Top Quark Physics

Nicholas Hadley
The University of Maryland

on behalf of
the ATLAS, CDF, CMS, Dzero, and LHCb experiments
Outline

• Selected top quark history
• $t\bar{t}$ cross section measurements
• Top mass measurements
• Single top cross section measurements
• Top Branching Ratios
• $ttV$
• AFB

• Disclaimer
  • 25 top talks in the parallel sessions. Many more results and details can be found there.
Selected History (1)

- 1964 Gell-Mann and Zweig - Quarks
- 1970 Glashow, Iliopoulos, and Maiani
  - Absence of flavor changing neutral currents implies charm (4th) quark
- 1973 Kobayashi and Maskawa
  - Extend Cabibbo’s 1963 work, six quarks can have CP violation
- 1975 Tau Lepton – Perl et al at SLAC
  - Third generation discovered
- 1975 H. Harari
  - “top” and “bottom” quarks in isodoublet
- 1977 Upsilon – Lederman et al at Fermilab
  - implied bottom Quark
Selected History (2)

• To avoid anomalies and flavor changing neutral currents, $b$ in an isodoublet with a “top” partner.
• Ginsparg, Glashow, and Wise 1983
  • $B$ lifetime long $\rightarrow$ small $V_{cb} + \varepsilon_{cp} \rightarrow$ heavy top
• By 1984, Petra has ruled out top quarks with mass less than 23.3 GeV.
• By late 1980’s at Tristan, $M_t > 30.2$ GeV
• Also by late 1980’s, SppS ruled out top quarks with mass less than 44 GeV.
  • 1984 hint of 40 GeV top quark was $W$ + jets background
• Top not observed at LEP as well and stage set for the Tevatron
By 1993, CDF and Dzero see striking individual events consistent with top, but low statistical sensitivity.

1994 CDF “evidence” paper 2.8σ
Selected History (4)

- CDF and Dzero had an agreement reached with Fnal Director John Peoples.
  - Either collaboration could trigger the end game by submitting a discovery paper to him. On receipt, a one week holding period would commence, during which the other collaboration could finalize its result if desired, after which publication submission would proceed.
- On Feb. 17, 1995, CDF delivered its paper to Peoples triggering the process.
- On Feb. 24, 1995 CDF and Dzero submit papers to PRL simultaneously.
  - Results embargoed until March 2 seminars at Fnal.
as well as in a QCD sample selected to approximate non-W background. After requiring an SVX or SLT b tag, 19 of the events remain, of which 6.9 \pm 2.5 are expected to be background. For these events, only solutions in which the tagged jet is assigned to one of the b quarks are considered. Figure 3 shows the mass distribution for the tagged events. The mass distribution in the current run is very similar to that from the previous run. Furthermore, we employed several mass fitting techniques which give nearly identical results.

To find the most likely top mass, we fit the mass distribution to a sum of the expected distributions from the SVX and SLT background, and a top signal of mass \( m_{top} \).

\[
\begin{align*}
\mathbf{m_{top} = 176 \pm 8 \text{ (stat)} \pm 10 \text{ (syst)} \text{ GeV}}
\end{align*}
\]

\[
\begin{align*}
\mathbf{m_{top} = 199^{+19}_{-21} \text{ (stat)} \pm 22 \text{ (syst)} \text{ GeV}}
\end{align*}
\]

\[
\begin{align*}
\mathbf{\sigma_{tt} = 6.8^{+3.6}_{-2.4} \text{ pb}}
\end{align*}
\]

\[
\begin{align*}
\mathbf{\sigma_{tt} = 6.4 \pm 2.2 \text{ pb}}
\end{align*}
\]

**Phys. Rev. Lett. 73, 225 (1994) evidence**  

The discovery data sets were 67 pb\(^{-1}\) for CDF and 50 pb\(^{-1}\) for Dzero.

- CDF 6 dilepton events
- Dzero 3 dilepton events

Starting from \(\approx 400\) ttbar pairs

- \(M_{\text{top}}\) uncertainty 13 GeV (CDF)
- \(\sigma_{\text{ttbar}}\) uncertainty 33%
Fast Forward to 2015
Why top is still important

- Only place to study the properties of a bare quark
  - Lifetime < hadronisation

- Special role in EWSB?
  - Yukawa coupling $\approx 1$
  - Mass much larger than other quarks/leptons

- First place a new particle could be observed
  - Particularly if new particle couples to mass

- Stability of the universe
ttbar production

Tevatron collides 980 GeV beams of protons and anti-protons: minimum $x=0.18$ so quark anti-quark annihilation dominates [85%]

LHC collides 3.5 TeV or 4 TeV or 6.5 TeV beams of protons minimum $x=0.043 (0.027)$, so gluon fusion dominates [above 80%]
Top Fundamentals (2)

- Common feature of ttbar events is two b-jets from weak decays $t \to Wb$
- Subsequent decay of $W^+W^-$ bosons gives final states
  - 4% “dilepton” (e + mu)
  - 30% single lepton+jets
  - 46% all jets
  - 20% tau + X
**Ttbar Cross Section - Tevatron**

### Tevatron Run II

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Cross Section (pb)</th>
<th>Luminosity ($fb^{-1}$)</th>
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<tbody>
<tr>
<td>CDF dilepton</td>
<td>$7.09 \pm 0.83$</td>
<td>$8.8$</td>
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<tr>
<td>CDF ANN lepton+jets</td>
<td>$7.82 \pm 0.56$</td>
<td>$4.6$</td>
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<td>CDF SVX lepton+jets</td>
<td>$7.32 \pm 0.71$</td>
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<td>CDF all-jets</td>
<td>$7.21 \pm 1.28$</td>
<td>$2.9$</td>
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<td>CDF combined</td>
<td>$7.63 \pm 0.50$</td>
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<tr>
<td>DØ dilepton</td>
<td>$7.36 \pm 0.85$</td>
<td>$5.4$</td>
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<tr>
<td>DØ lepton+jets</td>
<td>$7.90 \pm 0.74$</td>
<td>$5.3$</td>
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<tr>
<td>DØ combined</td>
<td>$7.56 \pm 0.59$</td>
<td>$5.3$</td>
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<tr>
<td><strong>Tevatron combined</strong></td>
<td>$7.60 \pm 0.41$</td>
<td>$5.3$</td>
</tr>
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</table>

Starting from $\approx 35,000 \text{ ttbar pairs}$

Theory $\sigma = 7.35 \pm 0.28 \pm 0.33 \text{ pb}$

**PRD 89, 072001 (2014)**

Uncertainty 5%
Ttbar Cross Section vs $\sqrt{s}$

- 8 TeV
  $\approx 1.2M - 5M$
ttbar pairs
Uncertainty 4%

- 7 TeV
  $\approx 170,000$ ttbar pairs
Uncertainty 5%
\[ \sigma_{tt} (13 \text{ TeV}) = 825 \pm 49 \text{ (stat)} \pm 60 \text{ (syst)} \pm 83 \text{ (lumi)} \text{ pb} \]
Ttbar differential distributions – LHC

Used in a search

CMS, 19.7 fb$^{-1}$ at $\sqrt{s} = 8$ TeV

Data

MadGraph+Pythia6

MC@NLO+Herwig6

Powheg+Pythia6

Powheg+Herwig6

NLO+NNLL

(JHEP 09 (2013) 032)

Data

Stat.

Stat. $\otimes$ Syst.

Theory

e/µ + Jets

$\frac{1}{\delta m_{t\bar{t}}}$ [GeV$^{-1}$]
Ttbar differential $\sigma$ - Tevatron

\[ \frac{d\sigma}{dp_T^{\text{top}}} \ [\text{pb/GeV}] \]

(a) DØ \hspace{1cm} \mathcal{L} = 9.7 \, \text{fb}^{-1}

- Data
- Alpgen
- MC@NLO
- approx.NNLO

\[ m_{\text{top}} = 173 \, \text{GeV} \]


approx.NNLO

\[ \frac{d\sigma}{dm(t\bar{t})} \ [\text{pb/GeV}] \]

(a) DØ \hspace{1cm} \mathcal{L} = 9.7 \, \text{fb}^{-1}

- Data
- Alpgen
- MC@NLO
- approx.NNLO

LHCB searches for t to W + b in the forward region

The inclusive top production cross-sections are in the fiducial region defined by:

- $p_T(\mu) > 25 \text{ GeV}$, $2.0 < (\eta) < 4.5$, $50 < p_T(b) < 100 \text{ GeV}$, $2.2 < (\eta_b) < 4.2$, $\Delta R(\mu; b) > 0.5$, and $p_T(\mu + b) > 20 \text{ GeV}$,

- $\sigma(\text{top}) \ [7\text{ TeV}] = 239 \pm 53 \ (\text{stat}) \pm 38 \ (\text{syst}) \ \text{fb} \ ; (1.0 \ \text{fb}^{-1})$
- $\sigma(\text{top}) \ [8\text{ TeV}] = 289 \pm 43 \ (\text{stat}) \pm 46 \ (\text{syst}) \ \text{fb} \ ; (2.0 \ \text{fb}^{-1})$

- 75% $t\bar{t}$bar production, 25% single top almost all t channel

Cross sections agree with theory (NLO using MCFM)

- $180^{+51}_{-41} \ \text{fb} \ [7 \ \text{TeV}]$ \quad $312^{+83}_{-68} \ \text{fb} \ [8 \ \text{TeV}]$

Top Mass - Importance

gfitter 2014

arXiv1307.3536
### Early top mass predictions

From NJH talk to the PEP-4 TPC group at Berkeley  
May 23, 1979

<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
<th>Mass (GeV)</th>
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</thead>
<tbody>
<tr>
<td>C. L. Bruggge</td>
<td>1979</td>
<td>5.0</td>
</tr>
<tr>
<td>D. Wijers</td>
<td></td>
<td>16.5</td>
</tr>
<tr>
<td>H. Harari et al.</td>
<td>1979</td>
<td>14</td>
</tr>
<tr>
<td>A. Elbashim</td>
<td>1979</td>
<td>30</td>
</tr>
<tr>
<td>H. Georgi and D.V. Nanopoulos</td>
<td>1979</td>
<td>14</td>
</tr>
<tr>
<td>G. Preparata</td>
<td>1979</td>
<td>20</td>
</tr>
<tr>
<td>S. Pakvasa and H. Sagawa</td>
<td>1979</td>
<td>26</td>
</tr>
</tbody>
</table>

\[
\langle M_t \rangle = 20.1 \pm 12 \text{ GeV}
\]
Indirect determinations of the top-quark mass from fits to electroweak observables (green circles) 95% confidence-level lower bounds on the top-quark mass inferred from direct searches, (broken line). Direct measurements by the CDF (blue triangles) and D0 (inverted red triangles) collaborations. The Tevatron averages from direct observations are shown as magenta squares. The first LHC averages are shown as a crossed box. The March 2014 World Average is represented as a cyan diamond.
Top Mass Tevatron

Tevatron combination
Top mass = 174.34 ± 0.64 GeV
0.37 (stat) ± 0.52 (syst.)

Light jet calibration and signal modeling dominant uncertainties
Top Mass LHC

Perhaps some tension

Tevatron $174.34 \pm 0.64$ GeV

CMS $172.38 \pm 0.65$ GeV

ATLAS $172.99 \pm 0.91$ GeV
Top Mass - Comments

- Masses in different modes and experiments are consistent.
- Top best known quark mass

- These are “Monte Carlo” masses.
- “Pole mass” could be different by $\approx 1$ GeV.
  - Measure from ttbar cross section or (current most accurate) ttbar + 1 jet events
    - $m_{t}^{\text{pole}} = 173.7 \pm 1.5 \, \text{(stat.)} \pm 1.4 \, \text{(syst.)} \, +1.0_{-0.5} \, \text{(theory)} \, \text{GeV}.$
    - (ATLAS arXiv 1507.01769v1)
Top Fundamentals (3) Single Top

s-channel

\[ u (\bar{d}) \leftrightarrow d (\bar{u}) \]

\[ \begin{array}{c}
  u \\
  d \\
\end{array} \quad \begin{array}{c}
  t \\
  b \\
\end{array} \]

Wt-production

\[ b \longrightarrow t \]

\[ g \quad W \]

\[ \begin{array}{c}
  b \\
\end{array} \quad \begin{array}{c}
  t \\
\end{array} \]

\[ \begin{array}{c}
  b \\
\end{array} \quad \begin{array}{c}
  W \\
\end{array} \]

LHC 8 TeV

\[ \frac{78.2\%}{17.1\%} \]

Tevatron

\[ \frac{63.6\%}{28.9\%} \]

\[ 7.5\% \]
Single Top - Tevatron

Tevatron Run II single top quark summary

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>CDF [25]</td>
<td>1.36 +0.37 -0.32</td>
<td></td>
<td></td>
<td>CDF [21]</td>
<td>1.65 +0.38 -0.36</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D0 [22]</td>
<td>1.10 +0.33 -0.31</td>
<td></td>
<td></td>
<td>D0 [22]</td>
<td>3.07 +0.54 -0.49</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tevatron [26]</td>
<td>1.29 +0.26 -0.24</td>
<td></td>
<td></td>
<td>Tevatron [this paper]</td>
<td>2.25 +0.29 -0.31</td>
</tr>
<tr>
<td></td>
<td></td>
<td>s+t:</td>
<td>CDF [21]</td>
<td>3.02 +0.49 -0.48</td>
<td></td>
<td>D0 [22]</td>
<td>4.11 +0.60 -0.55</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tevatron [this paper]</td>
<td>3.30 +0.52 -0.40</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

> 6σ s-channel discovery

“this paper”

Results agree with Standard Model theory

≈2σ Dzero CDF t-channel difference
Single Top – LHC - comments

• Systematic errors dominate the results
  • Jet energy scale and resolution, signal modeling

• No s-channel observation (yet)
$V_{tb}$ from single top

ATLAS+CMS Preliminary TOPLHCWG

$|V_{tb}| = \frac{\sigma_{\text{meas.}}}{\sigma_{\text{theo.}}}$ from single top quark production

$\sigma_{\text{theo.}}$: NLO+NLL MSTW2008nlo


$\Delta \sigma_{\text{theo.}}$: scale @ PDF

$m_{top} = 172.5$ GeV

<table>
<thead>
<tr>
<th>$V_{tb}$</th>
<th>(meas.) ± (theo.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.02 ± 0.06 ± 0.02</td>
<td></td>
</tr>
</tbody>
</table>

$V_{tb}$ from single top

$\sigma_{V_{tb}} \approx 1$ as expected.

**Tevatron combined**

$V_{tb} = 1.02 \pm 0.06 - 0.05$

$|V_{tb}| > 0.92$ (95% CL) from single top $\sigma$

$V_{tb} \approx 1$ as expected.
Top Branching Ratios

- $R = \frac{B(t \rightarrow Wb)}{B(t \rightarrow Wq)}$ has been measured by CDF, Dzero, and CMS.
  - $R = 0.87 \pm 0.07$ [CDF], $R = 0.90 \pm 0.04$ [Dzero]
  - $R = 1.014 \pm 0.003$ (stat) $\pm 0.032$ (syst) [CMS]
    - Implies $|V_{tb}| > 0.975$ (95% CL)
    - $\Gamma_t = 1.36 \pm 0.02$ (stat.) $+0.14/-0.11$ (syst.) GeV
      $\sigma$ (single top) as input, agrees with SM

- Flavor Changing neutral current decays
  - CDF, Dzero, CMS, and ATLAS have searched for FCNC
  - Representative limits
    - $B(t \rightarrow Zq) < 5 \times 10^{-4}$ (CMS), < $7 \times 10^{-4}$ (ATLAS)
    - $B(t \rightarrow ug) < 3.1 \times 10^{-5}$ (ATLAS)
    - $B(t \rightarrow cg) < 1.6 \times 10^{-4}$ (ATLAS)
**A_{FB} at the Tevatron**

- Forward-backward asymmetry of ttbar pairs at the Tevatron
  - Need protons and anti protons

\[ A_{FB}^{tt} = \frac{N(\Delta y_t > 0) - N(\Delta y_t < 0)}{N(\Delta y_t > 0) + N(\Delta y_t < 0)} \]

\[ |\Delta y_t = y_t - y_{\bar{t}}. \]

y = rapidity defined as positive along proton direction

- Asymmetries have been somewhat larger than SM predictions and show dependence on Δy

- Current status
  - CDF: A_{FB} 1.5σ higher than SM, slope of A_{FB} vs Δy 2σ high.
  - Dzero: A_{FB} and slope agree within 1σ of SM, but also do not disfavor CDF measurements.
Tevatron $A_{FB}^{\tau\tau}$

**CDF Lepton+jets (9.4 fb$^{-1}$)**
PRD 87, 092002 (2013)

$A_{FB}^{\tau\tau} = (16.4 \pm 4.7)$

**CDF Dilepton (9.1 fb$^{-1}$)**

$A_{FB}^{\tau\tau} = (12 \pm 13)$

**CDF Combination (9.4 fb$^{-1}$)**

$A_{FB}^{\tau\tau} = (16.0 \pm 4.5)$

**D0 Lepton+jets (9.7 fb$^{-1}$)**

PRD 90, 072011 (2014)

$A_{FB}^{\tau\tau} = (10.6 \pm 3.0)$

**D0 Dileptons (9.7 fb$^{-1}$)**

$A_{FB}^{\tau\tau} = (17.5 \pm 6.3)$

**D0 Combination (9.7 fb$^{-1}$)**

$A_{FB}^{\tau\tau} = (11.8 \pm 2.8)$

---

Tevatron $A_{FB}^{\tau\tau}$ vs. $|\Delta y|$ slope $\alpha$

- CDF Lepton+jets (9.4 fb$^{-1}$)
  PRD 87, 092002 (2013)
  $\alpha = 0.253 \pm 0.062$

- CDF Dilepton (9.1 fb$^{-1}$)
  CDF Public Note 11161
  $\alpha = 0.140 \pm 0.150$

- CDF combination (9.4 fb$^{-1}$)
  CDF Public Note 11161
  $\alpha = 0.227 \pm 0.057$

- D0 Lepton+jets (9.7 fb$^{-1}$)
  PRD 90, 072011 (2014)
  $\alpha = 0.154 \pm 0.043$

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**EPS Vienna July 27, 2015**
ttV production

CMS Preliminary

\[ \sigma(\bar{t}tW) = 382^{+117}_{-102} \text{ fb} \]
\[ \sigma(\bar{t}tZ) = 242^{+65}_{-55} \text{ fb} \]

ATLAS Preliminary

\[ \sigma_{\bar{t}\bar{t}W} = 369^{+86}_{-79} \text{ (stat)} \pm 44 \text{ (syst.)} \text{ fb} \]
\[ \sigma_{\bar{t}\bar{t}Z/\gamma^*} = 176^{+52}_{-48} \text{ (stat)} \pm 24 \text{ (syst.)} \text{ fb} \]
Top – More Properties

• Not covered due to time (see parallel sessions)
  • Top charge (-4/3 ruled out)
  • top spin correlations
  • Top charge asymmetry at LHC
  • W helicity in top decay – 5% measurements now
  • Top width (direct)
  • ttγ – seen – consistent with SM
  • Top couplings to Higgs (see Pierre Savard’s talk)
  • Searches for new physics with top
  • First plots from 13 TeV LHC data
Final Comments

- top quark mass is 173 GeV ≈ the mass of a gold atom.
- $t\bar{t}$ production cross section agrees with theory.
  - Top quark behaves like a point-like fundamental particle up to highest energies (8 TeV).
- Ranges of quark and lepton masses (neutrinos to tau and up/down to top) seem bizarre.
  - However, top fits in the Standard Model.
- $t\bar{t}$ as key to EWSB (??)
- With larger samples at LHC Run 2 (250M), still room for new physics in precision top measurements.
  - top coupling to electroweak bosons
- Future accelerators – even better measurements
Thanks to all who provided material and made comments on this talk.
Top Parallel Session Talks

• Thursday July 23 (5 talks)
  • 14:30 [132] Measurement of t-channel single top quark production in pp collisions (00h18’) FABOZZI, Francesco
  • 14:48 [133] Measurement of single top production in the tW-channel and search for s-channel in pp collisions (00h18’) MEROLA, Mario
  • 15:06 [683] Tevatron combined single top production cross sections (00h18’) RONZANI, Manfredi
  • 15:24 [654] Measurement of ttbar production cross section (00h18’) PETERS, Reinhild
  • 15:42 [61] Top-quark pair production at hadron colliders: differential cross section and phenomenological applications with DiffTop (00h18’) LIPKA, Katerina
Top Parallel Session Talks

- **Friday July 24 (10 talks)**
  - 09:00 [635] Flavour-changing top decays in the aligned two-Higgs-doublet model (00h18’) ABBAS, gauhar
  - 09:18 [714] Z’-induced FCNC Decays of Top, Beauty and Strange Quarks (00h18’) Dr. KOHDA, Masaya
  - 09:36 [628] Searching for anomalous top quark couplings and decays with the ATLAS detector (00h18’) BOUDREAU, Joseph
  - 09:54 [508] Hadroproduction of a charged vector boson pair in association with a b-quark pair at NLO accuracy matched with parton shower (00h18’) TROCSANYI, Zoltan Laszlo
  - 10:12 [444] Matching NLO QCD Corrections in WHIZARD with the POWHEG scheme (00h18’) CHOKOUFE, Bijan
  - 10:30 [307] Subleading P-wave, Higgs and nonresonant contributions to top-pair production near threshold (00h18’) Mr. RAUH, Thomas
  - 11:30 [128] CMS Measurements of the top quark mass (00h18’) KIRSCHENMANN, Henning
  - 11:48 [633] Measurements of the top quark mass with the ATLAS detector (00h18’) BRANDT, Oleg
  - 12:06 [679] Measurement of the top quark mass and spin correlations with the D0 detector (00h18’) TUCHMING, Boris
  - 12:25 [129] New approaches in determining m_{top}: alternative techniques and differential measurements (00h18’) KIESELER, Jan
Top Parallel Session Talks

• Saturday July 25 (10 talks)
  • 09:00 [175] Physics with jets at LHCb (00h18’) BARLOW, Roger
  • 09:18 [632] Top properties measurements with the ATLAS detector (00h18’) NEEP, Tom
  • 09:36 [130] Measurements of the top quark properties in ttbar production at the LHC (includes charge asymmetry, top quark polarization, spin correlations and tt+V) (00h18’) ROSCHER, Frank Sebastian
  • 09:54 [680] Measurements of forward-backward asymmetries and top quark polarization with the D0 detector (00h18’) HUSEMANN, Ulrich
  • 10:13 [131] Measurement of the properties of top quarks in decays (includes W polarization, top quark charge and couplings) (00h18’) PIEDRA GOMEZ, Jonatan
  • 10:31 [134] Measurement of top quark properties in single top production (00h18’) TIKO, Andres
  • 11:30 [673] Precision Electroweak measurements at the Future Circular Colliders (00h20’) DAM, Mogens
  • 11:50 [701] Top and EW physics at the LHeC (00h20’) ZHANG, Zhiqing Philippe
  • 12:10 [363] Top Quark Physics at a Future Linear Collider (00h20’) POESCHL, Roman
  • 12:30 [672] Precision measurements of the top quark couplings at the FCC (00h20’) JANOT, Patrick
Ttbar Cross Section - Tevatron

Tevatron Run II, \( \leq 8.8 \text{ fb}^{-1} \)

\[
\sigma_{t\bar{t}} (\text{pb})
\]

- Measured \( \sigma(p\bar{p} \rightarrow t\bar{t}+X) \)
- Measured dependence of \( \sigma \)
- NNLO+NNLL QCD

Top quark mass (GeV)
**Ttbar Cross Section - Tevatron**

TABLE IV. CDF and D0 measurements of $\sigma_{t\bar{t}}$ and their combination (in pb), with individual contributions to their uncertainties (in pb). Correlation indicates whether a given uncertainty is treated as fully correlated between the CDF and D0 measurements.

<table>
<thead>
<tr>
<th>Sources of systematic uncertainty</th>
<th>CDF</th>
<th>D0</th>
<th>Tevatron</th>
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<tbody>
<tr>
<td>Central value of $\sigma_{t\bar{t}}$</td>
<td>7.63</td>
<td>7.56</td>
<td>7.60</td>
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<tr>
<td>Modeling of the detector</td>
<td>0.17</td>
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<td>No</td>
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<tr>
<td>Modeling of signal</td>
<td>0.21</td>
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<tr>
<td>Modeling of jets</td>
<td>0.21</td>
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<td>Method of extracting $\sigma_{t\bar{t}}$</td>
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<td>Background modeled from theory</td>
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<tr>
<td>Background based on data</td>
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<td>Normalization of $Z/\gamma^*$ prediction</td>
<td>0.13</td>
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<td>Luminosity: inelastic $p\bar{p}$ cross section</td>
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<td>0.30</td>
<td>Yes</td>
</tr>
<tr>
<td>Luminosity: detector</td>
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<td>0.35</td>
<td>No</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>0.39</td>
<td>0.56</td>
<td>0.36</td>
</tr>
<tr>
<td>Statistical uncertainty</td>
<td>0.31</td>
<td>0.20</td>
<td>0.20</td>
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<tr>
<td>Total uncertainty</td>
<td>0.50</td>
<td>0.59</td>
<td>0.41</td>
</tr>
</tbody>
</table>
Top Cross Section – LHC 7 TeV

LHC combined
\[ \sigma = 173 \pm 2 \pm 8 \pm 6 \text{ pb} \]
stat. ± syst. ± lumi.

Starting from
\[ \approx 170,000 \text{ ttbar pairs} \]
### Ttbar Cross Section - LHC

**ATLAS+CMS Preliminary** \( \sigma_t \) summary, \( \sqrt{s} = 8 \) TeV  

<table>
<thead>
<tr>
<th>Source</th>
<th>ATLAS, lepton+jets</th>
<th>CMS prel., lepton+jets</th>
<th>CMS, lepton+( \tau )_( l )</th>
<th>ATLAS, dilepton ( e\mu )</th>
<th>CMS, dilepton (( e\mu, \mu\mu, e\mu ))</th>
<th>LHC combined ( e\mu ) (Sep 2014)</th>
</tr>
</thead>
<tbody>
<tr>
<td>arXiv:1504.04251, ( L_{\text{int}}=20.3 ) fb(^{-1} )</td>
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<td>CMS-PAS TOP-12-006, ( L_{\text{int}}=2.9 ) fb(^{-1} )</td>
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<td>FLB 739 (2014) 23, ( L_{\text{int}}=13.5 ) fb(^{-1} )</td>
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<td>EPJ C74 (2014) 3109, ( L_{\text{int}}=20.3 ) fb(^{-1} )</td>
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<td>JHEP 02 (2014) 024, ( L_{\text{int}}=5.3 ) fb(^{-1} )</td>
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<td>CMS-PAS TOP-14-016, ATLAS-CONF-2014-059, ( L_{\text{int}}=5.3-20.3 ) fb(^{-1} )</td>
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</tbody>
</table>

\[ \sigma_t = 241.5 \pm 1.4 \pm 5.7 \pm 6.2 \text{ pb} \]

Starting from \( \approx 1.2M - 4.8M \) ttbar pairs

---

LHC combined
\[ \sigma = 241.5 \pm 1.4 \pm 5.7 \pm 6.2 \text{ pb} \]

stat. \pm syst. \pm lumi.
Fast Forward to 2015
what we know about top

- Top is the heaviest known fundamental particle
  - pointlike
  - Mass ~ 173 GeV
- Produced by strong and weak interactions
- Quark with Charge 2/3e
- Spin ½
- Decays almost exclusively to Wb
\[ \sigma_{t\bar{t}\gamma}^{\text{fid}} \times \text{BR} = 63 \pm 8\text{(stat)}^{+17}_{-13}\text{(syst)} \pm 1\text{(lumi)} \text{ fb} \]

Pt(\gamma) > 20 \text{ GeV}, \quad \text{per lepton flavor}

\[ \sigma_{t\bar{t}+\gamma}^{\text{CMS}} = 2.4 \pm 0.2\text{ (stat.)} \pm 0.6\text{ (syst.) pb} \]