tW differential cross-sections with ATLAS at 13 TeV (dilepton)

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Context

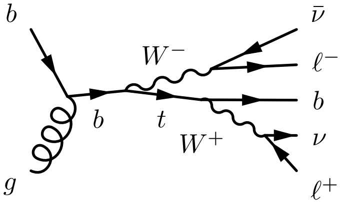
- Follow-up of the total tW cross-section in the dilepton final state ([arXiv:1612.07231 →], submitted to JHEP)
- Particle level **differential** measurement
- Planned for **Moriond EW** with the 2015+2016 ATLAS dataset

Overview

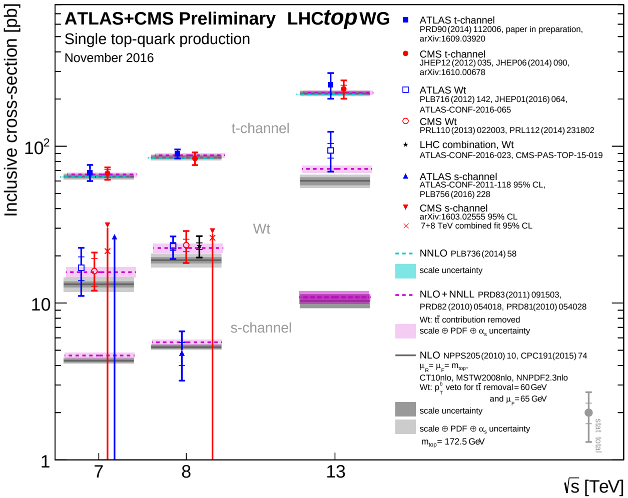
- Dilepton final state
- **BDT** to separate tW from $t\bar{t}$ background
- Unfold with **D'Agostini iterative Bayesian** method
- New plots in this presentation are **simulation only**

Motivation

- The tW channel probes the tWb vertex
- Unlike s- and t-channel it is not affected by the existence of four-fermion operators
- **Practical goal** is to compare Monte Carlo tools and models in this channel

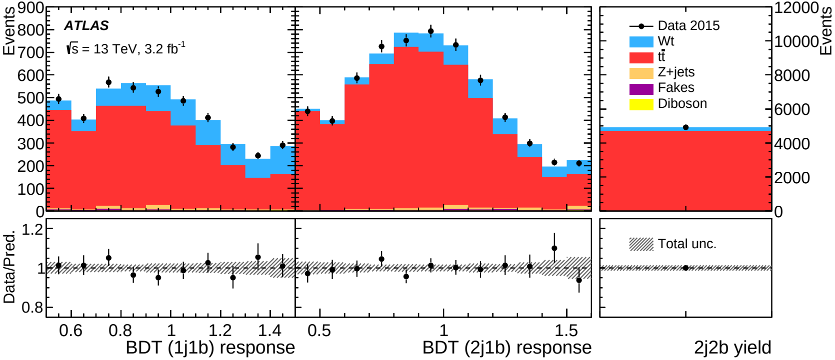


Reminder: Single top cross-sections at the LHC



LHC*top*WG preliminary summary, November 2016 [ATLAS →]

Reminder: 13 TeV inclusive tW cross-section



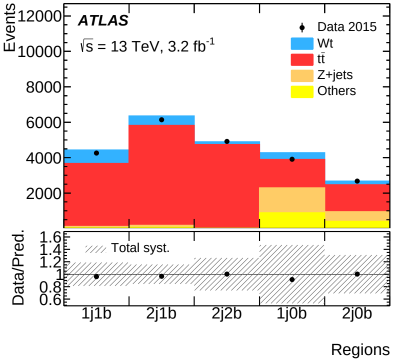
$$\sigma_{Wt} = 94 \ \pm 10\,(\text{stat.})\ ^{+28}_{-22}\,(\text{syst.})\ \pm 2\,(\text{lumi.})\ \text{pb}$$

submitted to JHEP [arXiv:1612.07231 →]

Selection and definitions

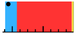
	≥ 1 jet with $p_T > 25$ GeV, $\lvert\eta\rvert < 2.5$ 2 leptons of opposite charge with $p_T > 20$ GeV, ≥ 1 lepton with $p_T > 27$ GeV, veto third with $p_T > 20$ GeV lepton matched to the trigger object	
DF	$E_T^{miss} > 50$ GeV,	if $m_{\ell\ell} < 80$ GeV
	$E_T^{miss} > 20$ GeV,	if $m_{\ell\ell} > 80$ GeV
SF	$E_T^{miss} > 40$ GeV,	always
	veto,	if $m_{\ell\ell} < 40$ GeV
	$4E_T^{miss} > 5m_{\ell\ell}$,	if $40 < m_{\ell\ell} < 81$ GeV
	veto,	if $81 < m_{\ell\ell} < 101$ GeV
	$2m_{\ell\ell} + E_T^{miss} > 300$ GeV,	if $m_{\ell\ell} > 101$ GeV
	Exactly one jet, which is a b-tagged jet (1j1b)	

- Summary plot (inclusive; 2015):



- Regions other than 1j1b will be used for validation only

Separating the $t\bar{t}$ background

- Almost entirely Wt+$t\bar{t}$  (1j1b bin)
- We use a **Boosted Decision Tree** (`TMVA`)
- Inputs are kinematic variables of subsets of objects plus some whole-event variables
- Procedure to narrow down the list:
    1. rank variables by **separation power**
    2. remove highly-correlated variables
    3. find combinations with best separation
    4. tie-break by preferring fewer variables

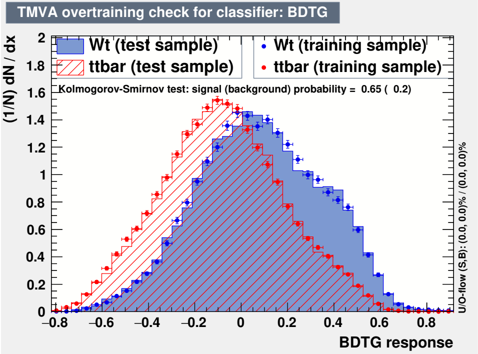
$$\langle S^2 \rangle = \frac{1}{2} \int \frac{(Y_S(y) - Y_B(y))^2}{(Y_S(y) + Y_B(y))} \, \mathrm{d}y$$

- **Cut** on BDT output value of 0.3 (chosen to minimise the total uncertainty)

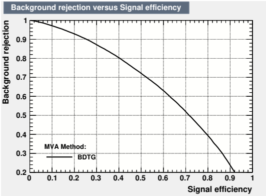
Variable	S $[10^{-2}]$
$p_{\mathrm{T}}^{\mathsf{sys}}(\ell_1 \ell_2 E_{\mathrm{T}}^{\mathrm{miss}} j_1)$	4.1
$\Delta p_{\mathrm{T}}(\ell_1 \ell_2 j_1, E_{\mathrm{T}}^{\mathrm{miss}})$	2.5
$\sum E_{\mathrm{T}}$	2.3
$\eta(\ell_1 \ell_2 E_{\mathrm{T}}^{\mathrm{miss}} j_1)$	1.3
$\Delta p_{\mathrm{T}}(\ell_1 \ell_2, E_{\mathrm{T}}^{\mathrm{miss}})$	1.1
$p_{\mathrm{T}}^{\mathsf{sys}}(\ell_1 \ell_2 j_1)$	1.0
$C(\ell_1 \ell_2)$	0.9
$m(\ell_2, j_1)$	0.2
$m(\ell_1, j_1)$	0.1

$p_{\mathrm{T}}^{\mathsf{sys}}$ is the vectorial sum of p_{T};
C is centrality (scalar sum of $p_{\mathrm{T}} / \, \Sigma E$)

Separating the $t\bar{t}$ background



ATLAS **WIP**



Theoretical considerations

- tW at NLO and $t\bar{t}$ at LO contain interfering diagrams ("doubly-resonant")
- Different schemes exist to handle this
- **Diagram subtraction** (DS) adds a gauge-invariant term to cancel the $t\bar{t}$ contribution
- **Diagram removal** (DR) discards all diagrams with resonant contributions
- A new scheme **DR2** also keeps the mixed term

$$|\mathcal{M}_{\text{tot}}|^2 = |\mathcal{M}_{\text{nr}}|^2 + 2\text{Re}(\mathcal{M}_{\text{nr}}\mathcal{M}_{\text{r}}) + |\mathcal{M}_{\text{r}}|^2$$

Unfolding

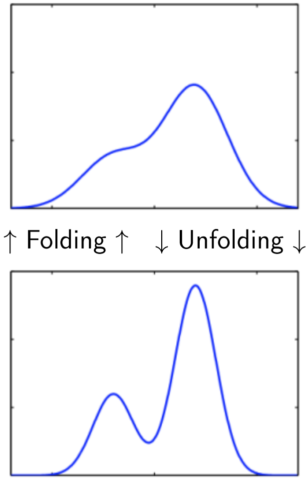
Overview

- Our definitions of top quark etc. depend on details of the detector (**reconstruction level**)
- Ideal: present in terms of the **physical** objects
- Compromise: use straightforward definitions for objects at **particle level**

- Reco → particle level is called **unfolding**

General procedure

- Account for **migration between bins** of reco-level and particle-level quantities
- Invert the response matrix



[source →]

Unfolding: choice of binning

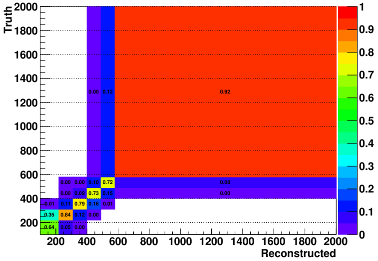
Binning goals

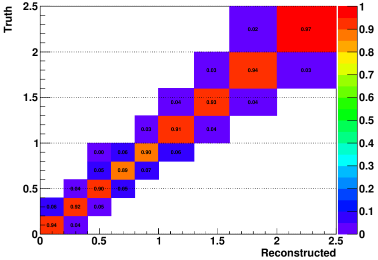
- **Stable**: $\sim$60% of entries on the diagonal
- **Balanced**: $\lesssim$20% statistical uncertainty per bin

Binning procedure

- Identical for particle and reco levels (negligible bias)
- First and last bins chosen based on statistical uncertainty
- Other bins are a **multiple of the resolution** of the variable in question

Note: top plot illustrates $m(\ell\ell\nu b)$, bottom $|\eta(b)|$





Unfolding: specific procedure

Unfolding procedure

- Iterative Bayes-inspired (D'Agostini) in `RooUnfold`
- Correct for efficiency to reco fiducial event [E^{-1}]
- Then iterative matrix unfolding
- Then correct for unmatched/non-fiducial events [A]

$$\frac{\mathrm{d}\sigma}{\mathrm{d}X} = \frac{N_i^{\mathrm{ufd}}}{L\Delta_i} \quad (\Delta_i = \text{bin width})$$

Number of iterations

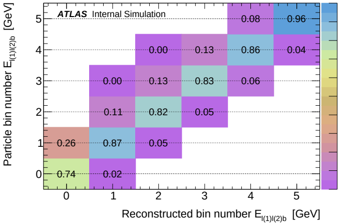
- Chose $N_{it.}$ to minimise χ^2 difference between testing and unfolded samples (per variable)
- Larger $N_{\text{it.}}$ emphasise finer-detailed features that are more likely to be statistical noise

Variable	$N_{\text{iterations}}$	
$E(\ell_1 \ell_2 b)$	5	
$m_T(\ell_1 \ell_2 \nu b)$	5	$*$
$m(\ell_1 \ell_2 b)$	3	
$m(\ell_1 b)$	5	†
$m(\ell_2 b)$	3	
$E(b)$	6	‡
$p_{\mathrm{T}}^{\text{sys}}(\ell_1 \ell_2 \nu b)$	10	

$*$: sensitive to DR vs. DS scheme
†: sensitive to spin correlation
‡: sensitive to theory modelling

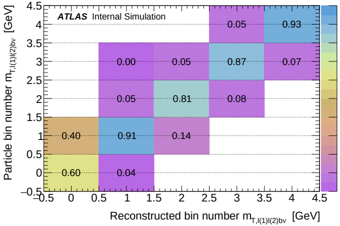
Normalised migration matrices

$E(\ell_1 \ell_2 b)$



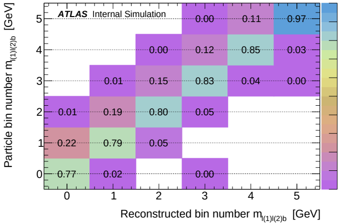
ATLAS WIP

$m_T(\ell_1 \ell_2 \nu b)$

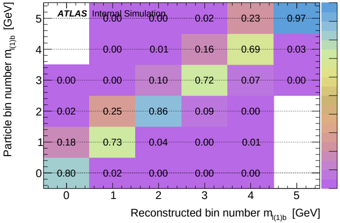


ATLAS WIP

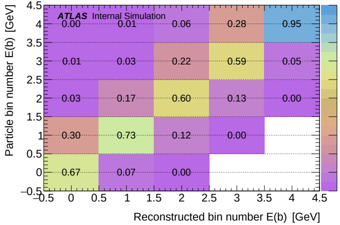
$m(\ell_1 \ell_2 b)$



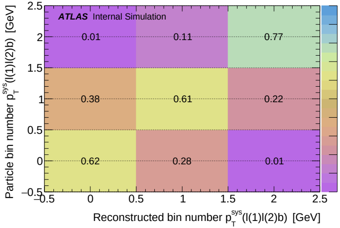
ATLAS WIP



$m(\ell_1 b)$



$E(b)$



$p_T^{sys}(\ell_1 \ell_2 \nu b)$

Propagation of systematics

$X^0 :=$ nominal, $X^\pm :=$ variation; unfolding always uses a response matrix made with tW^0

Signal-only uncertainties

- tW matrix element generator, parton shower/had. generator, DS vs. DR, initial-/final-state radiation tune
- $\mathrm{unfold}(tW^\pm) - \mathrm{truth}(tW^\pm)$
- Unfold variations with nominal, cf. truth
- Difference* at particle level is the uncertainty

Other uncertainties

- The background and signal are both varied
- $\mathrm{unfold}(tW^\pm + t\bar{t}^\pm - t\bar{t}^0) - \mathrm{truth}(tW^\pm)$

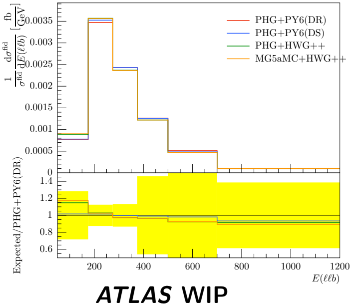
Background-only uncertainties

- $t\bar{t}$ matrix element gen., parton shower/had. generator, initial-/final-state radiation tune
- $\mathrm{unfold}(tW^0 + t\bar{t}^\pm - t\bar{t}^0) - \mathrm{truth}(tW^0)$
- Difference between background nominal and variation is added to nominal before unfolding
- This is unfolded and compared to truth

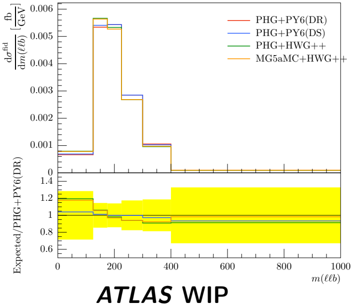
* for 2-point uncertainties we take half of the difference between the up and down variations

Normalised differential cross-sections

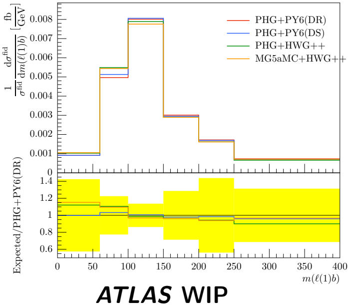
$E(\ell_1 \ell_2 b)$



$m(\ell_1 \ell_2 b)$

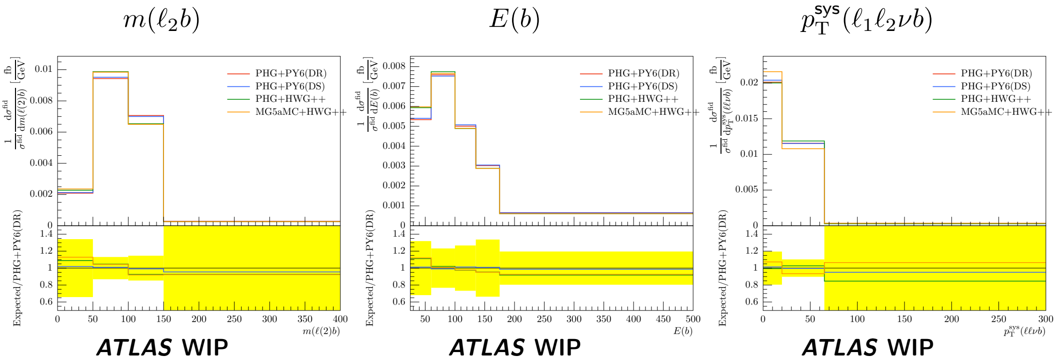


$m(\ell_1 b)$



- DR vs. DS: relative slope would suggest possibility to differentiate the schemes

Normalised differential cross-sections



- Theory modelling: differentiation between Herwig and Pythia samples

Future of the work

General direction

- This will be the first differential measurement in the tW channel
- Future measurments will include additional **features** and more data

Full reconstruction

- Due to the ν, the system is kinematically underconstrained
- **Reconstruction** of tW system possible
- **Top EFT**: lepton association
- At particle level: pseudo-top

Diagram interference

- The $t\bar{t}$ and tW interference issue is an active area of study
- $WWbb$ predictions are being studied
- $tW + t\bar{t}$ **fiducial measurement**
- Would need to look at extra jet bins

Additional channels

- So far we've only looked at the dilepton final state
- **Single lepton** channel is also interesting

(backup)

Triggers

	2015	2016
Electrons	`HLT_e24_lhmedium_L1EM20VH` or `HLT_e60_lhmedium` or `HLT_e120_lhloose`	`HLT_e26_lhtight_nod0_ivarloose` or `HLT_e60_lhmedium_nod0` or `HLT_e140_lhloose_nod0`
Muons	`HLT_mu20_iloose_L1MU15` or `HLT_mu50`	`HLT_mu26_ivarmedium` or `HLT_mu50`

At least one selected lepton must be matched to the trigger object

Note that the dataset is from the top working group's dilepton derivation

BDT cut optimisation

- Studies to optimise value of BDT cut: look at total syst. and stat. uncertatiny per bin
- Optimise for normalised cross-section- choose value of 0.1

	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5	Bin 6	simple sum
$\frac{1}{\sigma}\frac{d\sigma}{dm_{\ell\ell\nu b}}$, $r_{\mathrm{BDT}} > 0.2$							
Stat.	0.151	0.057	0.078	0.128	0.203	0.185	
Total syst.	0.154	0.052	0.063	0.141	0.118	0.12	
Total uncert.	0.216	0.077	0.100	0.190	0.235	0.221	1.039
$\frac{1}{\sigma}\frac{d\sigma}{dm_{\ell\ell\nu b}}$, $r_{\mathrm{BDT}} > 0.1$							
Stat.	0.14	0.053	0.07	0.11	0.175	0.171	
Total syst.	0.159	0.036	0.058	0.089	0.096	0.168	
Total uncert.	0.212	0.064	0.091	0.141	0.200	0.240	0.948
$\frac{1}{\sigma}\frac{d\sigma}{dm_{\ell\ell\nu b}}$, $r_{\mathrm{BDT}} > 0$							
Stat.	0.133	0.05	0.064	0.101	0.163	0.161	
Total syst.	0.162	0.038	0.051	0.105	0.154	0.177	
Total uncert.	0.210	0.063	0.082	0.146	0.224	0.239	0.963

Particle level definitions

Leptons are electrons and muons from W or Z boson decays, dressed by any non-hadronic photons in a ΔR cone of 0.1

Neutrinos are stable particles not from the decay of hadrons

Jets are anti-k_t jets with parameter 0.4, made from all stable particles excluding the leptons and neutrinos (and the photons used in dressing). ***b*-jets** are jets associated with a heavy flavour hadron with $p_{\mathrm{T}} > 5$ GeV using ghost matching[1].

The **pre-selection** requires two leptons with $p_{\mathrm{T}} > 20$ GeV and $|\eta| < 2.5$, vetoing a third such lepton. One lepton must have $p_{\mathrm{T}} > 27$ GeV. Exactly one b-jet with $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$ must be present. There is **no event-level cut** such as on $E_{\mathrm{T}}^{\mathrm{miss}}$ or $m_{\ell\ell}$.

[1] the hadron momentum is rescaled to be vanishingly small before adding them as input to the clustering algorithm; any jet conatining such a “ghost” hadron is b-tagged