New Results from CDF

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1. Introduction to the Standard Model
2. Role of Gauge Bosons
3. New Measurements of W and Z Properties
   - W mass
   - Direct measurement of trilinear couplings
4. Observation of the Top Quark
5. Future Prospects

Carleton University
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The Standard Model

The Standard Model of Elementary Particle Physics

- Three "generations" of quarks and leptons

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$$

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$$

"Isospin" doublets that dictate particle interactions

- Forces carried by bosons

Electromagnetic force	γ
Strong force	eight gluons
Weak force	$W^{\pm}, Z^{\circ}$ bosons
Gravity	gravitons

The Forces in the Model

The theory predicts a "simple" structure for the forces

$$\begin{aligned}
\mathcal{L} &= \sum_i \bar{\psi}_i \big(i\partial - m_i - \frac{g m_i H}{2 M_W} \big) \psi_i \\
&- \frac{g}{2\sqrt{2}} \sum_i \bar{\psi}_i \gamma^\mu (1-\gamma^5)(T^+ W_\mu^+ + T^- W_\mu^-) \psi_i \\
&- e \sum_i q_i \bar{\psi}_i \gamma^\mu \psi_i A_\mu \\
&- \frac{g}{2\cos\theta_W} \sum_i \bar{\psi}_i \gamma^\mu (g_V^i - g_A^i \gamma^5) \psi_i Z_\mu
\end{aligned} \tag{1}$$

Notable elements are:

- $\sin^2\theta_W = (1 - M_W^2/M_Z^2)$
- vector and axial-vector couplings g_A^i and g_V^i
- quark, lepton, W, Z and Higgs masses

The Role of Gauge Bosons

The Standard Model makes specific predictions

- ratio of W and Z masses
- Γ_Z and Γ_W
- vector and axial-vector couplings

Many of these are tested esquisitely at LEP

- measurements of Z lineshape and asymmetries
- partial widths $\Gamma(Z \to f\bar{f})$

W boson measurements provide complementary constraints

- Measure mass and width
- Measure trilinear gauge boson couplings (WWZ)
- But, real W's only produced in $p\bar{p}$ collisions

The CDF Experiment

CDF collaboration studies 1.8 TeV $p\bar{p}$ collisions

- Operates detector at Fermilab Tevatron Collider
- Designed to study high P_T collisions
- Collaboration consists of $\sim$ 450 physicists and 35 institutions

CDF has been collecting data for 2 years

- IN 1992-93, collected $\sim$ 20 pb^{-1} (Run IA)
- Since 1994, have collected $\sim$ 65 pb^{-1}(Run 1B)
  - Run 1B continuing through 1995
  - Ultimate goal is $\sim$ 140 pb^{-1}

W Mass Measurement

W production cross section is ~ 20 nb at Tevatron

- Can readily observe $W \to e\nu_e$ and $W \to \mu\nu_\mu$
- Select high E_T electron or muon
- Require significant $\not\!\!E_T$ to tag neutrino

Can M_W from transverse mass distribution

$$M_T = \sqrt{2 E_T \not\!\!E_T (1 - \cos\phi_{l\nu})}$$

- Sensitive to performance of entire calorimeter
- Sensitive to structure functions

Data Sample from Run 1A

Select events with clean electron or muon

- For muons, require
  - $p_T > 25$ GeV/c
  - satisfies standard muon ID cuts
- For electrons, require
  - $E_T > 25$ GeV
  - satisfies standard electron ID cuts
- Require $\not\!\!E_T > 25$ GeV
- Require no "significant" recoil system
  - $|\vec{u}| < 20$ GeV
  - No jets with $E_T > 30$ GeV
- Left with 4663 $\mu\nu$ and 8067 $e\nu_e$ candidates

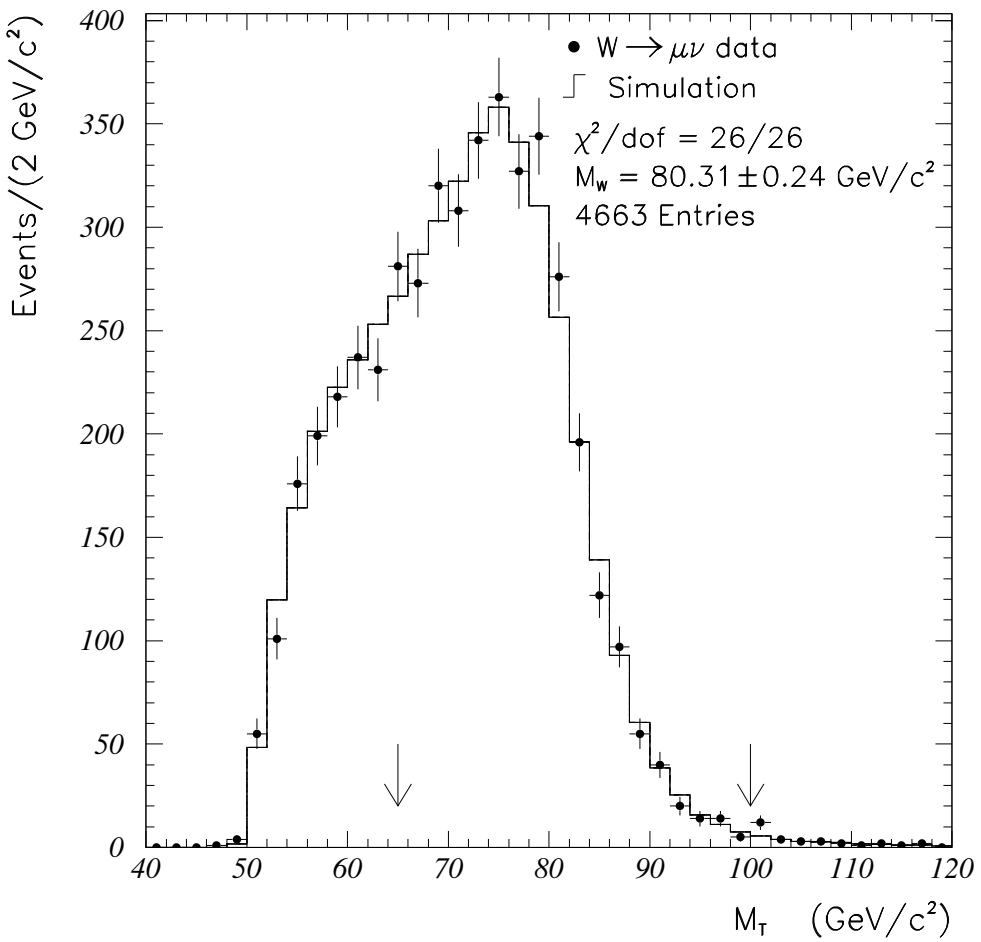
Fit $65 < M_T < 100$ GeV to predicted lineshape

- 5718 electron events
- 3268 muon events

Fit to Muon Data

Results of fit to muon data

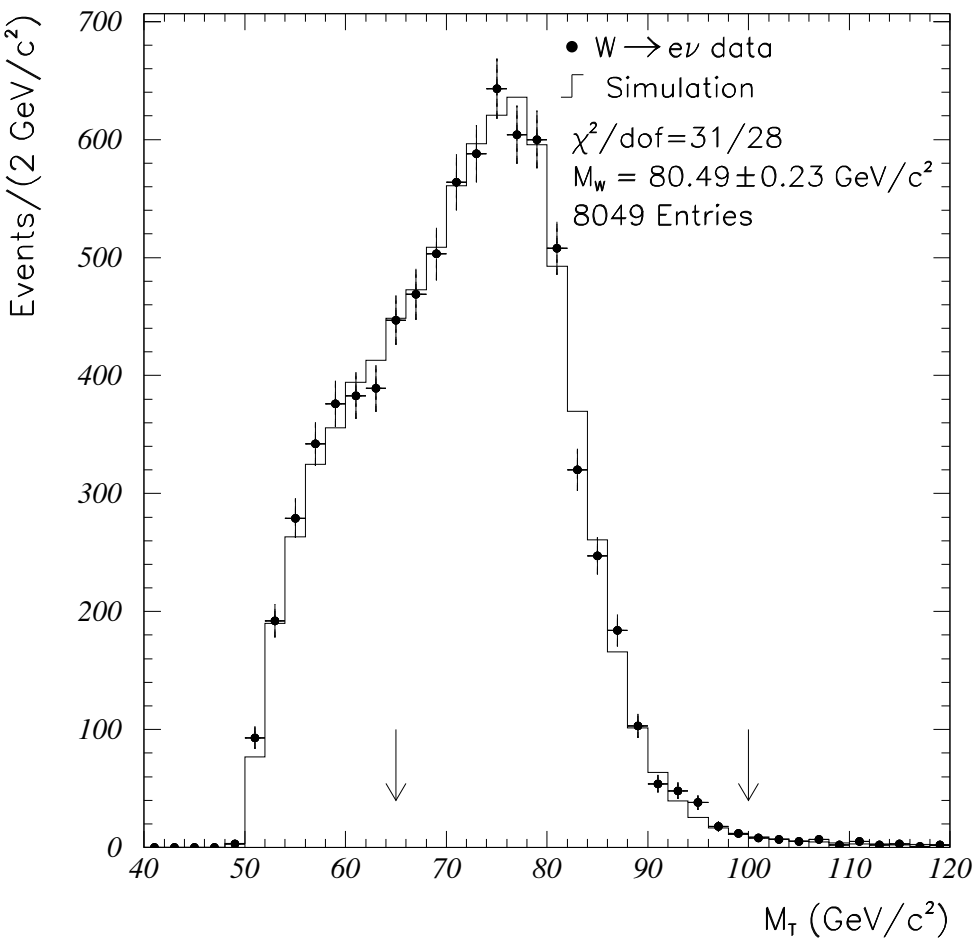
$$M_W = 80.310 \pm 0.205 \pm 0.130 \text{ GeV/c}^2$$



Fit to Electron Data

Results of fit to electron data

$$M_W = 80.490 \pm 0.145 \pm 0.175 \text{ GeV/c}^2$$



Systematic Uncertainties on W Mass

Control of systematics most challenging aspect

1. Energy and momentum scale (120 and 45 MeV/c^2)
   - Determined using $\Upsilon/\psi \to \mu^+\mu^-$ and $Z \to \mu^+\mu^-/e^+e^-$
   - calorimeter scale set by tracking system

2. Resolution function of "detector" ($\sim$ 80 MeV/c^2)
   - Constrained by studies of Z events

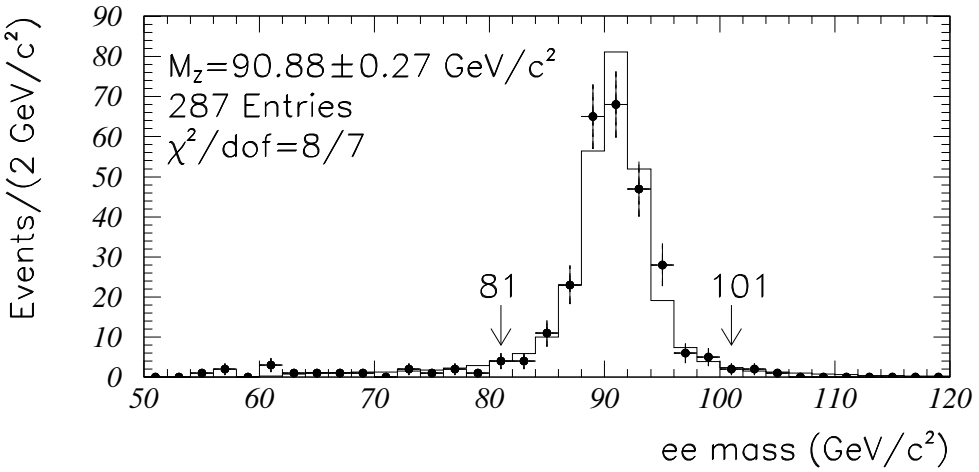
3. Uncertainies in "recoil" system physics ($\sim$ 60 MeV/c^2)
   - Limited by statistics on Z sample

4. Structure functions (50 MeV/c^2)
   - Use MRS D_$'$ as default
   - Check variation caused by other choices

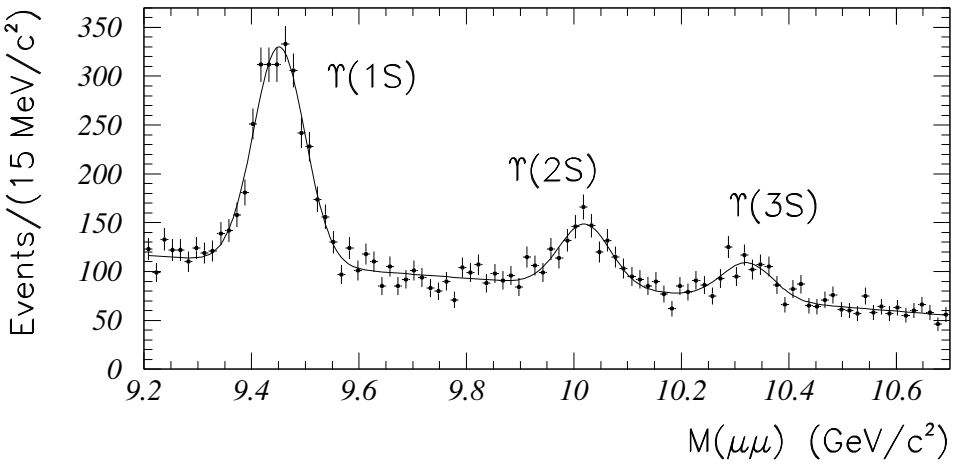
Accounting for correlations in these uncertainties

- Overall systematic uncertainty is 130 MeV/c^2

Z mass from electrons



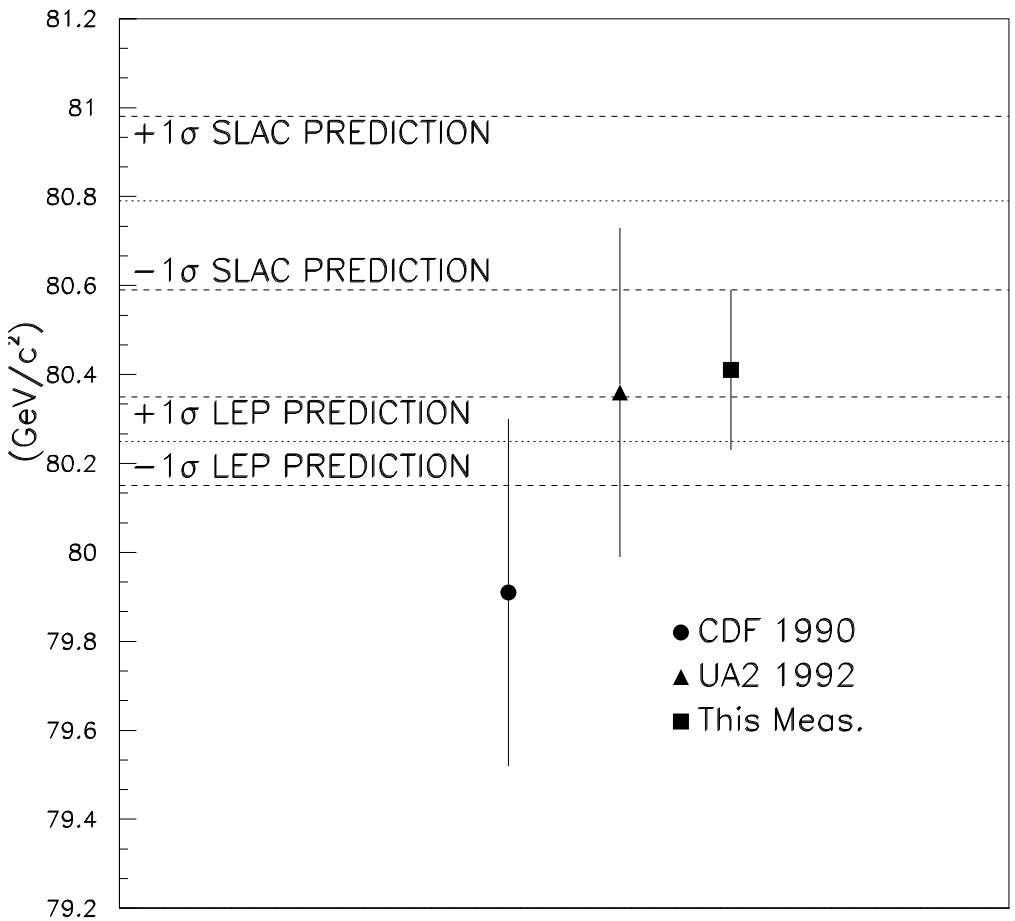
Dimuon mass distribution



Summary of W Mass

Combined mass from both channels is

$$M_W = 80.41 \pm 0.18 \text{ GeV/c}^2$$



Observation of WZ Production

SM predicts that W, γ and Z have trilinear couplings

- Sensitive to "new" physics
- Non-SM $WW\gamma$ couplings modify W dipole moments

$$\mu_W = \frac{e}{2M_W}(2 + \Delta\kappa + \lambda)$$
$$Q_W^e = \frac{-e}{2M_W^2}(1 + \Delta\kappa - \lambda)$$

  assuming that CP is conserved

Results to date have focused on $WW\gamma$ and $ZZ\gamma$ vertices

- $W\gamma$ and $Z\gamma$ production has been measured
- Limited $|\Delta\kappa| < 3.0$ and $\lambda < 0.95$ at 95% CL

New CDF data starting to be sensitive to WWZ

- Predicted cross section is 9.5 pb for WW
- Predicted cross section is 2.5 pb for WZ
- Can expect to see a few events in sample

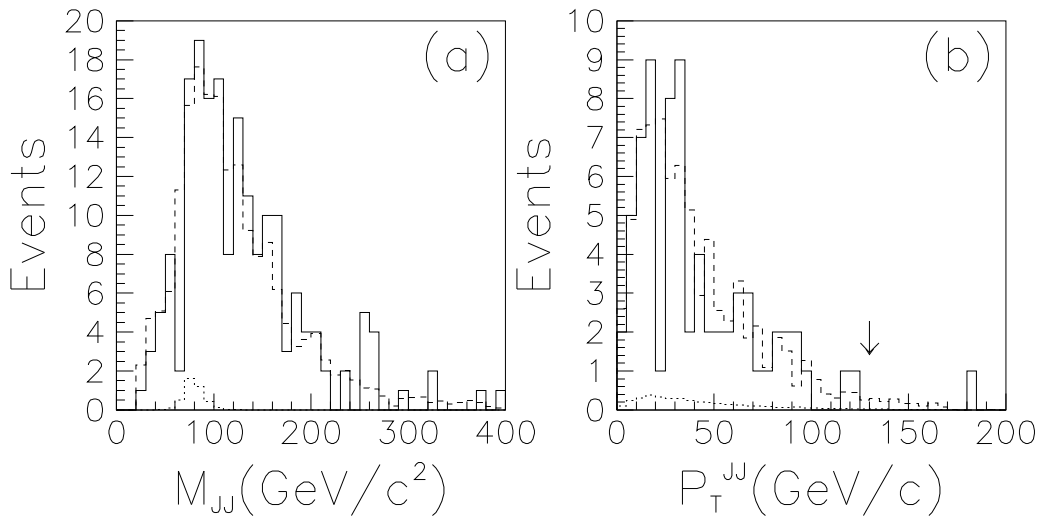
Search for DiVector Boson Events

We search for events where

- One W or Z decays hadronically into two jets
  - Require jet $E_T > 30$ GeV
  - Require dijet mass $60 < M_{jj} < 110$ GeV/c^2
- Other boson decays leptonically
- Sensitive to WW and WZ final states

To reduce backgrounds from W/Z + jet events

- Require dijet $P_T > 130$ for leptonic W candidates
- Require dijet $P_T > 100$ for leptonic Z candidates



Results of WW/WZ Search

Expect to see virtually no signal with SM couplings

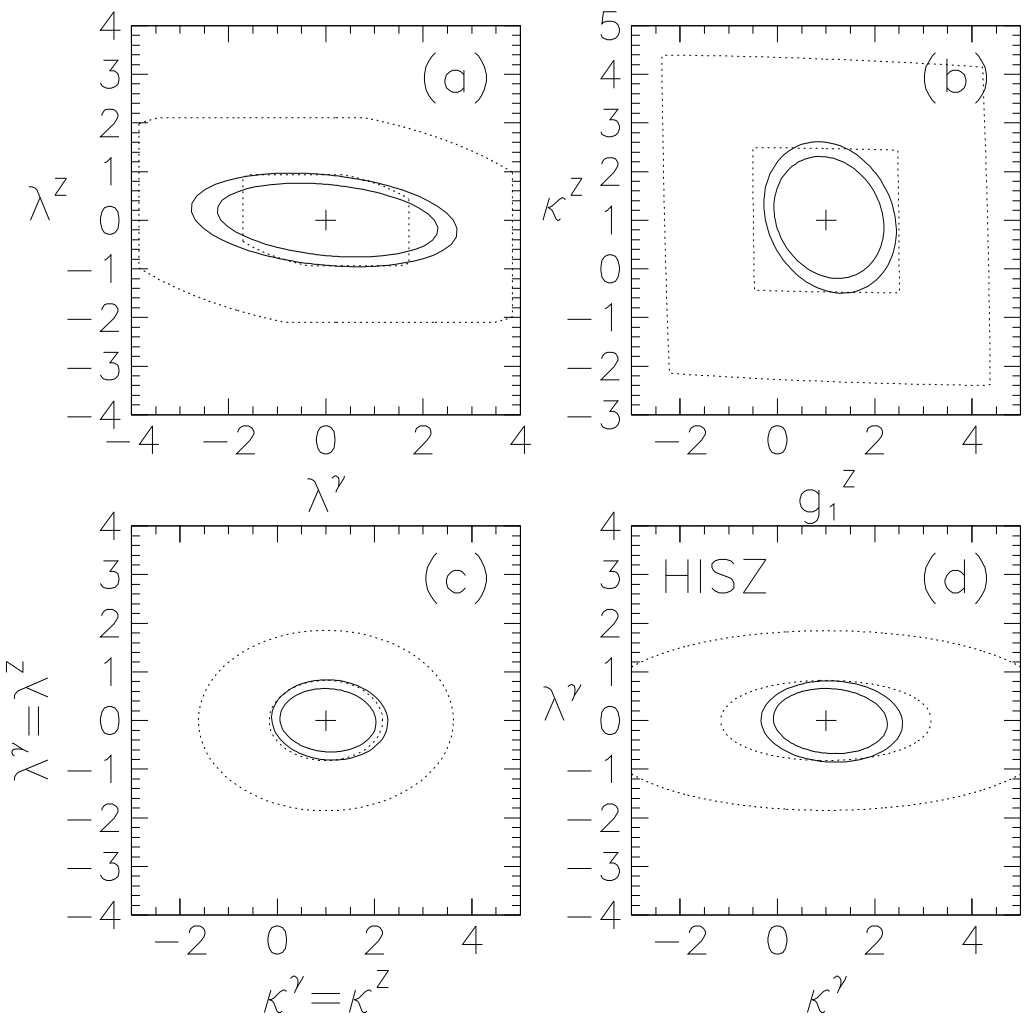
- Expect 0.13 events with leptonic W
- Expect 0.02 events with dileptonic Z
- Observe:
  - one event with leptonic W decay
  - no events with leptonic Z decay

Allows us to exclude anomalously large WWZ couplings

- Note that if WWZ coupling is zero, we would expect of order 15 events!
  - $\Rightarrow$ WWZ coupling is non-zero
- Can set limits on specific choices of κ and λ
- Most sensitive to WWZ couplings

Can set limits making assumptions

- For example, assume SM correct except for WWZ and $WW\gamma$
- Assume WWZ and $WW\gamma$ couplings equal
- Conclude $-0.11 \leq \kappa^Z \leq 2.27$ and $-0.81 \leq \lambda^Z \leq 0.84$



SM Predictions for Top Quarks

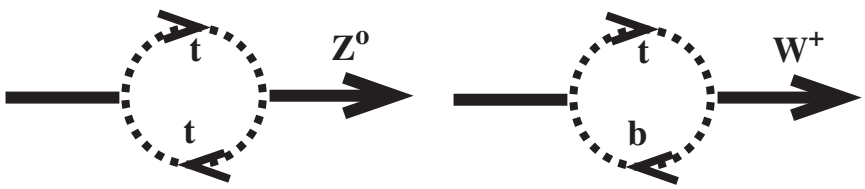
The asymmetry in $e^+e^- \rightarrow b\bar{b}$ scattering

- implies b quark in SU(2) doublet
- top quark has standard SU(2) couplings
- CKM matrix predicts dominant decay $t \rightarrow W^+b$

b quark unlikely to be $SU(2)$ singlet for other reasons

- Would expect flavour-changing neutral currents
- Limits on $B \rightarrow \mu^+\mu^-$ exclude them

Corrections to $W^\pm$ and Z° masses depend on heaviest fermion



- LEP, SLD measurements on the Z resonance require

$$M_{top} = 178 \pm 10^{+18}_{-19}\ \text{GeV/c}^2$$

D. Schaile, CERN-PPE/94-162

CDF Reported Evidence for Top in 1994

CDF reported observation of 2 dilepton events

- Expected ~ 0.5 events in this channel

Observed 10 lepton+jet events with b quark "tag"

- Expected 5.4 events background
- 7 events fully reconstructed

DØ had observed excess of events

- found 18 events when expected ~ 8 from background

What Does it Take to Discover Top?

- Observe "anomalous" production of W^+W^- events
  - Use dilepton events – both W's decay leptonically
- Observe W^+W^- events associated with a b quark
  - Use lepton + jet events
- Show events come from heavy fermion decays
- Confirm rate is consistent with $t\bar{t}$ production
  - Measure cross section using tagged events

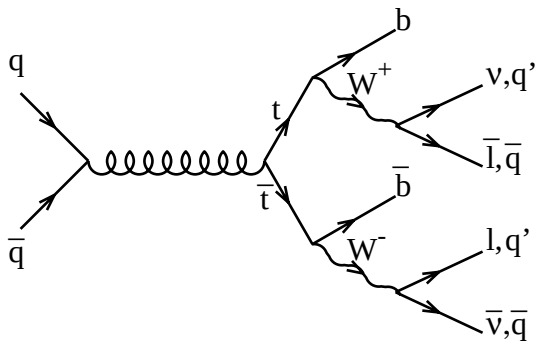
1992-95 Collider Run

CDF and DØ have collected $\times 3$ more data

- Run 1A (1992-93) provided ~ 20 pb^{-1}
- Run 1B (1994-95) has produced another ~ 65 pb^{-1}

By far the largest and most sensitive dataset to top

- For a top quark with a mass of 160 GeV/c^2
  - expect to observe 3-4 dilepton events
  - expect to observe 30 lepton + jet events



Dilepton Top Quark Search

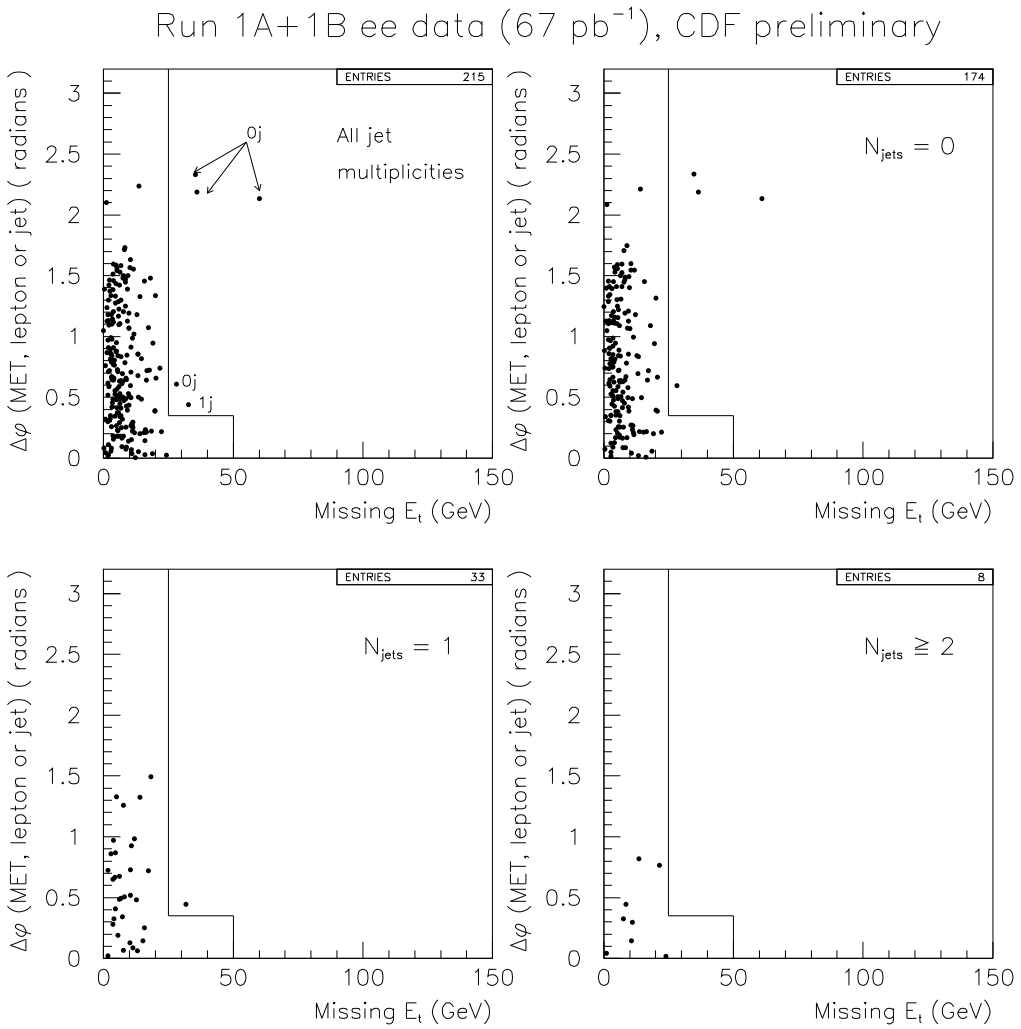
$t\bar{t}$ decaying into 2 leptons create unique signature

- Two charged leptons from $W^{\pm}$ decay
- Imbalance in total energy due to undetected neutrinos
- Two jets from bottom quarks

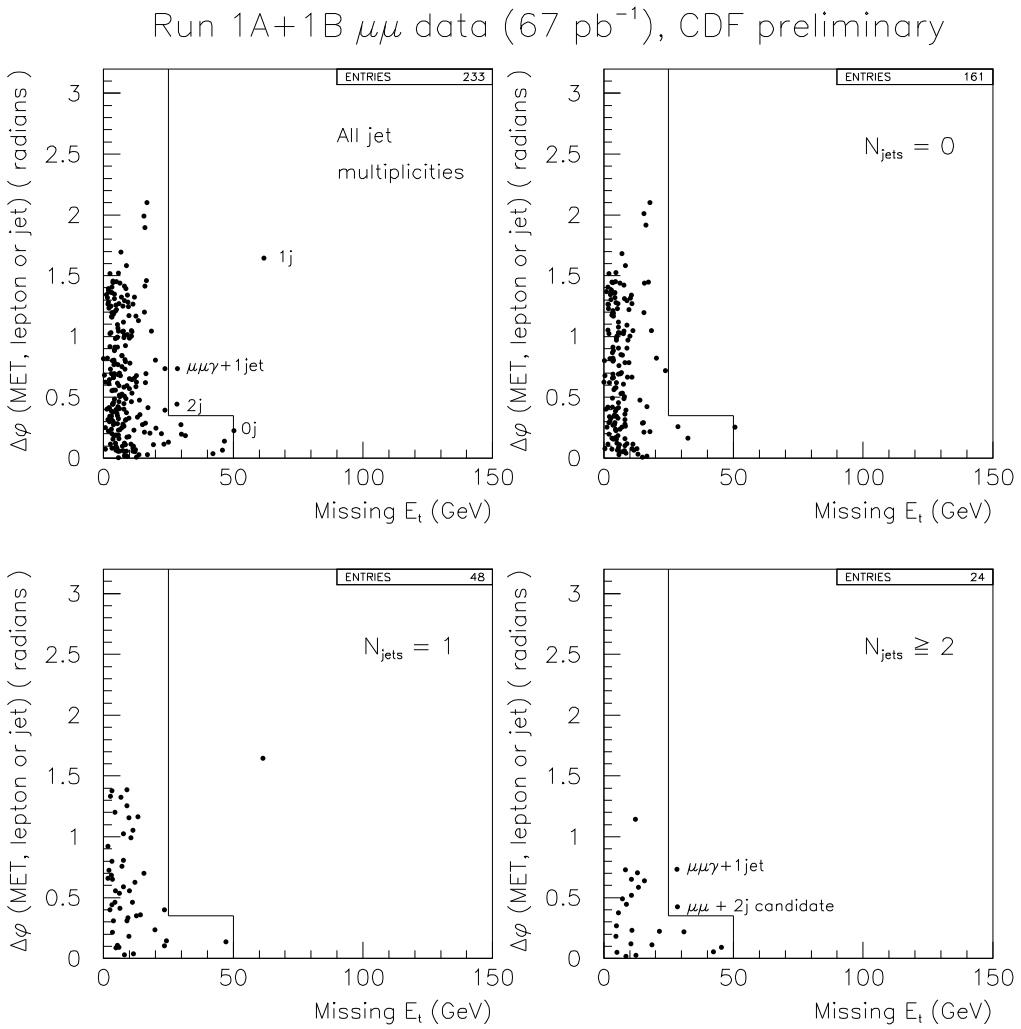
CDF performed a search requiring

- Two clean, high P_T lepton candidates
- Missing transverse energy $\not\!\!E_T > 25$ GeV
- Require two jets with $E_T >$ 10 GeV and $|\eta| < 2.0$
- Reject specific backgrounds (e.g. Z°)

Dielectron Data for Run 1A and 1B

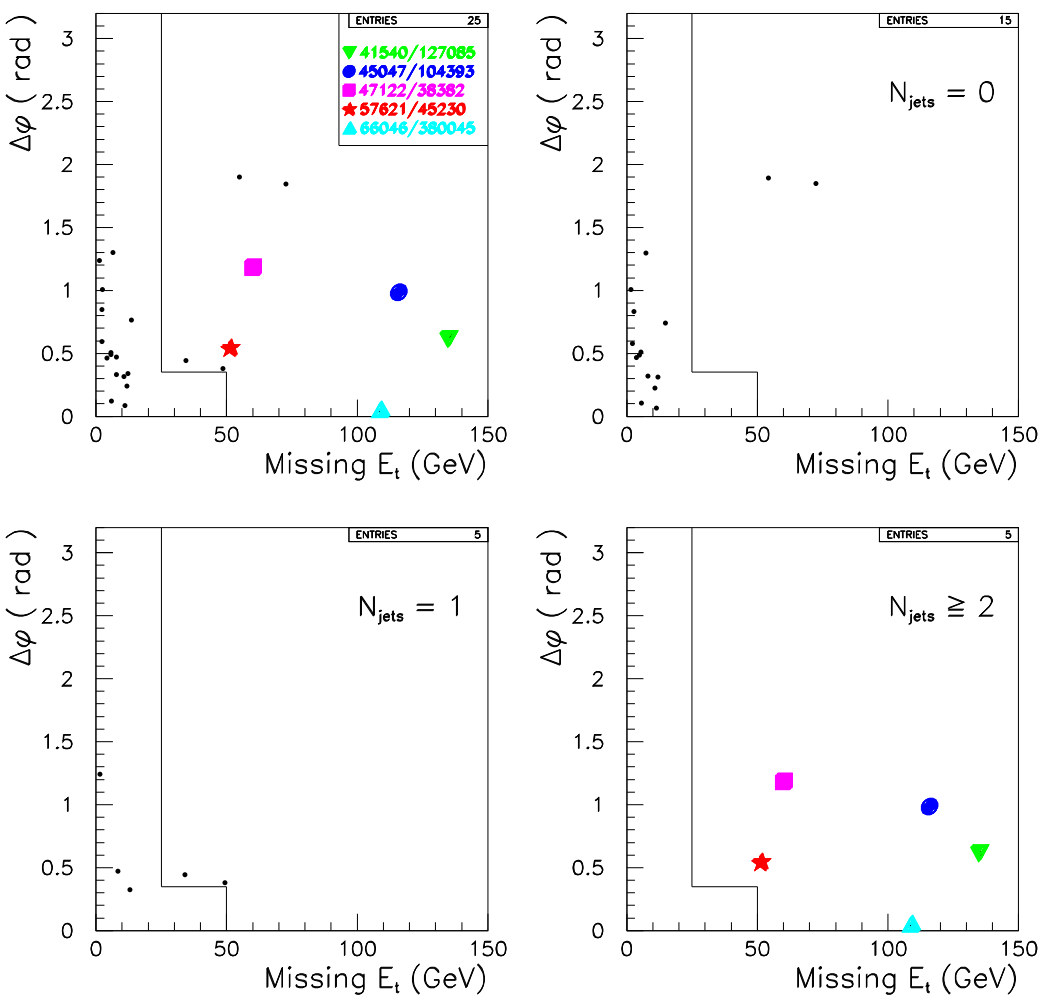


DiMuon Data for Run 1A and 1B



Electron-Muon Data for Run 1A and 1B

eμ data: Δφ (MET, lepton or jet) vs Missing E_t



Summary of Dilepton Search

Observe a total of 6 candidate events

- Observe 1 $\mu^+\mu^-$ event and 5 $e\mu$ events
- Expect 1.3 ± 0.3 events from background

Background	Expected Background Rate
$Z \to \tau^+\tau^-$	0.38 ± 0.07
One or both leptons fake	0.23 ± 0.15
$b\bar{b}$	0.03 ± 0.02
WW, WZ and ZZ	0.21 ± 0.07
Drell-Yan	0.44 ± 0.28
Total	1.3 ± 0.3

Probability of background fluctuation is 3.3×10^{-3}

Lepton + Jets Search Philosophy

Decay mode with the greatest sensitivity is "lepton+jets"

- About 30% of $t\bar{t}$ events decay this way
- Look for $W \to l\nu_l$ decay
- Require two jets from $W \to q\bar{q}$ decay
- Require at least one more jet from b quarks
  - must "tag" at least one b quark jet

Selection of W candidates straightforward

- Require high P_T isolated lepton candidate
- Require significant $\not\!\!E_T$
- Require three or more high P_T jets

Have now quadrupled our sample of $W+ \geq 3$ jet events

- Have 203 events before b tagging
- Expect ~ 30 to come from $t\bar{t}$ production

B Tagging Techniques

Use two properties of b quarks to identify them

1. About 20% of b's decay via

$$b \to e^- \nu_e X \quad \text{and} \quad b \to \mu^- \nu_\mu X$$

   - Look for jets with "soft" leptons in them
   - Call these soft-lepton tags (SLT's)
   - Expect 15% of $t\bar{t}$ events to have at least one SLT tag

2. "Long" b lifetime – $c\tau \sim 450$ microns

   - CDF uses Silicon Vertex Detector to identify jets with a secondary vertex
   - We call these "SVX" tags
   - Expect 42% of $t\bar{t}$ events to have at least one SVX tag

Idea is to just "count" number of tagged events

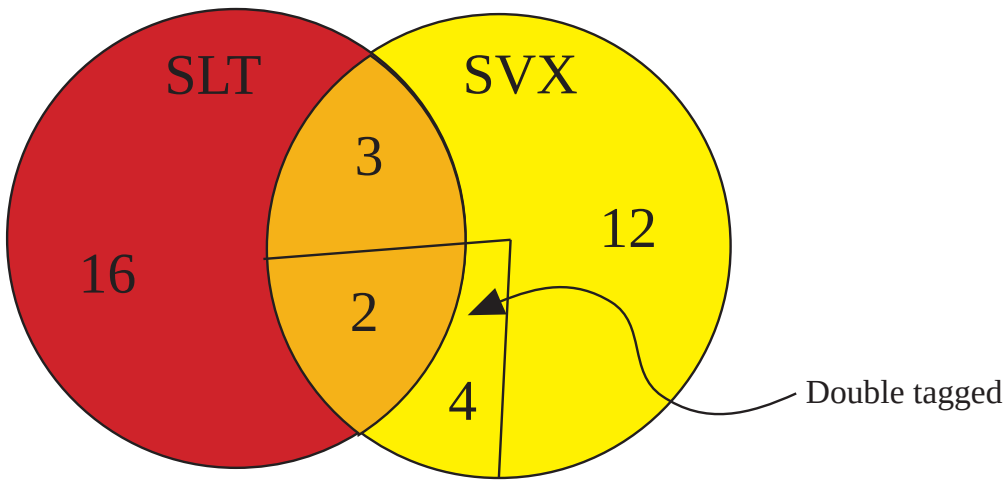
b Quark Tagging in W+Jet Events

Applied these tagging techniques to W+jet events

- The $W + 1$ and $W + 2$ jet samples are control samples
  - Don't expect significant top contribution
  - Theory predicts low b hadron content

Sample	SVX bkg	SVX tags	SLT bkg	SLT tags
W+1 jet	50 ± 12	40	159 ± 25	163
W+2 jet	21 ± 7	34	46 ± 7	55
W+$\geq$ 3 jet	6.7 ± 2.1	27	15.4 ± 2.3	23

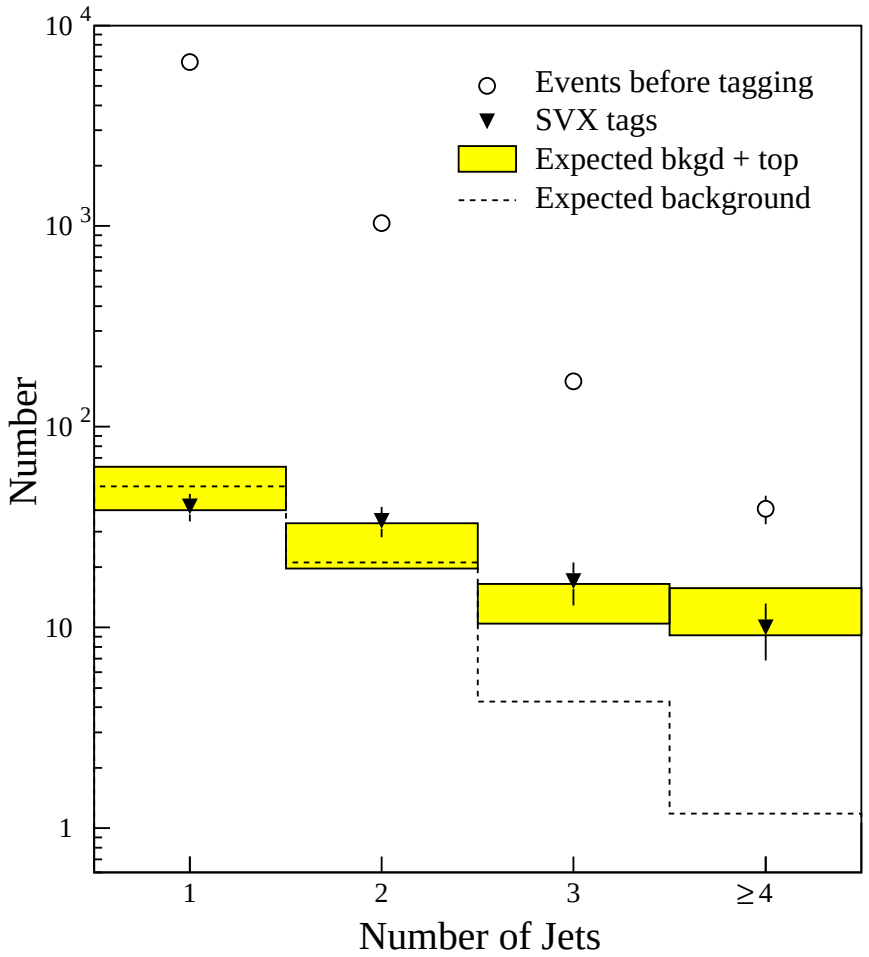
- Probability of background fluctuation is 1×10^{-6}
  - Combining SVX, SLT and DIL channels
- Agrees well with expected rate from $t\bar{t}$ production



SVX Tagging Results

The SVX tagged sample is single most significant observation

- Observe 27 tags when we expect 6.7 ± 2.1 background
- Probability of background fluctuation 2×10^{-5}



Measurement of Top Mass

We use event kinematics to estimate top quark mass

- Require events to have a fourth jet
  - Require $E_T > 8$ and $|\eta| < 2.4$ for 4rth jet
  - High efficiency ($\sim 85\%$ for $t\bar{t}$)
- Combine all possible jet pairs to form $W \to q\bar{q}$
  - Choose one with best χ^2
  - Require $\chi^2 < 10$
- Use b-tag information to identify b quark jet
- Fit events requiring kinematic constraints

This selection leaves us with 19 tagged events

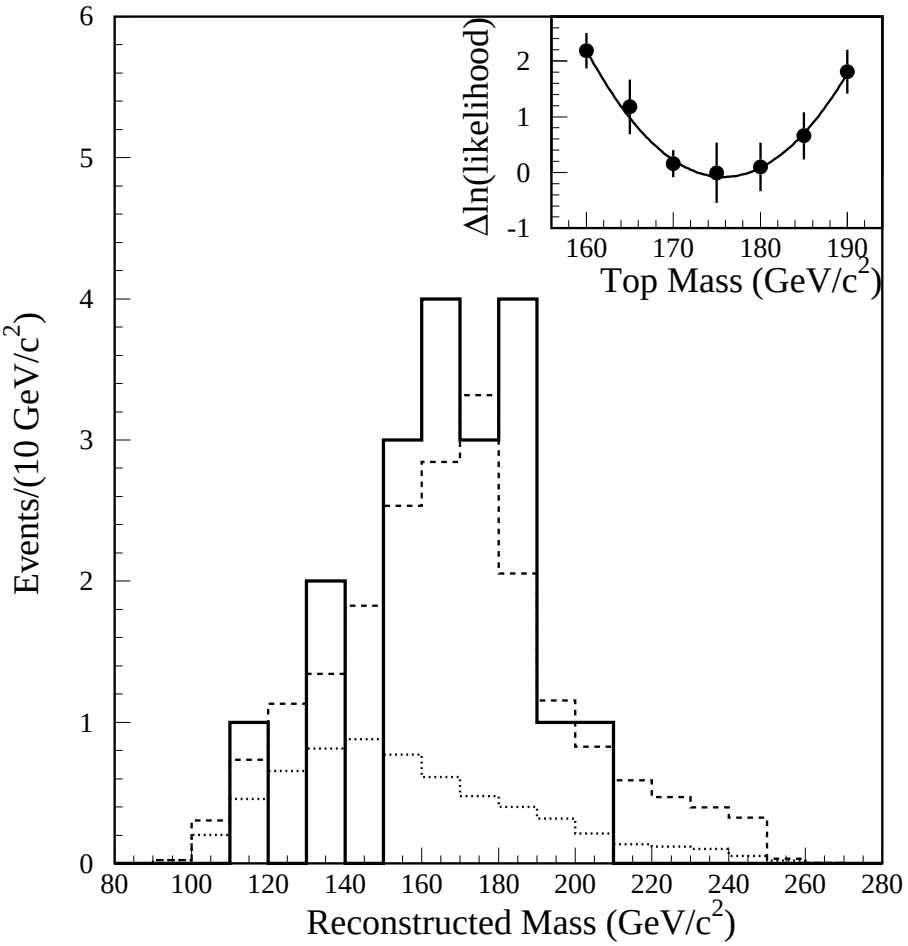
- Estimate background to be $6.9^{+2.5}_{-1.9}$ events
  - Primarily QCD W+jet

Procedure is dependent on theory predictions

Result of Mass Fits

The fitted mass for the 19 events is consistent with $t\bar{t}$

- Probability that background would fluctuate to give peak with similar significance is $< 2 \times 10^{-2}$

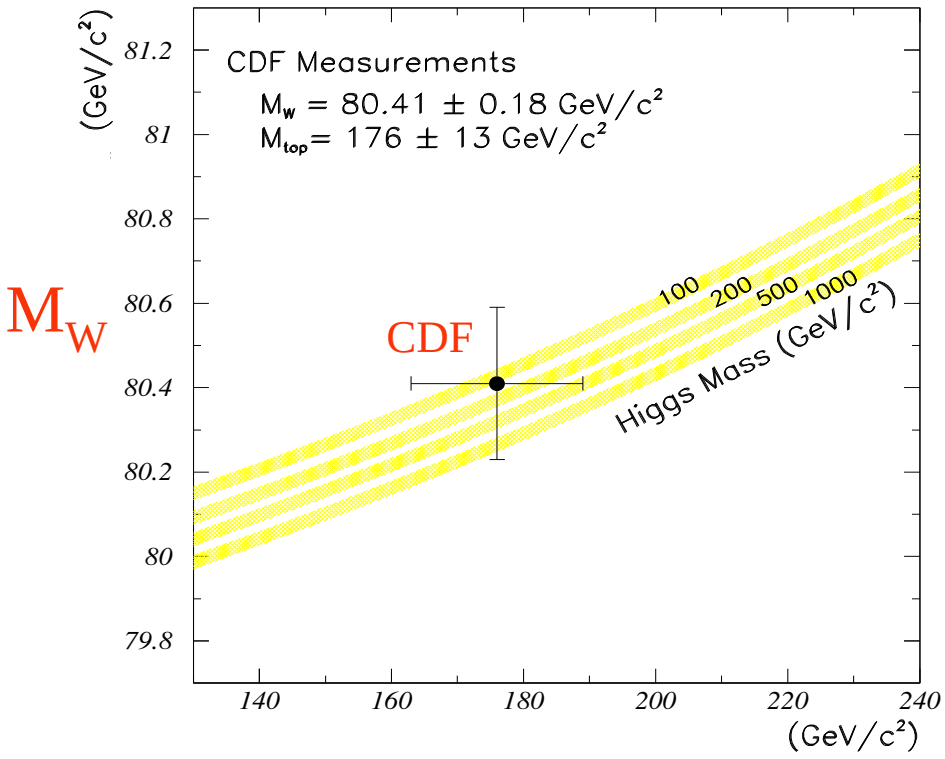


$$M_{top} = 176 \pm 8 \pm 10 \quad \text{GeV/c}^2$$

Does It Fit in the SM?

Interesting that everything now points to heavy top

W Mass vs. Top Mass



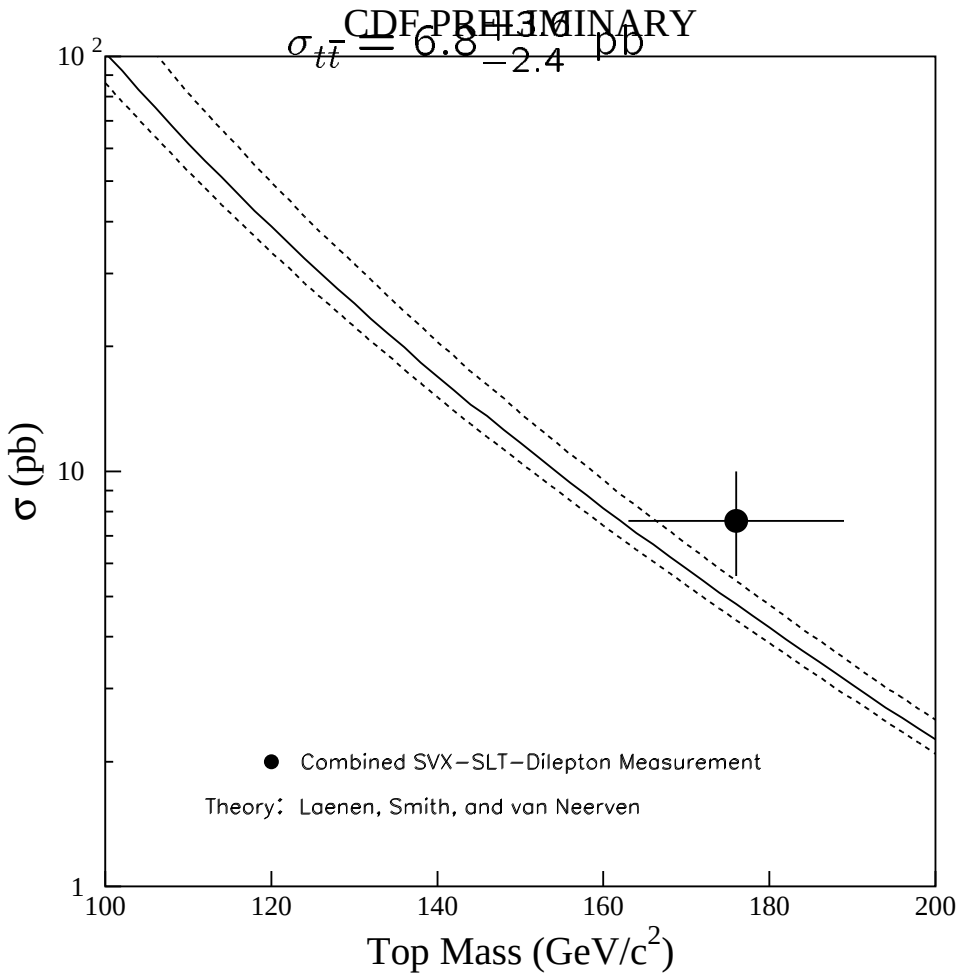
M_W

M_{top}

Cross Section Measurement

Use the channel with least background to estimate σ

- Subtract backgrounds from SVX-tags
  - Estimated background 5.5 ± 1.8 events
- Correct for tagging efficiency and acceptance
  - Efficiency is 0.0338 ± 0.0087



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

Consistency Checks Revisited

Two checks last year raised concern

- Rate of $W + 3$ jet versus $W + 4$ jet events
  - Didn't see "enough" $W + 4$ jet events
- Saw two $Z + 4$ jet b-tagged events – expected 0.6

Both appear to have been statistical fluctuations

1. Predicted rate of W+4 jet events now in good agreement

Process	Observed Events
Predicted QCD W+4 jet rate	13 ± 6.5
Observed W+4 jet rate	25 ± 6

2. Have not observed more tagged $Z + 4$ jet events

Number of Jets	Observed Tags	Predicted
1 jet	15	17.5
2 jet	3	4.2
≥ 3 jets	2	1.5

Prospects for Run 1A + Run 1B

Expect statistical uncertainty on M_{top} to scale as $1/\sqrt{N}$

- Have performed MC "toy" studies to evaluate this
- Expect statistical $\sigma_M \sim 6$ GeV/c^2
- Systematic σ_M hardest to control
  - Calibrate gluon radiation using other processes
    - Study of γ+ jet events allow us to calibrate energy flow out of jets
  - Sensitivity to background shape also should go as $1/\sqrt{N}$
    - Will have enough statistics to measure shape of non-W background
- Reasonable to expect systematic uncertainty to drop as $1/\sqrt{N}$

Can begin to estimate couplings

- Will have of order 10 dilepton events
- Expect of order 50 lepton + jet events
- Might expect $\sim 30\%$ measurement of

$$\frac{\text{BR(top} \rightarrow \text{leptons)}}{\text{BR(top} \rightarrow \text{hadrons)}}$$

EWK Conclusions

CDF has a new measurement of the W boson mass

$$M_W = 80.41 \pm 0.18 \text{ GeV/c}^2$$

Have measured Γ_W directly and indirectly

$$\begin{aligned} \Gamma_W &= 2.06 \pm 0.06 \pm 0.06 \text{ GeV/c}^2 \text{ (indirect)} \\ \Gamma_W &= 2.11 \pm 0.28 \pm 0.16 \text{ GeV/c}^2 \text{(direct)} \end{aligned}$$

Begun to explore WWZ vertex

Extended searches for new gauge bosons

$$\begin{aligned} M_{Z'} &> 505 \text{ GeV/c}^2 \text{ at 95\% CL} \\ M_{W'} &> 652 \text{ GeV/c}^2 \text{ at 95\% CL} \end{aligned}$$

TOP Conclusions

CDF has conclusively observed top quark production

- All three channels show significant signals
- Kinematic analysis confirms interpretation
- Probability of background fluctuation:
  - Counting experiment significance 1×10^{-6}
  - Mass analysis significance $< 2 \times 10{-}2$
  - Combined significance is 3.7×10^{-7}

Best estimate of top quark mass is

$$M_{top} = 176 \pm 8 \pm 10 \quad \text{GeV/c}^2$$

Result is confirmed by DØ

- Observe 17 events on background of 3.8 ± 0.6

$$M_{top} = 199^{+19}_{-21} \pm 22 \text{ GeV/c}^2$$

- Cross section $\sigma = 6.4 \pm 2.2$ pb

Continuing data collection for more detailed top studies