The Top Quark Discovery: From a CDF Viewpoint

Marina Cobal
University of Udine
A Simplified History of the Quark Model

- 1964 - Gell-Mann, Zweig - idea for 3 quarks - up, down, strange (u, d, s)
- 1970 - Glashow, Iliopoulos and Maiani - 4 quarks - up, down, strange, charm (u, d, s, c)
- 1973 - Kobayashi and Maskawa - add 2 quarks top and bottom (t, b) to explain CP violation
- 1974 - Ting, Richter discover charm
- 1977 - Lederman (Fermilab) discovers bottom
- B weak isospin = -1/2, need +1/2 partner

There must be a Top!
Top Mass Predictions and Discovery

- Several top mass predictions in late 70s
  - Predict $5 < M_{\text{top}} < 65$ GeV

- Rule of 3

<table>
<thead>
<tr>
<th>s</th>
<th>c</th>
<th>b</th>
<th>t</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>1.5</td>
<td>4.5</td>
<td>15</td>
</tr>
</tbody>
</table>

- Quark Mass (GeV)

- Jan. 1983 UA1 & UA1 discover W boson
- May 1983 UA1 discovers Z boson
- June-July 1984 Rubbia discovers Top!
  - Articles (*Nature*, *NY Times*) and press release
  - Mass peak between 30-50 GeV
Meanwhile back at Fermilab

- 1977 - First discussions of colliding p-pbar beams at Fermilab and a detector
- 1981 - CDF Design Report - general purpose detector with magnetic field
- Oct. ‘85 - CDF sees first p-pbar collisions - collect total 23 events
- Run 0 - June ‘88 - May ‘89, collect < 5 pb\(^{-1}\)
  - Set limits on \(M_{\text{top}} > 91\) GeV using Dilepton and L+jets channels (first use of SLT tagging)
  - Mass too high for CERN, Fermilab only game in town
A Quick Review on Top Production and Decay

- Top pair production via the strong interaction:
  - 90% $q\bar{q}$ 10% $gg$ at Tevatron $\sqrt{s} = 1.8$ TeV
  - 85% $q\bar{q}$ 15% $gg$ at Tevatron $\sqrt{s} = 1.96$ TeV
  - 10% $q\bar{q}$ 90% $gg$ at LHC $\sqrt{s} = 14$ TeV

- Top decays $t\rightarrow Wb \sim 100\%$

- Top lifetime $\sim 4 \times 10^{-25}$ sec
  - Doesn’t hadronize

- Decay of $W$ identifies channel
  - Dilepton, L+jets, All-hadronic
Top production

- \( t\bar{t} \) production (QCD)
- single top production (electro-weak)
- \( t\bar{t}b\bar{b} \)
- \( t\bar{t}H, t\bar{t}W^\pm, t\bar{t}Z \)
- \( t \)-quark production due to new interactions
Top cross section

<table>
<thead>
<tr>
<th>process</th>
<th>$\sigma_{t\bar{t}}$ [pb]</th>
</tr>
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<tbody>
<tr>
<td>Run I</td>
<td>90% $q\bar{q} \rightarrow t\bar{t}$</td>
</tr>
<tr>
<td></td>
<td>10% $gg \rightarrow t\bar{t}$</td>
</tr>
<tr>
<td>Run II</td>
<td>85% $q\bar{q} \rightarrow t\bar{t}$</td>
</tr>
<tr>
<td></td>
<td>15% $gg \rightarrow t\bar{t}$</td>
</tr>
<tr>
<td>LHC</td>
<td>10% $q\bar{q} \rightarrow t\bar{t}$</td>
</tr>
<tr>
<td></td>
<td>90% $gg \rightarrow t\bar{t}$</td>
</tr>
</tbody>
</table>

Cacciari, Kidonakis, Vogt, arXiv:0805.3844

Moch, Uwer, arXiv:0804.1476
Why top is different

- We do not expect the formation of top hadrons therefore, top quark decays before hadronization

\[ \tau_t = \frac{1}{\Gamma_{tot}} \approx \frac{1}{1.60 \Gamma_{\text{eB}}} = 4 \times 10^{-25} \text{ sec} \]

\[ \tau_{\text{адр}} \approx \frac{1}{\Lambda_{\text{КХД}}} \approx 5 \Gamma_{\text{eB}}^{-1} = 3.3 \times 10^{-24} \text{ sec} \]

- Top quark decays through ONE decay channel

\[ t \rightarrow bW^+, \text{ BR}(t \rightarrow \text{other}) \leq O(10^{-3}) \]

- The total and differential rates are calculated with O(10%) accuracy

- Top quark is unique and powerful instrument to study SM physics and search for manifestation of New Physics beyond SM
Top Decay Channels

- **Dilepton**
  - Few events but pure
  - final state: $l \nu l \nu bb$

- **Lepton + Jets**
  - More events, less pure
    - Add b-tags
  - final state: $l \nu q q bb$

- **All-Hadronic**
  - Lots of events, huge QCD bkg
  - final state: $q q q q bb$
  - Not used in discovery
Looking for Top in Run 0

- Believe $M_{\text{Top}} < M_W$
  - Decay mode would be $W \rightarrow tb$
    with $t \rightarrow bl\nu$

- Search strategies
  - Dilepton channel
    - $ee, e\mu, \mu\mu$
  - $L+\text{jets}$ channel
    - Added SLT tags

- Set limit $M_{\text{Top}} > 91$ GeV

- CDF had no silicon yet!

- Soft Lepton Tagging
- Identify semileptonic B decay
  - $b \rightarrow l$, $b \rightarrow c \rightarrow l$
- $\varepsilon(\text{SLT}) \approx 20\%$
Building the **Silicon Vertex Detector**

- Silicon used at fixed target to measure particle lifetimes and tag particles

- Not easy to sell idea to CDF
  - Hadron environment too messy to do precision tracking and heavy flavor physics (b and c)
  - No obvious physics case for device
    - Top discovery not a factor, didn’t consider b-tagging
  - Many technical challenges with construction and readout in collider environment
Fermilab Gets Serious Run Ia

- June ‘92 - May ‘93
- CDF now has SVX and muon upgrades
- D0 is taking data
- Developing strategies for discovering top
  - Counting experiments
  - Kinematic analyses
b-tagging using Secondary Vertices

- Use new SVX and b lifetime
  - $c\tau \sim 450\text{mm}$
  - b hadrons travel $L_{xy} \sim 3\text{ mm}$ before decay

- Run 1a had 3 SVX taggers
  - $\textbf{Jetvtx}$ - $\geq 2$ tracks form secondary vertex with $|L_{xy}|/\sigma_{L_{xy}} \geq 3$
  - $\textbf{Jet Probability}$ - use track impact parameter, probability of track consistent with primary vertex
  - $d\phi$ - Uses impact parameter, d, and azimuthal angle, $\phi$, of tracks

- $\textbf{Secondary Vertex} Tagging$
  - $\epsilon(\text{SVX}) \sim 50\%$
Silicon Vertex Detectors Work (in a hadron collider)!

**e + 4 jet event**
40758_44414
24-September, 1992

TWO jets tagged by SVX
fit top mass is 175±10 GeV/c^2

e^+, Missing E_t, jet #4 from top
jets 1,2,3 from top (2&3 from W)

**Two Vertex Views**
(note scales)

**Dijet Invariant Mass (GeV/c^2)**

Number of events / (10 GeV/c^2)

M_W = 77.2 ± 4.6 GeV
The Golden Event

- DPF event
  - Oct. 22, 1992
  - $e\mu + 2$ jet event
    - 1 jet tagged by both SLT and SVX
  - Decide not to declare discovery on 1 event
    - D0 similar experience

- Push for top is on!
The “Evidence” Paper

- July 1993 - CDF collaboration meeting
  - Seeing excess in all channels
  - Decide to write 4 PRLs

- Oct. ‘93 - CDF collab meeting
  - Reject PRLs and opt for giant PRD

- Jan. ‘94 - CDF collab meeting
  - Many questions and concerns (next slide)

- April 26, 1994 - Submit “Evidence for Top Quark Production” - PRD 50, p.2966-3026
Comments on “Evidence”

- 9 months of endless meetings answering questions while attempting to keep results quiet

- Some of the concerns raised:
  - Choice of official SVX b-tagger
    - Tuning on data
  - Method 1 vs. Method 2 background
    - Overestimate from data or trust MC
  - Role of kinematic analyses
    - Supporting evidence but not in significance
  - Calculate significance
    - Events or tags, weight of double tags
Results for Evidence Paper

- Combining all channels with 19 pb\(^{-1}\)
- Prob bkg fluctuate up to observed = 0.26% (2.8\(\sigma\))

<table>
<thead>
<tr>
<th>Channel:</th>
<th>SVX</th>
<th>SLT</th>
<th>Dilepton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected Bkg.</td>
<td>2.3±0.3</td>
<td>3.1±0.3</td>
<td>0.56±0.25</td>
</tr>
<tr>
<td>Observed Events</td>
<td>6</td>
<td>7</td>
<td>2</td>
</tr>
</tbody>
</table>

![Graph showing data before and after tagging with different methods.]
Run Ib and Observation

- Run Ib Feb. ‘94 - Dec. ‘95
  - New rad-hard silicon - SVX’
  - Optimized SVX b-tagger - Secvtx

- Jan ‘95 - CDF collaboration meeting
  - See significant excess in all channels
  - Slight changes to Evidence analyses
    - One optimized SVX b-tagger - Secvtx
    - Use Method 2 background (smaller # of bkg events)

- March ‘95 - D0 and CDF submit PRL’s
Top Discovery

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<tr>
<th>Channel</th>
<th>SVX</th>
<th>SLT</th>
<th>Dilepton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed</td>
<td>27 tags</td>
<td>23 tags</td>
<td>6 events</td>
</tr>
<tr>
<td>Exp. bkg</td>
<td>6.7±2.1</td>
<td>15.4±2.0</td>
<td>1.3±0.3</td>
</tr>
<tr>
<td>Probability</td>
<td>2x10⁻⁵</td>
<td>6x10⁻²</td>
<td>3x10⁻³</td>
</tr>
</tbody>
</table>

- Using 67 pb⁻¹ (includes Evidence data) combined Prob = 1x10⁻⁶ (4.8σ)
- If include mass distribution Prob = 3.7x10⁻⁷ (5.0σ)
Top Mass vs. Year

CDF “Evidence”

CDF and D0 “Observations”

Mass Limit

Summer 2005 combination
172.7 ± 2.9 GeV/c²
- 1.96 TeV p-anti p collider
- 396 ns between bunches
- Has delivered 8.7 fb\(^{-1}\) of data since 2001
- running smoothly, expect 10 fb\(^{-1}\) at the end of 2010

4 fb\(^{-1}\), ttbar pairs:
~15k (alljets)
~9k (e, mu+jets)
~3k (dileptons, including tau)
Analysis methods

**Counting events**
- Establish selection, estimate expected background
- Find number of data events
- Subtract expected background data from data events

**Templates/Likelihood**
- Reconstruct the best discriminating variable $X$ (ex. an invariant mass)
- Form signal and background templates of $X$
- Perform a maximum likelihood fit between data and templates

**Matrix Element**
- Form per-event probability using matrix elements
- Evaluate the probability of each event for signal and background hypotheses
- Use probability into one likelihood (discriminant type or as a function of a parameter)

**Neural Networks, Boosted Decision Trees**
- Find good discriminating variables (well modeled in MC)
- Input variables from MC to train a multivariate package
- Use output as a discriminant, likelihood fit between data and MC
Cross section measurements

DØ Run II

* = preliminary

March 2010

<table>
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<tr>
<th>Process</th>
<th>σ (pP → t̄t + X) [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>l+jets, dilepton, τ+lepton (PRD)</td>
<td>7.84 ± 0.36 ± 0.54 ± 0.46 pb</td>
</tr>
<tr>
<td>l+jets (b-tagged &amp; topological, PRL)</td>
<td>7.42 ± 0.36 ± 0.46 ± 0.45 pb</td>
</tr>
<tr>
<td>l+jets (neural network b-tagged, PRL)</td>
<td>8.20 ± 0.52 ± 0.77 ± 0.53 pb</td>
</tr>
<tr>
<td>dilepton (topological)</td>
<td>8.23 ± 0.52 ± 0.85 ± 0.63 pb</td>
</tr>
<tr>
<td>l+track (b-tagged)</td>
<td>5.3 ± 0.3 pb</td>
</tr>
<tr>
<td>tau+lepton (b-tagged)</td>
<td>2.2 ± 0.8 pb</td>
</tr>
<tr>
<td>tau+jets (b-tagged)</td>
<td>0.4 ± 0.2 pb</td>
</tr>
<tr>
<td>alljets (b-tagged, PRD)</td>
<td>1.0 ± 0.8 pb</td>
</tr>
</tbody>
</table>

m_w = 175 GeV
CTEQ6.6M

CDF


Dilepton
(L=4.3 fb⁻¹)
7.27 ± 0.71 ± 0.46 ± 0.42 pb
(stat) (syst) (lumi)

Lepton+Jets (ANN)
(L=4.6 fb⁻¹)
7.63 ± 0.37 ± 0.35 ± 0.15 pb

Lepton+Jets (SVX)
(L=4.3 fb⁻¹)
7.14 ± 0.35 ± 0.58 ± 0.14 pb

All-hadronic
(L=2.9 fb⁻¹)
7.21 ± 0.50 ± 1.10 ± 0.42 pb

CDF combined
χ²/DOF = 0.60
m_t = 172.5 GeV/c²
Mass

D0 matrix element analysis in l+jets channel

CDF Neural Network analysis in l+jets chann.

Mass of the Top Quark

<table>
<thead>
<tr>
<th>Mass of the Top Quark</th>
<th>July 2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF-I dilepton</td>
<td>167.4 ± 1.4 (±10.3 ± 4.9)</td>
</tr>
<tr>
<td>D0-I dilepton</td>
<td>168.4 ± 12.8 (±12.3 ± 3.6)</td>
</tr>
<tr>
<td>CDF-II dilepton *</td>
<td>170.6 ± 3.8 (± 2.2 ± 1.1)</td>
</tr>
<tr>
<td>D0-II dilepton *</td>
<td>174.7 ± 3.8 (± 2.0 ± 2.4)</td>
</tr>
<tr>
<td>CDF-I lepton+jets</td>
<td>176.1 ± 7.4 (± 5.1 ± 5.3)</td>
</tr>
<tr>
<td>D0-I lepton+jets</td>
<td>180.1 ± 5.3 (± 3.9 ± 1.6)</td>
</tr>
<tr>
<td>CDF-II lepton+jets *</td>
<td>173.0 ± 1.3 (± 0.7 ± 1.1)</td>
</tr>
<tr>
<td>D0-II lepton+jets *</td>
<td>173.7 ± 1.8 (± 0.8 ± 1.6)</td>
</tr>
<tr>
<td>CDF-I alljets</td>
<td>186.0 ± 11.5 (±10.0 ± 5.7)</td>
</tr>
<tr>
<td>CDF-II alljets</td>
<td>174.8 ± 2.5 (± 1.7 ± 1.0)</td>
</tr>
<tr>
<td>CDF-II track</td>
<td>175.3 ± 6.9 (± 6.2 ± 3.0)</td>
</tr>
<tr>
<td>Tevatron combination *</td>
<td>173.3 ± 1.1 (± 0.6 ± 0.9)</td>
</tr>
</tbody>
</table>

χ²/dof = 6.1/10 (81%)
Misure dirette

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

\[ D0 \ 900 \ \text{pb}^{-1} \quad R = 0.97^{+0.09}_{-0.08}; \quad R > 0.79 \ \text{@95\%CL} \]

\[ CDF \ 162 \ \text{pb}^{-1} \quad R = 1.12^{+0.21}_{-0.19} \text{(stat)}^{+0.17}_{-0.13} \text{(syst)} \quad R > 0.61 \ \text{@95\%CL} \]

\[ \Gamma_t^{\text{SM}} \approx 1.5 \ \text{GeV} \]

CDF 4.3 fb^{-1} Direct Fit \quad \Gamma_t < 7.5 \ \text{GeV}; \quad \tau_t > 8.7 \times 10^{-26} \ \text{s} \ \text{@ 95\% CL}; \quad \Gamma_t = 1.9^{+1.9}_{-1.5} \ \text{GeV} \]

D0 2.3 fb^{-1} Indirect Fit \quad \Gamma_t = 2.1 \pm 0.6 \ \text{GeV}; \quad \tau_t < 5 \times 10^{-25} \ \text{s} \ \text{@ 95\% CL} \]

\[ \Gamma_t = \frac{\sigma(t\text{-channel})}{\sigma(t\text{-channel})_{\text{SM}}} \]

D0 1 fb^{-1} direct top antitop mass difference: \quad m_{\text{top}} - m_{\text{antitop}} = 3.8 \pm 3.7 \ \text{GeV} \]

Top charge:

CDF 2.7 fb^{-1} measurement excludes top charge -4/3 with 95\% CL

D0 370 pb^{-1} measurement excludes top charge -4/3 with 92\% CL
Yesterday’s sensation is today’s calibration and tomorrow’s background.

- Feynman

- Calibration sample
  - Just like we used Ws, Zs
    - Jet Energy Scale
    - B-tagging

- Background
  - Higgs
Books on HEP Discoveries

- **Nobel Dreams** by Gary Taubes
  - Discovery of the W,Z bosons and Carlo Rubbia’s group

- **The Evidence for the Top Quark** by Kent Staley
  - Philosophy discussion of discovery in science but most of the book looks at CDF’s process for the Evidence and Observation papers