Review of Recent Top Quark Measurements

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- Theory
- Reconstruction
- Backgrounds
- Results
  - Top quark pairs
  - Single top quarks
  - Top properties
  - Top mass
- Future
Top Quarks

Spin 1/2 fermion, charge +2/3
- Isospin partner of the bottom quark

~40x heavier than its partner
- 178.0 ± 4.3 GeV from Tevatron Run I

Produced mostly in pairs at the Tevatron
- 85% $q\bar{q}$, 15% $gg$
- Cross section = $6.8 \pm 0.4$ pb at NNLO
Top Quark Decay

Top decays before it can hadronize

- **Lifetime** $\Gamma_{\text{top}}^{-1} = (1.5 \text{ GeV})^{-1} \ll \Lambda_{\text{QCD}}^{-1} = (200 \text{ MeV})^{-1}$

Top decays to $W^+b$ 99.9% of the time

Classify $t\bar{t}$ events by the decays of the $W$'s

- **Dileptons**
  - $e^+e^- + b\bar{b} + \not{E}_T$
  - $e\mu + b\bar{b} + \not{E}_T$
  - $\mu^+\mu^- + b\bar{b} + \not{E}_T$

- **Lepton+jets**
  - $e + jj + b\bar{b} + \not{E}_T$
  - $\mu + jj + b\bar{b} + \not{E}_T$

- **Alljets**
  - $jj + jj + b\bar{b}$

Need to reconstruct and identify:

- Electrons, muons, light-jets, $b$-jets, and missing transverse energy
Detection and Reconstruction

- Tevatron detectors have new tracking systems, many upgrades to calorimeters and muon systems
- Run II, April 2002 – July 2004
  - CDF has collected 500 pb^{-1} of data (400 pb^{-1} with SVXII)
  - DØ has collected 450 pb^{-1} of data
- Analyses shown here use 100–200 pb^{-1} → several million triggered events
- Select final samples to maximize measurement sensitivity
  - Find ~100 top quark events above background so far
Backgrounds

Events with real $W$ or $Z$ bosons
- $W$+jets
- $Z$+jets
- $WW, WZ, ZZ$

Events with misidentified leptons
- Multijet events with a jet misidentified as an electron
- $b\bar{b}$+jets with a misidentified electron or muon from a $b$ decay

Miscellaneous sources
- Cosmic rays, multiple $p\bar{p}$ interactions, pattern recognition mistakes, etc.

For most $t\bar{t}$ decay channels, processes with a real $W$ boson and real $b$ jets are the most difficult to remove.
**b-Jet Identification**

**DØ — “Silicon Microstrip Tracker”**
- 792,576 channels in barrels and disks
- **b-ID algorithms**
  - Secondary vertex (SVT)
  - Jet lifetime probability (JLIP)
  - Counting signed impact parameter (CSIP)
  - Muon-in-jet (SLT)

**CDF — “Silicon Vertex Detector II”**
- plus an inner layer and outer layers
  - 722,432 channels, in barrels
- **b-ID algorithms**
  - Secondary vertex (SVX)
  - Muon-in-jet (SLT)

Probability to tag at least one jet in a $t\bar{t}$ event = 55%
Probability for a fake tag = 0.4%

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**tt Overcross Section**

- Compare measurements with \( \sigma_{\text{theory}}(p\bar{p} \rightarrow t\bar{t} + X) = 6.8 \text{ pb} \)
  - 0.03% of the \( W \) cross section

- The CDF collaboration has made 10 measurements
  - Dileptons = 3, Lepton+jets = 6, Alljets = 1

- The DØ collaboration has made 7 measurements
  - Dileptons = 2, Lepton+jets = 4, Alljets = 1

- Baseline samples for measurements of top quark properties
CDF Dileptons and Alljets Xsecs

Two opposite-sign leptons, $H_T > 200$ GeV

Fit all SM processes in $E_T$--$N_{jets}$ plane

A lepton and an opposite-sign track

Cut on $A, C, E_T^{j1:j8}, E_T^{j3:j8},$ SVX-tag

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CDF Lepton+Jets Xsecs

Muon-in-jet tag

Fit to $H_T$ distribution (no tag)

Two or more SVX-tagged jets

SVX-tag and fit to $E_T$(jet1) distribution

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CDF L+Jets Xsecs

CDF Run II Preliminary

$\sigma(p\bar{p} \rightarrow t\bar{t}) \ (pb)$

$m_t=175 \ GeV/c^2$

Lepton + Track
$7.0 \pm 2.7 \pm 1.5 \ (L=200 pb^{-1})$

Lepton + Lepton
$8.4 \pm 3.2 \pm 1.6 \ (L=193 pb^{-1})$

Dileptons: SM Fit
$8.6 \pm 2.5 \pm 1.1 \ (L=200 pb^{-1})$

Lepton + Jets: Kinematic
$4.7 \pm 1.6 \pm 1.8 \ (L=195 pb^{-1})$

Lepton + Jets: Kinematic NN
$6.7 \pm 1.1 \pm 1.8 \ (L=195 pb^{-1})$

Lepton + Jets: Vertex Tag + Kinematic
$6.0 \pm 1.5 \pm 0.8 \ (L=162 pb^{-1})$

Lepton + Jets: Soft Muon Tag
$5.4 \pm 2.4 \pm 1.1 \ (L=162 pb^{-1})$

Lepton + Jets: Vertex Tag
$5.6 \pm 2.5 \pm 1.0 \ (L=162 pb^{-1})$

Lepton + Jets: Double Vertex Tag
$4.1 \pm 2.0 \pm 0.9 \ (L=126 pb^{-1})$

All Hadronic: Vertex Tag
$7.8 \pm 2.5 \pm 4.7 \ (L=165 pb^{-1})$

28%

SVX-tag and $H_T > 200 \ GeV$

Fit to output of 7-variable NN

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DØ Dileptons, Alljets, L+Jets Xsecs

Two opposite-sign leptons, $M_{ll}$ and $H_T$

Three NNs, 9+4 variables, SVT-tag

Electron+muon, SVT-tag

Muon-in-jet tag, loose $A$ and $H_T$ cuts

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DØ L+Jets Xsecs

DØ Results

DØ Run II Preliminary

Xsec in pb

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\[ \sigma(p\bar{p} \rightarrow t\bar{t}) \text{ [pb]} \]

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Cross Section Summary

- Run I results:  
  - CDF $\sigma(t\bar{t}) = 6.5^{+1.7}_{-1.4}$ pb  
  - DØ $\sigma(t\bar{t}) = 5.7 \pm 1.7$ pb  
  - 26–30% uncertainty  
  - Agree with calculation, 5.2 ± 0.3 pb

- Run II cross section is 30% higher than Run I ($\sqrt{s} = 1.8$ TeV → 1.96 TeV)  
  - Theory calculation is 6.8 ± 0.4 pb

- Best Run II measurements so far are CDF lepton+jets results  
  - SVX-tag and $H_T > 200$ GeV, 6.7 ± 1.9 pb with 162 pb⁻¹  
  - Neural network with 7 variables, 5.6 $^{+1.4}_{-1.2}$ pb with 195 pb⁻¹  
  - Consistent with theory

- Run II results from many channels not yet combined  
  - Best measurement uncertainties are 28% so far  
  - Aiming for 10% with 2 fb⁻¹
Single Top Quarks

- Electroweak production of top quarks not yet observed
- Two main production modes at the Tevatron

\[ \sigma(p\bar{p} \to t\bar{b}, \bar{t}b + X) = 0.88 \pm 0.07 \text{ pb} \]

- About half the cross section of \( t\bar{t} \), but backgrounds are much higher
- Single top events can be used to measure \(|V_{tb}|\) without assuming three quark generations, and hence to determine top quark width
- Observation is hoped for with 1–2 fb\(^{-1}\) of data
CDF Single Top

**Fit to** $H_T^{\ell\nu jj\ell}$ and SVX $b$-tag

\[ \sigma(s + t\text{-channels}) < 13.5 \text{ pb} \ (95\% \ CL) \]

**Fit to** $(Q \times \eta)$ and SVX $b$-tag

\[ \sigma(t\text{-channel}) < 8.5 \text{ pb} \ (95\% \ CL) \]

DØ Single Top

**New Results**

**Fit to** $(Q \times \eta)$ and SVX $b$-tag

\[ \sigma(s\text{-channel}) < 19 \text{ pb} \ (95\% \ CL) \]

\[ \sigma(t\text{-channel}) < 25 \text{ pb} \]

\[ \sigma(s + t\text{-channels}) < 23 \text{ pb} \]
Top Quark Properties

Many interesting measurements are possible – all need high statistics

- Production
  - $g_{tt}$ and $W_{tb}$ couplings
  - Spin correlations
  - New particles
- Decay
  - Width $\Gamma$
  - CKM matrix element $|V_{tb}|$
  - Gluon radiation
  - $W$ boson helicities
  - Branching fractions
  - $p_T$ spectra
  - Charge
  - Rare decays
CDF $W$ Helicity

(Run II)

Lepton+jets

Dileptons

Fit left-handed ($F_L$) and longitudinally polarized ($F_0$) $W$ boson fractions in lepton $p_T$

$F_0 = 0.88^{+0.12}_{-0.47}$ (lepton + jets)
$F_0 < 0.52$ 95% CL (dileptons)
$F_0 = 0.27^{+0.35}_{-0.24}$, $< 0.88$ (combined)

$F_0 = 0.70$ (Standard Model)

Low dilepton value caused by excess of events at low lepton $p_T$

DØ $W$ Helicity

(Run I Data)

Matrix element method to reconstruct $t\bar{t}$ events

$F_0 = 0.56 \pm 0.31$ (lepton+jets)

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Ten years of measuring the top quark mass

Methods have developed significantly over this time
- First, just kinematic fitting and compare to templates in $m_{\text{top}}$
- Then add more variables and use likelihoods
- Best methods use all available information

Measurement uncertainty improves with both time and more data
- The first measurements (1995) had a ≥7% uncertainty
- Current Run II measurements have a 5% uncertainty each
- Run I combined measurement has a 2.4% uncertainty
- Run II goal is a 1% uncertainty on $m_{\text{top}}$ (±1.5–2.5 GeV)
CDF Top Mass – Run II Data

Template Method, 6 Dilepton Events (1 ee, 3 eμ, 2 μμ)

\( m_{\text{top}} = 175.0 \text{ GeV} \pm 16.9 \text{ (stat)} \pm 8.4 \text{ (syst)} \)

(11% uncertainty)

Template Method, 28 Lepton+Jets Events with SVX \( b \)-tag

\( m_{\text{top}} = 174.9 \text{ GeV} \pm 7.7 \text{ (stat)} \pm 6.5 \text{ (syst)} \)

(5.8% uncertainty)

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CDF Top Mass – Run II Data

**Multivariate Template Method**, 33 Lepton+Jets Events with SVX b-tag

- $m_{\text{top}} = 179.6 \ GeV$
- $+6.4 \ (\text{stat}) \pm 6.8 (\text{syst})$
- (5.2% uncertainty)

**Dynamical Likelihood Method**, 22 Lepton+Jets Events with SVX b-tag

- $m_{\text{top}} = 177.8 \ GeV$
- $+4.5 \ (\text{stat}) \pm 6.2 (\text{syst})$
- (4.5% uncertainty)
DØ Top Mass – Run I Data

Matrix Element Method

- All features of individual events are included
- Well-measured events contribute more information than poorly-measured ones
- 22 Run I lepton+jets events re-analyzed

$$m_{\text{top}} = 180.1 \text{ GeV} \pm 3.6(\text{stat}) \pm 4.0(\text{syst})$$
(3.0% uncertainty)

- Result published in Nature, June 2004
- First experimental HEP paper published in that journal

Run II Data

Three measurements in progress
- Template Method
- Ideogram Method
- Matrix Element Method

Results available soon

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Top Quark Mass Summary

**Best result**
Average of DØ and CDF measurements using Run I data

(Run II results not yet combined)

**Top and the Higgs boson**
Top quark mass gives us information about the Higgs boson
- Top couples strongly to the Higgs
- Top plays a critical role in loop corrections

Most likely Higgs boson mass is 117 GeV
95% CL upper limit is 251 GeV

\[ m_{\text{top}} = 178.0 \pm 4.3 \text{ GeV} \]
Future Top Quark Physics

- Large Hadron Collider, \( pp \) at \( \sqrt{s} = 14 \) TeV, start-up April 2007
  - \( tt \) will be 90\% from \( gg \), 10\% from \( q\bar{q} \) (opposite to the Tevatron)
  - 10\(^7\) \( tt \) pairs per year for first three years, then 10\(^8\) per year
  - (Compare with Tevatron, 10\(^4\) produced per year)

- Linear Collider, \( e^+e^- \) at \( \sim \sqrt{s} = 360 \) GeV \( (m_{tt}) \) for top measurements
  - \( tt \) cross section lower than Tevatron, but luminosity much higher
  - 10\(^6\) \( tt \) pairs per year and much smaller backgrounds
Expected Future Sensitivities

All top quark properties, SM and non-SM couplings, rare production and decay modes will be studied in detail
(except rare SM decay $t \rightarrow WbZ$, which cannot be reached at the LHC)

Top quark mass

- Similar precision expected at LHC and Tevatron, $\sim 1$ GeV
  - Limited by final state radiation

- At LC, scan $t\bar{t}$ threshold,
  fit $m_{\text{top}}(1S), \alpha_s(M_Z), \Gamma_{\text{top}}, g_{tH}$
  to measurements of
  $\sigma_{t\bar{t}}, p_{\text{top}}, A_{FB}^{\text{top}}$,
  measure $m_{\text{top}}(1S)$ to 20 MeV

- Converting $m_{\text{top}}(1S)$ to $m_{\text{top}}(\overline{\text{MS}})$
  limits $m_{\text{top}}(\overline{\text{MS}})$ uncertainty to $\sim 100$ MeV
Summary

- The Tevatron is the only top quark factory until LHC turn-on in 2007
  - The collider is meeting performance expectations
  - DØ and CDF are collecting data at high efficiency

- Expect about 80x more data in Run II than Run I (100 pb $\rightarrow$ 8 fb$^{-1}$)

- Many first measurements now available
  - All consistent with the Standard Model
  - Need more data to reduce statistical and systematic uncertainties
  - Need more time to apply more sophisticated analysis methods

- Precision top quark physics program is just around the corner

- The top quark will provide a unique window into hidden parts of the Standard Model and many regions beyond