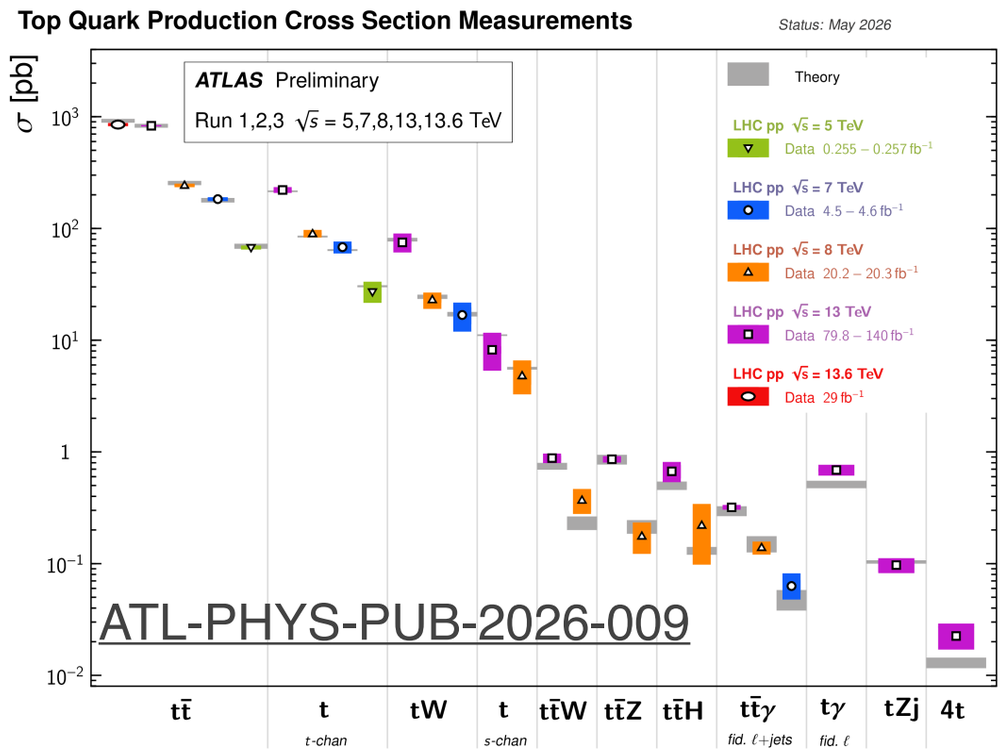
Overview of experimental results with top quarks with ATLAS

Rui Zhang (University of Nanjing)
on behalf of the ATLAS Collaboration

The 2026 International Workshop on the High Energy Circular Electron Positron Collider
21–26 Oct 2026

Introduction

- 31 years top quark physics after its discovery in 1995 at Tevatron by CDF and DØ
- The heaviest known elementary particle
  - High relevance for EW symmetry breaking with largest Yukawa coupling yt ≈1
  - Short lifetime (5×10^{-25} s), unique for studying bare quark properties
  - Main ingredient of many BSM scenarios, appearing in loops
- High production rate at the LHC: O(100M) $t\bar{t}$ O(40k) single top produced at Run-2
  - High precision SM measurements, stress-test Monte-Carlo modelling
  - Portal to BSM physics (loop corrections)
  - BR(t→Wb)~100% + very rare decays
- Covered in this talk:
  - Recent Highlights in top quark physics
  - All results used 140 fb^{-1} Run 2 data



New observations

- Observation of $t\bar{t}+\gamma\gamma$ - PLB 874 (2026) 140195
- Observation of single top s-chan - Submitted to PRL
- Observation of $t\bar{t}$ enhancement - Rep. Prog. Phys. 89 (2026) 057801
  - $t\bar{t}$ threshold effects in eμ differential distributions - Submitted to EPJC

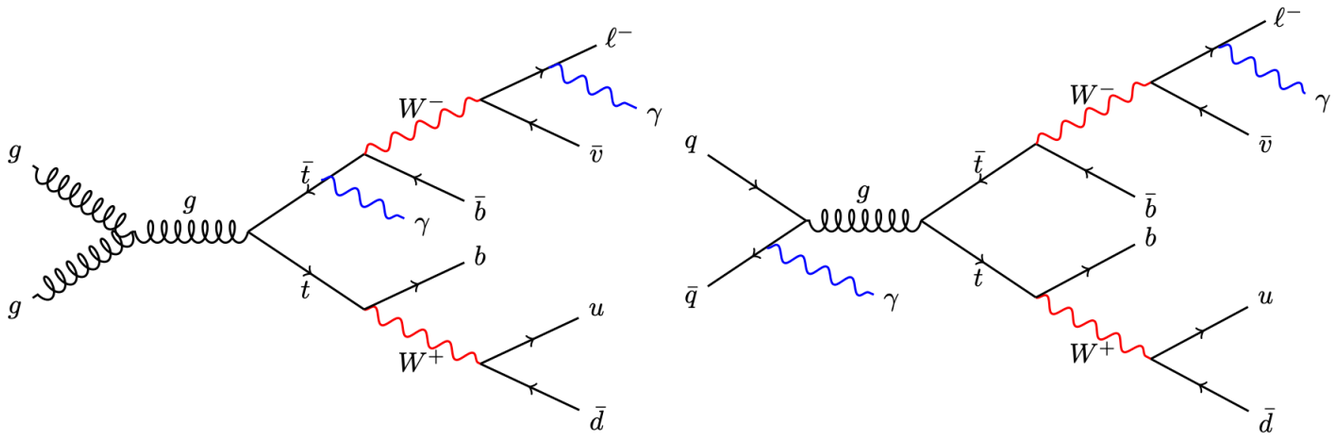
PLB 874 (2026) 140195

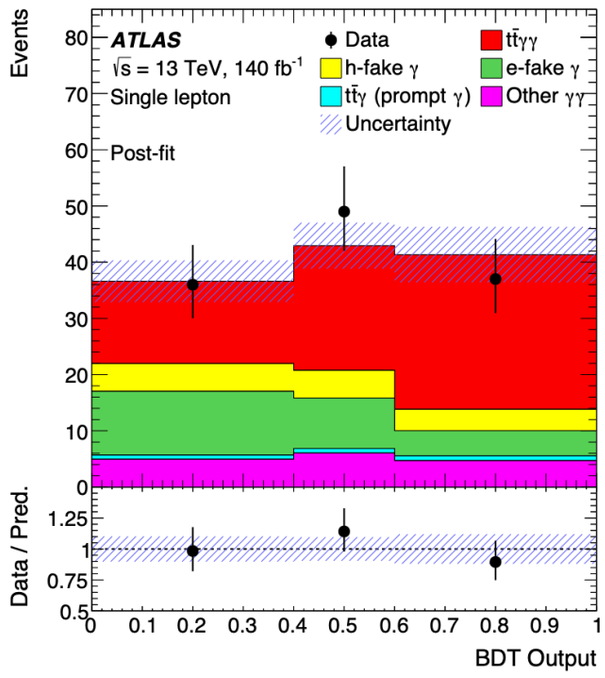
Observation of $t\bar{t}+\gamma\gamma$

- Very rarer process O(2 fb) at SM, 1000 smaller than $t\bar{t}+\gamma$
  - Direct radiative production probe for t-γ coupling
  - Ratio wrt to $t\bar{t}+\gamma$ can be used to constrain anomalous dipole moments
- No reliable SM calculation to compare
- Fiducial selections: =2 γ, =1 lepton, >=4 jets (>=1 b-jet), other kin. cut
- BDT to separate signal from bkg ($t\bar{t}+\gamma$, W/Z+γγ)
- Results: $\sigma_{t\bar{t}\gamma\gamma} = 2.42^{+0.58}_{-0.53}\ \text{fb} = 2.42^{+0.46}_{-0.38}\ (\text{stat})\ ^{+0.35}_{-0.38}(\text{syst})\ \text{fb}$ 23% unc

$$R_{t\bar{t}\gamma\gamma/t\bar{t}\gamma} = (3.30^{+0.70}_{-0.65}) \times 10^{-3} = (3.30^{+0.63}_{-0.55}\ (\text{stat})^{+0.32}_{-0.34}\ (\text{syst})) \times 10^{-3}$$ 20% unc

- Observed (expected) significance: 5.2 σ (5.7 σ)

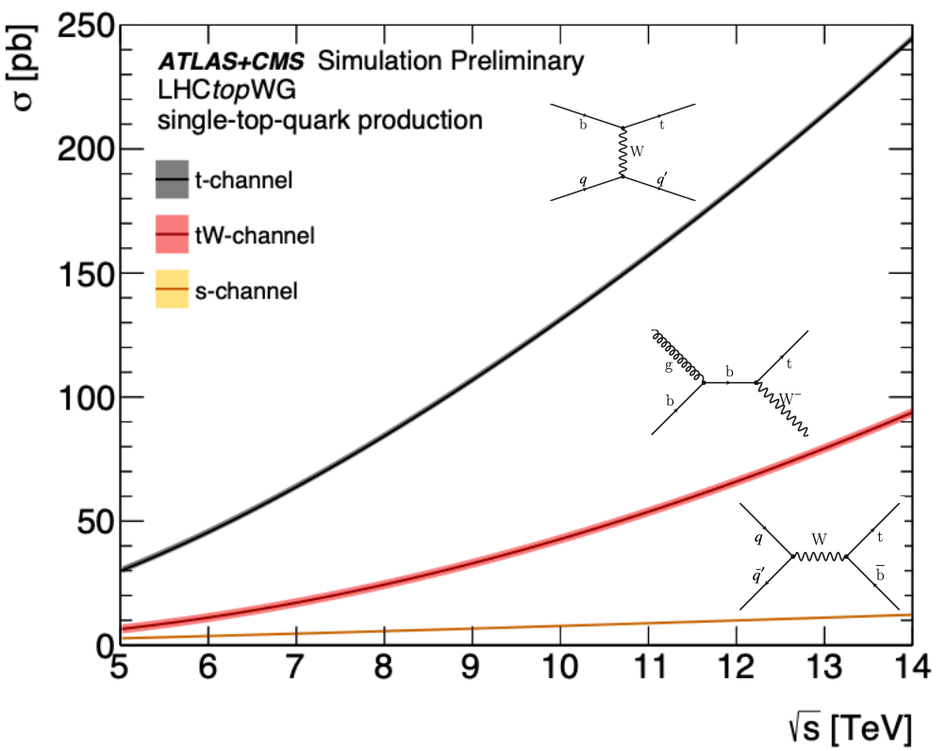


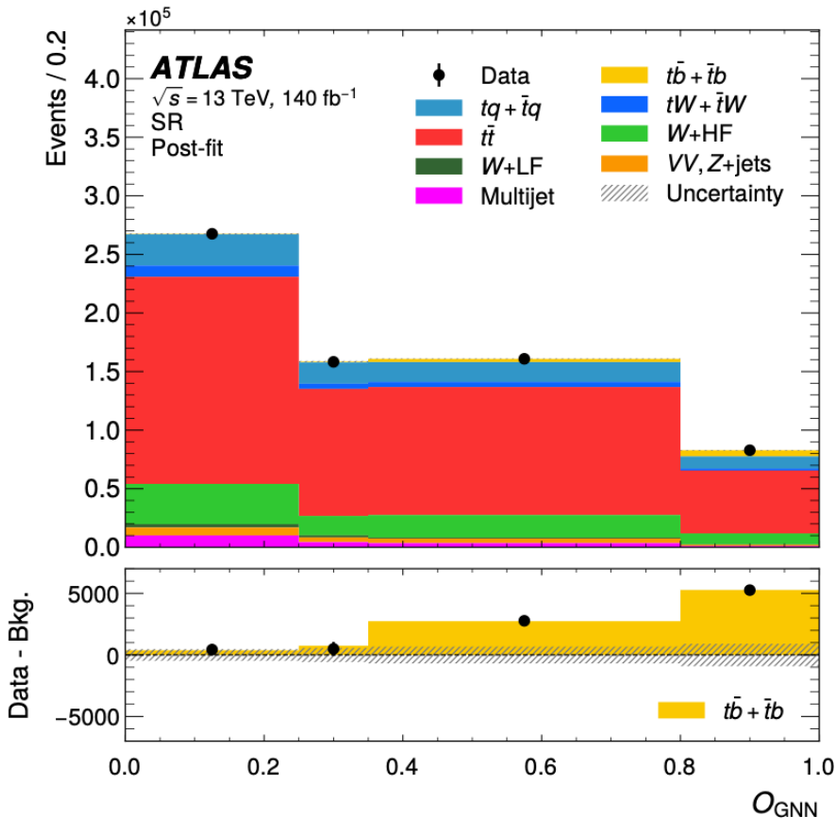


Submitted to PRL

Observation of single top s-chan

- Single top is produced in electroweak interaction through W_{tb} vertex
- s-channel is the smallest single top production but sensitivity to BSM heavy resonances
- Graph NN to separate signal from all other bkg
- Results: $\sigma_{t\bar{b}+\bar{t}b} = 10.8 \pm 1.5\,(\text{stat.}) \pm 1.6\,(\text{syst.})\,\text{pb}$ 20% unc
- Observed (expected) significance: 5.1 σ (5.2 σ)

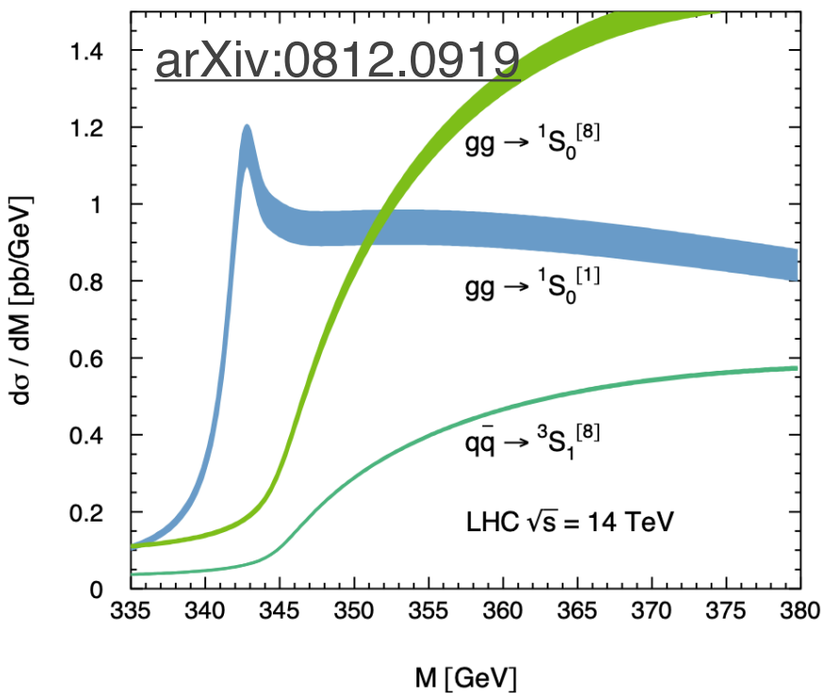


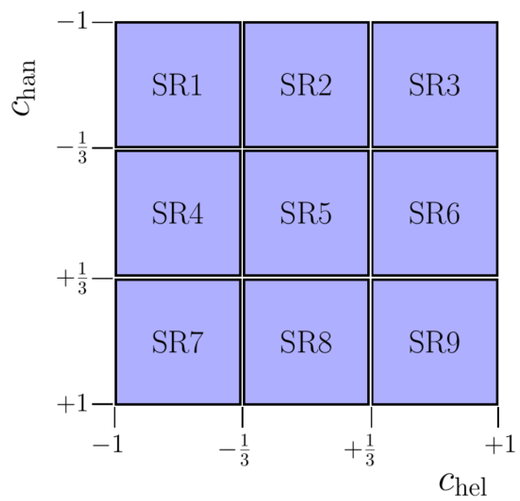


Rep. Prog. Phys. 89 (2026) 057801

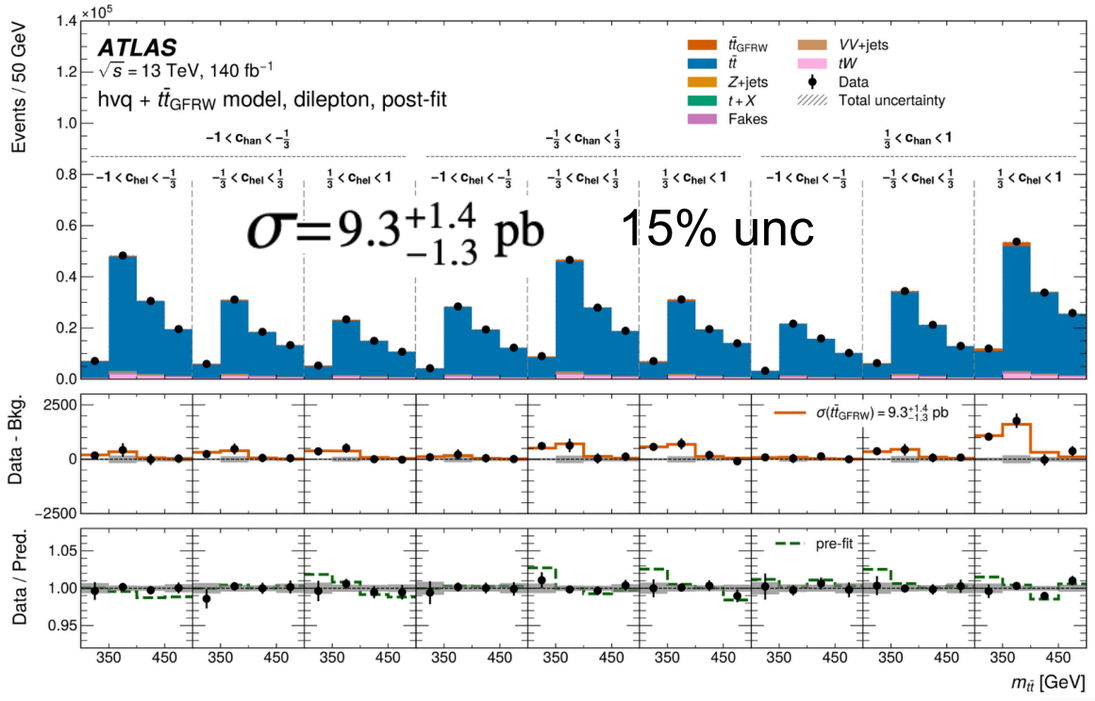
Observation of $t\bar{t}$ enhancement

- $t\bar{t}$ at ~350 GeV are with small relative velocity: non-relativistic (NR) QCD
  - Colour-singlet (quasi-) boundstate can be predicted by NRQCD with an enhanced xsec (broader than resonance peak due to top decays)
  - Challenges: besides NRQCD effects, higher-order pQCD, interference between $t\bar{t}$ and tW and off-shell top-quark effects can all contribute to an enhancement
- SRs split into 9 bins of the angular variables c_{hel} and c_{han}
  - c_{hel}: cosine of angle between leptons after boosting into $t\bar{t}$ and then parent top
  - c_{han}: cosine of same angle, with sign-flip parallel to the top
- Baseline hvq model (pure pQCD) is rejected with obs (exp) sig: 8σ (7σ)



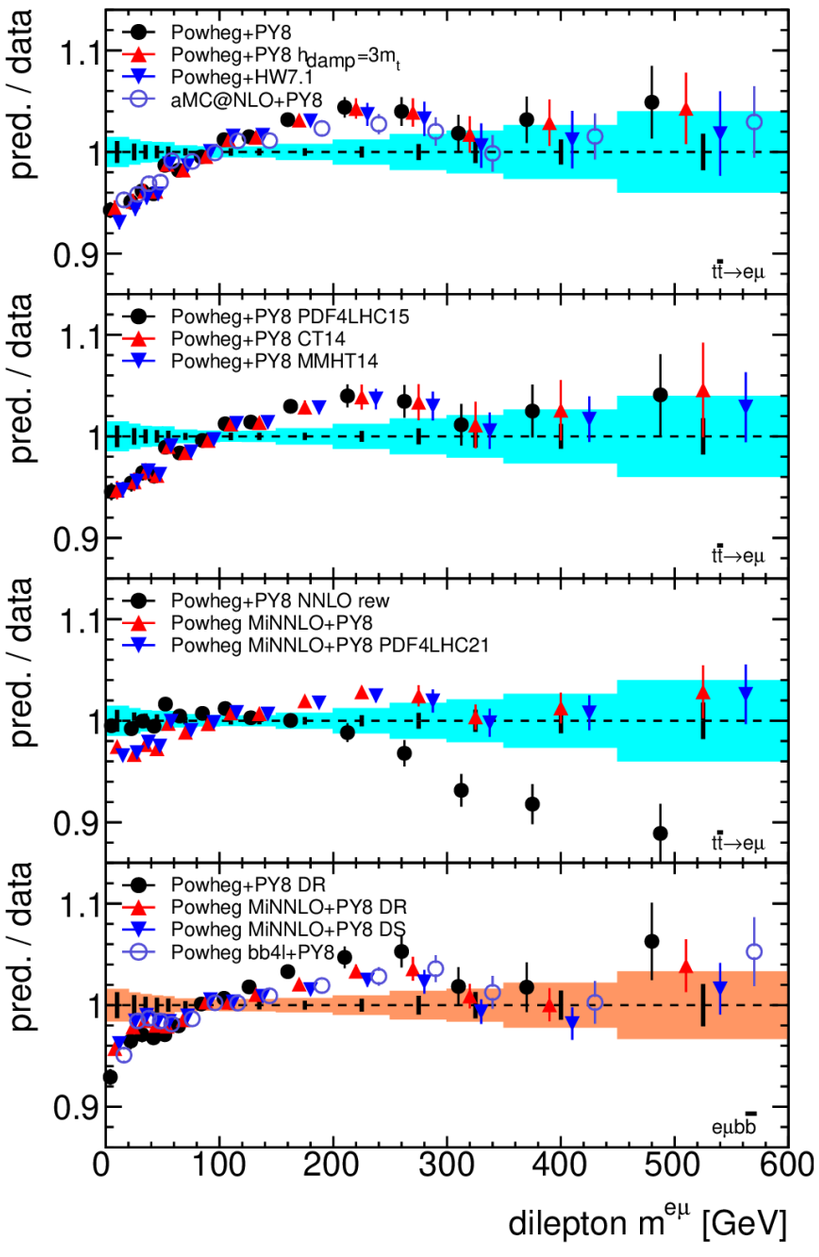


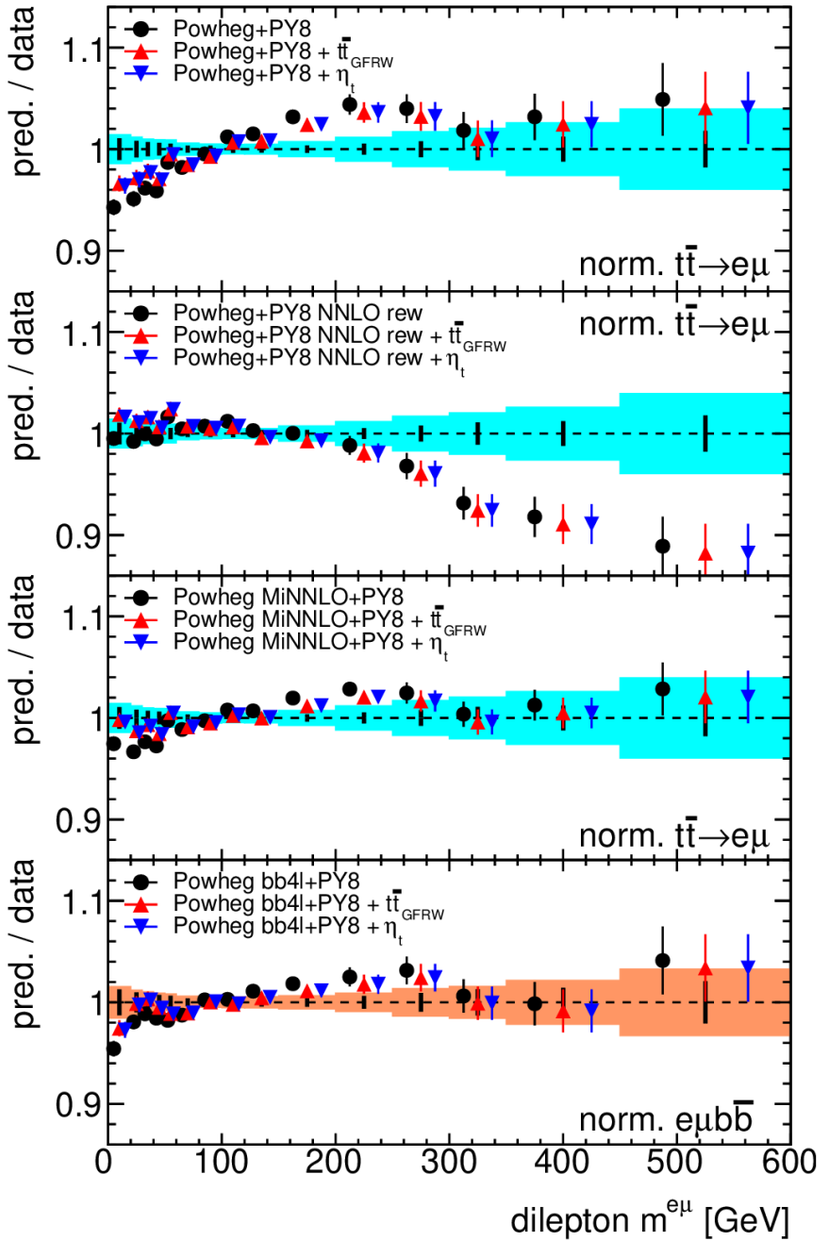
+ 2 CR (Z, fake)



$t\bar{t}$ threshold effects in eμ differential distributions

- Based on Run2 eμ differential measurent (EPJC 86 (2026) 470), test $t\bar{t}$ threshold effects
  - Modelling of $m^{e\mu}$ significantly improved by adding quasi-boundstate component





Precision measurements

- Four-fold differential decay in single top t-chan - JHEP07 (2026) 107
- V_{cb} measurement in $t\bar{t}$ - JHEP 07 (2026) 078
- Top-quark mass in $t\bar{t}$ with b to J/ψ to μμ decays - JHEP 04 (2026) 099

JHEP07 (2026) 107

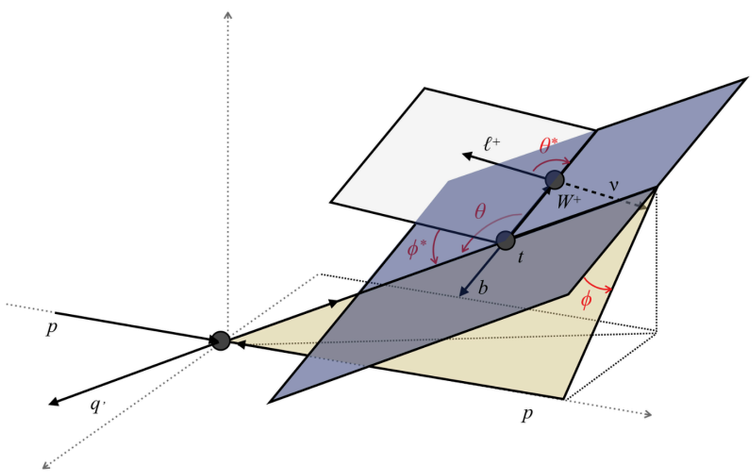
Four-fold differential decay in single top t-chan

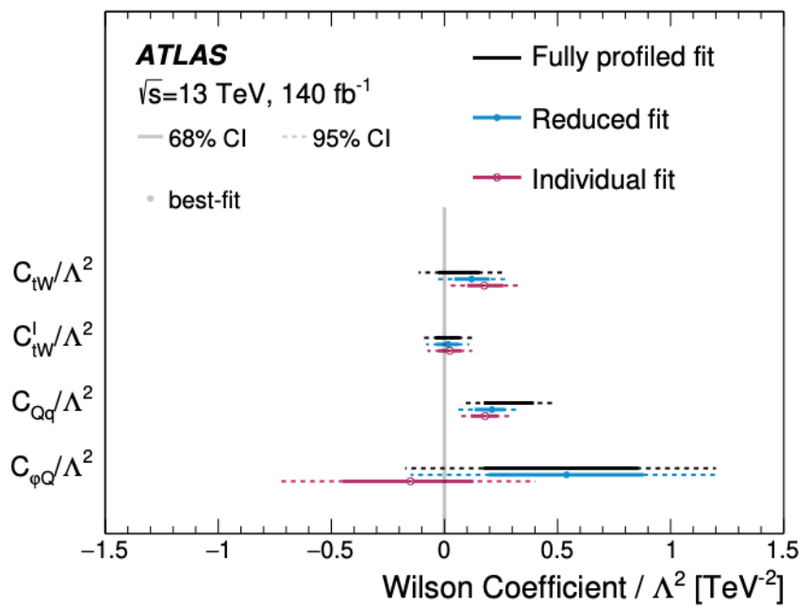
- Single-top t-channel is the only mode to produce polarised top quark
  - Unique access to the imaginary part of the Lagrangian via the angular differential decay rates
  - The full differential decay rates can be described in four angles
    - Spherical coordinates of W-boson in the top quark rest frame cosθ, ϕ
    - Spherical coordinates of charged lepton in the W-boson rest frame $\cos\theta^*$, ϕ^*
- Events split to high pT and low pT in t and $\bar{t}$

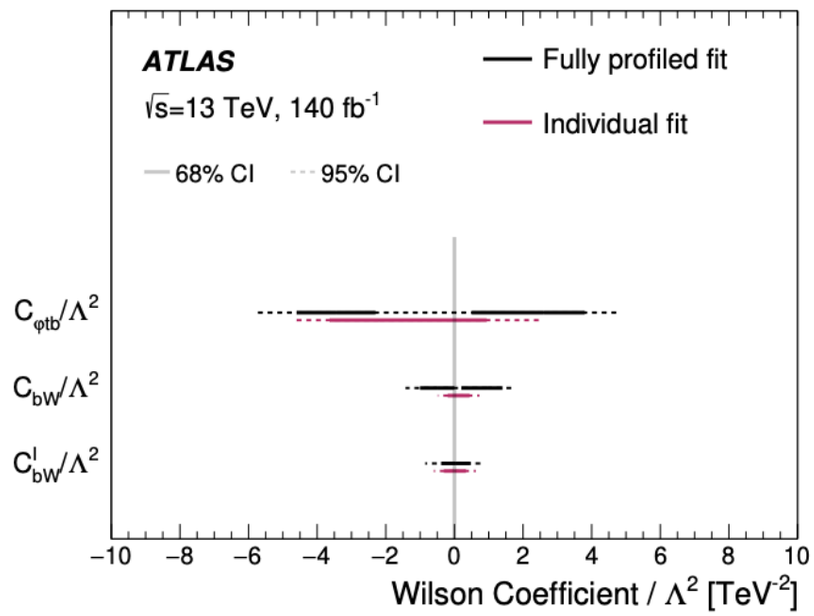
$$V_{\mathrm{L}} = V_{tb}\left(1 + \frac{v^2}{\Lambda^2} C_{\varphi Q}\right),$$

- Set constraints on 7 Wilson Coefficients

$$c_{tW} = C_{tW} + iC^I_{tW}, \quad c_{\varphi tb} = C_{\varphi tb},$$
$$c_{bW} = C_{bW} + iC^I_{bW}, \quad c_{Q,q} = C_{Qq},$$







JHEP 07 (2026) 078

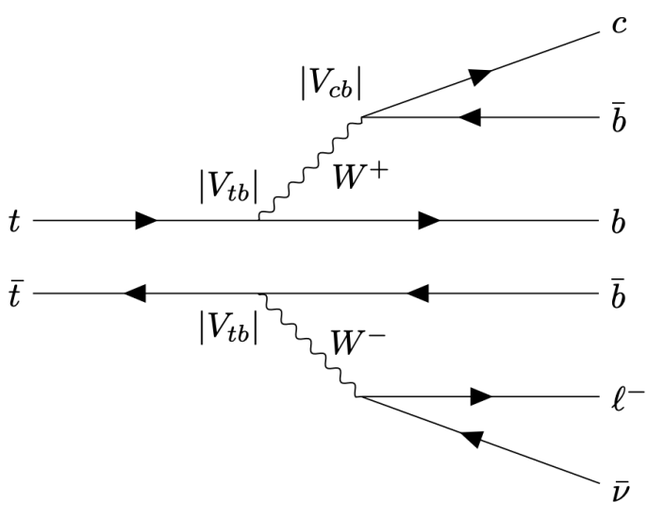
V_{cb} measurement in $t\bar{t}$

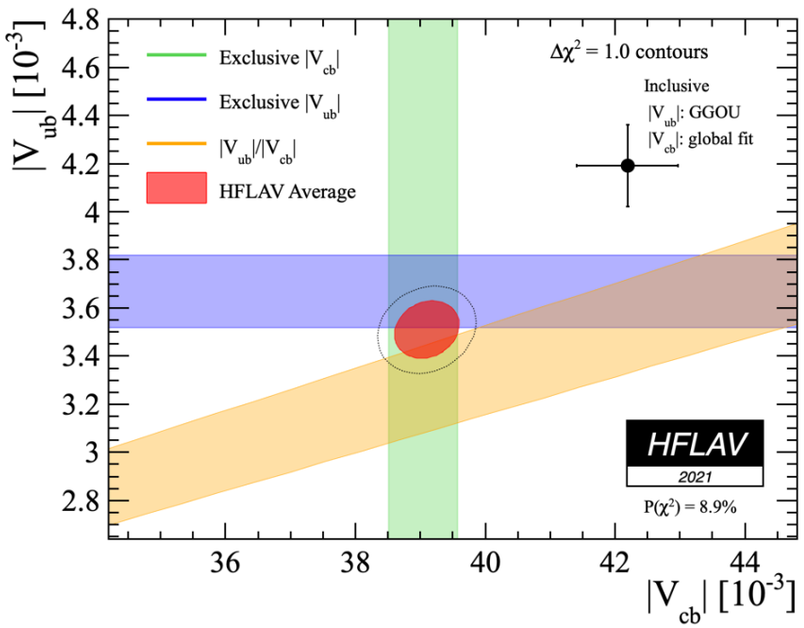
- $|V_{cb}|$ is the Cabibbo–Kobayashi–Maskawa matrix element that determines the strength of b→c quark transition (SM: 1.7×10^{-3})
  - Crucial for testing CKM unitarity
  - Measured in inclusive and exclusive B-hadron decays, but they have 3σ tension
  - Measurement in $t\bar{t}$ provides an independent test in on-shell W boson decay

$$|V_{cb}|^2 = \frac{|V_{cb}|^2}{\sum_q |V_{cq}|^2} = \frac{\mathcal{B}(W^+ \to c\bar{b})}{\mathcal{B}(W^+ \to c\bar{q})} = \frac{\mathcal{B}(t \to b\bar{b}c)}{\mathcal{B}(t \to b\bar{q}c)} = \frac{\mathcal{N}(t\bar{t} \to b\bar{b}c\ \bar{b}\ell^-\bar{\nu})}{\mathcal{N}(t\bar{t} \to b\bar{q}c\ \bar{b}\ell^-\bar{\nu})}$$

- Select single-lepton events, train neural network to separate from bkg
- 8 tagging categories × 3 NN score bins in fit

1b1c 1b2c 1b3c 2b0c 2b1c 2b2c 3b0c 3b1c
Low NN
Med NN — 24 bins
High NN





- Results:

$$|V_{cb}| = (50^{+11}_{-14}) \times 10^{-3}$$

Particle Data Group:

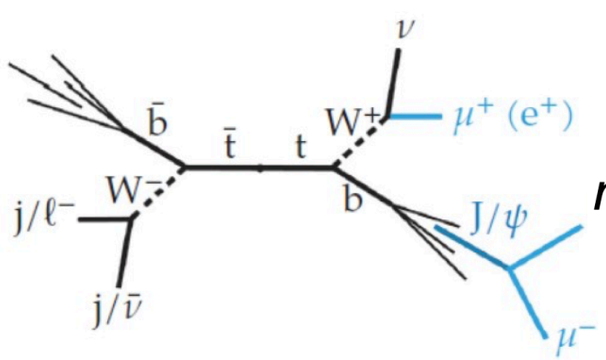
$$|V_{cb}| = (41.1 \pm 1.2) \times 10^{-3}$$

JHEP 04 (2026) 099

Top-quark mass in $t\bar{t}$ with b to J/ψ to μμ decays

- $t\bar{t}$ with final state B-hadron decaying into b→J/y→μμ offers alternative method to measure m(top) using the sensitivity of m(ℓJ/ψ) to m(top)
  - Leptonic final states, less sensitive to jet reconstruction (advantage of this channel)
  - Still sensitive to parton shower, hadronisation, b-quark fragmentation effects
- Template method:
  - Simulate $t\bar{t}$ and single-top samples with various m(top) values in 169—176 GeV
  - Build templates with m_{top} dependent (tt, single-top) and m_{top} independent (other bkg) distributions: $P^{m_{top}\text{-dep}}$ and $P^{m_{top}\text{-indep}}$; then maximise likelihood (N is # events; f are the fractions of events from dependent or independent components):

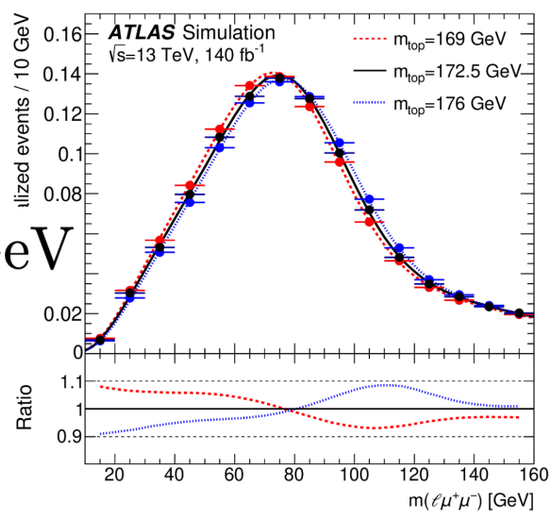
$$\mathcal{L}(m_{\text{top}}) = \prod_{i=1}^{N} f_{m_{\text{top}}\text{-dep.}} P^{m_{\text{top}}\text{-dep.}}(m^i(\ell\mu^+\mu^-)|m_{\text{top}}) + (1 - f_{m_{\text{top}}\text{-dep.}}) P^{m_{\text{top}}\text{-indep.}}(m^i(\ell\mu^+\mu^-))$$

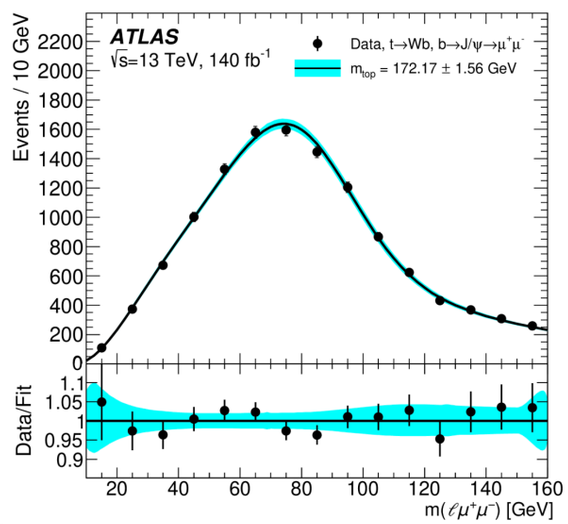


- Results:

$m_{top} = 172.17 \pm 1.56$ GeV

0.9% unc





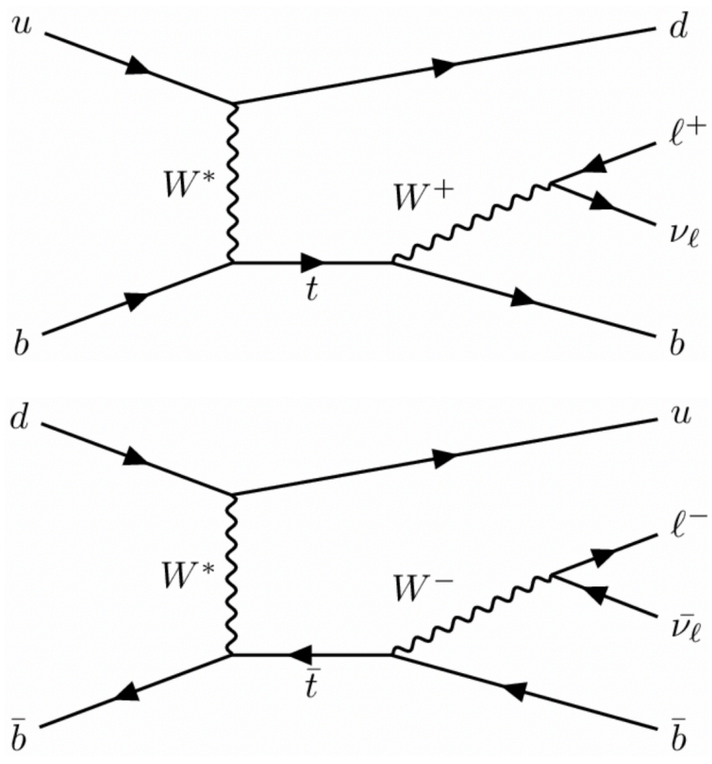
Stress test Monte-Carlo modelling

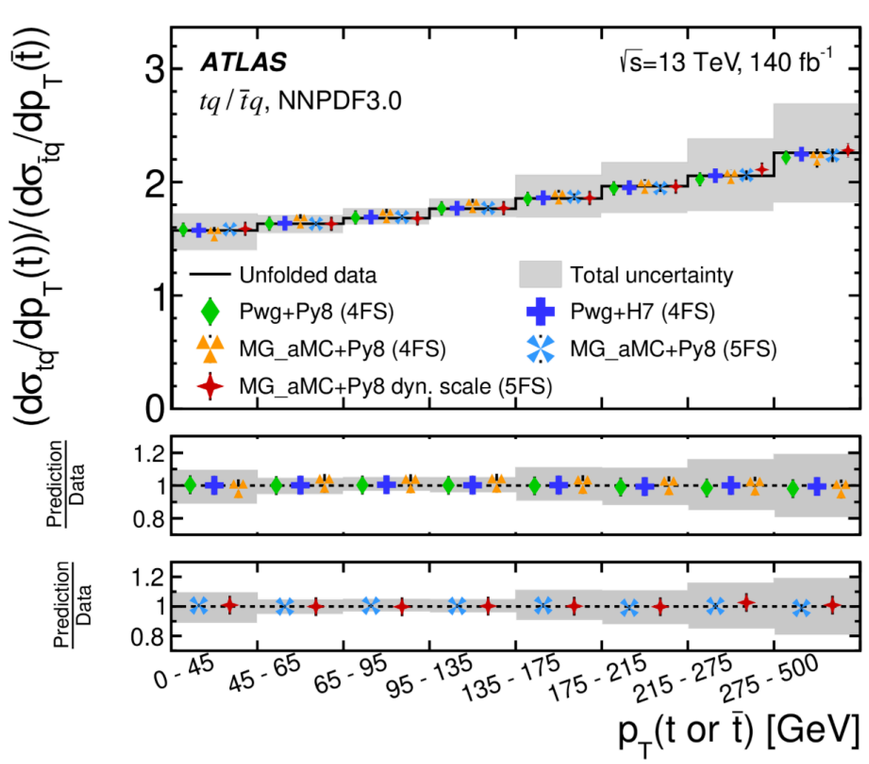
- Single top t-chan differential cross-sections - JHEP 05 (2026) 174
- WbWb differential measurements in lep+jet and dilepton - JHEP 07 (2026) 028, JHEP 02 (2026) 153
- Single top tZq inc. and diff. cross-section - Submitted to EPJC

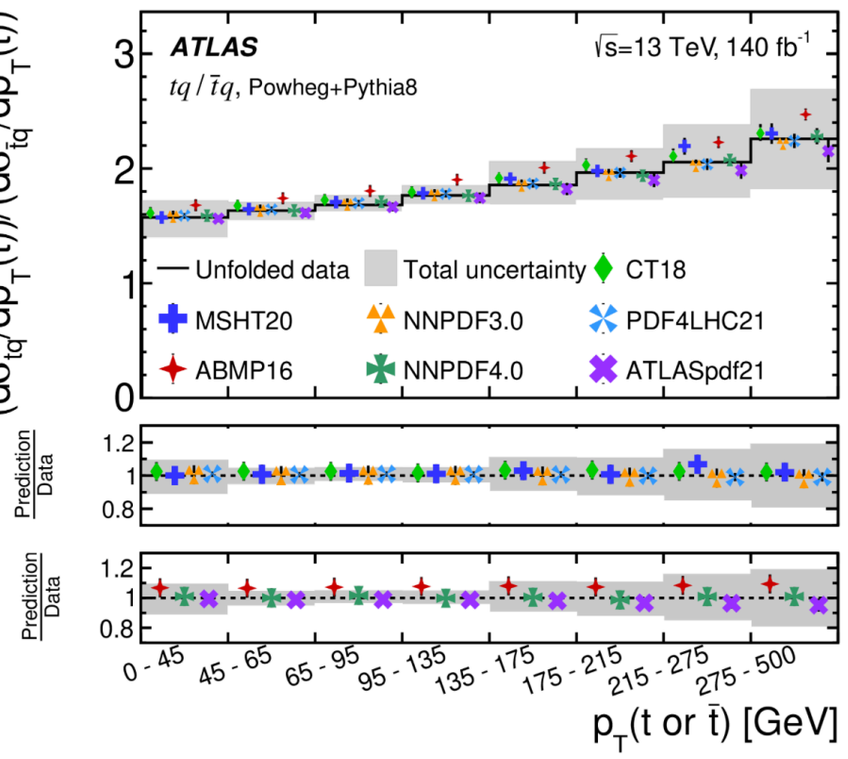
JHEP 05 (2026) 174

Single top t-chan differential cross-sections

- Most abundant single top at LHC separated in t or $\bar{t}$ productions
- Sensitive to Parton Density Functions (u/d ratio), parton shower, and Effective Field Theory four-quark operator $O_{Qq}^{3,1}$
- First separate differential measurement of tq and $\bar{t}q$, and first differential ratio $\sigma(tq)/\sigma(\bar{t}q)$
- Results: $-0.12\,\mathrm{TeV}^{-2} < C_{Qq}^{3,1}/\Lambda^2 < 0.12\,\mathrm{TeV}^{-2}$



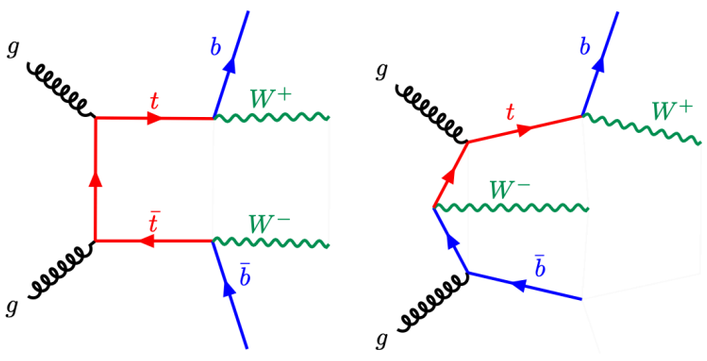


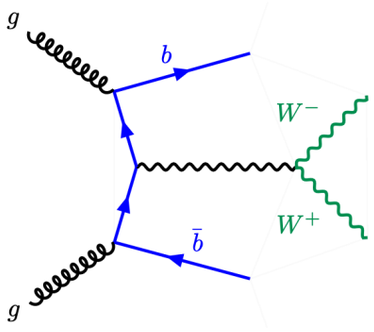


JHEP 07 (2026) 028, JHEP 02 (2026) 153

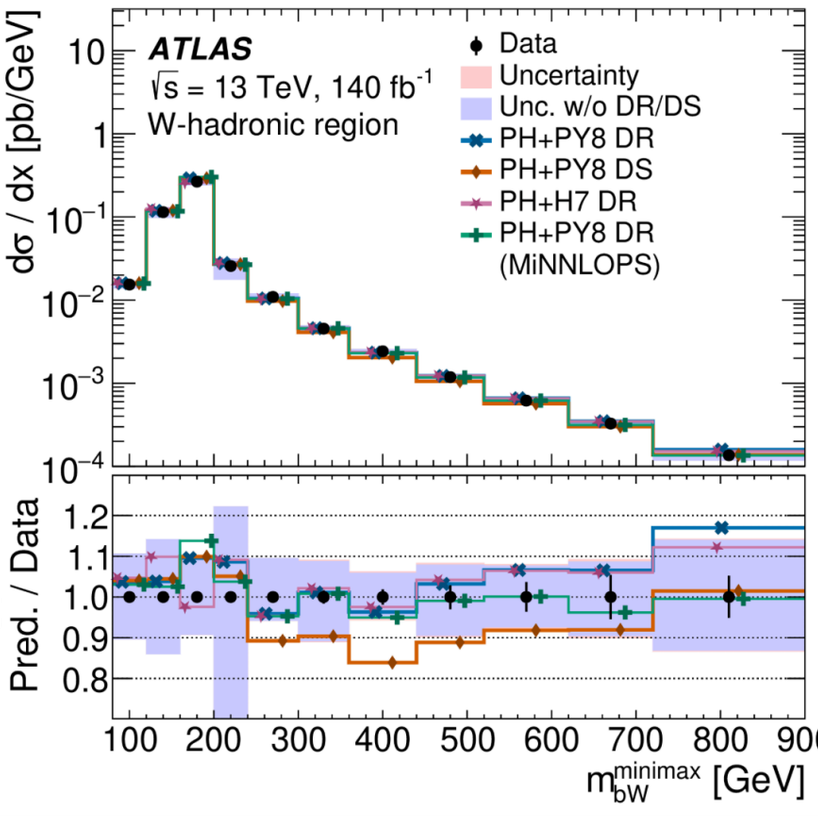
WbWb differential measurements

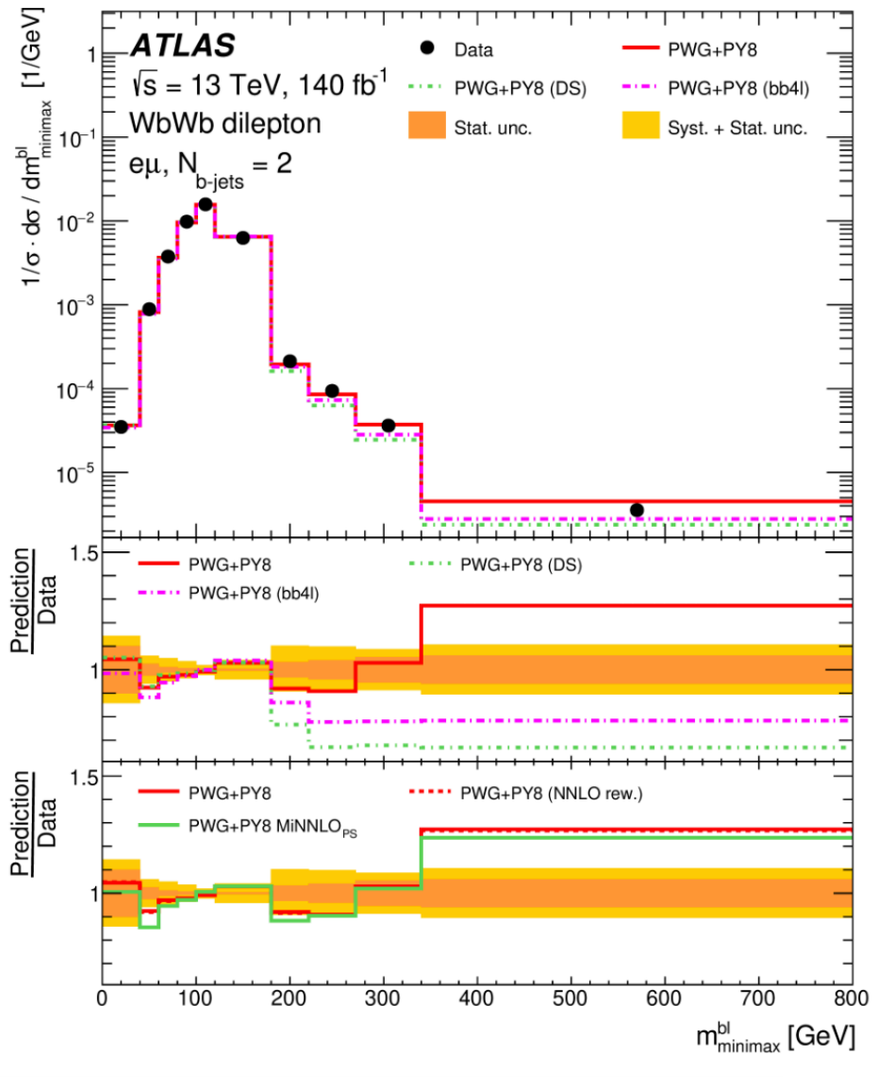
- Coherent production of singly and doubly resonant top quarks in $W^+W^-b\bar{b}$ final state, one-lepton channel
  - Probes interference and off-shell effects between single-top (tW) and $t\bar{t}$ production
- Many kinematic observables are measured for the first time
- Provide valuable constraints on WbWb modelling and interference between $t\bar{t}$ and tW





Neglected in 2lep; included in 1lep but small impact.





Submitted to EPJC

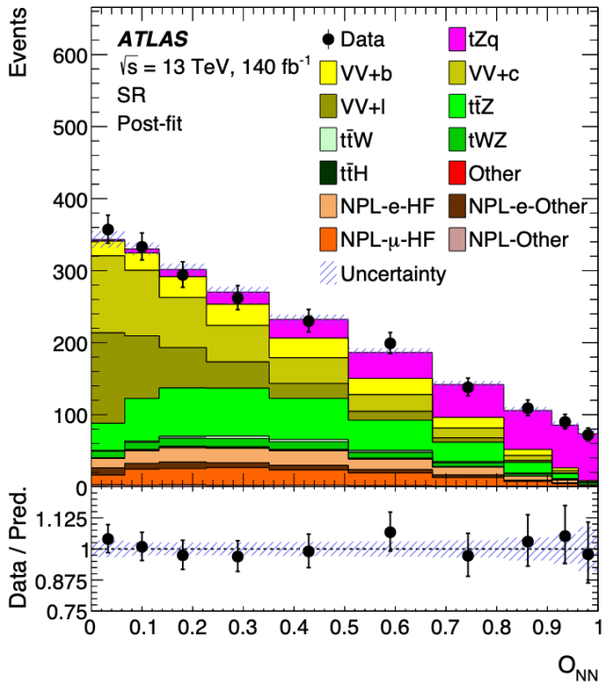
Single top tZq inc. and diff. cross-section

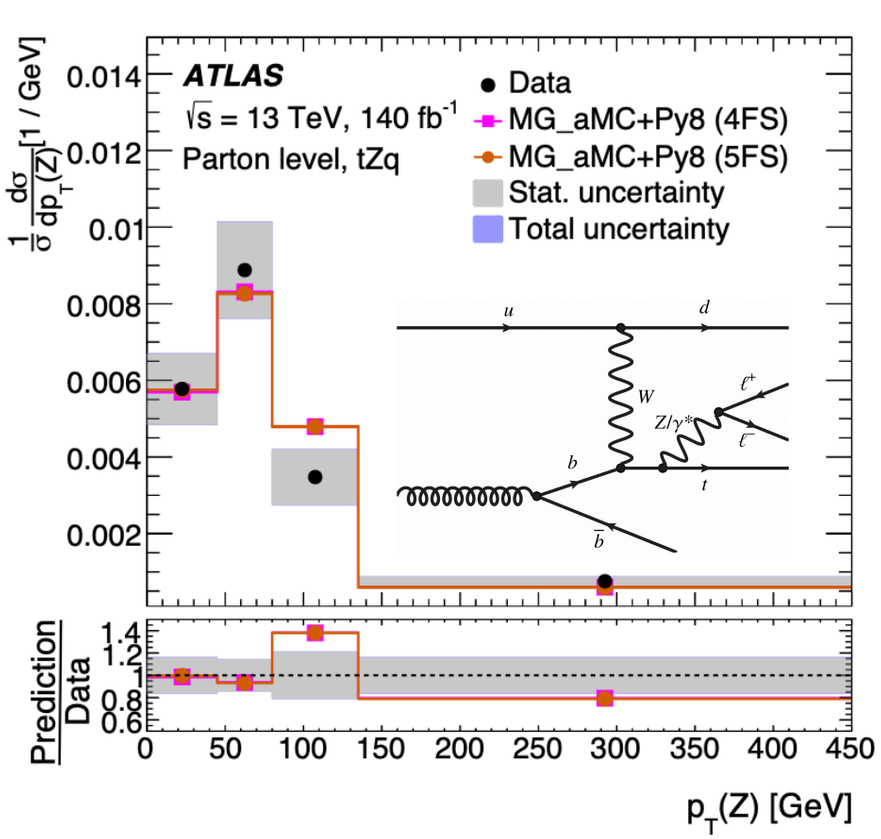
- t-chan of single top with a Z boson (tZq), measured in 3lep final state
- Neural network classifier is trained
- Results: inclusive cross-sections:
- Parton level and particle level absolute and normalised diff xsec are provided
- Interpreted to SMEFT and set constraints to 9 Wilson coefficients

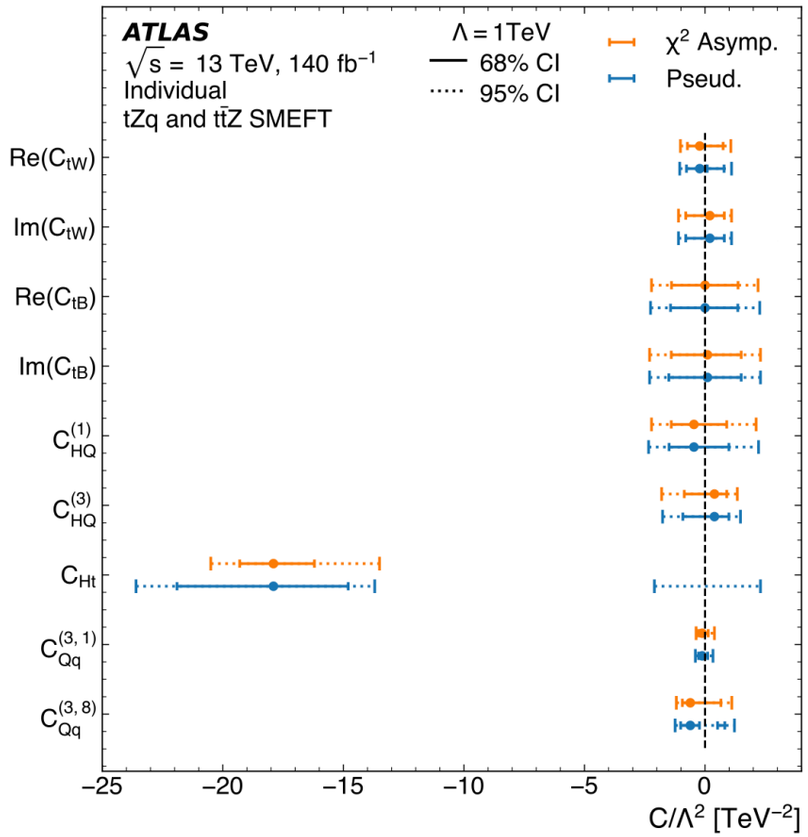
$$\sigma(tZq) = 95.2\ ^{+8.5}_{-7.9}\ (\text{stat.})\ ^{+5.5}_{-5.3}\ (\text{syst.})\ \text{fb}$$

$$\sigma\left(tZq(t)\right) = 56.0\ ^{+6.2}_{-5.6}\ (\text{stat.})\ ^{+3.6}_{-3.4}\ (\text{syst.})\ \text{fb}$$

$$\sigma\left(tZq(\bar{t})\right) = 39.3\ ^{+5.9}_{-5.3}\ (\text{stat.})\ ^{+3.1}_{-3.0}\ (\text{syst.})\ \text{fb}$$





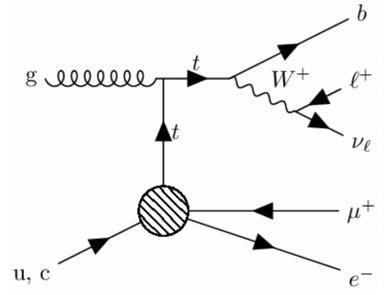


BSM exploration

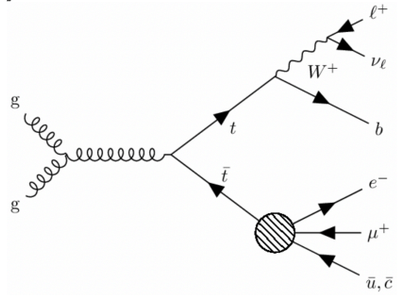
- Search for lepton flavour violation (eμ) in top quark - Submitted to JHEP

Submitted to JHEP

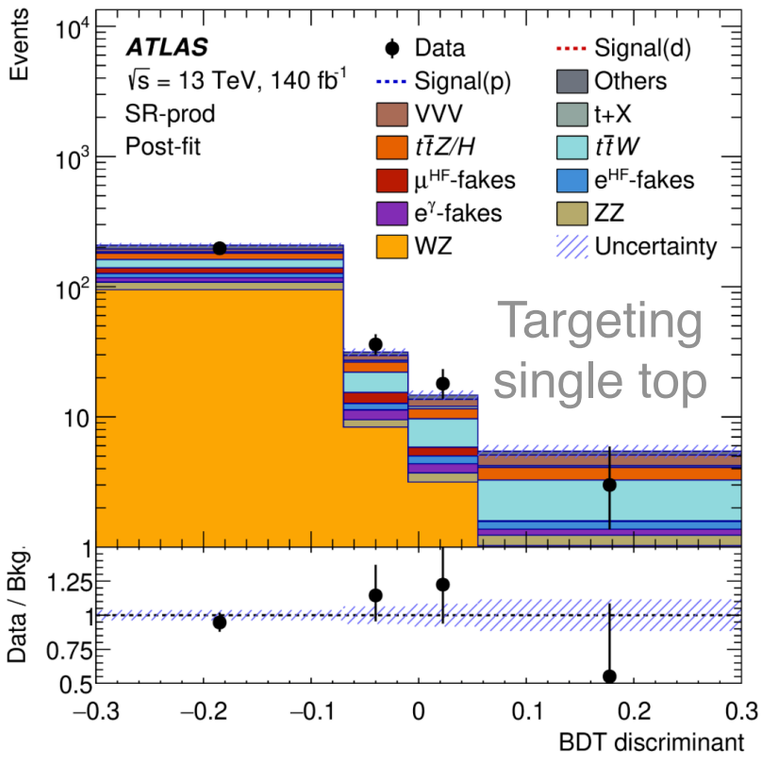
Search for lepton flavour violation (eμ) in top quark

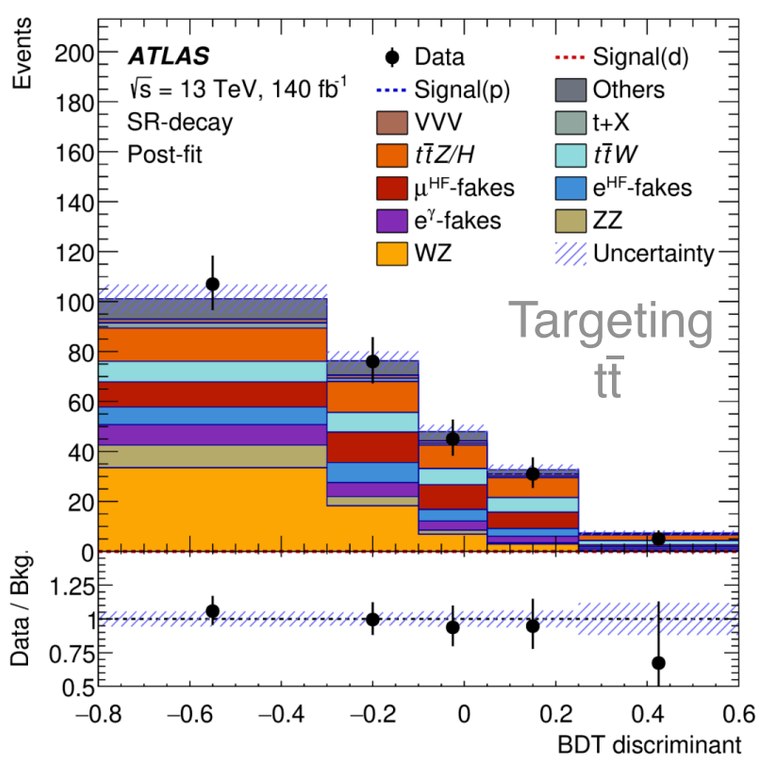


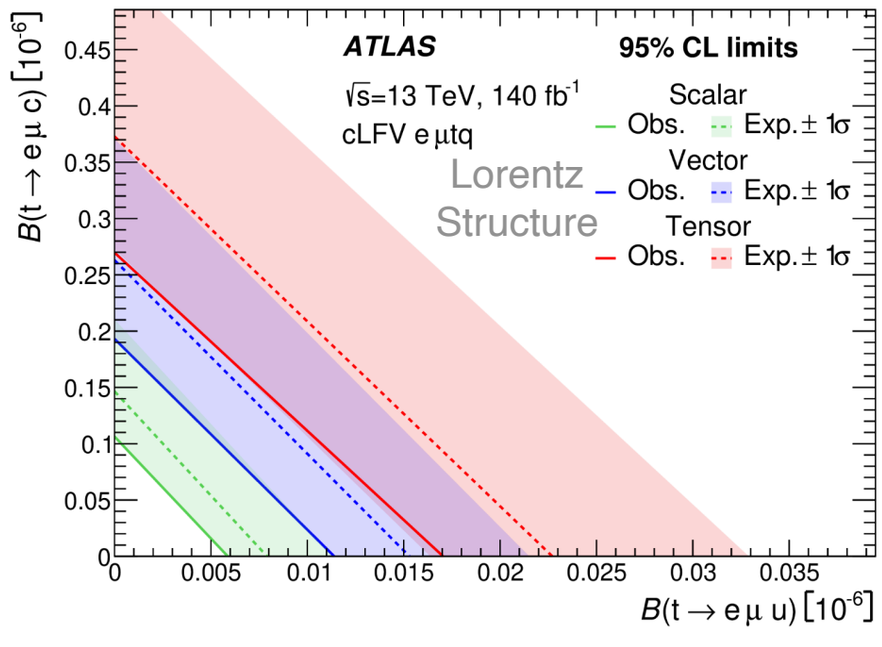
- Searched in two mechanisms with three lepton final states
  - Leptonically-decaying single top in association with a pair of eμ
  - $t\bar{t}$ where one top decays to eμ and a quark, the other decays to W(lν) and b



- BDT is trained to separate signal from all bkg
- No significant deviation from the SM observed
- Interpreted in an EFT framework, set upper limits on 6 Wilson coefficients







Summary

- Top-quark physics remains a vibrant field of basic research in particle physics.
- The LHC offers a rich and diverse top quark physics program including precise tests of the SM as well as studies sensitive to new physics.
- Recent ATLAS new results comprise the new observation of rare processes in SM and $t\bar{t}$ enhancement, precision measurement of $t\bar{t}$ and single top that can stress-test Monte-Carlo modelling, and BSM explorations.
- The upcoming HL-LHC data will allow us to explore rare processes in more detail and increase precision in tails of distributions.

Thank you for listening!

Backup

Observation of $t\bar{t}+\gamma\gamma$

Source	$\Delta\sigma_{t\bar{t}\gamma\gamma}/\sigma_{t\bar{t}\gamma\gamma}$ [%]	$\Delta R_{t\bar{t}\gamma\gamma/t\bar{t}\gamma}/R_{t\bar{t}\gamma\gamma/t\bar{t}\gamma}$ [%]
$t\bar{t}\gamma\gamma$ modelling	1.4	1.3
Prompt-photon background norm. & modelling	4.4	5.8
Fake-photon background estimates	6.5	0.5
Fake-lepton background estimate	–	0.9
Jet	9.7	5.9
Photon	6.5	4.0
b-tagging	3.4	1.0
Leptons	1.5	0.3
Luminosity	1.4	0.1
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.4	1.1
Pile-up	1.6	1.4
MC statistical uncertainties	2.5	2.8
Total systematic uncertainty	15.0	10.0

Observation of single top s-chan

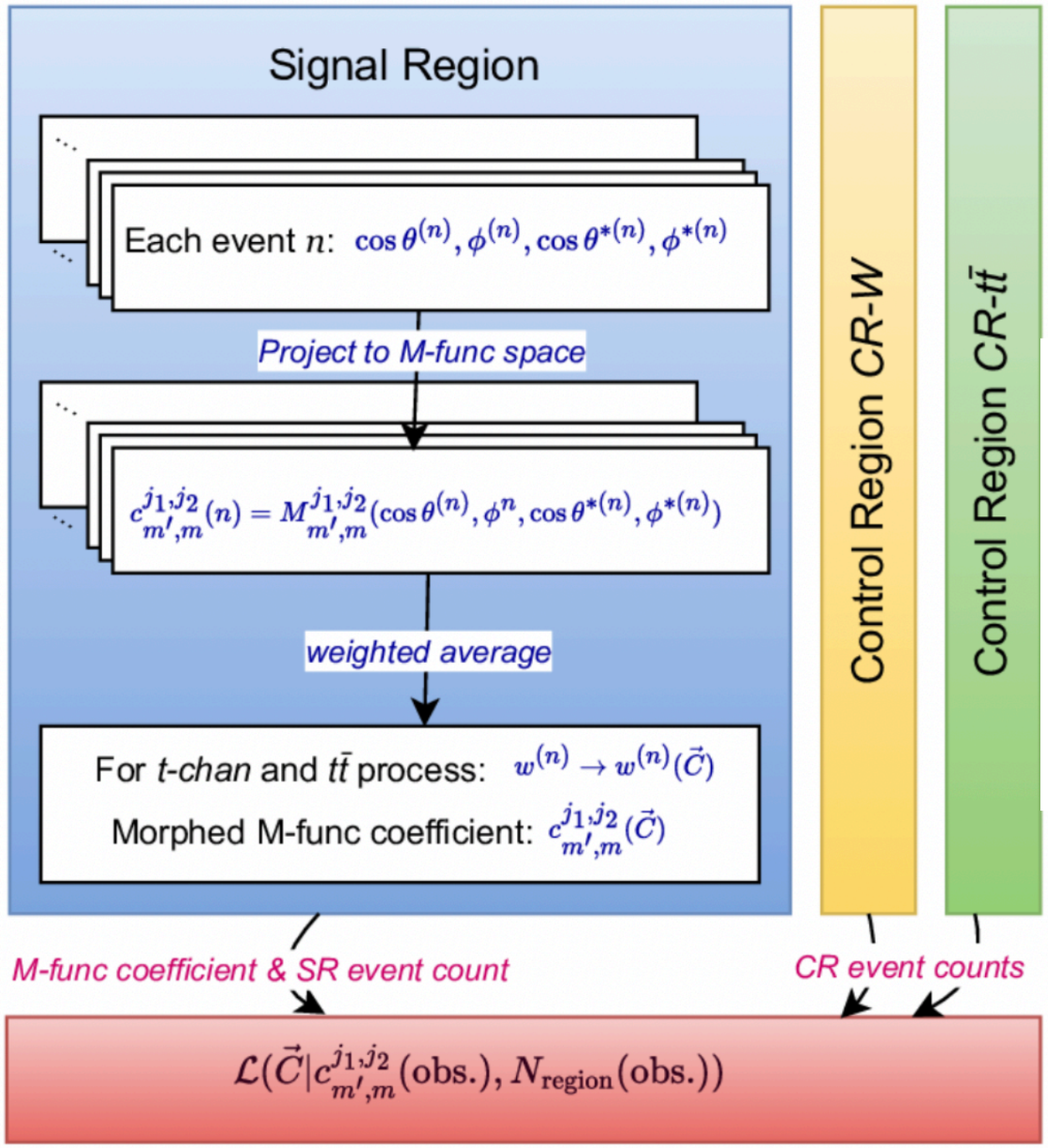
Uncertainty group	$\Delta\sigma_{t\bar{b}+\bar{t}b}/\sigma_{t\bar{b}+\bar{t}b}$ [%]
Background modeling	11.6
Signal modeling	4.1
Parton distribution functions	1.5
Jet calibration	7.9
b-tagging efficiency: b-jets	2.8
b-tagging efficiency: c-jets	0.6
b-tagging efficiency: light-jets	0.9
Integrated luminosity	1.0
Missing transverse momentum	0.8
Lepton calibration	0.3
MC statistical uncertainty	2.7
Total systematic uncertainty	15.2
Statistical uncertainty	13.5
Total uncertainty	20.4

Observation of $t\bar{t}$ enhancement

- $t\bar{t}$ samples:
  - bb4l / (hvq+tW) → How the off-shell effect changes the shape of m($t\bar{t}$)
  - (hvq+tW+$t\bar{t}_{GFRW}$) / (hvq+tW) → how the signal (quasi-bound state) change the shape of m($t\bar{t}$)
  - The off-shell effect in bb4l modelling is more or less spread equally by the four m($t\bar{t}$) bins
  - However, the tt_{GFRW} concentrates in the lowest m(tt) bins

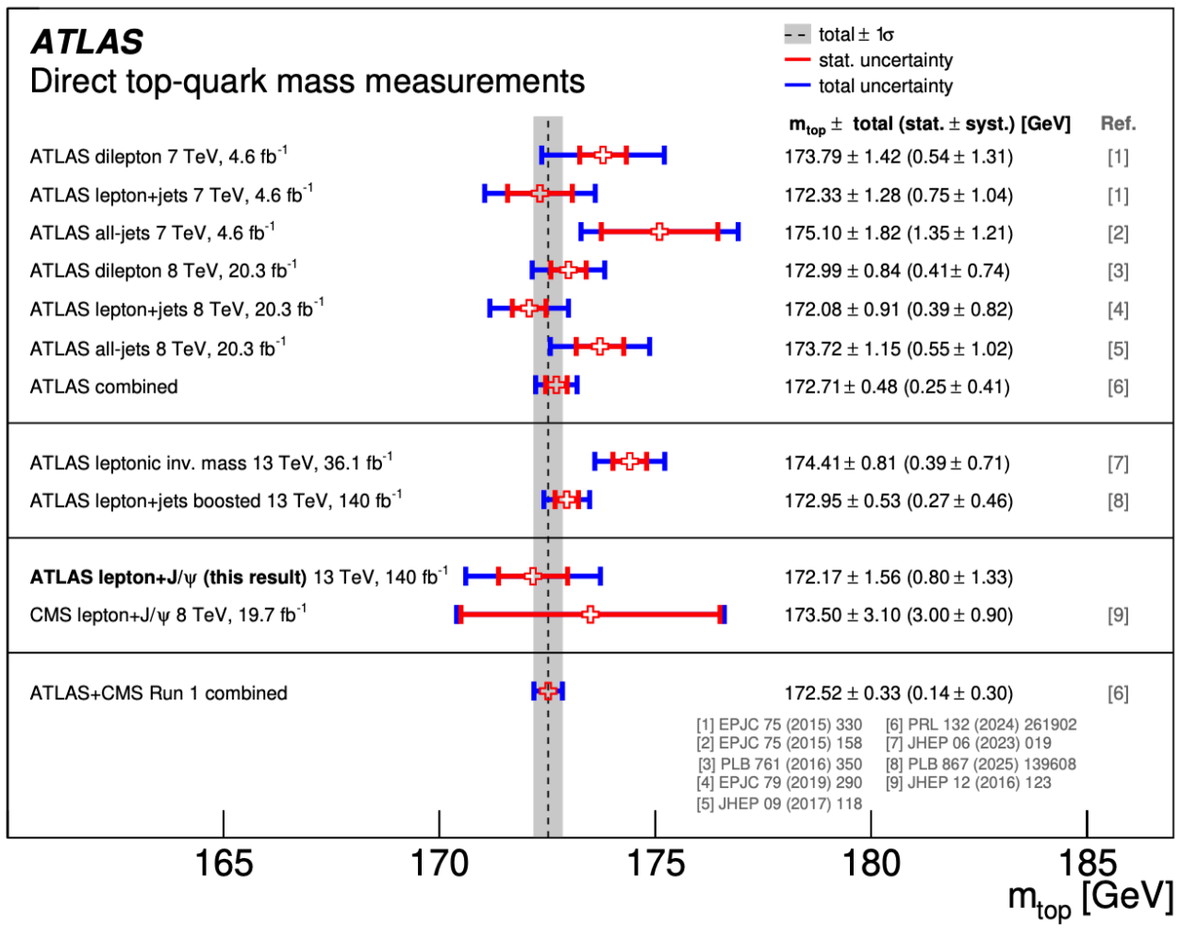
Category	Impact
$t\bar{t}_{\mathrm{GFRW}}$ modelling	6.9%
pQCD $t\bar{t}$ modelling	4.7%
JES pile-up	1.5%
b-tagging	1.3%
Instrumental (other)	0.9%
JES η inter-calibration	0.9%
Jet energy scale (JES)	0.6%
Background normalisations	0.6%
Leptons	0.6%
JES flavour	0.6%
tW modelling	0.5%
Limited MC statistics	0.3%
Jet energy resolution (JER)	0.2%
Total syst. uncertainties	8.8%
Total stat. uncertainties	11%

Four-fold differential decay in single top t-chan



Wilson coefficient [TeV^{-2}]	Fully profiled fit 68% CL interval	Fully profiled fit 95% CL interval	Individual fit 68% CL interval	Individual fit 95% CL interval
C_{tW}/Λ^2	[−0.03, +0.17]	[−0.12, +0.26]	[+0.10, +0.26]	[+0.02, +0.34]
C^I_{tW}/Λ^2	[−0.04, +0.07]	[−0.10, +0.13]	[−0.03, +0.07]	[−0.08, +0.12]
$C_{\varphi tb}/\Lambda^2$	[−4.6, −2.3] ∪ [+0.5, +3.8]	[−5.8, +4.8]	[−3.6, +1.0]	[−4.6, +2.6]
C_{bW}/Λ^2	[−1.0, 0.0] ∪ [+0.2, +1.4]	[−1.4, +1.8]	[−0.2, +0.4]	[−0.5, +0.7]
C^I_{bW}/Λ^2	[−0.4, +0.5]	[−0.9, +0.9]	[−0.3, +0.3]	[−0.6, +0.6]
C_{Qq}/Λ^2	[+0.17, +0.37]	[+0.08, +0.50]	[+0.12, +0.24]	[+0.05, +0.29]
$C_{\varphi Q}/\Lambda^2$	[+0.17, +0.86]	[−0.19, +1.2]	[−0.45, +0.13]	[−0.75, +0.41]

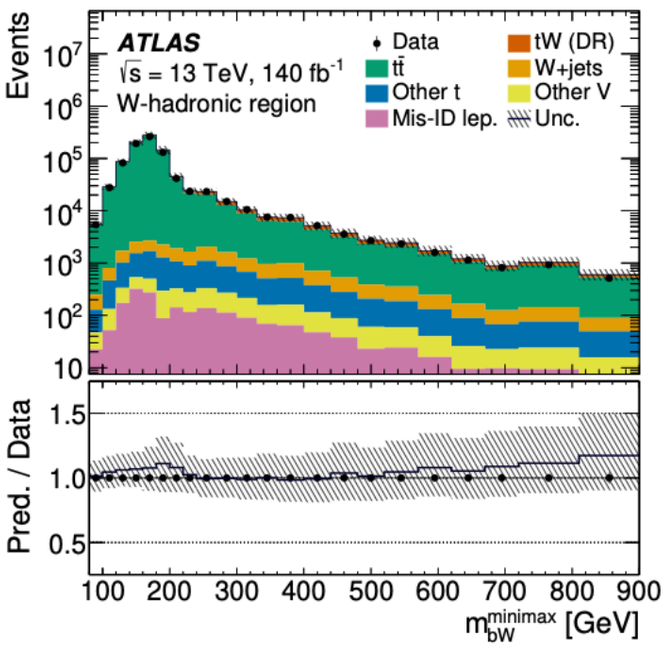
Top-quark mass in $t\bar{t}$ with b to J/ψ to μμ decays

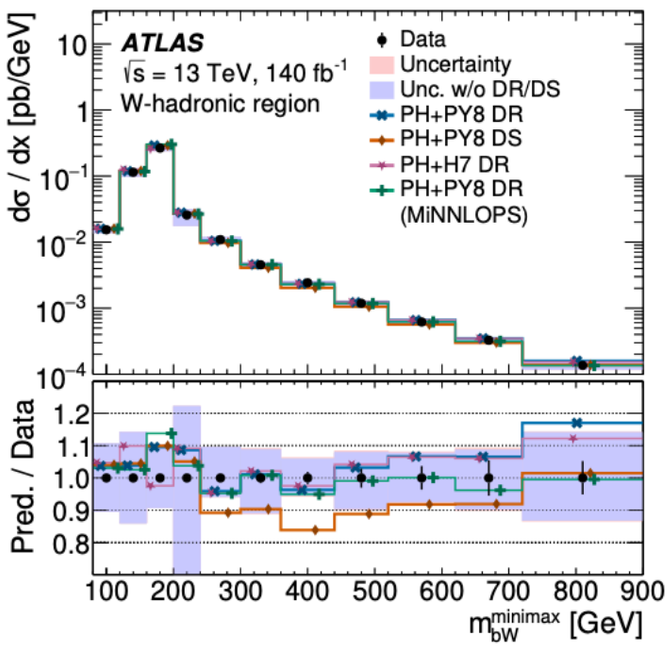


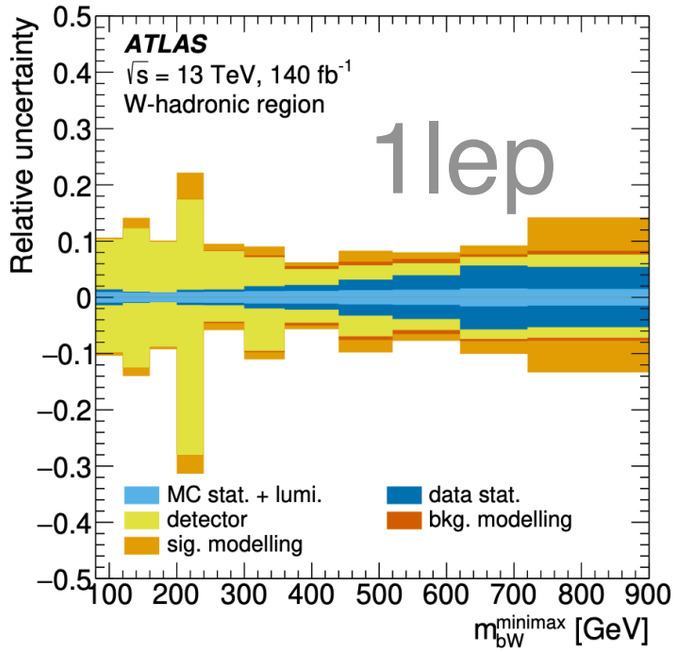
$$m_{\text{top}} = 172.17 \pm 0.80\,(\text{stat}) \pm 0.81\,(\text{syst}) \pm 1.07\,(\text{recoil})\ \text{GeV}$$

Source of uncertainty	Unc. in m_{top} [GeV]	Stat. precision [GeV]
Data and Monte Carlo samples		
Statistical error in data	0.80	
Statistical error in signal and background model	0.27	±0.06
Method	0.06	±0.10
Luminosity	0.01	< ±0.005
Pile-up	0.11	±0.02
Modelling of $t\bar{t}$ process		
Matrix element matching	0.14	±0.20
NNLO reweighting	0.01	±0.02
Top-quark decay lineshape	0.07	±0.02
Parton shower and hadronisation	0.40	±0.19
b-hadron production fractions	0.04	±0.02
b-hadron decay BR	0.08	±0.02
Initial-state QCD radiation	0.10	±0.07
Final-state QCD radiation	0.21	±0.05
Underlying event	0.20	±0.12
Colour reconnection	0.04	±0.28
Parton distribution function	0.03	< ±0.005
b-quark fragmentation r_b	0.15	±0.04
Modelling of single-top-quark process		
Matrix element matching	0.02	±0.11
$t\bar{t}$–tW interference	0.15	±0.07
Parton shower and hadronisation	0.09	±0.11
b-hadron production fractions	0.09	±0.07
b-hadron decay BR	0.02	< ±0.005
Initial-state QCD radiation	0.05	±0.04
Final-state QCD radiation	0.06	±0.04
Parton distribution function	0.01	< ±0.005
b-quark fragmentation r_b	0.05	±0.07
Modelling of background processes		
$t\bar{t}V + t\bar{t}H$, diboson	0.02	±0.01
W/Z+jets	0.40	±0.12
$W + J/\psi$	0.04	< ±0.005
Non-prompt and fake lepton	0.15	±0.01
Fake soft-μ	0.01	< ±0.005
Detector response		
Isolated leptons	0.08	±0.01
Soft-μ	0.12	±0.01
Light jet energy scale	0.07	±0.01
b-jet energy scale	0.04	±0.01
Jet energy resolution	0.02	±0.01
Flavour tagging	0.02	< ±0.005
Total systematic uncertainty (excluding recoil)	0.81	±0.15
Total stat. and syst. uncertainty (excluding recoil)	1.14	±0.15
Recoil uncertainty	1.07	±0.22
Total uncertainty	1.56	±0.18

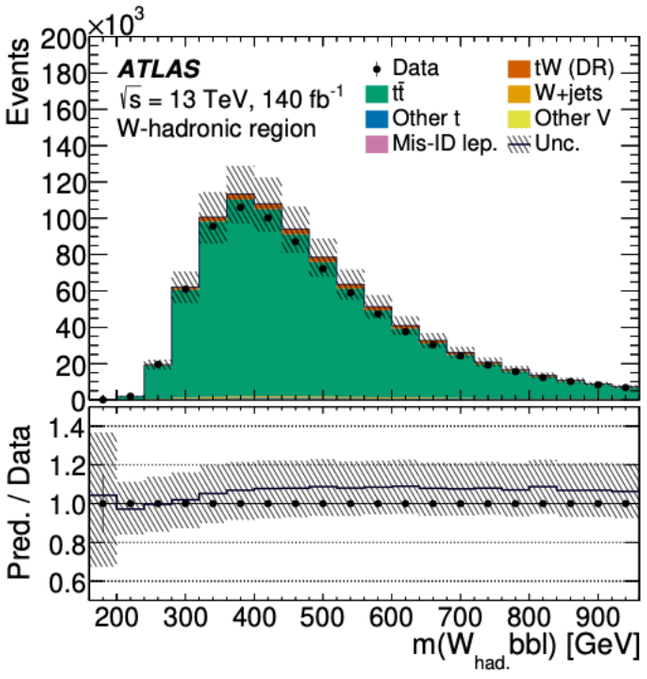
WbWb differential measurements

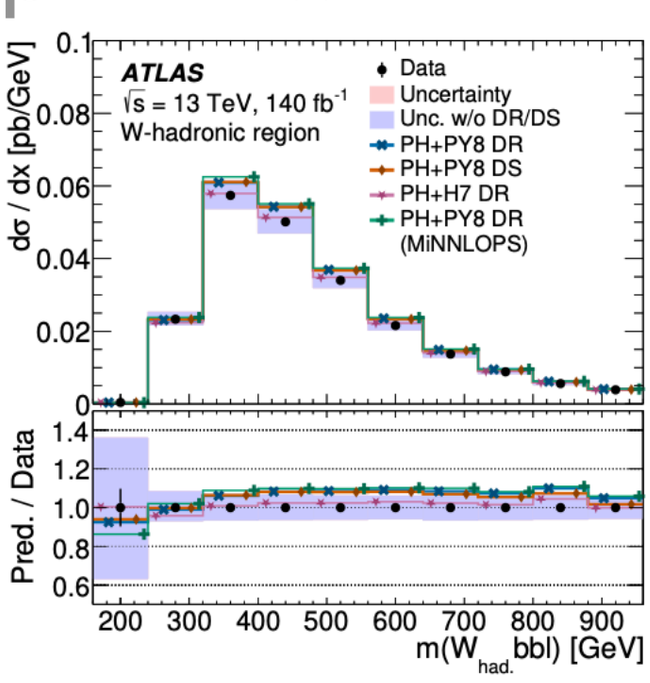






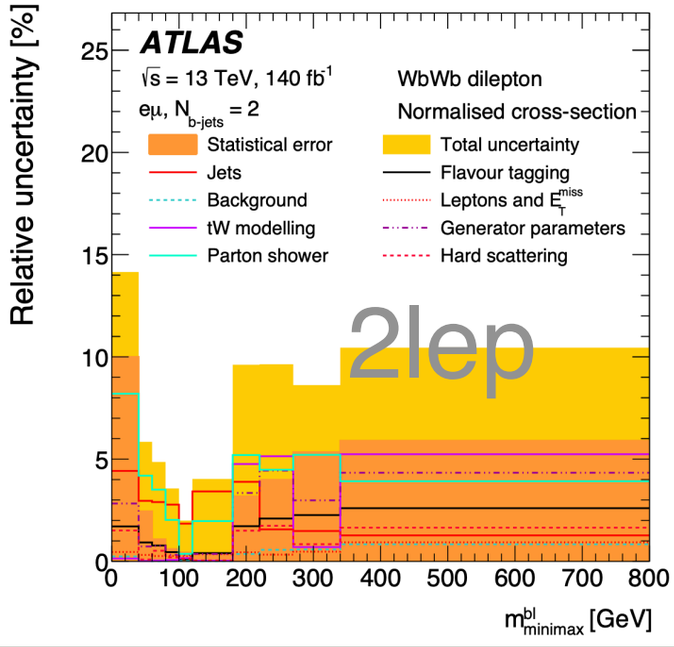
(a) 1lep (b)





(c) (d)

Around the top-quark mass, sensitive to jet energy scale and resolution



Single top tZq inc. and diff. cross-section

Uncertainty source	$\Delta\sigma(tZq)/\sigma$[%]
tZq modelling	4.3
Prompt background modelling	2.3
Jets	1.4
Leptons	1.3
b-tagging	1.2
Luminosity	0.8
MC statistics	0.8
Pile-up reweighting	0.7
Non-prompt-lepton background modelling	0.7
tZq PDF	0.4
Other background	0.1
Total systematic uncertainty	5.6
Statistical uncertainty	8.5
Total uncertainty	10.2

Search for lepton flavour violation (eμ) in top quark

cLFV coupling	Lorentz Structure	Branching ratio	Expected 95% CL limits $[10^{-6}]$ ($\pm 1\sigma$ range)	Observed 95% CL limits $[10^{-6}]$
$e\mu tu$	Tensor	$\mathcal{B}(t \to e\mu u)$	0.023 (0.016 – 0.033)	0.017
	Vector		0.015 (0.011 – 0.022)	0.011
	Scalar		0.008 (0.006 – 0.011)	0.006
$e\mu tc$	Tensor	$\mathcal{B}(t \to e\mu c)$	0.37 (0.27 – 0.52)	0.27
	Vector		0.26 (0.20 – 0.37)	0.19
	Scalar		0.15 (0.11 – 0.21)	0.11