Top Physics at the Tevatron

Physics at the LHC, 2010
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Julia Thom, Cornell University
Top Quark Physics

Most massive elementary particle
– Discovered in 1995, only few dozen candidates in 0.1 fb⁻¹

• Any effects from new physics?
  – Studies with 2-5 fb⁻¹ for this talk

• Top quark mass is a fundamental parameter in the Standard Model and beyond
  – Induces significant radiative corrections to W boson mass
  – Reduced uncertainty on top quark mass imposes tighter constraints on unknowns, like Standard Model Higgs boson or SUSY

• Significant background to many searches for new physics at LHC

Julia Thom, CU
Outline

• The top signature and how to separate signal from background
  • Top Quark Production
    – Top pairs, mass
    – Searches for anomalous production
    – Single top
  • Tests of Top Quark Decay
    – W boson helicity in top decays
    – Probe the W-t-b vertex

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Identifying top events

Events classified by decays of the two W bosons:

- **“lepton+jets”:** 4 jets (2 from b) and missing $E_T$ from $\nu$
  - BF=24/81, but significant background from W+jet production

- **“dilepton”:** 2 jets and missing $E_T$ from $\nu$
  - Clean, but low stat. BF=4/81

- **“hadronic”:** 6 or more jets
  - BF=36/81, but large QCD multijet background
  - Jet energy scale uncertainty, combinatorics
“l+jets” events, background suppression

- Key is identification of at least 1 b-jet. Background reduced to $W_{bb}$ (few % of $W$+jets background)

- 2 techniques:
  - Secondary vertex tag: find decay vertex of long-lived hadron in jet.
  - Soft lepton tag: lepton in jet from semileptonic decay of B

- Typically at least one b-tag required for a top l+jet candidate
Secondary vertex tag

Efficiency per b-jet: \(~50\%\) (top)
False positive rate: \(~1\%\)

CDF beampipe, \(r=1.26\) cm, and first layer of silicon microstrip detector

Tagged Jet 1: \(E_T = 111\) GeV, \(\Phi = 79\), \(L2d = 7\) mm
Tagged Jet 2: \(E_T = 38\) GeV, \(\Phi = 355\), \(L2d = 1\) mm

Number of Jets = 4
Missing \(E_T\) = 45 GeV
Muon \(P_T\) = 37 GeV
I+jets+btag analysis, limiting factors

- Dominant background is $W+bb, cc$ ("$W+HF$"), and predicting it leads to one of the dominant systematics
- Important to understand $W+HF$ normalization in exclusive jet bins (single top, Higgs discovery,..)

Control region
W+HF backgrounds

- Normalize ALPGEN W+jets (pretag) to data:

\[ N_{W+\text{jets}}^{\text{pretag}} = N_{\text{data}}^{\text{pretag}} - N_{\text{QCD}}^{\text{pretag}} - N_{\text{EWK}}^{\text{pretag}} - N_{\text{top}}^{\text{pretag}} \]

- determine heavy flavor fraction in ALPGEN W+jets
- Measure correction factor K to heavy flavor fraction
  \[ W+HF = \text{normalized } W+\text{jets} \times K \times \text{heavy flavor fraction} \]
- at CDF, K extracted in W+1 jet control region:

  \[ K_{\text{CDF}} = 1.4 \pm 0.4 \]
  \[ K_{\text{D0}} = 1.5 \pm 0.45 \]

Kin.observables: top decay products are more central and more energetic than background
• **Top quark production**
  – Top pairs, mass
  – Searches for anomalous production
  – Single top

• **Top quark decay**
  – *W* boson helicity in top decays
  – *Probe the W-t-b vertex*
pair production cross section

Produce top in pairs via strong interaction. At $m_t = 170$ GeV/c$^2$
$\sigma = 7.8 \pm 1$ pb


$\sigma_{tt} = \frac{N_{\text{data}} - N_{\text{bkg}}}{A \cdot \varepsilon \cdot L}$

85% at the Tevatron  15% at the Tevatron

candidate events

backgrounds from MC and data

geometric acceptance and efficiencies from MC (mostly)

integrated luminosity

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Cross section results 1

$\sigma_{tt} = 7.50 \pm 0.31(\text{stat}) \pm 0.34(\text{syst}) \pm 0.15(\text{Lumi}) \text{ pb}$

$\Delta \sigma / \sigma = 6.5\%$

CDF Run II Preliminary 4.6 fb$^{-1}$

CDFII
Cross section results 2

dilepton channel:

\[ \sigma_{tt} = 8.4 \pm 0.5(\text{stat}) \pm 0.9(\text{syst}) \pm 0.6(\text{Lumi}) \text{ pb} \]
Cross section results 2
Top Mass

- Challenge: associate measured objects to initial state quarks and leptons (incl. neutrino), extract best possible 4-vector for each
  - E.g. Matrix element method: determine probability density for each combination

- Major systematic: Jet Energy Scale
  - Run II: constrain JES uncertainty using reconstructed hadronic W ("in-situ calibration"), fit for both JES and top mass
March 2009 Tevatron combination:

\[ m_{\text{top}} = 173.1 \pm 0.6 \text{(stat)} \pm 1.1 \text{(syst)} \text{GeV/c}^2 \]

Precision now systematics limited, (but JES scaling with statistics)
Tevatron Combination (March 2009)
New CDF measurement: 4.6 fb$^{-1}$

- Most precise single measurement, l+jets channel
- As before, likelihood per event is calculated by integration over the matrix element. Assume all events are signal
- Neural Network distinguishes background, accounted for as a correction in the Likelihood

$$\log L_{\text{sig}}(m_t, \text{JES}) = \sum_{\text{events}} \left[ \log L_i(m_t, \text{JES}) - f_{\text{bg}}(q_i) \log L_{\text{avg}}(m_t, \text{JES} | bkg) \right]$$

\[ m_t = 172.8 \pm 0.7 \text{(stat)} \pm 0.6 \text{ (JES)} \pm 0.8 \text{ (syst)} \text{ GeV/c}^2 \]
Searches for Anomalous Production of $t\bar{t}$

Expect no resonance production in SM, but NP models predict $t\bar{t}$ bound states. Reconstruct invariant mass of the $t\bar{t}$ system:

$\frac{d\sigma}{d m_{t\bar{t}}}$

Tail is PDFs + new physics?

Threshold is $2M +$ smearing

vector color singlet
Hill, Parke ’94
Searches for massive $X \rightarrow t\bar{t}$

Threshold: $2m_t$ (+ smearing)

...but disappears with more data.

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Massive $X \to \ttbar$ search

- L+jets channel, at least 1 b tag
Massive $X \to \bar{t}t$ search

- Extract Poisson probability for signal consistency using simulation of resonance processes
- Largest excess less than 2 sigma at $X$ mass $\sim 650$ GeV
- Place limit on leptophobic $Z'$: $M_{Z'} > 820$ GeV/$c^2$
Search for Anomalous Production: Forward Backward Asymmetry

- $Z'$ can change top “charge asymmetry”: compare number of top and anti-top produced with momentum in a given direction
- Interpret as forward backward asymmetry (top moving for or against given direction), in pp lab frame
- $A_{fb} = \frac{N_t(p) - N_t(\bar{p})}{N_t(p) + N_t(\bar{p})}$
- Choosing $\Theta$ between top momentum and proton beam direction:
  \[ A_{fb} = \frac{N_t(\cos(\theta) > 0) - N_t(\cos(\theta) < 0)}{N_t(\cos(\theta) > 0) + N_t(\cos(\theta) < 0)} \]
- In $l+\text{jets}+\text{btag}$ channel: tag $t$ vs $\bar{t}$ with lepton charge, use hadronic side to measure top rapidity
Results, $A_{FB}$

- $\chi^2$ based kinematic fitter, correct for experimental effects
- small pp lab frame charge asymmetry expected in QCD at NLO, $A_{fb} = 0.05 \pm 0.015$ (interference ISR and FSR diagrams)
- Using 3.2 fb$^{-1}$:
  
  $A_{fb} = 0.193 \pm 0.065$ (stat) $\pm 0.024$ (syst) (pp$^-$lab frame)

consistent with 0.9 fb$^{-1}$
published D0 result

$A_{fb} = 0.12 \pm 0.08$ (stat)
$\pm 0.01$ (syst)
Results, $A_{FB}$

- Check modeling of background in sample with no btags
Single Top

- Observation in 2009 (2.3-3.2 fb\(^{-1}\))
- Charged EWK production only, direct probe of top weak coupling
  - Measure \( V_{tb} \) \( \sigma(q\bar{q}', qg \rightarrow tb) \propto |V_{tb}|^2 \)
- Important background to Higgs searches
- NP (e.g. FCNC) can alter rates

```
“t-channel”
2pb

“s-channel”
0.9pb
```
Single Top production

• Same selection as top pairs, but signal is in W+2j
• Difficult due to large W+2j background. S/B=1/20
• Expected signal yield is smaller than background uncertainties! Not a counting experiment..
Single Top analysis strategy

**full selected data set**

- **$W + 2$ jets**
  - 1 tag
  - $\geq 2$ tags

- **$W + 3$ jets**
  - 1 tag
  - $\geq 2$ tags

- **$W + 4$ jets**
  - 1 tag
  - $\geq 2$ tags

- **split in subsets of different purity**

**neural networks**

**matrix elements**

**likelihood discriminants**

$$L'(\vec{x}) = \frac{\prod_{i=1}^{n_{\text{me}}} p_i^j(x_i)}{\sum_{i=1}^{n_{\text{me}}} \prod_{j=1}^{n_{\text{me}}} p_i^j(x_i)}$$

**boosted decision trees**

**multivariate methods**

**combined search**

- t-channel + s-channel = one single-top signal
- cross section ratio is fixed to SM value.
- important for "discovery" and test $|V_{tb}| \ll 1$

**separate search**

- regard t-channel and s-channel as separate processes
- important to be sensitive to new physics processes

**cross section measurement**

Bayesian treatment

**hypotheses test**

modified Frequentist approach

**statistical analysis**

D0 only

CDF only

Thanks to Wolfgang Wagner
Kinematic modeling of input variables

- $P_T^{\text{lepton}}$
- $M_T(W)$
- $\eta (\text{jet 1})$
Single top results CDF
8 different l+jet+ET analyses combined…..

..into single “Super Discriminant”

CDF Run II Preliminary, $L = 3.2 \text{ fb}^{-1}$
- Single Top
- W+HF
- $t\bar{t}$
- QCD+Mistag
- Other
- Data
CDF results

8 l+jet+Et and 3 MET+jets analyses:

$|V_{tb}| = 0.91 \pm 0.11 \text{(exp.)} \pm 0.07 \text{ (theory)}$

$\sigma = 2.3 + 0.6 - 0.5 \text{ pb}$
2D fit for $\sigma_s$ and $\sigma_t$

Fitting $\sigma_s$ and $\sigma_t$ separately: $\sigma_t = 0.8 \pm 0.4$ pb
And $\sigma_s = 1.8^{+0.7}_{-0.5}$ pb
D0 results

- $s, t$ channel fit together, assuming SM ratio
- 2,3,4 jets, 1,2 b-tagged, 1 lepton, missing $E_T$
- 4519 events, 223$\pm$30 expected from ST
- Multivariate discriminant
D0 t-channel result

- Measured Peak
- SM
- Ztu FCNC $g_{Ztu} = 0.04 g_Z$
- $|V_{ts}| = 0.2$
- Top Flavor $m_{\chi} = 1\text{TeV}$
- Top Pion $m_{\pi} = 250\text{GeV}$

- 68% C.L.
- 90% C.L.
- 95% C.L.
$|V_{tb}| > 0.78$ @ 95% CL

$\sigma = 3.49 \pm 0.88$ pb

$\sigma (p\bar{p} \rightarrow tb+X, t\bar{q}b+X)$ [pb]
<table>
<thead>
<tr>
<th>Single Top Cross Section</th>
<th>Signal Significance</th>
<th>CKM Matrix Element $V_{tb}$</th>
</tr>
</thead>
</table>
| **DØ (2.3 fb$^{-1}$)**  | March 2009          | $|V_{tb}f^L_1| = 1.07 \pm 0.12$
   |                     | $|V_{tb}| > 0.78$ at 95% CL |
| 3.94 ± 0.88 pb          | 4.5 σ               |                           |
| 2.3 $^{+0.6}_{-0.5}$ pb | >5.9 σ              |                           |
| **CDF (3.2, 2.1 fb$^{-1}$)** | March 2009        | $|V_{tb}f^L_1| = 0.91 \pm 0.13$
   |                     | $|V_{tb}| > 0.71$ at 95% CL |
| 2.76 $^{+0.58}_{-0.47}$ pb |                   |                           |
• Top quark production and properties
  – Top pairs, mass
  – Anomalous production
  – Single top

• **Top quark decay**
  – W boson helicity in top decays
  – Probe the W-t-b vertex
W helicity fractions in t->Wb decay

- fraction of longitudinally ($f_0$) and right-handed ($f_+\) polarized W bosons from top-quark decay
- SM at $tWb$ vertex predicts 70% longitudinal W
- Measure via angular distribution:
W helicity results, 2D model independent fit (f0,f+)

CDF: matrix element analysis in lepton+jets channel.
\[ f_0 = 0.88 \pm 0.11 \text{ (stat)} \pm 0.06 \text{ (syst)} \]
\[ f^+ = -0.15 \pm 0.07 \text{ (stat)} \pm 0.06 \text{ (syst)} \]

D0: template analysis in dilepton and l+jets channels.
\[ f_0 = 0.490 \pm 0.106 \text{ (stat)} \pm 0.085 \text{ (syst)} \]
\[ f^+ = 0.110 \pm 0.059 \text{ (stat)} \pm 0.052 \text{ (syst)} \]
Anomalous couplings

SM lagrangian with form factors $f_1^L=1$, $f_1^R=f_2^L=f_2^R=0$

$$L_{tWb} = \frac{g}{\sqrt{2}} W_\mu^- b \gamma^\mu \left( f_1^L P_L + f_1^R P_R \right) t - \frac{g}{\sqrt{2} M} \partial_\nu W_\mu^- b \sigma^{\mu\nu} \left( f_2^L P_L + f_2^R P_R \right) t$$


D0 combines measurements of W helicity, single top kinematics into analysis of $tWb$ vertex, investigating pairs of form factors

find 95%CL if $f_1^L=1$, $|f_1^R|^2<0.72$, $|f_2^L|^2<0.19$, $|f_2^R|^2<0.20$
Top Spin

- Top anti-top spins are correlated only if top lifetime is short enough. Can observe correlation in top decay products
- Measure angle of decay products (leptons, jets) in top rest frame with respect to a chosen quantization axis, e.g. top helicity axis

CDF l+jets analysis: 4.3 fb-1

\[
\frac{1}{\sigma} \int d^2 \sigma = \frac{1}{4} (1 - C \cos \theta_1 \cos \theta_2)
\]

- Spin correlation parameter $C$
Top Spin results

D0: dilepton sample, measure angles with respect to beam axis. SM expectation NLO C = 0.78

\[
C = -0.17 \pm 0.64 - 0.53 \text{ (stat+syst)}
\]

CDF: l+jet sample, template analysis, 2D fit to angular distribution of quark to lepton. Using helicity basis. SM: C = 0.4 (NLO)

\[
C = 0.60 \pm 0.50 \text{ (stat)} \pm 0.16 \text{ (syst)}
\]
Top Charge

- Test hypothesis: top quark is an exotic particle with $q_t = -4/3$ ("XM")? D. Chang et al., PRD 59 (1999) 091503
- L+jets events with 2 tags
- Kinematic fitter associates b jets to had/lept. W decay

Soft e,m in b jet

OS : SM
SS : XM

in 2.7 fb$^{-1}$: 29 events consistent with SM and 16 events consistent with a $q = -4/3$ top quark.
Result: 95% exclusion of the -4/3 charge hypothesis
Top width

- SM prediction ~1.5 GeV at $m_t=175$ GeV/c$^2$
- $l+\text{jet}$ channel $\geq 1$ btag, $\geq 4$ jets
- Minimize $\chi^2$ function for $m_t$
- 2D template fit ($m_t, m_{jj}$) to data to extract top width

95% Confidence Level: $\Gamma_{\text{top}} < 7.5$ GeV
68% Confidence Level: $0.4$ GeV $< \Gamma_{\text{top}} < 4.4$ GeV
• Broad program of measurements of top quark properties ongoing at the Tevatron
• RunII dataset is beginning to provide sensitive searches for NP in top production and decay
  – SM agreement (so far)
  – results using up to 4.7fb$^{-1}$ of data
  – Have ~7fb$^{-1}$ on tape, expect >10fb$^{-1}$ until end of RunII
• Uncertainty on the top mass (individual measurements) is <1%!
• Work provides guidance and focus for LHC top program and beyond
Backup Slides
Search for Heavy Top $t' \rightarrow Wq$

Search for heavy top decay to $Wq$ final states (e.g. LHT)

- $l+jets$ (no $b$-tag requirement)
- Template method for top reconstruction
- Use observed $H_T$ and mass distribution to fit signal $t'$ and background (top, $W$, ..) distributions

- exclude a standard model fourth-generation $t'$ quark with mass below 335 GeV at 95% CL.
New CDF measurement: 4.6fb-1

- As before, signal likelihood calculated by integration over the matrix element (x: parton level, y: measured quantities)
- Gives probability that we observe an event with kinematic variables y as a function of true top mass and JES shift parameter “JES”

\[ L = \frac{1}{N(m_t)} \frac{1}{A(m_t, JES)} \sum_{i=1}^{24} w_i \int \frac{f(z_1) f(z_2)}{TF} \frac{M_{\text{eff}}(m_t, \bar{x})^2}{\Phi(\bar{x})} \]
Top mass in all hadronic channel

- Event selection in 6-8 jets (no MET) via NN:

\[ m_t = 174.8 \pm 1.7\text{(stat.)} \pm 1.9\text{(syst.)} \text{ GeV/c}^2 \]
QCD background estimation

3 techniques to evaluate QCD
• Met vs iso
• Matrix technique
• Anti-electron/jet technique

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

\[
N_{\text{tight}} = \varepsilon_{\text{fake-\ell}} N_{\text{loose}}^{\text{fake-\ell}} + \varepsilon_{\text{real-\ell}} N_{\text{loose}}^{\text{real-\ell}}
\]
classic top mass measurement

• Step 1: Associate measured objects with initial state using best match ($\chi^2$) to 3 constraints:
  - $M_{jj}=M_W$
  - $M_{l\nu}=M_W$
  - $M_{l\nu b}=M_{qqb}$

• Step 2: jet energy correction according to species
  - $E$ scale for light jets tuned to match $M_W$
  - $E$ scale for $b$ jets adjusted via tuned MC

• Step 3: one invariant mass per event
  – Final mass comes from best fit to MC template vs. $M_{top}$

3-4 years ago:
controlling the JES uncertainty

- Dominant contribution to $\delta m_t$ from Jet Energy Scale uncertainty
- $\sigma_{\text{JES}}/\text{JES}$ between 3 and 6%
- RunII: constrain JES uncertainty using reconstructed hadronic $W$ ("in-situ calibration")
  - JES uncertainty scales with statistics

constrain inv.mass of non-tagged jets to be 80.4 GeV
Matrix Element Method

Matrix Element Method: define probability $P_{evt}$ that the observed kinematics arise from possible signal or background kinematics at parton level, then maximize $L = \prod P_{evt}(M_{top}, JES)$

$$P_{evt}(\tilde{x}) = f_{top} \cdot P_{sig}(\tilde{x}, m_t, JES) + (1 - f_{top}) P_{bkg}(\tilde{x}, JES)$$

$$P_{sig}(\tilde{x}) = \frac{1}{\sigma(m_t, JES)} \int f(q_1) dq_1 f(q_2) dq_2 \times |M(\tilde{y})|^2 \phi(\tilde{y}) dy \times W(\tilde{x}, \tilde{y}; JES)$$

D0 3.6 fb$^{-1}$, l+jets

$m_t = 173.7 \pm 0.8$ (stat) 
$\pm 0.8$ (JES) 
$\pm 1.4$ (syst) GeV/c$^2$
Search for Anomalous Production: Forward Backward Asymmetry

- Z’ can change top “charge asymmetry”: compare number of top and anti-top produced with momentum in a given direction
- Interpret as forward backward asymmetry (top moving for or against given direction), in pp rest frame

\[ A_{fb} = \frac{N_t(p) - N_t(\bar{p})}{N_t(p) + N_t(\bar{p})} \]

- Measure top rapidity