TeVatron Results on Top Quark Physics

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PIC 2004
Discovery of top in 1995 ushered in a new experimental program
  - Fully explore the properties of this newest particle
- ~100 pb\(^{-1}\) of Run I data left every analysis statistically challenged
- Top is intriguing enough to pursue aggressively at Run II

Favorite motivational plot….
Top Quark Physics Opportunities

- A veritable cavalcade of interesting physics in the top sector
  - Studying EW interaction at high energy
  - Direct contact with $V_{tb}$
  - Unique opportunity to probe bare quark properties (spin? charge?)
- Top mass at EWSB scale (Yukawa coupling ~1)… what does this tell us?
  - Is top the gateway to new physics?
Top Production at the TeVatron

- **Pair production**
  - Main mode for top physics at Run II
  - $\sigma = 6.7$ pb
    - $\sim 30\%$ increase w/r/t Run I

![Pair production diagram](attachment:pair_production.png)

- **Single top**
  - Not yet observed
  - Slightly different final states than pair production
  - Larger background
Top Quark Decays

- ~100% $t \rightarrow Wb$ in SM (we’ll be testing that…)
- Categorize final states according to decay of the W bosons

- "DILEPTON:" $l\nu l\nu bb$
  - Both W’s decay to $e$, $\mu$ (maybe through a $\tau$)
  - Clean sample even w/o b-tagging
  - Main BGs: DY, fake leptons, dibosons

- "LEPTON+JETS:" $l\nu jj bb$
  - Something of a “golden mode”
  - ~3x as much BR as dileptons, good purity after b-tagging
  - Main BG: W+jets

- "ALL JETS:" $jjjj bb$
  - Largest BR
  - Huge BG from QCD multijets

- These final states determine what you need to do top physics…
Experimental Tools for Top Physics

- **MET measurement**
  - Cleanly identify final states with neutrinos
- **Jet E measurement**
  - For good mass resol’n and accurate reconstr’n of kinematics
- **Both require a well-calibrated calorimeter w/ as much of 4π as possible**
- **Lepton ID**
  - Need EM calorimeters, muon chambers with as much coverage as possible
  - Z,J/ψ→ll decays provide useful samples for ID efficiency calibration
  - Large jet samples to study fake rates

- **Bottom-quark tagging**
  - Exploit long lifetime of B hadrons
  - Requires precision tracking (Si microstrip detectors) with as much forward reach as possible
CDF and D0 in Run II

Run II upgrades
- New Si, central tracking
- Forward muon systems
- Trigger/DAQ
- CDF: forward calorimeter
- D0: new 2T magnet

Data samples
- About 400 pb$^{-1}$ in the can now
- Results here cut off in SEP-2003
- Varying data subsets for varying analyses; 150-200 pb$^{-1}$
A lepton + jets event at D0

Jet 1
Jet 2
Jet 3
Jet 4

Not shown: MET (58 GeV)
A dilepton event at CDF
Measuring the top pair cross section

• First step in any top physics program
  ▪ Establish baseline event selection for defining the top sample
  ▪ Validate top analysis tools (b-tagging, lepton ID, etc.)

• Interesting measurement
  ▪ Test SM: is $t\bar{t}$ produced via good old QCD? More exotic mechanism (e.g. heavy $t\bar{t}$ resonance)?
  ▪ Is there anything “unknown” in there with top?
Top Pair Cross Section -- dileptons

- Basic selection: two leps (e, μ), two jets, large MET
  - Second lep can be loose -- just an isolated track even!
- Main BGs are DY, dibosons, and j→lep fakes
- Counting experiment results:

<table>
<thead>
<tr>
<th></th>
<th>CDF l+trk (197 pb⁻¹)</th>
<th>CDF di-l (193 pb⁻¹)</th>
<th>D0 di-l (140 pb⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected top+BG</td>
<td>18.4±2.5</td>
<td>10.9±1.4</td>
<td>10.8±0.8</td>
</tr>
<tr>
<td>Observed</td>
<td>19</td>
<td>13</td>
<td>17</td>
</tr>
</tbody>
</table>

D0: \[ \sigma(t\bar{t}) = 14.3^{+5.1}_{-4.3} \text{(stat)}^{+2.6}_{-1.9} \text{(syst)} \pm 0.9 \text{(lum)} \text{ pb} \]
CDF: \[ \sigma(t\bar{t}) = 7.0^{+2.4}_{-2.1} \text{(stat)}^{+1.6}_{-1.1} \text{(syst)} \pm 0.4 \text{(lum)} \text{ pb} \]

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Top Pair Cross Section -- inclusive dileptons

- New CDF technique to measure $\sigma_{tt}$ in dileptons
- No cuts other than two-lep requirement
  - If same-flavor, $Z \rightarrow ee, \mu\mu$ dominates --- require significant MET
- Fit data for $tt$, $WW$, $Z \rightarrow \tau\tau$ contribution in 2D (MET, $N_{jet}$) plane

Result (~200 pb$^{-1}$):

$$\sigma(t\bar{t}) = 8.6^{+2.5}_{-2.4} (stat) \pm 1.1 (syst) \text{ pb}$$

Significant improvement over counting expt!
• b quark ID separates top from dominant W+jets bkgd
  ▪ Lifetime tag methods
    • Find displaced secondary vertex in jet
    • Find tracks with large impact parameters
  ▪ Soft lepton tag methods
    • Find “soft” muons from semileptonic B decay
• Extract cross section from tagged event sample

![Graphs showing D0 sec vtx (45 pb⁻¹) and CDF Run II Preliminary (-161.6 pb⁻¹)]
Top Pair Cross Section -- l+jets topological

- Use higher-statistics “pre-tagged” W+jet data
- Exploit large top mass
  - Top decay products more energetic than generic W+jets

- Simple: fit a discriminant distribution for top, BG
  - $H_T$: scalar sum of jet $E_T$, lepton $E_T$, MET

- Advanced: fit a quantity (ANN, Lhood) composed of several discriminant distribs
Top Pair Cross Section -- All-jet

- Challenging channel --- QCD multijet BG several orders of magnitude larger than top
- Exploit
  - Topological differences between top and BG (preselect top-like events)
  - b-content of top (requires good understanding of tagging rates for BG --- determine from data)
- D0: count single-tagged preselected events with high topo. ANN output
- CDF: count excess tags in preselected $N_{\text{jet}} \geq 6$ events

$$\sigma(t\bar{t}) = 7.7^{+3.4}_{-3.3} \text{ (stat)}^{+4.7}_{-3.7} \text{ (syst)} \text{ pb}$$

$$\sigma(t\bar{t}) = 7.8 \pm 2.5 \text{ (stat)}^{+4.7}_{-2.3} \text{ (syst)} \text{ pb}$$
Observed cross sections consistent with each other...

...and with the SM prediction for $m_t=175 \text{ GeV/c}^2$: $\sigma(t\bar{t}) = 6.7^{+0.7}_{-0.9} \text{ pb}$

Measuring the top mass

- Large mass makes top intimately connected with the Higgs boson
- $m_t$ combined with precision EW data constrains possible value of $m_H$
  - Ex: $\delta m_W^2 \propto (m_t^2, \log m_H)$
- Precision measurement of $m_t$ allows us to squeeze the Higgs mass even further
  - Run II goal: $\Delta m_t = 2--3$ GeV/c$^2$
Catch that article in *Nature* a few weeks ago? (429, pp. 638-642)

\[ m_t = 180.1 \pm 3.6 \text{(stat)} \pm 3.9 \text{(syst)} \text{ GeV/c}^2 \]

- Statistical uncertainty reduced from 5.6 to 3.6 GeV/c^2
  - Equivalent to a 2.4x larger dataset!
- Form an event-by-event likelihood vs. \( m_t \):

\[
P(x, m_t) = \frac{1}{\sigma(m_t)} \int d\sigma(x, m_t) dq_1 dq_2 f(q_1) f(q_2) W(x, y)\]

- “Sharpness” of likelihood effectively weights each event
- Maximize joint likelihood to extract \( m_t \)
Run-I-like “template” methods have been resurrected

- Reconstruct one top mass per event
- Compare resulting mass distribution with parameterized templates from simulated top of varying mass, form Lhood vs. $m_t$
- Minimize $-\ln L$ to extract top mass

Dileptons:

$$m_t = 175.0^{+17.4}_{-16.9} \, (\text{stat}) \pm 8.4 (\text{syst}) \, \text{GeV/c}^2$$

b-tagged l+jets:

$$m_t = 174.9^{+7.1}_{-7.7} (\text{stat}) \pm 6.5 (\text{syst}) \, \text{GeV/c}^2$$

• b-tagged l+jets w/ multivar templates:
  - Uses reconstructed mass and jet $E_T$ sum
  - Decrease sensitivity to BG
  - Weight events according to probability for chosen jet permutation to be correct

$$m_t = 179.6^{+6.4}_{-6.3} (\text{stat}) \pm 6.8 (\text{syst}) \, \text{GeV/c}^2$$
"Dynamical Likelihood Method" --- similar to new D0 method

- Form event-by-event Lhood vs. $m_t$ based on LO ME for $tt\rightarrow l+4j$, transfer functions for quark $E_T \rightarrow$ jet $E_T$
- Minimize $-\ln L$ (joint likelihood of event sample)

No BG ME used, instead correct pull on $m_t$ due to BG:

Mapping function: from measured mass to true mass for a given BG fraction (19% for b-tagged l+4j sample)

Result:

$$m_t = 177.8^{+4.5}_{-5.0} (\text{stat}) \pm 6.2 (\text{syst}) \text{ GeV}/c^2$$

most precise Run II measurement
Top Mass Summary

• New combined Run I mass
  - $m_t = 178.0 \pm 4.3 \text{ GeV/c}^2$
    - was: $174.3 \pm 5.1 \text{ GeV/c}^2$
  - Has implications for allowed Higgs mass --- see talk from S. Mattingly

• New mass measurement techniques being explored for Run II
  - Systematics (read: jet energy scale) quickly becoming limiting factor for individual results
    - *In situ* calibration with $Z\to bb$? $W\to qq$ in double-tagged top events?
Top Branching Ratios -- $t \rightarrow \tau \nu b$

- Taus generally excluded from the dilepton / lepton +jets / all-jets triumvirate
- $\text{BR}(\tau \rightarrow \text{hadrons}) \approx 65\%$
  - Difficult to distinguish from a low-multiplicity jet
- BUT, worth the challenge!
  - Leave no stone unturned
  - $t\rightarrow Wb \rightarrow \tau \nu b$ is all 3rd-generation --- good place for new physics to appear!

Ex: Charged Higgs

- Cleanest signature: $tt \rightarrow l\nu\tau_h\nu b b$
  - (dilepton-like)
- $\tau_h + \text{jets: no results yet!}$
t→τνb in Dilepton Channel

- Select events with high-p_T e or µ, 2 jets, MET, and a τ
- τ ID mainly exploits tendency for taus to be more isolated than jets
  ♣ Need to ensure that this is adequately modelled by simulation

W→τν data and MC: good agreement in shape and norm.

Results:

<table>
<thead>
<tr>
<th></th>
<th>eτ</th>
<th>µτ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total bkgd</td>
<td>0.77±0.18</td>
<td>0.53±0.11</td>
</tr>
<tr>
<td>tt (σ=6.7 pb)</td>
<td>0.59±0.11</td>
<td>0.47±0.08</td>
</tr>
<tr>
<td>Data (193 pb⁻¹)</td>
<td>2</td>
<td>0</td>
</tr>
</tbody>
</table>

\[ r_\tau = \frac{BR(t \to b\tau\nu)}{BR_{SM}(t \to b\tau\nu)} \]

\[ r_\tau < 5.0 @ 95\% CL \]
Top Branching Ratios -- $t \rightarrow Xb$

• Does top decay into something besides $Wb$?
  ▪ Like $Xb$, where $X \rightarrow qq'$? Or $Yb$, where $Y \rightarrow l\nu$?
  ♣ If so, then dilepton and $l+\text{jets}$ cross sections will disagree
• Measure the ratio of cross sections $R_{\sigma} = \sigma_{ll}/\sigma_{lj}$
  ♣ Assume efficiency for detecting $X,Y$ decays the same as for $W$ decays (i.e. similar masses), then

\[
R_{\sigma} = \frac{1}{1 + \frac{1}{B \beta}}
\]

or

\[
R_{\sigma} = 1 + \frac{1}{(1 - B)(1 - \beta')}
\]

B=BR($W \rightarrow \text{hadrons}$)
\[\beta=BR(t \rightarrow Xb)\]
\[\beta'=BR(t \rightarrow Yb)\]

Many systematics cancel in ratio!

• Lower limit on $R_{\sigma} \rightarrow$ upper limit on $\beta$
• Upper limit on $R_{\sigma} \rightarrow$ upper limit on $\beta'$
• SM: $R_{\sigma} = 1$
R_σ Results

- Create ensemble of pseudoexpts w/ mean N_{obs} equal to the data
  - Note: these results based on earlier (smaller) datasets

R_σ = 1.45^{+0.83}_{-0.55}
\beta < 0.46 @ 95% CL
\beta' < 0.47 @ 95% CL

Prospects (expected limits vs. luminosity):
• Assuming three-generation CKM unitarity, $|V_{tb}|=0.999$
  ♦ Implies $b = \frac{\text{BR}(t \rightarrow Wb)}{\text{BR}(t \rightarrow Wq)} > 0.998$

• Can measure “$b$” by checking the $b$-quark content of the top sample --- is it “polluted” with light quarks?
• If efficiency to tag a $b$-quark is $\epsilon_b$ (0.453 at CDF), then

$$\epsilon_2 = (b\epsilon_b)^2 \quad \text{“double-tagged”}$$
$$\epsilon_1 = 2b\epsilon_b(1-b\epsilon_b) \quad \text{“single-tagged”}$$
$$\epsilon_0 = (1-b\epsilon_b)^2 \quad \text{“no-tag”}$$

• Strategy: Take four subsamples of $tt$ $l+\text{jets}$ sample
  ♦ 3 jets, single- and double-tagged
  ♦ 4 jets, single- and double-tagged

• Form likelihood for observed number of events in each sample, maximize joint likelihood w/r/t $b\epsilon_b$
$$b = \frac{BR(t \rightarrow Wb)}{BR(t \rightarrow Wq)}$$

Results

<table>
<thead>
<tr>
<th>Observed (BG)</th>
<th>3 jet</th>
<th>≥4 jet</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 tag</td>
<td>12 (10.0)</td>
<td>19 (4.1)</td>
</tr>
<tr>
<td>2 tag</td>
<td>2 (0.6)</td>
<td>2 (0.4)</td>
</tr>
</tbody>
</table>

Dividing out $\epsilon_b$, 

$$b = 0.54^{+0.49}_{-0.39}$$

Immediate improvements: bringing in dilepton samples, no-tag samples
• Several events in Run I dilepton sample had large MET, lepton $p_T$ --- not very compatible with top
• Suggestion that the events are better described by cascade decays of heavy squarks [Barnett and Hall, *Phys. Rev. Lett.* 77 3506 (1996)]
• Develop search for this kind of anomaly in Run II
  ♣ Stay general --- frame search as null-hypothesis test ($\text{SM} = H_0$)
Four kinematic variables chosen *a priori* to test against SM

- Probability of consistency w/ SM (based on KS probabilities) = 1.0-4.5%
- Low probability driven by excess of low-$p_T$ leptons --- likely fluctuation of top
W Helicity in Top Decays

- Testing V-A in top decays
- Angular momentum conservation: top decays only into LH (negative-helicity) or longitudinally-polarized (0-helicity) W bosons

\[
F_0 = \frac{\Gamma(t \to W_0 b)}{\Gamma(t \to W_0 b) + \Gamma(t \to W_T b)} = \frac{1}{1 + 2(m_W / m_t)^2} = 0.70
\]

- Helicity of W manifests itself in decay product kinematics

Lepton \( p_T \): lepton thrown anti-\( \parallel \) to \( W_{\text{LH}} \), \( \parallel \) to \( W_{\text{RH}} \)

\[\text{Lepton } p_T: \text{ lepton thrown anti-}\parallel \text{ to } W_{\text{LH}}, \parallel \text{ to } W_{\text{RH}}\]

\[\cos \theta^*:\text{ different helicity amplitudes}\]

\[\text{W rest frame}\]

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**F₀ Results**

- New D₀ l+jets result from Run I
- Use mₜ technique
  - Event-by-event likelihood based on observables’ consistency with ME
  - Maximize joint likelihood w/r/t F₀
- Result: F₀ = 0.56 ± 0.31

- CDF result from Run II (l+jets and dilepton)
  - Fit lepton p_T spectrum for W₀ fraction
- Result: F₀ = 0.27 +0.35 −0.24
  - Low-p_T lepton excess seen in dileptons pulls result down
Search for Single Top Production

- Single top production is a direct probe of $|V_{tb}|^2$
- SM cross section too small to observe (for now) but could be increased by new physics (e.g. $W'$, anomalous couplings)
- Signature is lepton, MET, 2 jets w/ at least one b-tag
  - Select events based on these requirements
  - Sandwiched between $tt$ and a large non-top BG --- can’t just do a counting expt
Single Top in Run II

MC templates

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 tt

Fit data distributions for these components

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Run II Single Top Fit Results

\[ \sigma_t < 8.5 \text{ pb} @ 95\% \text{ CL} \]

\[ \sigma_{t+s} < 13.7 \text{ pb} @ 95\% \text{ CL} \]

Will be reporting observations with 2 fb\(^{-1}\)…

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A Few Results from Run I

...all on deck for Run II...
Search for Narrow $M_{tt}$ Resonances

- No SM particle decays to $tt$
  - $M_{tt}$ resonance = new physics
- Example model: topcolor-assisted technicolor (Harris, Hill, Parke, hep-ph/9911288)
  - Predicts leptophobic $Z'$ w/ strong 3rd-gen coupling
- Assume a top mass and go bump hunting!

![Graph showing D0 analysis](image)

$M_X > 560 \text{ GeV/c}^2$
Spin Correlations in $t\bar{t}$

- Particular choice of spin basis ("off-diagonal") provides $\sim 100\%$ correlation between spin of $t$, $t\bar{t}$ produced from $qq\bar{q}$ annihilation.
- Top decays before hadronization perturbs spin
  - $1/\Gamma_t << m_t/\Lambda^2_{\text{QCD}}$
  - Observation of correlations limits $\Gamma_t$, and therefore $|V_{tb}|$

$\frac{1}{\sigma} \frac{d\sigma}{d\cos\theta_+ d\cos\theta_-} = \frac{1 + \kappa \cos\theta_+ \cos\theta_-}{4}$

$\kappa = 0.88$ in SM

Detector effects, underconstrained kinematics...

D0 observed

$\kappa > -0.28$ @ 68\%CL
Conclusions

• A full-fledged experimental top program is underway at the TeVatron

• Analyses have been re-established, and…

• Lots of progress in “taking them to the next level”
  ▪ New techniques to better exploit the data

• Nothing unexpected about top turned up so far
  ▪ Attacking from many sides, but need to squeeze harder with more data

• The top picture will get clearer and clearer in the coming years