Top and EW Phenomenology [I]

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Top Questions 1

- 20 years of anticipation
  - why did we believe top existed?
  - why was the mass a surprise?
  - what did we look for?
  - what did we find?
  - what didn’t we find?
Why did we believe top existed?
Measurement of $R$: large scale view

$$R = \frac{\sigma(e^+e^-\rightarrow\text{hadrons})}{\sigma(e^+e^-\rightarrow\mu^+\mu^-)} = \sum_q (3Q^2_q)$$
Measurement of $R$: close-up view

3-loop pQCD

naive quark model

$$\sqrt{s} \text{ [GeV]}$$
Measurement of AFB:

\[ A_{FB} = \frac{\sigma(b, \theta > 90^\circ) - \sigma(b, \theta < 90^\circ)}{\sigma(b, \theta > 90^\circ) + \sigma(b, \theta < 90^\circ)} \]

Why was the mass a surprise?
Electroweak theory tests: loop level

Year

Top mass (GeV)


240 200 160 120 80 40 0

$e^{+}e^{-}$ annihilations

Standard decay modes

Indirect lower bound

Indirect inferences

CDF
d0
Tevatron average

Chris Quigg (FNAL)

Potential Discoveries at the LHC

Swieca XVI
What did we look for?
Top Pair Branching Fractions

- "alljets" 46%
- τ+jets 15%
- μ+jets 15%
- e+jets 15%
- "dileptons"
- "lepton+jets"
### Top Pair Decay Channels

<table>
<thead>
<tr>
<th></th>
<th>electron+jets</th>
<th>muon+jets</th>
<th>tau+jets</th>
<th>all-hadronic</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{c}s$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\bar{u}d$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tau^{-}\tau^{-}$</td>
<td>$e\tau$</td>
<td>$\mu\tau$</td>
<td>$\pi\pi$</td>
<td>tau+jets</td>
</tr>
<tr>
<td>$\bar{\mu}\bar{e}$</td>
<td>$e\mu$</td>
<td>$e\mu$</td>
<td>$\mu\tau$</td>
<td>muon+jets</td>
</tr>
<tr>
<td>$e^{-}e^{-}$</td>
<td>$e\bar{e}$</td>
<td>$e\mu$</td>
<td>$e\tau$</td>
<td>electron+jets</td>
</tr>
<tr>
<td>$W$ decay</td>
<td>$e^{+}$</td>
<td>$\mu^{+}$</td>
<td>$\tau^{+}$</td>
<td>$u\bar{d}$</td>
</tr>
</tbody>
</table>
SM Higgs Branching Ratios as function of Higgs Mass

Djouadi hep-ph/0503172
Mass of the Top Quark

March 2013  (* preliminary)

CDF-I dilepton  167.40 ± 11.41 (±10.30 ± 4.90)
DØ-I dilepton  168.40 ± 12.82 (±12.30 ± 3.60)
CDF-II dilepton  170.56 ± 3.79 (±2.19 ± 3.09)
DØ-II dilepton  174.00 ± 2.76 (±2.36 ± 1.44)
CDF-I lepton+jets  176.10 ± 7.36 (±5.10 ± 5.30)
DØ-I lepton+jets  180.10 ± 5.31 (±3.90 ± 3.60)
CDF-II lepton+jets  172.85 ± 1.11 (±0.52 ± 0.98)
DØ-II lepton+jets  174.94 ± 1.49 (±0.83 ± 1.24)
CDF-I alljets  186.00 ± 11.51 (±10.00 ± 5.70)
CDF-II alljets  172.47 ± 2.07 (±1.43 ± 1.49)
CDF-II track  166.90 ± 9.46 (±9.00 ± 2.90)
CDF-II MET+Jets *  173.95 ± 1.85 (±1.35 ± 1.26)
Tevatron combination *  173.20 ± 0.87 (±0.51 ± 0.71)

χ²/dof = 8.5/11 (67%)
Mass of the Top Quark in Different Decay Channels

March 2013

(* preliminary)

Lepton+jets

Dilepton

Alljets

MET+Jets *

Tevatron combination *

$M_t$ (GeV/c$^2$)

$168$ $169$ $170$ $171$ $172$ $173$ $174$ $175$ $176$ $177$ $178$ $179$

$173.18 \pm 0.92$ ($\pm 0.54 \pm 0.75$)

$171.02 \pm 2.06$ ($\pm 1.72 \pm 1.14$)

$172.70 \pm 1.94$ ($\pm 1.46 \pm 1.28$)

$173.76 \pm 1.79$ ($\pm 1.30 \pm 1.23$)

$173.20 \pm 0.87$ ($\pm 0.51 \pm 0.71$)

(\pm stat \pm syst)
What did we find?
and also in the dilepton channel, using the known \( b \)-tagging efficiency, the ratio

\[ R = \frac{B(t \to Wb)}{\sum q = d,s,b B(t \to Wq)} \]

can be extracted. In 5.4 of data, DØ measures \( R = 0.90 \pm 0.04, 2.5 \sigma \) from unity. A significant deviation of \( R \) from unity would imply either non-SM top decay (for example a flavor-changing neutral-current decay), or a fourth generation of quarks.

CDF also performs measurements of the \( t\bar{t} \) production cross section normalized to the \( Z \) production cross section in order to reduce the impact of the luminosity uncertainty.

\[
\begin{align*}
\sigma_{t\bar{t}}^{[pb]} &\begin{array}{cccc}
1 & 10 & 100 & 1000 \\
\text{ATLAS Preliminary} & 0.7 fb \\
\text{CMS Preliminary} & 0.8-1.1 fb \\
\text{CDF} & \text{NLO QCD (pp)} \\
\text{Approx. NNLO (pp)} & \\
\text{DØ} & \text{NLO QCD (p\bar{p})} \\
\text{Approx. NNLO (p\bar{p})} & \\
\end{array}
\end{align*}
\]

Figure 1: Measured and predicted \( t\bar{t} \) production cross sections from Tevatron energies in \( p\bar{p} \) collisions to LHC energies in \( pp \) collisions. Tevatron data points at \( \sqrt{s} = 1.8 \) TeV are from Refs. [25] and [26]. Those at \( \sqrt{s} = 1.96 \) TeV are from Refs. [17] and [18]. The ATLAS and CMS data points are from Refs. [20] and [22], respectively. Theory curves are generated using HATHOR [5] with input from Ref. [27] for the NLO curves and Ref. [2] for the approximate NNLO curves. Figure adapted from Ref. [19].

In Fig. 1, one sees the importance of \( p\bar{p} \) at Tevatron energies where the valence antiquarks in the antiprotons contribute to the dominant \( qq \) production mechanism. At LHC energies the dominant production mode is gluon-gluon fusion and the \( pp - p\bar{p} \) difference nearly disappears. The excellent agreement of the measurements with the theory calculations is a strong validation.
Top Pair-Production Channels
Parton Distribution Functions

MSTW 2008 NLO PDFs (68% C.L.)

$Q^2 = 10 \text{ GeV}^2$

$Q^2 = 10^4 \text{ GeV}^2$
Parton Luminosities at FNAL

$\sqrt{S}$ (GeV)

$\langle \tau / S \rangle \, dL / d\tau$ (µbarn)

$pp$ at $\sqrt{s} = 1.8$ TeV

$qq$

$gg$

Capagnari & Franklin, Rev. Mod. Phys. 69 (1997) 137
Top Quark Pair Production: Theory and Experiment

CMS Collaboration 2013

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

- CMS prelim. combined 8 TeV (2.8 fb$^{-1}$)
- LHC prelim. combined 7 TeV (0.7-1.1 fb$^{-1}$)
- CMS dilepton 7 TeV (2.3 fb$^{-1}$)
- Tevatron prelim. combined (up to 8.8 fb$^{-1}$)
- CDF prelim. combined (up to 8.8 fb$^{-1}$)
- D0 combined (5.4 fb$^{-1}$)

Approx. NNLO QCD (pp)
- Scale uncertainty
- Scale $\otimes$ PDF uncertainty

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

CMS Collaboration 2013
What didn’t we find?
II. Top Condensate, Higgsless, and Related Models

The top quark is much heavier than other fermions and must be more strongly coupled to the symmetry-breaking sector. It is natural to consider whether some or all of electroweak-symmetry breaking is due to a condensate of top quarks \([3,44]\). Top quark condensation alone, without additional fermions, seems to produce a top quark mass larger \([45]\) than observed experimentally, and is therefore not favored. Topcolor-as-sisted technicolor \([46]\) combines technicolor and top condensation. In addition to technicolor, which provides the bulk of electroweak symmetry breaking, top condensation and the top quark mass arise predominantly from “topcolor,” a new QCD-like interaction which couples strongly to the third generation of quarks.

An additional, strong, U(1) interaction (giving rise to a topcolor \(Z'\)) precludes the formation of a bottom-quark condensate. CDF has searched \([47]\) for the “topgluon,” a massive color-octet vector which couples preferentially to the third generation, in the mode \(p p \rightarrow g t \rightarrow b \bar{b}\). The results are shown in Figure 10.

**Figure 11:** 95\% C.L. exclusion limit on a narrow \(tt\) resonance as a function of the resonance mass by the DØ experiment \([49]\).
Top Single-Production Channels
Top Single-Production at the Tevatron (tb + tqb)

<table>
<thead>
<tr>
<th>Single Top Cross Section</th>
<th>Signal Significance</th>
<th>CKM Matrix Element $V_{tb}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DØ (2.3 fb$^{-1}$)</strong></td>
<td>March 2009</td>
<td>$</td>
</tr>
<tr>
<td>3.94 ± 0.88 pb</td>
<td>4.5 σ</td>
<td>$</td>
</tr>
<tr>
<td><strong>CDF (3.2, 2.1 fb$^{-1}$)</strong></td>
<td>March 2009</td>
<td>$</td>
</tr>
<tr>
<td>2.3 ±0.6 ±0.5 pb</td>
<td>&gt;5.9 σ</td>
<td>$</td>
</tr>
<tr>
<td><strong>DØ &amp; CDF combined</strong></td>
<td>August 2009</td>
<td>$</td>
</tr>
<tr>
<td>2.76 ±0.58 ±0.47 pb</td>
<td></td>
<td>$</td>
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</table>

http://www-d0.fnal.gov/Run2Physics/top/singletop_observation/
Top Quark Single Production: Rates in Multiple Channels

ATLAS Preliminary

$\sqrt{s} = 7$ TeV

<table>
<thead>
<tr>
<th>Channel</th>
<th>Single Top Cross Section [fb]</th>
<th>Theory (approx. NNLO)</th>
</tr>
</thead>
<tbody>
<tr>
<td>t-channel</td>
<td>1.04</td>
<td>$83^{+20}_{-20}$ pb</td>
</tr>
<tr>
<td>T-channel top</td>
<td>4.7</td>
<td>$53^{+11}_{-11}$ pb</td>
</tr>
<tr>
<td>T-channel antitop</td>
<td>4.7</td>
<td>$30^{+7}_{-8}$ pb</td>
</tr>
<tr>
<td>Wt-channel</td>
<td>2.05</td>
<td>$17^{+6}_{-6}$ pb</td>
</tr>
<tr>
<td>s-channel</td>
<td>0.70</td>
<td>$&lt; 26$ pb</td>
</tr>
</tbody>
</table>

arXiv:1205.3130

ATLAS-CONF-2012-056

arXiv:1205.5764

ATLAS-CONF-2011-118

ATLAS Experiment © 2013 CERN
More Top Information

The Discovery of the Top Quark. C. Campagnari & M. Franklin
Rev.Mod.Phys. 69 (1997) 137-212

Top Quark Physics at the LHC: A Review of The First Two Years.

D0:  http://www-d0.fnal.gov/Run2Physics/top/

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

ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults

CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP