Universidad de Oviedo
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TOP 2022

Inclusive and differential single top cross sections

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(ON BEHALF OF THE ATLAS AND CMS COLLABORATIONS)

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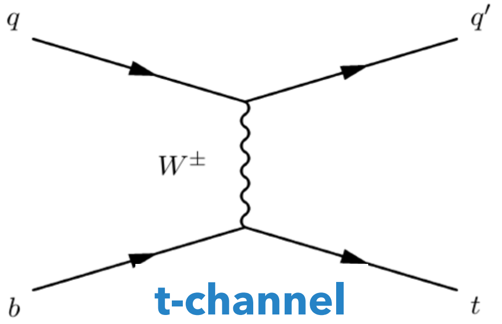
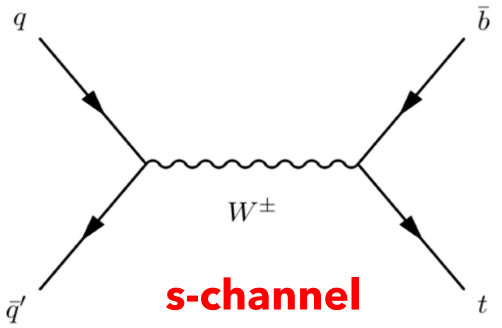
Introduction

- Top quark production occurs in two different ways: top pair (QCD) and **single top** (EW).
  - Single top quark production via *Wtb* vertex → probe and measure V_{tb}.



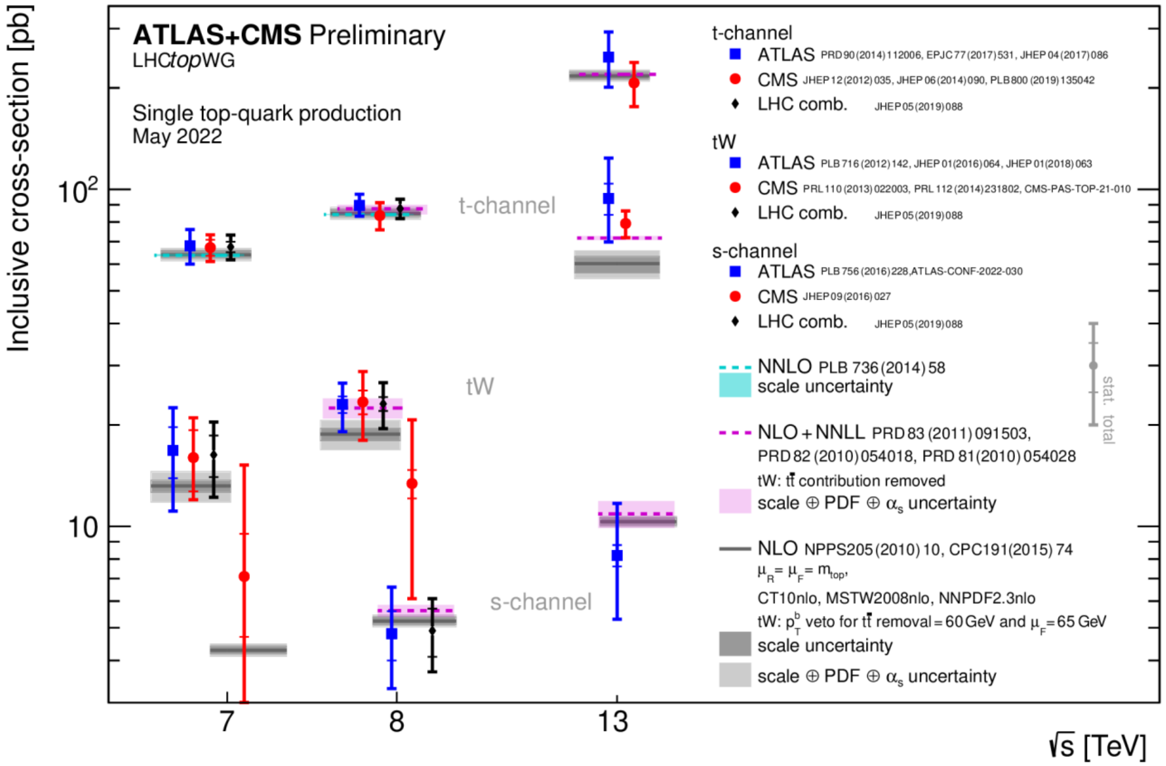


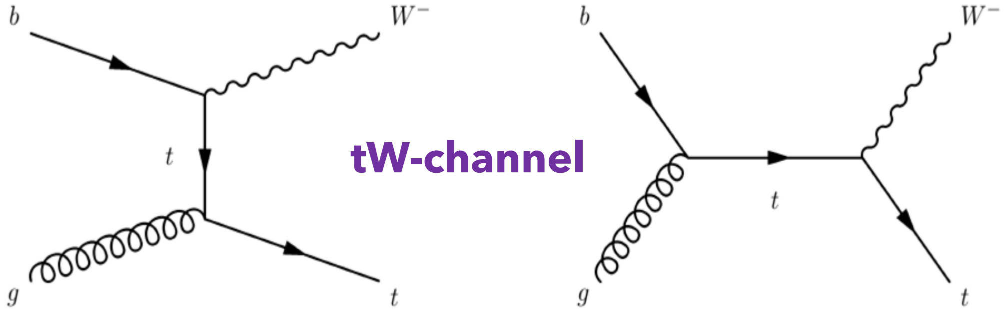
$$\sigma_{\mathrm{t\ ch.}}(13\ \mathrm{TeV}) = 217.0^{+6.6}_{-4.6}(\mathrm{scale}) \pm 6.2(\mathrm{PDF}, \alpha_S)\ \mathrm{pb}$$

$$\sigma_{\mathrm{s\ ch.}}(13\ \mathrm{TeV}) = 10.32^{+0.29}_{-0.24}(\mathrm{scale}) \pm 0.27(\mathrm{PDF}, \alpha_S)\ \mathrm{pb}$$

$$\sigma_{\mathrm{tW\ ch.}}(13\ \mathrm{TeV}) = 71.7 \pm 1.8(\mathrm{scale}) \pm 3.4(\mathrm{PDF}, \alpha_S)\ \mathrm{pb}$$

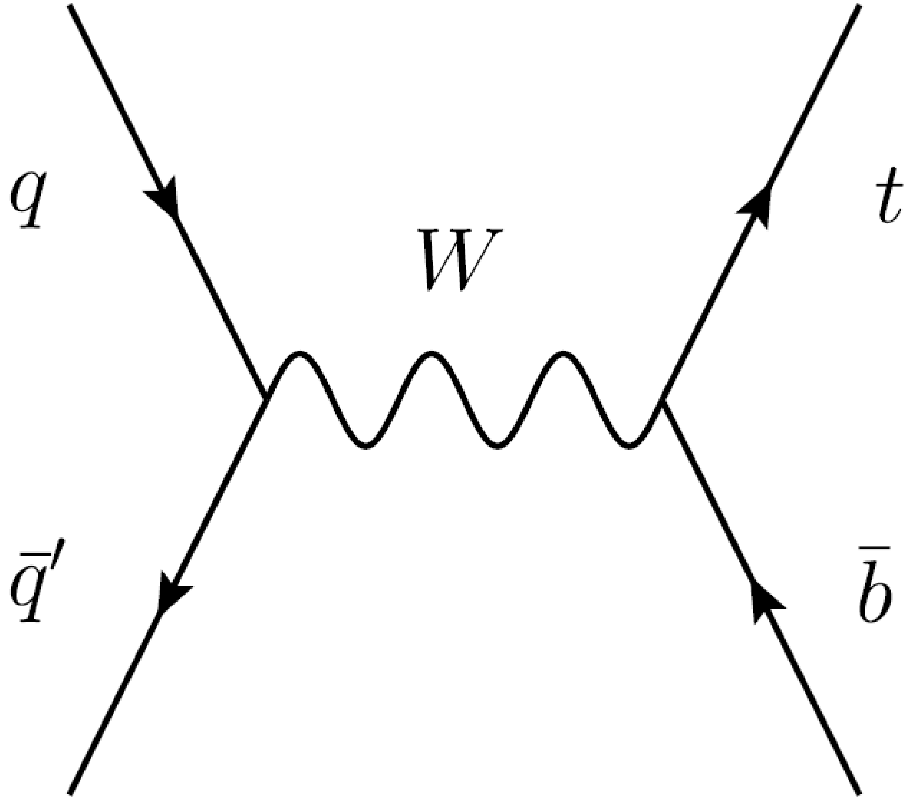
Latest single-top summary plot:





Results presented in this talk

- **s-channel**: Measurement of single top-quark production in the s-channel in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector. ATLAS-CONF-2022-030
- **t-channel**: Measurement of CKM matrix elements in single top quark t-channel production in proton-proton collisions at $\sqrt{s} = 13$ TeV. Phys. Lett. B 808 (2020) 135609
- **t-channel**: Measurement of the polarisation of single top quarks and antiquarks produced in the t-channel at $\sqrt{s} = 13$ TeV and bounds on the tWb dipole operator from the ATLAS experiment. Sub. to JHEP, arXiv: 2202.11382
- **tW channel**: Measurement of inclusive and differential cross sections for single top quark production in association with a W boson in proton-proton collisions at $\sqrt{s} = 13$ TeV. Sub. to JHEP, arXiv: 2208.00924
- **tW channel**: Measurement of single top-quark production in association with a W boson in the single-lepton channel at $\sqrt{s} = 8$ TeV with the ATLAS detector. Eur. Phys. J. C 81 (2021) 720
- **tW channel**: Observation of tW production in the single-lepton channel in pp collisions at $\sqrt{s} = 13$ TeV. JHEP 11 (2021) 111



s-channel

Measurement of single top-quark production in the s-channel

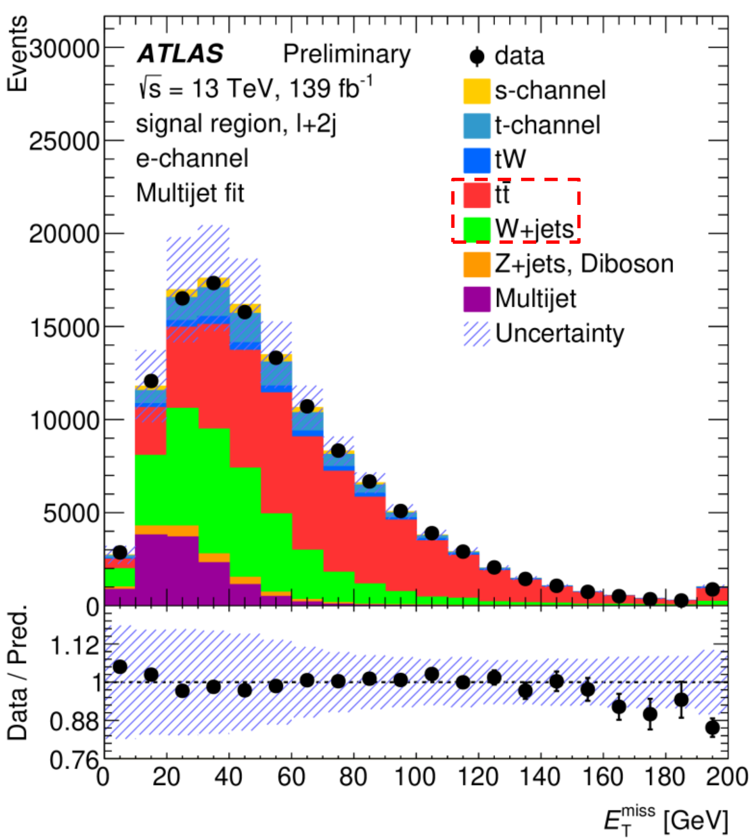
13 TeV, 139 $\mathbf{fb}^{-1}$, s-channel

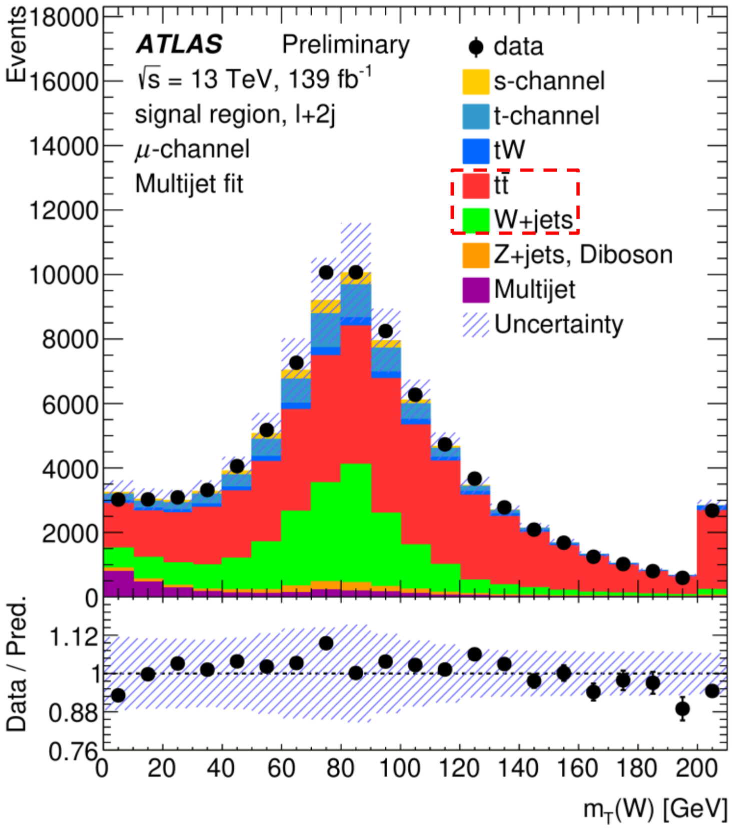
ATLAS-CONF-2022-030

- First 13 TeV measurement.
- Only observed at Tevatron (due to valence antiquarks).
- Main backgrounds: $t\bar{t}$ and W+jets (S/B ~ 3%).
- $t\bar{t}$ cross section grows steeper with $\sqrt{s}$ compared to s-channel (~3/2).
- ATLAS at 8 TeV: 3.2(3.9)σ obs.(exp.).
  - Limited by data statistics, JER and t-channel generator choice.

Baseline event selection:

- $1\ e/\mu\ (> 30\ \mathrm{GeV})$.
- $p_T^{miss} > 35$ GeV & $m_T(W) > 30$ GeV.





- Signal region (2j2b):
  - = 2 jets (> 30 GeV).
  - Both jets b-tagged.
  - Veto events with additional looser jets and leptons.

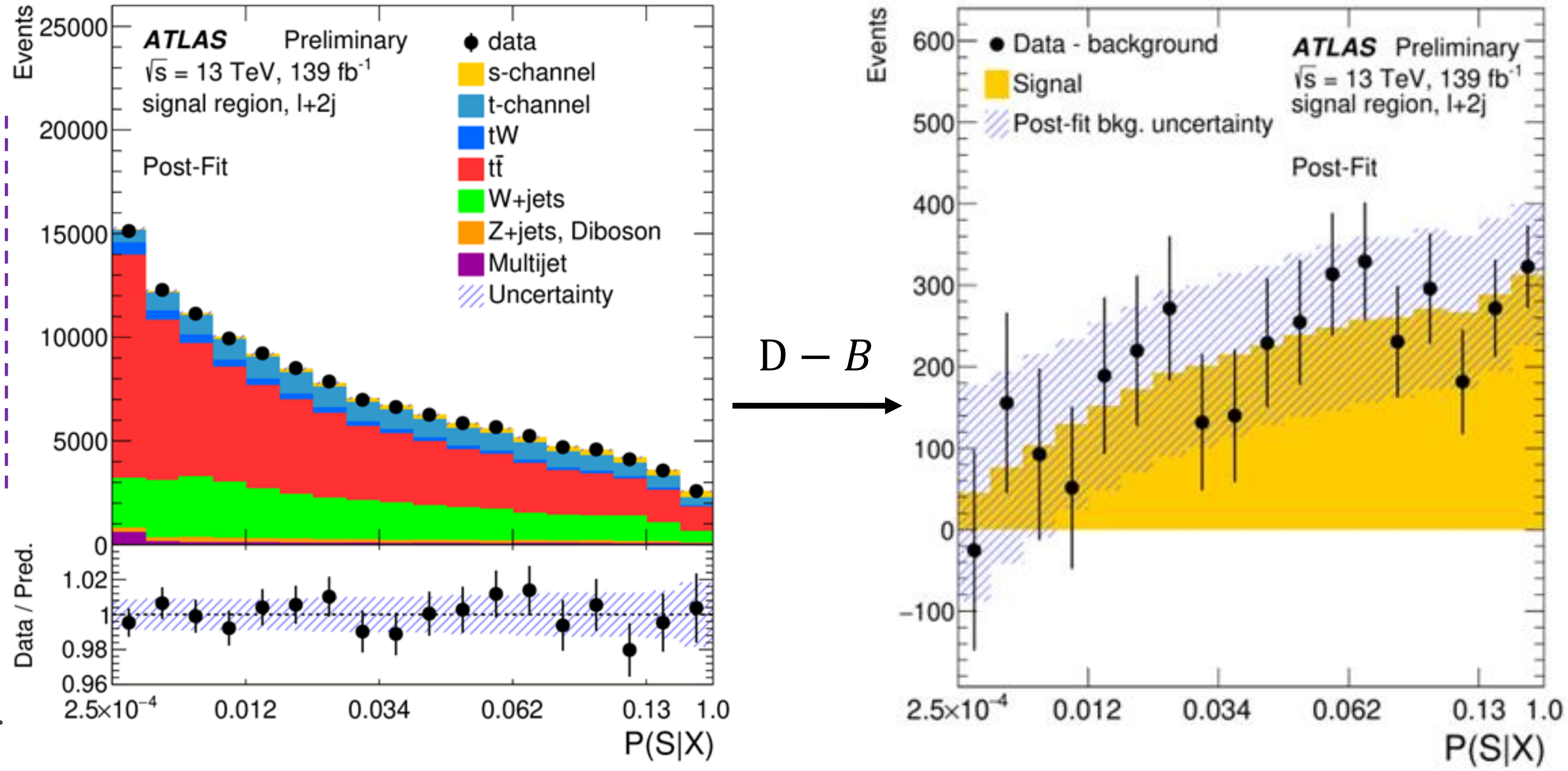
- $t\bar{t}$ VRs: 3j2b, 2j2b.
- W+jets VR: 2j2b (with looser b-tagging WP)

Measurement of single top-quark production in the s-channel

13 TeV, 139 $\mathbf{fb}^{-1}$, s-channel

ATLAS-CONF-2022-030

- **Strategy:**
  - Multijet production modelled in the e/μ channel by the jet-electron (anti-muon) method.
  - Normalisation extracted from data.
  - MC simulations for the rest of processes.
  - Signal extraction performed by binned profile likelihood fit in the SR.
  - A discriminant $P(S|\,X)$ based on matrix element calculations is used.
    - Good discrimination wrt. $\mathrm{t\bar{t}}$.
    - Takes into account the detector resolution: transfer functions.



More details in Jacob Kempsters' talk!

- **Result:**

$$\sigma_{\text{meas.}} = 8.2 \pm 0.6\,(\text{stat.})^{+3.4}_{-2.8}\,(\text{syst.})\ \text{pb}$$

  - Compatible with SM prediction:

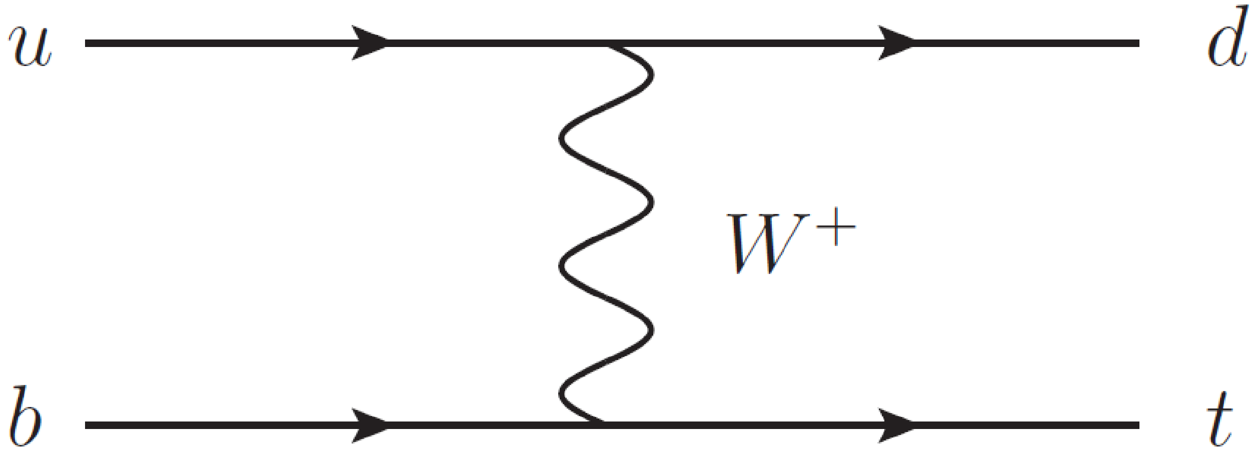
$$\text{NLO: } \sigma_{\text{pred.}} = 10.32^{+0.40}_{-0.36}\ \text{pb}$$

Hathor v2.1

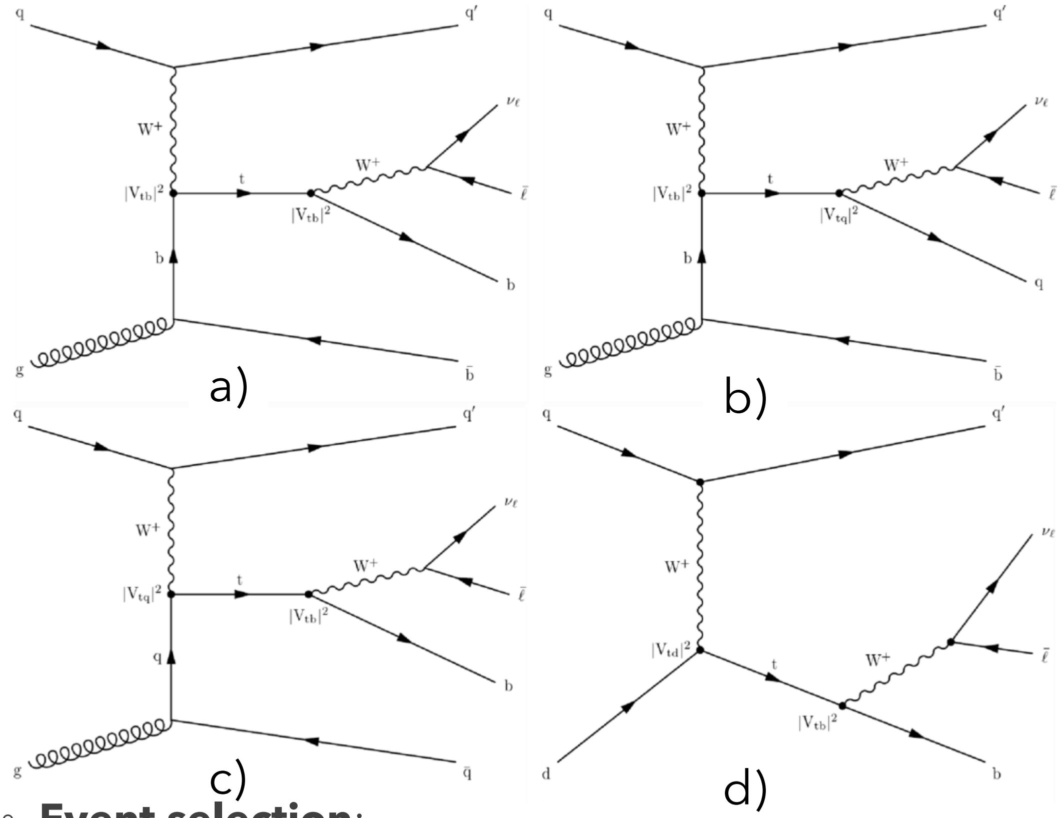
  - Significance: 3.3(3.9)σ obs. (exp.)

Measurement dominated by systematic uncertainties

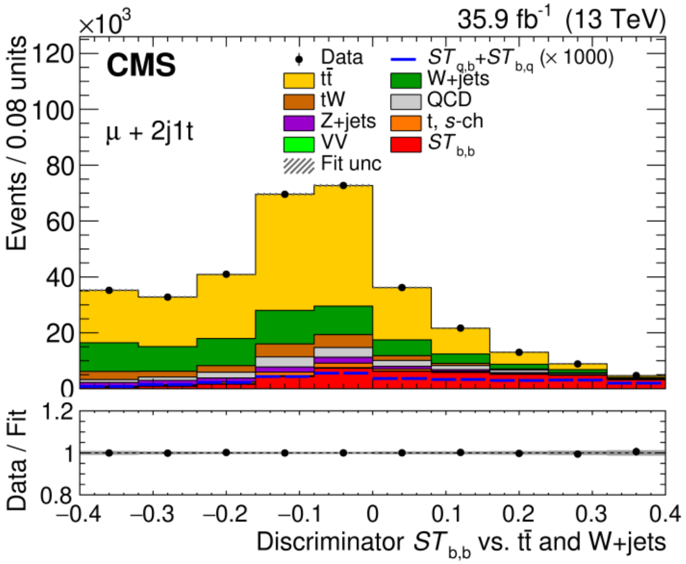
Source	$\Delta\sigma/\sigma$ [%]
$t\bar{t}$ normalisation	$+24/-17$
Jet energy resolution	$+18/-12$
Jet energy scale	$+18/-13$
Other s-channel modelling sources	$+18/-8$
Top-quark processes ISR/FSR	$+13/-11$
MC statistics	$+13/-11$
Other $t\bar{t}$ shape modelling sources	$+12/-10$
Flavour tagging	$+12/-10$
W+jets normalisation	$+11/-8$
Top-quark processes PDFs	$+10/-9$
W+jets μ_R/μ_F shape	$+6/-5$
Other processes normalisation	$+6/-5$
Pileup	$+5/-3$
Other t-channel modelling sources	±5
Luminosity	$+4/-3$
Other tW modelling sources	$+1/-2$
Missing transverse energy	±1
Multijet shape modelling	±1
Other sources	< 1
Systematic uncertainties	$+42/-34$
Data statistics	±8
Total	$+42/-35$

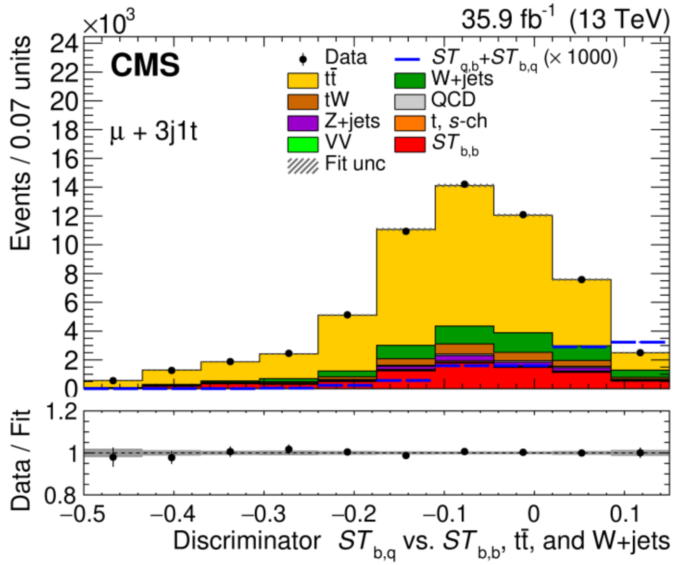


t-channel



- **Strategy**: ML fit on the 2j1t, 3j1t and 3j2t regions.
  - MVAs (BDT) are trained for each region.





- **Event selection**:
  - $1\ e(> 35\ \mathrm{GeV})/\mu(> 26\ \mathrm{GeV})$.
  - $m_{\mathrm{T}}(W) > 50$ GeV.

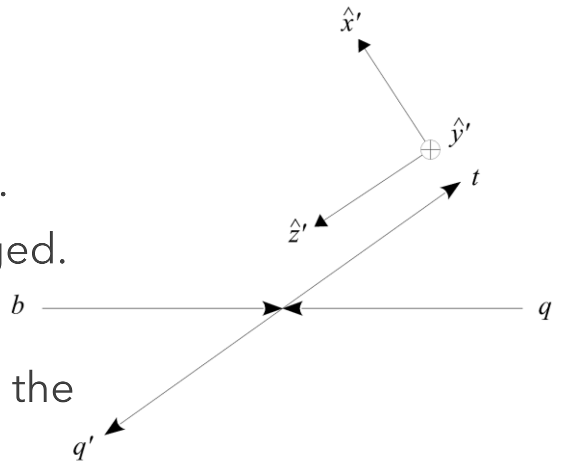
Category	Enriched in	Cross section × branching fraction	Feynman diagram
2j1t	$ST_{\mathrm{b,b}}$	$\sigma_{t\text{-ch,b}}\mathcal{B}(\mathrm{t} \to \mathrm{Wb})$	1a
3j1t	$ST_{\mathrm{b,q}}$, $ST_{\mathrm{q,b}}$	$\sigma_{t\text{-ch,b}}\mathcal{B}(\mathrm{t} \to \mathrm{Wq})$, $\sigma_{t\text{-ch,q}}\mathcal{B}(\mathrm{t} \to \mathrm{Wb})$	1b, 1c, 1d
3j2t	$ST_{\mathrm{b,b}}$	$\sigma_{t\text{-ch,b}}\mathcal{B}(\mathrm{t} \to \mathrm{Wb})$	1a

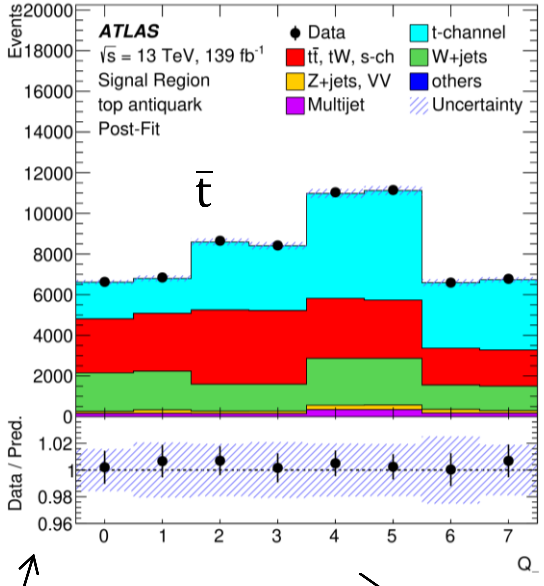
- **Results:**
  - **SM case** (imposing unitarity; 95% CL):

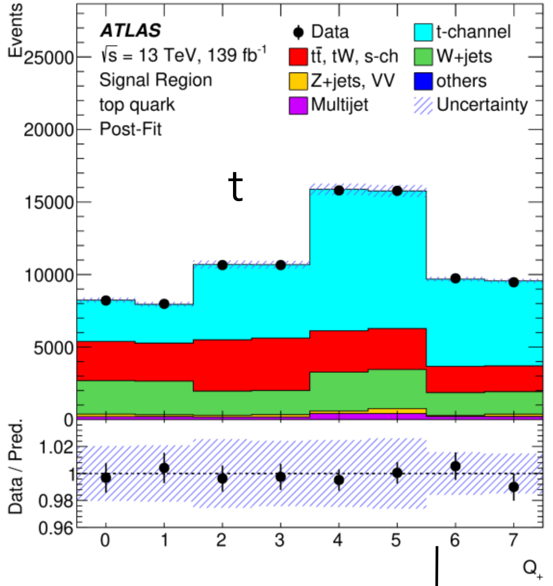
$$|V_{\mathrm{tb}}| > 0.970$$
$$|V_{\mathrm{td}}|^2 + |V_{\mathrm{ts}}|^2 < 0.057.$$

  - **Two BSM cases** show no deviation from the expected values.

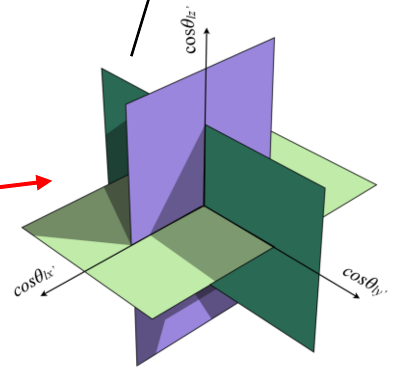
- **Event selection**:
  - 1 e/μ ($>$ 30 GeV).
  - Forward jets included → spectator jet.
  - $=$ 2 jets, of which one must be b-tagged.
  - $p_{\mathrm{T}}^{\mathrm{miss}}$> 35 GeV.
  - Cuts to avoid multijet background on the $m_{\mathrm{T}}(l, p_{\mathrm{T}}^{\mathrm{miss}})$ and $p_{\mathrm{T}}(l)$.



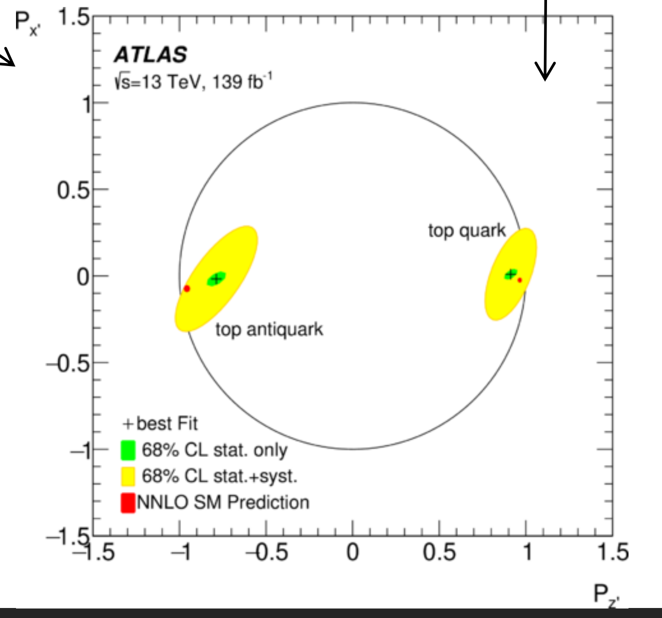




- **First aim**: polarisation vector of single top/antitop quarks.
  - The direction of the charged lepton in the top quark rest frame is obtained ($\cos\theta_{li'}$).
  - z' along spectator quark direction.
  - Events classified in octants (Q).
  - A fit using the quark (Q_+) and antiquark (Q_-) variables, and 4 control region bins (for $\mathrm{t\bar{t}}$ and W+jets) is done.
  - Result compatible with the prediction at NNLO JHEP 11 (2017) 158.



Main unc.: jet energy resolution.



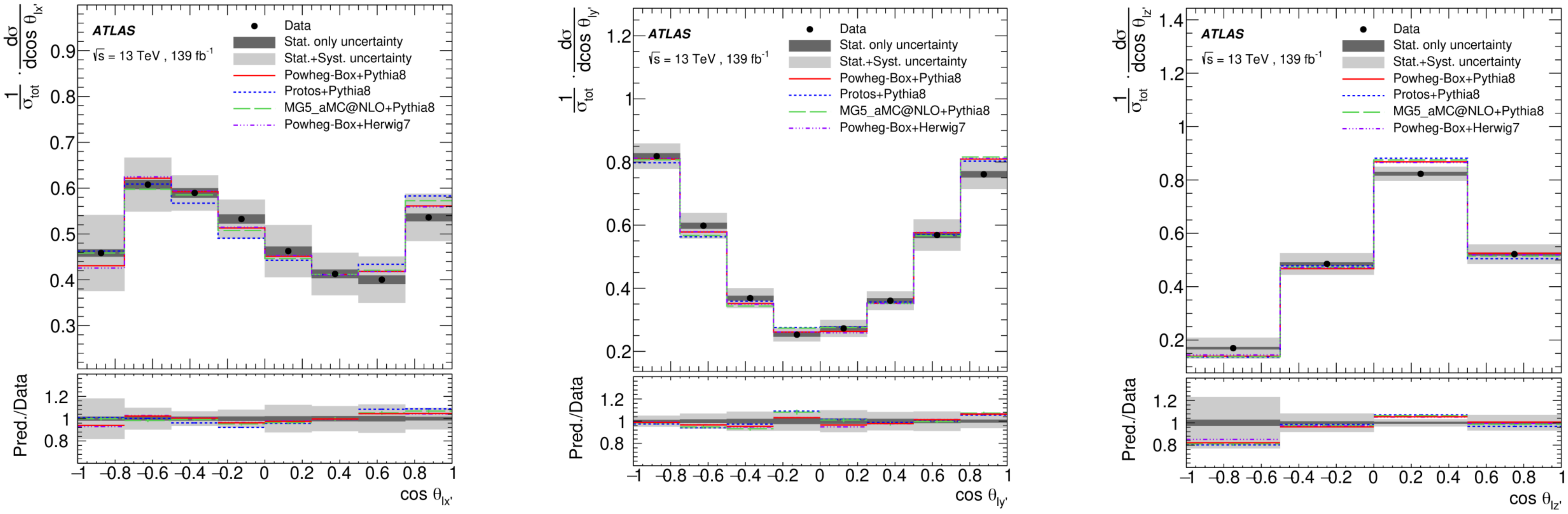
Polarisation measurement and bounds on the tWb dipole operator

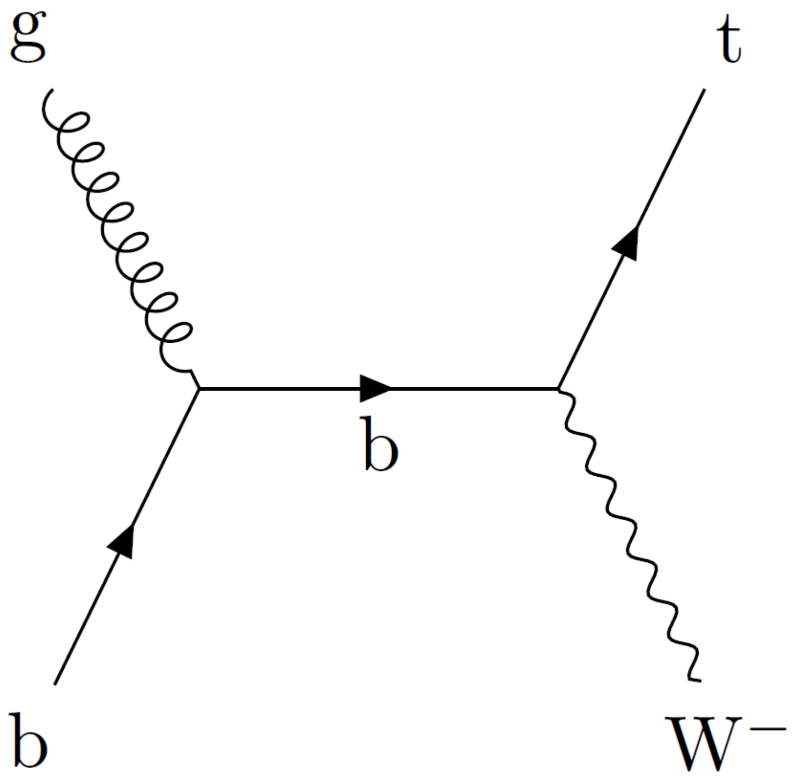
13 TeV, 139 $\mathbf{fb}^{-1}$, t-channel

Sub. to JHEP, arXiv: 2202.11382

- **Second aim**: differential cross section of angular observables.
  - Distributions unfolded to the particle level.
  - Binning is optimised to get a stable unfolding.
  - Result in agreement with predictions at NLO & LO QCD from generators interfaced with Pythia8 and Herwig7.
- **Third aim**: establish bounds on the tWb dipole operator:

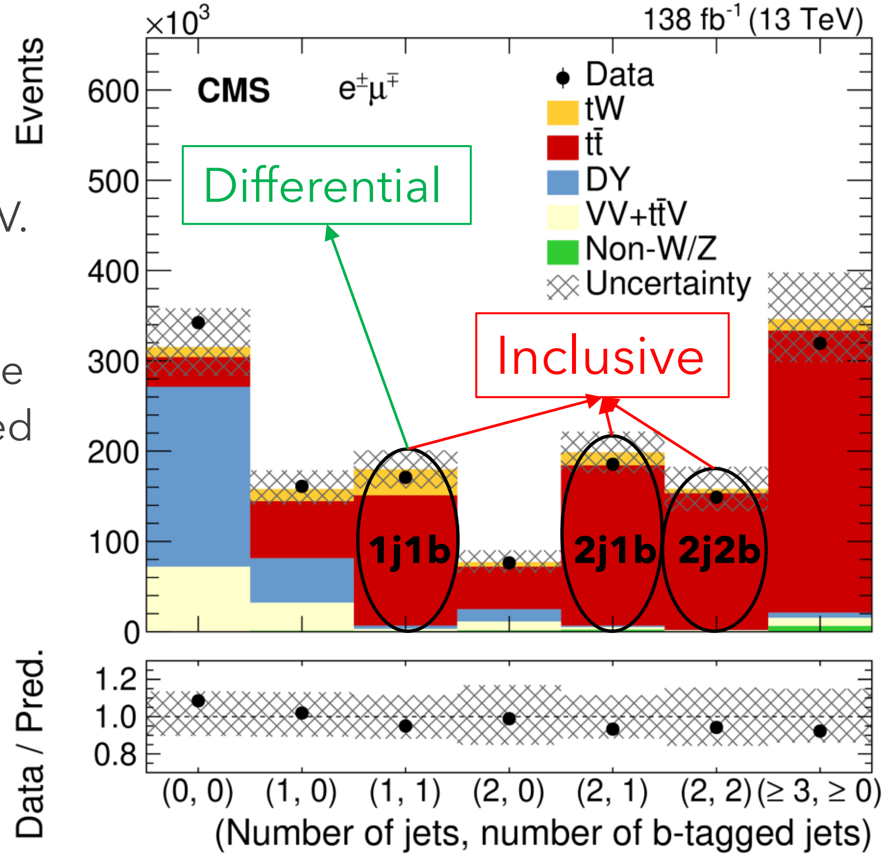
Details in Jon Wilson's talk!



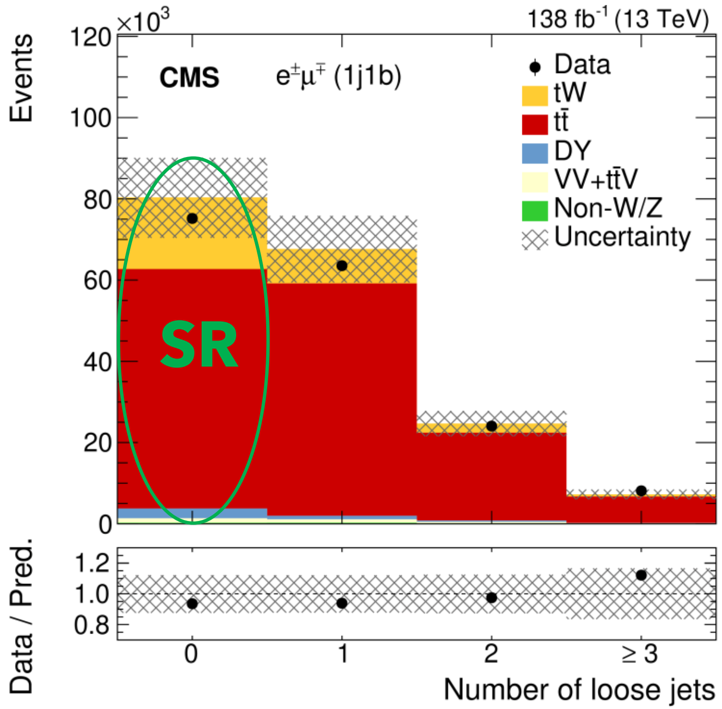


tW-channel

- The tW process **interferes** with $t\bar{t}$ at NLO in QCD.
- **DR** scheme is used.
- Difference with respect to DS → uncertainty.
- **Event selection**:
  - $1e^{\pm} + 1\mu^{\mp}$.
  - Leading lepton $p_T > 25$ GeV.
  - $m(e^{\pm}, \mu^{\mp}) > 20$ GeV.
  - Categorisation based on the number of jets and b-tagged jets.



- Differential measurement: veto events with ≥1 loose jets.



We define loose jets as jets with $p_T \in [20, 30]$ GeV.

- **Inclusive measurement strategy:**
  - BDT used to discriminate tW from $t\bar{t}$.
  - The 2j2b region is used as a $t\bar{t}$ control region.
  - To extract the signal, a ML-fit is performed using the two BDT output and the subleading jet p_T in the 2j2b region.
- The measured cross section is:

$$\sigma_{\mathrm{tW}} = 79.2 \pm 0.8\ (\mathrm{stat}) \pm^{7.0}_{7.2}\ (\mathrm{syst}) \pm 1.1\ (\mathrm{lumi})\ \mathrm{pb}$$

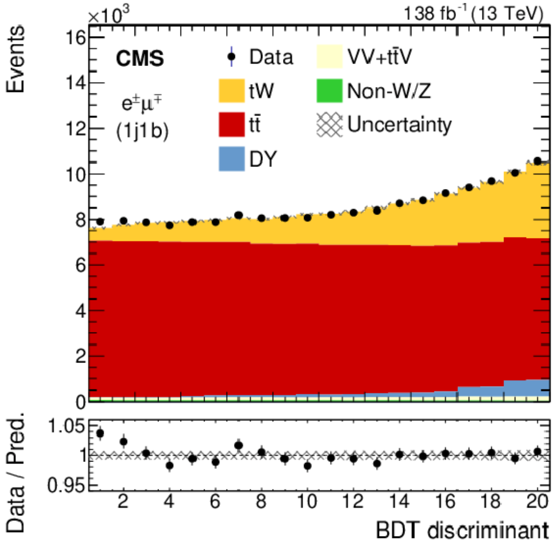
10% relative uncertainty

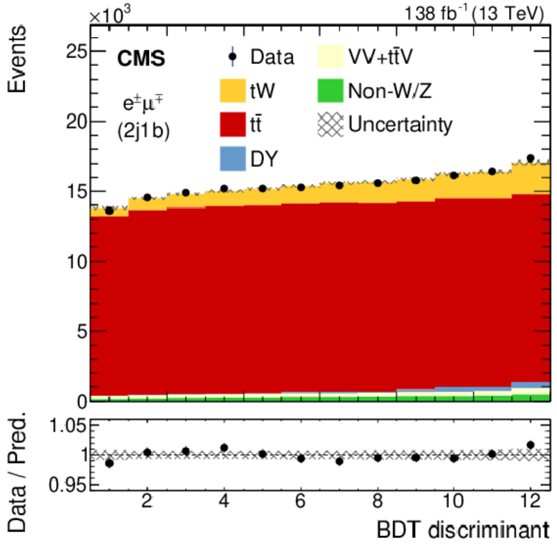
- Compatible with SM predictions:

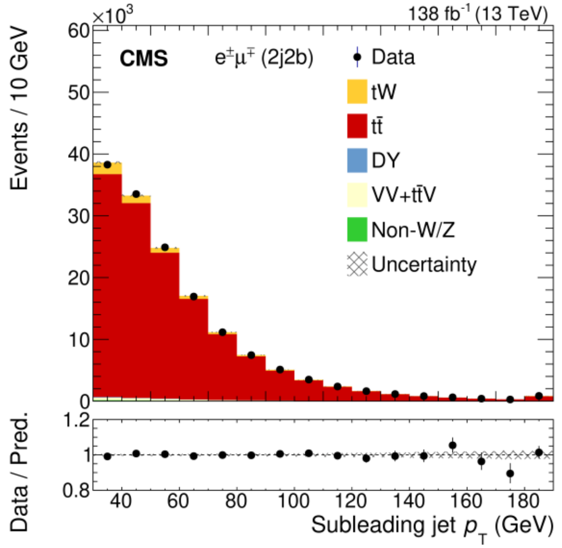
$$\mathrm{aNNLO(QCD)}:\ \sigma^{\mathrm{SM}}_{\mathrm{tW}} = 71.7 \pm 1.8\ (scale) \pm 3.4\ (\mathrm{PDF})\ \mathrm{pb}$$ (PoS DIS2015 (2015) 170)

$$\mathrm{aN^3LO(QCD)}:\ \sigma^{\mathrm{SM}}_{\mathrm{tW}} = 79.5 \pm^{1.9}_{1.8}\ (scale) \pm^{2.0}_{1.4}\ (\mathrm{PDF})\ \mathrm{pb}$$ (JHEP 2021, 278 (2021))

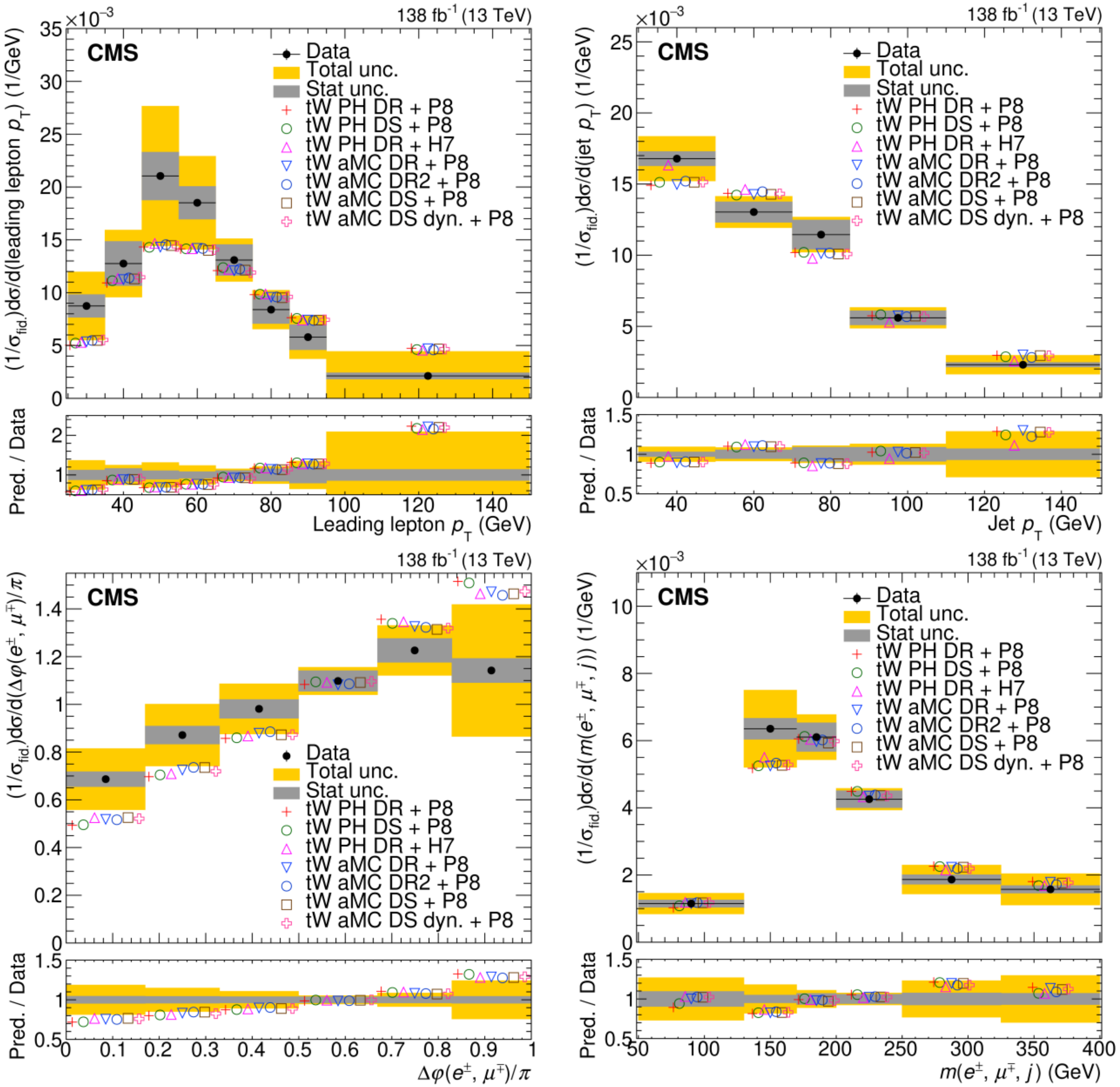
- Measurement dominated by systematic uncertainties.







- **Differential measurement strategy:**
  - **SR**: 1j1b + veto loose jets.
  - The differential cross sections are measured as a function of the leading lepton p_T, jet p_T, $\Delta\varphi(e^{\pm},\mu^{\mp})$, $m(e^{\pm},\mu^{\mp},j)$, $p_z(e^{\pm},\mu^{\mp},j)$ and $m_T(e^{\pm},\mu^{\mp},j,p_T^{miss})$.
  - Signal extraction and unfolding to a fiducial region in particle level (defined to mimic the signal region) are done at the same time in a maximum likelihood fit.
  - The results are normalised to the fiducial cross section.
  - Overall agreement between data and expectations within uncertainties.
  - Compatible results between the DR and DS schemes → small interference effects in this region.

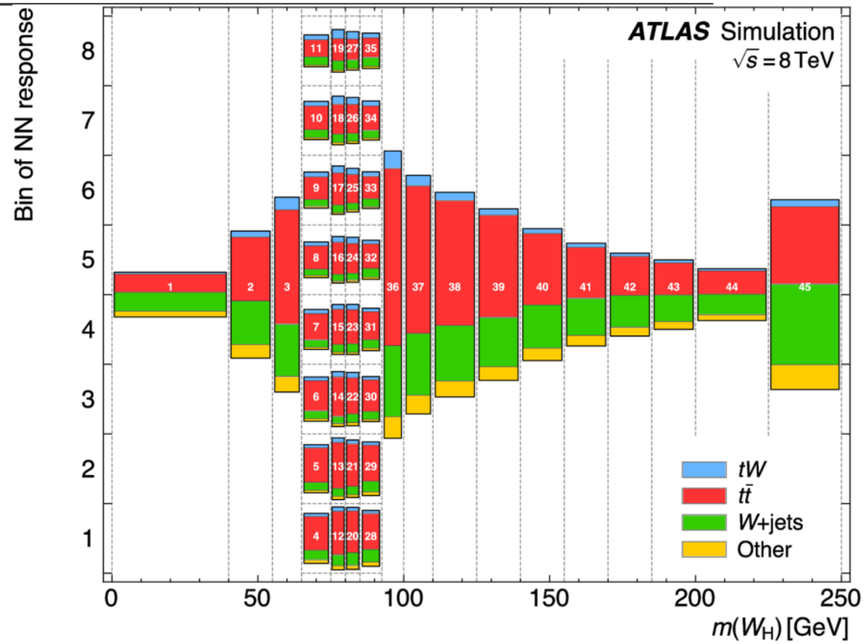


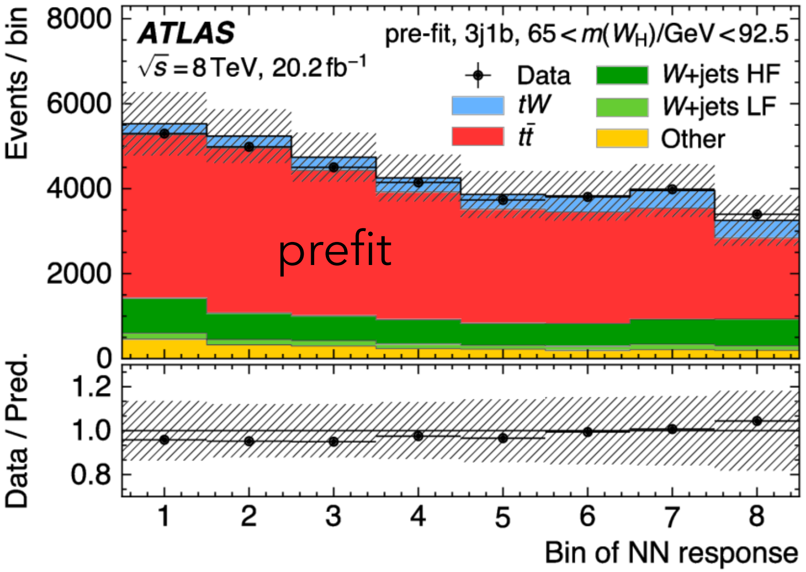
Measurement of tW production (semileptonic channel)

8 TeV, 20.2 $\mathbf{fb}^{-1}$, tW channel

Eur. Phys. J. C 81 (2021) 720

- **Event selection**:
  - $1\ e/\mu\ (> 30\ \mathrm{GeV})$.
  - Veto of additional leptons (> 25 GeV).
  - $p_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV.
  - $m_{\mathrm{T}}(W_{\mathrm{L}}) > 50$ GeV.
- **Strategy**:
  - Signal region: **3j1b**. Jets with $p_T > 30$ GeV.
  - A neural network is trained to separate between tW and $t\bar{t}$.
  - A 2-dimensional discriminant is constructed with the neural network output in 65 GeV < $m(W_{\mathrm{H}})$ < 92.5 GeV and with the remaining $m(W_{\mathrm{H}})$ variable.
  - The cross section is extracted from a binned profile maximum-likelihood fit to the 2-dimensional discriminant.





Eur. Phys. J. C 81 (2021) 720

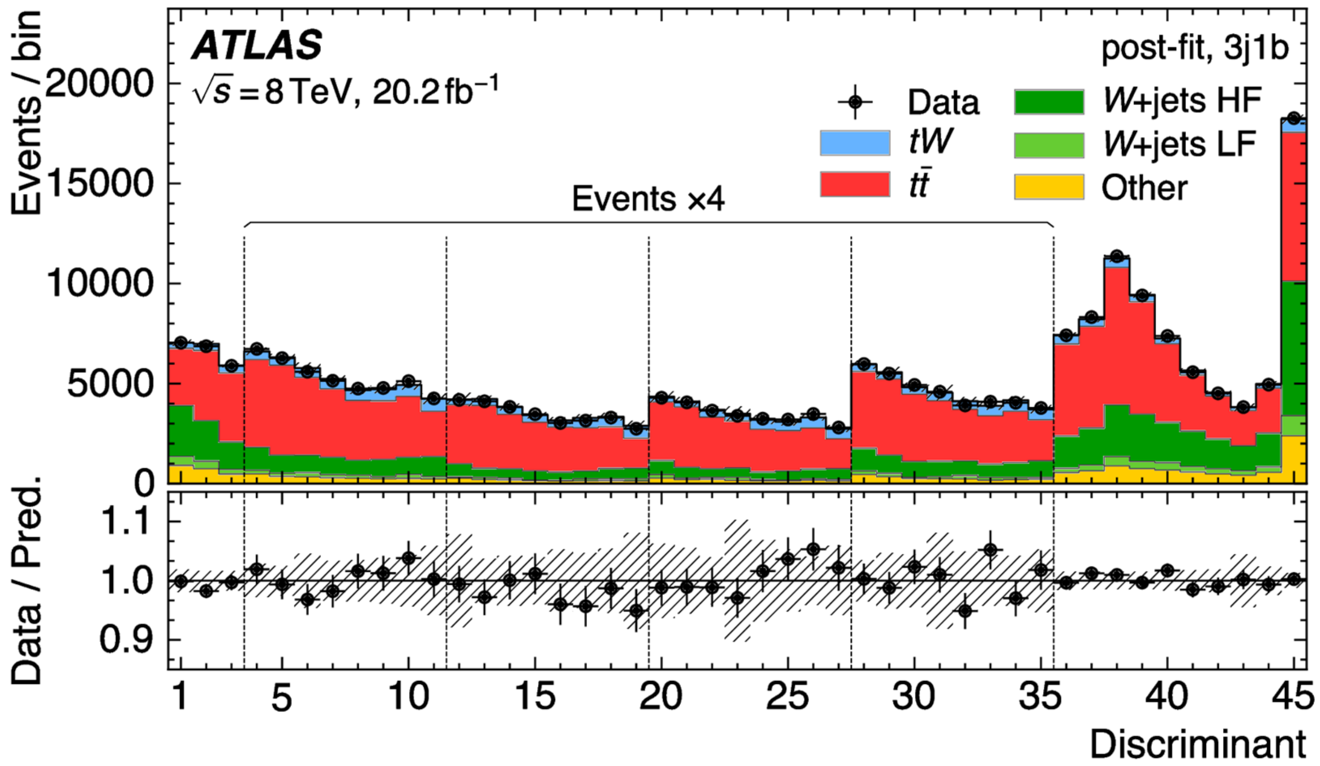
- Result is in good agreement with expectations at NLO+NNLL:

$$\sigma_{\mathrm{obs.}} = 26 \pm 7\mathrm{pb}$$

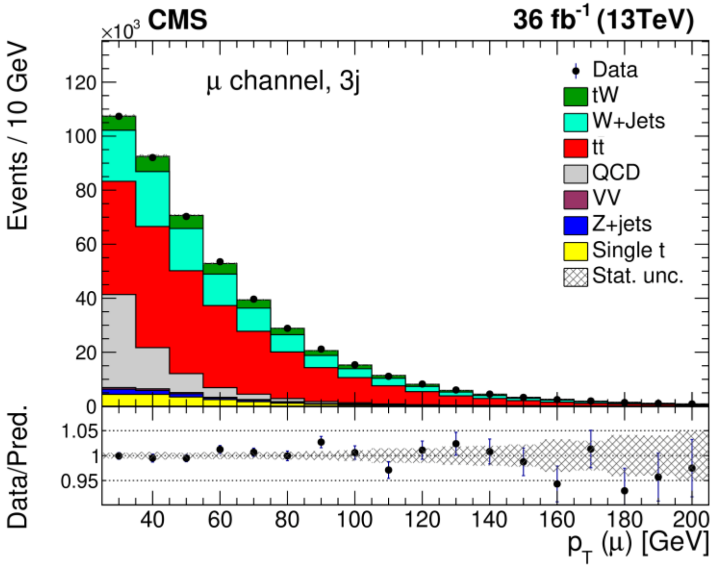
$$\sigma_{\mathrm{pred.}} = 22.4 \pm 1.5\mathrm{pb}$$

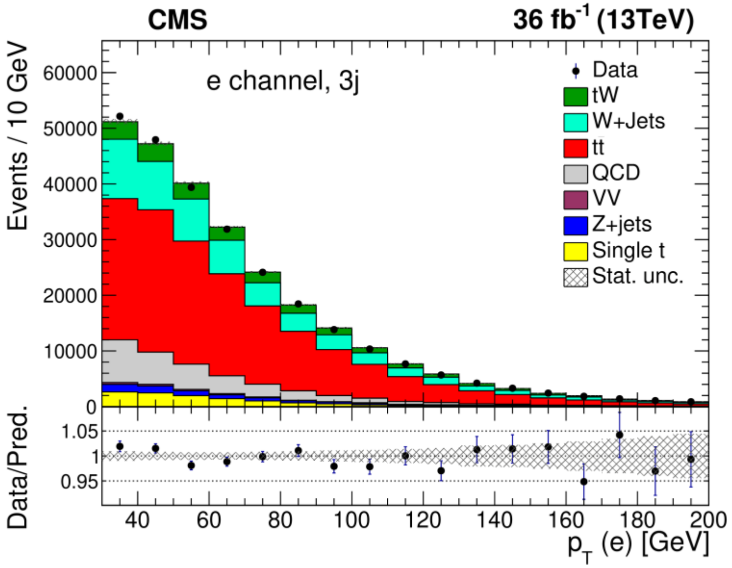
Phys. Rev. D 60, 113006

Source	Uncertainty [%]
Jet energy scale	10
b-tagging	8
Jet energy resolution	7
$E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction	7
Lepton reconstruction	4
Luminosity	3
Jet vertex fraction	3
$t\bar{t}$ radiation	10
tW radiation	9
tW–$t\bar{t}$ interference	7
$t\bar{t}$ cross-section normalisation	6
Other background cross-section normalisations	5
tW and $t\bar{t}$ parton shower	4
tW and $t\bar{t}$ NLO matching	3
PDF	1
Model statistics	11
Data statistics	4
Total	27



- **Event selection**:
  - $1\ e(> 30\ \mathrm{GeV})/\mu(> 26\ \mathrm{GeV})$.
  - Veto of additional leptons (> 10 GeV muons, > 20 GeV electrons).
  - ≥ 2 jets.
  - 1 jet must be b-tagged.
- **Strategy**:
  - Signal region: events with three jets (3j).
  - Control regions: events with two jets (2j; W+jets background CR) and events with four jets (4j; $t\bar{t}$ CR).
  - QCD/multijet background: templates and normalisation from data.
  - W+jets background: templates from simulation and normalisation from data.
  - **Two** (for muon and for electron) **MVA** (BDTs) are trained in the signal region to discriminate between tW and $t\bar{t}$.
  - Signal extraction by binned profile likelihood fit to BDT responses.





JHEP 11 (2021) 111

$$\sigma_{obs.} = 89 \pm 4(\text{stat.}) \pm 12(\text{syst.})\text{pb}$$

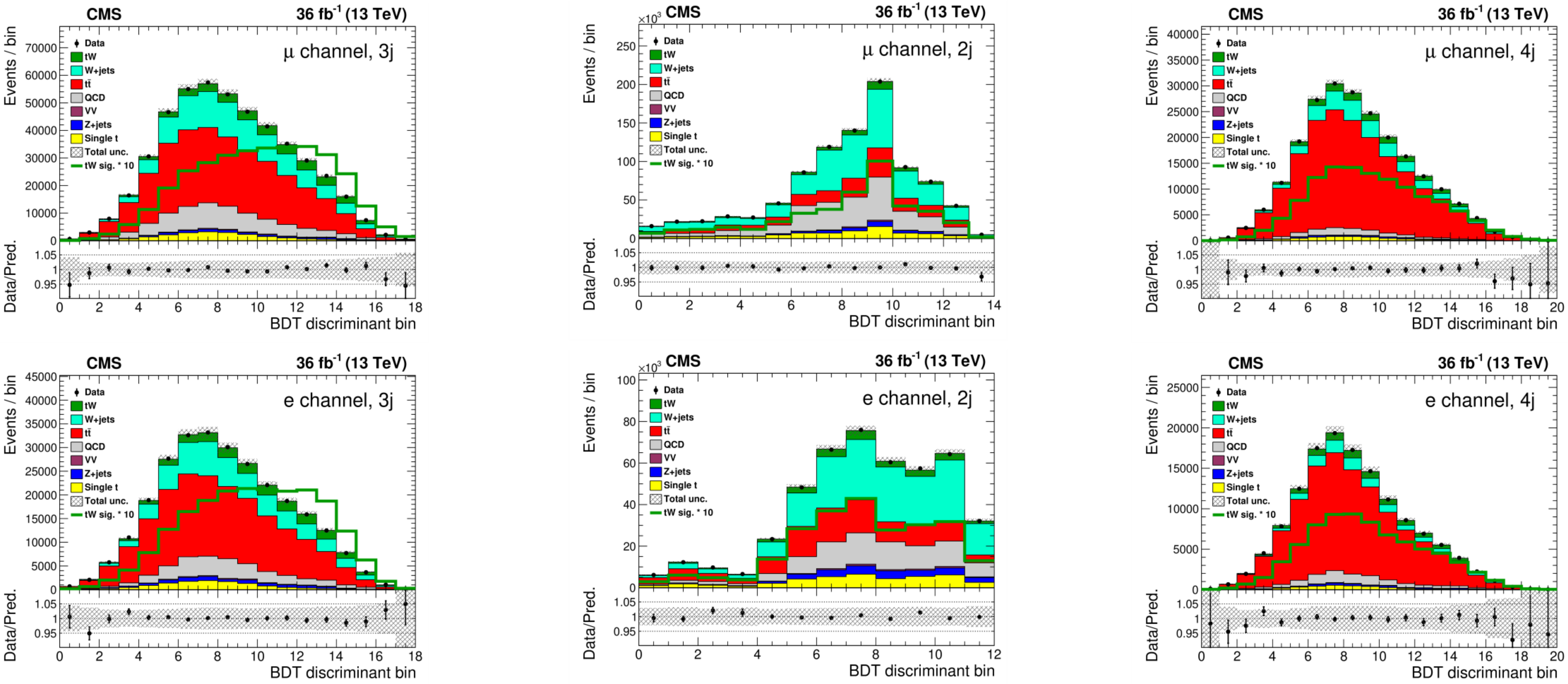
PoS DIS2015 (2015) 170 | aNNLO (QCD)

$$\sigma_{\text{pred.}} = 71.7 \pm 1.8(\text{scale}) \pm 3.4(\text{PDF})\text{pb}$$

JHEP 2021, 278 (2021) | aN^{3}LO (QCD)

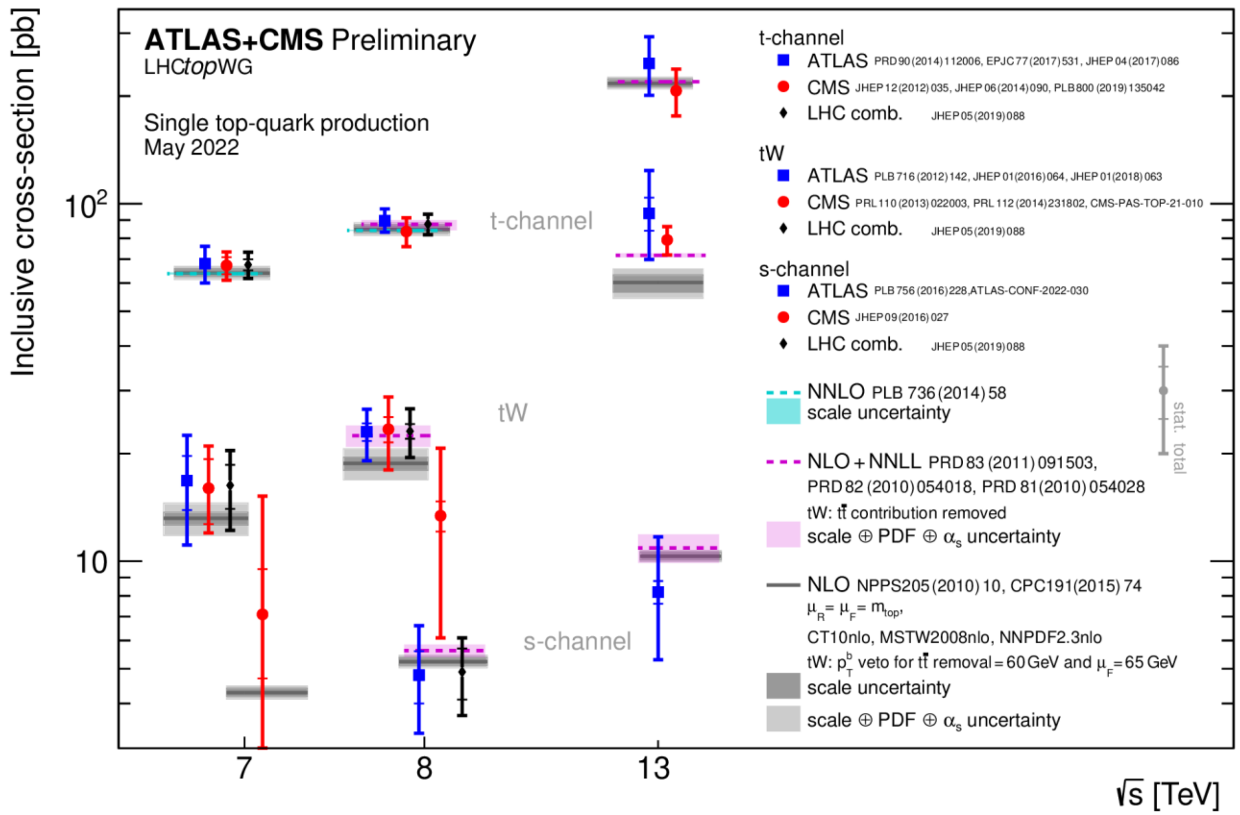
$$\sigma_{\text{pred.}} = 79.5^{+1.9}_{-1.8}(\text{scale})^{+2.0}_{-1.4}(\text{PDF})\text{pb}$$

- Leading uncertainties:
  - Jet energy scale.
  - QCD multijet normalisation.
  - W+jets normalisation.



Summary

- The latest measurements from single top processes have been made in the **s**, **t** and **tW channels**.
- The **s-channel** ATLAS measurement is the first performed at $\sqrt{s} = 13$ TeV giving 3.3σ of observed significance.
  - Main uncertainties: $t\bar{t}$ normalisation and JECs.
- The **t-channel** has been used to measure the top quark CKM elements, the top quark polarisation vector and differential cross sections depending on angular observables.
- The **tW channel** has been measured in the dileptonic (differential and inclusive cross sections) and semileptonic (inclusive) decay modes.



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University of Oviedo

ICTEA
Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias

CMS
Compact Muon Solenoid

ATLAS
EXPERIMENT

Thanks for your attention

Backup

s-channel ME method

- Build event by event likelihood for hypothesis that final state X is obtained from process H_{proc}.

$$\mathcal{P}(X \mid H_{\text{proc}}) = \int \mathrm{d}\Phi \boxed{\frac{1}{\sigma_{H_{\text{proc}}}} \frac{\mathrm{d}\sigma_{H_{\text{proc}}}}{\mathrm{d}\Phi}} \boxed{T_{H_{\text{proc}}}(X \mid \Phi)}$$

Normalised fully differential partonic cross section.

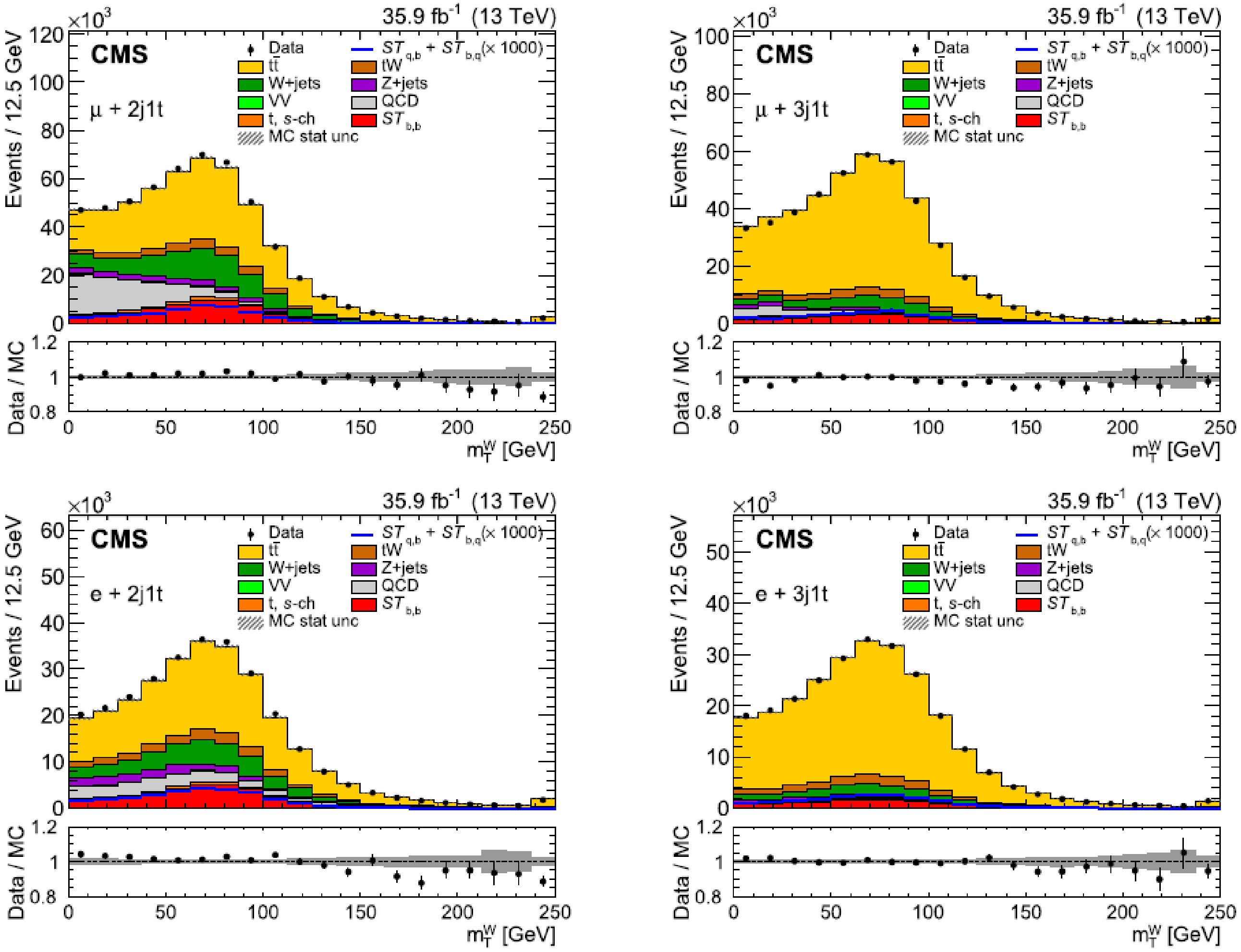
Transfer functions:

- Detector resolution.
- Reconstruction and b-tagging eff.
- …

- Build MEM discriminant with bayes theorem:

$$P(S \mid X) = \frac{\sum_i P(S_i)\mathcal{P}(X \mid S_i)}{\sum_i P(S_i)\mathcal{P}(X \mid S_i) + \sum_j P(B_j)\mathcal{P}(X \mid B_j)}$$

t-channel CKM CMS



Production	Decay	Cross section × branching fraction (pb)
tWb	tWb	217.0 ± 8.4
tWb	(tWs + tWd)	0.41 ± 0.05
tWd	tWb	0.102 ± 0.015
tWs	tWb	0.92 ± 0.11

t-channel CKM CMS

Treatment	Uncertainty	$\Delta\sigma_{ST_{b,b}}/\sigma$ (%)
Profiled	Lepton trigger and reconstruction	0.50
	Limited size of simulated event samples	3.13
	$t\bar{t}$ modelling	0.66
	Pileup	0.35
	QCD background normalisation	0.08
	W+jets composition	0.13
	Other backgrounds μ_R/μ_F	0.44
	PDF for background processes	0.42
	b tagging	0.73
	Total profiled	3.4
Nonprofiled	Integrated luminosity	2.5
	JER	2.8
	JES	8.0
	PDF for signal process	3.8
	Signal μ_R/μ_F	2.4
	ME-PS matching	3.7
	Parton shower scale	6.1
	Total nonprofiled	11.5
Total uncertainty		12.0

- BSM case 1 (the top quark decays as in the SM, but the CKM matrix is modified):

$$|V_{tb}| = 0.988 \pm 0.027\,(\text{stat+prof}) \pm 0.043\,(\text{nonprof})$$
$$|V_{td}|^2 + |V_{ts}|^2 = 0.06 \pm 0.05\,(\text{stat+prof})\,^{+0.04}_{-0.03}\,(\text{nonprof}).$$

- BSM case 2 (the top quark decays in new unknown ways):

$$|V_{tb}| = 0.988 \pm 0.011\,(\text{stat+prof}) \pm 0.021\,(\text{nonprof})$$
$$|V_{td}|^2 + |V_{ts}|^2 = 0.06 \pm 0.05\,(\text{stat+prof}) \pm 0.04\,(\text{nonprof})$$

t-channel ATLAS selection

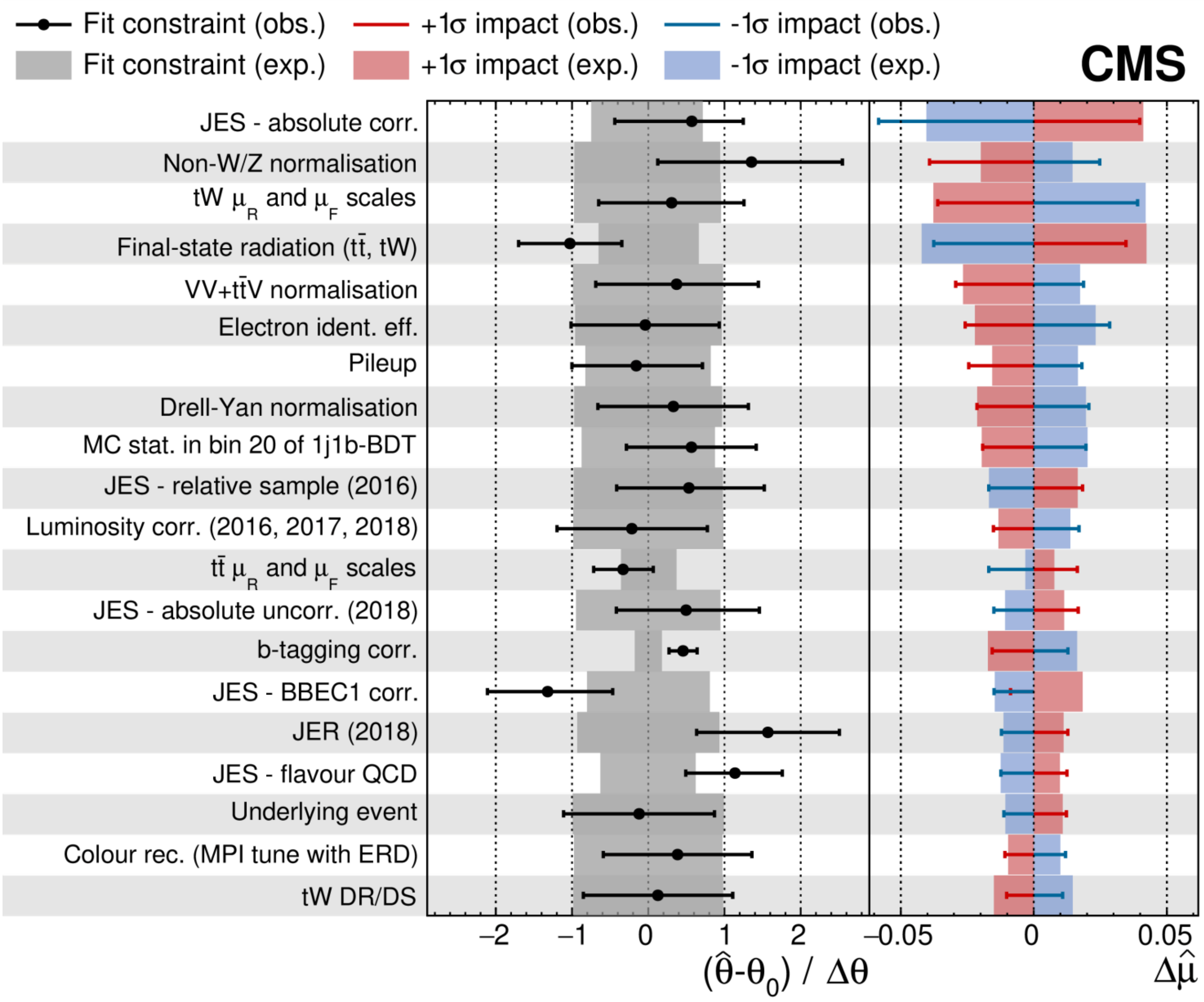
Common event selection criteria			
Exactly one electron or muon			
Veto secondary low-p_{T} charged loose leptons			
Exactly two jets			
$E_{\mathrm{T}}^{\mathrm{miss}} > 35$ GeV			
$m_{\mathrm{T}}(\ell, E_{\mathrm{T}}^{\mathrm{miss}}) > 60$ GeV			
$p_{\mathrm{T}}(\ell) > 50\left(1 - \frac{\pi - \lvert\Delta\phi(p_{\mathrm{T}}(j_1), p_{\mathrm{T}}(\ell))\rvert}{\pi - 1}\right)$ GeV			
Preselection region	**Signal region**	**$t\bar{t}$ control region**	**$W+$ jets control region**
Exactly one b-tagged jet	Exactly one b-tagged jet $m_{\ell b} < 153$ GeV $m_{j\ell\nu b} > 320$ GeV Trapezoidal requirement $H_{\mathrm{T}} > 190$ GeV	Exactly two b-tagged jet	Exactly one b-tagged jet $m_{\ell b} > 153$ GeV $m_{j\ell\nu b} < 320$ GeV Veto trapezoidal requirement $H_{\mathrm{T}} < 190$ GeV

Uncertainties in the polarisation measurement

Parameter	Extracted value	(stat.)
t-channel norm.	$+1.045 \pm 0.022$	(± 0.006)
W+jets norm.	$+1.148 \pm 0.027$	(± 0.005)
$t\bar{t}$ norm.	$+1.005 \pm 0.016$	(± 0.004)
$P^{t}_{x'}$	$+0.01 \pm 0.18$	(± 0.02)
$P^{\bar{t}}_{x'}$	-0.02 ± 0.20	(± 0.03)
$P^{t}_{y'}$	-0.029 ± 0.027	(± 0.011)
$P^{\bar{t}}_{y'}$	-0.007 ± 0.051	(± 0.017)
$P^{t}_{z'}$	$+0.91 \pm 0.10$	(± 0.02)
$P^{\bar{t}}_{z'}$	-0.79 ± 0.16	(± 0.03)

Uncertainty source	$\Delta P^{t}_{x'}$	$\Delta P^{\bar{t}}_{x'}$	$\Delta P^{t}_{y'}$	$\Delta P^{\bar{t}}_{y'}$	$\Delta P^{t}_{z'}$	$\Delta P^{\bar{t}}_{z'}$
Modelling						
Modelling (t-channel)	±0.037	±0.051	±0.010	±0.015	±0.061	±0.061
Modelling ($t\bar{t}$)	±0.016	±0.021	±0.004	±0.016	±0.003	±0.016
Modelling (other)	±0.013	±0.031	±0.003	±0.006	±0.026	±0.043
Experimental						
Jet energy scale	±0.045	±0.048	±0.005	±0.007	±0.033	±0.025
Jet energy resolution	±0.166	±0.185	±0.021	±0.040	±0.070	±0.130
Jet flavour tagging	±0.004	±0.002	<0.001	±0.001	±0.007	±0.009
Other experimental uncertainties	±0.015	±0.029	±0.002	±0.007	±0.014	±0.026
Multijet estimation	±0.008	±0.021	<0.001	±0.001	±0.008	±0.013
Luminosity	±0.001	±0.001	<0.001	<0.001	<0.001	<0.001
Simulation statistics	±0.020	±0.024	±0.008	±0.015	±0.017	±0.031
Total systematic uncertainty	±0.174	±0.199	±0.025	±0.048	±0.096	±0.153
Total statistical uncertainty	±0.017	±0.025	±0.011	±0.017	±0.022	±0.034

Impacts for the tW dileptonic measurement



Input variables of the BDT: CMS tW single lepton

Variable Description
Mass of the reconstructed Wboson decaying hadronically
Invariant mass of the b-tagged jet and sub-leading non b-tagged jet
Angular separation between the two non b-tagged jets
Angular separation between the reconstructed leptonic Wboson and leading non b-tagged jet
Transverse momentum of the selected lepton
Energy of the two non b-tagged jets system
Angular separation between the b-tagged jet and the selected lepton
Transverse momentum of the system made of the three jets, lepton and $p_{\mathrm{T}}^{\mathrm{miss}}$