Inclusive Top Cross Sections in ATLAS

17th International Workshop on Top Quark Physics (TOP2024, Saint-Malo, Brittany, France) [23/09/2024]

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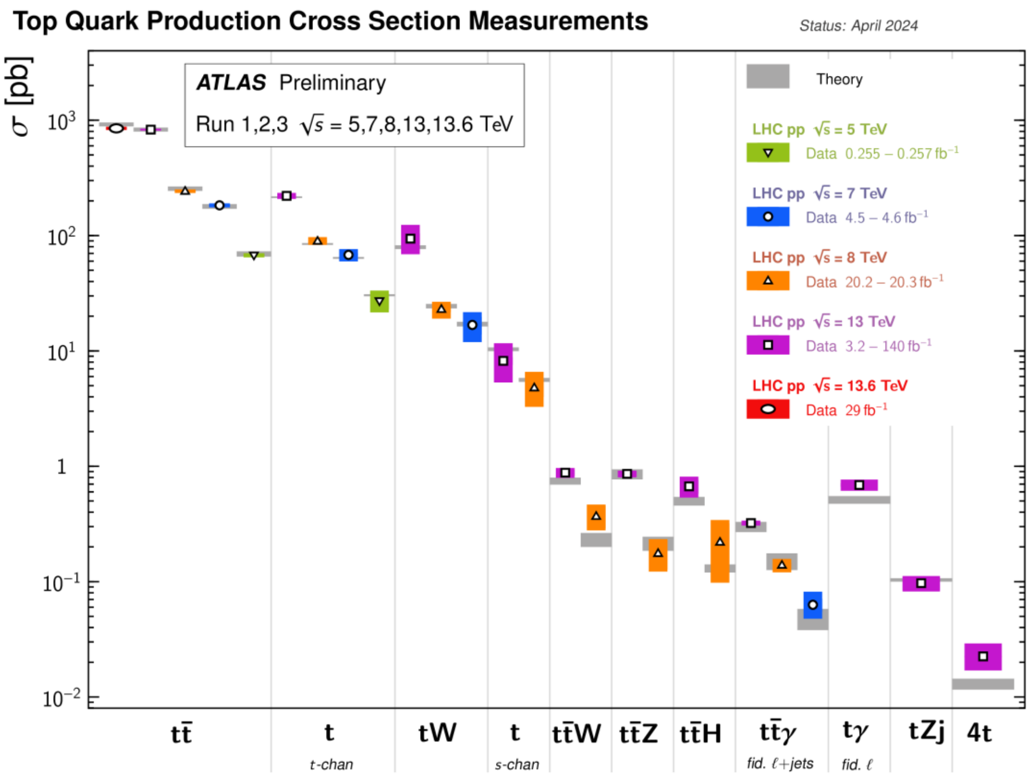
On behalf of the ATLAS Collaboration

Introduction

- The **top quark** has the largest mass of all known Standard Model particles and carries several unique properties.
  - Decays before hadronization, allowing for the study of a bare quark (through its decay products).
  - Most top properties can be directly measured (e.g., mass, decay width, branching ratio, polarization, cross-sections, etc.).



- As a "top factory", the LHC produces top quarks predominantly via the **strong interaction** in $t\bar{t}$ pairs or via the **electroweak interaction** in singly-resonant production.

- Measurements probe the limits of perturbative QCD at NNLO precision.
  - Top quark production is relatively well-modeled → discrepancies in measurements could be windows to **New Physics**.

- Top processes constitute the main background in many Beyond the Standard Model (BSM) searches.
  - Measurements constrain MC generator parameters and improves the **modeling of SM backgrounds**.

Contents

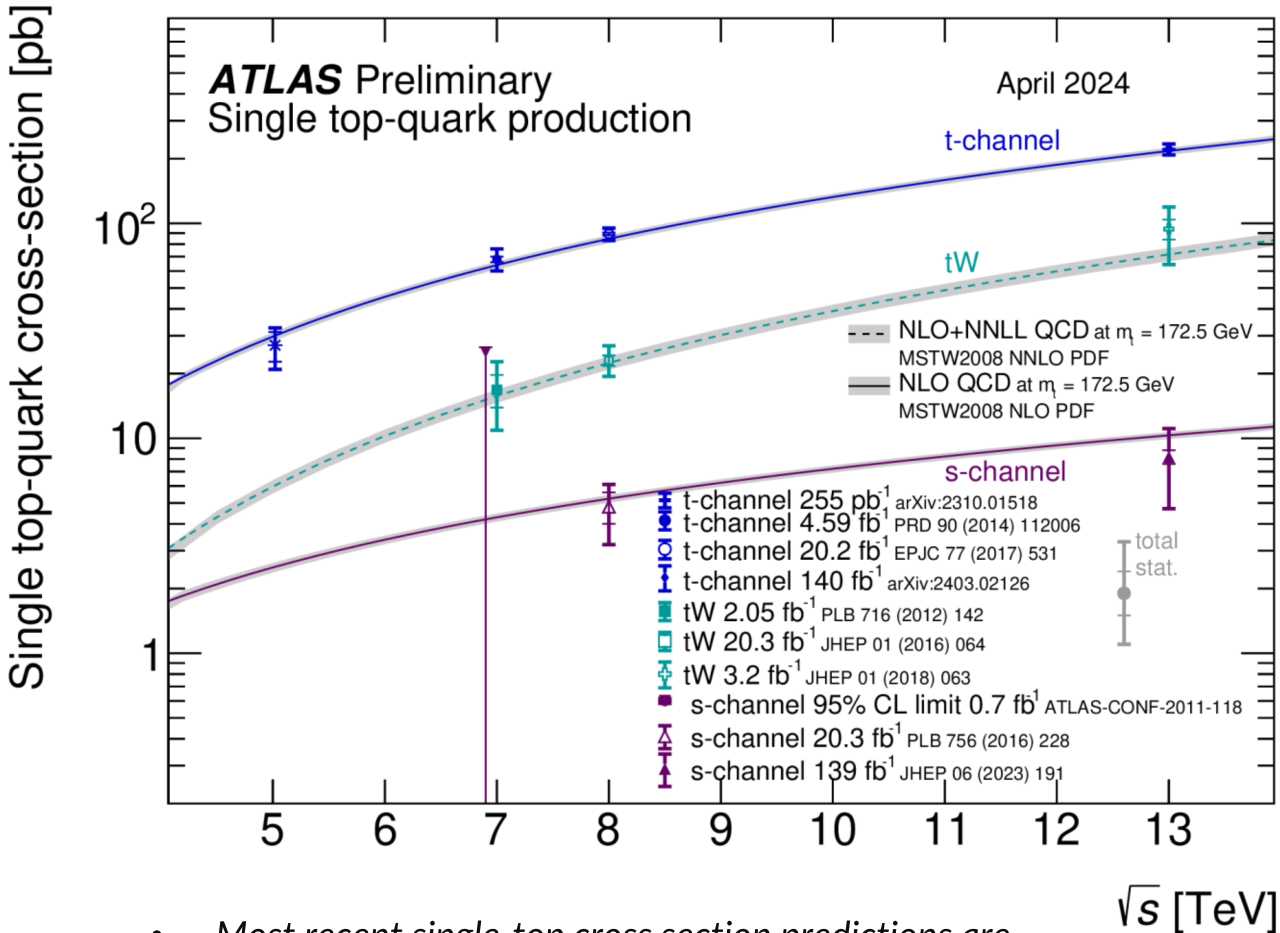
- This talk will highlight selected ATLAS Run 2 (13 TeV) and early Run 3 (13.6 TeV) results, including analyses involving heavy ion collisions.

- **Single top-quark inclusive production cross-section analyses:**
    - tW single-top measurement at 13 TeV (dilepton) - arXiv:2407.15594
    - Single top t-channel cross-section at 13 TeV - JHEP 05 (2024) 305
    - Single top t-channel cross-section at 5.02 TeV - Phys. Lett. B 854 (2024) 138726

- **$t\bar{t}$ inclusive production cross-section analyses:**
    - $t\bar{t}$ production cross-section and ratio to Z production cross-section at 13.6 TeV - Phys. Lett. B 848 (2024) 138376
    - Observation of top pair production in proton-lead collisions at 8.16 TeV - arXiv:2405.05078

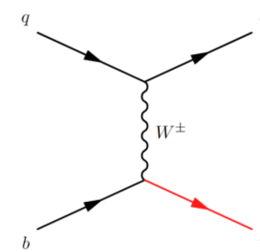
Single-Top Inclusive Cross-Section Measurements

- Two dominant channels for single-top production: **t-channel** and $\boldsymbol{tW}$.
  - Involves electroweak interaction containing a $t \rightarrow Wb$ vertex → measure V_{tb} CKM matrix element.



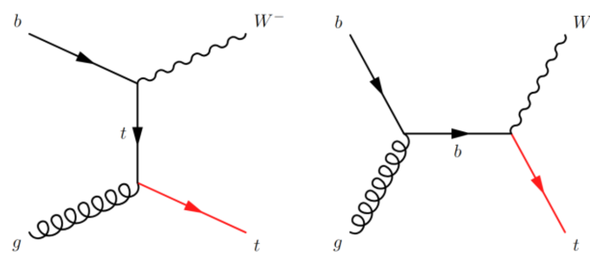
- *Most recent single-top cross section predictions are calculated at NNLO ([SingleTopNNLORef]).*

Single-top t-channel cross-sections



- $\sigma_{t-ch.}(5.02\ TeV) = 30.3^{+0.7}_{-0.5}\ pb$
- $\sigma_{t-ch.}(13\ TeV) = 214.2^{+4.1}_{-2.6}\ pb$

Single-top tW cross-sections

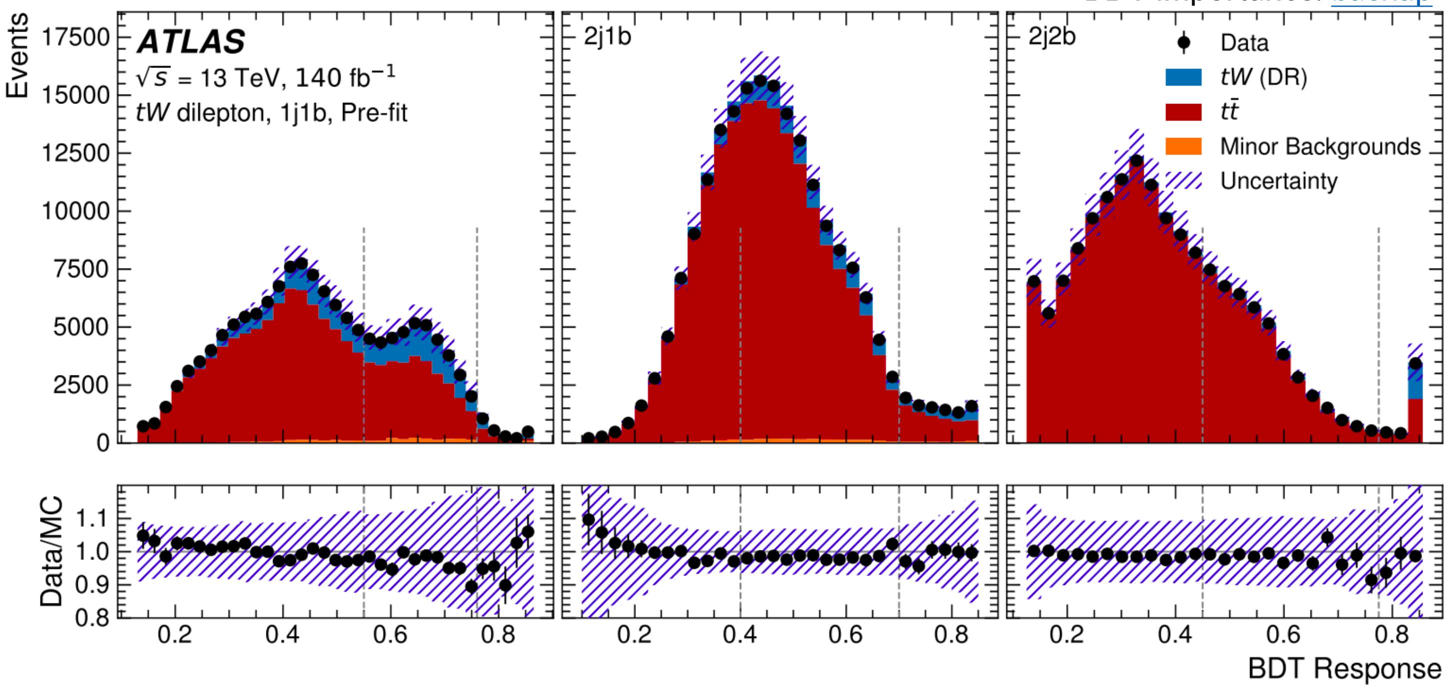


- $\sigma_{tW}(13\ TeV) = 79.3^{+2.9}_{-2.8}\ pb$

tW single-top measurement at 13 TeV (dilepton)

- **Event selection**: chosen to reduce backgrounds from $t\bar{t}$, *W+jets*, *Z+jets*, and *diboson*.
  - 2 leptons ($e^{\pm}\mu^{\pm}$), ≥ 1 b-jet.
  - Classify events into 3 signal regions, $1j1b,\ 2j1b,\ 2j2b$.
- **Profile Likelihood Fit (PLF)** applied to Boosted Decision Tree (BDT) discriminant.

BDT importance: backup



- *Fit is applied over specific BDT ranges.*

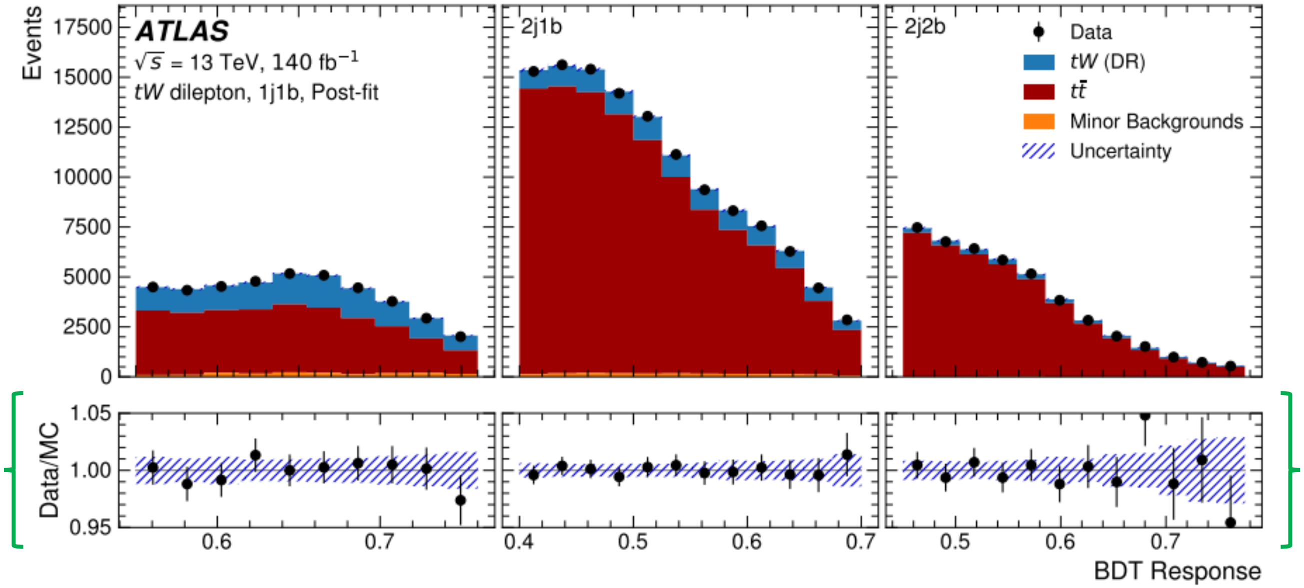
- Systematic uncertainties are taken as nuisance parameters included in the fit.
  - *$t\bar{t}$ modeling*: 13.2%
  - *Jet Energy Scale (JES)*: 12.0%
  - *E_T^{miss} recon. & calib.*: 11.0%

arXiv:2407.15594, $\sqrt{s} = 13\ TeV, 140\ fb^{-1}$

tW single-top measurement at 13 TeV (dilepton)

- Excluding certain BDT ranges relaxes constraints imposed on certain uncertainties (e.g. interference on double-counting between single-top and $t\bar{t}$, DR vs. DS) (see backup).
  - More reliable measurement at the cost of loss of precision.

BDT importance: backup



- *Post-fit uncertainties greatly reduced → ≥ 10% to ≤ 3-4%.*
- *All correlations between uncertainties accounted for.*

Agrees well with SM theory at 13 TeV ($79.3^{+2.9}_{-2.8}$ pb).

- Fit result: $\boldsymbol{\sigma_{tW} = 75 \pm 1\,(stat.)\,^{+15}_{-14}\,(syst.) \pm 1\,(lumi.)\,pb}$ 20%

- $|f_{LV}V_{tb}| = \sqrt{\frac{\sigma_{meas.}}{\sigma_{theo.}}}$ f_{LV}: *model-independent left-handed form factor that encapsulates non-SM Contributions.*

Agrees well with SM theory of unity.

- $\boldsymbol{|f_{LV}V_{tb}| = 0.97 \pm 0.10}$ 10%

arXiv:2407.15594, $\sqrt{s} = 13\,TeV, 140\,fb^{-1}$

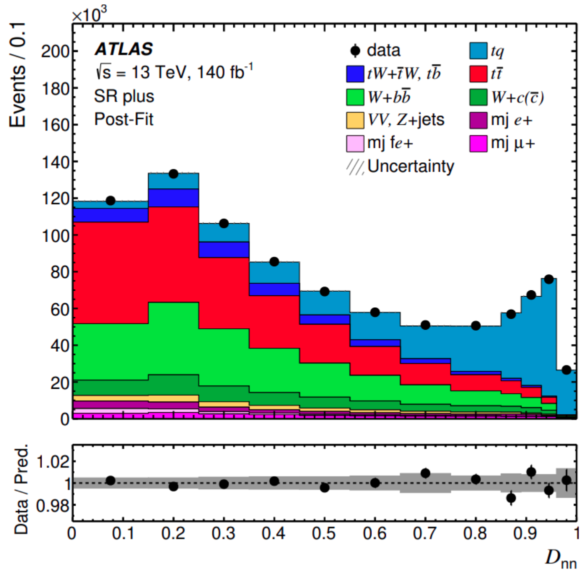
Single top t-channel cross-section at 13 TeV

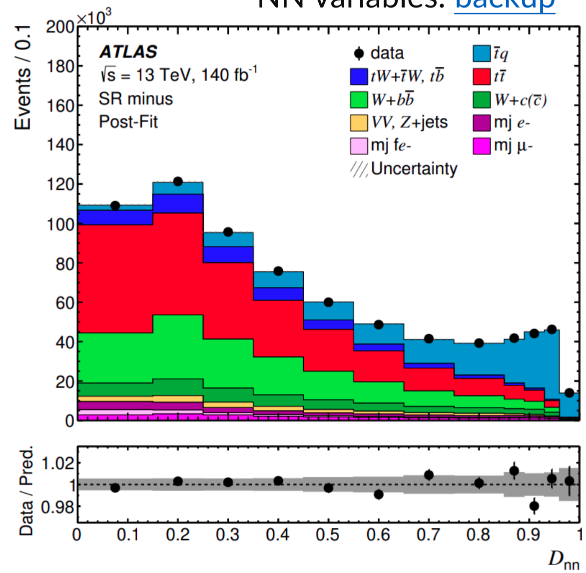
- **Event selection:**
  - Exactly 1 lepton ($p_T > 28\ GeV$).
  - Exactly 2 jets ($p_T > 30\ GeV$), exactly 1 b-jet.
  - Additional cuts on E_T^{miss}, $m_T(W)$ reduces multijet backgrounds.
  - Define 2 signal regions (*SR plus, SR minus).*

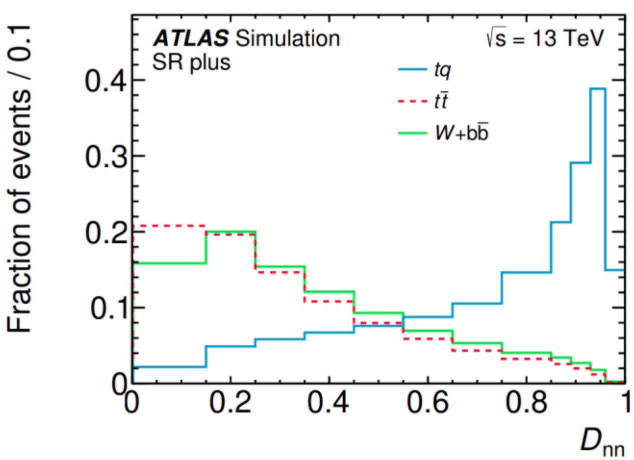
- D_{nn} distributions used in profile maximum likelihood fit (in each signal region) to determine signal yields and calculate total cross-section.

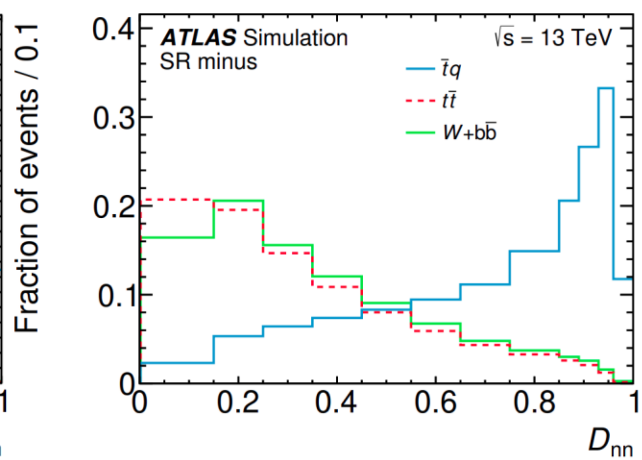
- *Neural Network (NN) model is trained on a combined tq and $\bar{t}q$ sample.*

NN variables: backup









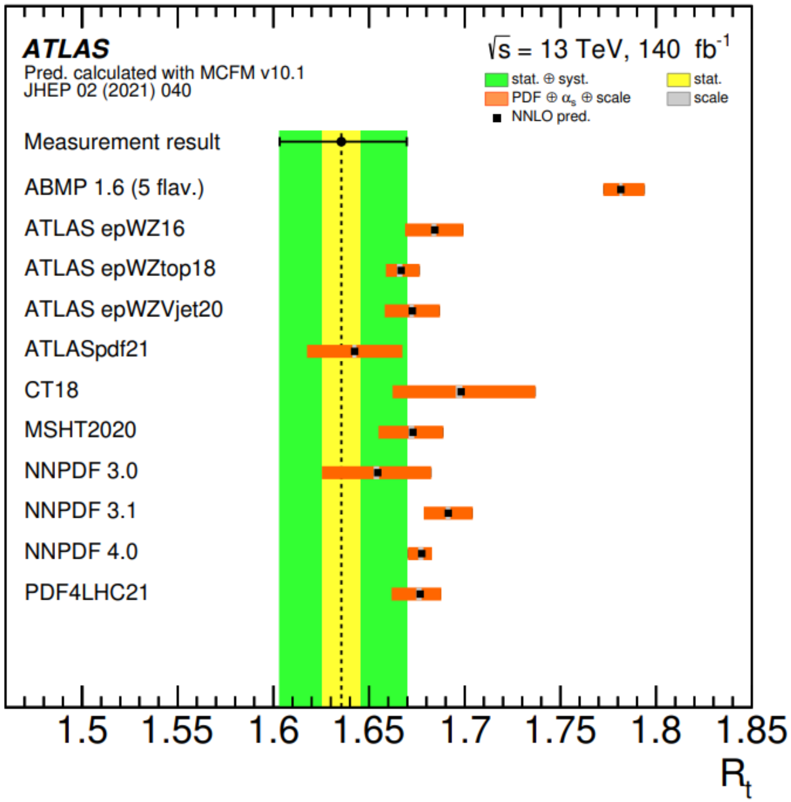
JHEP 05 (2024) 305, $\sqrt{s} = 13\ TeV, 140\ fb^{-1}$

Single top t-channel cross-section at 13 TeV

- Fit results:
  - $\boldsymbol{\sigma(tq) = 137^{+8}_{-8}\,pb}$ 6%
  - $\boldsymbol{\sigma(\bar{t}q) = 84^{+6}_{-5}\,pb}$ 7%
  - $\boldsymbol{R_t = \sigma(tq)/\sigma(\bar{t}q) = 1.636^{+0.036}_{-0.034}}$ 2%

Differences between $\sigma(tq)$ and $\sigma(\bar{t}q)$ driven by differences in PDFs for quarks and antiquarks.

Good agreement with SM predictions.
$\sigma(tq) = 134.2^{+2.6}_{-1.7}\,pb$
$\sigma(\bar{t}q) = 80.0^{+1.8}_{-1.4}\,pb$



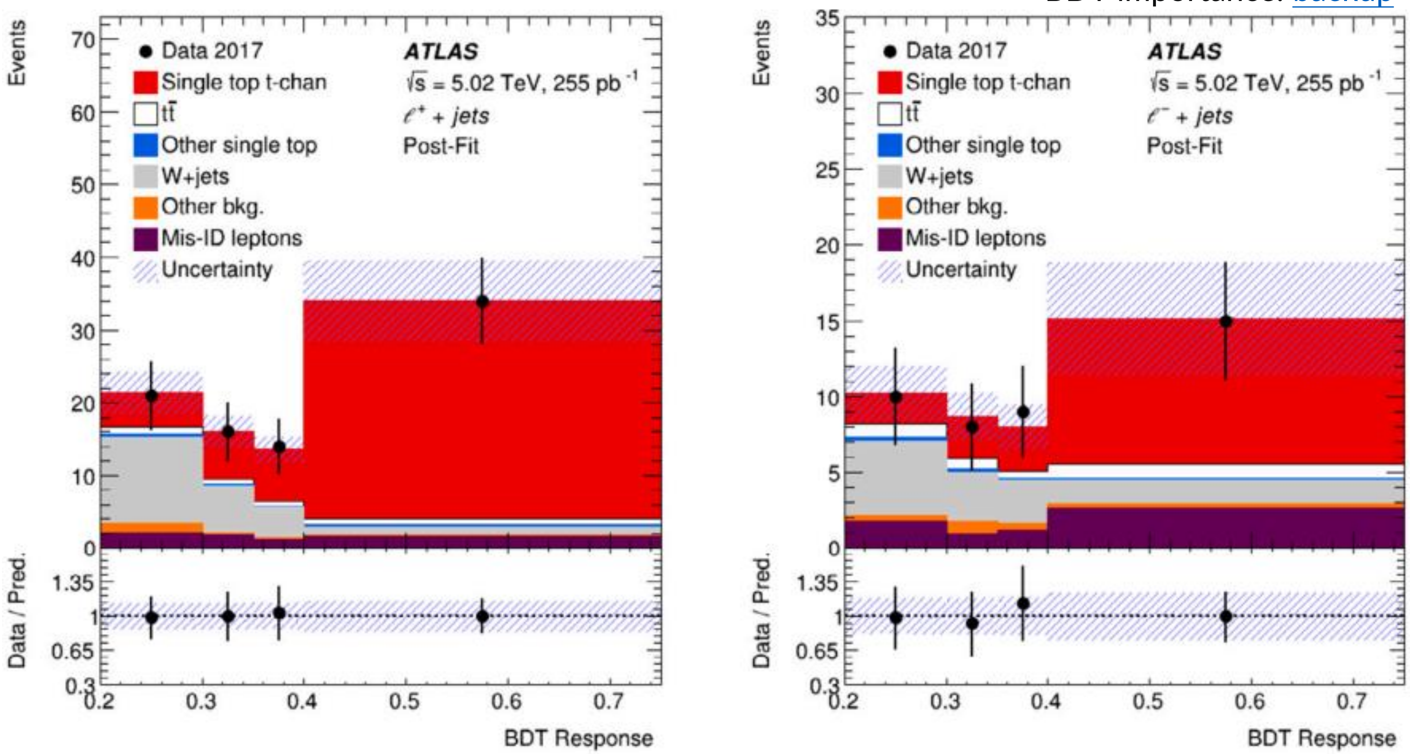
- Precision measurements of R_t are very useful.
  - Many systematic uncertainties cancel out.
  - Constrains PDFs if the measured R_t is included into future fits.
  - Distinguish between different PDF sets.
- $|f_{LV}V_{tb}| = \boldsymbol{1.015 \pm 0.031}$ 3%
- *The measured cross-sections can also be interpreted in an EFT framework (see backup).*
- *See Maren's talk at the YSF.*

JHEP 05 (2024) 305, $\sqrt{s} = 13\,TeV, 140\,fb^{-1}$

Single top t-channel cross-section at 5.02 TeV

- Measurement at 5.02 TeV provides an independent test of the SM with different backgrounds and detector uncertainties.
- **Event selection**: exactly 1 lepton ($p_T > 18\ GeV$), exactly 2 jets ($p_T > 23\ GeV$), exactly 1 b-jet.
  - Additional cuts on E_T^{miss}, $m_T(W)$ reduces multijet backgrounds.

BDT importance: backup



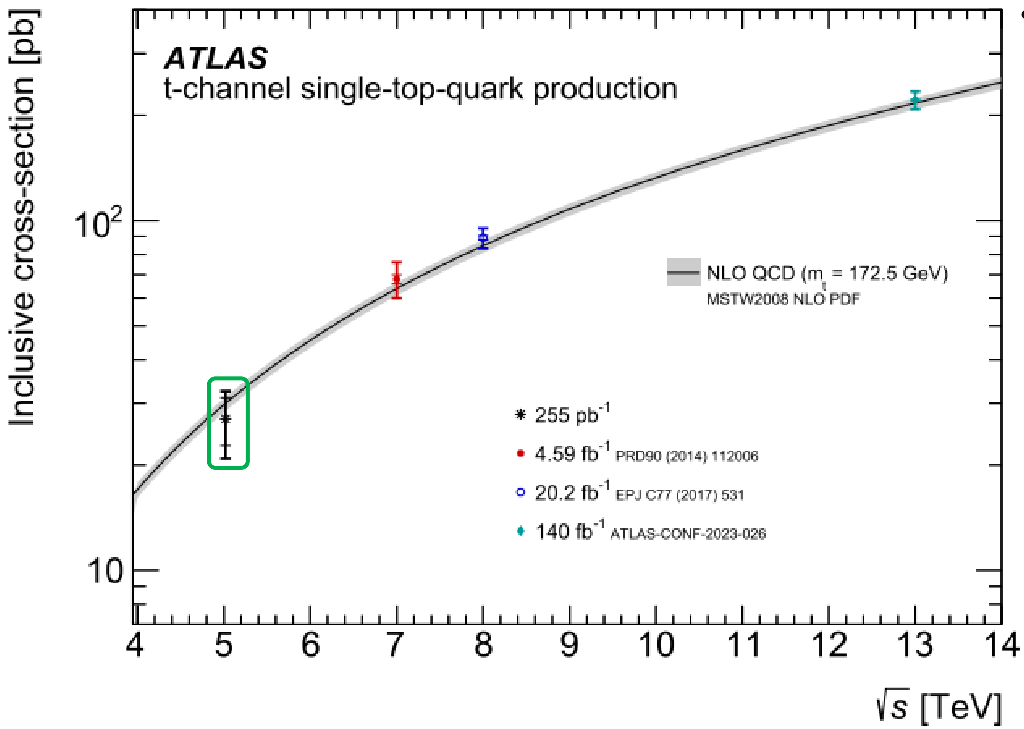
- $\sigma(tq)$ and $\sigma(\bar{t}q)$ determined in two signal regions.

- BDT response discriminates signal and background.

- Instrumental uncertainties estimated directly using the 5.02 TeV sample or extrapolated from high pileup 13 TeV sample.
  - Dominant uncertainties (see backup): *statistical* (16%), *single-top modeling* (8.6%), *mis-ID leptons* (6.3%), *jet uncertainties* (~ 4%).

Phys. Lett. B 854 (2024) 138726, $\sqrt{s} = 5.02\ TeV,\ 255\ pb^{-1}$

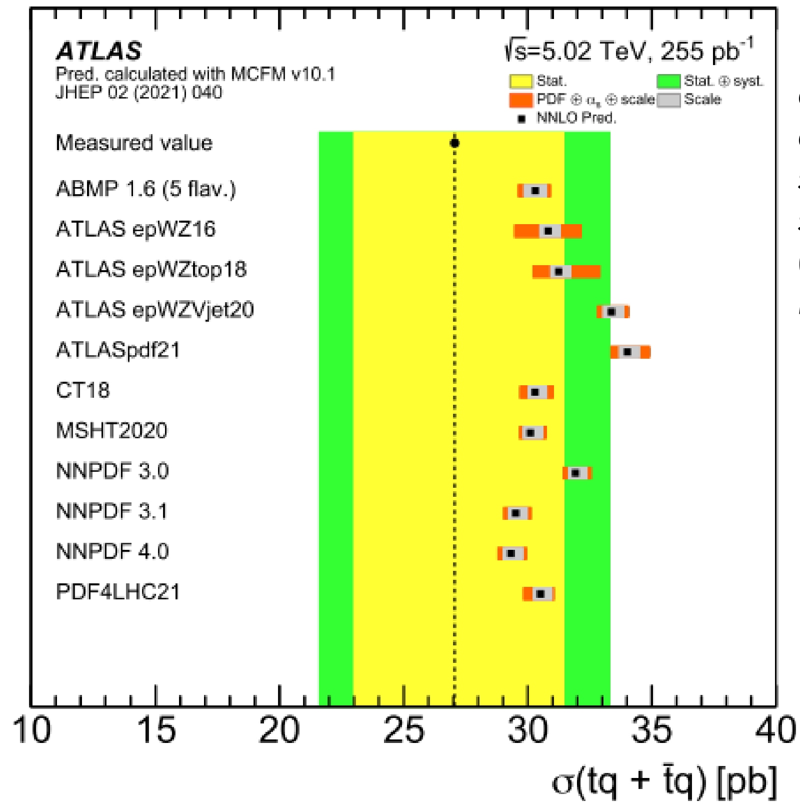
Single top t-channel cross-section at 5.02 TeV



- Fit results:
- $\boldsymbol{\sigma(tq) = 19.8^{+3.9}_{-3.1}\,(stat.)\,^{+2.9}_{-2.2}\,(syst.)\,pb}$ 24%
- $\boldsymbol{\sigma(\bar{t}q) = 7.3^{+3.2}_{-2.1}\,(stat.)\,^{+2.8}_{-1.5}\,(syst.)\,pb}$ 58%

Cross-sections consistent with SM, uncertainties 4-8× larger than similar measurements at higher CM energies.

- Combined total t-channel cross-section:
  - $\boldsymbol{\sigma(tq+\bar{t}q) = 27.1^{+4.4}_{-4.1}\,(stat.)\,^{+4.4}_{-3.7}\,(syst.)\,pb}$ 23%

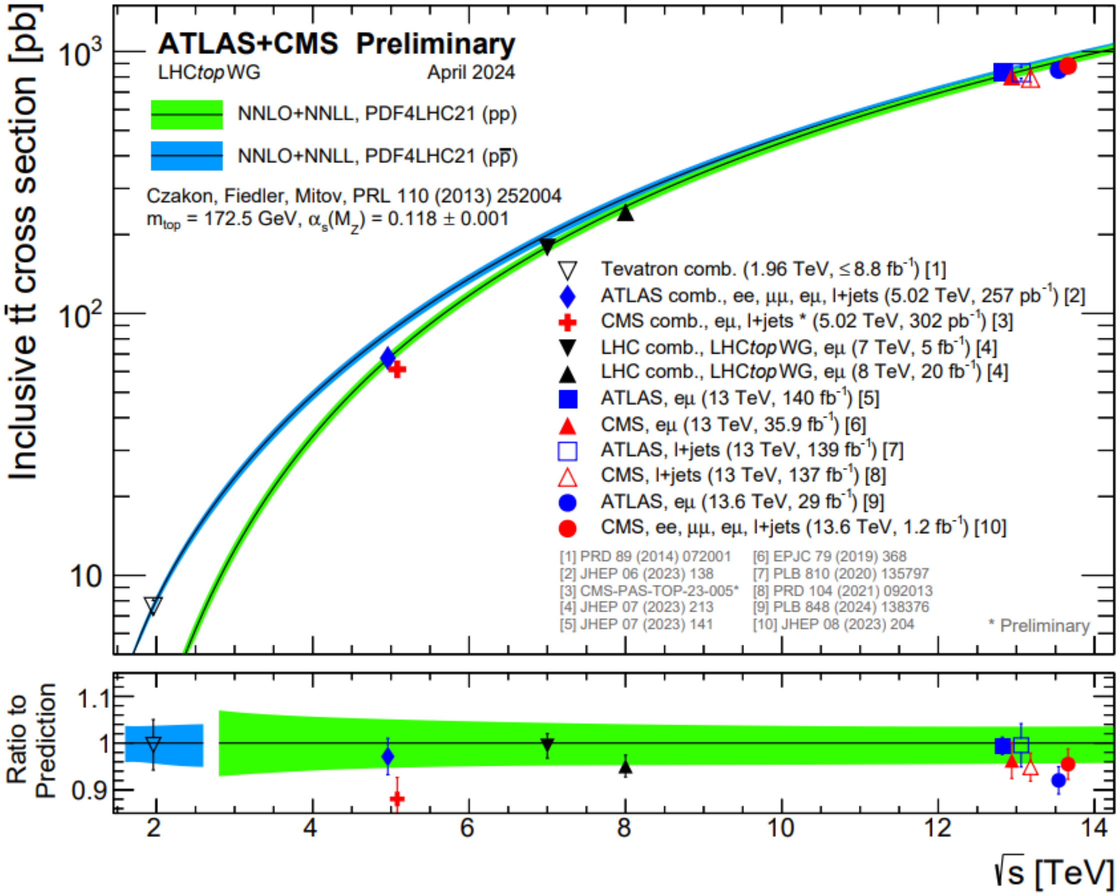


Uncertainties on predictions come from summing up scale variations (scale, PDF, α_S) in quadrature.

- R_t ratio:
  - $\boldsymbol{R_t = 2.73^{+1.43}_{-0.82}\,(stat.)\,^{+1.01}_{-0.29}\,(syst.)}$ 64%
- $|f_{LV}V_{tb}|$:
  - $\boldsymbol{|f_{LV}V_{tb}| = 0.94^{+0.11}_{-0.10}}$ 11%

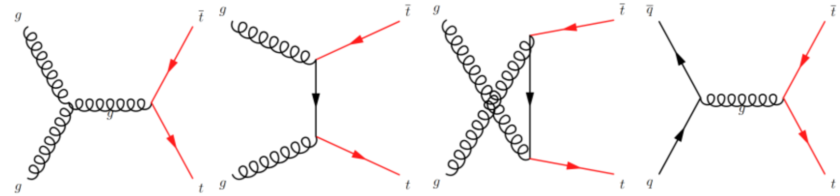
Phys. Lett. B 854 (2024) 138726, $\sqrt{s} = 5.02\,TeV,\ 255\,pb^{-1}$

$t\bar{t}$ Inclusive Cross-Section Measurements



- *Most recent $t\bar{t}$ cross section predictions (above) are calculated at NNLO+NNLL using soft gluon resummation (TtbarNNLO).*

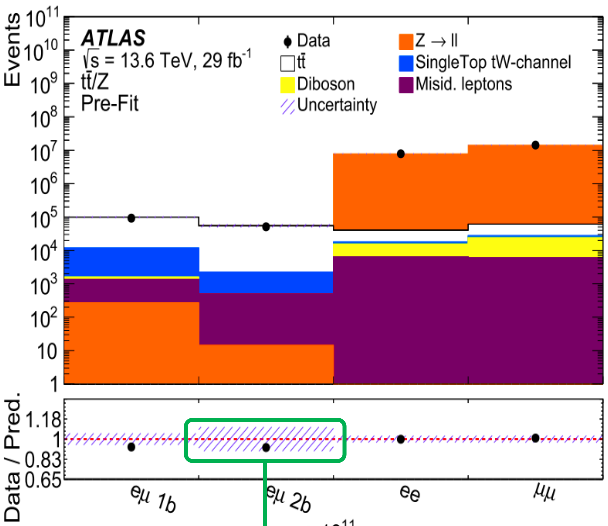
$t\bar{t}$ inclusive cross-sections



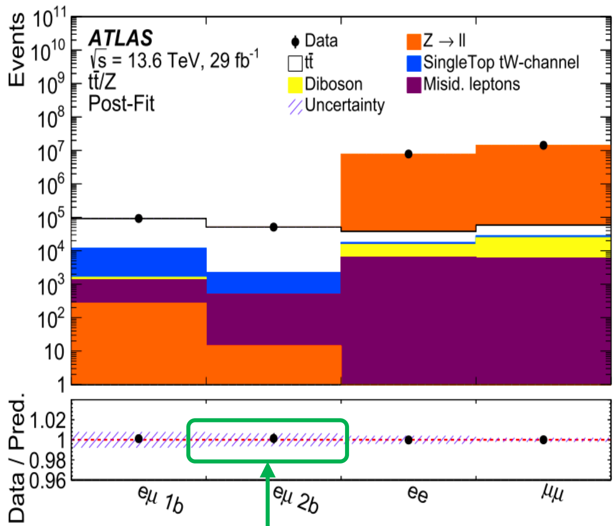
- $\sigma_{t\bar{t}}\,(13\,TeV) = 833.9 \pm 30.0\,(scale) \pm 21.0\,(PDF, \alpha_S)\,pb$

- Large $t\bar{t}$ production cross section results in very precise measurements, especially in the semileptonic and fully-leptonic channels.
  - Fine-tuning MC parameters.
  - Extract very precise measurements of m_t and α_S.
  - Used to provide inputs to and constrain PDFS.

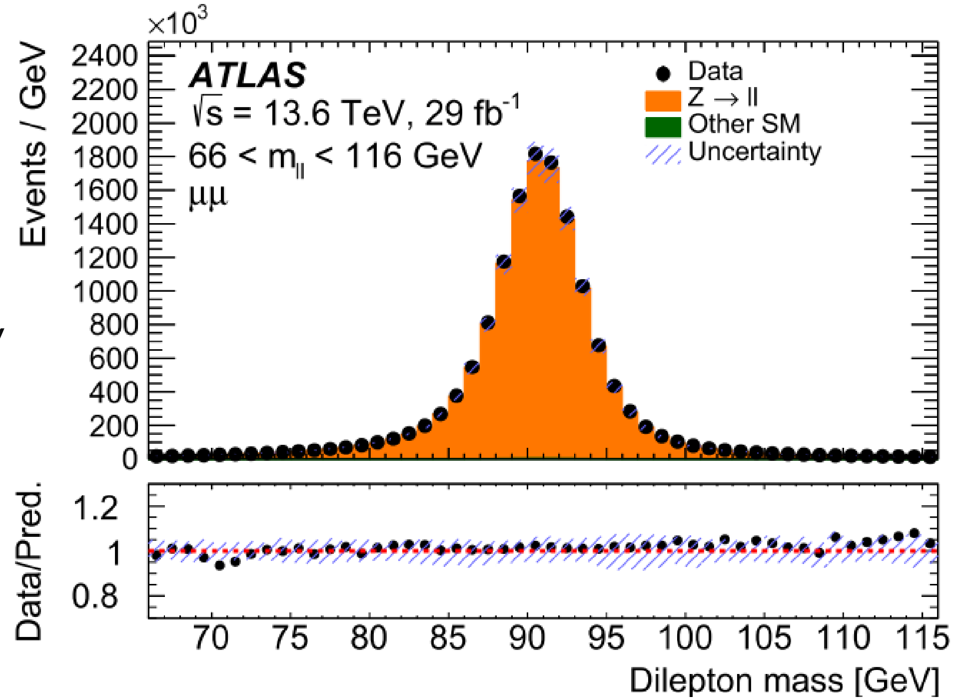
$t\bar{t}$ production and ratio to Z production cross-section at 13.6 TeV



- **Event Selection**: $t\bar{t}$ events with exactly two leptons (3 channels: $e\mu$, ee, $\mu\mu$).



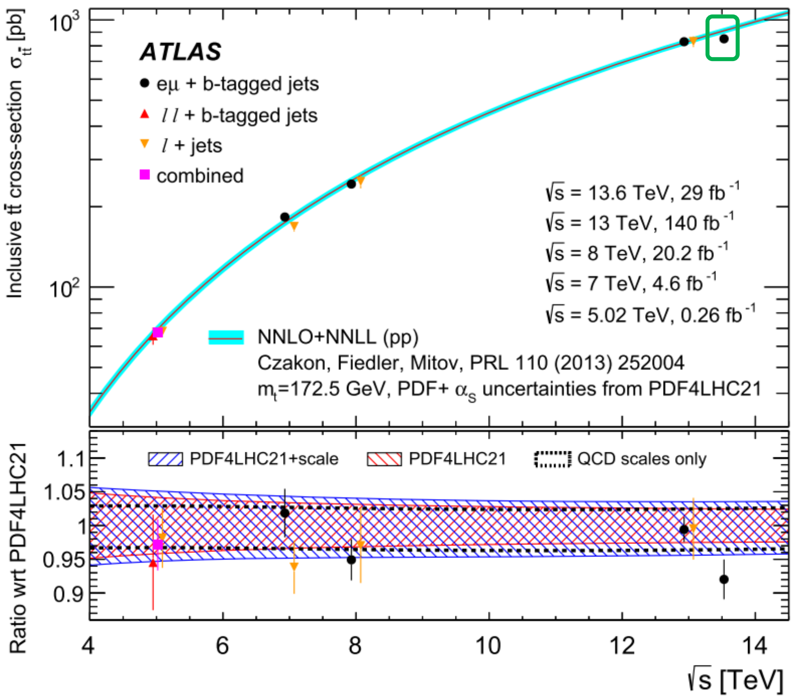
- *Fit reduces uncertainties in certain signal regions.*



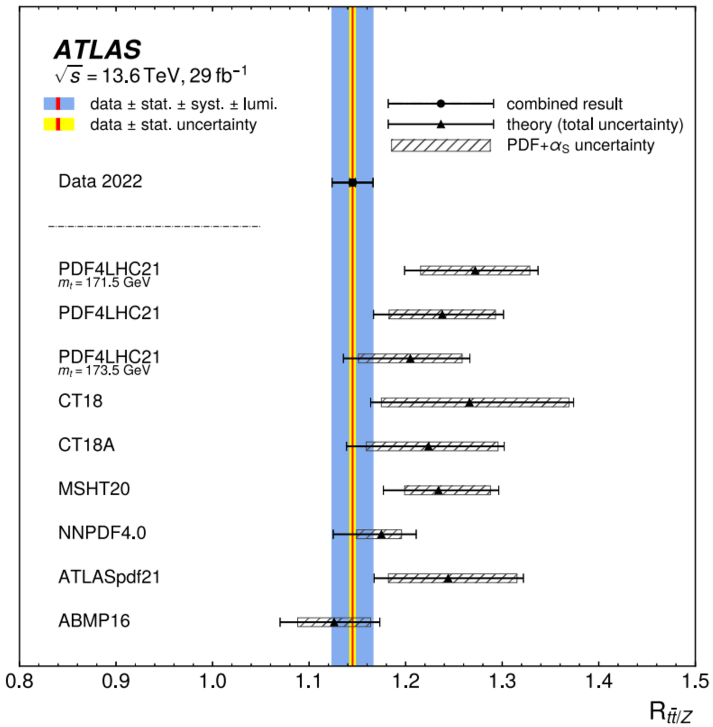
- Additional dilepton mass window applied in ee and $\mu\mu$ events → estimate $Z \rightarrow ll$ contribution.
- Allows for very precise measurement of $R_{t\bar{t}/Z}$.
  - Cancellation of several systematic uncertainties.
  - Sensitive to gluon-to-quark PDF ratio.
- Use a profile likelihood fit (left) to extract $\sigma_{t\bar{t}}$ and $R_{t\bar{t}/Z}$.

Phys. Lett. B 848 (2024) 138376, $\sqrt{s} = 13.6\,TeV,\ 29\,fb^{-1}$

$t\bar{t}$ production and ratio to Z production cross-section at 13.6 TeV



$R^{theo.}_{t\bar{t}/Z} = 1.238^{+0.063}_{-0.071}\ (scale + PDF + \alpha_S)$



- Largest uncertainties in both $\sigma_{t\bar{t}}$ and $\sigma_{Z\to\ell\ell}$ come from luminosity (2.3%) and lepton reconstruction uncertainties ($\sim 1.4\%$).
- These large uncertainties cancel out in the measurement of $R_{t\bar{t}/Z}$.

- Fit results:

$\boldsymbol{\sigma_{t\bar{t}} = 850 \pm 3\ (stat.) \pm 18\ (syst.) \pm 20\ (lumi.)\ pb}$ 3%

$\boldsymbol{\sigma_{Z\to\ell\ell} = 744 \pm 11\ (stat. + syst.) \pm 16\ (lumi.)\ pb}$ 3%

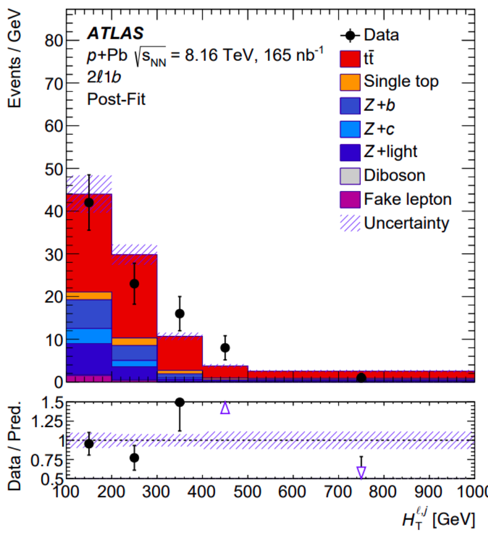
$\boldsymbol{R_{t\bar{t}/Z} = 1.145 \pm 0.003\ (stat.) \pm 0.021\ (syst.) \pm 0.002\ (lumi.)}$ 2%

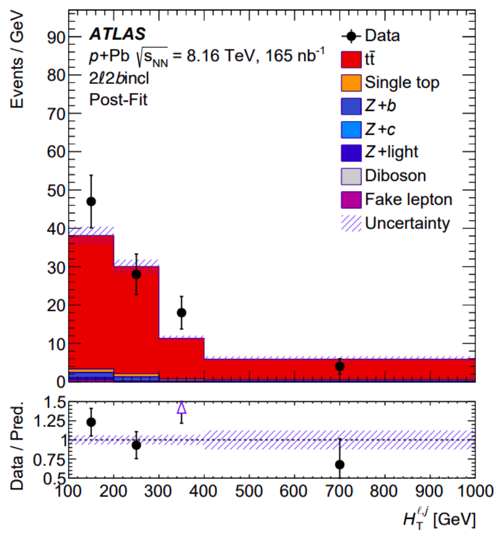
- *Measured cross-section is slightly lower than prediction but is still compatible within 1.5 standard deviations.*

Phys. Lett. B 848 (2024) 138376, $\sqrt{s} = 13.6\ TeV,\ 29\ fb^{-1}$

Observation of top pair production in proton-lead collisions at 8.16 TeV

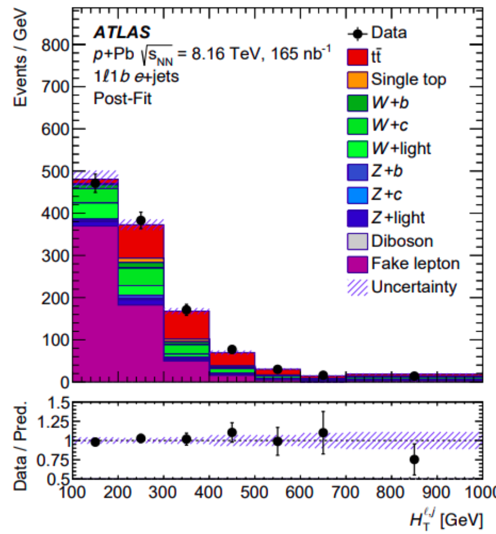
- In $p + Pb$ collisions, measurements of top quarks access regions of nuclear PDFs (nPDF) that are not well-constrained by other measurements (e.g., gluon nPDFs are not well constrained due to limited data).

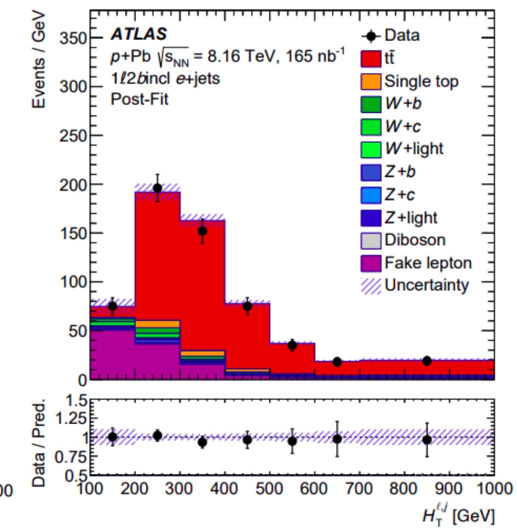




- **$2\ell 1b, 2\ell 2b$ event selection:**
  - Discard events with an invariant mass ($m_{\ell\ell}$) within a Z-mass window ($80 < m_{\ell\ell} < 100\ GeV$).
  - $m_{\ell\ell} > 15\ (45)\ GeV$ in the $e\mu$ (ee and $\mu\mu$) channel.
  - ≥ 2 jets (≥ 1 b-jet).

- **$1\ell 1b$ e+jets, $1\ell 2bincl$ e+jets, $1\ell 1b$ μ+jets, $1\ell 2bincl$ μ+jets) event selection.**
  - Exactly 1 lepton.
  - ≥ 4 jets, (≥ 1 b-jet).



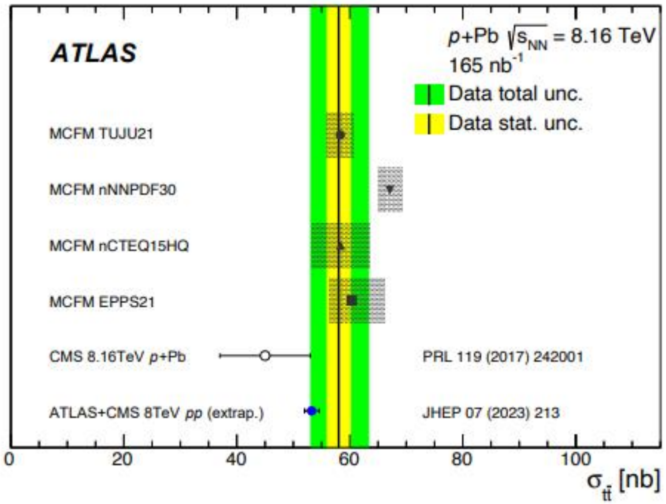


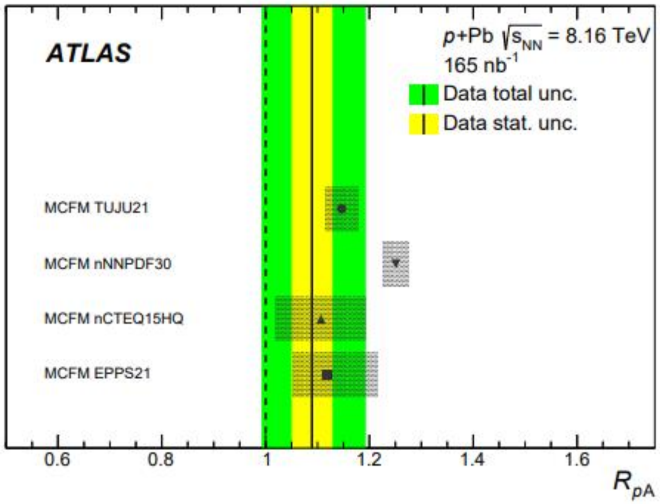
- *See backup for $1\ell 1b$ μ+jets, $1\ell 2bincl$ μ+jets control plots.*

arXiv:2405.05078, $\sqrt{s_{NN}} = 8.16\ TeV,\ 165\ nb^{-1}$

Observation of top pair production in proton-lead collisions at 8.16 TeV

- Each $H_T^{l,j}$ distribution is entered into a binned profile likelihood fit.
- Systematic uncertainties are represented as Nuisance Parameters and are included as additional fit parameters.





Source	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ unc. up [%]	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ unc. down [%]
Jet energy scale	+4.6	-4.1
$t\bar{t}$ generator	+4.5	-4.0
Fake-lepton background	+3.1	-2.8
Background	+3.1	-2.6
Luminosity	+2.8	-2.5
Muon uncertainties	+2.3	-2.0
W+jets	+2.2	-2.0
b-tagging	+2.1	-1.9
Electron uncertainties	+1.8	-1.5
MC statistical uncertainties	+1.1	-1.0
Jet energy resolution	+0.4	-0.4
$t\bar{t}$ PDF	+0.1	-0.1
Systematic uncertainty	+8.3	-7.6

Good agreement with SM predictions.

- *Largest uncertainties come from JES and $t\bar{t}$ event generators.*

- Fit results:
  - $\boldsymbol{\sigma(t\bar{t}) = 58.1 \pm 2.0\,(stat.)\,^{+4.8}_{-4.4}\,(syst.)\,nb}$ 9%
- Nuclear modification factor:
  - $\boldsymbol{R_{pA} = \frac{\sigma_{t\bar{t}}^{p+Pb}}{A_{Pb}\cdot\sigma_{t\bar{t}}^{pp}} = 1.090 \pm 0.039\,(stat.)\,^{+0.094}_{-0.087}\,(syst.)}$ 9%

arXiv:2405.05078, $\sqrt{s_{NN}} = 8.16\,TeV,\ 165\,nb^{-1}$

Summary

- The latest inclusive cross-sections measurements of single- and double-top quark production have been presented.
  - Single-top cross-sections measured very precisely at the nominal $13\ TeV$ in the fully-leptonic channel.
  - Multiple measurements of $|f_{LV}V_{tb}|$ in different single-top production channels → independent tests of this factor.
  - In a single-top t-channel measurement at a special $5.02\ TeV$ collision energy we studied different detector uncertainties in a low pileup environment.
  - Top quark pair production cross-section in the fully-leptonic channel measured using relatively new Run 3 data → estimate $Z \to ll$ contribution.
  - Top quark pair production cross-section measured using heavy-ion collisions (p+Pb) → constrain nuclear PDFS in regions that are not well-constrained by other measurements.

- Presently, we can measure $t\bar{t}$ cross-sections up to a precision of 1.8% (13 TeV).
- Have not yet observed s-channel single-top production due to large $t\bar{t}$ backgrounds and its uncertainties.

- All measurements agree well with current SM predictions.

Backup

tW single-top measurement at 13 TeV (dilepton)

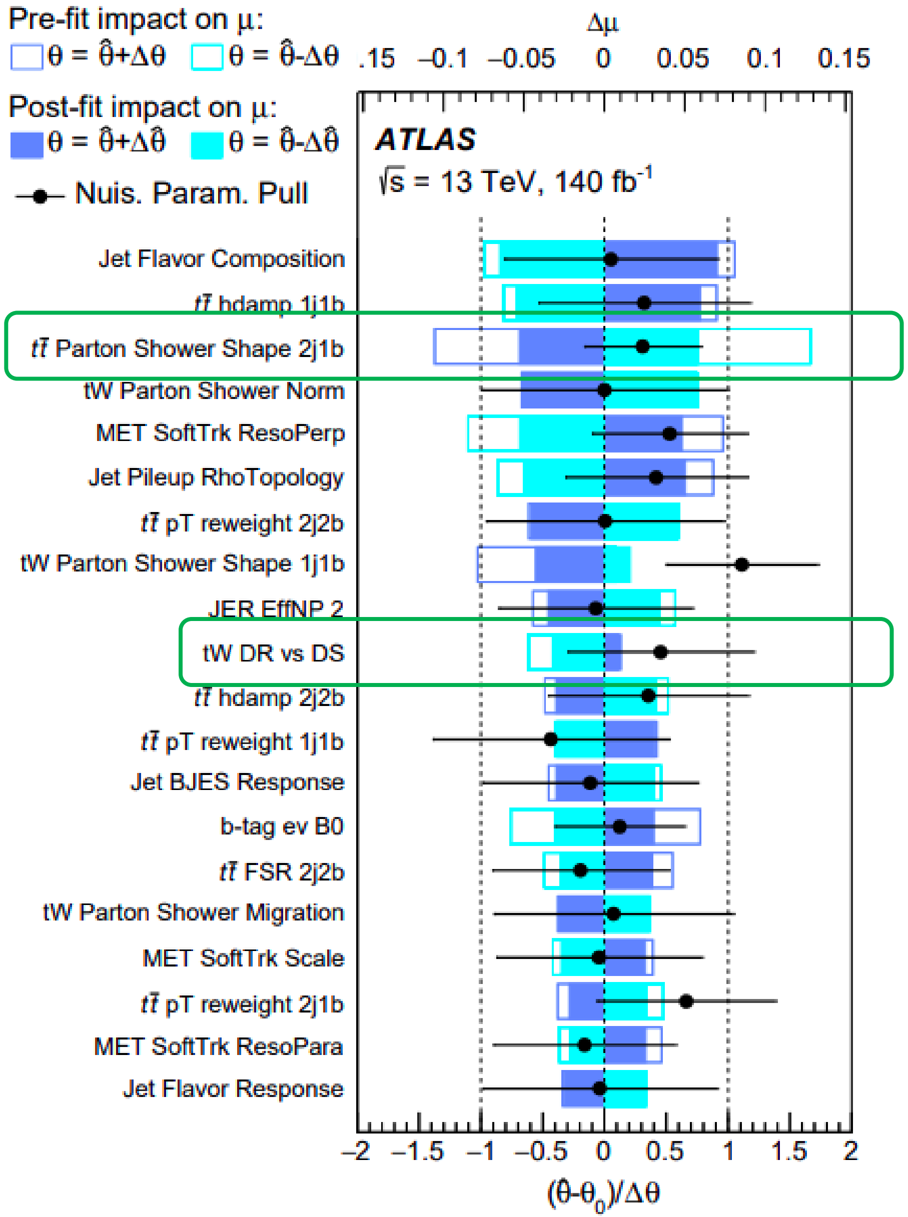
Variable	1j1b	2j1b	2j2b
$p_{\mathrm{T}}(\ell_1\ell_2 j_1 E_{\mathrm{T}}^{\mathrm{miss}})$	1	3	
$p_{\mathrm{T}}(j_{S1})$	2		
Centrality$(\ell_1\ell_2)$	3		
$m_{\mathrm{T}}(j_1 E_{\mathrm{T}}^{\mathrm{miss}})$	4		
$m(\ell_1 j_1)$	5	2	1
$m(\ell_2 j_1)$	6		4
$\Delta p_{\mathrm{T}}(\ell_1, \ell_2)$	7		
$p_{\mathrm{T}}(\ell_1\ell_2)$	8	5	
$m(\ell_2 j_1 E_{\mathrm{T}}^{\mathrm{miss}})$	9		
$p_{\mathrm{T}}(j_1 E_{\mathrm{T}}^{\mathrm{miss}})$	10		
$\Delta R(\ell_2, j_1)$		6	
$p_{\mathrm{T}}(\ell_1\ell_2 E_{\mathrm{T}}^{\mathrm{miss}})$			6
$m(\ell_1 j_2)$	–	1	2
$p_{\mathrm{T}}(\ell_1\ell_2 j_1 j_2 E_{\mathrm{T}}^{\mathrm{miss}})$	–	4	
$H_{\mathrm{T}}^{\mathrm{ratio}}(\ell_1\ell_2, \ell_1\ell_2 j_1 j_2 E_{\mathrm{T}}^{\mathrm{miss}})$	–	7	
$H_{\mathrm{T}}^{\mathrm{ratio}}(\ell_1\ell_2, \ell_1\ell_2 j_1 E_{\mathrm{T}}^{\mathrm{miss}})$	–	8	
$p_{\mathrm{T}}(j_2)$	–		3
$m(\ell_2 j_2)$	–		5

Variable	Definition
$p_{\mathrm{T}}(s)$	Transverse component of the vector sum of momenta
$m(s)$	Invariant mass of the system of multiple objects s
$H(s)$	Scalar sum of momenta
$H_{\mathrm{T}}(s)$	Scalar sum of transverse momenta
Centrality(s)	Centrality of the system s, given by $H_{\mathrm{T}}(s)/H(s)$
$\Delta R(\vec{s}_1, \vec{s}_2)$	$\eta - \phi$ separation between $\vec{s}_1$ and $\vec{s}_2$
$\Delta p_{\mathrm{T}}(\vec{s}_1, \vec{s}_2)$	Magnitude of the transverse component of $\vec{s}_1 - \vec{s}_2$
$H_{\mathrm{T}}^{\mathrm{ratio}}(s_1, s_2)$	Ratio of the H_{T} of the two systems: $H_{\mathrm{T}}(s_1)/H_{\mathrm{T}}(s_2)$
$p_{\mathrm{T}}(j_{S1})$	p_{T} of the leading soft jet
$m_{\mathrm{T}}(o_1 E_{\mathrm{T}}^{\mathrm{miss}})$	Transverse mass of object o_1 and $E_{\mathrm{T}}^{\mathrm{miss}}$: $m_{\mathrm{T}} = \sqrt{2p_{\mathrm{T}}(o_1)E_{\mathrm{T}}^{\mathrm{miss}}(1 - \cos\Delta\phi(o_1, E_{\mathrm{T}}^{\mathrm{miss}}))}$

- Several observables are constructed using the set of final-state objects $(o_1, \ldots, o_N)$ (top).
- These are used as input to the BDT, ranked by importance in each of the 3 defined signal regions (left).

arXiv:2407.15594, $\sqrt{s} = 13\ TeV, 140\ fb^{-1}$

tW single-top measurement at 13 TeV (dilepton)



- Certain BDT ranges are excluded → avoids over-constraining certain uncertainties (*DR* vs. *DS*, $t\bar{t}$ parton-showering) in non-physical ways.
  - Remove sources of uncertainty if their effects fall below a certain threshold (normalization: $< 0.05\%$, shape effects: at least one bin must vary $> 0.1\%$).
  - Ratio between post-fit to pre-fit uncertainties relaxed from 30-40% to 60-90%.
  - Results in loss of precision → post-fit error on fitted signal strength (μ_{tW}) increases from 13% to 19%.

arXiv:2407.15594, $\sqrt{s} = 13\ TeV, 140\ fb^{-1}$

Single top t-channel cross-section at 13 TeV

No.	Symbol	Description
1.	$m(jb)$	Invariant mass of the untagged jet (j) and the b-tagged jet (b)
2.	$\lvert\eta(j)\rvert$	Absolute value of the pseudorapidity of the untagged jet
3.	$\lvert\Delta p_{\mathrm{T}}(W, jb)\rvert$	Absolute value of the difference in transverse momentum between the reconstructed W boson and the jet pair
4.	$\lvert\Delta\phi(W, jb)\rvert$	Absolute value of the difference in azimuthal angle between the reconstructed W boson and the jet pair
5.	$m(t)$	Invariant mass of the reconstructed top quark
6.	$\lvert\Delta\eta(\ell, j)\rvert$	Absolute value of the difference in pseudorapidity between the charged lepton (ℓ) and the untagged jet
7.	$\Delta R(\ell, j)$	Angular distance of the charged lepton and the untagged jet
8.	$\lvert\Delta\eta(b, \ell)\rvert$	Absolute value of the difference in pseudorapidity between the b-tagged jet and the charged lepton
9.	$m_{\mathrm{T}}(W)$	Transverse mass of the W boson
10.	$m(\ell b)$	Invariant mass of the charged lepton and the b-tagged jet
11.	$H_{\mathrm{T}}(\ell, \mathrm{jets}, E_{\mathrm{T}}^{\mathrm{miss}})$	Scalar sum of the transverse momenta of the charged lepton and the jets and $E_{\mathrm{T}}^{\mathrm{miss}}$
12.	$\lvert\Delta\eta(b, j)\rvert$	Absolute value of the difference in the pseudorapidity of the two jets
13.	$\lvert\Delta\phi(j, t)\rvert$	Absolute value of the difference in the azimuthal angle between the untagged jet and the reconstructed top quark
14.	$\cos\theta^{*}(\ell, j)$	Cosine of the angle θ^{*} between the charged lepton and the untagged jet in the rest frame of the reconstructed top quark
15.	$\lvert\eta(\ell)\rvert$	Absolute value of the pseudorapidity of the charged lepton
16.	S	Sphericity defined as the sum of the 2nd and 3rd largest eigenvalues of the sphericity tensor multiplied by 3/2
17.	$\lvert\Delta p_{\mathrm{T}}(\ell, j)\rvert$	Absolute value of the difference in transverse momentum of the charged lepton and the untagged jet

- *Left: physical observables used for training of the NN, ordered by their discriminating power.*
- *Initially 30 variables were defined, marginal improvements found after including more variables.*

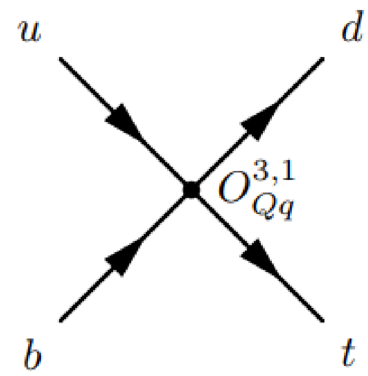
JHEP 05 (2024) 305, $\sqrt{s} = 13\ TeV, 140\ fb^{-1}$

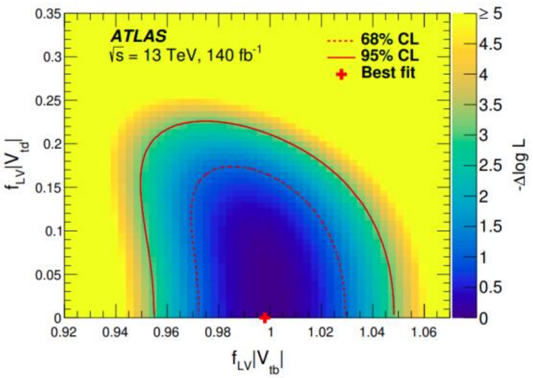
Single top t-channel cross-section at 13 TeV

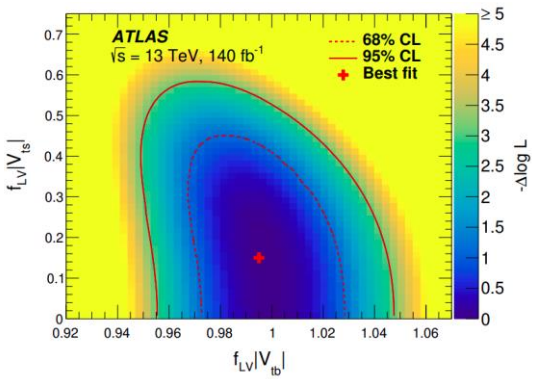
Good agreement with SM predictions.

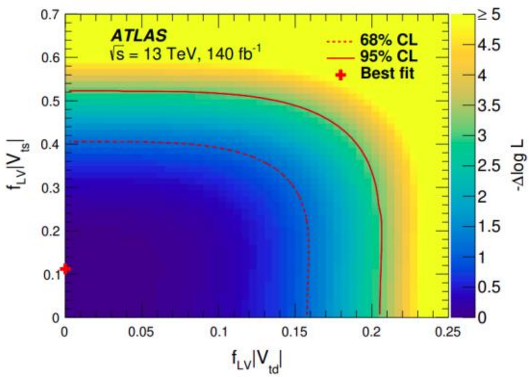
- Fit results:
  - $\boldsymbol{\sigma(tq) = 137^{+8}_{-8}\,pb}$ 6%
  - $\boldsymbol{\sigma(\bar{t}q) = 84^{+6}_{-5}\,pb}$ 7%
  - $\boldsymbol{R_t = \sigma(tq)/\sigma(\bar{t}q) = 1.636^{+0.036}_{-0.034}}$ 2%

Differences between $\sigma(tq)$ and $\sigma(\bar{t}q)$ driven by differences in PDFs for quarks and antiquarks.









- *Confidence contours calculated from maximum-likelihood scans in various $f_{LV}|V_{tq}|$ planes.*

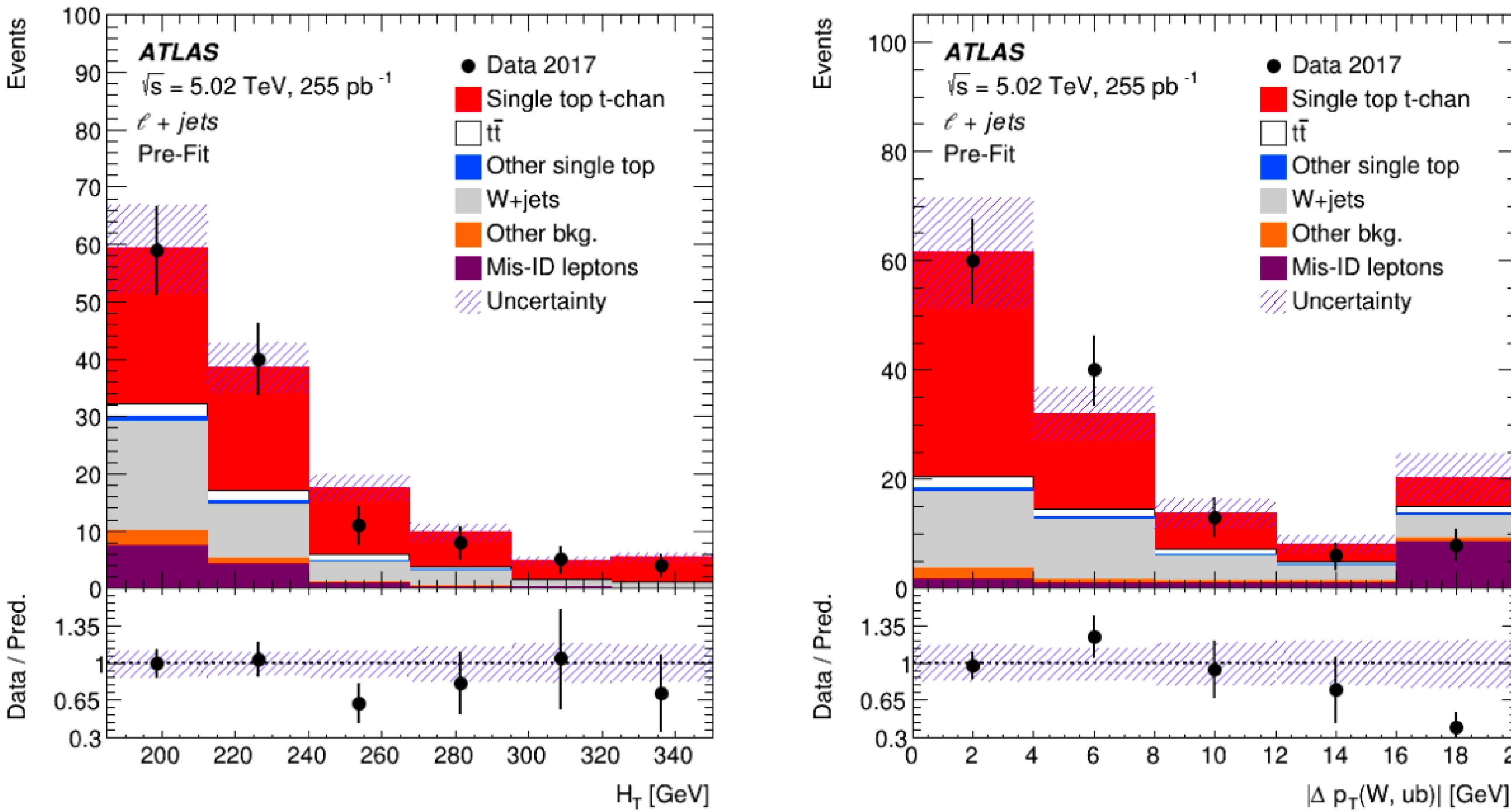
- Standard Model Effective Field Theory (SM) treats the current SM as a low-energy approximation of a more fundamental theory at an energy scale, Λ.
- In this SMEFT, two operators are considered: $\boldsymbol{O^{3,1}_{Qq}}$ (four-quark operator) and $\boldsymbol{O^{3}_{\phi Q}}$ (coupling the third quark generation to the Higgs boson doublet, ϕ).
- When interpreted in the EFT approach, 95% CL for these operators are estimated:

$$\boldsymbol{-0.37 < O^{3,1}_{Qq}/\Lambda^2 < 0.06}$$
$$\boldsymbol{-0.87 < O^{3}_{\phi Q}/\Lambda^2 < 1.42}$$

JHEP 05 (2024) 305, $\sqrt{s} = 13\,TeV, 140\,fb^{-1}$

Single top t-channel cross-section at 5.02 TeV

- BDT is trained using 9 input variables based on combinations of objects kinematics and global event topology.
  - Variables with highest discriminating power: scalar sum of transverse momentum of all objects (H_T), p_T difference between W four-vector sum of untagged and b-tagged jet ($|\Delta p_T(W, ub)|$).



Phys. Lett. B 854 (2024) 138726, $\sqrt{s} = 5.02\ TeV,\ 255\ pb^{-1}$

Single top t-channel cross-section at 5.02 TeV

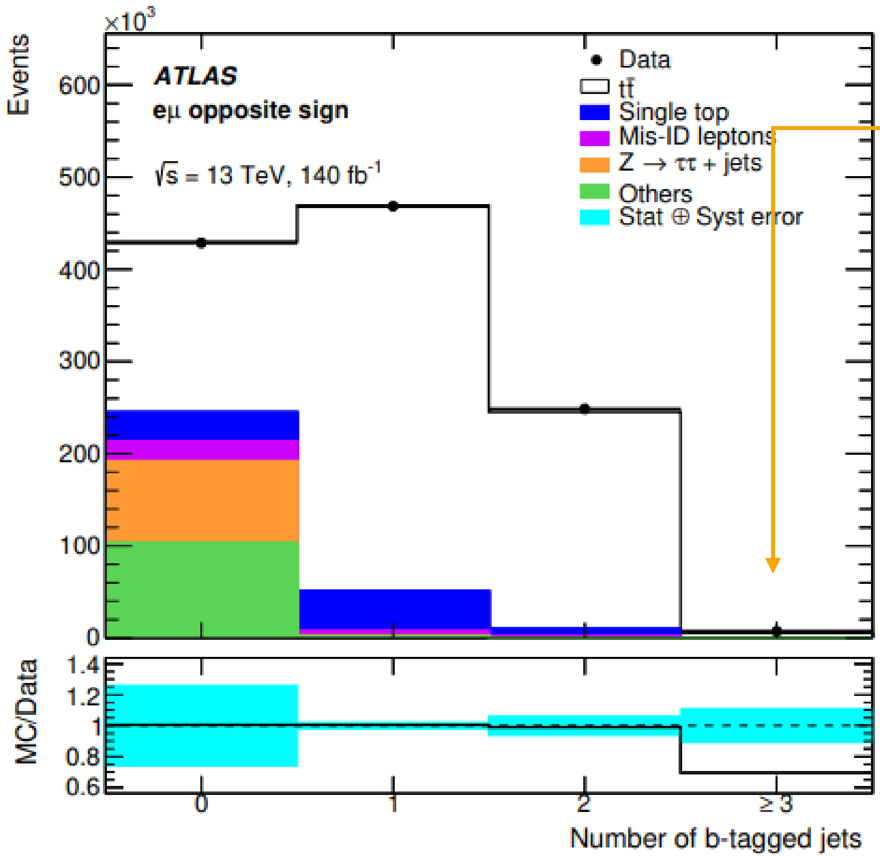
Category	$\delta\sigma(tq+\bar{t}q)/\sigma(tq+\bar{t}q)$ [%]	$\delta R_t/R_t$ [%]
Single-top quark signal modelling	8.6	4.1
Parton distribution functions	0.5	0.8
Misidentified leptons background	6.3	11.1
$W+\geq 1b$ jets modelling	3.9	4.4
$W+\geq 1c$ jets modelling	2.7	3.4
Z+jets normalisation	1.1	2.1
$t\bar{t}$ modelling	0.8	1.2
Single-top quark background modelling	0.6	2.1
$W+\geq 1$ light jets modelling	0.3	0.4
Diboson normalisation	0.1	0.3
Jet energy resolution	4.6	7.8
$\sqrt{s}=5.02$ TeV JES correction	4.4	5.1
Jet energy scale	4.0	5.3
Flavour tagging	2.0	1.3
Electron reconstruction	1.4	0.5
Muon reconstruction	1.3	0.7
Integrated luminosity	1.3	0.4
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.6	2.4
Jet-vertex tagging	0.07	0.05
Simulation's statistical uncertainty	2.3	6.5
Data's statistical uncertainty	16	38
Total systematic uncertainty	15	18
Total uncertainty	21	42

- Some sources of uncertainties increases significantly during the measurement of R_t (e.g. statistical.

Phys. Lett. B 854 (2024) 138726, $\sqrt{s}=5.02\,TeV,\ 255\,pb^{-1}$

Inclusive and differential cross-sections for dilepton $t\bar{t}$ production at 13 TeV

- Focus on the total inclusive cross-section measurement.
- Events must contain an electron, a muon, and either one or two b-tagged jets.
  - All reconstructed objects have $p_T > 25\ GeV$.



- Mismodeling of events with ≥ 3 b-jets are considered using an additional $t\bar{t}$ sample with an enriched rate of events generated with ≥ 3 b-jets.

- Unfold detector-level distributions, validated using bootstrapping.

- Count number of events in fiducial phase space and normalize by number of generated events to calculate total inclusive cross-section.

JHEP 07 (2023) 141, $\sqrt{s} = 13\ TeV,\ 140\ fb^{-1}$

Inclusive and differential cross-sections for dilepton $t\bar{t}$ production at 13 TeV

Source of uncertainty	$\Delta\sigma^{\rm fid}_{t\bar{t}}/\sigma^{\rm fid}_{t\bar{t}}$ [%]	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ [%]
Data statistics	0.15	0.15
MC statistics	0.04	0.04
Matrix element	0.12	0.16
$h_{\rm damp}$ variation	0.01	0.01
Parton shower	0.08	0.22
$t\bar{t}$ + heavy flavour	0.34	0.34
Top $p_{\rm T}$ 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

- The resulting computed total inclusive cross-section is the most precise measurement of the inclusive $t\bar{t}$ cross-section to date.

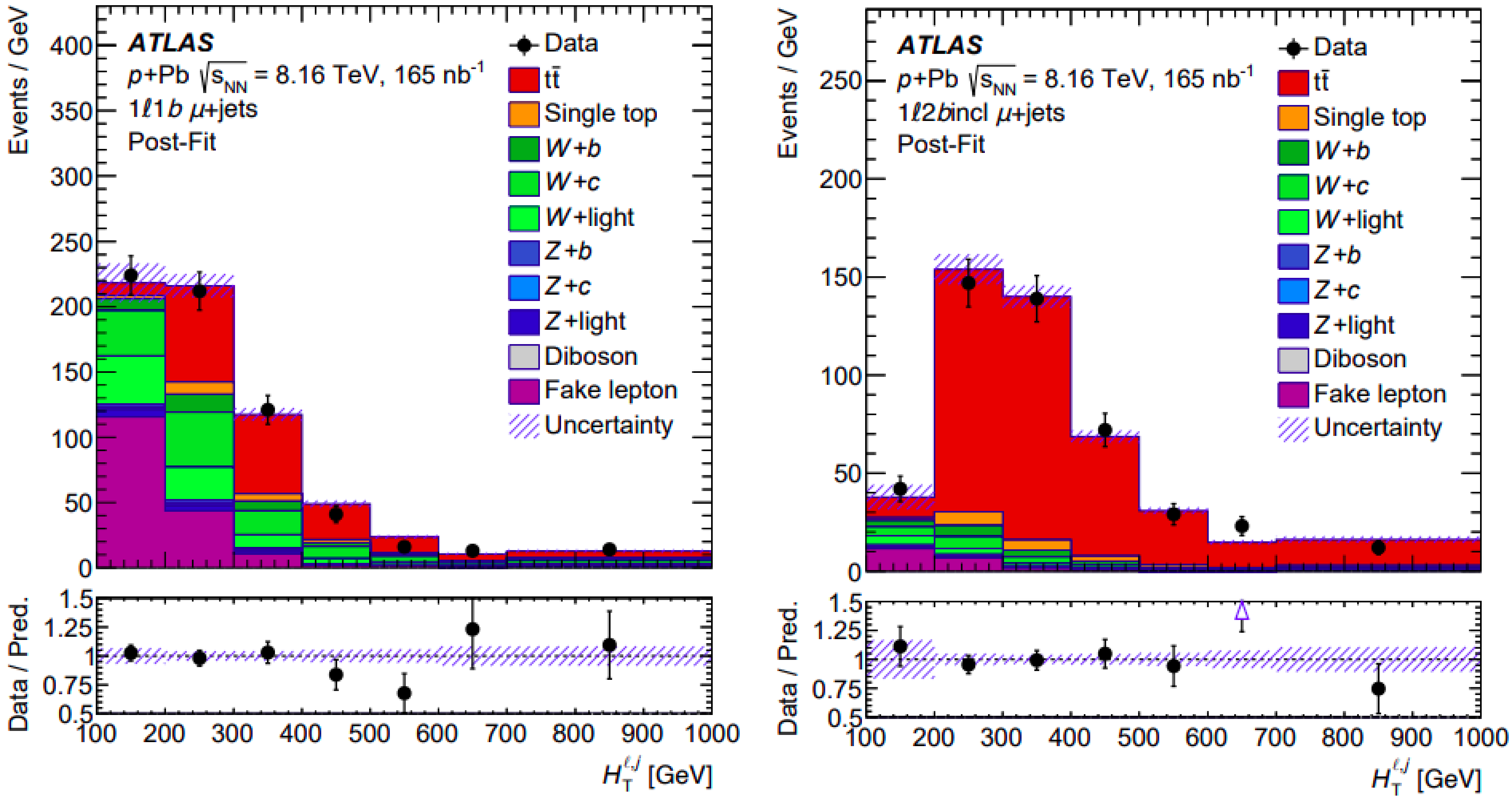
$$\boldsymbol{\sigma_{t\bar{t}} = 829 \pm 1\,(stat.) \pm 13\,(syst.) \pm 8\,(lumi.) \pm 2\,(beam)\,pb}$$

2%

- Improvements in precision can be traced to a reduction in the luminosity uncertainty.
- Final total cross-section is in very good agreement with SM predictions.

JHEP 07 (2023) 141, $\sqrt{s} = 13\,TeV,\ 140\,fb^{-1}$

Observation of top pair production in proton-lead collisions at 8.16 TeV



arXiv:2405.05078, $\sqrt{s_{NN}} = 8.16\ TeV,\ 165\ nb^{-1}$