Top pair and single top production in ATLAS

Federica Fabbri

On behalf of the ATLAS collaboration

Lomonosov18, Mosca

Why top quark and $\sigma(t)$ and $\sigma(t\bar{t})$?

Elementary particle with the largest mass:

World average: [arXiv:1403.4427](https://arxiv.org/abs/1403.4427)

$$m_t = 173.34 \pm 0.27^{(\text{stat})} \pm 0.71^{(\text{syst})} \text{ GeV}$$

$m_t \sim$ electroweak symmetry breaking scale

The only quark that decays before hadronize:

- Direct access to Wt coupling
- Direct access to “free quark” properties

Stringent test of the latest theoretical calculation (NNLO, NLO +NNLL)

Involved in many BSM theories

Hint of new physics:

- Observed in modification of $\sigma(t\bar{t})$ and $\sigma(t)$ shape
- Observed in a variation of coupling wrt SM expectations

Main background to many searches (graviton, Z' and stop searches, $t\bar{t}H$...), dominated from $\sigma(t\bar{t})$ theoretical uncertainties

Precise measurement input to:

- MC tuning

ATL-PHYS-PUB-2016-020

Really high production cross section at LHC

- PDF fitting:

$t\bar{t} \rightarrow$ gluons, $t(\bar{t}) \rightarrow b$, light quark PDFs

$t\bar{t}$ production and decay @ LHC

Due to the gluon PDF at 13 TeV at LHC.

~ 90 %

$t \rightarrow Wb$ (BR ~ 99%)

Analysis channel: Final states and analysis channels depend on the decay of the two W bosons.

$\sqrt{s}$	8 TeV	13 TeV
$\sigma(t\bar{t})$ (pb)	253^{+13}_{-15}	832^{+40}_{-46}

NNLOxs_TopLHCWG

So many interesting measurements, *also in 2017!!!*

	$\sqrt{s} =$	dilepton	l+jets	All jets
$\sigma(t\bar{t})$	8 TeV	Eur.Phys.J. C74 (2014) no .10, 3109	tau+jets: Phys. Rev. D 95 (2017) 07 2003 ATLAS-CONF-2017-054	
	13 TeV	Phys.Lett. B761 (2016) 1 36-157	ATLAS-CONF-2015-049	
$\frac{d\sigma(t\bar{t})}{dX}$	8 TeV	PhysRevD.94.092003	Resolved: Eur. Phys. J. C76 (2016) 538	
		Including m_t^t : ATLAS-CONF-2017-044	Boosted: Phys. Rev. D93 (2016) 032009	
	13 TeV	Eur. Phys. J. C77 (2016) 299	Resolved & Boosted: CERN-EP-2017-058	Boosted: ATLAS-CONF-2016-100

$\sigma(t\bar{t})$ in τ +jets @ 8 TeV

Good cross check to the cross section measurement in other channels.
BSM mass and flavour dependent couplings expected to enhance $t \rightarrow \tau \nu_\tau b$ (SUSY, 2HDM)
includes $t \rightarrow Hq \rightarrow \tau\tau q$

Analysis strategy:

- Final state: $t\bar{t} \rightarrow bbq\tau\nu_\tau$, τ decaying to hadrons
- τ identification using boosted decision tree (BDT), depending on the number of charged particles in τ decay

Background identification:

- MC Estimate:** events containing a real τ (Diboson, Single Top, V+jets) and with mis-identification of e, μ (mainly from $t\bar{t}$ decay)
- Data driven:** mis-identified jets from gluons or quarks

Result:

$$\sigma(pp \rightarrow t\bar{t} + X) = \frac{N_{\text{data}} - N_{\text{bkg-non}t\bar{t}}}{\text{BR} \times (\epsilon_{t\bar{t}} - \epsilon_{\text{FF-}t\bar{t}}) \times \int \mathcal{L}(t) dt}$$

$$\sigma_{t\bar{t}} = 239 \pm 4(\text{stat}) \pm 28(\text{syst}) \pm 5(\text{lumi}) \text{ pb}$$

Mainly modelling, b-tagging

Signal purity
80%

Observed data	1678
Expected SM background	1751 ± 42
$S_{\text{obs}(\text{exp})}^{95}$	$446 \text{ (} 444_{-21}^{+40} \text{)}$
$\langle \epsilon \sigma \rangle_{\text{obs}(\text{exp})}^{95} [\text{fb}]$	$22 \text{ (} 22_{-1}^{+2} \text{)}$

Phys. Rev. D 95 (2017) 072003

- Good agreement with the SM expectations and other channel measurements.
- Set a limit on the existence of the flavour changing neutral current process: $t \rightarrow qH \rightarrow q\tau\tau$

$\sigma(t\bar{t})$ in 1+jets @ 8 TeV using NN

Event selection

- One high- p_T e/ μ
- At least one b-tagged jet
- At least 4 jets

Define 3 signal regions and introduce a variable in each to discriminate signal and background

SR3: $\geq 4\text{jet} \geq 2\text{bjet}$

Events with extra heavy

SR2: $==4\text{jet} ==2\text{bjet}$

No ambiguity $t\bar{t}$ in system reconstruction

SR1: $==1\text{bjet}$

Large W+jets background radiation

Binned likelihood fit on the three signal regions to extract $\sigma(t\bar{t})$:

$$\sigma_{t\bar{t}} = 248.3 \pm 0.7 \text{ (stat.)} \pm 13.4 \text{ (syst.)} \pm 4.7 \text{ (lumi.) pb}$$

- Uncertainty constrained in the fit as nuisance parameters, dominant Jet Energy scale (JES) and $t\bar{t}$ modelling
- Good agreement with the SM expectations

ATLAS-CONF-2017-054

Differential measurements

- Different distributions are sensitive to different aspects of $t\bar{t}$ production
 - Very stringent test of QCD calculations
 - MC tuning, PDF fitting
- Identify presence of BSM in shape modifications
- Handle the limited resolution of the detector and correct for it
 - Use MC to evaluate a response matrix that accounts for mis-reconstruction of kinematic quantities.

Depending on the way the corrections are evaluated, the measurement can be performed at:

Particle Level:

- Truth: “objects”(leptons, jets) reconstructed from stable particles, before detector interactions.
- Apply on the “objects” fiducial cuts, similar to the reconstruction cuts
 - Smaller modelling uncertainties (smaller extrapolation)
 - Reduce dependencies from generators

Parton level:

- Truth: $\bar{t}$ and t , after radiations before decay.
- Measurement extrapolated to the full phase space
- Compare the result with the latest theoretical calculations not available at particle level

$d\sigma(t\bar{t})$ in $e\mu$ channel @ 8TeV

- Measurement of the $\sigma(t\bar{t})$ in $e\mu$ channel as a function of the lepton's kinematic property.
- Pre-selection requires $e\mu$ with opposite sign (OS) → Events afterward divided depending on the number of reconstructed b-tagged jets: N1,N2.

Cross section extracted bin-by-bin (i) from:

Binned efficiency and migration correction evaluated from MC.

$$N_1^i = L\sigma_{t\bar{t}}^i G_{e\mu}^i 2\epsilon_b^i (1 - C_b^i \epsilon_b^i) + N_1^{i,\text{bkg}}$$

$$N_2^i = L\sigma_{t\bar{t}}^i G_{e\mu}^i C_b^i (\epsilon_b^i)^2 + N_2^{i,\text{bkg}},$$

b-tagging efficiency: extracted with $\sigma(t\bar{t})$ to reduce uncertainty

Results:

Differential cross section

- Main uncertainty: statistics and background determination
- Good agreement with SM, dependence wrt the lepton p_T improved using HERAPDF and NNLO predictions.

ATLAS-CONF-2017-044

Extraction of the top mass

- Calculate χ^2 with various MC NLO m_t hypothesis, interpolation to derive m_t at minimum
- Most precise pole mass measurement

$d\sigma(t\bar{t})$ in $e\mu$ channel @13 TeV

Cleanest channel for $t\bar{t}$ measurements but lower BR

Challenge: reconstruct the two neutrinos using E_T^{miss}

Eur. Phys. J. C77 (2016) 299

Analysis strategy:

- Required one e and one $\mu(\text{OS})$, $p_T > 25 \text{ GeV}$ and 2 b -tagged jets
- Main backgrounds (MC estimate): $Z/\gamma \rightarrow \tau^+\tau^-$, Diboson, Fake lepton, Single top (85% signal purity)
- Reconstruct neutrinos from E_T^{miss} using neutrino weighting technique, constraint on m_t and m_W
- Unfolding to particle level

Results:

- Good agreement with SM expectations.
- Main uncertainty: top modelling

$d\sigma(t\bar{t})$ in l+jet channel @ 13 TeV

Leptonic top:

- Lepton
- ν : E_T^{miss} (use constraint on W mass to find p_z component)
- Closest b-jet to the lepton

Requirements:

- Single lepton with $p_T > 25$ GeV
- At least 4 jets with $p_T > 25$ GeV
- At least 2 bjet (if > 2 selected the highest p_T)

Hadronic top:

- Use the two light jets (invariant mass near to W mass)
- Other b-jet

Same algorithm used to define the $t\bar{t}$ system at **detector** and **particle level**

Cut and count analysis, reaches a signal purity 89%

- Dominant uncertainties: JES and b-tagging
- Good agreement with SM expectations.
- High discriminating power among various MC generator

Boosted measurements

- High energy reached from LHC allows to explore frontier kinematic regime (TeV scale)
- If the top quark is produced with high p_T the decay products have a large boost, and are contained in a:

$$\Delta R = \sqrt{\Delta y + \Delta \phi} \sim \frac{2m}{p_T}$$

($\Delta R = 1.0$ for $m_t = 173$, $p_T > 300$ GeV)

- Combine substructure properties (τ_{32} , mass) to define a tagger that select a large-R jet deriving from the top quark

Related to the number of “hard” axes in a large-R jet

- MC/data in l+jets channel in resolved and boosted regime, observed same trend.
- The two topologies combined provide a “differential description” on the full spectra

Boosted measurements @ 13TeV

l+jets channel:

Hadronic top: 1 large-R jet, $p_T > 300$ GeV, top tagged (80%)

CERN-EP-2017-058

- Main background: Single top, W+jets
- Main uncertainties: Large-R jets JES, stat
- Good agreement with SM, small tension shown at high p_T

All-had channel:

≥ 2 large-R jets top tag (50% WP), $122.5 \text{ GeV} < m_{\text{large-R jet}} < 222.5 \text{ GeV}$

ATLAS-CONF-2016-100

- Main background: Multijet (data driven)
- Main uncertainties: Large-R jets JES, stat, MC modeling.
- Good agreement with SM

Single top production

Many interesting results!! Also probing top coupling with W and Z bosons!

	s-channel	tW-channel	t-channel	tZ production
8 TeV	arXiv:1511.05980	JHEP 01 (2016) 064	arXiv:1702.02859	
13 TeV		arXiv:1612.07231	JHEP04(2017)086	ATLAS-CONF-2017-052

$d\sigma(t)$, t-channel @8TeV using NN

- Channel with highest production σ
- The top production is favored by PDF with respect to the anti-top production

Analysis strategy:

- Discriminate signal and background using a NN based on:
 - $m(l\nu b)$, $m(bj)$ and the (b,j) system
 - Kinematic and angular properties of $l, j, b, E_{\text{miss}}^T$
- Main backgrounds: $t\bar{t}$, W +jets. Estimated from MC prediction, constrained with a likelihood fit on NN output variable (O_{NN})
- Data-driven QCD background estimate

- Cut on O_{NN} allows to increase purity for $t(\bar{t})$ from 20(14)% $\rightarrow$ 68(57)
- Differential measurement at particle and parton level
- Good agreement with SM predictions

$\sigma(t)$, t-channel @ 8,13 TeV

- Same NN technique applied to extract inclusive cross section but applying a likelihood fit using full NN
- The total cross section measurement allows the extraction of the element of CKM $|V_{tb}|$
- Technique similar to 8 TeV applied to 13 TeV, slightly different NN
- Measurement of $R_t = \sigma(t)/\sigma(\bar{t})$ highly sensitive to PDFs

8 TeV

arXiv:1702.02859

$$\sigma_{\text{tot}}(tq) = 56.7^{+4.3}_{-3.8} \text{ pb} \quad \sigma_{\text{tot}}(\bar{t}q) = 32.9^{+3.0}_{-2.7} \text{ pb}$$

$$\sigma_{\text{tot}}(tq + \bar{t}q) = 89.6^{+7.1}_{-6.3} \text{ pb}$$

$$f_{LV} \cdot |V_{tb}| = 1.029 \pm 0.048$$

Main unc.: JES, top modelling

13 TeV

JHEP04(2017)086

$$\sigma(tq) = 156 \pm 5 \text{ (stat.)} \pm 27 \text{ (syst.)} \pm 3 \text{ (lumi.) pb}$$

$$\sigma(\bar{t}q) = 91 \pm 4 \text{ (stat.)} \pm 18 \text{ (syst.)} \pm 2 \text{ (lumi.) pb}$$

$$\sigma(tq + \bar{t}q) = 247 \pm 46 \text{ pb.}$$

$$f_{LV} \cdot |V_{tb}| = 1.07 \pm 0.09.$$

Main unc.: JES, b-tagging, top modelling

$\sigma(t)$ in Wt-channel @ 13TeV using BDT

- Second leading process in single top production.
- Not observable at Tevatron, production observed for the first time at LHC @8 TeV

Analysis Strategy:

- Event selection aims to detect Wt and $t\bar{t}$ events, highly reducing Z+jet background (m_{ll} and E_T^{miss} cuts)
- All backgrounds estimated by simulation

arXiv:1612.07231

- After pre-selection events divided into:
1j1b, 2j1b(SR), 2j2b(CR)
regions. BDT defined in each
region to separate Wt and $t\bar{t}$
- Binned likelihood fit used
to extract the Wt and $t\bar{t}$
yields and to constrain syst.

$$\sigma_{Wt} = 94 \pm 10 (\text{stat.})_{-22}^{+28} (\text{syst.}) \pm 2 (\text{lumi.}) \text{ pb.}$$

Significance: 4.5σ (3.9σ)

Main uncertainty: jet energy resolution, top modelling and jet energy scale

$\sigma(tZ)$ @ 13 TeV, using NN

Electroweak process no yet observed, very small production σ
Sensitive to tZ and WWZ coupling

Analysis strategy:

- Trilepton channel most pure for first observation, despite small BR (2.2%)
- Main background: Diboson (WZ), Z +jets events with mis-identified lepton (data driven), $t\bar{t}$ (data driven normalization), $t\bar{t}V$ (MC estimated)
- After pre-selection events are divided into SR(2j1b), and VR,CR to check the main background description and normalization
- NN is built to improve signal to the background separation, binned likelihood fit in SR used to extract $\sigma(tZq)$

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

$$\sigma_{tZq}^{\text{theor}} = 800^{+48.8}_{-59.2}\text{fb}$$

Significance: 4.2σ (5.4σ)

Main uncertainty: tZq modelling, jet

Summary

ATLAS provided a huge number of measurements for the t and $t\bar{t}$ production at 8 and 13 TeV.

Measurement of $t\bar{t}$:

- Inclusive and differential measurements show a **good agreement with the SM** expectations.
- Used as input for **MC tuning and PDF fitting**, a possible application is also the **pole mass** extraction.
- Used to **set limits** to the existence of new physics.
- **Boosted techniques** can be employed to extract the cross section also in region where the top has a very high p_T .

Single top measurement:

- Presented the latest measurement in t-channel, and Wt channel.
- Observed a general **good agreement with the SM expectations**.
- The measurements can be used to **improve PDF extraction** and **extract the $|V_{tb}|$** .
- Presented the **first measurement of $\sigma(tZ)$** (observed with a 4.2σ significance).

All the measurements will be tuned and improved with the incoming data that will allow to reduce uncertainty and increase the events produced in challenging channels and regimes.

Thank you for your attention!!!

Back Up

Multivariate approach

Take into account correlation

Combine in a smart way the variables, to get higher separation

Various approach to combine the informations

DT

NN

Measurement of $\sigma(t\bar{t})$ in τ +jets @ 8 TeV

- Good cross check to the cross section measurement performed in other channel
- BSM mass and flavour dependent couplings are expected to enhance the $t \rightarrow \tau \nu_t b$ cross section (SUSY, 2HDM includes $t \rightarrow Hq \rightarrow \tau \tau q$)

Event selection:

Decaying in hadrons.

Reconstructed employing a BDT, optimized to identify:

τ decaying in a charged particle (1 prong)

τ decaying in a three charged particles (3 prong)

Background estimate:

- Process containing a real τ (Diboson, Single Top, V+jets)
 - e, μ identified as τ (mainly from $t\bar{t}$ decay)
 - Jets from gluons or quark identified as τ
- MC Estimate
- Data driven fake factor.

Event counts	$\tau_{1\text{-prong}}$	$\tau_{3\text{-prong}}$	τ_{had}
$t\bar{t} \rightarrow e/\mu + \text{jets}$	21.8 ± 4.7	6.8 ± 2.5	28.3 ± 5.3
Single top	107 ± 10	33.9 ± 5.8	141 ± 12
$W + \text{jets}$	71.7 ± 8.5	27.1 ± 5.2	99 ± 10
$Z + \text{jets}$	7.2 ± 2.7	1.6 ± 1.3	8.7 ± 3.0
Diboson	1.0 ± 1.0	0.4 ± 0.6	1.5 ± 1.2
Misidentified- τ_{had}	46.6 ± 6.8	24.9 ± 5.0	74.9 ± 8.7
Expected $t\bar{t} \rightarrow \tau + \text{jets}$	1084 ± 33	312 ± 18	1398 ± 37
Total Expected	1339 ± 37	407 ± 20	1751 ± 42
Data	1278	395	1678

$\sigma(t\bar{t})$ in all-had channel @13 TeV

Event selection:

- no e/μ $p_T > 25$ GeV
- 2 large-R jets with $p_T > 350$ GeV and $|\eta| < 2.0$
- leading large-R jet $p_T > 500$ GeV
- A small-R (0.4) jet with $p_T > 25$ GeV and $|\eta| < 2.5$
- The two highest p_T large-R jets need to be top tagged (50% WP) and satisfy $122.5 \text{ GeV} < m_j < 222.5 \text{ GeV}$
- The two large-R jets need to be matched ($DR < 1.0$) with a b-tagged small-R jet.

$t\bar{t}$ (all-hadronic)	1 190	$\pm$	240
$t\bar{t}$ (non all-hadronic)	60	$\pm$	15
Single top-quark	9	$\pm$	5
Multijet events	^s 300	$\pm$	20
Prediction	1 570	$\pm$	260
Data (14.7 fb ⁻¹)	1 512		

$d\sigma(t\bar{t})$ in e/μ channel @ 8TeV

ATLAS-CONF-2017-044

Event counts	N_1	N_2
Data	21666	11739
Wt single top	2080 ± 210	350 ± 120
$Z(\rightarrow \tau\tau \rightarrow e\mu)+\text{jets}$	210 ± 40	7 ± 2
Diboson	120 ± 30	3 ± 1
Misidentified leptons	220 ± 80	78 ± 50
Total background	2630 ± 230	440 ± 130

→ Data, and expected signal and background after the pre-selection and in each bin of b-tagging.

Effect of the measurement of $|\eta^{\text{lep.}}|$, $|y^{\text{e}\mu}|$, and E^e+E^μ in $t\bar{t}$ events on PDF fitting in HERAPDF:

t-channel: R_t uncertainty

8 TeV

Source	$\Delta R_t / R_t$ [%]
Data statistics	± 3.0
Monte Carlo statistics	± 1.8
Background modelling	± 0.7
Jet reconstruction	± 0.5
E_T^{miss} modelling	± 0.6
tq ($\bar{t}q$) NLO matching	± 0.5
tq ($\bar{t}q$) scale variations	± 0.7
$t\bar{t}$ NLO matching	± 2.3
$t\bar{t}$ parton shower	± 1.7
PDF	± 0.7
Total systematic	± 3.9
Total (stat. + syst.)	± 5.0

13 TeV

Source	$\frac{\Delta\sigma(tq)}{\sigma(tq)}$ [%]	$\frac{\Delta\sigma(\bar{t}q)}{\sigma(\bar{t}q)}$ [%]	$\frac{\Delta R_t}{R_t}$ [%]
Data statistics	± 2.9	± 4.1	± 5.0
Monte Carlo statistics	± 2.8	± 4.2	± 5.1
Reconstruction efficiency and calibration uncertainties			
Muon uncertainties	± 0.8	± 0.9	± 1.0
Electron uncertainties	< 0.5	± 0.5	± 0.7
JES	± 3.4	± 4.1	± 1.2
Jet energy resolution	± 3.9	± 3.1	± 1.1
E_T^{miss} modelling	± 0.9	± 1.2	< 0.5
b -tagging efficiency	± 7.0	± 6.9	< 0.5
c -tagging efficiency	< 0.5	± 0.5	± 0.6
Light-jet tagging efficiency	< 0.5	< 0.5	< 0.5
Pile-up reweighting	± 1.5	± 2.2	± 3.8
Monte Carlo generators			
tq parton shower generator	± 13.0	± 14.3	± 1.9
tq NLO matching	± 2.1	± 0.7	± 2.8
tq radiation	± 3.7	± 3.4	± 3.7
$t\bar{t}$, Wt , $t\bar{b} + \bar{t}b$ parton shower generator	± 3.2	± 4.4	± 1.2
$t\bar{t}$, Wt , $t\bar{b} + \bar{t}b$ NLO matching	± 4.4	± 8.6	± 4.6
$t\bar{t}$, Wt , $t\bar{b} + \bar{t}b$ radiation	< 0.5	± 1.1	± 0.7
PDF	± 0.6	± 0.9	< 0.5
Background normalisation			
Multijet normalisation	± 0.3	± 2.0	± 1.8
Other background normalisation	± 0.4	± 0.5	< 0.5
Luminosity	± 2.1	± 2.1	< 0.5
Total systematic uncertainty	± 17.5	± 20.0	± 10.2
Total uncertainty	± 17.8	± 20.4	± 11.4

t-channel: NN comparison

8 TeV

Variable symbol	Definition
$m(jb)$	The invariant mass of the untagged jet (j) and the b -tagged jet (b).
$ \eta(j) $	The absolute value of the pseudorapidity of the untagged jet.
$m(\ell\nu b)$	The invariant mass of the reconstructed top quark.
$m_T(\ell E_T^{\text{miss}})$	The transverse mass of the lepton- E_T^{miss} system, as defined in Eq. (??).
$ \Delta\eta(\ell\nu, b) $	The absolute value of $\Delta\eta$ between the reconstructed W boson and the b -tagged jet.
$m(\ell b)$	The invariant mass of the charged lepton (ℓ) and the b -tagged jet.
$\cos\theta^*(\ell, j)$	The cosine of the angle, θ^* , between the charged lepton and the untagged jet in the rest frame of the reconstructed top quark.

13 TeV

Variable	Definition
$m(\ell\nu b)$	top-quark mass reconstructed from the charged lepton, neutrino, and b -tagged jet
$m(jb)$	invariant mass of the b -tagged and untagged jet
$m_T(\ell E_T^{\text{miss}})$	transverse mass of the reconstructed W boson
$ \eta(j) $	modulus of the pseudorapidity of the untagged jet
$m(\ell b)$	invariant mass of the charged lepton (ℓ) and the b -tagged jet
$\eta(\ell\nu)$	rapidity of the reconstructed W boson
$\Delta R(\ell\nu b, j)$	ΔR of the reconstructed top quark and the untagged jet
$\cos\theta^*(\ell, j)$	cosine of the angle θ^* between the charged lepton and the untagged jet in the rest frame of the reconstructed top quark
$\Delta p_T(\ell\nu b, j)$	Δp_T of the reconstructed top quark and the untagged jet
$\Delta R(\ell, j)$	ΔR of the charged lepton and the untagged jet