Recent Results from CDF
– Top Quark Physics, mainly –

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Outline:

- Introduction
- Top Quark Physics
  - $\sigma_{t\bar{t}}$ Measurements
  - Hadronic W Decays
  - V_{tb}
  - Rare Decays (FCNC)
  - Top Production and Decay Kinematics
  - M_{top} Measurements
- Other Topics
  - Evidence for B_c Production
  - Measurement of Strong Coupling α_s
  - Radiation Amplitude Zero in $W\gamma$ Production
- Prospects at the Tevatron RUN-II

A History of Top Quark Search

- **1977-1994: A fine collection of null results**

- **April, 1994: First Evidence**
  - **Phys. Rev. D50, 2966 (1994) CDF**
  - **15 events on a background of 6.0**
  - **2.8 σ excess**
  - $M_{top} = 174 \pm 17$ **GeV/c^2**
  - $\sigma_{t\bar{t}} = 13.9^{+6.1}_{-4.8}$ **pb**

- **February, 1995: Confirmation**
  - **PRL 74, 2626 (1995) CDF**
  - **4.8 σ excess**
  - $M_{top} = 176 \pm 8\ (\text{stat}) \pm 10\ (\text{syst})$ **GeV/c^2**
  - $\sigma_{t\bar{t}} = 6.8^{+3.6}_{-2.4}$ **pb**
  - **PRL 74, 2632 (1995) DO**
  - **4.6 σ excess**
  - $M_{top} = 199^{+19}_{-21}\ (\text{stat})^{+14}_{-21}\ (\text{syst})$ **GeV/c^2**
  - $\sigma_{t\bar{t}} = 6.4 \pm 2.2$ **pb**

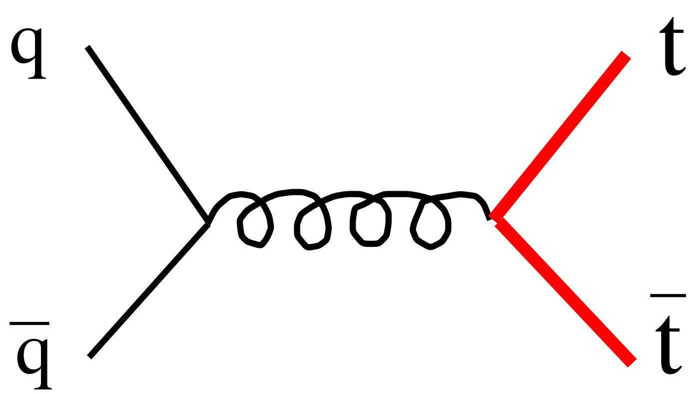
Final RUN-I CDF Top Results

- submitted to PRL
  - Cross Section and Mass (All Hadronic Channel)
  - Cross Section (Tau Dilepton Channel))
  - Limits on Flavor Changing Neutral Currents

- to be submitted soon
  - Cross Section and Mass (Dilepton Channel)
  - Mass (Combined)
  - Cross Section (Combined)
  - Observation of W-jj in Top Decays
  - Kinematics of Top Decays

Top Production at the Tevatron

Top quarks are predominantly produced in pairs by the process: $(p\bar{p} \rightarrow) q\bar{q} \rightarrow t\bar{t}$



In Tevatron RUN-I,

- **Integrated luminosity exceeded** $100\ pb^{-1}$ **(**$109\ pb^{-1}$**)**
- **over** $5 \times 10^{12}\ p\bar{p}$ **collisions**
- $\approx$ **500** $t\bar{t}$ **pairs produced,**

$$\frac{\sigma_{\mathbf{t\bar{t}}}}{\sigma_{\mathbf{inel}}} \sim \mathbf{10^{-10}}, \qquad \frac{\sigma_{\mathbf{t\bar{t}}}}{\sigma_{\mathbf{W}}} \sim \mathbf{10^{-3}}$$

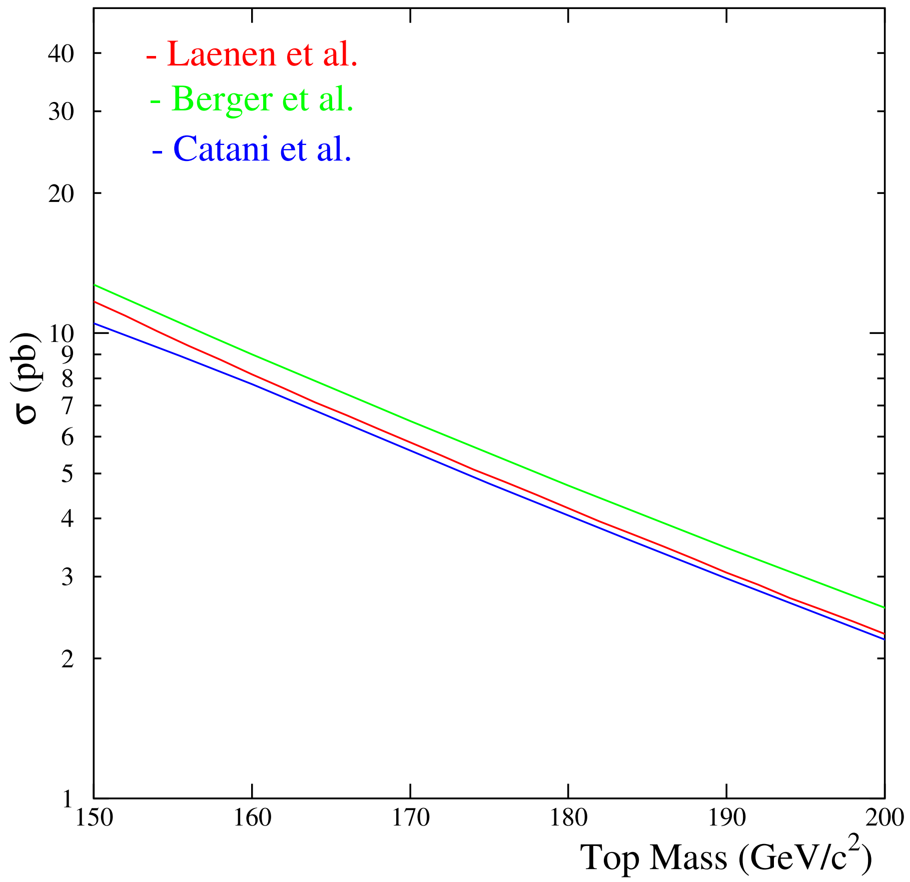
- **Single top production[1] has not yet been observed.**
  Wg **fusion** $\rightarrow t\bar{b} : \sigma \sim$ **1.4 pb**
  W^* **production** $\rightarrow t\bar{b} : \sigma \sim$ **0.7 pb**
  cf. $t\bar{t}$ **production:** $\sigma \sim$ **5 pb**

[1] T. Stelzer and S. Willenbrock, P.L. B357 (1995) 125.

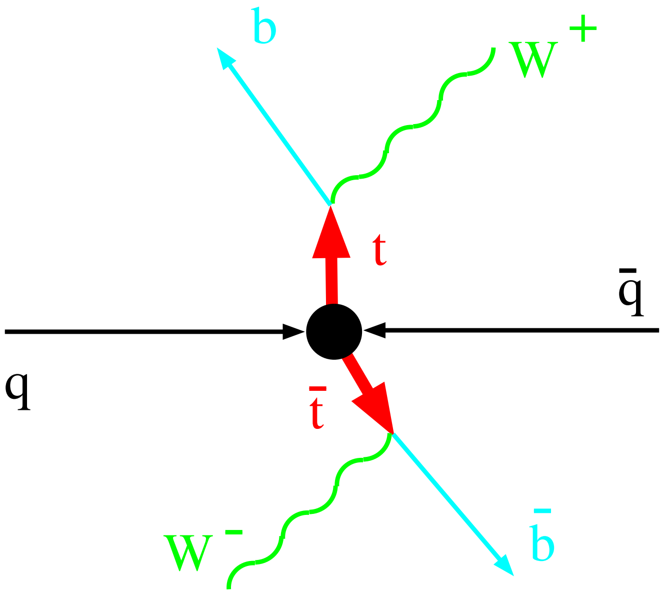
Theoretical Calculations

3 NLO Calculations:

- Laenen, Smith & van Neerven, Phys. Lett. B321, 254 (1994)
- Berger & Contopanagos, Phys. Rev. D54, 3085 (1996)
- S. Catani, M.L. Mangano, P. Nason, & L. Trentadue, Phys. Lett. B378, 329 (1996)



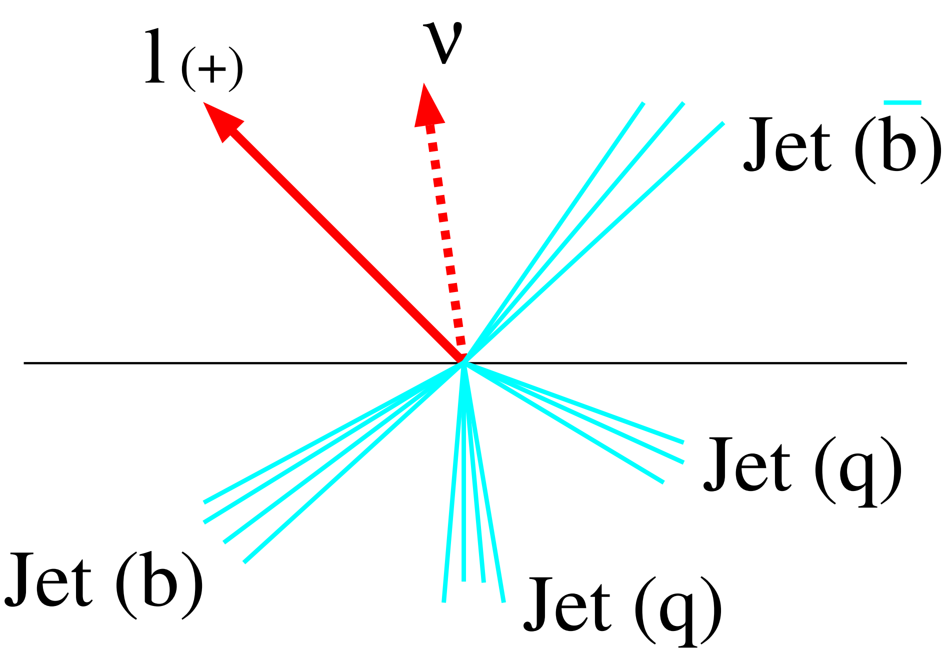
Top Quark Decay Signatures



Categorize the decay from decay modes of two W's:

- **Dilepton Channel: Both W's Decay $W \to \ell\nu$**
  final state: $(\ell^+\nu)(\ell^-\nu)b\bar{b}$ ($\ell = e$ or μ; 5%)
  S/N: super #evts: poor 2νs→-1C for mass
- **Lepton+Jets Channel: One W Decay $W \to \ell\nu$**
  final state: $(\ell^+\nu)(q\bar{q}^{'})b\bar{b}$ ($\ell = e$ or μ; 30%)
  S/N: moder. #evts: moder. 1ν→2C for mass
- **All Hadronic Channel: Both W's Decay $W \to q\bar{q}^{'}$**
  final state: $(q\bar{q}^{'})(q\bar{q}^{'})b\bar{b}$ (44%)
  S/N: poor #evts: good 0ν→3C for mass

Lepton + Jets Channels



Signature:

- One isolated high P_T lepton (e or μ (or τ))
- Missing Energy ($\not{E}_T$)
- 4 or more jets, 2 of which are from b-quarks

Dominant Backgrounds:

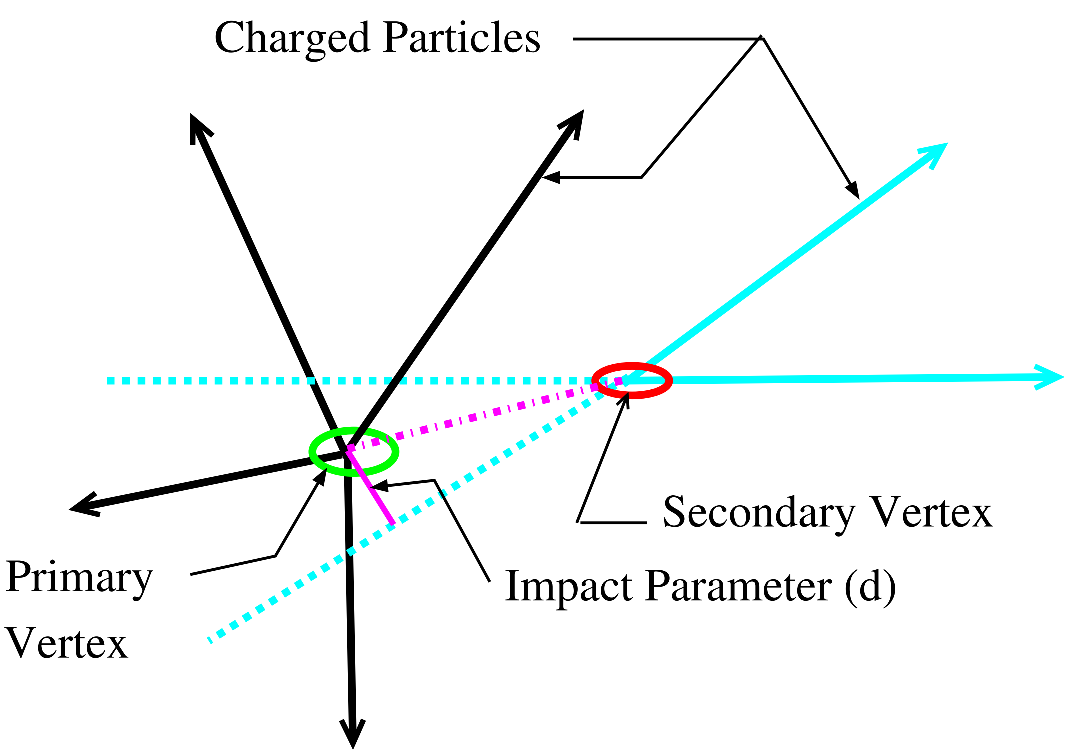
- $p\bar{p} \longrightarrow W + jets$
- QCD background (Fake leptons)

Two Distinct Differences between $t\bar{t}$ and W+jets

- $t\bar{t}$ events always contain b quarks: W+jet events usually do not.
- Jets in W+jet events have smaller E_T than in $t\bar{t}$

Further background suppression either with:

- **Topological/kinematic requirements:**
  - Aplanarity A
  - $H_T = E_T$(leptons)+$\not{E}_T + \Sigma E_T$(jets)
  - Form likelihood ($t\bar{t}$ vs. bkg) based on Jet E_T's
- **Tag b-quarks using semileptonic decays (SLT)**
  $b \rightarrow eX, \mu X$: $\varepsilon_{tag} \sim$ 18%
- **Tag b-quarks using displaced vertex (SVX)**
  Secondary vertex algorithm : $\varepsilon_{tag} \sim$ 41%



Summary of Event Counts (RUN-I)

Dilepton ($\mu\mu$, eμ, ee): 2 ℓ ($E_T > 20$) $\oplus$ 2 j ($E_T > 10$) $\oplus$ $\not{E}_T > 20$

Obs. Evt	9
Bkg Evt	2.4 $\pm$ 0.5
Expct Evt (ε%)	3.8 (0.74$\pm$0.08)

Tau-Dilepton ($e\tau$, $\mu\tau$): 2 ℓ ($E_T > 20, 15$) $\oplus$ $\geq$2 j $\oplus$ $\not{E}_T > 25$ $\oplus$ $H_T > 180$

Obs. Evt	4
Bkg Evt	1.3 $\pm$ 0.3
Expct Evt (ε%) for M_t=175	1.2 (0.13$\pm$0.03)

Lepton+Jets: ℓ ($E_T > 20$) $\oplus$ $\geq$3 j ($E_T > 15$) $\oplus$ $\not{E}_T > 20$ $\oplus$ SVX/SLT

Obs. Evt	34 (SVX) / 40 (SLT)
Bkg Evt	9.2$\pm$1.5 / 22.6$\pm$2.8
Expct Evt (ε%)	20 (3.7$\pm$0.5)/9.3 (1.7$\pm$0.3)

All Hadronic: $\geq$6 j $\oplus \Sigma E_T > 130 + 15 N_j > 0.75\sqrt{\hat{s}} \oplus A > -0.003 \Sigma E_T + 0.45 \oplus$ $\Delta R_{jj} > 0.5 \oplus$ SVX/2SVX

Obs. Evt	187 (SVX) / 157 (2SVX)
Bkg Evt	142$\pm$12 / 120$\pm$18
Expct Evt (ε%)	23 (4.4$\pm$1.0)/16 (3.0$\pm$1.0)

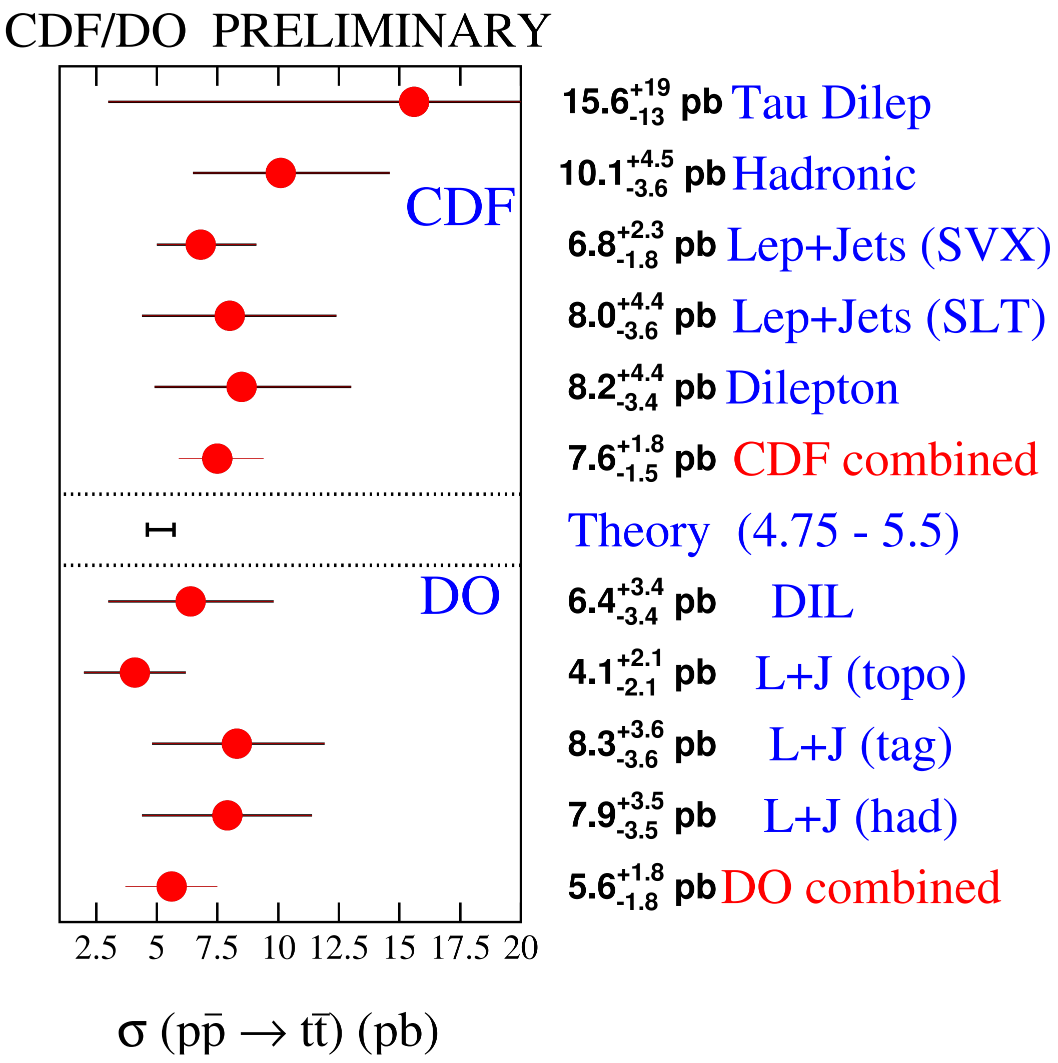
*Expected Events for σ=5 pb and M_t=175 GeV/c^2

$\sigma_{t\bar{t}}$ Measurements

$$\sigma = \frac{N_{\rm obs} - N_{\rm bkg}}{A \cdot \mathcal{L}}$$

CDF combined: $\sigma = 7.6^{+1.8}_{-1.5}$ pb

CDF value is consistent with the theoretical prediction (4.75–5.5 pb)

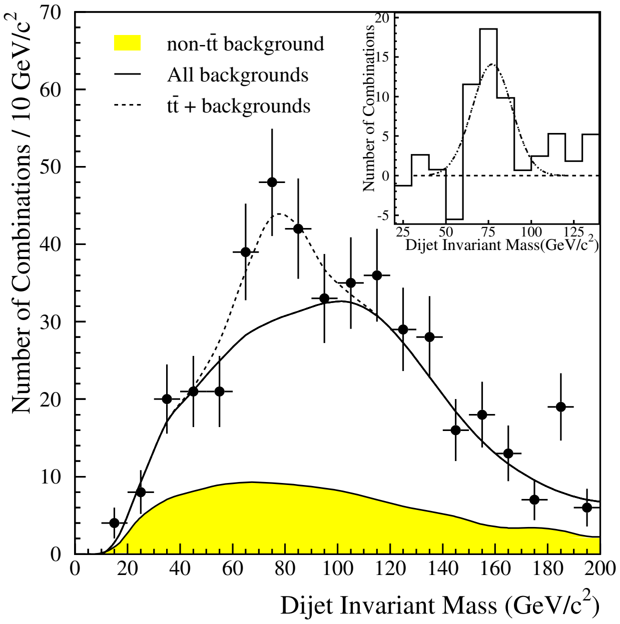


Hadronic W Decays

Reconstruct W $\rightarrow jj \Rightarrow E_T$ scale information

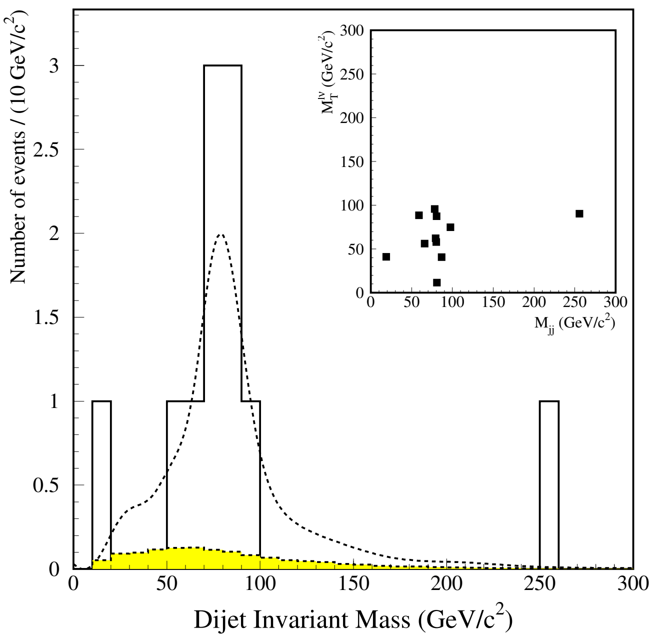
◇ $H_T >$ **310 GeV**

(Lepton+Jets events)



◇ **Two jets are b-tagged**

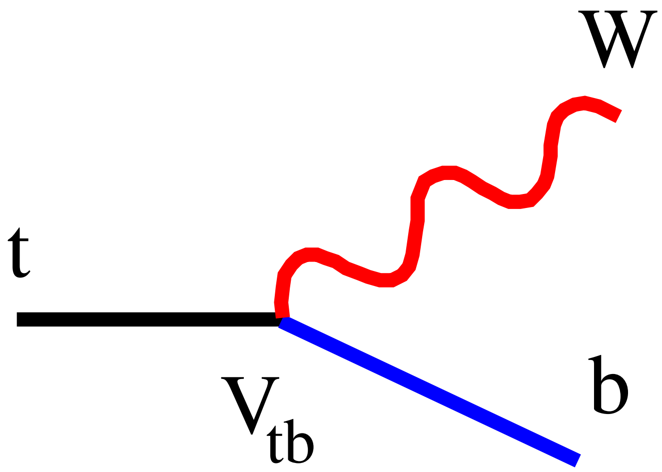
(Lepton+Jets events)



W mass significance: 3.3σ ($Prob$ = 5.4 $\times$ 10^{-4})

Measured mass = 77.2 ± 3.5 **(stat)** ± 2.9 **(sys) GeV/c^2**

Measurement of V_{tb}



- **From CKM unitarity with 3 generations:**
  $|V_{tb}| \sim 1 \; (> 0.9985)$
- **CDF has analyzed the $\ell + jets$ and dilepton samples:**
  - $f_2 = (B\varepsilon_{tag})^2$: **both jets are tagged**
  - $f_1 = 2B(\varepsilon_{tag})(1 - \varepsilon_{tag})$: **only 1 jet is tagged**
  - $f_0 = (1 - B\varepsilon_{tag})^2$: **untagged**

    where $B = \frac{Br(t \to Wb)}{Br(t \to WX)}$

  - **use the fractions to extract**

    $B = \frac{2}{\varepsilon_{tag}(f_1/f_2+2)}$ **or** $B = \frac{1}{\varepsilon_{tag}(2f_0/f_1+1)}$

By comparing ratios of these event fractions, this result is independent of the value of $\sigma_{t\bar{t}}$ and $\frac{Br(W \to \ell\nu)}{Br(W \to q\bar{q})}$

Results of a maximum likelihood combining all information

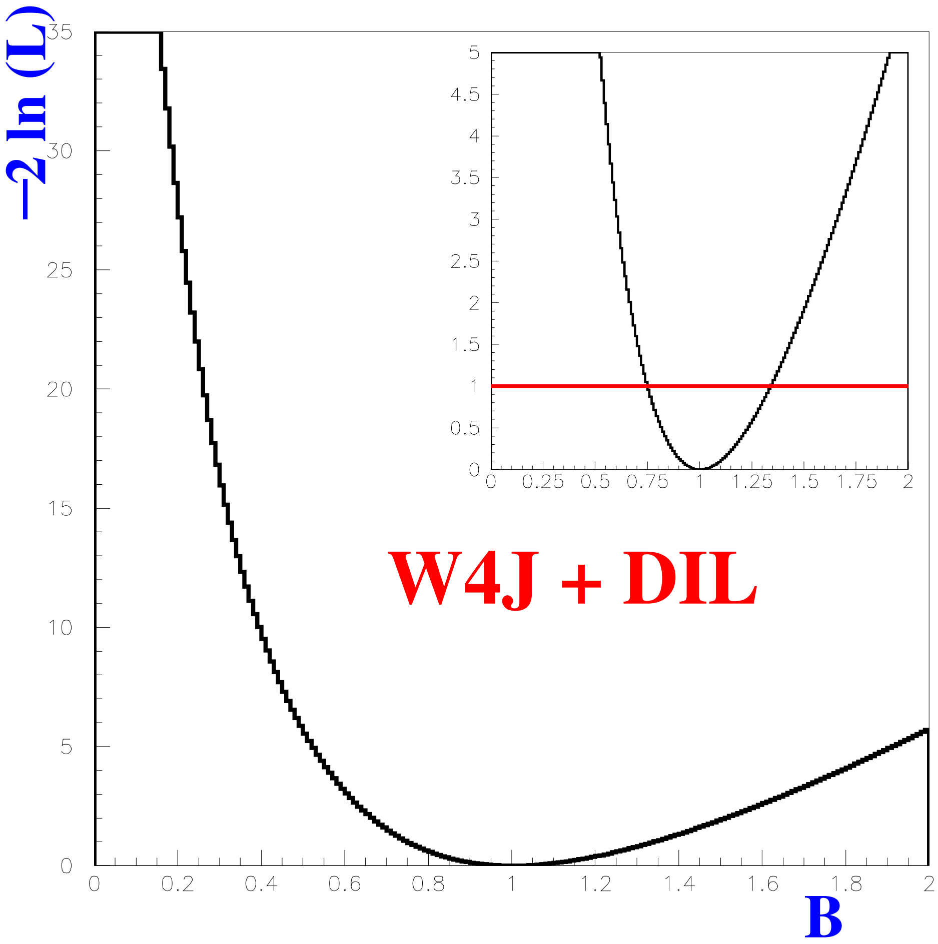
$$B \;=\; \frac{Br(t\to Wb)}{Br(t\to WX)} \;=\; 0.99 \pm 0.29 > 0.58 \text{ at 95\% C.L.}$$

In a three-generation Standard Model,

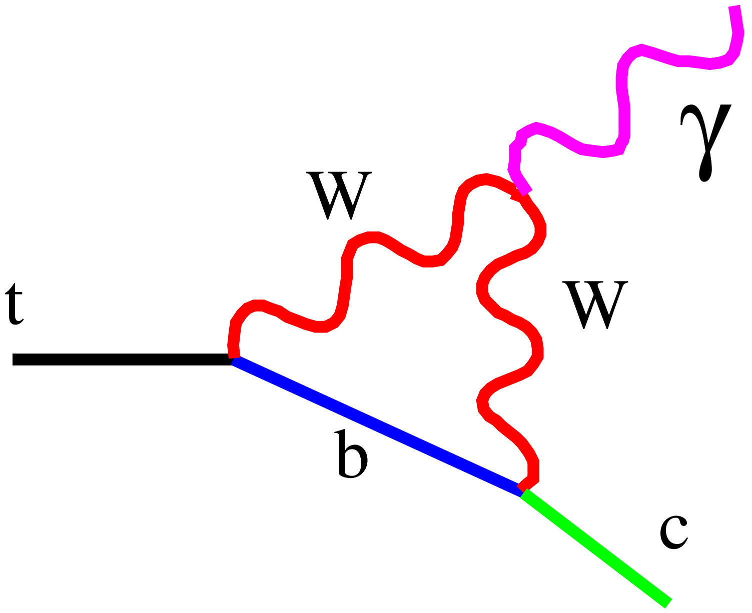
$$B \;=\; \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$$

Assuming 3-generation unitarity this yields:

$$|V_{tb}| \;=\; 0.99 \pm 0.15 > 0.76 \text{ at 95\% C.L.}$$



Search for Rare Decays



FCNC decays are suppressed[1] at 10^{-10}–10^{-12}
Any appearances would signal non SM physics

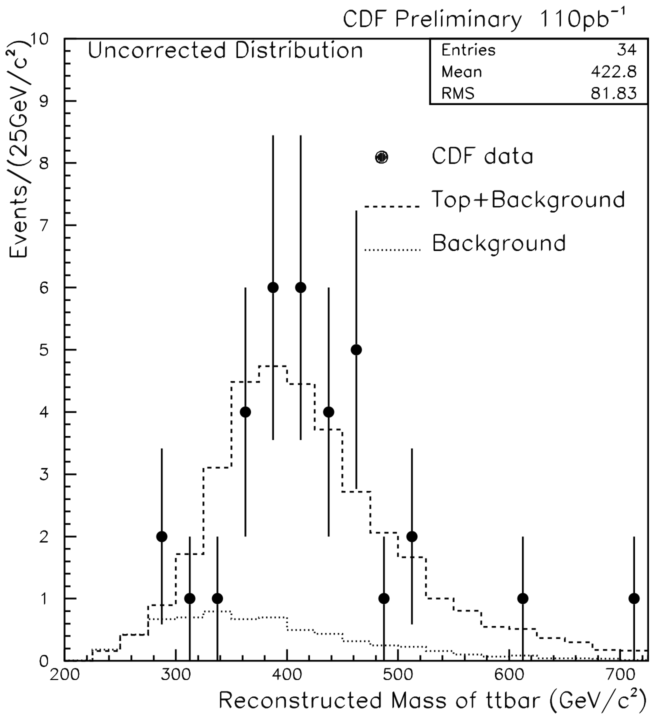
- Search $t\bar{t}$ events for one top decaying in $t \rightarrow Wb$ and the other top quark decaying to a rare mode:
  - $t \rightarrow \gamma\ c, \quad t \rightarrow \gamma\ u$
  - $t \rightarrow Zc$
- Search γ+4 jets and γ+lepton+jet+MET:
  $BF(t \rightarrow c\gamma) + BF(t \rightarrow u\gamma) <$ 2.9% (95% C.L.)
- Search for $t \rightarrow Zq$ ($Z \rightarrow l^+l^-$):
  $BF(t \rightarrow Zu) + BF(t \rightarrow Zc) <$ 33% (95% C.L.)

[1] S. Parke, FERMILAB-Pub94/322-T.

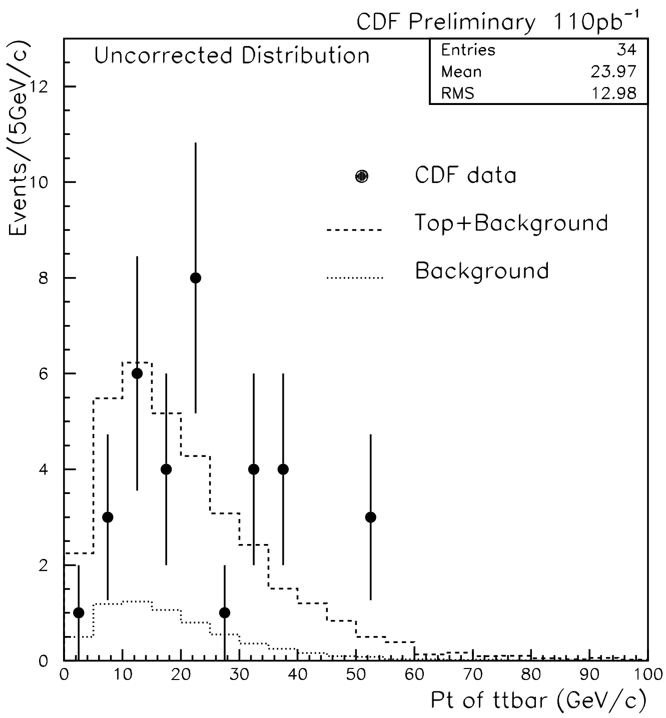
Top Production Kinematics

CDF data: 34 SVX tagged Lepton+$\geq$4Jets Events
MC: HERWIG Top + VECBOS W+nJets ($n \leq 3$)

$t\bar{t}$ invariant mass

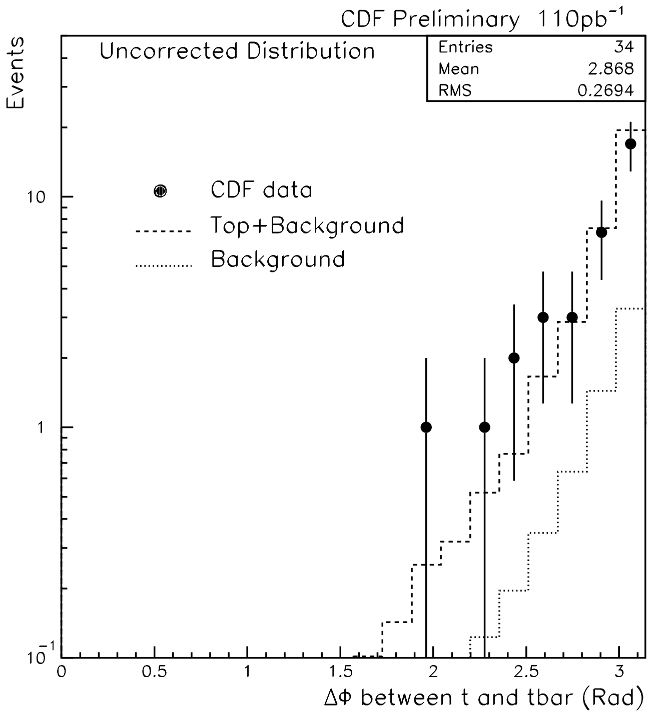


P_T of $t\bar{t}$ system

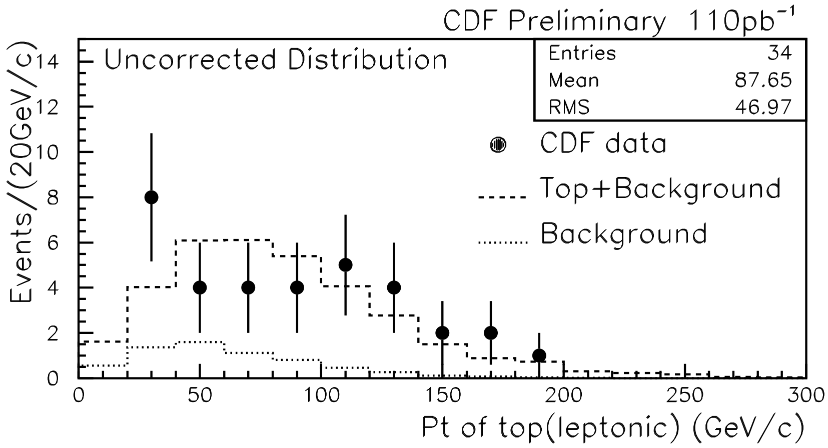


Top Production Kinematics (continued)

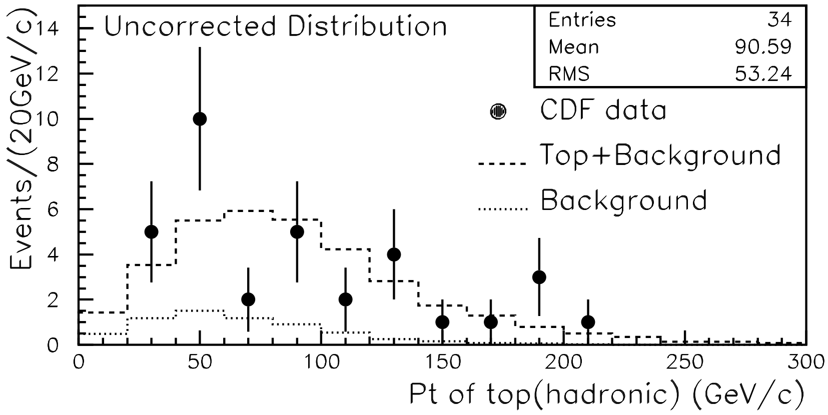
$\Delta\phi$ **between** t-$\bar{t}$



P_T **of** t

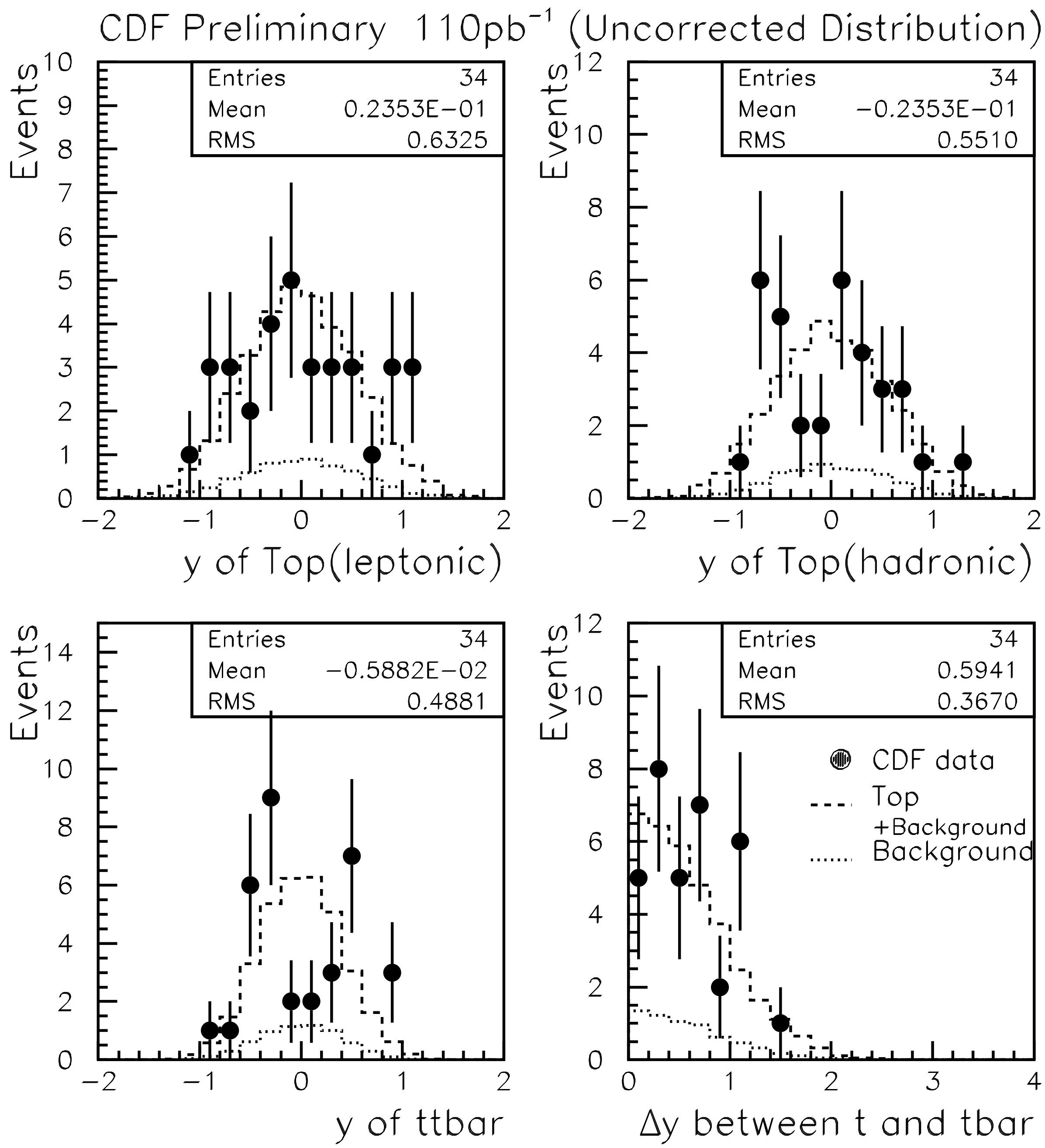


$t \longrightarrow bW(\longrightarrow \ell\nu)$



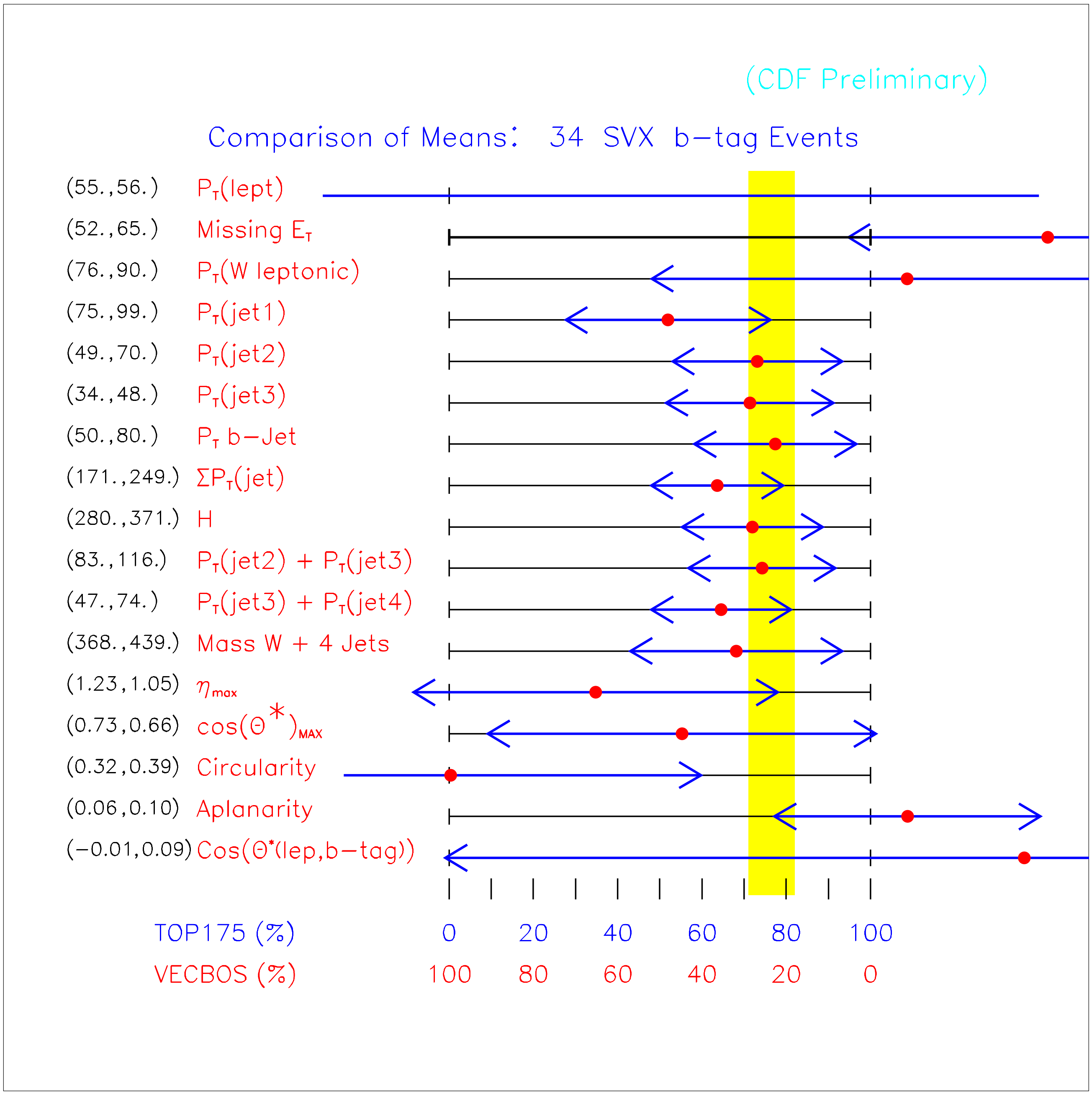
$t \longrightarrow bW(\longrightarrow q\bar{q})$

Top Production Kinematics (continued)



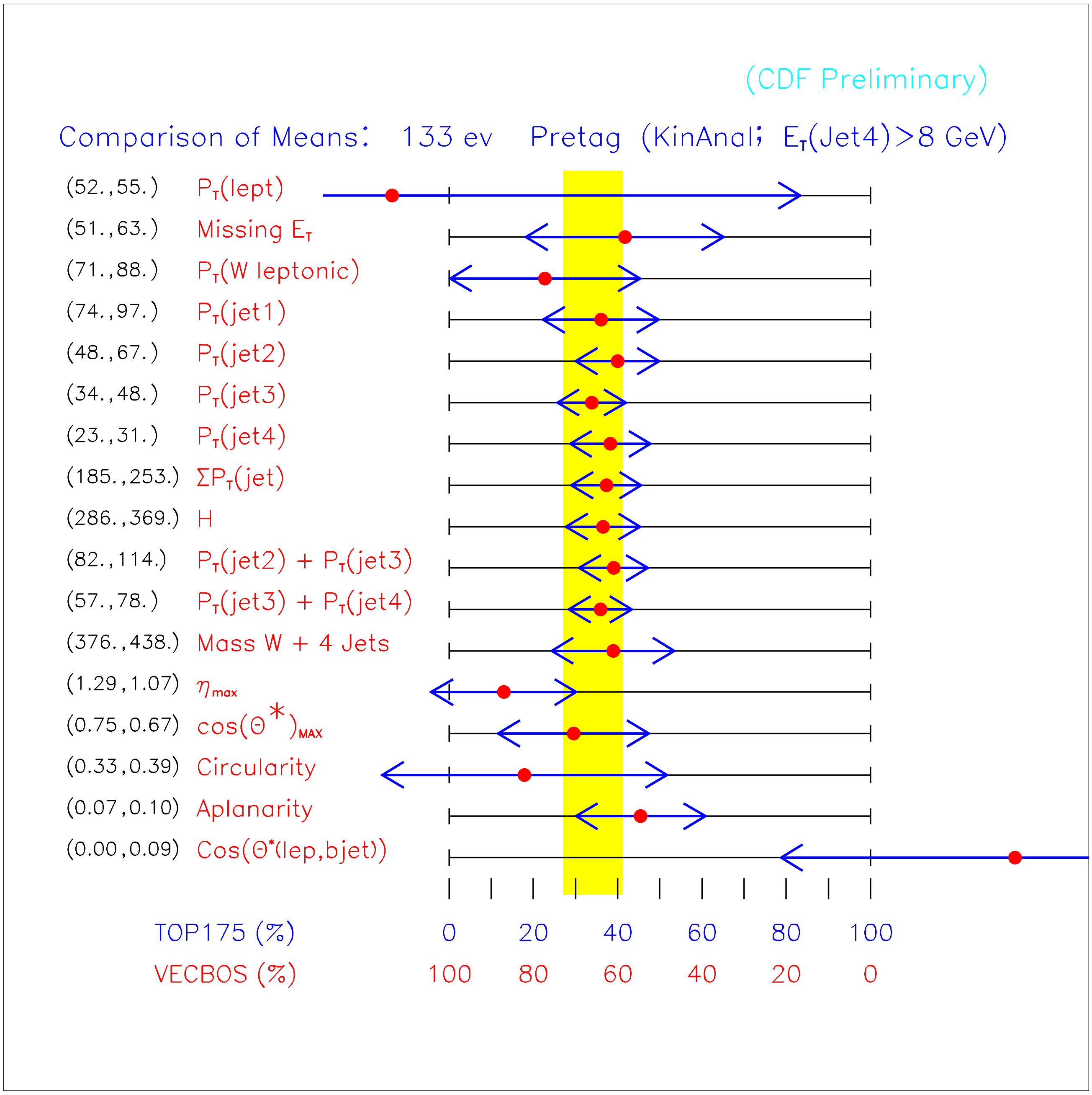
Top Decay Kinematics

Compare b-tagged Lepton+≥3Jets Events with MC's



Top Decay Kinematics (continued)

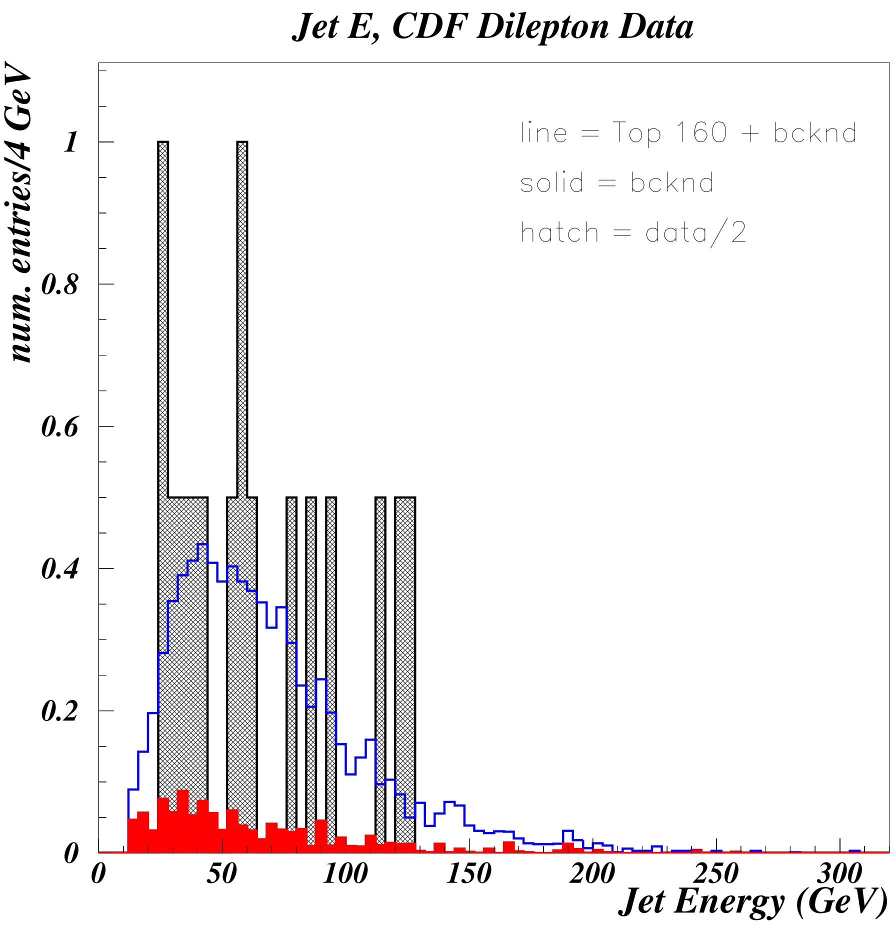
Compare Lepton+≥4Jets Events with MC's



Top Mass Measurements

Dilepton Channel

◇ compare the Jet energy distributions of two higher E_T of the dilepton sample ($H_T >$170 GeV) with Mon-ete Carlo



$\Rightarrow \quad M_t = 159^{+24}_{-22}$ (stat) $\pm$ 17 (syst) **GeV/c^2**

◇ use the approximate expression:

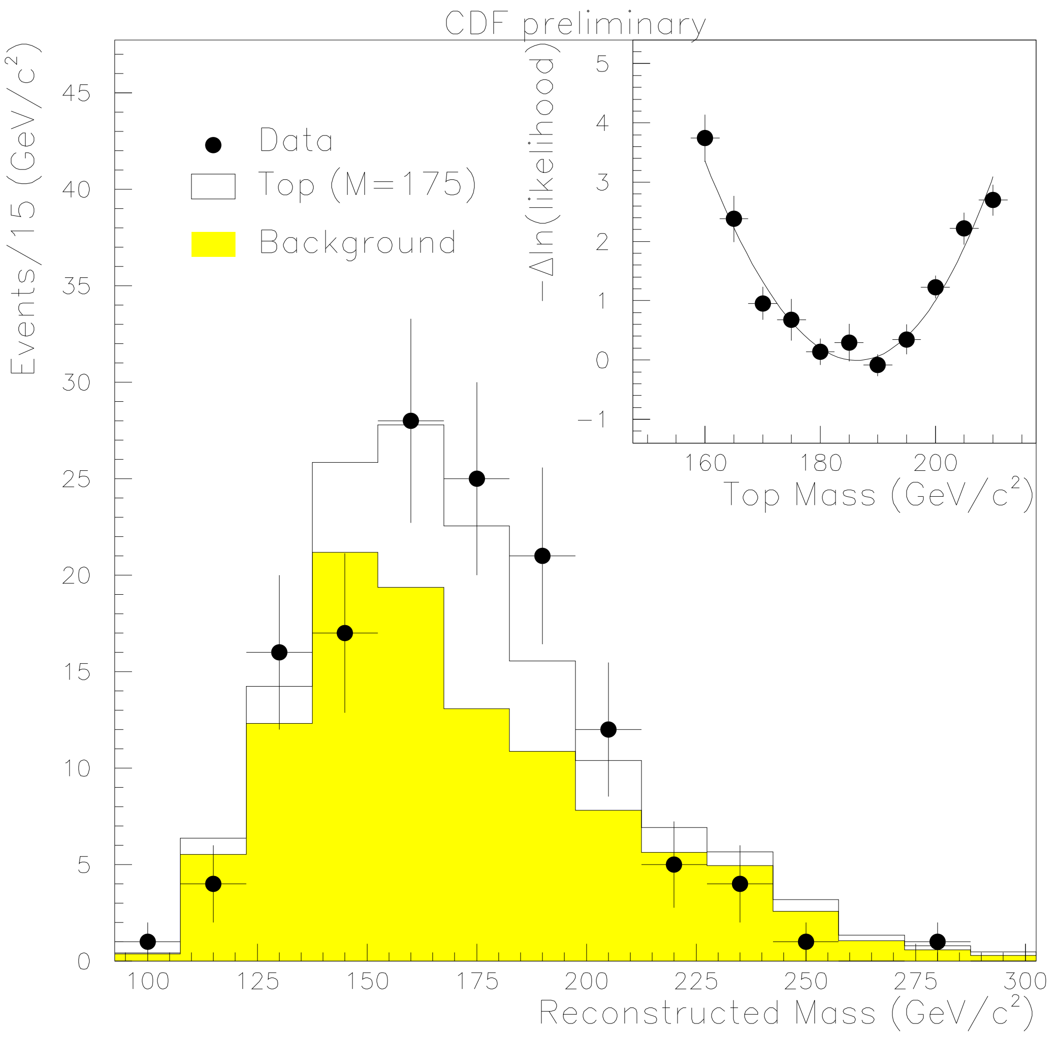
$$M_t^2 = M_W^2 + \frac{2 < M_{lb}^2 >}{1 - < \cos\theta_{lb} >}$$

$\Rightarrow \quad M_t = 162 \pm 21$ (stat) $\pm$ 7 (syst) **GeV/c^2**

All Hadronic Channel

◇ **All particles are measured: "3C fit"**

unknown:	M_t, $\vec{P}$ **of two tops** $\rightarrow$ **7**
	$\vec{P}$ **of two W's** $\rightarrow$ **6**
constraints:	**4-vectors** $\times$ **4** $\rightarrow$ **16**
	($t_i \rightarrow W_i b_i$, $W_i \rightarrow q_i \bar{q}'_i$, $i = 1, 2$)



$\Rightarrow \quad M_t = 186 \pm 10\ (\mathrm{stat}) \pm 12\ (\mathrm{syst})$ **GeV/c^2**

Lepton+Jets Channel

One-to-one mapping of jets to quarks (using the 4 highest E_T jets) assuming the decay chain:

$$p\bar{p} \rightarrow t_1 + t_2 + X$$
$$t_1 \rightarrow b_1 + W_1$$
$$t_2 \rightarrow b_2 + W_2$$
$$W_1 \rightarrow \ell + \nu$$
$$W_2 \rightarrow j_1 + j_2$$

Difficulties

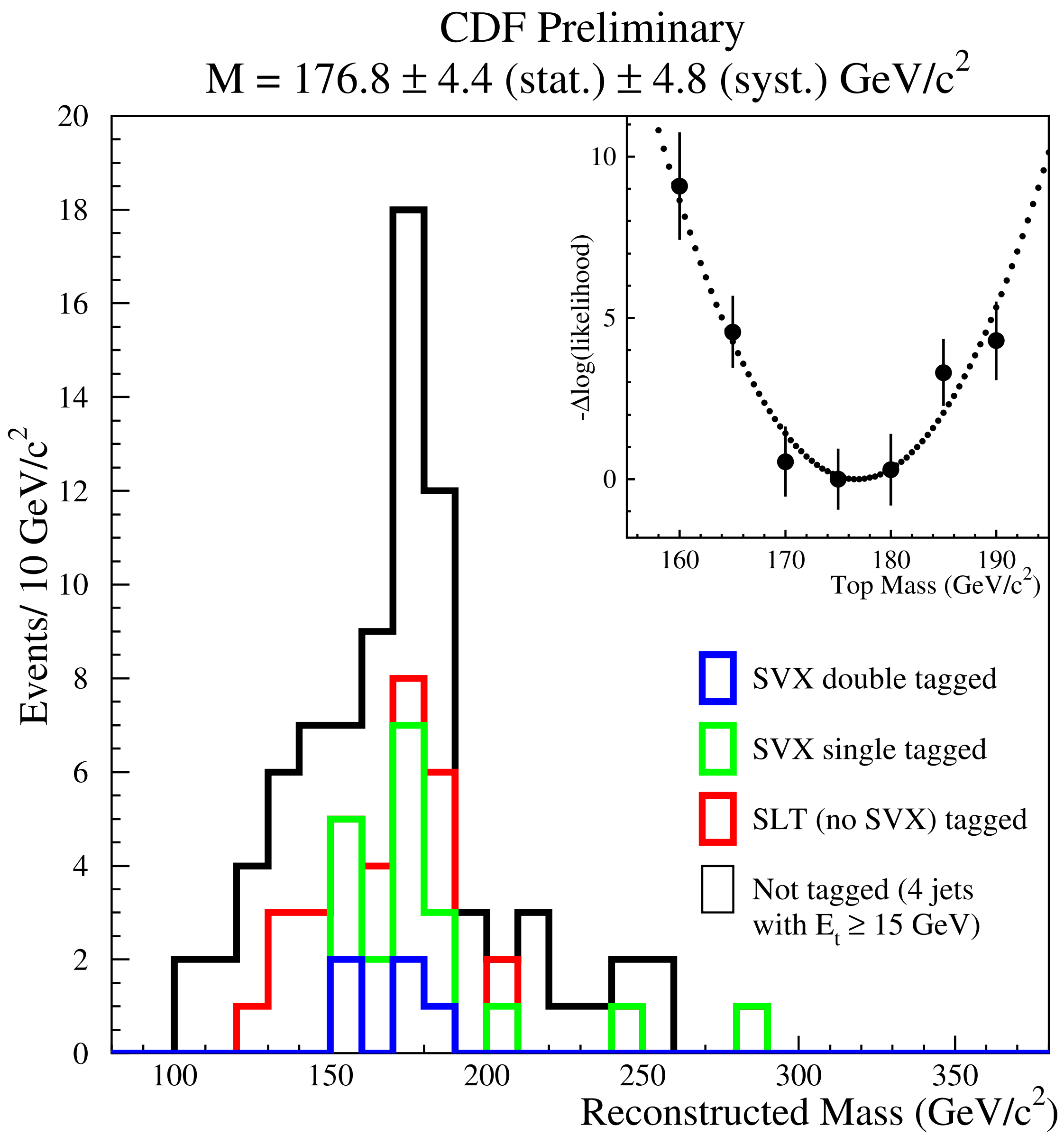
- ◇ **Mis-assignment $\leftarrow$ reduced by b-tagging**
- ◇ **Contamination of High E_T background jet**
- ◇ **Jet E_T scale determination**

Tables of Lepton+Jets Systematics

CDF L+Jet Mass Systematic	Value GeV/c^2
Soft Gluon + Jet $\mathrm{E_T}$ Scale	3.6
Different Generators	1.4
Hard Gluon Effects	2.2
Kinematic and Likelihood Fitting Methods	1.5
b-tagging Bias	0.4
Background Spectrum	0.7
Monte Carlo Statistics	0.8
Total	4.8

CDF ℓ+jets Mass Results

176.8 ± 4.4 **(stat)** ± 4.8 **(sys) GeV/c^2**



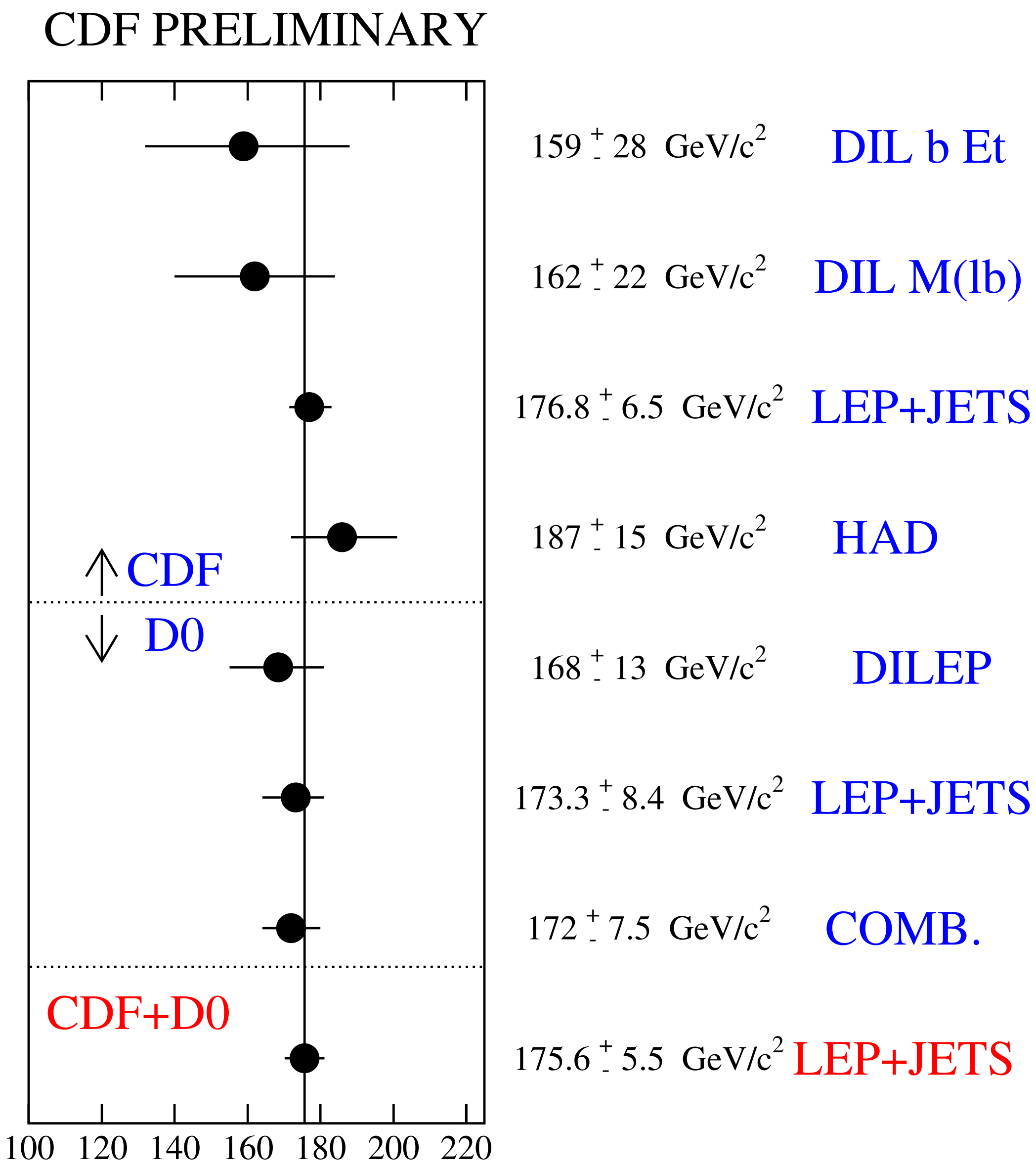
ΔM_t $\approx$ **30 GeV/c^2 per event**

$\Rightarrow$ $\approx$ **13 GeV/c^2, if jet-parton combination is correct**

Summary of M_{top} Measurements

CDF combined:

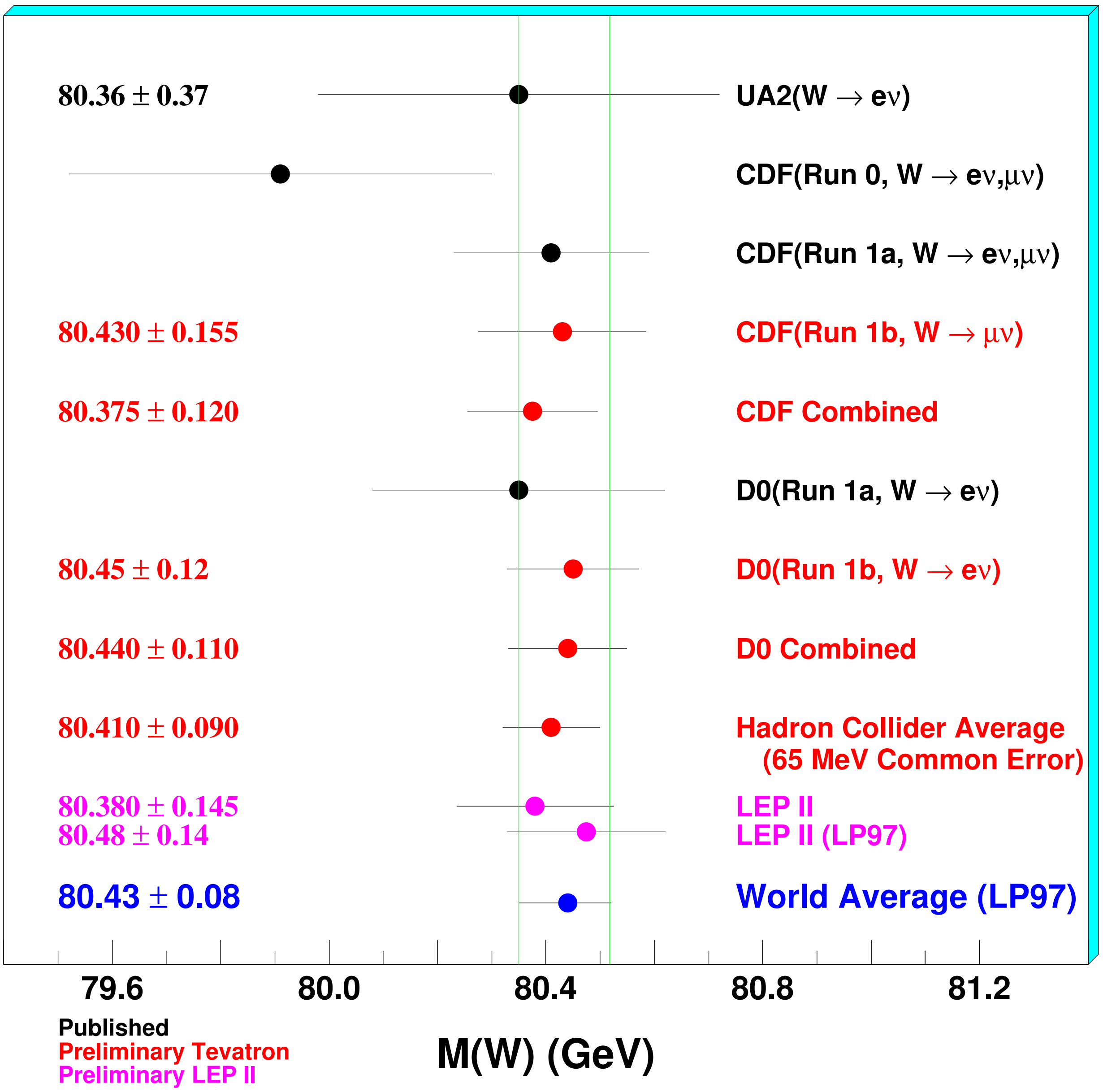
$M_{top} = 176.8 \pm 4.4$ **(stat)** $\pm\ 4.8$ **(syst) GeV/c²**



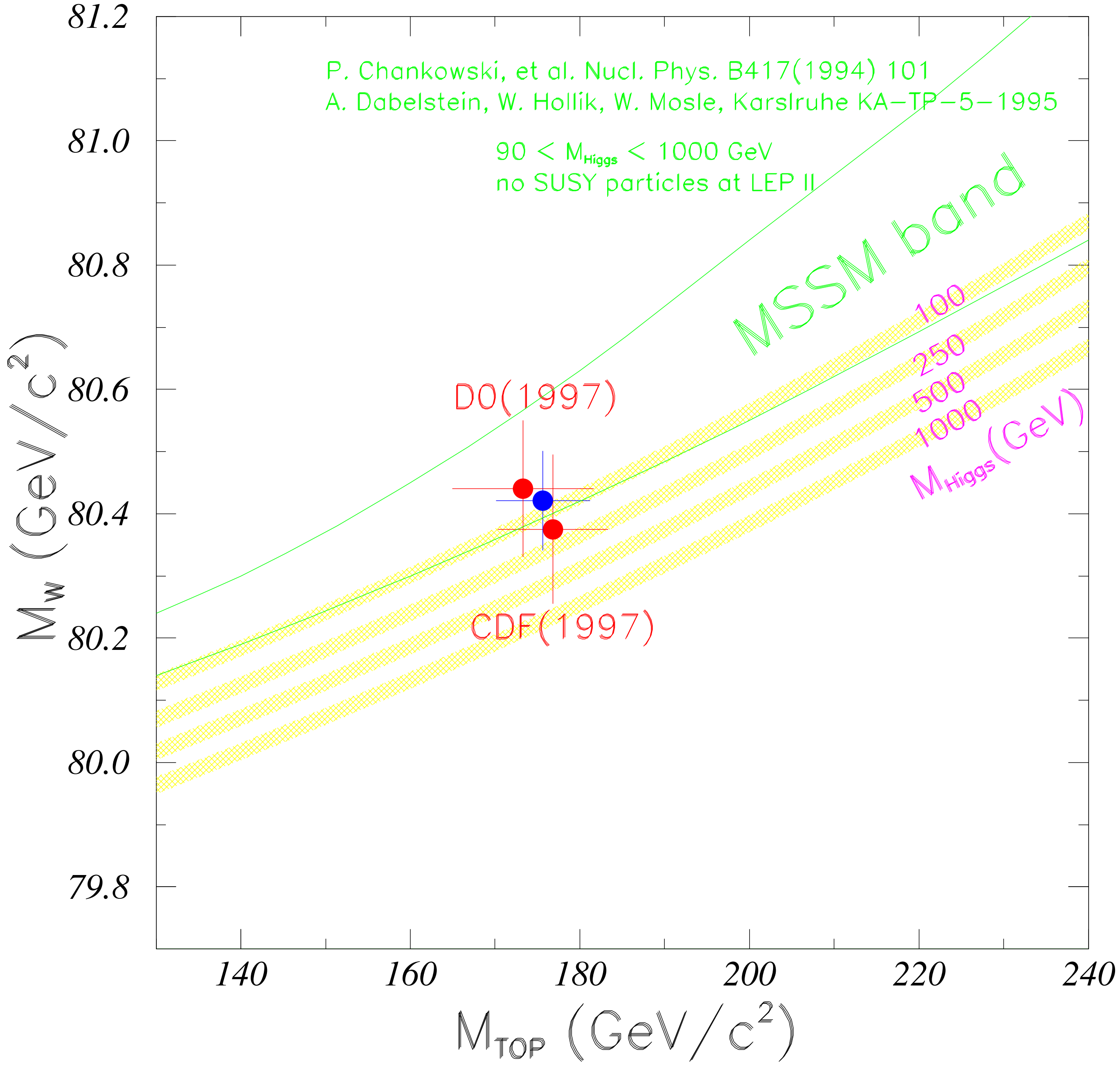
M_W vs M_T

CDF: $M_W = 80.375 \pm 0.120$ GeV/c^2

World Average : $M_W = 80.43 \pm 0.08$ GeV/c^2



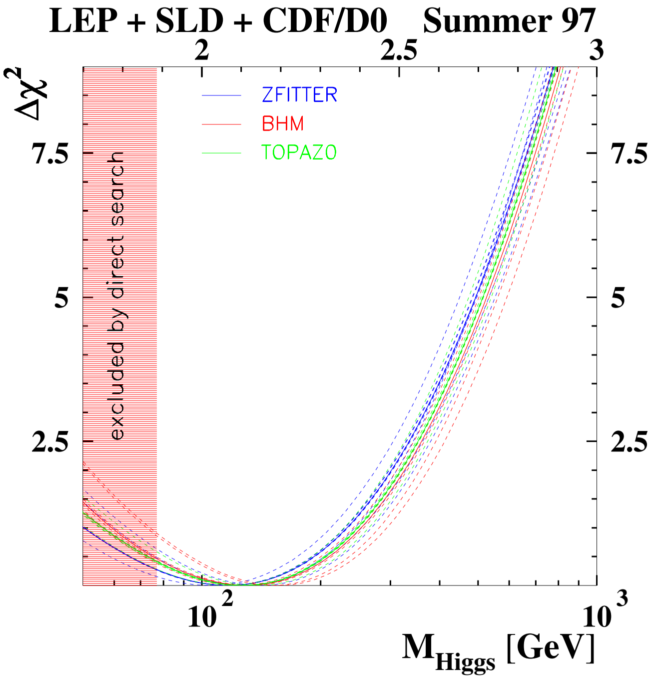
M_W vs M_T (continued)



From M_t (CDF+DO) + M_W (80.40:world average):

M_H $<$ 325 (68%CL) or $<$ 950 (95%CL) GeV/c^2

M_W vs M_T (continued)

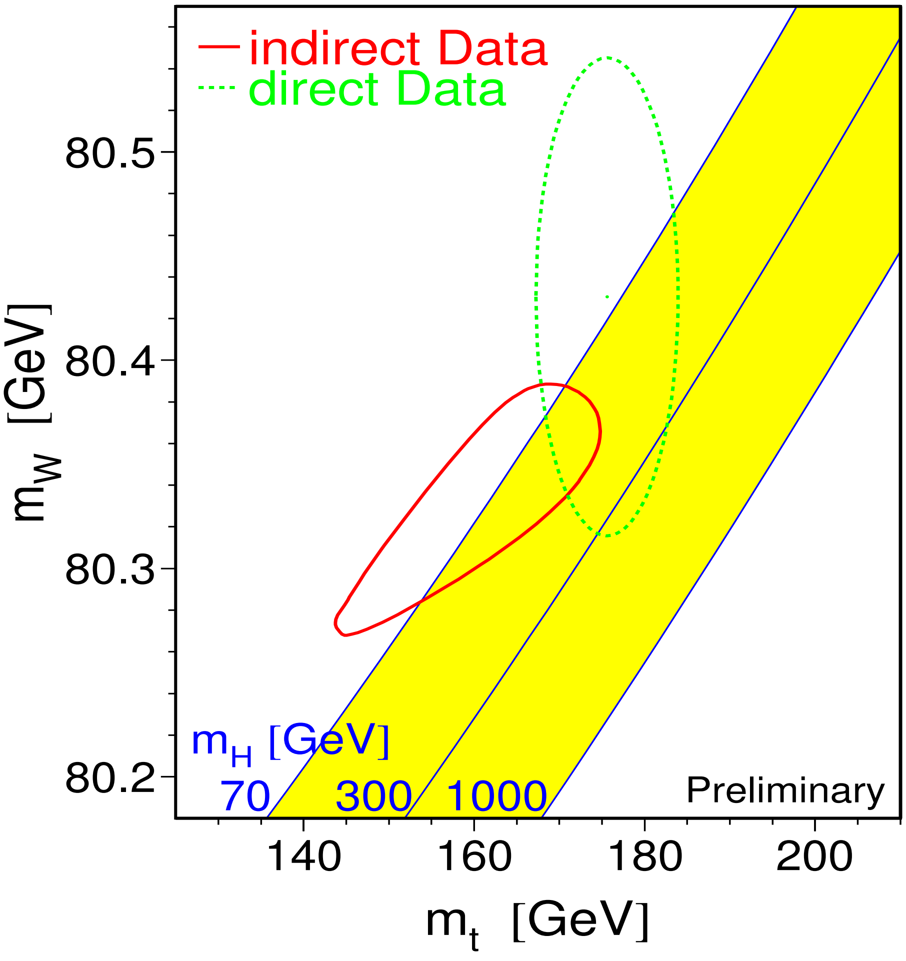


Lepton-Photon '97

M(H) = 120 $^{+120}_{-70}$ GeV

< 430 GeV at 95% CL

(global fitting)



Summary of Top Quark Physics

- **CDF has observed Top and measured $\sigma_{t\bar{t}}$ in many decay modes:**

$$t\bar{t} \rightarrow W + Jets + X$$
$$t\bar{t} \rightarrow W + b + Jets + X$$
$$t\bar{t} \rightarrow W + b + b + Jets + X$$
$$t\bar{t} \rightarrow \ell^+\ell^- + Jets + X$$
$$t\bar{t} \rightarrow \ell^+ + \tau + Jets + X$$
$$t\bar{t} \rightarrow 6\ Jets + X$$

- **Top Cross Section at 175 GeV/c^2:**

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

QCD predictions range from 4.75 to 5.6 pb

- **Recent Top mass result:**

$$M_{Top} = 176.8 \pm 6.5 \text{ GeV/c}^2$$

from CDF Lepton+Jets Channel

$$M_{Top} = 175.6 \pm 5.5 \text{ GeV/c}^2$$

from CDF + DO combined

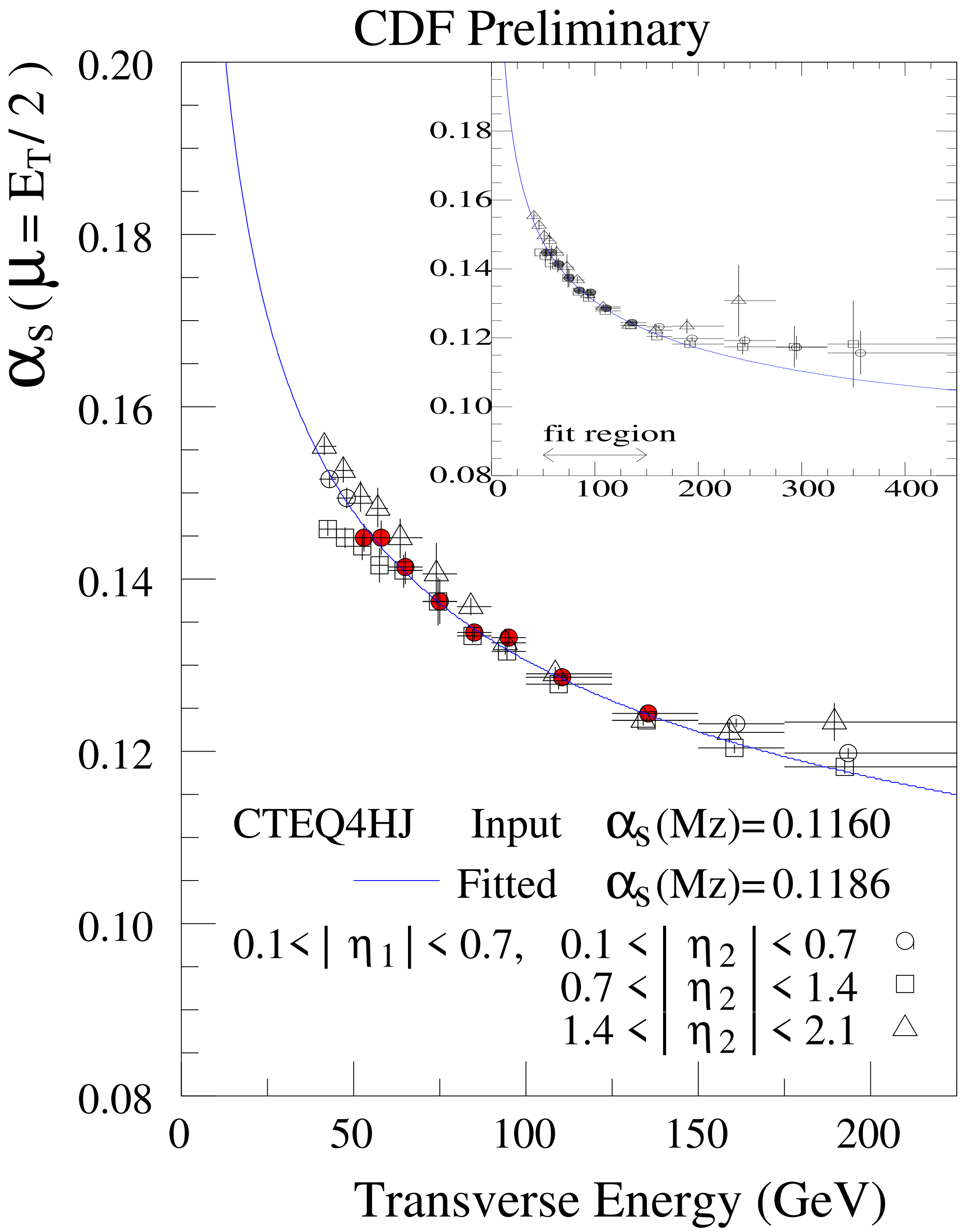
Nothing observed in top production and decay is inconsistent with the S.M.

Topics (2): Measurement of α_S

First α_S measurement by CDF

$\sigma(p\bar{p} \to jj) = \sigma_{\mathrm{LO}} \oplus \sigma_{\mathrm{NLO}}(\alpha_S) \oplus$ **Higher Orders**

$\Rightarrow$ **running feature of α_S**

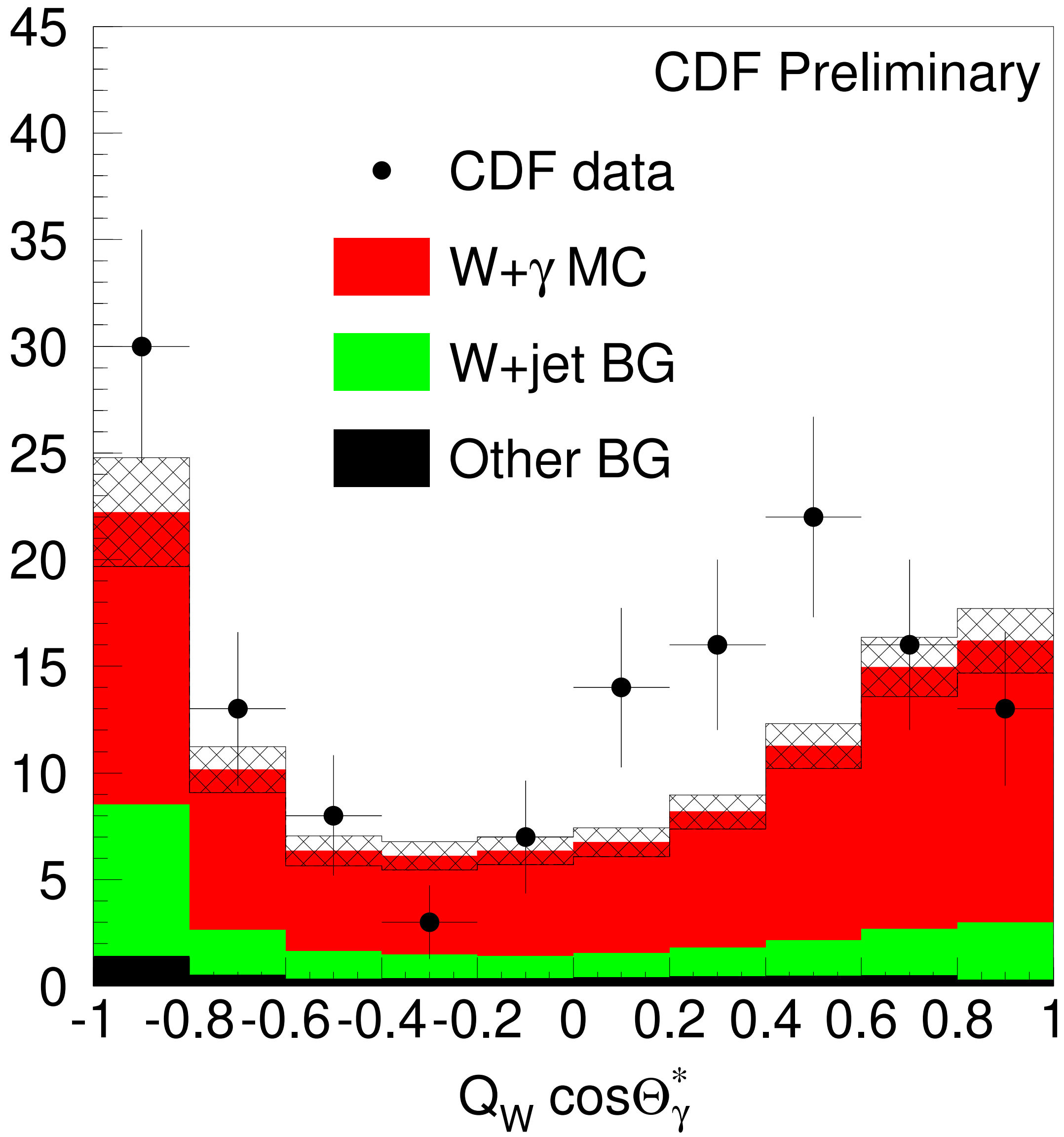


Topics (3): RAZ in Wγ Production

Direct Evidence for Gaugeness of W

$\mathcal{M}$ **= 0 at** $Q_W \cos\Theta^*_\gamma = -1/3$ **;**
Θ^*_γ **is angle between** γ **and "quark" in W-**γ **rest frame**

RUN I ($\int \mathcal{L}dt$ = 110 pb^{-1}), $|\eta_\gamma| < 2.4$



Prospects at the Tevatron RUN-II

RUN-II (will start in June 1999)

- **Accelerator Upgrade**
  - **CM Energy: 1.8TeV $\rightarrow$ 2.0TeV ($\sigma_{t\bar{t}} : \times 1.4$)**
  - **Integrated Luminosity: 0.1 fb^{-1} $\rightarrow$ 2 fb^{-1} ($\times 20$)**
- **Detector Upgrade**
  - **Acceptance for $t\bar{t} \rightarrow W(\rightarrow \ell\nu)+ \geq 3$ jets: 9.5% $\rightarrow$ 12% ($\times 1.3$)**
  - **b-tagging efficiency for b-jets: 42% $\rightarrow$ 80% ($\times 2$)**

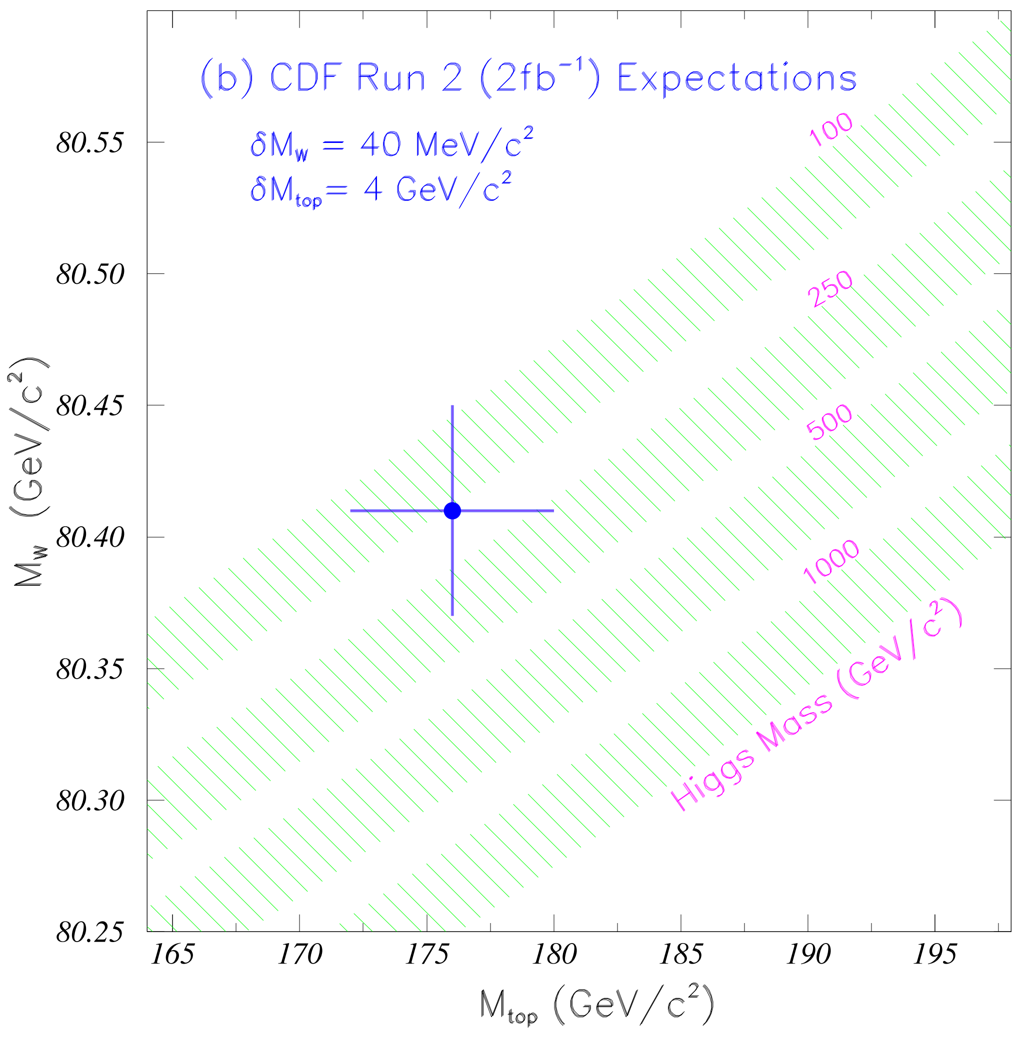
From the above, we will accumulate 70 times more events of $t\bar{t} \rightarrow W(\rightarrow \ell\nu)+ \geq 3$ jets with one b-tagged jet in RUN-II.

Number of $t\bar{t}$ events in RUN-II

- **$W(\rightarrow \ell\nu)+ \geq 4$ jets (1 b-tag): $\sim$ 1,200**
- **$W(\rightarrow \ell\nu)+ \geq 4$ jets (2 b-tags): $\sim$ 600**

Top Quark Physics in RUN-II

- **Top Quark Mass:** $\Delta M_{top} \approx 3 - 4$ **GeV/c^2**
- $\sigma_{t\bar{t}}$ **:** $\Delta\sigma/\sigma \sim 9\%$ $(\Delta\mathcal{L}/\mathcal{L} \sim \nabla\%)$
- Γ_{top} **from** $q\bar{q} \to W^* \to t\bar{b}$
- **New Particle Search**
  - $t \to H^+ b$
  - $X \to t\bar{t}$, **Z', ...**



Top Quark Mass in RUN-II

ΔM_{top} (GeV/c^2) = 4.4 (stat) $\oplus$ 4.8 (syst) in RUN-I

$\diamond$ Statistical error scales with $1/\sqrt{N}$:
4.4 GeV/c^2 $\rightarrow$ 1 GeV/c^2

- in lepton + $\geq$4 jets with ($\geq$1) b-tagged jet
- in lepton + $\geq$4 jets with 2 b-tagged jets
  $\Rightarrow$ ultimately better in understanding the systematics

$\diamond$ Systematics in reconstructed top mass spectrum
$\Leftarrow$ MC model (hard gluon radiation)
$\Leftarrow$ Detector (jet energy measurement)

use many *in situ* calibrations:

- Z+jets events to understand the energy scale and MC model
- W+jets, γ+jets events to understand MC model
- W $\rightarrow qq'$ in the top sample to understand the energy scale

Systematics also scales with the luminosity
$\Rightarrow$ 2 GeV/c^2, conservatively