Top Quark Cross Section and Mass Measurements at ATLAS and CMS

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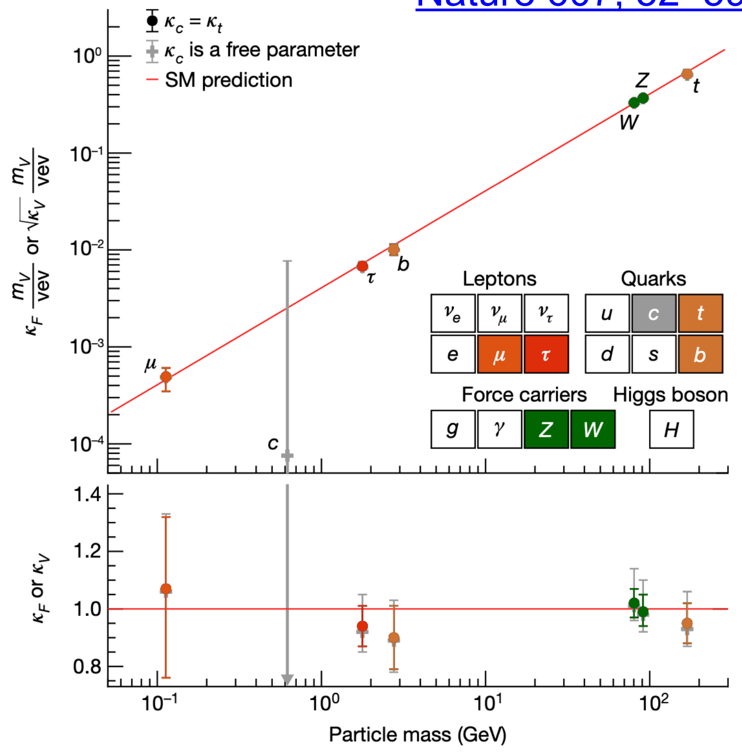
Introduction

- Top quark is very special. Heaviest quark in the SM. Has largest Yukawa coupling to the Higgs field ($y_t \sim 1$)
- Very short life time → decays before forming any real hadron → access to 'bare' quark

$$\underbrace{\frac{1}{m_t}}_{\substack{\text{production} \\ 10^{-27}\ \text{s}}} < \underbrace{\frac{1}{\Gamma_t}}_{\substack{\text{lifetime} \\ 10^{-25}\ \text{s}}} < \underbrace{\frac{1}{\Lambda_{QCD}}}_{\substack{\text{hadronization} \\ 10^{-24}\ \text{s}}} < \underbrace{\frac{m_t}{\Lambda^2}}_{\substack{\text{spin-flip} \\ 10^{-21}\ \text{s}}}$$

30th anniversary of the top-quark discovery

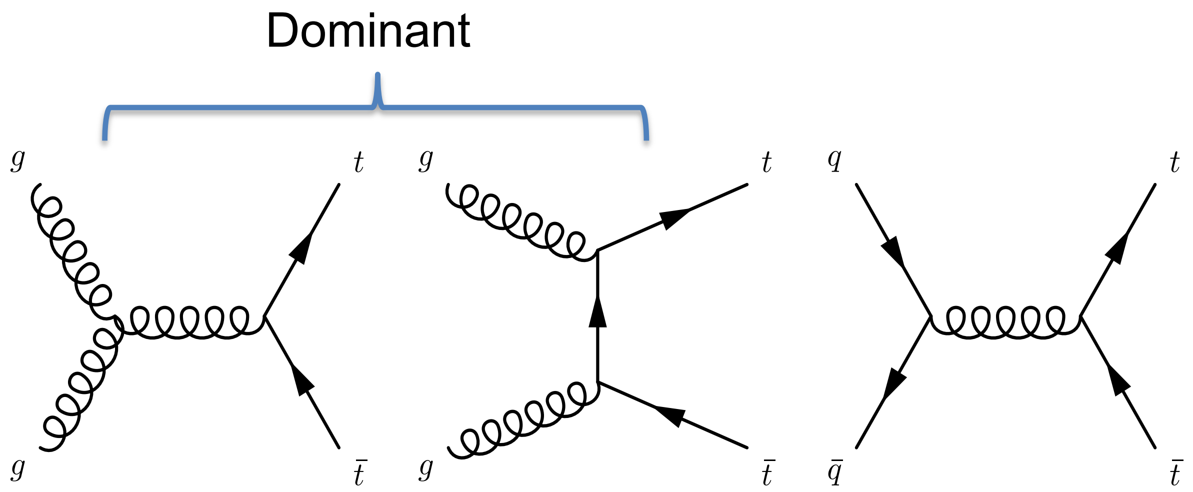
Nature 607, 52–59 (2022)



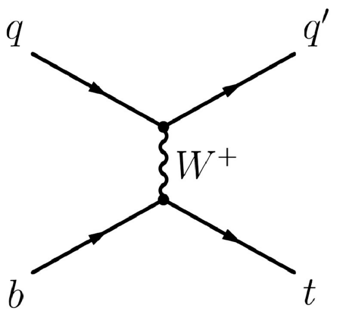
- Precision measurements of top quark: important for testing the SM and looking for new physics beyond SM

LHC is a top quark factory

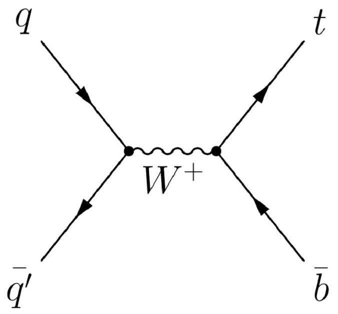
- $t\bar{t}$ production (QCD)
  - $\sigma_{t\bar{t}} = 834$ pb at LHC Run 2 (13 TeV)
  - 0.83M $t\bar{t}$ events per fb^{-1}



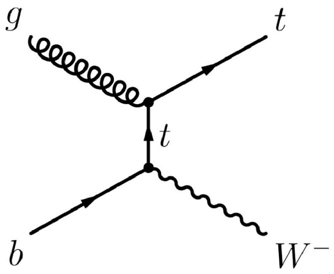
- Single top production (EW)



t-channel
~214 pb

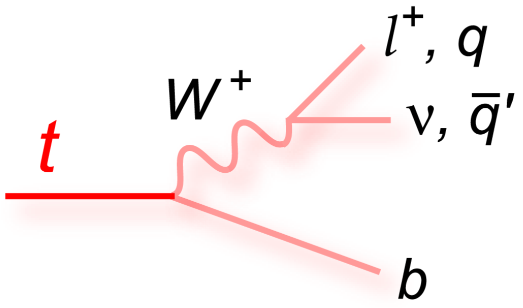


s-channel
~11 pb



tW
~79 pb

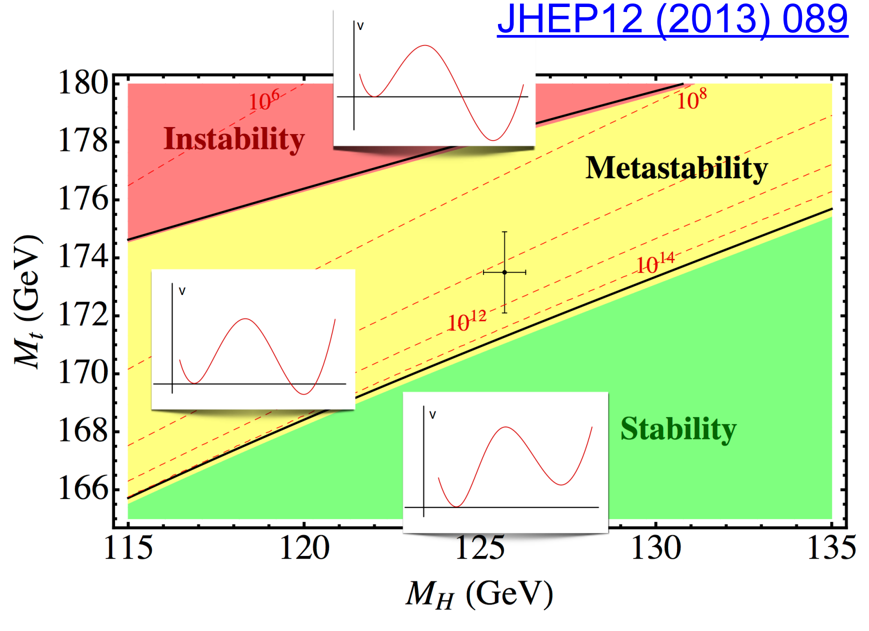
- Top decays (EW): almost 100% with



Top quark mass measurements

Top quark mass

- Top mass is one of the most important parameters in the SM
- Related to the shape of the Higgs potential and the stability of the electroweak vacuum



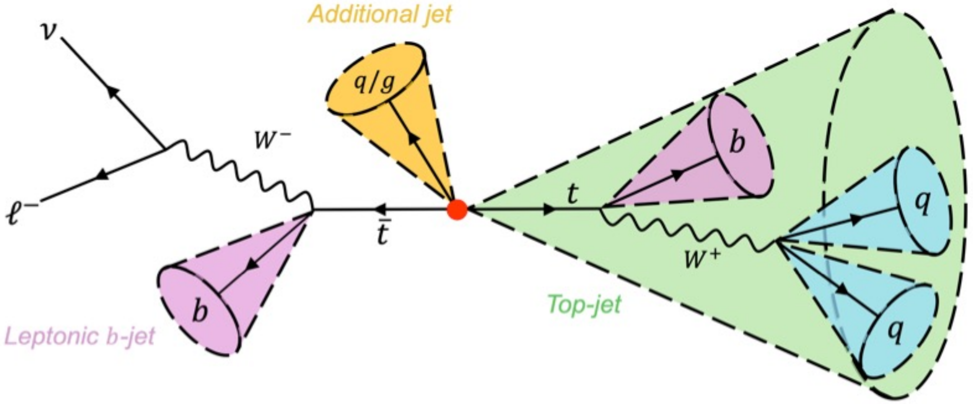
Top quark mass measurements:

- Direct methods
  - Compare data with MC generated with different masses
- Indirect methods
  - $t\bar{t}$ cross sections are compared to fixed-order calculations in a certain normalization scheme (*e.g.* pole mass, $\overline{\mathrm{MS}}$ mass)

Direct top quark mass using boosted $t\bar{t}$

Phys. Lett. B 867 (2025) 139608

- First ATLAS measurement of top quark mass using boosted $t\bar{t}$ events in semi-leptonic final states
- Simplifies the reconstruction of hadronically decaying top quarks

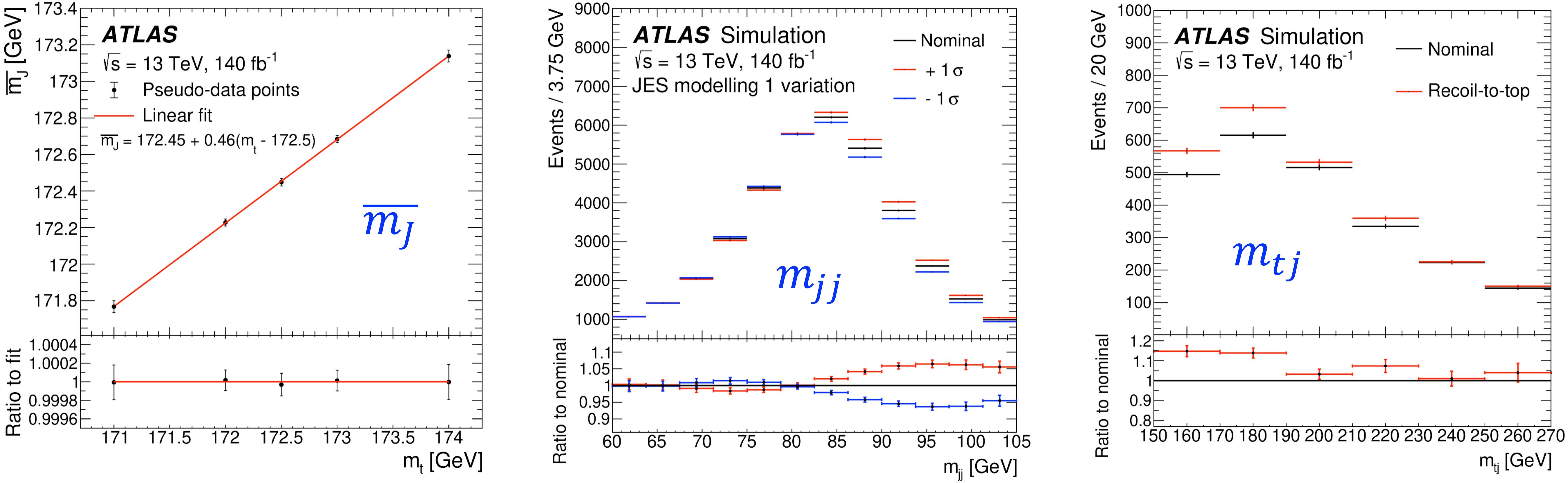


Top quark mass is extracted by fitting three observables

- $\overline{m_J}$: average top jet mass, linearly dependent on the top-quark mass
- m_{jj}: Invariant mass of the 2 leading light jets inside the top-jet, sensitive to jet energy scale
- m_{tj}: Invariant mass of the semi-leptonic top quark and closest jet, sensitive to the radiation from t→bW

Direct top quark mass using boosted $t\bar{t}$

Phys. Lett. B 867 (2025) 139608



Simultaneous profile likelihood fit to three observables to extract m_t

$$m_t = 172.95 \pm 0.53 \text{ GeV}$$

So far the most precise ATLAS top quark mass measurement in a single channel

Indirect top quark pole mass using $t\bar{t}+1\text{j}$

arXiv:2507.02632

NEW

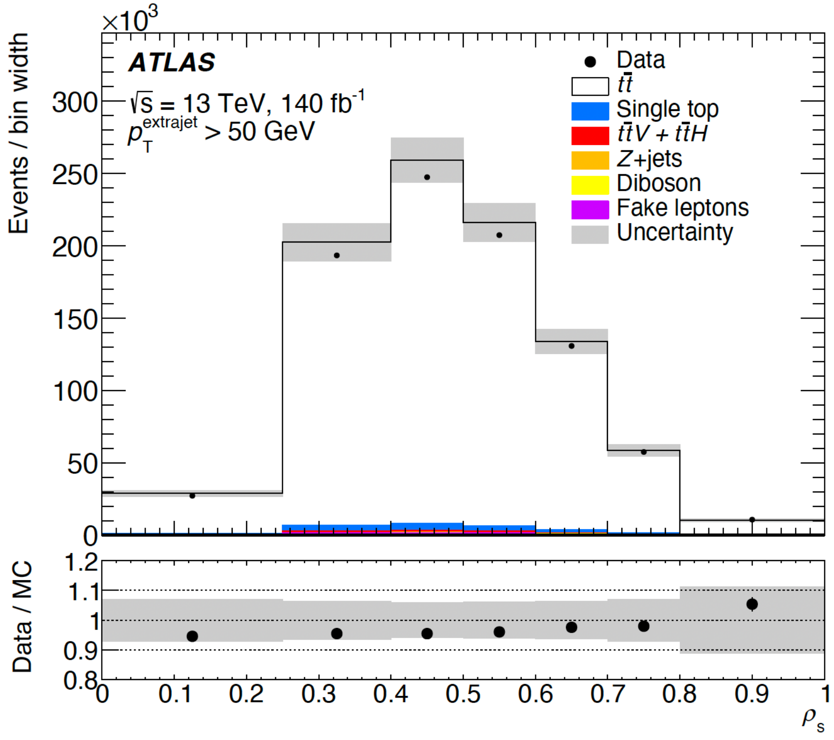
- Measurement based on fixed-order calculations with well-defined mass scheme
- The pole mass is extracted from $t\bar{t}+1\text{j}$ cross section as a function of ρ_s

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

m_0=170 GeV

$\sqrt{s_{t\bar{t}+1\text{-jet}}}$: invariant mass of the $t\bar{t}+1\text{j}$ system

- Using $t\bar{t}$ fully leptonic decays channel. Only consider $e\mu$



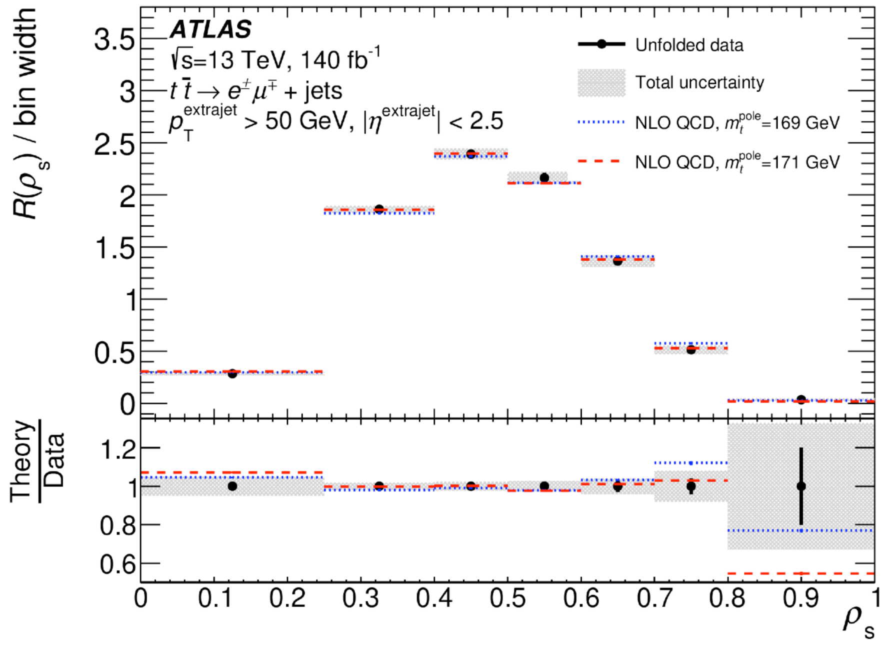
Detector level distribution

Indirect top quark pole mass using $t\bar{t}+1j$

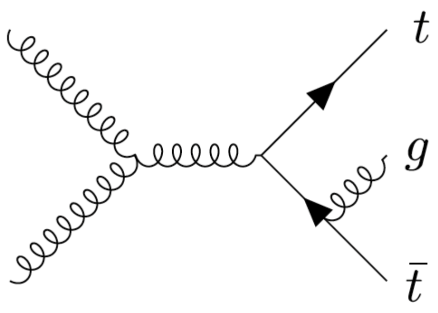
1. The ρ_s distribution is unfolded to particle level using Iterative Bayesian Unfolding method
2. Compare unfolded distribution with fixed-order calculations

NEW

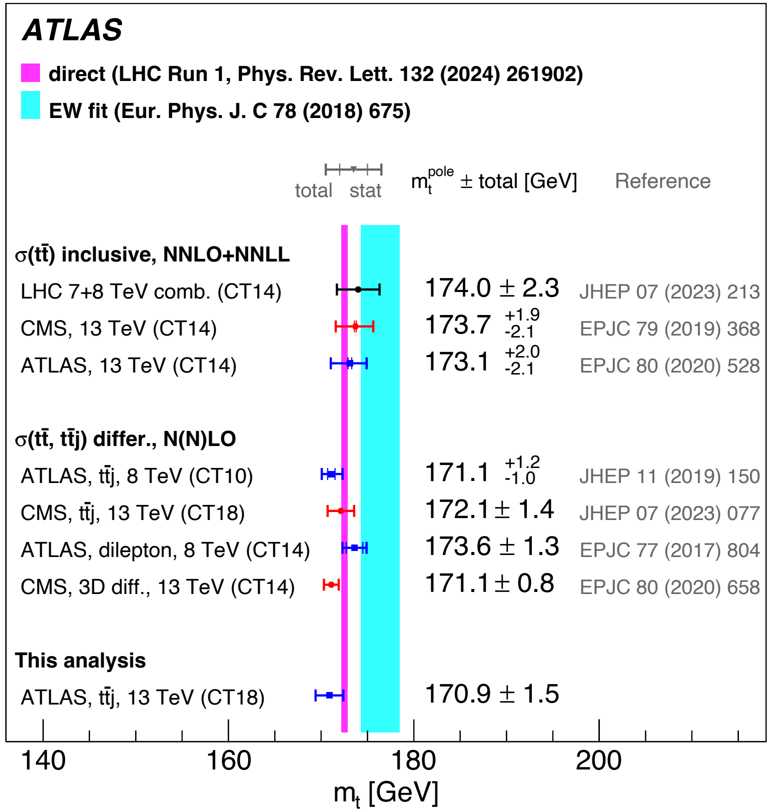
[arXiv:2507.02632](https://arxiv.org/abs/2507.02632)



2→3 process



NLO QCD accuracy, JHEP 05 (2022) 146



Results:

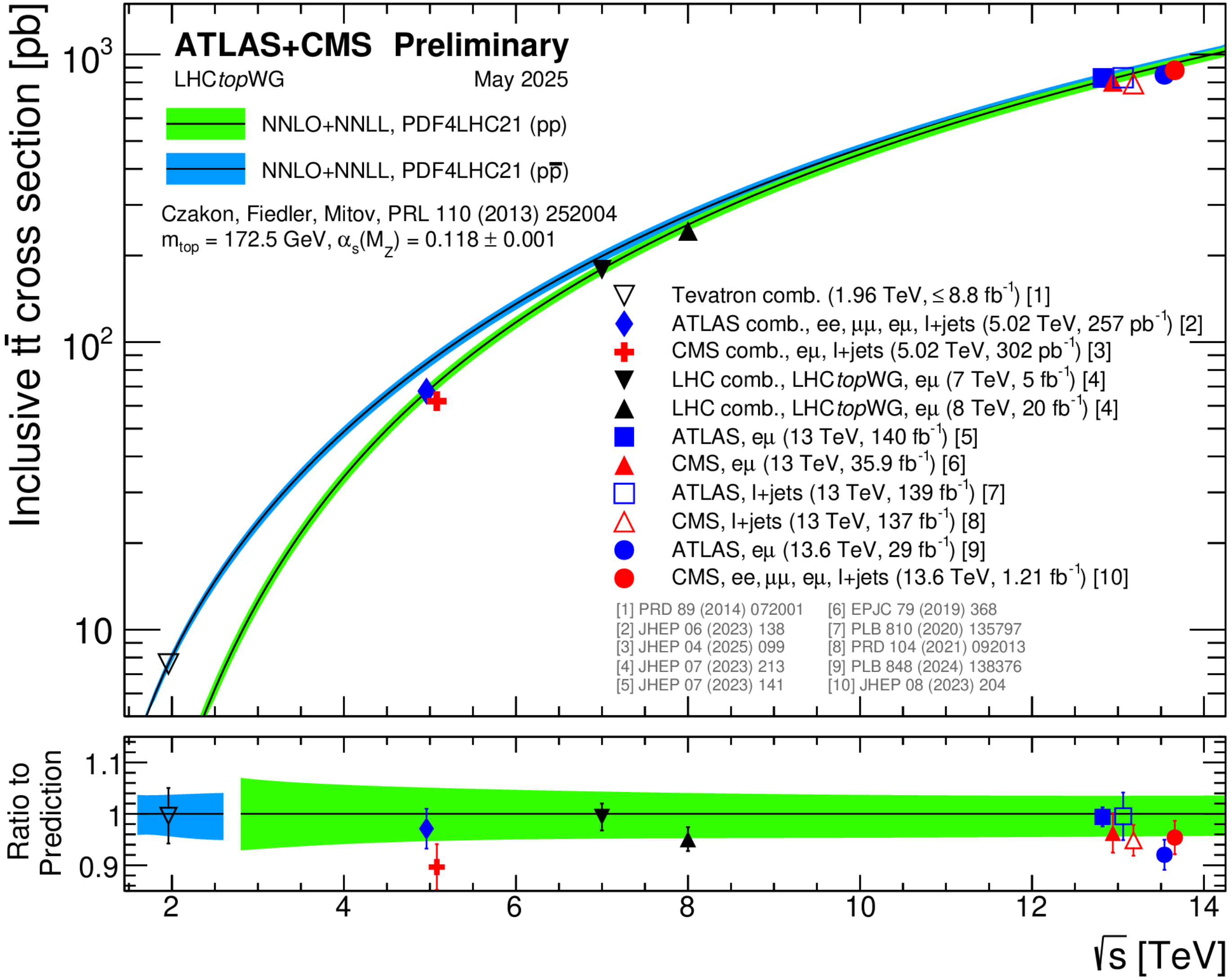
$$m_t^{\text{pole}} = 170.73 \pm 0.33\,(\text{stat.}) \pm 1.36\,(\text{syst.})\,{}^{+0.34}_{-0.28}\,(\text{scale}) \pm 0.24\,(\text{PDF} \oplus \alpha_s)\ \text{GeV}$$

Top quark cross section measurements

Inclusive top quark pair production

- $t\bar{t}$ cross section measurements at five different CME (including 13.6 TeV)
- Good agreement with NNLO+NNLL calculations
- Precision at the level of 2-3%

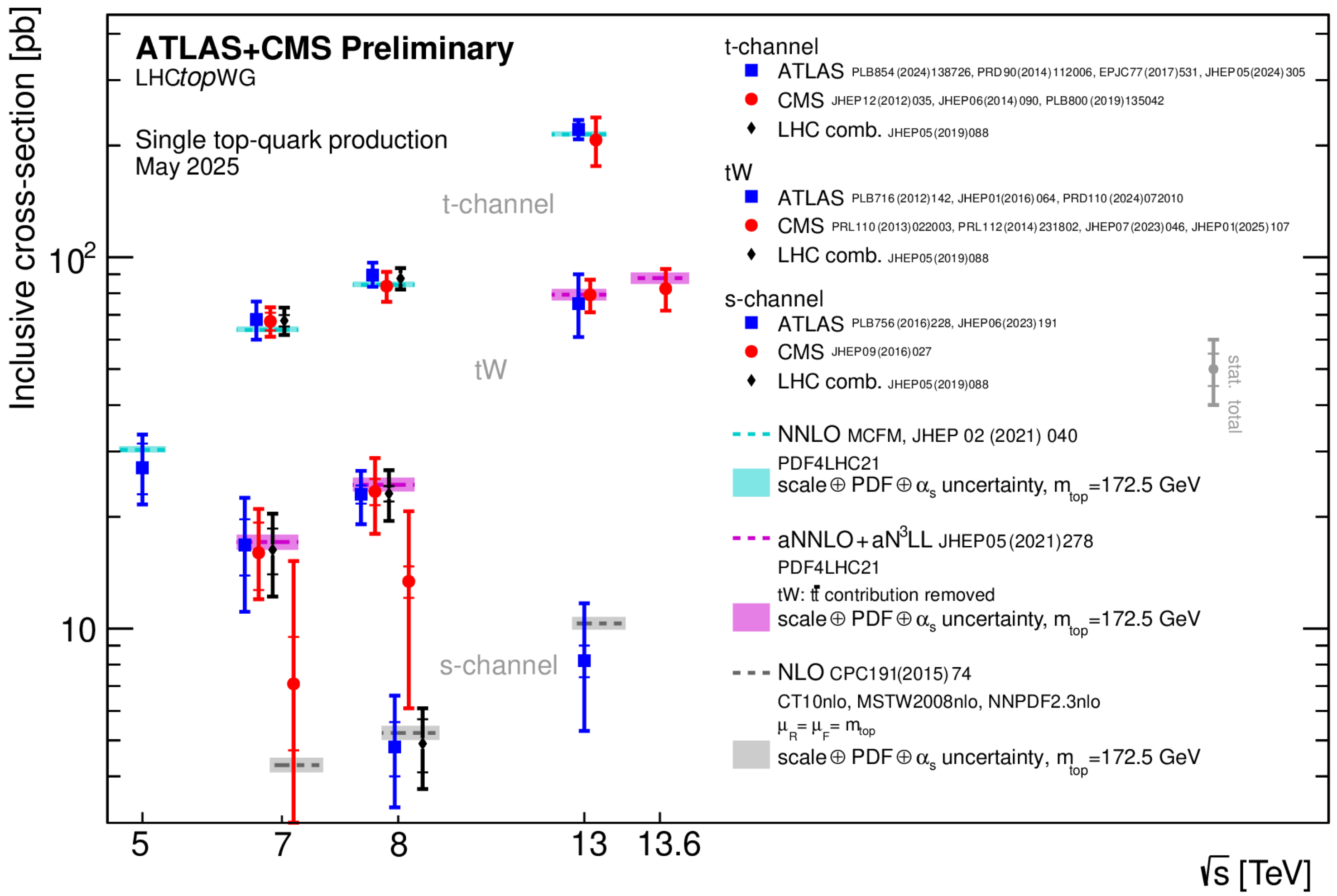
ATL-PHYS-PUB-2025-024



Inclusive single top production

ATL-PHYS-PUB-2025-024

- Single top cross-section measurements at five different CME (including 13.6 TeV)
- Good agreement with (N)NLO calculations

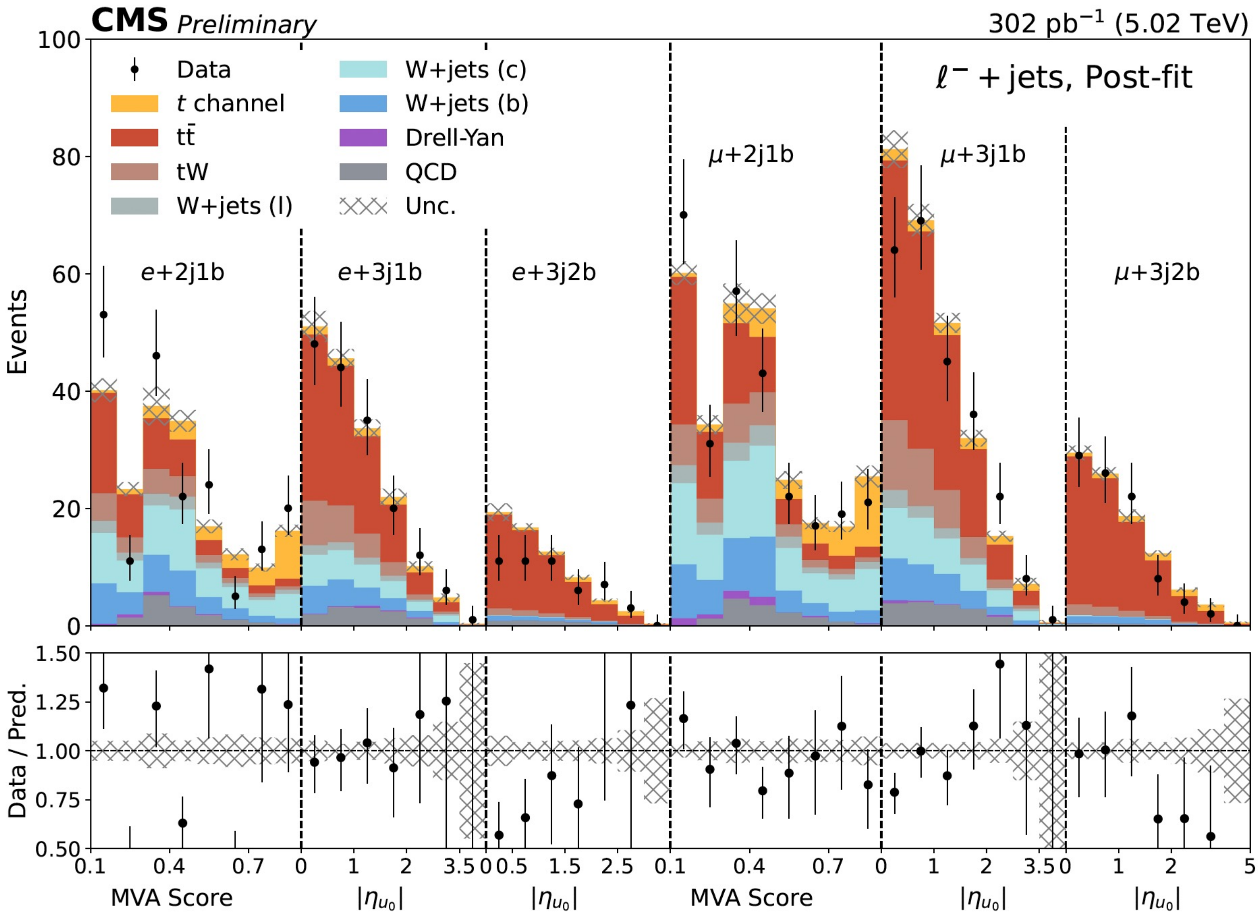


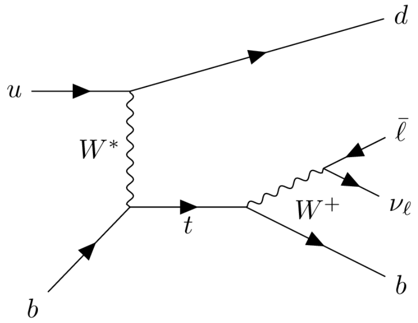
Inclusive t-channel cross section at 5 TeV

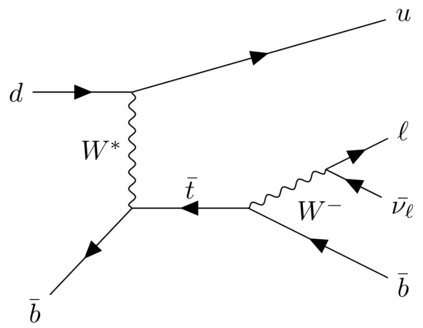
- Using low pileup data, 302 pb^{-1} at 5.02 TeV. Smaller detector systematics

NEW

CMS-PAS-TOP-24-011





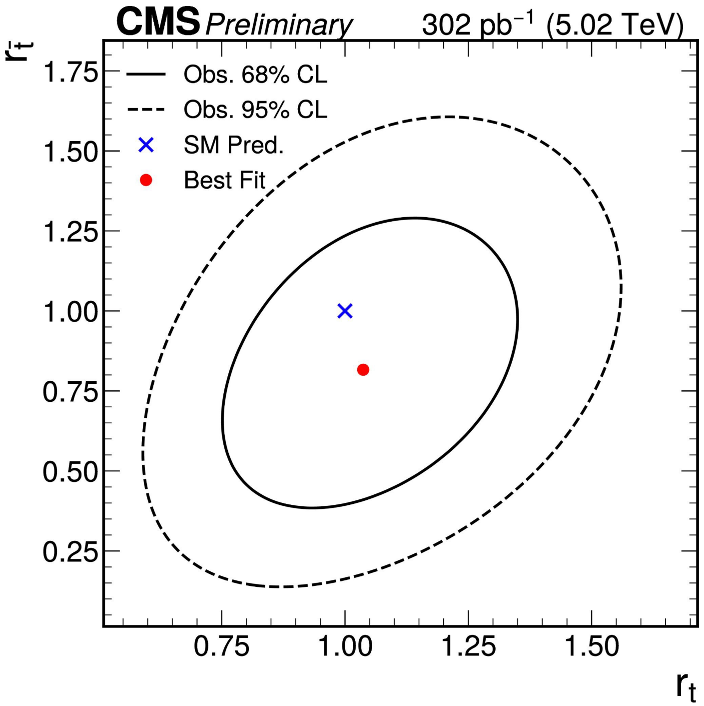


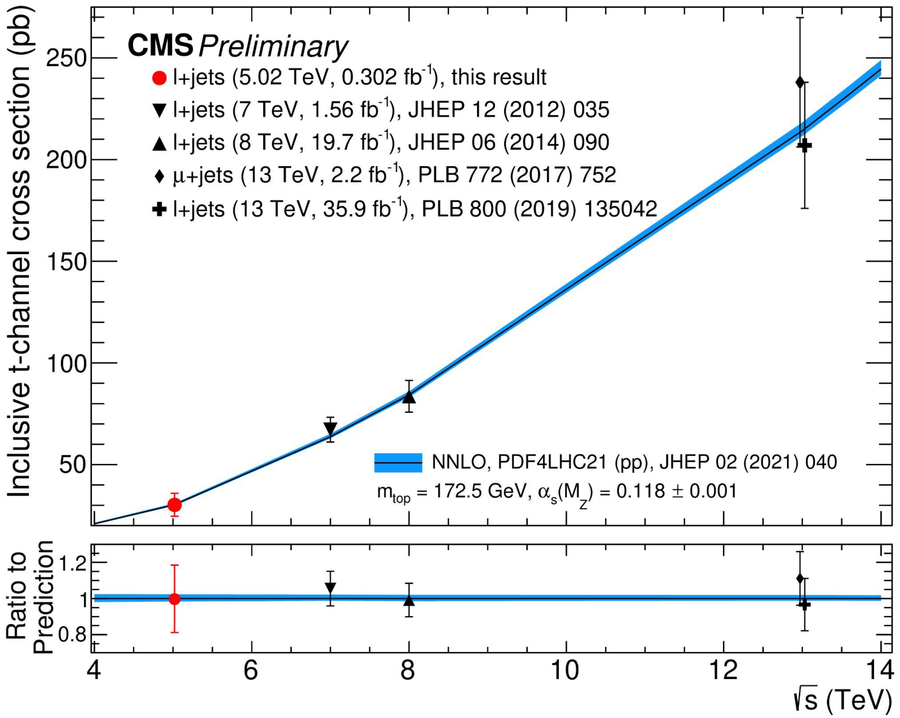
The fits are performed on the distribution of the MVA score for the 2j1b categories and $|\eta_{\mu0}|$ for the others

$|\eta_{\mu0}|$: the absolute value of η of the leading untagged jet

Inclusive t-channel cross section at 5 TeV

CMS-PAS-TOP-24-011





NEW

$r_t/r_{\bar{t}}$: signal strength

$$\sigma(\mathrm{tq}+\bar{\mathrm{t}}\mathrm{q}) = 30.2^{+3.7}_{-3.6}(\mathrm{stat})\,^{+4.4}_{-4.2}(\mathrm{syst}) \pm 0.6(\mathrm{lumi})\ \mathrm{pb}$$

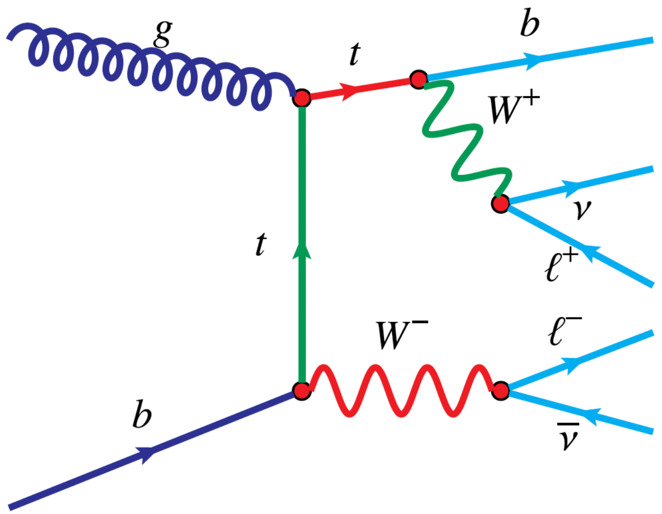
The ratio between $\sigma(tq)$ and $\sigma(\bar{t}q)$: $\mathcal{R}_{t\text{-ch}} = 2.6^{+1.1}_{-0.7}\,(\mathrm{stat})^{+0.7}_{-0.2}\,(\mathrm{syst}) = 2.6^{+1.3}_{-0.7}$

In good agreement with the standard model predictions

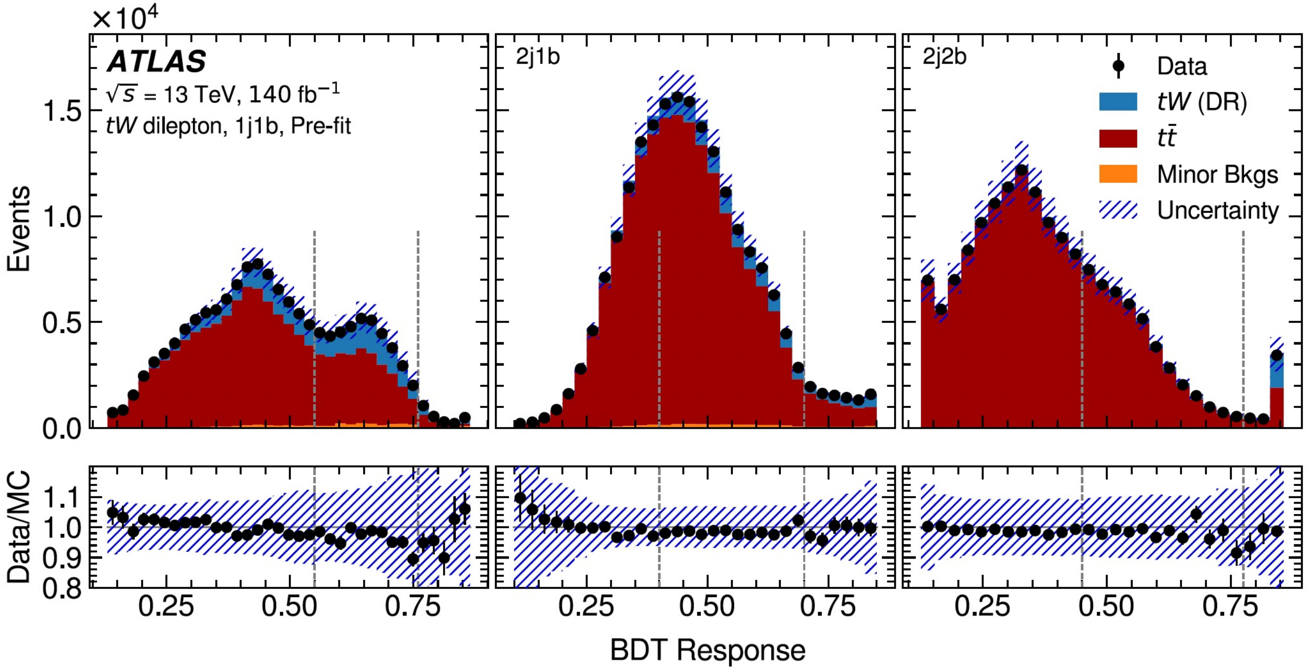
tW inclusive cross section

- Dilepton selection. Boosted Decision Trees to separate signal from background
- Measured inclusive cross section:

Phys. Rev. D 110, 072010 (2024)



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



- Consistent with theoretical prediction at NLO QCD + NNLL

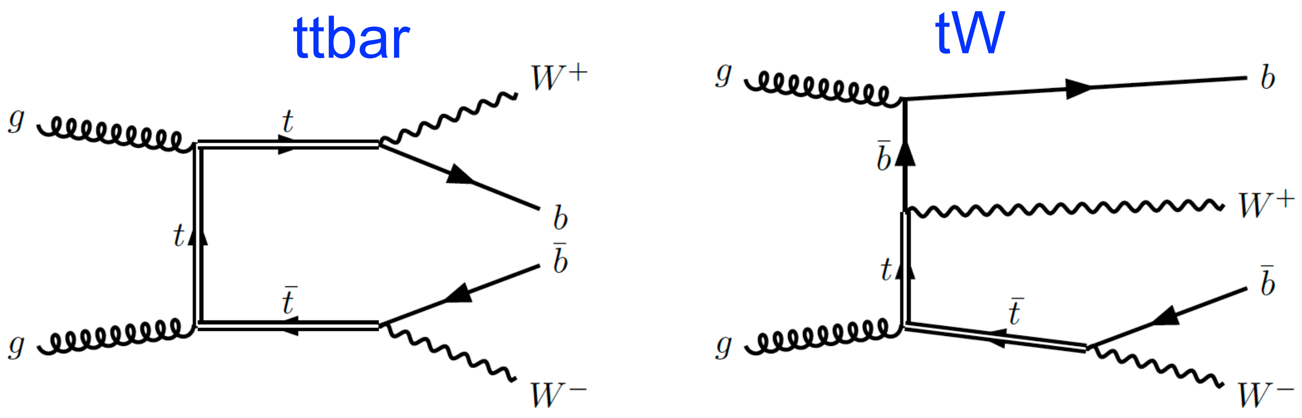
$$\sigma_{tW}^{\text{theory}} = 79.3^{+1.9}_{-1.8}(\text{scale}) \pm 2.2(\text{PDF})\ \text{pb}$$

WbWb differential cross section

NEW

arXiv:2506.14700

- Traditionally top quark modelling and fixed-order calculation rely on narrow-width approximation (NWA), for top quark
- But top quark has none-zero width. Beyond NWA, one has to consider the interference between ttbar and tW
- It's better to consider the process as a whole, pp→WbWb
- For MC side, Powheg bb4l
- Fixed order NNLO differential calculation is not available



Experimentally, it's important to measure the WbWb differential cross section to help improve the MC modelling of this process

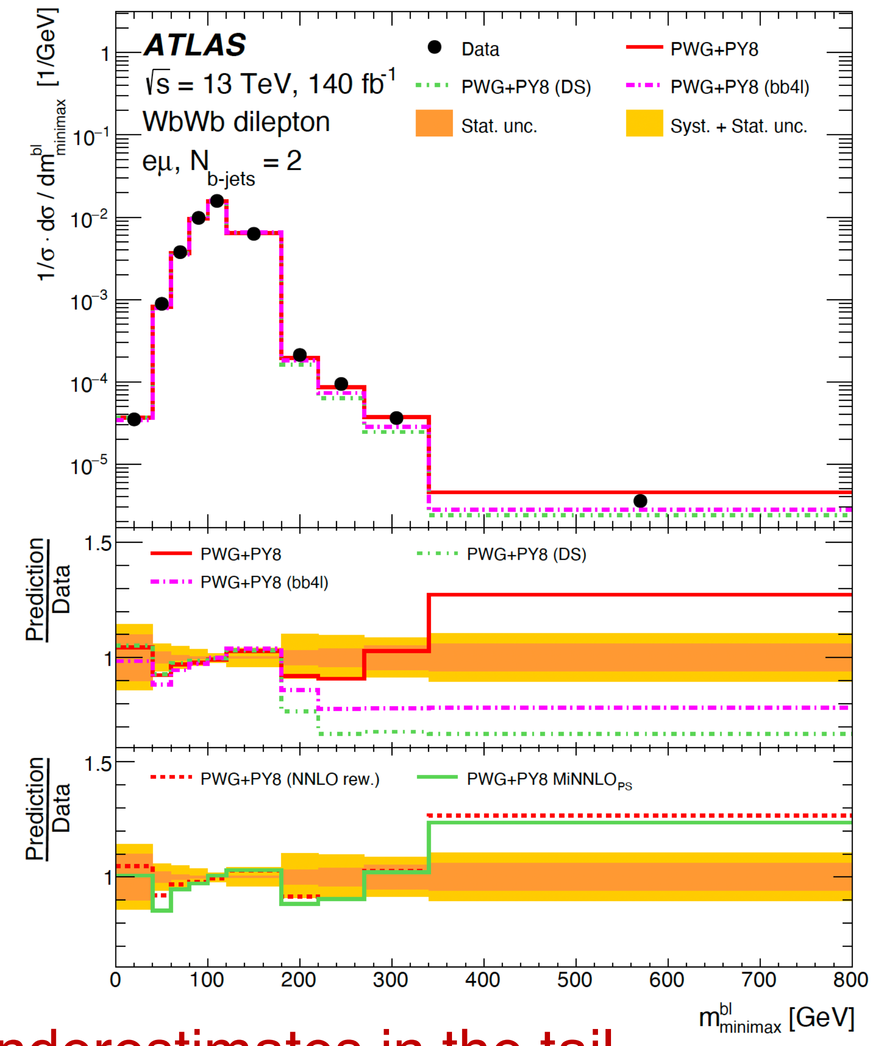
WbWb differential cross section

arXiv:2506.14700

- Using LHC Run2 data, 13 TeV. With dilepton channel
- One observable sensitive to the interference

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

- Unfold the $m_{minimax}$ and other kinematic variables using iterative Bayesian unfolding method

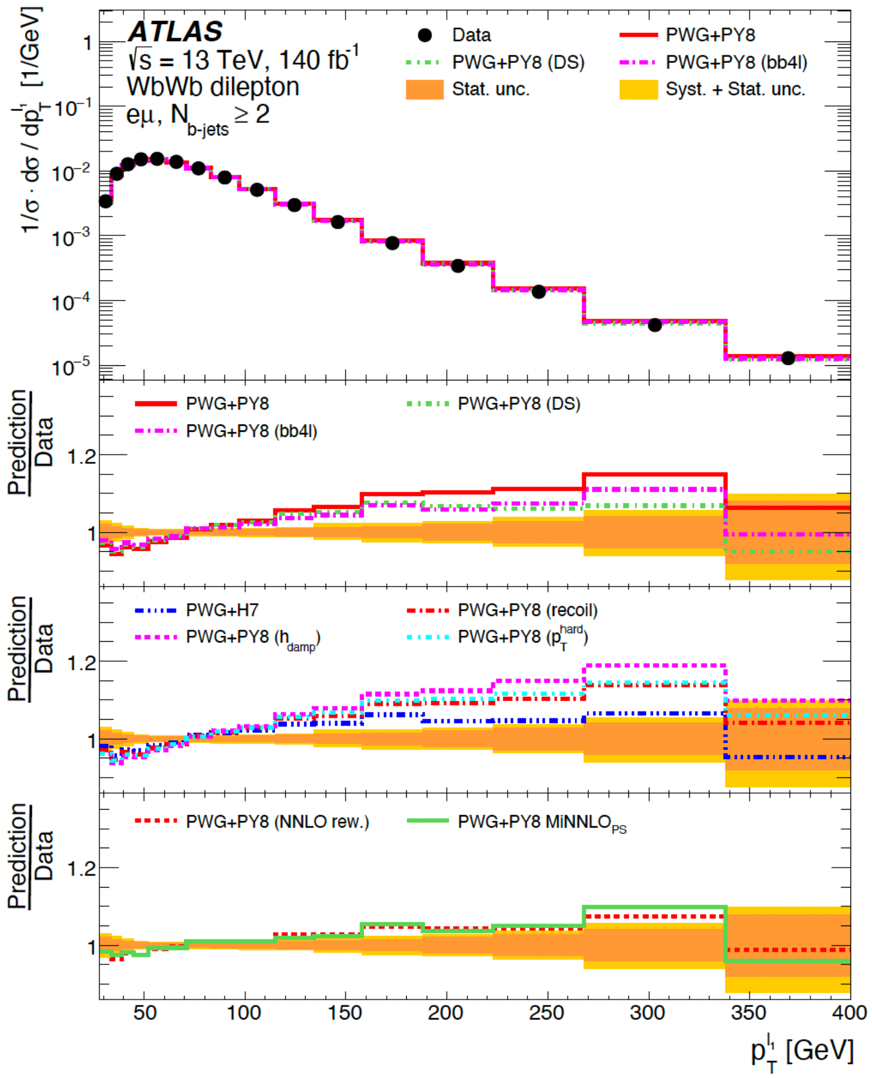


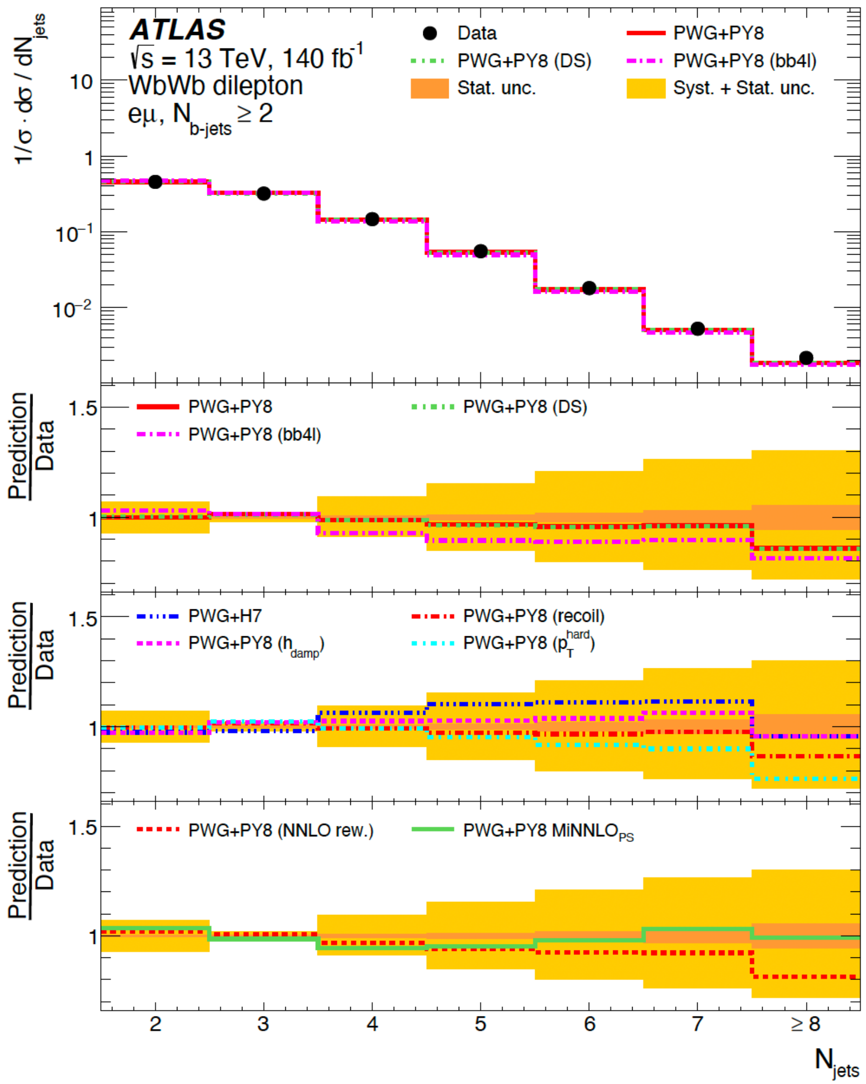
bb4l sample: underestimates in the tail

NEW

WbWb differential cross section

arXiv:2506.14700

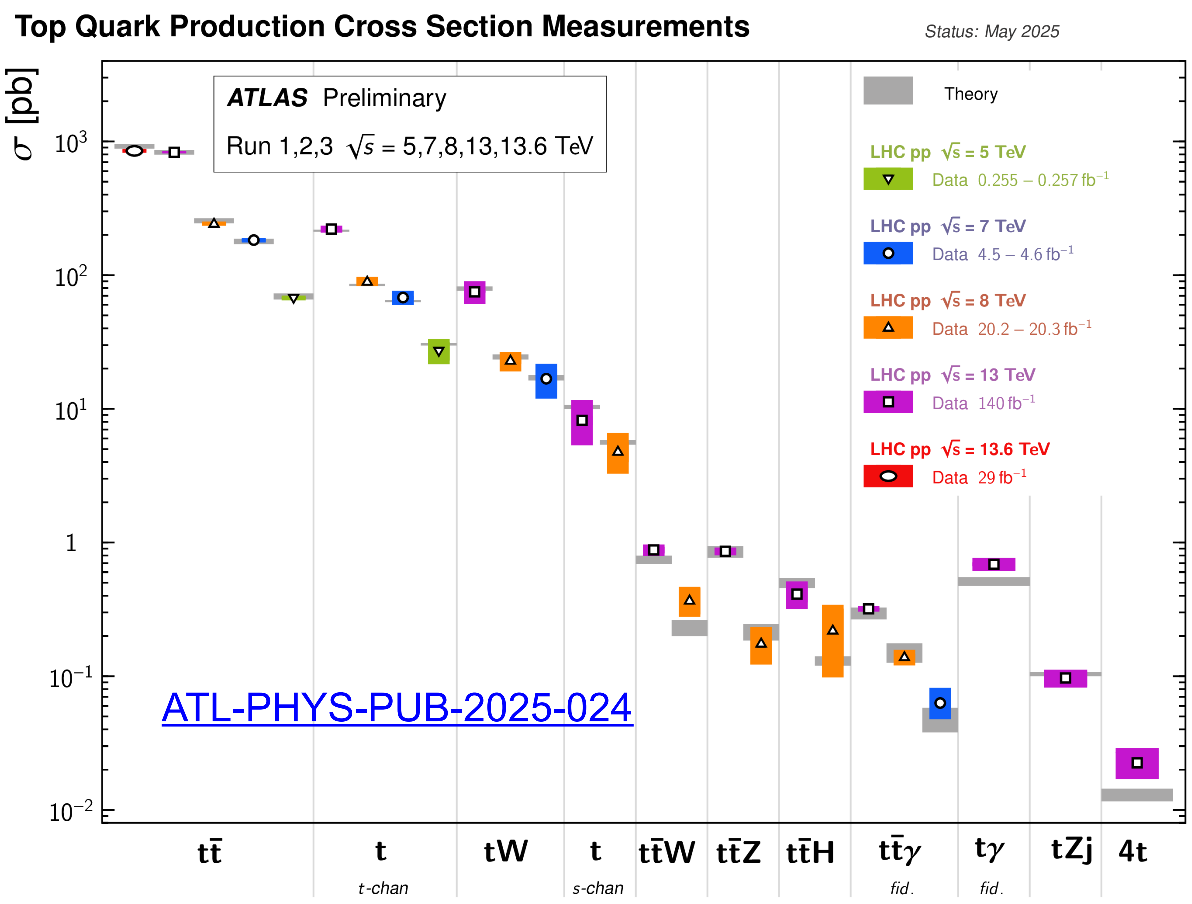


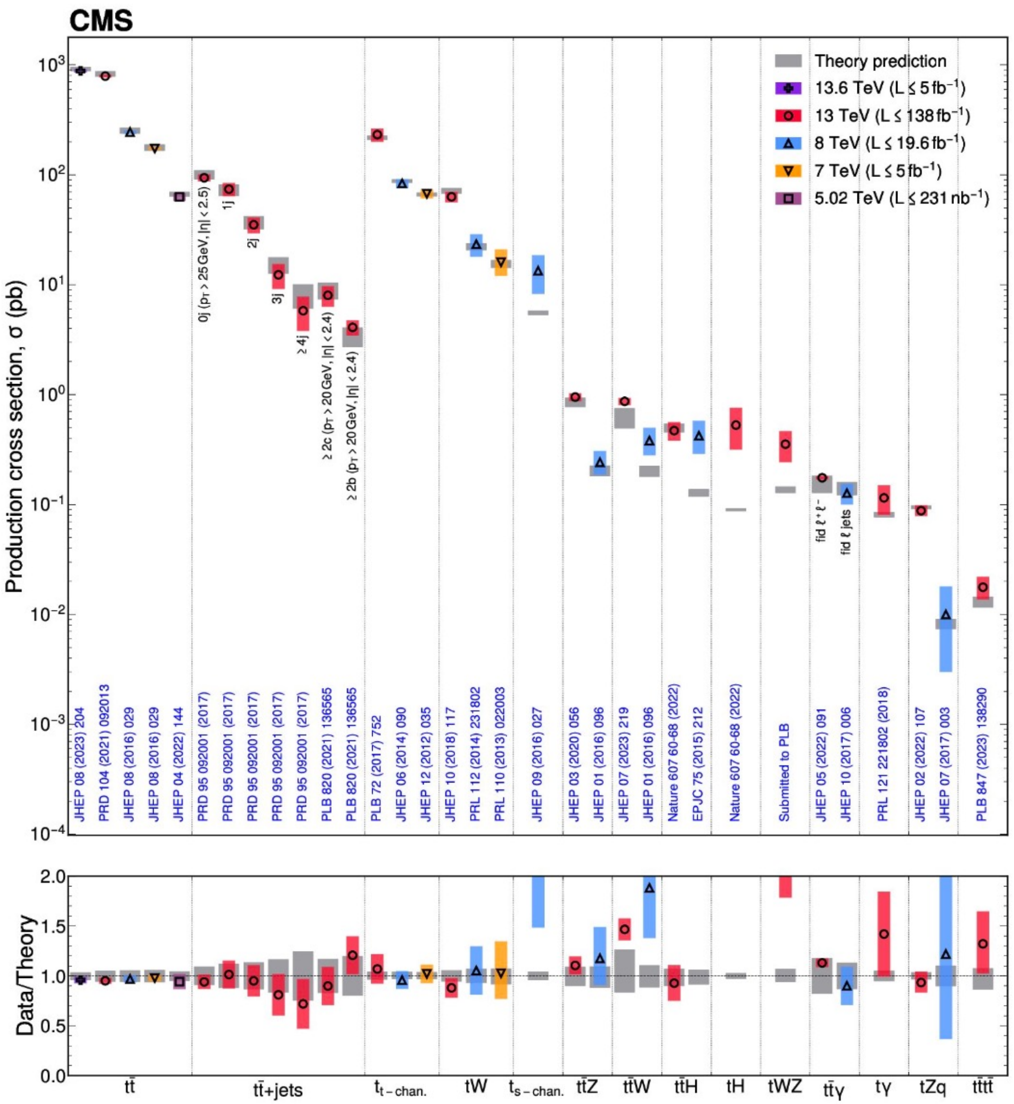


Need for further improvements of the modeling of this process

Top associated production

- Top rare production process



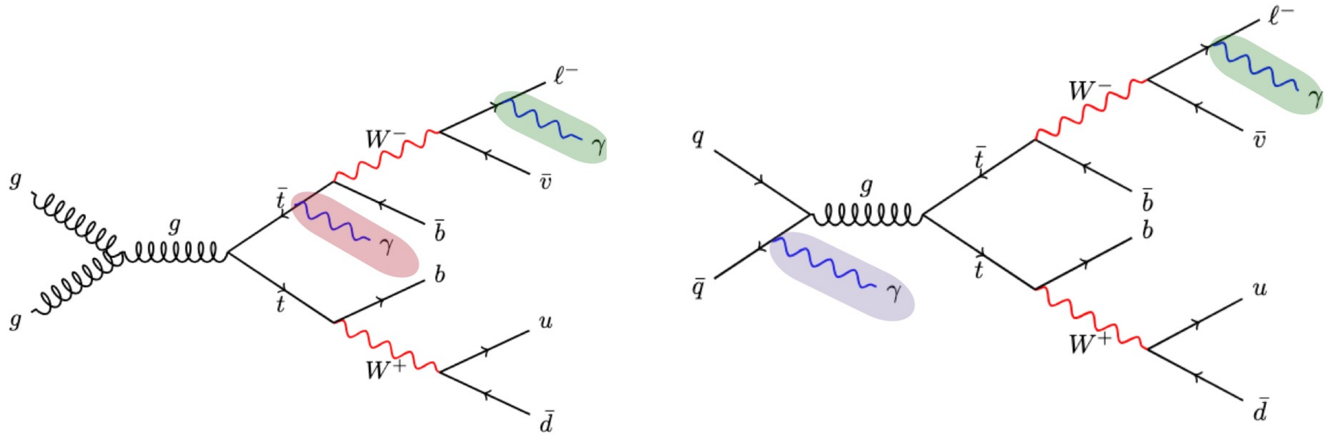


LHC Run 2 enable to access processes with XS < 1pb

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

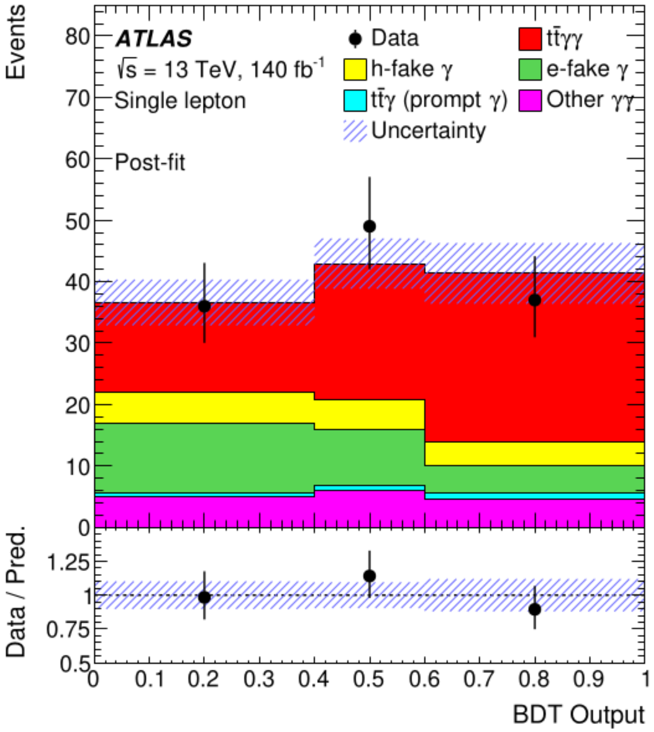
arXiv:2506.05018

- $t\bar{t}$ events with two photons
- Irreducible background to $t\bar{t}H$ with $H\to\gamma\gamma$
- Probe the $t\gamma$ electroweak coupling : electric charge and electroweak dipole moments



- With $t\bar{t}$ semileptonic decays (1-lepton channel)
- Using Bosted Decision Tress to separate signal and background
- Profile likelihood fit to BDT output
- Observed significance : 5.2σ (exp 3.8σ)

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

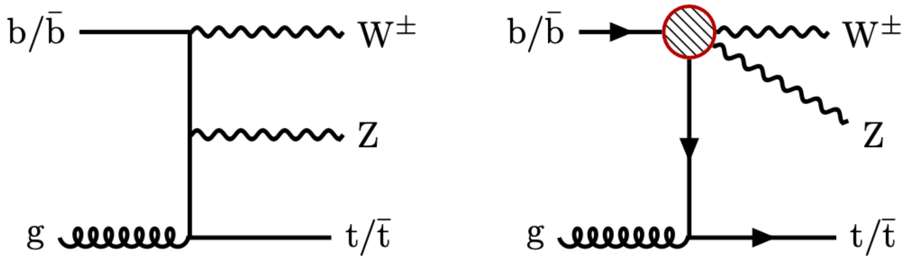


Observation of tWZ production

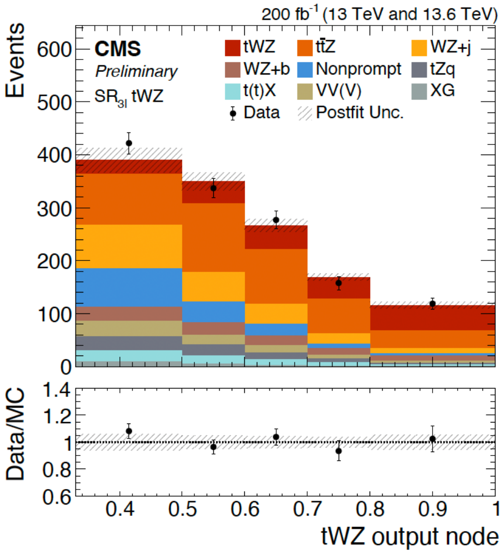
[CMS-PAS-TOP-24-009](CMS-PAS-TOP-24-009)

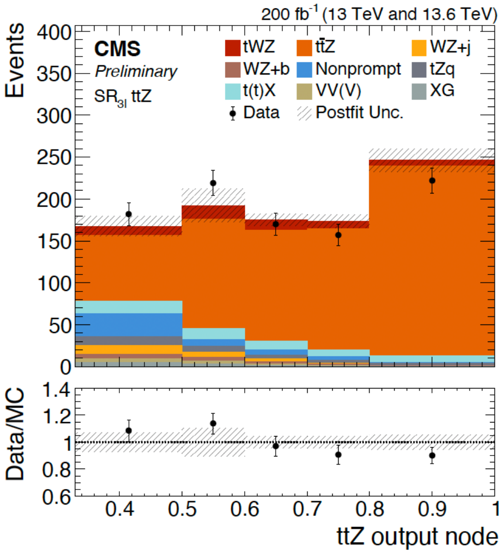
NEW

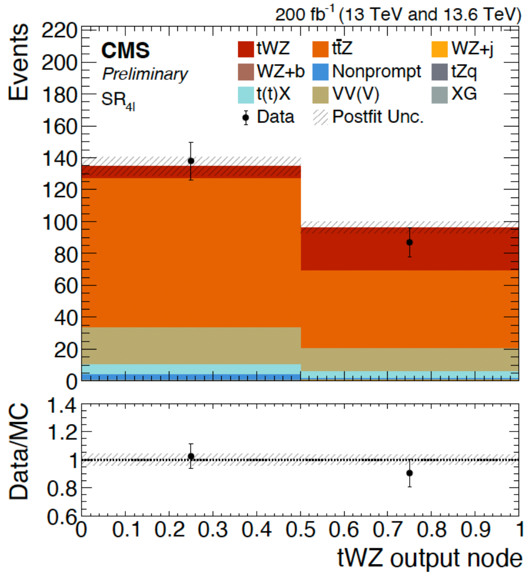
- New physics could arise from $bW \rightarrow tZ$ vertices
- Direct access to top electroweak couplings, test of the SM gauge structure
- With full Run 2 + 62 fb^{-1} of Run 3 data
- New for this around: Particle Transformer algorithm is used
- 3-lepton and 4-lepton signal regions

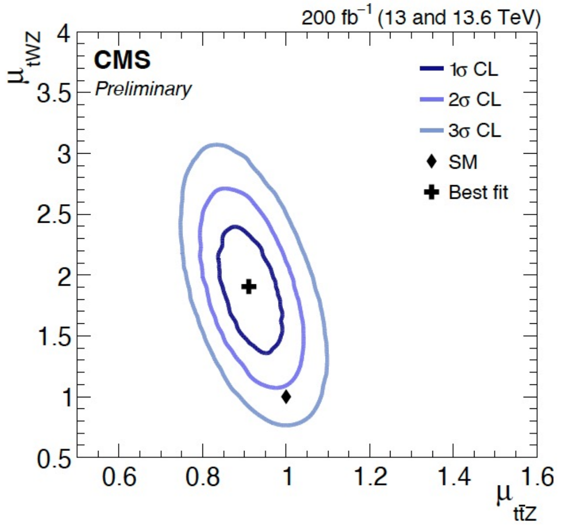


Observed significance : 5.8σ (exp 3.5σ)







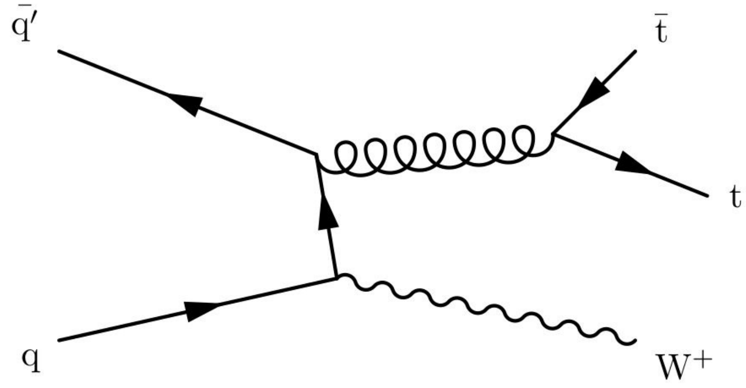


2D fit of the tWZ and tt̄Z

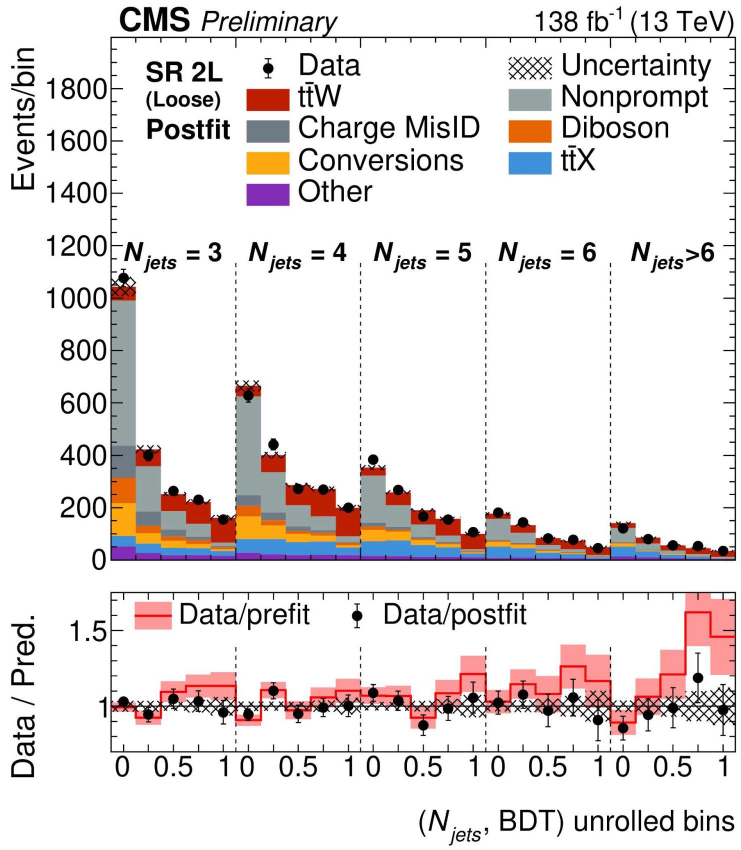
ttW differential cross section

CMS-PAS-TOP-24-003

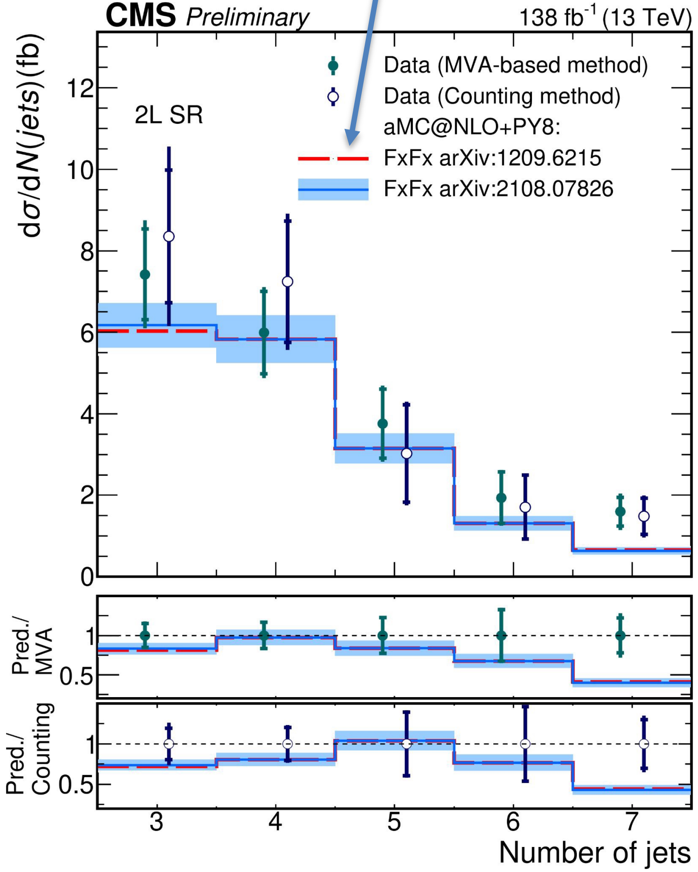
- Both 2-lepton (same sign) and 3-lepton channel
- Keep two analysis methods: MVA and counting



Likelihood-based unfolding



NLO prediction scaled to (approximate) NNLO cross-section.

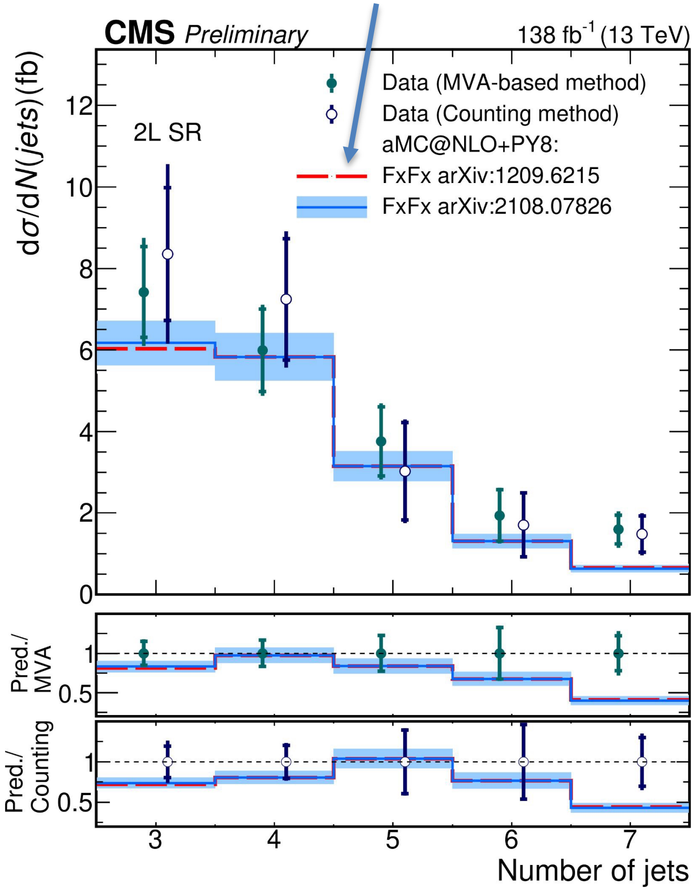


ttW differential cross section

CMS-PAS-TOP-24-003

- Both 2-lepton (same sign) and 3-lepton channel
- Keep two analysis methods: MVA and counting

NLO prediction scaled to (approximate) NNLO cross-section.

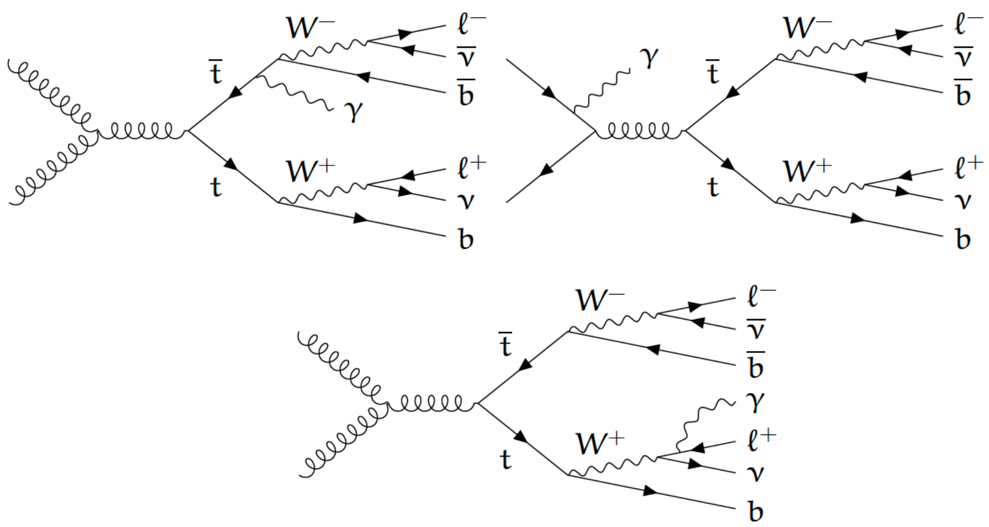


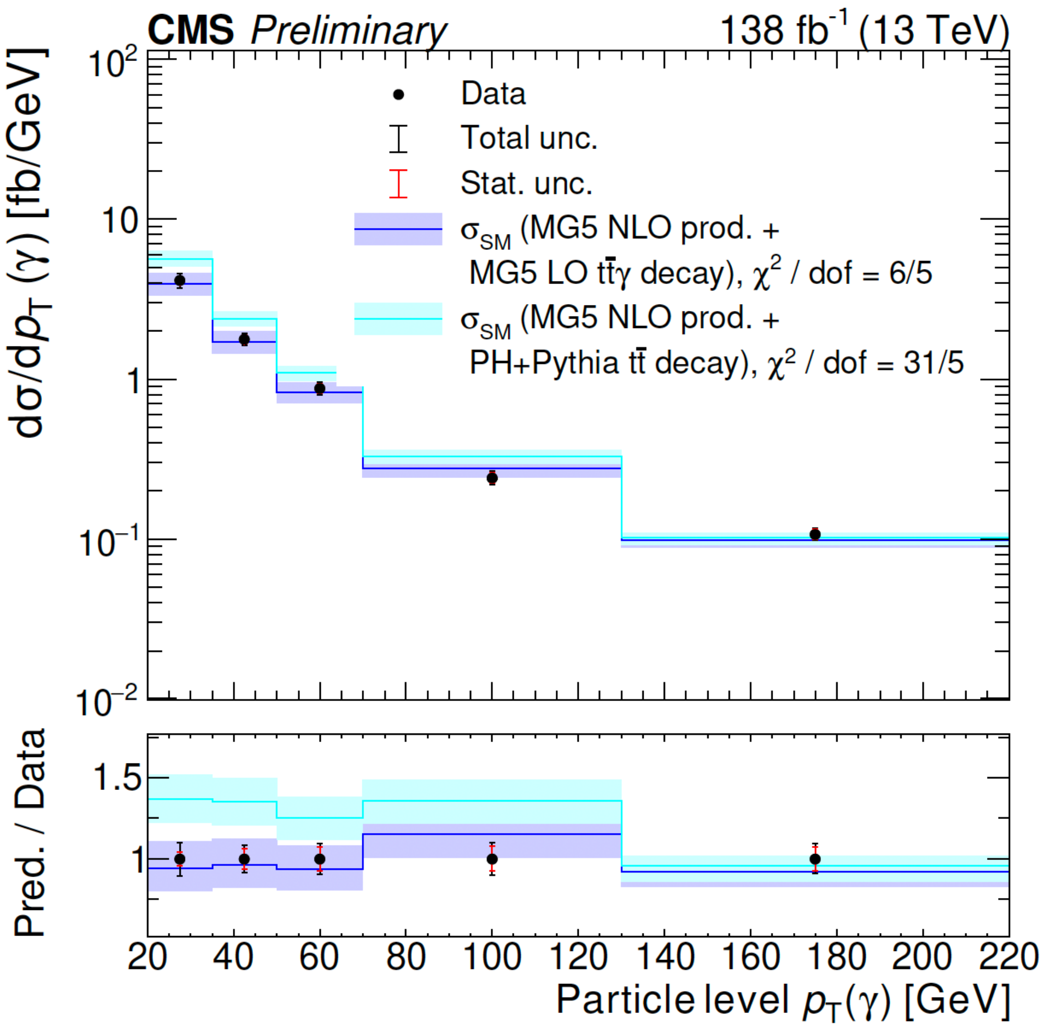
- The normalized cross section measurements align with SM expectations, while the absolute measurements are higher, consistent with previous inclusive results.
- The leptonic charge asymmetry of this process is also measured.

ttγ differential cross-section

CMS-PAS-TOP-23-002

- Photon: could be emitted from top quarks, the initial-state quarks, one of the two W bosons or b quarks, or the leptons in the final state





Inclusive cross section:

$$\sigma_{t\bar{t}\gamma} = 134 \pm 7(\text{syst}) \pm 3(\text{stat})\ \text{fb}$$

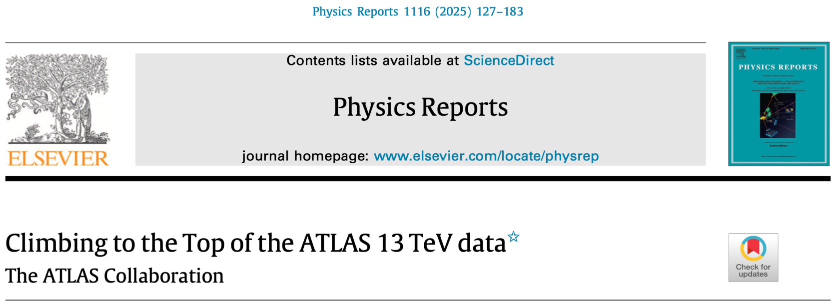
Conclusions

- Top quark physics is in its golden age
- Large LHC data, interplay between experimental side and theory side or modelling and fixed-order calculations
- LHC Run 2 data: precise cross section, differential cross section measurements. Access to new rare processes, $t\bar{t}$+boson, $t\bar{t}t\bar{t}$, $t\bar{t}$ + heavy flavor quarks
- Experimental side: improved object reconstruction and calibration with new technologies (*e.g.* ML). → Precision top physics
- LHC Run 3 data: just beginning, cross section with higher energy. More data coming
- Top quark mass measurement: direct and indirect methods

[ATLAS top quark results](#)

[CMS top quark results](#)

[Phys. Rep. 1116 (2025) 127-183](#)


Physics Reports 1116 (2025) 127–183

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Climbing to the Top of the ATLAS 13 TeV data☆

The ATLAS Collaboration