# Top-quark physics highlights from ATLAS

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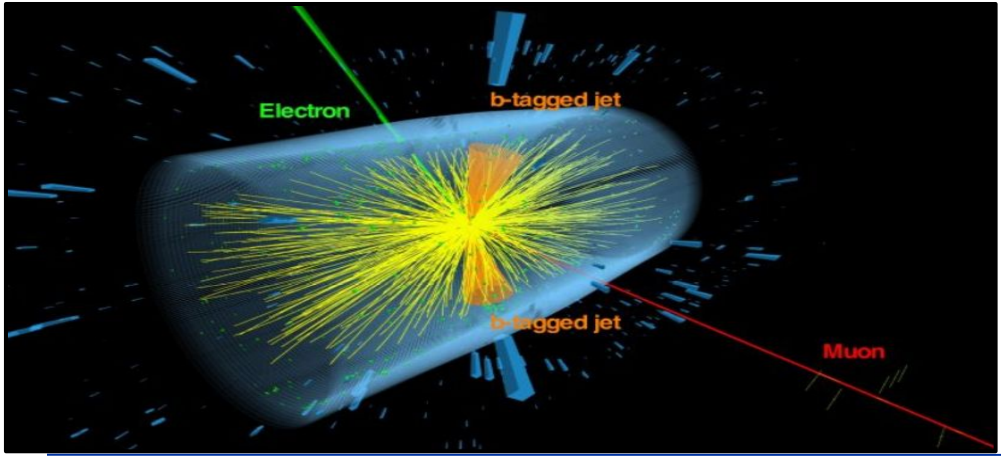
# Top quark physics: State of art

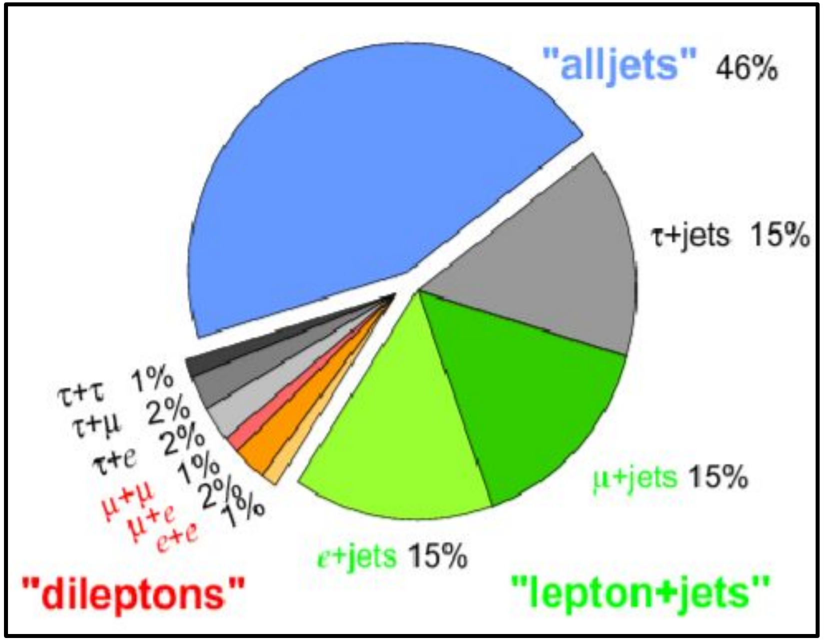
- Is the most massive of all known elementary particles, with a mass of approximately **173 GeV/c²** and carries an electric charge of **+⅔e.**

- Its **discovery in 1995** by the **CDF** and **DØ** collaborations at Fermilab completed the quark sector of the SM.



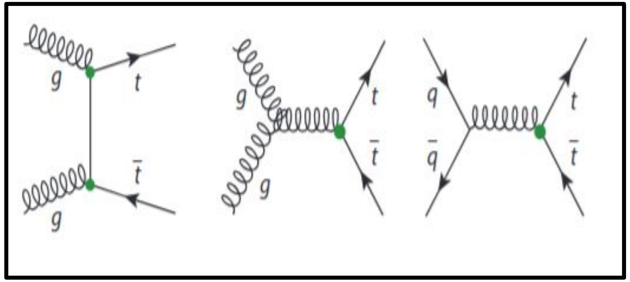

- **Decay characteristics:**
Predominantly into a W boson and a bottom quark (b), with a mean lifetime of about $5 \times 10^{-25}$ seconds, decaying before it can hadronize.

## Branching ratio of top decay

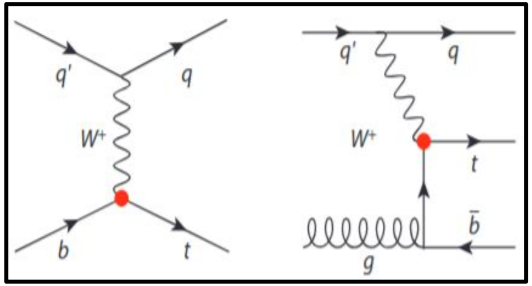


# Top quark physics: State of art

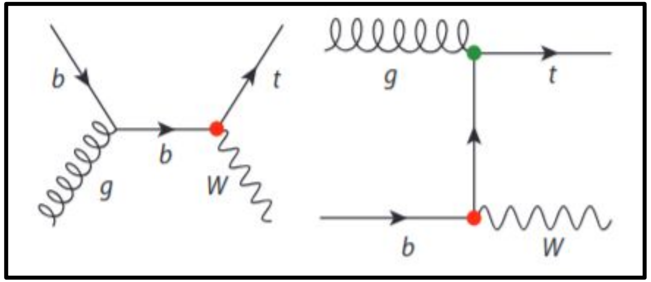
**Pair production**




**t-channel**




**W-associated production**




- **LHC center-of-mass energy** of favors the gluons dominance in the PDFs of the colliding protons;
- **$t\bar{t}$** production is the **dominant** top quark production;
- The inclusive **$t\bar{t}$** cross section allows to test QCD predictions and constraining parameters;
- The final state topology is given in term of W-boson decay mode;

$W \rightarrow l\nu$ (~ 30% ) / $qq'$ (~ 70% )

# Measurement of Single top + W @ $\sqrt{s}$ = 13 TeV

- ***Data Sample:*** proton-proton - **140 fb$^{-1}$** (2015-2018);
- ***Event Selection:***

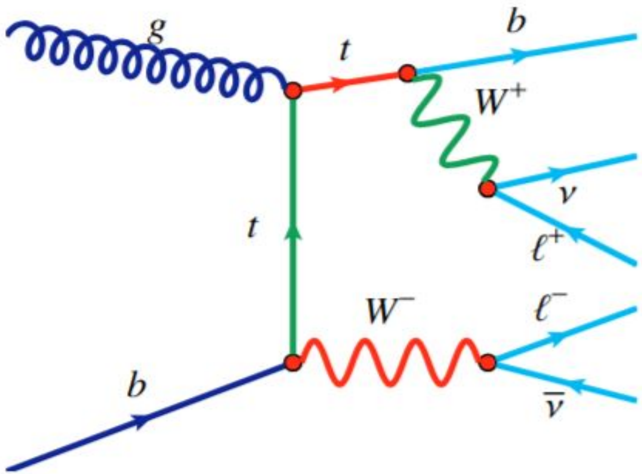
  Two charged oppositely leptons with lower pT threshold
  - **Electron: 24 GeV (26 GeV);**
  - **Muons: 20 GeV (26 GeV) ;**
  - at least **one jet** (originating from a **b-quark**);
- ***Analysis Technique:***
  - Multivariate discriminant to distinguish the **tW** signal from the **$t\bar{t}$** background;
- **Final states:**
  - Exactly one selected jet that is also b-tagged (**1j1b**);
  - Two selected jets one of which is b-tagged (**2j1b**);
  - Exactly two jets where each are $b$-tagged (**2j2b**);

## *Cross section measurements*

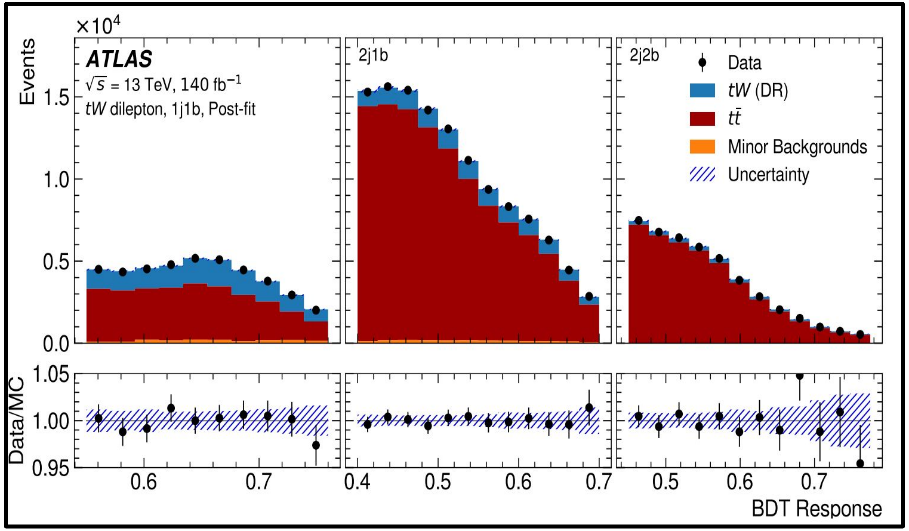
***Phys.Rev.D 110 (2024) 7, 072010***

- MC simulation for signal and background;

***$t\bar{t}$ and tW modelling: PowHegBoxv2@NLO***



# BDT: separate the signal from the tt background




- One BDT is trained for each analysis fit region: simulated tW events serving as signal and simulated $t\bar{t}$ events serving as background;
- Reconstructed final-state objects are used to construct various kinematic quantities ;

# Inclusive cross-section for tW production

$$\mu_{tW} = 0.95^{+0.19}_{-0.18}$$

$$\mu_{t\bar{t}} = 0.99^{+0.07}_{-0.06}$$

$$\sigma_{tW} = 75^{+15}_{-14}\ \text{pb} = 75 \pm 1(\text{stat})^{+15}_{-14}(\text{syst}) \pm 1(\text{lumi})\ \text{pb}$$

$$\sigma^{\text{theory}}_{tW} = 79.3^{+1.9}_{-1.8}(\text{scale}) \pm 2.2(\text{PDF})\ \text{pb}$$

- Likelihood function are Poisson distribution terms that account for the probability of observing the expected yields in data;
- The strength (free) parameters for both the processes as the ratio of the measured cross-section and the MC prediction;

# Major categories: Impact of relative uncertainties in the tW cross-section

| Uncertainty source | $\Delta\sigma_{tW}/\sigma_{tW}$ [%] |
|---|---|
| $t\bar{t}$ modeling | 13.2 |
| Jet energy scale | 12.0 |
| $E_T^{miss}$ reconstruction and calibration | 11.0 |
| $tW$ modeling | 7.9 |
| Jet energy resolution | 7.0 |
| Jet flavor tagging | 3.7 |
| Pileup | 2.5 |
| Lepton ($e$ and $\mu$) reconstruction and calibration | 1.9 |
| Other background modeling | 0.9 |
| Luminosity | 0.8 |
| PDF ($tW$ and $t\bar{t}$) | 0.6 |
| MC statistical uncertainty | 4.7 |
| Total systematic uncertainty | 19.2 |
| Data statistical uncertainty | 1.4 |
| Total uncertainty | 19.3 |

- **Conservative coverage**: some of modeling uncertainties are estimated from a comparison between two alternative MC generators;
- The uncertainty in the measured cross-section is reduced by around 40% compared with the previous ATLAS measurement using a partial Run 2 dataset;
- **Direct extraction of Wtb Vertex Constraint**: left-handed form factor at the Wtb vertex times CKM matrix element **$|f_{LV}V_{tb}|$ = 0.97 ± 0.10 compatible with SM prediction (unity);**

# $t\bar{t}$ + b-jets in eμ @ $\sqrt{s}$ = 13 TeV

- ***Data Sample***: **proton-proton - 140 fb$^{-1}$** (2015-2018);
- ***Event Selection***

- electrons: $p$T = **26, 60** and **140 GeV**;
- muons: $p$**T = 26** and **50 GeV;**

- **Final states:** **$t\bar{t}$+b-jets**:

- Two oppositely charged leptons ($e\pm\ \mu\mp$);
- At least 3 or 4 b-jets;

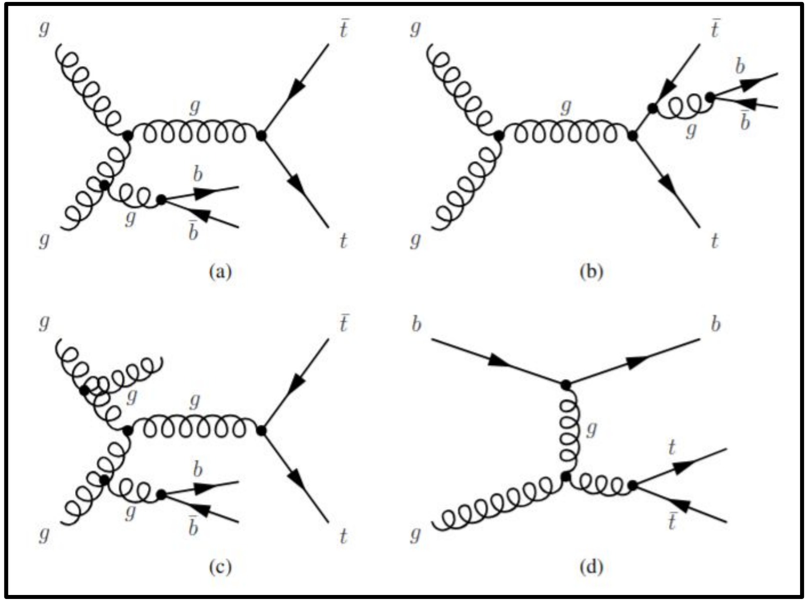
- **Backgrounds:**

- **$t\bar{t}Z$, $t\bar{t}W$, $t\bar{t}$H** (prompt leptons);
- ***tWZ*, *tWH*, *tHbj*, *tZ*** and **$t\bar{t}t\bar{t}$** (rare SM processes);
- Data-driven correction factors ($t\bar{t}$ events): mis-tagged jets in $t\bar{t}c$ and **$t\bar{t}$l** (sig. background).

## *Cross section measurements*

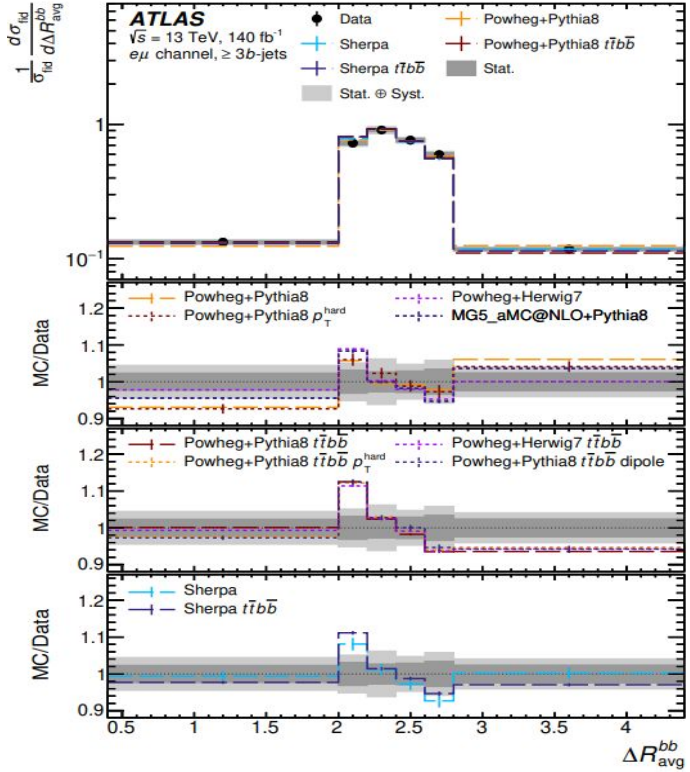
arXiv:2407.13473

***W bosons decay leptonically***




- Helps to probe the MC event generators;

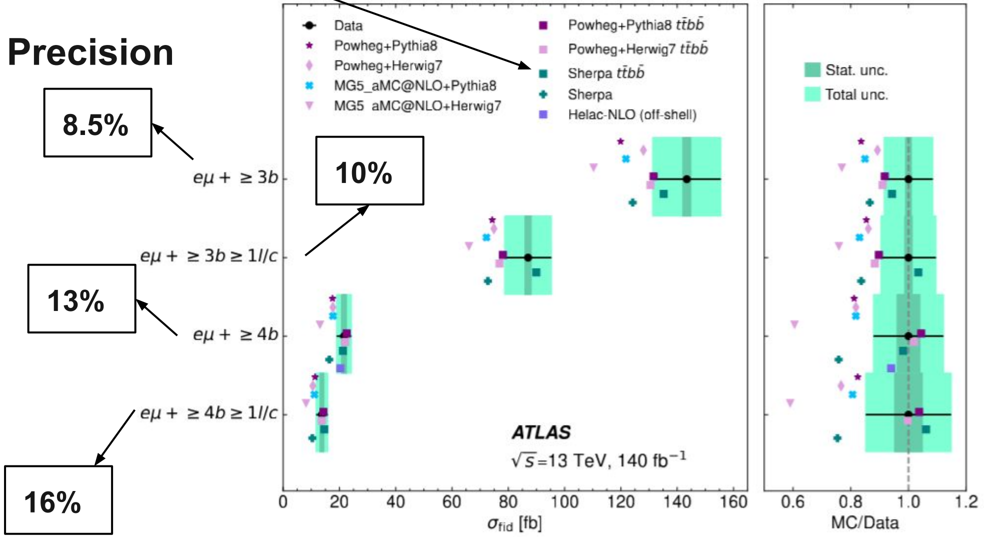
Measured normalised differential cross-section in the phase space with at least three $b$-jets;




## Fiducial cross sections

**Good consistency**

**Precision**




**Dedicated measurement of $t\bar{t}+\geq 2c$ and $t\bar{t}+1c$**

- Custom flavor-tagging algorithm: simultaneous identification of b-jets and c-jets;

**https://arxiv.org/abs/2409.11305**

# Main systematic uncertainties: particle-level measurement of fid. cross sections

| Source | Fiducial cross-section phase space | | | |
|---|---|---|---|---|
| | $\geq 3b$ Unc. [%] | $\geq 3b \geq 1l/c$ Unc. [%] | $\geq 4b$ Unc. [%] | $\geq 4b \geq 1l/c$ Unc. [%] |
| Data statistical uncertainty | 1.0 | 1.2 | 3.9 | 4.8 |
| Luminosity | 0.8 | 0.8 | 0.8 | 0.8 |
| Jet | 3.4 | 5.2 | 6.6 | 8.5 |
| $b$-tagging | 5.1 | 4.9 | 6.5 | 6.4 |
| Lepton and trigger | 1.4 | 1.4 | 1.2 | 1.2 |
| Pile-up | 0.9 | 0.7 | 0.6 | 0.3 |
| $t\bar{t}c/t\bar{t}l$ fit variation | 1.7 | 1.7 | 0.8 | 0.8 |
| $t\bar{t}c/t\bar{t}l$ shape variation | 0.2 | 0.5 | 0.3 | 1.6 |
| $t\bar{t}H/t\bar{t}V$ and non-$t\bar{t}$ background | 1.1 | 1.1 | 2.2 | 2.4 |
| Detector+background total syst. | 6.7 | 7.6 | 9.7 | 11.2 |
| Parton shower and hadronisation | 2.9 | 3.5 | 1.5 | 3.6 |
| $\mu_{\mathrm{R}}$ and $\mu_{\mathrm{F}}$ scale variations | 0.7 | 0.6 | 0.2 | 0.3 |
| Matrix element matching ($p_{\mathrm{T}}^{\mathrm{hard}}$) | 1.3 | 1.1 | 4.8 | 7.0 |
| $h_{\mathrm{damp}}$ | 1.8 | 1.5 | 2.9 | 3.2 |
| ISR | 0.1 | 0.4 | 0.2 | 0.3 |
| FSR | 3.1 | 3.6 | 3.3 | 3.1 |
| RecoilToTop | 1.8 | 1.9 | 2.4 | 3.4 |
| PDF | 0.2 | 0.2 | 0.1 | 0.1 |
| NNLO reweighting | 0.6 | 0.5 | 0.5 | 0.5 |
| MC statistical uncertainty | 0.2 | 0.2 | 0.5 | 0.6 |
| $t\bar{t}$ modelling total syst. | 5.2 | 5.7 | 7.2 | 9.7 |
| Total syst. | 8.5 | 9.6 | 12.1 | 14.8 |
| Total | 8.5 | 9.6 | 12.7 | 15.5 |

- **Dominant sources (unc.)**: $b$-tagging, jet energy scale $t\bar{t}$ modelling uncertainties;
- All models are consistent with data for 2-bjets - The main challenge is to accurately describe the additional $b$-jets production in events with three or more $b$-jets;
- The large uncertainties due to scale variations in the matrix elements are expected to largely cancel in the normalised predictions in fiducial phase space with three or more $b$-jets;
- More data is required to study event with 4 or more b-jets;
- Differences between any two nominal predictions are often smaller than the QCD scale variations of the theory predictions and the uncertainty of the measurement. Further refinement (theo + exp) is required;

# Differential Cross-Sections in $t\bar{t}$ and $t\bar{t}$+jets in lepton+jets channel

- ***Data Sample*:** proton-proton - 140 $fb^{-1}$;
- ***Event Selection*:**

- **Final states: e+jets, μ + jets.**
- **Electrons**:pT > 27 GeV, |η|<2.47*;
- **Muons**: pT > 27 GeV, |η|< 2.5;

- ***Background estimate:***

- Single top (t- and s- channel), W+jets and Z+jets @ NNLO;
- Diboson production: WW,ZZ,WZ - (had + lep) decay;

- Convention: **jet-rad1**(highest pT jet outside the ttbar system)

## *Cross section measurements*

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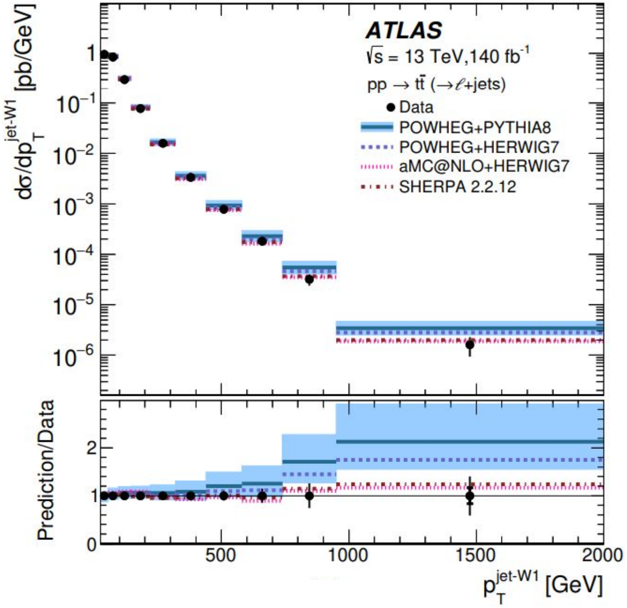
### Observables

**$t\bar{t}$:**pT(jet-W1), pT(jet-W2);
**$t\bar{t}$+1jet:**pT(jet-rad1),Δϕ(jet-W1-jet-rad1), m($t\bar{t}$-jet-rad1);
**$t\bar{t}$+2jets**: Δϕ(jet-W1-jet-rad2)

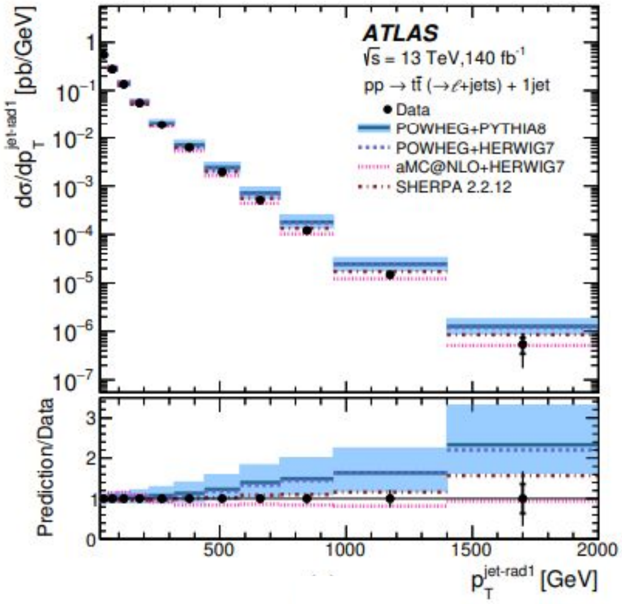
### Total relative systematic uncertainty in the absolute (normalised) cross-sections

- **$t\bar{t}$: ≈ 7% and dominated by the *b*-tagging calibration uncertainty;**
- **$t\bar{t}$ + 1jet: ≈ 10% - dominated by the detector energy scale and resolution;**
- **$t\bar{t}$ +2jets: ≈ 13% - dominated by the detector energy scale and resolution;**

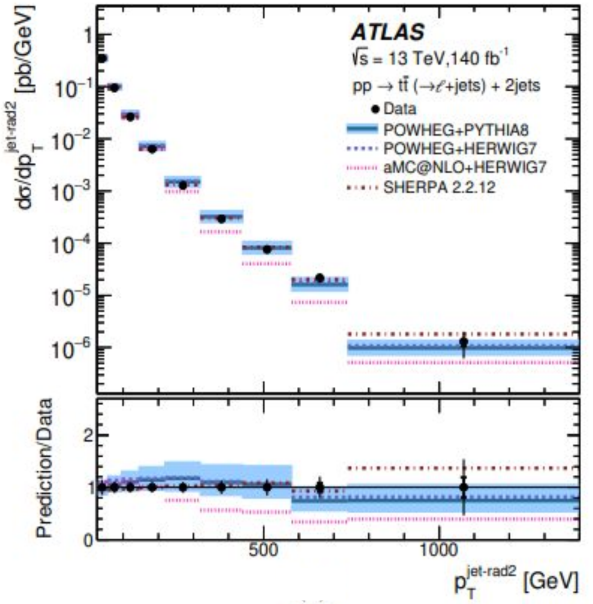
## $t\bar{t}$




## $t\bar{t}$ + 1 jet




## $t\bar{t}$ + 2 jets




- Measured differential cross-sections for $t\bar{t}$ production in the ℓ+jets decay modes;
- For the transverse momentum and invariant mass observables, the NNLO QCD predictions provide a significant improvement;
- NNLO predictions are compared with the measured cross-sections for the first time;

# Inclusive and Differential Cross-Sections in $t\bar{t}\gamma$

## *Cross section measurements*

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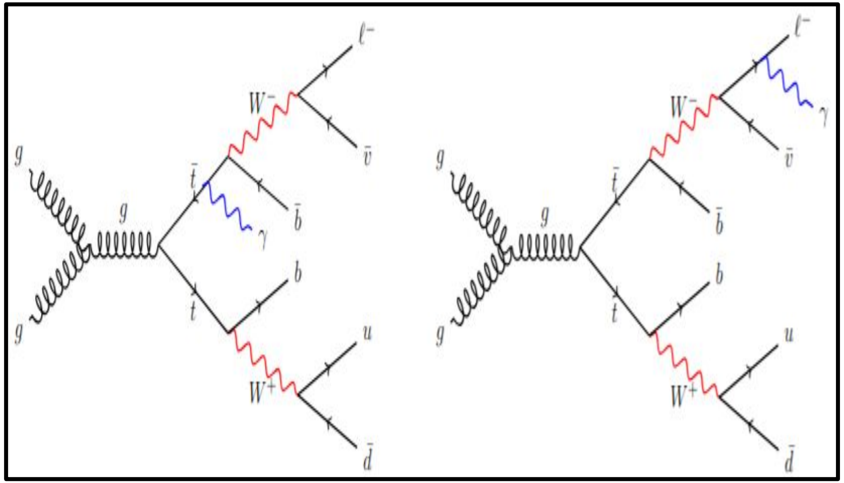
- ***Data Sample*:** **proton-proton - 140 fb$^{-1}$**;
- Inclusive fiducial cross-section for the **$t\bar{t}\gamma$** production process;
- Differential cross-sections: measured in both single-lepton and dilepton decay channels - compared with predictions from NLO simulations (MadGraph5_aMC@NLO + Pythia 8 and Herwig 7);
- Single-Lepton Channel Selection: **=1 (e or μ)**
  >= **4 jets** (>= **1 jet** id as a $b$-jet with **W.P. 70%**);
  **=1γ**: $E_T$ > 20 GeV, $|\eta|$ < 2.37 (1.37 < $|\eta|$ < 1.52);
- Double-Lepton Channel Selection: **=2 (e or μ)**
  >= **4 jets** (>= **2 jet** id as a $b$-jet with **W.P. 70%**);
  **=1γ**: $E_T$ > 20 GeV, $|\eta|$ < 2.37 (1.37 < $|\eta|$ < 1.52);
  MET > 30 GeV;

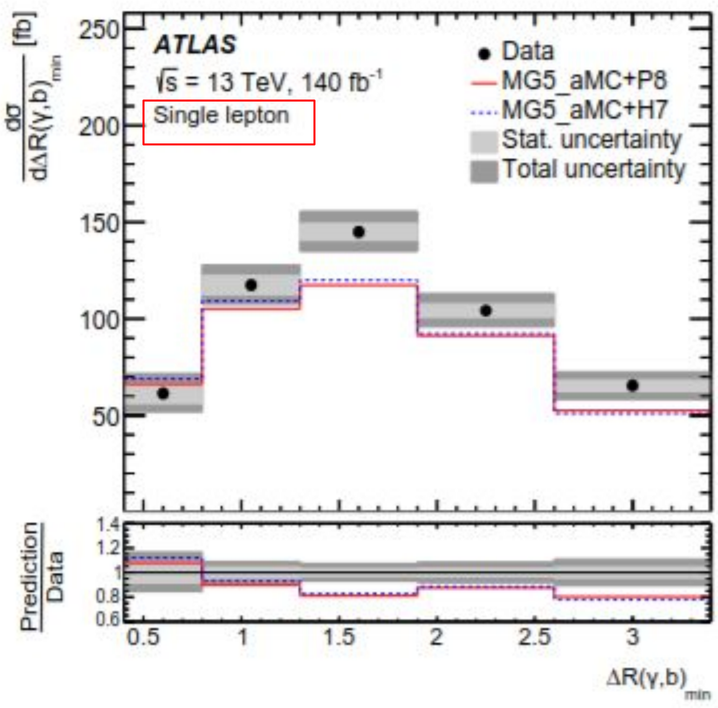



- SMEFT: setting limits on parameters related to the electroweak dipole moments of the top quark;

# Single-Lepton - Fiducial cross sections

**$t\bar{t}\gamma$**
**Total relative uncertainties: 7.8%**

$$\sigma^{\text{Single lepton}}_{t\bar{t}\gamma\text{ production}} = 288^{+21}_{-19}\text{ fb} = 288 \pm 5(\text{stat})^{+20}_{-19}(\text{syst})\text{ fb}$$




**MADGRAPH5_AMC@NLO + Pythia 8**

$$255^{+25}_{-26}(\text{scale})^{+6}_{-4}(\text{PDF})\text{ fb}$$

**$t\bar{t}\gamma$ - All decay modes**
**All $t\bar{t}\gamma$ events are considered (prod+ decay)**

$$\sigma^{\text{Single lepton}}_{t\bar{t}\gamma} = 704^{+49}_{-46}\text{ fb} = 704 \pm 5\,(\text{stat})\,^{+49}_{-46}\,(\text{syst})\text{ fb}$$

## Syst. uncertainties (most relevant)

**Stat: 1.8%, MC stat: 1.5%, $t\bar{t}\gamma$ prod modelling 5.1%, Experimental jet unc: 3.5%, Experimental B-tagging unc: 2.6%**

# Di-Lepton - Fiducial cross sections

$t\bar{t}\gamma$
**Total relative uncertainties: 7.7%**

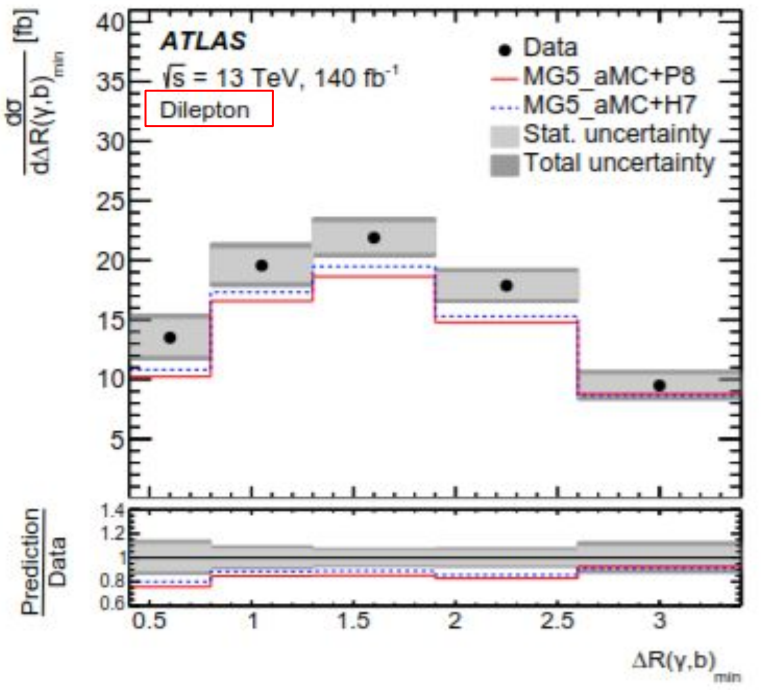
$$\sigma^{\text{Dilepton}}_{t\bar{t}\gamma\text{ production}} = 45.7^{+3.3}_{-3.1}\text{ fb} = 45.7^{+1.4}_{-1.3}(\text{stat})^{+3.0}_{-2.8}(\text{syst})\text{ fb}$$

**MADGRAPH5_AMC@NLO + Pythia 8**

$$40.9^{+3.9}_{-4.0}(\text{scale})^{+0.9}_{-0.5}(\text{PDF})\text{ fb}$$

$t\bar{t}\gamma$ - All decay modes
All $t\bar{t}\gamma$ events are considered (prod+ decay)

$$\sigma^{\text{Dilepton}}_{t\bar{t}\gamma} = 116.1^{+8.2}_{-7.7}\text{ fb} = 116.1 \pm 1.7\,(\text{stat})\,^{+8.0}_{-7.6}\,(\text{syst})\text{ fb}$$




**Syst. uncertainties (most relevant)**

Stat: 3.3%, MC stat: 1.5%, $t\bar{t}\gamma$ prod. PS 3.7%, Experimental jet unc: 3.0%, Experimental B-tagging unc: 2.1%

# SMEFT - $t\bar{t}X$ vertex

$$\mathcal{L}_{t\bar{t}X} = e\bar{t}\left[\gamma^{\mu}\left(C^{X}_{1,\mathrm{V}} + \gamma_5 C^{X}_{1,\mathrm{A}}\right) + \frac{i\sigma^{\mu\nu}q_{\nu}}{m_t}\left(C^{X}_{2,\mathrm{V}} + \gamma_5 C^{X}_{2,\mathrm{A}}\right)\right] tX_{\mu}$$

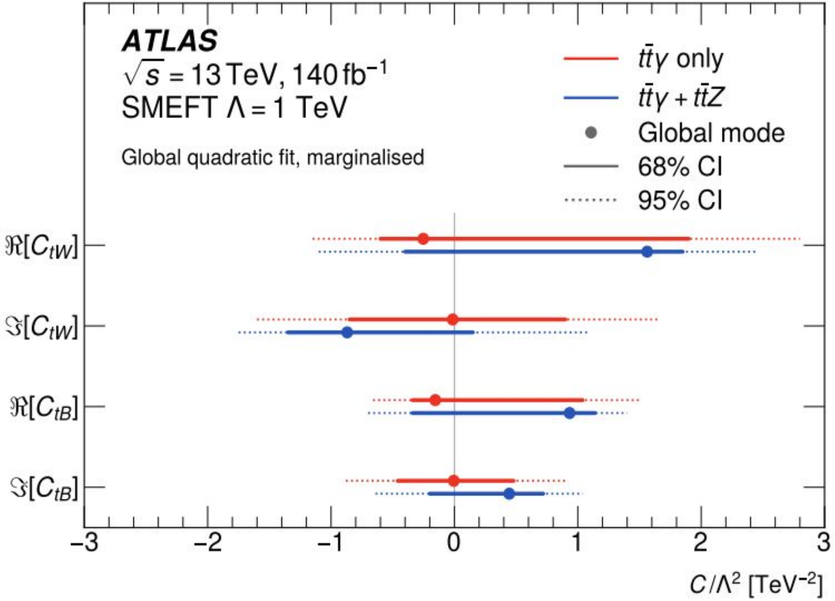
$$C^{Z}_{2,\mathrm{V}} = \frac{v^2 m_t}{\sqrt{2} c_W s_W m_Z \Lambda^2}\Re\left[C_{tZ}\right], \quad C^{Z}_{2,\mathrm{A}} = \frac{v^2 m_t}{\sqrt{2} c_W s_W m_Z \Lambda^2}\Im\left[C_{tZ}\right]$$

$$C^{\gamma}_{2,\mathrm{V}} = \frac{\sqrt{2} v m_t}{e\Lambda^2}\Re\left[C_{t\gamma}\right], \quad C^{\gamma}_{2,\mathrm{A}} = \frac{\sqrt{2} v m_t}{e\Lambda^2}\Im\left[C_{t\gamma}\right],$$

## Limits for $t\bar{t}\gamma$

| Wilson coefficient | | 68% CI (exp.) | 95% CI (exp.) | 68% CI (obs.) | 95% CI (obs.) | Best-fit |
|---|---|---|---|---|---|---|
| $\Re[C_{tW}]$ | $O(\Lambda^{-4})$ (marg.) | [−0.35, 1.9] | [−1.0, 2.7] | [−0.55, 1.9] | [−1.2, 2.8] | −0.21 |
| | $O(\Lambda^{-4})$ (indep.) | [−0.52, 0.60] | [−0.90, 0.98] | [−0.44, 0.46] | [−0.78, 0.84] | −0.01 |
| $\Im[C_{tW}]$ | $O(\Lambda^{-4})$ (marg.) | [−1.1, 1.1] | [−1.9, 2.0] | [−0.95, 0.95] | [−1.8, 1.8] | −0.01 |
| | $O(\Lambda^{-4})$ (indep.) | [−0.58, 0.56] | [−0.96, 0.94] | [−0.48, 0.44] | [−0.84, 0.80] | −0.01 |
| $\Re[C_{tB}]$ | $O(\Lambda^{-4})$ (marg.) | [−0.20, 1.0] | [−0.58, 1.5] | [−0.30, 1.0] | [−0.66, 1.5] | −0.13 |
| | $O(\Lambda^{-4})$ (indep.) | [−0.31, 0.31] | [−0.51, 0.52] | [−0.26, 0.23] | [−0.44, 0.44] | −0.03 |
| $\Im[C_{tB}]$ | $O(\Lambda^{-4})$ (marg.) | [−0.58, 0.62] | [−1.1, 1.1] | [−0.50, 0.54] | [−0.96, 0.98] | −0.01 |
| | $O(\Lambda^{-4})$ (indep.) | [−0.32, 0.31] | [−0.53, 0.51] | [−0.26, 0.24] | [−0.45, 0.44] | −0.01 |

## Limits for $t\bar{t}\gamma$ and $t\bar{t}\gamma$ + $t\bar{t}Z$




- SMEFT interpreted as a function of the photon $p$T;
- Combination with $t\bar{t}Z$ using Z-boson spectra slightly improves the limits;

# Observation of quantum entanglement with $t\bar{t}$ events @ $\sqrt{s}$ = 13 TeV

***Quantum Effects and Novel Observations***

***Nature* 633 (2024) 542**

- ***Data Sample***: **proton-proton - 140 fb$^{-1}$**;
- **Spin correlation between the top-antitop quark**: probe the effects of quantum entanglement;
- If two particles are entangled, the **quantum state of one particle cannot be described independently**;
- **Quantum entanglement** is a key test of the SM and probe for BSM physics;
- **Event selection**:

- **2 leptons: e±μ±,e±e±,μ±μ±;**
- **2 b-jets;**
- **High missing transverse energy;**

***Two-qubit system whose spin quantum state is described by the spin density matrix $\rho$***

$$\rho = \frac{1}{4}\left[I_4 + \sum_i \left(B_i^+\sigma^i \otimes I_2 + B_i^- I_2 \otimes \sigma^i\right) + \sum_{i,j} C_{ij}\sigma^i \otimes \sigma^j\right]$$

***Angular direction of each of these leptons is correlated with the direction of the spin***

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_+ d\Omega_-} = \frac{1 + \mathbf{B}^+ \cdot \hat{\mathbf{q}}_+ - \mathbf{B}^- \cdot \hat{\mathbf{q}}_- - \hat{\mathbf{q}}_+ \cdot \mathbf{C} \cdot \hat{\mathbf{q}}_-}{(4\pi)^2}$$

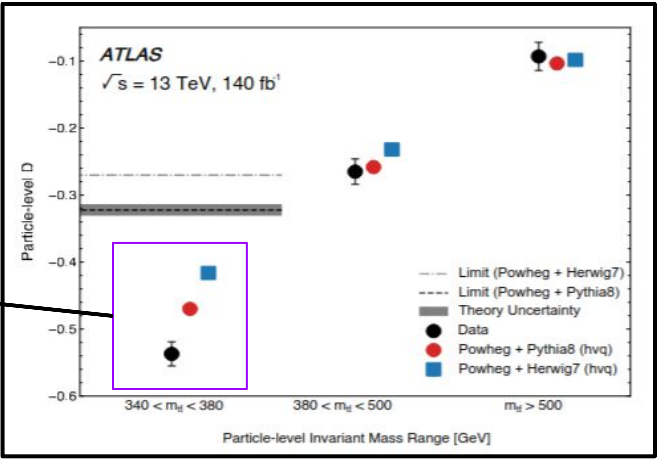
***Entanglement marker - Experimental approach***

$$D = -3 \cdot \langle \cos\varphi \rangle$$

# Measurement of Entanglement Observable (D)

- Angle between charged leptons in the rest frames of their parent top and antitop quarks.

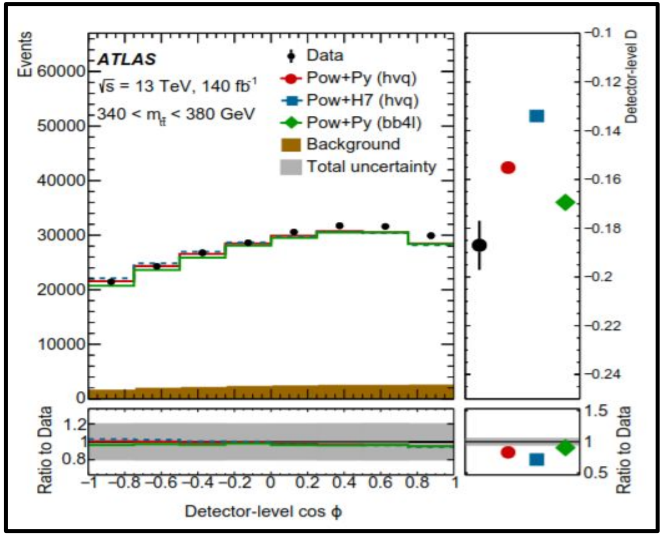
**For 340 < m($t\bar{t}$) < 380 GeV**




$$D = -0.537 \pm 0.002\,[\text{stat.}] \pm 0.019\,[\text{syst.}]$$ **Obs**

$$D = -0.470 \pm 0.002\,[\text{stat.}] \pm 0.017\,[\text{syst.}]$$ **Exp**

**Validation regions:** **380 < m($t\bar{t}$) < 500 GeV, m($t\bar{t}$) > 500 GeV**




**Uncertainties:**

- **Signal modelling: 3.2 (3.2)%;**
- **Backgrounds: 0.9 (1.1)%**
- **total: 3.5 (3.6)%;**

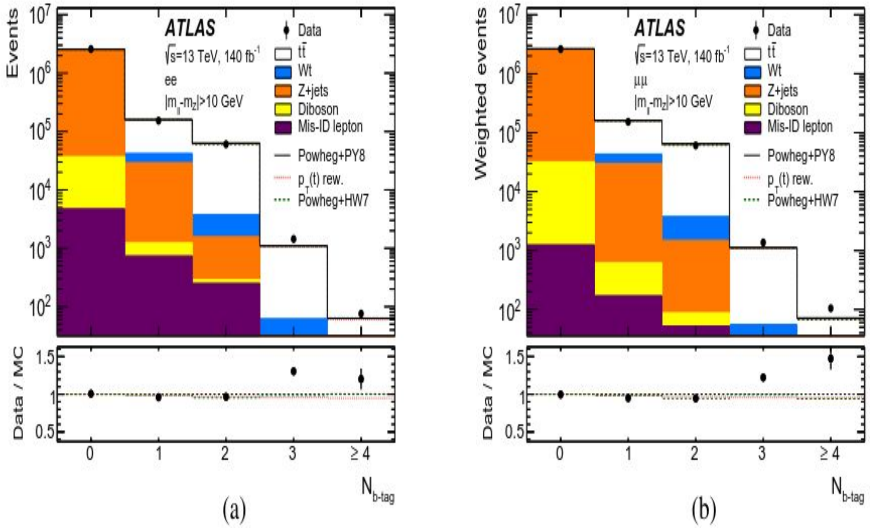
- This result deviates from the **non-entanglement scenario by more than five sigmas;**

# Precise test of lepton flavour universality in W-leptonic decay

**Eur. Phys. J. C 84 (2024) 993**

- ***Data Sample***: **proton-proton - 140 fb⁻¹**;
- **Assumption**: lepton flavour universality in the SM by analyzing the ratios of decay widths of particles into leptons (electrons, muons, and taus);
- **Event selection**: 2 leptons(**e, μ**): pT > 27.3 GeV, $|\eta|$ < 2.47 (2.5); **Events categorized into:** $t\bar{t}$ and Z-boson decay ($Z \to \ell\ell$) based on dilepton invariant mass and b-tagged jet multiplicity;
- **Fit**: number of selected events to predictions based on the assumed cross-sections and efficiencies(via maximum likelihood fit)

| Object selection | | |
|---|---|---|
| Electrons | $p_T > 27.3$ GeV, $\lvert\eta\rvert < 1.37$ or $1.52 < \lvert\eta\rvert < 2.47$ | |
| Muons | $p_T > 27.3$ GeV, $\lvert\eta\rvert < 2.5$ | |
| $b$-tagged jets | $p_T > 30.0$ GeV, $\lvert\eta\rvert < 2.5$, $b$-tagging DL1r 70% | |
| Event selection | $t\bar{t} \to \ell\ell b\bar{b}\nu\bar{\nu}$ | $Z \to \ell\ell$ |
| Dilepton flavour ($\ell^+\ell^-$) | $ee$, $e\mu$, $\mu\mu$ | $ee$, $\mu\mu$ |
| Dilepton invariant mass | $m_{\ell\ell} > 30$ GeV | 66 GeV $< m_{\ell\ell} <$ 116 GeV |
| $b$-tagged jet multiplicity | 1 or 2 | – |



# Fitted distributions

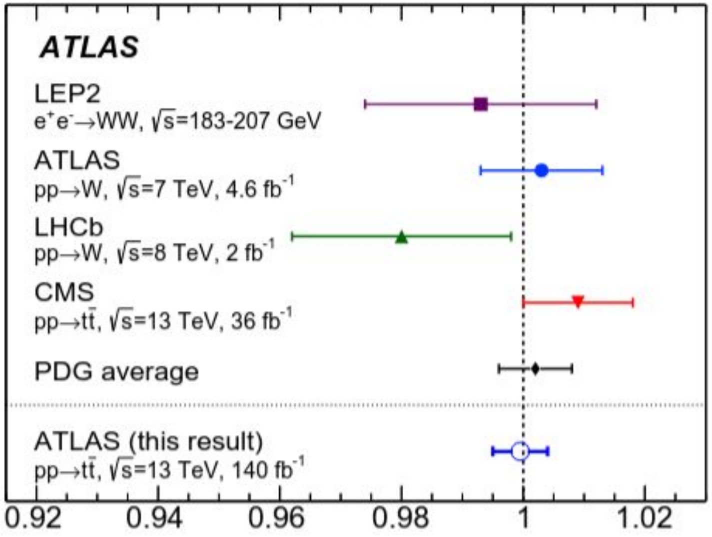
| Event selection | Variable | Bins | Event count |
|---|---|---|---|
| $e\mu$+1 or 2 $b$-tagged jets | $N_{b\text{-tag}}$ | 2 | $N_1^{e\mu}$, $N_2^{e\mu}$ |
| $ee$+1 $b$-tagged jet | $m_{\ell\ell}$ | 6 | $N_{1,m}^{ee}$ |
| $ee$+2 $b$-tagged jets | $m_{\ell\ell}$ | 6 | $N_{2,m}^{ee}$ |
| $\mu\mu$+1 $b$-tagged jet | $m_{\ell\ell}$ | 6 | $N_{1,m}^{\mu\mu}$ |
| $\mu\mu$+2 $b$-tagged jets | $m_{\ell\ell}$ | 6 | $N_{2,m}^{\mu\mu}$ |
| $Z \to ee$ or $\mu\mu$ | channel | 2 | $N_Z^{ee}$, $N_Z^{\mu\mu}$ |

$$\sigma_{t\bar{t}} = 809.5 \pm 1.1 \pm 20.1 \pm 7.5 \pm 1.9\,\text{pb}$$
$$\sigma_{Z\to\ell\ell} = 2019.4 \pm 0.2 \pm 20.7 \pm 16.8 \pm 1.8\,\text{pb}$$

$$R_{WZ}^{\mu/e} = 0.9990 \pm 0.0022 \pm 0.0036$$
$$R_{Z}^{\mu\mu/ee} = 0.9913 \pm 0.0002 \pm 0.0045$$

| Uncertainty [%] | $\sigma_{t\bar{t}}$ | $\sigma_{Z\to\ell\ell}$ | $R_{WZ}^{\mu/e}$ | $R_{Z}^{\mu\mu/ee}$ |
|---|---|---|---|---|
| Data statistics | 0.13 | 0.01 | 0.22 | 0.02 |
| $t\bar{t}$ modelling | 1.68 | 0.03 | 0.10 | 0.00 |
| Top-quark $p_T$ modelling | 1.42 | 0.00 | 0.06 | 0.00 |
| Parton distribution functions | 0.67 | 0.68 | 0.15 | 0.03 |
| Single-top modelling | 0.65 | 0.00 | 0.05 | 0.00 |

$$R_{W}^{\mu/e} = R_{WZ}^{\mu/e}\sqrt{R_{Z-\text{ext}}^{\mu\mu/ee}} = 0.9995 \pm 0.0022\,(\text{stat}) \pm 0.0036\,(\text{syst}) \pm 0.0014\,(\text{ext})$$




- Consistent with the assumption of LFU;
- Most precise measurement to date;
- Smaller unc. from the previous world average;

## Observation of $t\bar{t}$ production in p+Pb collisions in lepton+jets and dilepton channels at $\sqrt{s_{NN}}$ = 8.16 TeV

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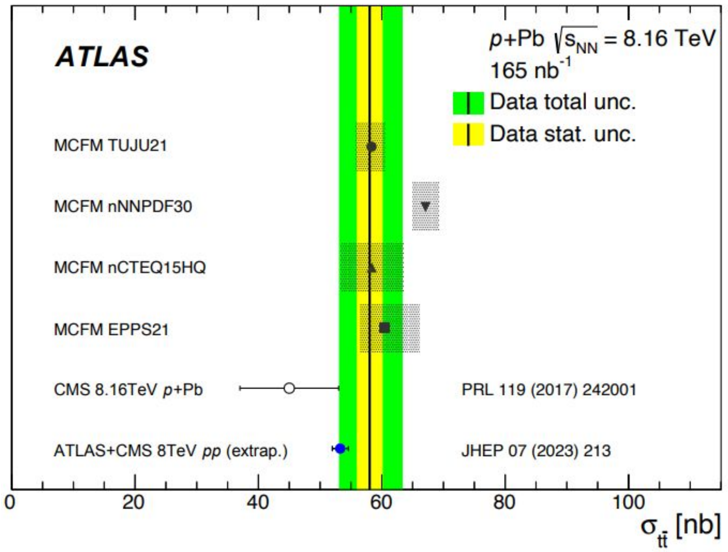
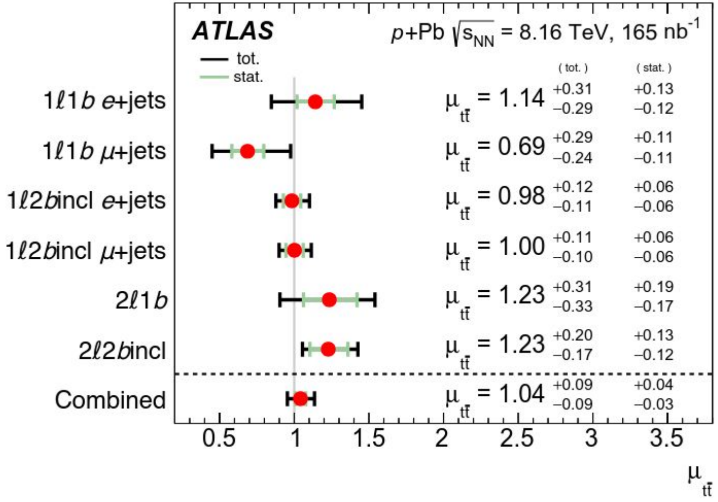
- ***Data Sample*: proton-lead - 165 $nb^{-1}$ (2016);**
- Measurement of the nuclear modification factor for $t\bar{t}$ pair production in p+Pb collisions;
- **Event selection: Single leptonic:** =1 lepton (electron or muon) with pT > 15 GeV and >= 4 jets (>= 1 b-tagged jet);
  **Dileptonic:** =2 opposite-charge leptons with additional Invariant mass cuts and >= 2 jets;
- **Top-quark pair cross section**: observed with a significance higher than 5 sigma in both channels with a total uncertainty of 9%;

$$\sigma_{t\bar{t}} = 58.1 \pm 2.0\ (\text{stat.})\ ^{+4.8}_{-4.4}\ (\text{syst.})\ \text{nb}$$




| Source | $\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ unc. up [%] | 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 |

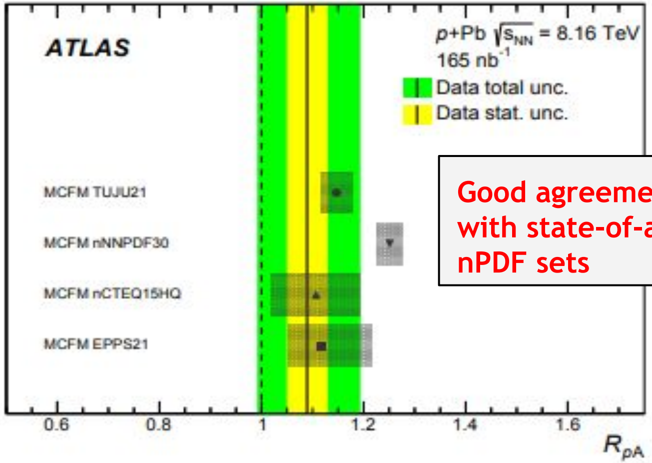
$$\sigma_{t\bar{t}} = \mu_{t\bar{t}} \cdot A_{\text{Pb}} \cdot \sigma_{t\bar{t}}^{\text{th}}$$




- $\mu_{t\bar{t}}$ are consistent with the SM predictions. Confirms the observation of $t\bar{t}$ production in p+Pb collisions for the first time at the LHC;

$$R_{pA} = \frac{\sigma_{t\bar{t}}^{p+\text{Pb}}}{A_{\text{Pb}} \cdot \sigma_{t\bar{t}}^{pp}}$$ → **Nuclear modification factor**

$$R_{pA} = 1.090 \pm 0.039\ (\text{stat.})\ ^{+0.094}_{-0.087}\ (\text{syst.})$$




Good agreement with state-of-art nPDF sets

- The measured value is found to be consistent with unity within the uncertainty.
- New way to constrain nPDFs in the high Bjorken-$x$;
- Input for upcoming measurements involving the extraction of QGP properties in Pb+Pb collisions;

# Observation of $t\bar{t}$ production in Pb+Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

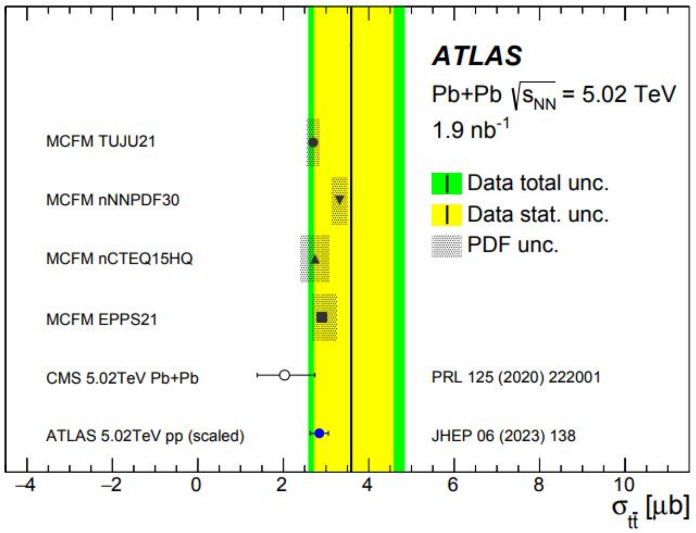
**arXiv: 2411.10186 - Submitted to Phys. Rev. Lett.**

- *Data Sample*: lead-lead - 1.9 $nb^{-1}$ (2015 and 2018);
- Investigate the **presence of all quark flavors** in the **pre-equilibrium stage of the QGP**;
- Event selection: =1 electron and =1 muon with m($e\mu$)> 30 GeV; >= 2 jets with pT ≥ 35 GeV;
- Centrality intervals using a Glauber model, focusing on the 0–80% (prevent photon-induced processes);

**Production cross section**

$$\sigma_{t\bar{t}} = 3.6^{+1.0}_{-0.9}\,(\text{stat.})\,^{+0.8}_{-0.5}\,(\text{syst.})\,\mu b$$

- Observed (expected) significance: **5.0 (4.1)**;




- Total relative uncertainty: 31%, primarily stat. unc.-limited data sample size;
- Statistical: 26%;
- Systematic: 18%;
- Good agreement with SM predictions; indicating the presence of all quark flavors in the pre equilibrium stage of QGP.

# Conclusions

## *Precision Cross-Sections*

- High-accuracy measurements of tt cross-section  for 13 TeV: differential studies exploring top quark kinematics and spin correlations;

## Single Top Quark Production

- Detailed studies of electroweak production modes tW,tb,ttZ and observation of rare tWZ production;

## Higgs-Top Coupling

- Direct measurements of the Yukawa coupling strength and evidence of top-mediated Higgs production;

## New Physics searches and HI Physics

- Strong portal do look for BSM physics;
- Top quark in pPb and PbPb collisions;

# Conclusions

- Joint contributions with CMS to (have) refine(d) SM predictions;
- Complementary results enhance understanding of the top quark’s role in electroweak symmetry breaking;

**More to come …**

## Toponium

- Hypothetical bound state of a $t\bar{t}$ pair analogous to quarkonium predicted in scenarios of strong coupling or near-threshold production;

- Sheds light on QCD at high energies and potential new interactions and provides constraints on top quark-antiquark dynamics in the threshold region;

## Challenges to overcome at LHC/ HL-LHC

- Precise id algorithms, solid computational setup to deal with high pile-up, quality of data acquisition.

See public results at: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults


**Dziękuję bardzo!**

# Thank you!

**Muito obrigado!**

## Behind every "plot", we have:

- Physicists, engineers, technicians and support staff from around the world;
- One of the largest collaborative efforts ever attempted in science;

# Back-up slides

# Measurement of single top-quark production in association with a $W$ boson in $pp$ collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

*Phys.Rev.D 110 (2024) 7, 072010*

## Table of events - yield

| | 1j1b | 2j1b | 2j2b |
|---|---|---|---|
| Pre-fit $tW$ | 13 000 ± 1400 | 11 900 ± 1200 | 2000 ± 400 |
| Pre-fit $t\bar{t}$ | 28 000 ± 4000 | 112 000 ± 8000 | 43 000 ± 4000 |
| Pre-fit $Z$+jets | 1130 ± 160 | 750 ± 100 | 38 ± 12 |
| Pre-fit diboson | 380 ± 80 | 570 ± 130 | 8.5 ± 1.3 |
| Pre-fit non-prompt | 140 ± 70 | 450 ± 220 | 54 ± 27 |
| Pre-fit total prediction | 43 000 ± 5000 | 126 000 ± 8000 | 45 000 ± 4000 |
| Post-fit $tW$ | 12 500 ± 2000 | 11 400 ± 2200 | 2000 ± 400 |
| Post-fit $t\bar{t}$ | 27 400 ± 2000 | 110 300 ± 2200 | 42 100 ± 500 |
| Post-fit $Z$+jets | 1100 ± 120 | 750 ± 80 | 38 ± 6 |
| Post-fit diboson | 380 ± 80 | 570 ± 120 | 8.6 ± 1.1 |
| Post-fit non-prompt | 140 ± 70 | 450 ± 220 | 53 ± 27 |
| Post-fit total prediction | 41 600 ± 210 | 123 500 ± 400 | 44 150 ± 210 |
| Data | 41 591 | 123 531 | 44 149 |

## BDT Parameters

| Region | Learning rate | Number of leaves | Minimum data in a leaf | Maximum depth |
|---|---|---|---|---|
| 1j1b | 0.2 | 20 | 50 | 4 |
| 2j1b | 0.1 | 20 | 120 | 7 |
| 2j2b | 0.2 | 20 | 50 | 4 |

# Measurements of inclusive and differential cross-sections of $t\bar{t}\gamma$ production in $pp$ collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

*JHEP* 10 (2024) 191

| Category | Single-lepton channel | Dilepton channel |
|---|---|---|
| $t\bar{t}\gamma$ production | 12450 ± 740 | 2400 ± 99 |
| $t\bar{t}\gamma$ decay | 13400 ± 3100 | 3100 ± 640 |
| h-fake | 3600 ± 1200 | 220 ± 82 |
| e-fake | 6900 ± 980 | 57.9 ± 7.0 |
| $W\gamma$ | 2700 ± 1400 | – |
| $tW\gamma$ | 1180 ± 580 | 290 ± 150 |
| Other prompt $\gamma$ | 2500 ± 600 | 820 ± 170 |
| Lepton fake | 640 ± 110 | – |
| Total | 43900 ± 4600 | 6900 ± 710 |
| Data | 47767 | 7379 |

## Combined results - Single Lepton

$$\sigma_{t\bar{t}\gamma\ \text{production}} = 319 \pm 15\ \text{fb} = 319 \pm 4\ (\text{stat})\ ^{+15}_{-14}(\text{syst})\ \text{fb}$$

## Combined results - Dilepton

$$\sigma_{t\bar{t}\gamma} = 788^{+38}_{-37}\ \text{fb} = 788 \pm 5\ (\text{stat})\ ^{+38}_{-37}\ (\text{syst})\ \text{fb}$$

## SMEFT Approach

**Lagrangian for the tt$X$ vertex (with $X = \gamma, Z$)**

$$\mathcal{L}_{t\bar{t}X} = e\bar{t}\left[\gamma^{\mu}\left(C^{X}_{1,\text{V}} + \gamma_5 C^{X}_{1,\text{A}}\right) + \frac{i\sigma^{\mu\nu}q_{\nu}}{m_t}\left(C^{X}_{2,\text{V}} + \gamma_5 C^{X}_{2,\text{A}}\right)\right] tX_{\mu}$$

$$C^{Z}_{2,\text{V}} = \frac{v^2 m_t}{\sqrt{2}c_W s_W m_Z \Lambda^2}\Re\left[C_{tZ}\right], \quad C^{Z}_{2,\text{A}} = \frac{v^2 m_t}{\sqrt{2}c_W s_W m_Z \Lambda^2}\Im\left[C_{tZ}\right],$$

$$C^{\gamma}_{2,\text{V}} = \frac{\sqrt{2}v m_t}{e\Lambda^2}\Re\left[C_{t\gamma}\right], \quad C^{\gamma}_{2,\text{A}} = \frac{\sqrt{2}v m_t}{e\Lambda^2}\Im\left[C_{t\gamma}\right],$$

$$C_{tZ} = c_W \cdot C_{tW} - s_W \cdot C_{tB}$$

$$C_{t\gamma} = s_W \cdot C_{tW} + c_W \cdot C_{tB}$$

# $t\bar{t}$ + b-jets in eμ @ √s = 13 TeV

| Fiducial phase space | Fiducial cross-sections [fb] $\geq 3b$ | $\geq 3b \geq 1l/c$ | $\geq 4b$ | $\geq 4b \geq 1l/c$ |
|---|---|---|---|---|
| Measured | 143 ±1 (stat) ±12 (syst) | 87 ±1 (stat) ±8 (syst) | 22 ±1 (stat) ±3 (syst) | 14 ±1 (stat) ±2 (syst) |
| Powheg+Pythia 8 $t\bar{t}b\bar{b}$ (4FS) | 132 | 78 | 23 | 14 |
| Powheg+Pythia 8 $t\bar{t}b\bar{b}$ $h_{bzd}$ (4FS) | 129 | 74 | 21 | 13 |
| Powheg+Pythia 8 $t\bar{t}b\bar{b}$ dipole (4FS) | 128 | 71 | 22 | 13 |
| Powheg+Pythia 8 $t\bar{t}b\bar{b}$ $p_{T}^{hard}$ (4FS) | 129 | 68 | 21 | 12 |
| Powheg+Herwig 7 $t\bar{t}b\bar{b}$ (4FS) | 130 | 77 | 22 | 14 |
| Sherpa $t\bar{t}b\bar{b}$ (4FS) | 135 | 90 | 21 | 15 |
| Helac-NLO (off-shell) $e\mu + 4b$ | – | – | 20 | – |
| Powheg+Pythia 8 $t\bar{t}$ (5FS) | 120 | 74 | 18 | 11 |
| Powheg+Herwig 7 $t\bar{t}$ (5FS) | 128 | 75 | 18 | 11 |
| MG5_aMC@NLO+Pythia8 $t\bar{t}$ (5FS) | 122 | 72 | 18 | 11 |
| MadGraph5_aMC@NLO+Herwig 7 $t\bar{t}$ (5FS) | 110 | 66 | 13 | 8 |
| Sherpa 2.2.12 $t\bar{t}$ (5FS) | 124 | 73 | 16 | 10 |