Experimental Top Quark Physics
Part I

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Outline

- Part I: top quark production
  - Tt production
  - Single top production
- Part II: Properties
  - Top quark mass
  - Spin correlations
- Part III: Asymmetry and searches
  - t\bar{t} asymmetry
  - Direct searches in the top sector (Overview)
Part I: Production

- $t\bar{t}$ cross section
  - Methods
  - Background determination
- Differential cross sections
- Single top
The Standard Model

- Described the fundamental particles and their interactions
  - 6 quarks and leptons + their antiparticles
  - 4 fundamental forces (Gravity not in SM)
- 1960: Electromagnetic and weak interaction unification by S. Glashow
- Weinberg and Salam 1967: incorporated Higgs mechanism into SM
- 1973: discovery of weak currents caused by $Z \rightarrow$ establishing of SM
- All this happened way before the discovery that a 3$^{rd}$ family existed!
**Brief History of the Top Quark**

- **1976:** Discovery of Upsilon at Fermilab
  - Contains a 5\(^{th}\) quark: the b-quark
  - Structure of quark families **suggested existence of a 6\(^{th}\) quark:** the top
- From here on the race to find the top began
  - Petra (e\(^+\)e\(^-\)): \(m_t > 23.3\text{GeV}\) in 1984
  - Tristan (e\(^+\)e\(^-\)) in Japan: \(m_t > 30.2\text{GeV}\) in late 80s
  - SPS (p\(\bar{p}\)): discovery of W and Z in 1983
  - UA1: \(m_t > 44\text{GeV}\) in 1988
    (after having an excess in 1984 which they thought was evidence for top)
  - LEP: \(m_t > 45.8\text{GeV}\) in 1990
  - UA2: \(m_t > 69\text{GeV}\)
    - \(W \rightarrow t\bar{b}\) search channel closed down
Searching again for $t\bar{t}$ production with top mass above $W$ mass

- **1992**: First lower limits on top from CDF ($m_t > 91\text{GeV}$)
- **1994**: First lower limits on top from DØ ($m_t > 131\text{GeV}$)
- Electroweak fits from LEP/SLC/Tevatron data: $155\text{GeV} < m_t < 185\text{GeV}$
- Early **1994**: “Evidence” for top at CDF
Discovery Datasets

- **February 24th 1995**: Simultaneous submission of Top Discovery papers to PRL, by CDF and DØ

  - 50 pb$^{-1}$ at DØ
    - $m_t = 199\pm30$ GeV
    - $t\bar{t} = 6.4\pm2.2$ pb
    - Background-only hypothesis rejected at 4.6

  - 67 pb$^{-1}$ at CDF
    - $m_t = 176\pm13$ GeV
    - $t\bar{t} = 6.8^{+3.6}_{-2.4}$ pb
    - Background-only hypothesis rejected at 4.8
TOP Announcement

- March 2nd, 1995: First announcement of Top Discovery in public seminar at Fermilab
Discovery of lonely Tops

- **2009**: Observation of top quarks in single top production
  - 5 by CDF & DØ!
- Single top: very challenging channel
  - Low signal: similar signature like W+jets!
  - Counting only: Uncertainty on background larger than expected signal
    → use of multivariate techniques

![Graph showing single top quark cross section](image)

**Single Top Quark Cross Section**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Process Description</th>
<th>Cross Section</th>
<th>December 2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>DØ</td>
<td>$e/\mu +$ jets</td>
<td>2.3 fb$^{-1}$</td>
<td>3.94 ±0.88 pb</td>
</tr>
<tr>
<td>DØ</td>
<td>$\tau +$ jets</td>
<td>4.8 fb$^{-1}$</td>
<td>3.4 ±2.0 pb</td>
</tr>
<tr>
<td>CDF</td>
<td>$e/\mu +$ jets</td>
<td>3.2 fb$^{-1}$</td>
<td>2.17 ±0.56 pb</td>
</tr>
<tr>
<td>CDF</td>
<td>$\ell_\tau +$ jets</td>
<td>2.1 fb$^{-1}$</td>
<td>5.0 ±2.6 pb</td>
</tr>
<tr>
<td>Tevatron Combination</td>
<td>Preliminary</td>
<td>2.76 ±0.58 pb</td>
<td></td>
</tr>
</tbody>
</table>

$m_{\text{top}} = 170$ GeV
Celebrating Single Top Discovery

- March 10th, 2009: Wine&Cheese seminar at Fermilab to announce single top observation
Where Top Quarks can be produced: The Tevatron

- Tevatron: proton antiproton collisions
  - Run I: 1992-1996 with $\sqrt{s}=1.8$ TeV
  - Run II: March 2001 to 30.09.2011, 14:00 with $\sqrt{s}=1.96$ TeV
Where Top Quarks can be produced: The LHC

- LHC: 7 (2011) or 8 (2012) TeV proton-proton collisions
  - Started operation in 2010
- Highest energies reached today
- Top Quark Factory
Top Quark Pair Production

- Via strong interaction
- At the Tevatron:

At LHC (7 TeV cms energy):

- Production cross section (@Tevatron): 
  \[ \sigma = 7.24^{+0.23}_{-0.27} \text{ pb} \] 
  @ \( m_t = 172.5 \text{ GeV} \)
- About 20 times higher at LHC

Baernreuther, Cakon, Mitov, PLB 710, 612 (2012)
Final States in $t\bar{t}$

t\bar{t} \to W^+bW^-\bar{b} : Final states are classified according to $W$ decay

$B(t\to W^+b)=100\%$
Final States in $t\bar{t}$

$t\bar{t} \rightarrow W^+ b W^- \bar{b}$: Final states are classified according to $W$ decay

$B(t \rightarrow W^+ b) = 100$

**pure hadronic:**
$\geq 6$ jets (2 b-jets)

**dilepton:**
2 isolated leptons;
High missing $E_T$ for neutrinos;
2 b-jets

**lepton+jets:**
1 isolated lepton;
Missing $E_T$ for neutrino;
$\geq 4$ jets (2 b-jets)
Cross Section: General

- The first thing we want to know: Production cross section

\[ N_{\text{production}} = \sigma \times L \]
The first thing we want to know: Production cross section

\[ N_{\text{production}} = \sigma \times L \]
The first thing we want to know: Production cross section

\[ N_{\text{production}} = \sigma \times L \]

Selection required

Background modeling crucial

\[ N_{\text{post-selection}} = \sigma \times L \times \epsilon \]
Signal and background events

**lepton+jets**

W+jets: Main background in l+jets

**dilepton**

Z+jets: Main background in dilepton

**pure hadronic**

Multijet: Modeled from Data Main background in allhadronic
Cross Section: Selection

- Knowing signal and background event signatures, we now need to enrich the data sample in signal events

- Important tools:
  - B-tagging
  - Multivariate analysis techniques
Selection: Example l+jets

- Select according to **topology and kinematics** of the final state

One **isolated lepton** with high $p_T$

Large **missing transverse energy** to account of the neutrino

At least 4 jets with high $p_T$ and central; sometimes certain number of tracks pointing to primary vertex required

Additional requirements on angles; e.g. angle between lepton and MET should not be back-to-back to reduce mismeasurements
Background Determinations: Multijet

Before Selection:

- W+jets
- $t\bar{t}$
Before Selection:

Require *loose* isolated lepton

\[ N_{\text{loose}} = N_{\text{fake}} + N_{W-\text{like}} \]
Background Determinations: Multijet

Before Selection:

Require loose isolated lepton

\[ N_{\text{loose}} = N_{\text{fake}} + N_{W-\text{like}} \]

Require tight isolated lepton

\[ N_{\text{tight}} = \epsilon_{\text{fake}} \cdot N_{\text{fake}} + \epsilon_{\text{true}} \cdot N_{W-\text{like}} \]
Background Determinations: Multijet

Before Selection:

W+jets

\( t\bar{t} \)

Require **loose** isolated lepton

\[ N_{\text{loose}} = N_{\text{fake}} + N_{W-\text{like}} \]

\[ N_{\text{tight}} = \epsilon_{\text{fake}} \cdot N_{\text{fake}} + \epsilon_{\text{true}} \cdot N_{W-\text{like}} \]

Require **tight** isolated lepton

\( N_{\text{fake}} \) from MM equation
Multijet Background
Determination: The Matrix Method

Matrix Method requires fake rate and true lepton rate

\[ N_{\text{loose}} = N_{\text{fake}} + N_{W-\text{like}} \]

\[ N_{\text{tight}} = \epsilon_{\text{fake}} \times N_{\text{fake}} + \epsilon_{\text{true}} \times N_{W-\text{like}} \]

\( \epsilon_{\text{fake}} \): determined from multijet-dominated dataset
  - For example for low missing transverse energy \( \rightarrow \) multijet dominated

\( \epsilon_{\text{true}} \): can be either
  - determined from \( W+\text{jets/}\bar{t}\bar{t} \) MC sample (DØ), or
  - From tag and probe in \( Z+\text{jets} \) sample (ATLAS)
Background Determinations: W+jets

- Main background in l+jets final state: W+jets contribution
- Challenge:
  - Theory predictions not accurate enough for background determination (esp. for events with many jets)
  - W+heavy flavor relative to W+light flavor contribution not known precisely enough
- Various methods for determination of total \( W+jets \) contribution
  - Fit to Data before b-jet identification
  - \( W+jets \) determination example at Atlas: charge asymmetry method
- Heavy Flavor Fraction determination usually by comparing yields in different b-tag bins
**W+jets background**

**Determination: Asymmetry Method**

- W-boson production at pp collider: charge asymmetric
  - $u\bar{d} \rightarrow W^+$ versus $d\bar{u} \rightarrow W^-$ (uud valence quarks, $\bar{d}, \bar{u}$ sea quarks)
- Well understood quantity:
  $$r = \frac{\sigma(pp \rightarrow W^+)}{\sigma(pp \rightarrow W^-)}$$
**W+jets background**

**Determination: Asymmetry Method**

- W-boson production at pp collider: charge asymmetric
  - \( u\bar{d} \rightarrow W^+ \) versus \( d\bar{u} \rightarrow W^- \) (uud valence quarks, \( \bar{d}, \bar{u} \) sea quarks)
- Well understood quantity:
  \[ r = \frac{\sigma(pp \rightarrow W^+)}{\sigma(pp \rightarrow W^-)} \]
- Calculate W+jets using \( r \):
  \[ N_{W^+} + N_{W^-} = \frac{N_{W^+}^{MC} + N_{W^-}^{MC}}{N_{W^+}^{MC} - N_{W^-}^{MC}} (D^+ - D^-) = \frac{r_{MC} + 1}{r_{MC} - 1} (D^+ - D^-) \]
  - \( D^+ \) and \( D^- \): data with positive (negative) charged leptons
    - Using approximation that all other backgrounds are charge symmetric
  - \( r_{MC} \): evaluated using MC, using signal region kinematic cuts
B-Tagging

- Further enrichment of $t\bar{t}$: b-jet identification
B-Tagging

- Further enrichment of $t\bar{t}$: b-jet identification
- B-Hadron: travels some millimeters before it decays
- Use properties of displaced vertices and/or displaced vertices to
**B-Tag Cross Section Example**

- Example from DØ: b-tagging
  - Counting only
  - Main systematic uncertainty usually from b-tagging uncertainties

**l+jets; 3 jets**

<table>
<thead>
<tr>
<th>Number of b-tagged jets</th>
<th>Number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>10^4</td>
</tr>
<tr>
<td>1</td>
<td>10^3</td>
</tr>
<tr>
<td>≥2</td>
<td>10^2</td>
</tr>
</tbody>
</table>

**l+jets; ≥4 jets**

<table>
<thead>
<tr>
<th>Number of b-tagged jets</th>
<th>Number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2000</td>
</tr>
<tr>
<td>1</td>
<td>1600</td>
</tr>
<tr>
<td>≥2</td>
<td>1200</td>
</tr>
</tbody>
</table>
Cross Section: Other Methods

- Base signal-background separation on kinematic properties
  - Use many variables with small discrimination
Cross Section: Other Methods

- Base signal-background separation on kinematic properties
  - Use many variables with small discrimination
  - Combine using multivariate analysis technique

![Graphs and diagrams illustrating signal-background separation techniques.](image-url)
Multivariate Analysis Techniques

- Variety of various techniques on the market
  - Boosted decision trees, random forests, neural networks, etc.
- Example: decision tree
  - Idea: divide multi-dimensional event-space into cells
  - For each cell, estimate the purity
  - Chose cuts to separate high and low purity regions
Decision Trees Example

- Start with one node containing the full sample
  - Find the cut that maximizes a splitting criteria (e.g. purity separation)
  - Repeat this step on each new node
  - The final “leaves” are reached once a stopping criteria is reached
  - Purity of leaves used as discriminator
- These trees can be “boosted”: misclassified events get increased weight for retraining of next tree
MVA Cross Section Example

- Example from DØ: cross section extraction using topological info
- Various combinations also possible
  - e.g. use MVA for some b-tag bins, counting in others...

l+jets; ≥4 jets
tt cross sections measured in all different final states

- Deviations between channels or from SM prediction could indicate new physics

DØ Run II

July 2011

<table>
<thead>
<tr>
<th>Cross Section (pb)</th>
<th>7.40 ( \pm 0.19 ) ( \pm 0.57 ) pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>lepton+jets + dileptons (PLB)</td>
<td>5.3 fb(^{-1})</td>
</tr>
<tr>
<td>lepton+jets (topo + b-tagged, PRD)</td>
<td>5.3 fb(^{-1})</td>
</tr>
<tr>
<td>dileptons (topo + b-tagged, PLB)</td>
<td>5.3 fb(^{-1})</td>
</tr>
<tr>
<td>lepton+track (b-tagged)*</td>
<td>1.0 fb(^{-1})</td>
</tr>
<tr>
<td>tau+lepton (b-tagged)*</td>
<td>2.2 fb(^{-1})</td>
</tr>
<tr>
<td>tau+jets (b-tagged, PRD)</td>
<td>1.0 fb(^{-1})</td>
</tr>
<tr>
<td>all+jets (b-tagged, PRD)</td>
<td>1.0 fb(^{-1})</td>
</tr>
</tbody>
</table>

\( m_{\text{top}} = 175 \) GeV

CTEQ6.6M


Assume \( M_t = 172.5 \text{ GeV}/c^2 \)

\pm (stat.) \pm (syst.) \pm (lum.)

CDF Run II Preliminary, 9.0 fb\(^{-1}\)

Dilepton (E.T. 812 pb)

7.40 \( \pm 0.58 \) \( \pm 0.63 \) \( \pm 0.45 \)

Lepton + jets (topolog.) (E.T. 46 pb)

7.82 \( \pm 0.38 \) \( \pm 0.37 \) \( \pm 0.15 \)

Lepton + jets (b-tagged) (E.T. 43 pb)

7.32 \( \pm 0.36 \) \( \pm 0.59 \) \( \pm 0.14 \)

All hadronic (E.T. 29 pb)

7.21 \( \pm 0.50 \) \( \pm 1.10 \) \( \pm 0.42 \)

MET + >3 jets (E.T. 22 pb)

7.99 \( \pm 0.55 \) \( \pm 0.76 \) \( \pm 0.46 \)

MET + >2 jets (E.T. 57 pb)

7.11 \( \pm 0.49 \) \( \pm 0.96 \) \( \pm 0.43 \)

Tau + Lepton (E.T. 50 pb)

8.18 \( \pm 2.27 \) \( ^{+1.22} \) \( _{-1.07} \) \( \pm 0.47 \)

\(|p\bar{p}| \rightarrow t\bar{t} + X) \text{ [pb]} \)
**t\bar{t} Cross Section Overview**

- t\bar{t} cross sections measured in all different final states
- Deviations between channels or from SM prediction could indicate new physics

### ATLAS Preliminary

<table>
<thead>
<tr>
<th>Data 2011</th>
<th>15 May 2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel &amp; Lumi.</td>
<td>Theory (approx. NNLO) for m_t = 172.5 GeV</td>
</tr>
<tr>
<td>Single lepton 0.70 fb(^{-1})</td>
<td>(\sigma_t \pm \text{(stat)} \pm \text{(syst)} \pm \text{(lumi)})</td>
</tr>
<tr>
<td>Dilepton 0.70 fb(^{-1})</td>
<td>179 (\pm 4 \pm 9 \pm 7) pb</td>
</tr>
<tr>
<td>All hadronic 1.02 fb(^{-1})</td>
<td>173 (\pm 6 \pm 14 \pm 9) pb</td>
</tr>
<tr>
<td>Combination</td>
<td>167 (\pm 18 \pm 78 \pm 6) pb</td>
</tr>
<tr>
<td>177 (\pm 3 \pm 8 \pm 7) pb</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>New measurements</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>(\tau_{\text{had}} + \text{jets}) 1.67 fb(^{-1})</td>
<td>200 (\pm 19 \pm 42 \pm 7) pb</td>
</tr>
<tr>
<td>(\tau_{\text{had}} + \text{lepton}) 2.05 fb(^{-1})</td>
<td>186 (\pm 13 \pm 20 \pm 7) pb</td>
</tr>
<tr>
<td>All hadronic 4.7 fb(^{-1})</td>
<td>168 (\pm 12 \pm 60 \pm 67 \pm 6) pb</td>
</tr>
</tbody>
</table>

### CMS Preliminary, \(\sqrt{s}=7\) TeV

- CMS e/\mu+jets
  - TOP-11-003 (L=0.8-1.1/fb): 164 \(\pm 3 \pm 12 \pm 7\) pb
  - (val. ± stat. ± syst. ± lumi.)
- CMS \(\tau\)-jets
  - TOP-11-004 (L=3.9/fb): 156 \(\pm 12 \pm 33 \pm 3\) pb
  - (val. ± stat. ± syst. ± lumi.)
- CMS dilepton (ee,\(\mu\mu\))
  - TOP-11-005 final (L=2.9/fb): 162 \(\pm 2 \pm 5 \pm 4\) pb
  - (val. ± stat. ± syst. ± lumi.)
- CMS dilepton (ee,\(\mu\mu\))
  - arXiv 1203.6810 (L=2.2/fb): 143 \(\pm 14 \pm 22 \pm 3\) pb
  - (val. ± stat. ± syst. ± lumi.)
- CMS all-hadronic
  - TOP-11-007 (L=1.1/fb): 136 \(\pm 20 \pm 40 \pm 8\) pb
  - (val. ± stat. ± syst. ± lumi.)

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**t\bar{t} Cross Section Overview**

- **t\bar{t} cross sections measured in all different final states**
- **Deviation new phys**
  - Deviations between channels or from SM prediction could indicate new physics

**ATLAS Prel**

Data 2011
Channel & Lumi.
Single lepton 0.70
Dilepton 0.70
All hadronic 1.02 fb⁻¹
Combination

**New measurem**

\( \tau_{\text{had}} + \text{jets} \) 1.67
\( \tau_{\text{had}} + \text{lepton} \) 2.05
All hadronic 4.7 fb⁻¹

**Graph:**

- CMS Preliminary
- LHC 7TeV
- LHC 8TeV
- Tevatron

- CMS combined 7 TeV (1.1 fb⁻¹)
- CMS combined 8 TeV (2.8 fb⁻¹)
- CDF
- D0

- \( \sqrt{s} \) (TeV)
- \( \sigma(t\bar{t}) \) (pb)

- Approx. NNLO QCD (pp)
- Scale uncertainty
- Scale \( \otimes \) PDF uncertainty
- Approx. NNLO QCD (p\bar{p})
- Scale uncertainty
- Scale \( \otimes \) PDF uncertainty

MSTW 2008 NNLO PDF, 90% C.L. uncertainty

- 164 ± 3 ± 12 ± 7 pb
- (val. ± stat. ± syst. ± lumi.)
- 156 ± 12 ± 33 ± 3 pb
- (val. ± stat. ± syst. ± lumi.)
- 162 ± 2 ± 5 ± 4 pb
- (val. ± stat. ± syst. ± lumi.)
- 143 ± 14 ± 22 ± 3 pb
- (val. ± stat. ± syst. ± lumi.)
- 136 ± 20 ± 40 ± 8 pb
- (val. ± stat. ± syst. ± lumi.)
**ttbar Differential Cross Section**

- Test of perturbative QCD calculations
- Generic probe of non-SM physics
- Mostly l+jets events used
  - Allows reconstruction of final state with good resolution
  - Use kinematic fit to reconstruct invariant tt mass
- Correct for experimental resolution, e.g. with regularized unfolding
  - After subtracting background from data
- Correction for acceptance on unfolded distributions
**tt̅ Differential Cross Section**

- Test of higher-order QCD calculations
- Generic test of SM; e.g. narrow resonances in $m_{t\bar{t}}$

![Graph showing differential cross section](image)

**ATLAS**

$$\int L \, dt = 2.05 \text{ fb}^{-1}$$

CMS Preliminary, 1.14 fb$^{-1}$ at $\sqrt{s}=7$ TeV

- Data
- MadGraph
- MC@NLO
- POWHEG

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Single Top Cross Sections

- Single top quark production via electroweak interaction

Collider | s-channel: $\sigma_{tb}$ | t-channel: $\sigma_{tqb}$ | Wt-channel: $\sigma_{tW}$
--- | --- | --- | ---
Tevatron: $p\bar{p}$ (1.96 TeV) | 1.04 pb | 2.26 pb | 0.28 pb
LHC: $pp$ (7 TeV) | 4.6 pb | 64.6 pb | 15.7 pb

- Wt-channel: negligible at the Tevatron
- s-channel: challenging at the LHC
The Challenge

- Production cross section about $1/2$ of $t\bar{t}$
- Single top signature similar to $W+$jets background

- Other important backgrounds: $t\bar{t}$ and multijet
Before b-jet identification: single top signal hardly visible!
After Event Selection and after b-jet Identification

- Before b-jet identification: single top signal hardly visible!

- After b-jet identification: single top visible – but uncertainty on background model larger than signal

- Extensive use of multivariate analysis techniques!
  - Less extreme at LHC: t-channel extraction via cut-based analysis possible
Training and cross section extraction

- Train MVA on
  - s+t channel using SM ratio between s- and t-channel
  - t-channel with s-channel as background in training (not in fit)
  - s-channel with t-channel as background in training (not in fit)

- Bayesian method to extract cross section results
  - Integration over systematic uncertainties (modeled as Gaussian priors)

- Example: t-channel trained discriminant
Training and cross section extraction

- Train MVA on
  - s+t channel using SM ratio between s- and t-channel
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- Example: t-channel trained discriminant

- LHC: t-channel much easier visible
Single Top: Other Measurements

- s- and t-channel are differently sensitive to new physics
  - Measure both channels simultaneously
- Direct extraction of $V_{tb}$ from single top cross section $|V_{tb}|^2 \propto \sigma(s+t)$
  - No assumption about number of generations
  - Assumption: $|V_{ts}|^2 + |V_{td}|^2 << |V_{tb}|^2$

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$|V_{tb}| > 0.79 \quad @ \quad 95\% \quad C.L.$$
Summary Production

- Top production mechanisms:
  First thing to understand about top quarks

- Modeling of signal and background events crucial

- Various methods available to enrich data in signal events
  - b-tagging
  - Multivariate analysis techniques

- Single top: more challenging to measure
  → most properties measurements performed in $t\bar{t}$
BACKUP