Measurement of $t\bar{t} + X$ using the ATLAS detector

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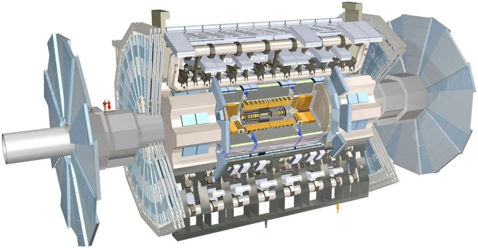


What is X ?

$X = W/Z/\gamma \to$ probe t-Z/γ coupling

- $t\bar{t} + W/Z$ @8 TeV JHEP 11 (2015) 172
- $t\bar{t} + W/Z$ @13 TeV ATLAS-CONF-2016-003
- $t\bar{t} + \gamma$ @7 TeV Phys. Rev. D 91, 072007 (2015)

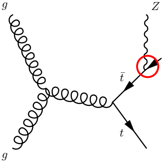
X = light/heavy quark $\to$ test QCD, background to NP

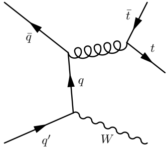
- $t\bar{t} +$ jets @8 TeV arXiv:1606.09490 (submitted to JHEP)
- $t\bar{t} +$ jets @13 TeV ATLAS-CONF-2015-065
- $t\bar{t} + b$-jets @8 TeV Eur. Phys. J. C (2016) 76:11

* data with 4.6/20.3/3.2 fb^{-1} integrated luminosity used for $\sqrt{s} = 7/8/13$ TeV

$t\bar{t}+W/Z$ @8 TeV: Introduction

- $t\bar{t}Z$: probe tZ coupling, which was never directly measured; BSM sensitivity (technicolor, little Higgs, etc.)
- $t\bar{t}W$: background for new physics search in same-sign dilepton events





- Depending on decay mode of $t\bar{t}$ and W/Z, 0-4 leptons in final state ($t\bar{t} \to$ 0-2 ℓs, $W \to$ 0-1 ℓ, $Z \to$ 0 or 2 ℓs): dilepton, trilepton, tetralepton channels
- Channel further split for multiple times according to ℓ flavors, ℓ charges, etc. either to disentangle $t\bar{t}W$ and $t\bar{t}Z$ or to do separate optimization to enhance signal sensitivity

Opposite-sign dilepton (2L OS)		Same-sign dilepton (2L SS)			Trilepton (3L)		Tetralepton (4L)	
different flavor (DF)	same flavor (SF)	ee	$e\mu$	$\mu\mu$	W enriched	Z enriched	DF	SF
$t\bar{t} \to \ell^{\pm}$ & $W \to \ell^{\mp}$	$t\bar{t} \to \ell^{+}\ell^{-}$ or $Z \to \ell^{+}\ell^{-}$	$t\bar{t} \to \ell^{\pm}$ & $W \to \ell^{\pm}$			$t\bar{t} \to \ell^{+}\ell^{-}$ $W \to \ell$	$t\bar{t} \to \ell$ $Z \to \ell^{+}\ell^{-}$	$Z \to \ell^{+}\ell^{-}$ $t\bar{t} \to$ DF	$Z \to \ell^{+}\ell^{-}$ $t\bar{t} \to$ SF
......								

$t\bar{t} + W/Z$ @8 TeV: Backgrounds

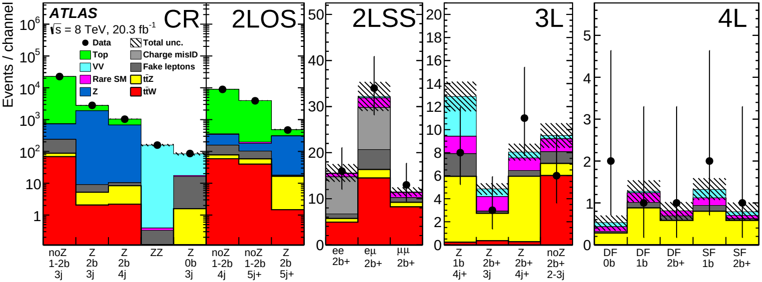
- Background (Bkg) compositions vary across different channels

Channel	Sub-channel	Main Background
2L OS	different (same) flavor	$t\bar{t}$ (Z) dileptonic decay
2L SS	ee,$e\mu$ $(\mu\mu)$	charge mis-ID (fake ℓ)
3L	$t\bar{t}Z$ $(t\bar{t}W)$ enriched	leptonic decay WZ (rare SM)
4L	$t\bar{t} \to$ same (different) flavor	leptonic decay ZZ (rare SM)

(* rare SM mainly means $t\bar{t}H$, tZ, WtZ)

- Backgrounds estimated via MC or data, or normalized via control region (CR)

$t\bar{t}/Z/VV$ via CRs, instrumental bkg via data, others small bkgs via MC



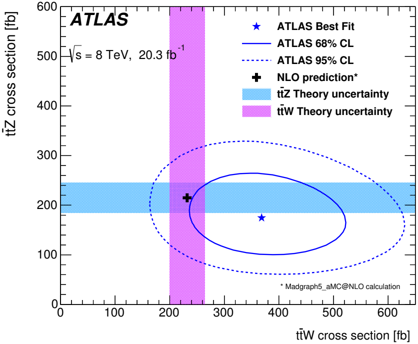
$t\bar{t} + W/Z$ @8 TeV: Results

- Measured total cross sections

$$\sigma_{t\bar{t}W} = 369^{+86}_{-79}(\text{stat.}) \pm 44(\text{syst.})\ \text{fb}$$
$$\sigma_{t\bar{t}Z} = 176^{+52}_{-48}(\text{stat.}) \pm 24(\text{syst.})\ \text{fb}$$

- To be compared with NLO prediction of 232 ± 32 ($t\bar{t}W$) and 215 ± 30 ($t\bar{t}Z$) fb
- Statistical uncertainty dominates
- Systematic uncertainty mainly from background estimation

Uncertainty	$\sigma_{t\bar{t}W}$	$\sigma_{t\bar{t}Z}$
Luminosity	3.2%	4.6%
Reconstructed objects	3.7%	7.4%
Backgrounds from simulation	5.8%	8.0%
Fake leptons and charge misID	7.5%	3.0%
Signal modelling	1.8%	4.5%
Total systematic	12%	13%
Statistical	+24% / −21%	+30% / −27%
Total	+27% / −24%	+33% / −29%



- 5.0σ (4.2σ) significance of $t\bar{t}W$ ($t\bar{t}Z$) signal over signal-free model
- bkg-only hypothesis with neither $t\bar{t}W$ nor $t\bar{t}Z$ excluded with 7.1σ

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

- Check of SM at new energy regime
- Similar to 8 TeV analysis
- Only the most sensitive channels used

significance in 8 TeV measurement

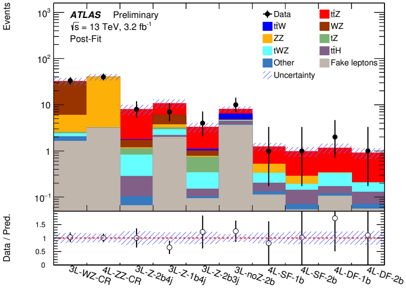
Channel	$t\bar{t}W$ significance Expected	$t\bar{t}W$ significance Observed	$t\bar{t}Z$ significance Expected	$t\bar{t}Z$ significance Observed
2ℓOS	0.4	0.1	1.4	1.1
2ℓSS	2.8	5.0	-	-
3ℓ	1.4	1.0	3.7	3.3
4ℓ	-	-	2.0	2.4
Combined	3.2	5.0	4.5	4.2

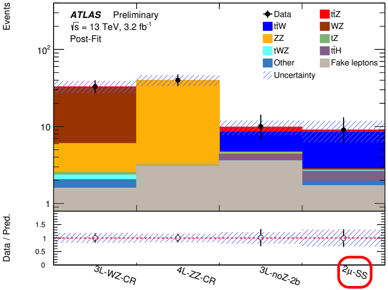
- Measured cross sections

$$\sigma_{t\bar{t}W} = 1.38 \pm 0.70(\text{stat.}) \pm 0.33(\text{syst.})\ \text{pb}$$

$$\sigma_{t\bar{t}Z} = 0.92 \pm 0.30(\text{stat.}) \pm 0.11(\text{syst.})\ \text{pb}$$

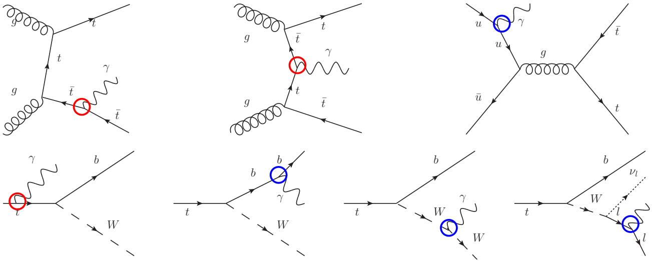
- Compare to NLO prediction of 0.57 ± 0.06 ($t\bar{t}W$) and 0.76 ± 0.08 ($t\bar{t}Z$) pb





$t\bar{t} + \gamma$ @7 TeV: Introduction

- Process not established before (1st evidence reported by CDF)
- Direct probing of $t\gamma$ coupling, BSM sensitivity (composite/excited *top*)
- Analysis performed in single lepton channel (more statistics)
- Events with 1 photon selected: γ radiation not from $t\gamma$ vertex (e.g. $\ell\gamma$ or $q\ell$ vertex) suppressed by rejecting event with γ too close to ℓ or jet



- Fake photon event should be removed/subtracted
  hadron fake: jet$\rightarrow \gamma$, by exploiting the discrimination power of γ isolation
  egamma fake: $e \rightarrow \gamma$, by estimating $e \rightarrow \gamma$ fake rate with Tag & Probe method
- Prompt γ backgrounds (minor) estimated from MC or data-driven
  W, Z, single *top*, diboson processes with prompt γ radiation

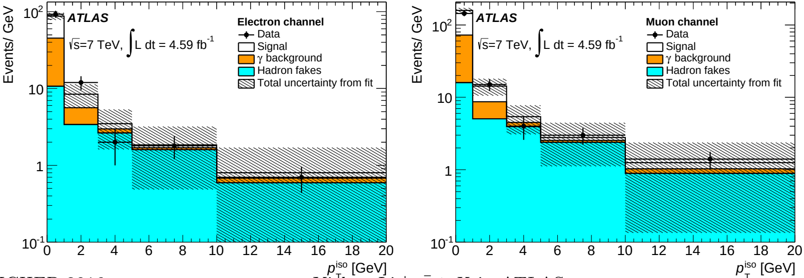
$t\bar{t} + \gamma$ @7 TeV: Results

- Cross section per lepton flavor flavor measured to be

  $\sigma^{\text{fid}}_{t\bar{t}\gamma} \times \text{BR} = 63 \pm 8(\text{stat.})^{+17}_{-13}(\text{syst.}) \pm 1(\text{lumi.})$ fb

  in a fiducial region
  $p_T(\gamma/\ell/j) > 20/20/25$ GeV
  $|\eta(\gamma/\ell/j)| < 2.37/2.5/2.5$
  $\Delta R(\gamma, j) > 0.5$ and $\Delta R(\gamma, \ell) > 0.7$
- WHIZARD (MadGgraph) prediction with NLO k-factor: 48 (47) $\pm$ 10 fb
- Systematics dominated by jet modelling
- Signal significance of 5.3σ

Uncertainty source	Uncertainty [%]
Background template shapes	3.7
Signal template shapes	6.6
Signal modeling	8.4
Photon modeling	8.8
Lepton modeling	2.5
Jet modeling	16.6
b-tagging	8.2
$E_{\mathrm{T}}^{\mathrm{miss}}$ modeling	0.9
Luminosity	1.8
Background contributions	7.7



$t\bar{t}$ + jets @8 TeV: Introduction

- Measurement of the activity of *additional* jets in $t\bar{t}$ events: jets originating from quark and gluon radiation in association with $t\bar{t}$ system

- Test QCD at the highest accessible energy scale (large m_t)
- Primary source of background for new physics search
- Check generator modelling and parton shower tuning

- Analysis performed in $e\mu$ final state plus 2 b-jets

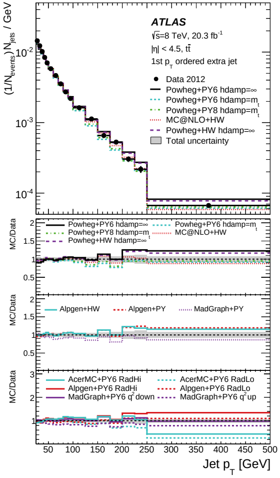
	$e\mu$	[%]	≥ 2 b-jets	[%]
Data	70854		12437	
Total simulation	66200	100.0	12400	100.0
$t\bar{t}$	40300	60.8	11900	96.3
Wt single top	3840	5.8	360	2.9
$Z(\rightarrow \tau\tau \rightarrow e\mu)$+jets	12800	19.4	6	0.1
Dibosons	8030	12.3	2	0.0
Misidentified leptons	1200	1.8	96	0.8

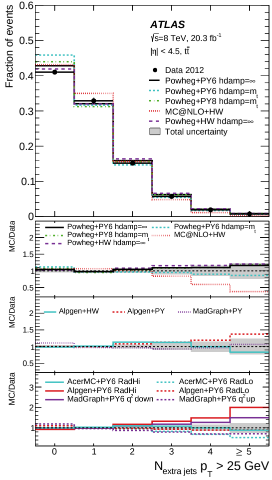
- $t\bar{t}$ highly enriched SR
- bkgs: Wt, fake lepton, $Z \rightarrow \tau\tau$, diboson
- All from simulation
- doubling/removing to evaluate bkg systematics

- Jet activities at particle level in fiducial region are measured: additional jet multiplicity with different p_T thresholds, normalized additional jet p_T specturms, gap fractions with different thresholds in different regions

$t\bar{t}$ + jets @8 TeV: Jet p_T and Multiplicity

- NLO generators provide reasonable description of the leading jet
- LO generators give reasonable agreement with appropriate parameter choice
- MC@NLO + Herwig gives much less radiation in high jet multiplicity



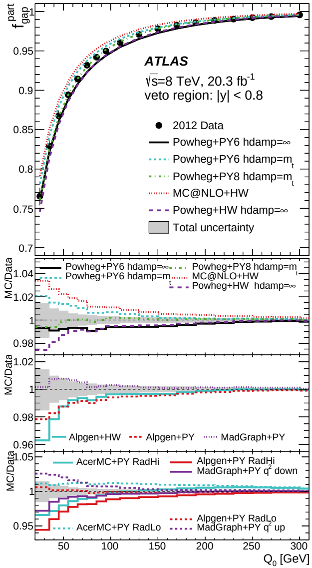


- low (high) radiation tune of Alpgen (MG) + Pythia describes better the data than nominal tune
- χ^2 test (41 d.o.f) of compatibility

Generator	χ^2	p-value
Powheg+Pythia6 $h_{\text{damp}} = \infty$	55.3	6.7×10^{-2}
Powheg+Pythia6 $h_{\text{damp}} = m_t$	57.4	4.6×10^{-2}
Powheg+Pythia8 $h_{\text{damp}} = m_t$	78.0	4.4×10^{-4}
MC@NLO+Herwig	108.2	5.8×10^{-8}
Powheg+Herwig $h_{\text{damp}} = \infty$	51.4	1.3×10^{-1}
Alpgen+Herwig	64.0	1.2×10^{-2}
Alpgen+Pythia6	55.5	6.4×10^{-2}
MadGraph+Pythia6	54.7	7.4×10^{-2}
AcerMC+Pythia6 RadHi	138.4	1.8×10^{-12}
AcerMC+Pythia6 RadLo	148.1	4.9×10^{-14}
Alpgen+Pythia6 RadHi	104.7	1.8×10^{-7}
Alpgen+Pythia6 RadLo	47.9	2.1×10^{-1}
MadGraph+Pythia6 q^2 down	50.2	1.5×10^{-1}
MadGraph+Pythia6 q^2 up	78.7	3.6×10^{-4}

$t\bar{t}$ + jets @8 TeV: Gap Fraction

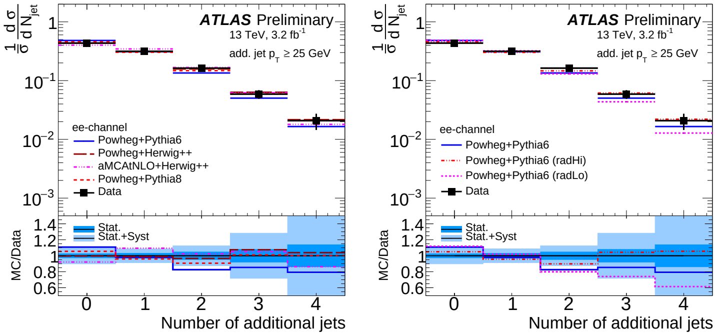
- Gap fraction: fraction of events without additional jet activity in given detector rapidity region
  $f(Q_0)$: no jet with $p_T > Q_0$, sensitive to 1st additional radiation
  $f(Q_{\text{sum}})$: scalar $\sum_j p_T < Q_{\text{sum}}$, $p_T > 25$ GeV, sensitive to all additional radiation
- Measured in 4 rapidity regions $|y|$: (0,0.8) (0.8,1.5), (1.5,2.1), (0,2.1)
- Measured in 4 $m_{e\mu bb}$ regions with $|y| < 2.1$: (0,300), (300,425), (425,600), (600,∞)
- Powheg + Pythia8 describes best of $f(Q_0)$
- Powheg + Pythia6 disfavored from $f(Q_{\text{sum}})$
- There are also some similar conclusions e.g. MC@NLO+Herwig disfavoured
  non-nominal tune preferred over nominal tune for some LO generators



$t\bar{t}$ + jets @13 TeV

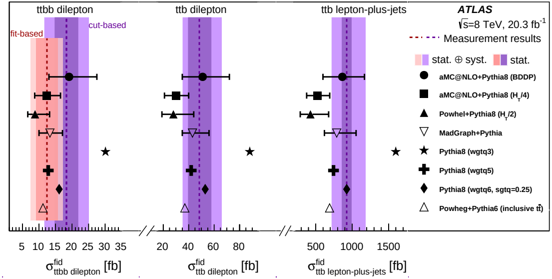
- Analysis performed in all OS 2-ℓ ($ee/\mu\mu/e\mu$) channels
- Normalized additional jet multiplicity with different p_T thresholds
- Dominating systematics from $t\bar{t}$ modelling and jet modelling

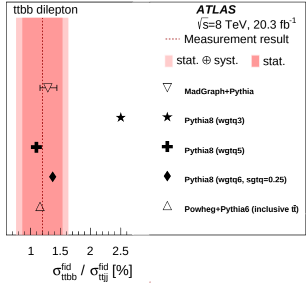
- Good agreement between data and several NLO generators
- Radiation high tuning for Powheg + Pythia6 describes better the data than the nominal tuning



$t\bar{t} + b$-jets @8 TeV

- Important bkg to other measurement (e.g. $t\bar{t}H \to t\bar{t}b\bar{b}$)
- Analysis performed both in single lepton and dilepton channels
- Fiducial cross section for 1 or 2 additional b-jets separately measured
- Background dominated by light or charm jet
- Systematics dominated by $t\bar{t}$/jet modeling and b-tagging uncertainty
- Generally good agreement between data and NLO / LO generators
- Measurement sensitive to $g \to b\bar{b}$ splitting modelling in the parton shower





Summary

With the large mass of top quark and high $t\bar{t}$ production rate at LHC, pertabative QCD and top coupling at EW sector are tested at highest accessible energy scale with high precision

- Associated production of top pair with vector boson is measured; good agreement with SM prediction is achieved; with the incoming 13 TeV data, these measurements will be greatly improved
- QCD radiation in top pair production is measured and compared with several generators, implying good QCD modelling and providing information for further tuning of these models
- Other analyses where $t\bar{t} + X$ backgrounds are important can benifit from these measurements