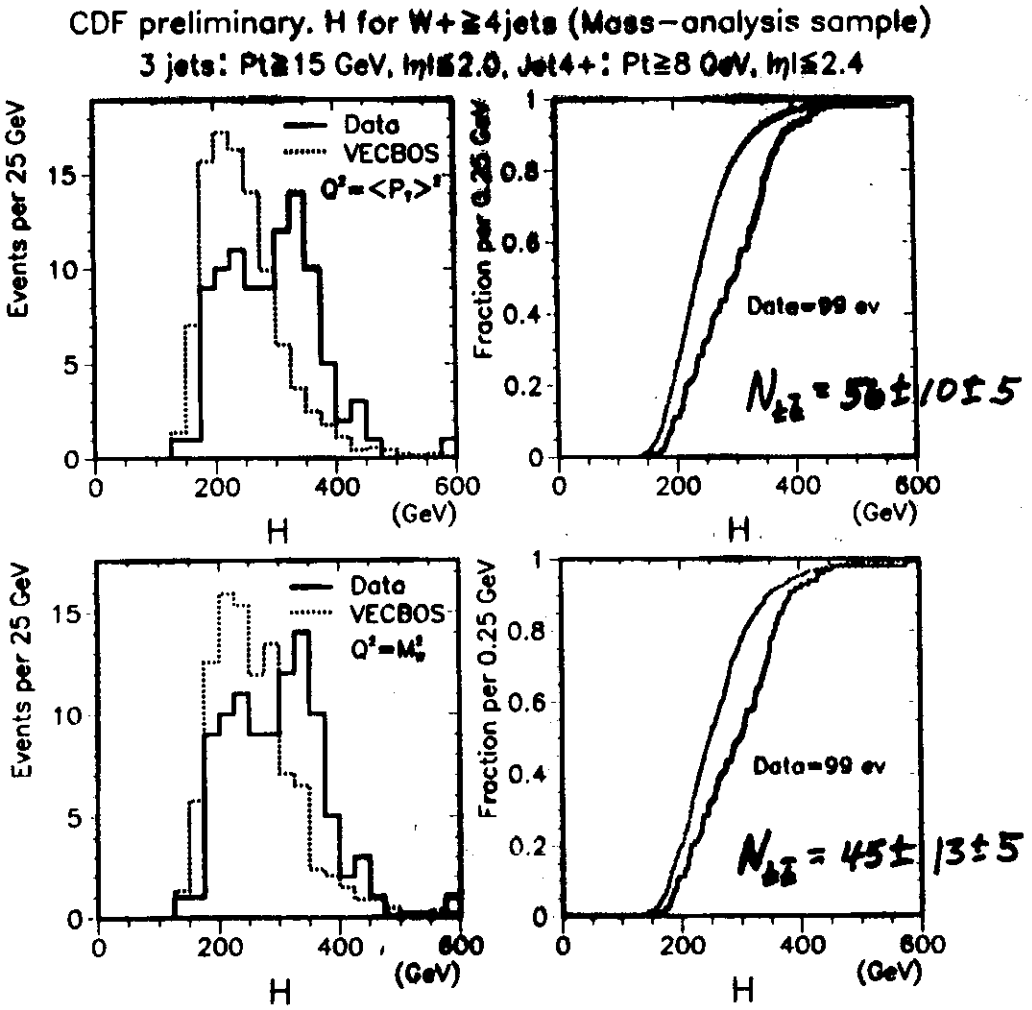


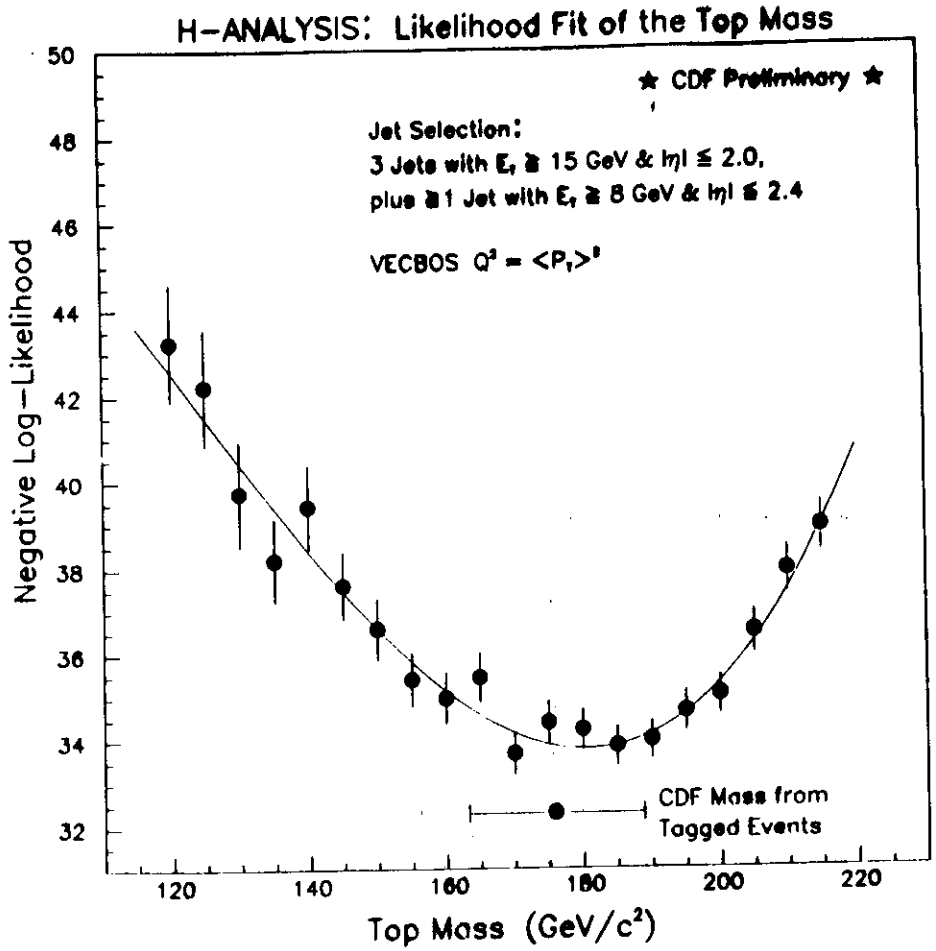






VECBOS Prediction normalized to the data





FIGURES

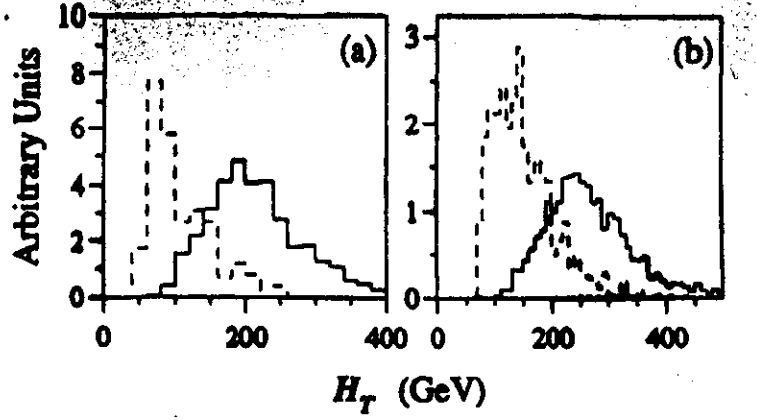


FIG. 1. Shape of $\not\!\!E_T$ distributions expected for the principal backgrounds (dashed line) and 200 GeV/c^2 top quarks (solid line) for (a) $e\mu$ + jets and (b) untagged single-lepton + jets.

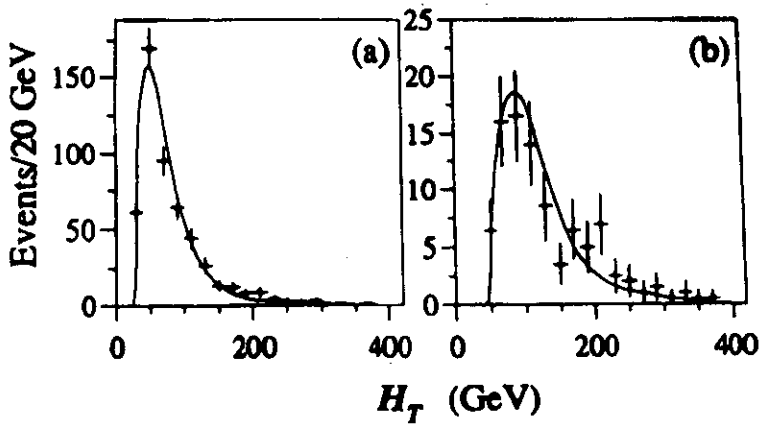


FIG. 2. Observed $\not\!\!E_T$ distributions (points) compared to the distributions expected from background (line) for $\not\!\!E_T > 25$ GeV/c and (a) $e + \geq 2$ jets and (b) $e + \geq 3$ jets.

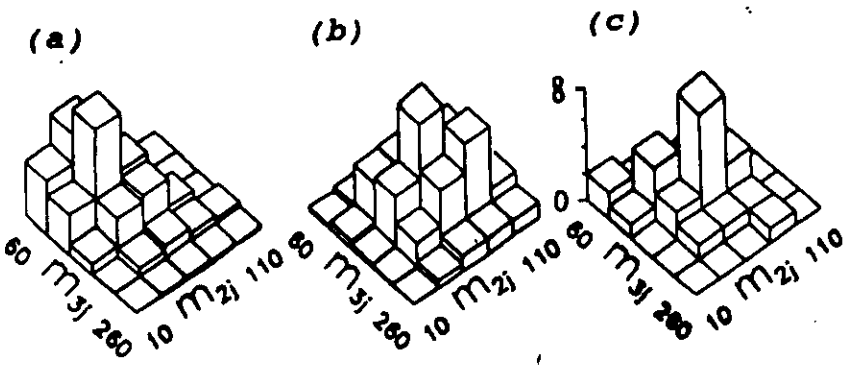


FIG. 4. Single-lepton + jets two-jet vs. three-jet invariant mass distribution for (a) background, (b) 200 GeV/c^2 top Monte Carlo (ISAJET), and (c) data.

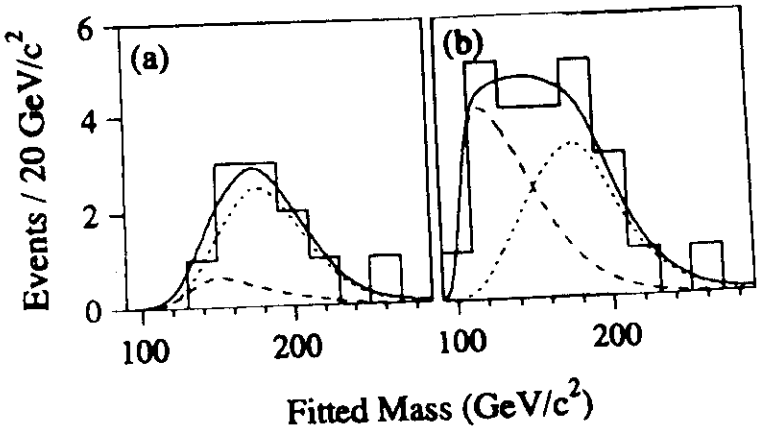


FIG. 5. Fitted mass distribution for candidate events (histogram) with the expected mass distribution for 199 GeV/c^2 top quark events (dotted curve), background (dashed curve), and the sum of top and background (solid curve) for (a) standard and (b) loose event selection.

Invariant Mass of $t\bar{t}$ System

$\int \mathcal{L}dt = 67\ pb^{-1}$, b-tagged events