From Inclusive to Differential: Precision Measurements of $t\bar{t}W$ Production at 13 TeV with the ATLAS detector

Nihal Brahimi

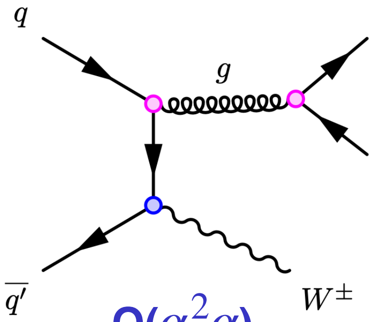
On behalf of the ATLAS collaboration

IRN TERASCALE @ IPHC Strasbourg

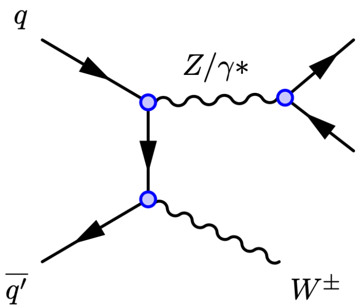
$t\bar{t}W$ process: Rare, Complex and Relevant

- $t\bar{t}W$ is a **rare and challenging** process to model theoretically
  - ➡ significant higher order QCD and EWK corrections, off-shell effects, spin correlations

Charge asymmetric production from PDF (LO1, LO3)

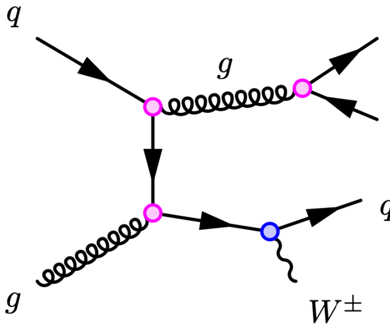


$O(\alpha_s^2\alpha)$



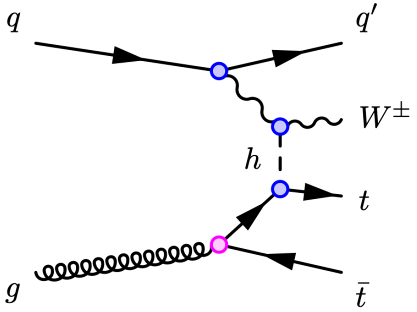
$O(\alpha^3)$

Higher order QCD and EWK corrections (NLO1, NLO3)

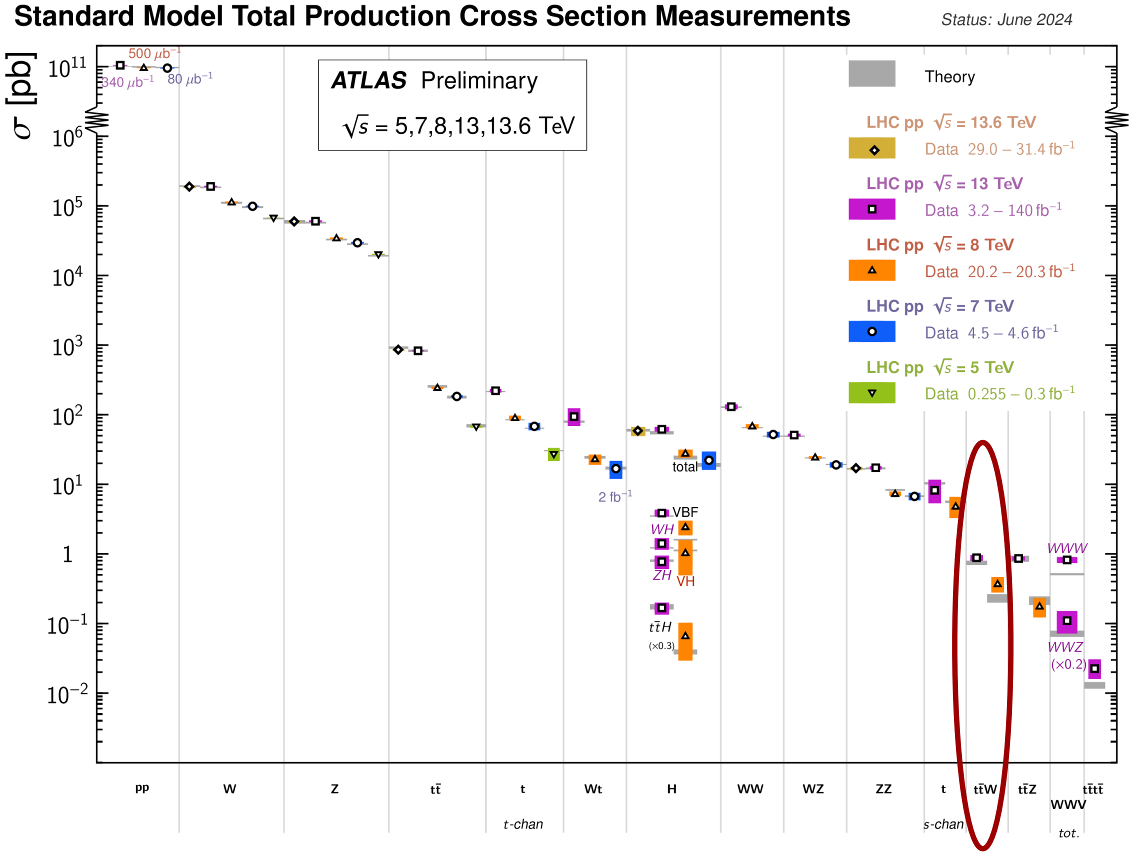


$O(\alpha_s^3\alpha)$

JHEP 05 (2024) 131



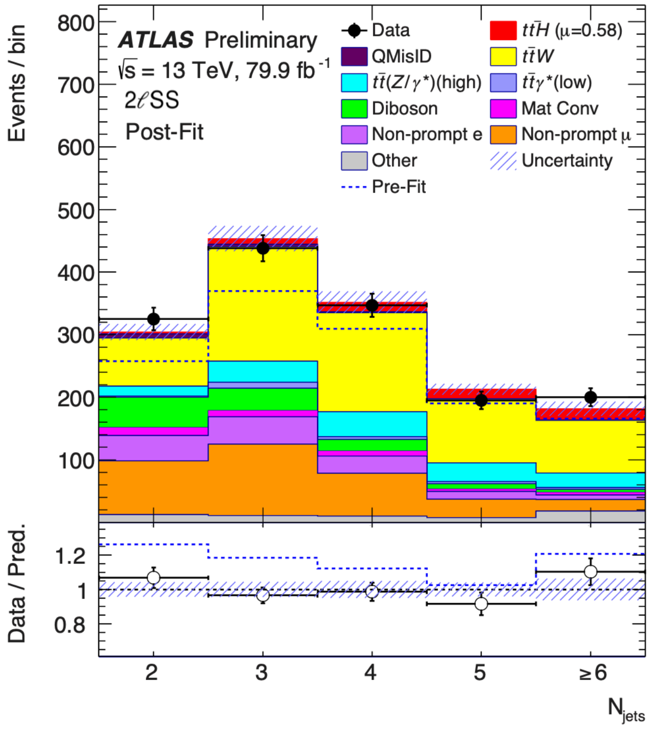
$O(\alpha_s\alpha^3)$



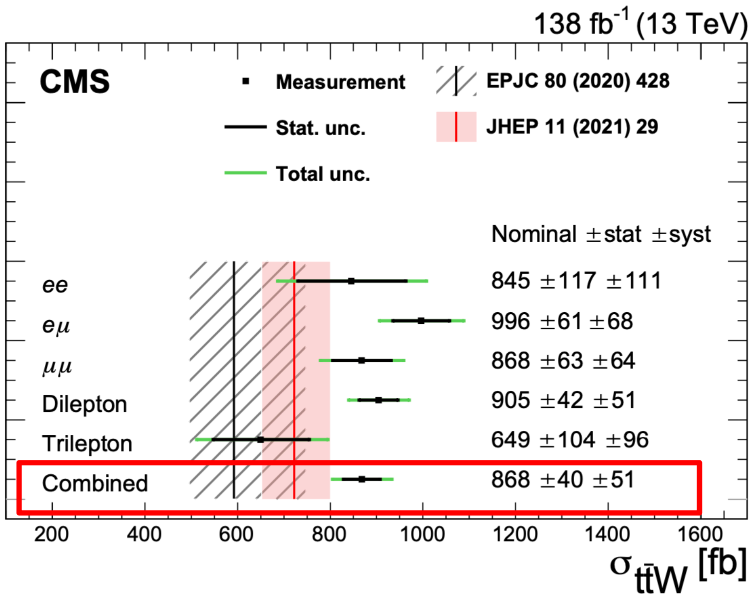
ATL-PHYS-PUB-2024-011

$t\bar{t}W$ process: Rare, Complex and Relevant

- $t\bar{t}W$ **is an irreducible background** to many SM and BSM searches including $t\bar{t}H$ and $t\bar{t}t\bar{t}$ → **limiting factor to their sensitivity**
- $t\bar{t}W$ **mismodeling** observed by ATLAS and CMS → measurements consistently yield **20-50% higher cross-section than prediction**
- **Inclusive and differential cross-section measurements of $t\bar{t}W$ are a key input to improve its modelling**



ATL-CONF-2019-045



JHEP07(2023)219

NNLO [15]		FxFx [27]	
Order	σ [fb]	Order	σ [fb]
LO QCD: $\alpha_s^2\alpha$	420^{+106}_{-79}	$t\bar{t}W$+0,1,2j@NLO	691^{+66}_{-74}
NLO QCD: $+\alpha_s^3\alpha$	622^{+79}_{-72}		
NNLO QCD: $+\alpha_s^4\alpha$	$711^{+35}_{-46}\pm 14$		
NLO EWK: $+\alpha_s\alpha^3+\alpha_s^2\alpha^2+\alpha^4$	$745\pm 50\pm 13$	$+\alpha_s\alpha^3$	739^{+75}_{-81}
		$+\alpha_s^2\alpha^2+\alpha^4$	722^{+70}_{-78}

JHEP 05 (2024) 131

Full Run 2 $t\bar{t}W$ analysis: measurement strategy JHEP 05 (2024) 131

- $t\bar{t}W$ production cross-section measured in multilepton final states
  - ➡ 1 Same-Sign (SS) lepton pair or 3L (e/μ)
  - ➡ $N_{\text{jets}} \geq 2$, $N_{\text{b-jets}} \geq 1(60\%)$ or $\geq 2(77\%)$
  - ➡ 3L: events w/ OSSF and 3L invariant mass in Z peak excluded

- **Inclusive measurement:**
  - ➡ Signal Regions split based on N_{jets},$N_{\text{b-jets}}$ and lepton charge
  - ➡ SS further split by lepton flavour
  - ➡ 48 (SS) + 8 (3L) signal regions
- Measured parameters:
  - ➡ Inclusive and fiducial $t\bar{t}W$ cross-sections
  - ➡ $t\bar{t}W^{+}$ and $t\bar{t}W^{-}$ cross-sections and their ratio (R)
  - ➡ Relative Charge asymmetry

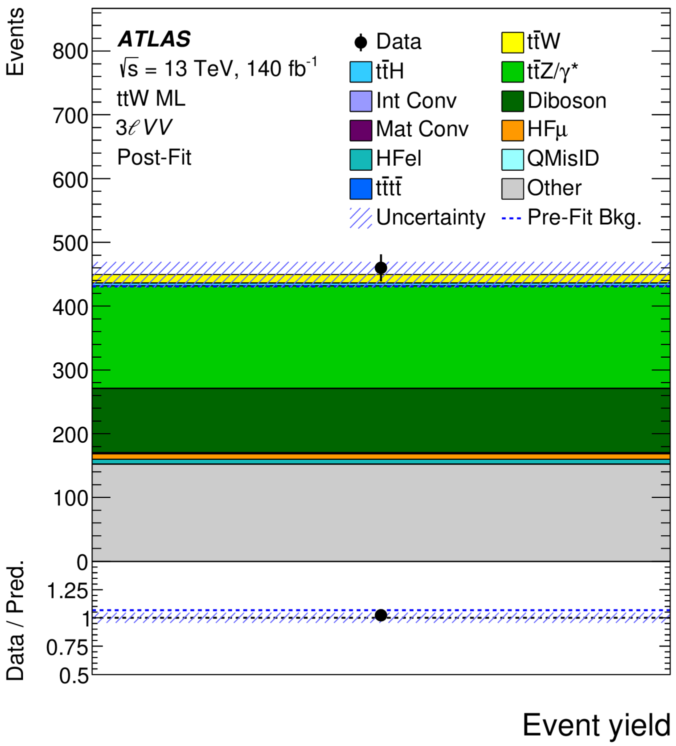
- **Differential measurement:**
  - ➡ Signal Regions split by lepton charge: SS (++/- -), 3L (+/-)
- **Measured distributions:**
  - ➡ Absolute and normalised cross-sections at particle level
  - ➡ Relative Charge asymmetry at particle level
- **8 observables sensitive to modelling differences:**
  - ➡ N_{jets}, H_T^{jet}, H_T^{lep}, $\Delta R_{\ell b,\text{lead}}$, $M_{\ell b,\text{lead}}$, $M_{\ell\ell,\text{SS}}$, $|\Delta\phi_{\ell\ell,\text{SS}}|$ and $|\Delta\eta_{\ell\ell,\text{SS}}|$

- **Main backgrounds:**
  - ➡ **Irreducible:** $t\bar{t}Z$, diboson
  - ➡ **Reducible:** fake/non-prompt leptons from $t\bar{t}$ decays, charge misID electrons

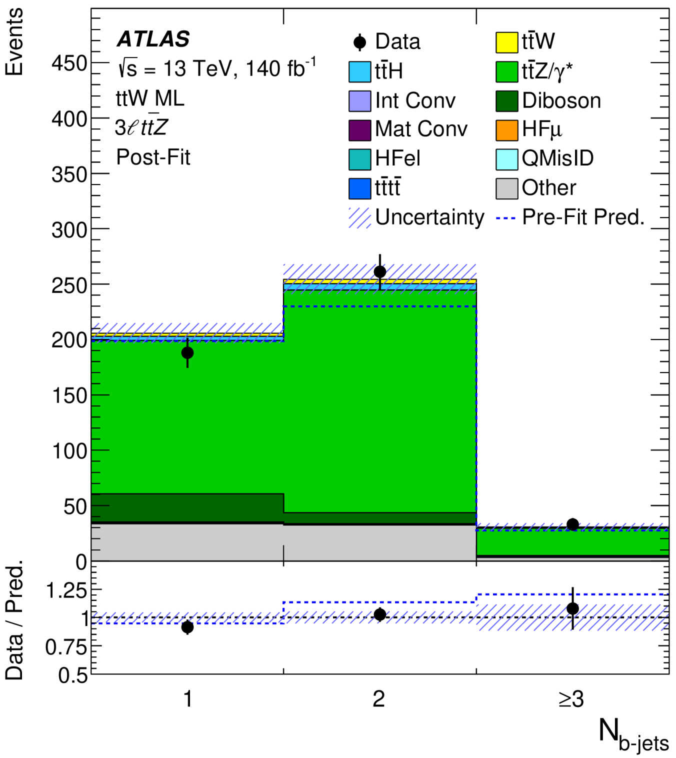
Irreducible backgrounds: $\mathrm{t\bar{t}Z}$ and diboson

- **Dedicated $\mathrm{t\bar{t}Z}$ and VV control regions** w/ different jet multiplicities and w/ same flavour dilepton pair invariant mass near the Z peak
  - ➡ Normalisation extracted from fit to data (with signal extraction)

$$\lambda_{\mathrm{VV}} = 0.87 \pm 0.33$$



$$\lambda_{\mathrm{t\bar{t}Z}} = 1.16 \pm 0.15$$

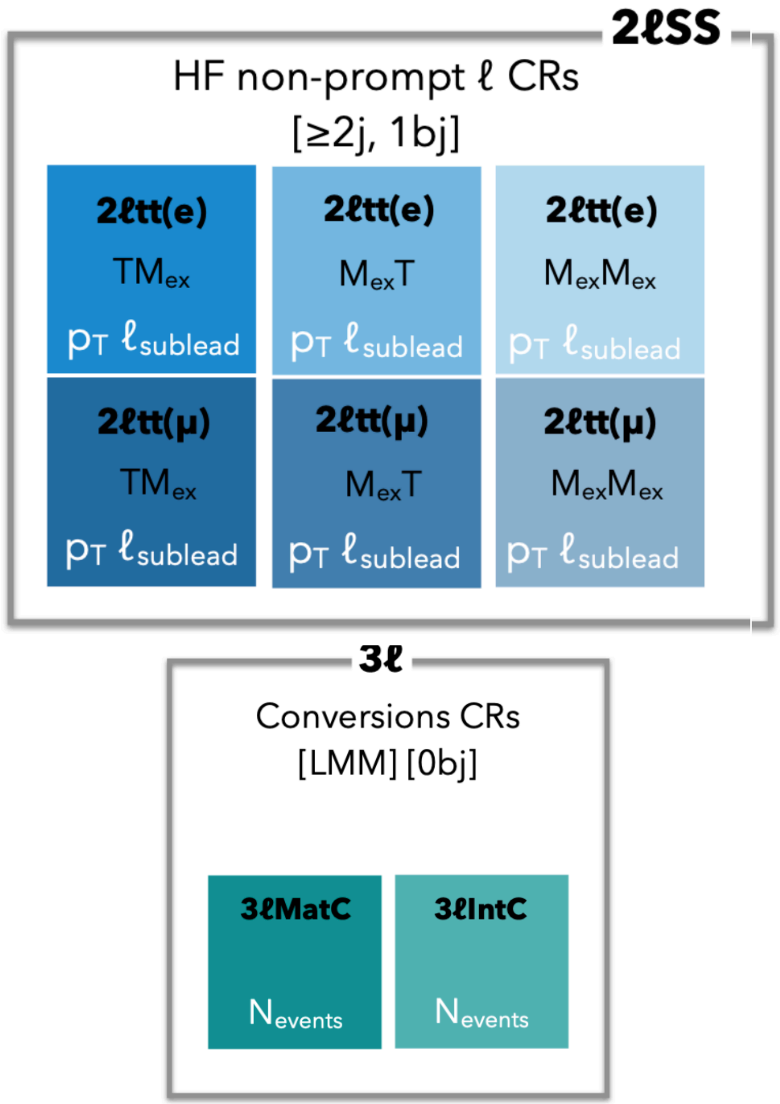


Control regions for:	Diboson	$t\bar{t}Z$
Lepton requirement		3ℓ
Lepton definition		(L, M, M)
Lepton p_{T} [GeV]		(10, 20, 20)
$m^{\mathrm{SF}}_{\ell^+\ell^-}$ [GeV]		> 12
$\lvert m^{\mathrm{SF}}_{\ell^+\ell^-} - m_Z \rvert$ [GeV]		< 10
$\lvert m_{3\ell} - m_Z \rvert$ [GeV]		> 10
$m_{\mathrm{T}}(\ell_0, E_{\mathrm{T}}^{\mathrm{miss}})$ [GeV]		—
N_{jets}	2 or 3	≥ 4
$N_{b\text{-jets}}$	$1\ b^{60\%}$	$\geq 1\ b^{60\%}$ or $\geq 2\ b^{77\%}$
Region split	—	—
Region naming	3ℓVV	3ℓttZ

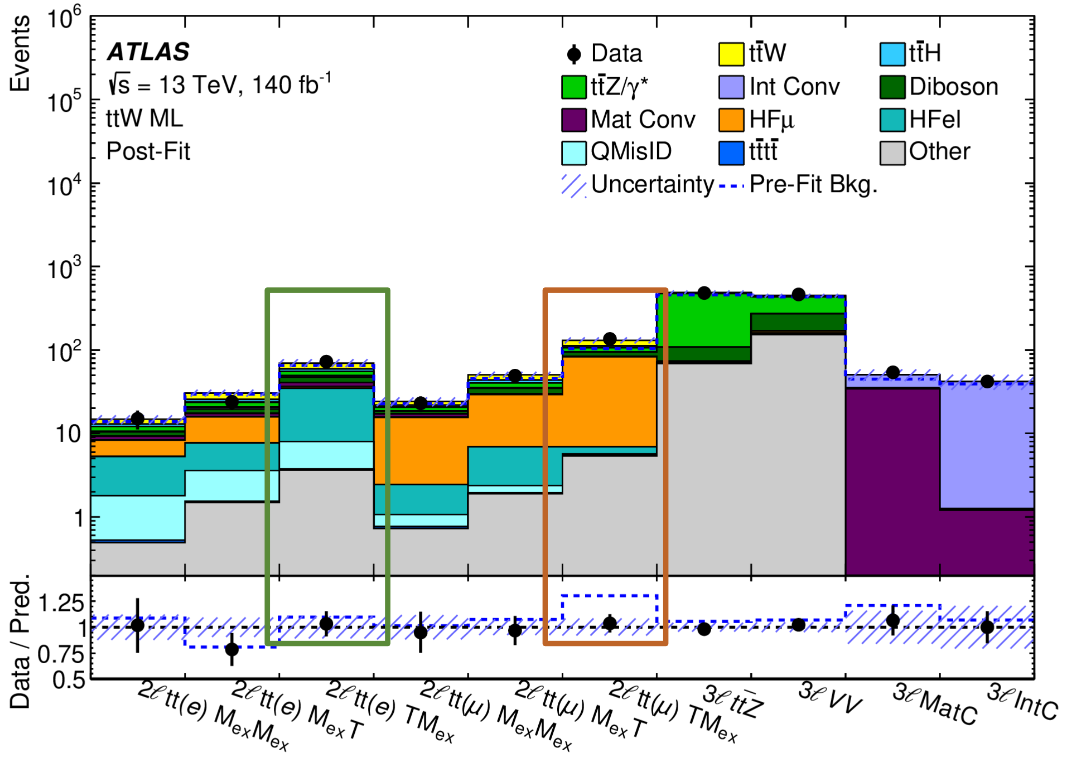
Reducible background: Template Method

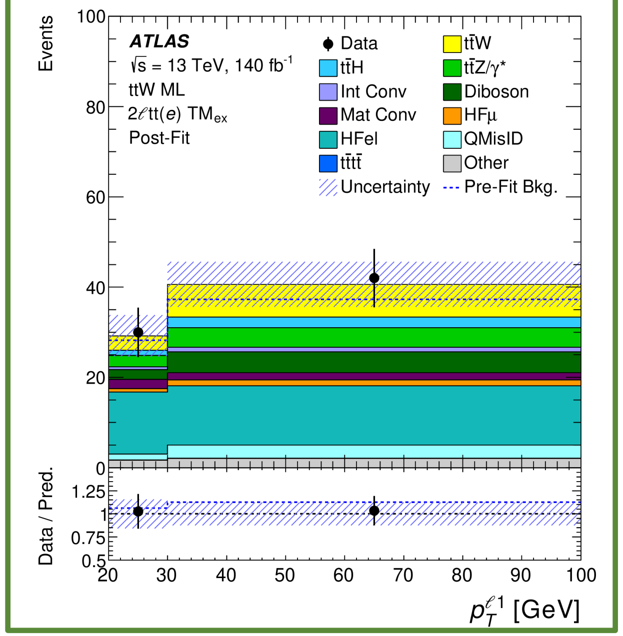
- 6 Control Regions enriched in **HF non-prompt leptons (e, μ)**
  - ➡ defined using exclusive BDT-based isolation working points M_{ex}
- 2 Control Regions enriched in **electrons from conversions**:
  - ➡ Material conversions
  - ➡ Internal (virtual photons) conversions
- Non-prompt lepton templates shapes taken from simulation
  - ➡ normalisation free-floated in the signal extraction fit

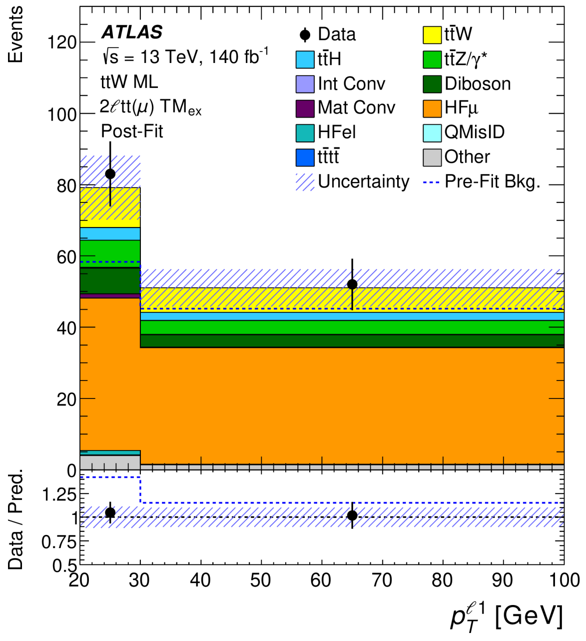
- Electron Charge mis-ID background is estimated using data-driven method
  - ➡ negligible for muons



Reducible background: Template Method



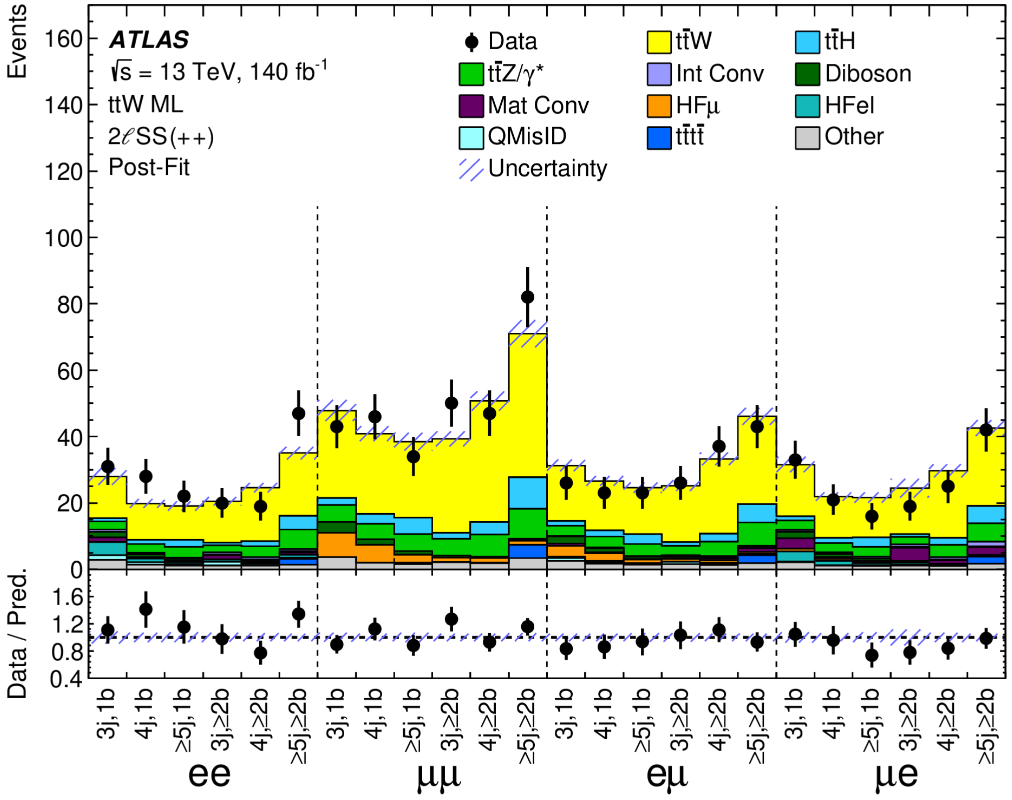


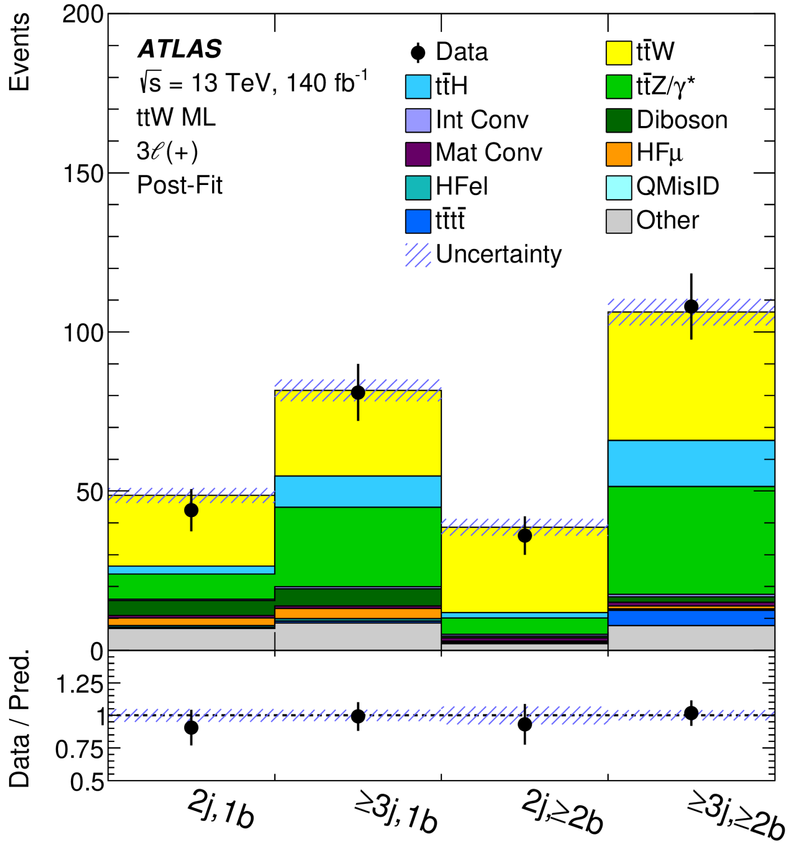


λ_e^{had}	λ_μ^{had}	λ_e^{MatC}	λ_e^{IntC}
0.83 ± 0.31	1.01 ± 0.21	1.15 ± 0.31	1.07 ± 0.24

Inclusive $t\bar{t}W$ cross-section measurement

- Simultaneous profile likelihood fit to data using event yields in 56 SR and 10 CR with 6 free parameters (backgrounds normalisation)



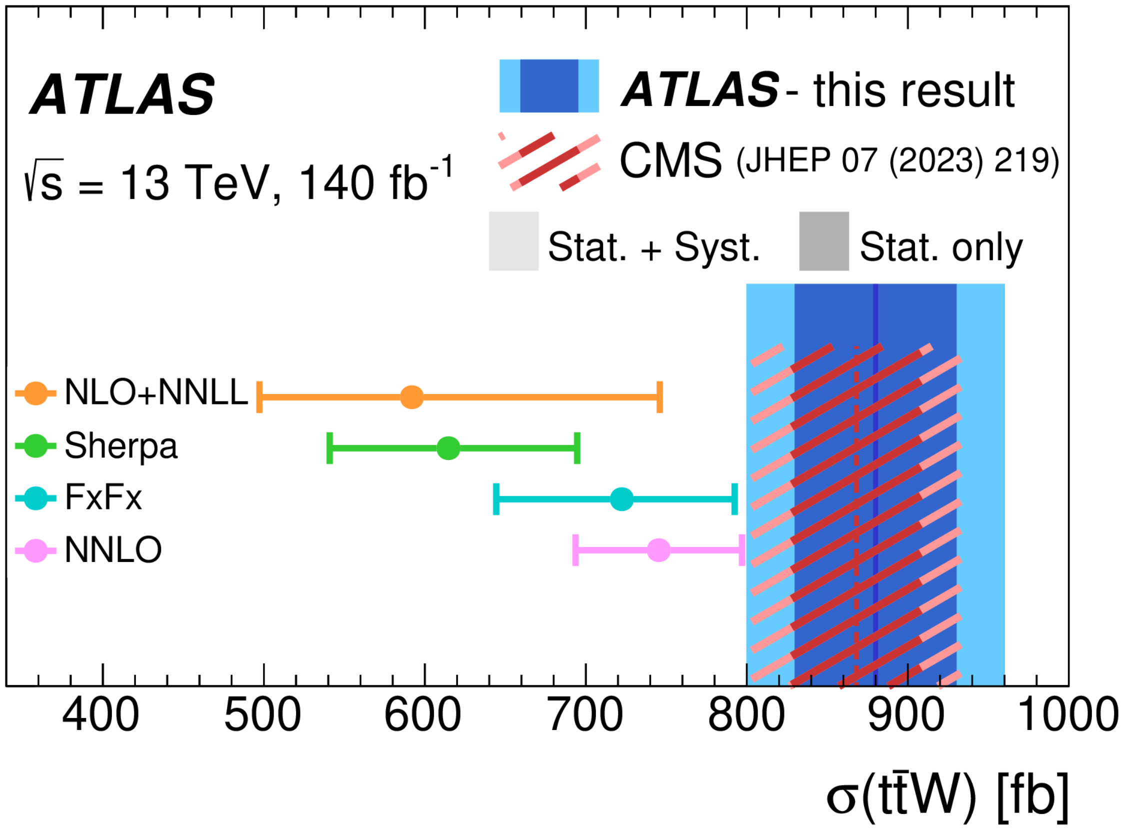


$$\sigma(t\bar{t}W) = 880 \pm 50 \textbf{ (stat.)} \pm 70 \textbf{ (syst.) fb}$$

9% relative uncertainty

Inclusive $t\bar{t}W$ cross-section measurement

- Simultaneous profile likelihood fit to data using event yields in 56 SR and 10 CR with 6 free parameters (backgrounds normalisation)



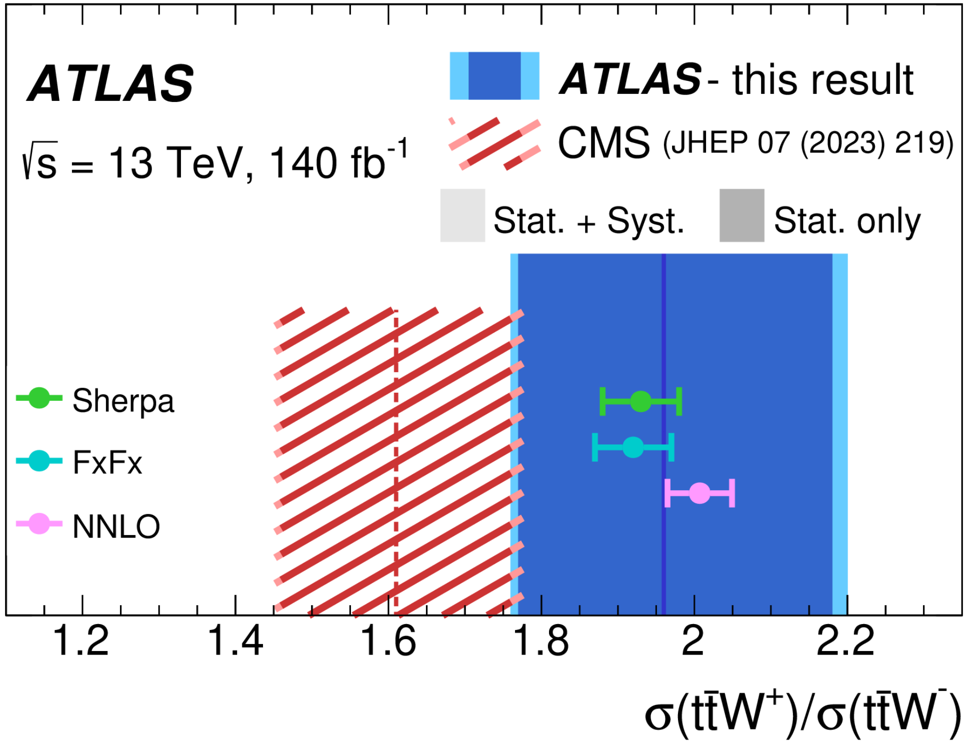
- Consistent at **1.4σ** with latest **SM NNLO theory** calculation

745 ± 50 **(scale)** $\pm\, 13$ **(2-loop approx.)** $\pm\, 19(\mathrm{PDF}, \alpha_s)$ **fb**

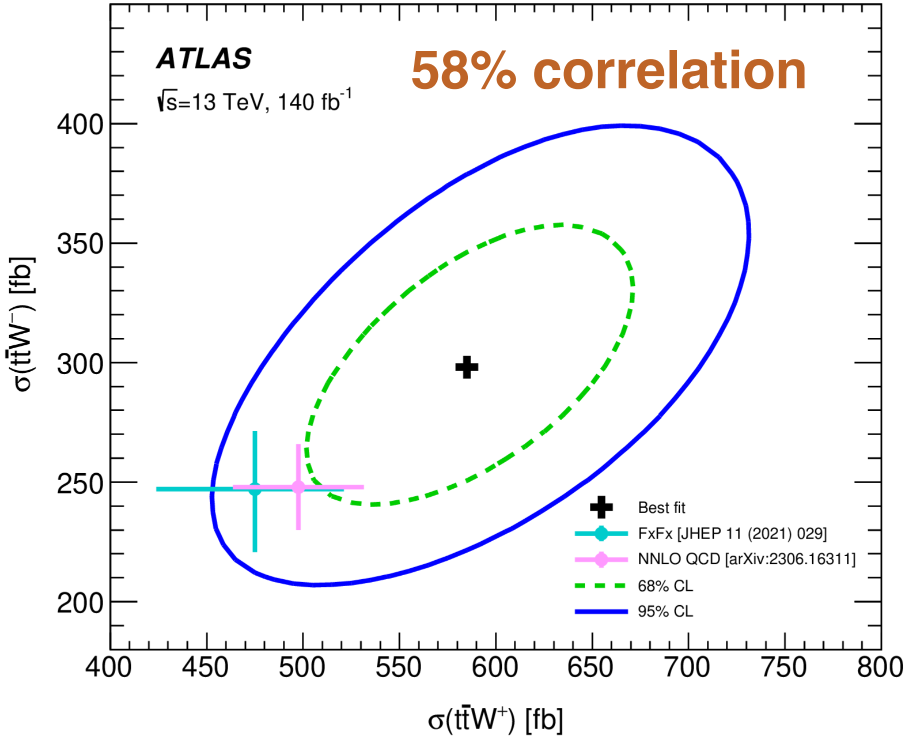
- Leading sources of systematic uncertainties:
  - ➡ $t\bar{t}W$ modeling (generator, parton shower)
  - ➡ $t\bar{t}H$, $t\bar{t}t\bar{t}$ background normalisation
  - ➡ b-tagging
  - ➡ Non-prompt isolation BDT calibration

$t\bar{t}W$ Ratio and Asymmetry measurements

- $t\bar{t}W^+$ **and** $t\bar{t}W^-$ **production rates and their ratio measured inclusively**
- Relative charge asymmetry A_C^{rel} also measured
- **Both measurements consistent with MC predictions**



$$\frac{\sigma_{t\bar{t}W^+}}{\sigma_{t\bar{t}W^-}} = 1.96 \pm 0.21 \textbf{ (stat.)} \pm 0.09 \textbf{ (syst.)}$$



$$A_C^{rel} = \frac{\sigma(t\bar{t}W^+) - \sigma(t\bar{t}W^-)}{\sigma(t\bar{t}W^+) + \sigma(t\bar{t}W^-)}$$

$$A_C^{rel} = 0.33 \pm 0.05 \textbf{ (stat.)} \pm 0.02 \textbf{(syst.)}$$

$$A_C^{rel}\textbf{(Sherpa 2.2.10)} = 0.322 \pm 0.003 \textbf{ (scale)} \pm 0.007 \textbf{(PDF)}$$

$t\bar{t}W$ differential measurements

- **First time differential measurements carried out for $t\bar{t}W$ process at the LHC**
- **Fiducial phase space** definition follows closely the **detector level selection** using **quasi-stable objects** (mean lifetime > 30 ps)
- **Unfolding** performed using a **profile likelihood approach**

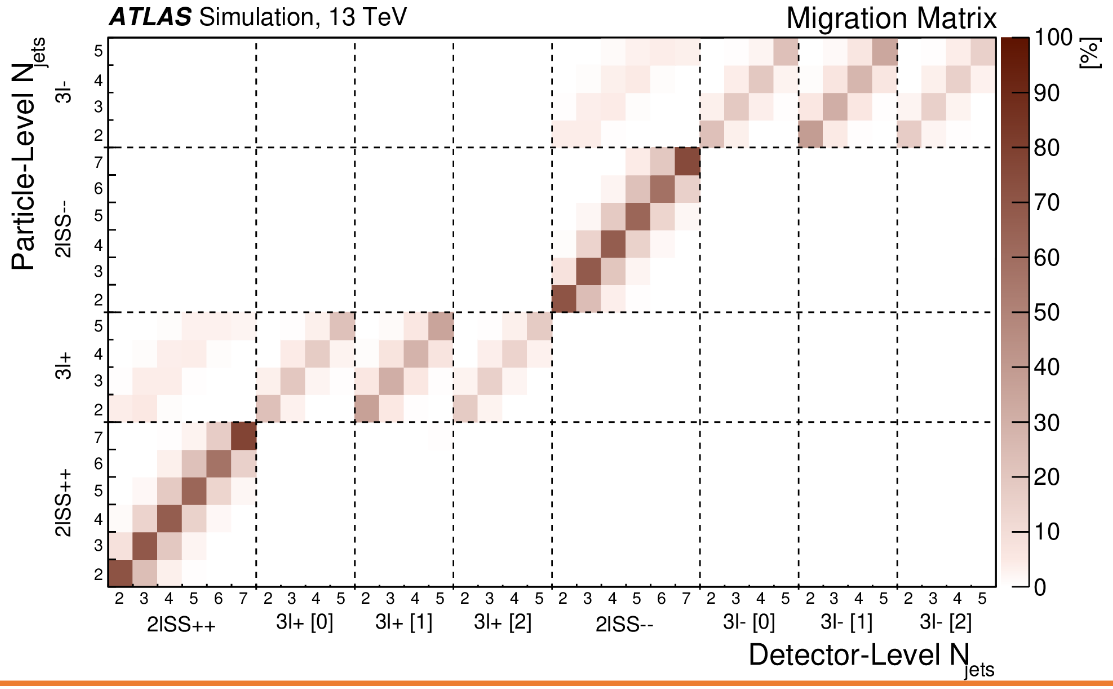
$$\mathcal{L}(\sigma, \vec{\theta}, \vec{\lambda}) = \prod_i P\left(N_i | L_{\text{int}} \sum_j \boxed{\mathcal{R}_{ij}(\vec{\theta})} \sigma_j(\vec{\theta}) + B_i(\vec{\theta}, \vec{\lambda})\right) \times \prod_k G(\theta_k) \times \boxed{\prod_l R(\sigma_l, \tau_l)},$$

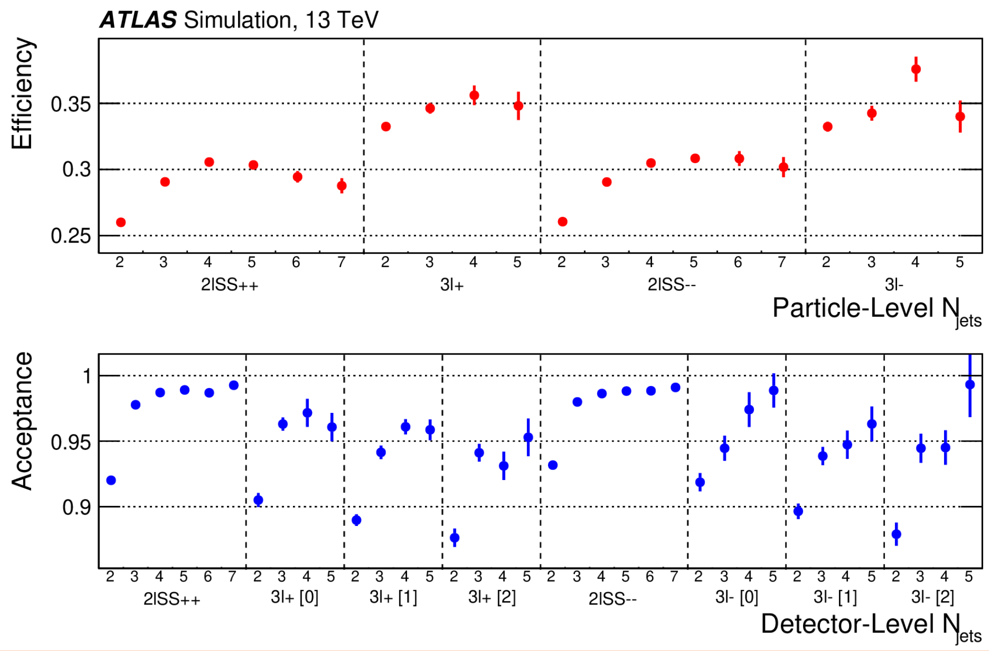
  ➡ same background model and CR from inclusive fit included

  ➡ Tikhonov regularisation applied with optimised strength for each observable/fiducial volume

  ➡ Dedicated binning scheme optimisation, closure and stress tests carried out

  ➡ signal extracted for each particle-level bin by a fit to the detector level events in several SR





$t\bar{t}W$ differential measurements

- **First time differential measurements carried out for $t\bar{t}W$ process at the LHC**
- **Fiducial phase space** definition follows closely the **detector level selection** using **quasi-stable objects** (mean lifetime > 30 ps)
- **Unfolding** performed using a **profile likelihood approach**

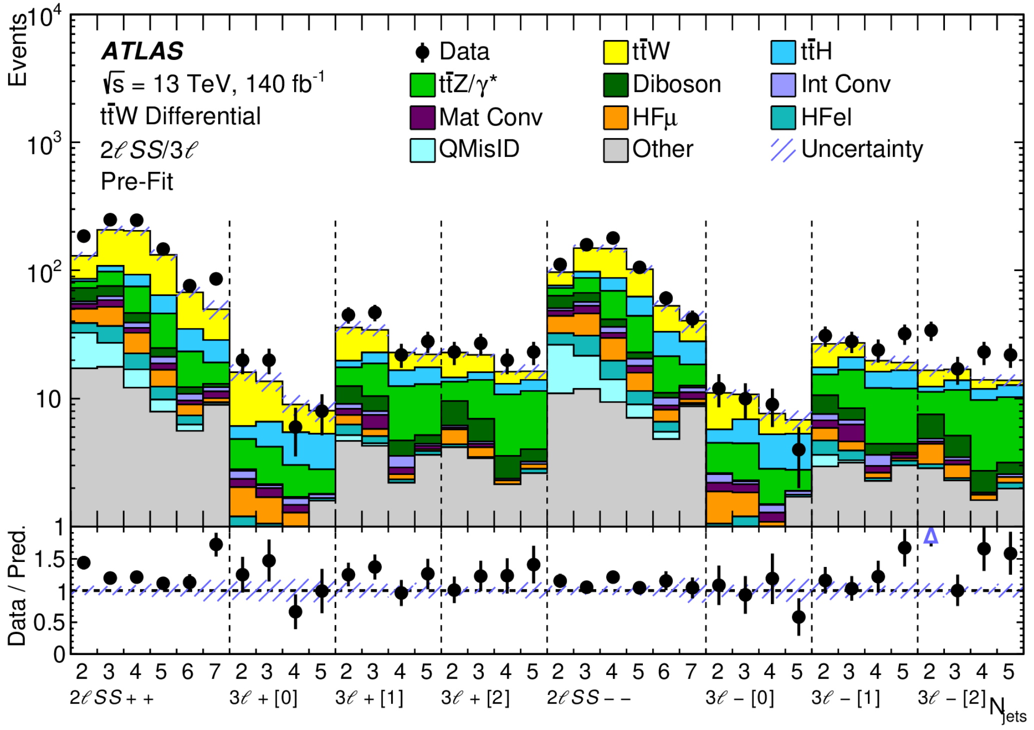
$$\mathcal{L}(\sigma, \vec{\theta}, \vec{\lambda}) = \prod_i P\left(N_i | L_{\text{int}} \sum_j \boxed{\mathcal{R}_{ij}(\vec{\theta})} \sigma_j(\vec{\theta}) + B_i(\vec{\theta}, \vec{\lambda})\right) \times \prod_k G(\theta_k) \times \boxed{\prod_l R(\sigma_l, \tau_l)},$$

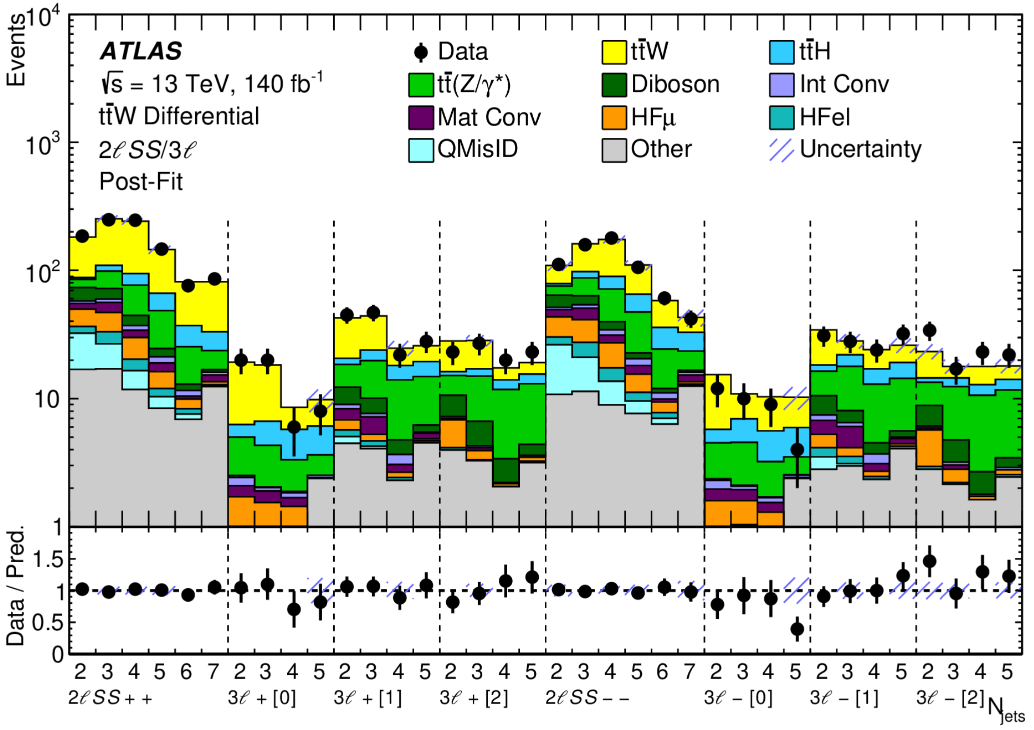
  ➡ same background model and CR from inclusive fit included

  ➡ Tikhonov regularisation applied with optimised strength for each observable/fiducial volume

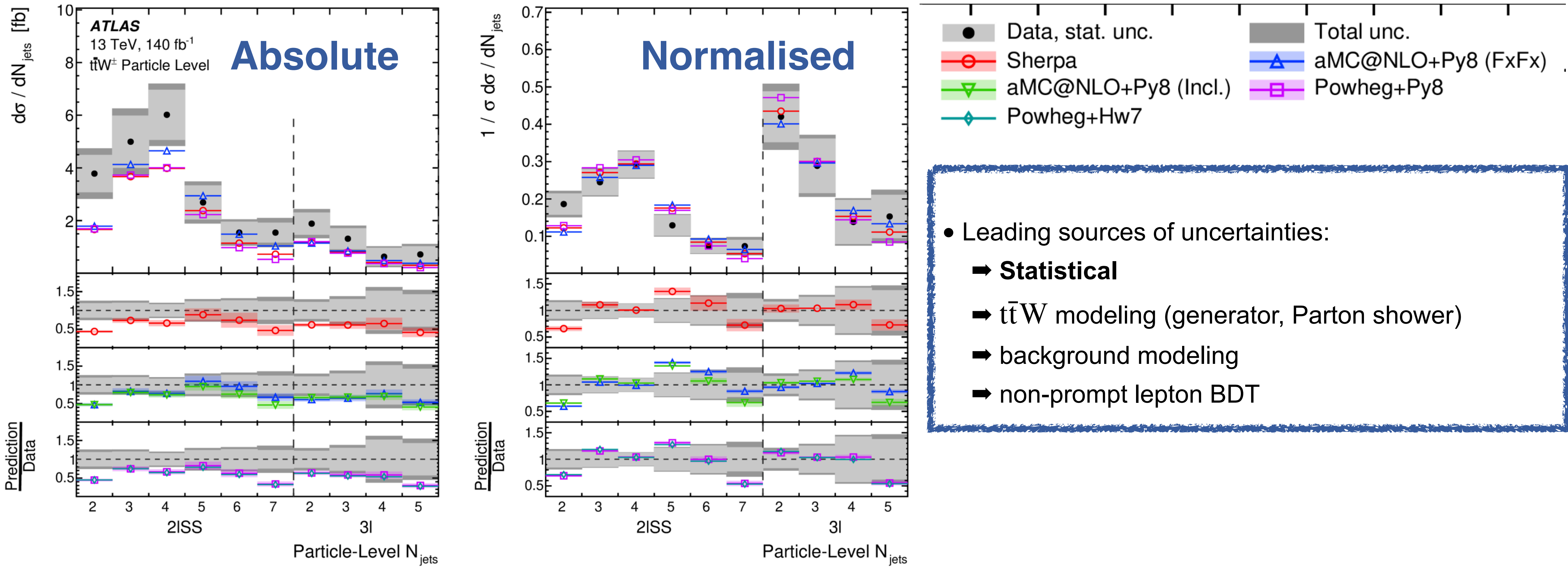
  ➡ Dedicated binning scheme optimisation, closure and stress tests carried out

  ➡ signal extracted for each particle-level bin by a fit to the detector level events in several SR





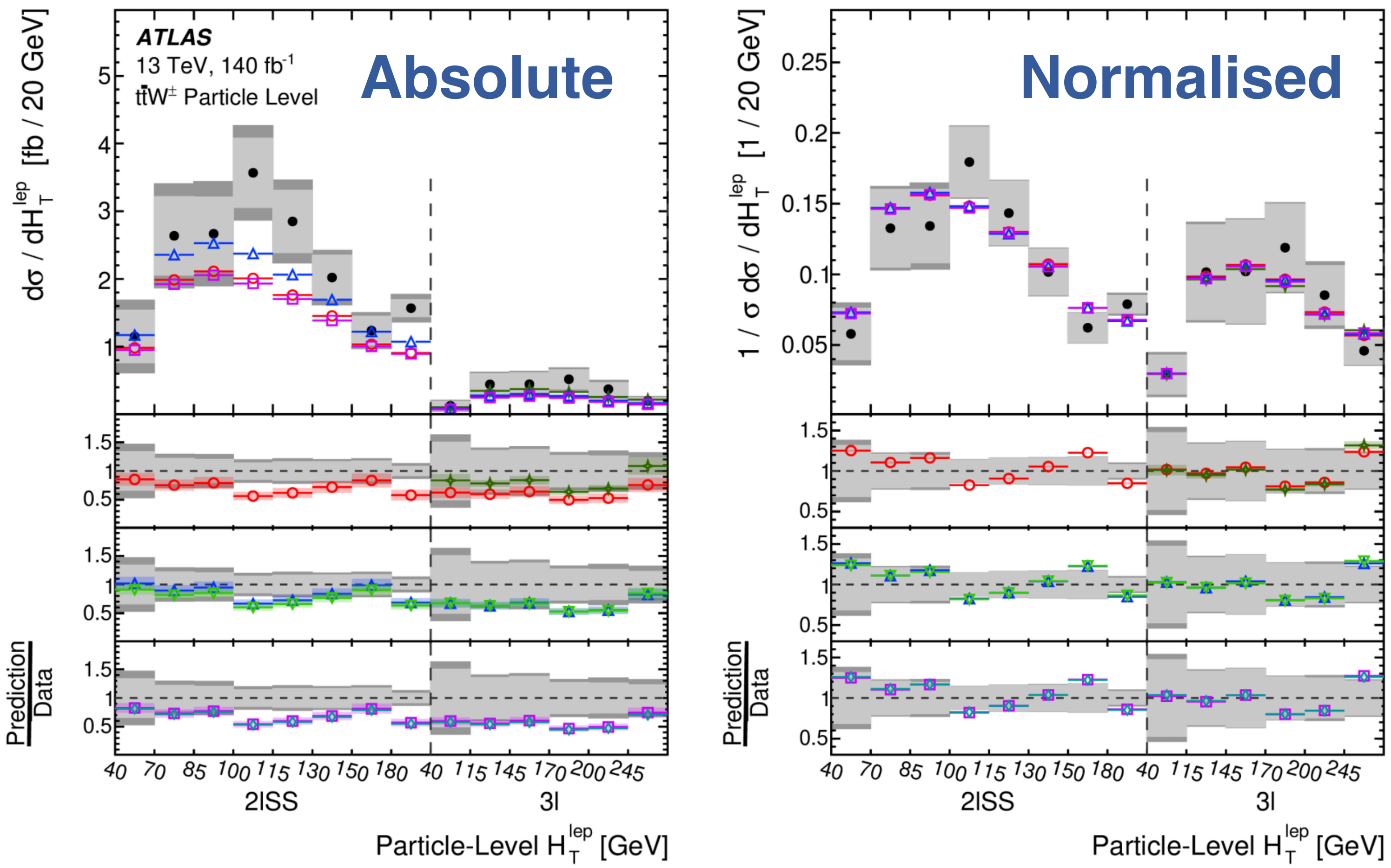
$t\bar{t}W$ differential measurements: cross-section vs N_{jets}

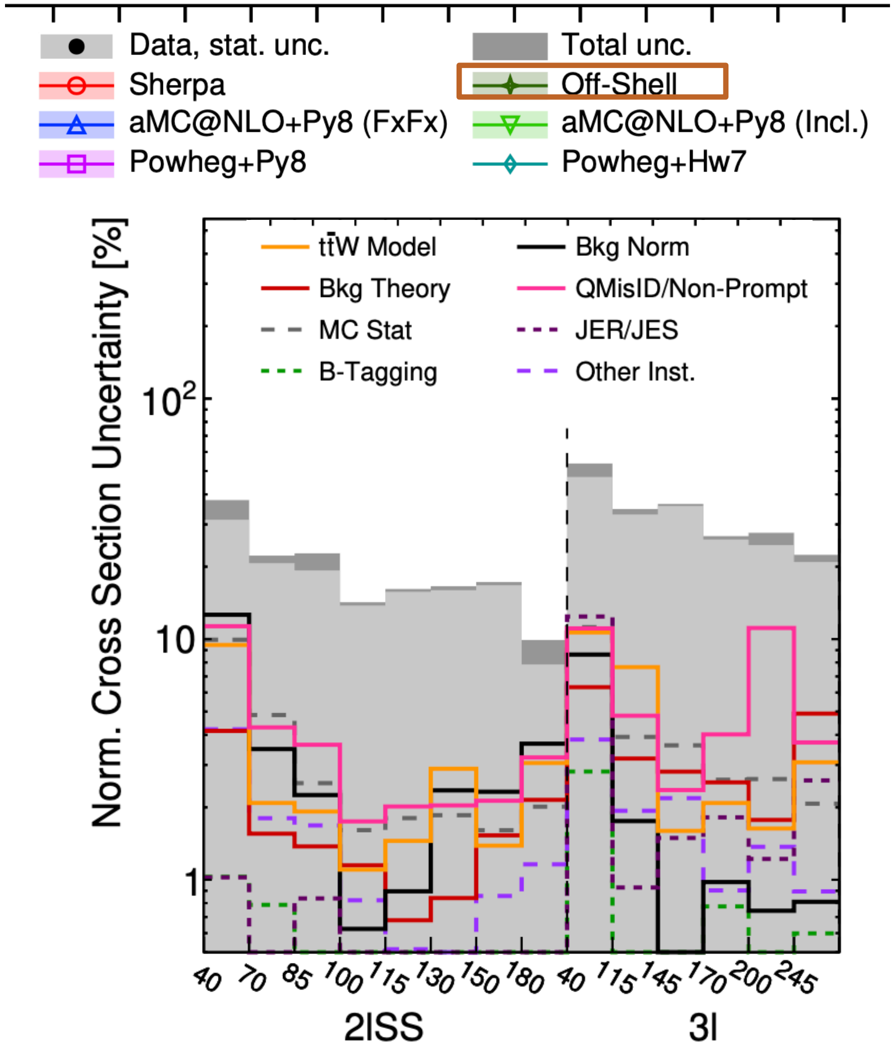


- Leading sources of uncertainties:
  - ➡ **Statistical**
  - ➡ $t\bar{t}W$ modeling (generator, Parton shower)
  - ➡ background modeling
  - ➡ non-prompt lepton BDT

- Unfolded cross-sections compared to **several theoretical predictions** (accounting for higher order QCD and EWK corrections)
  - ➡ absolute cross-sections higher than predictions (consistent with inclusive measurements)
- Good agreement with all MC setups for N_{jets} with p-values ~ 17%-96%

$t\bar{t}W$ differential measurements: cross-section vs H_T^{lep}





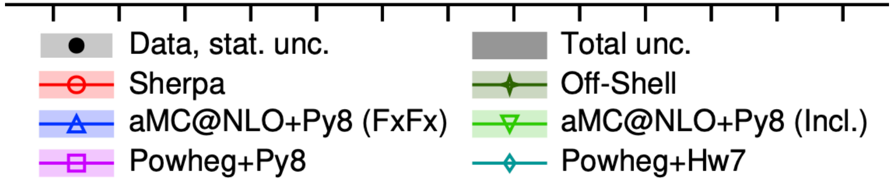
- **Good agreement with all MC setups with p-values ~ 50%-90%**
- Comparison to calculation including off-shell effects (Eur. Phys. J. C 81 (2021) 675) in 3L channel for a subset of observables
  - ➡ slightly higher cross-sections than other predictions

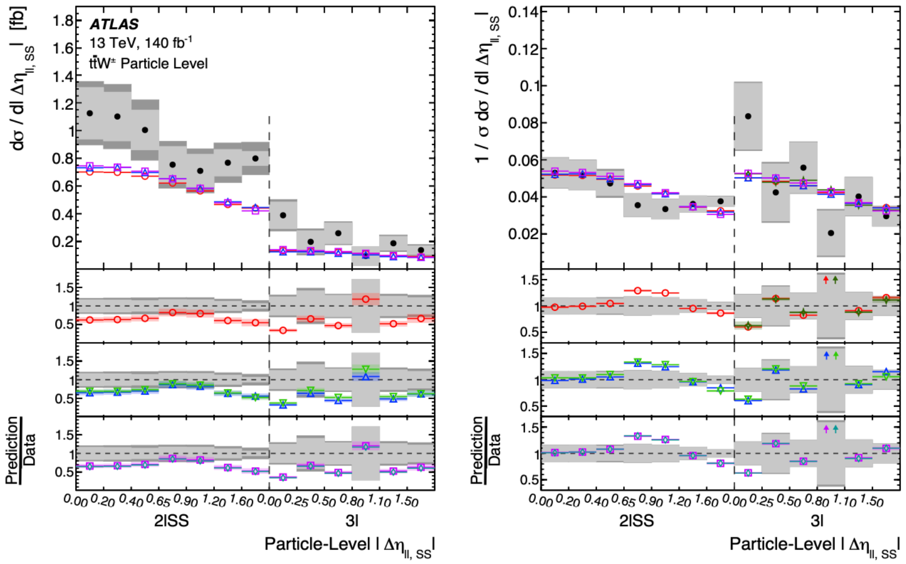
$t\bar{t}W$ differential measurements: compatibility with predictions

χ^2 and p-values for unfolded normalised cross-section distributions in the 2lSS region

Observable	NDF	Sherpa 2.2.10		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
N_{jets}	5	6.5	0.26	7.8	0.17	6.9	0.23	7.2	0.21	6.8	0.24
$H_{\text{T}}^{\text{jet}}$	5	2.0	0.85	2.3	0.81	1.9	0.86	2.5	0.78	2.7	0.75
$H_{\text{T}}^{\text{lep}}$	7	6.1	0.53	6.3	0.51	5.9	0.55	5.9	0.56	5.9	0.55
$\Delta R_{\ell b,\,\text{lead}}$	7	6.8	0.45	7.2	0.41	7.2	0.41	7.2	0.40	7.1	0.41
$\lvert\Delta\phi_{\ell\ell,\,\text{SS}}\rvert$	7	1.7	0.97	1.7	0.98	1.9	0.96	1.8	0.97	1.9	0.97
$\lvert\Delta\eta_{\ell\ell,\,\text{SS}}\rvert$	6	7.0	0.32	8.1	0.23	12.1	0.06	10.2	0.12	10.1	0.12

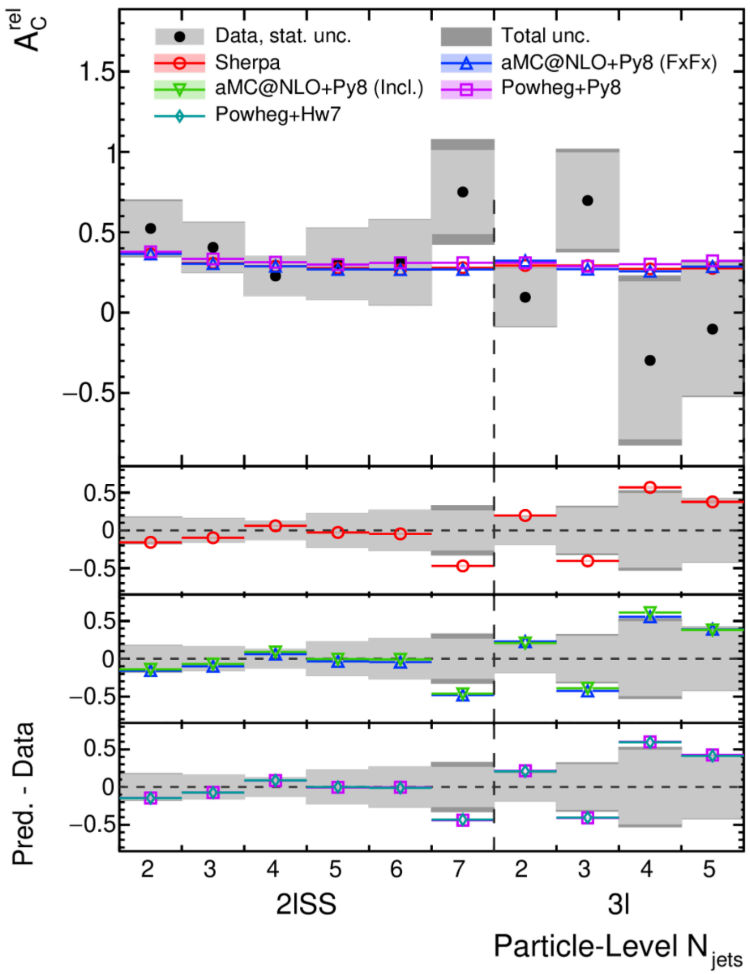
- Overall good agreement with MC predictions for unfolded cross-sections
  - ➡ **mild tensions** in some observables e.g $\lvert\Delta\eta_{\ell\ell,SS}\rvert$

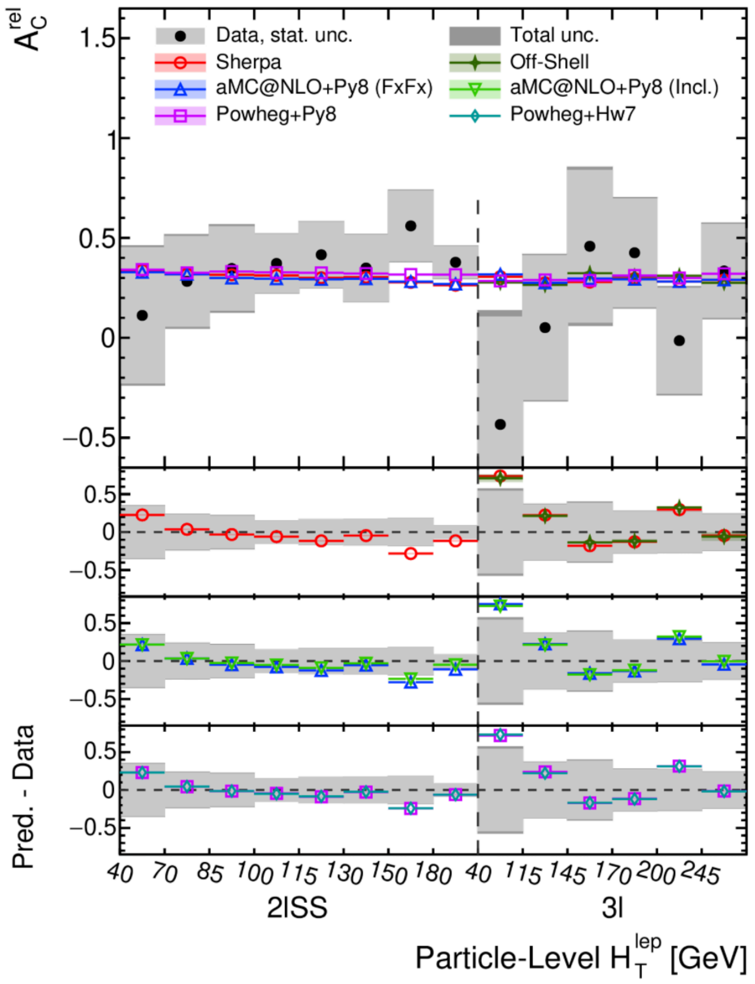




$t\bar{t}W$ differential measurements: A_C^{rel}

$$A_C^{rel} = \frac{\sigma(t\bar{t}W^+) - \sigma(t\bar{t}W^-)}{\sigma(t\bar{t}W^+) + \sigma(t\bar{t}W^-)}$$



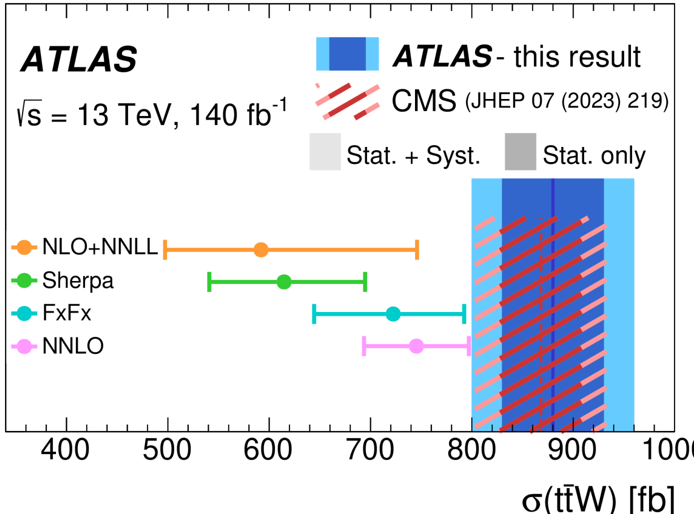


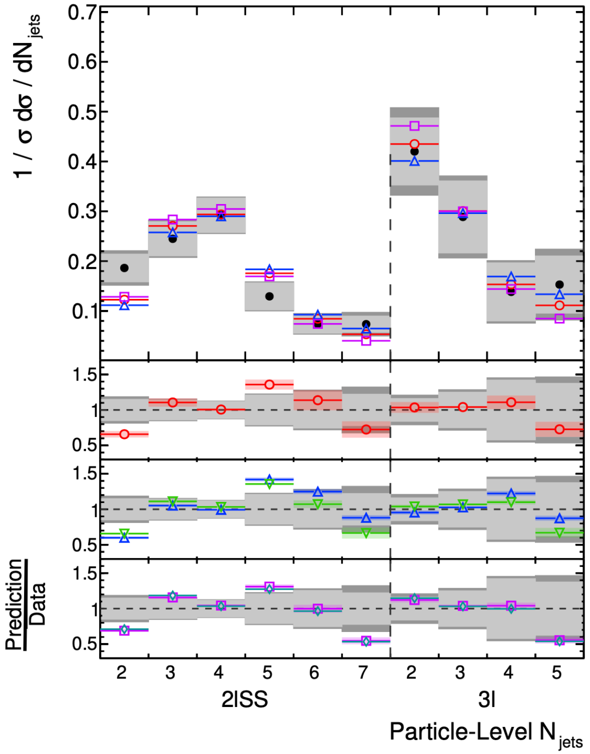
- **Statistical uncertainty dominant**
  - ➡ Many systematic uncertainties cancel out
- **Some tension** between data and MC predictions
  - ➡ Not statistically significant
  - ➡ Good p-values obtained

Observable	NDF	Sherpa 2.2.10	
		χ^2	p-value
N_{jets}	4	4.3	0.37
H_T^{jet}	5	4.1	0.53
H_T^{lep}	6	3.6	0.73
$\Delta R_{\ell b,\text{ lead}}$	6	3.3	0.77
$\lvert\Delta\phi_{\ell\ell,\text{ SS}}\rvert$	6	7.2	0.30
$\lvert\Delta\eta_{\ell\ell,\text{ SS}}\rvert$	6	4.9	0.56

Summary

- **Largest ever dataset available** allowing to evolve from inclusive to first time differential $t\bar{t}W$ **measurements**
  - ➡ overview of the ATLAS **inclusive and differential** $t\bar{t}W$ **production cross-sections** measurements given
- **Inclusive cross-section** found to be ~ 20% higher than state-of-the-art predictions despite including higher order QCD/EWK effects
  - ➡ compatible at the level of 1.4σ with NNLO prediction of 745 ± 50 (scale) $\pm\ 13$ (2-loop approx.) $\pm\ 19(\mathrm{PDF}, \alpha_s)$ fb
- **Normalised differential distributions are consistent with predictions** within uncertainties → **dominated by statistical component**
  - ➡ some observables exhibit mild tensions in parts of the distributions but not significant at current accuracy of the measurements
- These measurements are a **key input to improve the modelling of this process**
  - ➡ HEPdata entry (bootstrap replicas, HISTFactory workspaces for inclusive and differential fits)
- **With Run 3 and beyond an unprecedented amount of data awaits!**
  - ➡ would enhance significantly the precision of $t\bar{t}W$ **measurements…stay tuned**!





Backup

Definition of unfolded observables

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

Variable	Definition
$M_{\ell b,\,\text{lead}}$	Invariant mass of the leading lepton and the leading b-tagged jet
$M_{\ell\ell,\,\text{SS}}$	Invariant mass of the two leptons of the same-sign pair

Tikhonov regularisation parameter

Observable	2ℓSS$++$	$3\ell+$	2ℓSS$--$	$3\ell-$
N_{jets}	0.7	0.3	0.4	0.2
$H_{\mathrm{T}}^{\mathrm{jet}}$	0.6	0.3	0.4	0.2
$H_{\mathrm{T}}^{\mathrm{lep}}$	0.5	0.1	0.2	0.1
$\Delta R_{\ell b,\,\mathrm{lead}}$	0.3	0.2	0.3	0.3
$\lvert\Delta\phi_{\ell\ell,\,\mathrm{SS}}\rvert$	0.1	0	0	0
$\lvert\Delta\eta_{\ell\ell,\,\mathrm{SS}}\rvert$	0.1	0.1	0.1	0

$$\rho = \left\langle \sqrt{1 - \left(V_{ii} V_{ii}^{-1}\right)^{-1}} \right\rangle_{i \in 1,\ldots,N_{\mathrm{bins}}}$$

- **Tikhonov** regularisation is implemented through the R term in the PLU which constrains the discrete second derivative of the particle level bin normalisation factor to be close to zero
- Optimisation based on bootstrapping to estimate the value of the parameter that minimises the global correlation coefficient of the unfolded covariance matrix

Examples of stress/closure tests

- Building an Asimov dataset with changed normalisation in certain regions or applying linear slopes in the particle level distributions which are then retrieved by the PLU
- Stress test evaluating the bias in the unfolding using an alternative signal model
- Stress test evaluating the sensitivity to the limited number of simulated events by splitting the signal sample into 2 parts of equal size (for unfolding and as Asimov dataset)
- Data-driven stress test to evaluate the bias in the unfolded observed data (unfolding without regularisation to build pseudo Asimov dataset using a second order polynomial fitting)