Jianming Qian
*The University of Michigan*

**Outline**

- Production and decays
- Pair production cross section
- Top quark mass
- Event kinematics

*China Center of Advanced Science & Technology*
*Beijing, China*
*December 19, 2000*
Building Blocks of Matter

- **1975** – discovery of the $\tau$ lepton
  Perl et al, PRL 35, 1489 (1975)

- **1977** – discovery of the b quark
  Herb et al, PRL 39, 252 (1977)
  - weak isospin = -0.504
  - no flavor changing neutral current
  - need weak isospin partner

- **1995** – discovery of the top quark
  CDF, PRL 74, 2626 (1995)
  DØ, PRL 74, 2632 (1995)

- **2000** – observation of tau neutrinos
# Hunt for the Top Quark

## Direct searches at colliders

<table>
<thead>
<tr>
<th>Year</th>
<th>Experiment</th>
<th>Process</th>
<th>Lower Limit m_{top} (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1979-84</td>
<td>PETRA (DESY)</td>
<td>e^+e^-</td>
<td>&gt;23.3</td>
</tr>
<tr>
<td>1987-90</td>
<td>TRISTAN (KEK)</td>
<td>e^+e^-</td>
<td>&gt;30.2</td>
</tr>
<tr>
<td>1989-90</td>
<td>SLC (SLAC)</td>
<td>e^+e^-</td>
<td>&gt;45.8</td>
</tr>
<tr>
<td></td>
<td>LEP (CERN)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1990</td>
<td>SppS (CERN)</td>
<td>pp</td>
<td>&gt;69</td>
</tr>
<tr>
<td>1991</td>
<td>Tevatron (FNAL)</td>
<td>pp</td>
<td>&gt;77</td>
</tr>
<tr>
<td>1992</td>
<td>Tevatron (FNAL)</td>
<td>pp</td>
<td>&gt;91</td>
</tr>
<tr>
<td>1994</td>
<td>Tevatron (FNAL)</td>
<td>pp</td>
<td>&gt;131</td>
</tr>
</tbody>
</table>

## Indirect constraints from radiative corrections

\[ W \xrightarrow{t} W \]

\[ b \]

\[ m_t [\text{GeV}/c^2] \]

\[ m_t \leq 186 \pm 16 \text{ GeV} \]

\[ m_t \leq 166 \pm 11 \text{ GeV} \]

\[ m_t \leq 141 \pm 10 \text{ GeV} \]

\[ m_t \leq 123 \pm 9 \text{ GeV} \]

\[ m_t \leq 108 \pm 8 \text{ GeV} \]
Top Quark Production

Top-antitop quark pair production

\[ q\bar{q} \rightarrow t\bar{t} \]

\[ gg \rightarrow t\bar{t} \]

Single top quark production

\[ q\bar{q} \rightarrow t\bar{b} \]

\[ qg \rightarrow q' t\bar{b} \]
Top Quark Decay

In the standard model, the top quark is short lived and decay almost exclusively to W and b quark

\[ t \rightarrow b q (\ell) \quad (W \rightarrow \ell v, W \rightarrow \ell v) \Rightarrow \ell \ell \]
\[ \quad (W \rightarrow \ell v, W \rightarrow \text{qq'}) \Rightarrow \ell + \text{jets} \]
\[ \quad (W \rightarrow \text{qq'}, W \rightarrow \text{qq'}) \Rightarrow \text{All-jet} \]

44% 21%

15% 15%

- tau+X
- mu+jets
- e+jets
- e+e
- e+mu
- mu+mu
- all hadronic

\[ \ell = e, \mu \]

Dilepton
Lepton+jets
Alljets

\[ t \bar{t} \Rightarrow \]
\[ (\ell \bar{v}b)(\ell v b) \rightarrow \ell \ell ' j^2 E_T \]
\[ (\ell \bar{v}b)(q q' b) \rightarrow \ell j^4 E_T \]
\[ (q q' \bar{b})(q q' b) \rightarrow j^6 \]
Data Sample

- Tevatron Run I (1992–1996): accumulated \(~120 \, \text{pb}^{-1}\) integrated luminosity at a center-of-mass energy of 1.8 TeV

![Graph showing integrated luminosity over time]

- Tevatron Run II (2001–2006): expect to accumulate \(~20 \, \text{fb}^{-1}\) (2 fb^{-1} Run IIa) at 2.0 TeV

**Key for top quark physics:**
- good lepton identification
- good missing \(E_T\) resolution
- efficient b-jet tagging capability
Dilepton Final State

\[ tt \rightarrow (\ell \nu \bar{b})(\ell' \nu b) \rightarrow \ell \ell' j^2 E_T \]

Small rate (5%) but lowest backgrounds

**Characteristics:**
- two isolated high pT leptons
- 2 jets from b-quarks
- significant missing transverse energy

**Major backgrounds:**
- \( Z(\rightarrow \ell \ell )+\text{jets}, WW, Z\rightarrow \tau \tau \)
- \( \text{QCD: } b\bar{b}, c\bar{c} \rightarrow \ell \ell \)
- instrumental: misidentification

![Graphs showing event distributions for different lepton combinations (e\mu, ee, \mu\mu) with H_T (GeV) on the x-axis and events on the y-axis.](image-url)
Lepton+Jets Final State

$$t\bar{t} \to (\ell \nu \bar{b})(q\bar{q}'b) \to \ell j^4 E_T$$

Moderate rate (15%) and reasonable backgrounds

**Characteristics:**
- One isolated high pT lepton
- Large transverse momentum imbalance
- Multiple jets

**Major backgrounds:**
- W+jets production
- Instrumental:
  - Misidentification and mismeasurement

**Strategies:**
- Explore the difference in topologies
- b-jets identification through ($b\to\mu$) decays
Alljets Final State

\[ t\bar{t} \rightarrow (q\bar{q}'\bar{b})(q\bar{q}'b) \rightarrow j^6 \]

Largest rate (44%) but highest backgrounds

**Characteristics:**
- Six or more jets (two b-jets)
- No high pT lepton nor large transverse momentum imbalance

**Backgrounds:**
- Huge QCD multi-jet production (S/B=1/2000 on tape)

**Strategies:**
- Tag b-jets using \( b \rightarrow \mu \) decays
- Neural network to separate signal from backgrounds
Event Selection

Top quark pair events are topologically different from most of the background events

- top quark events are more spherical
- every event has two jets from b-quarks
- leptonic decays of W bosons:
  - high $p_T$ isolated leptons
  - large missing transverse momentum

Depending on the final state, sophisticated selection criteria were developed to distinguish signal events from backgrounds

Selection of $\ell +$ jets events

![Scatter plots showing the distribution of aplanarity versus $H_T$ for different event categories: Data 105 pb$^{-1}$, MC 7 fb$^{-1}$, Multijet 700 pb$^{-1}$, W+4 jets MC 1 fb$^{-1}$.]
Candidate Events

run #40758, event #44414
24 September, 1992

$M^{\text{Fit}}_{\text{top}} = 170 \pm 10 \text{ GeV/c}^2$

24 September, 1992
run #40758, event #44414
### Selection Criteria

#### Dilepton Final State

<table>
<thead>
<tr>
<th>Lepton</th>
<th>$E_T$ (GeV)</th>
<th>$\geq 15$</th>
<th>$\geq 20$</th>
<th>$\geq 15$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$</td>
<td>\eta</td>
<td>$</td>
<td>$&lt;2.5$ (e)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$&lt;1.7$ (µ)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Missing $E_T$ (GeV)</td>
<td>$\geq 20$</td>
<td>$\geq 25$</td>
<td>$-$</td>
<td></td>
</tr>
<tr>
<td>Jets</td>
<td>#</td>
<td>$\geq 2$</td>
<td>$\geq 2$</td>
<td>$\geq 2$</td>
</tr>
<tr>
<td></td>
<td>$E_T$ (GeV)</td>
<td>$\geq 20$</td>
<td>$\geq 20$</td>
<td>$\geq 20$</td>
</tr>
<tr>
<td></td>
<td>$</td>
<td>\eta</td>
<td>$</td>
<td>$&lt;2.5$</td>
</tr>
<tr>
<td>$H_T$ (GeV)</td>
<td>$\geq 120$</td>
<td>$\geq 120$</td>
<td>$\geq 100$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(jets+e)</td>
<td>(jets+e)</td>
<td>(jets)</td>
<td></td>
</tr>
</tbody>
</table>

#### Lepton+Jets Topological Analysis

<table>
<thead>
<tr>
<th>Lepton</th>
<th>$E_T$ (GeV)</th>
<th>$&gt;20$</th>
<th>$&gt;20$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$</td>
<td>\eta</td>
<td>$</td>
</tr>
<tr>
<td>Missing $E_T$ (GeV)</td>
<td>$&gt;25$</td>
<td>$&gt;20$</td>
<td></td>
</tr>
<tr>
<td>2 Jets</td>
<td>$E_T$ (GeV)</td>
<td>$&gt;15$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$</td>
<td>\eta</td>
<td>$</td>
</tr>
<tr>
<td>Shape</td>
<td>$E_T^l + E_T$</td>
<td>$&gt;60$ GeV</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\Sigma E_T^{jets}$</td>
<td>$&gt;180$ GeV</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Aplanarity</td>
<td>$&gt;0.065$</td>
<td></td>
</tr>
<tr>
<td>Others</td>
<td>$</td>
<td>\eta_{wl}</td>
<td>&lt; 2$</td>
</tr>
</tbody>
</table>
Selection Criteria

Lepton+Jets Tagged Analysis

- two b-quark jets in each signal events
- background events have minimal heavy flavor content
- tag b-jet by presence of $\mu$ in jet
  - $\sim 20\%$ of the signal events have a detectable $\mu$ associated with a jet
  - $\sim 2\%$ of W+jets background events have a $\mu$ associated with a jet
- relax shape cuts to require only 3 jets

Event Selection

<table>
<thead>
<tr>
<th>Lepton</th>
<th>e+jets/µ</th>
<th>µ +jets/µ</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_T$ (GeV)</td>
<td>&gt;20</td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
<td>&lt;$</td>
</tr>
<tr>
<td>Missing $E_T$ (GeV)</td>
<td>&gt;20</td>
<td></td>
</tr>
<tr>
<td>$Z\rightarrow\mu\mu$ fit</td>
<td>$-$</td>
<td>Prob($\chi^2$)&lt;0.01</td>
</tr>
<tr>
<td>Soft $\mu$</td>
<td>$p_T&gt;4$ GeV and $\Delta R(\mu,\text{jet})&lt;0.5$</td>
<td></td>
</tr>
<tr>
<td>Jets</td>
<td>$\geq 3$ jets, $E_T&gt;20$ GeV, $</td>
<td>\eta</td>
</tr>
<tr>
<td>Shape</td>
<td>Aplanarity$&gt;0.04$</td>
<td>$H_T&gt;110$ GeV</td>
</tr>
</tbody>
</table>
Event Sample

\[ t\bar{t} \rightarrow (\ell \bar{\nu}b)(\ell' \nu b) \rightarrow \ell \ell' j^2 E_T \]

<table>
<thead>
<tr>
<th></th>
<th>DØ</th>
<th>CDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>data</td>
<td>5 (4)</td>
<td>9</td>
</tr>
<tr>
<td>background</td>
<td>1.4±0.4 (1.2±0.4)</td>
<td>2.4±0.5</td>
</tr>
</tbody>
</table>

\[ t\bar{t} \rightarrow (\ell \nu b)(q \bar{q}' b) \rightarrow j^4 E_T \]

<table>
<thead>
<tr>
<th></th>
<th>DØ</th>
<th>CDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>data</td>
<td>19</td>
<td>11</td>
</tr>
<tr>
<td>background</td>
<td>8.7±1.7</td>
<td>2.4±0.5</td>
</tr>
</tbody>
</table>

11 events in common

\[ t\bar{t} \rightarrow (q \bar{q}' b)(q \bar{q}' b) \rightarrow j^6 \]

<table>
<thead>
<tr>
<th></th>
<th>DØ</th>
<th>CDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>data</td>
<td>41</td>
<td>187</td>
</tr>
<tr>
<td>background</td>
<td>24±2.4</td>
<td>151±10</td>
</tr>
</tbody>
</table>
Cross Section

- **CDF di-lepton**: $8.4^{+4.5}_{-3.3}$ pb
- **DØ di-lepton**: $6.4 \pm 3.3$ pb
- **DØ topological**: $4.1 \pm 2.1$ pb
- **CDF lepton-tag**: $9.2 \pm 4.3$ pb
- **DØ lepton-tag**: $8.3 \pm 3.5$ pb
- **CDF SVX-tag**: $5.1 \pm 1.5$ pb
- **CDF hadronic**: $7.6^{+3.5}_{-2.7}$ pb
- **DØ hadronic**: $7.1 \pm 3.2$ pb
- **CDF combined**: $6.5^{+1.7}_{-1.4}$ pb
- **DØ combined**: $5.9 \pm 1.7$ pb
- **theory**: $4.7 - 6.2$ pb

**DØ**: PRL 79, 1203 (1997); **CDF**: PRL 80, 2773 (1998) (+updates)

**Theoretical uncertainty is about 10% - 20%**

**Run II precision**: ~8% (stat: 4%, syst: 4%, lumi: 4%)
Lepton+Jets Mass Method

\( \ell + \text{jets} \bar{t}t \) candidates

What happened

What we observed

For a signal event, we have one unknown \( p_z^\nu \) and three constraints

\[
\begin{align*}
  m(\ell \nu) &= m(jj) = M_W \\
  m(j\ell \nu) &= m(jjj)
\end{align*}
\]

Top quark mass can be determined through a 2-constraint fit to event kinematics
Lepton+Jets Mass Method

\[ t\bar{t} \rightarrow (\ell v\bar{b})(q\bar{q}'b) \rightarrow \ell j^4 E_T \]

Jet assignment ambiguity

- 12 if no jets is b-tagged
- 6 if one of the jets is b-tagged
- 2 if two jets are b-tagged

Additional complications from

- background events
- detector effect (mismeasurement + resolution)
- initial and final state radiations

Compare to Monte Carlo to measure the top quark mass

Ideal Case +Detector Effect +Combinatorics
Lepton+Jets Mass Method

Jet Energy Scale

Resolutions and Combinatorics

(a) Unsmear, parton level, no radiation.
  Mean: 170
  Width: 2.4

(b) Unsmear, generator level, radiation on.
  Mean: 163
  Width: 25.6

(c) Full detector simulation.
  Mean: 165
  Width: 24.7
Lepton+Jets Mass Method

The measured distribution \( f(x) \) is compared to those from signal \( g_s(x, m_t) \) and from background \( g_b(x) \) to extract the top quark mass using a likelihood method.

\[
L(n_s, n_b, m_t) = e^{-\left(n_s + n_b\right)} \frac{(n_s + n_b)^N}{N!} \times \frac{1}{\sqrt{2\pi}\sigma_b} e^{-\frac{(n_b - \langle n_b \rangle)^2}{2\sigma_b^2}} \times \prod_{i=1}^{N} \frac{n_s g_s(x_i, m_t) + n_b g_b(x_i)}{n_s + n_b}
\]

- \( n_s \) = # of signal events
- \( n_b \) = # of background events
- \( m_t \) = top quark mass

Poisson statistics  
Background constraint  
Probability density distribution for the measured variable
Multivariate Discriminants

- Some of the cross section selection are mass biased and need to be replaced
- DØ used four-variable multivariate discriminants

\[ x_1 = E_T \text{ (transverse momentum imbalance)} \]
\[ x_2 = A \text{ (Aplanarity)} \]
\[ x_3 = \frac{\sum_{i=2}^{N} E_T^j}{\sum_{i=1}^{N} E_L^j} \text{ (centrality)} \]
\[ x_4 = \frac{(\Delta R_{ij}^{\min}) E_T^{\min}}{E_T^L} \text{ (clusterness)} \]

**Likelihood:**

\[ L_i(\vec{x}) = \frac{s_i(\vec{x})}{b_i(\vec{x})} \text{ for each event} \]

\[ D_{LB} = \frac{\prod_{i=1}^{N} L_i(\vec{x})}{1 + \prod_{i=1}^{N} L_i(\vec{x})} \Rightarrow \{0 - 1\} \]

**Neural Network:**

\[ D_{NN} = \frac{s(\vec{x})}{s(\vec{x}) + b(\vec{x})} \Rightarrow \{0 - 1\} \]
Multivariate Discriminants

(a) $D_{LB}$

(b) $D_{NN}$

(c)

Fit top quark mass (GeV/c$^2$)
Lepton+Jets Mass Analysis

Analysis Details

\[ E_T^\ell > 20 \text{ GeV} \quad |\eta_e| < 2.0 \quad |\eta_\mu| < 1.7 \]
\[ E_T > 20 \text{ GeV} \]
\[ E_T^{cal} > 25 \text{ GeV} \text{ for } e+\text{jets}; \ E_T^{cal} > 20 \text{ GeV} \text{ for } \mu+\text{jets} \]
\[ \geq 4 \text{ jets}, \ E_T > 15 \text{ GeV}, \ |\eta_{\text{jet}}| < 2.0 \]

For events with $b \rightarrow \mu$ tagging
\[ p_T^\mu > 4 \text{ GeV} \text{ and } \Delta R = \sqrt{(\delta \eta)^2 + (\delta \phi)^2} < 0.5 \text{ of a jet} \]

For events without $b \rightarrow \mu$ tagging
\[ E_T^L \equiv (E_T^\ell + E_T) > 60 \text{ GeV} \text{ and } |\eta_W| < 2.0 \]

91 events selected (7 events have $b \rightarrow \mu$ tagged)

Perform kinematic fit on this sample
require $\chi^2 < 10$ and select fit with smallest $\chi^2$
⇒ 77 events fitted successfully (5 $b \rightarrow \mu$ tagged events)
Mass from Lepton+Jets

\[ t\bar{t} \rightarrow (\ell \nu \bar{b})(q\bar{q}'b) \]

173.3±5.6±5.5 GeV

Largest systematics
Jet energy \quad 4.0 \text{ GeV}
Monte Carlo \quad 3.1 \text{ GeV}
Noise/pile-up \quad 1.3 \text{ GeV}

PRL 79, 1197 (1997)
PRD 58, 052001 (1998)

176.1±5.1±5.3 GeV

Largest systematics
Jet energy \quad 4.4 \text{ GeV}
Monte Carlo \quad 2.6 \text{ GeV}
Background \quad 1.3 \text{ GeV}
Mass from Alljets

\[ t\bar{t} \to (q\bar{q}'b)(q\bar{q}'\bar{b}) \to j^6 \]

\( m_t \) can also determined from alljets final state from a 3-constraint fit

\[ m_t = 186.0\pm10.0\pm5.7 \text{ GeV} \]

Largest systematics
- Jet scale: 4.4 GeV
- Monte Carlo: 1.8 GeV
- Background: 1.3 GeV
Dilepton Mass Method

\[ t\bar{t} \rightarrow (\ell\nu b)(\ell'\nu b) \rightarrow \ell\ell' j^2 E_T \]

The final state is underconstrained

- among the 6 neutrino momentum components, only \( \Sigma p_T^\nu \) are measured \( \Rightarrow \) four unknowns

- three constraints:
  \[
  \begin{align*}
  m(\ell\nu) &= m(\ell'\nu) = M_W \\
  m(\ell\nu b) &= m(\ell'\nu b)
  \end{align*}
  \]

Nevertheless, the final state momentum and angular information is sensitive to the top quark mass.

- assuming a \( m_t \), calculate a weight for every event characterizing how likely that the event is consistent with the assumed \( m_t \)

- sum the weight over candidate events

- repeat the process for different values of \( m_t \)
  \( \Rightarrow \) weight function \( W(m_t) \)

- the top quark mass is extracted by fitting the observed \( W(m_t) \) distribution to those from MC

**Dilepton Mass Method**

\[ t\bar{t} \rightarrow (\ell \nu b)(\ell' \nu b) \rightarrow \ell \ell' j^2 E_T \]

**Matrix element and neutrino weightings**

\[
w_i^M(m_t) \sim f(x) f(\bar{x}) p(E_i^\ell^+ | m_t) p(E_i^\ell^- | m_t)
\]

\[
w_i^\nu(m_t) \sim \int d\eta d\bar{\eta} g(\eta|m_t) g(\bar{\eta}|m_t) \exp\left[-\frac{(\vec{p}_T - \vec{p}_T^\nu - \vec{p}_T^\bar{\nu})^2}{2\sigma^2}\right]
\]

- \( f(x) \): parton distribution function
- \( p(E_i^\ell | m_t) \): lepton energy probability for a given \( m_t \)
- \( g(\eta|m_t) \): lepton \( \eta \) probability for a given \( m_t \)
Mass from Dilepton

\[ tt \rightarrow (\ell \bar{\nu}_\ell)(\ell' \nu_{\ell'}) \]

168.4±12.3±3.6 GeV

Largest systematics
Jet energy 2.4 GeV
Monte Carlo 1.8 GeV
Noise/pile-up 1.3 GeV
(combining both methods)
PRL 80, 2063 (1998)
PRD 60, 05001 (1999)

167.4±10.3±4.8 GeV

Largest systematics
Jet energy 3.8 GeV
Gluon radiation 2.7 GeV
Top Quark Mass Summary

**CDF dilepton**

167.4 ± 10.3 ± 4.8

**CDF lepton+jets**

175.9 ± 4.8 ± 5.3

**CDF all hadronic**

186 ± 10 ± 5.7

**CDF average**

176.0 ± 4.0 ± 5.1

**D0 dilepton**

168.4 ± 12.3 ± 3.6

**D0 lepton+jets**

173.3 ± 5.6 ± 5.5

**D0 average**

172.1 ± 5.2 ± 4.9

**Tevatron average**

174.3 ± 3.2 ± 4.0

\[ m_t = 174.3 \pm 3.2 \text{(stat)} \pm 4.0 \text{(syst)} \text{ GeV} \]

\[ = 174.3 \pm 5.1 \text{ GeV} \]

Relative weight in top mass average
Standard Model Comparison

- Good agreement between observation and theoretical calculations
- Data prefer a low Higgs mass
Run II Mass Measurement

Statistical and systematic errors contribute equally to the total errors of the present measurements.

Most of the errors are expected to scale with $1/\sqrt{N}$, the $\delta m_t$ is expected to reduce to 3 GeV or less.

DØ Run II

$\delta M_W=0.04$ GeV/c$^2$

$\delta m_{top}=3.0$ GeV/c$^2$

Combined with the data from LEP/SLC, the Higgs mass can be constrained to be within 30%.
Single Top Production

Single top quark is produced through electroweak processes

\[ \sigma(p\bar{p} \rightarrow tb + X) \propto \Gamma(t \rightarrow Wb) \propto |V_{tb}|^2 \]
\[ \sigma(W^* \rightarrow tb) = 0.72 \pm 0.10 \text{ pb} \]
\[ \sigma(Wg \rightarrow tbq) = 1.7 \pm 0.2 \text{ pb} \]

Measure single top quark cross section

- Direct access to the Wtb vertex
- Directly measure the top quark decay width and CKM matrix element
- Probe anomalous couplings

**Final State**
\[ W^* \rightarrow tb \rightarrow Wb\bar{b} \rightarrow (\ell \nu)b\bar{b} \]
\[ Wg \rightarrow tbq \rightarrow Wb\bar{b}q \rightarrow (\ell \nu)b\bar{b}q \]

(In Wg mode, one of the b-jets is very soft)

Major backgrounds: \( t\bar{t} \) and \( Wb\bar{b} \) production
Single Top Production

In many kinematic distributions, the signal is sandwiched between two major background sources.

Neither experiment were able to extract a signal in Run I.

**CDF:**
\[
\sigma < 13.5 \text{ pb @ 95\% CL}
\]

**DØ:**
\[
W^* \rightarrow tb: \quad \sigma < 39 \text{ pb} \\
Wg \rightarrow tbq: \quad \sigma < 58 \text{ pb}
\]
Single Top Production

Single top search suffers from
• small production cross section
• in Wg production, one of the two b-jets is soft and mostly in the forward region
• jet multiplicity is low
• inefficient b-jet tagging

In Run IIa
• a factor of 20 increase in luminosity
• expect to have a factor of 2.5 more from the improved detector and tools

We expect to observe this process in Run II and measure $\delta \Gamma_t \sim 20\% \Gamma_t$
Spin Correlation

The spins of \( t \) and \( \bar{t} \) produced from \( q\bar{q} \) annihilation are expected to have strong correlations

1) Since \( \Gamma_t = \Gamma(t \rightarrow Wb) \approx 1.5 \text{ GeV} \gg \Lambda_{QCD} \approx 150 \text{ MeV} \), top quarks decay before hadronization.

2) The polarization of the top quark is carried by its decay products.

3) At \( \sqrt{s} = 1.8 \text{ TeV} \), 90% of \( t\bar{t} \) is produced through \( q\bar{q} \) annihilation.

The top quark polarization can be reconstructed, not possible for other quarks!
Spin Correlation

Charged leptons and down-type quarks are most sensitive to the top quark polarization

\[ \frac{1}{\Gamma} \frac{d\Gamma}{d(\cos \theta_i)} = \frac{1 + \alpha_i \cos \theta_i}{2} \]

<table>
<thead>
<tr>
<th>Particle (i)</th>
<th>(\alpha_i)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(l^+ \text{ or } d)</td>
<td>1</td>
</tr>
<tr>
<td>(\nu \text{ or } u)</td>
<td>-0.31</td>
</tr>
<tr>
<td>(W^+)</td>
<td>0.41</td>
</tr>
<tr>
<td>(b)</td>
<td>-0.41</td>
</tr>
</tbody>
</table>

• **Down-type quarks are impractical to identify, only dilepton events are considered**

• **In an optimized spin quantization basis, only like-spin combinations are produced**
  (G. Mahlon and S. Parke, PLB 411, 173 (1997))

• **In this basis, the spin correlation can be expressed using angles**

\[ \frac{1}{\sigma} \frac{d^2\sigma}{d(\cos \theta_+)d(\cos \theta_-)} = \frac{1 + \kappa \cos \theta_+ \cos \theta_-}{4} \]

Correlation parameter

SM value \(\approx 0.9\)
Spin Correlation

- direct probes the properties of ‘bare’ quarks, free of hadronization effect
- probes for non-standard interactions at the production as well as at the decay vertices

Six dilepton events are analyzed assuming $t\bar{t}$ decay hypothesis and $m_t = 175$ GeV

Both lepton and jet pairings and multiple Neutrino solutions are considered and weighted

The sensitivity is limited by statistics!

$\kappa > -0.25$ @ 68% CL

DØ: PRL 85, 256 (2000)
Spin Correlation

No spin correlation \( \kappa = 0 \)

Helicity basis \( \kappa = 0.40 \)

Beamline basis \( \kappa = 0.68 \)

Off-diagonal basis \( \kappa = 0.87 \)

More than 150 dilepton events expected are expected from Run IIa

\( \kappa = 0 \) and \( \kappa = 1 \) can be separated at more than 2\( \sigma \) level
Top Quark Differential Cross Section

\[ R_1 + R_2 = 0.72^{+0.13}_{-0.13} \text{(stat)}^{+0.06}_{-0.06} \text{(syst)} \]

\[ R_4 < 0.114 \text{ at 95\% C.L.} \]

CDF PRELIMINARY

One Standard Deviation Confidence Intervals

Measurements in different \( p_T \) bins are correlated

![Graph showing one standard deviation confidence intervals](image)

<table>
<thead>
<tr>
<th>( p_T ) Bin</th>
<th>Measured Fraction of Top Quarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 0 &lt; p_T &lt; 75 \text{ GeV/c} )</td>
<td>( R_1 = 0.29^{+0.18}<em>{-0.18} \text{(stat)}^{+0.08}</em>{-0.08} \text{(syst)} )</td>
</tr>
<tr>
<td>( 75 &lt; p_T &lt; 150 \text{ GeV/c} )</td>
<td>( R_2 = 0.42^{+0.18}<em>{-0.18} \text{(stat)}^{+0.05}</em>{-0.05} \text{(syst)} )</td>
</tr>
<tr>
<td>( 150 &lt; p_T &lt; 225 \text{ GeV/c} )</td>
<td>( R_3 = 0.29^{+0.12}<em>{-0.10} \text{(stat)}^{+0.06}</em>{-0.05} \text{(syst)} )</td>
</tr>
<tr>
<td>( 225 &lt; p_T &lt; 300 \text{ GeV/c} )</td>
<td>( R_4 = 0.000^{+0.035}<em>{-0.000} \text{(stat)}^{+0.019}</em>{-0.000} \text{(syst)} )</td>
</tr>
</tbody>
</table>

Another tool for investigating anomalous \( tt \) production mechanisms
Top-Antitop Mass

- Unlike the bottom quark, top-antitop are not expected to form bound states due to its short lifetime

- However, many models predict the existence of top and antitop resonances
  - technicolor $gg \rightarrow \eta_T \rightarrow (tt, gg)$
  - topcolor $qq \rightarrow V_8 \rightarrow (tt, bb)$

- Top-antitop invariant mass distribution is a tool for searching for new physics
W Boson Helicity

Top quark decays before hadronization via V- A interaction

Top quarks can only decay to longitudinal ($W_0$) or left-hand ($W_{-1}$) polarized $W$ bosons

In the standard model $F_0 \equiv \frac{W_0}{W_0 + W_{-1}} \approx \frac{m_t^2}{2 M_W^2 + m_t^2} \approx 70\%$

$W$ polarizations can be analyzed from the angular or pT distributions of the charged leptons

Top rest frame
W Boson Helicity

- Top quark decays provide the first opportunity for studying longitudinally polarized Ws
- Non-standard top quark decays may result in different W polarization

Using dilepton and lepton+jets events, CDF has measured

\[ F_0 = 0.91 \pm 0.37 \text{(stat)} \pm 0.12 \text{(syst)} \]
\[ F_{+1} = 0.11 \pm 0.15 \text{(stat)} \pm 0.06 \text{(syst)} \]

Fit for Fraction of W with \( h_W = 0 \) (\( F_0 \))

(CDF Preliminary)
CKM Matrix Element $|V_{tb}|$

- $|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2 = 1$ assuming 3 generations and $|V_{tb}|$ is expected to be very close to 1
- no constraints if more than 3 generations
- any departure of $|V_{tb}|$ from 1 indicates physics beyond the standard model

Extract $|V_{tb}|$ from the measurement of $R$

$$R = \frac{B(t \rightarrow Wb)}{B(t \rightarrow Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$$

Count dilepton and lepton+jets events with zero, single and double b-taggs,
CDF has determined:
$|V_{tb}| > 0.75$ @ 95% CL assuming 3 generations
$|V_{tb}| > 0.046$ @ 95% CL without the assumption

In Run IIa with 2 fb$^{-1}$, $\delta|V_{tb}| \approx 10\%$
benefit from large statistics and improved b-tagging capability
Search for Charged Higgs

- The standard model with two Higgs doublets will result in five Higgs particles:
  \[ h^0 \quad H^0 \quad A^0 \quad H^+ \quad H^- \]

- The Higgs sector will have six free parameters:
  - \( m_{h^0}, m_{H^0}, m_{A^0}, m_{H^\pm} \)
  - \( \tan \beta = \frac{v_2}{v_1} \): the ratio of VEVs
  - \( \alpha \): Higgs mixing angle

- If charged Higgs bosons are sufficiently light, they can be produced in \( t \to Hb \) decays

- The new decay mode with compete with the standard model \( t \to Wb \) mode:
  \[ W \to \beta \quad \gamma \quad H \to \tau \nu \quad Wb \bar{b} \]

- Since \( W \) and \( H \) decay differently
  \( t \to Hb \) decay will lead to different signatures for top quark pair events

Signature for charged Higgs production:
- disappearance of standard \( WWbb \) signature
- anomalous \( \tau \) lepton production
Search for Charged Higgs

Disappearance Search

• The measured top quark pair production cross section agrees with standard model prediction

• Sensitive only to the regions of parameter space with large $B(t \rightarrow Hb)$

• Sensitive only to topologies different from $WWbb$ of the SM top quark pair

Both CDF and DØ studied the implication of the cross section measurement on the charged Higgs parameter space
Search for Charged Higgs

**Appearance Search**

- **CDF searched for** $t \rightarrow Hb$ decay via $\tau$ appearance for high $\tan\beta$ (where $H \rightarrow \tau \nu$)  
  *Phys. Rev. D54, 735 (1996)*

- For the $\tau$ appearance analyses, $qjX$ and acoplanar $\tau\tau$ events were searched

- The major backgrounds are fake taus, W+jets, Z+jets and WW, WZ, ZZ productions

- 7 events were observed with 7.4±2.0 events expected. No excess of events
Heavy Top Quark

• Besides negative searches, the other indication of a heavy top quark is from the $B^0\overline{B}^0$ mixing measurement by ARGUS and CLEO

• Theoretically it was known since early 80s that some super-gravity models require top quark mass to be above 150 GeV

Consequences of a heavy top

• Yukawa couplings: 
  \[ \lambda_t = \frac{\sqrt{2} m_t}{v} \approx 1 \]  for top quarks and
  \[ \lambda_e = \frac{\sqrt{2} m_e}{v} \approx 3 \times 10^{-6} \]  for electrons

• Generates electroweak symmetry breaking through radiative correction

Is it “Why the top quark is so heavy?” Or Is it “Why other particles are so light?”
Top Physics in Run II

Expect to have a factor of 50 increase in top quark sample in Run Ila

• Improved measurement of top quark mass and pair production cross section

• Measure top quark decay branching ratios and test of standard model predictions

• Study kinematic distributions
  • spin correlation
  • top polarization
  • transverse momentum
  • mass of top quark pair
  • ....

• Observation of single top quark production and determination of its decay width

• Search for new physics from top quark decays

Hope to answer the question
“Does the top quark play a role in electroweak symmetry breaking?”

A rich top physics program!