Top Quark Physics

Mousumi Datta
Fermi National Accelerator Laboratory for the CDF and DØ Collaborations

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Outline

- Introduction
- Exploring top properties
  - Top quark production
  - Top quark mass
  - Other top properties
    - Forward backward asymmetry, tWb coupling, spin correlation
  - Search for beyond the Standard Model (SM) physics
- Summary and prospects
Top Quark Physics

- Existence required by the SM
  - Spin 1/2 fermion, charge +2/3, weak-isospin partner of the bottom quark
- Discovered in 1995 at Tevatron
- Mass surprisingly large $\Rightarrow \sim 40\times$ heavier than the bottom quark
  - Only SM fermion with mass at the EW scale
- Top decays before hadronization: $\Gamma \sim 1.4$ GeV $\gg \Lambda_{\text{QCD}}$
  - Provide an unique opportunity to study a "bare" quark
- Currently only produced at Tevatron
Why Study Top Properties?

Try to address some of the questions:

- Why is top so heavy?
- Is top related to the EWSB mechanism?
  - Seesaw theory of EWSB ((PRD 59, 075003 (1999); PRD 65, 055006 (2002)))
- Is it the SM top?
- Search for beyond SM physics: Does top decay into new particles? Couple via new interactions?

**Pair production**
- Cross section
- $t\bar{t}$ resonance search
- Forward-backward asymmetry
- Production mechanism
- Spin-correlations, FCNC,

**EW-single top**
- Cross section
- Anomalous coupling
- $W'$ search, ...

**Decay**
- W helicity
- Anomalous couplings
- Charged Higgs

**Characteristics**
- Mass
- Life-time, Charge, Spin....
Accelerators

Tevatron Run II
Proton-antiproton collider (2001-2011)
$\sqrt{s} = 1.96$ TeV
$\sigma_{tt} = \sim 6.7$ pb at $m_{top} = 175$ GeV/c$^2$
$\sigma_{\text{single top}} = \sim 2.9$ pb at $m_{top} = 175$ GeV/c$^2$
Experiments: CDF, DØ

Large Hadron Collider (LHC)
Proton-proton collider (2009-)
$\sqrt{s} = 10-14$ TeV
$\sigma_{tt} = \sim 833$ pb at $m_{top} = 175$ GeV/c$^2$
$\sigma_{\text{single top}} = \sim 315$ pb at $m_{top} = 175$ GeV/c$^2$
Experiments: ATLAS, CMS
Tevatron Run II Performance

- Doubled data set each year for four years
- Peak Luminosity record $3.18 \times 10^{32}$ cm$^{-2}$-sec
- Total integrated luminosity delivered $\sim 6.7$ fb$^{-1}$
- $\sim 6$ fb$^{-1}$ recorded per experiment
The CDF and DØ Detectors

- Silicon tracking
- Large radius drift chamber (r=1.4m)
- 1.4 T solenoid
- Projective calorimetry (|\(\eta\)| < 3.5)
- Muon chambers (|\(\eta\)| < 1.0)
- Particle identification
- Silicon Vertex Trigger

- Silicon tracking
- Outer fiber tracker (r=0.5m)
- 2.0 T solenoid
- Hermetic calorimetry (|\(\eta\)| < 4)
- Muon chambers (|\(\eta\)| < 2.0)
- New trigger and more silicon in Summer 2006 (Run2b)

All crucial for top physics!

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Top Quark Production

- At hadron colliders
  - Predominantly pair produced via strong interaction
  - Electro-weak single top production

Tevatron: $\sigma_{s\text{-channel}}=0.9$ pb, $\sigma_{t\text{-channel}}=2.0$ pb
(for $m_{\text{top}}=175$ GeV/c²)

Tevatron ~85%  ~15%
Top Quark Production (Cont’)

One top pair per 10 billion inelastic collisions at Tevatron
Top Quark Decay

- In the SM: $\text{Br}(t \rightarrow Wb) \sim 100\%$
- Decay channels classified by W decays
- Top pair decay channels ($l=e, \mu$)
  - Dilepton: $lvlvbb$
  - Lepton+jets: $lvqqbb$
  - All-hadronic: $qqqqbb$
- Single top decay channels
  - s-channel: $tb \rightarrow Wbb \rightarrow lvbb$
  - t-channel: $tq(b) \rightarrow Wbq(b) \rightarrow lvbq(b)$
  (overwhelming background prevents using hadronic W decays for single top)
Experimental Challenges

b-tagging

Jet Energy Scale

- And more: background and signal modeling, background estimation, etc.
Signal-to-Background Ratio (S/B)

- b-tagging provides significant background suppression
- Dilepton: Manageable S/B even without b-tagging
- Lepton+Jets: Good S/B after b-tagging
  - Remaining dominant background from W+jets
- All-hadronic: Huge QCD background
  - S/B ~1/1000 at trigger level
  - Needs additional effort for background suppression
    - Neural network (NN) based event selection has been used

<table>
<thead>
<tr>
<th>S/B at Tevatron</th>
<th>Dilepton (≥4 jets)</th>
<th>Lepton+Jets (≥4 jets)</th>
<th>All-hadronic (After NN Selection)</th>
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</thead>
<tbody>
<tr>
<td>0 b-tag</td>
<td>1:1</td>
<td>~1:4</td>
<td>~1:20</td>
</tr>
<tr>
<td>1 b-tag</td>
<td></td>
<td>4:1</td>
<td>1:5</td>
</tr>
<tr>
<td>2 b-tags</td>
<td>20:1</td>
<td>20:1</td>
<td>1:2</td>
</tr>
</tbody>
</table>

Most top properties analyses use relatively clean event sample
Top Physics at Tevatron

Robust program of top quark measurements

- Many measurements in all the different channels → **consistency**
- Different methods of extraction with different sensitivity → **confidence**
- Combine all channels and all methods → **precision**
Top Quark Production

Top pair production cross section
Single top production cross section
Top Pair Production Cross-Section

- Tests QCD in very high $Q^2$ regime.
- Compare measured cross sections among various $t\bar{t}$ final states
  - Anomalies in the $t\bar{t}$ rate would indicate the presence of non-QCD production channels: for example resonant state $X \rightarrow t\bar{t}$
- Provides important sample composition for all other top property measurements.
Measure using b-tagged ($\geq 1$ b-tags) and pre-tag ($\geq 0$ b-tags) events

$$\sigma_{tt}(\text{b-tagged}) = 7.2 \pm 0.4 \text{(stat)} \pm 0.5 \text{(syst)} \pm 0.4 \text{(lumi)} \text{ pb}$$

$$\sigma_{tt} \text{ (pre-tag) } = 7.1 \pm 0.4 \text{(stat)} \pm 0.4 \text{(syst)} \pm 0.4 \text{(lumi)} \text{ pb}$$

$$\Delta \sigma / \sigma = \sim 10 \% \text{. Dominated by uncertainty on luminosity}$$
Reduce luminosity systematic by normalizing with respect to Z cross section

\[ \sigma_{\bar{t}t} / \sigma_Z \]

\[ \sigma_{\bar{t}t} = R \sigma_{z \to \ell \ell}^{\text{theory}}, \quad R = \frac{\sigma_{\bar{t}t}}{\sigma_z} \]

\[ \sigma_{z \to \ell \ell}^{\text{theory}} = 251.3 \pm 5.0 \quad \text{pb} \]

\[ \sigma_{\bar{t}t} \text{ (pre-tag)} = 7.0^{+0.4}_{-0.4} \text{ (stat)}^{+0.4}_{-0.4} \text{ (syst)} \pm 0.4 \text{ (lumi)} \text{ pb} \]

\[ \sigma_Z = 253.3 \pm 1.0 \text{ (stat)}^{+4.4}_{-4.6} \text{ (syst)}^{+16.6}_{-13.7} \text{ (lumi)} \text{ pb} \]

\[ \frac{1}{R} = 36.5^{+2.1}_{-2.3} \text{ (stat)}^{+1.9}_{-2.0} \text{ (syst)} \]

\[ \sigma_{\bar{t}t} \text{ (pre-tag)} = 6.9 \pm 0.4 \text{ (stat)} \pm 0.4 \text{ (syst)} \pm 0.1 \text{ (theory)} \text{ pb}, \quad \Delta \sigma_{\bar{t}t} / \sigma_{\bar{t}t} = \sim 8\% \]

\[ \sigma_{\bar{t}t} \text{ (b-tagged)} = 7.0 \pm 0.4 \text{ (stat)} \pm 0.6 \text{ (syst)} \pm 0.1 \text{ (theory)} \]
All-Hadronic Channels

Measurement performed using the signal yields derived from a previous top quark mass measurement

\[ \sigma_{tt} = 7.2 \pm 0.5 \text{(stat)} \pm 1.4 \text{(syst)} \pm 0.4 \text{ (lumi)} \text{ pb} \]

for \( M_{\text{top}} = 172.5 \text{ GeV/c}^2 \)
ttbar Cross Section Results

- Consistent among channels, methods and experiments
- Limited by systematic uncertainties
- Uncertainties comparable to the theoretical uncertainty

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ttbar + jet Cross Section

- Test of pQCD
- Use events in lepton+jets channel with ≥1 b tag and ≥3 jets
- Break up ttbar sample into 2 samples 0j and +j
- Simultaneously measure cross sections for both samples

\[ \sigma_{t\bar{t}+j} = 1.6 \pm 0.2_{\text{stat}} \pm 0.5_{\text{syst}} \text{ pb} \]
\[ \sigma_{t\bar{t}+j}^{\text{theory}} = 1.79^{+0.16}_{-0.31} \]

\[ \sigma_{t\bar{t}+0j} = 5.5 \pm 0.4_{\text{stat}} \pm 0.7_{\text{syst}} \text{ pb} \]

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Physics of EW Single Top Production

- The SM predictions (PRD70, 114012 (2004))
  - $\sigma_{s\text{-channel}} = 0.88 \pm 0.11 \text{ pb}$
  - $\sigma_{t\text{-channel}} = 1.98 \pm 0.25 \text{ pb}$
    (for $m_{\text{top}} = 175 \text{ GeV/c}^2$)

- Direct measurement of $V_{tb}$: (S. Willenbrock, Rev. Mod. Phys. 72, 1141-1148)
  \[ \sigma_{\text{single top}} \propto |V_{tb}|^2 \]

- Produced $\sim 100\%$ polarized top, can be used to test the V-A structure of the top EW interaction. (G. Mahlon, hep-ph/9811219)

- Sensitive to beyond SM physics
  - $t\text{-channel}$: 4th family, FCNC
  - $s\text{-channel}$: $W'$, $H^+$
Experimental Challenge

- **Experimental signatures:**
  - One high $P_T$ isolated $e$ or $\mu$
  - Large missing transverse energy
  - $\geq 2$ jets ($\geq 1$ $b$-tag)
- Suffers from large amount of $W$+jets backgrounds

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Extracting Single Top Signal

- No single variable provides significant signal-background separation
- Perform multivariate analysis ⇒ take advantage of small signal background separation in many variables
Single Top Measurements

CDF Preliminary Single Top Summary
For $M_{top} = 175$ GeV/c$^2$

- S-Channel Likelihood Function (3.2 fb$^{-1}$) $1.5 \pm 0.9$ pb
- Neural Network (3.2 fb$^{-1}$) $1.8 \pm 0.6$
- Matrix Element (3.2 fb$^{-1}$) $2.5 \pm 0.7$
- Likelihood Function (3.2 fb$^{-1}$) $1.6 \pm 0.8$
- Boosted Decision Tree (3.2 fb$^{-1}$) $2.1 \pm 0.7$
- Combination (Lepton+Jets) (3.2 fb$^{-1}$) $2.1 \pm 0.6$
- MET+Jets (2.1 fb$^{-1}$) $4.9 \pm 2.6$
- Combination (All Channels) (3.2 fb$^{-1}$) $2.3 \pm 0.6$

Single Top Production Cross Section (pb)


DØ 2.3 fb$^{-1}$

- Decision Trees $3.74 \pm 0.95$ pb
- Bayesian NNs $4.70 \pm 1.18$ pb
- Matrix Elements $4.30 \pm 0.99$ pb
- BLUE Combination $4.16 \pm 0.84$ pb
- BNN Combination $3.94 \pm 0.88$ pb

$\sigma (p\bar{p} \rightarrow tb+X, tqb+X)$ [pb]

March 2009

N. Kidonakis, PRD 74, 014012 (2006) $m_{top} = 170$ GeV
Observation of Single Top Production

- CDF and D0 both report >5σ observation Mar-2009
- $V_{tb}$ measurement
  - CDF: $|V_{tb}| = 0.91 \pm 0.11$ (exp.) $\pm 0.07$ (theory), $|V_{tb}| > 0.71$ at 95% CL
  - D0: $|V_{tb}^{fl_1}| = 1.07 \pm 0.12$, $|V_{tb}| > 0.78$ at 95% CL

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Top Mass
Why measure the Top Quark Mass?

- Related to standard model observables and parameters through loop diagrams
- Consistency checks of SM parameters
- Precision measurements of the $M_{\text{top}}$ (and $M_W$) allow prediction of the $M_{\text{Higgs}}$
- Constraint on Higgs mass can point to physics beyond the standard model

$\Delta M_W \propto M_{\text{top}}^2 \quad \Delta M_W \propto \ln M_H$

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Uncertainty on JES ⇒ About 3% systematic uncertainty on Top mass measurement when convoluted with ttbar $p_T$ spectrum
**In-situ Measurement of JES**

- Additionally, we use $W \rightarrow jj$ mass resonance ($M_{jj}$) to measure the jet energy scale (JES) uncertainty.

Measurement of JES scales directly with statistics!
Top Mass : Lepton+Jets Channel

- Use event-by-event likelihood based on leading order \( t\bar{t} \) cross section.

  - **Most precise top mass measurements from single channels**

  \[ m_{\text{top}} \text{ with 3.6 fb}^{-1} \text{ D0 data:} \]
  \[
  173.7 \pm 1.3 \text{ (stat+JES)} \pm 1.4 \text{ (syst)} \text{ GeV/c}^2
  \]

  \[ m_{\text{top}} \text{ with 3.2 fb}^{-1} \text{ CDF data:} \]
  \[
  172.1 \pm 1.2 \text{ (stat+JES)} \pm 1.1 \text{ (syst)} \text{ GeV/c}^2
  \]
Combine Run I measurements with most recent Run II measurements
Take into account the statistical and systematic uncertainties and their correlations (NIM A270 (1988) 110, NIM A500 (2003) 391)
Combined top mass

\[ 173.1 \pm 1.3 \text{ GeV}/c^2 \]

\[ \chi^2/\text{ndof} = 6.3/10 \Rightarrow 79\% \text{ prob} \]
- Good agreement among all input measurements

Top mass known with relative precision of 0.75%
Uncertainties on Measured Top Mass

<table>
<thead>
<tr>
<th>Source</th>
<th>$\Delta M_t$ (GeV/c²)</th>
</tr>
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<tbody>
<tr>
<td>jet energy scale:</td>
<td>0.73</td>
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<tr>
<td>t-tbar modeling:</td>
<td>0.71</td>
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<tr>
<td>background:</td>
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</tr>
<tr>
<td>lepton energy scale:</td>
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<tr>
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<tr>
<td>Systematic:</td>
<td>1.07</td>
</tr>
<tr>
<td>Statistical:</td>
<td>0.65</td>
</tr>
</tbody>
</table>

- Uncertainty dominated by sources which should continue scale with the statistics of the sample
- With full Run II data set could reach a total uncertainty of $\Delta M_t \sim 1$ GeV/c²
Direct Measurement of the Mass Difference Between Top and Anti-top

- Test of CPT invariance
- Use lepton+Jets events and matrix element method
- $M_{\text{top}} - M_{\text{anti-top}} = 3.8 \pm 3.7 \text{ GeV/c}^2$
- Relative mass difference (2.2±2.2)%
- The first measurement of a mass difference of bare quarks.
Other Top Properties
Forward Backward Asymmetry $(A_{fb})$ in Top Pair Production

- Asymmetry caused by interference of ME amplitudes for same final state
- The SM prediction:
  - In $tt\bar{t}$ frame: $A_{fb}^{tt\bar{t}} = 0.05 \pm 0.015$ (QCD at NLO)
- Can be significantly enhanced in different BSM models:
Forward Backward Asymmetry ($A_{fb}$) in Top Pair Production

- $A_{fb}$ measured in the ttbar rest frame

$$A_{\bar{t}t}^{fb} = \frac{N(\Delta Y > 0) - N(\Delta Y < 0)}{N(\Delta Y > 0) + N(\Delta Y < 0)}$$

$$\Delta Y = -Q_\ell \cdot (Y_{t,\text{leptonic}} - Y_{t,\text{hadronic}})$$

- CDF apply unfolding to go from reconstructed to parton level

$$A_{fb} = 0.193 \pm 0.065 \text{ (stat)} \pm 0.024 \text{ (syst)}$$

SM Prediction: $A_{fb} = 0.05 \pm 0.015$

- DØ: no unfolding and acceptance correction: $A_{fb} = (12 \pm 8 \pm 1) \%$ (PRL 100, 142002 (2008))
  - Set limits on $Z'$ production
A_{fb} Dependence on the Invariant Mass of ttbar

- Scan for A_{fb} above and below 8 different M_{tt} thresholds
- Sensitive to new physics effect

**Parton Level A_{FB}**

- Below M_{tt} Edge
  - CDF II Preliminary L=3.2 fb^{-1}
  - A_{FB} ± σ_{stat}
  - ± σ_{syst}
  - Integral A_{FB} = 19.3% with flat mass dependence
  - NLO Model

- Above M_{tt} Edge
  - CDF II Preliminary L=3.2 fb^{-1}
  - A_{FB} ± σ_{stat}
  - ± σ_{syst}
  - Integral A_{FB} = 19.3% with flat mass dependence
  - NLO Model

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The SM top decays via EW interaction: $\text{Br}(t \rightarrow bW) \sim 100\%$
- Top decays as a bare quark $\Rightarrow$ spin info transferred to final states

V-A coupling in the SM $\Rightarrow$
- longitudinal fraction $f_0 \sim 70\%$
- left-handed fraction $f_- \sim 30\%$
- right-handed fraction $f_+ \sim 0\%$

The SM prediction modified in various new physics models

Can use $\cos \theta^*$ to measure $f_0$, $f_+$, $f_-$. 
- $\cos \theta^*$ : Angle between lepton and $b$ in $W$ rest frame.
W-boson Helicity Fractions

- Measure $f_0$ and $f_+$ simultaneously $\Rightarrow$ model independent
- D0 Lepton+jet and Dilepton 2.7 fb$^{-1}$
  
  $f_0 = 0.49 \pm 0.11$ (stat) $\pm 0.09$ (syst)

  $f_+ = 0.11 \pm 0.06$ (stat) $\pm 0.05$ (syst)

- CDF Lepton+Jets 2 fb$^{-1}$
  
  $f_0 = 0.62 \pm 0.10$ (stat) $\pm 0.05$ (syst)

  $f_+ = -0.04 \pm 0.04$ (stat) $\pm 0.03$ (syst)

Consistent with the Standard Model
Generic Wtb Coupling

- Constrain form factors for anomalous tWb coupling
  - Combine information from single top production and W helicity measurement from ttbar decay

\[ L_{tWb} = \frac{g}{\sqrt{2}} W^-\bar{b} \gamma^\mu \left( f^L_1 P_L + f^R_1 P_R \right) t - \frac{g}{\sqrt{2} M_W} \partial_\nu W^-\bar{b} \sigma^{\mu\nu} \left( f^L_2 P_L + f^R_2 P_R \right) t \]

- Standard Model  \( f^L_1 = 1, \quad f^L_2 = f^R_1 = f^R_2 = 0 \)

\[ |f^R_1|^2 < 0.72 \]

for  \( |f^L_1|^2 = 1 \)

\[ |f^L_2|^2 < 0.19 \text{ @ } 95\% \text{ CL} \]

\[ |f^R_2|^2 < 0.20 \]

Consistent with Standard Model

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**ttbar Spin Correlations**

- Use off-diagonal basis: \( \tan \xi \equiv \sqrt{1-\beta^2} \tan \theta^* \). In ttbar frame: \( \beta \equiv \text{top velocity} \) and \( \theta^* \equiv \text{top flight direction w.r.t. proton direction} \).
- Templates: angular distribution of (cos \( \theta_+ \), cos \( \theta_- \)) and (cos \( \theta_b \), cos \( \theta_{\bar{b}} \)).
- **CDF Results**
  - \(-0.455 < \kappa < 0.865\) (68\% C.L.) or \( \kappa = 0.320^{+0.545}_{-0.775} \) for \( M_t = 175 \text{ GeV/c}^2 \)
  - The SM predicts \( \kappa \sim 0.8 \).

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ttbar Spin Correlations (Cont’)

- D0 measures decay products (l⁺,l⁻) angular correlation coefficient C

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

- θ₁ (θ₂): angle between the flight direction of l⁺ (l⁻) and direction of flight of one of the colliding hadrons in the ttbar rest frame

- D0 result:

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

<table>
<thead>
<tr>
<th>coefficient</th>
<th>LO</th>
<th>NLO</th>
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</thead>
<tbody>
<tr>
<td>C</td>
<td>0.928</td>
<td>0.777</td>
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</tbody>
</table>
Search for Beyond the Standard Model Physics
Resonant ttbar Production

- Search for resonant ttbar production from the decays of massive Z-like bosons
- Set upper limits on Leptophobic Z’ boson with mass $M_{Z'}$
- Lepton+Jets channel: $M_{Z'} > 820 \text{ GeV/c}^2$ at 95% CL
- All-hadronic channel: $M_{Z'} > 805 \text{ GeV/c}^2$ at 95% CL
More Top Physics Results From Tevatron

Apologies for my many omissions.

For a full listing of results go to:

http://www-cdf.fnal.gov/physics/new/top/top.html

http://www-d0.fnal.gov/Run2Physics/WWW/results/top.htm
Summary and Outlook

- Top quark properties are currently being studied at Tevatron
  - ttbar cross-section and top mass measurements
    - Most measurements are systematically limited
    - Mass measured to 0.8% precision
  - First observation of single top
  - Study other properties of top quark, search for new physics
    - Almost all the measurements are limited by statistics at present
    - Increasing data from Tevatron will further help reveal the true nature of top quark ⇒ Expect ~10 fb⁻¹ by 2011
- LHC will open up a new era of Top physics ⇒ Top factory
  - Understanding of systematic uncertainties would become crucial
  - Top is a standard candle, tool for calibrating JES, b-tagging
- Tevatron’s top physics program and understanding of systematic effects will continue to play a significant role for years to come