Single top-quark production and properties measurements using the ATLAS detector

By Marcel Vreeswijk (Nikhef/UvA-IoP) on behalf of the ATLAS Collaboration
Top quarks in ATLAS

- Top Quarks are abundantly produced in ATLAS at the LHC.
- Production in pairs (strong, $\sigma \sim 800 \text{pb} @ 13\text{TeV}$) or single (weak, $\sigma \sim 300 \text{pb} @ 13\text{TeV}$).
- Unique: top quark decays before it hadronizes.
- Standard Model decay: $t \rightarrow Wb$ ($\sim 100\%$) $W$ leptonic ($\sim 33\%$) or hadronic ($\sim 66\%$).
- Measurements in this talk: $W$ decay to $e+\nu_e$ or $\mu+\nu_\mu$ ($\sim 22\%$).

LHC is a top factory
Single top-quark production

- **t-channel**
  \[ \sigma(13\text{TeV}) = 217^{+10}_{-10}\text{pb} \]

- **tW-channel**
  \[ \sigma(13\text{TeV}) = 72^{+4}_{-4}\text{pb} \]

- **s-channel**
  \[ \sigma(13\text{TeV}) = 10.3^{+0.4}_{-0.4}\text{pb} \]

- **tZq channel** (rare SM process)
  \[ \sigma(13\text{TeV}) = 0.8^{+0.05}_{-0.05}\text{pb} \]

All interesting processes by themselves: enable tests of the Standard Model $Wtb$ vertex

Sensitive to Beyond Standard Model physics:
- Direct: Flavour Changing Neutral Currents, Heavy Bosons, Charged Higgs
- Indirect: Effective Field Theory operators
# Single top-quark measurements

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In this talk we focus on the indicated results.

All Publications and public notes can be googled: [ATLAS Public Top Physics](https://www.google.com/search?q=ATLAS+Public+Top+Physics)
t-channel
t-channel: analysis @8TeV (and 13 TeV)

Signal Region (8TeV):
• Forward untagged jet ($P_T > 30$ GeV)
• Isolated $e, \mu$ ($P_T > 25$ GeV)
  (isolation eff: 90%[99%] for $P_T = 25[60]$ GeV)
• Missing $E_T$ ($MET > 30$ GeV)
• 1 tagged $b$-jet ($P_T > 30$ GeV)
  (eff 50%, mis-eff: 3.9%charm, 0.07% light)

• Analysis separately for $l^+$ and $l^-$
• Neural Net (NN) to separate signal from background
• Signal obtained from binned likelihood fit.
• Multijet determined data driven.
• Largest Backgrounds: ttbar, $W$+jets checked in Validation Regions and normalisations simultaneously obtained in fit.

(13 TeV analysis in a manner similar)
t-channel: cross sections @8TeV and 13TeV

8 TeV: **EPJC 77 (2017) 531**

Cross section obtained in Fiducial region with uncertainty ~5%

Main systematic unc sources:
jet energy scale, lepton reco., flavour tagging

Total cross section @8TeV

\[
\sigma = 89.6 \pm 1.2 \text{ (stat.)} \pm 5.1 \text{ (exp.)} +4.1_{-2.5} \text{ (scale)} \\
\pm 0.7 \text{ (PDF)} \\
\pm 1.7_{-1.6} \text{ (NLO-matching method)} \\
\pm 1.6 \text{ (parton shower)} \pm 1.7 \text{ (lumi.) pb}
\]

\[
= 89.6^{+7.1}_{-6.3} \text{ pb.} \sim 7.5\
\]

Predicted \( \sigma(8\text{TeV}) = 84.6^{+3.9}_{-3.4} \text{pb} \)

Also 13 TeV result available

\[
\sigma = 247 \pm 6 \text{ (stat.)} \pm 45 \text{ (syst.)} \pm 5 \text{ (lumi.) pb}
\]

Predicted \( \sigma(13\text{TeV}) = 217^{+10}_{-10} \text{pb} \)

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**JHEP 04 (2017) 086**

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t-channel: differential cross sections @8TeV

Differential Cross section at particle level. Iterative Bayesian unfolding uses events with $NN > 0.8$. (distributions also available at parton level)
t-channel

-- \( Wtb \) vertex --
t-channel: $Wtb$ vertex

(Very) brief summary of 8 TeV analysis

**JHEP 04 (2017) 124**

Top quark is spin polarized at production.
Spin information is transferred to its decay products

- the untagged jet is taken as the spin direction in top rest frame
- For any decay product:
  \[
  \frac{1}{\Gamma} \frac{\mathrm{d}\Gamma}{\mathrm{d}(\cos \theta_X)} = \frac{1}{2} \left( 1 + \alpha_X P \cos \theta_X \right)
  \]

Top quark polarisation: $P = 0.97 \pm 0.12$
Predicted NLO: $P \sim 0.9$

Main systematics:
- MC stats
- Jet Reconstruction
- ttbar generator

 ALSO RESULTS AVAILABLE ON ANGULAR DISTRIBUTION RELATED TO BSM-COUPINGS/ EFT OPERATORS.
$tW$-channel
**tW-channel: analysis @13TeV**

**Signal Region:**
- Exactly two isolated $e$ and/or $\mu$.
- MET $>$ 20 GeV
- 1 jet which is $b$-tagged ($p_T$ $>$ 25 GeV)
  (EFF 77%, CHARM 22%, LIGHT 0.07%)
- mass($ll$) vs MET cuts to reduce Z+jets.

- BDT used to separate Signal and Background
- Main background $t\bar{t}$

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**Graphical Representation:**
- The diagram illustrates the decay processes of the $tW$ channel, including the production and decays of top quarks, W bosons, and leptons.

**ATLAS**
\[ \sqrt{s} = 13 \text{ TeV}, \ 36.1 \text{ fb}^{-1} \]

**Plots:**
- Histo of $p_T(\ell_1 \ell_2 E_T^{\text{miss}})$
- Histo of $\Delta p_T(\ell_1 \ell_2 b, E_T^{\text{miss}})$
- Histo of $\Sigma E_T$
- Histo of $\eta(\ell_1 \ell_2 E_T^{\text{miss}})$
- Histo of $\Delta p_T(\ell_1 \ell_2 E_T^{\text{miss}})$
- $p_T(\ell_1 \ell_2 b)$
- $C(\ell_1 \ell_2)$
- $m(\ell_2, b)$
- $m(\ell_1, b)$

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**Final Cut:**
- Data
- $tW$
- $t\bar{t}$
- Z+jets
- Others
**tW channel: differential cross section @13 TeV**

Cut on BDT>0.3 to reduce syst

Unfolding with Iterative Bayesian method

Differential cross section are normalised by the fiducial cross section

- In high tail mc<data
- Also seen in $M(\ell_2 b)$, and $E(\ell b)$

Largest systematic:
- tW generator parton shower,
- ttbar modelling (ISR/FSR)

Results are sensitive to quantum interference tW and ttbar.
Nominal MC: Diagram-Removal (DR)
For syst. Check:
Diagram-Substraction (DS)

$tW$ MC: powheg-box v1 for ME; ct10 DR; PS: Pythia6.428 CTEQ6l1pdfset

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**tW-channel: interference with ttbar**

**Novel method to study interference**

\[ m_{b\ell}^{\text{minimax}} = \min \{ \max (m_{b_1\ell_1}, m_{b_2\ell_2}), \max (m_{b_1\ell_2}, m_{b_2\ell_1}) \} \]

**SAME FINAL STATE @LO**

ATLAS

\[ \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \]

**submitted to prl**
$t\!Z\!q$ production
--a rare SM channel--

Sensitive to $WWZ$ and $tZ$ coupling
→ Not seen before
→ Background to $tH$ channel

**Signal Region**
- Three charged leptons in final state $P_T > 28, 25, 15$ GeV
- 1 b-tagged jet ($P_T > 30$ GeV) (eff 77%, charm 17%, light 1%)
- 1 untagged jet ($P_T > 30$ GeV)
- Transverse mass $W$, $M_T(\text{lepton, MET}) > 20$ GeV
- $Z$ mass window 80-100 GeV (and a opposite charge, same lepton flavour pair)
Two Control Regions for Backgrounds:

- “Fake Z” background from ttbar: opposite flavour lepton combination
- “Real Z” background diboson: 1 untagged jet, tightened $M_T$

Background Z+jets from ratio in data ($M_T < 20$) with a third lepton failing isolation criteria.

VR ttbar: like signal, but outside Z-mass window

VR diboson: like signal, only 1 jet, (no b-tagging)

Neural net to separate signal and background Output checked in validation regions (VR)
**tZq production, cross section @13 TeV**

Signal obtained in Likelihood fit
Background also fitted with constrains according to uncertainties

$$\sigma = 600 \pm 170 \text{ (stat.)} \pm 140 \text{ (syst.) fb}$$

(Theory NLO 800 fb $\pm 7\%$ (scale))

Main systematics:
- Radiation signal MC
- Jet Energy Scale
- b-tagging

Significance 4.2 (5.4 expected)

**EVIDENCE**

**Signal MC:**
LO [MG5 AMC@NLO2.2.1](https://github.com/ATL-PHYS-Papers/MG5_aMC@NLO), 4FS; PS: CTEQ6L1 (LO)
Summary

• Main three single top channel being pinned down
• Many results available
• The hunt for rare single-top processes started
LHC SCHEDULE

Run 1
- LS1: splice consolidation button collimators R2E project
- 7 TeV
- 2011

Run 2
- EYETS
- 13 TeV
- 2015

Run 3
- LS2: Injector upgrade cryo Point 4 DS collimation P2-P7(11 T dip.) Civil Eng. P1-P5
- 13.5-14 TeV
- 2017

Run 4 - 5...
- LS3: HL-LHC installation
- 14 TeV
- 2021

Experiment upgrade phase 1
- 150 fb⁻¹
- 2019

Experiment upgrade phase 2
- 300 fb⁻¹
- 2024

75% nominal luminosity

30 fb⁻¹

14 TeV

5 to 7 x nominal luminosity

2 x nominal luminosity

3000 fb⁻¹ Integrated luminosity

Radiation damage

Energy

Nominal luminosity

Cryomount interaction regions
t-channel: CROSS-SECTION MEASUREMENT @8TEV

BACKGROUND (DATA-DRIVEN)

Multijet shape from di-jet MC. Multijet normalisation from MET distribution

ttbar shape from NLO MC Validation Region (VR) to check NN (VR is SR but with 2 b-jets)

W+jets shape from NLO MC Validation Region (VR) to check NN (VR uses relaxed b-jet requirement)
t-channel: ratio $\sigma(\text{top})/\sigma(\text{antitop})$ 8TeV and 13TeV

Many additional result available
Shown here: ratio $\sigma(\text{top})/\sigma(\text{antitop})$

Note: also 13TeV paper is out!
In a manner similar analysis as 8 TeV
(cross section shown later this talk)

Main systematic unc.: Background modelling, Jet Reconstruction, MET modelling
ICHEP 2018, SEOUL, SOUTH KOREA

SINGLE TOP-QUARK MEASUREMENTS: t-channel

\[ \mathcal{L}_{Wtb} = \frac{g}{\sqrt{2}} \bar{b} \gamma^\mu (V_L P_L + V_R P_R) t W^-_\mu - \frac{g}{\sqrt{2}} \bar{b} \not{q}^{\mu \nu} q_\nu \left( g_L P_L + g_R P_R \right) t W^-_\mu \]

Example: \( g_R \) is CP violating

\[ A_{FB}^N = 0.64 P \text{ Im } g_R \]

Main systematic unc. (on \( A_{FB}^N \)):
MC stats, Jet reconstruction, ttbar parton shower, t-channel (scales)

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s-CHANNEL

s-channel evidence 8 TeV

PLB 756 (2016) 228
**tW-channel: differential cross section @13TeV**

Fiducial cuts=Signal Region:
- Exactly two isolated $e$ and/or $\mu$.
- MET>$20$ GeV
- 1 jet which is $b$-tagged ($pt>$25 GeV)
  (EFF 77%, CHARM 22%, LIGHT 0.07%)
- $mass(ll)$ vs MET cuts to reduce Z+jets.

- Main background $tt\bar{t}$
- Several Validation Regions for checks, one Signal Region "1j1b"
- Separation in SR with BDT

$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

**ATLAS**

- Data
- $tW$
- $tt$
- $Z+$jets
- Others

$\Delta p_T(l_1l_2, E_T^{miss})$
$\sum E_T$
$\eta(l_1l_2, E_T^{miss})$
$\Delta p_T(l_1l_2b, E_T^{miss})$
$pt(l_1l_2b)$
$C(l_1l_2)$
$m(l_2, b)$
$m(l_1, b)$

**Final cut**

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