The discovery of Top quark
Graduate Seminar PHY 599
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Outline of the seminar

- Brief history and theoretical background
- Experimental details
- Relation to Higgs and other recent developments
What is a top quark?

- The heaviest elementary particle
- A third generation quark
- Has an extremely short lifetime ($0.4 \times 10^{-24}$ seconds)
- Generally gets produced in top-antitop pairs via strong interaction but can also be generated as a single particle via weak interaction.
- Decays via weak interaction
In 1973, Kobayashi and Maskawa predicted the existence of a third generation of quarks (top and bottom) to explain CP violation in kaon decay.

In 1977, bottom quark was found at Fermilab.
Attempts to find the top

- No conclusive evidence was found till 1995 with SLAC (Stanford Linear Accelerator Center), DESY (German Electron Synchrotron at Hamburg), CERN, CDF (Collider detector at Fermilab), D0 collaboration in the hunt.

**Improvements along the way**

Progression of the observed lower limit on the mass of the top:
- CERN: 41 GeV/c^2
- CERN: 77 GeV/c^2
- D0: 131 GeV/c^2
In March 1995, the D0 collaboration reported the observation of top quark.

In April 1995, the CDF collaboration also reported the observation of the top.
General experimental methodology

- Identifying the dominant production and decay modes
- Background estimation and optimizing selection criteria
- Fixing the signature
- Data collection
- Deriving conclusion by correlating with the expected results
Top quark production

- Dominant modes of production:

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

  \[ g \rightarrow t, \bar{g} \rightarrow \bar{t} \]
Decay modes

- Dominant decay modes:

  $g \rightarrow t \rightarrow b e^+ \mu^+ \tau^+ q$
  $\bar{t} \rightarrow W^- \rightarrow \bar{b} \nu_e, \nu_{\mu}, \nu_\tau, q'$
  $W^+ \rightarrow t \nu_e, \nu_{\mu}, \nu_\tau, q'$
  $b \rightarrow W^- \rightarrow \bar{t} e^-, \mu^-, \tau^-, \bar{q}$
  $\bar{b} \rightarrow W^+ \rightarrow t \bar{\nu}_e, \bar{\nu}_{\mu}, \bar{\nu}_\tau, q'$
The channels

Dilepton modes:
- The $ee$ mode: $t\bar{t} \rightarrow W(e\nu)W(e\nu)b\bar{b}$
- The $\mu\mu$ mode: $t\bar{t} \rightarrow W(\mu\nu)W(\mu\nu)b\bar{b}$
- The $e\mu$ mode: $t\bar{t} \rightarrow W(e\nu)W(\mu\nu)b\bar{b}$

Untagged single lepton modes:
- The $e + \text{jets}$ mode: $t\bar{t} \rightarrow W(e\nu)W(q\bar{q})b\bar{b}$
- The $\mu + \text{jets}$ mode: $t\bar{t} \rightarrow W(\mu\nu)W(q\bar{q})b\bar{b}$

Tagged single lepton modes:
- The $e + \text{jets}/\mu$ mode: $t\bar{t} \rightarrow W(e\nu)W(q\bar{q})b(\mu)\bar{b}$
- The $\mu + \text{jets}/\mu$ mode: $t\bar{t} \rightarrow W(\mu\nu)W(q\bar{q})b(\mu)\bar{b}$
The parameters which were observed and used in the selection criteria were:

- Transverse energy $E_T$
- Transverse momentum $p_T$
- $H_T$: Scalar sum of transverse energies $E_T$ of the jets (for the single lepton and $\mu\mu +$ jets channels) or the scalar sum of the $E_T$’s of the leading electron and the jets (for the $e\mu +$ jets and $ee +$ jets channels).
- Missing transverse energy
- Aplanarity
Significance of $H_T$

FIG. 1. Shape of $H_T$ distributions expected for the principal backgrounds (dashed line) and 200 GeV/$c^2$ top quarks (solid line) for (a) $e\mu +$ jets and (b) untagged single-lepton + jets.
TABLE I. Minimum kinematic requirements for the standard event selection (energy in GeV).

<table>
<thead>
<tr>
<th>Channel</th>
<th>Leptons</th>
<th>Jets</th>
<th>A</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$E_T(e)$</td>
<td>$p_T(\mu)$</td>
<td>$N_{jet}$</td>
</tr>
<tr>
<td>$e\mu + jets$</td>
<td>15</td>
<td>12</td>
<td>2</td>
</tr>
<tr>
<td>$ee + jets$</td>
<td>20</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>$\mu\mu + jets$</td>
<td>15</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>$e + jets$</td>
<td>20</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>$\mu + jets$</td>
<td>15</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>$e + jets/\mu$</td>
<td>20</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>$\mu + jets/\mu$</td>
<td>15</td>
<td></td>
<td>3</td>
</tr>
</tbody>
</table>
The actual data collected by the D0 collaboration in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV along with the expected numbers:

<table>
<thead>
<tr>
<th>$m$, (GeV/$c^2$)</th>
<th>$e\mu$ + jets</th>
<th>$ee$ + jets</th>
<th>$\mu\mu$ + jets</th>
<th>$e$ + jets</th>
<th>$\mu$ + jets</th>
<th>$e$ + jets/$\mu$</th>
<th>$\mu$ + jets/$\mu$</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>140 $\varepsilon \times B$ (%)</td>
<td>$0.17 \pm 0.02$</td>
<td>$0.11 \pm 0.02$</td>
<td>$0.06 \pm 0.01$</td>
<td>$0.50 \pm 0.10$</td>
<td>$0.33 \pm 0.08$</td>
<td>$0.36 \pm 0.07$</td>
<td>$0.20 \pm 0.05$</td>
<td></td>
</tr>
<tr>
<td>$\langle N \rangle$</td>
<td>$1.36 \pm 0.21$</td>
<td>$1.04 \pm 0.19$</td>
<td>$0.46 \pm 0.08$</td>
<td>$4.05 \pm 0.94$</td>
<td>$2.47 \pm 0.68$</td>
<td>$2.93 \pm 0.68$</td>
<td>$1.48 \pm 0.42$</td>
<td>$13.80 \pm 2.07$</td>
</tr>
<tr>
<td>160 $\varepsilon \times B$ (%)</td>
<td>$0.24 \pm 0.02$</td>
<td>$0.15 \pm 0.02$</td>
<td>$0.09 \pm 0.02$</td>
<td>$0.80 \pm 0.10$</td>
<td>$0.57 \pm 0.13$</td>
<td>$0.50 \pm 0.08$</td>
<td>$0.25 \pm 0.06$</td>
<td></td>
</tr>
<tr>
<td>$\langle N \rangle$</td>
<td>$0.94 \pm 0.13$</td>
<td>$0.69 \pm 0.12$</td>
<td>$0.34 \pm 0.07$</td>
<td>$3.13 \pm 0.54$</td>
<td>$2.04 \pm 0.53$</td>
<td>$1.95 \pm 0.39$</td>
<td>$0.92 \pm 0.24$</td>
<td>$10.01 \pm 1.41$</td>
</tr>
<tr>
<td>180 $\varepsilon \times B$ (%)</td>
<td>$0.28 \pm 0.02$</td>
<td>$0.17 \pm 0.02$</td>
<td>$0.10 \pm 0.02$</td>
<td>$1.20 \pm 0.30$</td>
<td>$0.76 \pm 0.17$</td>
<td>$0.56 \pm 0.09$</td>
<td>$0.35 \pm 0.08$</td>
<td></td>
</tr>
<tr>
<td>$\langle N \rangle$</td>
<td>$0.57 \pm 0.07$</td>
<td>$0.40 \pm 0.07$</td>
<td>$0.19 \pm 0.04$</td>
<td>$2.42 \pm 0.67$</td>
<td>$1.41 \pm 0.36$</td>
<td>$1.14 \pm 0.22$</td>
<td>$0.64 \pm 0.16$</td>
<td>$6.77 \pm 1.09$</td>
</tr>
<tr>
<td>200 $\varepsilon \times B$ (%)</td>
<td>$0.31 \pm 0.02$</td>
<td>$0.20 \pm 0.03$</td>
<td>$0.11 \pm 0.02$</td>
<td>$1.70 \pm 0.20$</td>
<td>$0.96 \pm 0.21$</td>
<td>$0.74 \pm 0.11$</td>
<td>$0.41 \pm 0.08$</td>
<td></td>
</tr>
<tr>
<td>$\langle N \rangle$</td>
<td>$0.34 \pm 0.04$</td>
<td>$0.25 \pm 0.05$</td>
<td>$0.11 \pm 0.02$</td>
<td>$1.84 \pm 0.31$</td>
<td>$0.95 \pm 0.24$</td>
<td>$0.81 \pm 0.16$</td>
<td>$0.41 \pm 0.10$</td>
<td>$4.71 \pm 0.66$</td>
</tr>
<tr>
<td>Background</td>
<td>$0.12 \pm 0.04$</td>
<td>$0.28 \pm 0.14$</td>
<td>$0.25 \pm 0.04$</td>
<td>$1.22 \pm 0.42$</td>
<td>$0.71 \pm 0.28$</td>
<td>$0.85 \pm 0.14$</td>
<td>$0.36 \pm 0.08$</td>
<td></td>
</tr>
<tr>
<td>$\int L dt$ (pb$^{-1}$)</td>
<td>$47.9 \pm 5.7$</td>
<td>$55.7 \pm 6.7$</td>
<td>$44.2 \pm 5.3$</td>
<td>$47.9 \pm 5.7$</td>
<td>$44.2 \pm 5.3$</td>
<td>$47.9 \pm 5.7$</td>
<td>$44.2 \pm 5.3$</td>
<td>$3.79 \pm 0.55$</td>
</tr>
<tr>
<td>Data</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>17</td>
</tr>
</tbody>
</table>
FIG. 5. Fitted mass distribution for candidate events (histogram) with the expected mass distribution for 199 GeV/c$^2$ top quark events (dotted curve), background (dashed curve), and the sum of top and background (solid curve) for (a) standard and (b) loose event selection.
Conclusion

The D0 collaboration reported the observation of top quark with mass $199^{+19}_{-21}$ (stat.) $\pm$ 22 (syst.) GeV/$c^2$.

The CDF collaboration then also observed the top quark with a mass of $176 \pm 8$ (stat.) $\pm 10$ (syst.) GeV/$c^2$.

Implications of the discovery

- A major confirmation of the validity of the standard model
- A new dimension to the search for Higgs boson.
Current status

- Current value for the mass of the top quark: $173.34 \pm 0.27 \text{ (stat.)} \pm 0.71 \text{ (syst.)} \text{ GeV}/c^2$.

- Satisfies the constraining relation between the masses of the Higgs boson, the $W$ boson and the top quark with the current values of the masses of the Higgs and the $W$ being:
  \[
  m_{\text{Higgs}} = 125.09 \pm 0.21 \text{ (stat.)} \pm 0.11 \text{ (syst.)} \text{ GeV}/c^2
  \]
  \[
  m_W = 80.385 \pm 0.015 \text{ GeV}/c^2
  \]
Open areas of study regarding the top:

- Further fine-tuning of the top mass as it greatly affects our understanding of the Higgs field, radioactive decay and the rate of energy production in the sun.
- The role of the top quark in cosmology.
References

- S. Abachi et al. (D0 collaboration), Phys. Rev. Lett. 72, 2138 (1994)
- S. Abachi et al. (D0 collaboration), Fermilab-Pub-94/354-E, 1994
- Chris Quigg, Discovery of the Top quark, http://lutece.fnal.gov/Papers/PhysNews95.html