Universidad de Oviedo

GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN

ATLAS-CMS Comparison: Latest $t\bar{t}W$ Results

Marcel Niemeyer[1], Carlos Vico Villalba[2]

[1]University of Göttingen [2]Universidad de Oviedo

on behalf of the ATLAS and CMS Collaborations

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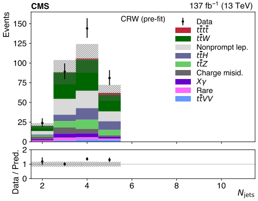
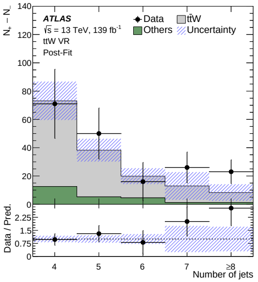
LHC Top WG Meeting

GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

FSP ATLAS
Erforschung von Universum und Materie

- $t\bar{t}W$ is a background process in multi-lepton final states for many analyses:
  - $t\bar{t}H$
  - 4 top production
  - searches: g2HDM, SUSY RPV models
- so far, measurements have consistently found an excess over predicted cross-sections
  - top right: $t\bar{t}W$ CR in 4 tops search[a]
  - bottom right: $t\bar{t}W$ VR of 4 tops evidence paper, largest systematic in analysis[b]
- modelling difficult due to higher order contributions
- have seen mismodelling, important to measure cross-section and differential distributions





[a] Eur. Phys. J. C 80 (2020) 75
[b] Eur.Phys.J.C 80 (2020) 11, 1085

$t\bar{t}W$ Cross-Sections
Predictions

Multiℓ latest analyses	$\mathcal{L}$ [fb^{-1}]	σ_{ref} [fb]	μ	μ_{YR4}
tt̄W ATLAS Phys. Rev. D 99 (2019) 072009	36.1	600 ± 70	1.44 ± 0.32	1.44 ± 0.32
tt̄W CMS arXiv:2208.06485	138	592^{+155}_{-97} (NLO QCD + EW, QCD NNLL)	1.47 ± 0.11	1.49 ± 0.11
tt̄H ATLAS ATLAS-CONF-2019-045/	80	727 ± 92 (NLO QCD + full NLO EW, +0,1j@NLO)	$1.39^{+0.17}_{-0.16}$	$1.68^{+0.21}_{-0.19}$
tt̄H CMS Eur. Phys. J. C 81 (2021) 378	137	650 (NLO QCD + full NLO EW [1] [2])	1.43 ± 0.21	1.55 ± 0.23
tt̄tt̄ BSM ATLAS arXiv:2211.01136	139	639 (Sherpa 2.2.10 NLO QCD + full NLO EW*)	1.3 ± 0.3	1.22 ± 0.28
tt̄tt̄ CMS Eur. Phys. J. C 80 (2020) 75	137	610 (from https://arxiv.org/abs/2010.05915)	1.3 ± 0.2	1.3 ± 0.2
g2HDM ATLAS ATLAS-CONF-2022-039/	139	615 (Sherpa 2.2.10 NLO QCD + full NLO EW*)	1.50 ± 0.14	1.46 ± 0.14
SUSY RPV ATLAS Eur. Phys. J. C 81 (2021) 1023	139	Fully data-driven		

Table by Tamara Vazquez Schroeder

- predictions are difficult due to large NLO corrections
- many different predictions available
- agreed on common reference cross-section for $t\bar{t}W$ by Frederix & Tsinikos [1] during last LHC Top+Higgs WG meeting[2]:

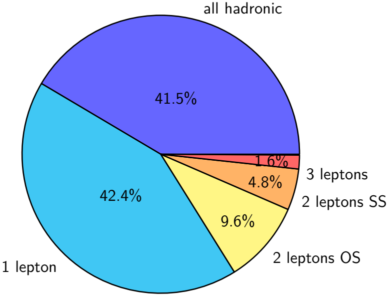
$$\sigma_{t\bar{t}W}^{\text{NLO}+0,1,2\text{j}} = 722^{+70}_{-78}(\text{scale}) \pm 7(\text{PDF})\ \text{fb}$$

[1] JHEP 11 (2021) 029
[2] https://indico.cern.ch/event/1219500

$t\bar{t}W$ Production

Final States

- highest BR in all hadronic and single lepton channels
  - large backgrounds
  - not yet used in analyses
- most sensitive channels are di-lepton same-sign and trilepton
  - used in the analyses presented here
  - significant backgrounds: $t\bar{t}H$, $t\bar{t}Z$, fake leptons
  - small branching ratio of 4.8% (2lSS) and 1.6% (3l)



Latest $t\bar{t}W$ Measurements

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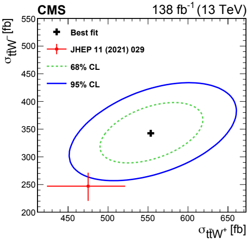
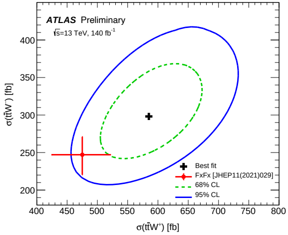
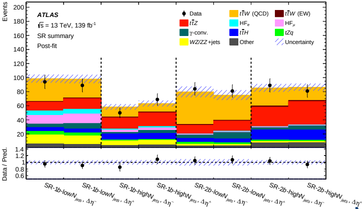
CMS Cross-Section:

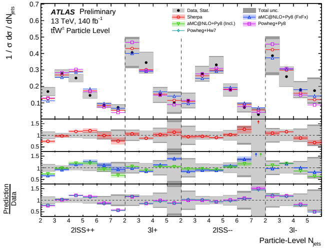


Atlas Cross-Section:



Atlas Charge-Asymmetry:





Selections

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CMS:

- 2lSS and 3l channel
- $m_{\ell\ell} > 30$ (12) GeV in 2lSS (3l)
- Z veto on ee (2lSS) and $ee, \mu\mu$ (3l)
- $p_T^{miss} > 30$ GeV
- $N_{jets} \geq 2$
- ≥ 1 b-jet (85% efficiency) or ≥ 2 b-jets (90% efficiency) in 2lSS
- ≥ 1 b-jet (85% efficiency) in 3l

Atlas:

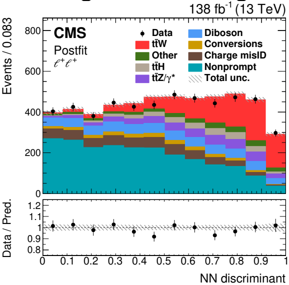
- 2lSS and 3l channel
- $m_{\ell\ell}^{(OS+SF)} > 12$ in 2lSS (3l)
- Z veto on $ee, \mu\mu$ pairs and $m_{\ell\ell\ell}$ in 3l
- no cut on p_T^{miss} / E_T^{miss}
- $N_{jets} \geq 2$
- ≥ 1 b-jet (60% efficiency) or ≥ 2 b-jets (77% efficiency)

⇒ Much looser b-tagging requirements in CMS measurement, approximately 2 times more statistics

- Atlas measurement inclusive & **differential**, needs purer selection

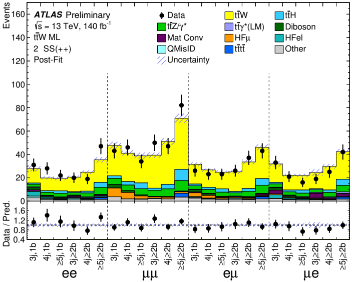
CMS:

- split into 8 regions based on lepton charge, flavour
- use DNN to distinguish 4 event categories: $t\bar{t}W$, $t\bar{t}H/Z$, $t\bar{t}\gamma$, non-prompt
- only use $t\bar{t}W$ node as discriminant between signal and background



Atlas:

- split channel into 48 regions according to lepton charge, flavour, (b-)jet multiplicity
- fitting total yield in each region
- background estimation via template fit



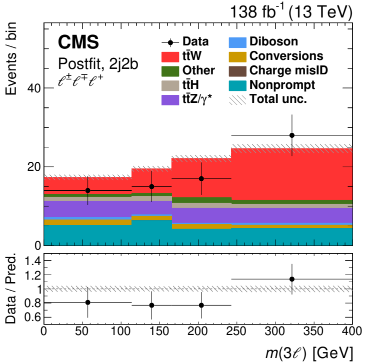
Both: Combined profile likelihood fit of all SRs and CRs to extract cross-section

Methodology

3l Channel

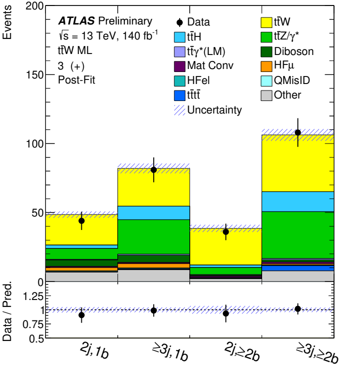
<u>CMS:</u>

- use $m_{3\ell}$ as discriminant
- split into 12 regions according to (b-)jet multiplicity, charge



<u>Atlas:</u>

- 3l channel split into 8 regions according to lepton charge, (b-)jet multiplicity



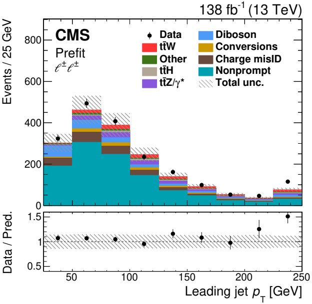
Both: Combined profile likelihood fit of all SRs and CRs to extract cross-section

Methodology

Background - Fakes/Non-Prompt

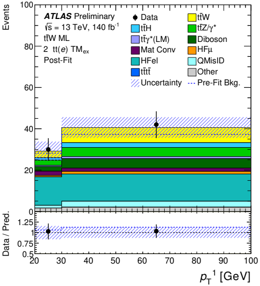
CMS:

- BDT for prompt lepton discrimination
- non-prompt estimation data-driven
  - misID rate from QCD multijet enriched region
  - prompt contribution subtracted from simulation
- validation region non-prompt enriched



Atlas:

- template fit method
- BDT to identify non-prompt leptons
- based on isolation and lifetime
- fakes CRs (HFe, HFμ) based on medium-not-tight WP
- 6 fake CRs, int/ext conversion CRs
- 4 free-floating normalisation factors



CMS:

$t\bar{t}Z$ and VV:

- 2 CRs: $WZ/t\bar{t}Z$ and $ZZ/t\bar{t}Z$
- inverting Z veto on nominal selection, 4 tight leptons in $ZZ/t\bar{t}Z$ CR
- all CRs present in final fit

Charge misassignment:

- rate from simulation of DY and $t\bar{t}$
- applied to 2lOS events to estimate background
- only applied to *ee* in 2l channel

Atlas:

$t\bar{t}Z$ and VV:

- 2 CRs: $t\bar{t}Z$ and VV
- included in template fit method
- two additional normalisation factors
- template fit combined with cross-section extraction

Charge misassignment:

- rate from data, DY enriched
- applied to 2lOS events to estimate background
- only applied to *ee* in 2l channel

Signal Modelling

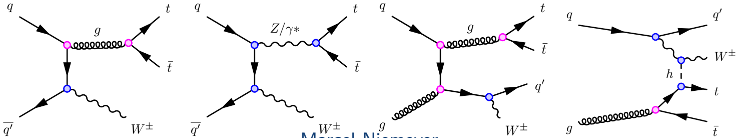
nominal samples:

- CMS:
  - MadGraph5_aMC@NLO v2.6.0 FxFx + Pythia8 (LO1 + NLO1 and NLO3)
- Atlas:
  - Sherpa 2.2.10 QCD sample (LO1 + NLO1 and -3.9% from LO3+NLO2) and EW sample (NLO3)

systematic variations:

- both: μ_R, μ_F, alternative PDF & α_S
- CMS:
  - ISR & FSR scale
  - colour reconnection (from alternate models, 1%)
- Atlas:
  - generator uncertainty (Sherpa vs MG5_aMC@NLO +Pythia8 FxFx)
  - parton shower (Powheg+Pythia8 vs Powheg+Herwig7)
  - EW fraction (varying relative composition of QCD/EW based on MG5)

LO1: $\alpha_S^2 \alpha_{EW}$ LO3: α_{EW}^3 NLO1: $\alpha_S^3 \alpha_{EW}$ NLO3: $\alpha_S \alpha_{EW}^3$



Inclusive Cross-Section

Results

<u>CMS:</u>

$$\sigma_{t\bar{t}W} = 868 \pm 40(\text{stat}) \pm 51(\text{syst})\ \text{fb}$$

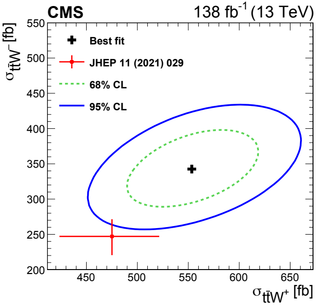
<u>Atlas:</u>

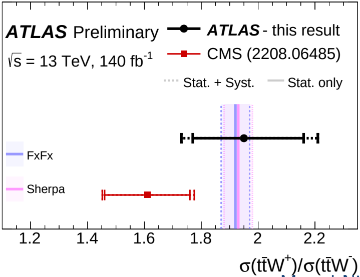
$$\sigma_{t\bar{t}W} = 890 \pm 50(\text{stat}) \pm 70(\text{syst})\ \text{fb}$$

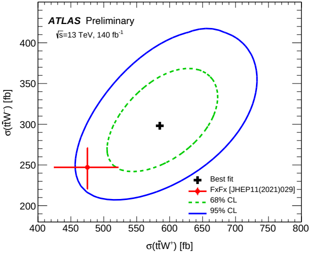
$$A_C^R = 0.32 \pm 0.05(\text{stat}) \pm 0.03(\text{syst})$$

<u>LHC reference:</u>

$$\sigma_{t\bar{t}W}^{\text{NLO+0,1,2j}} = 722^{+70}_{-78}(\text{scale}) \pm 7(\text{PDF})\ \text{fb}$$







Inclusive Cross-Section

Results

Source	Uncertainty [%]
Experimental uncertainties	
Integrated luminosity	1.9
b tagging efficiency	1.6
Trigger efficiency	1.2
Pileup reweighting	1.0
L1 inefficiency	0.7
Jet energy scale	0.6
Jet energy resolution	0.4
Lepton selection efficiency	0.4
Background uncertainties	
tt̄H normalization	2.6
Charge misidentification	1.6
Nonprompt leptons	1.3
VVV normalization	1.2
tt̄VV normalization	1.2
Conversions normalization	0.7
$t\bar{t}\gamma$ normalization	0.6
ZZ normalization	0.6
Other normalizations	0.5
tt̄Z normalization	0.3
WZ normalization	0.2
tZq normalization	0.2
tHq normalization	0.2
Modeling uncertainties	
tt̄W scale	1.8
tt̄W color reconnection	1.0
ISR & FSR scale for tt̄W	0.8
$t\bar{t}\gamma$ scale	0.4
VVV scale	0.3
tt̄H scale	0.2
Conversions	0.2
Simulation statistical uncertainty	1.8
Total systematic uncertainty	5.8

	$\frac{\Delta\sigma(t\bar{t}W)}{\sigma(t\bar{t}W)}$ [%]
$t\bar{t}W$ ME and PS modelling	6.0
Prompt lepton bkg. norm.	2.6
Lepton isolation BDT	2.3
Fakes/VV/$t\bar{t}Z$ norm. (free-floated)	2.3
Non-prompt lepton bkg. modelling	1.9
Trigger	1.9
MC statistics	1.5
$t\bar{t}W$ PDF	1.5
Jet energy scale	1.4
Prompt lepton bkg. modelling	1.3
Luminosity	1.0
Charge Mis-ID	0.7
Jet energy resolution	0.5
Flavour tagging	0.28
$t\bar{t}W$ Scale	0.21
Electron/photon reco.	0.15
MET	<0.10
Muon	<0.10
Pile-up	<0.10
Total syst.	8
Data statistics	5
Total	9

- dominant systematics in CMS (**left**): luminosity, $t\bar{t}H$ normalisation, $t\bar{t}W$ scale
- dominant systematics in Atlas (**right**): $t\bar{t}W$ ME and PS
- closest categories in same colour
- Atlas w/o $t\bar{t}W$ ME and PS syst: 5.6%

- CMS: higher impact from *b*-tagging, pile-up, charge misassignment
- Atlas: higher impact from JES, trigger; similar impact from JER

Fiducial Cross-Section

Atlas

	$\frac{\Delta\sigma(t\bar{t}W)}{\sigma(t\bar{t}W)}$ [%]	$\frac{\Delta\sigma_{\text{fid}}(t\bar{t}W)}{\sigma_{\text{fid}}}$ [%]
$t\bar{t}W$ ME and PS modelling	6.0	7.0
Prompt lepton bkg. norm.	2.6	2.5
Lepton isolation BDT	2.3	2.3
Fakes/VV/$t\bar{t}Z$ norm. (free-floated)	2.3	2.7
Non-prompt lepton bkg. modelling	1.9	1.7
Trigger	1.9	1.8
MC statistics	1.5	1.6
$t\bar{t}W$ PDF	1.5	1.4
Jet energy scale	1.4	1.9
Prompt lepton bkg. modelling	1.3	1.3
Luminosity	1.0	1.0
Charge Mis-ID	0.7	0.7
Jet energy resolution	0.5	0.6
Flavour tagging	0.28	0.33
$t\bar{t}W$ Scale	0.21	0.9
Electron/photon reco.	0.15	0.2
MET	<0.10	<0.10
Muon	<0.10	<0.10
Pile-up	<0.10	0.25
Total syst.	8	10
Data statistics	5	5
Total	9	11

- correct signal systematics for acceptances on particle level
- fiducial volume very close to detector level selection
- removal of acceptance effects often reduces total syst uncertainty
- $\sigma_{\text{fid}} = 21.7 \pm 1.1(\text{stat})^{+2.1}_{-1.9}(\text{syst})$ fb (11%, inclusive: 9%)
- uncertainty slightly larger due to MG5 FxFx acceptance (higher than nominal Sherpa sample)
- on detector level, differences between Sherpa and MG5 FxFx reconstruction efficiency
- effects have opposite impact and partially cancel on detector level, but not in fiducial fit

Differential Cross-Section

Methodology

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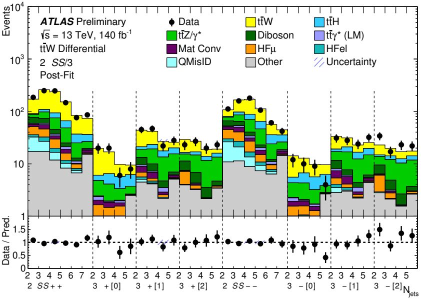
Atlas only

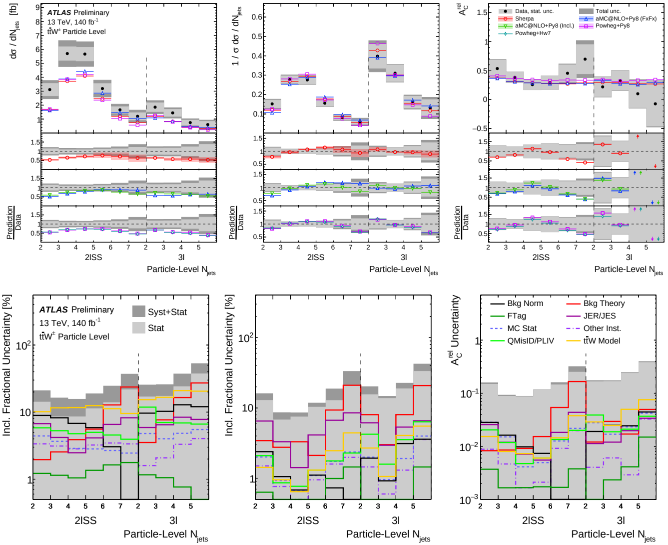


- using same fiducial volume as for the fiducial measurement (except $N_{\text{jets}} \geq 2$ in 2lSS channel)

- 4 SRs, 2ℓSS (++/--) and 3ℓ (+/-)
- same template fit for background estimation as for inclusive $t\bar{t}W$
- profile likelihood unfolding to particle level for seven observables:
  - N_{jets}, $H_{\text{T,jets}}$, $H_{\text{T,lep}}$, $\Delta R_{\text{lb,lead}}$, $|\Delta\phi_{\text{ll,SS}}|$, $|\Delta\eta_{\text{ll,SS}}|$, $M_{\text{jj,lead}}$
- Tikhonov regularisation, constraint on discrete 2nd derivative of truth-bin POIs
- measure absolute and normalised cross-sections and differential A_C^R
- assess compatibility between data and predictions via χ^2 test
- overlay fixed order off-shell calculations in 3ℓ (Phys. Rev. D 105 (2022) 1, 014018)

Differential Cross-Section

N_{jets} - Asymmetry Parameterisation



- left: absolute
- centre: normalised
- right: $A_C^R = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$
- statistics dominated in 3l and edges of 2lSS
- largest systematics: JES/JER and background modelling, ($t\bar{t}W$ modelling)

Differential Cross-Section

N_{jets}, $\Delta R_{\text{lb,lead}}$ - split by charge

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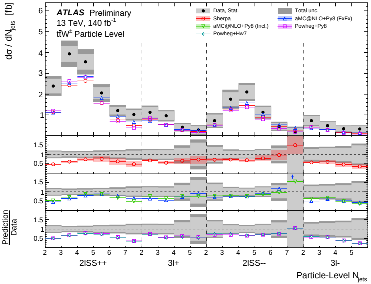
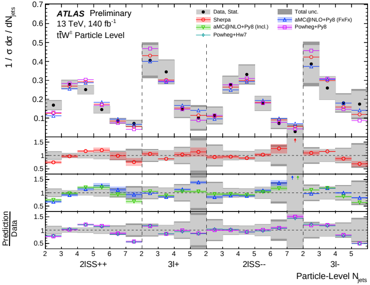
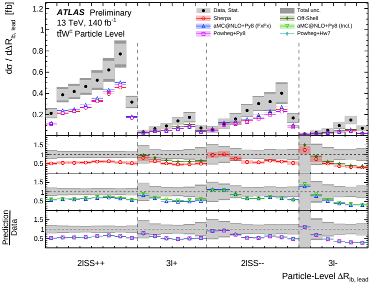
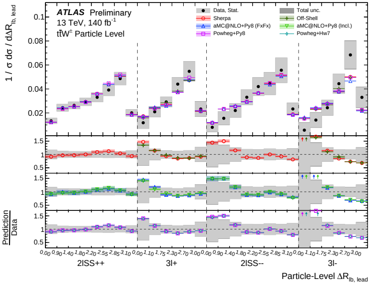


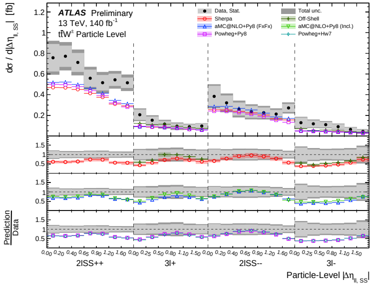


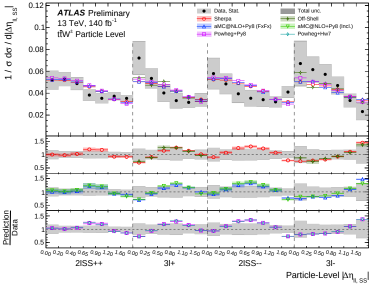




Differential Cross-Section

$|\Delta\eta_{ll,SS}|$ and χ^2 - split by charge





Observable	NDF	Sherpa 2.2.10		Off-Shell		MG5aMC+Py8 FxFx		MG5aMC+Py8 Incl.		Powheg+Py8		Powheg+H7	
		χ^2	p-value	χ^2	p-value	χ^2	p-value	χ^2	p-value	χ^2	p-value	χ^2	p-value
N_{jets}	3	0.2	0.98	-	-	0.2	0.98	0.3	0.97	1.0	0.80	1.1	0.79
$H_{\text{T,jets}}$	4	1.4	0.84	-	-	0.9	0.92	1.9	0.75	2.4	0.66	3.3	0.51
$H_{\text{T,lep}}$	5	1.0	0.96	3.4	0.64	1.3	0.94	1.7	0.88	1.5	0.91	1.4	0.93
$\Delta R_{\text{lb, lead}}$	5	4.0	0.55	3.5	0.63	5.0	0.42	3.7	0.59	3.7	0.60	3.8	0.58
$\|\Delta\phi_{\text{ll, SS}}\|$	5	2.7	0.75	2.2	0.81	2.6	0.76	2.2	0.82	2.4	0.79	2.3	0.80
$\|\Delta\eta_{\text{ll, SS}}\|$	5	2.6	0.77	5.6	0.35	2.9	0.72	2.3	0.80	2.0	0.84	2.1	0.83
$M_{\text{jj, lead}}$	5	0.1	1.00	-	-	0.2	1.00	0.4	0.99	0.7	0.98	1.0	0.96

Table for 2lSS selection in backup - ask a question if you want to see it

- Atlas (9%) and CMS (6%) provided the most precise measurement of the production cross-section to date
- confirmed previous trend of higher than predicted cross-sections
- inclusive measurements limited by systematic uncertainties
  - signal modelling seems especially challenging, dominating Atlas measurement
  - have to better understand differences in implementation between different generators, e.g. Sherpa and MG5 FxFx
- ratio measurements of $t\bar{t}W^+$ and $t\bar{t}W^-$ limited by statistics
  - repeat in Run 3?
- first differential measurements limited by statistics
  - some mild tensions in parts of the normalised distributions
  - χ^2 doesn't show any incompatibilities

$t\bar{t}W$ Charge-Asymmetry

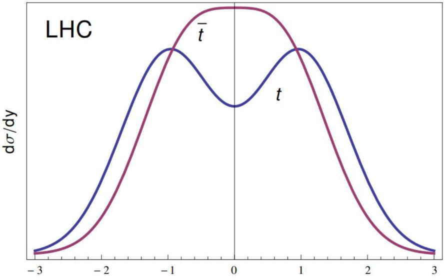
Overview

Definition:

$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

with

$$\Delta|y| = |y(t)| - |y(\bar{t})|$$



- forward-backward asymmetry in $t\bar{t}$ production, in case of $q\bar{q}$ initial state
- at LHC, $t\bar{t}$ production is gg dominated, charge-symmetric initial state
- $t\bar{t}W$ production at LO is exclusively $q\bar{q}$ initial state, gg IS only at NNLO
- W emission polarises the initial $q/\bar{q}$

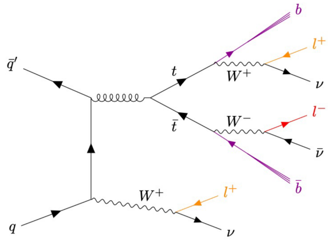
→ asymmetry should be larger in $t\bar{t}W$, but lower statistics

$$\text{leptonic } A_C = A_C^\ell = \frac{N(\Delta|\eta^\ell| > 0) - N(\Delta|\eta^\ell| < 0)}{N(\Delta|\eta^\ell| > 0) + N(\Delta|\eta^\ell| < 0)}$$

$$\text{with } \Delta|\eta^\ell| = |\eta_\ell(t)| - |\eta_\ell(\bar{t})|$$

Selection

- three leptons, charge$= \pm 1$
- $m_{\ell\ell}^{\text{OSSF}} \geq 30$ GeV
- 4 SRs: split according to $N_{b-\text{jets}}$ ($1, \geq 2$) and N_{jets} ($[2,3], \geq 4$)
- if $= 1$ b-jet, $E_{\text{T}}^{\text{miss}} \geq 50$ GeV
- Z-veto



- consider 3l channel (2lSS has no dileptonic $t\bar{t}$ decay)
- define odd OS lepton, even SS leptons
- correctly assigning even lepton to top quark is challenging $\rightarrow$ machine learning approach

$t\bar{t}W$ Charge-Asymmetry
Methodology

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Lepton-top assignment:

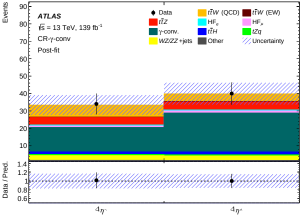
- use BDT to find correct assignments of even leptons to t/W
- BDT input variables: m_{lb} and ΔR_{lb} for two closest b-jets, lepton p_{T}
- if no 2 b-jets, jet with highest DL1r score or closest untagged jet
- estimated 71% correct assignments by highest BDT score

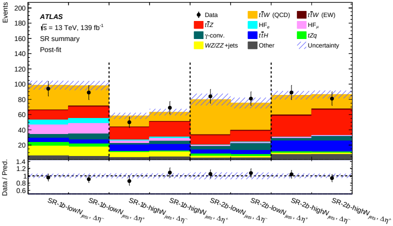
Background estimation:

- 4 CRs: $t\bar{t}Z$ (largest prompt bkg), fakes (HF e/μ), and γ conversions
- fit with 8 free-floating normalisation factors, one per CR and $\Delta|\eta^{\ell}|$ region

Cross-section extraction:

- profile-likelihood fit to event yields in SRs and CRs





nominal samples:

- Sherpa 2.2.10, same as in the cross-section measurement
- QCD sample (LO1+NLO1, NLO2+LO3 as weights) as signal
- EW sample (NLO3) as background

systematic variations:

- μ_R and μ_F scale variations
- alternative PDF sets and α_S
- generator uncertainty: Sherpa 2.2.10 vs MG5 FxFx + Pythia8
- parton shower uncertainty: Powheg+Pythia8 vs Powheg+Herwig7

comparison with cross-section analysis:

- very similar systematics scheme
- no EW fraction uncertainty
- different PDF variations, following PDF4LHC recommendations

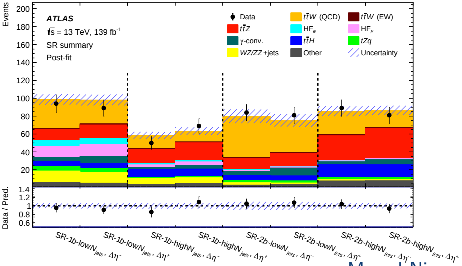
$t\bar{t}W$ Charge-Asymmetry

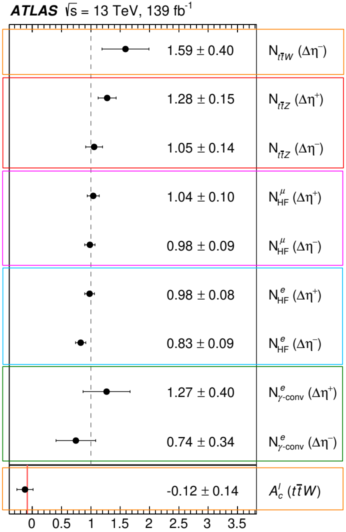
Results

- A_C^ℓ extracted directly, profiled uncertainties
- $t\bar{t}W$ NF 1.59 ± 0.40 compatible with cross-section measurements
- split bkg NF can capture data asymmetries
  - separate uncertainty to cover potential spurious impact ($\Delta\eta^\pm$ CR dependency)

$$A_C^\ell = -0.12 \pm 0.14(\text{stat}) \pm 0.05(\text{syst})$$

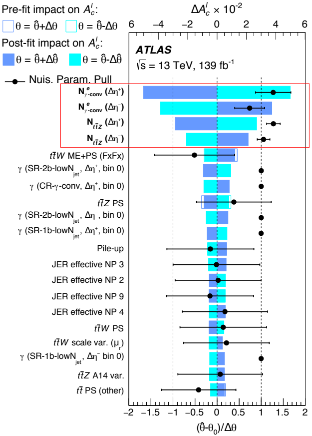
$$A_C^{\ell,\text{SM}} = -0.084^{+0.005}_{-0.003}(\text{scale}) \pm 0.006(\text{MC stat})$$





$t\bar{t}W$ Charge-Asymmetry

Uncertainties



	$\Delta A_c^\ell(t\bar{t}W)$
Experimental uncertainties	
Jet energy resolution	0.013
Pile-up	0.007
b-tagging	0.005
Leptons	0.004
E_T^{miss}	0.004
Jet energy scale	0.003
Luminosity	0.001
MC modelling uncertainties	
$t\bar{t}W$ modelling	0.013
$t\bar{t}Z$ modelling	0.010
$HF_{e/\mu}$ modelling	0.006
$t\bar{t}H$ modelling	0.005
Other uncertainties	
$\Delta\eta^\pm$ CR-dependency	0.046
MC statistical uncertainty	0.019
Data statistical uncertainty	0.136
Total uncertainty	0.145

- analysis dominated by statistics and $\Delta\eta^\pm$ CR dependency

$t\bar{t}W$ Charge-Asymmetry
Unfolding to Particle Level

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Fiducial volume definition:

- three leptons, $p_T > 15$ GeV, $|\eta| < 2.5$
- $m_{ll}^{\text{OSSF}} > 25$ GeV
- no Z candidate
- ≥ 2 jets, $p_T > 20$ GeV, ≥ 1 of them b-tagged

Unfolding:

- unregularised profile-likelihood unfolding
- introduce bias uncertainty via injection tests

$$A_C^{\ell} = -0.11 \pm 0.17(\text{stat}) \pm 0.05(\text{syst})$$

$$A_C^{\ell,\text{SM}} = -0.063^{+0.007}_{-0.004}(\text{scale}) \pm 0.004(\text{MC stat})$$

	$\Delta A_c^{\ell}(t\bar{t}W)^{\text{PL}}$
Experimental uncertainties	
Leptons	0.014
Jet energy resolution	0.011
Pile-up	0.008
Jet energy scale	0.004
E_T^{miss}	0.002
Luminosity	0.001
Jet vertex tagger	0.001
MC modelling uncertainties	
$t\bar{t}W$ modelling	0.022
$t\bar{t}Z$ modelling	0.017
$\text{HF}_{e/\mu}$ modelling	0.015
Others modelling	0.015
WZ/ZZ + jets modelling	0.014
$t\bar{t}H$ modelling	0.006
Other uncertainties	
Unfolding bias	0.004
$\Delta\eta^{\pm}$ CR-dependency	0.039
MC statistical uncertainty	0.027
Response matrix	0.009
Data statistical uncertainty	0.170
Total uncertainty	0.179

- Atlas (9%) and CMS (6%) provided the most precise measurement of the production cross-section to date
- confirmed previous trend of higher than predicted cross-sections
- inclusive measurements limited by systematic uncertainties
  - need improvement of signal modelling uncertainties
- ratio measurements of $t\bar{t}W^+$ and $t\bar{t}W^-$ limited by statistics
- first differential measurements limited by statistics
  - some mild tensions in parts of the normalised distributions
  - χ^2 doesn't show any incompatibilities
- measurement of charge-asymmetry in Atlas showed no incompatibility with SM predictions (on detector level or particle level)
  - limited by statistical uncertainty

back-up

Selection

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Muon			
Observable	Loose	Fakeable	Tight
p_T	$p_T > 10$ GeV	$p_T^{cone} > 10$ GeV	$p_T^{cone} > 10$ GeV
$\|\eta\|$	< 2.4	< 2.4	< 2.4
$\|d_{xy}\|$	< 0.05 cm	< 0.05 cm	< 0.05 cm
$\|d_z\|$	< 0.1 cm	< 0.1 cm	< 0.1 cm
d/σ_d	< 8	< 8	< 8
$miniIso$	< 0.4	< 0.4	< 0.4
p_T^{ratio}	–	$-(> 0.45)$	–
Top lepton MVA	–	$> 0.4(< 0.4)$	> 0.4

The cuts in parentheses are applied only when leptons fail tight lepton MVA cut.

Electrons			
Observable	Loose	Fakeable	Tight
p_T	$p_T > 10$ GeV	$p_T^{cone} > 10$ GeV	$p_T^{cone} > 10$ GeV
$\|\eta\|$	< 2.5	< 2.5	< 2.5
$\|d_{xy}\|$	< 0.05 cm	< 0.05 cm	$< 0.05cm$
$\|d_z\|$	< 0.1 cm	< 0.1 cm	$< 0.1cm$
d/σ_d	< 8	< 8	< 8
$miniIso$	< 0.4	< 0.4	< 0.4
$\sigma_{i\eta i\eta}$	–	$<\{0.011/0.030\}$	$<\{0.011/0.030\}$
H/E	–	< 0.10	< 0.10
1/E - 1/p	–	> -0.04	> -0.04
Missing hits	≤ 1	≤ 1	≤ 1
p_T^{ratio}	–	$-(> 0.5)$	–
Top MVA	–	$> 0.4(< 0.4)$	> 0.4

	Same-sign dilepton	Three leptons
Lepton p_T	> 30 (25) GeV for leading e (μ) > 20 GeV for sub-leading ℓ	> 25, 15, 15 GeV
$m(\ell\ell)$	> 30 GeV $\|m(ee) - m(Z)\| > 15$ GeV	> 12 GeV $\|m(\ell^{\pm}\ell^{\mp}) - m(Z)\| > 10$ GeV
Jets	≥ 2 jets	≥ 2 jets
B-tagged jets	≥ 2 loose bJets or ≥ 1 medium bJets	≥ 1 medium bJets
p_T^{miss}	> 30 GeV	-
Categories	Flavour and charge of leptons	Jet, b-tagged jet multiplicities and lepton charge

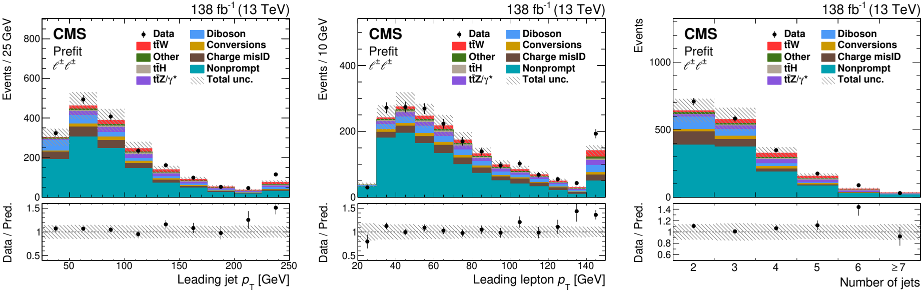
Background Estimation

Non-prompt backgrounds

- tight-to-loose ratio method
- lepton misidentification rate $f = P(\text{tight selection}|\text{loose}) = f(p_{\text{T}}, \eta)$
- measured in data enriched in QCD multijet events
- apply weight to events with ≥ 1 loose-not-tight lepton

$$w = (-1)^{n+1} \prod_{i=1}^{n} \frac{f_i}{1 - f_i}$$

- prompt contributions subtracted based on simulation
- validation in dedicated regions



Non-prompt Estimation

weights - JHEP 07 (2022) 032

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- application region: at least one loose-not-tight lepton
- T: tight, L: loose, P: prompt, F: fake; N_{TTT}: number of events with non-prompt leptons in analysis region

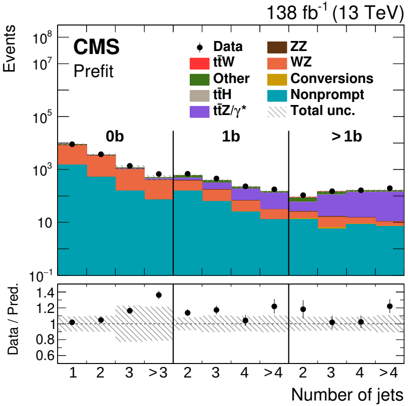
$$N_{TTT} = f_1 N_{FPP} + f_2 N_{PFP} + f_3 N_{PPF} + f_1 f_2 N_{FFP} + f_2 f_3 N_{PFF} + f_1 f_3 N_{FPF} + f_1 f_2 f_3 N_{FFF}$$
$$N_{TTL} = (1 - f_3) N_{PPF} + f_2 (1 - f_3) N_{PFF} + f_1 (1 - f_3) N_{FPF} + f_1 f_2 (1 - f_3) N_{FFF}$$
$$N_{TLT} = (1 - f_2) N_{PFP} + f_3 (1 - f_2) N_{PFF} + f_1 (1 - f_2) N_{FFP} + f_1 f_3 (1 - f_2) N_{FFF}$$
$$N_{LTT} = (1 - f_1) N_{FPP} + f_2 (1 - f_1) N_{FFP} + f_3 (1 - f_1) N_{FPF} + f_3 f_2 (1 - f_1) N_{FFF}$$
$$N_{TLL} = (1 - f_2)(1 - f_3) N_{PFF} + f_1 (1 - f_2)(1 - f_3) N_{FFF}$$
$$N_{LTL} = (1 - f_1)(1 - f_3) N_{FPF} + f_2 (1 - f_1)(1 - f_3) N_{FFF}$$
$$N_{LLT} = (1 - f_2)(1 - f_1) N_{FFP} + f_3 (1 - f_2)(1 - f_1) N_{FFF}$$
$$N_{LLL} = (1 - f_1)(1 - f_2)(1 - f_3) N_{FFF}$$

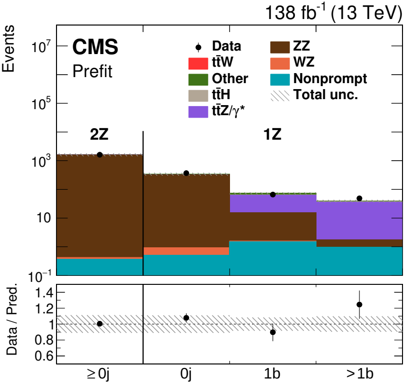
$$N_{TTT} = \frac{f_1}{1 - f_1} N_{LTT} + \frac{f_2}{1 - f_2} N_{TLT} + \frac{f_3}{1 - f_3} N_{TTL} + \frac{f_1 f_2 f_3}{(1 - f_1)(1 - f_2)(1 - f_3)} N_{LLL} - \frac{f_1 f_2}{(1 - f_1)(1 - f_2)} N_{LLT} - \frac{f_1 f_3}{(1 - f_1)(1 - f_3)} N_{LTL} - \frac{f_2 f_3}{(1 - f_2)(1 - f_3)} N_{TLL}$$

Background Estimation

Backgrounds including Z

- dominant processes including Z: WZ, ZZ, $t\bar{t}Z$
- define 2 CRs by inverting Z veto in nominal selection and requiring 4 tight leptons (ZZ and $t\bar{t}Z$ CR)
- WZ and $t\bar{t}Z$ CR split into 4 more categories according to lepton flavour
- all CRs present in the final fit





Selection

Event selection:

- ≥ 2j (≥ 1j) in 2ℓSS (3ℓ) channel,
- ≥ 1b (hybrid WP, =1b @ 60% OR ≥ 2 @ 77%)*
- Di-lepton Triggers (lowest unprescaled)
- $m_{\ell\ell} > 12$ GeV, on-shell Z-veto (3ℓ SR)

Overlap removal ("b-jet aware"):

- **e/μ**: OR if $\Delta R(e, \mu) < 0.01$
  remove μ if calo-tagged, else remove e
- **e/j**: OR if $\Delta R(\text{jet}, e) < 0.2$
  remove jet if not b-tagged
- **μ/j**: OR if $\Delta R(\text{jet}, \mu) < 0.4$ (ghost-matched)
  remove jet if not b-tagged, < 3 tracks
- **j/e,μ**: $R = 0.04 + 10 / p_T(e/\mu) < 0.4$
  remove e/μ if OR within the above cone

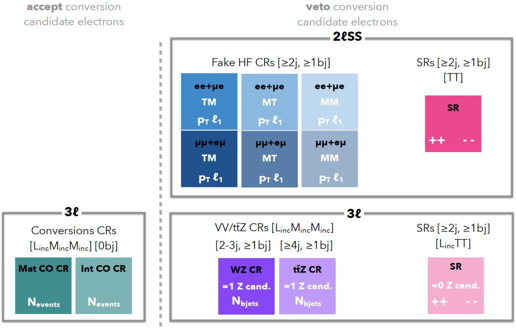
Object selection:

- **e, μ**:
  - ⇒ **"Loose"** definition (for OR and channel definition):
    - $p_T > 10$ GeV, FCLoose isolation, LooseLH (Loose) ID for e (μ), standard impact parameter cuts, e not in the LAr crack region ($1.37 < |\eta| < 1.52$)
  - ⇒ **"Tight"** definition (in region definition):
    - $p_T > 20$ GeV (SS), > 10 GeV (OS in 3ℓ)
    - e (SS): Tight LH, FCLoose isolation, ECIDS cut > 0.7, ambiguity cut, conversion cuts, PromptImprovedLeptonVeto (PLIV)
    - μ (SS): Medium, FCLoose isolation, PromptImprovedLeptonVeto (PLIV)
- **jets**:
  AntiKt4EMPFlowJets, passJVT, $p_T > 25$ GeV, DL1r b-tagging

* but = 0b in $Z\gamma^*$ control regions

Template fit

- Estimate background using a template fit method
- Use exclusive PLIV WP to construct CRs
- PLIV is a non-prompt lepton BDT
- takes isolation and lifetime information into account, p_T dependent
- Tight WP: efficiency of 60%-95%, rejection of 20 to 50
- VeryTight WP: efficiency of 55%-90%, rejection of 33 to 100



- Uses 6 free floating normalisation factors for
  - internal and external conversion
  - heavy flavour with non-prompt electron/muon
  - $t\bar{t}Z$, and diboson backgrounds

Grouped Impacts

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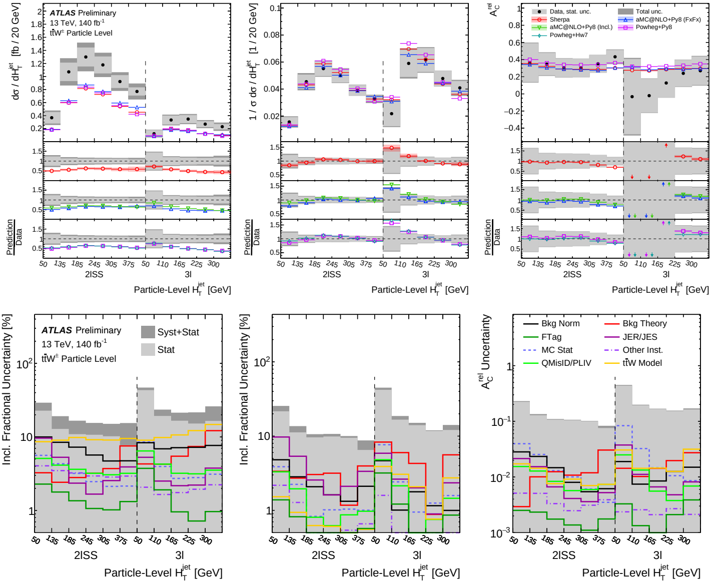
	$\frac{\Delta\sigma(t\bar{t}W)}{\sigma(t\bar{t}W)}$ [%]	$\frac{\Delta\sigma_{\text{fid}}(t\bar{t}W)}{\sigma_{\text{fid}}}$ [%]	$\frac{\Delta R(t\bar{t}W)}{R(t\bar{t}W)}$ [%]	$\frac{\Delta A_C^{\text{rel}}}{A_C^{\text{rel}}}$ [%]
$t\bar{t}W$ ME and PS modelling	6.0	7.0	6.0	8.0
Prompt lepton bkg. norm.	2.6	2.5	1.6	2.2
Lepton isolation BDT	2.3	2.3	1.0	1.2
Fakes/VV/$t\bar{t}Z$ norm. (free-floated)	2.3	2.7	1.8	2.5
Non-prompt lepton bkg. modelling	1.9	1.7	2.3	3.1
Trigger	1.9	1.8	0.5	0.7
MC statistics	1.5	1.6	1.9	2.5
$t\bar{t}W$ PDF	1.5	1.4	2.1	2.8
Jet energy scale	1.4	1.9	0.8	1.1
Prompt lepton bkg. modelling	1.3	1.3	1.3	1.9
Luminosity	1.0	1.0	0.08	0.13
Charge Mis-ID	0.7	0.7	0.4	0.5
Jet energy resolution	0.5	0.6	0.7	0.31
Flavour tagging	0.28	0.33	0.5	1.0
$t\bar{t}W$ Scale	0.21	0.9	1.4	1.9
Electron/photon reco.	0.15	0.2	0.12	0.3
MET	<0.10	<0.10	0.17	0.4
Muon	<0.10	<0.10	<0.10	0.4
Pile-up	<0.10	0.25	<0.10	0.3
Total syst.	8	10	8	10
Data statistics	5	5	10	16
Total	9	11	13	19

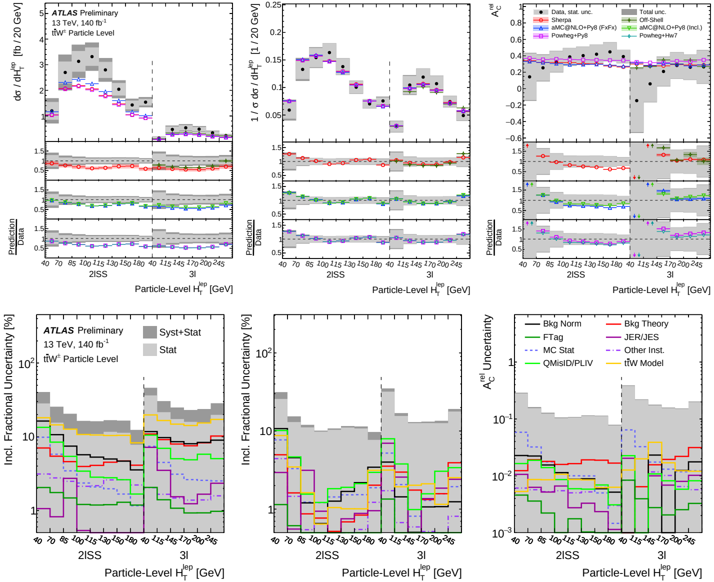
Fiducial Volume Definition:

Objects	
Electrons	$p_{\mathrm{T}} \geq 10$ GeV and $\lvert\eta\rvert < 2.47$ (excluding the LAr crack region with $1.37 < \lvert\eta\rvert < 1.52$)
Muons	$p_{\mathrm{T}} \geq 10$ GeV and $\lvert\eta\rvert < 2.5$
Jets	anti-k_t $R = 0.4$ jets with $p_{\mathrm{T}} \geq 25$ GeV and $\lvert\eta\rvert < 4.5$ (with N_{jets} restricted to $\lvert\eta\rvert < 2.5$)
b-jets	Tagged if jet contains a ghost-matched b-hadron with $p_{\mathrm{T}} > 5$ GeV
$E_{\mathrm{T}}^{\mathrm{miss}}$	Vector sum of $p_{\mathrm{T}}(\nu)$ for all neutrinos in the event not from hadron decays
Overlap removal	
Electron–jet	If $\Delta R(e, \mathrm{jet}) < 0.2$ (excluding b-jets with $p_{\mathrm{T}} > 200$ GeV) remove jet
Jet–lepton	If $\Delta R(\ell, \mathrm{jet}) < \min(0.4, 0.04 + 10\,\mathrm{GeV}/p_{\mathrm{T},\ell})$ remove lepton
Selections	
2ℓ	Exactly two leptons with the same charge Both leptons have $p_{\mathrm{T}} \geq 20$ GeV $N_{\mathrm{jets}} \geq 3$ ($N_{\mathrm{jets}} \geq 2$) with at least one b-jet for inclusive (differential) fit $m_{\ell\ell} > 12$ GeV for same-flavour pairs
3ℓ	Exactly three leptons with a total charge of $\pm 1e$ Both leptons from the same-sign lepton pair are required to have $p_{\mathrm{T}} \geq 20$ GeV $N_{\mathrm{jets}} \geq 1$ with at least one b-jet $m_{\ell\ell} > 12$ GeV & $\lvert m_{\ell\ell} - m_Z\rvert > 10$ GeV (for $\ell\ell$ with same-flavour & opposite-charge) $\lvert m_{\ell\ell\ell} - m_Z\rvert > 10$ GeV

Differential plots



Differential plots



Differential Cross-Section

$H_{\mathrm{T,jets}}$, $H_{\mathrm{T,lep}}$

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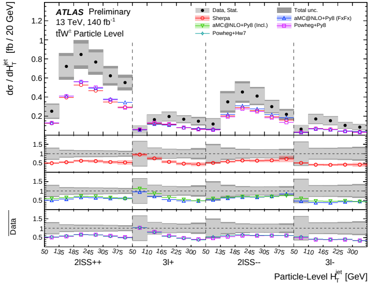

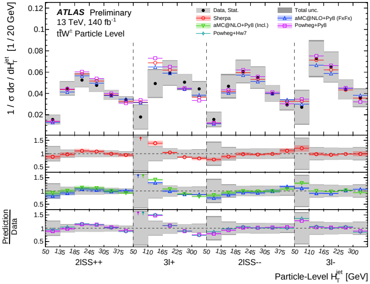

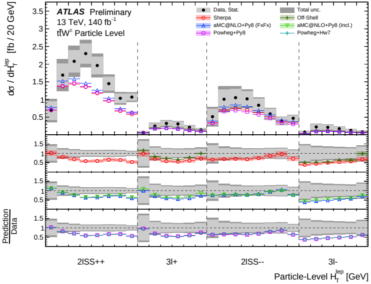

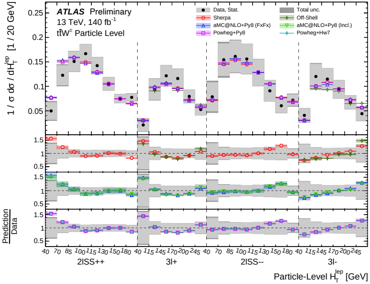

Differential plots

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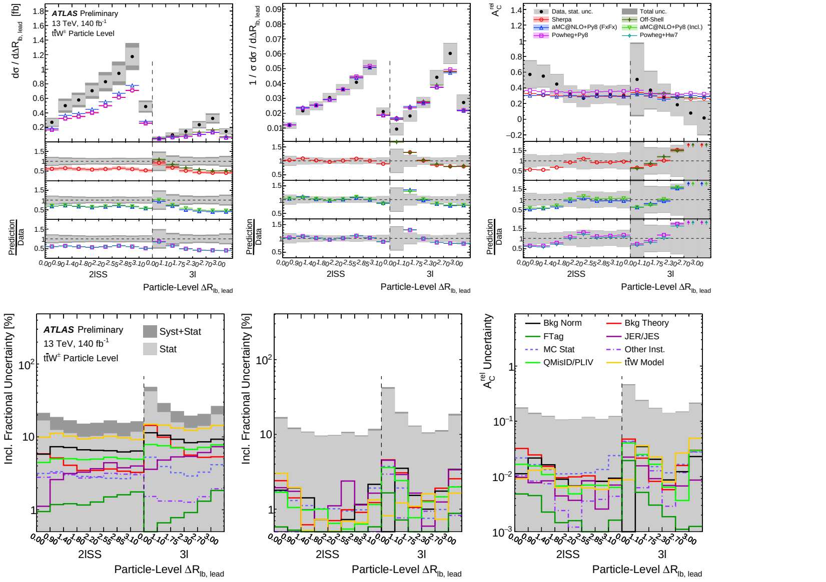

Differential plots

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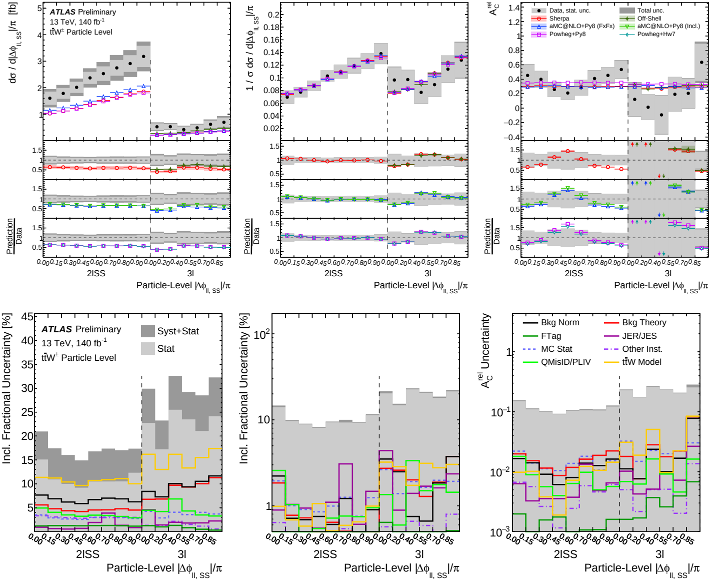
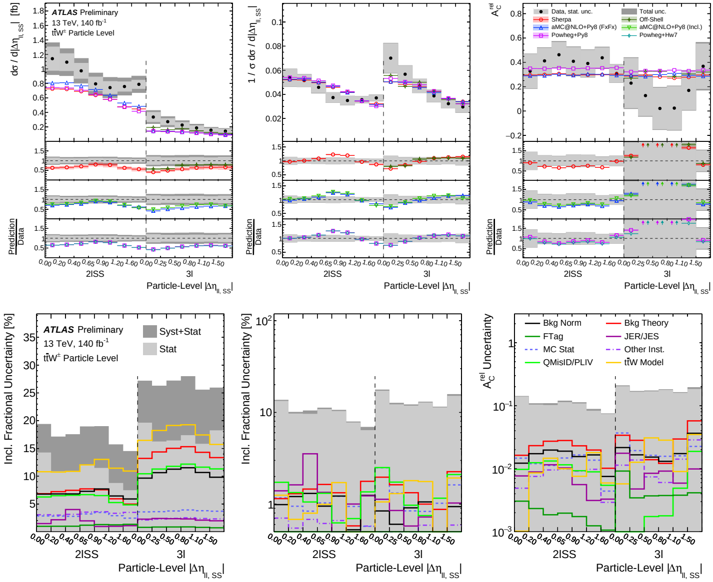
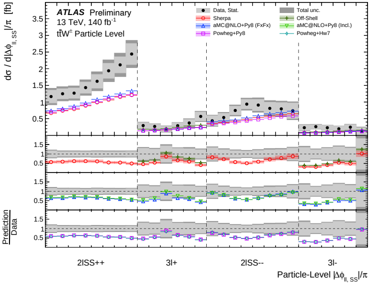


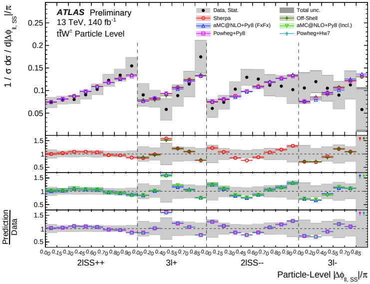
Differential plots

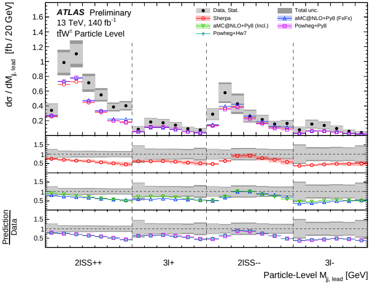


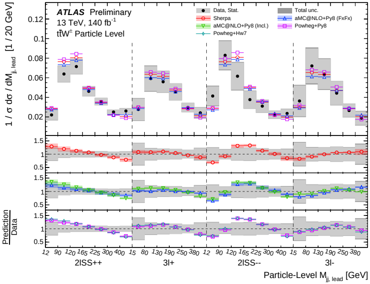
Differential Cross-Section

$|\Delta\phi_{ll,SS}|$, $M_{jj,lead}$









Differential plots

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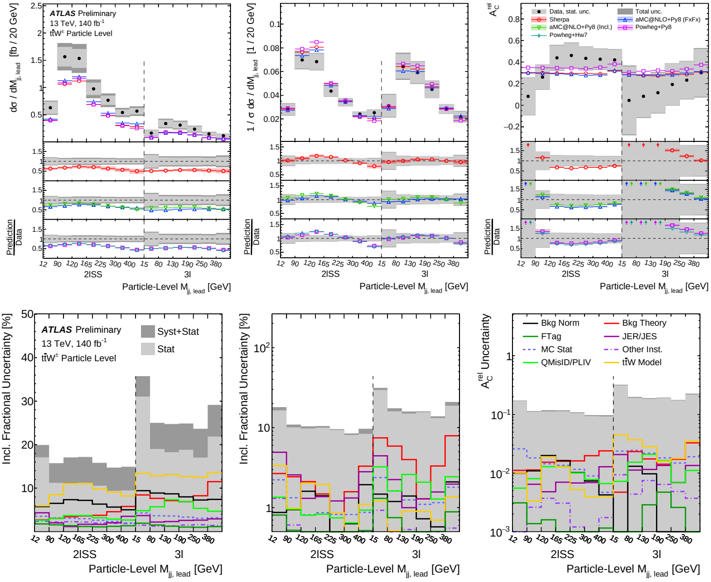


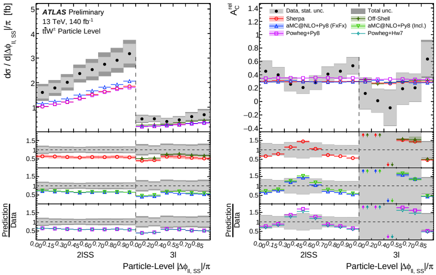
Differential Results

Observable	NDF	Sherpa 2.2.10		MG5aMC+Py8 FxFx		MG5aMC+Py8 Incl.		Powheg+Pythia8		Powheg+Herwig7	
		χ^2	p-value	χ^2	p-value	χ^2	p-value	χ^2	p-value	χ^2	p-value
N_{jets}	5	2.4	0.79	4.2	0.52	2.8	0.73	2.9	0.72	2.6	0.76
$H_{\text{T,jets}}$	5	0.7	0.98	1.1	0.95	0.8	0.98	1.5	0.91	2.0	0.85
$H_{\text{T,lep}}$	7	3.6	0.82	3.8	0.80	3.4	0.84	3.4	0.85	3.5	0.84
$\Delta R_{\text{lb, lead}}$	7	2.0	0.96	2.4	0.93	2.6	0.92	2.6	0.92	2.5	0.93
$\|\Delta\phi_{\text{ll, SS}}\|$	7	0.6	1.00	0.7	1.00	0.9	1.00	0.8	1.00	0.9	1.00
$\|\Delta\eta_{\text{ll, SS}}\|$	6	6.5	0.37	7.3	0.29	11.4	0.08	9.5	0.15	9.4	0.15
$M_{\text{jj, lead}}$	6	4.9	0.56	2.7	0.84	7.2	0.30	9.0	0.17	10.9	0.09

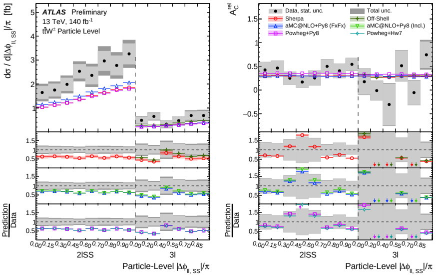
Observable	NDF	Sherpa 2.2.10		MG5aMC+Py8 FxFx		MG5aMC+Py8 Incl.		Powheg+P8		Powheg+H7	
		χ^2	p-value	χ^2	p-value	χ^2	p-value	χ^2	p-value	χ^2	p-value
N_{jets}	6	3.1	0.79	3.2	0.79	2.7	0.84	2.3	0.89	2.6	0.86
$H_{\text{T,jets}}$	6	2.7	0.84	2.9	0.82	1.6	0.95	0.9	0.99	1.4	0.96
$H_{\text{T,lep}}$	8	5.3	0.72	5.2	0.74	2.5	0.96	1.9	0.98	2.8	0.94
$\Delta R_{\text{lb, lead}}$	8	4.1	0.85	4.5	0.81	3.3	0.91	2.9	0.94	3.4	0.91
$\|\Delta\phi_{\text{ll, SS}}\|$	8	6.7	0.56	7.5	0.49	6.0	0.65	5.8	0.67	6.1	0.64
$\|\Delta\eta_{\text{ll, SS}}\|$	7	4.5	0.72	4.5	0.72	3.3	0.86	3.2	0.86	3.6	0.82
$M_{\text{jj, lead}}$	7	5.3	0.62	5.7	0.58	4.4	0.74	3.5	0.84	4.0	0.78

Observable	NDF	Sherpa 2.2.10		Off-Shell		MG5aMC+Py8 FxFx		MG5aMC+Py8 Incl.		Powheg+Py8		Powheg+H7	
		χ^2	p-value	χ^2	p-value	χ^2	p-value	χ^2	p-value	χ^2	p-value	χ^2	p-value
N_{jets}	4	1.5	0.83	-	-	1.9	0.76	1.7	0.78	2.5	0.65	1.8	0.77
$H_{\text{T,jets}}$	5	2.4	0.80	-	-	2.6	0.76	2.7	0.74	3.6	0.61	2.8	0.73
$H_{\text{T,lep}}$	6	1.5	0.96	3.1	0.79	1.6	0.96	1.5	0.96	2.0	0.92	1.5	0.96
$\Delta R_{\text{lb, lead}}$	6	1.6	0.95	2.2	0.90	2.6	0.86	2.5	0.87	3.0	0.81	2.3	0.89
$\|\Delta\phi_{\text{ll, SS}}\|$	6	4.8	0.57	5.0	0.55	5.4	0.49	5.3	0.50	6.1	0.41	5.4	0.50
$\|\Delta\eta_{\text{ll, SS}}\|$	6	2.5	0.86	3.6	0.73	3.1	0.79	3.0	0.80	3.5	0.75	3.0	0.81
$M_{\text{jj, lead}}$	6	1.3	0.97	2.2	0.90	1.5	0.96	1.6	0.95	2.3	0.89	1.6	0.95

with regularisation



without regularisation

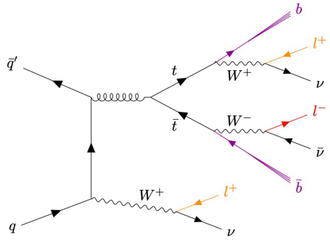


$$\mathcal{L}(\sigma, \vec{\theta}, \vec{\lambda}) = \prod_i P\left(N_i \middle| L_{\text{int}} \sum_j \mathcal{R}_{ij}(\vec{\theta}\sigma_j(\vec{\theta}) + B_i(\vec{\theta}, \vec{\lambda})\right) \times \prod_k G(\theta_k) \times R(\sigma_j, \tau_j)$$

- regularisation parameter τ optimised per channel and observable
- optimisation by statistical bootstrapping: toy experiments based on alternative model, find largest τ that doesn't increase χ^2 wrt truth
- reduces impact of fluctuations, no increase in bias

- Asimov fit $\rightarrow$ perfect closure
- injection of normalisation, linear slopes on particle level $\rightarrow$ perfect retrieval of injected templates
- unfolding of alternative Asimov sample to check bias
- splitting sample in two (equal size) to check impact of statistical fluctuations. One for unfolding, one for Asimov data
- injecting shapes seen in previous measurements
- good closure in all cases
- injection of quadratic shapes $\rightarrow$ at 200% enhancement, median bias between 1% and 30%

	Pre-selection			
N_ℓ ($\ell = e/\mu$)	$= 3$			
p_T^ℓ ($1^{st}/2^{nd}/3^{rd}$)	$\geq$ 30GeV, $\geq$ 20GeV, $\geq$ 15GeV			
$\sum$ lep. charges	± 1			
$m_{\ell\ell}^{\mathrm{OSSF}}$	$\geq$ 30GeV			
	Region-specific requirements			
	SR-1b-lowN_{jets}	SR-1b-highN_{jets}	SR-2b-lowN_{jets}	SR-2b-highN_{jets}
N_{jets}	$[2, 3]$	≥ 4	$[2, 3]$	≥ 4
$N_{b\text{-jets}}$	$= 1$	$= 1$	≥ 2	≥ 2
E_T^{miss}	$\geq$ 50GeV	$\geq$ 50GeV	–	–
$N_{Z\text{-cand.}}$	$= 0$			
Tight leptons	TTT			
e/γ ambiguity-cuts	all pass			
	CR-Z	CR-HF$_e$	CR-HF$_\mu$	CR-γ-conv.
$\ell^{1st/2nd/3rd}$	$\ell\ell\ell$	$\ell\ell e$	$\ell\ell\mu$	$\ell\ell e$, $\ell e\ell$, $e\ell\ell$
N_{jets}	≥ 4	≥ 2	≥ 2	≥ 2
$N_{b\text{-jets}}$	≥ 2	$= 1$	$= 1$	≥ 1
E_T^{miss}	–	$<$ 50GeV	$<$ 50GeV	–
$N_{Z\text{-cand.}}$	$= 1$	$= 0$	$= 0$	$= 0$
Tight leptons	TTT	$TT\bar{T}$	$TT\bar{T}$	TTT
e/γ ambiguity-cuts	all pass	all pass	all pass	$\geq$ 1 fail



- consider 3l channel (2lSS has no dileptonic $t\bar{t}$ decay)
- define odd OS lepton, even SS leptons
- correctly assigning even lepton to top quark is challenging $\rightarrow$ machine learning approach