Top Quark Physics at the LHC

Outline of Lectures

1. Discovery of Top Quark
2. Top Quark in the Standard Model
3. Production Mechanisms
4. Precision Measurement of Top Quarks
5. Other Top Quark Properties
6. Things That We Don’t Know (But Should)

Pekka K. Sinervo, F.R.S.C.
University of Toronto
Some Introductory Comments

- Standard approach to these sorts of lectures
  - Begin with theoretical background
  - Focus on the phenomenological issues
    > What does theory tell us?
    > What have we learned from measurements?
    > What next?

- Approach here will be a little more experimental
  - Start with discovery with top, then talk about formal stuff
  - Work to develop an appreciation of what top quark production & decay looks like
  - Talk about all the stuff that you need to know
    > But work to hide “under the carpet” the details
  - Objective is to give audience a flavour of what we will learn at the LHC by studying the top quark system
The Top Quark Revealed

- Experiments at Fermilab Tevatron
  - studying p-pbar collisions at 1.8 TeV
  - Looked at $\sim 2 \times 10^{12}$ collisions
  - Searching for events with
    - Evidence of a W boson
      - Decaying leptonically into either $e\nu$ or $\mu\nu$nn
    - 3 or more jets
      - At least one showing evidence of a $b$ quark decay ("b tag")

- Observed an excess of events above SM & instrumental backgrounds

- Evidence for a previously unobserved process
  - Excess of events equivalent to a $>5$ standard deviation fluctuation of background

- Concluded that the top quark had been observed

CDF, PRL 74, 2626 (1995)
D0, PRL 74, 2632 (1995)
Why Were We So Sure?

- Case based on experimental & theoretical evidence starting in 1970’s
  - Observation of CP violation and charm begins the case
  - Properties of b quark strengthened it
    > Couldn’t be an SU(2) singlet within SM framework

- Searches pushed the technological envelope
  - Rarest process observed in high energy hadron collisions
    > Best measurements to date
    \[ \sigma_{tt} = 7.0 \pm 0.3\text{(stat)} \pm 0.4\text{(syst)} \pm 0.4\text{(lumi)} \text{ pb} \text{ (CDF)} \]
    \[ \sigma_{tt} = 8.18_{-0.87}^{+0.98} \text{ pb} \text{ (DZero)} \]

- Precision EWK measurements clinched it for most people
  - Had to develop b-tagging tools
  - Reconstruct 6-parton final states

CDF, Conference Note 9448 (2009)
D0, Fermilab-PUB-09-092-E (2009)

Interest in Top Quark at LHC

- Heaviest fermion in theory
  - Couples most strongly to Higgs field
    - Or whatever is responsible for EWK symmetry-breaking
  - Direct access to part of CKM matrix, $V_{tb}$
    - Single top production as well as $\Gamma_t$ measurement
  - In many models, new particles couple preferentially to $t$-$\bar{t}$

- Properties are predicted in SM
  - Some are quite sensitive to “new” or “beyond-SM” physics

- Important calibration tool for LHC experiments
  - Leverage Tevatron experience to more rapidly understand detectors and environment

- Both general purpose experiments have increasingly prioritized top studies
  - CMS published host of notes
  - ATLAS recently published its “CSC” book

- Basis for these talks are
  - Studies at Tevatron
  - Studies at 14 TeV pp collisions
  - More recent studies at 10 TeV

CMS Collaboration, TOP-08-XX, TOP-09-YY.
What I Will and Will Not Cover

- **Going to talk about**
  - Top quark cross section
    - Use dileptons
  - Top quark mass measurement
    - Use lepton+jets
  - Top quark charge measurement
    - Event reconstruction
  - Top quark spin correlations
    - Illustrates some of the finer points of top quark physics
  - High mass top quark pairs
    - What happens at higher mass

- **Not going to talk about measurements of**
  - Single top production
  - Top quark rare decays
  - Width of top quark
  - $P_T$ distribution of top quarks
  - Production mechanisms
  - Anomalous decays
    - $t\rightarrow H^+b$, for example
  - Etc.

- **Not because they aren’t interesting (they are)**
  - But we don’t have a week….
Anatomy of a pp Collision

- **Pick apart the collision**
  - **Incoming proton bunches**
    - + beam halo and other garbage
  - **Assume time of interaction $\ll$ timescale of any other process**
    - Treat hadron as a “bag” of free partons
  - **Two partons interact**
    - Hard scattering process
  - **Rest of hadrons “fragment” into an underlying event (UE)**
    - Caused by initial acceleration?
  - **Maybe (usually?) have one or more independent collisions (pileup)**
    - Increases low-energy particle multiplicities
    - Has effects on instrumentation

- **Acceleration process produces**
  - Initial State Radiation (ISR)
  - Final State Radiation (FSR)

- **UE characterized by**
  - ~60 particles
  - Average PT $\sim 0.5$ GeV/c
  - Distributed uniformly in $\eta$

- **Multiple interactions depend on**
  - Instantaneous luminosity and crossing rate
    - Increases low-energy particle multiplicities
    - Long read-out times result in “pileup” effects from one crossing to the next
Picturing a Hard Scatter
We assume two partons interact

- Each has momentum fraction $x_1, x_2$ of hadron
  - Given by parton distribution function (PDFs)
  - Either valence (u,d) or gluons & sea quarks
- Cross section given by

$$\sigma = \sum_{i}^{\text{initial partons}} \sum_{j}^{\text{colour}} C_{ij} \int_{0}^{1} d\tau \int_{\tau}^{1} dx_1 \frac{d\sigma_{\text{part}}^i}{d\tau} \left[ f_1(x_1) f_2(x_2) \right] \sigma_{\text{part}}^i (\tau)$$

$\sigma_{\text{part}}^i$ is partonic cross section for process $i$

$\tau = x_1 x_2$

“Factorize” the problem:

- Subprocess cross section
  - Summed over colours & spins
- Colour average factors ($C_{ij}$)
  - $C_{ij} = 1/9$ for quarks
  - $C_{ij} = 1/64$ for gluons
- Parton distribution functions (PDF)

\[ 2M_{\text{top}} \approx \sqrt{s x_1 x_2} \]
Top Quark Production

- Start with primary partonic process

\[ \sigma_{gg}(\hat{s}) = \frac{\pi \alpha_s^2}{3\hat{s}} \left[ \left(1 + \rho + \frac{\rho^2}{16}\right) \ln \left(\frac{1 + \beta}{1 - \beta}\right) - \beta \left(\frac{7}{4} + \frac{31}{16}\rho\right) \right] \]

- \( \rho = 4m_t^2/\hat{s}, \beta \) velocity
  - \( gg \) is dominant source at LHC
  - \( q\bar{q} \) annihilation modest addition

- Lowest order process dominates
  - Much work done on higher-order effects

- Total cross section sensitive to
  - Top quark mass \( m_t \)
  - Resummation effects
  - Centre of mass energy

Single Top Quark Production

- Single top quark production also occurs
  - Challenge here is that backgrounds are significant
  - At Tevatron, took x100 more data to observe

- Situation is expected to be just as challenging given rates
  - Three mechanisms
    - t-channel (dominant - 230 pb)
    - Wt channel (66 pb)
    - s-channel (11 pb)

- An important process to study
  - One of the few ways that one can measure $V_{tb}$
  - Final state is similar to that arising from Higgs production
    - $W^+b$-$\bar{b}$ accessible because of leptonic decay of $W$

LHC a Top Quark Factory?

- **Calculate the rates:**
  - See where some of the numbers come from later
  
  \[ \sigma_{_{tt}} \approx 830 \text{ pb} \left( \sqrt{s} = 14 \text{ TeV} \right) \]
  
  \[ \Rightarrow r_{_{tt}} \approx \sigma_{_{tt}} \times L \times \epsilon_{\text{acc}} \times \epsilon_{\text{eff}} \]
  
  \[ = \left( 8.3 \times 10^{-34} \right) \left( 1.0 \times 10^{32} \right) \left( 4 \times 10^{-2} \right) \]
  
  \[ = 3.3 \times 10^{-3} \text{ s}^{-1} = 1.2 / \text{hour} \]

  - **With 200 pb\(^{-1}\), can expect**
    - 166,000 produced events
    - 6,600 lepton+jet events

- **Very good calibration source**
  - Lepton ID efficiencies
  - Missing Et
  - Jet Energy Scales
  - B tagging efficiencies

- **Biggest challenge is correctly constructing final state**
  - Tagging b’s reduces this problem
    - But also reduces the rate of candidate events
Top Quark Decays

- **Top decays are unique**
  - Quark doesn’t have time to hadronize
    - Weak decay of bare quark
  - Weak decay dominated by $V_{tb}$
    - CKM unitarity implies $\text{BR}(t \rightarrow Wb) > 0.999$
      - $\text{BR} = 0.97 \pm 0.09$ (DZero)

- **Top quark width**
  - Determined by SM couplings and mass
  - Prediction is $\Gamma_t = 1.3 \text{ GeV/c}^2$
    - Measure $\Gamma_t < 12.7 \text{ GeV/c}^2$ at 95% C.L.
    - Observed width dominated by resolution

- **Two-body decay kinematics**
  - W decay results in 3-body final state
  - SM predicts W is longitudinally polarized
    - Smaller left-handed component
    - No right-handed decay

- **This effects decay kinematics**
  - Can measure polarization using, e.g., spectra of final state particles
Assuming SM, decay modes defined by

- 100% decay to Wb
- W decay to
  - $e\nu, \mu\nu, \tau\nu$ (10.8±0.1)% each
  - c-sbar, u-dbar (33.8±0.2)% each

Since top quarks most readily studied via pair-production

- All-hadronic (multijet) final states
- Lepton + jets final states
- Dileptons

Experimental challenges include

- Reconstruction of 6-parton final state
  - Identify partons as final state “objects”
    - Perhaps most complex final state studied
  - Associate objects to correct partons
    - Best algorithms in l+jets mode is ~60% correct
- Very “busy” final state
  - Additional jets produced
    - Initial & final state radiation
- Multiple neutrinos
  - Particularly problematic in dilepton modes
Top Quark Kinematics

- Top quark is produced “centrally”
  - Mode of $P_T$ distribution $\sim$ 90 GeV/c
  - Most tops are within $|\eta|<3$
  - Produced back-to-back
  - $t\bar{t}$ system has modest $P_T$

- Defines kinematics of final state daughters

Figure 16: top and anti-top quarks $p_T$, $\eta$ and $\delta R$ (spherical angle between $t$ and $\bar{t}$ quarks) distributions in the $t\bar{t}$ events. The histogram with black circle markers correspond to CTEQ6 sample. The histogram with the red squares correspond to the CTEQ6.6 sample. Histograms are filled with MC@NLO event weights, $\pm 1$. 
Acceptance x Efficiency

- **Have to decide channel to focus on**
  - Semi-leptonic channel is favourite “whipping boy”
  - **Require**
    - One W to decay leptonically (e/μ required in final state)
      - Charged lepton with $<P_T> \sim 50$ GeV/c
      - Neutrino with energy $<P_T> \sim 50$ GeV/c
      - This also accepts some $W \rightarrow \tau \nu$
    - One W to decay hadronically
      - 2 jets with average $<P_T> \sim 50$ GeV/c
    - Two b jets
      - Maybe require jets, maybe tagged?
      - On average, a little harder…
    - **Estimate BR = (2/9)x(2/3)x2=8/27=30%**
      - But need to run full MC! Why?

- **Have to decide on trigger:**
  - **Inclusive e or μ**
    - $P_T > 20-25$ GeV/c
    - $|\eta| < 2.5$
    - **Acceptance ~ 85 %**
    - **Efficiency ~ 90-95%**

- **Offline selection requirements**
  - **Lepton ID**
  - $E_T^{miss} > 20$ GeV
  - **3-4 jets**
    - $E_T > 20-60$ GeV
    - $|\eta| < 2.5$
  - **B tagging?**
    - Single b-tag efficiency around 50-60%
Think “Trigger!”

- Triggering on top quarks straightforward
  - Rely on inclusive lepton & dilepton triggers
    > $E_T$ thresholds around 20 GeV
  - Multijets are harder
    > Use complex jet criteria, e.g.
      - $\geq 4$ jets $P_T > 60$ GeV/c
      - $\geq 2$ jets $P_T > 100$ GeV/c
      - $\geq 1$ jets $P_T > 170$ GeV/c
    > S/B still poor
  - $E_T^{\text{miss}}$ + jets provides redundant trigger

- Example:
  - Inclusive lepton triggers
    > Efficiency of ~90% for selected lepton+jet events

<table>
<thead>
<tr>
<th>Trigger</th>
<th>Signal Efficiency [%]</th>
<th>Relative Background Rate</th>
<th>S/B</th>
</tr>
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<tr>
<td>4j60.2j100.j170</td>
<td>6</td>
<td>0.13</td>
<td>$2.8 \times 10^{-3}$</td>
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<tr>
<td>5j45.2j60.j100</td>
<td>16</td>
<td>0.34</td>
<td>$3.0 \times 10^{-3}$</td>
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<tr>
<td>6j35_5j45.4j50.3j60</td>
<td>10</td>
<td>0.18</td>
<td>$3.7 \times 10^{-3}$</td>
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</table>
Detector Acceptance & Efficiency

- Detectors designed with specific physics processes in mind
  - Break these down into
    - Total transverse energy
    - Charged leptons (e, µ, τ)
    - Jets (quarks & gluons)
    - Missing transverse energy
  - Huh? But aren’t we supposed to be discovering stuff?
    - Hope is that by focusing in detection and triggering of “basic elements”, one will have a broad enough menu that new phenomena will be recorded
  - Doesn’t seem like a bad idea
    - But creates practical challenges
    - Very large “trigger” menus

- Helpful to separate detector effects:
  - Acceptance: Fraction of events of a given process “contained” within the detector
  - Efficiency: Fraction of contained events/objects ultimately passing some set of criteria (“cuts”)
  - Resolution: Accuracy of measurements of specific event-related quantities

- Warning: Not a strict convention on how these terms used!!
  - Always make sure you define what you mean
Tools for Top Reconstruction

- **Lepton Identification**
  - Electron & muon ID critical
    - Reject QCD backgrounds
    - Allow precise kinematic measurements

- **Jet reconstruction**
  - Messy objects
    - spatially large and hard to measure
  - Algorithms are important
    - Emphasize “small” jets
    - Cone sizes ~ 0.4-0.5 in R
  - B tagging critical
    - Efficiencies ~ 0.6
    - Rejections ~ 200

- **Missing Transverse Energy**
  - Needs good calorimetry
  - Have largely lost $P_z$ information

- **Efficiency is a key issue**
  - Detecting top quarks important over large backgrounds
    - Intrinsic S/N = $10^{-10}$
  - Important for rare processes

- **Two additional challenges are**
  - Calibration (especially of jets)
    - Talk about this later
  - Full event reconstruction
    - Lots of jets produced

![W reconstruction in Lepton+Jets Events](image)
How Are These Chosen?

- **Study acceptance**
  - Learn that top quark production ~ “central”
  - Primary backgrounds (W+bb+jets) more distributed in $\eta$
  - Lepton ID and jet reconstruction limiting factors

- **Maximize efficiency**
  - Requires S/N studies
  - Look at different algorithms for event reconstruction
  - Need to be systematic
    - But recognize that one has to make compromises
Top Quark Cross Section

- **Standard technique to measure cross section** is
  \[
  \sigma = \frac{N_{\text{obs}} - N_{\text{bkgd}}}{\varepsilon A \int L \, dt}
  \]
  \(N_{\text{obs}}, N_{\text{bkgd}}\) = number observed, background events
  \(\varepsilon A\) = efficiency times acceptance
  \(\int L \, dt\) = integrated luminosity

- **Problem breaks down into**
  - Define selection to
    - Get good efficiency
    - Reject backgrounds
    - Understand uncertainties
  - Estimate the uncertainties

- Look at cross section in dilepton mode
  - Intrinsically cleaner
    - Lower QCD and W+bb backgrounds
  - Also intrinsically smaller
    - Efficiencies are <1%
  - Have some challenges
    - \(\tau\) decays
      - Decaying leptonically
    - Leptons from b & c decay

<table>
<thead>
<tr>
<th>2 Electrons</th>
<th>Total</th>
<th>2 W</th>
<th>1W 1b</th>
<th>1W 1c</th>
<th>1W 1Tau</th>
<th>1W 1Other</th>
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<td># Events</td>
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<td>1,246</td>
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<td>1</td>
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<td>7</td>
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<tr>
<td>rate</td>
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<td>83.4</td>
<td>2.5</td>
<td>0.1</td>
<td>11.8</td>
<td>0.5</td>
</tr>
<tr>
<td>2 Muons</td>
<td>Total</td>
<td>2 W</td>
<td>1W 1b</td>
<td>1W 1c</td>
<td>1W 1Tau</td>
<td>1W 1Other</td>
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<td>2,203</td>
<td>313</td>
<td>6</td>
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<td>0.1</td>
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<tr>
<td>1 E 1Mu</td>
<td>Total</td>
<td>2 W</td>
<td>1W 1b</td>
<td>1W 1c</td>
<td>1W 1Tau</td>
<td>1W 1Other</td>
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<td>7.7</td>
<td>0.1</td>
<td>10.9</td>
<td>0.4</td>
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</table>
Dilepton Cross Section

- Intrinsic backgrounds are large
  - Z/W boson production
    > Eliminate by identifying Z mass peak

- Motivates selection:
  - Two clean lepton candidates
    > $P_T > 20$ GeV/c
  - $E_T^{\text{miss}} > 30$ GeV
  - $\geq 2$ jets $P_T > 60$ GeV/c
  - Reject Z’s

<table>
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<tr>
<th>Sample</th>
<th>$\sigma$(pb)</th>
<th>Filter(%)</th>
<th>$\sigma_{\text{eff}}$(pb)</th>
<th>$e\mu$</th>
<th>$ee$</th>
<th>$\mu\mu$</th>
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<td>$\ell\ell$ (di-lepton)</td>
<td>833</td>
<td>7(2)</td>
<td>55</td>
<td>699</td>
<td>312</td>
<td>381</td>
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<tr>
<td>$\ell\ell$ (semi-leptonic)</td>
<td>48(11)</td>
<td>397</td>
<td></td>
<td>31</td>
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<td>8</td>
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<td>$Z\rightarrow e^+e^-$</td>
<td>2015</td>
<td>86</td>
<td>1733</td>
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<td>31</td>
<td>99</td>
<td>5</td>
<td>3</td>
<td>2</td>
</tr>
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</table>

Number of events
For 100 pb$^{-1}$
Cross Section Results

- Have significant yield for selection
  - Backgrounds under control as well
    - Dimuons are in worst shape
  - Expect about 987 signal events with 228 background in 100 pb⁻¹

- Systematic uncertainties
  - First pass would suggest ~5%
    - Dominated by jet energy scale
  - Luminosity uncertainty also ~5%
  - Statistical uncertainty
    - 4% for 100 pb⁻¹

- Overall, looks straightforward
  - But note where Tevatron has had greatest challenge

<table>
<thead>
<tr>
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<th>eμ</th>
<th>ee</th>
<th>μμ</th>
<th>all channels</th>
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<td>tt (di-lepton)</td>
<td>555</td>
<td>202</td>
<td>253</td>
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<tr>
<td>e [%]</td>
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<td>Z → e⁺e⁻</td>
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<td>9</td>
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<td>20</td>
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<td>79</td>
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<tr>
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<td>7</td>
<td>33</td>
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<td>0.7</td>
<td>0.5</td>
<td>0.0</td>
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<tr>
<td>single top s-chann.</td>
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<td>0.0</td>
<td>0.0</td>
<td>0.1</td>
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<td>single top t-chann.</td>
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<td>0.8</td>
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<tr>
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<td>86</td>
<td>36</td>
<td>73</td>
<td>228</td>
</tr>
<tr>
<td>S/B</td>
<td>6.3</td>
<td>5.6</td>
<td>3.4</td>
<td>4.3</td>
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<table>
<thead>
<tr>
<th>Δσ/σ (%)</th>
<th>eμ</th>
<th>ee</th>
<th>μμ</th>
<th>All</th>
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<tr>
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<td>2.9</td>
<td>2.0</td>
<td>2.4</td>
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<td>MRST2001E Variation</td>
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<td>1.1</td>
<td>0.7</td>
<td>0.9</td>
</tr>
<tr>
<td>JES -5%</td>
<td>(2.0)</td>
<td>-</td>
<td>(3.1)</td>
<td>(2.1)</td>
</tr>
<tr>
<td>JES + 5%</td>
<td>2.4</td>
<td>4.1</td>
<td>4.7</td>
<td>4.6</td>
</tr>
<tr>
<td>FSR</td>
<td>2.0</td>
<td>2.0</td>
<td>4.0</td>
<td>2.0</td>
</tr>
<tr>
<td>ISR</td>
<td>1.1</td>
<td>1.1</td>
<td>1.2</td>
<td>1.1</td>
</tr>
<tr>
<td>Total</td>
<td>5.0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Tevatron Data with B-Tagging

- Most accurate top quark cross section
  - Lepton+jets
  - SECVTX b-tagging

- Strategy
  - Use MC to determine overall acceptance
  - Measure trigger efficiency with W->lν
  - Measure lepton ID efficiency with Z->ll
  - Measure b-tagging efficiency in data
  - Estimate systematic uncertainties

<table>
<thead>
<tr>
<th>Systematic</th>
<th>Inclusive (Tight)</th>
<th>Double (Loose)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton ID</td>
<td>1.8</td>
<td>0.2</td>
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<tr>
<td>ISR</td>
<td>0.5</td>
<td>0.2</td>
</tr>
<tr>
<td>FSR</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>PDFs</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>Pythia vs. Herwig</td>
<td>2.2</td>
<td>1.1</td>
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<tr>
<td>Luminosity</td>
<td>6.2</td>
<td>6.2</td>
</tr>
<tr>
<td>JES</td>
<td>6.1</td>
<td>4.1</td>
</tr>
<tr>
<td>b-Tagging</td>
<td>5.8</td>
<td>12.1</td>
</tr>
<tr>
<td>c-Tagging</td>
<td>1.1</td>
<td>2.1</td>
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<td>t-Tagging</td>
<td>0.3</td>
<td>0.7</td>
</tr>
<tr>
<td>Non-W</td>
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<td>1.3</td>
</tr>
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<td>W+HF Fractions</td>
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<td>2.0</td>
</tr>
<tr>
<td>Mistag Matrix</td>
<td>1.0</td>
<td>0.3</td>
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<tr>
<td>Total</td>
<td>11.5</td>
<td>14.8</td>
</tr>
</tbody>
</table>

D. Acosta et al., PRD 71, 052003 (2005)
Top Quark Mass

- A precision measurement of top quark mass $m_t$ scientifically important
  - Tests consistency of Standard Model
  - Bare quark – first opportunity to study one directly
  - Heaviest fermion, so couples strongly to Higgs boson

- Not just “another” quark mass
  - Heaviest fermion in theory
    - Couples to Higgs boson in SM
    - $m_Z$, $m_W$, $m_t$ and $m_H$ are all related
  - At a level of $\sim 0.5 \text{ GeV}/c^2$, start to test other aspects of theory
    - Stability of pole mass with respect to MS-bar mass
    - Non-perturbative QCD effects become important

- Presents important experimental challenges
  - Requires us to understand
    - Jet energy scales very well
    - Effects of underlying event

- Tevatron experiments have “raised the bar”
  - Precision $\sim 0.7\%$, or 1.1 GeV/$c^2$
  - Found solutions to many problems
  - Achieving comparable precision at LHC will be a challenge!
Latest Tevatron Results

- Measured mass in essentially all modes
  - With half of available Tevatron data, systematics limited
  - Most precise measurement is in l+jets mode

![Graph showing mass of the top quark](image)
Mass Measurement Techniques

- All techniques based on simple kinematics
  - Heavier the object, the more energetic the daughters

- Variations in how one correlates observed final state with $m_t$
  - Directly measure using 4-momentum reconstruction
    - Correct for resolution effects
  - Employ matrix element approach
    - Use “transfer functions” for detector resolution
  - Look at subset of information
    - Example, lepton $P_T$

- Many complications
  - Cannot reconstruct final state of 6 partons correctly
  - Jet energy calibrations
  - Background sources

- Example of how well one can do:
  - Mass reconstruction in double-tagged lepton+jet events

![Graph showing mass reconstruction in double-tagged events]
Example LHC Analysis

- **Select l+jets mode**
  - Require e(µ) with $P_T > 25(20) \text{ GeV/c}$
  - Require Missing $E_T > 20 \text{ GeV}$
  - 4 or more jets
    - $P_T > 40 \text{ GeV/c}$ and $|\eta| < 2.4$
  - Require two b-tagged jet
  - Use inclusive lepton trigger
    - About 90% efficient on e/µ + jets

- **Selection has 1.8% efficient**
  - Expect 16 pb of selected events
  - Jet and b-tag cuts selected to reject backgrounds

- **Reconstruct final state**
  - Choose 4 highest $P_T$ jets
  - Use a $\chi^2$ to choose best parton assignments
  - Use dijet mass to constrain jet energy scale
    - Perform a fit to extract $m_t$

<table>
<thead>
<tr>
<th>Process</th>
<th>Number of events</th>
<th>1 isolated lepton $P_T &gt; 20 \text{ GeV}$ and $E_T &gt; 20 \text{ GeV}$</th>
<th>$&gt; = 4$ jets $P_T &gt; 40 \text{ GeV}$</th>
<th>2 b-jets $P_T &gt; 40 \text{ GeV}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal</td>
<td>313200</td>
<td>132380</td>
<td>43370</td>
<td>15780</td>
</tr>
<tr>
<td>$W$ boson backgrounds</td>
<td>$9.5 \times 10^3$</td>
<td>154100</td>
<td>9450</td>
<td>200</td>
</tr>
<tr>
<td>all-jets (top pairs)</td>
<td>466480</td>
<td>1020</td>
<td>560</td>
<td>160</td>
</tr>
<tr>
<td>di-lepton (top pairs)</td>
<td>52500</td>
<td>16470</td>
<td>2050</td>
<td>720</td>
</tr>
<tr>
<td>single top, $t$ channel</td>
<td>81800</td>
<td>24400</td>
<td>1230</td>
<td>330</td>
</tr>
<tr>
<td>single top, $W$ $t$ channel</td>
<td>9590</td>
<td>8430</td>
<td>770</td>
<td>170</td>
</tr>
<tr>
<td>single top, $s$ channel</td>
<td>720</td>
<td>640</td>
<td>11</td>
<td>5</td>
</tr>
</tbody>
</table>

![ATLAS 1 fb⁻¹](image)
LHC $m_t$ Precision

- **Statistical accuracy**
  - At 0.2 GeV/c², not limiting factor
  - Resolution ~11-12 GeV/c²

- **Systematic uncertainties dominate**
  - Mass depends linearly on jet energy scale (JES) uncertainties
    > Light quark jet JES constrained by W mass to <1%
    > B-jet JES comes from MC modelling
      - Tevatron estimates ~0.5%
  - Model uncertainties are likely larger in practice
    > This will be area of intense work

\[ m_t = 174.8 \pm 0.2 \text{ GeV/c}^2 \]

<table>
<thead>
<tr>
<th>Systematic uncertainty</th>
<th>( \chi^2 ) minimization method</th>
<th>geometric method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light jet energy scale</td>
<td>0.2 GeV/%</td>
<td>0.2 GeV/%</td>
</tr>
<tr>
<td>b jet energy scale</td>
<td>0.7 GeV/%</td>
<td>0.7 GeV/%</td>
</tr>
<tr>
<td>ISR/FSR</td>
<td>( \sim 0.3 \text{ GeV} )</td>
<td>( \sim 0.4 \text{ GeV} )</td>
</tr>
<tr>
<td>b quark fragmentation</td>
<td>( \leq 0.1 \text{ GeV} )</td>
<td>( \leq 0.1 \text{ GeV} )</td>
</tr>
<tr>
<td>Background</td>
<td>negligible</td>
<td>negligible</td>
</tr>
<tr>
<td>Method</td>
<td>0.1 to 0.2 GeV</td>
<td>0.1 to 0.2 GeV</td>
</tr>
</tbody>
</table>
Many Other Mass Measurements

- Use all channels
  - Dileptons
  - Multijets

- More importantly, use different techniques with different systematics
  - Decay length of b
  - Lepton $P_T$ distribution
  - Multivariate techniques
    - Neural networks
    - Maximum likelihood

- Very quickly systematics-limited
  - More statistics helps, but only if systematics are tackled
    - For example, colour reconnection effects

---

CDF Top Mass Uncertainty
(projection from 680 pb$^{-1}$)

- CDF Results
- Run IIa LJ goal (TDR 1996)
- Scale $\Delta$ (stat) / $\sqrt{N}$, Fix $\Delta$ (syst)
  (assumes no improvements)
- Scale $\Delta$ (total) / $\sqrt{N}$
  (improvements required)

D. Wicke and P. Skands, arXiv:0807.3248V1
Top Quark Properties

- Many important properties, e.g.,
  - Top quark charge
  - Spin polarizations
  - Flavour-changing neutral currents (FCNC) in top decays
  - $t$-$\bar{t}$ resonances

- In many cases, there are early Tevatron results
  - Suffer from low statistics
  - “Top factory” mode allows one to extend all of these in significant ways
  - Area where there will be much new territory to cover

\[
\frac{d\sigma}{dM_{tt}} \propto (M_{tt})^{(-6.1\pm0.9)}
\]
What We Know Already?

Compendium of CDF Results

- $M_t = 172.6 \pm 0.9_{\text{stat}} \pm 1.2_{\text{sys}} \text{ GeV/c}^2$
- $\Gamma_t < 13.1 \text{ GeV at 95\% CL}$
- Exclude $q = -4/3$ at 87\%CL
- 95\% CL upper limit on BR: $115 < M_{\text{stop}} < 185 \text{ GeV}$
- $M_t < 311 \text{ GeV at 95\% CL}$

95\% CL upper limit on BR: $90 < H^+ < 150 \text{ GeV}$

$\text{BR}(t \rightarrow Zq) < 3.7\%$ at 95\% CL

$F_0 = 0.62 \pm 0.11$ & $F_+ = -0.04 \pm 0.05$

\[
\begin{align*}
\sigma_{H+\text{jets}} &= 6.9 \pm 0.4_{\text{stat}} \pm 0.4_{\text{sys}} \pm 0.1_{\text{theory}} \text{ pb} \\
\sigma_{H\ell} &= 6.7 \pm 0.8_{\text{stat}} \pm 0.4_{\text{sys}} \pm 0.2_{\text{lumi}} \text{ pb} \\
\sigma_{\text{all-jets}} &= 8.3 \pm 1.0_{\text{stat}} \pm 2.0_{\text{sys}} \pm 0.5_{\text{lumi}} \text{ pb} \\
F_{\text{FR}} &= 0.07 ^{+0.15}_{-0.07} \text{ (stat+sys)} \\
A_{\text{fb}}^{\text{lab}} &= 0.19 \pm 0.07_{\text{stat}} \pm 0.02_{\text{sys}} \\
M_{Z'} &< 800 \text{ GeV at 95\% CL}
\end{align*}
\]
Top Quark Charge

- To directly measure the top quark charge
  - Need to show correlation
    - $W+b$ versus $W-b$
  - One technique is to fully reconstruct $t\bar{t}$ events

- Employ “standard” selection
  - Isolated $e(\mu)$
    - $P_T > 20(25)$ GeV/c and $|\eta| < 2.5$
  - $\geq 4$ jets
    - $P_T > 30$ GeV/c and $|\eta| < 2.5$
    - At least two b-tagged jets
  - $E_T^{\text{miss}} > 20$ GeV

- Yield is about 2.5% of total production
  - So about 21,000 events in 1 fb$^{-1}$

- Associate W and b using kinematics
  - Invariant $l+b$ mass $< 155$ GeV/c$^2$
    - Maximizes $\epsilon(2P-1)^2$
      - $\epsilon$ being efficiency
      - $P$ being “purity”

- Use method to determine b jet charge
  - Track counting algorithm
  - Semi-leptonic b decay
Charge Results

- One intuitive algorithm
  - Sum charges of all tracks in a jet
    \[ Q_{\text{jet}} = \frac{\sum_i q_i |j_i \cdot p_i|^\kappa}{\sum_i |j_i \cdot p_i|^\kappa} \]
    \[ j_i = \text{b jet axis} \]
    \[ q_i, p_i = \text{track charge, vector} \]
    \[ \kappa = 0.5 \]
  - Have to use MC to calibrate
    > Results in \( Q_b/Q_{\text{meas}} = 3.54 \pm 0.16 \)
    > Source of largest systematic uncertainty

- Results in top charge distribution
  - With 1 fb\(^{-1}\)
    \[ Q_t = 0.67 \pm 0.06 \text{ (stat)} \pm 0.08 \text{ (syst)} \]
    > 20 \( \sigma \) measurement
    > Relies on good modelling of b jets!

- Background Assumed Symmetric!
Top Quark Spin Effects

- Two sources of “spin” effects
  - Top quark decay vertex
  - Top quark spin correlations

- Top quark decay results in polarized W boson
  - Three possible polarization states
    - “Longitudinal” ($F_0$) is preferred

$$\frac{1}{N} \frac{dN}{d \cos \Psi} = \frac{3}{2} \left[ F_0 \left( \frac{\sin \Psi}{\sqrt{2}} \right)^2 + F_L \left( \frac{1 - \cos \Psi}{2} \right)^2 + F_R \left( \frac{1 + \cos \Psi}{2} \right)^2 \right]$$

  - SM: $F_0 = 0.695$, $F_L = 0.304$
  - Look at lepton decay angle $\Psi$ in top quark rest frame
  - Sensitive to physics of top quark decay vertex

Need to be careful about selection

- Standard selection creates some bias in $\Psi$
- Have to correct with MC
- In 1 fb$^{-1}$, expect to measure $F_0$
  - Statistical uncertainty $\sim 0.04$
  - Systematic uncertainty $\sim 0.02$
Top Quark Spin Correlations

- Top quark spin correlations at production
  - Reveal nature of the production mechanism
    - SM predicts s-channel gg fusion will dominate
    - At threshold, forces top quarks to be anti-aligned
      - At least in “beam-line” basis

- Strategy is to use top quark decay products as spin analyzers
  - Measure the correlations and compare with expectations
  - Use angle of decay lepton ($\theta_i$) with respect to parent top
    - In t-tbar rest frame

- Have to measure analyzing power with MC
  - Can measure A with 1 fb$^{-1}$
    - Statistical uncertainty of ~0.2
    - Systematics are less well-understood (0.2-0.3?)
  - Remains a challenge

\[
\frac{1}{N} \frac{d^2N}{d\cos \theta_1 d\cos \theta_2} = \frac{1}{4} (1 - A |\alpha_1 \alpha_2| \cos \theta_1 \cos \theta_2).
\]
Top Pair Resonances

- Top quark pairs unique probe to search for high mass objects
  - Many BSM interactions couple preferentially to t-tbar
  - Expect to see effects at high $M_{tt}$
- Default approach: use standard event selection
  - Look for excess of events

- Works till $M_{tt} \sim 0.75-1$ TeV/c²
  - Suffer from jet “merging”
    > Efficiency for $Z' \rightarrow t\bar{t}$ drops precipitously
High Mass Top Pairs

- Much recent work to understand high mass top system
  - “top jets” become interesting
  - But significant challenges
    - Lose lepton ID
      - QCD backgrounds explode
    - Mass reconstruction strategy changes

- Example is shown below
  - Using R=0.4 cone jet algorithm

- Challenge is understanding QCD background
  - Signal ($P_T > 1$ TeV/c) ~ 100 fb
  - Background from QCD ~ 10 pb

- Looking at jet shape variables
  - Very early days in strategy development
  - Clearly a high-statistics measurement (>20 fb$^{-1}$)

What We Don’t Know (But Should)

- Sense of “certainty” around top quarks perhaps misplaced
  - Don’t understand experimental conditions well
    - Effects of pileup will be a challenge
    - ISR/FSR models aren’t very predictive
  - Underlying physics is uncertain
    - What really causes mass?
    - What are the top quark’s couplings?
    - How does the t-tbar system get produced?

- Not going to get answers to these until we have real data
  - One example: extra jet production
    - Look at dilepton events at Tevatron
    - See lots of extra jets!

CDF Public Note 9647 (2008)
Summary

- Hope this has given you a flavour of top quark physics at the LHC
  - High statistics provides a unique environment for top studies
    - Trade off between analyzing power and systematic effects
  - Environment is still challenging
    - Backgrounds are large
    - High luminosity environment

- Can do much with restrictive selections
  - However, somewhat “brute force”
  - Analyses will require greater sophistication than studies to date

- Data is now essential
  - Allow us to prepare for next decade of top quark physics