New measurements of $t\bar{t}W$ production with the ATLAS and CMS experiments

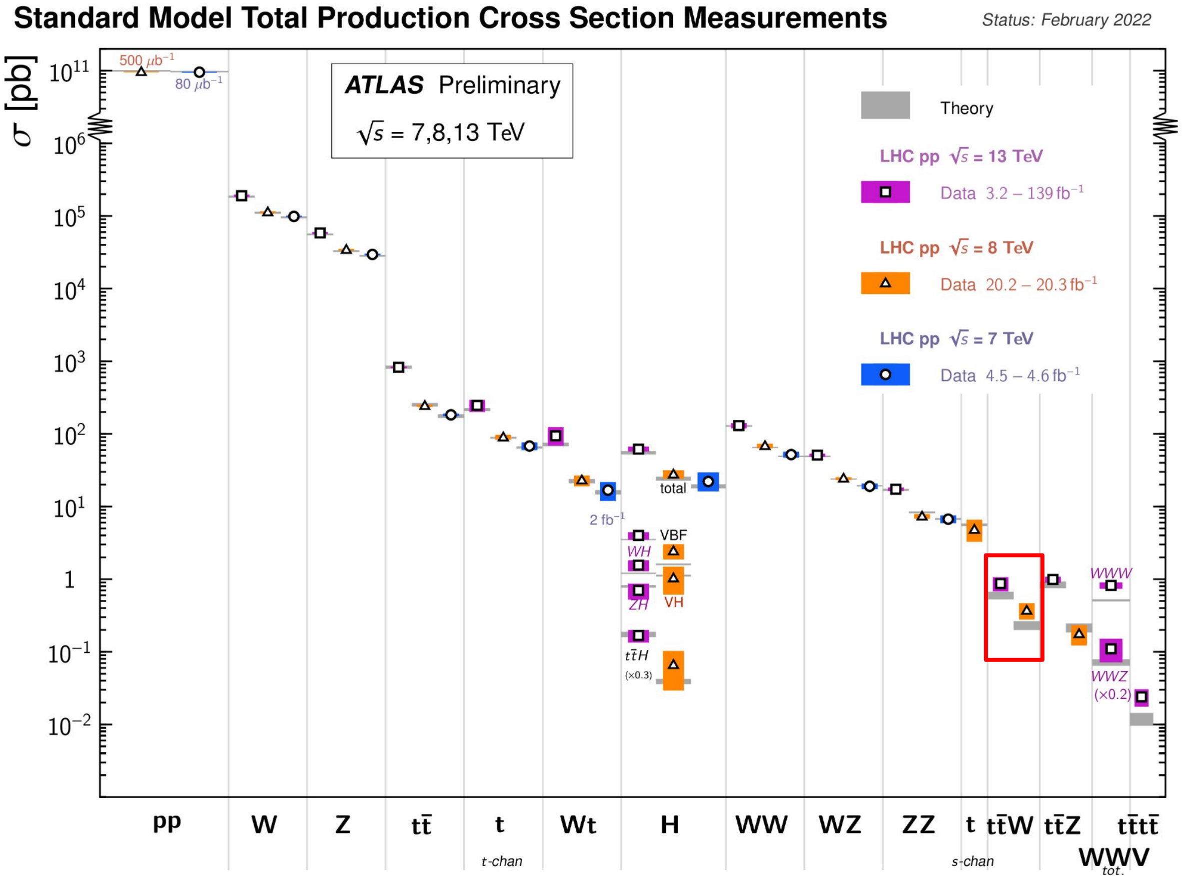
Matt Klein (Southern Methodist University)

2023 September 25

Introduction

In this talk, will discuss three $t\bar{t}W$ results from ATLAS and CMS

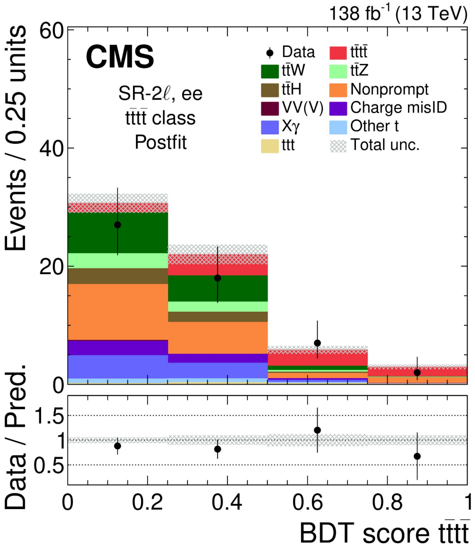
- ATLAS cross-section ATLAS-CONF-2023-019
- CMS, cross-section JHEP 07 (2023) 219
- ATLAS charge asymmetry JHEP 07 (2023) 033

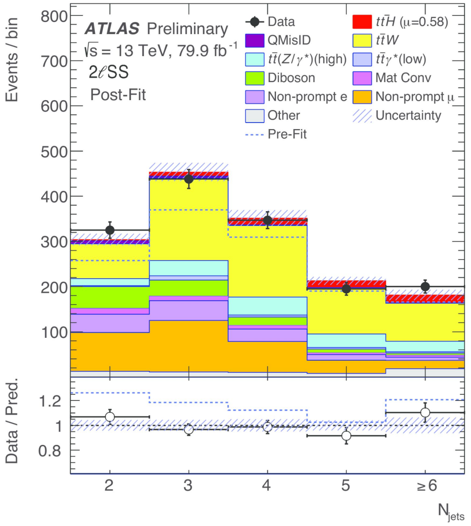


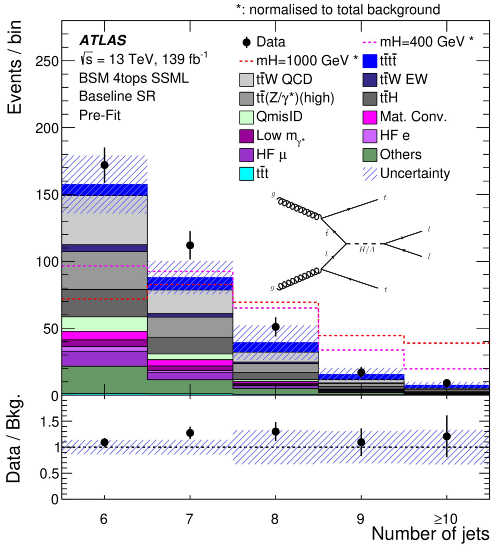
$t\bar{t}W$ Cross-section Measurements

Rare but important process in the SM - sensitive to complex higher order corrections and a background for other SM and BSM processes that can give same-sign or multilepton signatures, e.g.:

- $t\bar{t}t\bar{t}$
  [2305.13439 (sub to PLB)](2305.13439)
- Multilepton $t\bar{t}H$
  ATLAS-CONF-2019-045
- $t\bar{t}H(t\bar{t})$
  JHEP 07 (2023) 203







CMS and ATLAS have performed $t\bar{t}W$ measurements with the full LHC Run 2 dataset

- CMS Paper: JHEP 07 (2023) 219
- ATLAS Note: ATLAS-CONF-2023-019

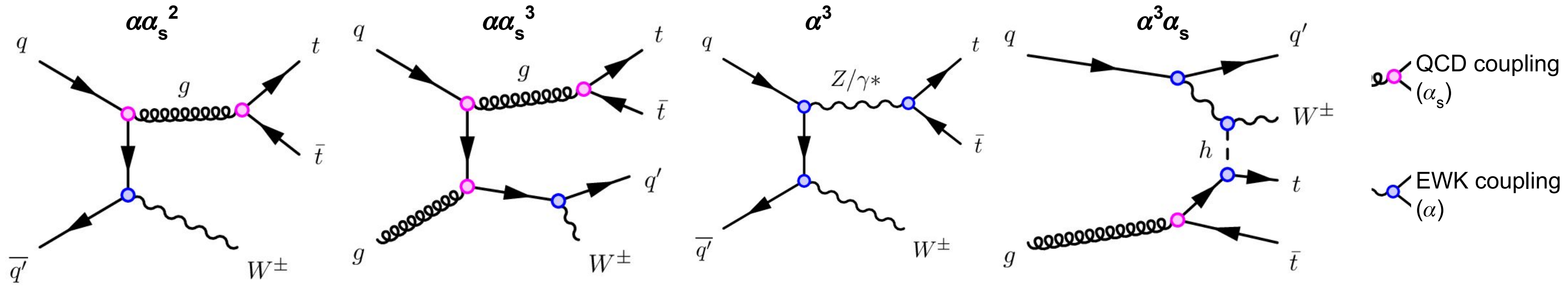
$t\bar{t}W$ Simulation

ATLAS signal samples:

- Nominal sample produced in Sherpa2.2.10 (includes $\alpha\alpha_s^2$ and $\alpha\alpha_s^3$ contributions)
- Event-by-event corrections to account for $\alpha^2\alpha_s^2$ and α^3
- Separate sample produced in Sherpa2.2.10 that corresponds to $\alpha^3\alpha_s$ contributions

CMS signal samples

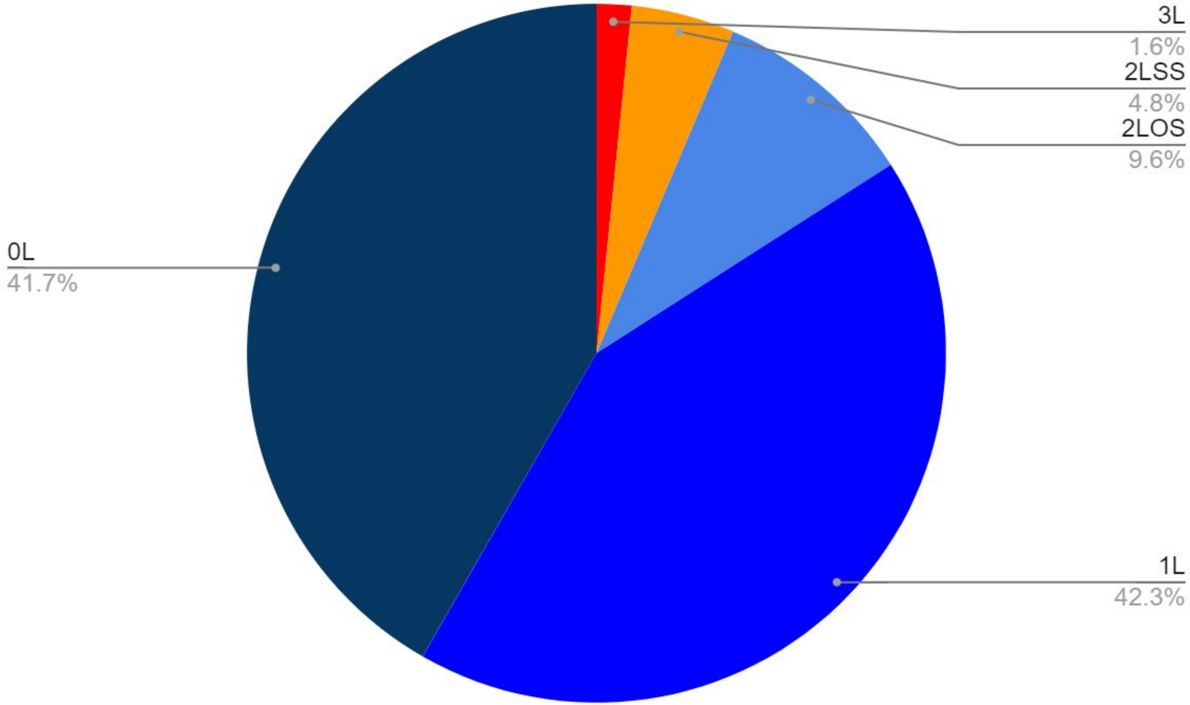
- Nominal samples produced in MadGraph5_aMC@NLO v2.6.0
- Take into account $\alpha\alpha_s^2$ and $\alpha\alpha_s^3$ (QCD contributions) and α^3 and $\alpha^3\alpha_s$ (EWK contributions)



Event Categorization

Both ATLAS and CMS analyses consider events with 2 same-sign or 3 e/μ

Drops most $t\bar{t}W$ events, but SM background with ≥2 same-sign leptons is small



ATLAS-CONF-2023-019

ATLAS Yields

Strategy: Divide events into $\ell^\pm\ell^\pm$ and $\ell^\pm\ell^\pm\ell^\mp$

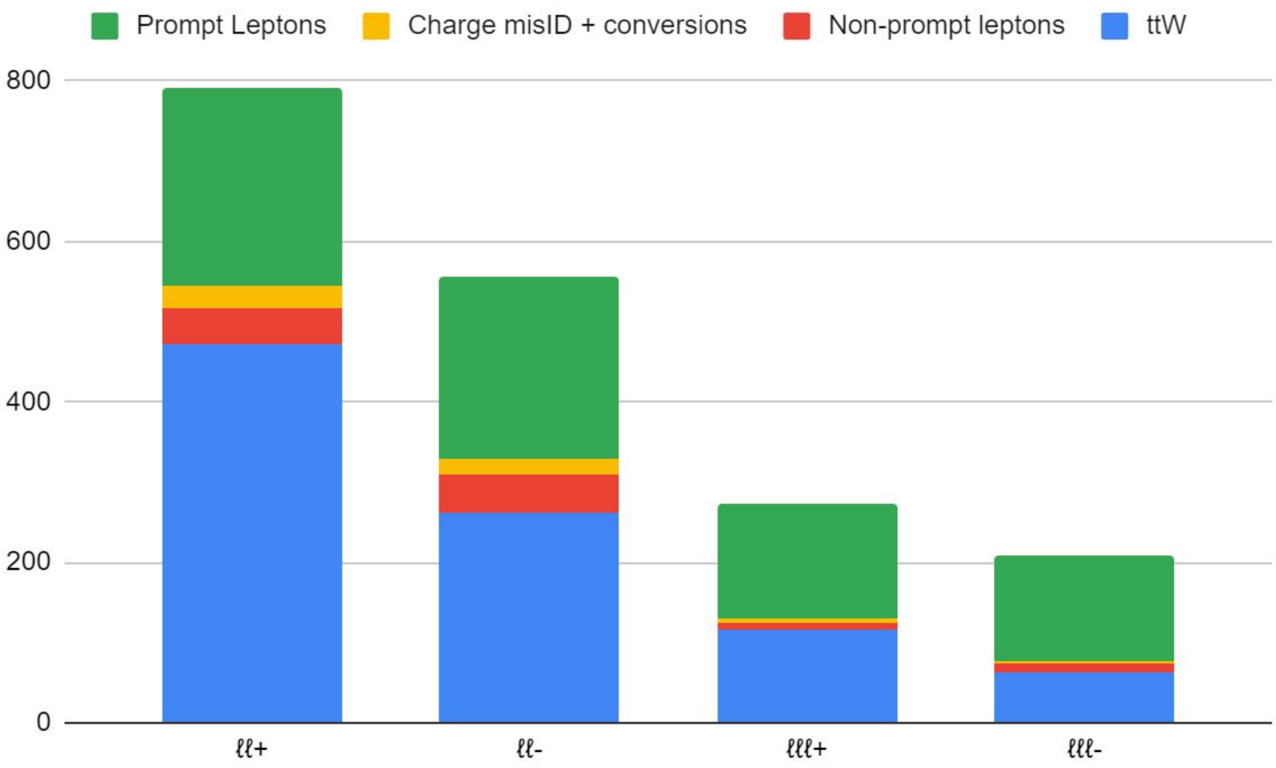
Background estimates:

Prompt leptons: from MC

Charge misID+conv.: misID from data, conv. from MC

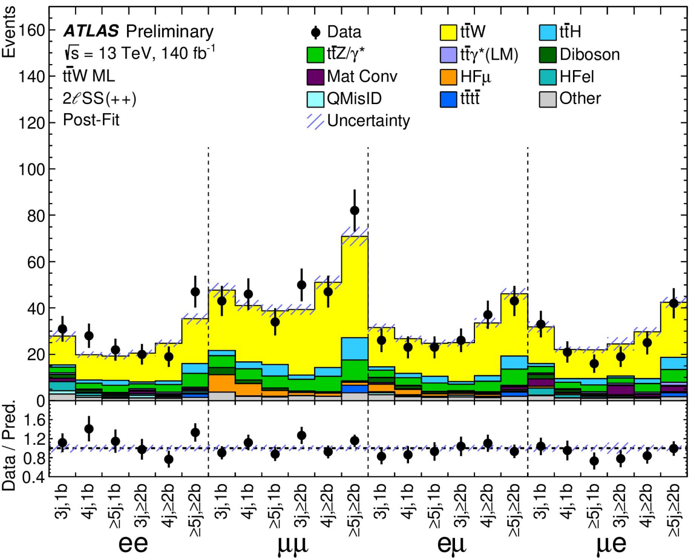
Non-prompt: from MC

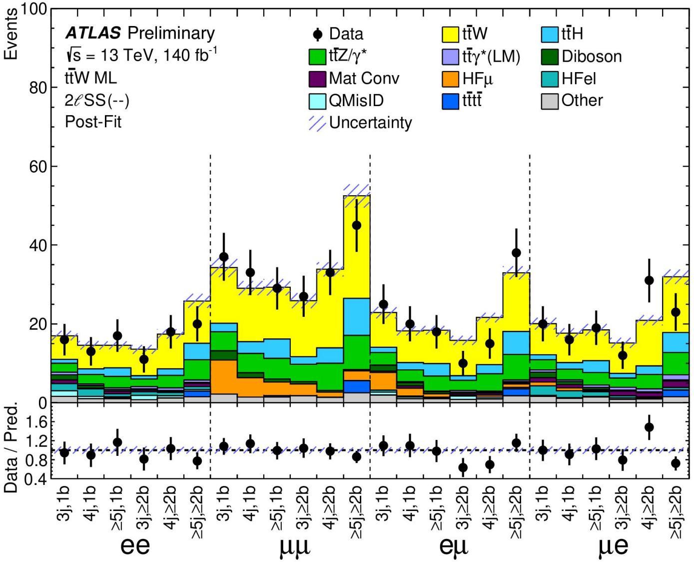
$t\bar{t}W$: Signal, from fits

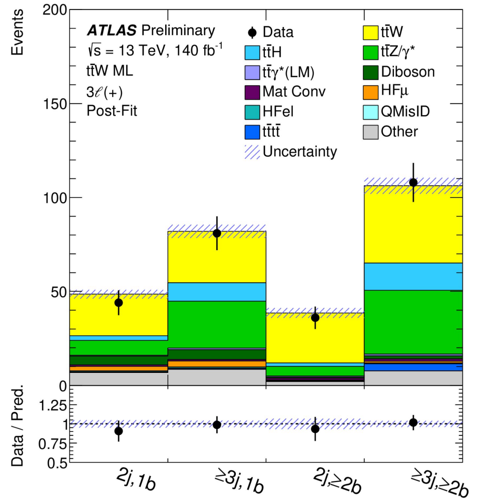


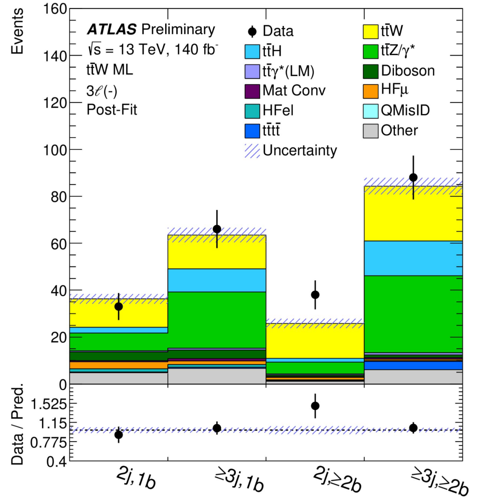
ATLAS Signal Extraction

Events categorized by
- Lepton charges and types
- Number of jets
- Number of b-jets



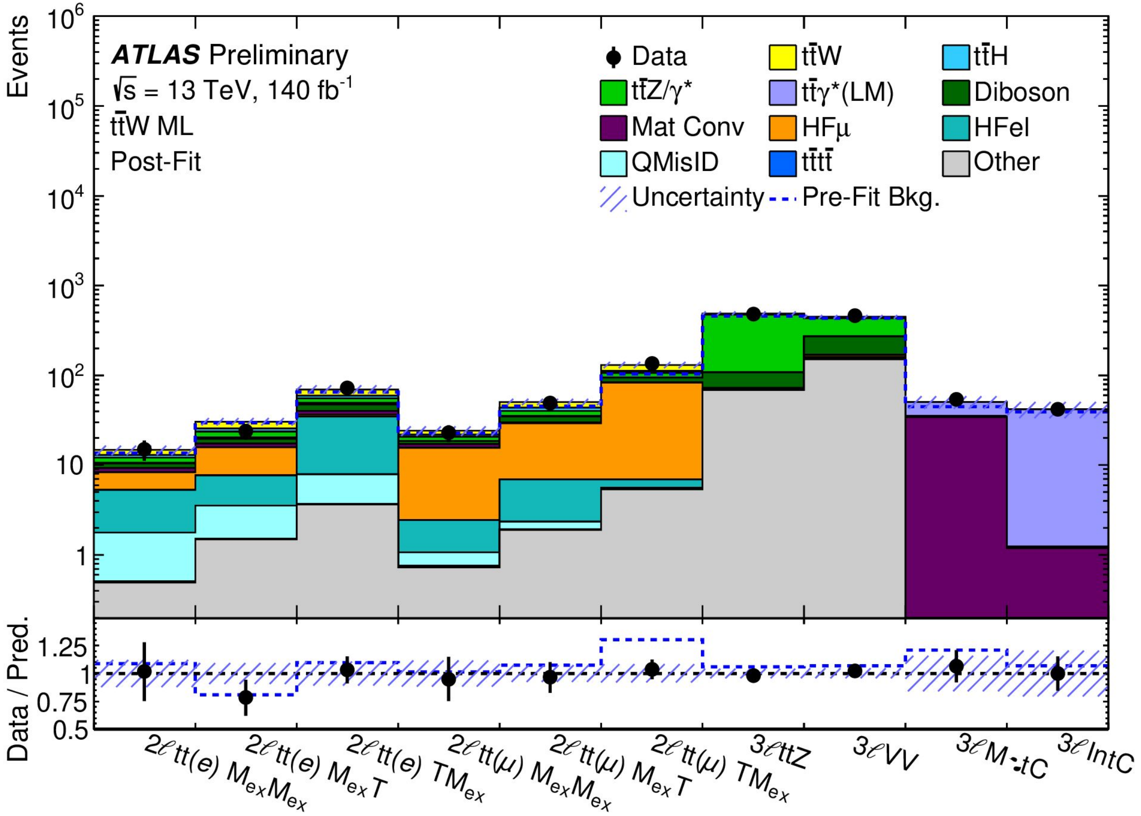






ATLAS Control Regions

Normalizations constrained by dedicated control regions for Diboson, ttZ, conversions, and non-prompt heavy flavor lepton background



JHEP 07 (2023) 219

CMS Yields

Strategy: Divide events into $\ell^{\pm}\ell^{\pm}$ and $\ell^{\pm}\ell^{\pm}\ell^{\mp}$

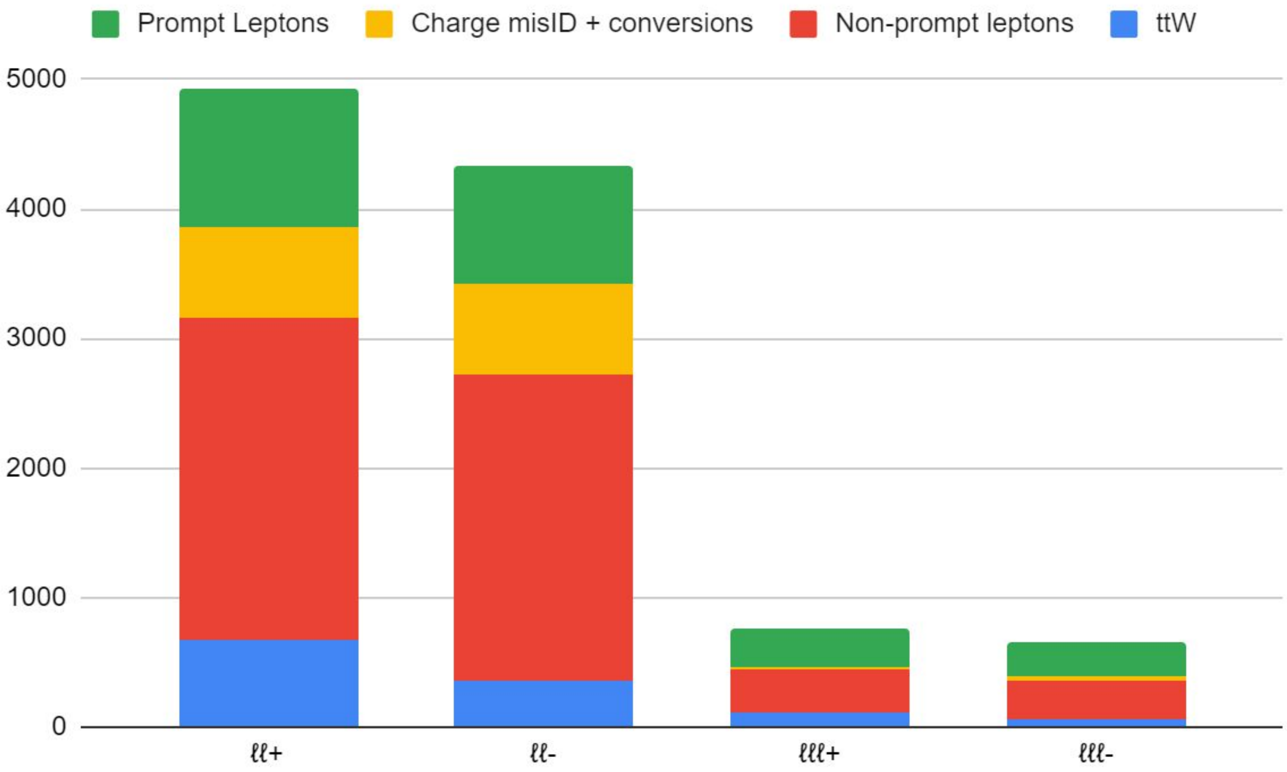
Background estimates:

Prompt leptons: from MC

Charge misID+conv.: misID from data, conv. from MC

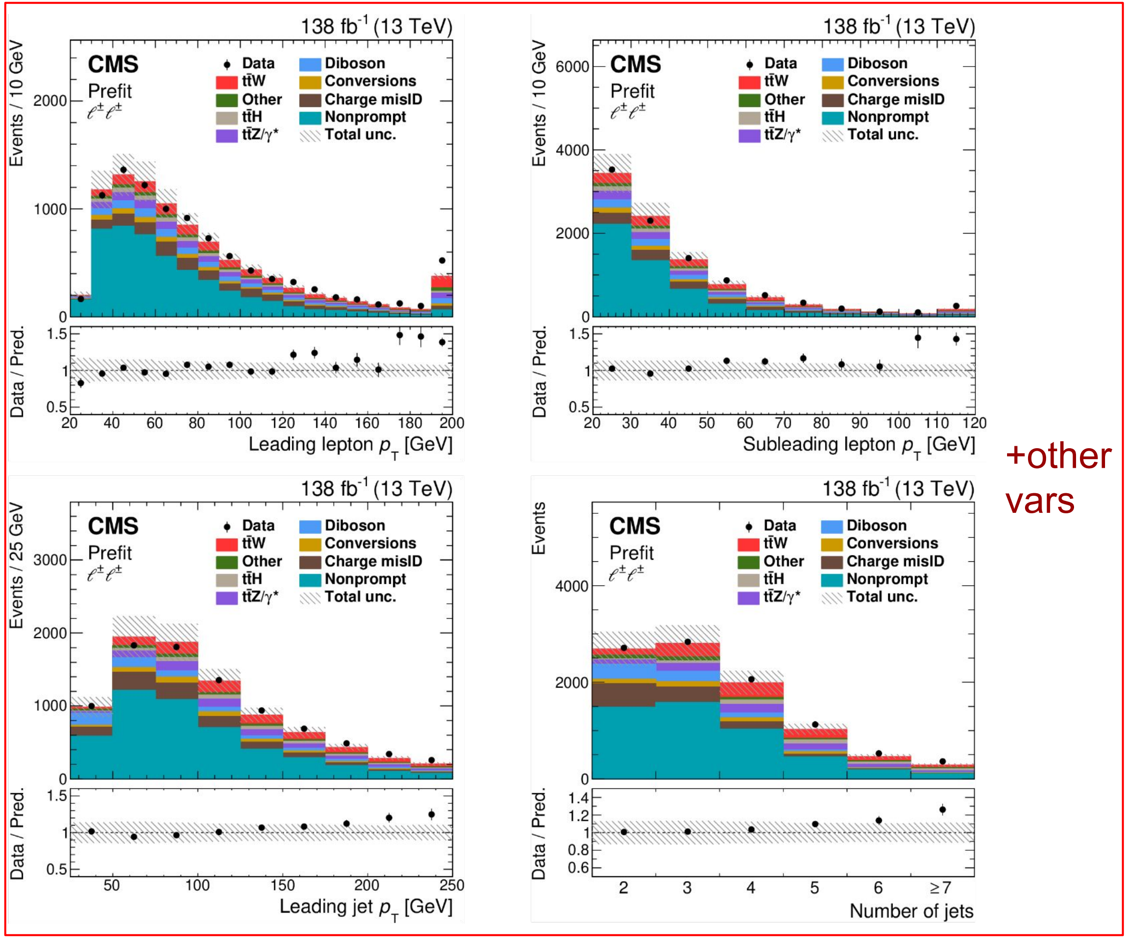
Non-prompt: from data

$t\bar{t}W$: Signal, from fits



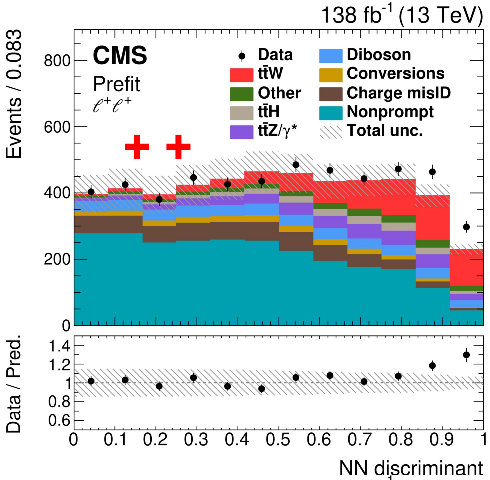
JHEP 07 (2023) 219

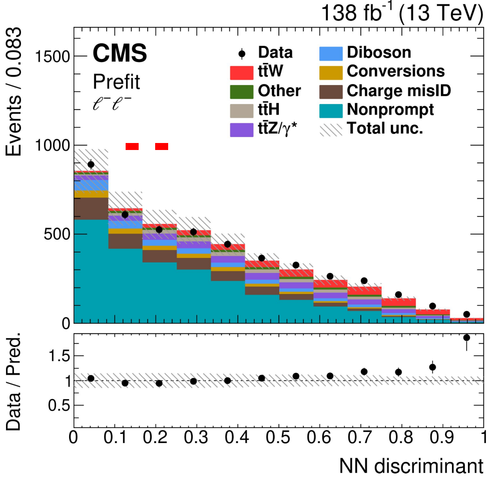
CMS: 2L Signal Extraction



+other vars

Fit Neural Net



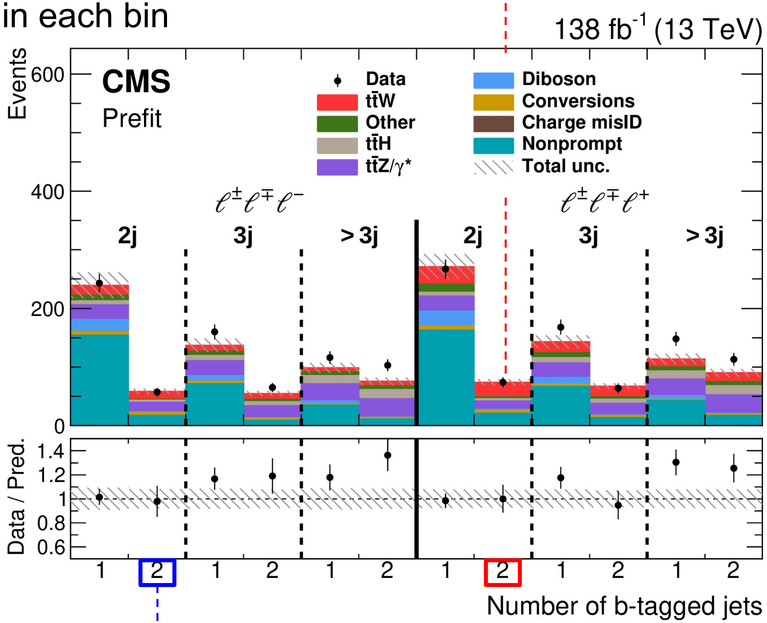


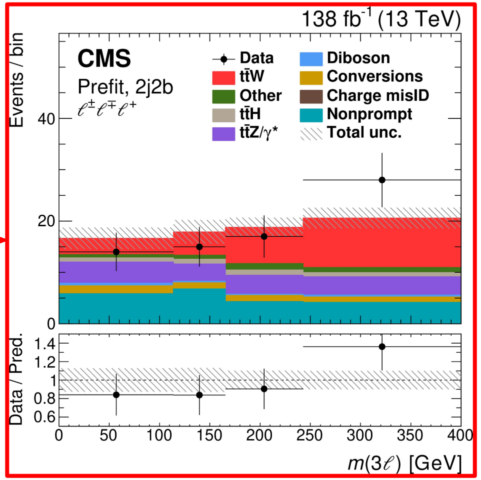
CMS 3L Signal Extraction

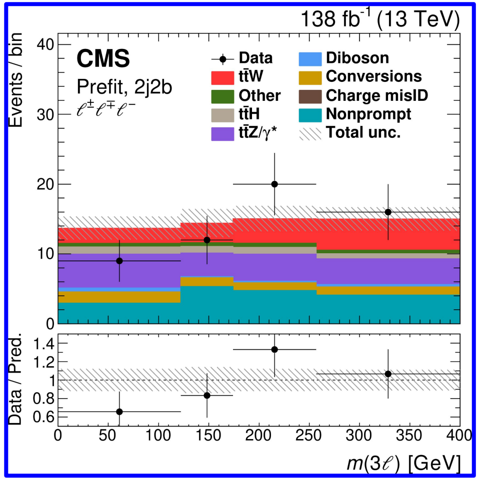
Categorize events based on:

- Sum of lepton charges (+1 or -1)
- Number of b-jets
- Number of jets

Fit m(3ℓ) in each bin





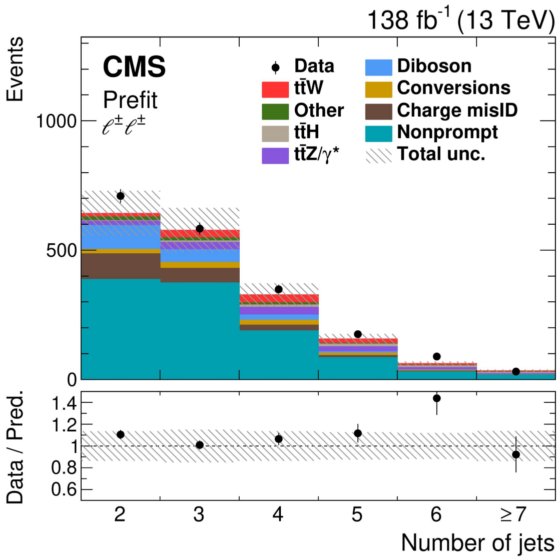


JHEP 07 (2023) 219

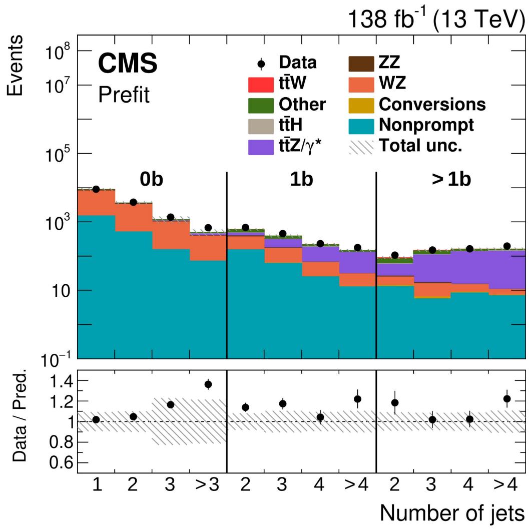
CMS Control Regions

Main backgrounds: **non-prompt leptons**

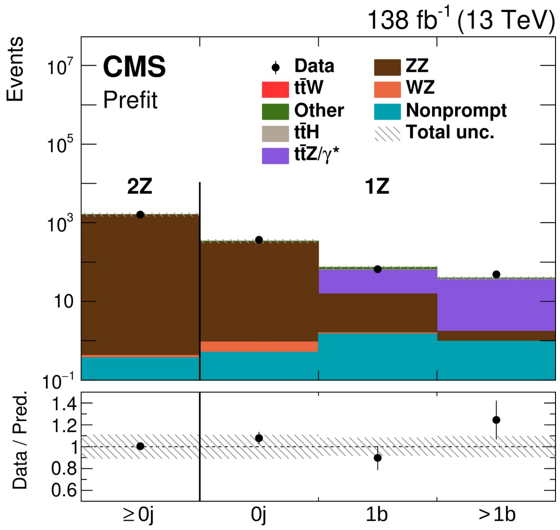
Matrix method to estimate, validated in regions formed by inverting p_T^{miss} cut



ttZ+WZ CR: 3L with $|m(\ell\ell) - mZ| < 10$ GeV



ttZ+ZZ CR: 4L with $|m(\ell\ell) - mZ| < 10$ GeV



JHEP 07 (2023) 219
ATLAS-CONF-2023-019

Uncertainty Breakdown

Largest difference in uncertainty treatment - ME and PS systematic included in ATLAS, defined as:

- Comparison of **Sherpa2.2.10** vs. **MadGraph5_aMC@NLO+Pythia8 FxFx**
- Comparison of **Powheg+Pythia8** vs. **Powheg+Herwig7**

ATLAS

	$\frac{\Delta\sigma(t\bar{t}W)}{\sigma(t\bar{t}W)}$ [%]
$t\bar{t}W$ 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

[red box] $t\bar{t}W$ modeling uncertainties

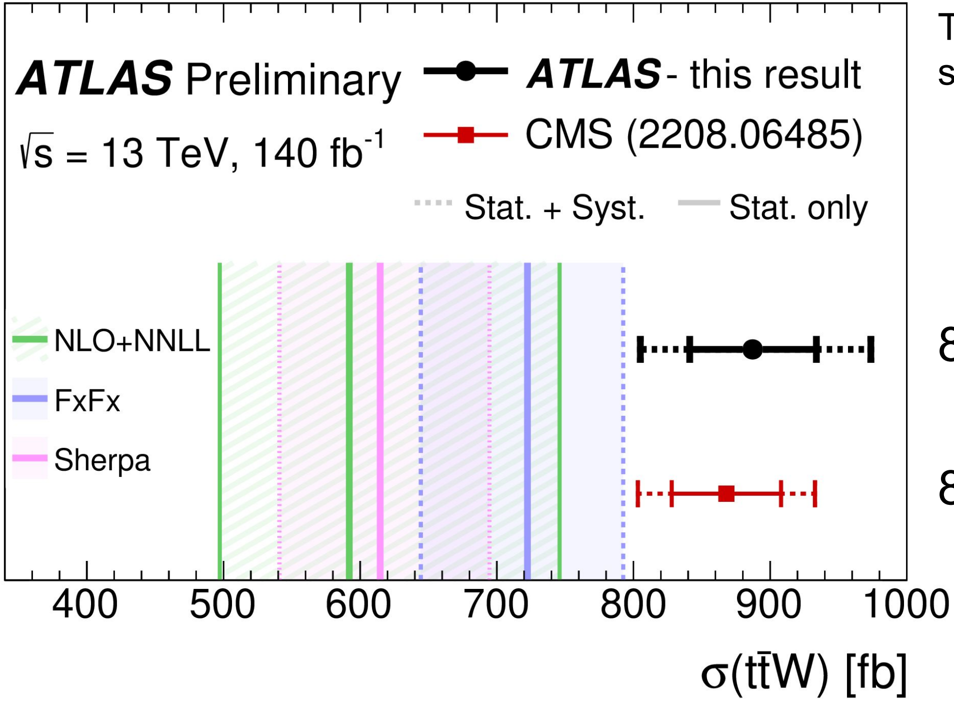
CMS

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	
$t\bar{t}H$ normalization	2.6
Charge misidentification	1.6
Nonprompt leptons	1.3
VVV normalization	1.2
$t\bar{t}VV$ normalization	1.2
Conversions normalization	0.7
$t\bar{t}\gamma$ normalization	0.6
ZZ normalization	0.6
Other normalizations	0.5
$t\bar{t}Z$ normalization	0.3
WZ normalization	0.2
tZq normalization	0.2
tHq normalization	0.2
Modeling uncertainties	
$t\bar{t}W$ scale	1.8
$t\bar{t}W$ color reconnection	1.0
ISR & FSR scale for $t\bar{t}W$	0.8
$t\bar{t}\gamma$ scale	0.4
VVV scale	0.3
$t\bar{t}H$ scale	0.2
Conversions	0.2
Simulation statistical uncertainty	1.8
Total systematic uncertainty	5.8

JHEP 07 (2023) 219
ATLAS-CONF-2023-019

Inclusive $t\bar{t}W$ Cross-section

NLO+NNLL	592^{+155}_{-97} fb	JHEP 08 (2019) 039 Eur. Phys. J. C 80 (2020) 428
FxFx	722^{+71}_{-78} fb	JHEP 11 (2021) 029



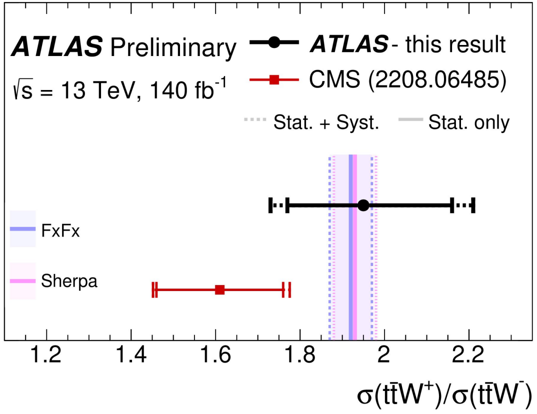
Theory cross-section uncertainties include scale variations+PDF uncertainties

890 ± 50 (stat.) ± 70 (syst.) fb

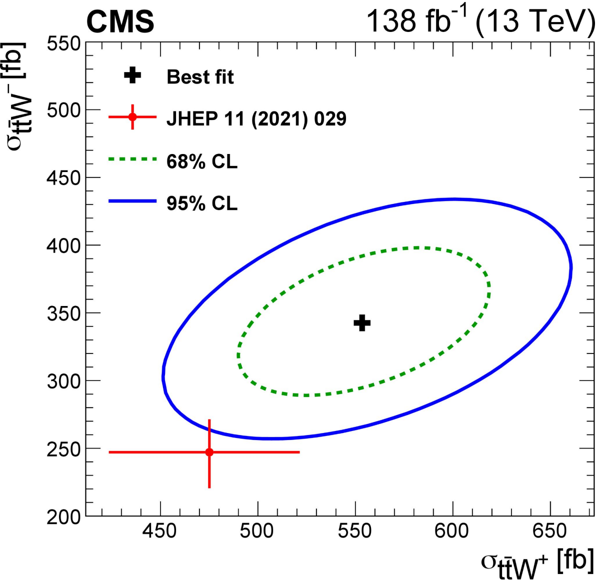
868 ± 40 (stat.) ± 51 (syst.) fb

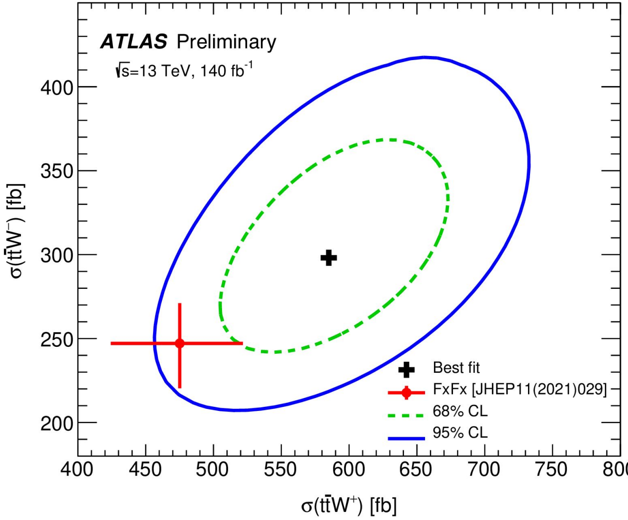
JHEP 07 (2023) 219
ATLAS-CONF-2023-019

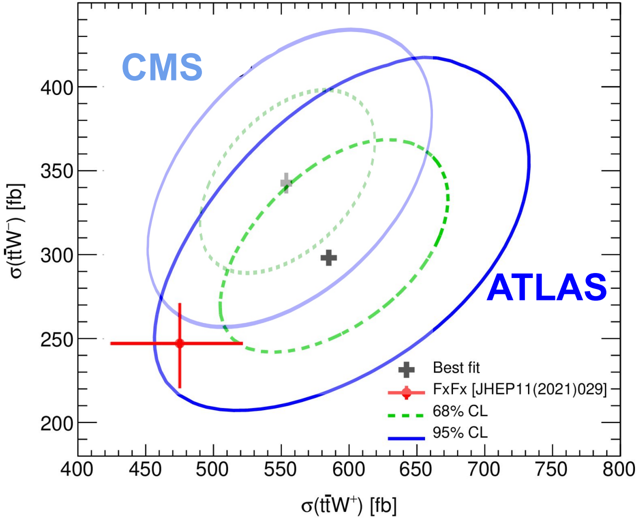
$t\bar{t}W^+$ vs. $t\bar{t}W^-$



Simultaneous measurements of $\sigma(t\bar{t}W^+)$ and $\sigma(t\bar{t}W^-)$, as well as measurement of their ratio







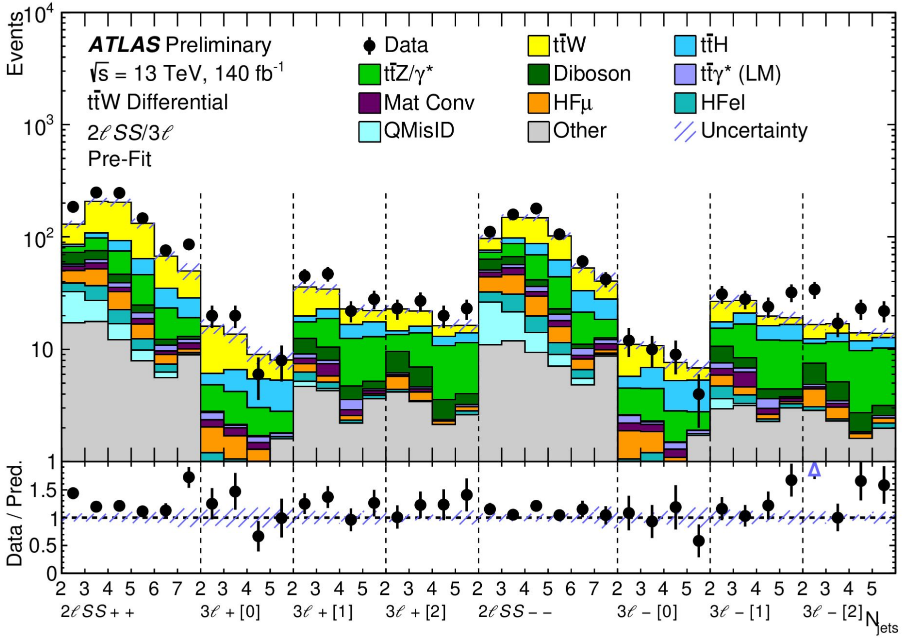
ATLAS-CONF-2023-019

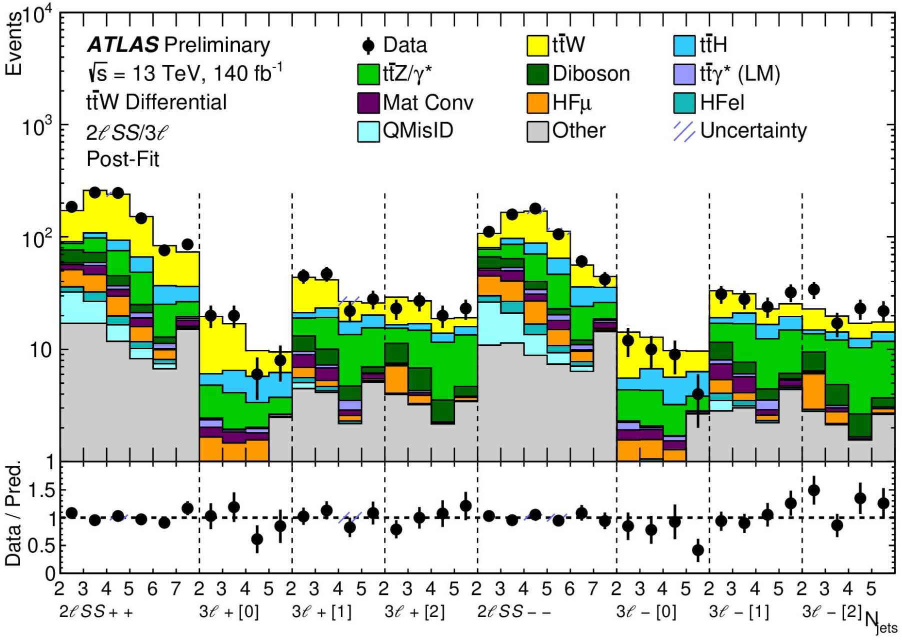
Inclusive and Differential Fiducial Cross-sections

$$\sigma_{\text{fid}}(t\bar{t}W) = 21.7\ ^{+1.1}_{-1.1}\ (\text{stat.})\ ^{+2.1}_{-1.9}\ (\text{syst.}) = 21.7\ ^{+2.4}_{-2.2}\ (\text{tot.})\ \text{fb}$$

Absolute and normalised cross section at particle level measured as function of different kinematic variables

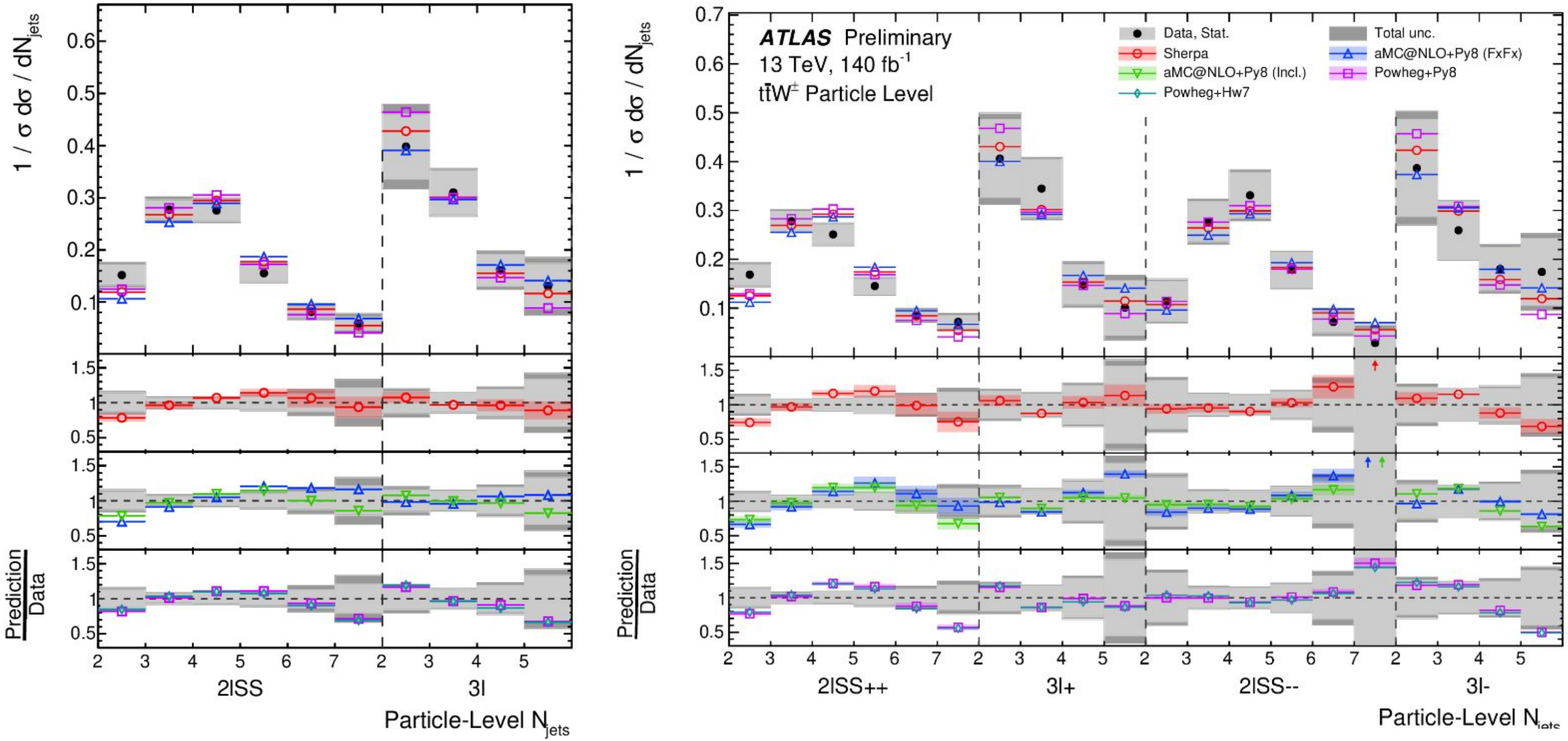
N_{jets} distributions in the SRs used as input for the profile-likelihood unfolding (left) and postfit distributions (right)





Differential Cross-sections: N jets (Example)

Example differential results, for absolute and normalized x-sections
Results shown for N_{jets}; analysis also measures:
$H_{T,jets}$, $H_{T,lep}$, $\Delta R_{lead\ b,\ lead\ l}$, $|\Delta\eta_{SS\ lep}|$, $|\Delta\varphi_{SS\ lep}|$, $M_{lead\ JJ}$



Leptonic Charge Asymmetry

Top quarks (antiquarks) expected to be produced with more forward (central) rapidities from $q\bar{q}$ initial states

Can probe leptonic charge asymmetry in $t\bar{t}W$:

$$A_c^{\ell} = \frac{N(\Delta\eta^{\ell} > 0) - N(\Delta\eta^{\ell} < 0)}{N(\Delta\eta^{\ell} > 0) + N(\Delta\eta^{\ell} < 0)}$$

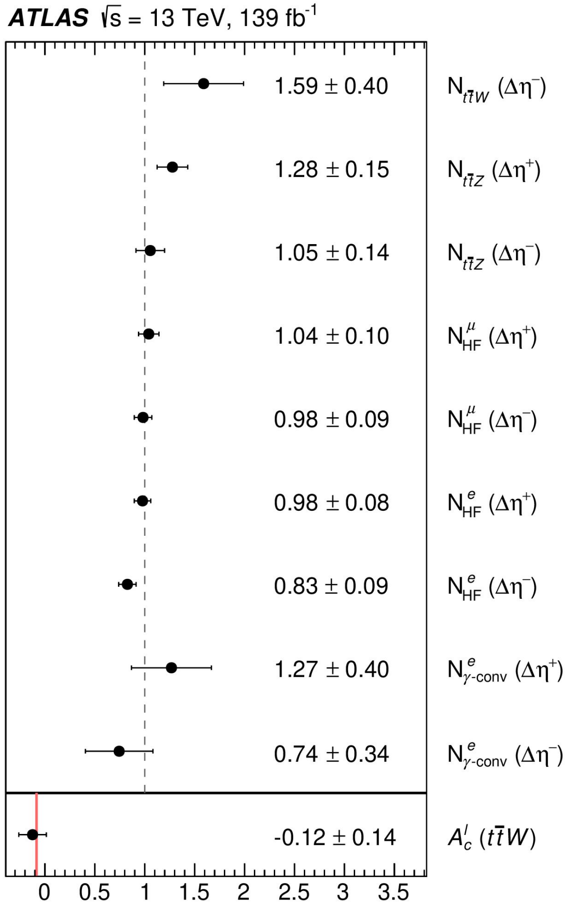
gg initial states dominate in $t\bar{t}$, which complicates asymmetry measurements. In $t\bar{t}W$, $q\bar{q}$ initial states dominate.

Additionally, the W boson in the initial state causes polarisation of the $t\bar{t}$ pair, which further leads to observable asymmetry.

A_c^{ℓ} measurement probes both effects

JHEP 07 (2023) 033

Measurement and Results



Similar to overall strategy in cross-section measurement

Primary differences:
- 3 lepton only
- Normalizations of backgrounds with $\Delta\eta^+$ and $\Delta\eta^-$ treated separately

Reconstruction level:

Observed: −0.12±0.14 (stat.) ± 0.05 (syst.)
Expected: −0.084 +0.005 −0.003 (scale) ± 0.006 (MC stat.)

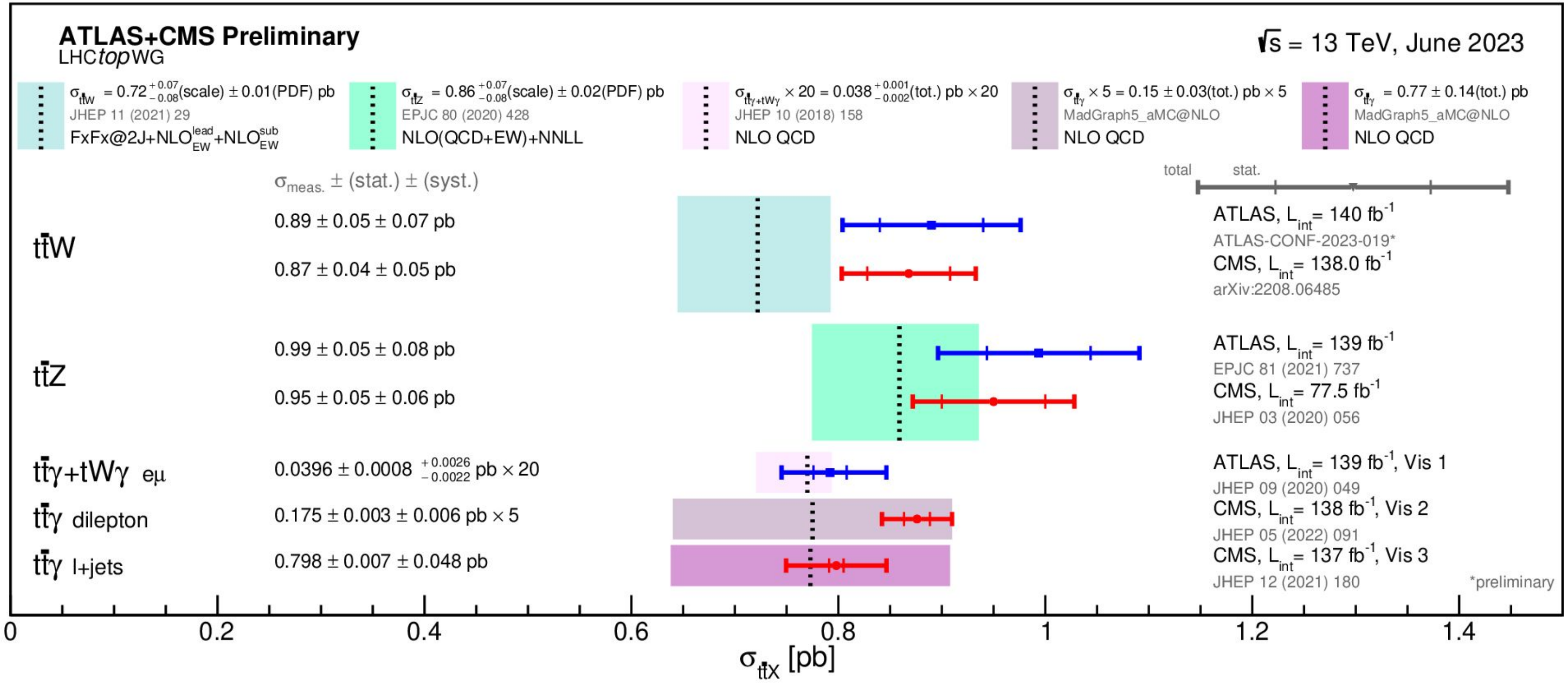
Particle level:

Observed: −0.11 ± 0.17 (stat.) ± 0.05 (syst.)
Expected: −0.063 +0.007 −0.004 (scale) ± 0.004 (MC stat.)

Results compatible with SM expectation

Conclusion

- CMS and ATLAS have performed $t\bar{t}W$ measurements with the full LHC Run 2 dataset
- Measure larger-than-expected cross-sections, with statistically consistent results between the experiments
- Also performed leptonic charge asymmetry measurement, which, as with other charge asymmetry measurements, shows agreement with the SM



Backup

JHEP 07 (2023) 219

CMS Event Selection

- Same-sign
  - p_T(lead ℓ)>30 (25) for μ (e)
  - p_T(other ℓ) > 20 GeV
  - m(ℓℓ) > 30 GeV
  - ΔR(ℓℓ) > 0.4
  - |m(ee) − mZ| > 15 GeV
- Trilepton
  - p_T(lead ℓ) > 25 GeV
  - p_T(other ℓ) > 15 GeV
  - |m(ℓℓ) − mZ| > 10 GeV
  - m(ℓℓ) > 12 GeV
  - Njets≥2
  - Nbjets≥1

Process	$\ell^+\ell^+$	$\ell^-\ell^-$	$\ell^\pm\ell^\mp\ell^+$	$\ell^\pm\ell^\mp\ell^-$
$t\bar{t}W$	677 ± 21	355 ± 12	119.4 ± 9.2	65.3 ± 5.4
Nonprompt	2490 ± 600	2360 ± 570	325 ± 75	298 ± 71
Charge misID	520 ± 110	520 ± 111	—	—
$t\bar{t}H$	167 ± 34	169 ± 34	56 ± 12	57 ± 12
$t\bar{t}Z/\gamma^*$	335 ± 26	333 ± 26	145 ± 13	147 ± 13
Diboson	382 ± 88	285 ± 65	46.8 ± 9.1	38.0 ± 7.5
Other	178 ± 34	126 ± 27	43.4 ± 8.2	33.5 ± 7.4
Conversions	177 ± 54	192 ± 59	22.9 ± 7.1	24.0 ± 7.4
Total background	4250 ± 620	4000 ± 590	639 ± 80	600 ± 76
Total prediction	4920 ± 620	4350 ± 590	758 ± 81	663 ± 76
Data	5143	4486	834	744

ATLAS Signal Region Selection

Signal region preselection	2ℓSS	3ℓ
Lepton definition	TT	LTT
Lepton p_{T} [GeV]	(20, 20)	(10, 20, 20)
N_{jets}	≥ 2	
$N_{b-\mathrm{jets}}$	$\geq 1\ b^{60\%}$ or $\geq 2\ b^{77\%}$	
$m^{SF}_{\ell^{\pm}\ell^{\pm}}$ or $m^{SF}_{\ell^{+}\ell^{-}}$ [GeV]	> 12	
$\lvert m^{SF}_{\ell^{+}\ell^{-}} - m_Z\rvert$ [GeV]	–	> 10
$\lvert m_{\ell\ell\ell} - m_Z\rvert$ [GeV]	–	> 10
	Inclusive cross section measurement	
Lepton charge split	$(\ell^{+}\ell^{+}, \ell^{-}\ell^{-})$	$(\ell^{+}\ell^{-}\ell^{-}, \ell^{-}\ell^{+}\ell^{+})$
Lepton flavour split	$(\mu\mu,\ e\mu,\ \mu e,\ ee)$	-
Jet multiplicity split	(3, 4, $\geq$5)	(2, $\geq$3)
b-jet multiplicity split	(1, $\geq$2)	
Total inclusive SRs	48	8
	Differential cross section measurement	
Lepton charge split	$(\ell^{+}\ell^{+}, \ell^{-}\ell^{-})$	$(\ell^{+}\ell^{-}\ell^{-}, \ell^{-}\ell^{+}\ell^{+})$
Number of OS-SF pairs split	–	(0, 1, 2)
Total differential SRs	2	6

	$\ell^{-}\ell^{-}$ **SR**	$\ell^{+}\ell^{+}$ **SR**	$\ell^{+}\ell^{-}\ell^{-}$ **SR**	$\ell^{-}\ell^{+}\ell^{+}$ **SR**
$t\bar{t}W$	261 ± 20	472 ± 30	64 ± 6	116 ± 10
$t\bar{t}H$	66 ± 9	66 ± 9	29 ± 4	28 ± 4
$t\bar{t}Z/\gamma^{*}$	95 ± 9	100 ± 10	69 ± 8	72 ± 8
$t\bar{t}\gamma^{*}$(LM)	9 ± 5	9 ± 5	2.6 ± 1.5	2.6 ± 1.5
Diboson	16 ± 5	22 ± 6	9.0 ± 2.7	12 ± 4
Mat Conv	11.1 ± 3.3	19 ± 5	2.5 ± 0.8	3.9 ± 1.1
HFμ	35 ± 11	30 ± 10	6.2 ± 2.6	6.6 ± 2.6
HFel	14 ± 6	15 ± 6	2.9 ± 1.3	2.0 ± 0.8
QMisID	8.2 ± 2.7	8.2 ± 2.7	0.69 ± 0.15	0.66 ± 0.13
$t\bar{t}t\bar{t}$	9 ± 7	9 ± 7	4.0 ± 3.2	4.2 ± 3.3
Other	32 ± 5	42 ± 6	18.6 ± 3.1	25.0 ± 3.3
Total	557 ± 16	790 ± 24	208 ± 7	273 ± 9
Data	546	803	225	269

ATLAS Object Selection

	Electron				Muon			
Lepton definition	L	M	M_{ex}	T	L	M	M_{ex}	T
Isolation	Yes				Yes			
Non-prompt lepton WP	No	*Tight*	*Tight-not-VeryTight*	*VeryTight*	No	*Tight*	*Tight-not-VeryTight*	*VeryTight*
Identification	Loose	Tight			Loose	Medium		
Electron charge-misassignment veto	No	Yes			N/A			
Electron conversion candidate veto	No	Yes (except e^*)			N/A			
Transverse impact parameter significance $\lvert d_0\rvert/\sigma_{d_0}$	< 5				< 3			
Longitudinal impact parameter $\lvert z_0 \sin\theta\rvert$	< 0.5 mm							

ATLAS-CONF-2023-019

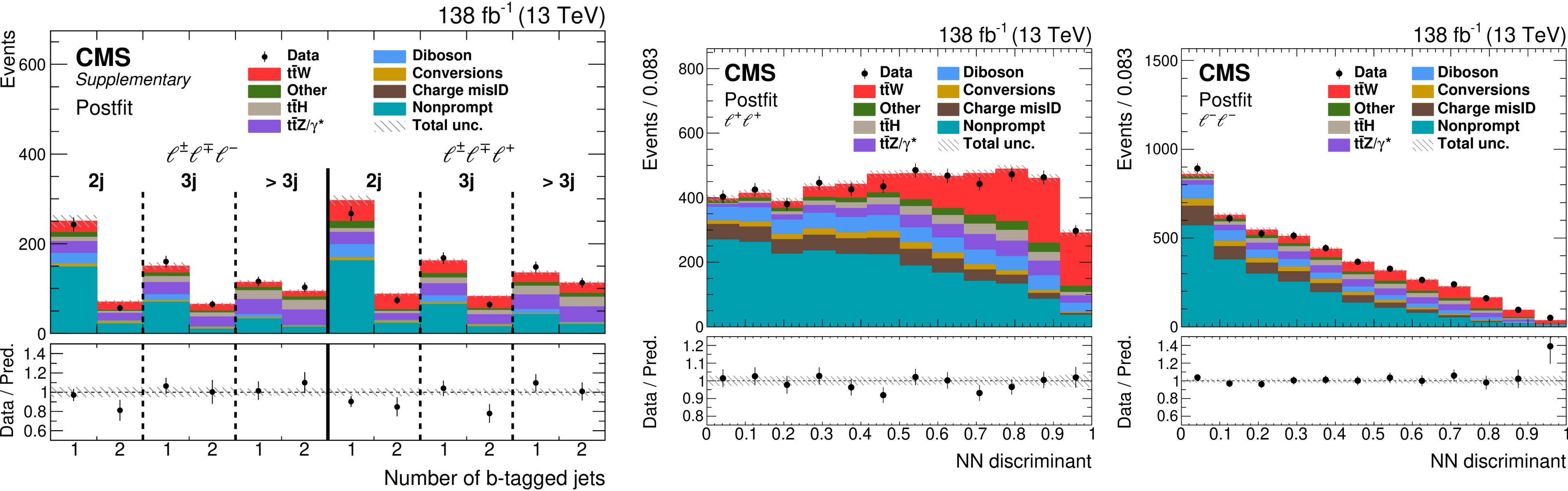
ATLAS Control Region Selection

Control regions for:	Diboson	$t\bar{t}Z$	Conversions	HF non-prompt
N_{jets}	2 or 3	≥ 4	≥ 0	≥ 2
$N_{b-\text{jets}}$	$1\ b^{60\%}$	$\geq 1\ b^{60\%}$ or $\geq 2\ b^{77\%}$	$0\ b^{77\%}$	$1\ b^{77\%}$
Lepton requirement	3ℓ		$\mu\mu e^*$	2ℓSS
Lepton definition	(L, M, M)			(T, M_{ex}) —— (M_{ex}, T) —— $(M_{\text{ex}}, M_{\text{ex}})$
Lepton p_{T} [GeV]	(10, 20, 20)			(20, 20)
$m^{SF}_{\ell^+\ell^-}$ [GeV]	> 12		> 12	–
$\lvert m^{SF}_{\ell^+\ell^-} - m_Z\rvert$ [GeV]	< 10		> 10	–
$\lvert m_{\ell\ell\ell} - m_Z\rvert$ [GeV]	–		< 10	–
$m_T(\ell_0, E_{\text{T}}^{\text{miss}})$ [GeV]	–			< 250 for TM_{ex} and $M_{\text{ex}}T$ pairs
Region split	–	–	internal / material	subleading e/μ × $(TM_{\text{ex}}, M_{\text{ex}}T, M_{\text{ex}}M_{\text{ex}})$
Region naming	3ℓVV	3ℓttZ	3ℓIntC 3ℓMatC	$2\ell\text{tt(e)}_{TM_{\text{ex}}}$, $2\ell\text{tt(e)}_{M_{\text{ex}}T}$, $2\ell\text{tt(e)}_{M_{\text{ex}}M_{\text{ex}}}$ $2\ell\text{tt}(\mu)_{TM_{\text{ex}}}$, $2\ell\text{tt}(\mu)_{M_{\text{ex}}T}$, $2\ell\text{tt}(\mu)_{M_{\text{ex}}M_{\text{ex}}}$

	3ℓIntC	3ℓMatC	3ℓttZ	3ℓVV
$t\bar{t}W$	–	–	7.3 ± 0.7	13.0 ± 0.9
$t\bar{t}H$	–	–	10.0 ± 1.5	4.3 ± 0.6
$t\bar{t}Z/\gamma^*$	–	–	360 ± 40	160 ± 23
$t\bar{t}\gamma^*$(LM)	41 ± 9	15 ± 4	0.056 ± 0.032	0.41 ± 0.25
Diboson	0.035 ± 0.020	0.88 ± 0.20	35 ± 11	99 ± 28
Mat Conv	1.2 ± 0.9	34 ± 9	0.48 ± 0.3	2.1 ± 0.7
HFμ	–	–	1.20 ± 0.35	8.4 ± 2.7
HFel	–	–	0.40 ± 0.22	7.1 ± 2.4
QMisID	–	–	0.19 ± 0.13	0.8 ± 0.4
$t\bar{t}t\bar{t}$	–	–	1 ± 1	0.022 ± 0.018
Other	–	–	68 ± 19	151 ± 20
Total	42 ± 9	50 ± 8	487 ± 21	446 ± 20
Data	42	54	482	460

	$2\ell\text{tt}(\mu)_{TM_{\text{ex}}}$	$2\ell\text{tt}(\mu)_{M_{\text{ex}}T}$	$2\ell\text{tt(e)}_{TM_{\text{ex}}}$	$2\ell\text{tt(e)}_{M_{\text{ex}}T}$	$2\ell\text{tt}(\mu)_{M_{\text{ex}}M_{\text{ex}}}$	$2\ell\text{tt(e)}_{M_{\text{ex}}M_{\text{ex}}}$
$t\bar{t}W$	18.0 ± 2.5	7.3 ± 1.2	10.4 ± 1.4	5.1 ± 0.5	2.4 ± 0.7	1.8 ± 0.5
$t\bar{t}H$	5.8 ± 1.0	2.8 ± 0.5	3.5 ± 0.6	1.72 ± 0.32	1.11 ± 0.21	0.79 ± 0.19
$t\bar{t}Z/\gamma^*$	11.5 ± 1.4	5.3 ± 0.6	6.8 ± 0.7	3.2 ± 0.4	2.08 ± 0.29	1.5 ± 0.19
$t\bar{t}\gamma^*$(LM)	0.27 ± 0.16	0.54 ± 0.33	1.6 ± 0.9	0.9 ± 0.5	0.11 ± 0.07	0.19 ± 0.12
Diboson	10.6 ± 2.2	5 ± 1	6.7 ± 1.4	2.3 ± 0.6	1.4 ± 0.4	1.16 ± 0.3
Mat Conv	1.3 ± 0.8	1.0 ± 0.4	3.6 ± 1.7	1.5 ± 1.3	1.5 ± 0.5	0.95 ± 0.31
HFμ	75 ± 11	22 ± 4	2.0 ± 0.9	8.1 ± 1.6	13.1 ± 2.5	3.0 ± 0.8
HFel	1.3 ± 0.9	4.5 ± 1.5	27 ± 9	4.1 ± 1.2	1.4 ± 0.5	3.5 ± 1.0
QMisID	0.21 ± 0.09	0.43 ± 0.35	4.2 ± 2.1	2.0 ± 1.4	0.31 ± 0.2	1.3 ± 0.8
$t\bar{t}t\bar{t}$	0.06 ± 0.05	0.029 ± 0.024	0.030 ± 0.026	0.018 ± 0.016	0.032 ± 0.026	0.013 ± 0.011
Other	5.3 ± 0.8	1.88 ± 0.17	3.6 ± 0.4	1.49 ± 0.17	0.72 ± 0.09	0.49 ± 0.07
Total	129 ± 11	50 ± 4	69 ± 7	30.4 ± 2.8	24.0 ± 2.8	14.6 ± 1.8
Data	135	49	72	24	23	15

CMS Post-fit Plots

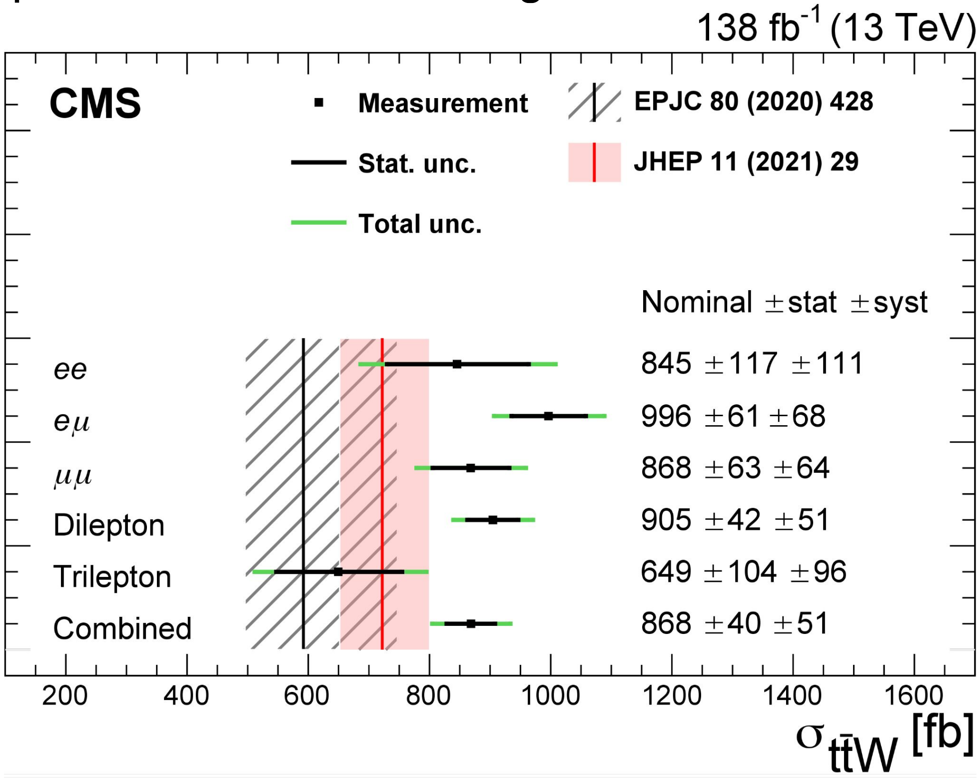


JHEP 07 (2023) 219

CMS Results

Sensitivity mostly comes from dilepton channels

Compatible results across regions



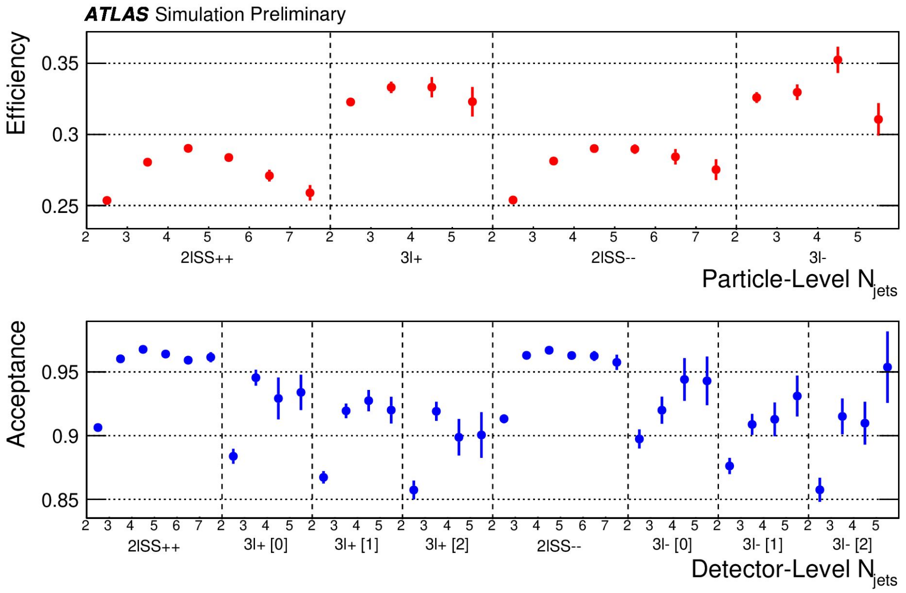
Fiducial Cross-section

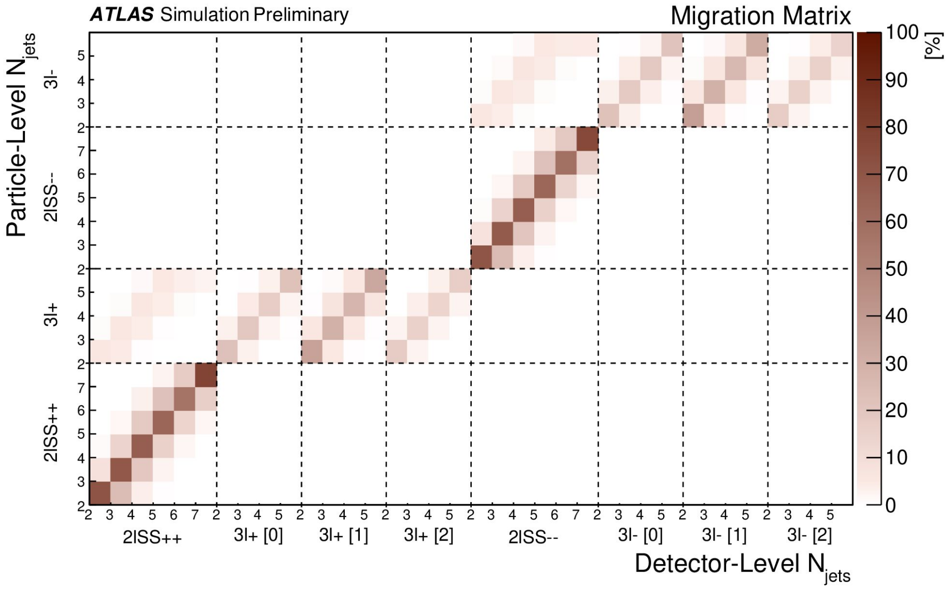
Objects	
Electrons	$p_T \geq 10$ GeV and $\|\eta\| < 2.47$ (excluding the LAr crack region with $1.37 < \|\eta\| < 1.52$)
Muons	$p_T \geq 10$ GeV and $\|\eta\| < 2.5$
Jets	Anti-k_t $R = 0.4$ jets with $p_T \geq 25$ GeV and $\|\eta\| < 2.5$
b-jets	Tagged if jet contains a ghost-matched b-hadron with $p_T > 5$ GeV
E_T^{miss}	Vector sum of $p_T(\nu)$ for all neutrinos in the event not from hadron decays
Overlap removal	
Electron–jet	If $\Delta R(e, \text{jet}) < 0.2$ (excluding b-jets with $p_T < 200$ GeV) remove jet
Jet–lepton	If $\Delta R(\ell, \text{jet}) < \min(0.4, 0.04 + 10\,\text{GeV}/p_{T,\ell})$ remove lepton
Selections	
2ℓ	Exactly two leptons with the same charge Both leptons have $p_T \geq 20$ GeV $N_{jets} \geq 3$ ($N_{jets} \geq 2$) 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 $p_T \geq 20$ GeV $N_{jets} \geq 1$ with at least one b-jet $m_{\ell\ell} > 12$ GeV & $\|m_{\ell\ell} - m_Z\| > 10$ GeV (for OS-SF $\ell\ell$) $\|m_{\ell\ell\ell} - m_Z\| > 10$ GeV

$$\sigma_{fid}(t\bar{t}W) = 21.7\ ^{+1.1}_{-1.1}\ (\text{stat.})\ ^{+2.1}_{-1.9}\ (\text{syst.}) = 21.7\ ^{+2.4}_{-2.2}\ (\text{tot.})\ \text{fb}$$

Differential Measurements

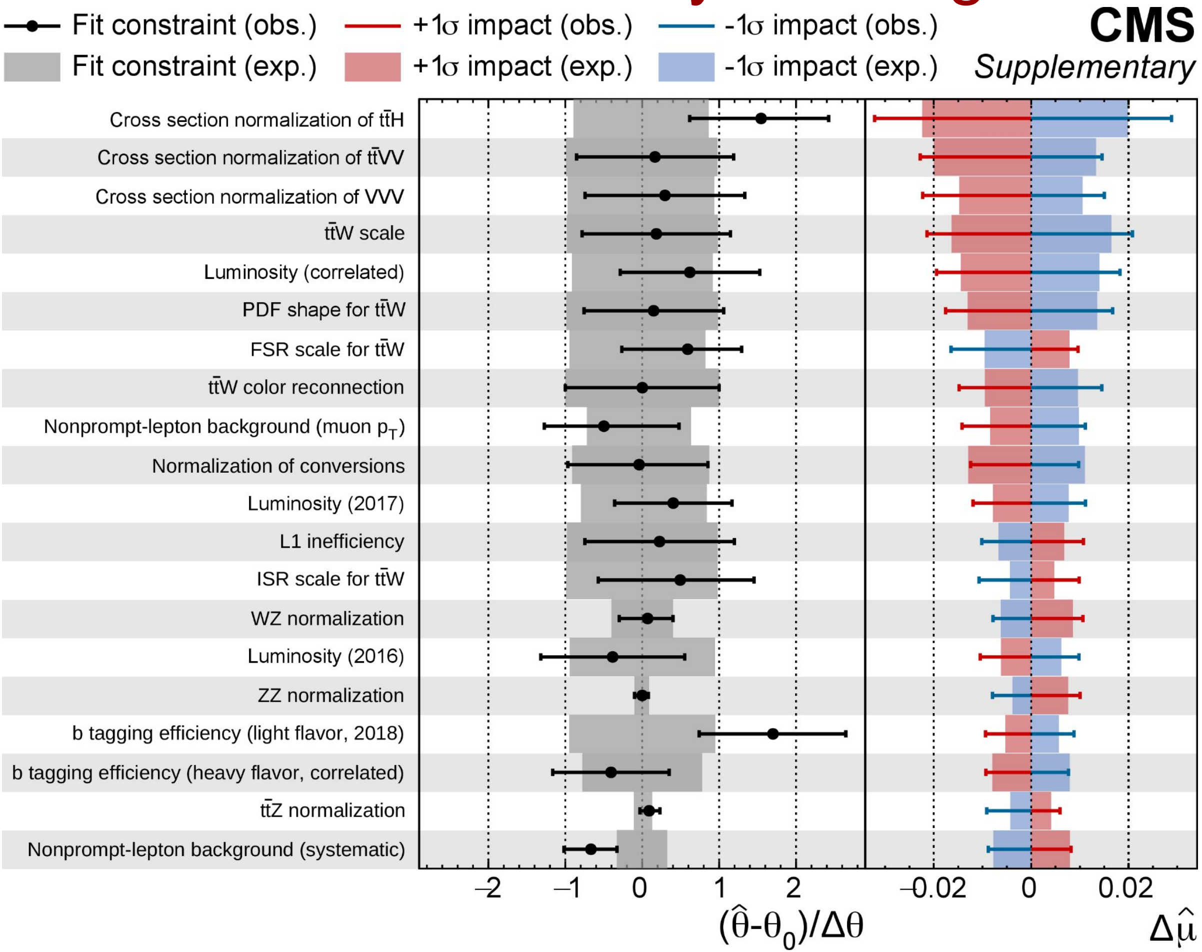
Efficiency/acceptance correction and normalised migration matrix and for N_{jets} calculated in Sherpa 2.2.10 with EWK corrections.





JHEP 07 (2023) 219

CMS Uncertainty Ranking



ATLAS-CONF-2023-019

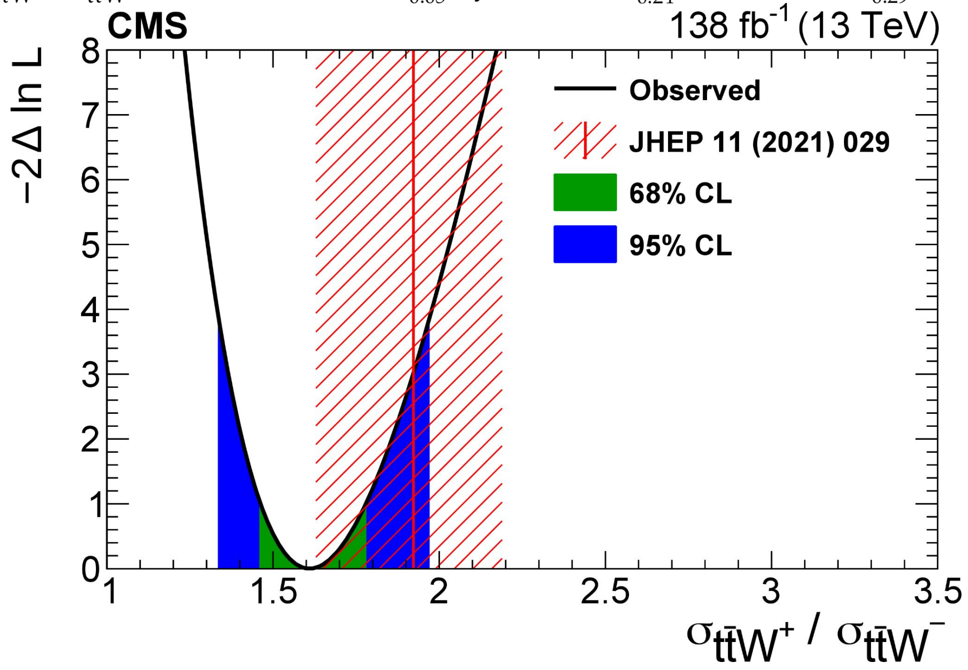
ATLAS Uncertainty Breakdown

	$\frac{\Delta\sigma(t\bar{t}W)}{\sigma(t\bar{t}W)}$ [%]	$\frac{\Delta\sigma_{\text{fid}}(t\bar{t}W)}{\sigma_{\text{fid}}}$ [%]	$\frac{\Delta R(t\bar{t}W)}{R(t\bar{t}W)}$ [%]	$\frac{\Delta A_{C}^{\text{rel}}}{A_{C}^{\text{rel}}}$ [%]
$t\bar{t}W$ 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

JHEP 07 (2023) 219

CMS Charge Split

Observable	Measurement	SM prediction NLO + NNLL	SM prediction NLO + FxFx
$\sigma_{t\bar{t}W}$	$868 \pm 40\,(\text{stat}) \pm 51\,(\text{syst})$ fb	$592\,^{+155}_{-97}\,(\text{theo})$ fb	$722\,^{+71}_{-78}\,(\text{theo})$ fb
$\sigma_{t\bar{t}W+}$	$553 \pm 30\,(\text{stat}) \pm 30\,(\text{syst})$ fb	$384\,^{+53}_{-33}\,(\text{theo})$ fb	$475\,^{+46}_{-52}\,(\text{theo})$ fb
$\sigma_{t\bar{t}W-}$	$343 \pm 26\,(\text{stat}) \pm 25\,(\text{syst})$ fb	$198\,^{+26}_{-17}\,(\text{theo})$ fb	$247\,^{+24}_{-27}\,(\text{theo})$ fb
$\sigma_{t\bar{t}W+}/\sigma_{t\bar{t}W-}$	$1.61 \pm 0.15\,(\text{stat})\,^{+0.07}_{-0.05}\,(\text{syst})$	$1.94\,^{+0.37}_{-0.24}\,(\text{theo})$	$1.92\,^{+0.27}_{-0.29}\,(\text{theo})$



Leptonic Charge Asymmetry

Other results that include charge-asymmetry measurements:

- ATLAS+CMS Run 1 combination: JHEP 04 (2018) 033
- CMS Run 2 boosted top-antiquark: 2208.02751 (accepted by PLB)
- CMS Run 2 top-antiquark (partial dataset): JHEP 02 (2019) 149
- ATLAS, top-antiquark: JHEP 08 (2023) 077
- ATLAS, ttγ: Phys. Lett. B 843 (2023) 137848

Differential Cross-section Variables

Variable	Definition
N_{jets}	Number of selected jets with $p_{\text{T}} > 25$ GeV and $\lvert\eta\rvert < 2.5$
$H_{\text{T,jets}}$	Scalar sum of the transverse momenta of selected jets with $p_{\text{T}} > 25$ GeV and $\lvert\eta\rvert < 2.5$
$H_{\text{T,lep}}$	Scalar sum of the transverse momenta of selected leptons
$\Delta R_{\text{lb, lead}}$	Angular distance between the leading lepton and the leading b-tagged jet
$\lvert\Delta\phi_{\text{ll, SS}}\rvert$	Absolute azimuthal separation between the two leptons of the same-sign pair
$\lvert\Delta\eta_{\text{ll, SS}}\rvert$	Absolute pseudo-rapidity separation between the two leptons of the same-sign pair
$M_{\text{jj, lead}}$	Invariant mass of the two leading jets with $p_{\text{T}} > 25$ GeV and $\lvert\eta\rvert < 2.5$

ATLAS-CONF-2023-019

Differential Measurement, p-values

2LSS, normalized x-sec

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
$H_{T,\text{jets}}$	5	0.7	0.98	1.1	0.95	0.8	0.98	1.5	0.91	2.0	0.85
$H_{T,\text{lep}}$	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
$\lvert\Delta\phi_{\text{ll, SS}}\rvert$	7	0.6	1.00	0.7	1.00	0.9	1.00	0.8	1.00	0.9	1.00
$\lvert\Delta\eta_{\text{ll, SS}}\rvert$	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

3L, normalized x-sec

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
$H_{T,\text{jets}}$	4	1.4	0.84	-	-	0.9	0.92	1.9	0.75	2.4	0.66	3.3	0.51
$H_{T,\text{lep}}$	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
$\lvert\Delta\phi_{\text{ll, SS}}\rvert$	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
$\lvert\Delta\eta_{\text{ll, SS}}\rvert$	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

2LSS, asymmetry

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
$H_{T,\text{jets}}$	6	2.7	0.84	2.9	0.82	1.6	0.95	0.9	0.99	1.4	0.96
$H_{T,\text{lep}}$	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
$\lvert\Delta\phi_{\text{ll, SS}}\rvert$	8	6.7	0.56	7.5	0.49	6.0	0.65	5.8	0.67	6.1	0.64
$\lvert\Delta\eta_{\text{ll, SS}}\rvert$	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

3L, asymmetry

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
$H_{T,\text{jets}}$	5	2.4	0.80	-	-	2.6	0.76	2.7	0.74	3.6	0.61	2.8	0.73
$H_{T,\text{lep}}$	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
$\lvert\Delta\phi_{\text{ll, SS}}\rvert$	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
$\lvert\Delta\eta_{\text{ll, SS}}\rvert$	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

ATLAS-CONF-2023-019

Differential Measurement, Full Example