ATLAS EXPERIMENT

Top quark pair production cross-section measurements with ATLAS

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On behalf of the ATLAS Collaboration

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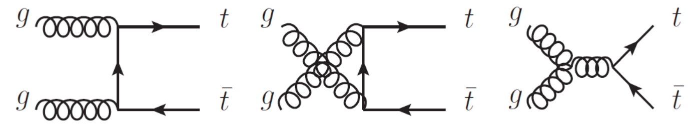
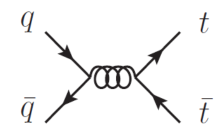
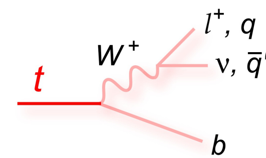
Top quarks pair production

- Studying the top quark sector is a fundamental component of the overall ATLAS research program
  - cross-section and properties measurements
    - precision tests of the Standard Model
  - a window to new physics if deviation found
    - non-SM production: $X \to t\bar{t}$
    - non-SM decay: $t \to Xb$
    - top plays an important role in several BSM theories
  - decay topologies are a background to several BSM searches and other SM measurements
  - important for $t\bar{t}H$ measurement







Theory NNLO+NNLL soft gluon resum.
(Czakon, Mitov; Top++ program)

$\sigma_{t\bar{t}} = 253^{+13}_{-15}$ pb (8 TeV)

$\sigma_{t\bar{t}} = 832^{+40}_{-46}$ pb (13 TeV)

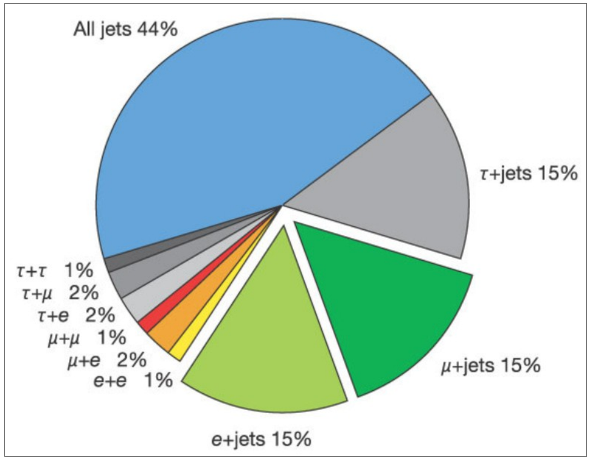
(m_t=172.5 GeV)

Czakon, Fiedler, Mitov
PRL **110** (2013) 252004

- The LHC is a top factory (large abundance):
  - perform various differential cross-section measurements ($d\sigma/dX$)
    - important to study QCD effects, PDF's, and Parton Showers implementation in various Monte Carlo's for further tuning.

Cross-section measurements

- Several analyses performed and measurements reported today:
  - at 8 TeV (full 20.3 fb^{-1}dataset from 2012)
    - $d\sigma/dX$ of top, $t\bar{t}$ system, event-level kinematics
    - $d\sigma/dX$ of top p_T in a highly boosted regime
  - at 13 TeV: with 85 pb^{-1} & 3.2 fb^{-1} of 2015 data
    - inclusive $t\bar{t}$ production
    - $t\bar{t} + W$, and $t\bar{t} + Z$ production
    - $t\bar{t}$ + jets , $d\sigma/dX$ of additional jet multiplicity
- All analyses require basic ingredients:
  - electrons and muons
  - jets
  - missing E_T
  - b-tagged jets
- dilepton channel (multi-leptons for $t\bar{t}+V$):
  - used for inclusive cross-sections
- lepton+jets channel:
  - used for both inclusive & differential cross-sections



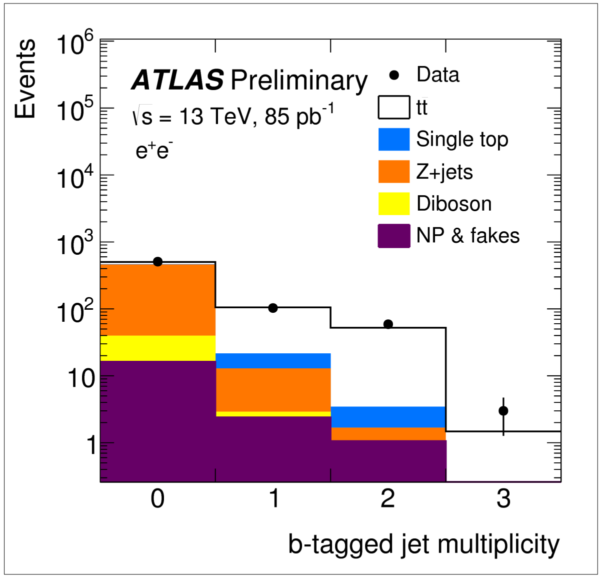
ee, μμ, e/μ + jets inclusive (13 TeV)

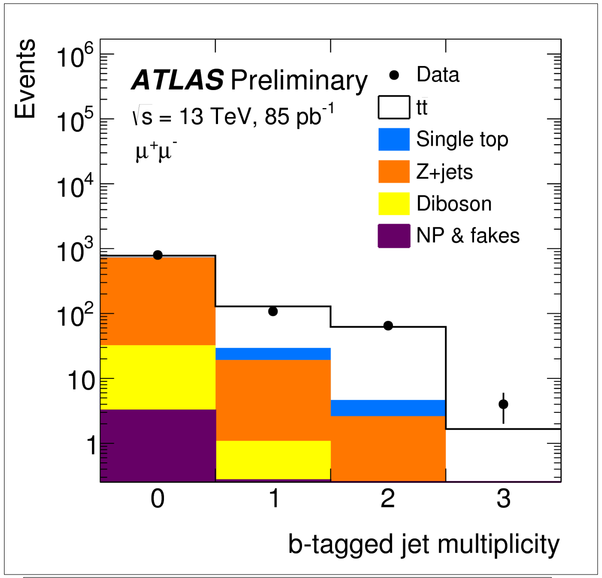
- dilepton: same flavour opposite sign leptons *ee* or *μμ*; exactly 1 or 2 b-tagged jets; missing E_T.

$$
\begin{aligned}
N_1^{ee} &= L\sigma_{t\bar{t}}\,\epsilon^{ee}_{\rm presel} 2\epsilon^{ee}_b (1 - C^{ee}_b \epsilon^{ee}_b) + N_1^{{\rm bkg},ee}\\
N_2^{ee} &= L\sigma_{t\bar{t}}\,\epsilon^{ee}_{\rm presel} C^{ee}_b \epsilon^{ee}_b \epsilon^{ee}_b + N_2^{{\rm bkg},ee}\\
N_1^{\mu\mu} &= L\sigma_{t\bar{t}}\,\epsilon^{\mu\mu}_{\rm presel} 2\epsilon^{\mu\mu}_b (1 - C^{\mu\mu}_b \epsilon^{\mu\mu}_b) + N_1^{{\rm bkg},\mu\mu}\\
N_2^{\mu\mu} &= L\sigma_{t\bar{t}}\,\epsilon^{\mu\mu}_{\rm presel} C^{\mu\mu}_b \epsilon^{\mu\mu}_b \epsilon^{\mu\mu}_b + N_2^{{\rm bkg},\mu\mu},
\end{aligned}
$$

  - simultaneous fit to obtain $\sigma_{t\bar{t}}$ and b-tagging efficiencies
- lepton+jets: one lepton and at least 4 jets
  - 1 b-tagged jet
  - requirement on missing E_T and/or M^W_T
  - $\sigma_{t\bar{t}}$ = (N-B)/(Efficiency*L)

Channel	Cross-section measurement
ee	824 ± 88 (stat) ± 91 (syst) ± 82 (lumi) pb
μμ	683 ± 74 (stat) ± 76 (syst) ± 68 (lumi) pb
ee and *μμ* combined	749 ± 57 (stat) ± 79 (syst) ± 74 (lumi) pb
e+jets	775 ± 17 (stat) ± 123 (syst) ± 85 (lumi) pb
μ+jets	862 ± 18 (stat) ± 93 (syst) ± 94 (lumi) pb
e+jets and *μ*+jets combined	817 ± 13 (stat) ± 103 (syst) ± 88 (lumi) pb

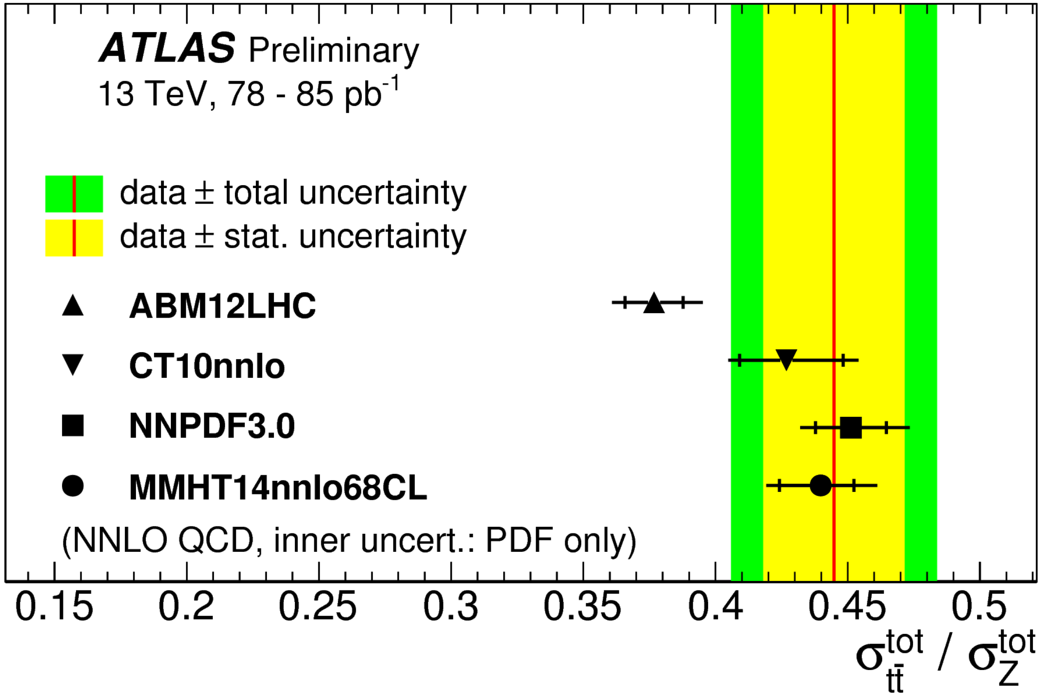




ATLAS-CONF-2015-049

$\sigma_{t\bar{t}}$ / σ_Z ratio (13 TeV)

- Measurements of $\sigma_{t\bar{t}}$ and σ_Z limited by large systematics
- In the $\sigma_{t\bar{t}}/\sigma_Z$ ratio large cancellations occur:
  - integrated luminosity & lepton ID
- $\sigma_{t\bar{t}}$ used is from dilepton ($e\mu$) channel (78 pb^{-1})
- Ratio compared to NNLO QCD predictions with different PDF's:
  - provides constraints on gluon to sea-quark ratio in PDFs.



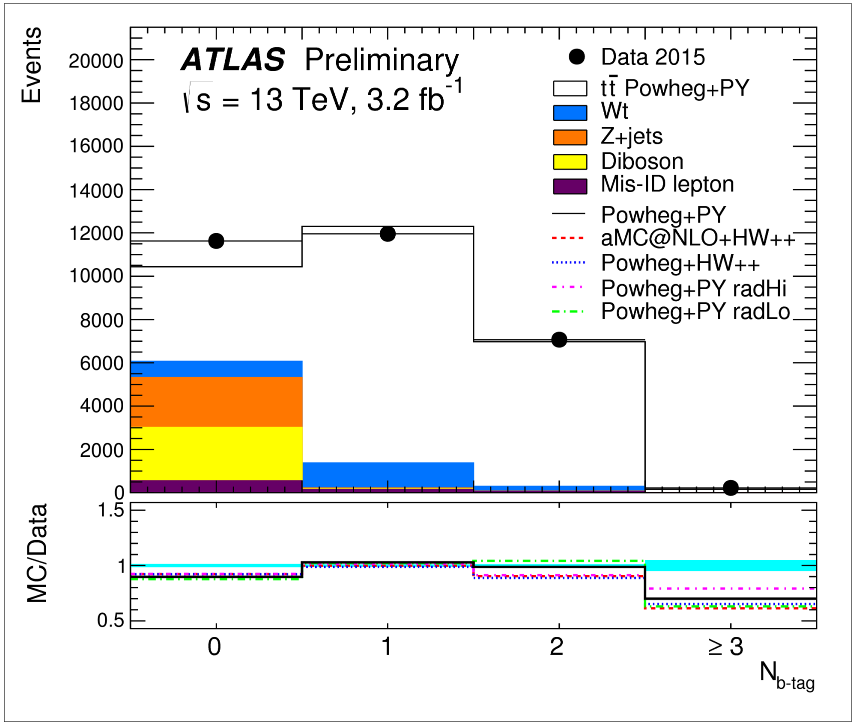
$$R_{t\bar{t}/Z} = \frac{\sigma_{t\bar{t}}}{0.5\left(\sigma_{Z\to ee} + \sigma_{Z\to\mu\mu}\right)}$$

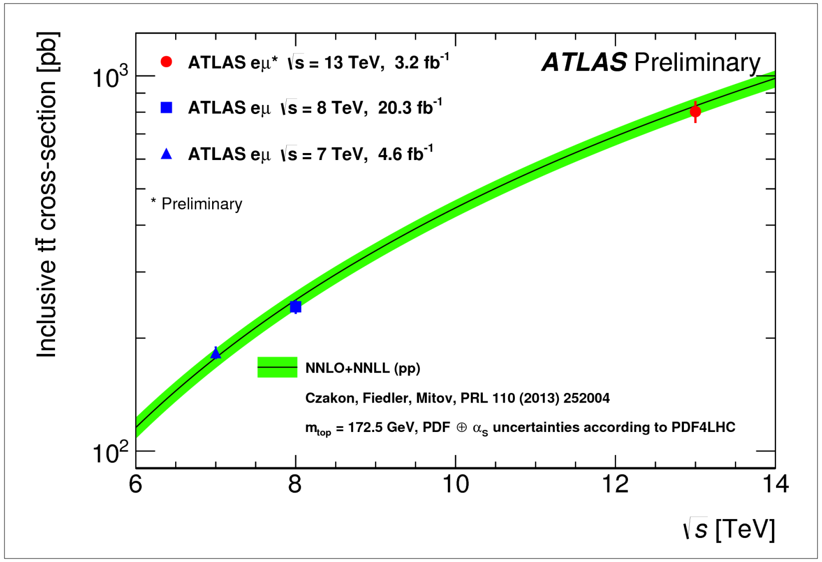
ATLAS-CONF-2015-049

$e\mu$, inclusive (13 TeV)

- Opposite sign $e\mu$ pair
- Events with exactly 1 or 2 b-tagged jets (N_1 and N_2)
- missing E_T
- Simultaneous fit to obtain $\sigma_{t\bar{t}}$ and b-tagging efficiency (exploit correlations)

$$N_1 = L\sigma_{t\bar{t}}\,\epsilon_{e\mu}2\epsilon_b(1 - C_b\epsilon_b) + N_1^{\rm bkg}$$
$$N_2 = L\sigma_{t\bar{t}}\,\epsilon_{e\mu}C_b\epsilon_b{}^2 + N_2^{\rm bkg}$$





ATLAS-CONF-2016-005

$$\sigma_{t\bar{t}} = 803 \pm 7\ (\mathrm{stat}) \pm 27\ (\mathrm{syst}) \pm 45\ (\mathrm{lumi}) \pm 12\ (\mathrm{beam})\ \mathrm{pb}$$

$t\bar{t}$ + jets (13 TeV)

- Additional jet activity is sensitive to higher-order QCD effects
  - source of uncertainty in precision measurements such as $\sigma_{t\bar{t}}$ or m_t
  - $t\bar{t}$ +jets is a dominant background to BSM searches and Higgs studies
- Aim is to test NLO Monte Carlo models
- Extra jet activity in the dilepton channel:
  - 2 opposite sign *ee, μμ,* or *eμ*
  - 2 b-tagged jets
  - missing E_T
- Unfolding to particle jet multiplicity
- Various jet p_T cut (>25,40,60, 80)

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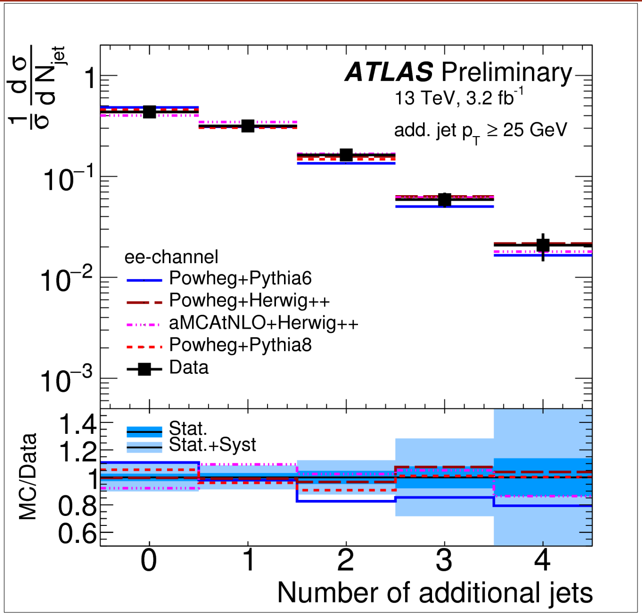
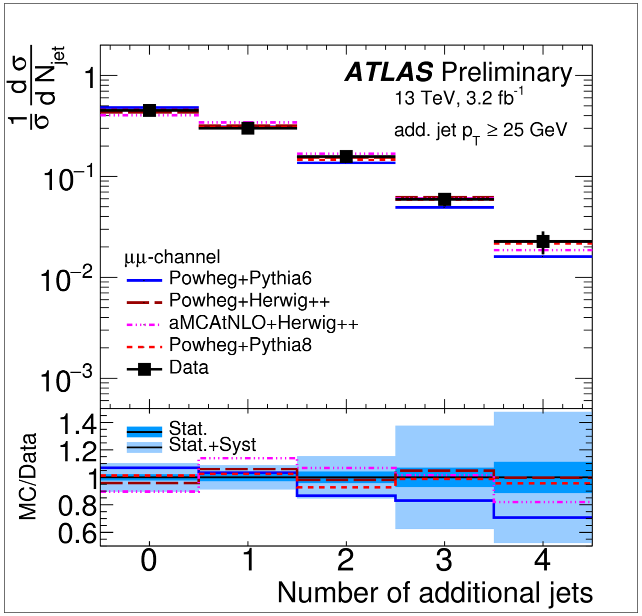
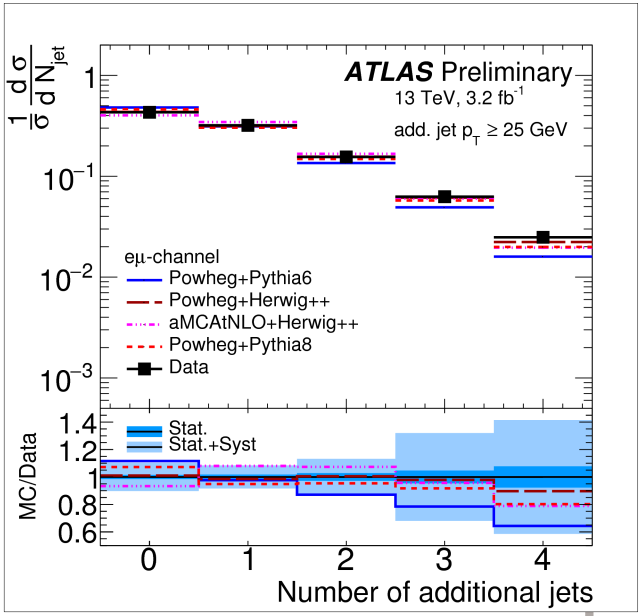






$t\bar{t}$ + W/Z (13 TeV)

- Important for top EW coupling, BSM searches and $t\bar{t}H$ measurement (irreducible background)
- Several decay topologies with different signal & background compositions

Process	$t\bar{t}$ decay	Boson decay	Channel
$t\bar{t}W^{\pm}$	$(\mu^{\pm}\nu b)(q\bar{q}b)$	$\mu^{\pm}\nu$	SS dimuon
	$(\ell^{\pm}\nu b)(\ell^{\mp}\nu b)$	$\ell^{\pm}\nu$	Trilepton
$t\bar{t}Z$	$(\ell^{\pm}\nu b)(q\bar{q}b)$	$\ell^{+}\ell^{-}$	Trilepton
	$(\ell^{\pm}\nu b)(\ell^{\mp}\nu b)$	$\ell^{+}\ell^{-}$	Tetralepton

  - selection: multi-leptons, jets, b-tagged jets, and missing E_T

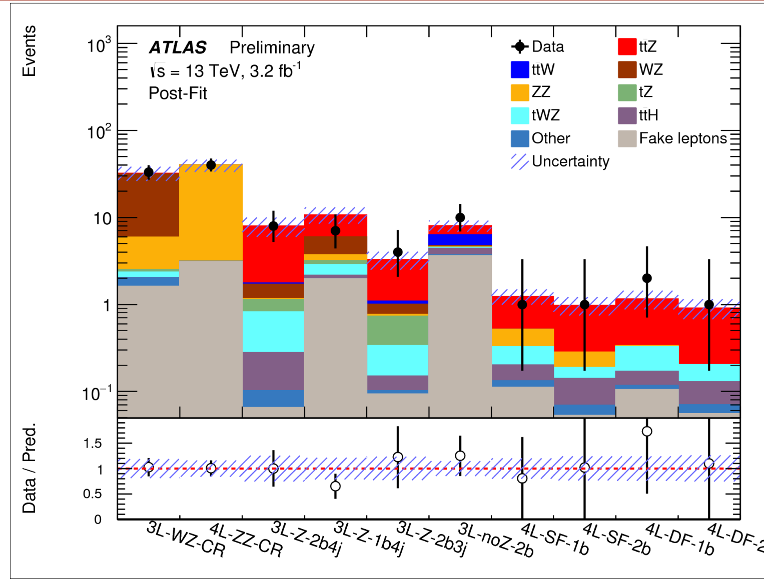
- $t\bar{t}$+Z: 8 signal and 2 control regions (fit)
- $t\bar{t}$+W: 2 signal and 2 control regions (fit)

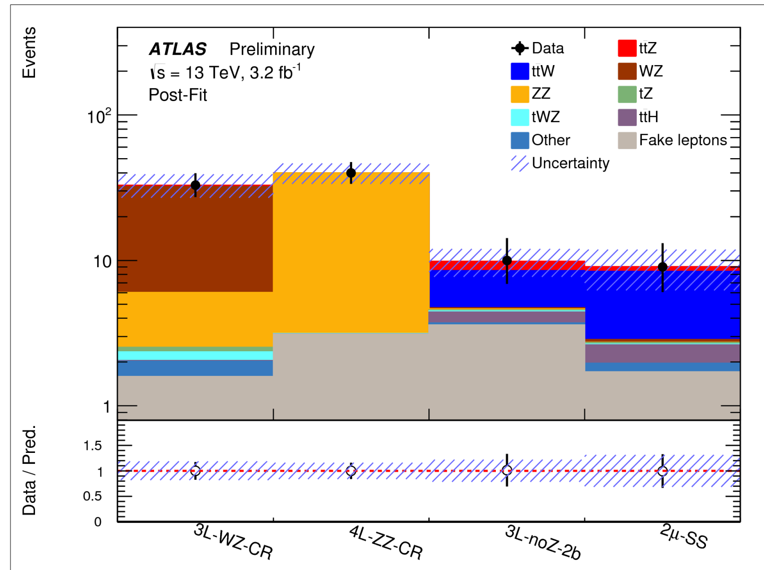
Measurements:

$$\sigma_{t\bar{t}Z} = 0.9 \pm 0.3 \text{ pb} \quad ; \quad \sigma_{t\bar{t}W} = 1.4 \pm 0.8 \text{ pb}$$

NLO QCD calculation:

$$\sigma_{t\bar{t}Z} = 0.76 \pm 0.08 \text{ pb} \quad ; \quad \sigma_{t\bar{t}W} = 0.57 \pm 0.06 \text{ pb}$$



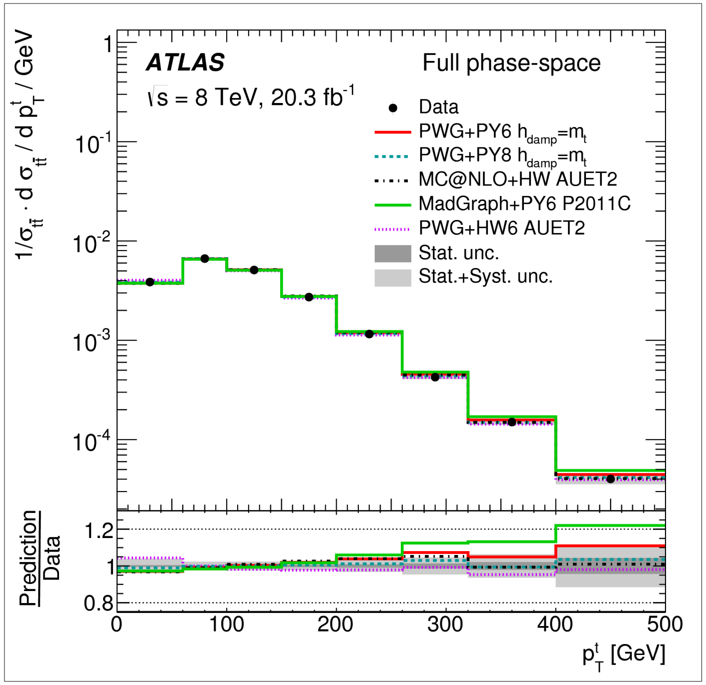


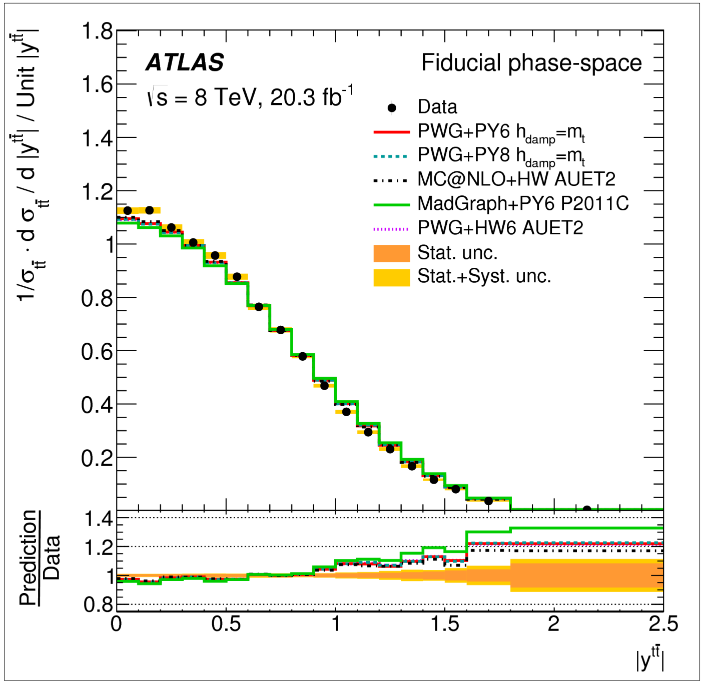
ATLAS-CONF-2016-003

lepton+jets, $d\sigma/dX$ (8 TeV)

- Important to understand and simulate top or $t\bar{t}$ system kinematics properly (a background to many searches)
- Variables chosen to be sensitive to ISR/FSR effects, choice of PDF's and higher order corrections.
- Results are compared to several Monte Carlo's
- Most MC's predict a harder top p_T a higher values
- Using recent sets of PDF's improves the modeling.

ArXiv 1511.04716

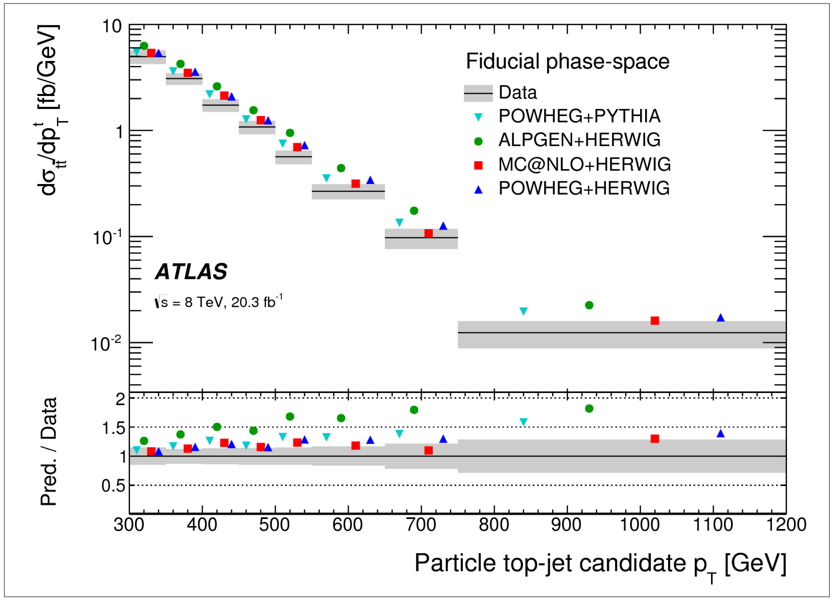


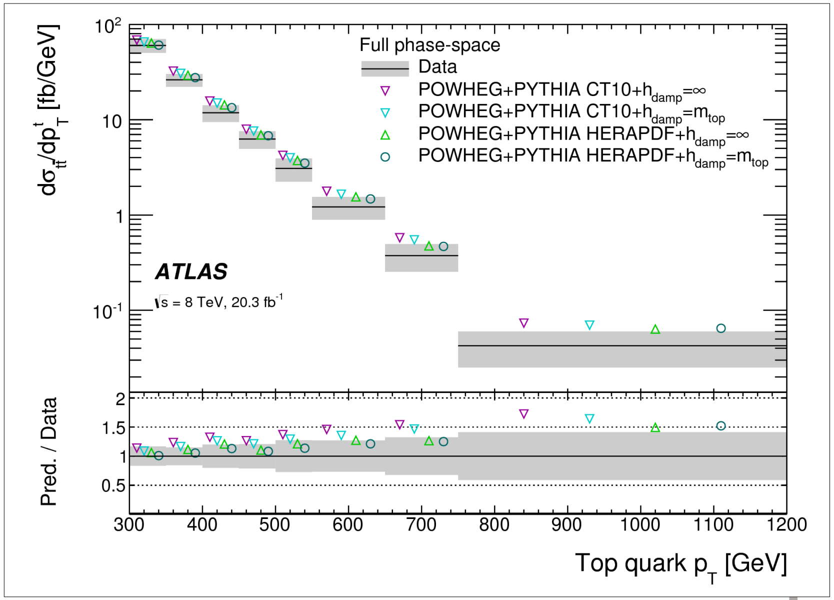


lepton+jets, boosted tops (8TeV)

- New physics could distort top p_T spectrum.
- Highly boosted regime with top p_T>300 GeV, selected as a large jet (anti-k_t , R=1.0) using substructure techniques (hadronically decaying top).
- $d\sigma/dp^t_T$ measured in fiducial particle-level and full phase space parton-level (unfolding procedure from reconstructed objects)
- Normalized to NNLO+NNLL
- LO and NLO MC predictions generally harder than data at higher p_T.

Phys. Rev. D 93 (2016), 032009





Conclusion

- Various $t\bar{t}$ inclusive production cross-sections have been measured by ATLAS:
  - reaching high precision, effectively challenging the best theoretical calculations at NNLO+NNLL
  - provides a robust test of the Standard Model.
- Differential cross-section measurements provides a framework to study Monte Carlo generators and machinery
  - helps improve modeling with better tuning.
  - important for BSM physics searches
- Initial measurements of $t\bar{t}$+W/Z at 13 TeV in agreement with the Standard Model predictions.
- For more interesting top quarks results, see ATLAS twiki page:
  - **https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults**

EXTRA / BACKUP MATERIAL

Uncertainties (I), 13 TeV

ee, *μμ* inclusive

Uncertainty	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)
Data statistics	7.6
$t\bar{t}$ NLO modelling	2.6
$t\bar{t}$ hadronisation	7.9
Initial/final state radiation	1.5
PDF	3.7
Single-top Wt cross-section	0.6
Single-top interference	<0.05
Diboson cross-section	0.4
Z+jets $\rightarrow ee/\mu\mu$ modelling	1.5
Z+jets $\rightarrow \tau\tau$ modelling	0.1
Electron energy scale	0.3
Electron energy resolution	0.2
Electron identification	3.6
Electron trigger	0.2
Electron isolation	1.0
Muon momentum scale	0.1
Muon momentum resolution	1.1
Muon identification	0.8
Muon trigger	0.6
Muon isolation	1.0
Jet energy scale	1.2
Jet energy resolution	0.2
b-tagging efficiency	0.8
Missing transverse momentum	0.3
NP & fakes	1.5
Analysis systematics	11
Integrated luminosity	10
Total uncertainty	16

e/*μ* + jets inclusive

Uncertainty	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)
Data statistics	1.5
$t\bar{t}$ NLO modelling	0.6
$t\bar{t}$ hadronisation	4.1
Initial/final state radiation	1.9
PDF	0.7
Single top cross-section	0.3
Diboson cross-sections	0.2
Z+jets cross-section	1.0
W+jets method statistics	1.7
W+jets modelling	1.0
Electron energy scale/resolution	0.1
Electron identification	2.1
Electron isolation	0.4
Electron trigger	2.8
Muon momentum scale/resolution	0.1
Muon identification	0.2
Muon isolation	0.3
Muon trigger	1.2
$E_{\mathrm{T}}^{\mathrm{miss}}$ scale/resolution	0.4
Jet energy scale	$^{+10}_{-8}$
Jet energy resolution	0.6
b-tagging	4.1
NP & fakes	1.8
Analysis systematics	$^{+13}_{-11}$
Integrated luminosity	$^{+11}_{-9}$
Total uncertainty	$^{+17}_{-14}$

$\sigma_{t\bar{t}}/\sigma_Z$ ratio

Uncertainty (%)	$\sigma_{Z\rightarrow ee}$	$\sigma_{Z\rightarrow\mu\mu}$	$\sigma_{t\bar{t}}$	$R_{t\bar{t}/Z}$
Data statistics	0.5	0.5	6.0	6.0
$t\bar{t}$ NLO modelling	-	-	2.2	2.2
$t\bar{t}$ hadronisation	-	-	4.5	4.5
Initial/final state radiation	-	-	1.2	1.2
Parton distribution functions ($t\bar{t}$, Wt)	-	-	1.4	1.4
Single-top modelling	-	-	0.5	0.5
Single-top/$t\bar{t}$ interference	-	-	0.1	0.1
Single-top Wt cross-section	-	-	0.5	0.5
Diboson modelling	-	-	0.1	0.1
Diboson cross-sections	-	-	0.0	0.0
Z+jets extrapolation	-	-	0.2	0.2
Electron energy scale/resolution	0.2	-	0.2	0.1
Electron identification	3.8	-	3.2	1.3
Electron charge identification	0.8	-	-	0.4
Electron isolation	1.0	-	1.1	1.2
Muon momentum scale/resolution	-	0.1	0.1	0.0
Muon identification	-	0.9	0.5	0.1
Muon isolation	-	0.5	1.1	1.1
Lepton trigger	0.5	1.1	0.8	0.7
Jet energy scale	-	-	0.3	0.3
Jet energy resolution	-	-	0.1	0.1
b-tagging	-	-	0.3	0.3
Misidentified leptons	-	-	1.4	1.4
Pileup modelling	0.9	0.9	-	0.9
Z acceptance	1.5	1.5	-	1.5
Z backgrounds	0.1	0.1	-	0.1
Analysis systematics	4.4	2.3	6.7	6.3
Integrated luminosity	9.0	9.0	10.0	1.0
Total uncertainty	10.0	9.3	13.5	8.8

Uncertainties (II), 13 TeV

$t\bar{t}$ + W/Z

Uncertainty	$\sigma_{t\bar{t}Z}$	$\sigma_{t\bar{t}W}$
Luminosity	6.4%	7.0%
Reconstructed objects	7.0%	7.3%
Backgrounds from simulation	5.5%	3.7%
Fake leptons and charge misID	3.9%	21%
Total systematic	12%	24%
Statistical	32%	51%
Total	34%	56%

$t\bar{t}$ + jets

Sources	0 additional jets [%]	1 additional jet [%]	2 additional jets [%]	3 additional jets [%]	4 additional jets [%]
ee channel					
Statistics	2.6	3.1	4.8	8.0	13.8
Signal modelling	5.9	7.2	7.0	17.6	41.0
Jets	6.0	4.5	8.4	19.1	30.4
Other	1.6	2.8	5.1	6.6	14.4
Total	**9.0**	**9.4**	**12.8**	**27.9**	**54.8**
$\mu\mu$ channel					
Statistics	2.2	2.8	4.2	7.0	11.4
Signal modelling	6.5	6.8	7.2	22.8	30.3
Jets	7.4	5.1	10.9	28.3	34.8
Other	1.0	3.5	4.2	4.8	11.0
Total	**10.1**	**9.6**	**14.4**	**37.3**	**48.8**
$e\mu$ channel					
Statistics	1.5	1.8	2.8	4.6	7.7
Signal modelling	6.3	7.3	5.1	22.0	32.8
Jets	6.7	3.9	11.3	22.2	21.5
Other	0.3	1.4	1.3	3.3	9.5
Total	**9.3**	**8.6**	**12.7**	**31.8**	**41.1**

Observed & Expected (I)

l+jets, boosted tops (8 TeV)

	e+jets	μ+jets
$t\bar{t}$ ℓ+jets	3880 ± 430	3420 ± 380
$t\bar{t}$ dilepton	199 ± 27	169 ± 24
W+jets	235 ± 54	226 ± 50
Single top	133 ± 22	134 ± 29
Multijet	91 ± 17	3 ± 1
Z+jets	34 ± 18	14 ± 8
Dibosons	22 ± 12	18 ± 10
Prediction	4600 ± 470	3980 ± 410
Data	4145	3603

e-mu, inclusive (13 TeV)

Event counts	N_1	N_2
Data	11958	7069
Single top	1160 ± 120	224 ± 70
Dibosons	34 ± 12	1 ± 0
$Z(\rightarrow \tau\tau \rightarrow e\mu)$+jets	37 ± 16	2 ± 1
Misidentified leptons	165 ± 65	116 ± 55
Total background	1390 ± 140	343 ± 89

tt+W/Z (13 TeV)

Region	$t+X$	Bosons	Fake leptons	Total bkg.	$t\bar{t}W$	$t\bar{t}Z$	Data
3ℓ-WZ-CR	0.51 ± 0.13	26.9 ± 2.5	1.6 ± 1.7	29.0 ± 3.0	0.017 ± 0.005	0.71 ± 0.08	33
4ℓ-ZZ-CR	0.007 ± 0.006	37.9 ± 2.5	3.1 ± 0.9	41.0 ± 2.7	< 0.001	0.031 ± 0.006	40
2μ-SS	1.00 ± 0.19	0.14 ± 0.06	1.7 ± 1.5	2.9 ± 1.5	2.28 ± 0.34	0.65 ± 0.07	9
3ℓ-Z-2b4j	1.06 ± 0.25	0.5 ± 0.4	0.1 ± 0.6	1.7 ± 0.8	0.061 ± 0.013	5.1 ± 0.5	8
3ℓ-Z-1b4j	1.23 ± 0.26	3.4 ± 2.2	2.0 ± 1.7	6.6 ± 2.8	0.037 ± 0.010	4.0 ± 0.4	7
3ℓ-Z-2b3j	0.64 ± 0.23	0.25 ± 0.18	0.1 ± 0.4	1.0 ± 0.5	0.082 ± 0.015	1.75 ± 0.20	4
3ℓ-noZ-2b	0.95 ± 0.15	0.18 ± 0.09	3.6 ± 2.2	4.7 ± 2.2	1.55 ± 0.24	1.35 ± 0.16	10
4ℓ-SF-1b	0.198 ± 0.035	0.22 ± 0.08	0.112 ± 0.032	0.53 ± 0.09	< 0.001	0.59 ± 0.05	1
4ℓ-SF-2b	0.130 ± 0.035	0.11 ± 0.05	0.053 ± 0.016	0.29 ± 0.07	< 0.001	0.57 ± 0.05	1
4ℓ-DF-1b	0.21 ± 0.04	0.022 ± 0.011	0.105 ± 0.027	0.34 ± 0.05	< 0.001	0.67 ± 0.05	2
4ℓ-DF-2b	0.15 ± 0.05	< 0.001	0.055 ± 0.017	0.20 ± 0.05	< 0.001	0.58 ± 0.05	1

Observed & Expected (II)

e-e,mu-mu inclusive (13 TeV)

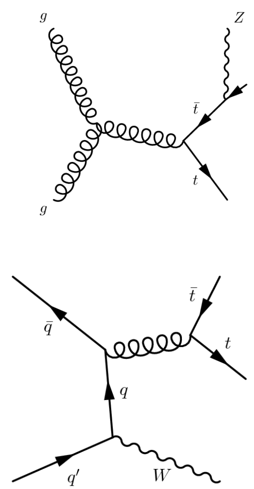
Sample	N_1^{ee}	N_2^{ee}	$N_1^{\mu\mu}$	$N_2^{\mu\mu}$
$t\bar{t}$	84 ± 12	49 ± 18	100 ± 13	58 ± 21
$Z(\to \ell\ell)$+jets	9.9 ± 2.3	0.6 ± 0.7	18 ± 6	2.5 ± 2.0
$Z(\to \tau\tau \to \ell\ell\nu\nu\nu\nu)$+jets	0.14 ± 0.11	< 0.01	0.11 ± 0.12	0.02 ± 0.05
Diboson	0.5 ± 0.4	0.02 ± 0.06	0.8 ± 0.6	0.07 ± 0.08
NP & fakes	2.4 ± 0.5	1.1 ± 0.4	0.27 ± 0.23	0.08 ± 0.16
Single top	8.7 ± 1.6	1.8 ± 0.9	10.3 ± 1.6	2.0 ± 0.9
Total background	21.6 ± 2.8	3.4 ± 1.8	29.4 ± 3.0	4.6 ± 1.8
Total expected	105 ± 12	52 ± 18	129 ± 14	62 ± 21
Observed	103	59	108	65

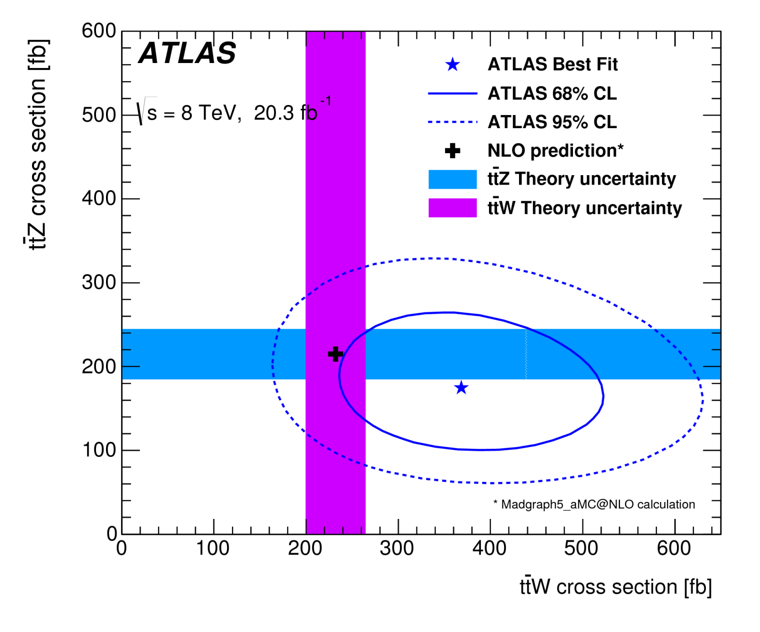
l+jets, inclusive (13 TeV)

Sample	e + jets	μ + jets
$t\bar{t}$	2800 ± 400	2620 ± 340
W+jets	340 ± 100	230 ± 60
Single top	192 ± 34	180 ± 30
Z+jets	71 ± 35	45 ± 22
Dibosons	10 ± 5	10 ± 5
Fakes	200 ± 70	130 ± 60
Total background	820 ± 130	600 ± 100
Total expected	3600 ± 500	3220 ± 350
Observed	3439	3314

t-tbar + W/Z (8 TeV)

- Processes established at 8 TeV; significantly lower production cross-sections than at 13 TeV.
- Multi-leptons selections
  - 2 leptons: SS, OS,
  - 3 leptons





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