differential $t\bar{t}$ cross section measurements

in the ℓ +jets channel at $\sqrt{s} = 13$ TeV

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Introduction

- ▶ measured ***differential*** $t\bar{t}$ production cross section (as a function of several observables) in pp collision at $\sqrt{s} = 13$ TeV data collected in ATLAS in 2015 (3.2 fb^{-1})
- ▶ ***fiducial*** measurement to avoid large model-dependent corrections to full phase-space
- ▶ kinematic properties of top-quark-proxy objects constructed from final-state particles (***particle-level***), again to minimise modelling uncertainties and dependence
- ▶ distributions corrected for detector effects (***unfolded***)
- ▶ in short: ***fiducial differential measurements unfolded to particle level***
- ▶ presenting normalised and absolute cross sections
- ▶ preliminary results first presented at ICHEP ([ATLAS-CONF-2016-040](#)), paper in preparation

Motivation

- ▶ test of QCD calculations – clear slope in top p_T seen at 7 and 8 TeV, needed NNLO calculations to fix this, which came only recently
- ▶ can constrain gluon PDF
- ▶ sensitive to new physics
- ▶ important background for ttH and exotics searches
- ▶ both, modelling and new physics interesting at high p_T – enhance reach with the boosted selection

LO

NLO

NNLO

Recent results

7 TeV

Resolved:

ATLAS: JHEP 06 (2015) 100

CMS: Eur. Phys. J. C 73 (2013) 2339

8 TeV

Resolved:

ATLAS: Eur. Phys. J. C 76 (2016) 538 →

CMS: Eur. Phys. J. C 75 (2015) 542

Boosted:

ATLAS: Phys. Rev. D93 (2016) 032009

CMS: arXiv:1605.00116

13 TeV

Resolved:

ATLAS: ATLAS-CONF-2016-040 (this talk)

CMS: arXiv:1610.04191 →

Boosted:

ATLAS: ATLAS-CONF-2016-040 (this talk)

CMS: no public result yet

Analysis strategy and object selection

Analysis strategy

- ▶ trigger, object and event selection
- ▶ background subtraction
- ▶ unfolding
- ▶ uncertainties propagation

Detector-level object selection

- ▶ **leptons**: electrons or muons, including those from tau decays
- ▶ **jets**: anti- k_T calorimetric jets with $\Delta R = 0.4$ (small-R) or $\Delta R = 1.0$ (large-R)
- ▶ E_T^{miss} : computed from vector sum of all reconstructed object p_T and unassociated calorimeter cells energy
- ▶ **b-tagging**: multivariate algorithm MV2c20 at $\epsilon_b = 77\%$, $\epsilon_c = 16\%$, $\epsilon_{\text{light}} = 0.7\%$
- ▶ **top-tagging**: simple algorithm based on jet mass and N-subjettiness, 80% efficiency

Event selection

Resolved topology:

=1 lepton

>=4 small-R jets

>=2 b-tags

Pseudo-top object definitions:

$\hat{t}^{\text{lep}} = \ell + E_{\text{T}}^{\text{miss}} + \text{b-jet closest to } \ell$

$\hat{t}^{\text{had}} = \text{other b-jet} + 2 \text{ jets with min. } |m_{jj} - m_W|$

Boosted topology:

=1 lepton

>=1 large-R jet and >=1 small-R jet

>=1 top-tag (large-R)

>=1 b-tag (small-R) within the top-jet
or close to the lepton

+ some additional topological cuts

Highest- p_{T} top-jet serves as $\hat{t}^{\text{had}}$

Background estimation

data-driven *matrix method*
based on real/fake lepton selection efficiency measured in control regions

kinematic distributions from MC **simulation** with **data-driven** normalisation and heavy-flavour fraction corrections

kinematic distributions from MC **simulation** normalised to highest-order available cross-section calculations

Observables

cross section measured as a function of the following observables:

- ▶ p_T and y of hadronically decaying top quark (boosted and resolved)
- ▶ p_T , y and m of the $t\bar{t}$ system (resolved only)

Unfolding procedure

Unfolding formula

($\mathcal{M}_{ij}^{-1}$ denotes iterative Bayesian unfolding as implemented in RooUnfold)

$$\frac{d\sigma^{\text{fid}}}{dx^i} \equiv \frac{1}{\mathcal{L} \cdot \Delta x^i} \cdot \frac{1}{\varepsilon^i} \cdot \sum_j \mathcal{M}_{ij}^{-1} \cdot f_{\text{match}}^i \cdot f_{\text{acc}}^i \cdot (N_{\text{reco}}^j - N_{\text{bkg}}^j)$$

Efficiency

$$\varepsilon = \frac{N(\text{part} \wedge \text{reco} \wedge \text{match})}{N(\text{part})}$$

Migration matrix

$$\mathcal{M}_{ij} = P(j_{\text{reco}} | i_{\text{part}})$$

Matching correction
(resolved only)

$$f_{\text{match}} = \frac{N(\text{part} \wedge \text{reco} \wedge \text{match})}{N(\text{part} \wedge \text{reco})}$$

Acceptance correction

$$f_{\text{acc}} = \frac{N(\text{part} \wedge \text{reco})}{N(\text{reco})}$$

Uncertainties

leading sources of systematic uncertainty include jet resolution, b-tagging and signal modelling

Results (1)

fair agreement with predictions over a wide kinematic range, but softer p_T distribution in data

Results (2)

$m^{t\bar{t}}$ best described by POWHEG+PYTHIA6/8, $y^{t\bar{t}}$ shows slight slope at higher values

- Data
- PWG+PY6 $h_{\text{damp}}=m_t$
- - - PWG+PY6 $h_{\text{damp}}=2m_t$ radHi
- PWG+PY6 $h_{\text{damp}}=m_t$ radLo
- PWG+PY8 $h_{\text{damp}}=m_t$
- PWG+H++ $h_{\text{damp}}=m_t$
- - - aMC@NLO+H++
- Stat. unc.
- Stat.+Syst. unc.

*relative measurements only,
absolute results in backup slides*

Summary

- ▶ presented fiducial differential measurements of $t\bar{t}$ production cross section
- ▶ resolved and boosted event selection efficiently covering low- and high- p_T regimes
- ▶ results are consistent with 7 and 8 TeV observations
- ▶ fair agreement with the predictions over a wide kinematic range
- ▶ most event generators predict a harder top-quark p_T distribution at high values than what is observed in the data
- ▶ preliminary results first presented at ICHEP ([ATLAS-CONF-2016-040](#)), paper in preparation

backup slides

Absolute cross sections (1)

- Data
- PWG+PY6 $h_{\text{damp}}=m_t$
- - PWG+PY6 $h_{\text{damp}}=2m_t$ radHi
- PWG+PY6 $h_{\text{damp}}=2m_t$ radLo
- PWG+PY8 $h_{\text{damp}}=m_t$
- PWG+PY8 $h_{\text{damp}}=m_t$ radLo
- · PWG+H++ $h_{\text{damp}}=m_t$
- · aMC@NLO+H++
- Stat. unc.
- Stat.+Syst. unc.

Absolute cross sections (2)

- Data
- PWG+PY8 $h_{\text{damp}}=m_t$
- - - PWG+PY8 $h_{\text{damp}}=2m_t$ radHi
- - - PWG+PY8 $h_{\text{damp}}=2m_t$ radLo
- PWG+PY8 $h_{\text{damp}}=m_t$
- - - PWG+H++ $h_{\text{damp}}=m_t$
- - - aMC@NLO+H++
- Stat. unc.
- Stat.+Syst. unc.

MC samples

Physics process	Generator	Cross-section normalisation	PDF set for hard process	Parton shower	Tune
$t\bar{t}$ Signal	POWHEG-Box v2	NNLO+NNLL	CT10	PYTHIA 6.428	Perugia2012
$t\bar{t}$ PS syst.	POWHEG-Box v2	NNLO+NNLL	CTEQ6L1	HERWIG++2.7.1	UE-EE-5
$t\bar{t}$ ME syst.	MADGRAPH5_ aMC@NLO	NLO	CT10	HERWIG++2.7.1	UE-EE-5
$t\bar{t}$ rad. syst.	POWHEG-Box v2	NNLO+NNLL	CT10	PYTHIA 6.428	'radHi/Lo'
s top t -channel	POWHEG-Box v1	NLO	CT10f4	PYTHIA 6.428	Perugia2012
s top s -channel	POWHEG-Box v2	NLO	CT10	PYTHIA 6.428	Perugia2012
s top Wt -channel	POWHEG-Box v2	NLO+NNLL	CT10	PYTHIA 6.428	Perugia2012
$t\bar{t}+W/Z/WW$	MADGRAPH5_ aMC@NLO	NLO	NNPDF2.3LO	PYTHIA 8.186	A14
$W(\rightarrow \ell\nu)+$ jets	SHERPA 2.1.1	NNLO	CT10	SHERPA	SHERPA
$Z(\rightarrow \ell\bar{\ell})+$ jets	SHERPA 2.1.1	NNLO	CT10	SHERPA	SHERPA
WW, WZ, ZZ	SHERPA 2.1.1	NLO	CT10	SHERPA	SHERPA

Object and event selection

Level	Detector		Particle
Topology	Resolved	Boosted	
Leptons	$ d_0/\sigma(d_0) < 5$ and $ z_0\sin\theta < 0.5$ mm Track-Calo-based Isolation $ \eta < 1.37$ or $1.52 < \eta < 2.47$ (e) $ \eta < 2.5$ (μ) $E_T(e), p_T(\mu) > 25$ GeV		$ \eta < 2.5$ $p_T > 25$ GeV
Small- R jets	$p_T > 25$ GeV $ \eta < 2.5$ JVT cut (if $p_T < 60$ GeV and $ \eta < 2.4$)		$ \eta < 2.5$ $p_T > 25$ GeV
Num of small- R jets	≥ 4 jets	≥ 1 jets	
E_T^{miss}, m_T^W		$E_T^{\text{miss}} > 20$ GeV, $E_T^{\text{miss}} + m_T^W > 60$ GeV	same as detector level
Leptonic top		At least one small- R jet with $\Delta R(\ell, \text{small-}R \text{ jet}) < 2.0$	
Hadronic top	kinematic top quark reconstruction for detector and particle level	the leading- p_T trimmed large- R jet has: $300 \text{ GeV} < p_T < 1500 \text{ GeV}$, $m > 50 \text{ GeV}$, TopTagging at 80% efficiency $\Delta R(\text{large-}R \text{ jet}, \text{small-}R \text{ jet}) > 1.5$, $\Delta\phi(\ell, \text{small-}R \text{ jet}) > 1.0$	Boosted: $300 < p_T < 1500 \text{ GeV}$ Top-tagging: $m > 100 \text{ GeV}$, $\tau_{32} < 0.75$
b -tagging	at least 2 b -tagged jets	at least one of: 1) the leading- p_T small- R jet with $\Delta R(\ell, \text{small-}R \text{ jet}) < 2.0$ is b -tagged 2) at least one small- R jet with $\Delta R(\text{large-}R \text{ jet}, \text{small-}R \text{ jet}) < 1.0$ is b -tagged	ghost-matched B -hadron

Background and signal yields

Process	Expected Events	
	Resolved	Boosted
$t\bar{t}$	120500 ± 11700	6700 ± 1100
Single top	6100 ± 800	400 ± 80
Multijets	5700 ± 3000	300 ± 80
W+jets	3300^{+1900}_{-3600}	500^{+200}_{-300}
Z+jets	1300 ± 700	60 ± 40
$t\bar{t}V$	400 ± 100	70 ± 10
Diboson	300 ± 200	60 ± 10
Total prediction	137900 ± 14900	8100 ± 1300
Data	155593	7368

Detector-level distributions – resolved

Detector-level distributions – boosted

Pseudo-top reconstruction algorithm

- ▶ Require exactly 1 electron or exactly 1 muon, and ≥ 4 jets with ≥ 2 b-jets
- ▶ Select the two highest- p_T b-jets as the b-jets to be used for the pseudo-top-quark definition
- ▶ Define the leptonic W by combining the lepton with the E_T^{miss} and solving for p_z assuming the W mass (highest p_z from two-fold ambiguity)
- ▶ Combine the b-jet closest to the lepton with the leptonic W, to form the leptonic pseudo-top-quark
- ▶ Define the hadronic W from the two jets giving the dijet mass closest to the W mass, excluding the two selected b-jets
- ▶ Combine the remaining b-jet with the hadronic W, to form the hadronic pseudo-top-quark

Top-tagging

- ▶ particle-level: $m > 100$ GeV and $\tau_{32} < 0.75$
- ▶ detector-level: algorithm described in [ATL-PHYS-PUB-2015-053](#), 80% signal efficiency
- ▶ $\tau_{32} = \tau_3/\tau_2$ where τ_N is the N-subjettiness, which is a measure of how much the large-R jet is consistent with containing N sub-jets when the jet constituents are reclustered with a smaller-R jet algorithm

W+jets background

Overall normalisation calculated from charge asymmetry:

$$N_{W^+} + N_{W^-} = \frac{r_{MC} + 1}{r_{MC} - 1} (D^+ - D^-)$$

where D^+/D^- are the positive/negative lepton yields from data after the subtraction of other charge-asymmetric backgrounds and r_{MC} is taken from MC:

$$r_{MC} = \frac{\sigma(pp \rightarrow W^+)}{\sigma(pp \rightarrow W^-)} = \frac{N_{W^+}^{MC}}{N_{W^-}^{MC}}$$

HF scale factors for W_{bb} , W_{cc} , W_c and W +light jets are obtained from events with exactly 2 jets and extrapolated to the higher jet multiplicity bins.

An iterative procedure is applied to extract the normalisation and the HF scale factors simultaneously.

Matrix method (1)

In our sample S , we have a set of loose leptons L and a set of tight leptons T which are disjoint. We know which lepton is tight and which is loose. We can also define disjoint sets of real leptons R and fake leptons F , however, we do not know which lepton is real and which is fake. The relation $L + T = F + R = S$ holds.

We can define fake and real efficiencies:

$\epsilon_r = P(T|R)$ – probability of a real lepton to be identified as tight,

$\epsilon_f = P(T|F)$ – probability of a fake lepton to be identified as tight,

which are measured in F-dominated and R-dominated regions and can be calculated for different phase-space regions, i.e. parametrised.

The MM equation is the following:

$$\begin{pmatrix} \langle n_T \rangle \\ \langle n_F \rangle \end{pmatrix} = \begin{pmatrix} \epsilon_r & \epsilon_f \\ \overline{\epsilon}_r & \overline{\epsilon}_f \end{pmatrix} \begin{pmatrix} n_R \\ n_F \end{pmatrix}$$

where $\overline{\epsilon}_i = 1 - \epsilon_i$. n_R and n_F are the (unknown) numbers of real and fake leptons, whereas $\langle n_T \rangle$ and $\langle n_F \rangle$ are the expected values for a number of tight and loose leptons, given the n_R , n_F and the efficiencies. It can be easily and legitimately inverted (once $\epsilon_r \neq \epsilon_f$):

$$\begin{pmatrix} n_R \\ n_F \end{pmatrix} = \frac{1}{\epsilon_r - \epsilon_f} \begin{pmatrix} \overline{\epsilon}_f & -\epsilon_f \\ -\overline{\epsilon}_r & \epsilon_r \end{pmatrix} \begin{pmatrix} \langle n_T \rangle \\ \langle n_F \rangle \end{pmatrix}$$

Matrix method (2)

What we want to estimate is the number of fake leptons in tight selection n_{TF} . The Matrix Method calculates it simply as $\epsilon_f n_F$ where n_F comes from the last equation:

$$\hat{n}_{TF} = \frac{\epsilon_f}{\epsilon_r - \epsilon_f} (\epsilon_r (n_L + n_T) - n_T)$$

with the caveat of using observed n_T and n_L in place of expected values. In practice, the estimate is obtained as a sum of weighted events:

$$\hat{n}_{TF} = \sum_{i \in (L+T)} \frac{\epsilon_f^i}{\epsilon_r^i - \epsilon_f^i} (\epsilon_r^i - \delta^{i \in T})$$

where $\delta^{i \in T}$ equals 1 if the event passes the tight selection criteria and 0 otherwise. ϵ_r^i and ϵ_f^i are obtained for each event i from histograms or functions depending on some kinematic variables.

Due to limited statistics it is not feasible to measure the efficiency as a function of many observables simultaneously, thus geometric means of efficiencies measured independently in 1D or 2D are used, e.g.

$$\epsilon = \sqrt[3]{\epsilon(p_T) \cdot \epsilon(\eta) \cdot \epsilon(E_T^{\text{miss}})}$$