Top Physics via Dilepton Final States

Robert Kehoe

10/18/04
Southern Methodist U.
Dept. of Physics Seminar
Top in the Electroweak Model...

- top firmly predicted to complete 3rd quark doublet
  - no anomalies
  - absence of flavor changing neutral current interactions
  - weak isospin measurement of b-quark

\[ T_{3b} = -1/2 \]

- coupling to Higgs near unity
  - why?
  - fermion masses
    - related to couplings to Higgs boson
    - couplings not predicted
    - haven’t explained fermion masses

- high top mass
  - strongly correlated with Higgs mass

3/31/05
Robert Kehoe (SMU.): Top Quark Dilepton Physics
Particle ID

- electrons
- photons
- muons
- taus
- jet from gluons and light quarks
- $b$-quark jets
- missing Et from neutrinos
A Generic High Energy Detector

- **Tracking:**
  - charged particle directions and momenta
- **Calorimeter:**
  - main energy depositions in event
- **Muon Detection:**
  - identify penetrating muons
Jets and Top

- Jets are a prominent element of many $p\bar{p}$ interactions.

- However, top is special among quarks.
  - Jets used as fundamental objects to reconstruct events:
    - Analogous to tracks for lighter quarks.

- Once $m_{\text{top}} > 130$ GeV:
  - B-jets very energetic.
  - Signature to permit discrimination from background:
    - Thru jet multiplicity, kinematics, and flavor identification.

- So, jets have become a crucial element of top analysis:
  - Jet systematics have strong impact on ability to do top physics:
    - Jet energy scale.
  - Even more critical when trying to measure top’s properties:
    - Eg. Initial and final state radiation complications for kinematic fitting.
- **strength of strong interaction**
  - increases with increasing distance

- **when two colored particles interact**
  - nature does not permit ‘naked’ color
  - energy in strong interaction
    - grows as particles move apart
  - when energy greater than masses of fundamental particles
    - a ‘jet’ of particles ‘pulled’ out of the virtual sea or vacuum
    - extremely messy and poorly understood process

‘hadronization’ or ‘fragmentation’
Fragmentation

➢ **Field-Feynman**
  - independent fragmentation
  - particle multiplicity near jets independent of rest of event

➢ **Lund String Model**
  - color connections in event dictate where particles go
  - better reflects experimental observations
Jet Algorithms

- ‘fixed-cone’
  - begin with significant energy cells or towers
    - draw cone and calculate Et and position in eta, phi
    - iterate until stable
    - merge-split criteria
  - standard algorithm at hadron colliders
    - likely to be important at ATLAS (F. Merritt, S. Rajagopalan)

- Kt or Durham algorithms
  - cluster without fixed size
  - group particles which have small Pt w/respect to each other (‘kt’)
  - does not seem to work well at hadron colliders due to physics ‘noise’

- energy flow
  - holy grail to some to get optimal energy resolution for dijet resonances
  - identify individual clusters and group them
    - replace calorimeter clusters with track momentum when possible
    - correct remaining clusters by known non-linearites PER-PARTICLE
  - difficult at hadron colliders, worse with many multiple interactions
    - confusion of overlapping clusters, unreconstructed energy, tracking ambiguities
Identifying Neutrinos: Missing Transverse Energy

- Neutrinos do not interact with the detector
  - we infer presence from imbalance in transverse momentum

- total energy: unknown
- total longitudinal momentum: unknown
- total transverse momentum: zero

- neutrinos: missing $E_T$
  - from calorimeter, plus muons and jet energy scale corrections
Jet Energy Scale

\[ E_{\text{corr}} = \frac{(E_{\text{uncorr}} - O)}{R \times S} \]

- **O**: underlying event, noise
  - minimum bias events
- **R**: non-linearities, dead material
  - direct photon candidate events
  - statistics up to 200 GeV energy
- **S**: particle showers
  - jet transverse shapes in data

- uncertainties
  - large statistical errors
  - substantial systematic errors
    - increase with energy due to extrapolation
The Top Quark: Production

- in proton-antiproton collisions
  - top-antitop pair strong production
    - mainly quark-antiquark annihilation
    - Run I measurement (DØ @ 1.8 TeV):
      \[ \sqrt{s}(t\bar{t}) = 5.7 \pm 1.7 \text{ pb} \]
    - Run II cross section (@ 1.96 TeV)
      - expected to be \(~35\%\) higher
      - i.e. \(~7\) pb

- dominant @ LHC

\(\sim 85\%\) @ TeV
\(\sim 15\%\)
The Top Quark: Decays and Final States

- BR(t → Wb) ~ 100%
- W and b-quark decays
  - specify final states
  - W decays to
    - quark-antiquark
    - OR lepton-neutrino
  - b-quark gives a jet
    - b may decay semileptonically
    - b decay displaces jet vertex
    - isolated high \( P_T \) leptons (from W’s)
    - soft leptons in jets (from b’s)
    - detached vertices in jets (from b’s)

<table>
<thead>
<tr>
<th></th>
<th>( l\bar{l} )</th>
<th>( l\bar{q} )</th>
<th>( q\bar{q}qq )</th>
</tr>
</thead>
<tbody>
<tr>
<td>topo</td>
<td>x</td>
<td>x</td>
<td>---</td>
</tr>
<tr>
<td>SLT</td>
<td>---</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>b-tag</td>
<td>---</td>
<td>x</td>
<td>---</td>
</tr>
</tbody>
</table>
Dilepton Channels

- event selection
  - 2 high $P_T$ isolated charged leptons ($e$, $\mu$)
  - large missing $E_T$ (from 2 neutrinos)
  - > 2 jets (from b-quarks)
  - a `topological' analysis:
    - i.e. large total transverse energy ($H_T$)

- few physics processes leave energetic lepton pairs
  - $WW$, $Z\ell\ell$ estimated from Monte Carlo
  - $Z/\ell^*$ is most common, but doesn’t produce neutrinos
    - fake missing $E_T$: determine from data

- leptons can, rarely, be faked by detector imperfections
  - due to noise, or similarities of photon and electron showers
  - fake leptons in $W$+jets
  - fake missing $E_T$ and leptons from QCD
  - determined from data
Dielectron Channel

- both Ws decay to electron-neutrino
- primary backgrounds
  - $Z\rightarrow ee + \text{fake missing Et}$
  - $WW \rightarrow ee + 2\nu$
  - $Z\rightarrow \tau\tau\rightarrow ee + 4\nu$
  - $W\rightarrow\ell\nu + 1\text{ fake electron}$
  - QCD $4\text{jets} \rightarrow 2\text{ fake 'e's} + \text{fake missing Et}$

Data:
$2\text{jt}>20\text{ GeV}$
Instrumental Backgrounds - $ee$

- **fake electrons**
  - $b\rightarrow c + e\nu$ negligible
  - different than in muon case
  - $\pi^0$ jet passing all ID cuts
    - $\pi^0$ gives 2 photons
      - can convert or overlap other
  - fake rates $\sim 10^{-5}$

- **fake missing Et**
  - calorimeter noise
  - multiple interactions
  - jet resolution
### ee Results

<table>
<thead>
<tr>
<th>Category</th>
<th>Yield</th>
<th>Stat Err</th>
<th>Sys Err</th>
</tr>
</thead>
<tbody>
<tr>
<td>WW</td>
<td>0.16</td>
<td>0.06</td>
<td>+0.08</td>
</tr>
<tr>
<td>Z → ττ</td>
<td>0.23</td>
<td>0.06</td>
<td>-0.07</td>
</tr>
<tr>
<td>E_T Fakes</td>
<td>0.59</td>
<td>0.09</td>
<td>-</td>
</tr>
<tr>
<td>EM Fakes</td>
<td>0.07</td>
<td>0.03</td>
<td>0.00</td>
</tr>
<tr>
<td><strong>Total Bkg</strong></td>
<td><strong>1.05</strong></td>
<td><strong>0.13</strong></td>
<td><strong>+0.12</strong></td>
</tr>
<tr>
<td>Expected signal</td>
<td>2.13</td>
<td>0.08</td>
<td>+0.17</td>
</tr>
<tr>
<td>Selected Events</td>
<td>5.00</td>
<td>2.24</td>
<td>-</td>
</tr>
</tbody>
</table>
Electron-Muon Channel

- one $W$ decays to electron, one to muon
- backgrounds
  - $Z \rightarrow \tau \tau \rightarrow \text{emu} + 4 \text{nus}$
  - $WW \rightarrow \text{emu} + 2 \text{nus}$
  - $WZ \rightarrow \text{emu} + 1 \text{nu}$
  - $W+Z\rightarrow 1$ or 2 mu + fake $'e'$
  - $W+jets \rightarrow \text{mu} + 1 \text{nu} +$ fake $'e'$
  - $W+jets \rightarrow e + 1 \text{nu} +$ fake isolated $'\mu'$
**e⁻e⁺ - Results**

<table>
<thead>
<tr>
<th>Category</th>
<th>Yield</th>
<th>Stat Err</th>
<th>Sys Err</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z/γ* → ττ</td>
<td>0.39</td>
<td>0.06</td>
<td>+0.07</td>
</tr>
<tr>
<td>WW</td>
<td>0.37</td>
<td>0.00</td>
<td>+0.17</td>
</tr>
<tr>
<td>Wγ</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Fakes</td>
<td>0.18</td>
<td>0.02</td>
<td>0.06</td>
</tr>
<tr>
<td>Total bckg</td>
<td>0.96</td>
<td>0.06</td>
<td>+0.16</td>
</tr>
<tr>
<td>Expected Signal</td>
<td>5.47</td>
<td>0.28</td>
<td>0.55</td>
</tr>
<tr>
<td>Selected Events</td>
<td>8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Lifetime b-tagging in $e^\pm$

- secondary vertex tag (SVT)
  - look for displaced vertices (> 2 tracks): 10x reduction in background
  - jet tagged as b-jet if
    - signed decay length significance > 5
Tag Rates

- **b-tag efficiency**
  - tracking efficiency in jets
  - position resolution of tracker
    - dictates how well discriminate late decaying hadrons

- **mis-tag rate**
  - tracks in jets mismeasured
  - look like don’t come from event primary vertex
<table>
<thead>
<tr>
<th>Sample</th>
<th>$N_{\text{jets}} = 0$</th>
<th>$N_{\text{jets}} = 1$</th>
<th>$N_{\text{jets}} \geq 2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}$</td>
<td>0.052 ± 0.009</td>
<td>1.14 ± 0.04</td>
<td>4.58 ± 0.09</td>
</tr>
<tr>
<td>$WW$</td>
<td>7.40 ± 0.08</td>
<td>0.84 ± 0.03</td>
<td>0.46 ± 0.03</td>
</tr>
<tr>
<td>$Z \rightarrow \tau\tau$</td>
<td>1.6 ± 0.1</td>
<td>2.7 ± 0.2</td>
<td>0.6 ± 0.1</td>
</tr>
<tr>
<td>$Z \rightarrow \mu\mu$</td>
<td>1.2 ± 0.4</td>
<td>0.6 ± 0.3</td>
<td>0.10 ± 0.04</td>
</tr>
<tr>
<td>QCD and $W +$jets</td>
<td>2.9 ± 0.1</td>
<td>1.05 ± 0.07</td>
<td>0.33 ± 0.04</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>13.2 ± 0.4</td>
<td>6.3 ± 0.3</td>
<td>6.1 ± 0.2</td>
</tr>
</tbody>
</table>

**Expected number of preselected events**

**Observed number of preselected events**

- Data: 13
- $ttbar$: 7
- Backgrounds: 8

---

**DØ Run II Preliminary**

Number of events vs Jet multiplicity.
Dielectron: $\sigma = 12.7^{+8.0}_{-6.5}\text{ (stat)} \pm 0.8\text{ (sys)} \pm 0.8\text{ (lumi)}\text{ pb}$

<table>
<thead>
<tr>
<th>Cut</th>
<th>Data</th>
<th>Total</th>
<th>Fakes</th>
<th>$Z\rightarrow ee$</th>
<th>$Z\rightarrow \tau\tau$</th>
<th>WW, WZ $\rightarrow e\mu$</th>
<th>$\gamma$-processes</th>
<th>$t\bar{t}$</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 EM</td>
<td>14408</td>
<td>14321.97+132.37</td>
<td>97.40+3.50</td>
<td>14160.69+132.30</td>
<td>49.38+2.50</td>
<td>8.52+0.23</td>
<td>5.18+0.11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1jt</td>
<td>1896</td>
<td>1815.56+19.89</td>
<td>13.37+0.74</td>
<td>1789.59+19.87</td>
<td>6.88+0.45</td>
<td>0.68+0.05</td>
<td>5.04+0.11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2jt</td>
<td>276</td>
<td>275.81+16.68</td>
<td>2.11+0.25</td>
<td>268.54+16.68</td>
<td>1.12+0.14</td>
<td>0.35+0.12</td>
<td>3.69+0.11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Mz$</td>
<td>67</td>
<td>65.51+3.03</td>
<td>0.91+0.13</td>
<td>60.16+3.02</td>
<td>1.03+0.13</td>
<td>0.29+0.10</td>
<td>3.12+0.08</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MET</td>
<td>7</td>
<td>3.76+0.17</td>
<td>0.10+0.04</td>
<td>0.80+0.11</td>
<td>0.32+0.07</td>
<td>0.20+0.07</td>
<td>2.34+0.08</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spericity</td>
<td>5</td>
<td>3.18+0.15</td>
<td>0.07+0.03</td>
<td>0.59+0.09</td>
<td>0.23+0.06</td>
<td>0.16+0.06</td>
<td>2.13+0.08</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Electron-Muon: $\sigma = 9.2^{+4.8}_{-3.5}\text{ (stat)} \pm 0.6\text{ (sys)} \pm 0.6\text{ (lumi)}\text{ pb}$

<table>
<thead>
<tr>
<th>Cut</th>
<th>Data</th>
<th>Total</th>
<th>Fakes</th>
<th>$Z/\gamma \rightarrow \tau\tau$</th>
<th>WW, WZ $\rightarrow e\mu$</th>
<th>$\gamma$-processes</th>
<th>$t\bar{t}$</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>EM and Muon</td>
<td>214</td>
<td>15.45 ± 1.74</td>
<td>–</td>
<td>96.76 ± 5.64</td>
<td>18.41 ± 0.48</td>
<td>77.64 ± 7.01</td>
<td>9.57 ± 0.47</td>
<td>217.85 ± 9.23</td>
</tr>
<tr>
<td>$\Delta R(e, \mu) &gt; 0.25$</td>
<td>164</td>
<td>13.14 ± 1.48</td>
<td>6.59 ± 3.71</td>
<td>96.75 ± 5.64</td>
<td>18.38 ± 0.48</td>
<td>77.64 ± 7.01</td>
<td>9.57 ± 0.47</td>
<td>167.33 ± 6.25</td>
</tr>
<tr>
<td>$\geq 1$ jet</td>
<td>32</td>
<td>3.07 ± 0.35</td>
<td>0.82 ± 0.46</td>
<td>13.22 ± 0.88</td>
<td>1.69 ± 0.07</td>
<td>3.54 ± 0.40</td>
<td>9.41 ± 0.47</td>
<td>30.92 ± 1.13</td>
</tr>
<tr>
<td>$\geq 2$ jets</td>
<td>11</td>
<td>0.51 ± 0.06</td>
<td>0.09 ± 0.05</td>
<td>1.86 ± 0.14</td>
<td>0.74 ± 0.01</td>
<td>0.29 ± 0.12</td>
<td>7.13 ± 0.36</td>
<td>9.87 ± 0.41</td>
</tr>
<tr>
<td>$p_T &gt; 25$ GeV</td>
<td>10</td>
<td>0.35 ± 0.04</td>
<td>0.07 ± 0.04</td>
<td>1.08 ± 0.10</td>
<td>0.64 ± 0.00</td>
<td>0.11 ± 0.03</td>
<td>6.43 ± 0.33</td>
<td>8.61 ± 0.35</td>
</tr>
<tr>
<td>$H_T^{leading \text{ lepton}} &gt; 140$ GeV</td>
<td>10</td>
<td>0.19 ± 0.02</td>
<td>0.02 ± 0.01</td>
<td>0.48 ± 0.07</td>
<td>0.41 ± 0.00</td>
<td>0.02 ± 0.01</td>
<td>5.8 ± 0.3</td>
<td>6.91 ± 0.31</td>
</tr>
<tr>
<td>$\Delta \phi(\mu, p_T) &gt; 0.25$</td>
<td>8</td>
<td>0.18 ± 0.02</td>
<td>–</td>
<td>0.39 ± 0.06</td>
<td>0.37 ± 0.00</td>
<td>0.02 ± 0.01</td>
<td>5.47 ± 0.28</td>
<td>6.43 ± 0.29</td>
</tr>
</tbody>
</table>

$e\mu + b$-tag: $\sigma = 11.1^{+5.8}_{-4.3}\text{ (stat)} \pm 1.4\text{ (sys)} \pm 0.6\text{ (lumi)}\text{ pb}$

3/31/05

Robert Kehoe (SMU.): Top Quark Dilepton Physics

22
The Top Quark Mass

- factor 2 improvement in measurement comes at LHC
  - $\mathcal{O}$(Tev.) = 1.5 GeV
  - $\mathcal{O}$(LHC) <~1 GeV

- window on EWSB
  - enters calculation of SM parameters as radiative correction
  - $m_H \sim 115$ GeV/c$^2$?

Run I measurements

![Graph showing the relationship between Higgs mass and top quark mass.]

3/31/05 Robert Kehoe (SMU.): Top Quark Dilepton Physics 23
Measurement of $m_t$ in Dilepton Events

- **dilepton channels**
  - provide ~ 1/5 the # of candidate events as lepton+jets channels
    - higher efficiency, but much lower Branching fraction
    - analysis statistically dominated, unlike single lepton channels
  - **jets**
    - always b-quarks
    - higher Pt than b’s from W’s
  - fewer jets, lower background: substantially lower systematic uncertainties than $l+jets$

<table>
<thead>
<tr>
<th>Error (GeV)</th>
<th>Run I</th>
<th>Run IIa (2 fb$^{-1}$)</th>
<th>LHC (10 fb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>statistical</td>
<td>12.3</td>
<td>2.8</td>
<td>&lt; 0.5 GeV</td>
</tr>
<tr>
<td>systematic</td>
<td>3.6</td>
<td>2.0</td>
<td>~ 1 GeV</td>
</tr>
<tr>
<td>Total</td>
<td><strong>12.8</strong></td>
<td><strong>3.5</strong></td>
<td>~ 1 GeV</td>
</tr>
</tbody>
</table>

3/31/05  Robert Kehoe (SMU.): Top Quark Dilepton Physics 24
Dilepton Event Characterization

- final state defined by 4-vectors of 6 decay products
  - 18 independent quantities
  - measure 14 directly: lepton and jet momenta, missing $E_x$ and $E_y$
  - 3 constraints:
    - $l$-nu pairs give $M_W$
    - $m_t = m_{t\bar{t}}$
  - still have -1C fit!

- sample expected neutrino eta-distribution
Event Weight

- use constraints to solve for nu momentum

\[
M_w^2 = (E^y + E^l)^2 - (p_x^y + p_x^l)^2 - (p_y^y + p_y^l)^2 - (p_z^y + p_z^l)^2
\]

\[
m_t^2 = (E^y + E^l + E^b)^2 - (p_x^y + p_x^l + p_x^b)^2 - (p_y^y + p_y^l + p_y^b)^2 - (p_z^y + p_z^l + p_z^b)^2
\]

- obtain 4 solutions, only 1 correct
- can calculate solved missing Et

- calculate weight from missing Et agreement

\[
w = \frac{1}{N_{\text{iter}}} \sum \exp\left(\frac{-(E_x^{\text{calc}} - E_x^{\text{obs}})^2}{2\sigma_{E_x}}\right) \exp\left(\frac{-(E_y^{\text{calc}} - E_y^{\text{obs}})^2}{2\sigma_{E_y}}\right)
\]

- integrate weights for many configurations for each top mass

Entries: 50200
Mean: 187.7
RMS: 37.57

Blue = No Corrections
Red = PLC applied
Green = PLC and EM res
Black = PLC, EM and Jet res

template for \( m_{\text{top}} = 175 \) GeV
w/ and w/o parton corrections

All evts have only 2 jets, both b's.
Mass Sensitivity

- for different input top masses
  - does method give correct result?
  - depends on how reconstruct event
    - 3 jet events confuse things
      - which are b’s
      - can sum up pairs of nearby jets
Dilepton Mass: Steps to Complete Analysis

very preliminary!

- create templates from weight distributions
  - weight distribution characteristics
    - peak, width, whole shape, secondary peaks...
    - what gives best sensitivity to $m_{\text{top}}$?
  - current example: 40 GeV bins
  - obtain for many different top masses
  - also for background

- extracting a mass from a data sample
  - maximum likelihood fit to S and B distributions
  - ensemble tests of 10 event samples
    - average of many experiments: 173 GeV (175 input)
    - large statistical errors

10 events from 175 GeV sample
Minimum at 167 GeV
Prospects at LHC

- cross section ~100x at Tevatron
  - 10 fb\(^{-1}\) gives 100s to 1000s more tops
    - i.e. O(10k) dilepton events identified
    - and O(100k) single lepton events

- top cross section and branching ratio
  - constrain non-SM decays
    - eg. t->H+b would produce anomalous ratio of ee to mumu (to tautau) events
    - t-> Zq...

- top spin correlations
  - can be indication of CP-violation in top sector
  - leptons from top provide best indication of top spin direction
  - dileptons excellent place to look

- mass measurement
  - might use \(M_{lb}\)
    - also has information about W helicity
  - two leading jets methods
  - event reconstruction as earlier

\[
\cos \theta^* = \frac{2 \cdot M_{lb}^2}{M_t^2 - M_W^2} \quad \Box 1
\]