
# Highlights on top quark physics with the ATLAS Experiment at the LHC

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ATLAS EXPERIMENT


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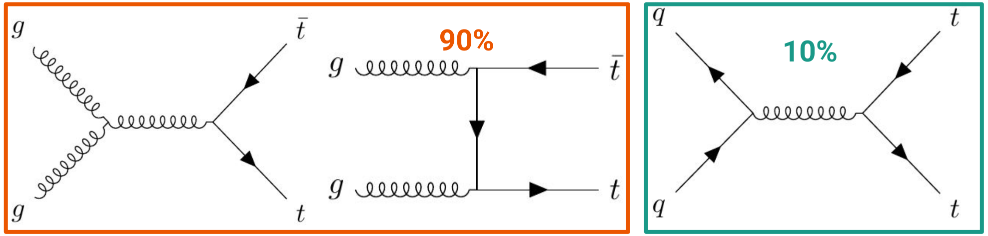
# Top quark physics

In pp collision at 13TeV:



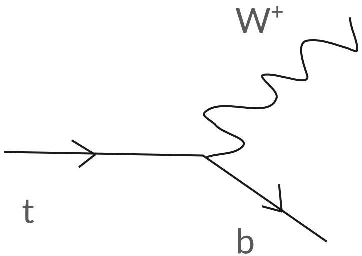

## Top quark has unique properties

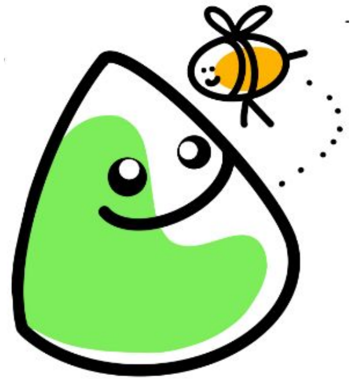
- The **heaviest** known fundamental particle
- The **largest Yukawa** coupling to **Higgs** $\lambda_t \sim 1$
- Lifetime ~$10^{-25}$s  smaller than hadronization time ~$10^{-24}$s = **possibility to study "bare" quark properties**, e.g. spin is transferred to decay products (leptons, down-type quarks)
- Plays important role in EWSB

**LHC** is a top-quark factory ~ **200M top quarks** produced in Run2!

- Top quark dominantly produced in $t\bar{t}$ pairs
- Allows to perform precise measurements

**Top decays** almost exclusively to **W** and **b quark**

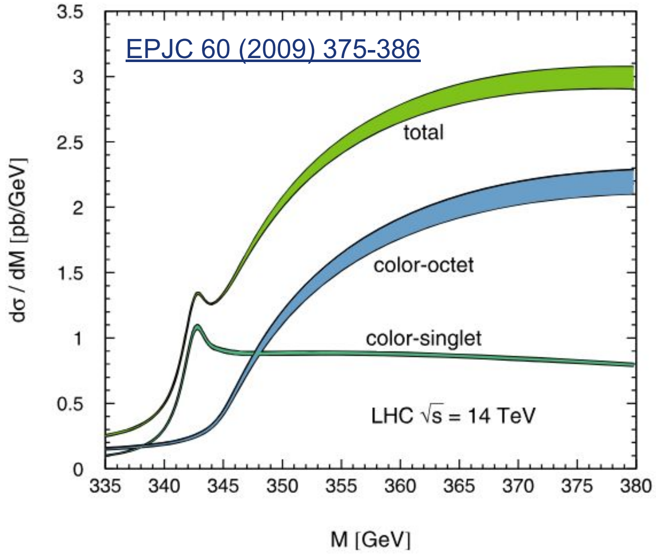


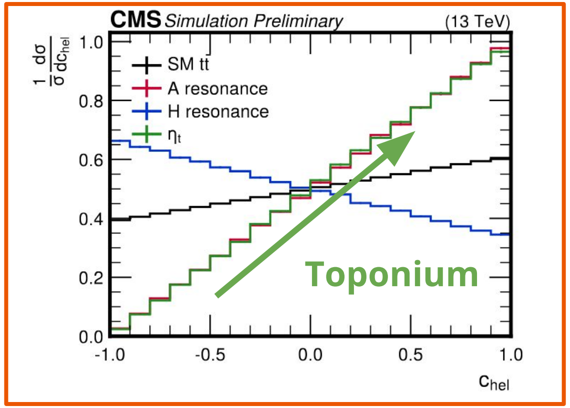



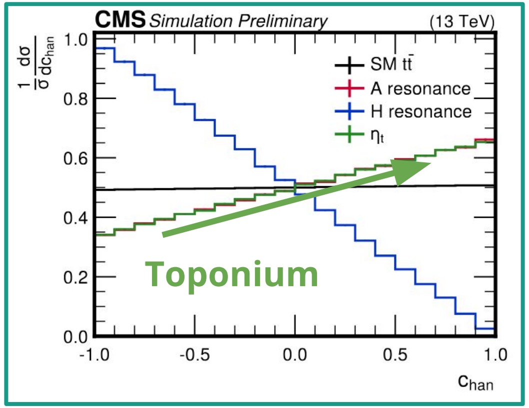
# Observation of Xsection enhancement near $t\bar{t}$ threshold

**Toponium** = Quasi-bound state of top quarks predicted by SM

- Not the same as $b\bar{b}$/$c\bar{c}$ (**not a s-channel resonance**)
  - one of top decays first, they do not annihilate themselves
- Pseudoscalar nature dominant - translated to angular properties of top decay products
- Not sensitive enough to be observed in $m_{t\bar{t}}$ spectrum
  - Use variables $c_{hel}$ and $c_{han}$ sensitive to spin-correlations



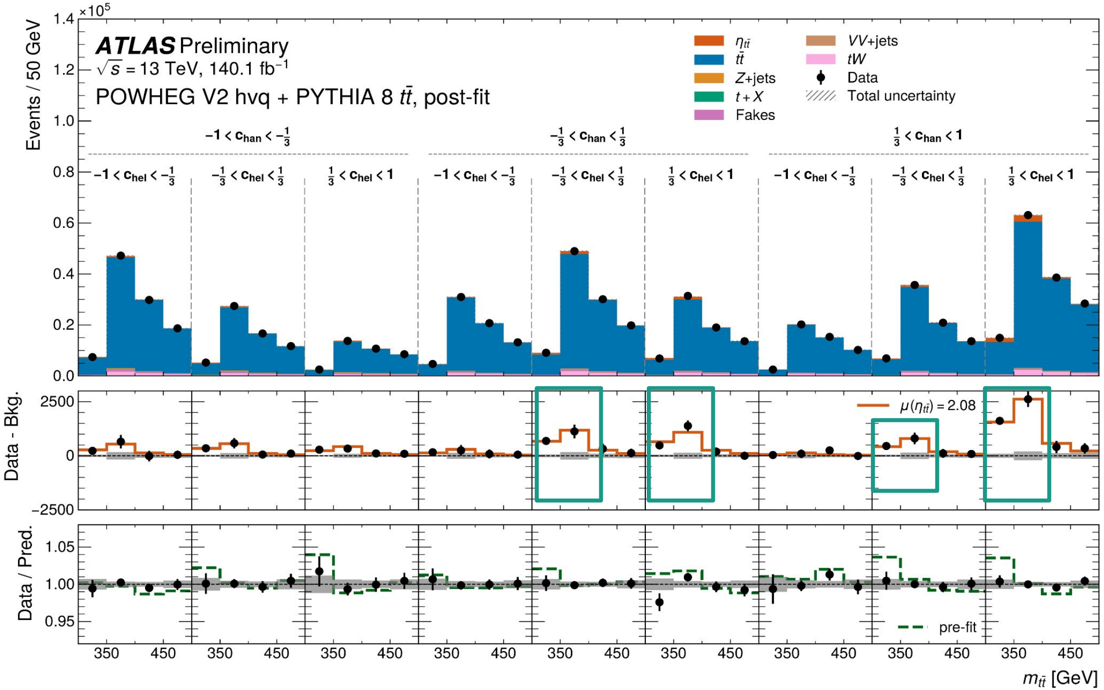

Observed previously by CMS [CMS-TOP-24-007, CMS-PAS-HIG-22-013]

$\eta_t$ = BSM-like pseudoscalar color-singlet resonance

CMS-PAS-HIG-22-013

# Observation of Xsection enhancement near $t\bar{t}$ threshold

- Dileptonic $t\bar{t}$ events with $\mathbf{m_{t\bar{t}} \leq 500}$ **GeV**, events divided into 9 SR in $c_{hel}$, $c_{han}$ and $m_{t\bar{t}}$
- Formation of quasi-bound-state described in non-relativistic QCD (NR-QCD) = $t\bar{t}_{NR\text{-}QCD}$ model NEW!
  - Focuses on a toponium-like spin-singlet colour-singlet component




Profile-likelihood fit of 2 models to data (with/without $t\bar{t}_{NR\text{-}QCD}$)

$t\bar{t}$ reconstructed via Ellipse method [Nucl. Instrum. Meth. A 736 (2014) 169]

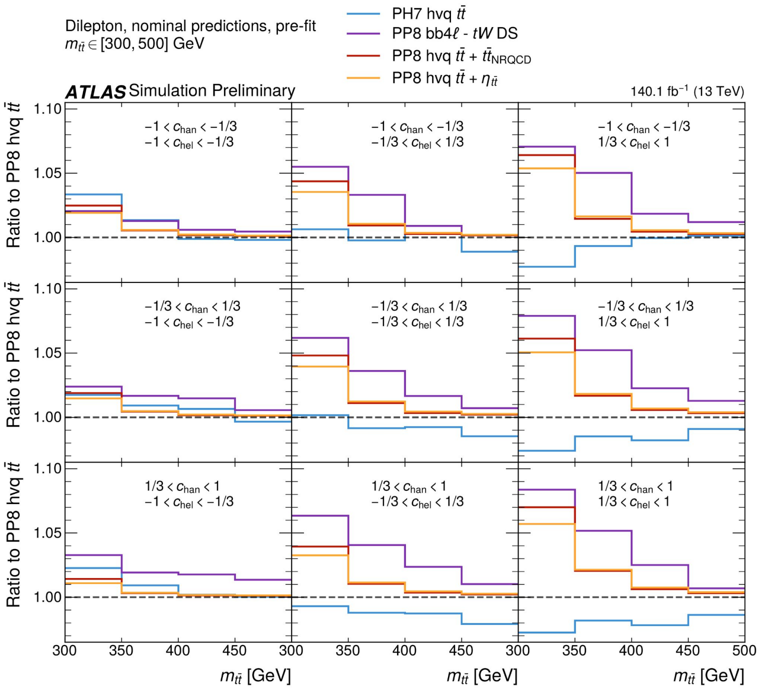
**Excess** of events compared to baseline (without $t\bar{t}_{NR\text{-}QCD}$ effects) in all SRs **at low** $\mathbf{m_{t\bar{t}}}$-values, notably for **larger** $\mathbf{c_{hel}}$ **and** $\mathbf{c_{han}}$ values

**Baseline** model is **rejected** with an observed (expected) **significance** of **7.7σ** (5.7σ)

# Observation of Xsection enhancement near $t\bar{t}$ threshold

Measured Xsection of $t\bar{t}$ quasi-bound state:

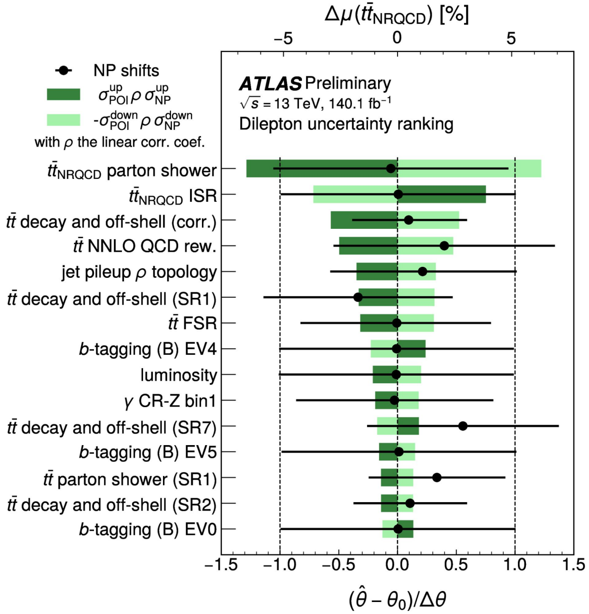
$$\sigma(t\bar{t}_{\text{NR-QCD}}) = 9.0 \pm 1.3 \text{ pb} = 9.0 \pm 1.2 \text{ (stat.)} \pm 0.6 \text{ (syst.)}$$




**Extremely challenging measurement**:

Need more precise models of the threshold region and toponium signal, understanding of NLO EW and NNLO QCD corrections to production
NLO and off-shell effects in decay, etc.

**Further studies needed to investigate the nature of this excess**




Measurement precision limited by signal and background modelling uncertainties.

# Top pole mass from tt̄+j events (dilepton channel)

**First time tt̄+1 jet $m_t^{pole}$ analysis in dilepton channel!**

Top-quark mass $\mathbf{m_t^{pole}}$ is a free parameter of the SM
Motivation: consistency checks of SM, electroweak vacuum stability

Special observable **R**

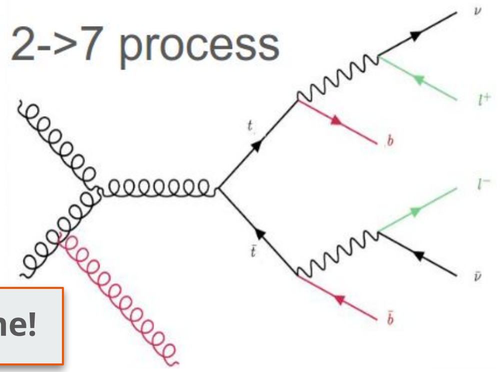
$$\mathcal{R}(\rho_s; m_t^{\text{pole}}) = \frac{1}{\sigma_{t\bar{t}+1\text{-jet}}} \cdot \frac{d\sigma_{t\bar{t}+1\text{-jet}}}{d\rho_s}, \text{ with } \rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}+1\text{-jet}}}}$$

- **High sensitivity** to top-quark mass ($\varrho_s > 0.7$)
- **Normalized** = many uncertainties reduce in ratio
- $m_0$ = 170 GeV → R ∈ [0,1] (convention has no impact on result)

Two fixed-order NLO QCD calculations used to extract $m_t^{pole}$ from Xsection (provides consistency in theoretical definition of $m_t$):

- **New** calculations with **decayed top quarks** available (off-shell effects) [JHEP 11 (2016) 098]

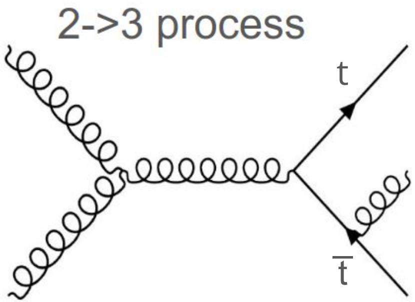
pp→ bb4ℓj




**Used for the first time!**

- Improved settings for **stable top-quarks** calculation [JHEP 05 (2022) 146]

pp→ tt̄ + jet

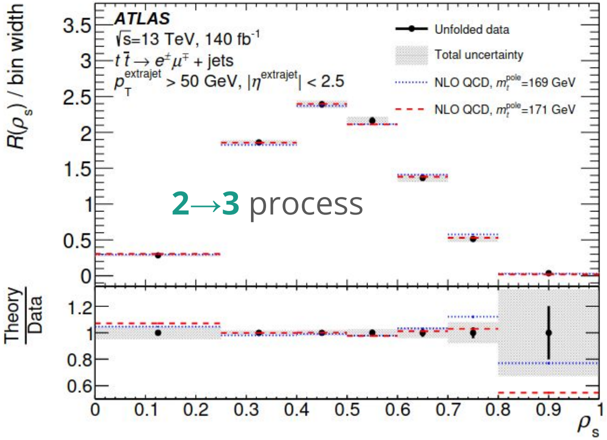



**R** is defined for both, but effectively 2 different observables

# Top pole mass from $t\bar{t}$+j events (dilepton channel)

Measure **normalized Xsection** in $e^{\pm}\mu^{\mp}$ channel of $t\bar{t}$ system + at least 1 jet as a **function of** $m_{t\bar{t}+1\text{-jet}} = \varrho_s$

- Unfolded to parton level with Iterative Bayesian Unfolding
  - Parton level definition depends on the process (**2→3** or **2→7**)
- $\chi^2$ fit of $R(\varrho_s; m_t^{pole})$ to fixed-order NLO QCD predictions dependent on $m_t^{pole} \in [166.0, 179.0]$ GeV to extract $m_t^{pole}$

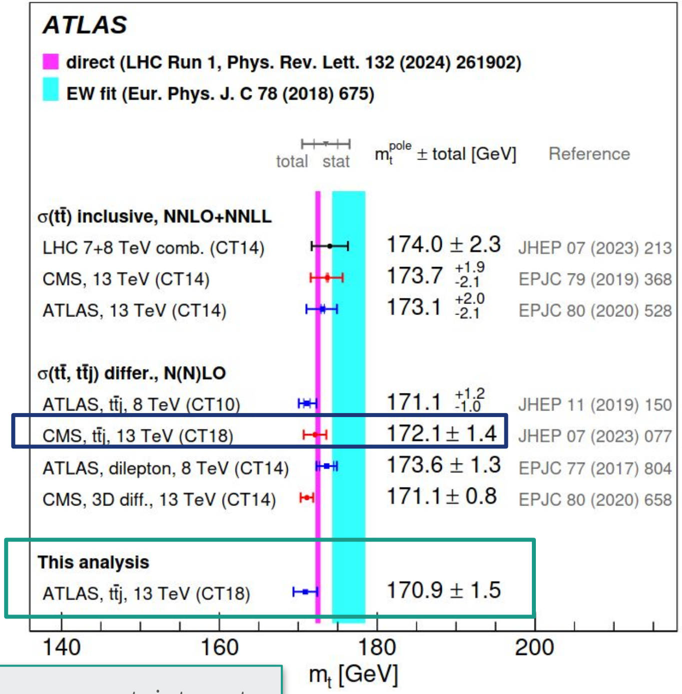



Dominant systematic sources:

- $t\bar{t}$ modelling, jet-related uncertainties

$m_t^{pole}$ from **2→3** and **2→7** agree within theoretical uncertainties

- $m_t^{pole}$ from **2->7** less precise




Slightly larger uncertainty wrt **CMS** [ JHEP 07 (2023) 077] = more extensive set of modeling unc.

Agrees with precise direct top mass meas. from Run1!

**2→3** process, main result:

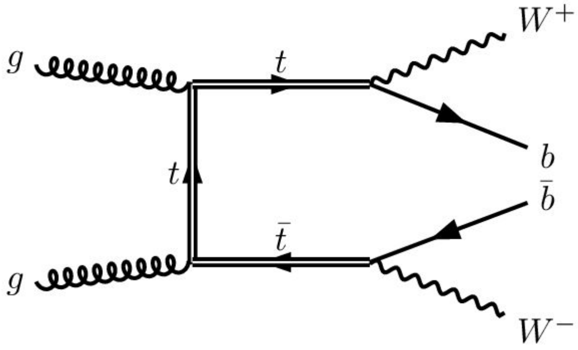
$$m_t^{pole} = 170.73 \pm 0.33\ (\text{stat.}) \pm 1.36\ (\text{syst.})\ {}^{+0.34}_{-0.28}\ (\text{scale})\ {}^{+0.24}_{-0.24}\ (\text{PDF} \oplus \alpha_s)\ \text{GeV}$$

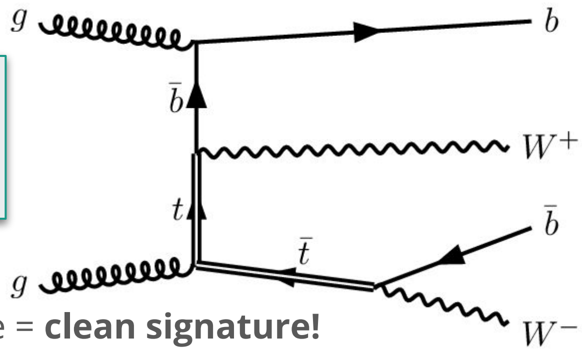
arXiv:2506.14700 (JHEP)

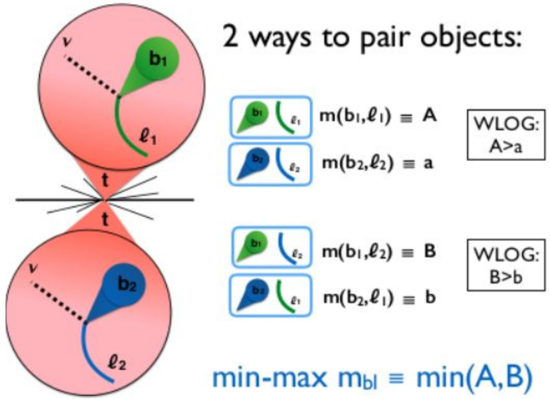
# Differential cross sections of WbWb in dilepton channel

- Addresses **$t\bar{t}$/tWb interference**: measures Xsection in specific variable **$m^{b\ell}_{minmax}$** in sensitive region (**2b-jets exclusive**)
- Helps with WbWb modelling: Xsection for several kinematic variables in more inclusive phase space

$$m^{bl}_{\text{minimax}} \equiv \min\left\{\max\left(m^{b_1 l_1}, m^{b_2 l_2}\right), \max\left(m^{b_1 l_2}, m^{b_2 l_1}\right)\right\}$$




For $t\bar{t}$: **$m^{b\ell}_{minmax} < m_{top}$** if $N_{b\text{-jets}} = 2$

For tWb: **$m^{b\ell}_{minmax}$ unconstrained**

**Fiducial phase** space:
At least **two b-jets**, **eμ** of opposite charge = **clean signature!**

Spectra corrected for detector effects and **unfolded to particle level** by Iterative Bayesian Unfolding (**IBU**)

arXiv:2506.14700 (JHEP)

# Differential cross sections of WbWb in dilepton channel

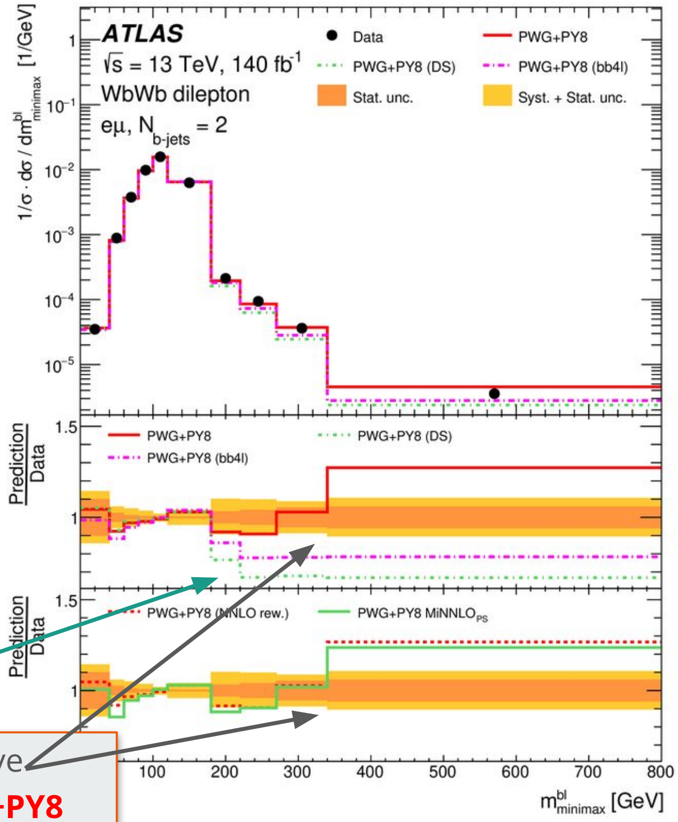
$\mathbf{M^{b\ell}_{minmax}}$ compared with predictions of various MC generators

Nominal = **Powheg+Pythia8** (tW DR scheme)

- **Best agreement** with data, but **fails** to reproduce the **shape of the tail**

Powheg+Pythia8 (**bb4ℓ**)

- Expected to be the most precise model, but still under investigation, also not complete set of uncertainties
- **Underestimates** Xsection in the **tail** (the largest interference impact) => **this measurement provides crucial info for its improvement!!**




**PWG+PY8 (DS)** [dashed line] = worst agreement above 180 GeV

NNLO corrections for $\mathbf{m^{b\ell}_{minmax}}$ have no major impact wrt **nominal PWG+PY8**

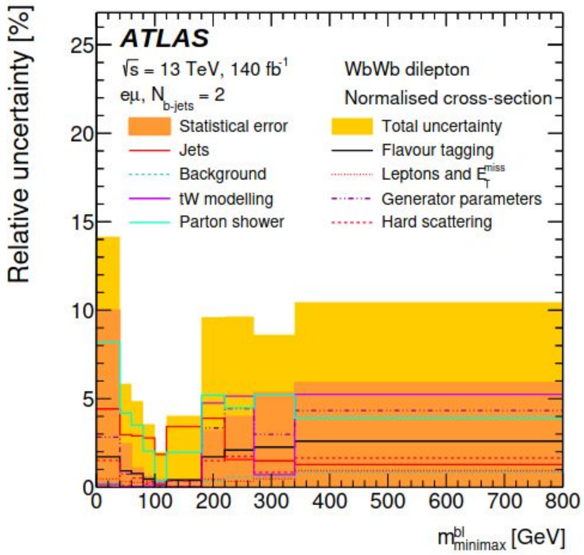
For $m^{b\ell}_{minmax}$:

| Models | $\chi^2$/NDF | $p$-value |
|---|---|---|
| PWG+PY8 | 12.8/9 | 0.17 |
| PWG+PY8 (DS) | 39.1/9 | <0.01 |
| PWG+PY8 (*bb4l*) | 28.6/9 | <0.01 |
| PWG+PY8 (NNLO rew.) | 12.8/9 | 0.17 |
| PWG+PY8 MiNNLO$_{PS}$ | 17.6/9 | 0.04 |

arXiv:2506.14700 (JHEP)

# Differential cross sections of WbWb in dilepton channel

Differential Xsections of 11 observables in 2b inclusive phase space:
$p_T^{jet1}$, $p_T^{jet2}$, $p_T^{\ell1}$, $p_T^{\ell2}$, $m^{bb4\ell}$, $p_T^{bb4\ell}$, $p_T^{bb}$, $p_T^{bb\ell\ell}$, $m^{bb\ell\ell}$, $N_{jets}$
No model describes simultaneously all observables **except PWG+PY8 (NNLO rew.)**

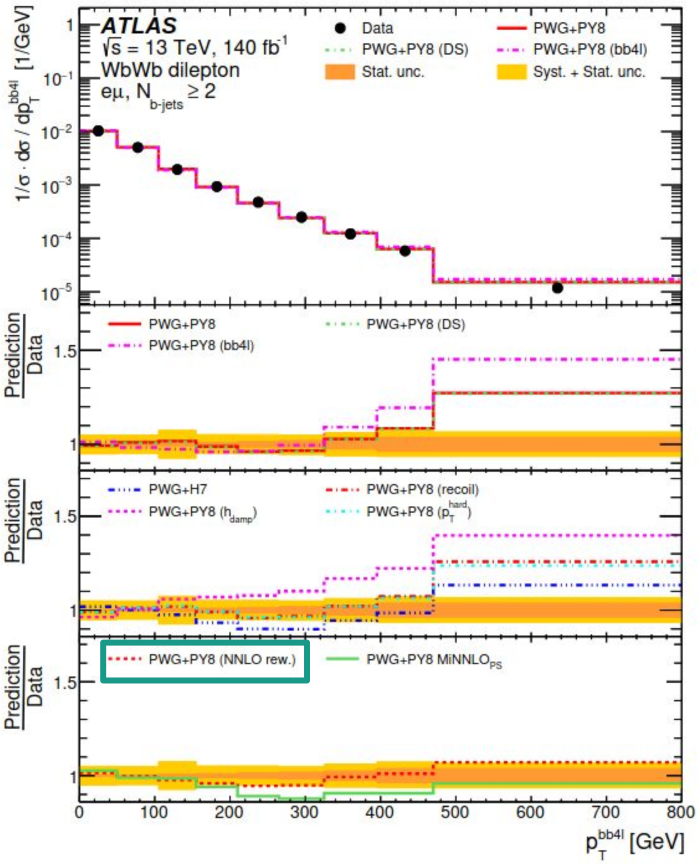



Uncertainties:

- **Signal** modelling and **flavor-tagging** dominant
- ½ of uncertainty wrt previous results!

**Legacy ATLAS measurement @ 13 TeV!**

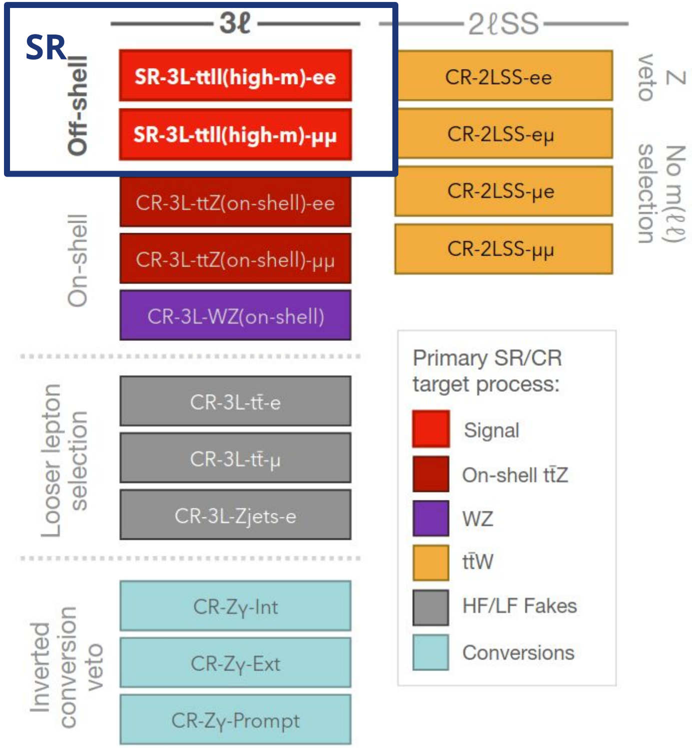
**Guidance for future MC tuning, WbWb, $t\bar{t}$ and tW interference modelling**



arXiv:2504.05919 (EPJC)

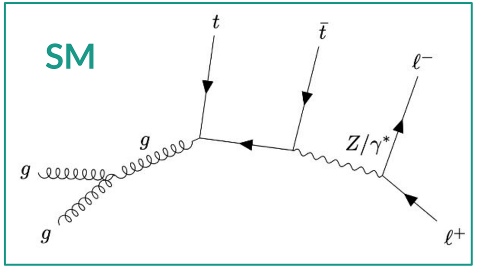
# High mass $t\bar{t}\ell^+\ell^-$ and LFU-inspired EFT interpretation

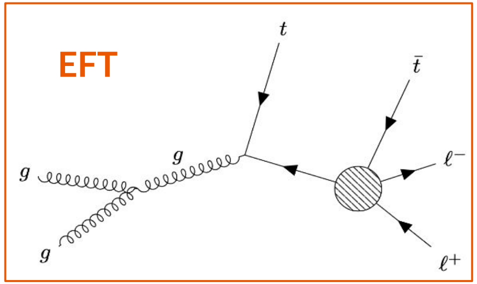
Measure $\mathbf{t\bar{t}\ell^+\ell^-}$ ($\ell$ = e,μ) & high mass: $\mathbf{m_{\ell\ell} > m_Z + 10}$ **GeV** => **sensitivity to some 4-fermion EFT operators**




Flavour-specific EFT operators can probe flavour universality violation!

$$\mathcal{L}_{eff} = \mathcal{L}_{SM}^{(4)} + \frac{1}{\Lambda}\sum_i C_i^{(5)} O_i^{(5)} + \frac{1}{\Lambda^2}\sum_i C_i^{(6)} O_i^{(6)} + \mathcal{O}\left(\Lambda^{-3}\right)$$



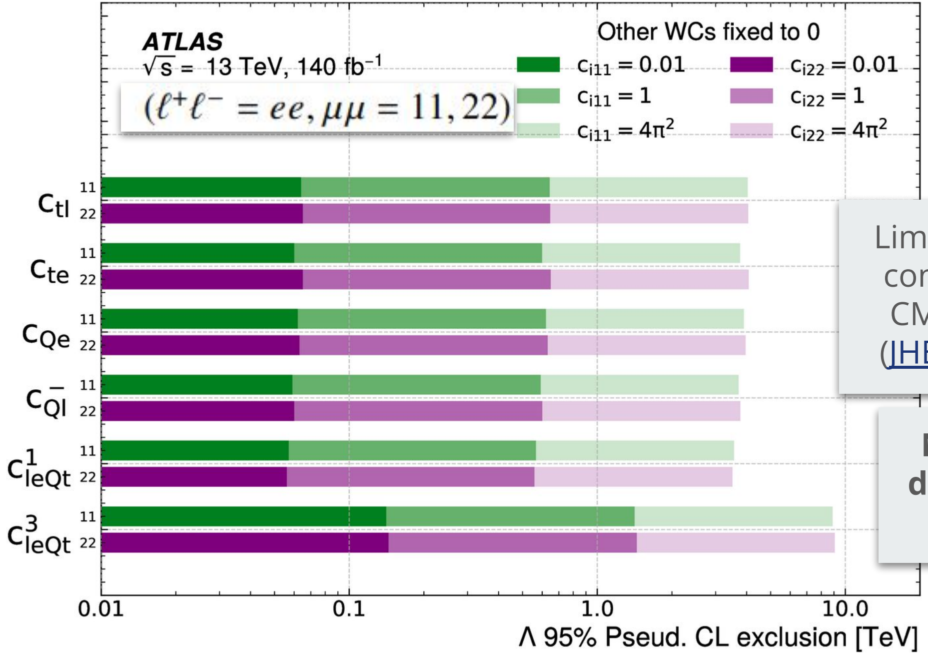




**Large impact of EFT in high $\mathbf{m_{\ell\ell}}$ bins**, but very low $t\bar{t}\ell^+\ell^-$ statistics ($m_{\ell\ell}$ > 550 GeV)
→ CR to constrain $t\bar{t}W$, SM $t\bar{t}Z$, WZ+jets, fake leptons

**Maximum-likelihood fits** of the signal and control categories to data performed.
Statistical uncertainties due to the limited size MC samples handled via dedicated parameters (the Beeston–Barlow "lite" technique)

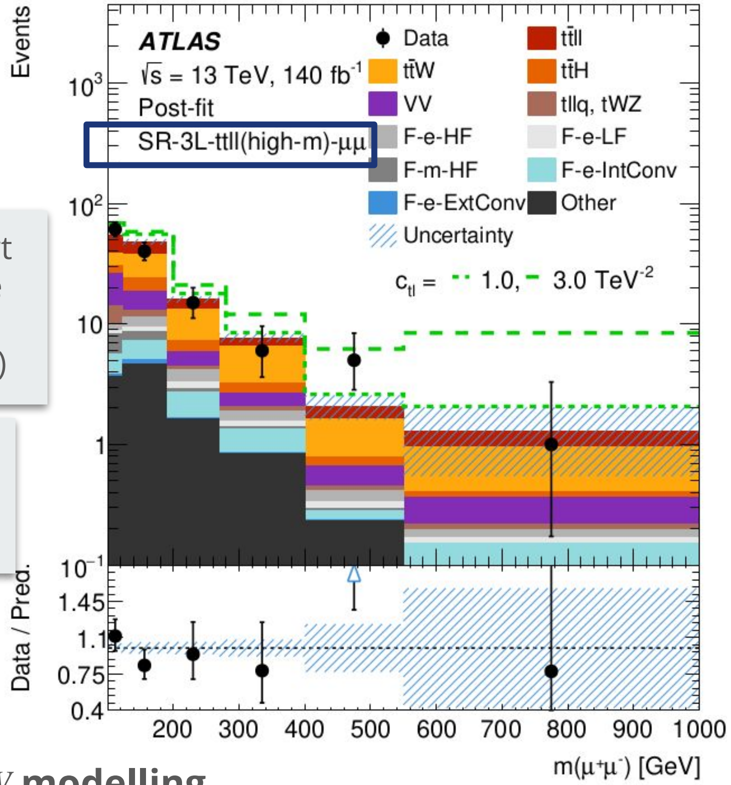
arXiv:2504.05919 (EPJC)

# High mass $t\bar{t}\ell^+\ell^-$ and LFU-inspired EFT interpretation




Limits **improved** wrt constraint from the CMS Collaboration (JHEP 12 (2023) 068)

**No significant deviations** from **SM**



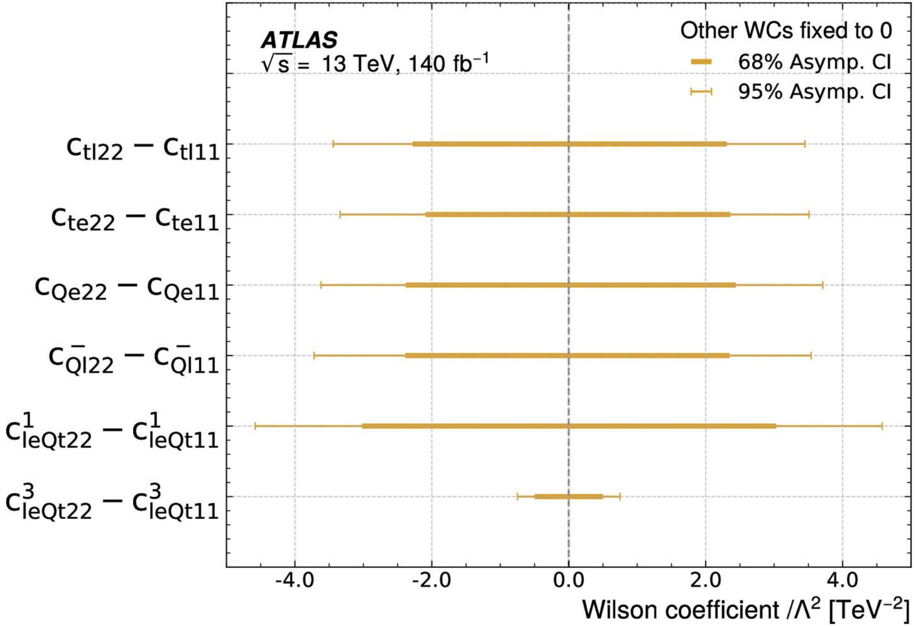

**NEW: Pseudodata (toys) used to obtain true coverage!**

The largest systematic uncertainties are due to the SM $t\bar{t}\ell^+\ell^-$ and $t\bar{t}W$ **modelling**, and the **limited size of MC samples** in some of the high $m(\ell^+\ell^-)$ bins full Run 2 data: 140 $fb^{-1}$

arXiv:2504.05919 (EPJC)

# High mass $t\bar{t}\ell^+\ell^-$ and LFU-inspired EFT interpretation

$(\ell^+\ell^- = ee, \mu\mu = 11, 22)$




Maximum-likelihood fits are performed with the signal parameterised by EFT Wilson Coefficients (WCs); WCs are treated as free floating

LFU-violating signals tested by the difference between electron and muon WC for each operator, e.g.

$$\Delta(c_{tl(22)} - c_{tl(11)})$$

=> **Tested for the first time at the LHC!**

**Limited by Run 2 statistical precision**, but **cancellation of systematic uncertainties possible**

=> with more data higher-precision test of SM possible!

**No deviations from** the **SM** or **signs of lepton flavour universality violation!**

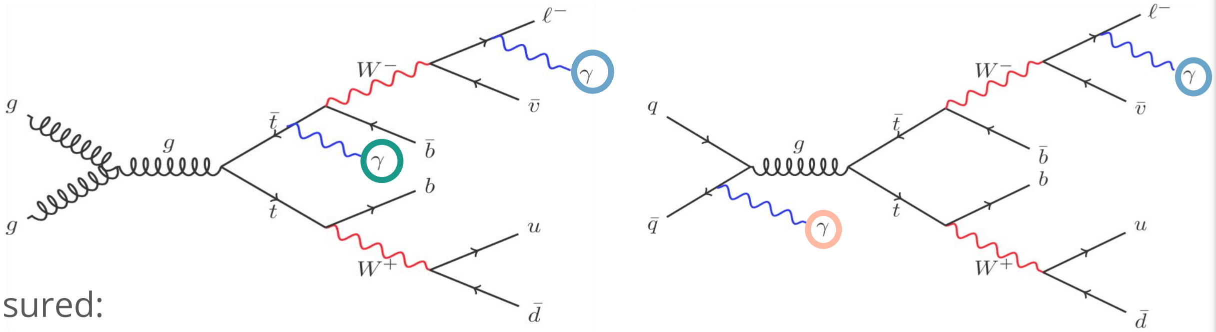
arXiv:2506.05018 (PLB)

# First observation of $t\bar{t}\gamma\gamma$ process

**$t\bar{t}\gamma\gamma$ = Rare process** with small Xsection in SM, **not studied before**

- $\gamma$ from: **off-shell top**, **initial state radiation**, **charged top-decay products**

2→8 process




Measured:

- **$t\bar{t}\gamma\gamma$ fiducial Xsection** at particle level in single-lepton events with exactly 2 high-$p_T$ isolated photons
- Measure **ratio of $t\bar{t}\gamma\gamma$ to $t\bar{t}\gamma$** ($R = \sigma_{t\bar{t}\gamma\gamma}/\sigma_{t\bar{t}\gamma}$) - test the impact of cancelation of systematics, **constrain to the CP-violating coupling terms**
  - $t\bar{t}\gamma$ already measured JHEP10(2024)191 (here used for background estimates, synchronization of systematics btw measurements)

**Motivation**:

Probe of $t$-$\gamma$ coupling

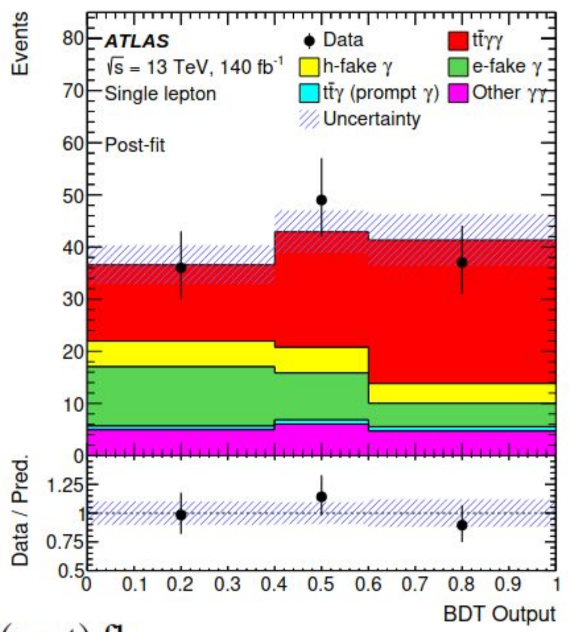
**Irreducible background** to $t\bar{t}H$ ($H\rightarrow\gamma\gamma$)

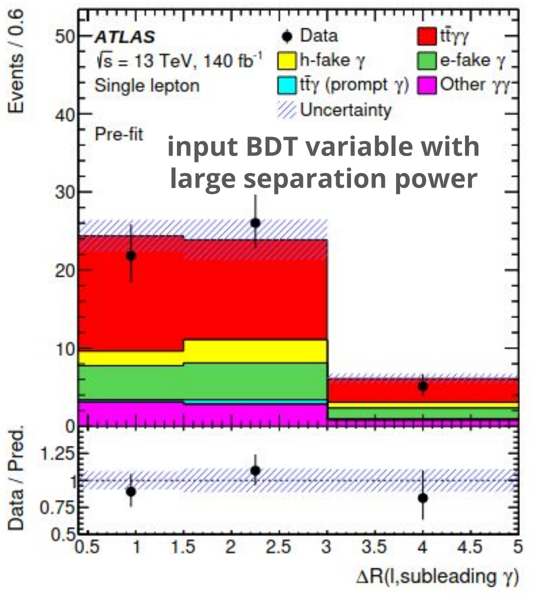
Sensitive to chromoelectric, chromomagnetic dipole moments = higher order corrections in many BSM [Phys. Rev. D 98, 035040, 2018, Chinese Phys. C 45 113101, (2021)] arXiv:2506.05018 (PLB)

# First observation of $t\bar{t}\gamma\gamma$ process

**Inclusive $t\bar{t}\gamma\gamma$ Xsection** obtained by **Profile Likelihood Unfolding** to Boosted Decision Tree (BDT) output

- BDT used for signal-background discrimination




**Dominant systematic** uncertainties: jet related, fake photon estimates, $W\gamma\gamma$ normalisation, photon isolation and identification

$$\sigma_{t\bar{t}\gamma\gamma} = 2.42^{+0.58}_{-0.53}\ \text{fb} = 2.42^{+0.46}_{-0.38}\ (\text{stat})\ ^{+0.35}_{-0.38}\ (\text{syst})\ \text{fb}$$

**Observed significance for $t\bar{t}\gamma\gamma$ process: 5.2σ**

Relative total uncertainty is ~23%, **rel. statistical uncertainty dominant** ~17%

**First observation of $t\bar{t}\gamma\gamma$ process!**

# First observation of $t\bar{t}\gamma\gamma$ process

Simultaneous fit performed to the $t\bar{t}\gamma\gamma$ **BDT** and the variables used in **four regions from the $t\bar{t}\gamma$** measurement (JHEP10(2024)191).

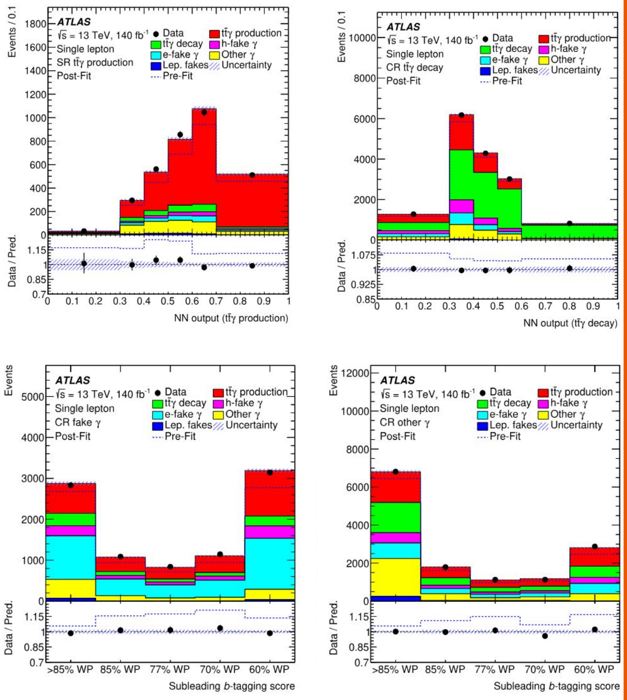
$$R = (3.30^{+0.70}_{-0.65}) \times 10^{-3} = (3.30\,^{+0.63}_{-0.55}(\text{stat})\,^{+0.32}_{-0.34}(\text{syst})) \times 10^{-3}$$

Event reconstruction and selection designed to avoid any statistical overlap between measurements.

**All common** sources of **systematic uncertainties** (experimental, background normalisation, modelling of common MC processes) **correlated.**

- **Cancelation of correlated systematics** in R wrt $t\bar{t}\gamma\gamma$ Xsection measurement
  - Mainly **experimental** source and **data-driven estimations of fake-photon backgrounds** cancel out significantly
- **Dominant systematic** uncertainties - jet flavour composition, $W\gamma\gamma$ normalisation, photon isolation and identification, $t\bar{t}\gamma$ modelling
- But **statistical uncertainty is prevailing** ~18% relative unc.

$t\bar{t}\gamma$ measurement (JHEP10(2024)191)



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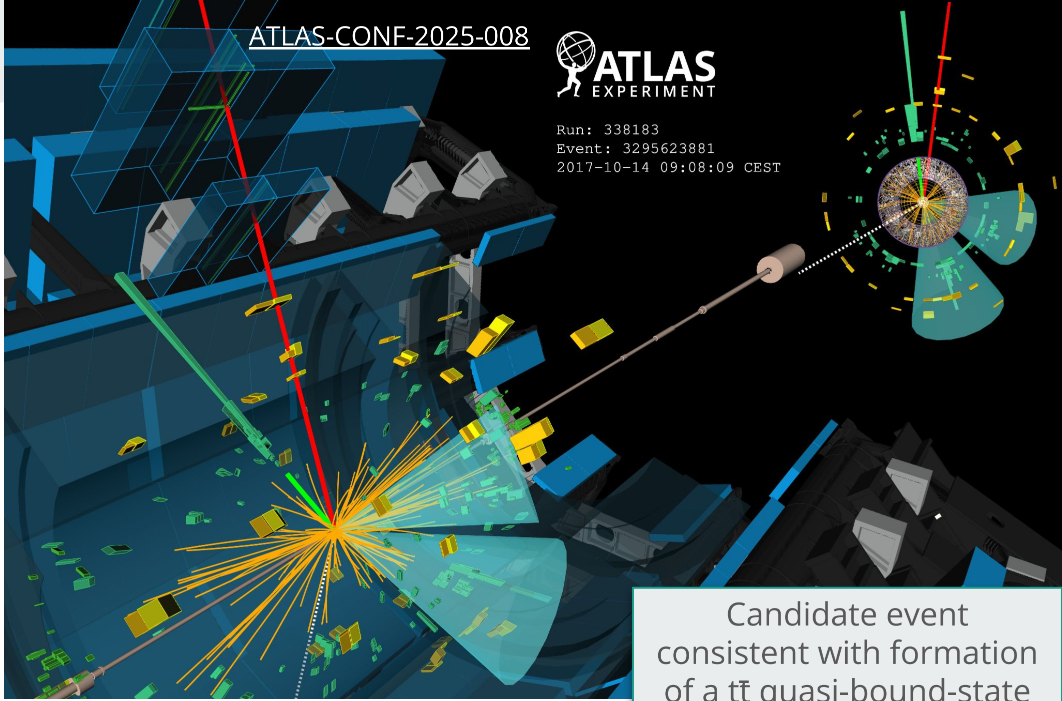
# Summary

- **Xsection enhancement** near **$t\bar{t}$ threshold** observed with **7.7$\sigma$ significance**!
- Rare **$t\bar{t}\gamma\gamma$ process observed for the first time!**

ATLAS-CONF-2025-008




Candidate event consistent with formation of a $t\bar{t}$ quasi-bound-state

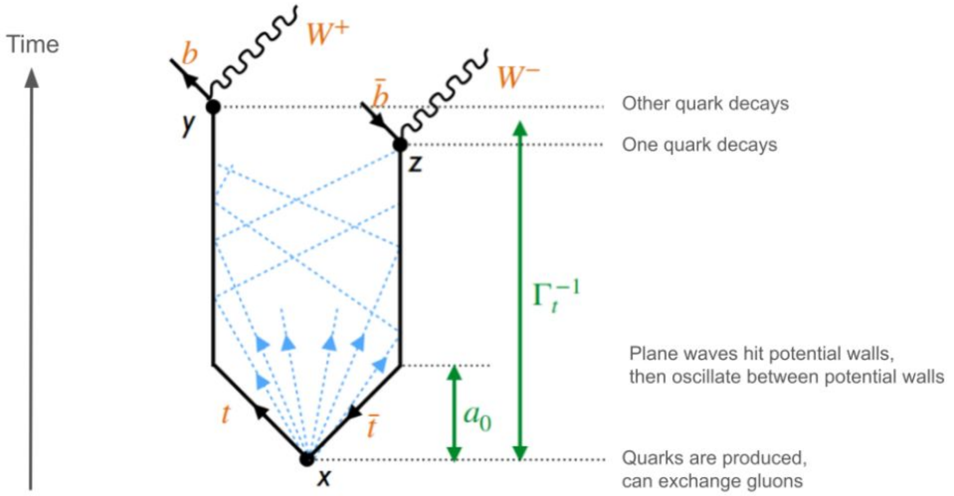
- **Differential Xsections with WbWb** final state have large potential to **help with MC simulations** and understanding of $t\bar{t}$ and tW interference
- **LFU violation tested** by difference between flavour-dependent EFT operators in $t\bar{t}\ell^{+}\ell^{-}$ process
- Unprecedented precision achieved in many measurements
- Data from Run 3 will help a lot with the precision of statistically dominated measurements
- **Many more results from ATLAS top quark group!**

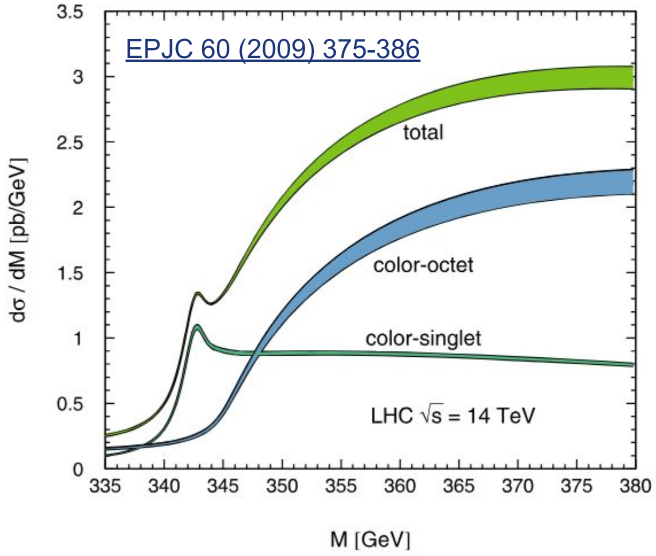
# Back up

# Observation of Xsection enhancement near $t\bar{t}$ threshold

**Toponium** = Quasi-bound state of top quarks predicted by SM

- Not the same as $b\bar{b}$/$c\bar{c}$ (**not a s-channel resonance**)
  - one of top decays first, they do not annihilate themselves
- Coulomb potential with gluon and soft gluon emissions between tops




**color-singlet**: attractive potential

**color-octet**: repulsive potential

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- **Normalized** = many uncertainties reduce in ratio
- $m_0$ = 170 GeV → R ∈ [0,1] (convention has no impact on result)

$$\mathcal{R}(\rho_s; m_t^{\text{pole}}) = \frac{1}{\sigma_{t\bar{t}+1\text{-jet}}} \cdot \frac{d\sigma_{t\bar{t}+1\text{-jet}}}{d\rho_s} \quad \text{, with} \quad \rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}+1\text{-jet}}}}$$

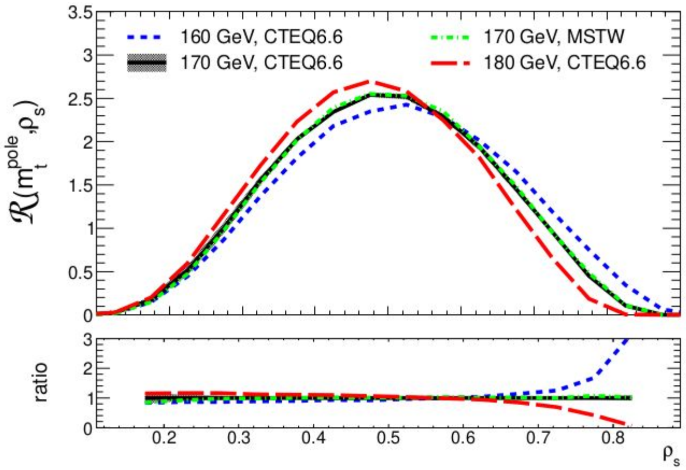


**Fig. 4.** $\mathcal{R}(m_t^{\text{pole}}, \rho_s)$ calculated at NLO accuracy for different masses $m_t^{\text{pole}} = 160$, 170 and 180 GeV. For $m_t^{\text{pole}} = 170$ GeV the scale and PDF uncertainties evaluated as discussed in the text are shown. The ratio with respect to the result for $m_t^{\text{pole}} = 170$ GeV is shown in the lower plot.

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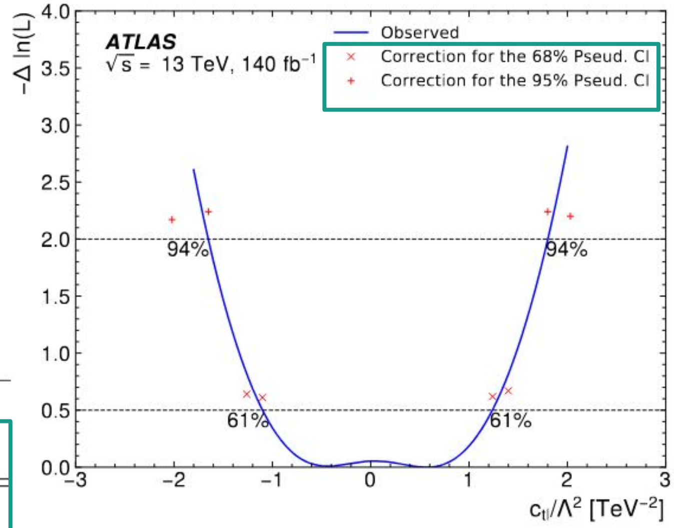
arXiv:2504.05919 (EPJC)

# High mass $t\bar{t}\ell^+\ell^-$ and LFU-inspired EFT interpretation

**For the first time psedodata (toys)** were used to calculate 68% (95%) coverage together with standard asymptotic assumption of profile-likelihood ratio

Wilks` theorem (standard asymptotic method) may not be valid to use in some cases (when **pure-EFT terms dominant**) => true coverage calculated from toy pseudodata!

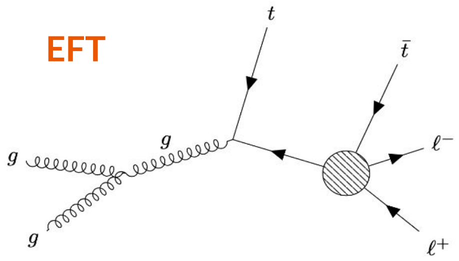



| | $O(\Lambda^{-4})$ [TeV$^{-2}$] | | | | |
|---|---|---|---|---|---|
| | Best fit | 68% Asymp. CI | 68% Pseud. CI | 95% Asymp. CI | 95% Pseud. CI |
| $c_{tl}$ | −0.44 | [−1.10, 1.24] | [−1.17, 1.31] | [−1.65, 1.80] | [−1.71, 1.86] |
| $c_{te}$ | −0.45 | [−1.05, 1.18] | [−1.21, 1.41] | [−1.57, 1.79] | [−1.64, 1.96] |
| $c_{Qe}$ | −0.54 | [−1.23, 1.19] | [−1.32, 1.32] | [−1.82, 1.83] | [−1.87, 1.88] |
| $c^{-}_{Ql}$ | 0.69 | [−0.98, 1.41] | [−1.15, 1.74] | [−1.57, 2.03] | [−1.66, 2.33] |
| $c^{1}_{leQt}$ | −0.61 | [−1.51, 1.50] | [−1.55, 1.54] | [−2.27, 2.27] | [−2.32, 2.33] |
| $c^{3}_{leQt}$ | −0.12 | [−0.26, 0.26] | [−0.27, 0.27] | [−0.37, 0.37] | [−0.38, 0.38] |

# High mass $t\bar{t}\ell^+\ell^-$ and LFU-inspired EFT interpretation

Measure **$t\bar{t}\ell^+\ell^-$** & high mass: **$m_{\ell\ell}$ > $m_Z$ + 10 GeV** => **sensitivity to many 4-fermion operators in EFT** = some sensitive to flavour universality violation

EFT




$$\mathcal{L}_{eff} = \mathcal{L}_{SM}^{(4)} + \frac{1}{\Lambda}\sum_i C_i^{(5)} O_i^{(5)} + \frac{1}{\Lambda^2}\sum_i C_i^{(6)} O_i^{(6))} + \mathcal{O}\left(\Lambda^{-3}\right)$$

| Operator | Definition | Description |
|---|---|---|
| $O_{te}$ | $(\bar{e}_p\gamma_\mu e_r)(\bar{t}\gamma^\mu t)$ | R-handed leptons and R-handed quarks in the $t\bar{t}\ell^+\ell^-$ vertex |
| $O_{Qe}$ | $(\bar{Q}\gamma_\mu Q)(\bar{e}_p\gamma^\mu e_r)$ | R-handed leptons and L-handed quarks in the $t\bar{t}\ell^+\ell^-$ and $b\bar{b}\ell^+\ell^-$ vertices |
| $O_{tl}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{t}\gamma^\mu t)$ | L-handed leptons and R-handed quarks in the $t\bar{t}\ell^+\ell^-$ vertex |
| $O^1_{Ql}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{Q}\gamma^\mu Q)$ | L-handed leptons and L-handed quarks in the $t\bar{t}\ell^+\ell^-$ and $b\bar{b}\ell^+\ell^-$ vertices, weak-singlet |
| $O^3_{Ql}$ | $(\bar{l}_p\sigma^i\gamma_\mu l_r)(\bar{Q}\sigma^i\gamma^\mu Q)$ | L-handed leptons and L-handed quarks in the $t\bar{t}\ell^+\ell^-$ and $b\bar{b}\ell^+\ell^-$ vertices, weak-triplet |
| $O^1_{leQt}$ | $(\bar{l}^j_p e_r)\epsilon_{jk}(\bar{Q}^k t)$ | Mixed L-/R-handed quarks and leptons in the $t\bar{t}\ell^+\ell^-$, $t\bar{b}\ell^+\ell^-$ and $b\bar{b}\ell^+\ell^-$ vertices, scalar |
| $O^3_{leQt}$ | $(\bar{l}^j_p\sigma_{\mu\nu}e_r)\epsilon_{jk}(\bar{Q}^k\sigma^{\mu\nu}t)$ | Mixed L-/R-handed quarks and leptons in the $t\bar{t}\ell^+\ell^-$, $t\bar{b}\ell\nu$, $\bar{t}b\ell\nu$ and $b\bar{b}\ell^+\ell^-$ vertices, tensor |

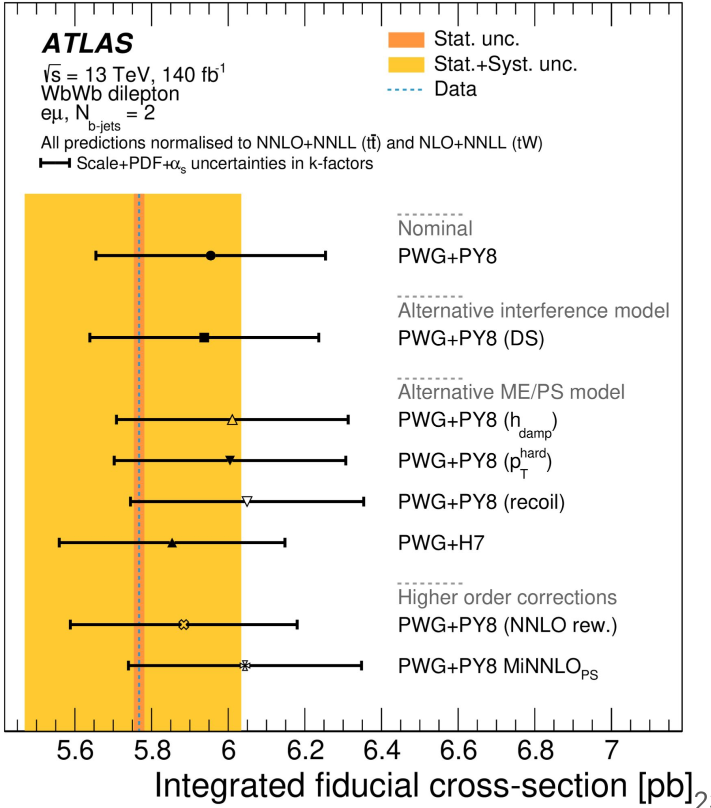
# Differential cross sections of WbWb in dilepton channel

Differential Xsections corrected for detector effects and unfolded to particle level by Iterative Bayesian Unfolding (IBU)

Compared with predictions of various MC generators at NNLO in QCD

Improvements (previously only interference studied):

- measured diff Xsection of additional kinematic variables
- refined modelling of uncertainties
- latest object calibration



# Differential cross sections of WbWb in dilepton channel

Samples:

Nominal **PWG+PY8 (DR)** = recoiling the gluon against $b$-quarks (default strategy in Powheg), $p_{T,hard}$ = 0, $h_{damp}$ = 1.5 $m_{top}$

$tW$ PWG+PY8 (DS) => **PWG+PY8 (DS)**, like nominal (tW and $t\bar{t}$) but DS scheme used

$t\bar{t}$ and $tW$ PWG+PY8 ($h_{damp}$ = 3$m_{top}$) = **PWG+PY8 ($h_{damp}$)**

$t\bar{t}$ and $tW$ PWG+H7 = **PWG+H7** (DR scheme used to treat the interference of tW and $t\bar{t}$)

$t\bar{t}$ and $tW$ PWG+PY8 ( $p_{T,hard}$ = 1) = **PWG+PY8 ($p_{T,hard}$)** $p$T,hard parameter regulates how the Pythia 8 radiation phase space is determined to avoid overlaps with the regions of the phase space already covered by Powheg

$t\bar{t}$ PWG+PY8 (recoil) = **PWG+PY8 (recoil)** ttbar: gluon recoils against the top-quark itself during the second and subsequent gluon emissions in the $t \rightarrow W\,b$ process, tW nominal sample

**PWG+PY8** $bb4l$ = generalization of Powheg producing $l^+\nu l^-\bar{\nu}b\bar{b}$ (accounts for quantum interference effects between the ttbar and tW production modes, and off-shell and non-resonant effects, not complete set of uncertainties, still under scrutiny of the ATLAS (NLO+PS)

$t\bar{t}$ NNLO reweighting = **PWG+PY8(NNLO rew.)** (ttbar reweighted at parton level to match the NNLO QCD + NLO electroweak (EW) parton-level, tW nominal sample)

$t\bar{t}$ NNLO+PS = **PWG+PY8 MiNNLOPS** (ttbar at NNLO+NNLL in QCD, tW nominal sample)