Top Quark Physics at DØ

Breese Quinn
FNAL
The Standard Model

- up/down 1968 SLAC
- strange 1964 BNL
- charm 1974 SLAC/BNL
- bottom 1977 Fermilab
- top 1995 Fermilab D0/CDF
- photon 1905 Planck/Einstein
- gluon 1979 DESY
- W/Z 1983 CERN
- electron 1897 Thomson
- e-neutrino 1956 Reactor
- muon 1937 Cosmic Rays
- mu-neutrino 1962 BNL
- tau 1976 SLAC
- tau-neutrino 2000 Fermilab
- Higgs 200? Fermilab???
The Standard Model

This model has successfully described or predicted almost everything we’ve seen in almost 100 years of particle physics.

However it does have some weaknesses

- Too many free parameters (19)
- Predictive powers wane as we move past the Electroweak (EW) regime towards the TeV scale and beyond
- Where is the Higgs?
The Standard Model (SM) predicts all top properties given $m_t$. It’s huge!
Why Study the Top?

- The Standard Model (SM) predicts all top properties given $m_t$
- In the SM, the top and W mass constrain the mass of the Higgs Boson via EW radiative corrections
- In 1964, Peter Higgs postulated a physics mechanism which gives all particles their mass.
- This mechanism is a field which permeates the universe and is mediated by a particle called the Higgs boson.

\[ \Box m_W \quad m_t^2 / m_W^2 \]

\[ \Box m_W \quad \ln(m_H / m_W) \]
Why Study the Top?

- The Standard Model (SM) predicts all top properties given $m_t$
- In the SM, the top and $W$ mass constrain the mass of the Higgs Boson via EW radiative corrections
- Since the top is so heavy, it should have particularly strong coupling to the Higgs
  - Likely to play a significant role in EW Symmetry Breaking ($m_W, m_Z$)

Top could shed light on electroweak symmetry breaking

**Electromagnetic**

$m_\square = 0$

**Weak**

$m_W = 80$ GeV

$m_Z = 91$ GeV

Big Bang $t$  E

10^{-10}$ s

13.7 Gyr now
Why Study the Top?

- The Standard Model (SM) predicts all top properties given $m_t$.
- In the SM, the top and W mass constrain the mass of the Higgs Boson via EW radiative corrections.
- Since the top is so heavy, it should have particularly strong coupling to the Higgs.
  - Likely to play a significant role in EW Symmetry Breaking ($m_W, m_Z$).
- Top decay time ($\sim 4 \times 10^{-25} \text{s}$) < hadronization time.
  - Opportunity to study bare quarks.

In general, quarks do not exist as free particles. $qq$ pairs are pulled from the vacuum to produce stable hadrons with 2 quarks (mesons) or 3 quarks (baryons).

- This process is called hadronization.

Since the top quark decays before that happens, we can study quark properties such as spin polarzization here and no where else.
### Top Physics: Production

<table>
<thead>
<tr>
<th>Strong production</th>
<th>EW production</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>tt</strong></td>
<td><strong>single t</strong></td>
</tr>
</tbody>
</table>

#### Production cross section (pb)

<table>
<thead>
<tr>
<th></th>
<th>Run I (1.8 TeV)</th>
<th>Run II (2 TeV)</th>
<th>LHC (14 TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>tt</td>
<td>4.5</td>
<td>6.0</td>
<td>40</td>
</tr>
<tr>
<td>EW</td>
<td>0.5</td>
<td>1.0</td>
<td>760</td>
</tr>
<tr>
<td></td>
<td>0.7</td>
<td>0.9</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>1.7</td>
<td>2.4</td>
<td>250</td>
</tr>
</tbody>
</table>
Top Physics: Decays

BR(t→Wb) ~ 100%

- Significant deviation would indicate new physics

Top decays before hadronization

- Can study polarization of a free quark

Jets: showers of particles produced from quarks
Top Physics

- Branching ratios
- W helicity
- Couplings
- Rare decays
- CKM matrix element $|V_{tb}|$
- Non SM decays
- Top mass

Physics beyond SM?

Cross section
Top spin polarization
Production kinematics
Top-antitop resonance states

Top Physics

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The Fermilab Tevatron

The world’s most powerful particle accelerator

Run I
1.8 TeV
1992-1996

Run II
1.96 TeV
2001-?

Main Injector
(new)

Booster

CDF

DØ

Tevatron

p source

Chicago

…until LHC at CERN, 14 TeV, ~2007-?

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Protons and antiprotons are bags of quarks and gluons

Collisions take place between individual constituents

Each quark and gluon carries some fraction, \( x \), of the total proton momentum
If one of the constituents has small $x$, $E_{\text{COM}}$ is small and the decay products are boosted along the beam direction.

If both constituents have large $x$, $E_{\text{COM}}$ is large, massive particles (i.e. top) can be produced and the decay products have a large momentum component transverse to the beam.

High-$P_t$ physics
Production: Luminosity & # of Events

**Instantaneous luminosity**

\[
L = \frac{N_p N_{\bar{p}} B f_o}{4\pi \sigma^2} \quad \text{(events / cm}^2\text{s)}
\]

<table>
<thead>
<tr>
<th>Run 1</th>
<th>Run 2(a)</th>
<th>Run 2(b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(N_p) (protons/bunch)</td>
<td>2.3</td>
<td>2.7</td>
</tr>
<tr>
<td>(N_{\bar{p}}) (antiprotons/bunch)</td>
<td>5.5</td>
<td>3</td>
</tr>
<tr>
<td>(B) (# of antiproton bunches)</td>
<td>6</td>
<td>36</td>
</tr>
<tr>
<td>(f_o) (revolution frequency)</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>(\sigma) (beam “size” at interaction)</td>
<td>3</td>
<td>2</td>
</tr>
</tbody>
</table>

\(< L >\) \(1.6 \times 10^{30}\) \(2 \times 10^{30}\) \(5 \times 10^{32}\) \(cm^{-2} s^{-1}\)

**Integrated luminosity**

\[
L = \int dt \quad N(\text{top}) = \int (p\bar{p} \quad t\bar{t}) \quad \ne L
\]

<table>
<thead>
<tr>
<th>Run 1</th>
<th>Run 2(a)</th>
<th>Run 2(b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(L)</td>
<td>0.1 fb(^{-1})</td>
<td>2 fb(^{-1})</td>
</tr>
<tr>
<td>(\sigma(pp \rightarrow tt))</td>
<td>5 pb</td>
<td>7 pb</td>
</tr>
<tr>
<td>(N(\text{top events produced}))</td>
<td>500</td>
<td>14000</td>
</tr>
</tbody>
</table>
Top events are very rare
- One collision out of every $3 \times 10^9$ produced a $t\bar{t}$ pair

To study processes with small cross sections, one needs
- High luminosity to produce enough interesting events
- Methods for distinguishing those events from more copious backgrounds
Decay: What Does a Top Event Look Like?

- $\text{BR}(t \rightarrow Wb) \sim 100\%$
- $W \rightarrow q\bar{q}$ or $W \rightarrow l\pm\nu$
- So top events should have either
  - 6 jets from quarks
  - 4 jets, 1 charged lepton, 1 neutrino
  - 2 jets, 2 charged leptons, 2 neutrinos

- 2 jets must come from $b$ quarks
  - These jets can be distinguished from light quark jets
  - Powerful background rejection tool
How do we “see” the events?
- Observe, identify, and measure the decay particles

Charged particle trajectories, vertices

Charged particle momentum (DØ didn’t have one in Run I)
- $e^\pm$, $\pi^\pm$, $\rho$, $\eta$, etc.
- $p$, $n$, $\nu\pm$, etc. energy

$\nu\pm$ identification

A detector cross-section, showing particle paths

- Beam Pipe (center)
- Tracking Chamber
- Magnet Coil
- E-M Calorimeter
- Hadron Calorimeter
- Magnetized Iron
- Muon Chambers
A Specific Detector: DØ
A Specific Collaboration: DØ

A collaboration of ~600 physicists from more than 75 institutions in 18 countries
Run I → Run II: Tevatron Upgrade

- New Main Injector and Recycler, and improved Antiproton Source and Booster
  - Increased luminosity
- Increase number of bunches
  - Reduce number of interactions per crossing
- Increase beam energy from 900 GeV to 980 GeV
  - Increased top cross sections

<table>
<thead>
<tr>
<th></th>
<th>Run Ib</th>
<th>Run IIa</th>
<th>Run IIb</th>
</tr>
</thead>
<tbody>
<tr>
<td>#bunches</td>
<td>6x6</td>
<td>36x36</td>
<td>140x103</td>
</tr>
<tr>
<td>bunch xing (ns)</td>
<td>3500</td>
<td>396</td>
<td>132 or 396</td>
</tr>
<tr>
<td>interaction/xing</td>
<td>2.5</td>
<td>2.3</td>
<td>4.8</td>
</tr>
<tr>
<td>? s (TeV)</td>
<td>1.8</td>
<td>1.96</td>
<td>1.96</td>
</tr>
<tr>
<td>typ L (cm⁻²s⁻¹)</td>
<td>1.6x10³⁰</td>
<td>8.6x10³¹</td>
<td>5.2x10³²</td>
</tr>
<tr>
<td>?Ldt (fb⁻¹)</td>
<td>0.1</td>
<td>2</td>
<td>15</td>
</tr>
</tbody>
</table>
Run I → Run II: DØ Upgrade

Along with most electronics, DAQ, online and offline computing

- Beamline Shielding
- Preshowers
- 2T Solenoid
- Fiber Tracker
- Silicon ?-strip Tracker
- Forward Muon Tracking+Trigger
- Central Muon Scintillators
- Preshowers
- Forward Muon Tracking+Trigger
- Beamline Shielding
- Central Muon Scintillators
- Silicon ?-strip Tracker
- 2T Solenoid
- Fiber Tracker
912 silicon devices, 800k channels
- 4 layer barrels + disks
  - Good pattern recognition
  - 3D track reconstruction
- 10 mm hit resolution
- Primary and secondary vertex reconstruction
  - b-tagging
  - triggering
Electron Identification

Max ET = 41.9 GeV
Sum ET = 111.4 GeV
VTX z = -30.3 cm
Muon Identification

Max ET = 9.8 GeV
CAEH ET SUM = 119.8 GeV
VTX in Z = 41.2 (cm)

0.2 < E < 1.2
1.2 < E < 2.2
2.2 < E < 3.2
3.2 < E < 4.2
4.2 < E

D0 Top View   5-OCT-1995 16:17    Run   58006 Event   10239   23-DEC-1992 17:06
Neutrino "Identification"

- Neutrinos do not interact with our detector
- What about the kinematics?
  - Total energy is unknown
  - Longitudinal momentum is unknown
  - Transverse momentum is zero!
- Neutrinos are inferred from an imbalance in the transverse momentum of the observed objects

\[
\sum_{i=1}^{n} \vec{p}_{T}^i = \sum_{1(2)} \vec{p}_{T} \quad \text{(invisible)}
\]
Neutrino “Identification”

Max ET = 42.7 GeV
Miss ET = 34.7 GeV
In the process of hadronization a quark appears in the detector as a spray of hadrons called a *jet*.
Soft lepton tagging

- Used for semileptonic b decays
- e.g. try to match a soft muon to a jet for:

2 b-quarks in each tt event
Tag with soft
b\rightarrow c \overline{b} b \rightarrow c \overline{s}
**b-Quark Identification**

Soft □ tagging

\( p_T^{\text{rel}} \): transverse momentum relative to the jet direction
**b-Quark Identification**

**Lifetime**
- 1.5 ps \(\pm\) 0.5 mm
- Displaced secondary vertex
- Requires precise tracking near the primary collision point: *silicon trackers*, new for DØ in Run II!

![Diagram of b-Quark Identification](image)
A few big challenges

- **Backgrounds**
  - There are many different copious processes that look like top events (Remember the cross section plot? Primary W and Z backgrounds are ~10,000 times more plentiful).
  - We try to identify the unique features of top which will separate it from background.
    - e.g. b-tagging

- **Detector limitations**
  - Some of the particles’ energy is deposited in dead material, necessitating calibrations.
  - The detector is not perfect – we must determine the inefficiency for observing events.
Lepton+jets channel

1 unknown ($p_z^\perp$)

3 constraints:
- $m(l^n) = m(qq) = m_W$
- $m(l^n b) = m(qqb)$

2-constraint kinematic fit

up to 24-fold combinatoric ambiguity

compare to MC to measure $m_t$

Combinatorics

2 solutions for $p_z^\perp$

12 assignments of the 4 jets to the 4 quarks.
- 6 if one jet is b-tagged.
- 2 if two jets are b-tagged.

Gluon radiation produces extra jets
Run I: Top Mass, lepton+jets

Basic analysis procedure

- In a data sample of $t\bar{t}$ candidates, for each candidate make a measurement of $X=f(m_t)$, where $X$ is a suitable estimator for $m_t$.
- In this case, a top “probability” discriminant built on kinematic quantities sensitive to signal/background discrimination.

From signal MC determine the shape of $X$ as a function of $m_t$.
Determine the shape of $X$ for background from MC and data.
Add these together and compare with data. Perform a likelihood fit for $m_t$.
Run I: Top Mass, lepton+jets

$m_t = 173.3 \pm 5.6 \pm 5.5\text{GeV}$

largest systematics
- jet energy: 4.0 GeV
- MC generator: 3.1 GeV
- noise/pile-up: 1.3 GeV

Background-rich

Signal-rich

Likelihood fit
Run I: Top Mass, combined

168.4 ± 12.8 GeV
D0 ll PRL 80, 2063 (1998)

173.3 ± 7.8 GeV
D0 lj PRD 58, 52001 (1998)

172.1 ± 7.1 GeV
D0 Combined

167.4 ± 11.4 GeV
CDF ll PRL 82, 271 (1999)

176.1 ± 7.4 GeV
CDF lj PRL 80 2767 (1998)

186.0 ± 11.5 GeV

176.1 ± 6.6 GeV
CDF Combined

174.3 ± 5.1 GeV
Tevatron FERMILAB-TM-2084
Run I: Top Mass, New Matrix Element Method

The probabilities for each event being signal and for being background are calculated using the full kinematic information of the event, and the results are combined into one likelihood function.

The probability is calculated using the matrix element for production and decay.

\[ P_{ii} = \int \int dm_1^2 dM_1^2 dm_2^2 dM_2^2 \left| M \right|^2 \frac{f(q_1)f(q_2)}{|q_1||q_2|} W(x, y) \]

\[ m_t = 179.9 \pm 3.6 \text{ (stat)} \pm 5.9 \text{ (syst)} \text{ GeV} \]

previous DØ, \[ m_t = 173.3 \pm 5.6 \text{ (stat)} \pm 5.5 \text{ (syst)} \text{ GeV} \]

The improved statistical error is equivalent to a factor of 2.4 increase in the number of events.

Well measured events contribute more than poorly measured ones.
Run I: Cross section

- Test of SM predictions
- Deviations would indicate
  - Non-Wb decay modes

Measurements and theory errors

<table>
<thead>
<tr>
<th>Channel</th>
<th>CDF (pb)</th>
<th>D0 (pb)</th>
<th>Berger et al.</th>
<th>Laenen et al.</th>
<th>Catani et al.</th>
<th>All Channels Combined (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ee</td>
<td>2.4 ± 4.6 pb</td>
<td>5.7 ± 1.6 pb</td>
<td>6.0 ± 3.2 pb</td>
<td>4.7 - 5.5 pb</td>
<td>5.7 ± 1.6 pb</td>
<td>5.7 ± 1.6 pb</td>
</tr>
<tr>
<td>eµ</td>
<td>6.8 ± 4.6 pb</td>
<td>5.3 ± 1.7 pb</td>
<td>5.6 ± 3.7 pb</td>
<td></td>
<td>5.3 ± 1.7 pb</td>
<td>5.3 ± 1.7 pb</td>
</tr>
<tr>
<td>µµ</td>
<td>2.1 ± 8.8 pb</td>
<td>6.0 ± 3.6 pb</td>
<td>6.0 ± 3.6 pb</td>
<td></td>
<td>6.0 ± 3.6 pb</td>
<td>6.0 ± 3.6 pb</td>
</tr>
<tr>
<td>ev</td>
<td>9.1 ± 7.2 pb</td>
<td>11.3 ± 6.6 pb</td>
<td></td>
<td></td>
<td>9.1 ± 7.2 pb</td>
<td>9.1 ± 7.2 pb</td>
</tr>
<tr>
<td>Dilepton Combined</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>e+jets/topo</td>
<td>2.8 ± 2.1 pb</td>
<td>5.1 ± 1.9 pb</td>
<td>5.1 ± 1.9 pb</td>
<td></td>
<td>5.1 ± 1.9 pb</td>
<td>5.1 ± 1.9 pb</td>
</tr>
<tr>
<td>µ+jets/topo</td>
<td>5.6 ± 3.7 pb</td>
<td></td>
<td></td>
<td></td>
<td>5.6 ± 3.7 pb</td>
<td>5.6 ± 3.7 pb</td>
</tr>
<tr>
<td>e+jets/µ</td>
<td>6.0 ± 3.6 pb</td>
<td></td>
<td></td>
<td></td>
<td>6.0 ± 3.6 pb</td>
<td>6.0 ± 3.6 pb</td>
</tr>
<tr>
<td>µ+jets/µ</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>11.3 ± 6.6 pb</td>
<td>11.3 ± 6.6 pb</td>
</tr>
</tbody>
</table>

- 9 events
- 30 events
- 41 events
Run II: W\(\not{\ell}\) e\(\not{\ell}\) Candidates

- W+jets and Z+jets are the primary backgrounds to top
- Assess detector performance
- QCD background derived from data

- Inclusive jet multiplicity in background subtracted W\(\not{\ell}\) e\(\not{\ell}\) sample
- Follows linear log law: Berends scaling
- With higher stats and b-tagging, enhancement at W+4jets will indicate \(t\bar{t}\) e\(\not{\ell}\)b+jj candidate sample
- Further separation using b-tagging and event topology

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\[ L = 41.8 \text{ pb}^{-1} \]

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2/18/03
Run II: $Z \rightarrow l^+l^-$ Candidates

- $Z$'s are major background to the dilepton channels
- $Z \rightarrow e^+e^-, Z \rightarrow \mu^+\mu^-$ are very important calibration samples

$Z \rightarrow e^+e^-$ candidate event
$m_{ee} = 93.2$ GeV

$Z \rightarrow \mu^+\mu^-$ candidate event
$m_{\mu\mu} \sim 103$ GeV
Run II: $\square+\text{jets Candidate}$

- $\square pt$ 48 GeV
- MEt 55 GeV
- $W pt$ 51 GeV
- $\text{JetEt}$ 154 GeV
- Apla 0.160
- $Ht$ 517 GeV

$t\bar{t}jjjjjj$ candidate

2 jets are tagged as $b$-jets
passes topological selection
Run II: \( \square + \) jets Candidate

2 jets tagged with displaced secondary vertices

Track in the calorimeter and muon tracker
Run II: $e^\pm$ Candidate

<table>
<thead>
<tr>
<th>$e$</th>
<th>$p_T = 20.3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \phi )</td>
<td>5.22</td>
</tr>
<tr>
<td>( \eta )</td>
<td>1.09</td>
</tr>
<tr>
<td>Charge</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\mu$</th>
<th>$p_T = 58.1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \phi )</td>
<td>1.74</td>
</tr>
<tr>
<td>( \eta )</td>
<td>-0.44</td>
</tr>
<tr>
<td>Charge</td>
<td>-1</td>
</tr>
<tr>
<td>Halo</td>
<td>0.6</td>
</tr>
<tr>
<td>TrHalo</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$j$</th>
<th>$p_T = 141.0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \phi )</td>
<td>4.57</td>
</tr>
<tr>
<td>( \eta )</td>
<td>-0.335</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$j$</th>
<th>$p_T = 55.2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \phi )</td>
<td>2.39</td>
</tr>
<tr>
<td>( \eta )</td>
<td>-0.97</td>
</tr>
</tbody>
</table>
There are many improvements

- b-tagging will improve combinatorics and triggering
- Better jet energy scale calibration with higher W and Z statistics
- MC modeling of gluon radiation will be improved with data comparisons
- Reduction in other systematic and background errors will scale with higher statistics

### Run II Prospects: Mass & Cross Section

<table>
<thead>
<tr>
<th>Top Mass</th>
<th>Run I</th>
<th>Run IIa (2 fb⁻¹)</th>
<th>Run IIb (15 fb⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>statistics</td>
<td>5.6 GeV</td>
<td>1.3 GeV</td>
<td></td>
</tr>
<tr>
<td>jet $p_T$ scale</td>
<td>4.0 GeV</td>
<td>2.2 GeV</td>
<td></td>
</tr>
<tr>
<td>MC generator</td>
<td>3.1 GeV</td>
<td>0.7 GeV</td>
<td></td>
</tr>
<tr>
<td>MC model</td>
<td>1.6 GeV</td>
<td>0.4 GeV</td>
<td></td>
</tr>
<tr>
<td>fit procedure</td>
<td>1.3 GeV</td>
<td>0.3 GeV</td>
<td></td>
</tr>
<tr>
<td>Total syst</td>
<td>5.5 GeV</td>
<td>2.3 GeV</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>7.8 GeV</td>
<td>2.7 GeV</td>
<td>1.4 GeV</td>
</tr>
</tbody>
</table>

With $\Delta m_W \sim 16$ MeV, constrain Higgs mass to 25%
Summary

The DØ and CDF top physics programs in Run I were unqualified successes.
- The top quark was discovered in 1995.
- Top mass and cross sections were measured in several channels.
- Investigations into a whole range of top properties were begun.
- All measurements have been consistent with the Standard Model, but they are statistics limited
  - Everything we know is based on ~100 events/experiment!

Run II promises to push top physics much further.
- So far, we’ve collected about half the data of all of Run I. The first Run II cross sections and masses will be appearing soon.
- Quite an array of exciting opportunities are opening up
  - Precision top mass measurements
  - Much more stringent tests of the Standard Model (let’s hope it fails some!)
  - Tight constraints on the Higgs mass
  - Will it shed light on mass generation or EWSB?
  - Excellent place to look for new physics!
Run II: Tracking Performance

$K^0$ Invariant Mass

$D\bar{O}$ Run 2 Preliminary

Mean $= 0.497 \pm 0.002$ GeV
Sigma $= 0.021 \pm 0.002$ GeV

Silicon only Tracking
Run II: Tracking Performance

- Impact parameter resolutions
  - Initial SMT and no CFT alignment
  - ~30 μm beam spot
  - Approaching design specs