

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

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Introduction

- At the LHC, top quark pairs in association with other final state particles provide a unique opportunity to test pQCD and Standard Model (SM)
- Also important as dominant background for several Beyond the Standard Model (BSM) searches

This talk covers

- ✓ $t\bar{t}$ + additional jet activity @13 TeV EPJ C**77** (2017) 220
- ✓ tt̄ + W/Z production @13 TeV
 EPJ C77 (2017) 40
- ✓ $t\bar{t}$ + γ @ 8TeV arXiv:1706.03046, submitted to JHEP



 $t\bar{t}$ + H covered 7 July, 12:00

$t\bar{t}$ + jets in eµ-channel@13 TeV EPJ C77 (2017) 220

- Measurement of QCD radiation produced with top quark pair is crucial to tune MC parameters
 - Improve modelling of parton shower and hadronization
 - Improve overall top kinematics description
- Focus on dilepton eµ channel;
 - Clean signature & small systematic uncertainties
- Additional jets are identified as jets above $p_{\rm T}$ thresholds of 25, 40, 60 and 80 GeV
 - Additional jets produced in addition to the two highest- p_T b-jets
- Backgrounds ~ 4.5% only
- Discrepancy found on jet multiplicity
- Unfolded to particle level

Event selection

- 1 elctron, p_T>25 GeV, |η|<2.47
- 1 muon, p_T >25 GeV , $|\eta|$ <2.5
- Oppositely charged
- 2 or more b-jets (WP:77%)



Number of additional jets

$t\bar{t}$ + jets results

- Major source of uncertainty
 - Jet energy scale (JES), matrix element generator and parton shower (**PS**) modeling, initial and final state radiation
 - − Statistical uncertainties @ jets \ge 3 or 4
- In agreement with MC predictions
- Sensitive to PS models and QCD radiation scale



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$t\bar{t}$ + jets results (higher p_T)

- Major source of uncertainty
 - Jet energy scale (JES), matrix element generator and parton shower (**PS**) modeling, initial and final state radiation
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jet p_T spectra

- Particle-level normalized differential cross-sections vs b-jets and additional jet p_T
- Significant systematic sources; JES/JER, NLO generator and PS/hadronization modeling



jet p_T spectra (PS modeling)

- Comparison with various PS models
 - Basically in good agreement again…
- For leading additional jet p_T; "Powheg+Herwig++" and "MG5_aMC@NLO+Pythia8" and "with Herwig7" do not give a good description



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Gap fraction measurement

 Gap fraction; fraction of event with no jet activity above given p_T threshold and rapidity region

$$f_{\text{gap}}(Q_0) = \frac{n(Q_0)}{N_{t\bar{t}}}, \quad f_{\text{gap}}(Q_{\text{sum}}) = \frac{n(Q_{\text{sum}})}{N_{t\bar{t}}}$$

- Sensitive to hard emissions accompanying the top-pair
- Powheg+Pythia8 has slightly higher gap fractions



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ttt + V (Z/W)@13 TeV



- $t\bar{t} + Z$: Sensitive to neutral current coupling between top and Z
- BSM processes would change the $t\bar{t}$ +V cross-sections
- Important background of searches for $t\bar{t}$ +Higgs, VLQ, SUSY
- Sensitive to EFT operators that affect t-Z coupling
 EFT; Effective Field theory

(± 1)			
$(\mu^{\pm}\nu b)(qqb)$ $(\ell^{\pm}\nu b)(\ell^{\mp}\nu b)$	$\mu^{\pm}\nu \\ \ell^{\pm}\nu$	SS dimuon Trilepton	$\sigma_{t\bar{t}W} = 0.60 \pm 0.08 \mathrm{pb}$
$(\ell^{\pm}\nu b)(q\bar{q}b)$ $(\ell^{\pm}\nu b)(\ell^{\mp}\nu b)$	$\ell^+\ell^-$ $\ell^+\ell^-$	Trilepton Tetralepton	$\sigma_{t\bar{t}Z} = 0.84 \pm 0.09 \mathrm{pb}$ JHEP 06 , 184 (2015)
	$\ell^{\pm} vb)(\ell^{\pm} vb)$ $\ell^{\pm} vb)(q\bar{q}b)$ $\ell^{\pm} vb)(\ell^{\mp} vb)$	$\ell^{\pm} vb)(\ell^{\pm} vb) \qquad \ell^{\pm} v$ $\ell^{\pm} vb)(q\bar{q}b) \qquad \ell^{+} \ell^{-}$ $\ell^{\pm} vb)(\ell^{\pm} vb) \qquad \ell^{+} \ell^{-}$	$ \ell^{\pm} vb)(\ell^{\pm} vb) \qquad \ell^{\pm} v \qquad \text{Trilepton} $ $ \ell^{\pm} vb)(q\bar{q}b) \qquad \ell^{+} \ell^{-} \qquad \text{Trilepton} $ $ \ell^{\pm} vb)(\ell^{\mp} vb) \qquad \ell^{+} \ell^{-} \qquad \text{Tetralepton} $

Background estimation

- Main backgrounds
 - SS dimuon;
 Fake lepton ⇒ Estimate using Opposite Sign (OS) dilepton Control Region (CR)
 - Trilepton;
 Fake lepton
 WZ diboson
- \Rightarrow Validated in Validation region (VR)
- \Rightarrow using 3leptons WZ CR (no b-jet)
- Tetralepton;
 ZZ diboson

\Rightarrow using 4leptons ZZ CR



Uncertainties and fit

- Major uncertainties
 - Measurement limited by statistical uncertainty
 - Fake lepton (ttW)
 - Object reconstruction
- Inclusive cross-sections extracted using profiled likelihood fit
 - using 9 signal regions and 2 control regions

Uncertainty	$\sigma_{t\bar{t}Z}(\%)$	$\sigma_{t\bar{t}W}(\%)$
Luminosity	2.6	3.1
Reconstructed objects	8.3	9.3
Backgrounds from simulation	5.3	3.1
Fake leptons and charge misID	3.0	19
Signal modelling	2.3	4.2
Total systematic	11	22
Statistical	31	48
Total	32	53

Results



 $\sigma_{t\bar{t}Z} = 0.9 \pm 0.3 \text{ pb} \text{ and } \sigma_{t\bar{t}W} = 1.5 \pm 0.8 \text{ pb}$ NLO QCD $\sigma_{t\bar{t}Z} = 0.84 \pm 0.09 \text{ pb} \sigma_{t\bar{t}W} = 0.60 \pm 0.08 \text{ pb}$

Analysis ongoing with 2015+2016 data (36fb⁻¹), STAY TUNE!

*tt***¯** + γ @8 TeV

arXiv:1706.03046, submitted to JHEP





- $t\bar{t} + \gamma$ measurements can probe the ty electroweak coupling
- Deviation from SM expectation could point to new physics through anomalous dipole moments of the top quark
- Measurement performed in the **lepton+jets** final state – Enrich photons radiated from a top quark ($\Delta R_{\ell y} > 0.7$)

See also poster **TE-14**

Result



- The fiducial inclusive cross-section is extracted by a combined fit of signal and background templates p_T^{iso}; sum of the p_T of all tracks around the γ (R=0.2)
- In good agreement with NLO prediction[×]



arXiv:1706.03046, submitted to JHEP **Differential cross-section**



- Particle level differential cross-sections wrt photon p_T and $|\eta|$ are also measured
- These results also agree with the theoretical predictions at NLO



Summary

 High centre-of-mass energy and luminosity at the LHC allows for precision measurements of top-quark pairs with additional final state particles

This talk covered

- *tt* + additional jets @13 TeV
 Test of pQCD and SM
- $t\bar{t} + Z/W = 13 \text{ TeV}, t\bar{t} + \gamma = 8 \text{ TeV}$
 - sensitive to most of the leading EFT operators
 - can probe the top electroweak coupling
 - Measurement limited by statistical uncertainty

In general, good agreement with SM observed

Thank you.

Backup slides

$t\bar{t}$ + jets; Systematic uncertainties

p_T threshold = 25 GeV

Sources	Relative uncertainty in [%] in additional jets multiplicity						
	0	1	2	3	≥4		
Data statistics	2.1	2.7	4.0	6.0	9.0		
JES/JER	5.0	1.8	7.0	12.0	16.0		
<i>b</i> -tagging	0.5	0.2	0.7	1.4	2.0		
ISR/FSR modelling	0.4	0.5	2.2	3.8	6.0		
Signal modelling	1.9	2.0	5.6	6.0	11.0		
Other	1.4	0.9	2.5	3.3	5.0		
Total	6.0	4.0	10.0	16.0	24.0		

p_T threshold = 60 GeV

Sources	Relative uncertainty in [%] in additional jets multiplicity						
	0	1	2	≥3			
Data statistics	1.5	3.0	7.0	15.0			
JES/JER	0.9	2.3	4.2	7.0			
<i>b</i> -tagging	0.2	0.6	1.2	2.0			
ISR/FSR modelling	0.2	1.2	2.2	1.1			
Signal modelling	0.7	1.6	5.0	9.0			
Other	0.8	0.8	3.2	10.0			
Total	2.0	4.4	10.0	22.0			

Sources	Relative uncertainty in leading additional jet $p_{\rm T}$ [GeV] in [%]								
	25-40	40–60	60-85	85-110	110-150	150-250	> 250		
Data statistics	3.8	6.0	6.0	8.0	8.0	6.0	8.0		
JES/JER	2.9	3.3	2.1	2.7	3.8	3.8	4.2		
<i>b</i> -tagging	0.3	0.2	0.6	0.4	0.6	0.4	1.3		
ISR/FSR modelling	0.6	1.6	1.4	0.7	2.4	4.0	2.1		
Signal modelling	2.5	4.0	3.6	10.0	8.0	8.0	4.0		
Other	1.5	2.8	1.8	3.4	2.4	1.6	1.8		
Total	6.0	8.0	8.0	13.0	12.0	11.0	11.0		

$t\bar{t}$ + V; 3L/4L selections

Variable		3ℓ-Z-1b4j	3ℓ-Z-2b3j	3ℓ-Z-2b4j	3ℓ-noZ-2b	
Leading leptons $p_{\rm T}$		>25 GeV	>25 GeV	>25 GeV	>25 GeV	
Other leptons' $p_{\rm T}$		>20 GeV	>20 GeV	>20 GeV	>20 GeV	
Sum of leptons' charges		± 1	± 1	± 1	± 1	
OSSF $ m_{\ell\ell} $ –	m_Z	<10 GeV	<10 GeV	<10 GeV	>10 GeV	
n _{jets}		<u>≥</u> 4	3	≥ 4	≥ 2 and ≤ 4	
<i>n</i> _{b-jets}		1	<u>≥</u> 2	≥ 2	≥ 2	
Region	Z_2 leptons	<i>Р</i> Т34	$ m_{Z_2} - m_Z $	$E_{\mathrm{T}}^{\mathrm{miss}}$	<i>n</i> _{b-tags}	
4ℓ-DF-1b	$e^{\pm}\mu^{\mp}$	>35 GeV	_	_	1	
4ℓ-DF-2b	$e^{\pm}\mu^{\mp}$	_	_	_	≥ 2	
4 <i>l</i> -SF-1b	$e^{\pm}e^{\mp}, \mu^{\pm}\mu^{\mp}$	>25 GeV	$\begin{cases} > 10 \text{ GeV} \\ < 10 \text{ GeV} \end{cases}$	>40 GeV >80 GeV	1	
4ℓ-SF-2b	$e^{\pm}e^{\mp}, \mu^{\pm}\mu^{\mp}$	_	$\begin{cases} > 10 \text{ GeV} \\ < 10 \text{ GeV} \end{cases}$	- >40 GeV	≥ 2	

$t\bar{t} + V;$ Fit



None of the uncertainties are found to be significantly constrained or pulled from their initial values

$t\bar{t} + \gamma$; Systematic uncertainties

Source	Relative uncertainty [%]
Hadron-fake template	6.3
$e \rightarrow \gamma$ fake	6.3
Jet energy scale	4.9
$W\gamma$ +jets	4.0
$Z\gamma$ +jets	2.8
Initial- and final-state radiation	2.2
Luminosity	2.1
Photon	1.4
Single top+ γ	1.2
Muon	1.2
Electron	1.0
Scale uncertainty	0.6
Parton shower	0.6
Statistical uncertainty	5.1
Total uncertainty	13

Range	$t\bar{t}\gamma$	Hadronic fake	$e \rightarrow \gamma$ fake	$W\gamma$ +jets	$Z\gamma$ +jets	Single top+ γ	Multijet+γ	Diboson+ γ	Data
Total	1060 ± 130	1020 ± 90	710 ± 90	160 ± 40	73 ± 32	32 ± 15	16 ± 6	5.1 ± 2.4	3072
$15 \le p_{\mathrm{T}} < 25 \mathrm{GeV}$	280 ± 40	360 ± 40	240 ± 35	47 ± 13	23 ± 10	7 ± 4	4.4 ± 2.3	1.3 ± 0.7	966
$25 \le p_{\rm T} < 40 { m GeV}$	309 ± 34	233 ± 26	171 ± 7	37 ± 10	22 ± 10	6.4 ± 3.3	3.8 ± 2.4	1.8 ± 0.9	783
$40 \le p_{\rm T} < 60 { m GeV}$	220 ± 40	205 ± 21	111 ± 30	28 ± 8	13 ± 6	10 ± 5	1.6 ± 1.9	0.5 ± 0.3	589
$60 \le p_{\rm T} < 100 { m GeV}$	160 ± 40	116 ± 16	100 ± 40	24 ± 7	10 ± 5	8 ± 4	3.4 ± 2.1	1.0 ± 0.6	420
$100 \le p_{\rm T} < 300 \; {\rm GeV}$	150 ± 25	71 ± 10	50 ± 20	23 ± 7	4 ± 2	0.9 ± 0.7	0.8 ± 1.0	0.3 ± 0.2	298
$ \eta < 0.25$	246 ± 34	121 ± 21	93 ± 24	18 ± 6	9 ± 4	4.0 ± 2.2	5.2 ± 1.8	1.0 ± 0.6	497
$0.25 \le \eta < 0.55$	260 ± 40	130 ± 20	116 ± 29	29 ± 8	11 ± 6	3.7 ± 2.1	0.0 ± 0.4	1.5 ± 0.8	552
$0.55 \le \eta < 0.90$	180 ± 40	198 ± 27	150 ± 40	31 ± 9	16 ± 7	2.2 ± 1.3	4.0 ± 1.8	0.4 ± 0.2	578
$0.90 \le \eta < 1.37$	200 ± 40	233 ± 33	169 ± 50	35 ± 10	17 ± 8	9 ± 5	5.7 ± 2.1	1.0 ± 0.5	663
$1.37 \le \eta < 2.37$	150 ± 40	344 ± 33	200 ± 12	48 ± 13	19 ± 9	13 ± 6	5.4 ± 2.5	1.4 ± 0.7	782

$t\bar{t} + \gamma$; Template

 p_T^{iso} ; the sum of the transverse momenta of all tracks within a cone with an opening angle around the photon of 0.2 rad

