Top quark studies

(Introduction)
→ Production
→ Production asymmetries, spin correlations and W helicity
→ Anomalous couplings
→ $tt + W, Z, \gamma$ cross sections
→ Mass
→ Conclusions & Outlook

Andreas Jung (Purdue) for the ATLAS & CMS collaboration

PASCOS

July 11th, 2016
Top quark introduction

- Top is the heaviest fundamental particle discovered so far
  - \( m_t = 173.34 \pm 0.76 \text{ GeV} \)
    - [arxiv:1403.4427]

- Lifetime: \( \tau \sim 5 \times 10^{-25} \text{ s} \ll \Lambda_{QCD} \)
  - Observe bare quark properties

- Large Yukawa coupling to Higgs boson
  - \( \lambda_t \sim 1 \)
  - special role in electroweak symmetry breaking?

- If we could calculate the Higgs mass:
  - Large corrections to the Higgs mass from top quark “loops” (Hierarchy problem)

High precision tests of QCD/SM
Tops are background to many searches
  - Top quarks as window to new physics

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Top quark studies
Content

Top mass (difference)
Top width, Lifetime
Top Charge

Production cross sections
Top kinematics
Production via resonance
New particles

$\bar{t} t + W, Z, B$

Branching Ratios $|V_{tb}|$
Anomalous couplings
Rare decays

Spin Correlations
Production Asymmetries
Polarization

$W^+$ helicity

Selection of results, focus on most recent and/or precise results

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Top quark introduction

- Strong interaction: Top pairs
  - LHC (7/8 TeV):
    - $q\bar{q}$: $\sim 15/13\%$ ($\sim 10\%$, 13 TeV)
    - $gg$: $\sim 85/87\%$ ($\sim 90\%$, 13 TeV)

- Decay channels:
  - $gg$ fusion

Top Pair Branching Fractions

- BR, bg decrease
- BR, bg increase

Theory (NNLO+NNLL):

<table>
<thead>
<tr>
<th>Collider</th>
<th>$\sigma_{tot}$ [pb]</th>
<th>scales [pb]</th>
<th>pdf [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tevatron</td>
<td>7.164</td>
<td>$+0.110(1.5%)$</td>
<td>$+0.169(2.4%)$</td>
</tr>
<tr>
<td>LHC 7 TeV</td>
<td>172.0</td>
<td>$+4.4(2.6%)$</td>
<td>$+4.7(2.7%)$</td>
</tr>
<tr>
<td>LHC 8 TeV</td>
<td>245.8</td>
<td>$-5.8(3.4%)$</td>
<td>$-4.8(2.8%)$</td>
</tr>
<tr>
<td>LHC 13 TeV</td>
<td>$\sigma = 832^{+40}_{-46}$ pb</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Top quark studies
Top quark production

- Extremely clean, very high purity
- Method: simultaneously determine \( \sigma(t\bar{t}) \) and the efficiency to reconstruct & \( b \)-tag jets
  → reduces related systematic uncertainties!

\[
N_1 = L \sigma_{t\bar{t}} \epsilon_{e\mu} 2\epsilon_b (1 - C_b \epsilon_b) + N_{1}^{bkg}
\]

\[
N_2 = L \sigma_{t\bar{t}} \epsilon_{e\mu} C_b \epsilon_b^2 + N_{2}^{bkg}
\]

- Event selection:
  - Single e- or \( \mu \)-trigger
  - ≥ 1 jets: \( p_T > 25 \text{ GeV}, |\eta| < 2.5 \)
  - Reconstructed e and \( \mu \) with \( p_T > 25 \text{ GeV}, |\eta| < 2.5 \)
  - 1 or 2 jets identified as \( b \)-jet

\[
\sigma = 818 \pm 8 \text{ (stat.)} \pm 27 \text{ (syst.)} \pm 19 \text{ (lumi.)} \pm 12 \text{ (beam) pb}
\]

\[ \frac{\delta \sigma}{\sigma} = 4.4\% \]
Top quark production

- CMS 1st cross section measurement at 5 TeV in eμ dilepton
  - Relative precision: $\frac{\delta \sigma}{\sigma} = 28\%$
  - $\sigma = 82 \pm 20 \text{ (stat.)} \pm 5 \text{ (syst.)} \pm 10 \text{ (lumi.) \, pb}$

- CMS cross section measurement in the dilepton channel @13 TeV, $\frac{\delta \sigma}{\sigma} = 5.6\%$
  - Dominated by Hadronisation, JES
  - $\sigma = 793 \pm 8 \text{ (stat.)} \pm 38 \text{ (syst.)} \pm 21 \text{ (lumi.) \, pb}$

### Source and Number of events

<table>
<thead>
<tr>
<th>Source</th>
<th>Number of e$^\pm$μ$^{\mp}$ events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drell–Yan</td>
<td>$24 \pm 9 \pm 4$</td>
</tr>
<tr>
<td>Non-W/Z leptons</td>
<td>$109 \pm 50 \pm 33$</td>
</tr>
<tr>
<td>Single top quark</td>
<td>$463 \pm 6 \pm 145$</td>
</tr>
<tr>
<td>VV</td>
<td>$15 \pm 2 \pm 5$</td>
</tr>
<tr>
<td>t\bar{t} V</td>
<td>$31 \pm 1 \pm 10$</td>
</tr>
<tr>
<td>Total background</td>
<td>$642 \pm 52 \pm 149$</td>
</tr>
<tr>
<td>t\bar{t} dilepton signal</td>
<td>$10199 \pm 14 \pm 462$</td>
</tr>
<tr>
<td>Data</td>
<td>10368</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source</th>
<th>Number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drell–Yan</td>
<td>1.6 ± 0.4</td>
</tr>
<tr>
<td>Non W/Z</td>
<td>1.0 ± 0.9</td>
</tr>
<tr>
<td>tW</td>
<td>0.89 ± 0.02</td>
</tr>
<tr>
<td>WV</td>
<td>0.41 ± 0.02</td>
</tr>
<tr>
<td>Total background</td>
<td>3.9 ± 0.8</td>
</tr>
<tr>
<td>Signal (t\bar{t} → eμ)</td>
<td>16.7 ± 0.2</td>
</tr>
<tr>
<td>Data</td>
<td>24</td>
</tr>
</tbody>
</table>
Top quark production

- New measurements at 2, 5 and 13 TeV – agreement with the SM
- Profile log-LH fit by D0:
  - Reduced uncertainties
  - Optimized to extract pole mass

Combination of dilepton & l+jets:

$$\sigma = 7.26 \pm 0.13 \text{ (stat.)} \pm 0.57/0.50 \text{ (syst.) pb}$$

$$\delta\sigma/\sigma = 7.6\%$$

D0 [arxiv:1605.06168]
Run I top $p_T$ measurements at ATLAS/CMS not described by NLO and most MCs

Data is more soft: consistently seen in all decay channels

Spectra are described by NNLO+NNLL calculations by Czakon et al.
Differential cross sections

- CMS: 13 TeV data shows less jets than MC
  - Regime of the parton showers (PS)
  - NNLO describes top pT
  - Already systematically limited, better understanding of signal model needed

- ATLAS measures # additional jets with different thresholds
  - Systematically limited, JES will improve

Dilepton CMS-PAS-TOP-16-011
l+jets CMS-PAS-TOP-16-008

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Differential cross section as a function of event variables:
Submitted to PRD
CMS-PAG-TOP-12-042
**ATLAS boosted regime:** $p_T > 300$, trimmed large-R 1.0

- Consistent picture in boosted and resolved phase space
- Parton level results receive larger systematic uncertainties
- CMS 13 TeV all-hadronic combined resolved and boosted analysis

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- Test of EW interactions
- Single top cross section as high as $tt$ at 8 TeV – large samples
- Extract $V_{tb}$
- Search for flavor changing neutral currents, highly suppressed in SM
- Sensitivity to proton PDFs: especially $b$ and $u/d$-ratio

<table>
<thead>
<tr>
<th>Energy</th>
<th>Process</th>
<th>Cross section [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tevatron (1.96 TeV)</td>
<td>$t$</td>
<td>$2.10 \pm 0.13$</td>
</tr>
<tr>
<td></td>
<td>$s$</td>
<td>$1.05 \pm 0.06$</td>
</tr>
<tr>
<td></td>
<td>$Wt$</td>
<td>$0.25 \pm 0.03$</td>
</tr>
<tr>
<td>LHC (7 TeV)</td>
<td>$t$</td>
<td>$65.9^{+2.1}<em>{-0.7}$ (scale) $^{+1.5}</em>{-1.7}$ (PDF)</td>
</tr>
<tr>
<td></td>
<td>$s$</td>
<td>$4.56 \pm 0.07$ (scale) $^{+0.18}_{-0.17}$ (PDF)</td>
</tr>
<tr>
<td></td>
<td>$Wt$</td>
<td>$15.6 \pm 0.4$ (scale) $\pm 1.1$ (PDF)</td>
</tr>
<tr>
<td>LHC (8 TeV)</td>
<td>$t$</td>
<td>$87.2^{+2.8}<em>{-1.0}$ (scale) $^{+2.0}</em>{-2.2}$ (PDF)</td>
</tr>
<tr>
<td></td>
<td>$s$</td>
<td>$5.55 \pm 0.08$ (scale) $\pm 0.21$ (PDF)</td>
</tr>
<tr>
<td></td>
<td>$Wt$</td>
<td>$22.2 \pm 0.6$ (scale) $\pm 1.4$ (PDF)</td>
</tr>
<tr>
<td>LHC (13 TeV)</td>
<td>$t$</td>
<td>$216.99^{+6.62}_{-6.64}$ (scale) $\pm 6.16$ (PDF)</td>
</tr>
<tr>
<td></td>
<td>$s$</td>
<td>$10.3 \pm 0.4$</td>
</tr>
<tr>
<td></td>
<td>$Wt$</td>
<td>$71.1 \pm 3.8$</td>
</tr>
</tbody>
</table>
**s-channel single top**

- CMS combines 7 and 8 TeV data
  - Categorized by $b$-tags, $\#jets$
  - Binned maximum-likelihood fit to a BDT discriminant

\[ \sigma = 13.4 \pm 7.3 \text{ (stat. + syst.) pb} \] $[\delta \sigma/\sigma = 55\%]$ 
Observed 2.5 SD (1.0 SD expected)

- ATLAS sees evidence for s-channel at 8 TeV
  - Applies ME-method improving BDT result by about 50%
  - Other half of improvement from object Ids, evt selection, etc.
  - Binned maximum likelihood fit to ME discriminant and lepton charge

\[ \sigma = 4.8 \pm 0.8 \text{ (stat.)} \pm 1.6/1.3 \text{ (syst.) pb} \] $[\delta \sigma/\sigma = 35\%]$ Observed 3.2 SD (3.9 SD expected)

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CMS 1\textsuperscript{st} tW-channel observation at 8 TeV
- Categorized by \#b-tags, \#jets
- Binned maximum-likelihood fit to a BDT discriminant

\[ \sigma = 23.4 \pm 5.4 \text{ (stat. + syst.) pb} \ [\delta \sigma/\sigma=23\%] \]
6.1 SD (5.4 SD expected)

ATLAS observes tW-channel at 8 TeV
- Two oppositely charged leptons
- Profile likelihood fit for signal + bg
- First measure fiducial volume than full phase space (uncertainty of 9\%)

\[ \sigma = 23.0 \pm 1.3 \text{ (stat.)} \pm 3.4/3.7 \text{ (syst.) pb} \]
[\delta \sigma/\sigma=17\%] and 7.7 SD (6.9 SD expected)
CMS: First differential measurement of \textbf{t-channel top} production @13 TeV

- Muon-channel only employing a BDT discriminator and maximum likelihood fit
- Correct detector and measure parton level cross section for pT and y

**Single top goes differential**

![Graphs showing differential measurements and cross sections](image-url)
Decay channels:

Single top quark - summary

ATLAS+CMS Preliminary LHC topWG
Single top-quark production
June 2016

Decay channels:

Inclusive cross-section [pb]
Flavor Changing Neutral Currents are highly suppressed in SM.

Still above SM predictions but reached sensitivity to certain BSM models.

$|V_{tb}|^2$ enters in production and decay: $\sigma \sim |V_{tb}|^2$
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W helicity

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Measurements at Tevatron & LHC are complementary
- Variety of models (large parameter space) still allowed → $W', G, \omega, \phi, \Omega$
- $q\bar{q}$ initial state, in gg is zero
- NLO is 1st appearance

$A_C = \frac{N(\Delta|y_t| > 0) - N(\Delta|y_t| < 0)}{N(\Delta|y_t| > 0) + N(\Delta|y_t| < 0)}$

NLO+EW prediction (Bernreuther, et al.)
$A_C^{t\bar{t}} = +0.011 \pm 0.0004$

Top quark asymmetries

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More on asymmetries: D. Millar
**Charge asymmetries**

- Lepton+jets & Dilepton
- Fully Baysian unfolding
- Individual channels (ee, $\mu\mu$, e\(\mu\)) are combined

\[ A_C^{ll} = 0.008 \pm 0.006 \text{ (tot)} \]
\[ A_C^{\bar{t}t} = 0.021 \pm 0.016 \text{ (tot)} \]
\[ A_C^{t\bar{t}} = 0.009 \pm 0.005 \text{ (tot) [l+jets]} \]

→ Measure top and lepton based asymmetry, as well as differential

In agreement with SM:
**Summary of the current Situation:**

- **Experiment:** Dominated by stats & signal model dominates systematic unc's
- **Theory:** Need QCD predictions at NNLO

- All measurements are (so far) in agreement with SM
- At 13 TeV and new methods: expect to observe SM asymmetries
  - Larger gg fraction reduces them → improved methods, e.g. [arxiv:1309.2889]
Top quark spin correlations

- Top quark spins expected to be correlated in SM (short life time)
- Spin analyzing power of leptons is 1, measure lepton distributions
- Powerful handle to search for BSM in difficult phase space regions

Spin correlation strength:

\[ A = \frac{(N_{\uparrow\uparrow} + N_{\downarrow\downarrow}) - (N_{\uparrow\downarrow} + N_{\downarrow\uparrow})}{(N_{\uparrow\uparrow} + N_{\downarrow\downarrow}) + (N_{\uparrow\downarrow} + N_{\downarrow\uparrow})} \]

\[ f = \frac{N^{t\bar{t}}_{SM}}{N^{t\bar{t}}_{SM} + N^{t\bar{t}}_{uncor}} \]

\[ A_{\text{meas}} = A_{\text{basis}} \cdot f \]

- A depends on basis, energy, production mechanism
- f represents degree of SC relative to the SM

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Top quark studies
Top quark spin correlations

- Top quark spins expected to be correlated in SM
- Reconstruction based on leptons → Dilepton decay channel, ≥ 2 jets
- Inclusive and differential measurements @ parton level by reg. Unfolding
- Dominated by: Unfolding & top $p_T$ reweighting

Results agree with NLO QCD: Spins correlated!

$\Re(\mu_t) = -0.006 \pm 0.024$ (tot.)

$-0.053 < \Re(\mu_t) < 0.042$ at 95% CL

$-0.068 < \Re(d_t) < 0.067$ at 95% CL

*Search for top chromomagnetic anomalous couplings using differential cross section distribution*

PRD 93, 052007 (2016)

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Top quark spin correlations

- High precision SM measurements, more and more important in Run II
- Access top squarks (MSSM: 100% $t \rightarrow \tilde{t} \tilde{u}$) of similar mass as $m_t$
- Uncertainties dominated by: signal model (Hadronization and ISR/FSR)

Exclusion between $m_t$ and 191 GeV at 95% CL, difficult to access by “standard” searches
W helicity

- W helicity in SM: \( f_L = 0.30 \), \( f_0 = 0.70 \), \( f_R = 0 \)

- W helicity in top pair \( l+\)jets channel
- CMS also measured W helicity in single top events
  - Similar precision but orthogonal systematic uncertainties in single top channels
  - Signal model & template statistics

Most accurate experimental determination

\[
\begin{align*}
F_0 &= 0.681 \pm 0.012 \text{ (stat.)} \pm 0.023 \text{ (syst.)} \\
F_L &= 0.323 \pm 0.008 \text{ (stat.)} \pm 0.014 \text{ (syst.)} \\
F_R &= 0.004 \pm 0.005 \text{ (stat.)} \pm 0.014 \text{ (syst.)}
\end{align*}
\]
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→ Selection of results, focus on most recent and/or precise results
Associated production of $W$ and $Z$ in the SM (different mechanisms)
Observations at 8 TeV at ATLAS and CMS
13 TeV ATLAS & CMS:
   - Extract $\sigma$ employing binned profile LH fit
   - ATLAS various signal & control regions, CMS includes 3 & 4 lepton final states
   - Systematic uncertainties dominated by:
     - Lepton ID, signal model

$\sigma(t\bar{t}Z) = 1.1 \pm 0.4$ (stat.) $\pm 0.2$ (syst.) pb
[$\delta\sigma/\sigma=36\%$] Observe 3.6 SD (3.1 expected)
Associated production of $W$ and $Z$ in the SM (different mechanisms)

Observations at 8 TeV at ATLAS and CMS

13 TeV ATLAS & CMS:
  - Extract $\sigma$ employing binned profile LH fit
  - ATLAS various signal & control regions, CMS includes 3 & 4 lepton final states
  - Systematic unc's dominated by:
    - Lepton ID, signal model

$\sigma(t\bar{t}Z) = 0.9 \pm 0.3 \text{ (stat.)} \pm 0.1 \text{ (syst.)} \text{ pb}

$\sigma(t\bar{t}W) = 1.4 \pm 0.7 \text{ (stat.)} \pm 0.3 \text{ (syst.)} \text{ pb}$
Top mass (difference)  
Top width, Lifetime  
Top Charge

Production cross sections  
Top kinematics  
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\( \bar{t}t + W, Z, B \)

Branching Ratios \(|V_{tb}|\)  
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\( W \) helicity

Selection of results, focus on most recent and/or precise results

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Top quark studies
Self-consistency test of the SM & stability of the EW vacuum both rely/use pole mass – what we measure depends on the method
- Indirect extraction from e.g. cross section, end point, J/psi method
  → top quark pole mass
- Direct methods e.g. template, matrix element, likelihood, ideogram
  → “MC” mass with O(1 GeV) difference to pole mass

More on EW stability: K. Mukaida
Top quark mass

- Direct measurements combined using BLUE
  - Takes correlations into account
- Latest ATLAS combination
  - Precision of 0.4% (!)
    \[ m_{\text{top}} = 172.84 \pm 0.70 \text{ GeV} \]
- Latest update (dilepton)
  \[ m_{\text{top}} = 172.99 \pm 0.84 \text{ GeV} \]
- Latest CMS combination
  - Precision of 0.3% (!)
    \[ m_{\text{top}} = 172.44 \pm 0.48 \text{ GeV} \]
- World average
  \[ m_{\text{top}} = 174.34 \pm 0.76 \text{ GeV} \]
- Latest D0 update (dilepton)
  \[ m_{\text{top}} = 173.93 \pm 1.83 \text{ GeV} \]
  [arXiv:1606.02814]

<table>
<thead>
<tr>
<th>ATLAS+CMS Preliminary LHCtopWG</th>
<th>[ m_{\text{top}} ] summary, ( \sqrt{s} = 7\text{-}8 \text{ TeV} )</th>
<th>Sep 2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_{\text{top}} ) total (stat: syst)</td>
<td>( 172.31 \pm 1.55 ) (0.75 ± 1.35)</td>
<td>7 TeV [1]</td>
</tr>
<tr>
<td>ATLAS, l+jets (*)</td>
<td>( 173.09 \pm 1.63 ) (0.64 ± 1.50)</td>
<td>7 TeV [2]</td>
</tr>
<tr>
<td>CMS, l+jets</td>
<td>( 173.49 \pm 1.06 ) (0.43 ± 0.97)</td>
<td>7 TeV [3]</td>
</tr>
<tr>
<td>CMS, dilepton</td>
<td>( 172.50 \pm 1.52 ) (0.43 ± 1.46)</td>
<td>7 TeV [4]</td>
</tr>
<tr>
<td>CMS, all jets</td>
<td>( 173.49 \pm 1.41 ) (0.69 ± 1.23)</td>
<td>7 TeV [5]</td>
</tr>
<tr>
<td>LHC comb. (Sep 2013)</td>
<td>( 173.29 \pm 0.95 ) (0.35 ± 0.88)</td>
<td>7 TeV [6]</td>
</tr>
<tr>
<td>World comb. (Mar 2014)</td>
<td>( 173.34 \pm 0.76 ) (0.36 ± 0.67)</td>
<td>1.96-7 TeV [7]</td>
</tr>
<tr>
<td>ATLAS, l+jets</td>
<td>( 172.33 \pm 1.27 ) (0.75 ± 1.02)</td>
<td>7 TeV [8]</td>
</tr>
<tr>
<td>ATLAS, dilepton</td>
<td>( 173.79 \pm 1.41 ) (0.54 ± 1.30)</td>
<td>7 TeV [8]</td>
</tr>
<tr>
<td>ATLAS, all jets</td>
<td>( 175.1 \pm 1.8 ) (1.4 ± 1.2)</td>
<td>7 TeV [9]</td>
</tr>
<tr>
<td>ATLAS, single top</td>
<td>( 172.2 \pm 2.1 ) (0.7 ± 2.0)</td>
<td>8 TeV [10]</td>
</tr>
<tr>
<td>ATLAS comb. (Mar 2015)</td>
<td>( 172.99 \pm 0.91 ) (0.48 ± 0.78)</td>
<td>7 TeV [8]</td>
</tr>
<tr>
<td>CMS, l+jets</td>
<td>( 172.35 \pm 0.51 ) (0.16 ± 0.48)</td>
<td>8 TeV [11]</td>
</tr>
<tr>
<td>CMS, dilepton</td>
<td>( 172.82 \pm 1.23 ) (0.19 ± 1.22)</td>
<td>8 TeV [11]</td>
</tr>
<tr>
<td>CMS, all jets</td>
<td>( 173.2 \pm 0.64 ) (0.25 ± 0.59)</td>
<td>8 TeV [11]</td>
</tr>
<tr>
<td>CMS comb. (Sep 2015)</td>
<td>( 172.44 \pm 0.48 ) (0.13 ± 0.47)</td>
<td>7+8 TeV [11]</td>
</tr>
</tbody>
</table>

(*) Superseded by results shown below the line

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Extraction from production cross section not (yet) competitive with direct measurements – but getting closer.

- CMS precision at 1%; ATLAS: 1.45%
- D0 precision (best at Tevatron): ~ 1.9%

With ~5% theory uncertainty and ~2% exp can reach 0.5% on pole mass

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 aggressively

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{top_quark_mass_plot.png}
\end{figure}

CMS \[\text{arXiv:1603.02303}\]
ATLAS EPJC 74 (2014) 3109

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|}
\hline
Top-quark pole mass measurements & May 2016 \\
\hline
D0 $\alpha$(tt), 1.96 TeV & 167.50 $\pm$ 5.20 & -4.70 GeV \\
PLB 703 (2011) 422 & 169.50 $\pm$ 3.30 & -3.40 GeV \\
MSTW08 approx. NNLO & \\
D0 $\alpha$(tt), 1.96 TeV & 172.80 $\pm$ 3.40 & -3.20 GeV \\
D0 Note 6453-CONF (2015) & 172.90 $\pm$ 2.50 & -2.60 GeV \\
MSTW08 NNLO & \\
D0 $\alpha$(tt), 1.96 TeV & 173.70 $\pm$ 2.28 & -2.11 GeV \\
arXiv:1605.06168 & 173.80 $\pm$ 1.70 & -1.80 GeV \\
ATLAS tt+j shape, 7 TeV & 169.90 $\pm$ 4.52 & -3.66 GeV \\
JHEP 10 (2015) 121 & 173.34 $\pm$ 0.76 & -0.76 GeV \\
CMS $\alpha$(tt), 7+8 TeV & \\
CMS tt+j shape, 8 TeV & \\
TOP-13-006 (2016) & \\
ATLAS, CDF, CMS, D0 & \\
arXiv:1403.4427, standard measurements & \\
World combination & \\
\hline
\end{tabular}
\end{table}

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Top quark studies

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$\Delta \chi^2$ vs. $m_t$ [GeV]

- "pole" means extracted from production cross sections
- "kin" means direct measurements, e.g. matrix element method

$m_t$ [GeV]

- $m_t^{\text{pole}}$ from Tevatron $\sigma_{t\bar{t}}$ [arXiv:1207.0980]
- $m_t^{\text{pole}}$ from CMS $\sigma_{t\bar{t}}$ [arXiv:1307.1907v3]
- $m_t^{\text{pole}}$ from ATLAS $\sigma_{t\bar{t}}$ [arXiv:1406.5375]
- $m_t^{\text{kin}}$ world average [arXiv:1403.4427]
- $m_t^{\text{kin}}$ D0 measurement [arXiv:1405.1756]

SM fit w/o $m_t$ measurements
SM fit w/o $m_t$ and $M_H$ measurements
Conclusions

- Large data sets allow to constrain PDFs, understand signal modeling
- High precision top quark property measurements, also accessible now in **single top quark production** \((t\text{-channel})\)
- Single top now differential – opening up a new realm
- Results on Asymmetry are not yet completely conclusive...

**Evidence** for associated production of \(W, Z, \gamma\)

\[ \rightarrow \] No significant deviations seen from SM expectations at LHC Run I or early Run II results

Only small limited selection of results shown, more information:

- ATLAS Top Web pages
- CMS Top Web pages
- CDF Top Web pages
- D0 Top Web pages

Thank you!
Outlook

Run II just started!
→ We will get about 80 million $t\bar{t}$ events
→ Allows for multi-dimensional & simultaneous measurements of $\sigma$, $\alpha_S$, PDFs and properties as well – ultra precision results
→ FCNCs and other statistically limited processes will significantly improve!

![Graph showing inclusive $t\bar{t}$ cross section vs. $\sqrt{s}$]

**Today**

100/fb
\[ \sqrt{s} = 7/8 \text{ TeV} \]

- Peak luminosities: \(8 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}\)
- \(~5 \text{ (25) fb}^{-1}/\text{experiment recorded}\)
- LHC consolidation/upgrades till 2015
Single top production

- Combine CDF (l+jets and MET+jets) & D0 discriminants (l+jets)
- Include all systematic uncertainties and correlations
- First observation of s-channel single top (6.3 s.d.)


![Graph showing s-channel single top quark, Tevatron Run II, L_{int} ≤ 9.7 fb⁻¹]
**Single top production**

- Not assuming $O/O \text{ SM value}$
- Concludes single top Tevatron program
- Agreement with the SM, no indications for non-SM contributions

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**Single top quark, Tevatron Run II, $L_{int} \leq 9.7 \text{ fb}^{-1}$**

- **t-channel**
  - CDF [21]: $1.65^{+0.38}_{-0.36}$
  - D0 [22]: $3.07^{+0.54}_{-0.49}$
  - Tevatron [this paper]: $2.25^{+0.29}_{-0.29}$

- **s-channel**
  - CDF [21]: $3.02^{+0.49}_{-0.48}$
  - D0 [22]: $4.11^{+0.60}_{-0.52}$
  - Tevatron [this paper]: $3.30^{+0.53}_{-0.50}$

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**Top quark studies**

A. Jung
Differential cross sections

ATLAS Preliminary
\( \sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \)
veto region: \( |y| < 2.1 \)
- 2012 Data
- Powheg+PY6 hdamp\( \rightarrow \)
- Powheg+PY6 hdamp=\( m_t \)
- Powheg+PY6 hdamp=\( m_t \)
- MC@NLO+HW
- Powheg+HW hdamp\( \rightarrow \)
- Total uncertainty

Data / (Madgraph + Pythia6)

CMS

\[ r = -0.123 \left( \frac{p_T}{100 \text{ GeV}} \right) + 1.12 \]

Subleading top \( p_T \) (GeV)

Parton level
- lepton+jets
- dilepton
- all-jets
- linear fit

A. Jung
Top quark studies
Ttbar + X: W, Z, B

- Tight photon ID requirements and cuts to suppress the bg
- Observation at 7 TeV by ATLAS and first measurement at 8 TeV by CMS

\[ R = \frac{\sigma_{\tilde{t}\tilde{t}+\gamma}}{\sigma_{\tilde{t}\tilde{t}}} \]
\[ = (1.07 \pm 0.07{\text{(stat.)}} \pm 0.27{\text{(syst.)}}) \times 10^{-2} \]
\[ \sigma_{\tilde{t}\tilde{t}+\gamma} = R \cdot \sigma_{\tilde{t}\tilde{t}}^{\text{CMS}} \]
\[ = 2.4 \pm 0.2{\text{(stat.)}} \pm 0.6{\text{(syst.)}} \text{ pb} \]

- Dominated by object IDs (jets, photon, btag) and signal model related

A. Jung  Top quark studies
2D fit of $ttW$ and $ttZ$ cross sections, dominated by statistical unc's

- SM (NLO): $\sigma(ttZ) = 206 \pm 29$ fb and $\sigma(ttW) = 203 \pm 25$ fb

### ATLAS Preliminary

\[ \int L \, dt = 20.3 \, \text{fb}^{-1} \]
\[ \sqrt{s} = 8 \, \text{TeV} \]

### CMS Preliminary

\[ \sqrt{s} = 8 \, \text{TeV}, \quad L_{\text{int}} = 19.5 \, \text{fb}^{-1} \]

### Process Cross section Sign.

<table>
<thead>
<tr>
<th>Process</th>
<th>Cross section</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ttZ$</td>
<td>$150^{+55}_{-50}$ (stat.) $\pm 21$ (syst.) fb</td>
<td>3.1$\sigma$</td>
</tr>
<tr>
<td>$ttW$</td>
<td>$300^{+120}<em>{-100}$ (stat.) $^{+70}</em>{-80}$ (syst.) fb</td>
<td>3.1$\sigma$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Process</th>
<th>Cross section</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}W$</td>
<td>$170^{+90}<em>{-80}$ (stat.) $^{+70}</em>{-70}$ (syst.) fb</td>
<td>1.6$\sigma$</td>
</tr>
<tr>
<td>$t\bar{t}Z$</td>
<td>$200^{+80}<em>{-70}$ (stat.) $^{+40}</em>{-30}$ (syst.) fb</td>
<td>3.1$\sigma$</td>
</tr>
<tr>
<td>$t\bar{t}W + t\bar{t}Z$</td>
<td>$380^{+100}<em>{-90}$ (stat.) $^{+80}</em>{-70}$ (syst.) fb</td>
<td>3.7$\sigma$</td>
</tr>
</tbody>
</table>
Top quark polarization

- In $t\bar{t}$ production: New physics polarizes top quarks
- Polarization introduced by CP conserving or violating process:

$$\varepsilon_{P_{\text{CP}}} = -0.035 \pm 0.014 \text{ (stat.)} \pm 0.037 \text{ (syst.)}$$

$$\varepsilon_{P_{\text{CPV}}} = 0.020 \pm 0.016 \text{ (stat.)} \pm 0.013 \text{ (syst.)}$$

$\varepsilon$: Spin analyzing power, $P_{\text{CPX}}$: top quark polarization

- Good agreement with SM (negligible polarization), also seen by:
  - CMS:
  - D0:

- In single top production, measure polarized top quarks as expected

$$P_t = 0.82 \pm 0.12 \text{ (stat.)} \pm 0.32 \text{ (syst.)}$$

A. Jung

Top quark studies
\( W \) helicity in \( \text{SM} \):

- \( f_L = 0.30 \)
- \( f_0 = 0.70 \)
- \( f_R = 0 \)

Complements results in pair production

Similar precision but orthogonal systematic uncertainties in single top channels

Signal model & template statistics

**CMS** (19.7 fb\(^{-1}\) (8 TeV))

- **Combination**
  - \( \mu+\text{jets} \)
  - \( e+\text{jets} \)

**ATLAS and CMS preliminary**

\( \sqrt{s} = 7 \text{ TeV}, L_{\text{int}} = 35 \text{ pb}^{-1} - 2.2 \text{ fb}^{-1} \)

- NNLO QCD
- Combination
- Data \( (F_R/F_L/F_0) \)

ATLAS 2010 (single lepton)
ATLAS 2011 (single lepton)
ATLAS 2011 (dilepton)
CMS 2011 (single muon)
LHC combination
Top quark asymmetries

- Interference appears at NLO QCD:
  
  ![Diagram](image)

  - Only occurs in $qq$ initial state; $gg$ is fwd-bwd symmetric
  - This is a forward-backward asymmetry at Tevatron
  - No valence anti-quarks at LHC → $\bar{t}$ more central

- SM predictions at NLO (QCD+EWK)
  
  - Tevatron: $A_{FB} \sim 8-9\%$ vs. LHC: $A_c \sim 1\%$
    
    (waiting for full NNLO pQCD predictions)

- Experimentally: Asymmetries based on decay leptons or fully reconstructed top quarks

  $A_c = \frac{N(\Delta|y_t| > 0) - N(\Delta|y_t| < 0)}{N(\Delta|y_t| > 0) + N(\Delta|y_t| < 0)}$

  $A_{lep}^{\text{easier}} = \frac{N(\Delta|\eta_\ell| > 0) - N(\Delta|\eta_\ell| < 0)}{N(\Delta|\eta_\ell| > 0) + N(\Delta|\eta_\ell| < 0)}$

  “easier”

  “harder”

A. Jung  Top quark studies  45
Top quark asymmetries

- All Tevatron results use full data sets
- Expect final results and Tevatron combination very soon
- Agreement with latest theory predictions

### Tevatron Top Asymmetry

#### $t\bar{t}$ Δy Asymmetry ($A_{FB}^{t\bar{t}}$)

- **CDF Lepton+jets (9.4 fb$^{-1}$)**
  PRD 87, 052002 (2013)
  $16.4 \pm 4.7$

- **CDF Dilepton (9.1 fb$^{-1}$)**
  PRD 93, 112005 (2016)
  $12 \pm 13$

- **D0 Lepton+jets (9.7 fb$^{-1}$)**
  PRD 90, 072011 (2014)
  $10.6 \pm 3.0$

- **D0 Dileptons (9.7 fb$^{-1}$)**
  PRD 92, 052007 (2015)
  $17.5 \pm 6.3$

#### Lepton qη Asymmetry ($A_{FB}^{l\eta}$)

- **CDF Lepton+jets (9.4 fb$^{-1}$)**
  PRD 88, 072003 (2013)
  $9.4 \pm 3.2$

- **CDF Dileptons (9.1 fb$^{-1}$)**
  PRL 113, 042001 (2014)
  $7.2 \pm 6.0$

- **D0 Lepton+jets (9.7 fb$^{-1}$)**
  PRD 90, 072011 (2014)
  $5.0 \pm 3.4$

- **D0 Dileptons (9.7 fb$^{-1}$)**
  PRD 88, 112002 (2013)
  $4.4 \pm 3.9$

#### Lepton Δη Asymmetry ($A_{FB}^{l\eta}$)

- **CDF Dileptons (9.1 fb$^{-1}$)**
  PRL 113, 042001 (2014)
  $7.6 \pm 8.2$

- **D0 Dileptons (9.7 fb$^{-1}$)**
  PRD 88, 112002 (2013)
  $12.3 \pm 5.6$

### Figures


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Top quark studies
Top quark asymmetries

\[ A_C (m_{\tilde{t}} > 1.3 \text{ TeV}) \]

\[ A_{FB} (\text{pp, 1.96 TeV}) \]

ATLAS 8 TeV, 20 fb\(^{-1}\)

Tevatron: PRD87/092002; PRD84/112005
Models: PRD 84/115013; JHEP 1109/097

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Top quark studies
Top quark: FCNC

- Flavor Changing Neutral Currents are highly suppressed in SM, but enhancement in many models of new physics
- Search for FCNC involving Z bosons:
  \[
  \begin{align*}
  B(t \to ug) &< 5.7 \cdot 10^{-5} & B(t \to ug) &< 3.55 \cdot 10^{-4} \\
  B(t \to cg) &< 2.7 \cdot 10^{-4} & B(t \to cg) &< 3.44 \cdot 10^{-3}
  \end{align*}
  \]
- Search for Higgs boson production in the dilepton (same sign) and trilepton channel
- Systematic uncertainties dominated by: Background modeling / cross sections
- Limit on top-charm flavor-violating Higgs Yukawa coupling & upper limits for branching fractions:
  \[\sqrt{(|\lambda^H_{tc}|^2 + |\lambda^H_{ct}|^2)} < 0.18 \text{ at } 95\% \text{ CL}\]

<table>
<thead>
<tr>
<th></th>
<th>$-\sigma$</th>
<th>$\text{BR}_{\exp}(t \to Hc)$</th>
<th>$+\sigma$</th>
<th>$\text{BR}_{\text{obs}}(t \to Hc)$</th>
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<tbody>
<tr>
<td>trilepton</td>
<td>0.95</td>
<td>1.33</td>
<td>1.87</td>
<td>1.26</td>
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<tr>
<td>same-sign dilepton</td>
<td>0.68</td>
<td>0.93</td>
<td>1.26</td>
<td>0.99</td>
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<tr>
<td>combined</td>
<td>0.65</td>
<td>0.89</td>
<td>1.22</td>
<td>0.93</td>
</tr>
</tbody>
</table>
Top quark: FCNC

- Search in single top production (t-channel)
- MVA technique to: suppress QCD, separate signal & bg, search for $Wtb$ couplings & FCNC interactions
- Systematic uncertainties dominated by: Background normalization

CMS preliminary, $\sqrt{s} = 7$ TeV, $L = 5.0$ fb$^{-1}$

Data points and distributions for various processes:

- Top quark pair production
- Single top, s-channel
- Single top, tW-channel
- $W$+jets, “WQQ”
- $W$+jets, “$Wc$”
- $W$+jets, “$W$+light”
- $W$+jets, “WQX (UE)”
- QCD (data-driven)
- Drell-Yan process
- $WW$, $WZ$, $ZZ$

CMS-PAS-TOP-14-007

<table>
<thead>
<tr>
<th>Process</th>
<th>Uncertainty</th>
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<tbody>
<tr>
<td>top-quark pair production</td>
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</tr>
<tr>
<td>single top, s-channel</td>
<td>15%</td>
</tr>
<tr>
<td>single top, tW-channel</td>
<td>13%</td>
</tr>
<tr>
<td>$W$+jets, “WQQ”</td>
<td>100%</td>
</tr>
<tr>
<td>$W$+jets, “$Wc$”</td>
<td>100%</td>
</tr>
<tr>
<td>$W$+jets, “$W$+light”</td>
<td>50%</td>
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<tr>
<td>$W$+jets, “WQX (UE)”</td>
<td>50%</td>
</tr>
<tr>
<td>QCD (data-driven)</td>
<td>100%</td>
</tr>
<tr>
<td>Drell-Yan process</td>
<td>30%</td>
</tr>
<tr>
<td>$WW$, $WZ$, $ZZ$</td>
<td>30%</td>
</tr>
</tbody>
</table>

(Limits on left & right vector and tensor couplings in backup)
Flavor Changing Neutral Currents are highly suppressed in SM
Analyses assume all anomalous couplings zero but one
Still above SM predictions but reached sensitivity to certain BSM models
**Measurement methods**

- **Matrix Element method** (leading order) calculates event probability densities from $d\mathcal{O}/dX$

  $$P(x, m_t) = \frac{1}{\sigma(m_t)} \int \sum d\sigma(y, m_t) \, dq_1 dq_2 \, f(q_1) f(q_2) \, W(y, x, k_{\text{JES}})$$

- **Ideogram method** event likelihood based on Breit-Wigner (signal) convoluted with detector resolutions

  $$\mathcal{L} \left( \text{sample} | m_t, \text{JSF} \right) = \prod_{\text{events}} \left( \sum_{i=1}^{n} P_{\text{gof}}(i) \left( \sum_{j} f_{j} P_{j}(m_{t,i} | m_t, \text{JSF}) \times P_{j}(m_{W,i} | m_t, \text{JSF}) \right) \right)^{w_{\text{event}}}$$

- **Template method** compares histograms in data to simulations (including detector resolutions)

- Depend on MC → We measure “MC mass”

- **Alternative methods** (“End-point”, J/$\Phi$, “O’")

---

**W boson fully reconstructed:**

→ In-situ calibration, Constrain reconstructed $m_w$ to $m_w$
Top quark mass

CMS Preliminary

May 2016

b hadron lifetime
TOP-12-030 (2013)

173.50 ± 1.50 ± 2.91 GeV

Kinematic endpoints
EPJC 73 (2013) 2494

173.90 ± 0.90 ±1.70 ± 2.10 GeV

b-jet energy peak

172.29 ± 1.17 ± 2.66 GeV

Lepton+J/Ψ
TOP-15-014 (2016)

173.50 ± 3.00 ± 0.90 GeV

Lepton+SecVtx

173.68 ± 0.20 ±1.58 ± 0.97 GeV

Dilepton kinematics
TOP-16-002 (2016)

171.70 ± 1.10 ± 2.68 ± 3.09 GeV

Single top enriched
TOP-15-001 (2016)

172.60 ± 0.77 ± 0.97 ± 0.93 GeV

CMS tt+j shape, 8 TeV
TOP-13-006 (2016)

169.90 ± 1.10 ± 4.38 ± 3.49 GeV

c(t) 7+8 TeV

173.60 ±1.70 ± 1.80 GeV

CMS 7+8 TeV (2015)
arXiv:1509.04044

172.44 ± 0.13 ± 0.47 GeV

World combination
ATLAS, CDF, CMS, D0

173.34 ± 0.27 ± 0.71 GeV (value ± stat. ± syst.)

CMS 2010, dilepton
JHEP 07 (2011) 049, 36 pb⁻¹

175.50 ± 4.60 ± 4.60 GeV (value ± stat. ± syst)

CMS 2011, dilepton
EPJC 72 (2012) 2202, 5.0 fb⁻¹

172.50 ± 0.43 ± 1.43 GeV (value ± stat. ± syst)

CMS 2011, all-jets
EPJC 74 (2014) 2758, 3.5 fb⁻¹

173.49 ± 0.69 ± 1.21 GeV (value ± stat. ± syst)

CMS 2011, lepton+jets
JHEP 12 (2012) 105, 5.0 fb⁻¹

173.49 ± 0.43 ± 0.98 GeV (value ± stat. ± syst)

CMS 2012, dilepton
This analysis, 19.7 fb⁻¹

172.82 ± 0.19 ± 1.22 GeV (value ± stat. ± syst)

CMS 2012, all-jets
This analysis, 18.2 fb⁻¹

172.32 ± 0.25 ± 0.59 GeV (value ± stat. ± syst)

CMS 2012, lepton+jets
This analysis, 19.7 fb⁻¹

172.35 ± 0.16 ± 0.48 GeV (value ± stat. ± syst)

CMS combination

172.44 ± 0.13 ± 0.47 GeV (value ± stat. ± syst)

Tevatron combination (2014)
arXiv:1407.2682

174.34 ± 0.37 ± 0.52 GeV (value ± stat. ± syst)

World combination 2014
ATLAS, CDF, CMS, D0
arXiv:1403.4427

173.34 ± 0.27 ± 0.71 GeV (value ± stat. ± syst)

A. Jung

Top quark studies
With the Higgs discovery the SM can be extrapolated to Planck scale energies.

“Test” the stability of the electroweak vacuum, under assumption of no new physics:

→ meta-stable, life time $\gg O(10^{80})$ t

→ but new physics can change that dramatically

$$V(\phi) = \frac{\lambda}{4} \phi^4 + \frac{\lambda_6}{6} \frac{\phi^6}{M_P^2} + \frac{\lambda_8}{8} \frac{\phi^8}{M_P^4}$$

SM Higgs potential

**dim 6 & 8 BSM modifications**
Add latest measurements:
D0 $m_t = 174.98 \pm 0.76$ GeV

CMS $m_t = 172.02 \pm 0.77$ GeV

“MC mass” vs. pole mass: all QCD effects taken into account?

Internal inter-collaboration study group

Members of the group working on this subject as well

A. Jung

New physics & the top quark at the LHC