Highlights on top quark physics with the ATLAS experiment at the LHC

International Workshop on Future Linear Colliders 2023
SLAC

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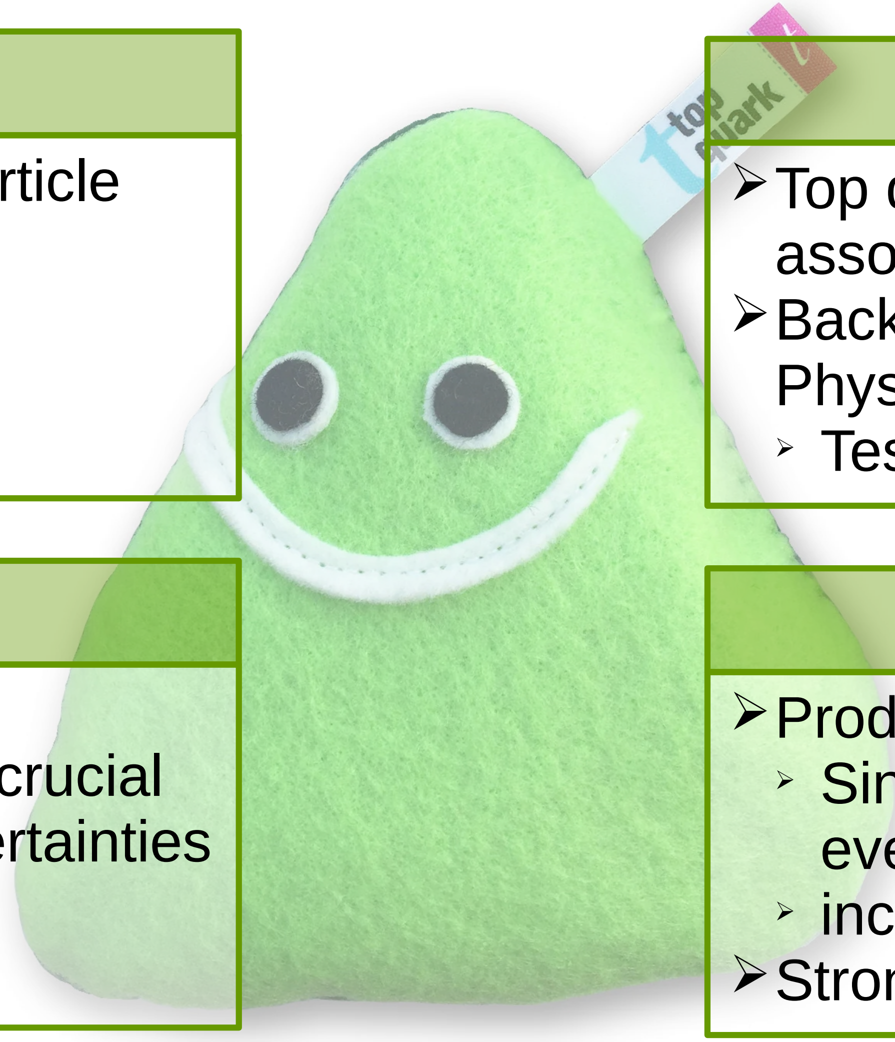
on behalf of the ATLAS Collaboration

Top quark working group in ATLAS



Properties

- Heaviest elementary particle
- Measurements on
  - Mass (direct / indirect)
  - Spin (polarization…)
  - Couplings (Yukawa...)

Modelling

- MC generators
- Precise predictions are crucial
- reduce MC related uncertainties
  - b-fragemntation
  - color reconnection

Top+X

- Top quark processes with associated particles ($t\bar{t}V$,tγ,...)
- Background to Higgs and new Physics
  - Test SM and BSM theories!

Cross-section

- Production cross-section
  - Single, pair, triple… even four! → in this talk!
  - inclusive / differential
- Strong and electro-weak prod.

New!

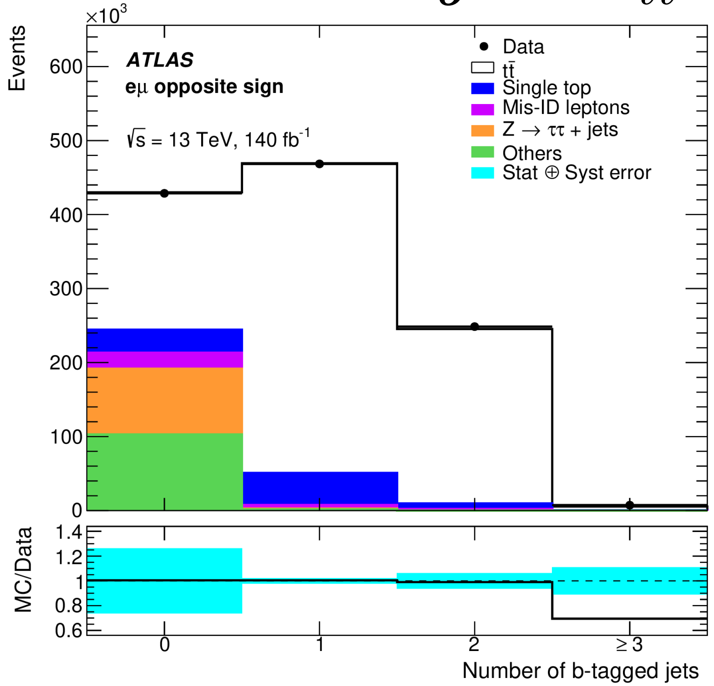
Inclusive & differential $t\bar{t}$ production cross-section measurement

- **Full Run2 dataset** at √s = 13 TeV used
- **Dilepton** events selected
  - Exactly one electron & one muon
  - Exactly one or two b-tagged jets
- **Minimal level** of background

Log-Likelihood Fit

$$N_1^i = \mathcal{L}\sigma_{t\bar{t}}^i G_{e\mu}^i 2\epsilon_b^i \left(1 - \epsilon_b^i C_b^i\right) + N_{1,\mathrm{bkg}}^i$$
$$N_2^i = \mathcal{L}\sigma_{t\bar{t}}^i G_{e\mu}^i \left(\epsilon_b^i\right)^2 C_b^i + N_{2,\mathrm{bkg}}^i$$

- Simultaneously determination of ϵ_b and $\sigma_{t\bar{t}}$



Inclusive cross-section

$$\boldsymbol{\sigma_{t\bar{t}} = 829 \pm 1(\mathrm{stat}) \pm 13(\mathrm{syst}) \pm 8(\mathrm{lumi}) \pm 2(\mathrm{beam})\ \mathrm{pb}}$$

- New **luminosity measurement** helps with incredible precision
  - relative luminosity uncertainty: **0.83%**
- This result shows strength of LHC as a **precision machine**

arXiv:2303.15340

New!

Inclusive & differential $t\bar{t}$ production cross-section measurement

Differential measurement

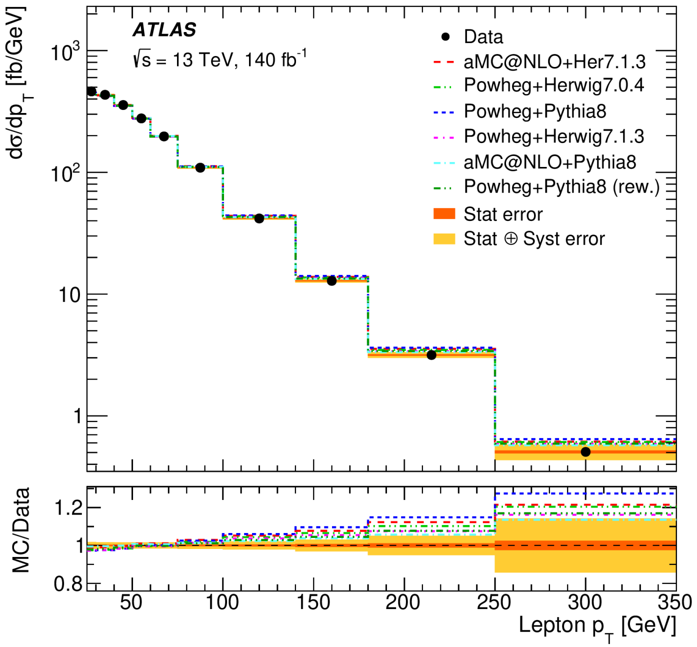
- In eight **lepton kinematic variables**, four double-differential distributions
- Bin-by-bin unfolding procedure

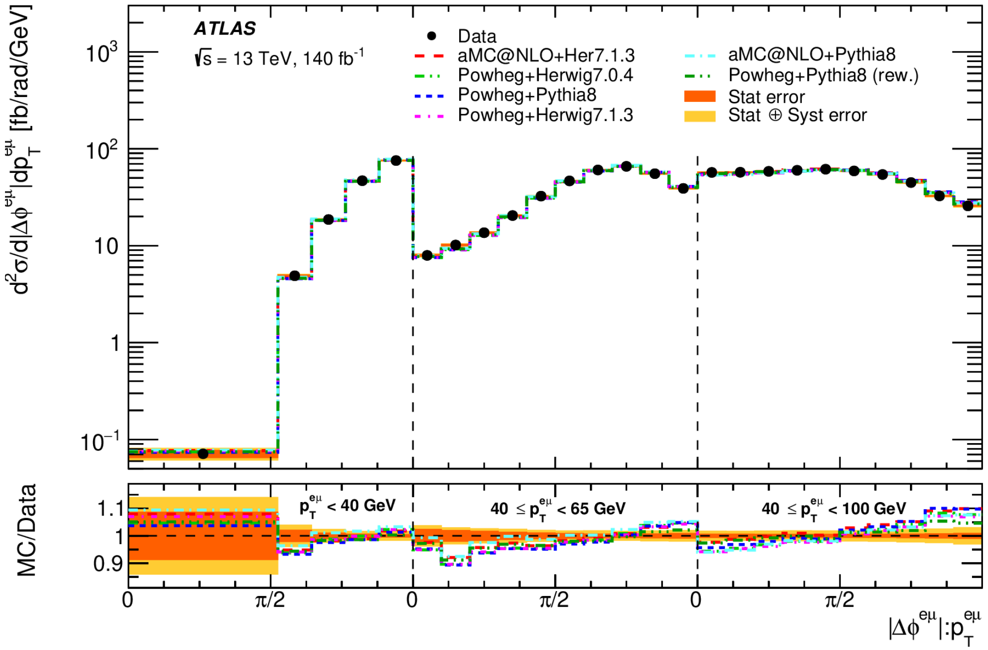
Log-Likelihood Fit

$$N_1^i = \mathcal{L}\sigma_{t\bar{t}}^i G_{e\mu}^i 2\epsilon_b^i \left(1 - \epsilon_b^i C_b^i\right) + N_{1,\mathrm{bkg}}^i$$
$$N_2^i = \mathcal{L}\sigma_{t\bar{t}}^i G_{e\mu}^i \left(\epsilon_b^i\right)^2 C_b^i + N_{2,\mathrm{bkg}}^i$$

- Full Run2 dataset allows for **wider range and finer granularity**

- **Discrepancies with predictions** from several NLO event-generators
- need more refined theoretical modelling



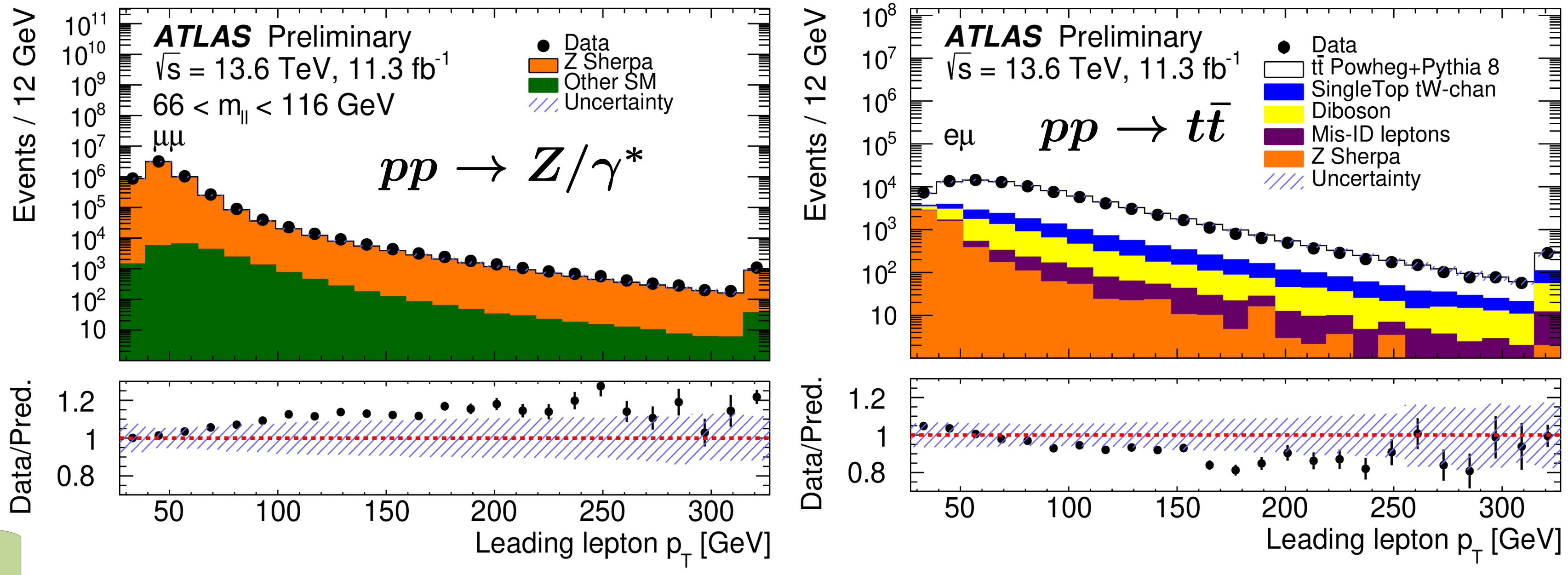


arXiv:2303.15340

$t\bar{t}$ and Z-boson cross sections and their ratio at $\sqrt{s}$ = 13.6 TeV

New!

- First **Run3** measurement
  → 11.3 fb^{-1} data collected in August 2022
- Events with an opposite-charge lepton pair and b-tagged jets selected



Systematic uncertainties

- precise measurements of luminosity (2.2%) and in-situ calibrations for leptons and jets
- But still: measurement already limited by **systematic uncertainties**
- absolute cross-section measurements limited by luminosity uncertainties and lepton efficiency uncertainties
- uncertainties **partially cancel** for **ratio** $\frac{\sigma_{t\bar{t}}}{\sigma_Z}$ (e.g. luminosity)

ATLAS-CONF-2023-006

$t\bar{t}$ and Z-boson cross sections and their ratio at $\sqrt{s}$ = 13.6 TeV

New!

Profile Likelihood fit

$$N_1 = L\sigma_{t\bar{t}}\epsilon_{e\mu}2\epsilon_b\left(1 - C_b\epsilon_b\right) + N_1^{\text{bkg}}$$
$$N_2 = L\sigma_{t\bar{t}}\epsilon_{e\mu}C_b\epsilon_b^2 + N_2^{\text{bkg}}$$

$$\boldsymbol{\sigma_{t\bar{t}} = 859 \pm 4\,(\text{stat}) \pm 22\,(\text{syst}) \pm 19\,(\text{lumi})\ \text{pb}}$$

$$\boldsymbol{\sigma^{\text{fid.}}_{Z\to\ell\ell} = 751 \pm 0.3\,(\text{stat.}) \pm 15\,(\text{syst.}) \pm 17\,(\text{lumi})\,\text{pb}}$$

$$\boldsymbol{R_{t\bar{t}/Z} = 1.144 \pm 0.006\,(\text{stat.}) \pm 0.022\,(\text{syst}) \pm 0.003\,(\text{lumi})}$$

- cross-sections simultaneously extracted
- results **in agreement** with SM predictions

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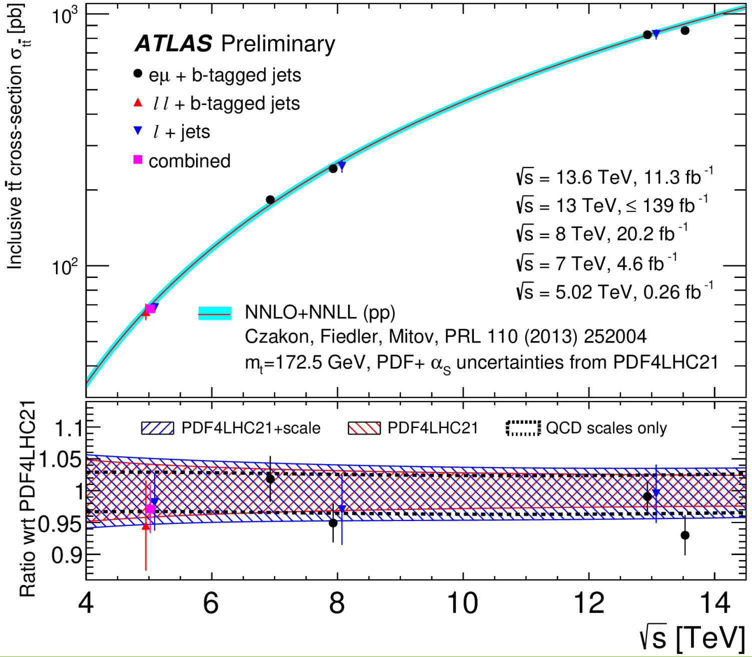

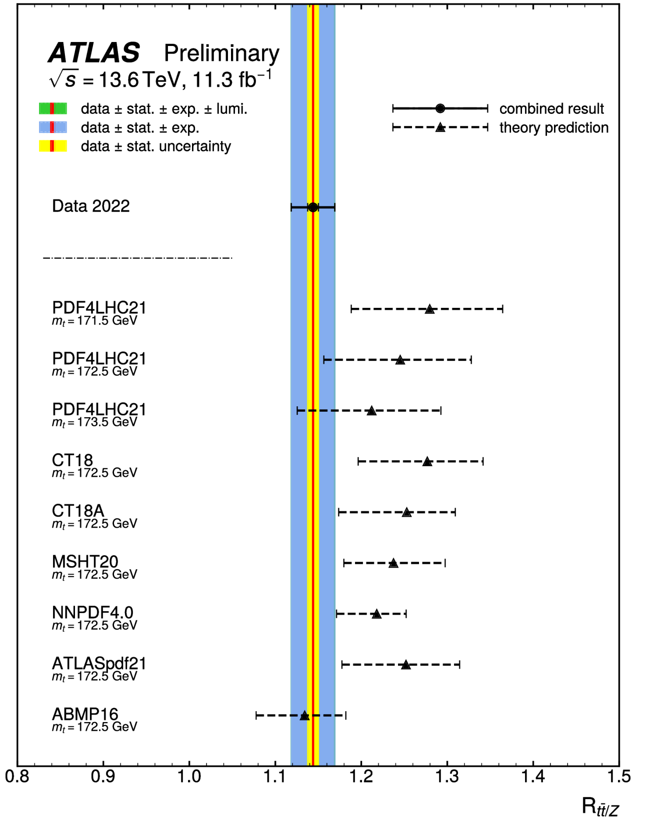

$t\bar{t}$ and Z-boson cross sections and their ratio at $\sqrt{s}$ = 13.6 TeV

New!

Profile Likelihood fit

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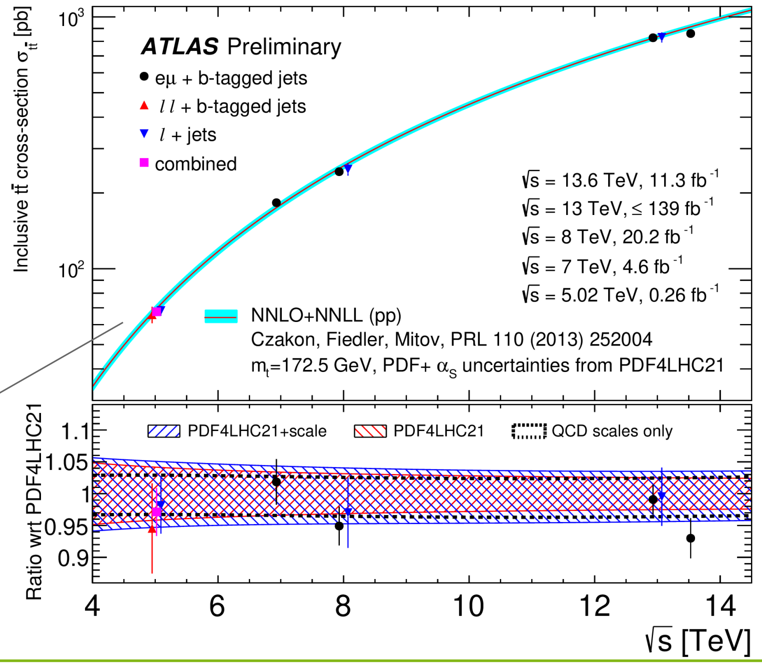
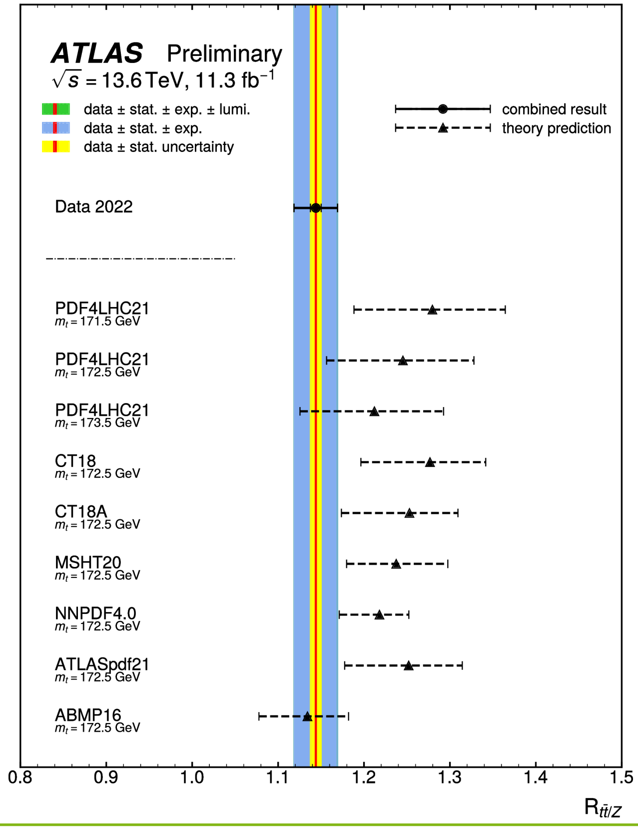




- 5.02 TeV measurement in Run 2 done

arXiv:2207.01354

Measurement of total and differential $t\bar{t}W$ cross-section

New!

- At LO in QCD $t\bar{t}W$ produced in $q\bar{q}$ initial states
  - Large background for many analyses
  - **Excess** in $t\bar{t}W$ events observed in many analyses
  - forward-central asymmetry measurable
- **Full Run2 dataset** allows first differential measurement

Event selection

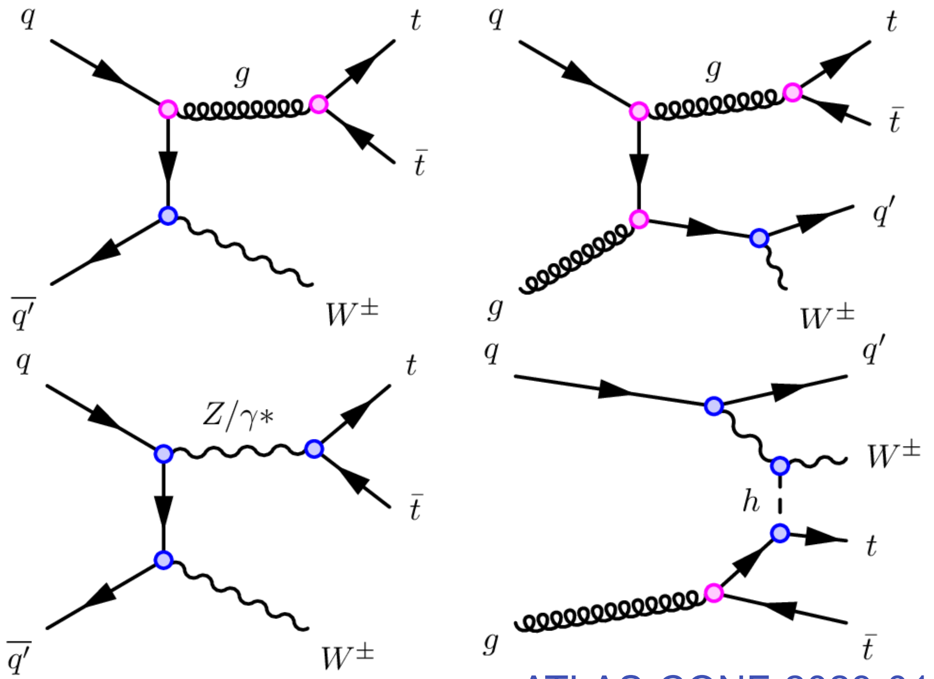
Exactly two or three leptons

At least two jets

At least one or two b-tagged jets

- Main <u>backgrounds</u>:
  - **tt̄Z/ttγ, VV** and tt̄H
  - **non-prompt leptons**
  - **charge** mis-identified leptons

  → 10 Control regions assigned



ATLAS-CONF-2023-019

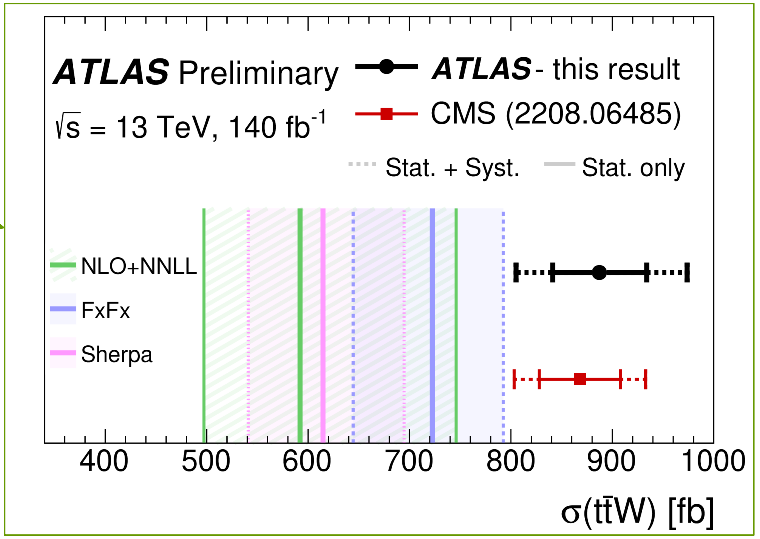
Measurement of total and differential $t\bar{t}W$ cross-section

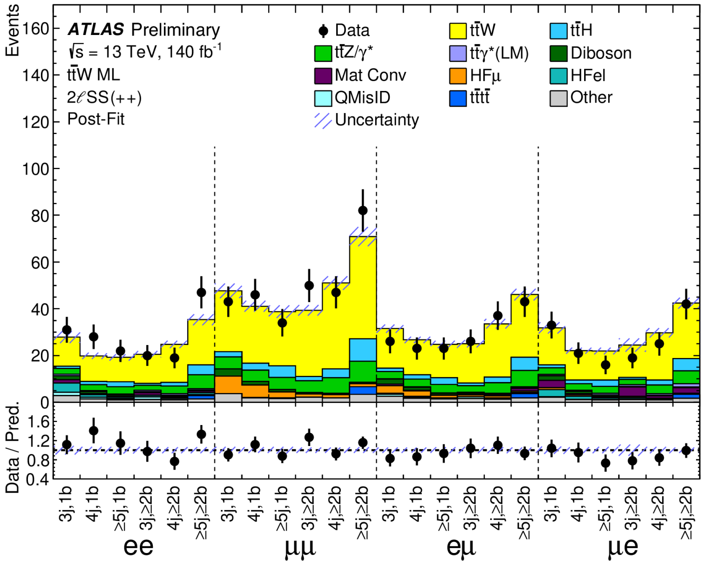
New!

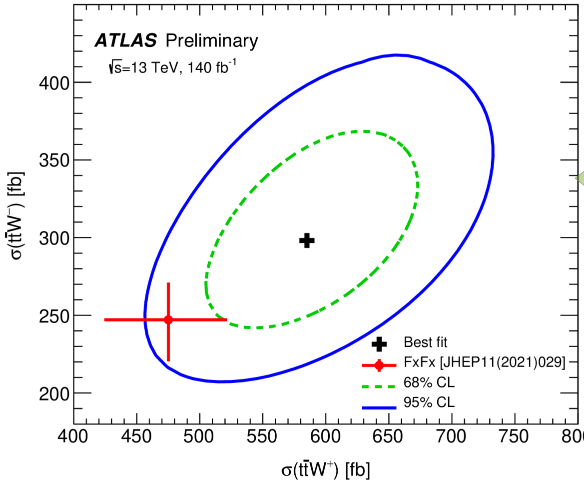
Inclusive cross-section measurement

- **Maximum likelihood fit**
- Excess visible → **within 1.5σ in agreement** with SM
- Signal modelling and prompt lepton background uncertainties dominant
- relative uncertainty improved by more than factor 5 compared to previous analysis

$$\sigma\,(t\bar{t}W) = 890 \pm 50\,(\mathrm{stat}) \pm 70\,(\mathrm{syst})\ \mathrm{fb}$$







Asymmetry measurement

$$\sigma\,(t\bar{t}W^{+}) = 585^{+35}_{-34}\,(\mathrm{stat})^{+47}_{-44}\,(\mathrm{syst})\ \mathrm{fb}$$

$$\sigma\,(t\bar{t}W^{-}) = 301^{+28}_{-27}\,(\mathrm{stat})^{+35}_{-31}\,(\mathrm{syst})\ \mathrm{fb}$$

$$R\,(t\bar{t}W) = 1.95^{+0.21}_{-0.18}\,(\mathrm{stat})^{+0.16}_{-0.13}\,(\mathrm{syst})$$

- **Ratio in good agreement with prediction**

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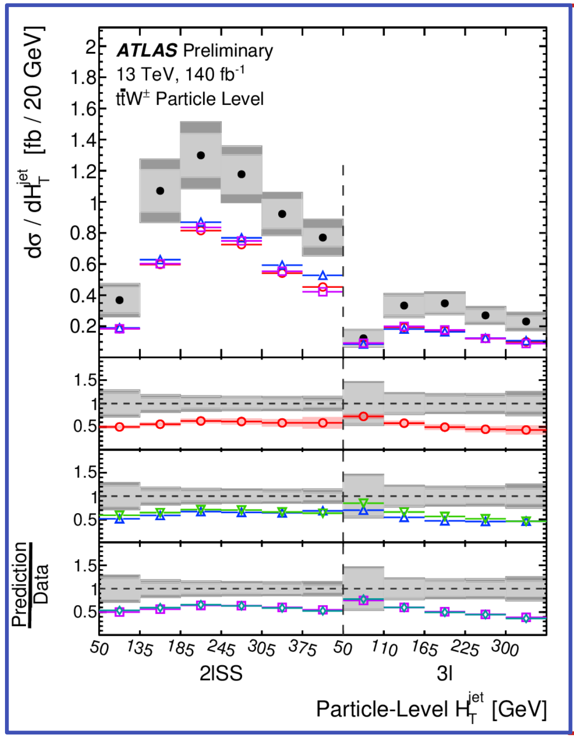
Measurement of total and differential $t\bar{t}W$ cross-section

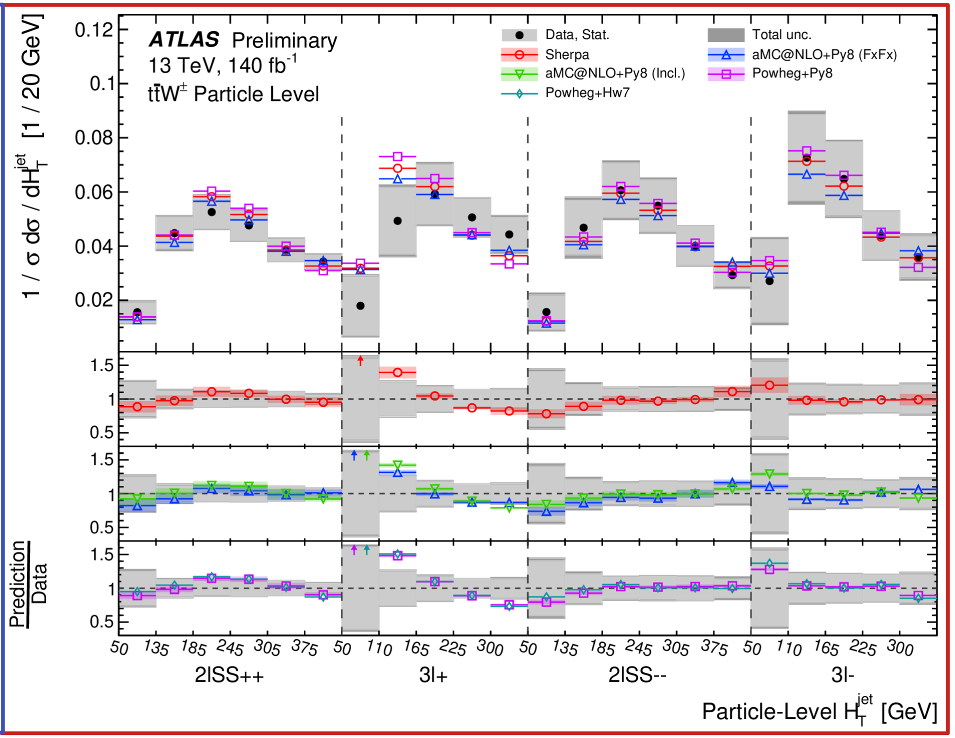
New!

Differential cross-section measurement

- **7 Observables**
- **Profile-likelihood unfolding**
- Systematic uncertainties impact through modifications of the response matrix

- absolute and normalised cross-section measurements are performed
- Absolute differential cross-sections larger than theoretical predictions → consistent with inclusive measurement





- Theory calculations indicate that disagreements are **not** due to missing singly-resonant contributions
- Future theoretical developments (predictions at NNLO in QCD) needed
- **Run3 of LHC** will provide more data to further probe this final state

ATLAS-CONF-2023-019

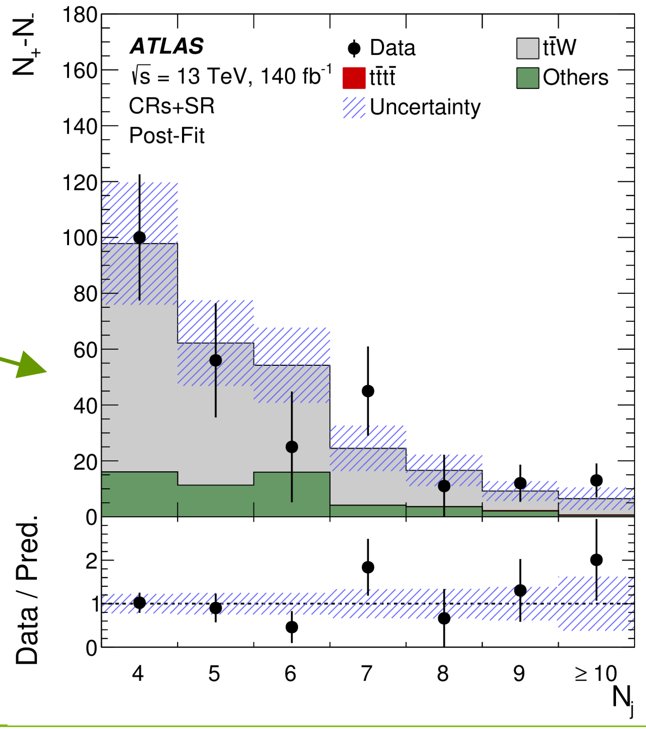
Observation of four-top-quark production

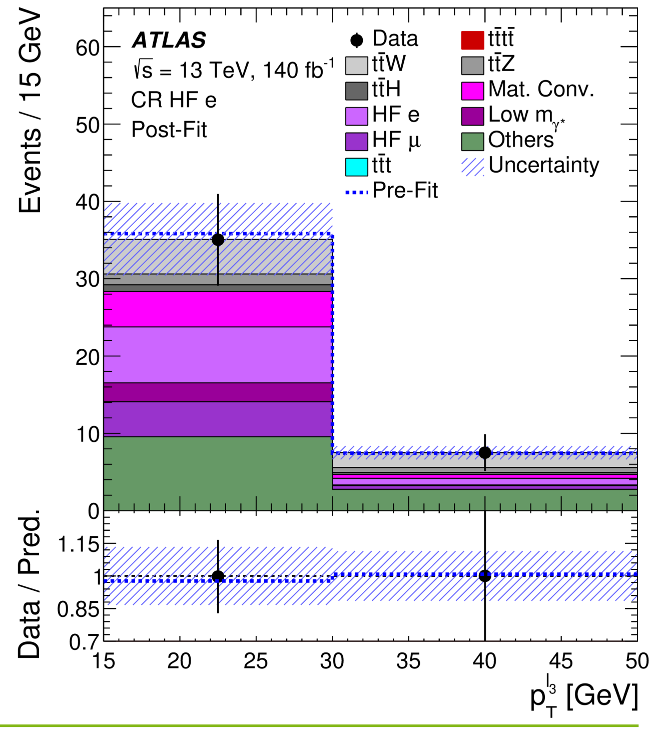
New!

- new particles or forces could alter the **probability** of producing four top quarks
- Previous analysis found evidence (4.3σ) for four-top-quark production
- Many **improvements** implemented:
  - Improved particle identification
    - lower p_T requirements used
  - data-driven background estimates for $t\bar{t}W$, mis-identified or non-prompt leptons
  - Improved treatment of $t\bar{t}t$
  - more sensitive machine-learning technique used
- revised set of systematic uncertainties

Event selection

- exactly two same-charge leptons or at least three leptons
- at least 6 jets → two b-tagged jets





arXiv:2303.15061

New!

Observation of four-top-quark production

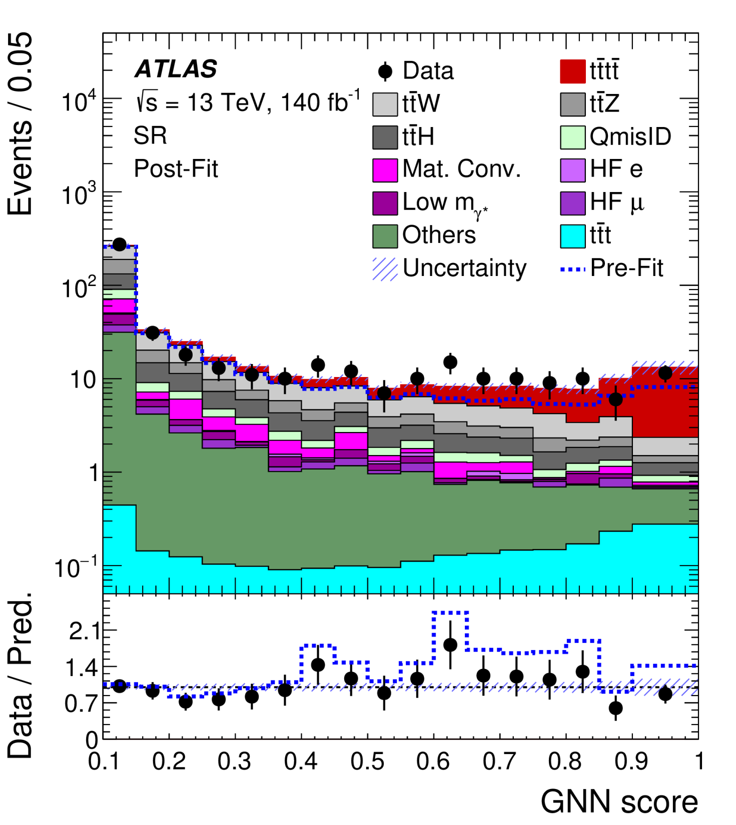
Graph Neural Network

- Used to distinguish signal
- GNN output chosen as observable in signal region

Binned profile-likelihood fit

- Cross section and normalisation of backgrounds simultaneously derived
- Signal generator choice and statistical uncertainties largest source of uncertainties
- Result **1.8σ above** of SM prediction
  - 1.7σ above resummed calculation

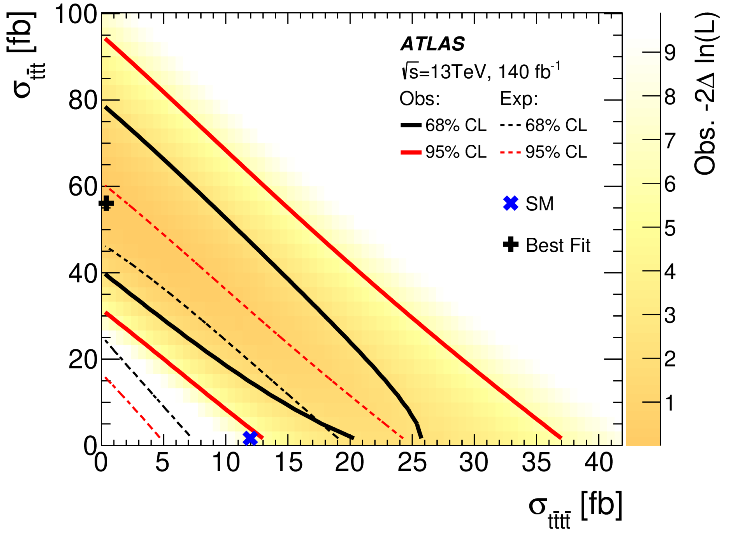
arXiv:2303.15061



$$\sigma_{t\bar{t}t\bar{t}} = 22.5^{+6.6}_{-5.5}\,\text{fb}$$

6.1σ significance!

- 95% CL limit set on $t\bar{t}t$ cross-section



ATLAS Physics Briefing

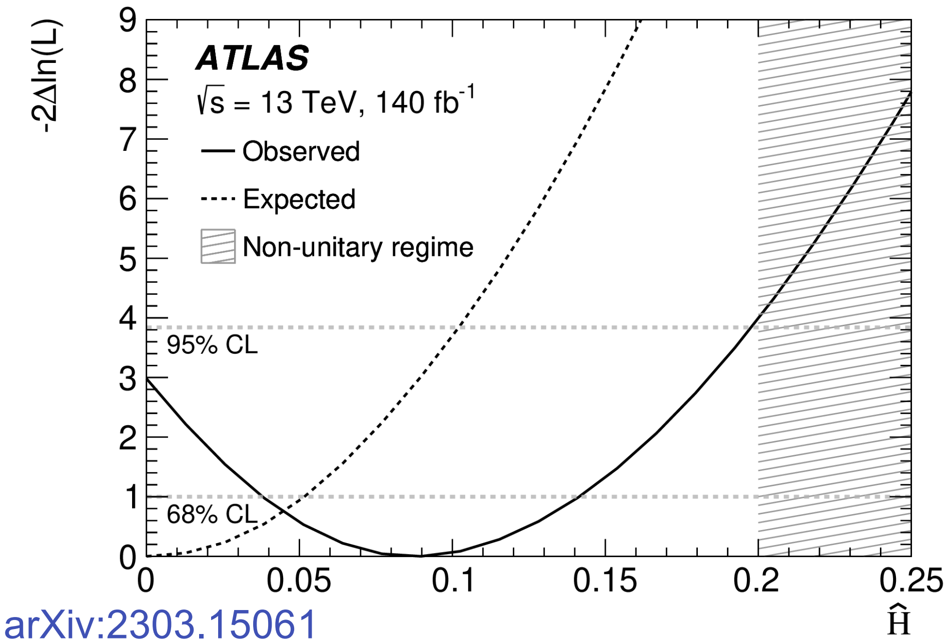
ATLAS observes the simultaneous production of four top quarks

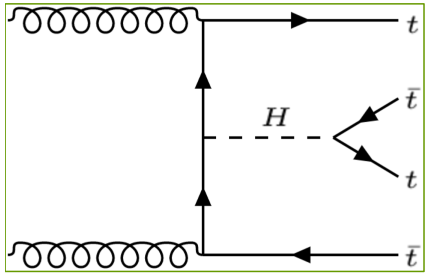
New!

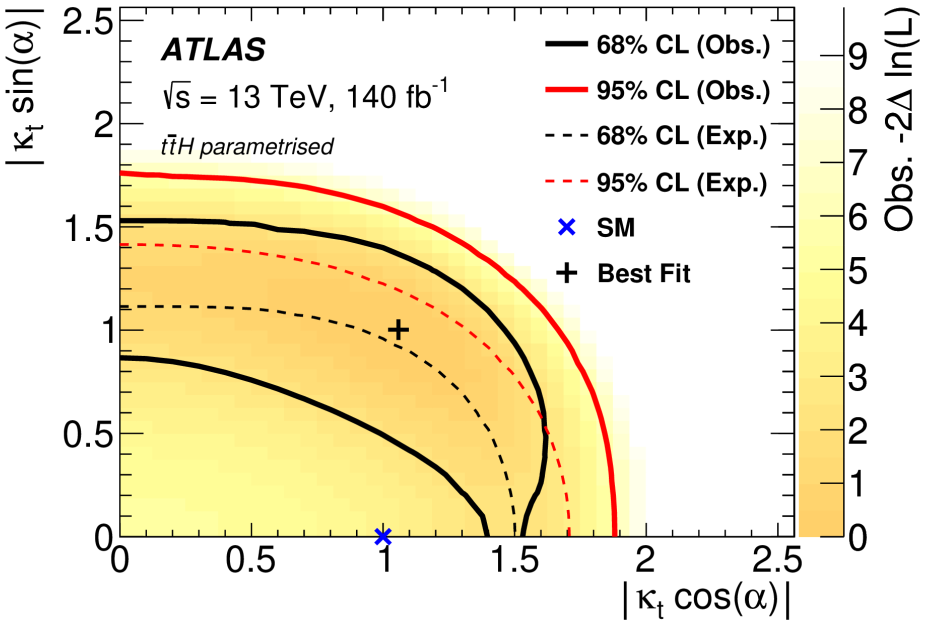
Observation of four-top-quark production

- Looking for sights of new physics
  → three **interpretations** done
- Four **heavy flavour fermion EFT** operators
- Top-quark **Yukawa coupling**
- **Higgs oblique parameter**

Operators	Expected C_i/Λ^2 [TeV $^{-2}$]	Observed C_i/Λ^2 [TeV $^{-2}$]
O^1_{QQ}	[-2.4, 3.0]	[-3.5, 4.1]
O^1_{Qt}	[-2.5, 2.0]	[-3.5, 3.0]
O^1_{tt}	[-1.1, 1.3]	[-1.7, 1.9]
O^8_{Qt}	[-4.2, 4.8]	[-6.2, 6.9]







arXiv:2303.15061

Observation of single-top-quark production with a photon

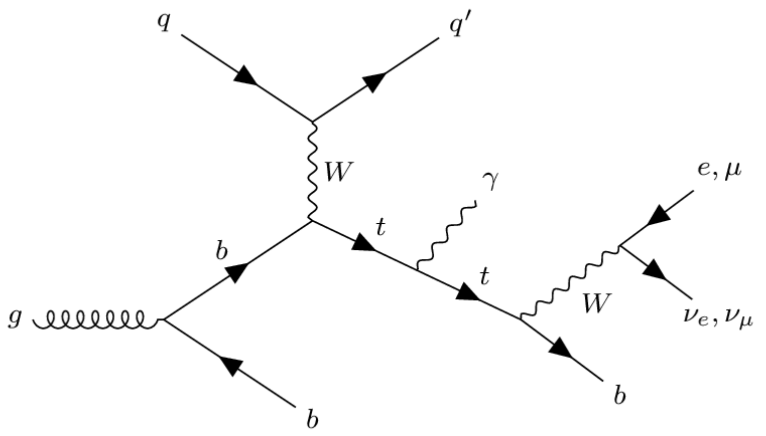
Event selection

Exactly one photon

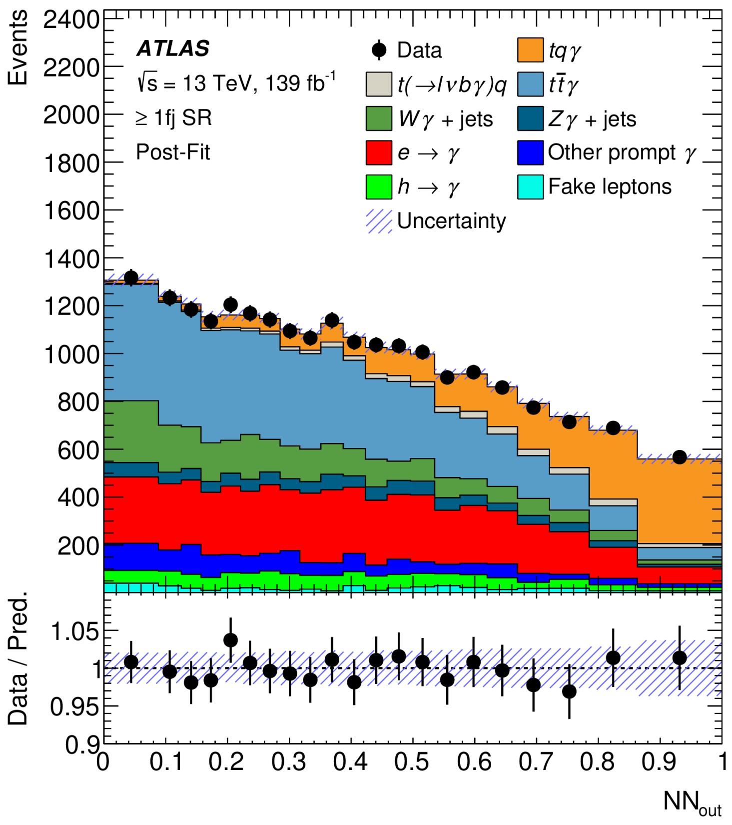
Exactly one lepton

Exactly one b-tagged jet

zero or one forward jet
(2.5 < |η| < 4.5)



- **Photon fakes** estimated using data-driven methods
- Control Regions for main backgrounds: $t\bar{t}\gamma$ and $W\gamma$
- **DNN** used to separate signal from backgrounds
- **Profile likelihood fit** done to extract cross-sections
- Observed (expected) significance: **9.3σ** (6.8σ)
- Modelling systematics dominant



$$\sigma_{tq\gamma} \times B\,(t \to \ell\nu b) = 688 \pm 23\,(\text{stat.})^{+75}_{-71}\,(\text{syst})\ \text{fb}$$

arXiv:2302.01283

$$\sigma_{tq\gamma} \times \mathcal{B}\,(t \to \ell\nu b) + \sigma_{t(\to\ell\nu b\gamma)q} = 303 \pm 9\,(\text{stat})^{+33}_{-32}\,(\text{syst})\ \text{fb}$$

Measurement of top quark mass m_{top} using a template method

- **Full Run2 dataset**
- **Dileptonic top pairs** selected
- Also **single top quark** events

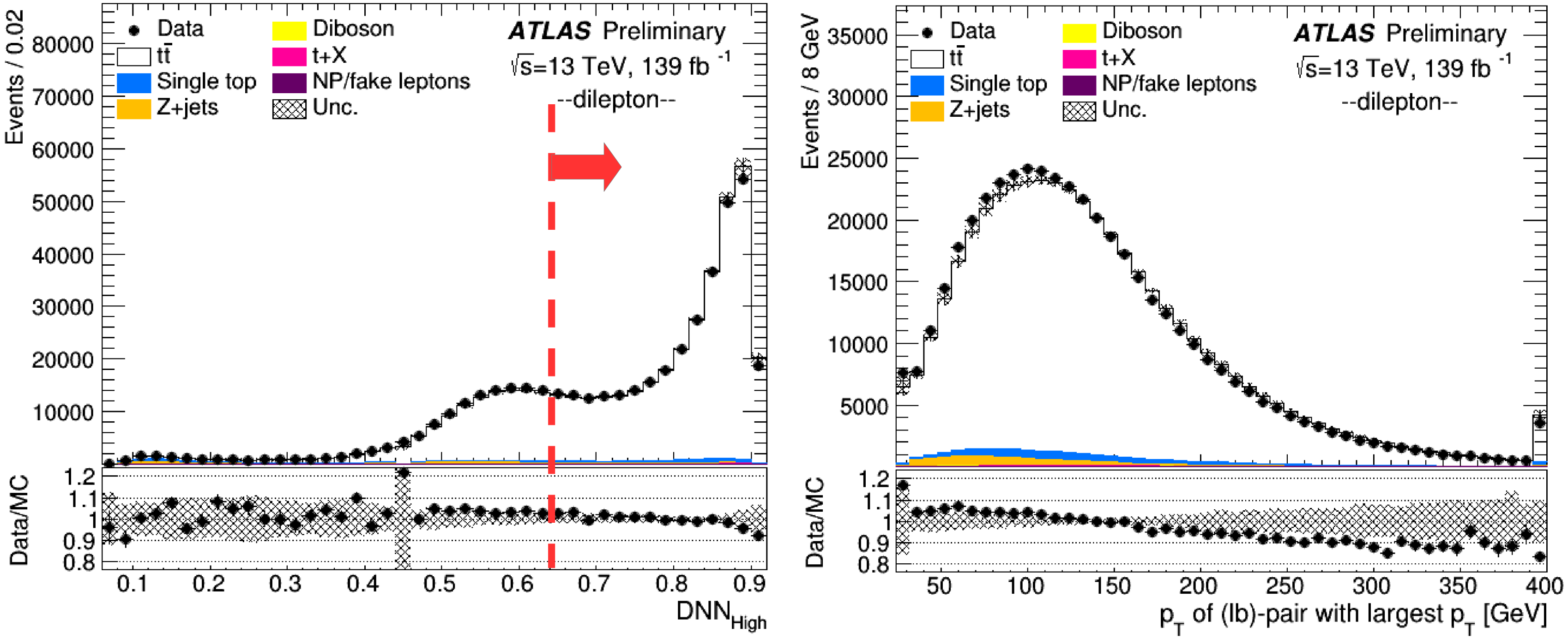
- <u>Improved</u> event reconstruction
  - **Deep Neural Network** used to find correct m_{lb} value → sensitive to top quark mass
- Signal modelling and jet related uncertainties <u>reduced</u>

Event selection

Exactly two leptons

At least two jets

At least 2 b-tagged jets



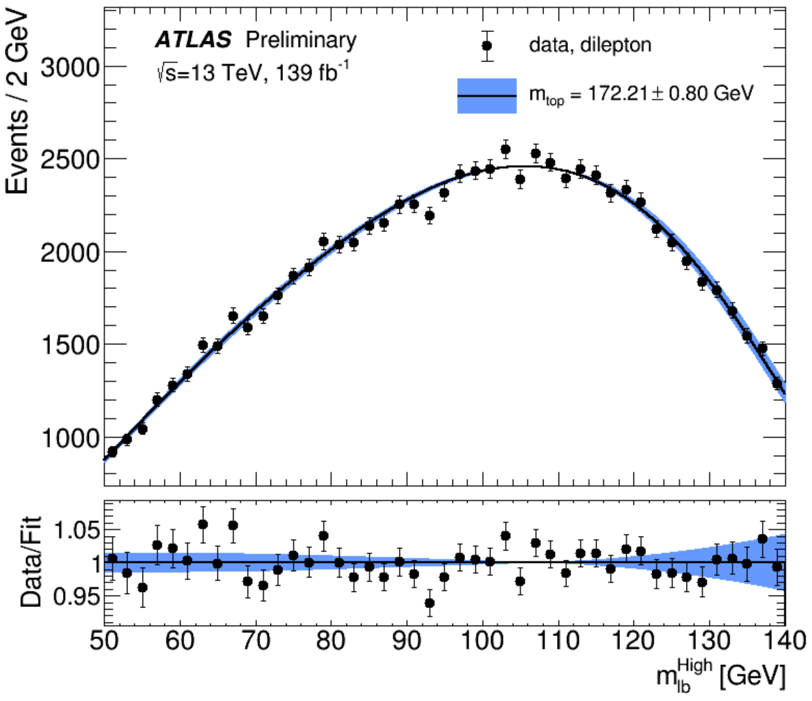
ATLAS-CONF-2022-058

Measurement of top quark mass m_{top} using a template method

Template method

- Distributions constructed for a number of discrete values of top quark mass
- final template function only depends on m_{top}
- Unbinned **maximum-likelihood fit** to data
- fit range optimised to minimise the total uncertainty

- Signal modelling uncertainties significantly improved
- Implemented **gluon radiation** recoiling against the top-quark → likely overestimated the effect



	m_{top} [GeV]
Result	172.21
Statistics	0.20
Method	0.05 ± 0.04
Matrix-element matching	0.40 ± 0.06
Parton shower and hadronisation	0.05 ± 0.05
Initial- and final-state QCD radiation	0.17 ± 0.02
Underlying event	0.02 ± 0.10
Colour reconnection	0.27 ± 0.07
Parton distribution function	0.03 ± 0.00
Single top modelling	0.01 ± 0.01
Background normalisation	0.03 ± 0.02
Jet energy scale	0.37 ± 0.02
b-jet energy scale	0.12 ± 0.02
Jet energy resolution	0.13 ± 0.02
Jet vertex tagging	0.01 ± 0.01
b-tagging	0.04 ± 0.01
Leptons	0.11 ± 0.02
Pile-up	0.06 ± 0.01
Recoil effect	0.39 ± 0.09
Total systematic uncertainty (without recoil)	0.67 ± 0.05
Total systematic uncertainty (with recoil)	0.77 ± 0.06
Total uncertainty (without recoil)	0.70 ± 0.05
Total uncertainty (with recoil)	0.80 ± 0.06

$$m_{top} = 172.21 \pm 0.20(\text{stat}) \pm 0.67(\text{syst}) \pm 0.39(\text{recoil})\ \text{GeV}$$

ATLAS-CONF-2022-058

Evidence for charge asymmetry in $pp \rightarrow t\bar{t}$ production

- Central-forward asymmetry **very small** effect at LHC → $\mathcal{O}(1\%)$

$$A_C^{t\bar{t}} = \frac{N(\Delta|y_{t\bar{t}}|>0) - N(\Delta|y_{t\bar{t}}|<0)}{N(\Delta|y_{t\bar{t}}|>0) + N(\Delta|y_{t\bar{t}}|<0)}$$

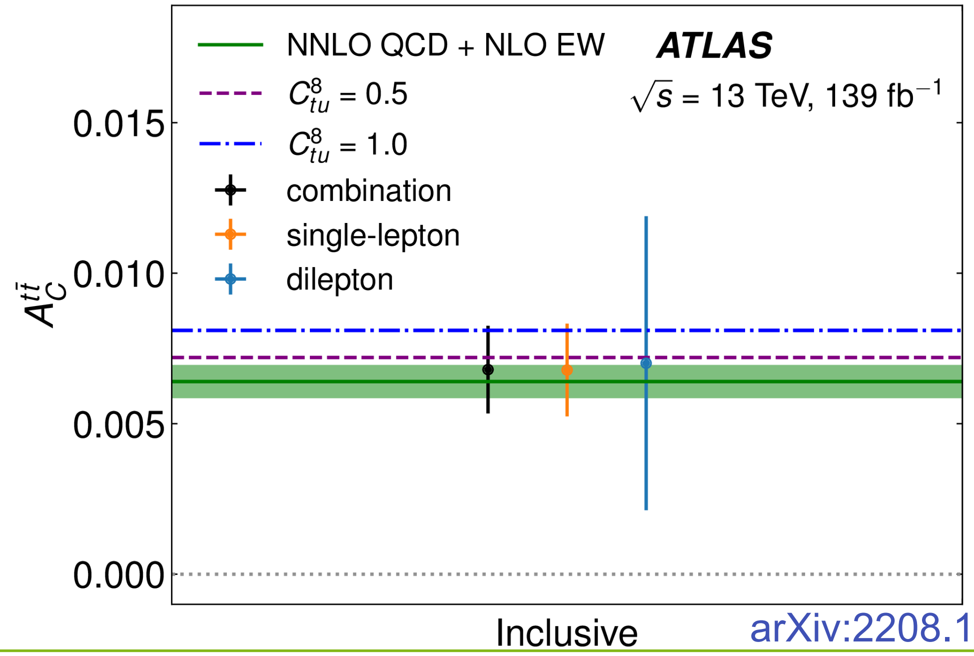
- **Challenging** even with Full Run2 dataset

Analysis Strategy

- **Single** or **dilepton** events selected
  - High pT hadronic top decays also targeted
  - Data-driven methods for fake lepton bkg
- **BDT** used to separate signal from background
- **Fully Bayesian Unfolding** used
  - compare to fixed-order theory prediction

- **Precision** of the combination is dominated by lepton+jets channel
- Overall limited by statistical uncertainties
- Result **4.7σ** from zero → strong evidence

$$A_C^{t\bar{t}} = 0.0068 \pm 0.0015\,(\text{stat} + \text{syst})$$



arXiv:2208.12095

Summary of Top quark measurement highlights at ATLAS

- Many **interesting results** produced by ATLAS
  - **Statistical precision** of full Run2 dataset is exploited
  - Top properties are measured with **exceptional precision**
    → Asymmetry measurements, top quark mass measurement
  - Differential cross-section measurements (tt, ttW, ...)
    help **understanding MC generator predictions**
  - Observation of **rare processes** (four-top-production, tqγ, ...)
- Only small fraction of recent results were presented today
  - Many more can be found here: **ATLAS Top Public results**
- **LHC Run3 has started**
  - Allows for even **higher precision measurements** and stronger limits to BSM theories
  - First measurement of tt and Z cross-section presented today

Thank you for your attention!

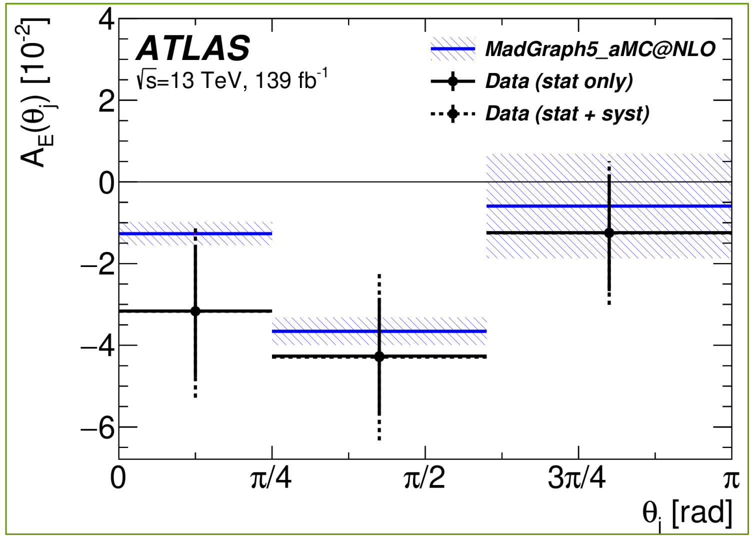
BACKUP

Asymmetry measurements in top quark processes

Energy asymmetry in top pair production

- Highly sensitive to chirality of the top and antitop quark

$$A_E(\theta_j) \equiv \frac{\sigma^{\text{opt}}(\theta_j|\Delta E>0)-\sigma^{\text{opt}}(\theta_j|\Delta E<0)}{\sigma^{\text{opt}}(\theta_j|\Delta E>0)+\sigma^{\text{opt}}(\theta_j|\Delta E<0)}$$



arXiv:2110.05453

Energy asymmetry in ttγ

- Interference between QED ISR and FSR contribute
- Only present if γ is radiated from initial state parton or one of the top quarks

$$A_C = \frac{N(y_t>y_{\bar{t}})-N(y_t<y_{\bar{t}})}{N(y_t>y_{\bar{t}})-N(y_t<y_{\bar{t}})}$$

- Result in agreement with NLO SM prediction

$$A_C = -0.003 \pm 0.024\,(\text{stat}) \pm 0.017\,(\text{syst})$$

arXiv:2212.10552

Energy asymmetry in ttW

- W boson polarizes tt state
- Leptonic charge asymmetry

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

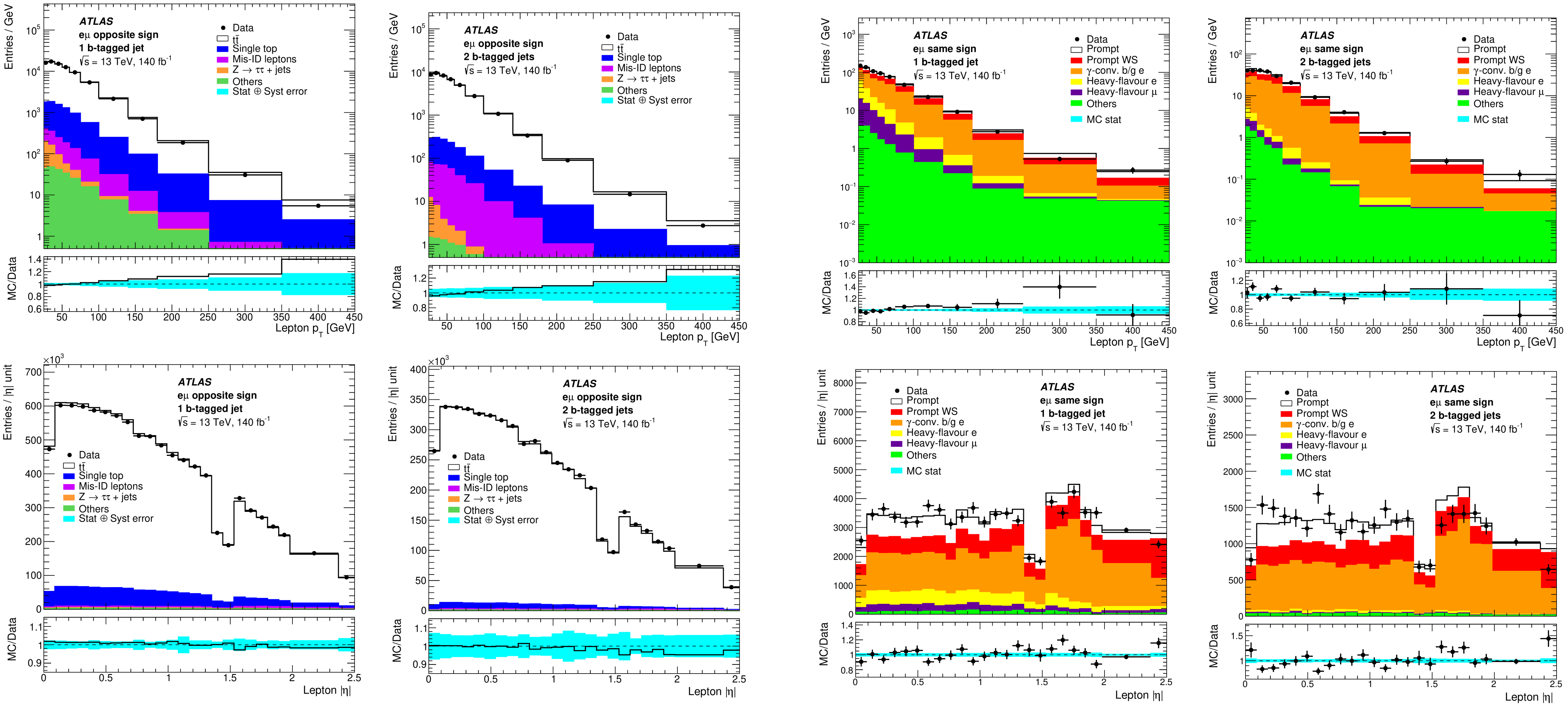
- ℓ-t matching done with BDT
- Reco and particle level
- results consistent with SM prediction

$$A_c^{\ell} = 0.123 \pm 0.136\,(\text{stat}) \pm 0.051\,(\text{syst})$$

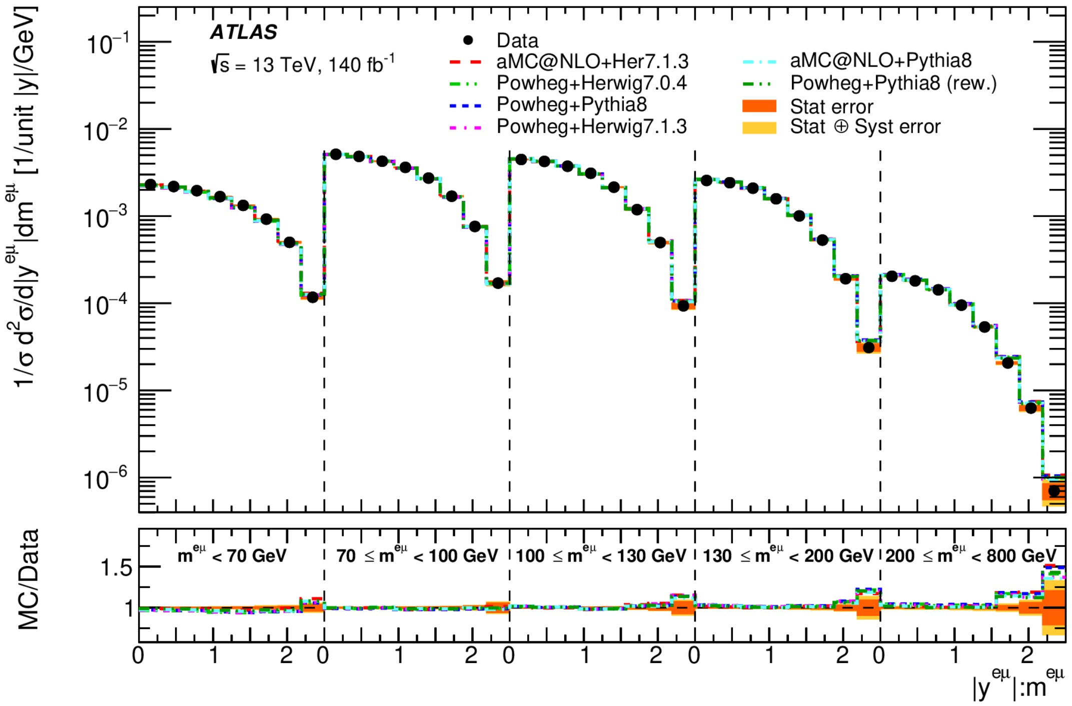
$$A_c^{\ell} = 0.112 \pm 0.170\,(\text{stat}) \pm 0.054\,(\text{syst})$$

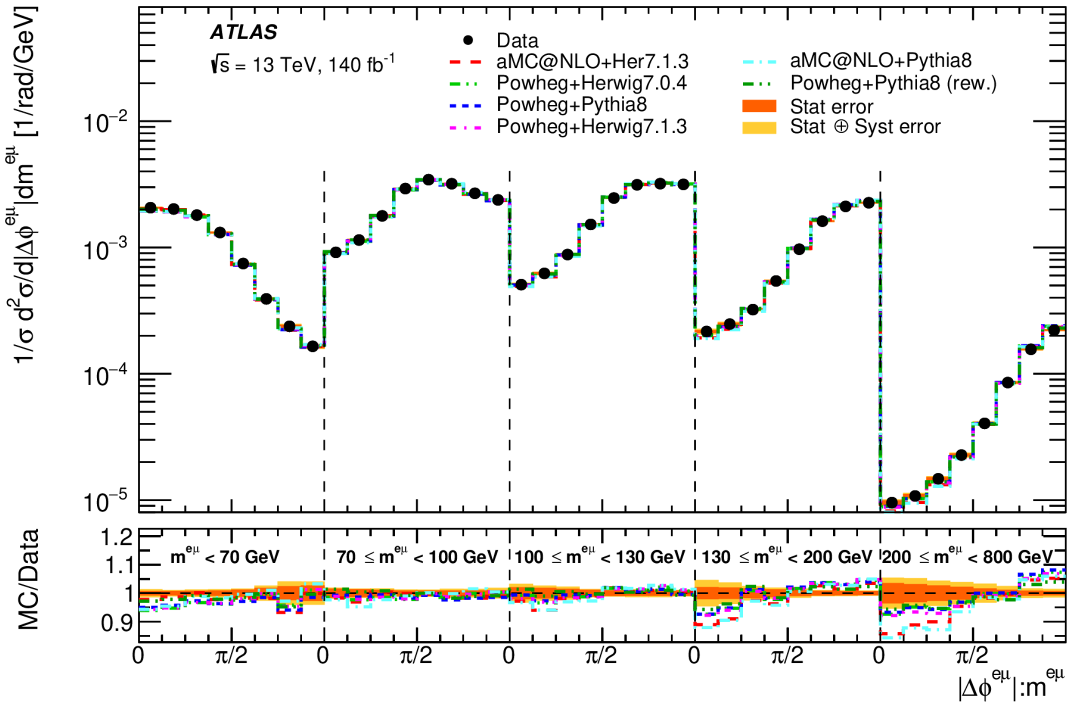
arXiv:2301.04245

Inclusive & differential *tt* production cross-section measurement

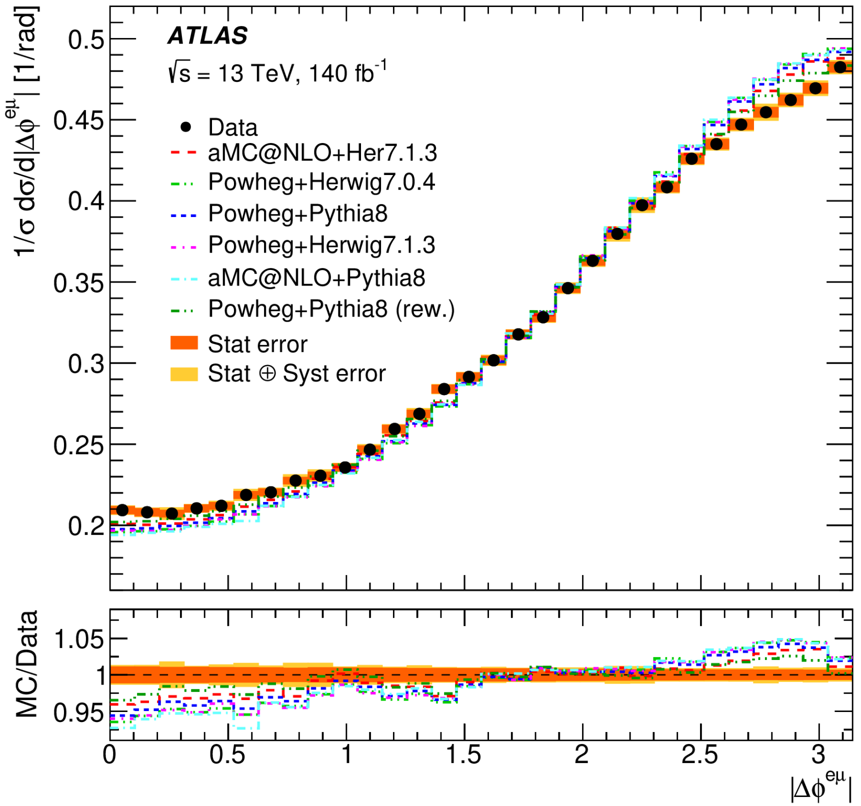


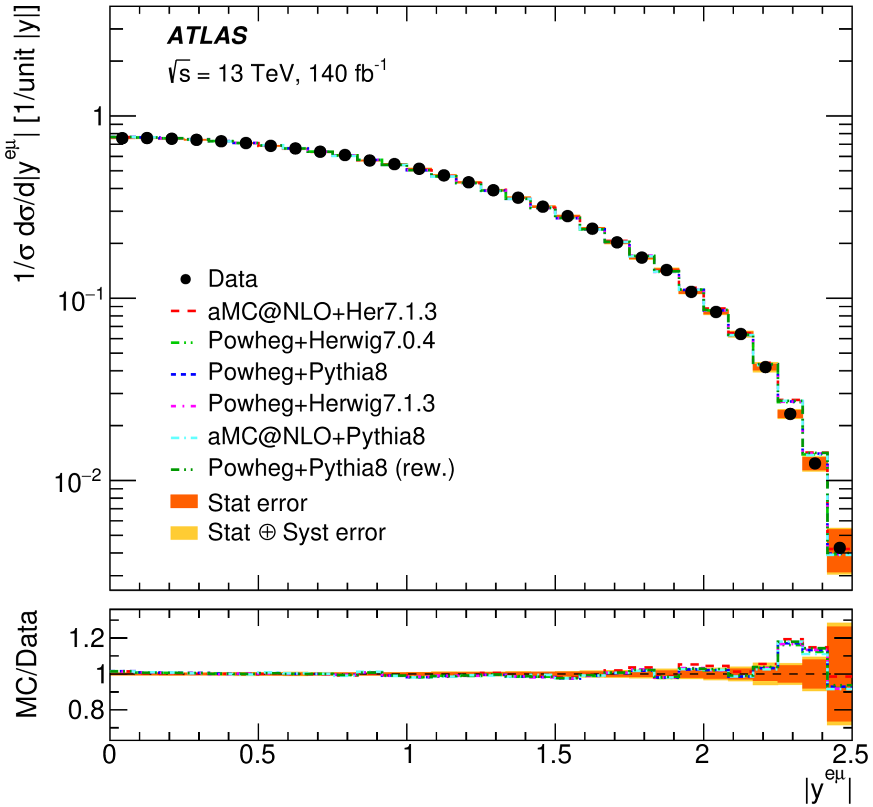
Inclusive & differential *tt* production cross-section measurement





Inclusive & differential *tt* production cross-section measurement





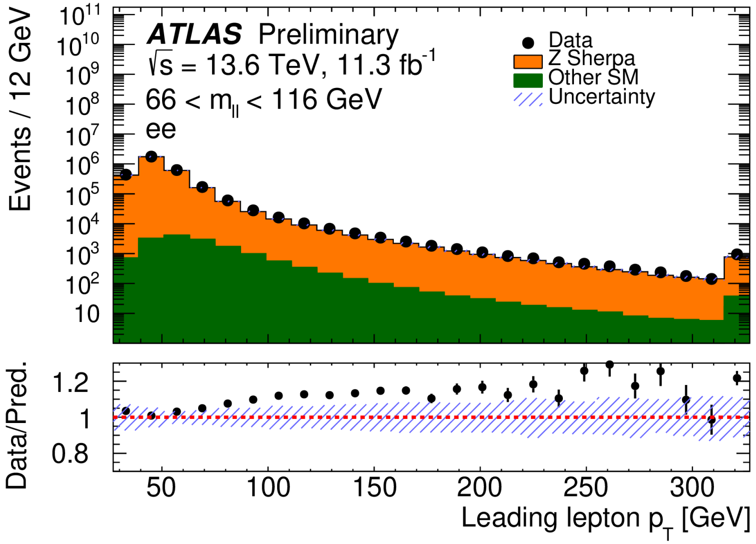
Inclusive & differential *tt* production cross-section measurement

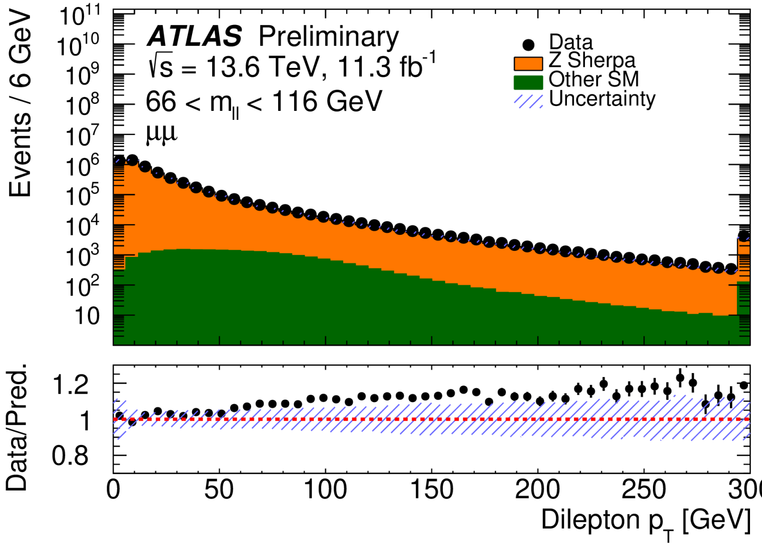
	OS		SS	
	N_1	N_2	N_1	N_2
$t\bar{t}$	418780 ± 130	235937 ± 95	-	-
Single t	42944 ± 77	7295 ± 31	-	-
$Z+$jets	1552 ± 66	96.5 ± 7.5	-	-
Diboson	1406.1 ± 9.5	49.9 ± 1.1	223.0 ± 2.4	10.58 ± 0.30
Charge-misid. lepton	1.90 ± 0.14	0.614 ± 0.061	858 ± 11	364.0 ± 7.1
Misidentified lepton	4880 ± 100	1990 ± 67	2550 ± 57	906 ± 35
Other	1192.6 ± 4.1	807.1 ± 3.3	407.0 ± 1.7	238.3 ± 1.3
Total MC prediction	470760 ± 190	246180 ± 120	4039 ± 58	1519 ± 36
Data events	468450	248560	3995	1501
Data/MC	0.995 ± 0.002	1.010 ± 0.002	0.989 ± 0.021	0.988 ± 0.035

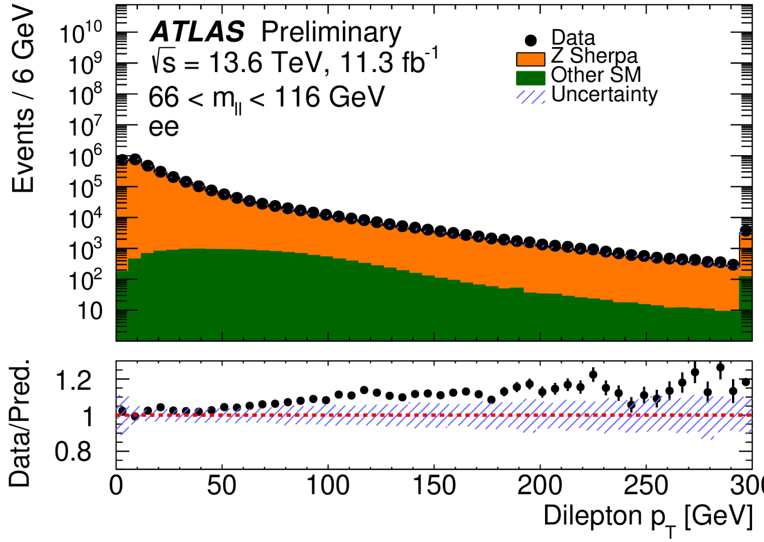
Source of uncertainty	$\Delta\sigma^{\text{fid}}_{t\bar{t}}/\sigma^{\text{fid}}_{t\bar{t}}$ [%]	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ [%]
Data statistics	0.15	0.15
MC statistics	0.04	0.04
Matrix element	0.12	0.16
h_{damp} variation	0.01	0.01
Parton shower	0.08	0.22
$t\bar{t}$ + heavy flavour	0.34	0.34
Top p_{T} reweighting	0.19	0.58
Parton distribution functions	0.04	0.43
Initial-state radiation	0.11	0.37
Final-state radiation	0.29	0.35
Electron energy scale	0.10	0.10
Electron efficiency	0.37	0.37
Electron isolation (in situ)	0.51	0.51
Muon momentum scale	0.13	0.13
Muon reconstruction efficiency	0.35	0.35
Muon isolation (in situ)	0.33	0.33
Lepton trigger efficiency	0.05	0.05
Vertex association efficiency	0.03	0.03
Jet energy scale & resolution	0.10	0.10
b-tagging efficiency	0.07	0.07
$t\bar{t}/Wt$ interference	0.37	0.37
Wt cross-section	0.52	0.52
Diboson background	0.34	0.34
$t\bar{t}V$ and $t\bar{t}H$	0.03	0.03
$Z+$jets background	0.05	0.05
Misidentified leptons	0.32	0.32
Beam energy	0.23	0.23
Luminosity	0.93	0.93
Total uncertainty	1.6	1.8

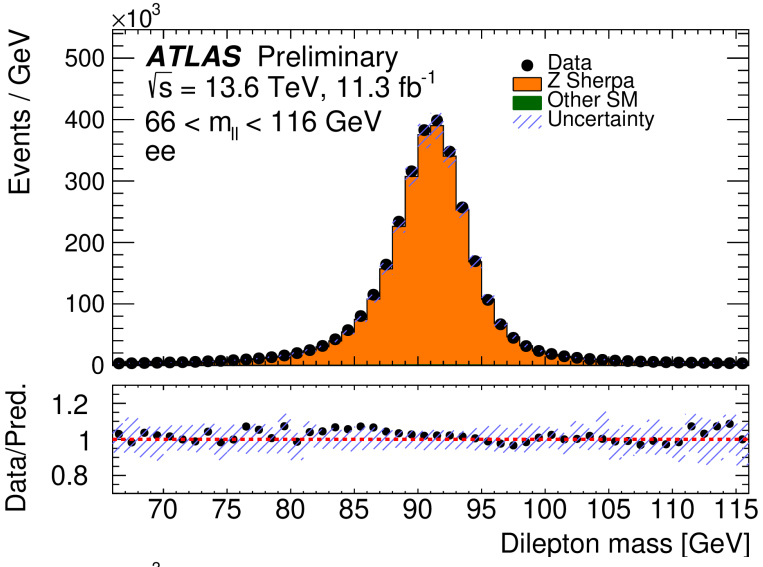
tt and *Z*-boson cross sections and their ratio at $\sqrt{s}$ = 13.6 TeV

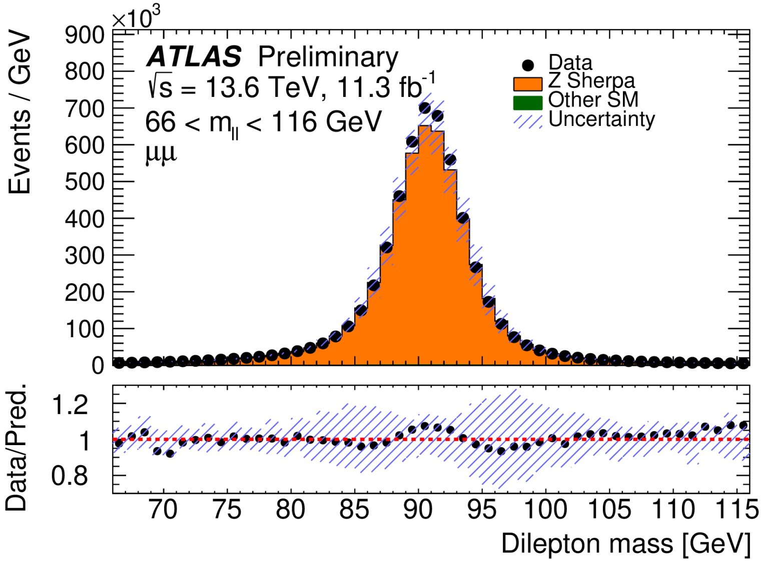
Data/MC control plots in region with same flavour leptons





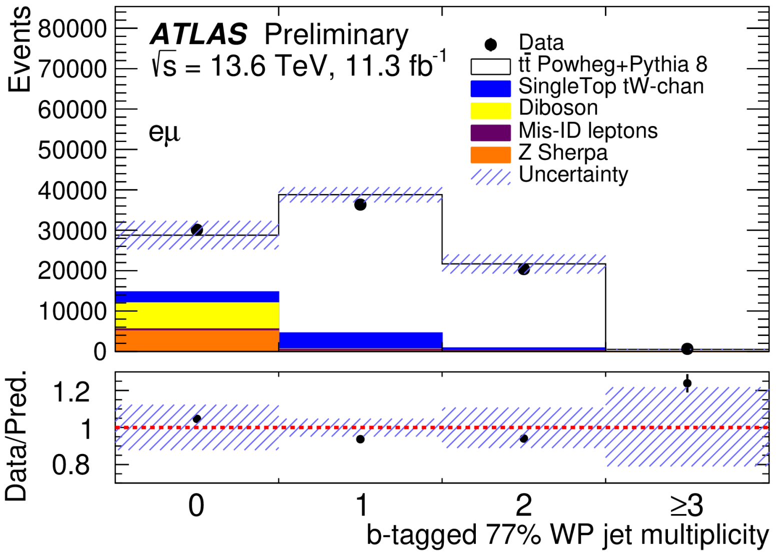


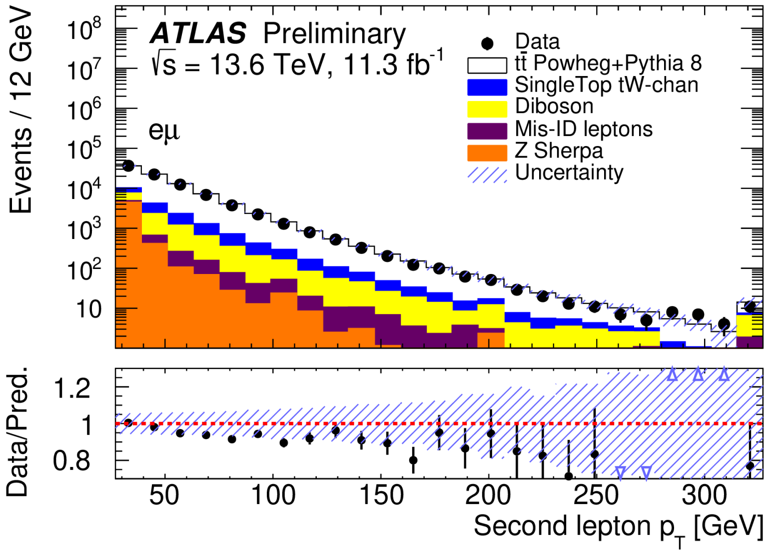


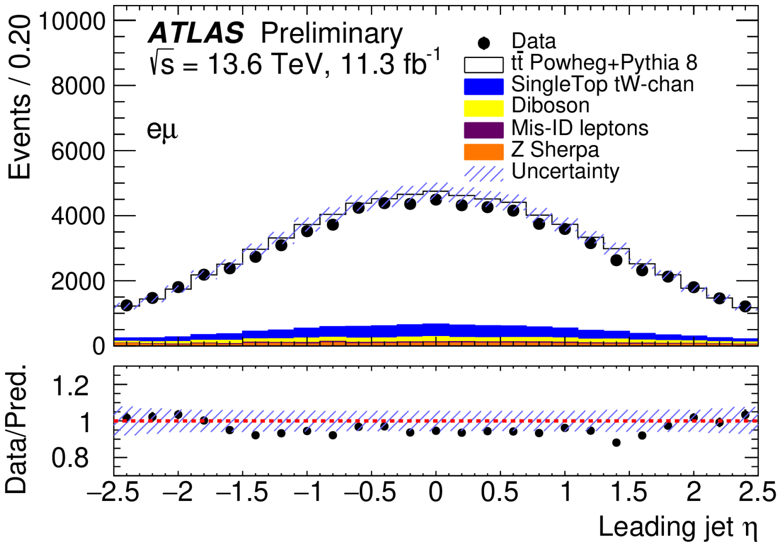


tt and *Z*-boson cross sections and their ratio at √*s* = 13.6 TeV

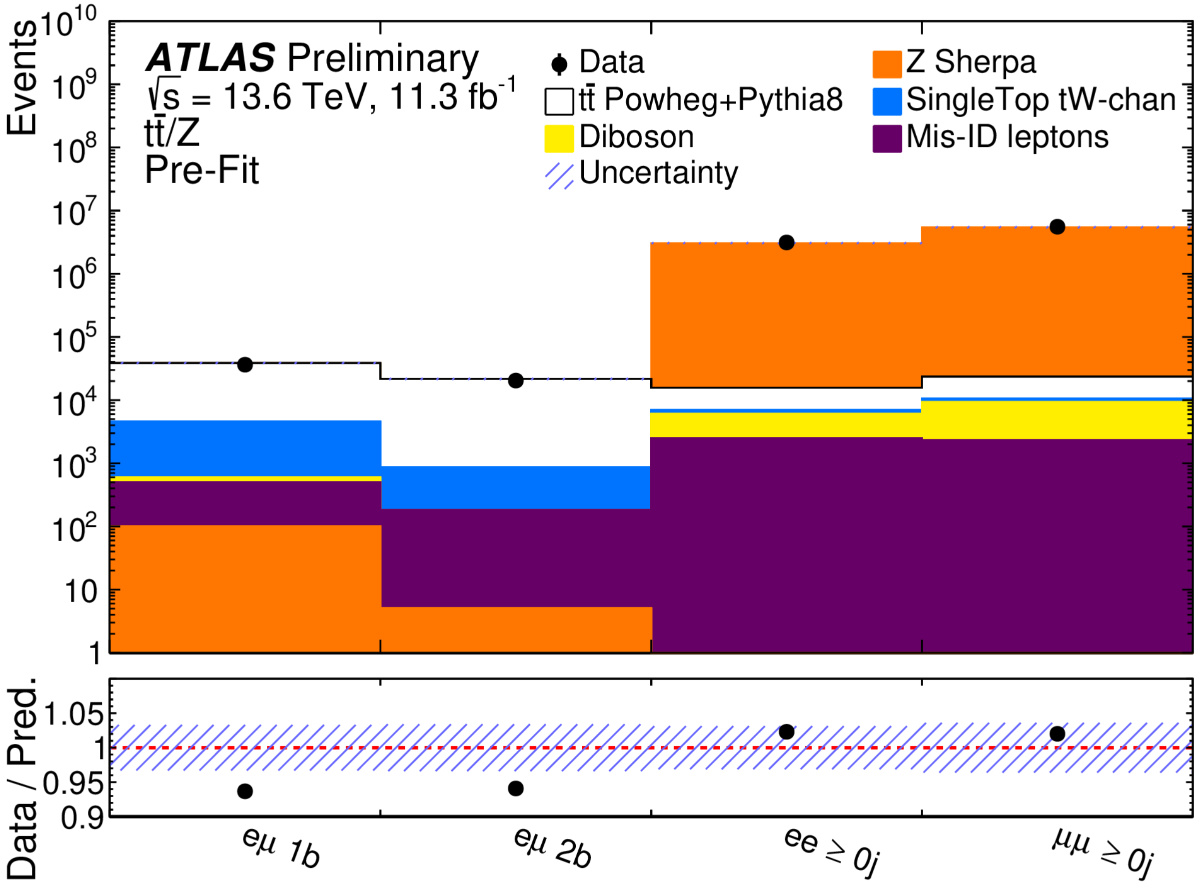
Data/MC control plots
in region with
opposite flavour leptons

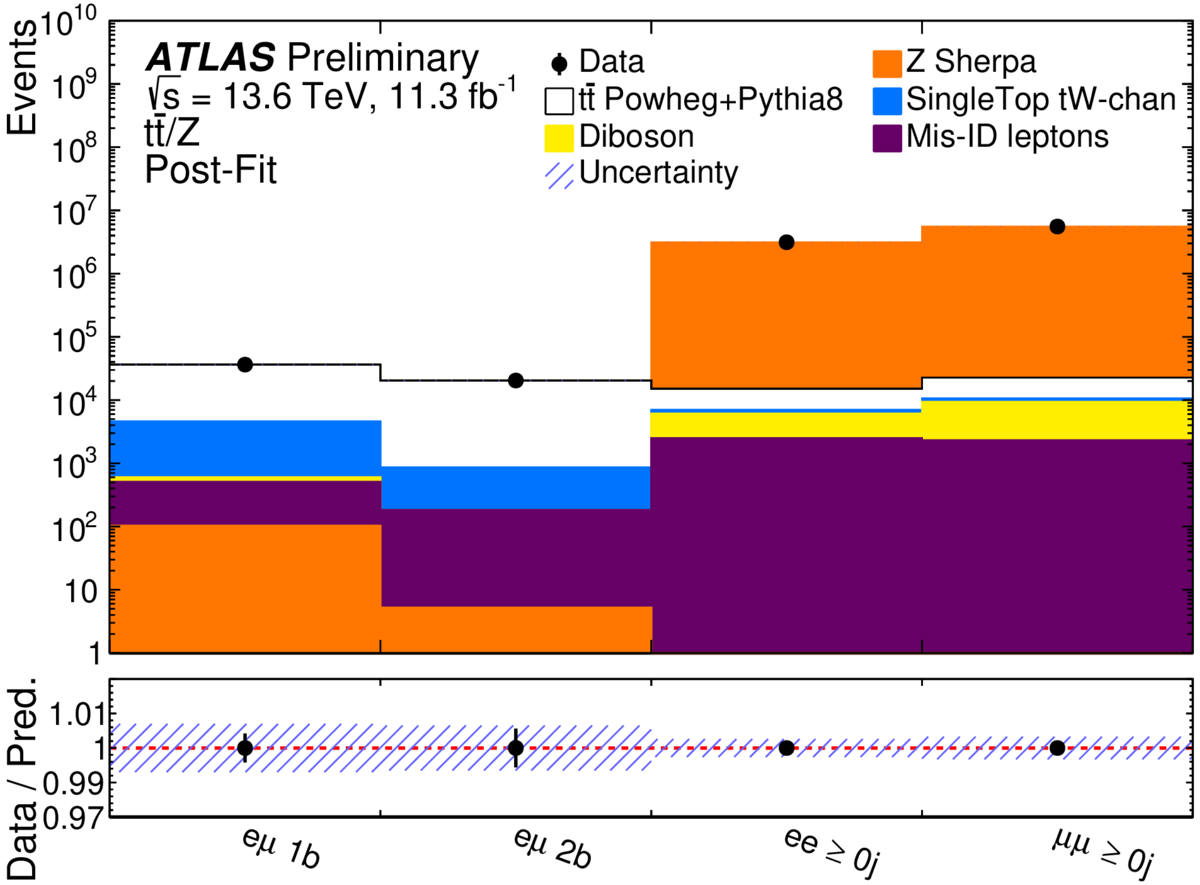






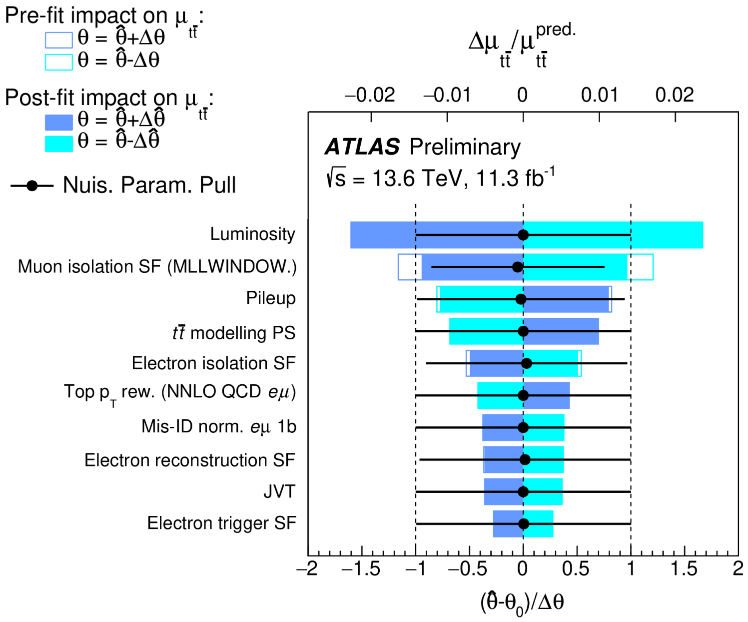
$t\bar{t}$ and Z-boson cross sections and their ratio at $\sqrt{s}$ = 13.6 TeV

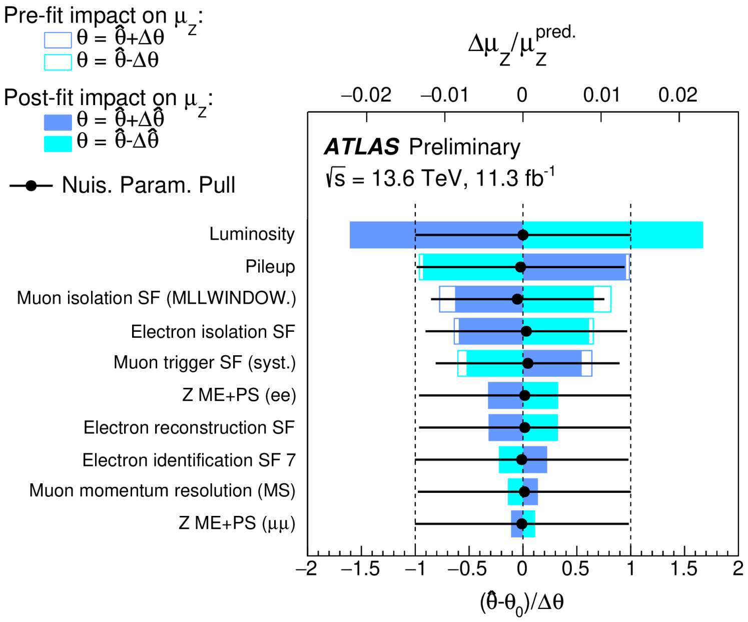


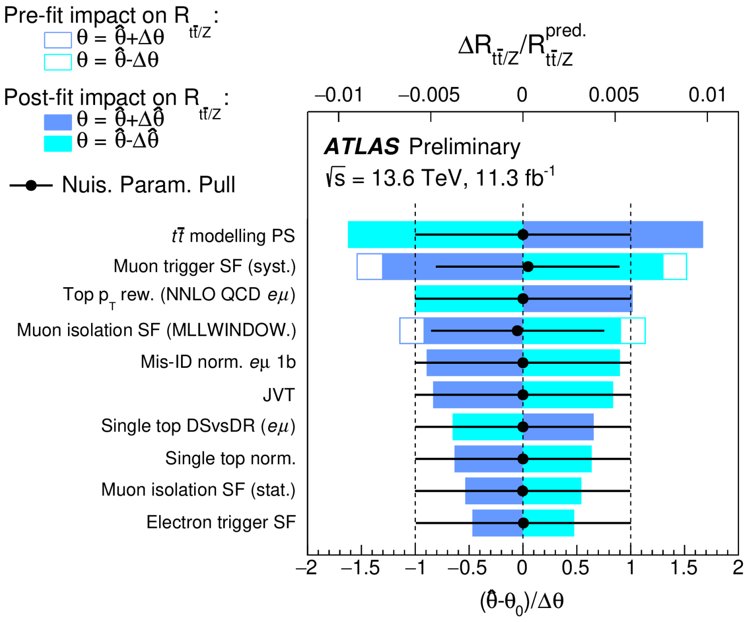


tt and *Z*-boson cross sections and their ratio at √*s* = 13.6 TeV

Ranking plots of
the impact of the
systematic uncertainties
on the POIs







Measurement of total and differential *ttW* cross-section

- **Systematic uncertainties:**
- tt parton shower + modelling of tt+HF (50% uncertainty, uncorrelated between tt+b and tt+c)
- uncertainty for Z-enriched → tt-enriched → taken from validation regions → Internal conversion: 50%, material: 10%
- Mis-ID charge: 10-60%. Increases with electron pT, decreases with |η|: 0.7%, 11% (at low $H_{T,lep}$), reduces to 1% at higher pT
- Charge asymmetry parameter: $$A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

$$A = 0.32 \pm 0.05\,(\mathrm{stat}) \pm 0.03\,(\mathrm{syst})$$

- in very good agreement with theoretical prediction from Sherpa:

$$A = 0.322 \pm 0.003\,(\mathrm{scale}) \pm 0.007\,(\mathrm{PDF})$$

Observation of four-top-quark production

Region	Channel	N_j	N_b	Other selection	Fitted variable
CR Low m_{γ^*}	SS, ee or eμ	$4 \leq N_j < 6$	≥ 1	ℓ_1 or ℓ_2 is from virtual photon (γ^*) decay ℓ_1 and ℓ_2 are not from photon conversion	counting
CR Mat. Conv.	SS, ee or eμ	$4 \leq N_j < 6$	≥ 1	ℓ_1 or ℓ_2 is from photon conversion	counting
CR HF μ	e$\mu\mu$ or $\mu\mu\mu$	≥ 1	$= 1$	$100 < H_T < 300$ GeV $E_T^{miss} > 50$ GeV total charge $= \pm 1$	$p_T^{\ell_3}$
CR HF e	eee or eeμ	≥ 1	$= 1$	$100 < H_T < 275$ GeV $E_T^{miss} > 35$ GeV total charge $= \pm 1$	$p_T^{\ell_3}$
CR $t\bar{t}W^+$+jets	SS, eμ or $\mu\mu$	≥ 4	≥ 2	$\lvert\eta(e)\rvert < 1.5$ when $N_b = 2$: $H_T < 500$ GeV or $N_j < 6$ when $N_b \geq 3$: $H_T < 500$ GeV total charge > 0	N_j
CR $t\bar{t}W^-$+jets	SS, eμ or $\mu\mu$	≥ 4	≥ 2	$\lvert\eta(e)\rvert < 1.5$ when $N_b = 2$: $H_T < 500$ GeV or $N_j < 6$ when $N_b \geq 3$: $H_T < 500$ GeV total charge < 0	N_j
CR 1b(+)	2LSS+3L	≥ 4	$= 1$	ℓ_1 and ℓ_2 are not from photon conversion $H_T > 500$ GeV total charge > 0	N_j
CR 1b(-)	2LSS+3L	≥ 4	$= 1$	ℓ_1 and ℓ_2 are not from photon conversion $H_T > 500$ GeV total charge < 0	N_j
SR	2LSS+3L	≥ 6	≥ 2	$H_T > 500$ GeV	GNN score

Observation of four-top-quark production

- Graph Neural Network
  - uses information from: jets, leptons, missing transverse momentum
  - features of each node: four momenta, jet PCBT, lepton charge, internal labeling of object type
  - edges carry features like angular separation between the objects they connect
  - jet multiplicity is a global feature
  - goal: maximise AUC score
  - comparison with BDT (previously used) done:
    similar separation power but 12% higher expected significance
- Binned profile Likelihood fit: cross section and norm of background and ttW modelling extracted
- Instrumental uncertainties and background modelling uncertainties quite small

Observation of four-top-quark production

	Pre-fit		Post-fit	
	SR	GNN≥0.6	SR	GNN≥0.6
$t\bar{t}W$	130 ± 40	9 ± 4	127 ± 35	12 ± 4
$t\bar{t}Z$	72 ± 15	3.4 ± 1.8	79 ± 15	4.4 ± 2.0
$t\bar{t}H$	65 ± 11	4.6 ± 1.3	68 ± 10	5.0 ± 1.4
QmisID	27 ± 4	1.78 ± 0.26	27 ± 4	1.80 ± 0.24
Mat. Conv.	16.5 ± 2.3	0.73 ± 0.25	30 ± 8	1.4 ± 0.5
HF e	3.1 ± 1.0	0.4 ± 0.5	2.3 ± 2.4	0.3 ± 0.4
HF μ	7.1 ± 1.2	0.31 ± 0.15	9 ± 4	0.41 ± 0.22
Low m_{γ^*}	14.1 ± 2.0	0.52 ± 0.19	15 ± 5	0.56 ± 0.22
Others	47 ± 11	3.9 ± 1.2	50 ± 10	4.3 ± 1.2
$t\bar{t}t$	2.9 ± 0.9	1.5 ± 0.5	2.9 ± 0.9	1.5 ± 0.5
Total bkg	390 ± 50	26 ± 5	412 ± 21	32 ± 4
$t\bar{t}t\bar{t}$	38 ± 4	25.2 ± 3.2	69 ± 15	45 ± 10
Total	430 ± 50	51 ± 7	480 ± 19	77 ± 8
Data	482	83	482	83

Uncertainty source	$\Delta\sigma$ [fb]		$\Delta\sigma/\sigma$[%]	
Signal modelling				
$t\bar{t}t\bar{t}$ generator choice	+3.7	−2.7	+17	−12
$t\bar{t}t\bar{t}$ parton shower model	+1.6	−1.0	+7	−4
Other $t\bar{t}t\bar{t}$ modelling	+0.8	−0.5	+4	−2
Background modelling				
$t\bar{t}H$+jets modelling	+0.9	−0.7	+4	−3
$t\bar{t}W$+jets modelling	+0.8	−0.8	+4	−3
$t\bar{t}Z$+jets modelling	+0.5	−0.4	+2	−2
Other background modelling	+0.5	−0.4	+2	−2
Non-prompt leptons modelling	+0.4	−0.3	+2	−2
$t\bar{t}t$ modelling	+0.3	−0.2	+1	−1
Charge misassignment	+0.1	−0.1	+0	−0
Instrumental				
Jet flavour tagging (b-jets)	+1.1	−0.8	+5	−4
Jet uncertainties	+1.1	−0.7	+5	−3
Jet flavour tagging (light-flavour jets)	+0.9	−0.6	+4	−3
Jet flavour tagging (c-jets)	+0.5	−0.4	+2	−2
Simulation sample size	+0.4	−0.3	+2	−1
Other experimental uncertainties	+0.4	−0.3	+2	−1
Luminosity	+0.2	−0.2	+1	−1
Total systematic uncertainty	+4.6	−3.4	+20	−16
Statistical				
Intrinsic statistical uncertainty	+4.2	−3.9	+19	−17
$t\bar{t}W$+jets normalisation and scaling factors	+1.2	−1.1	+6	−5
Non-prompt leptons normalisation (HF, Mat. Conv., Low m_{γ^*})	+0.4	−0.3	+2	−1
Total statistical uncertainty	+4.7	−4.3	+21	−19
Total uncertainty	+6.6	−5.5	+29	−25

Observation of four-top-quark production

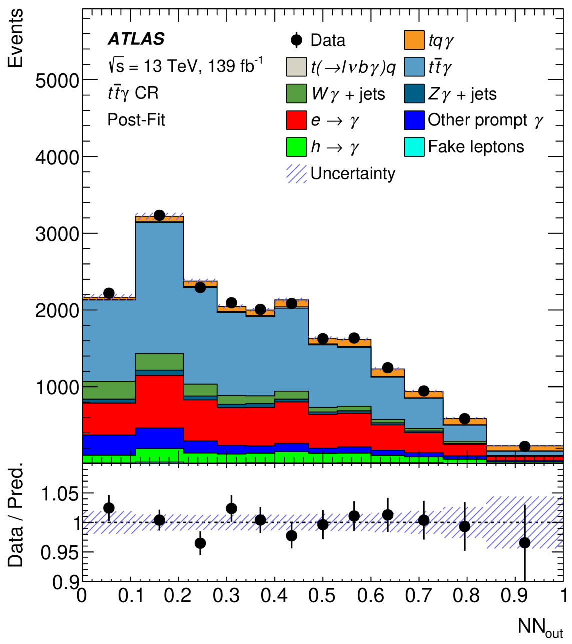
Processes	95% CL cross section interval [fb]	
	$\mu_{t\bar{t}t\bar{t}} = 1$	$\mu_{t\bar{t}t\bar{t}} = 1.9$
$t\bar{t}t$	[4.7, 60]	[0, 41]
$t\bar{t}tW$	[3.1, 43]	[0, 30]
$t\bar{t}tq$	[0, 144]	[0, 100]

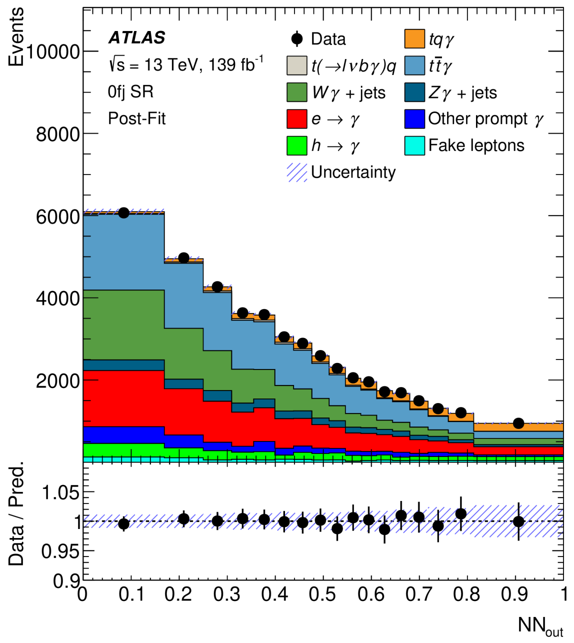
- Interpretations
- 4 top cross-section can be parametrised by two parameters:
  - Yukawa coupling strength modifier κ (ratio of measured Yukawa coupling/SM prediction)
  - CP-mixing angle α (in SM: α=0, CP-even; α=90 → CP-odd)
- EFT operators
  - 4 top yield in each bin of GNN output parametrised as a quadratic function of the coefficient to the corresponding operator
  - fit to data (assumption: only one operator contributes to the 4top cross section, te others are fixed to zero (SM))
- Higgs oblique parameter
  - self-energy corection term applied to electroweak propagators on the SM
  - affects of-shell Higgs interactions

Observation of single-top-quark production with a photon

- Statistical analysis: profile-likelihood fit
- simultaneously in SRs and CRs
  → NN output used in SRs and CR ttγ, inclusive event yield used in CR Wγ
  - normalisations of both background are free floating in the fit
  - Fitted normalisations are consistend with nominal prediction (13/14% ttγ, 20/17% Wγ)

- Systematic Uncertainties: [parton (particle)]
- largest: ttγ modelling 5.5% (5.5%)
- limited number of MC events from background processes 3.5% (4.6%)
- limited number of MC events for tqγ 3.3% (3.0%)
- modelling of top decay products with photon 1.9% (3.3%) -> fixed to SM expectation in particle-level fit within the uncertainties
- modelling of tt: 2.4% (2.3%)

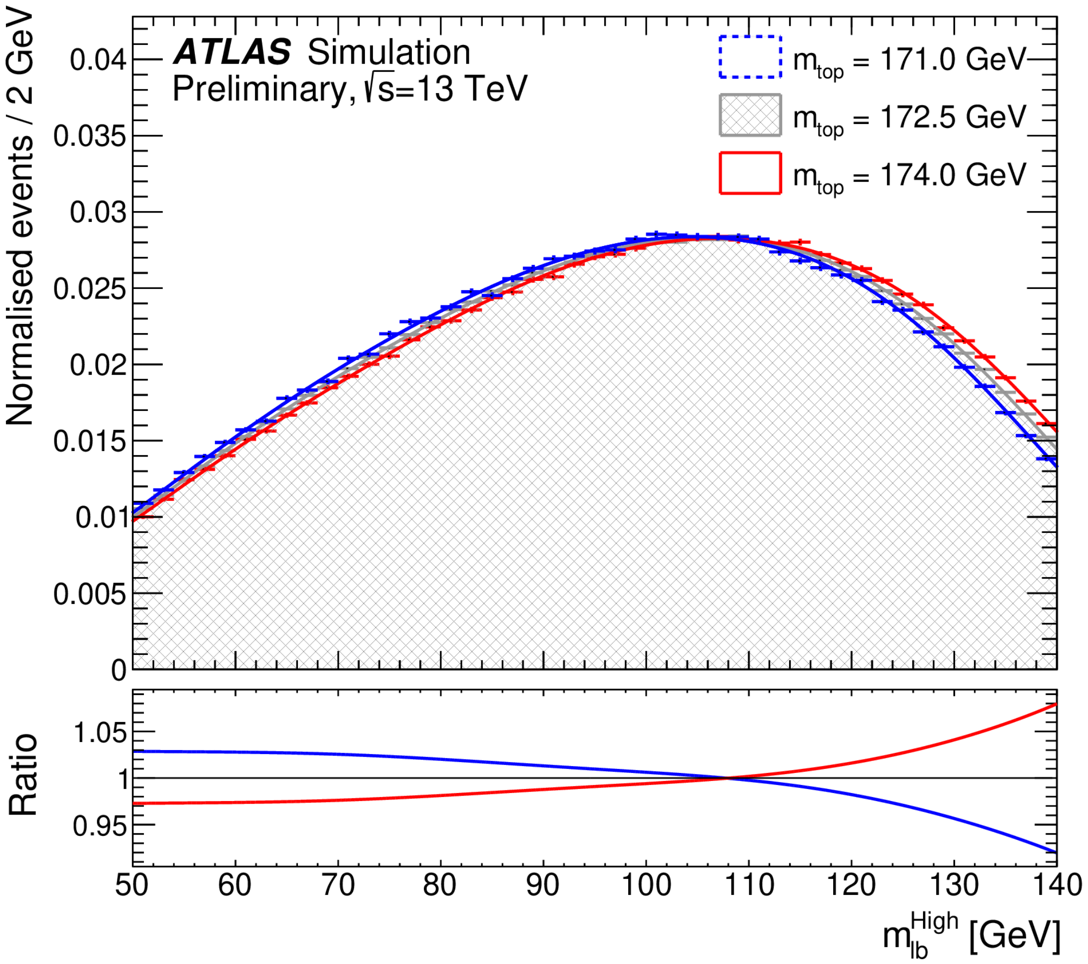


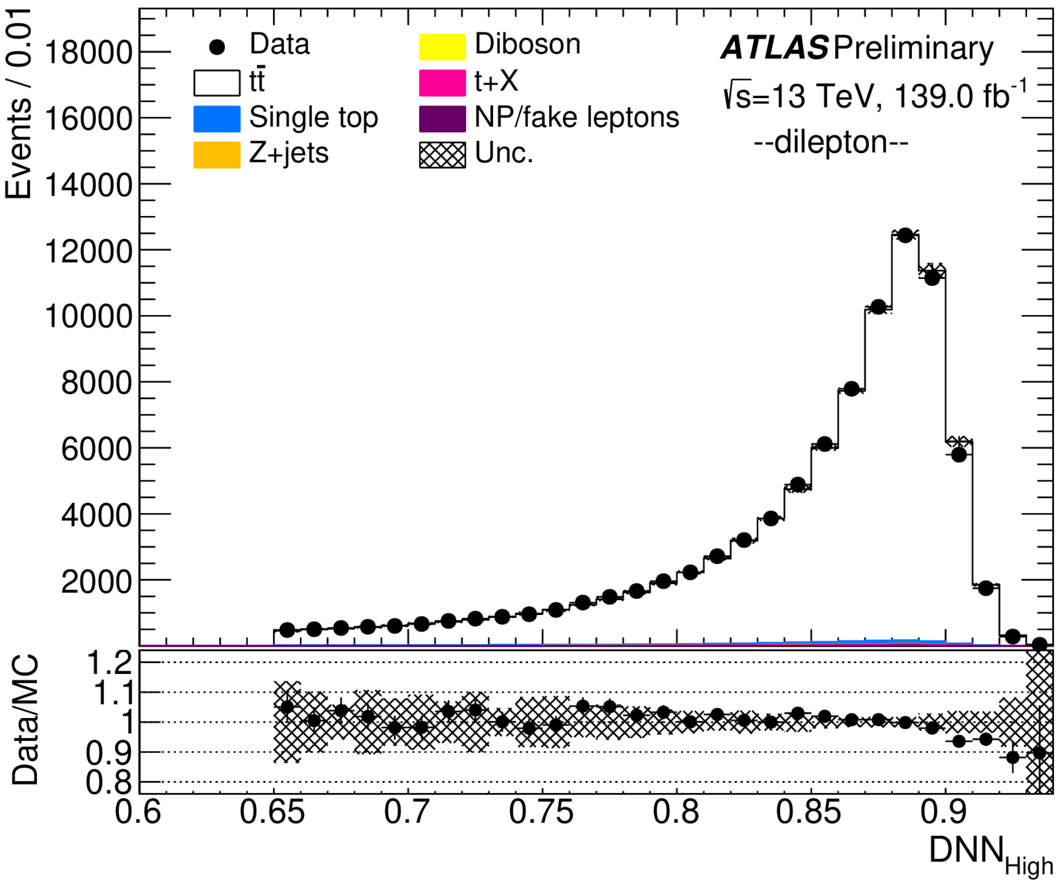


Measurement of top quark mass m_{top} using a template method

- Recoil effect (In Powheg: b-quarks are produced in the decay of a coloured resonance, the top quark. After the emission of the first gluon, any following gluon radiation recoils against the b-quark. Due to the more collinear radiation from a coloured particle, the recoil-to-colour scheme results in too small out-of-cone radiation. This affects the b-jets shape and results in narrower reconstructed top-mass distributions. A more recent setup allows the top quark itself to be the recoiler for the gluon radiation. Pythia authors made this available. With this recoil scheme, more out-of-cone radiation is possible, changing the shape of the b-jets in the event. While it is theoretically the most consistent setup, the recoil-to-top simulation used in this measurement likely overestimates the effect, since no dedicated tune for this sample has been performed yet. The full difference between the top-quark values extracted from pseudo-data sets using these two recoil settings is used as an additional uncertainty, and is quoted separately in the final result.)
- The measurement presented here uses the template method and thus the fitted mtop corresponds to the mass parameter in the ATLAS signal generator setup. This ensures an unambiguous definition of the fitted m_{Top} and eases the combination with previous results.

Measurement of top quark mass m_{top} using a template method

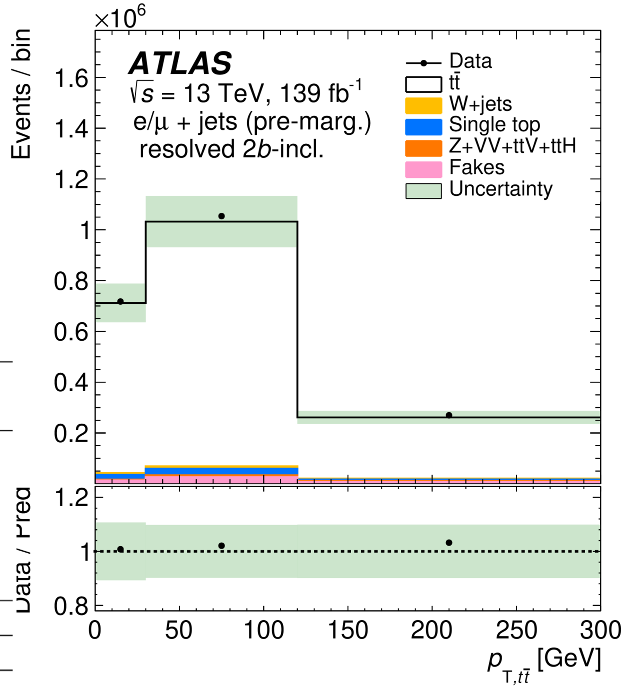


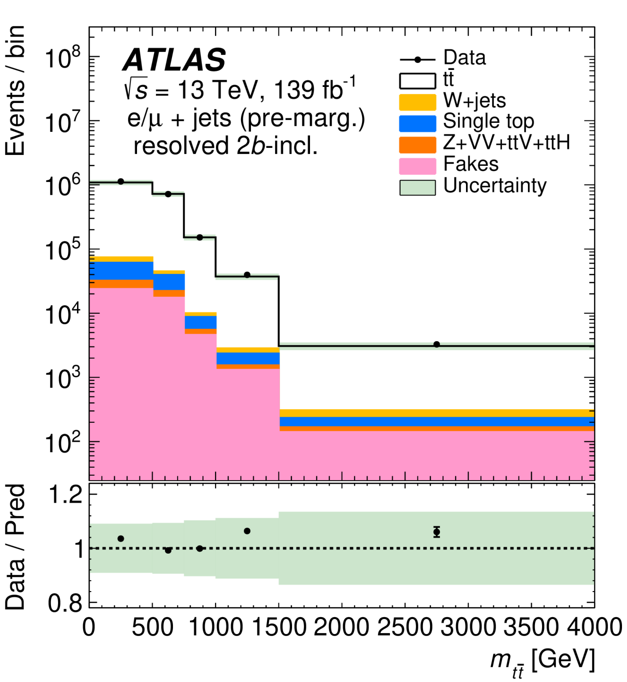


Evidence for charge asymmetry in $pp \rightarrow tt$ production

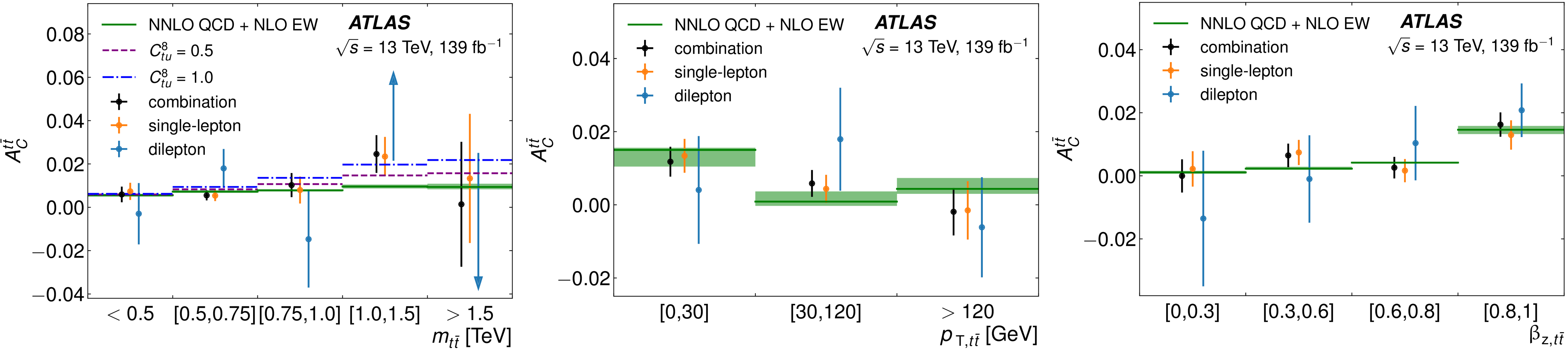
- boosted regions:
  - aim: identify one high p_T hadronic top quark decay and at least one smallR jet close to lepton ($\Delta R < 1.5$)
  - at least one largeR jet as the hadronically decaying top quark candidate
    → top tagging algorithm, 80% efficiency operating point.
  - additional requirements as tops are expected to be back to back
    → leading largeR jet p_T = top quark p_T
- The MC prediction's overestimation of the yield by about 20% in the single-lepton boosted regions is confirmed by differential cross-sections measurements!

Process:	Single-lepton resolved 1b-excl.	Single-lepton resolved 2b-incl.	Single-lepton boosted 1b-excl	Single-lepton boosted 2b-incl.
$t\bar{t}$	1 540 000 ± 140 000	1 870 000 ± 170 000	50 000 ± 12 000	74 000 ± 18 000
Single top	90 000 ± 11 000	51 000 ± 8 000	3 600 ± 1 100	3 000 ± 1 100
W+jets	180 000 ± 100 000	20 000 ± 9 000	8 900 ± 2 600	1 600 ± 500
$Z + VV + t\bar{t}X$	48 000 ± 25 000	14 000 ± 7 000	2 400 ± 1 200	1 400 ± 700
Fake	90 000 ± 50 000	47 000 ± 24 000	3 000 ± 1 500	2 300 ± 1 200
Total Prediction	1 940 000 ± 190 000	2 010 000 ± 180 000	68 000 ± 14 000	83 000 ± 18 000
Data	1 964 127	2 041 063	54 750	66 571

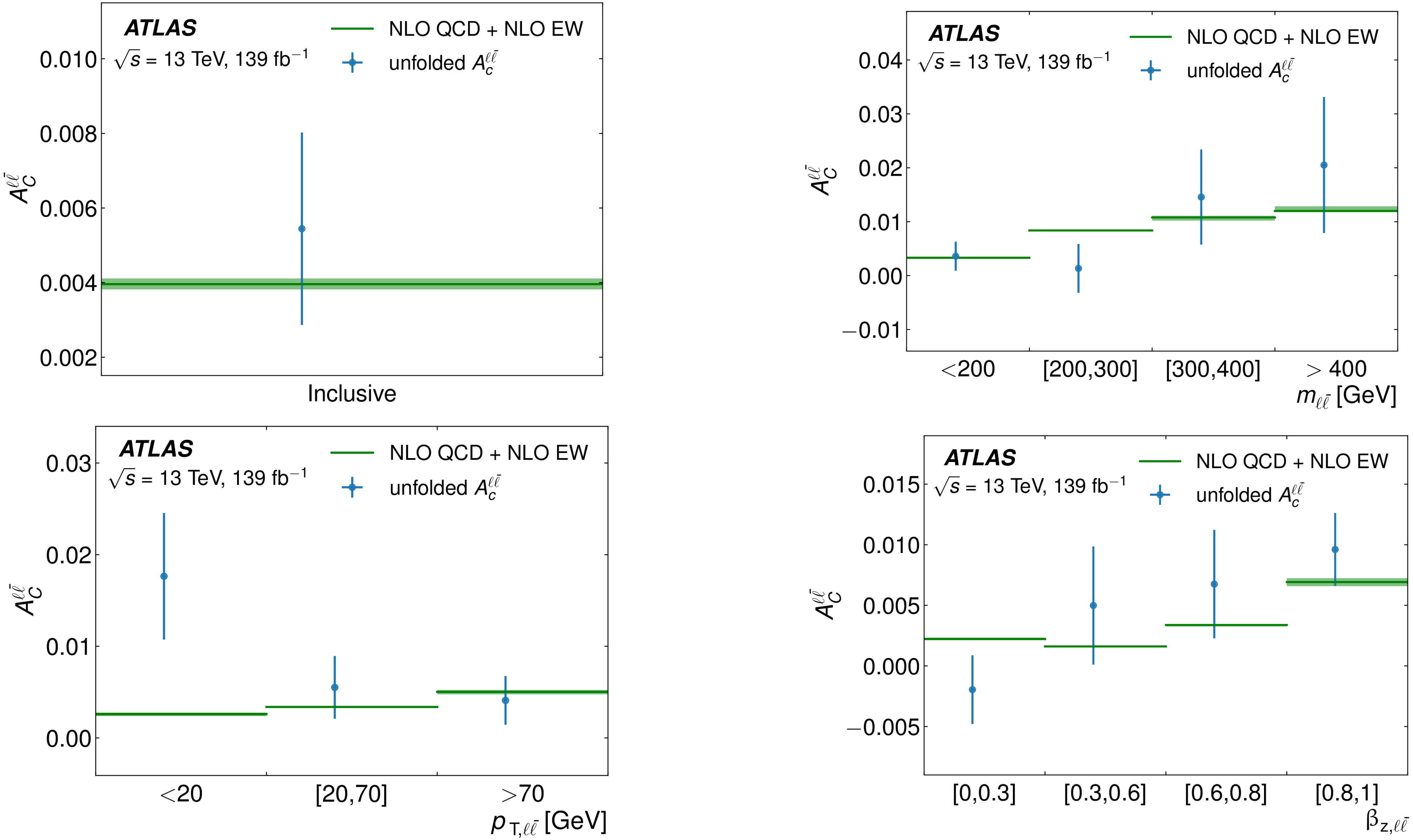




Evidence for charge asymmetry in $pp \to tt$ production



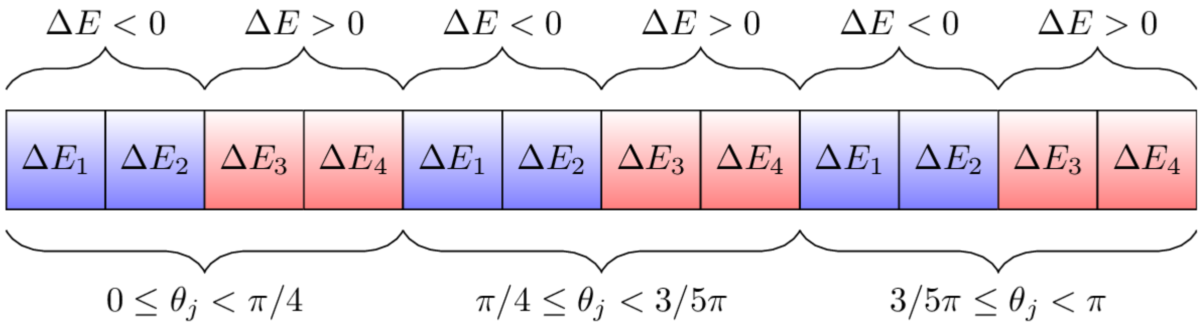
Evidence for charge asymmetry in $pp \to tt$ production

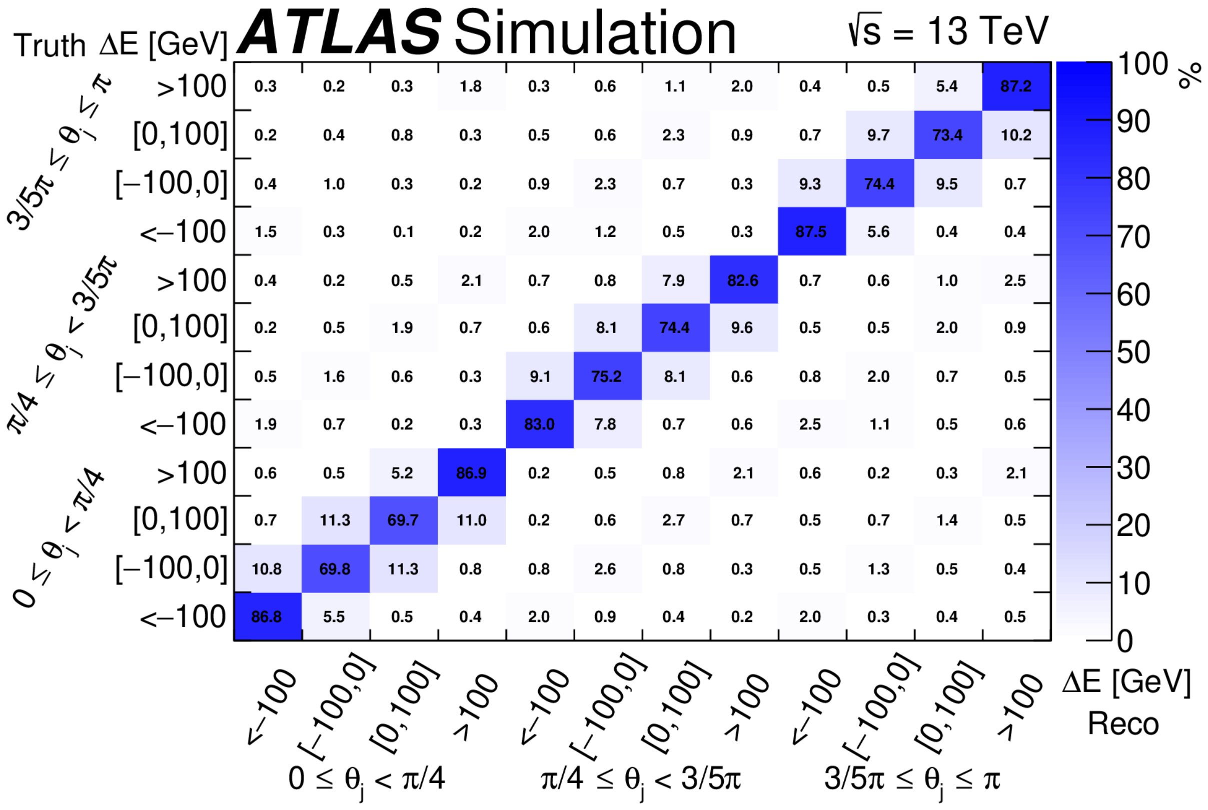


Energy asymmetry in top quark pair + jet production

- To measure the energy asymmetry the difference of the top and antitop energies $\Delta E = E_t - E_{\bar{t}}$ is determined as a function of the jet angle θ_j. Both ΔE and θ_j are defined in the ttj rest frame, which corresponds to the partonic centre-of-mass frame in tree-level processes. The angle θ_j is defined as the angle between the jet direction and the positive z-axis, i.e., the direction of parton p1 in the process p1 p 2 → ttj
- The energy asymmetry is mainly generated in the partonic process qg → ttq. The outgoing quark-jet is boosted in the direction of the incoming valence quark. This boost is reflected in the rapidity of the ttj system in the laboratory frame, y_{ttj}.
- By combining 'forward' events having y > 0 with 'backward' events having y < 0 in the optimised cross section $\sigma^{opt}(\theta_j)$, the statistical sensitivity to the energy asymmetry is optimised
- The analysis selects events with a high-p_T jet, one leptonic W decay from one of the top quarks and one hadronic W decay from the other top quark
- The decay products of the hadronically decaying top are required to be collimated in one large-radius jet, as is characteristic of the boosted regime.
- By focusing on this boosted regime, the additional jet is easily distinguished from the top-quark decay products. Moreover, the energy asymmetry increases with the transverse momentum of the associated jet

Energy asymmetry in top quark pair + jet production

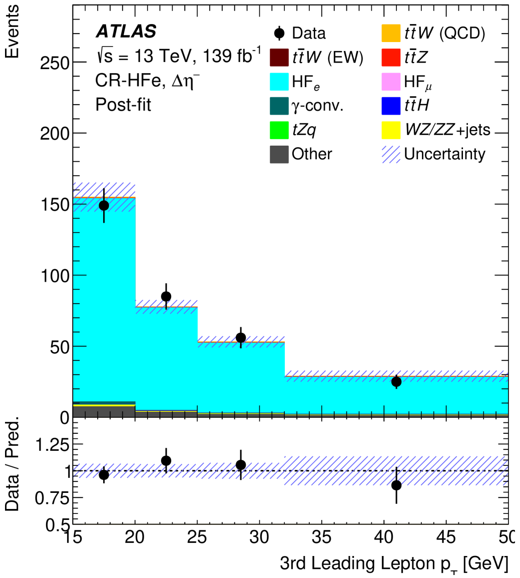


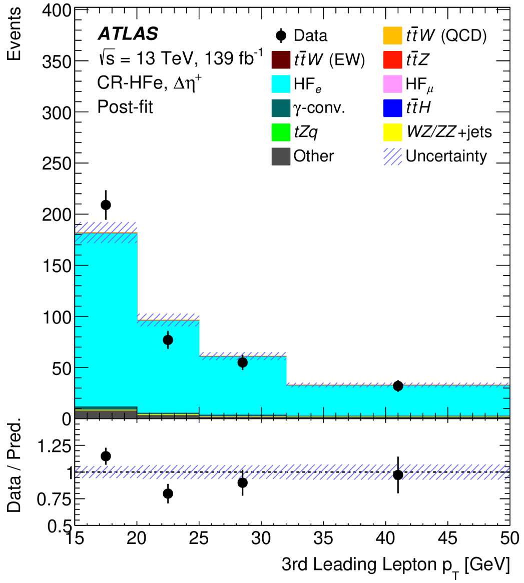


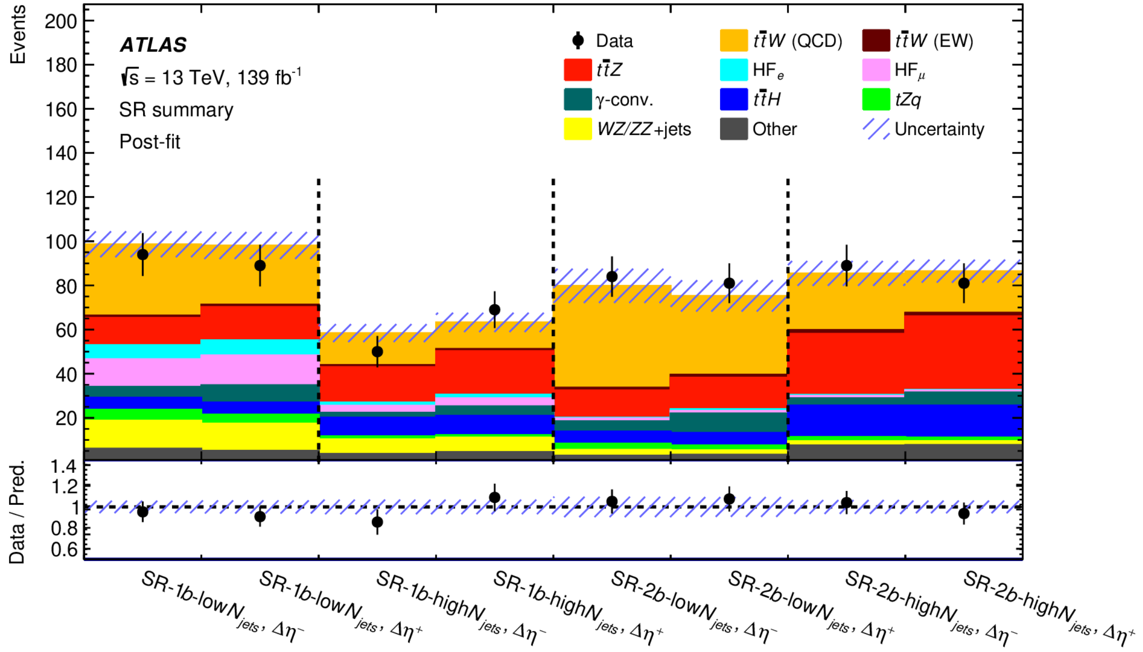
Energy asymmetry in ttW

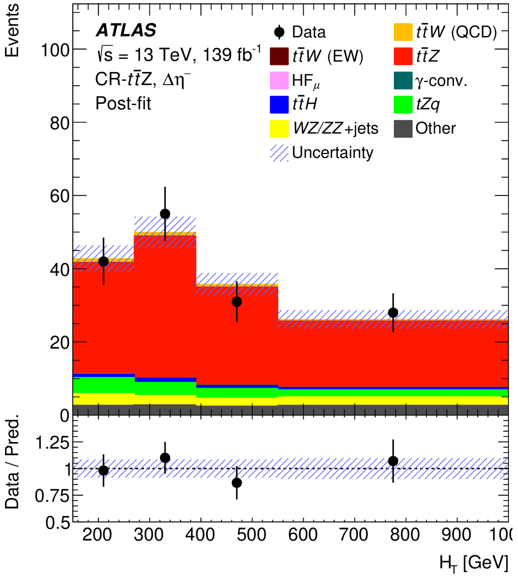
	Preselection			
N_ℓ ($\ell = e/\mu$)	$= 3$			
p_T^ℓ ($1^{st}/2^{nd}/3^{rd}$)	≥ 30 GeV, ≥ 20 GeV, ≥ 15 GeV			
Sum of lepton charges	± 1			
$m_{\ell\ell}^{OSSF}$	≥ 30 GeV			
	Region-specific requirements			
	SR-1b-lowN_{jets}	**SR-1b-highN_{jets}**	**SR-2b-lowN_{jets}**	**SR-2b-highN_{jets}**
N_{jets}	$[2, 3]$	≥ 4	$[2, 3]$	≥ 4
$N_{b\text{-jets}}$	$= 1$	$= 1$	≥ 2	≥ 2
E_T^{miss}	≥ 50 GeV	≥ 50 GeV	–	–
$N_{Z\text{-cand.}}$	$= 0$			
Lepton criteria	TTT			
e/γ ambiguity-cuts	satisfy all			
	CR-$t\bar{t}Z$	**CR-HF$_e$**	**CR-HF$_\mu$**	**CR-γ-conv**
$\ell^{1st/2nd/3rd}$	$\ell\ell\ell$	$\ell\ell e$	$\ell\ell\mu$	$\ell\ell e$, $\ell e\ell$, $e\ell\ell$
N_{jets}	≥ 4	≥ 2	≥ 2	≥ 2
$N_{b\text{-jets}}$	≥ 2	$= 1$	$= 1$	≥ 1
E_T^{miss}	–	< 50 GeV	< 50 GeV	< 50 GeV
$N_{Z\text{-cand.}}$	$= 1$	$= 0$	$= 0$	$= 0$
Lepton criteria	TTT	TT$\overline{\text{T}}$	TT$\overline{\text{T}}$	TTT
e/γ ambiguity-cuts	satisfy all	satisfy all	satisfy all	≥ 1 fail

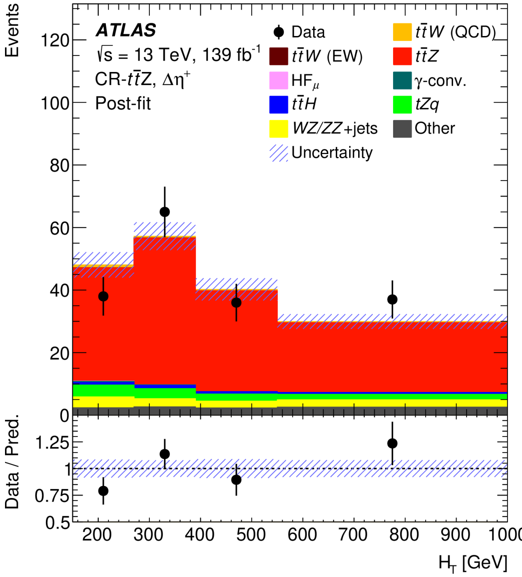
Energy asymmetry in ttW

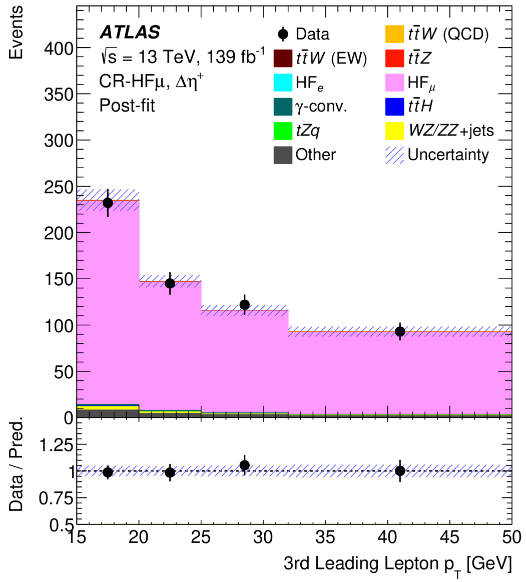


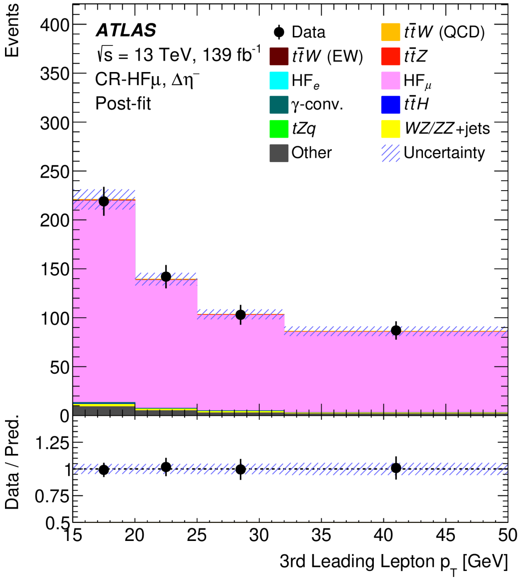












FCNC Summary Plot

- Many other measurements done in ATLAS
- BSM scenarios such as FCNCs are measured
- No FCNCs found
  - Limits set at 95% CL
- Some BSM model already excluded
- Run 3 measurements can help to further probe (and possibly exclude) branching ratios
  - Need improved systematic uncertainty handling