Search for Electroweak Top Quark Production at DØ

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The Top Quark

• Discovered in 1995 at the Tevatron

• Heaviest particle to date:

\[ m_t = 171.4 \pm 2.1 \text{ GeV} / c^2 \]

close to the scale of electroweak symmetry breaking.

➡ Beyond the Standard Model effects?

➡ Has a large effect in loop corrections that are in powers of \( m_t \)

• Predicted lifetime of \( \approx 0.5 \times 10^{-24} \) s, too short to form bound states

➡ Retains more information from the fundamental collision
Top Pair Production

• So far, the top quark has only been observed in pairs, produced by the strong force.

Best Independent Measurements of the Mass of the Top Quark  (*=Preliminary)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Method</th>
<th>Mass [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF-I</td>
<td>dilepton</td>
<td>167.4 ± 11.4</td>
</tr>
<tr>
<td>DØ-I</td>
<td>dilepton</td>
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\[ \chi^2 / \text{dof} = 10.6/10 \]

Tevatron Run-I/II*  171.4 ± 2.1

CDF-II  alljets*  174.0 ±  5.2
CDF-II  b decay length*  183.9 ± 15.8

85% \( q\bar{q} \) annihilation at the Tevatron

15% gluon fusion

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Electroweak Top Quark Production

\[
\sigma_{tb} = 0.88 \pm 0.07 \text{ pb}
\]

\[
\sigma_{tqb} = 1.98 \pm 0.23 \text{ pb}
\]

### DØ Limits (95% confidence level)

<table>
<thead>
<tr>
<th>Methodology</th>
<th>Integrated Luminosity</th>
<th>s-channel</th>
<th>t-channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cut-based</td>
<td>230 pb(^{-1})</td>
<td>10.6 pb</td>
<td>11.3 pb</td>
</tr>
<tr>
<td>Neural Network</td>
<td>230 pb(^{-1})</td>
<td>6.4 pb</td>
<td>5.0 pb</td>
</tr>
<tr>
<td>Likelihood</td>
<td>370 pb(^{-1})</td>
<td>5.0 pb</td>
<td>4.4 pb</td>
</tr>
</tbody>
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### CDF Limits

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<th>s+t-channel</th>
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</thead>
<tbody>
<tr>
<td>Neural Network</td>
<td>695 pb(^{-1})</td>
<td>(\sigma &lt; 3.4 \text{ pb} @ 95% \text{ CL})</td>
</tr>
<tr>
<td>Likelihood</td>
<td>955 pb(^{-1})</td>
<td>(\sigma &lt; 2.7 \text{ pb} @ 95% \text{ CL})</td>
</tr>
<tr>
<td>Matrix Element</td>
<td>955 pb(^{-1})</td>
<td>(\sigma = 2.7^{+1.5}_{-1.3} \text{ pb})</td>
</tr>
</tbody>
</table>

NLO cross sections at \(m_t = 175\) GeV, Phys.Rev. D70 (2004) 114012

tW production is negligible at the Tevatron
Why is Electroweak Production Interesting?

- Electroweak production is directly proportional to $|V_{tb}|^2$
  \[
  \begin{pmatrix}
  d' \\
  s' \\
  b'
  \end{pmatrix} = \begin{pmatrix}
  V_{ud} & V_{us} & V_{ub} \\
  V_{cd} & V_{cs} & V_{cb} \\
  V_{td} & V_{ts} & V_{tb}
  \end{pmatrix} \begin{pmatrix}
  d \\
  s \\
  b
  \end{pmatrix}
  \]

  - Current limits to $|V_{tb}|^2$ assume the CKM matrix is unitary. Without that assumption, it is virtually unconstrained:
    \[0.07 \leq |V_{tb}| \leq 0.9993 \text{ (90\% CL)}\]
    
    - Single top production tests that assumption

- Good place to study the V–A charged current interaction
  
    - The Standard Model predicts the top quark to be produced highly polarized
    
    - Because the top quark decays before it has time to hadronize, it preserves its polarization
Why is Electroweak Production Interesting?

- Sensitive to new physics.
- s-channel and t-channel have different sensitivities.
  - The s-channel is more sensitive to charged resonances, like top pions or charged Higgs particles.
  - The t-channel is more sensitive to FCNC and other new interactions.
Fermilab and the Tevatron

- The Tevatron is a pðp collider with √s = 1.96 TeV

- Just a few weeks ago reached the milestone: 2 fb⁻¹ have been delivered in Run II.

- Where the top quark was discovered 10 years ago using less than 100 pb⁻¹

- It is currently the only place to study the top quark.
The Tevatron Performance: over 2 fb$^{-1}$ Delivered

Run II Integrated Luminosity

19 April 2002 - 3 December 2006

End of Run IIA

Current Single Top Analyses End Here

Delivered
Recorded

Luminosity (/fb)

Apr-02 Jul-02 Oct-02 Jan-03 Apr-03 Jul-03 Oct-03 Jan-04 Apr-04 Jul-04 Oct-04 Jan-05 Apr-05 Jul-05 Oct-05 Jan-06 Apr-06 Jul-06 Oct-06
The DØ Detector

The diagram illustrates the layout of the DØ detector, highlighting various components such as the Forward Mini-Drift Tubes, Muon Toroid, Muon Scintillation Counters, VLPC Readout System, and the Tracking System, which includes Silicon, Fiber Tracker, Solenoid, Central & Forward Preshowers. The diagram also shows the Shielding and the general orientation with north and south labeled.
How does Single Top Look?

• The event signature for single top is:
  • a charged lepton and a neutrino (missing $E_T$) coming from the $W$ decay
  • a bottom quark coming from the top quark decay
  • in s-channel, the other bottom quark ($b\bar{b}$ on the diagram)
  • in t-channel, the light quark ($q$ in the diagram). This one is often quite forward.
  • in t-channel, the second bottom quark from gluon splitting ($b\bar{b}$ on the diagram) is usually not observed.
Single Top Parton Distributions

**s-channel**

- **pT [GeV/c]**
- **Q(lepton) × η**

**t-channel**

- **pT [GeV/c]**
- **Q(lepton) × η**

*Figure 2 shows the transverse momenta and pseudorapidities for the partons in our Monte Carlo models of the s-channel ... low-pT b quark produced with the top quark in the t-channel from the 2→2 and 2→3 processes and their combination.*
Why hasn’t Single Top been observed yet?

- The single top cross section is not that much smaller than that of $t\bar{t}$, which was first observed over 10 years ago
  - Top pair production has a much more unique event signature.
  - Single-top is kinematically between top pair and $W$+jets.

- The main background is $W$+jets.
  - $W$+bb$\bar{b}$
  - $W$+charm and $W$+light jets that get tagged

- B-tagging is key to reducing the large background

- Other Backgrounds
  - Multijet (i.e. fake lepton)
  - $t\bar{t}$ (more so in higher jet multiplicity bins)
Analysis Overview

- Loose event selection (leave more to the NN, DT, ME).
- Work in separate lepton, jet, and tag bins.
- Background Modeling
  - $W$+jets and $t\bar{t}$: Alpgen/Pythia with MLM matching
    - The heavy flavor content for the $W$+jets sample is measured in data and a k-factor of 1.5 is applied to the $W+c\bar{c}$ and $W+b\bar{b}$ MC samples.
  - multijet (fake lepton) background: orthogonal data sample.
- Before $b$-tagging (where single-top is negligible), the multijet sample is scaled to the fake lepton yield, and the $W$+jets sample is scaled to the real lepton yield minus the $t\bar{t}$ yield.
- We model the single-top signal with the Monte Carlo generator SingleTop, a version of CompHEP modified to reproduce NLO distributions.
Event Selection

- Good data quality
- Good primary vertex
- lepton+jets triggered data
- Leptons: “tight” electron with $p_T > 15 \text{ GeV}$, $|\eta| < 1.1$, or “tight” muon with $p_T > 18 \text{ GeV}$, $|\eta| < 2.0$.
- Veto on second charged lepton
- Jets: leading $p_T > 25 \text{ GeV}$, second jet $p_T > 20 \text{ GeV}$, others $p_T > 15 \text{ GeV}$.
  - leading $|\eta| < 2.5$, $|\eta| < 3.4$ for subsequent jets.
- $15 \text{ GeV} < E_T < 200 \text{ GeV}$
- “Triangle” cuts: don’t take events that have the missing $E_T$ aligned or anti-aligned with the lepton or the leading jet, since that’s probably due to mismeasurement.
Yields Before $b$-Tagging

<table>
<thead>
<tr>
<th></th>
<th>Electron Channel</th>
<th>Muon Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 jet</td>
<td>2 jets</td>
</tr>
<tr>
<td><strong>Signals</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$tb$</td>
<td>4</td>
<td>14</td>
</tr>
<tr>
<td>$tq$</td>
<td>9</td>
<td>27</td>
</tr>
<tr>
<td>$tb+tq$</td>
<td>14</td>
<td>41</td>
</tr>
<tr>
<td><strong>Backgrounds</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$t\bar{t} \rightarrow ll$</td>
<td>9</td>
<td>35</td>
</tr>
<tr>
<td>$t\bar{t} \rightarrow l+jets$</td>
<td>2</td>
<td>26</td>
</tr>
<tr>
<td>$Wb\bar{b}$</td>
<td>659</td>
<td>358</td>
</tr>
<tr>
<td>$Wc\bar{c}$</td>
<td>1,592</td>
<td>931</td>
</tr>
<tr>
<td>$Wjj$</td>
<td>23,417</td>
<td>5,437</td>
</tr>
<tr>
<td>Multijets</td>
<td>1,691</td>
<td>1,433</td>
</tr>
<tr>
<td><strong>Background Sum</strong></td>
<td>27,370</td>
<td>8,220</td>
</tr>
<tr>
<td><strong>Data</strong></td>
<td>27,370</td>
<td>8,220</td>
</tr>
</tbody>
</table>
Data/MC Comparisons Before $b$-Tagging
(2 jet bin, electron channel)
**B-Tagging**

- As mentioned in the introduction, $b$-tagging is one of the key ways we decrease the large background.
- One of the recent improvements at DØ is the new Neural Network Tagger.
- The plots on the right show its performance on data in comparison to JLIP, an older tagger.

<table>
<thead>
<tr>
<th>Rank</th>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$SVT_{SL}$ DLS</td>
<td>Decay Length Significance of the Secondary Vertex (SV)</td>
</tr>
<tr>
<td>2</td>
<td>CSIP Comb</td>
<td>Weighted combination of the tracks’ IP Significances</td>
</tr>
<tr>
<td>3</td>
<td>JLIP Prob</td>
<td>Probability that the jet originates from the PV</td>
</tr>
<tr>
<td>4</td>
<td>$SVT_{SL} \chi^2_{dof}$</td>
<td>Chi Square per degree of freedom of the SV</td>
</tr>
<tr>
<td>5</td>
<td>$SVT_{L} N_{Tracks}$</td>
<td>Number of tracks used to reconstruct the SV</td>
</tr>
<tr>
<td>6</td>
<td>$SVT_{SL}$ Mass</td>
<td>Mass of the SV</td>
</tr>
<tr>
<td>7</td>
<td>$SVT_{SL}$ Num</td>
<td>Number of SV found in the jet</td>
</tr>
</tbody>
</table>

Table 1: NN input variables ranked in order of power.

“TIGHT” operating point
Efficiency: 50%, Fake Rate: 0.5%
Signal : Background

### Percentage of s-channel \( tb \) selected events and S:B ratio

<table>
<thead>
<tr>
<th>Electron + Muon</th>
<th>1 jet</th>
<th>2 jets</th>
<th>3 jets</th>
<th>4 jets</th>
<th>≥ 5 jets</th>
</tr>
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<tbody>
<tr>
<td>0 tags</td>
<td>8%</td>
<td>19%</td>
<td>9%</td>
<td>3%</td>
<td>1%</td>
</tr>
<tr>
<td></td>
<td>1 : 11,000</td>
<td>1 : 1,600</td>
<td>1 : 1,200</td>
<td>1 : 1,100</td>
<td>1 : 1,100</td>
</tr>
<tr>
<td>1 tag</td>
<td>6%</td>
<td>24%</td>
<td>12%</td>
<td>3%</td>
<td>1%</td>
</tr>
<tr>
<td></td>
<td>1 : 270</td>
<td>1 : 55</td>
<td>1 : 73</td>
<td>1 : 130</td>
<td>1 : 200</td>
</tr>
<tr>
<td>2 tags</td>
<td>9%</td>
<td>4%</td>
<td>1%</td>
<td>0%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 : 12</td>
<td>1 : 27</td>
<td>1 : 92</td>
<td>1 : 110</td>
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### Percentage of t-channel \( tqb \) selected events and S:B ratio

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<tbody>
<tr>
<td>0 tags</td>
<td>10%</td>
<td>27%</td>
<td>13%</td>
<td>4%</td>
<td>1%</td>
</tr>
<tr>
<td></td>
<td>1 : 4,400</td>
<td>1 : 520</td>
<td>1 : 400</td>
<td>1 : 360</td>
<td>1 : 300</td>
</tr>
<tr>
<td>1 tag</td>
<td>8%</td>
<td>20%</td>
<td>11%</td>
<td>4%</td>
<td>1%</td>
</tr>
<tr>
<td></td>
<td>1 : 150</td>
<td>1 : 32</td>
<td>1 : 37</td>
<td>1 : 58</td>
<td>1 : 72</td>
</tr>
<tr>
<td>2 tags</td>
<td>1%</td>
<td>2%</td>
<td>1%</td>
<td>0%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 : 100</td>
<td>1 : 36</td>
<td>1 : 65</td>
<td>1 : 70</td>
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Yields with One $b$-Tagged Jet

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<td>3</td>
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</tr>
<tr>
<td>$tb+tqb$</td>
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<td>74</td>
</tr>
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<td>66</td>
</tr>
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<td>348</td>
</tr>
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<td>445</td>
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Data/MC Comparisons After $b$-Tagging
(2 jet bin, electron channel, one tag)
How to proceed

- Method 1: Optimized cuts-based, but shown not to be competitive

- Method 2: Neural Networks. Bayesian Neural Networks show lots of promise

- Method 3: Boosted Decision Trees

- Method 4: Matrix Element. This is the focus of this presentation
Matrix Element Method

• The matrix element encodes all the kinematic information.

\[ d\sigma = \frac{|M|^2}{F} dQ \]

Where \( F \) is the flux factor and \( dQ \) is the Lorentz invariant phase space factor.

• The method makes maximal use of the information. The matrix element contains all the properties of the interaction. (practical limitation: LO matrix element.)

• The method requires no training. It is firmly grounded in the physics.
The Main Idea of the Matrix Element Method

- Assume a particular process (e.g. t-channel single top). The probability to observe a particular configuration of jets and leptons given that process is proportional to the differential cross section of that process for such an configuration.

\[
P(\text{config} \mid \text{process}) \sim \frac{d\sigma_{\text{process}}}{d(\text{config})}
\]

- Can determine the probability of an observed configuration assuming (given) signal and its probability assuming (given) background.

- Bayes’ rule:

\[
P(\text{signal} \mid \text{config}) = \frac{P(\text{config} \mid \text{signal}) P(\text{signal})}{P(\text{config} \mid \text{signal}) P(\text{signal}) + P(\text{config} \mid \text{back}) P(\text{back})}
\]
The Matrix Element Analysis

- Being more explicit:

\[ D(x) = \frac{P(x|S)}{P(x|S) + P(x|B)} \]

where

\[ P(x|S) = \frac{1}{\sigma_s} \left( \frac{d\sigma_s}{dx} \right) \quad P(x|B) = \sum_i w_i P(x|B_i) \quad P(x|B_i) = \frac{1}{\sigma_{b_i}} \left( \frac{d\sigma_{b_i}}{dx} \right) \]

\[ \frac{d\sigma}{dx} \sim \sum_{i_{\text{perm}}} \int d^n y \frac{|M(y, i)|^2}{F(y)} f_1(y)f_2(y)\text{TF}(y, x, i) \]

\[ \sigma = \int dx \frac{d\sigma}{dx} \]

- \( y \): the parton-level information
- \( x \): the reconstructed information
- \( F \): the flux factor
- \( f_1 \) and \( f_2 \): the two PDFs
- \( \text{TF} \): the transfer function, relating parton and reconstructed information.
The Transfer Functions

- We measure reconstructed values, but the Matrix Element uses parton values.
  - Transfer Functions

- We assume:
  - can use per-object transfer functions
  - the angles are perfectly measured

- For jets, we use a double Gaussian form parameterized in energy in $\eta$ bins. There are separate parameterizations for light, $b$, and $b(\rightarrow \mu)$ jets jets.

\[
W_{\text{object}}(E_{\text{parton}}, E_{\text{object}}) = \frac{1}{\sqrt{2\pi}(p_2 + p_3 p_5)} \times (e^{-\frac{(E_{\text{object}} - E_{\text{parton}} - p_1)^2}{2p_2^2}} + p_3 e^{-\frac{(E_{\text{object}} - E_{\text{parton}} - p_4)^2}{2p_3^2}})
\]

- For electrons, we use a single Gaussian parameterized in energy and $\eta$.
- For muons we use a single Gaussian parameterized in $(q/p_T)$, $\eta$, and if there are silicon tracker hits.
Transfer Functions (cont.)

The jet transfer function for b-jets

Applying the jet transfer function on the bottom quark from the top decay (blue) vs. full GEANT simulation (yellow)

The electron transfer function, $E_p = 30$ GeV, $\eta = 0.3$
B-Tagging

- Another feature that I view as part of the transfer function is the assignment of jets to partons. We sum all possible assignments.

- If we do not have extra information, we weigh each permutation equally:

\[ d\sigma = 0.5d\sigma(j_1 \rightarrow q_1, j_2 \rightarrow q_2) + 0.5d\sigma(j_2 \rightarrow q_1, j_1 \rightarrow q_2) \]

- However, if we do have one $b$-tagged jet, and we are calculating the t-channel cross-section, where we are using diagrams of the type $b u \rightarrow e^+ v_e b d$, we can do better:

\[ d\sigma = \epsilon_b(j_{tag})[1 - \epsilon_l(j_{untag})]d\sigma(j_{tag} \rightarrow b, j_{untag} \rightarrow d) \]
\[ + [1 - \epsilon_b(j_{untag})]\epsilon_l(j_{tag})d\sigma(j_{untag} \rightarrow b, j_{tag} \rightarrow d) \]

- The extension to 3 jets is straightforward.
Muon Charge

- The s-channel, which has a $b$-jet and a $\bar{b}$-jet as the two jets, can benefit from $b$-tagging since the tagging efficiency depends on $\eta$ and $p_T$.

- But maybe if a $b$-quark decays leptonically we can use the muon charge:
  
  - all good: $b \rightarrow \mu^- \bar{\nu} c$  
  - but also: $b \rightarrow x \bar{c} \rightarrow \mu^+ \bar{\nu} s$  
  $b \rightarrow x \bar{c} \rightarrow \mu^- \bar{\nu} s$

- Use $p_{\text{Trel}}$, or the $p_T$ of the muon relative to the jet. Muons from charm quarks are expected to have a lower $p_{\text{Trel}}$. Do the same as for $b$-tagging.

- It will be used in the next round.
The Details

• We are using MadEvent LO matrix elements, and CTEQ6L1 pdfs.
• We look at events with 2 and 3 jets.
• The Matrix Elements we now use are:
  • Signal: s-channel or t-channel single-top
  • Background: $W_{bb}$, $W_{cg}$, and $W_{gg}$ (2 jets); $W_{bbg}$ (3 jets)

$$P(x|B) = w_{W_{bb}}P(x|W_{bb}) + w_{W_{cg}}P(x|W_{cg}) + w_{W_{gg}}P(x|W_{gg})$$

• Major upgrade under way: $t\bar{t}$ matrix elements.
• Also adding extra 3 jet $W$+jets and signal matrix elements.
s-Channel Discriminant Plots, 2 Jets

![Plot 1: DØ Run II Preliminary](image1)

![Plot 2: DØ Run II Preliminary](image2)

![Plot 3: DØ Run II Preliminary](image3)

![Plot 4: DØ Run II Preliminary](image4)
t-Channel Discriminant Plots, 2 Jets

DØ Run II Preliminary

- tqb
- Wbb

DØ Run II Preliminary

- tqb
- Wjj

DØ Run II Preliminary

- tqb
- tt → l+jets

DØ Run II Preliminary

- tqb
- tt → l+jets
Discriminant Results, 2 Jets

![Graphs showing s-channel and t-channel discriminants for 2 jets and tags combined.](image)
Discriminant Results, 3 Jets

**tb Discriminant : e+\(\mu\) w/ =3 Jets and Tags Combined**

![Graph](image)

KS: 0.912

**tq Discriminant : e+\(\mu\) w/ =3 Jets and Tags Combined**

![Graph](image)

KS: 1

**t-channel discriminant**

**s-channel discriminant**

**tb Discriminant : e+\(\mu\) w/ =3 Jets and Tags Combined**

![Graph](image)

KS: 0.988

**tq Discriminant : e+\(\mu\) w/ =3 Jets and Tags Combined**

![Graph](image)

KS: 0.915
Systematics

- We have two types of systematics: overall normalization and shape-changing.

- Currently, we treat the jet energy scale and the tag rate function systematics as shape-changing systematics, everything else is flat.

<table>
<thead>
<tr>
<th>Components for Normalization</th>
<th>Single-Tagged Two-Jets Electron Channel Percentage Errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>6.1 6.1 6.1 — — — —</td>
</tr>
<tr>
<td>Cross section</td>
<td>16.0 15.0 18.0 18.0 — — — —</td>
</tr>
<tr>
<td>Branching fraction</td>
<td>1.0 1.0 1.0 1.0 — — — —</td>
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<tr>
<td>Matrix method</td>
<td>— — — — 18.2 18.2 18.2 18.2</td>
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<td>Primary vertex</td>
<td>2.4 2.4 2.4 2.4 — — — —</td>
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<tr>
<td>Electron ID</td>
<td>5.5 5.5 5.5 5.5 — — — —</td>
</tr>
<tr>
<td>Jet ID</td>
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</tr>
<tr>
<td>Jet fragmentation</td>
<td>5.0 5.0 7.0 5.0 — — — —</td>
</tr>
<tr>
<td>Trigger</td>
<td>3.0 3.0 3.0 3.0 — — — —</td>
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<tr>
<td>Components for Normalization and Shape</td>
<td></td>
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<tr>
<td>Jet energy scale</td>
<td>1.4 0.3 9.9 1.7 — — — —</td>
</tr>
<tr>
<td>Flavor-dependent TRFs</td>
<td>2.1 5.9 4.6 2.4 4.4 6.3 7.4 —</td>
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<tr>
<td>Statistics</td>
<td>0.7 0.7 1.3 0.8 0.9 0.9 0.4 5.6</td>
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<tr>
<td>Combined</td>
<td></td>
</tr>
<tr>
<td>Acceptance uncertainty</td>
<td>10.8 12.1 — — — — — —</td>
</tr>
<tr>
<td>Yield uncertainty</td>
<td>19.3 19.3 24.1 21.1 18.8 19.3 19.7 19.1</td>
</tr>
</tbody>
</table>

TABLE 29: Electron channel uncertainties, requiring exactly one tag and two jets.
Expected Sensitivity

- We build a 2-D histogram of s-channel vs t-channel discriminant and run our Bayesian limit setting framework to determine the posterior. We can require the SM ratio, $\sigma_t/\sigma_s = 2.25$, or in future updates, not.

**Assuming SM ratio**

**Not assuming SM ratio**
MC Ensemble Test Results

Cross Section Per Ensemble

Input: 0 pb
Entries: 400
Mean: 0.622
Mode: 0.1
RMS: 0.859

Input: 2 pb
Entries: 200
Mean: 2.34
Mode: 2.5
RMS: 2.73

Input: 7.89 pb
Entries: 200
Mean: 8.28
Mode: 7.5
RMS: 8.46

Input: 2.86 pb
Entries: 400
Mean: 3.18
Mode: 3.5
RMS: 3.52

Input: 5.92 pb
Entries: 199
Mean: 6.58
Mode: 6.5
RMS: 6.79

Input: 0 pb
Entries: 400
Mean: 0.622
Mode: 0.1
RMS: 0.859

ME analysis

$\chi^2$/ndof = 0.64/4
Slope = 1.05 ± 0.08
Intercept = 0.21 ± 0.28

Ensemble response s+t cross section [pb] vs. Input s+t cross section [pb]
Observed Results (Matrix Element)

Posterior Density: $e^+\mu$ w/ 2+3 Jets and $\geq 1$ Tag

Cross Section $[pb]$

$\sigma_{s+t} = 4.6^{+1.8}_{-1.5}$

$\delta \sigma_{s+t} \sigma_{s+t} = 0.35$

Cross Section For Zero Signal Ensembles

DØ Run II Preliminary

Entries: 19938
p-Value: 0.00211
Sigma: 2.87

$\sigma_{s+t}^{Obs} = 4.6 \text{ pb}$

DØ Run II Preliminary

<table>
<thead>
<tr>
<th>Process</th>
<th>0.9 $fb^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e / 2jets / 1tag$</td>
<td>$2.0^{+2.0}_{-1.7} \text{ pb}$</td>
</tr>
<tr>
<td>$e / 2jets / 2tags$</td>
<td>$6.0^{+7.3}_{-5.3} \text{ pb}$</td>
</tr>
<tr>
<td>$e / 3jets / 1tag$</td>
<td>$2.9^{+5.3}_{-2.9} \text{ pb}$</td>
</tr>
<tr>
<td>$e / 3jets / 2tags$</td>
<td>$16.0^{+17.0}_{-16.0} \text{ pb}$</td>
</tr>
<tr>
<td>$\mu / 2jets / 1tag$</td>
<td>$8.4^{+3.9}_{-3.2} \text{ pb}$</td>
</tr>
<tr>
<td>$\mu / 2jets / 2tags$</td>
<td>$5.9^{+6.5}_{-5.0} \text{ pb}$</td>
</tr>
<tr>
<td>$\mu / 3jets / 1tag$</td>
<td>$5.0^{+5.4}_{-4.2} \text{ pb}$</td>
</tr>
<tr>
<td>$\mu / 3jets / 2tags$</td>
<td>$7.1^{+8.8}_{-7.1} \text{ pb}$</td>
</tr>
<tr>
<td>Combined (Matrix elements)</td>
<td>$4.6^{+1.8}_{-1.5} \text{ pb}$</td>
</tr>
</tbody>
</table>

Z. Sullivan PRD 70, 114012 (2004), $m_t = 175$ GeV
Observed Results (Preliminary Evidence!)

Decision Trees - p-value

A $3.4\sigma$ excess!!

**DØ Run II Preliminary 910, pb$^{-1}$**

<table>
<thead>
<tr>
<th>tbqqb</th>
<th>Entries</th>
<th>Mean</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>68150</td>
<td>0.525</td>
<td>0.7963</td>
</tr>
</tbody>
</table>

- **e+\mu-channel**
- **Full systematics**
- 24 entries above observed cross section
- **p-value: 3.5e-04**
- **sigma: 3.4**
Observed Results

DØ Run II Preliminary 0.9 fb⁻¹

<table>
<thead>
<tr>
<th>Method</th>
<th>Cross Section [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decision trees</td>
<td>4.9 ±1.4 ±1.5</td>
</tr>
<tr>
<td>Matrix elements</td>
<td>4.6 ±1.8 ±1.5</td>
</tr>
<tr>
<td>Bayesian NNs</td>
<td>5.0 ±1.9 ±2.0</td>
</tr>
</tbody>
</table>

Z. Sullivan PRD 70, 114012 (2004), \( m_t = 175 \) GeV

SM compatibility = 21%
Summary / Outlook

• Preliminary first evidence for single-top production!

• The matrix element method is being updated with the addition of $t\bar{t}$ matrix elements and other improvements.

• An extra $\sim 100$ pb$^{-1}$ of data will probably be added soon.

• In the longer term, the Tevatron is gathering new data as we speak. By the end or Run IIb, it is on track to have delivered 7-8 fb$^{-1}$.

• Run IIb has improvements that will help the physics.
  • The new Silicon Tracker Layer 0 will improve b-tagging.
  • Upgraded trigger will ensure we can keep triggering on the data we need.

• At the LHC the cross section is two orders of magnitude greater.

• The excitement is just beginning!
Backup Slides
Estimating the Multijet Background Yield

- The multijet background yield is estimated by solving the following system equations for the real and fake lepton yields:
  \[
  N_{\text{loose}} = N_{\text{loose}}^{\text{fake-\ell}} + N_{\text{loose}}^{\text{real-\ell}} \\
  N_{\text{tight}} = N_{\text{tight}}^{\text{fake-\ell}} + N_{\text{tight}}^{\text{real-\ell}} = \varepsilon_{\text{fake-\ell}} N_{\text{loose}}^{\text{fake-\ell}} + \varepsilon_{\text{real-\ell}} N_{\text{loose}}^{\text{real-\ell}}
  \]

- \(N_{\text{loose}}\) is the data yield with a “loose” lepton ID.
- \(N_{\text{tight}}\) is the data yield with a “tight” lepton ID.
- \(\varepsilon_{\text{real-\ell}}\) is the probability of a real lepton to pass the tight requirements given it has passed the loose. It is measured in MC, with a data/MC scale factor measured in \(Z \rightarrow l^+l^-\) events.
- \(\varepsilon_{\text{fake-\ell}}\) is the probability of a “fake” lepton to pass the tight requirements given it has passed the loose. It is measured in data with the standard selections but missing \(E_T < 10\text{ GeV}\).

**Loose vs. Tight**
- Loose electron: isolation EM fraction, shower shape, track match.
- Tight electron: loose + likelihood
- Loose muon: “medium” muon with cosmic veto, \(\Delta r(\text{jet}, \text{muon}) > 0.5\)
- Tight muon: loose + track isolation
Yields Before b-Tagging

For all MC, apply:

- Cross section weights (including heavy flavor corrections)
- Trigger weights: the trigger efficiency for such an event measured in data.
- Object ID weights: correction factors to take into account differences in data and MC object reconstruction efficiency.

Create an orthogonal sample by reversing the tight lepton criteria, and normalize it to $N_{\text{tight fake-l}}^{\text{tight}}$. This is the multijet sample.

From $N_{\text{real-l}}^{\text{tight}}$, subtract the $t\bar{t}$ yield. Scale the $W+\text{jets}$ MC sample to this amount. This is the $W$ sample.
The Matrix Method

- The multijet background yield is estimated by solving the following equations:

  \[ N_{\text{loose}} = N_{\text{loose}}^{\text{fake-l}} + N_{\text{loose}}^{\text{real-l}} \]

  \[ N_{\text{tight}} = N_{\text{tight}}^{\text{fake-l}} + N_{\text{tight}}^{\text{real-l}} = \epsilon_{\text{fake-l}} N_{\text{loose}}^{\text{fake-l}} + \epsilon_{\text{real-l}} N_{\text{loose}}^{\text{real-l}} \]

- Measure \( \epsilon_{\text{fake-l}} \) on data using the same selection except missing \( E_T < 10 \) GeV

- Measure \( \epsilon_{\text{real-l}} \) in three steps:
  - Measure \( \epsilon_{\text{MC}}^{\text{real-l}} \) using MC truth and the analysis selection criteria
  - Measure \( \epsilon_{\text{Z-data}}^{\text{real-l}} / \epsilon_{\text{Z-MC}}^{\text{real-l}} \) using the EM-ID or Muon ID tools
  - \( \epsilon_{\text{real-l}} = \frac{\epsilon_{\text{Z-data}}^{\text{real-l}}}{\epsilon_{\text{Z-MC}}^{\text{real-l}}} \epsilon_{\text{MC}}^{\text{real-l}} \)
### Yields

#### Yields Before b-Tagging

<table>
<thead>
<tr>
<th></th>
<th>Electron Channel</th>
<th>Muon Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 jet 2 jets 3 jets 4 jets 5+ jets</td>
<td>1 jet 2 jets 3 jets 4 jets 5+ jets</td>
</tr>
<tr>
<td><strong>Signals</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>4 14 7 2 0</td>
<td>3 10 5 1 0</td>
</tr>
<tr>
<td>$t\bar{t}b$</td>
<td>9 27 14 5 1</td>
<td>6 20 11 3 1</td>
</tr>
<tr>
<td>$t\bar{t}+tq\bar{b}$</td>
<td>14 41 21 6 2</td>
<td>9 31 16 5 1</td>
</tr>
<tr>
<td><strong>Backgrounds</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$t\bar{t}+t\ell$</td>
<td>9 35 28 10 4</td>
<td>5 27 22 8 3</td>
</tr>
<tr>
<td>$t\bar{t}+t\ell+jets$</td>
<td>2 26 103 128 67</td>
<td>1 14 71 99 43</td>
</tr>
<tr>
<td>$Wbb$</td>
<td>659 358 149 42 5</td>
<td>431 312 161 47 10</td>
</tr>
<tr>
<td>$Wc\bar{e}$</td>
<td>1,592 931 389 93 10</td>
<td>1,405 1,028 523 131 21</td>
</tr>
<tr>
<td>$Wjj$</td>
<td>23,417 5,437 1,546 343 51</td>
<td>15,476 4,723 1,591 385 85</td>
</tr>
<tr>
<td>Multijets</td>
<td>1,691 1,433 860 256 86</td>
<td>498 329 223 58 10</td>
</tr>
<tr>
<td><strong>Background Sum</strong></td>
<td>27,370 8,220 3,075 874 223</td>
<td>17,816 6,434 2,592 727 172</td>
</tr>
<tr>
<td><strong>Data</strong></td>
<td>27,370 8,220 3,075 874 223</td>
<td>17,816 6,432 2,590 727 173</td>
</tr>
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</table>

#### Yields with One b-Tagged Jet

<table>
<thead>
<tr>
<th></th>
<th>Electron Channel</th>
<th>Muon Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 jet 2 jets 3 jets 4 jets 5+ jets</td>
<td>1 jet 2 jets 3 jets 4 jets 5+ jets</td>
</tr>
<tr>
<td><strong>Signals</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>2 7 3 1 0</td>
<td>1 5 2 1 0</td>
</tr>
<tr>
<td>$t\bar{t}b$</td>
<td>3 11 6 2 1</td>
<td>2 9 5 2 0</td>
</tr>
<tr>
<td>$t\bar{t}+tq\bar{b}$</td>
<td>5 18 9 3 1</td>
<td>3 14 7 2 1</td>
</tr>
<tr>
<td><strong>Backgrounds</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$t\bar{t}+t\ell$</td>
<td>4 16 13 5 2</td>
<td>2 13 10 4 1</td>
</tr>
<tr>
<td>$t\bar{t}+t\ell+jets$</td>
<td>1 11 47 58 30</td>
<td>0 6 32 45 20</td>
</tr>
<tr>
<td>$Wbb$</td>
<td>188 120 50 14 2</td>
<td>131 110 56 16 4</td>
</tr>
<tr>
<td>$Wc\bar{e}$</td>
<td>81 74 36 9 1</td>
<td>64 74 46 13 2</td>
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<tr>
<td>$Wjj$</td>
<td>175 61 20 5 1</td>
<td>125 58 23 6 2</td>
</tr>
<tr>
<td>Multijets</td>
<td>36 66 48 18 7</td>
<td>17 26 24 8 2</td>
</tr>
<tr>
<td><strong>Background Sum</strong></td>
<td>484 348 213 110 43</td>
<td>340 286 191 93 30</td>
</tr>
<tr>
<td><strong>Data</strong></td>
<td>445 357 207 97 35</td>
<td>289 287 179 100 38</td>
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</table>

#### Yields with Zero b-Tagged Jets

<table>
<thead>
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<th>Electron Channel</th>
<th>Muon Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 jet 2 jets 3 jets 4 jets 5+ jets</td>
<td>1 jet 2 jets 3 jets 4 jets 5+ jets</td>
</tr>
<tr>
<td><strong>Signals</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>3 5 2 1 0</td>
<td>1 4 2 1 0</td>
</tr>
<tr>
<td>$t\bar{t}b$</td>
<td>6 16 7 2 1</td>
<td>4 11 6 2 0</td>
</tr>
<tr>
<td>$t\bar{t}+tq\bar{b}$</td>
<td>9 21 10 3 1</td>
<td>5 15 7 2 1</td>
</tr>
<tr>
<td><strong>Backgrounds</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$t\bar{t}+t\ell$</td>
<td>5 14 11 4 1</td>
<td>3 10 8 3 1</td>
</tr>
<tr>
<td>$t\bar{t}+t\ell+jets$</td>
<td>2 13 43 47 24</td>
<td>1 7 28 35 15</td>
</tr>
<tr>
<td>$Wbb$</td>
<td>471 222 92 27 3</td>
<td>300 187 97 28 6</td>
</tr>
<tr>
<td>$Wc\bar{e}$</td>
<td>1,511 856 352 84 9</td>
<td>1,300 953 475 117 19</td>
</tr>
<tr>
<td>$Wjj$</td>
<td>23,242 5,376 1,526 338 50</td>
<td>15,351 4,665 1,569 379 84</td>
</tr>
<tr>
<td>Multijets</td>
<td>1,655 1,365 808 236 78</td>
<td>481 302 198 49 7</td>
</tr>
<tr>
<td><strong>Background Sum</strong></td>
<td>26,886 7,845 2,832 735 165</td>
<td>17,476 6,124 2,375 610 131</td>
</tr>
<tr>
<td><strong>Data</strong></td>
<td>26,925 7,833 2,831 732 178</td>
<td>17,327 6,122 2,378 599 125</td>
</tr>
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#### Yields with Two b-Tagged Jets

<table>
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<th></th>
<th>Electron Channel</th>
<th>Muon Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 jet 2 jets 3 jets 4 jets 5+ jets</td>
<td>1 jet 2 jets 3 jets 4 jets 5+ jets</td>
</tr>
<tr>
<td><strong>Signals</strong></td>
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</tr>
<tr>
<td>$t\bar{t}$</td>
<td>2.3 1.1 0.3 0.1</td>
<td>1.9 0.9 0.3 0.1</td>
</tr>
<tr>
<td>$t\bar{t}b$</td>
<td>0.3 0.8 0.4 0.2</td>
<td>0.2 0.7 0.4 0.1</td>
</tr>
<tr>
<td>$t\bar{t}+tq\bar{b}$</td>
<td>2.6 1.9 0.7 0.2</td>
<td>2.1 1.6 0.6 0.2</td>
</tr>
<tr>
<td><strong>Backgrounds</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$t\bar{t}+t\ell$</td>
<td>5.5 4.6 1.7 0.7</td>
<td>4.6 3.8 1.4 0.5</td>
</tr>
<tr>
<td>$t\bar{t}+t\ell+jets$</td>
<td>1.7 13.6 21.8 11.7</td>
<td>1.0 10.2 18.0 8.1</td>
</tr>
<tr>
<td>$Wbb$</td>
<td>16.2 6.8 1.8 0.3</td>
<td>15.3 8.2 2.3 0.6</td>
</tr>
<tr>
<td>$Wc\bar{e}$</td>
<td>1.6 1.1 0.4 0.1</td>
<td>1.6 1.5 0.5 0.1</td>
</tr>
<tr>
<td>$Wjj$</td>
<td>0.1 0.1 0.0 0.0</td>
<td>0.1 0.1 0.0 0.0</td>
</tr>
<tr>
<td>Multijets</td>
<td>2.5 3.2 2.7 1.4</td>
<td>1.5 1.9 0.4 0.8</td>
</tr>
<tr>
<td><strong>Background Sum</strong></td>
<td>27.5 29.4 28.4 14.2</td>
<td>24.1 25.7 22.7 10.1</td>
</tr>
<tr>
<td><strong>Data</strong></td>
<td>30 37 22 10</td>
<td>23 32 27 10</td>
</tr>
</tbody>
</table>
Compatibility of the New Results

Compatibility of the two new results?

• Performed common pseudo-experiments
  - Fitting EPD and LF discriminants
  - Correlation among fit results: \(~53\%\)
  - \(~6\%\) of the pseudo-experiments had a difference in fit results at least as bad as the difference observed in data

• The results we observe in the data are compatible at the \(~6\%\) level
Measuring Heavy Flavor Fraction in Data

<table>
<thead>
<tr>
<th>Scale Factor $\alpha$ to Match Heavy Flavor Fraction to Data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Electron Channel</strong></td>
</tr>
<tr>
<td>0 tags</td>
</tr>
<tr>
<td>1.53 $\pm$ 0.10</td>
</tr>
<tr>
<td>1.48 $\pm$ 0.10</td>
</tr>
<tr>
<td>1.50 $\pm$ 0.20</td>
</tr>
<tr>
<td>1.72 $\pm$ 0.40</td>
</tr>
<tr>
<td>1 tag</td>
</tr>
<tr>
<td>1.29 $\pm$ 0.10</td>
</tr>
<tr>
<td>1.58 $\pm$ 0.10</td>
</tr>
<tr>
<td>1.40 $\pm$ 0.20</td>
</tr>
<tr>
<td>0.69 $\pm$ 0.60</td>
</tr>
<tr>
<td>2 tags</td>
</tr>
<tr>
<td>—</td>
</tr>
<tr>
<td>1.71 $\pm$ 0.40</td>
</tr>
<tr>
<td>2.92 $\pm$ 1.20</td>
</tr>
<tr>
<td>-2.91 $\pm$ 3.50</td>
</tr>
<tr>
<td><strong>Muon Channel</strong></td>
</tr>
<tr>
<td>0 tags</td>
</tr>
<tr>
<td>1.54 $\pm$ 0.10</td>
</tr>
<tr>
<td>1.50 $\pm$ 0.10</td>
</tr>
<tr>
<td>1.52 $\pm$ 0.10</td>
</tr>
<tr>
<td>1.38 $\pm$ 0.20</td>
</tr>
<tr>
<td>1 tag</td>
</tr>
<tr>
<td>1.11 $\pm$ 0.10</td>
</tr>
<tr>
<td>1.52 $\pm$ 0.10</td>
</tr>
<tr>
<td>1.32 $\pm$ 0.20</td>
</tr>
<tr>
<td>1.86 $\pm$ 0.50</td>
</tr>
<tr>
<td>2 tags</td>
</tr>
<tr>
<td>—</td>
</tr>
<tr>
<td>1.40 $\pm$ 0.40</td>
</tr>
<tr>
<td>2.46 $\pm$ 0.90</td>
</tr>
<tr>
<td>3.78 $\pm$ 2.80</td>
</tr>
</tbody>
</table>

TABLE 21: Scale factor $\alpha$ for the $Wb\bar{b}$ and $Wc\bar{c}$ yields to match the data in each jet bin, for 0 tag, 1 tag, and 2 tag samples. The uncertainties are statistical only.
**Background Sample Optimization**

- Different W+jets backgrounds have different processes, so ideally, for $P(x|B)$ we would use a background model that well describes the data. Alternately, we can treat it as optimization:

$$P(x|B) = w_{Wbb}P(x|Wbb) + w_{Wcg}P(x|Wcg) + w_{Wgg}P(x|Wgg)$$

We optimized the discriminator by assigning different weights:

<table>
<thead>
<tr>
<th>weight per background</th>
<th>wbb</th>
<th>wcb</th>
<th>wgg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron 1tag</td>
<td>0.2</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Electron 2tag</td>
<td>0.67</td>
<td>0</td>
<td>0.33</td>
</tr>
<tr>
<td>Muon 1tag</td>
<td>0.4</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>Muon 2tag</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Cross Checks

- **tb Discriminant - Ht < 175: e+H w/ =2 Jets and Tags Combined**
  - KS: 1
  - Data
  - tb
  - tqb
  - Wbb
  - wcc
  - Wjj
  - QCD
  - tt → ll
  - tt → l+jets

- **tb Discriminant - Ht > 300: e+H w/ =2 Jets and Tags Combined**
  - KS: 0.718
  - Data
  - tb
  - tqb
  - Wbb
  - wcc
  - Wjj
  - QCD
  - tt → ll
  - tt → l+jets

- **tq Discriminant - Ht < 175: e+H w/ =2 Jets and Tags Combined**
  - KS: 1
  - Data
  - tb
  - tqb
  - Wbb
  - wcc
  - Wjj
  - QCD
  - tt → ll
  - tt → l+jets

- **tq Discriminant - Ht > 300: e+H w/ =2 Jets and Tags Combined**
  - KS: 0.429
  - Data
  - tb
  - tqb
  - Wbb
  - wcc
  - Wjj
  - QCD
  - tt → ll
  - tt → l+jets

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