Top Quark Production at 8 TeV

Kate Shaw
ATLAS Udine/ICTP Group
On behalf of the ATLAS and CMS Collaborations

The XLIXth Rencontres de Moriond
QCD and High Energy Interaction
22nd – 29th March 2014
La Thuile, Italy
25th March 2014

Top Quark Production at 8TeV

**Introduction**

5fb\(^{-1}\) @ 7TeV + 20 fb\(^{-1}\) @ 8TeV
5.5 million top pairs
2.7 million single tops


---

**ATLAS Online Luminosity**

- 2010 pp \(\sqrt{s} = 7\) TeV: 0.05/fb
- 2011 pp \(\sqrt{s} = 7\) TeV: 5.6/fb
- 2012 pp \(\sqrt{s} = 8\) TeV: 23.3/fb

Data included from 2010-03-30 11:21 to 2012-12-16 20:49 UTC

---

4th July seminar

---

**CMS Integrated Luminosity**

- 2010, 7 TeV, 44.2 pb\(^{-1}\)
- 2011, 7 TeV, 6.1 fb\(^{-1}\)
- 2012, 8 TeV, 23.3 fb\(^{-1}\)
Top Production at 8 TeV

- Top quark is heaviest elementary particle
- Lifetime shorter than timescale of hadronisation
- Decays \(~100\%\) to W-boson and b-quark \( |V_{tb}| \sim \) unity
- Final state topology depends on W decay
- Yukawa coupling to Higgs is order unity
- Top quark studies provide important information of fundamental interactions at the electroweak breaking scale and beyond.
Single top production

- Single top quark production by charged-current electroweak interactions
- LO classification:

\[ s\text{-channel} \]

\[ t\text{-channel (dominant)} \]

\[ W_t \text{ associated production channel} \]

NLO+NNLO with \( m_t = 173.3 \text{ GeV} \) at 8TeV @LHC

- \( \sigma_{\text{singletop}} \propto |V_{tb}|^2 \), probes the electroweak \( Wtb \) vertex

- Measuring polarization observables tests the left-handed nature of the charged-current

- Sensitivity to different manifestations of BSM physics

Single top production

CMS Preliminary
Single top-quark production

\[ \sigma [\text{pb}] \]

- t-channel
- tW
- s-channel

\[ \sqrt{s} \text{ [TeV]} \]

- CMS, JHEP12(2012) 035
- CMS, to be sub. to JHEP
- Approx. NNLO Kidonakis, PRD 82, 054018 (2010)
- CMS, PAS-TOP-12-040
- Approx. NNLO Kidonakis, PRD 83, 091503 (2011)
- CMS, PAS-TOP-13-009 ( FC interval )

ATLAS Preliminary
single top-quark production

\[ \text{NLO+NNLL at } m_t = 172.5 \text{ GeV} \]

\[ \text{MSTW2008 NNLO PDF} \]

\[ \text{stat. uncertainty} \]

- t-channel 1.04 fb\(^{-1}\) \text{ PLB 717 (2012) 330}
- t-channel 5.8 fb\(^{-1}\) \text{ ATLAS-CONF-2012-132}
- Wt 2.05 fb\(^{-1}\) \text{ PLB 716 (2012) 142}
- Wt 20.3 fb\(^{-1}\) \text{ ATLAS-CONF-2013-100}

s-channel 95\% C.L. limit 0.7 fb\(^{-1}\) \text{ ATLAS-CONF-2011-118}

\[ \sqrt{s} \text{ [TeV]} \]
CMS performed first search at LHC in leptonic channel at 8 TeV using 19.3 fb$^{-1}$

- Samples: exactly one isolated $e$ or $\mu$ and 2-jets 0-tags, 2jets 2-tags, or 3-jets 2tags
- Multivariate approach using BDT measure $\sigma_{s\text{-channel}} = 6.2^{+0.8}_{-5.1}$ pb (0.7$\sigma$ signal significance)
- Measured upper limit 2.1 times SM cross-section 11.5 pb at 95% CL.
- Sensitivity limited by theoretical systematic
Single top production

t-channel

ATLAS Inclusive and Fiducial cross-section with 20.3 fb^{-1}

- Events selected with exactly one lepton exactly two jets, one b-tagged
- Cross-section extracted using binned maximum-likelihood fit to neutral-network discriminant using 14 variables (MC modelling, JES dominant systematic)

\[
\sigma_f = 3.37 \pm 0.05 \text{(stat.)} \pm 0.47 \text{(syst.)} \pm 0.09 \text{(lumi.) pb.}
\]
Single top production
t-channel

\[ \sigma_t = 82.6 \pm 1.2 \text{(stat.)} \pm 11.4 \text{(syst.)} \pm 3.1 \text{(PDF)} \pm 2.3 \text{(lumi.) pb} \]

- Cross-section extrapolated to full phase space using acceptance of different MC generators

Assuming aMC@NLO + Herwig generator
Coupling at the W-t-b vertex

\[ |V_{tb}| = 0.97^{+0.09}_{-0.10} \]
CMS inclusive t-channel cross-section and ratio of t to tbar with 19.7fb⁻¹

- \( R_{t\text{-ch}} = \frac{\sigma_{t\text{-ch, top}}}{\sigma_{t\text{-ch, anti-top}}} \) provides effective handle to constrain proton PDF models, sensitive to new physics

- Selection: Exactly one lepton, two jets 1 btag

- Yield extracted from binned maximum-likelihood fit to the pseudorapidity of recoil quark in events with positively and negatively charged leptons

- Dominant systematics JES JER MET PU, signal modeling

\[ \sigma_{t\text{-ch.}} = 83.6 \pm 2.3 \text{ (stat.)} \pm 7.4 \text{ (syst.) pb.} \]
Single top production
\[ t \text{-channel} \]

CMS, \( L = 19.7 \text{ fb}^{-1} \), \( \sqrt{s} = 8 \text{ TeV} \)

\[
\begin{align*}
\text{CMS} & \\
1.95 \pm 0.10 \text{ (stat.)} & \pm 0.19 \text{ (syst.)} \\
\text{ABM11} & \\
\text{CT10} & \\
\text{CT10w} & \\
\text{HERAPDF} & \\
\text{MSTW2008} & \\
\text{NNPDF 2.3} & \\
\end{align*}
\]

\[ R_{t,\text{ch.}} = \frac{\sigma_{t,\text{ch.}}(t)}{\sigma_{t,\text{ch.}}(t)} = 1.95 \pm 0.10 \text{ (stat.)} \pm 0.19 \text{ (syst.)} \]

\[ |f_{\text{LV}} V_{tb}| = 0.979 \pm 0.045 \text{ (exp.)} \pm 0.016 \text{ (theo.)} \]
CMS: Dilepton channel (12.2 fb⁻¹)
- Cross-section determined with multivariate technique
- Event selection includes exactly two leptons and a b-tagged jet
- Dominant systematic uncertainty from MC modeling
- Measured cross-section 23.4 ± 5.4 pb (6.1 σ significance)
**Single top production**

**Wt associated production**

**ATLAS:** $\mu\mu$ Dilepton channel (20.3 fb$^{-1}$)
- Cross-section determination using maximum likelihood fit to 1 and 2 jet events
- Boosted Decision Trees (BDT) used to distinguish Wt from $t\bar{t}$
- Dominant systematic uncertainty from b-tagging performance and JES
- Cross-section $27.2 \pm 2.8$ (stat) $\pm 5.4$ (syst) pb (4.2 $\sigma$)

$$|V_{tb} \cdot f| = 1.10 \pm 0.12 \text{ (exp)} \pm 0.03 \text{ (theory)}$$
Top pair production

- Top quark pair production governed by strong interactions (gg fusion dominant (~80%))
- NNLO + NNLL with $m_t = 172.5$ GeV at 8TeV CM Energy $\sigma_{tt} = 252.9 \pm 11.7^{+6.4}_{-8.6}$ pb

- Sensitive to new physics
- Can constrain modeling (PDF, ISR/FSR)
- Important background to many Higgs and BSM searches

Top pair production

Inclusive $t\bar{t}$ cross section [pb]

- Tevatron combination: $L = 8.8 \text{ fb}^{-1}$
- ATLAS dilepton: $L = 0.7 \text{ fb}^{-1}$
- CMS dilepton: $L = 2.3 \text{ fb}^{-1}$
- ATLAS lepton+jets: $L = 0.7 \text{ fb}^{-1}$
- CMS lepton+jets: $L = 2.3 \text{ fb}^{-1}$
- TOPLHCWG combination: $L = 1.1 \text{ fb}^{-1}$
- ATLAS dilepton: $L = 20.3 \text{ fb}^{-1}$
- CMS dilepton: $L = 5.3 \text{ fb}^{-1}$
- ATLAS lepton+jets: $L = 5.8 \text{ fb}^{-1}$
- CMS lepton+jets: $L = 2.8 \text{ fb}^{-1}$

* Preliminary

$\sqrt{s}$ [TeV]

Czakon, Fiedler, Mitov, PRL 110 (2013) 252004
$m_{top} = 172.5 \text{ GeV}$, PDF $\otimes \alpha_s$ uncertainties according to PDF4LHC
Top Pair Production
Dilepton channel with CMS

CMS top-quark pair production in dilepton channel using 5.3 fb⁻¹
- Events are selected with two leptons (eμ, ee, μμ) and two jets one b-tagged
- Cross-section extracted by optimising cuts and event counting
- Dominant uncertainties include JES and JER, DY modeling (ee and μμ)
- Combination using BLUE method

\[ \sigma_{\text{tt}} = 239.0 \pm 2.1 \text{ (stat.)} \pm 11.3 \text{ (syst.)} \pm 6.2 \text{ (lum.) pb} \]
Top Pair Production
Dilepton channel with ATLAS

- ATLAS dilepton channel (tt→eµvvbb) 20.3 fb⁻¹

- Cross-section obtained by counting number of opposite sign eµ events with 1 and 2 btagged jets

- Simultaneously determines b-tag reconstruction efficiency minimising systematic uncertainties

\[ \sigma_{tt} = 237.7 \pm 1.7 \text{ (stat)} \pm 7.4 \text{ (syst)} \pm 7.4 \text{ (lumi)} \pm 4.0 \text{ (beam energy)} \text{ pb} \]

- Precision matches theory uncertainty

\[
\begin{align*}
N_1 & = L \sigma_{tt} \epsilon_{e\mu} 2 \epsilon_b (1 - C_b \epsilon_b) + N_{1}^{bkg} \\
N_2 & = L \sigma_{tt} \epsilon_{e\mu} C_b \epsilon_b^2 + N_{2}^{bkg}
\end{align*}
\]

- \( \epsilon_b \): Probability t -> Wq quark to be reconstructed and tagged as b-jet within acceptance
Differential cross-section measurements by CMS using 12 fb-1 of data in single- and dilepton channels show good agreement between data and theory predictions:

- Normalised differential cross-section measured as a function of kinematic properties of the final state charged lepton(s), b-tagged jets, top quarks and the $tt$ system.
- Approximate NNLO gives an improved description of the data.
CMS measurement of cross-section ratio $\sigma(ttbb) / \sigma(ttjj)$ 19.6 fb$^{-1}$

- Top quark pair production in association with bb pair irreducible background to ttH
- Test of NLO QCD theory, which suffers from large factorisation and renormalisation uncertainties
- Ratio measurement allows experimental uncertainties to cancel

Selection: At least four jets, two leptons, two b-tagged jets
Dominant uncertainties: b-jet tagging efficiency, mistagging
Top Pair Production Associated with a photon

CMS top-quark pair + photon production in muon+jets channel using 19.7 fb$^{-1}$

- Events selection: exactly one muon, at least four jets and a hard photon $p_T > 20$ GeV
- $R = \sigma_{tt+\gamma} / \sigma_{tt}$ calculated using selection parameters and a template fit
- Cross-section extracted by multiplying $R$ with recent top-quark pair cross-section

- Binned maximum likelihood template fit estimates photon misidentification contribution
- Dominant misidentified photon source is hadronic
- Normalised cross-section $R$ reduces uncertainties
- Background modeling is dominant systematic (23%)

$$\sigma_{tt+\gamma}^{SM} = 1.8 \pm 0.5 \text{ pb}$$  \[5\]

$$\sigma_{tt+\gamma} = R \sigma_{tt}^{CMS} = 2.4 \pm 0.2 \text{ (stat.)} \pm 0.6 \text{ (syst.) pb}$$
Summary

Measurements are presented from ATLAS and CMS of the top production cross-sections in proton-proton collisions at 8 TeV

- New s-channel searches at LHC presented
- New t-channel and tW-channel single-top cross-section measurements at 8 TeV
- Measurements of inclusive top-quark pair production match high precision (NNLO) theory calculations
- Differential distributions generally well described by MC (NLO+PS) models. Improved descriptions by yet higher order calculations?
- Many more 8 TeV Top cross-section results underway
Top pair production

CMS Preliminary, $\sigma_{tt}$ summary, $\sqrt{s} = 8\text{ TeV}$

Feb 2014

CMS dilepton (ee, $\mu\mu$, $\mu\nu$)

JHEP 02 (2014) 024 (L=5.3/fb)

$239 \pm 2 \pm 11\pm 6 \text{ pb}$

(val. ± stat. ± syst. ± lumi.)

CMS prel. $e/\mu+$jets

TOP-12-006 (L=2.8/fb)

$228 \pm 9 \pm 29\pm 26 \pm 10 \text{ pb}$

(val. ± stat. ± syst. ± lumi.)

ATLAS Preliminary

12 Sep 2013

Data 2012, $\sqrt{s} = 8\text{ TeV}$

Channel & Lumi.

NNLO+NNLL (top++ 2.0)
PDF4LHC $m_{top} = 172.5\text{ GeV}$

scale uncertainty
scale+PDF uncertainty
stat. uncertainty
total uncertainty

$\sigma_{tt}$ ±(stat) ±(syst) ±(lumi) ±(E_{beam})

Single lepton 5.8 fb$^{-1}$

$241 \pm 2 \pm 31 \pm 9 \text{ pb}$

Dilepton ($e\mu$) 20.3 fb$^{-1}$

$238 \pm 2 \pm 7 \pm 7 \pm 4 \text{ pb}$

$\sigma_{tt}$ [pb]

100 150 200 250 300 350 400

25th March 2014

Top Quark Production at 8TeV

21
ATLAS measured top pair production cross-section in single lepton channel using kinematic fits with b-tagging using 5.8 fb$^{-1}$ of data

- Multivariate technique used with b-tagging to separate $tt$ signal from backgrounds
- Dominant systematics include MC modeling of signal and Jet/MET reconstruction and calibration

\[ \sigma_{tt} = 241 \pm 2 \text{ (stat.)} \pm 31 \text{ (syst.)} \pm 9 \text{ (lumi.) pb} \]

CMS measured top pair production in single lepton channel using 2.8 fb$^{-1}$ of data

- Cross-section extracted using binned maximum likelihood template fit (utilising $M_{lb}$)
- Dominant systematics include b-tagging efficiency, MC modeling

\[ \sigma_{tt} = 228.4 \pm 9.0 \text{ (stat.)}^{+29.0}_{-26.0} \text{ (syst.)} \pm 10.0 \text{ (lum.) pb} \]
Single top production
t-channel

- **ATLAS** selected events with exactly one lepton two or three jets and one b-tagged jet
- **CMS** selected events with exactly one muon and two jets and one b-tagged jet

- Cross-section extracted in a simultaneous likelihood fit to a neutral network discriminant
- Cross-section extracted using a maximum-likelihood fit to pseudorapidity of light-quark jet

**ATLAS** Preliminary $\int L\, dt = 5.8 \text{ fb}^{-1}$, $\sqrt{s} = 8 \text{ TeV}$

**CMS** Preliminary, $5.0 \text{ fb}^{-1}$, $\sqrt{s} = 8 \text{ TeV}$
Single top production t-channel

- Best linear unbiased estimator (BLUE) used to combine t-channel single top-quark production cross-section measurements from ATLAS and CMS

- Contribution to combined cross-section uncertainty

**Table:**

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistics</td>
<td>4.1</td>
</tr>
<tr>
<td>Luminosity</td>
<td>3.4</td>
</tr>
<tr>
<td>Simulation and modelling</td>
<td>7.7</td>
</tr>
<tr>
<td>Jets</td>
<td>4.5</td>
</tr>
<tr>
<td>Backgrounds</td>
<td>3.2</td>
</tr>
<tr>
<td>Detector modelling</td>
<td>5.5</td>
</tr>
<tr>
<td>Total systematics (excl. lumi)</td>
<td>11.0</td>
</tr>
<tr>
<td>Total systematics (incl. lumi)</td>
<td>11.5</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>12.2</td>
</tr>
</tbody>
</table>

**Combined t-channel single top cross-section**

\[
\sigma_{t\text{-ch.}} = 85 \pm 4 \text{ (stat.)} \pm 11 \text{ (syst.)} \pm 3 \text{ (lumi.)} \text{pb} = 85 \pm 12 \text{ pb}
\]
Top (85%) anti-top (74%) quark inherits sign of the charge from the initial light quark
Charge asymmetry due to larger contribution from u quark than d quark

Ratio measurement \( R_{t-ch} = \frac{\sigma_{t-ch,\text{top}}}{\sigma_{t-ch,\text{anti-top}}} \) provides effective handle to constrain proton PDF models, and is sensitive to new physics (anomalous coupling, FCNCs)

Selection: Exactly one lepton, two jets and b-tagged jet

Backgrounds include \( tt, W+jets \) and multijet QCD

Yield extracted from binned maximum-likelihood fit to the pseudorapidity of recoil quark in events with positively and negatively charged leptons

Measurements: \( \sigma_{t-ch,\text{top}} = 49.9 \pm 9.1 \) pb
\( \sigma_{t-ch,\text{anti-top}} = 28.3 \pm 5.5 \) pb

\( R_{t-ch} = \frac{\sigma_{t-ch,\text{top}}}{\sigma_{t-ch,\text{anti-top}}} = 1.76 \pm 0.27 \)