Roadmap

- The Tevatron
- The CDF and DØ Detectors
- Review of the Top Quark
- Top Branching Fraction
- Search for Single Top Production
- Summary
The TeVatron

- Proton-antiproton collisions at $1.96$ TeV (Run I: $1.8$ TeV)

- Peak Luminosity: > $10^{32}$ cm$^{-2}$ s$^{-1}$.

- What’s new for Run II?
  - Main Injector: $150$ GeV proton storage ring.
  - Recycler: Antiproton storage ring
    - Currently being commissioned and working well.

- Total Integrated luminosity:
  - Currently, over $800$ pb$^{-1}$.
  - Should have between $4$ fb$^{-1}$ and $9$ fb$^{-1}$ by 2009.
The Run II CDF Detector

- Similar to most colliding detectors:
  - Inner silicon tracking
  - Drift Chamber
  - Solenoid
  - EM and Hadronic Calorimeters
  - Muon Detectors

- New for Run II:
  - Tracking: 8 layer silicon and drift chamber
  - Trigger/DAQ
  - Better silicon, calorimeter and muon coverage
The Run II DØ Detector

- New central tracking inside 2 T solenoid
  - Silicon vertex detector
    - b-tagging
    - Scintillating fiber tracker
- New forward muon system
- New readout / trigger electronics
Top Review

- The top quark was discovered (in pairs) by CDF and D0 in 1995.
- The **Golden** quark ($\sim 180 \text{ GeV}/c^2$)
  - Only fermion with mass near EW scale; 35 times heavier than the bottom quark
- Very Wide (1.5 GeV/$c^2$)
  - The top quarks decay before they can hadronize.
    - We can study the decay of the bare quark.
- From what we already know about CKM matrix, we expect $\text{BR}(t \rightarrow Wb) \sim 100\%$
A Quick Note About Scale

Since we’re not all intimately familiar with hadron colliders.

Top: 1 in 10 billion
Top Branching Fraction: The Data Sample

- To date, we have only confirmed seeing top produced in pairs.
- For this analysis, we use two distinct samples (classified by W decays):
  - Dilepton events
  - Lepton + jet events

**Dileptons**
- Two high $p_T$ leptons ($e$, $\mu$)
- Two high energy jets
- Large missing transverse energy
- Large scalar sum $E_T$ ($H_T$)

**Lepton + Jets**
- One high $p_T$ lepton ($e$, $\mu$)
- Four high energy jets
- Large missing transverse energy
Top Dilepton Event at CDF

We use these displacements to "tag" b jets (SecVtx b tagging algorithm).
According to what we know about the CKM matrix, \( \text{BR}(t \rightarrow Wb) \sim 100\% \).

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

We can measure \( R \) by looking at the relative rates of top candidate events with zero, one, or two b-tagged jets.

Assuming no background and that b-jets are identified with efficiency \( \varepsilon_b \),
- \( N_0 = N_{tt} (1 - R \varepsilon_b)^2 \equiv N_{tt} \varepsilon_0 \),
- \( N_1 = 2 N_{tt} R \varepsilon_b (1 - R \varepsilon_b) \equiv N_{tt} \varepsilon_1 \),
- \( N_2 = N_{tt} (R \varepsilon_b)^2 \equiv N_{tt} \varepsilon_2 \).

The \( R \) measurement is therefore:
- Sensitive to \( \varepsilon_b \),
- Over determined, and
- Largely independent of \( N_{tt} \) and \( \sigma(tt) \).

\( \varepsilon_b \) is measured separately (40%).

Assuming no background:

\[
\mathcal{R} \cdot \varepsilon_b = \frac{2}{N_1/N_2 + 2} \quad = \quad \frac{1}{2N_0/N_1 + 1} \quad = \quad \frac{1}{\sqrt{N_0/N_2 + 1}}
\]
Our $R$ Likelihood

- We first need to estimate the total number of $tt$ candidates:

$$N_{tt} = \frac{\sum_{b \text{ tags}} N_{obsi} - N_{backi}}{\sum_{b \text{ tags}} \epsilon_i}$$

- Our likelihood is:

$$\mathcal{L}(R) = \prod P(N_{obsi} | N_{expi}) \quad \text{where} \quad N_{expi} = N_{tt} \cdot \epsilon_i + N_{backi}$$

- Remember:

$\epsilon_i$ and therefore $N_{tt}$ depend on $R \epsilon_b$. 

Charles Plager
CDF Dilepton and L+J Numbers

<table>
<thead>
<tr>
<th>Lepton + Jets (L+J)</th>
<th>0-tag</th>
<th>1-tag</th>
<th>2-tag</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\epsilon_i (R = 1)$</td>
<td>0.45 ± 0.03</td>
<td>0.43 ± 0.02</td>
<td>0.12 ± 0.02</td>
</tr>
<tr>
<td>a priori background</td>
<td>N/A</td>
<td>4.2 ± 0.7</td>
<td>0.2 ± 0.1</td>
</tr>
<tr>
<td>ANN background</td>
<td>62.4 ± 9.2</td>
<td>5.8 ± 5.1</td>
<td>0.1 ± 0.1</td>
</tr>
<tr>
<td>Total expected</td>
<td>80.4 ± 5.2</td>
<td>21.5 ± 4.1</td>
<td>5.0 ± 1.4</td>
</tr>
<tr>
<td>Observed</td>
<td>79</td>
<td>23</td>
<td>5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dileptons (DIL)</th>
<th>0-tag</th>
<th>1-tag</th>
<th>2-tag</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\epsilon_i (R = 1)$</td>
<td>0.47 ± 0.03</td>
<td>0.43 ± 0.02</td>
<td>0.10 ± 0.02</td>
</tr>
<tr>
<td>a priori background</td>
<td>2.0 ± 0.6</td>
<td>0.2 ± 0.1</td>
<td>negl.</td>
</tr>
<tr>
<td>Total expected</td>
<td>6.1 ± 0.4</td>
<td>4.0 ± 0.2</td>
<td>0.9 ± 0.2</td>
</tr>
<tr>
<td>Observed</td>
<td>5</td>
<td>4</td>
<td>2</td>
</tr>
</tbody>
</table>

• In addition to using a priori background estimates, we also use an artificial neural net in the L+J sample.
  – Our best 0-tag estimate
• We see very good agreement bin by bin.
The CDF $\mathcal{R}$ Measurement

- We use both the Dilepton and the Lepton + Jets data samples.
  \[ \mathcal{R} = 1.12^{+0.27}_{-0.23} = 1.12^{+0.21}_{-0.19} \text{(stat)} +^{0.17}_{-0.13} \text{(syst)} \]
- We use a Feldman-Cousins construction find our final answer: $\mathcal{R} > 0.61$ at the 95% C.L.
- Assuming three generations of quarks: $|V_{tb}| > 0.79$ at the 95% C.L.
- All uncertainties are stat. + syst.
The DØ $R$ Measurement

- Uses 160 pb$^{-1}$
- DØ has two results, each from different tagging methods
  - SVT – Displaced secondary vertices (same as CDF)
  - CSIP – Counts the number of displaced tracks ($i.e.$, $|d_0| > x$ cm)

- $R_{SVT} = 0.70^{+0.27}_{-0.24} (stat) + 0.11 (syst)$
- $R_{CSIP} = 0.65^{+0.34}_{-0.30} (stat) + 0.17 (syst)$

- Results not independent of top cross section.
Our $R$ Reach

- Quick-and-Dirty back of the envelop calculation.
- Assume $R = 1$.
  - Assumed 3 generations of quarks for $|V_{tb}|$ limits ($|V_{tb}| = 1$).
- If we keep systematic uncertainties down, can be a very promising measurement.
- Ignores innovation

95% lower limit of 0.99 at 20 fb$^{-1}$!
Search for Single Top at CDF

Why look for single top?
- Direct measurement of $|V_{tb}|^2$.
- SM cross section is still too small to see, but could be enhanced by new physics.
- This decay is a background to the Higgs search (WH production, $H \rightarrow bb$) and must be understood.

How do we look for single top?
- Signature is a lepton, MET and two jets (require at least one be tagged as a b jet).
- Much harder than simple counting experiments used in tt.
  - Kinematically wedged in between tt and non-top ($W + jets$) backgrounds.

\[ \sigma_{\text{theory}} \sim 1 \text{ pb} \]

\[ \sigma_{\text{theory}} \sim 2 \text{ pb} \]
CDF Single Top in Run II

MC templates

Fit data distributions for these components

- **t-channel only**: quark tends to follow proton direction, antiquark follows antiproton direction.

- **Both channels**: single top busier than non-top BG, but not as busy as $t\bar{t}$.
CDF Single Top Fit Results

CDF Run II Preliminary

Data versus SM expectation

\[ \int L \, dt = 162 \text{ pb}^{-1} \]

Events per 0.4 units

- Data
- t-channel
- s-channel
- ttbar
- non-top

\( \sqrt{s} = 1.96 \text{ TeV} \)

\begin{align*}
\text{NLO Cross-sections} & \\
\text{t-channel} & 1.98 \pm 0.25 \text{ pb} \\
\text{s-channel} & 0.88 \pm 0.11 \text{ pb}
\end{align*}


CDF Run II Preliminary

Events / 15 GeV

162 pb^{-1}

- Data
- single top
- tt
- non-top

\[ \sigma_{t\text{-channel}} < 10.1 \text{ pb at 95\% C.L.} \]

\[ \sigma_{s\text{-channel}} < 13.6 \text{ pb at 95\% C.L.} \]

\[ \sigma_{t+s\text{-channel}} < 17.8 \text{ pb at 95\% C.L.} \]
230 pb\(^{-1}\)

- Using several neural nets, DØ has drastically reduced both s and t channel limits:
  \[\sigma_s \text{ channel} < 6.4 \text{ pb at } 95\% \text{ C.L.}\]
  \[\sigma_t \text{ channel} < 5.0 \text{ pb at } 95\% \text{ C.L.}\]

- The limits are extracted from a binned likelihood fit to the 2D distribution of NN(single top vs. \(t\bar{t}\)) and NN(single top vs. Wbb).

- Theory is 1 and 2 pb, for s and t channel respectively. Recall, CDF's limits are 10pb (s-channel) and 13 pb (t-channel).
Looking Forward

- Lots of exciting top physics happening at the Tevatron.

- Top branching fraction
  - CDF measurement is the best direct limit to date:
    \[ |V_{tb}| > 0.79 \]
    at the 95% C.L.
  - Assumption about number of generations.

- Single top
  - DØ has the best limits to date
  - Direct measurement of \( V_{tb} \).
  - Need more data for observation, but DØ and CDF are getting close.
Backup Slides
Top Production at the Tevatron

• Pair production
  – \( \sigma_{\text{pair-theory}} = 6.7 \text{ pb.} \)

\[
\begin{aligned}
q & \quad \sim 85\% \\
\bar{q} & \quad \bar{t} \\
g & \quad \sim 15\%
\end{aligned}
\]

\[ \begin{array}{c}
q \\
\bar{q} \\
g \\
\bar{t}
\end{array} \]

All of these theoretical values assume a top quark mass of 175 GeV/c\(^2\) at a center of mass energy of 1.96 TeV.

• Single top
  – Not yet observed
  – \( \sigma_{s\text{-channel - theory}} = 0.88 \text{ pb.} \)
  – \( \sigma_{t\text{-channel - theory}} = 1.98 \text{ pb.} \)
Calibrating the b-tagging Efficiency

Measure ratio of single- and double-tagged events in b-enriched sample with soft ($p_T > 8$ GeV) electrons

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<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>$\epsilon_{\text{data}}$</td>
<td>24.0 ± 1.6%</td>
</tr>
<tr>
<td>$\epsilon_{\text{MC}}$</td>
<td>29.2 ± 1.1%</td>
</tr>
</tbody>
</table>

ratio 82 ± 6%

“Scale factor” measured on this sample is applied to other samples, even if the efficiencies differ
Other $V_{tb}$ Results


$$|V_{tb}| = 0.77^{+0.24}_{-0.17}$$