Top cross-section measurements and rare t+X processes

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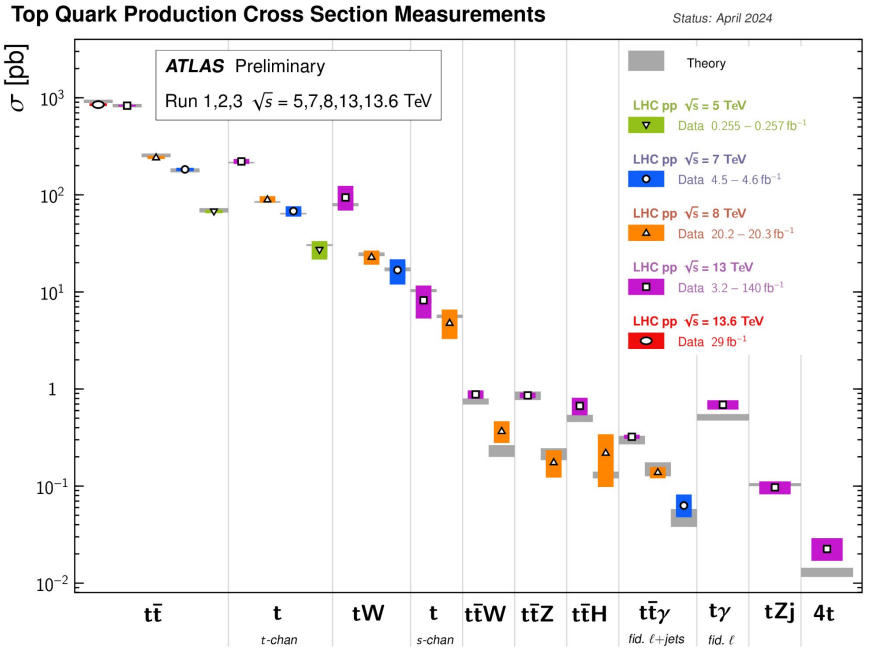
On behalf of the ATLAS and CMS Collaborations

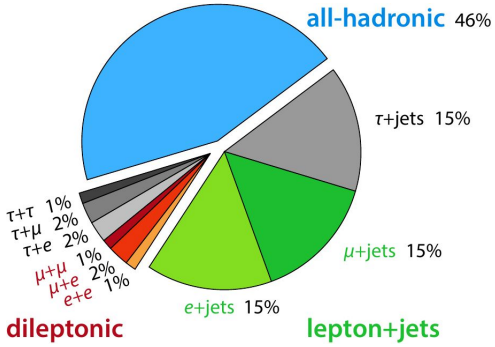
LHCP 2024, 6th June 2024

Introduction

- Top quark has **unique properties**
  - **Large mass**
    - Decays before hadronization
    - Produced at large scales -> “small” coupling strength
  - **Yukawa coupling ~ 1**
    - Important for EW physics



In this talk: **Top**, **top-antitop** and **top-antitop+X** (X = γ, Z, W, jets) cross-section



Top cross-section

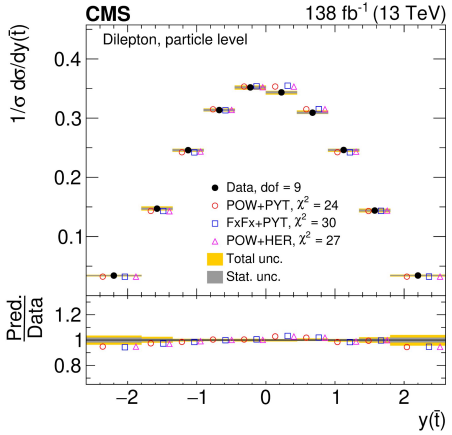
Differential x-section $t\bar{t}$(+jets) in 2L channel, CMS

- **Full run 2**, ee + mumu + emu
- Standard dilepton selection
- **Full kinematic reconstruction**
  - Apart from $m_{t\bar{t}}$ related observables
- **<u>Very complete measurement</u>**
  - Particle + parton, absolute + normalized
  - $t\bar{t}$, $t\bar{t}$+1jet
  - Top quark + top decay (lepton, b-jets)
  - Single, double and triple differential

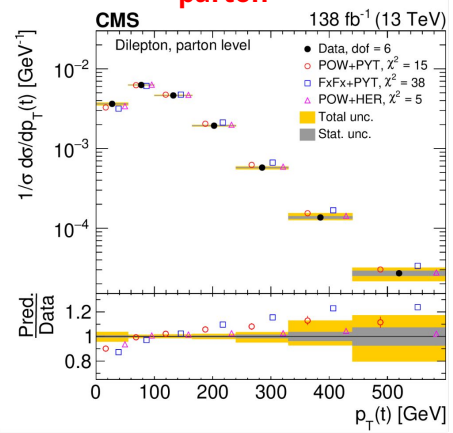
arXiv:2402.08486

Dominant uncertainties:

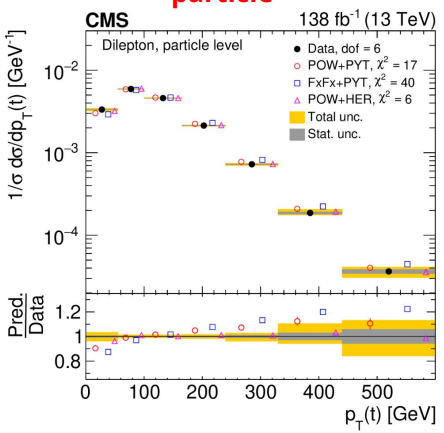
- JES
- Signal modeling
- B-tagging

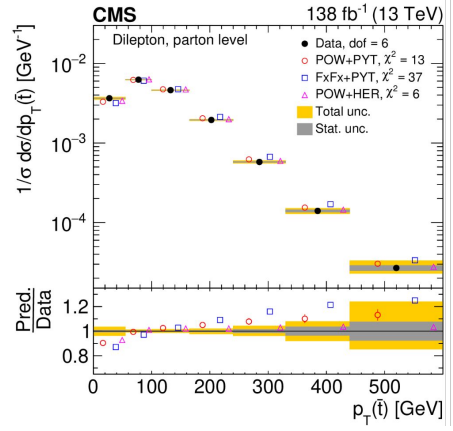


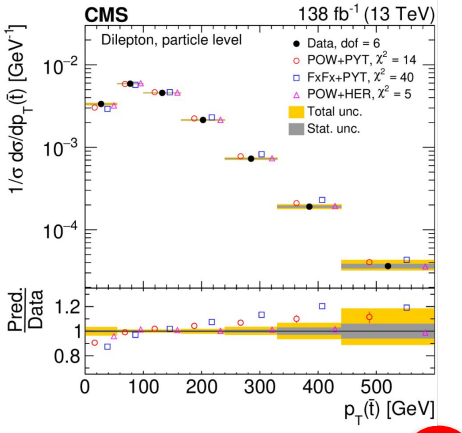
parton

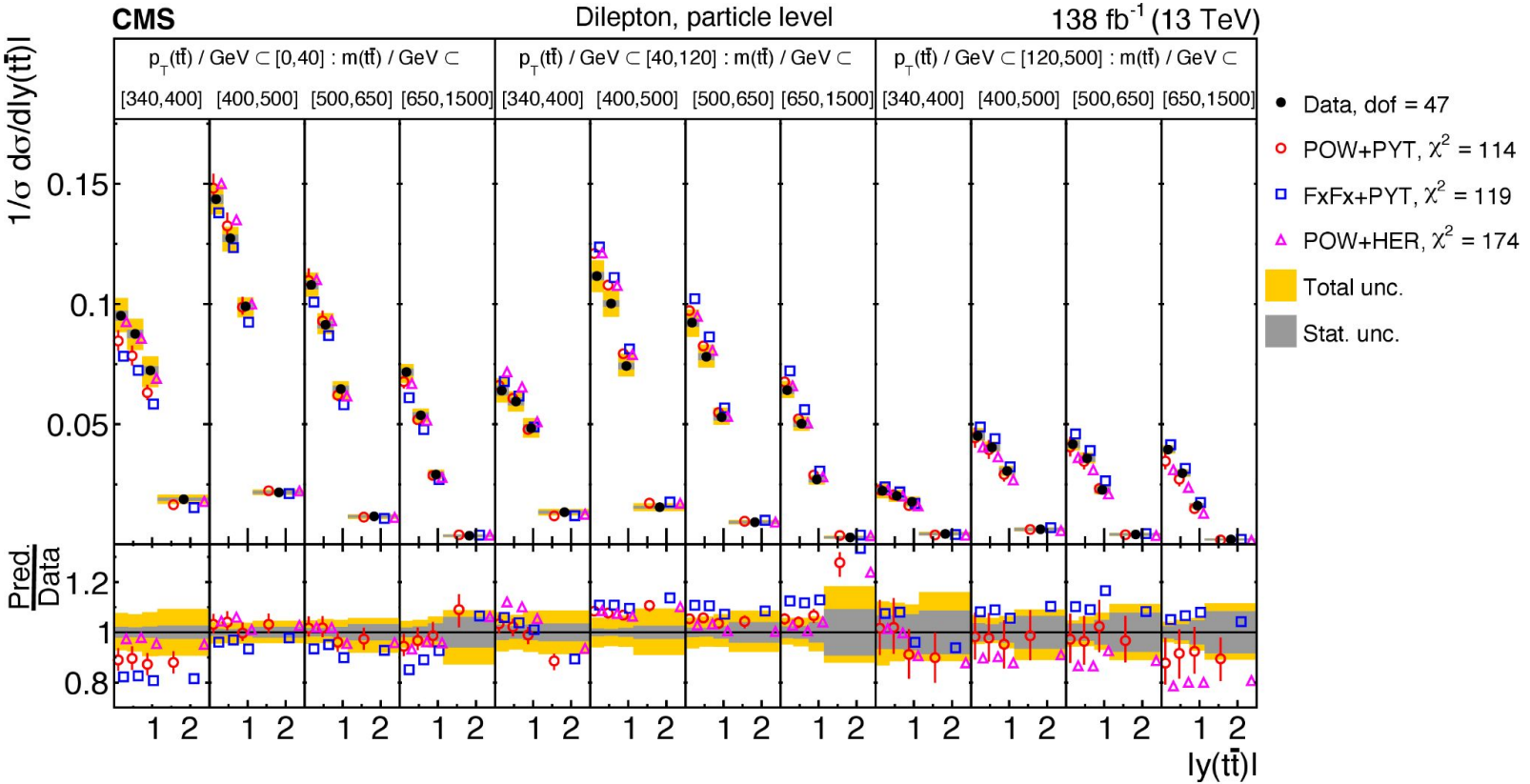


particle



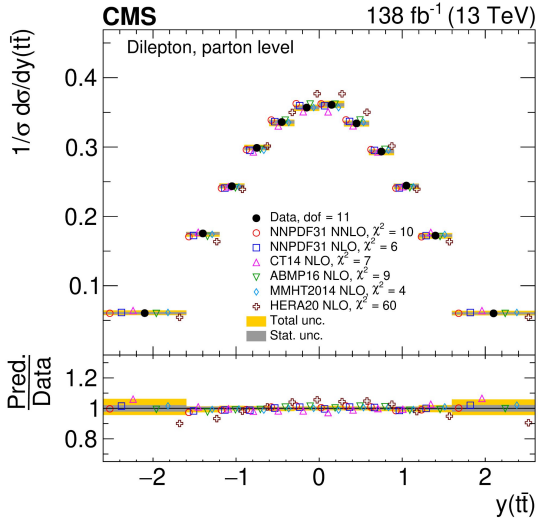






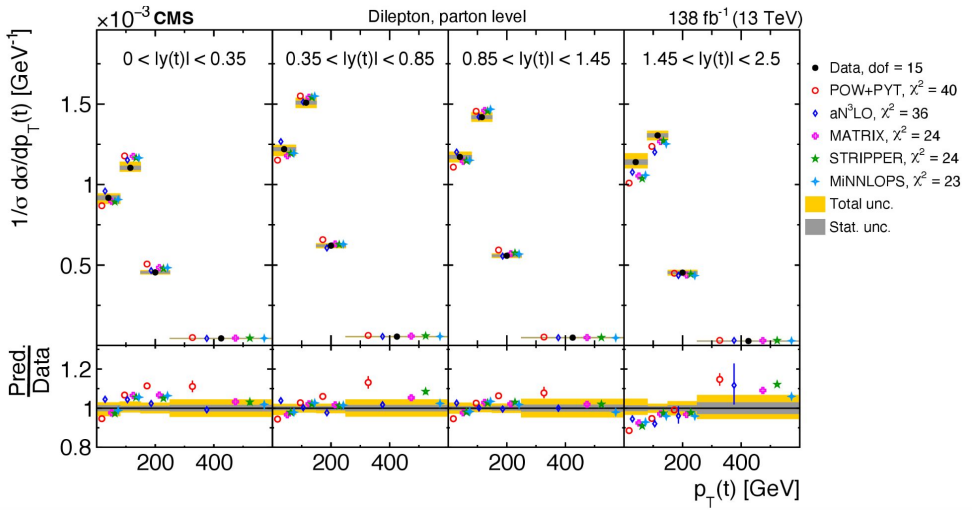
- **1D** distributions reasonably **well described**
  - p_T of top/antitop and $m_{t\bar{t}}$ worse agreement
- **2D/3D** distributions **often not well described** by any generator

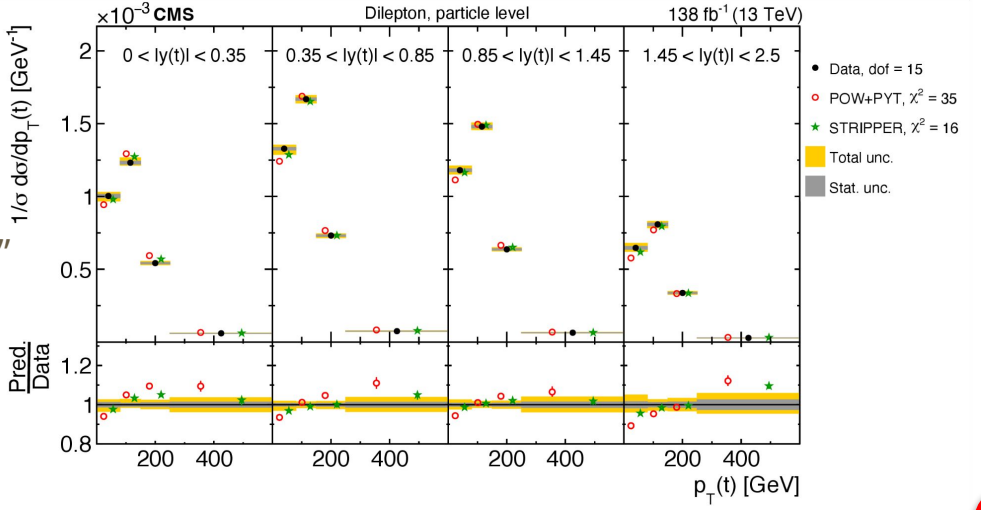
- **Comparison of different PDFs**



- **Comparison to beyond NLO predictions**
  - aN^{3}LO - NNLO + NNLL
  - MATRIX - “qT-slicing”
  - STRIPPER - “sector improved residues”
  - MiNNLOPS - NNLO + PS

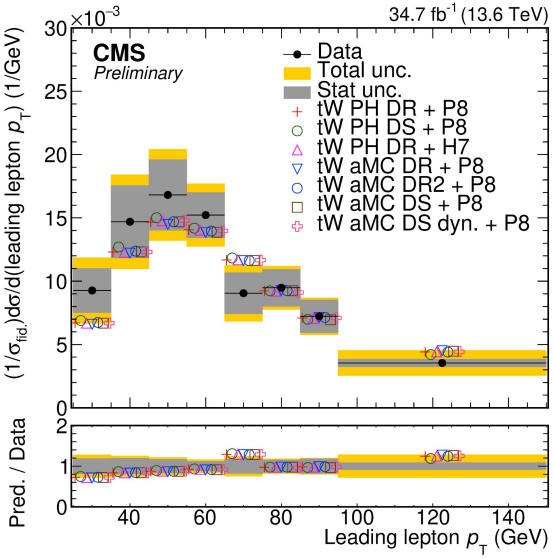
- **Beyond NLO predictions closer to measured data**

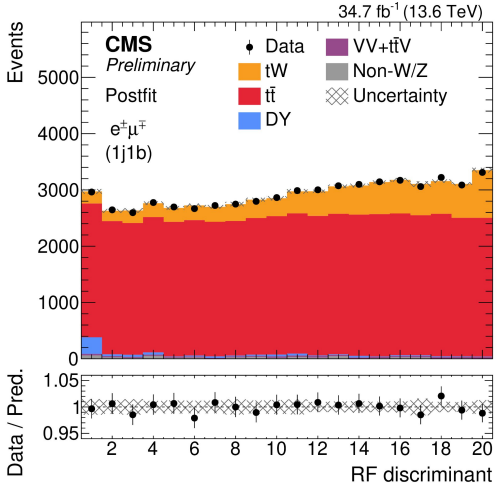


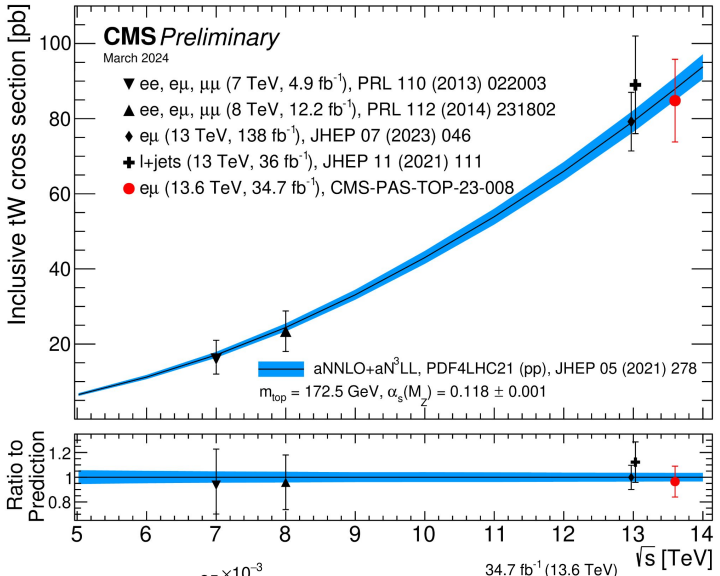


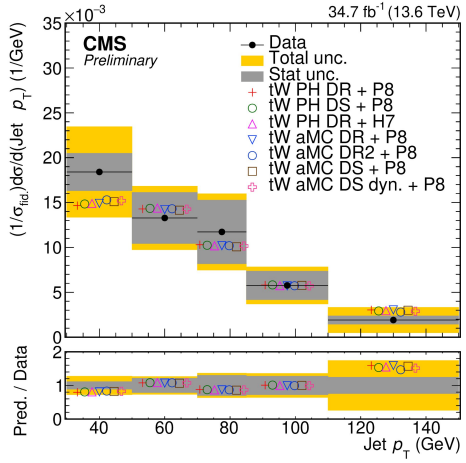
tW Run 3 cross-section, CMS

- **√s = 13.6 TeV**, 2022 dataset, **34.7 fb^{-1}** CMS PAS TOP-23-008
- e-mu channel
- Inclusive + differential
- Random forest (MVA)
- Most sensitive channel 1j1b
  - Used for **unfolding**









Predicted cross-section:
87.9 +2.0/−1.9 (scale) ± 2.4 (PDF+α_S) pb

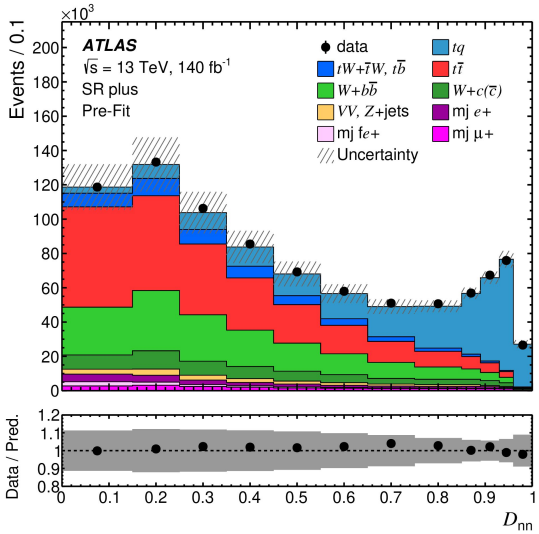
Measured cross-section:
84.1 ± 2.1 (stat) −10.2/+9.8 (syst) ± 3.3 (lumi) pb

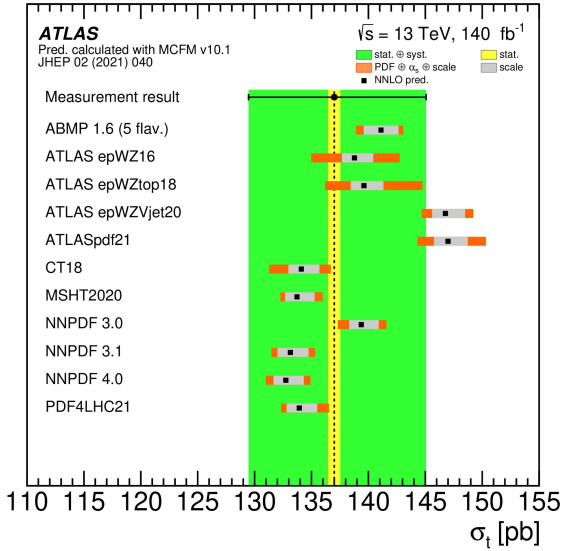
Dominant uncertainties:
JES, background normalisation, b-tagging

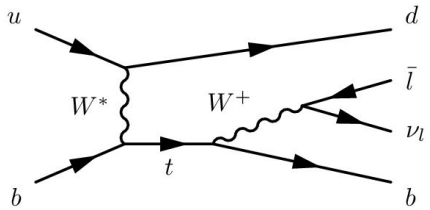
t-channel single top, ATLAS

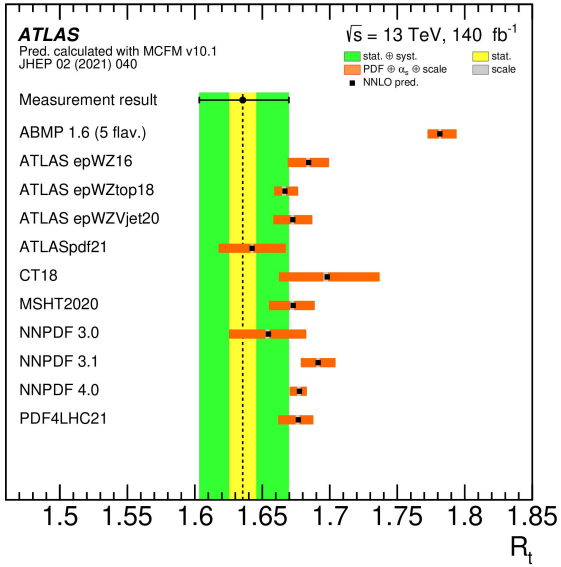
arXiv:2403.02126

- Measuring **top**, **antitop** and **ratio** cross-sections
  - Sensitivity to **PDFs**
- NN to separate signal from background
  - W+jets and fake leptons
  - Separated by lepton charge









$\sigma(tq)$ = 137±8 pb (5.8% unc.)

Dominant uncertainties:

Signal modeling, JES

Previous result:

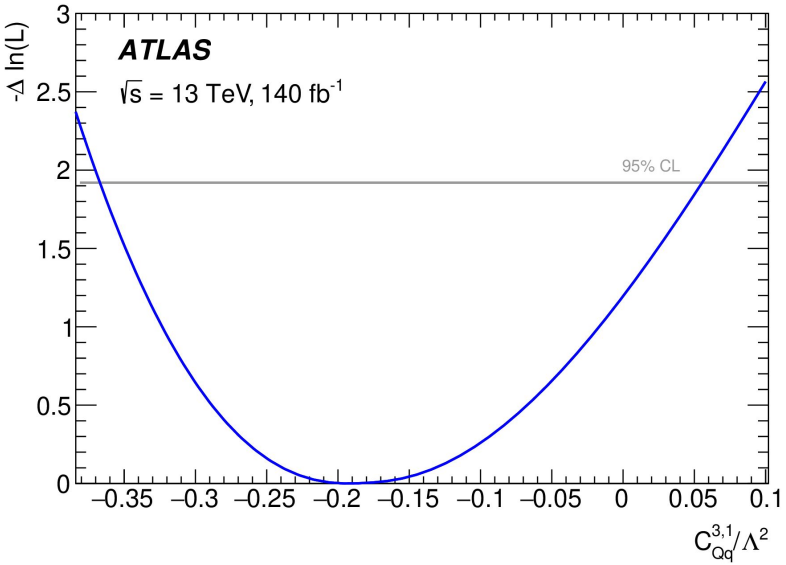
3.2 fb^{-1} analysis: 20 % unc.

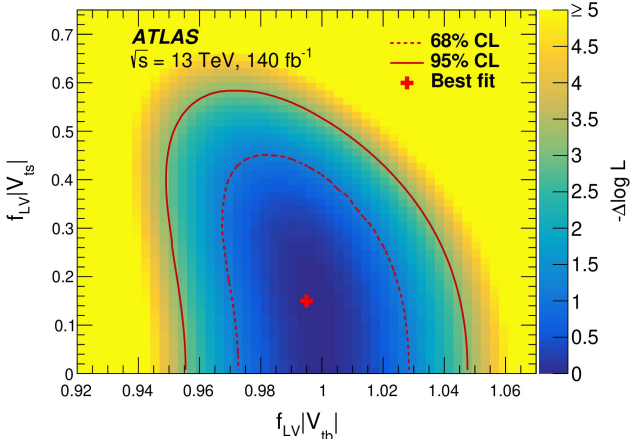
t-channel single top, ATLAS - EFT + CKM

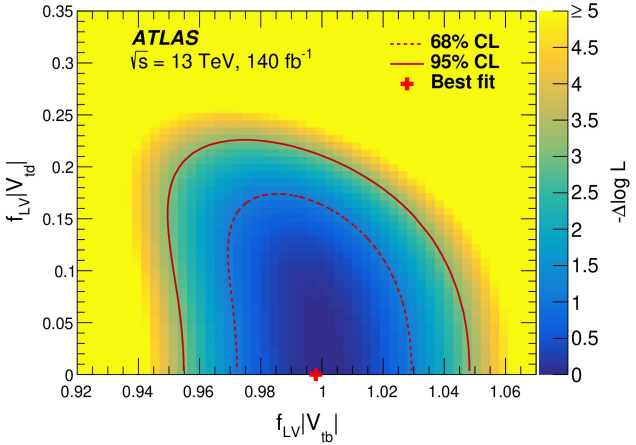
- **CKM matrix interpretation**
- Detector level fit for **EFT limit estimate**

$$f_{LV} \cdot |V_{tb}| = 1.015 \pm 0.031$$

$$-0.87 < C^{3}_{\phi Q}/\Lambda^{2} < 1.42 \text{ @95\% CL}$$

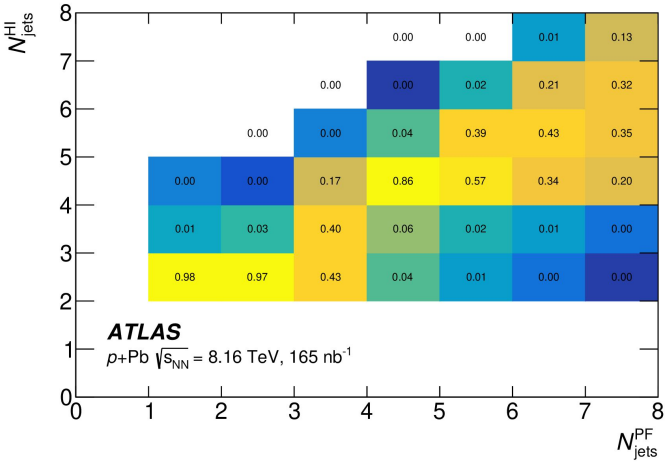


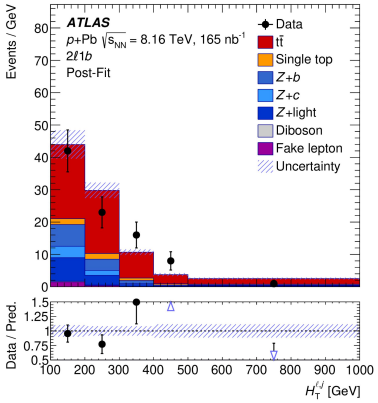


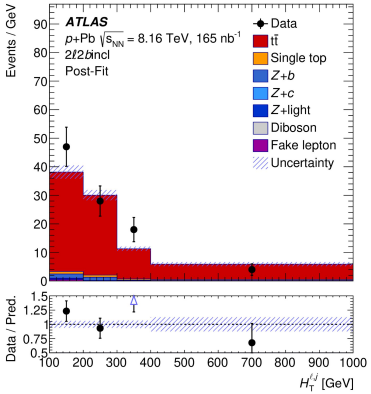


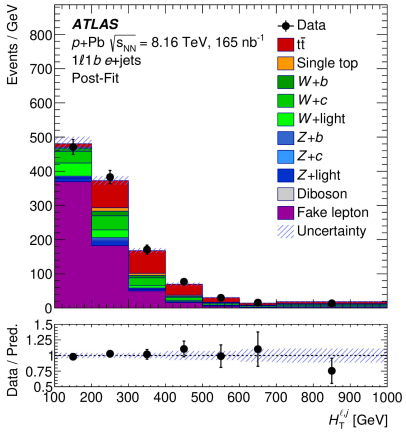
Observation of $t\bar{t}$ production in p-Pb, ATLAS

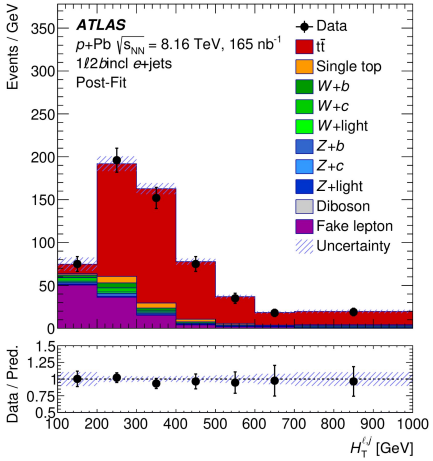
- **p-Pb collisions**, $\sqrt{s}$NN = 8.16 TeV, **165 nb^{-1}**
- 1L and 2L $t\bar{t}$ final state [arXiv:2405.05078]
- Sensitivity to **nuclear PDFs**
- **Dedicated jet calibration** - "HI jets"
  - Absolute calibration
  - In-situ calibration extrapolated from pp
- "Standard" PFlow jets
  - Used for b-tagging











Observation of $t\bar{t}$ production in p-Pb II, ATLAS

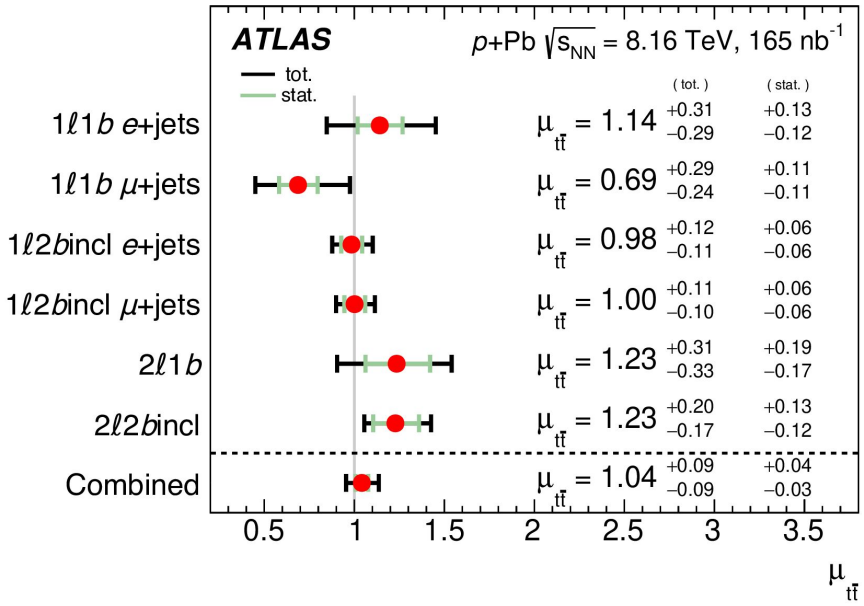
$\sigma_{t\bar{t}}$ = 58.1 ± 2.0 (stat.) −4.4/+4.8 (syst.) nb (9% unc.)

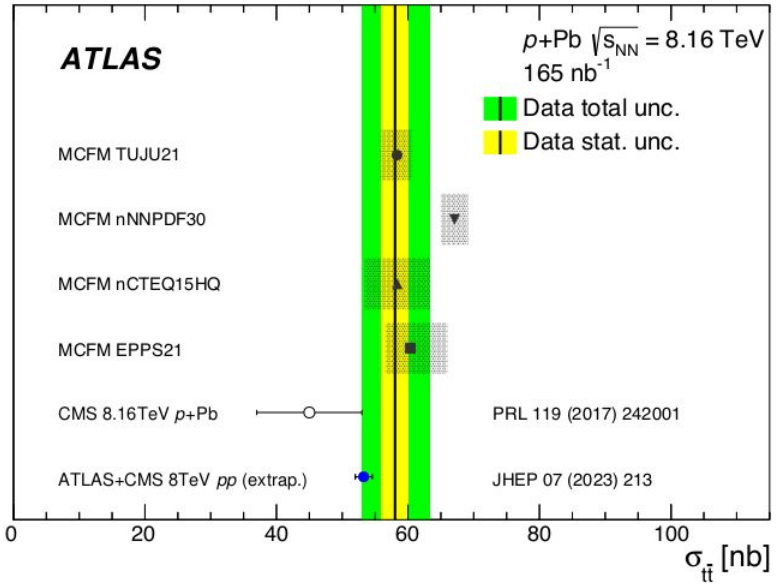
- > 5 sigma in both channels (1L and 2L)

R_{pA} = 1.090 ± 0.039 (stat.) −0.087/+0.094 (syst.)

$$R_{pA} = \frac{\sigma_{t\bar{t}}^{p+\mathrm{Pb}}}{A_{\mathrm{Pb}} \cdot \sigma_{t\bar{t}}^{pp}}$$

Older CMS measurement: [arXiv:1711.03143]

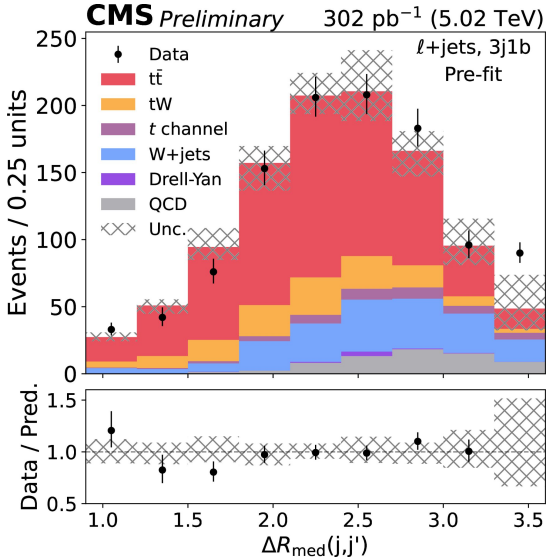


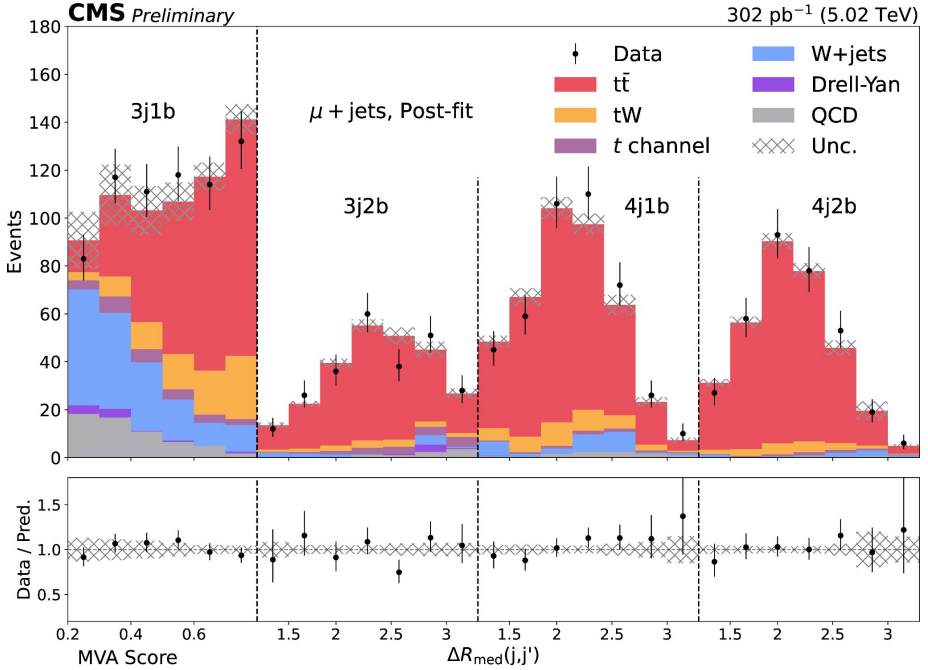


$t\bar{t}$ production at $\sqrt{s}$ = 5.02 TeV, CMS

CMS-PAS-TOP-23-005

- **302 pb^{-1}**, low pile-up
- **Lepton+jets channel**
  - Split by jet, bjet and lepton categories
  - Starting from at least 3 jets
- MVA separation for 3j1b channel
  - Larger W+jets contribution





SM prediction (NNLO in QCD): 69.5 −3.1/+2.9 pb

Result: 61.4 ± 1.6 (stat) −2.6/+2.7 (syst) ± 1.2 (lumi) pb

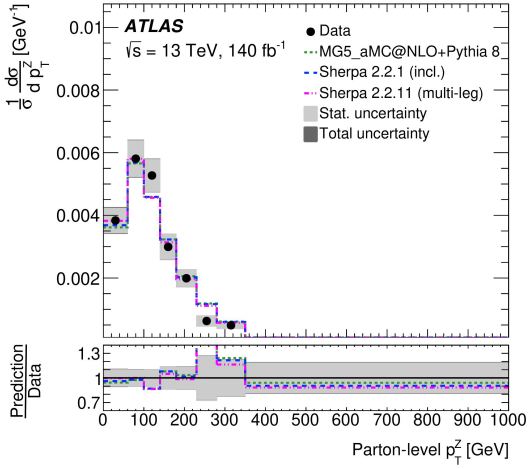
Combination with 2L channel: **61.2 −1.5/+1.6 (stat) −2.3/+2.6 (syst) ± 1.2 (lumi) pb**

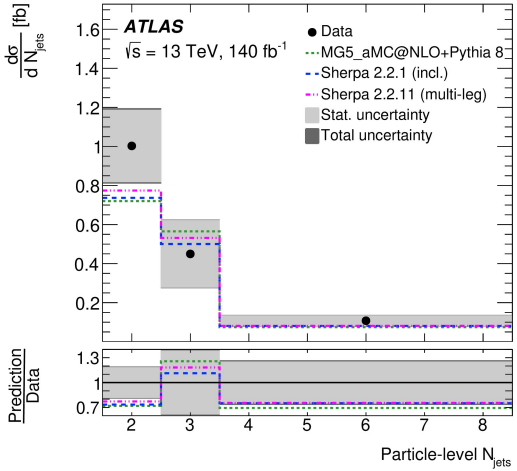
t+X cross-section

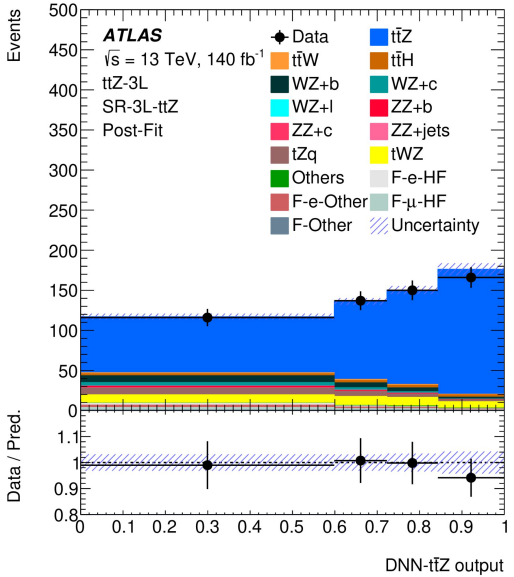
ttZ ATLAS

arXiv:2312.04450

- Inclusive: **2L** + **3L + 4L** channels
  - NN to separate signal
    - 3L channel: multiclass including tZq
- Differential: **3L + 4L** channels
  - Parton and particle
  - Absolute and normalized
  - 3L, 4L separate + combination
  - **Regularization** for hard-to-reconstruct observables





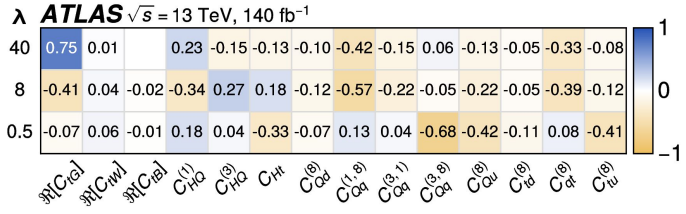


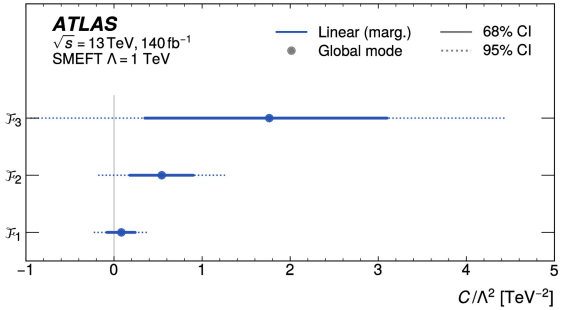
- **Measured cross-section:**
  0.86 ± 0.04(stat.) ± 0.04(syst.) pb
  Precision 6.5%

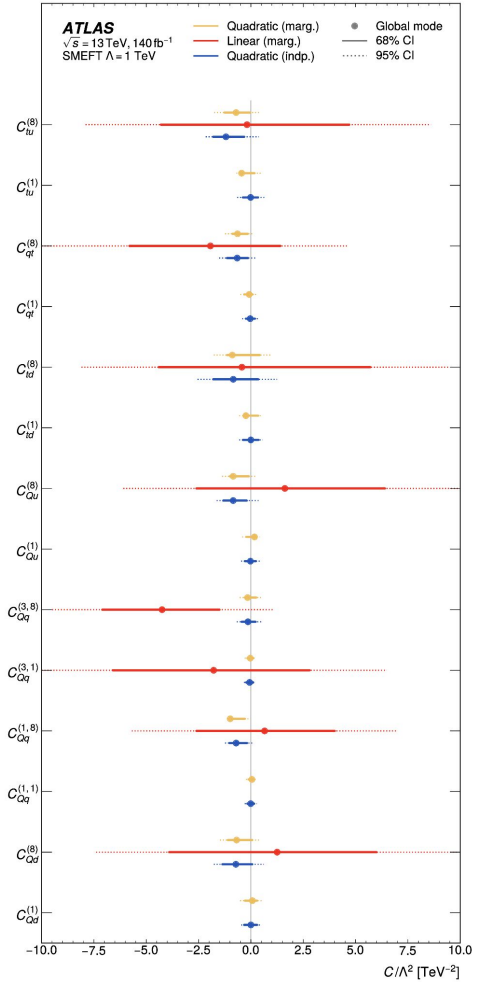
- Significantly **improved over previous result** (using the same dataset)
  - Looser selection + NN
  - Inclusion of 2L channel

ttZ ATLAS - interpretations

- **EFT limit extraction** from unfolded distributions
- Fisher matrix -> sensitive directions







- **Spin correlation interpretation**

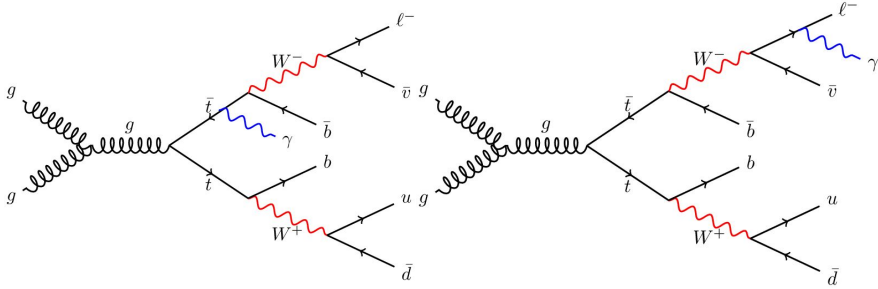
$$O = f_{\mathrm{SM}} \cdot O_{\text{spin-on}} + (1 - f_{\mathrm{SM}}) \cdot O_{\text{spin-off}}$$

$$f_{\mathrm{SM}}^{\text{obs.}} = 1.20 \pm 0.63\ (\text{stat.}) \pm 0.25\ (\text{syst.}) = 1.20 \pm 0.68\ (\text{tot.})$$

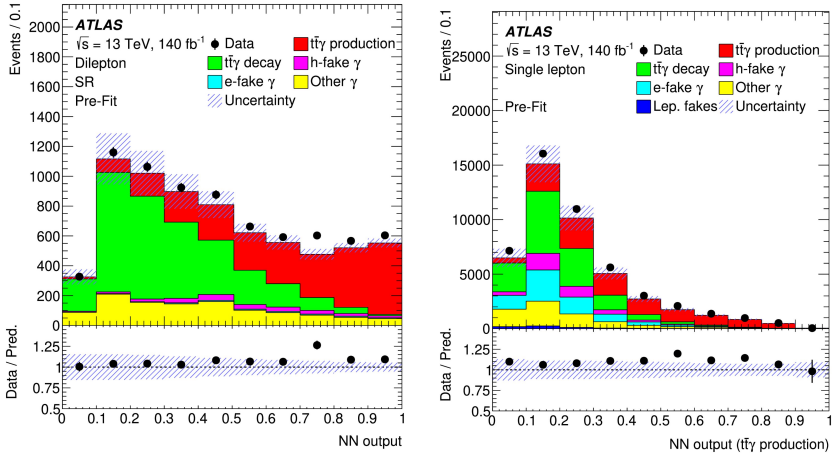
Heavily statistically limited

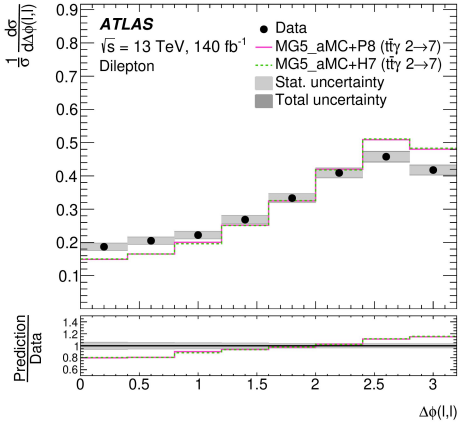
$t\bar{t}\gamma$ ($+t\bar{t}Z$) ATLAS

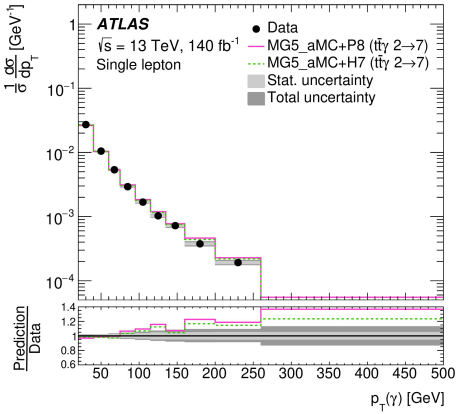
arXiv:2403.09452



- **Inclusive** and **differential** cross-sections
- **$t\bar{t}\gamma$ with γ from production** vs **decay**
  - Interference negligible in narrow width app.
- 1L and 2L channels
- **Data driven** e->photon and hadron->photon fakes
- DNN for separation
  - 1L: multiclass
  - 2L: binary
- Profile-likelihood unfolding







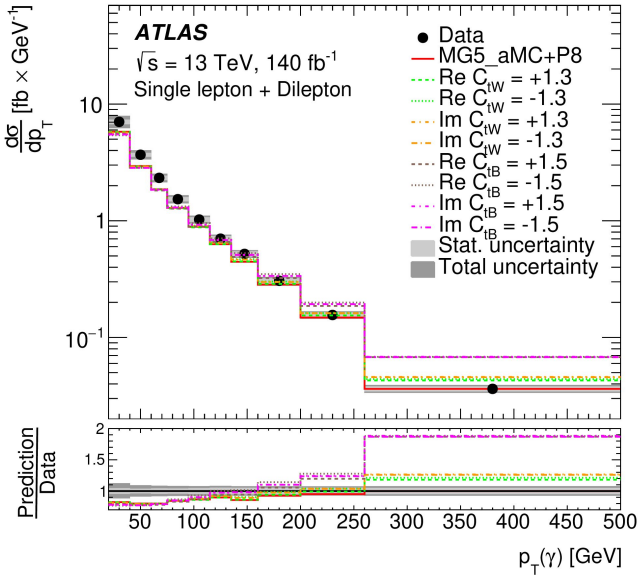
Particle level - phase space close to detector acc.

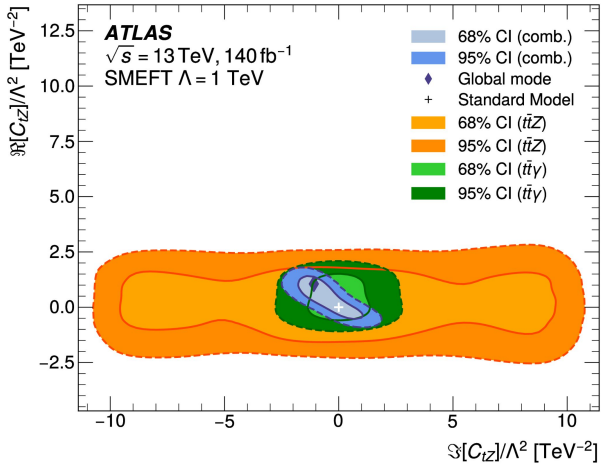
1L + 2L combination

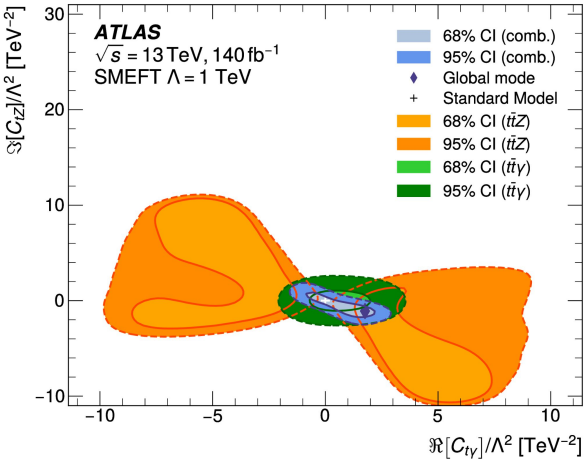
- **Production x-sec** : 322 ± 5 (stat) ±15 (syst) fb
- **Prod+decay x-sec**: 793 ± 5 (stat) −37/+38 (syst) fb

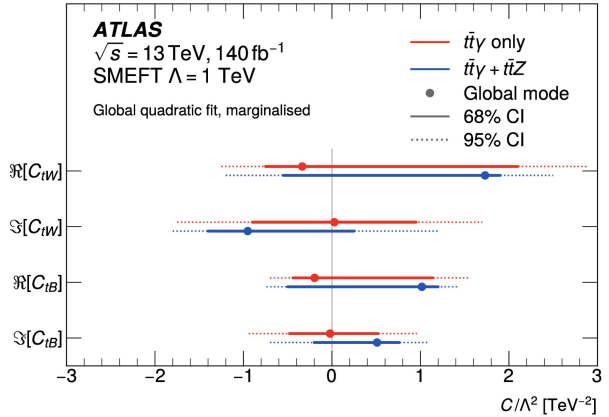
$t\bar{t}\gamma$ ($+t\bar{t}Z$) EFT, ATLAS

- Sensitivity to C_{tW} and C_{tb}, **real** and **imaginary**
  - Also rotated to C_{tZ} and C_{ty}
- EFT extraction from unfolded distributions
- **Combination** with $t\bar{t}Z$ measurement
  - **Simultaneous unfolding**
  - Combined EFT interpretation





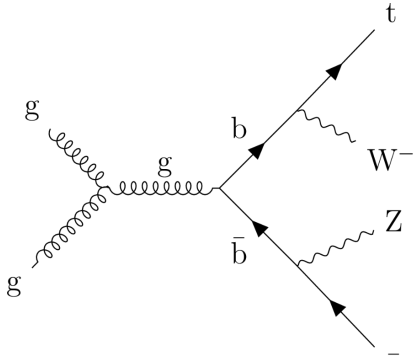


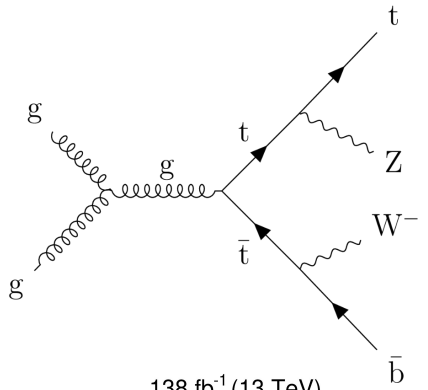


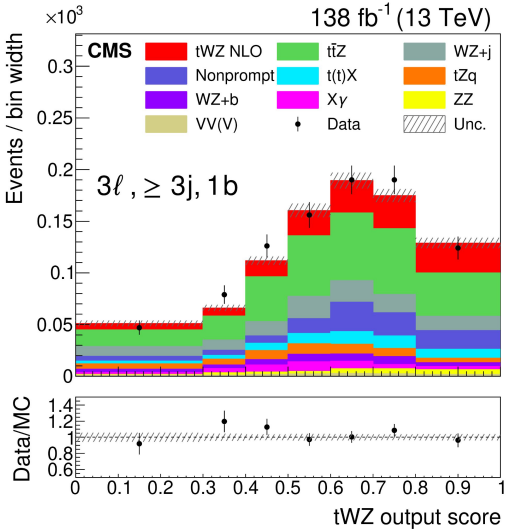
Evidence for tWZ, CMS

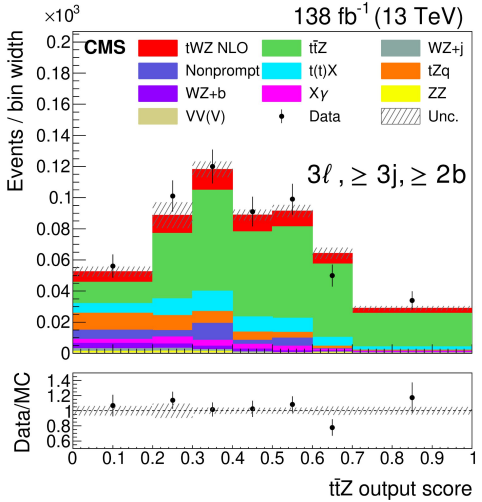
arXiv:2312.11668

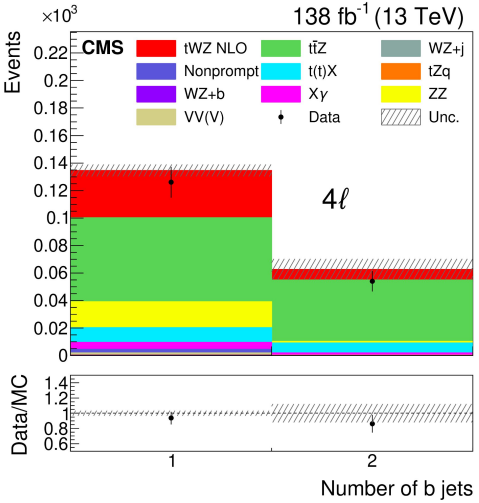
- **Interferes with $t\bar{t}Z$** at NLO
- Multilepton final state
  - 3L or 4L
- Low pt and high-p_T (**boosted**) regions
- Multiclass DNN for separation







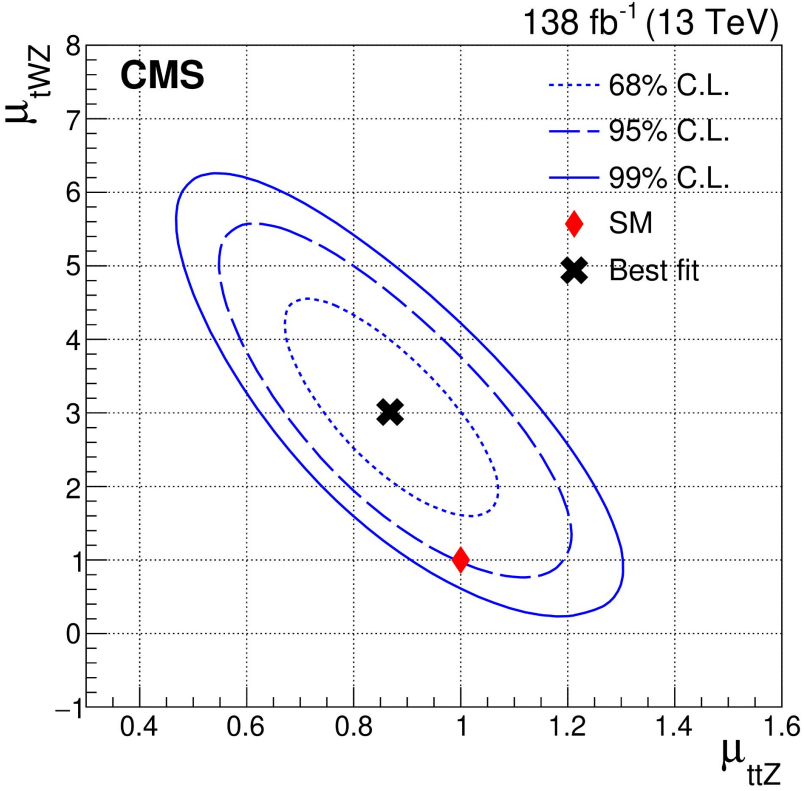




Evidence for tWZ, CMS

- Predicted x-section: 136 -8/+9 fb (NLO in QCD)
- Measured x-section: 354 ± 54 (stat) ± 95 (syst) fb
  - **Two sigma away from prediction**
- **Significance 3.4 sigma** (1.3 expected)
  - Boosted region adds 0.2 sigma (stat)

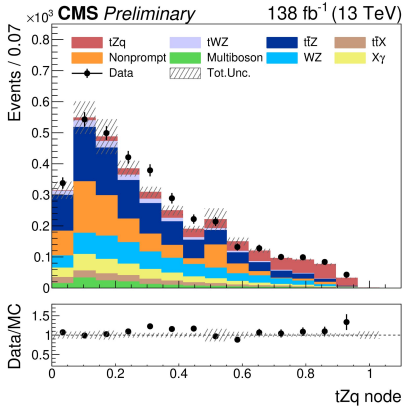
- **Large anticorrelation to ttZ**
  - Fixing $t\bar{t}Z$ -> significance still above 3 sigma
- **Dominant uncertainties**
  - Non-$t\bar{t}Z$ background normalisation
  - Signal modelling

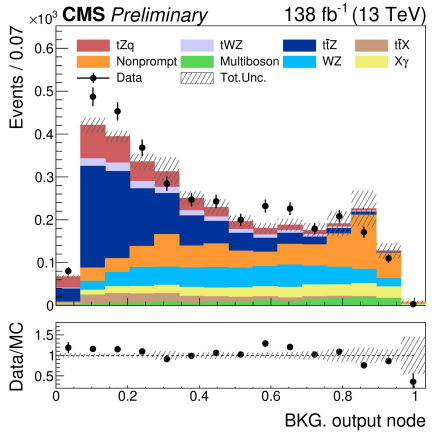


t(+$\bar{t}$)Z + tWZ, CMS

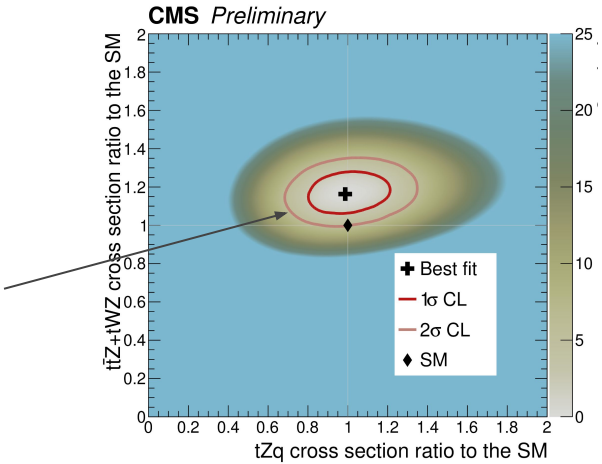
CMS PAS TOP-23-004

- **3L final state**
  - **$t\bar{t}Z$ + tWZ**
  - **tZq**
- Multi-class NN for separation
- **Inclusive** measurement
  - With 4L and 0b channels
- **Differential** cross-section measurement
  - Simultaneous extraction of $t\bar{t}Z$(+tWZ) and tZq distributions

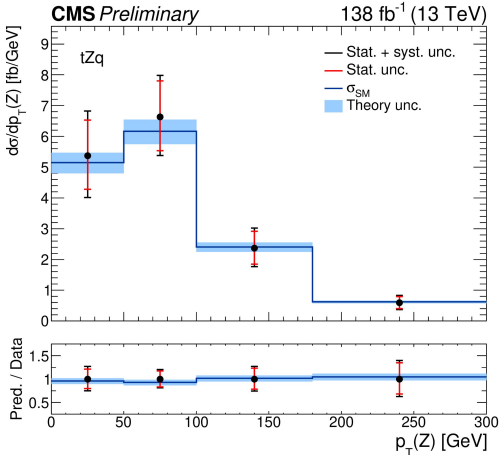


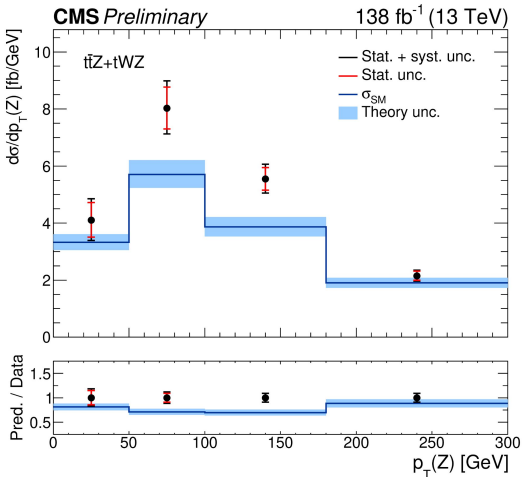


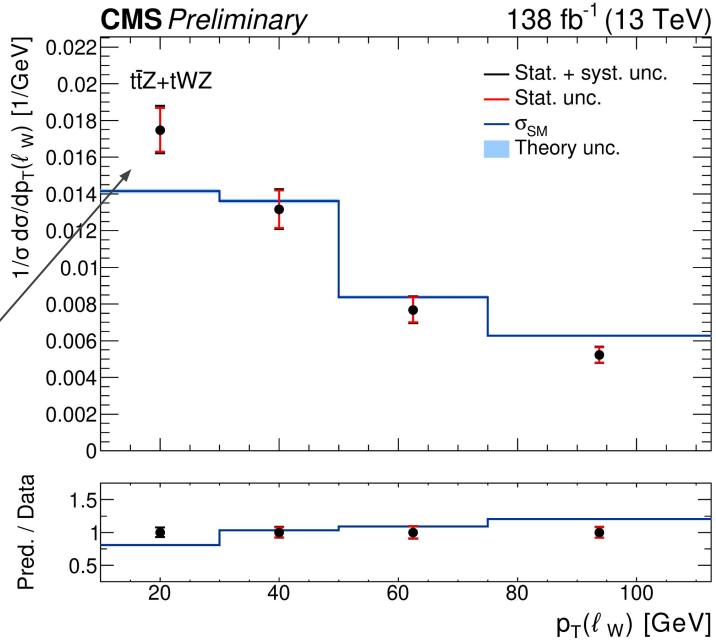
- tZq signal strength as predicted
- **$t\bar{t}Z$+tWZ slightly higher than predicted**



$t(+\bar{t})Z$ + tWZ CMS - differential







- Slope in p_T of lepton from top decay
  - **Reason for the cross-section discrepancy**

$t\bar{t}W$, ATLAS

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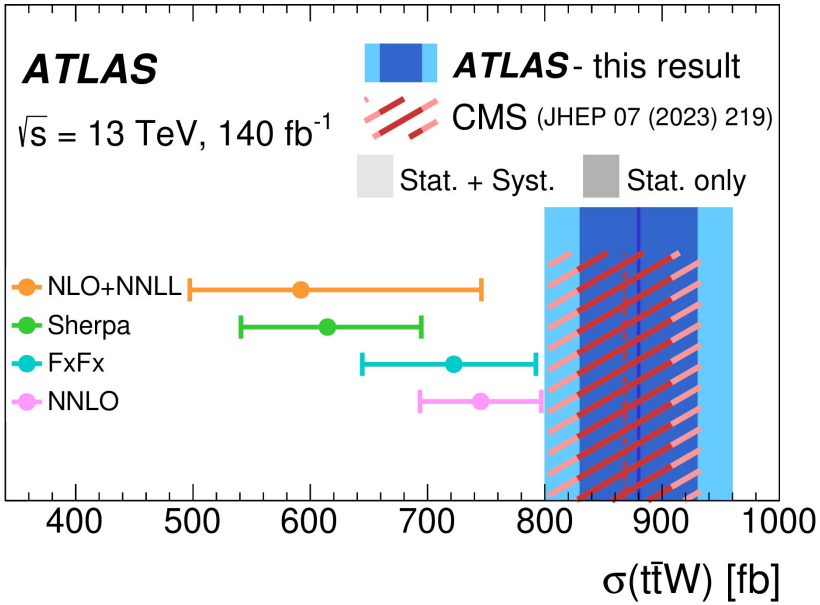
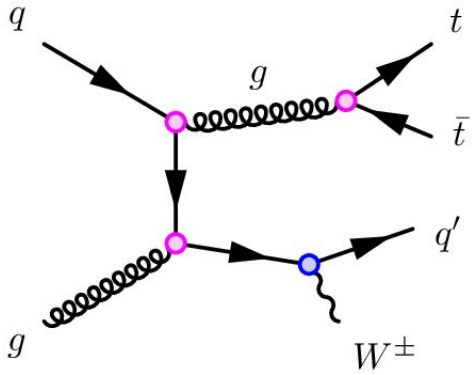
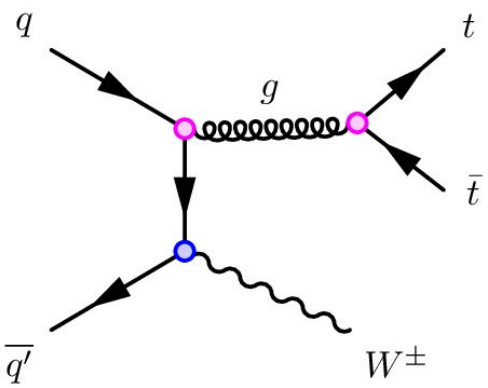
- Important background for SM processes and BSM searches
- **2L SS and 3L final state**
  - Significant fake lepton background
- **Inclusive** and **differential** measurements





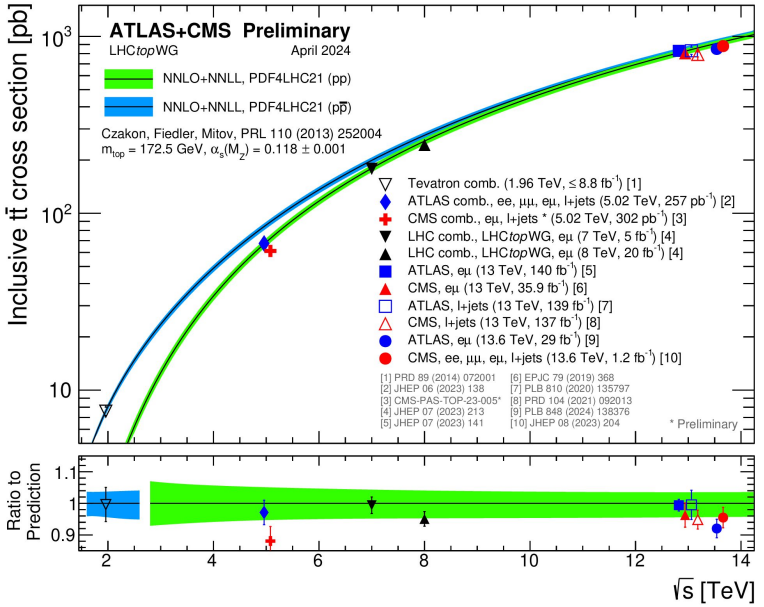


- **Theory getting closer to data**
- **Still slightly higher x-sec than predicted**

Summary and Conclusions

Summary

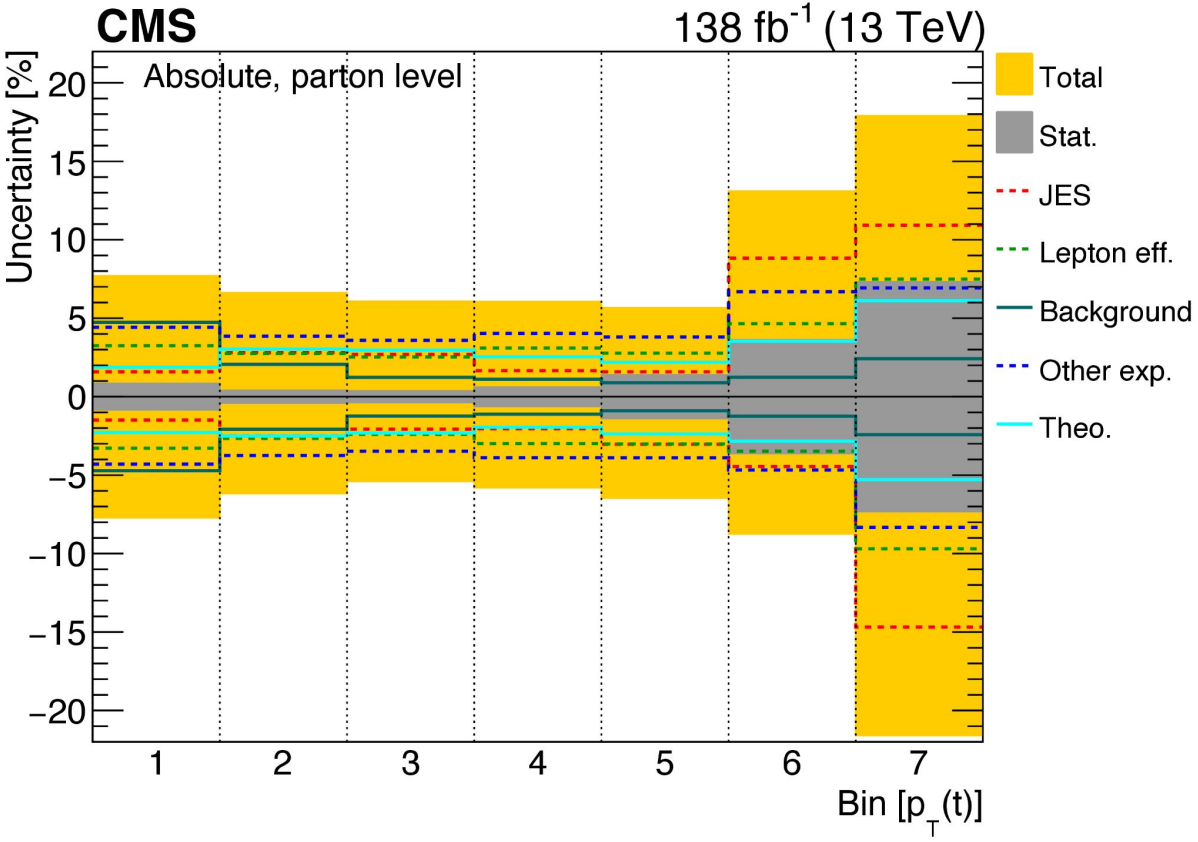
- Top cross-sections are **reaching unprecedented precision**
  - Including measurements at **5 TeV**, **13.6 TeV** and **p-Pb collisions!**
- **New measurements in top+X sector**
  - Going **differential**
- Many measurements are **dominated by modeling**
  - Even rare processes!
- Differential distributions in **top+X need more data**



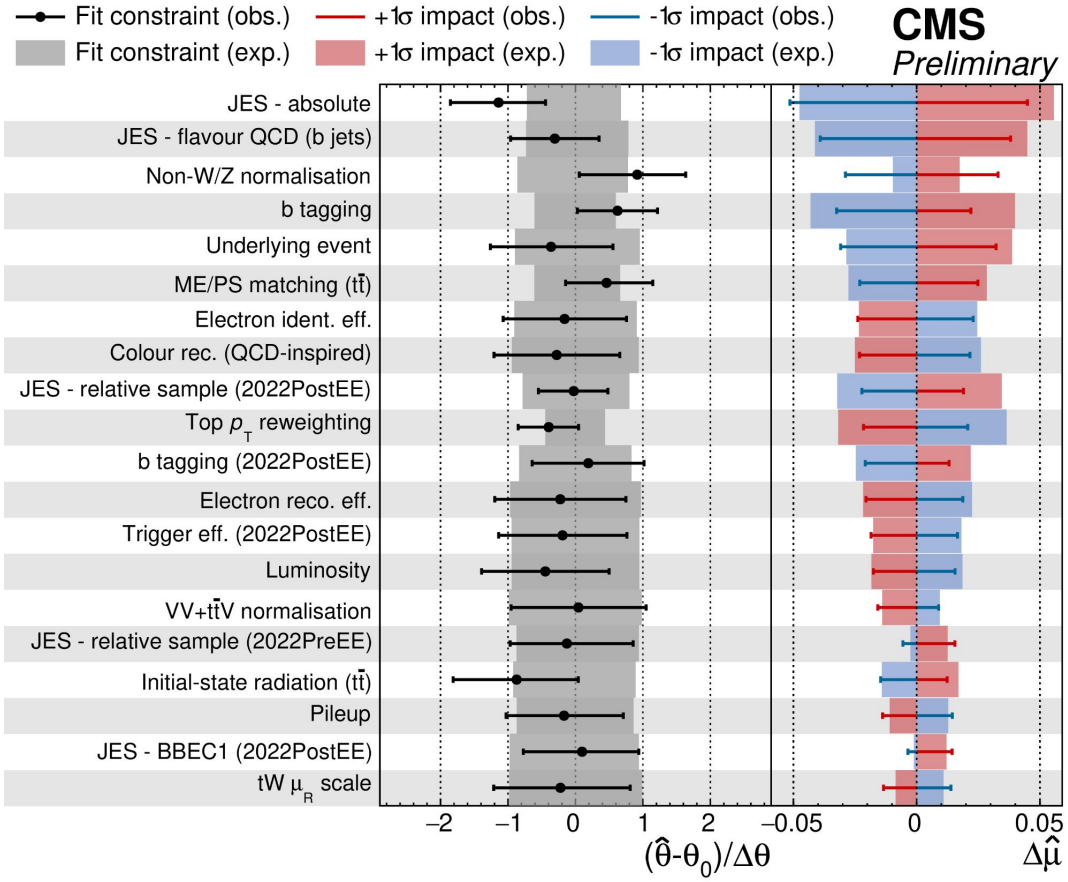
- **Top+boson measurements talks later today**
  - ATLAS talk (Lucia Keszeghova)
  - CMS talk (Jose Enrique Palencia Cortezon)
- **Top cross-section measurements talks yesterday**
  - ATLAS talk (Peter Hansen)
  - CMS talk (Sebastian Wuchterl)

BACKUP

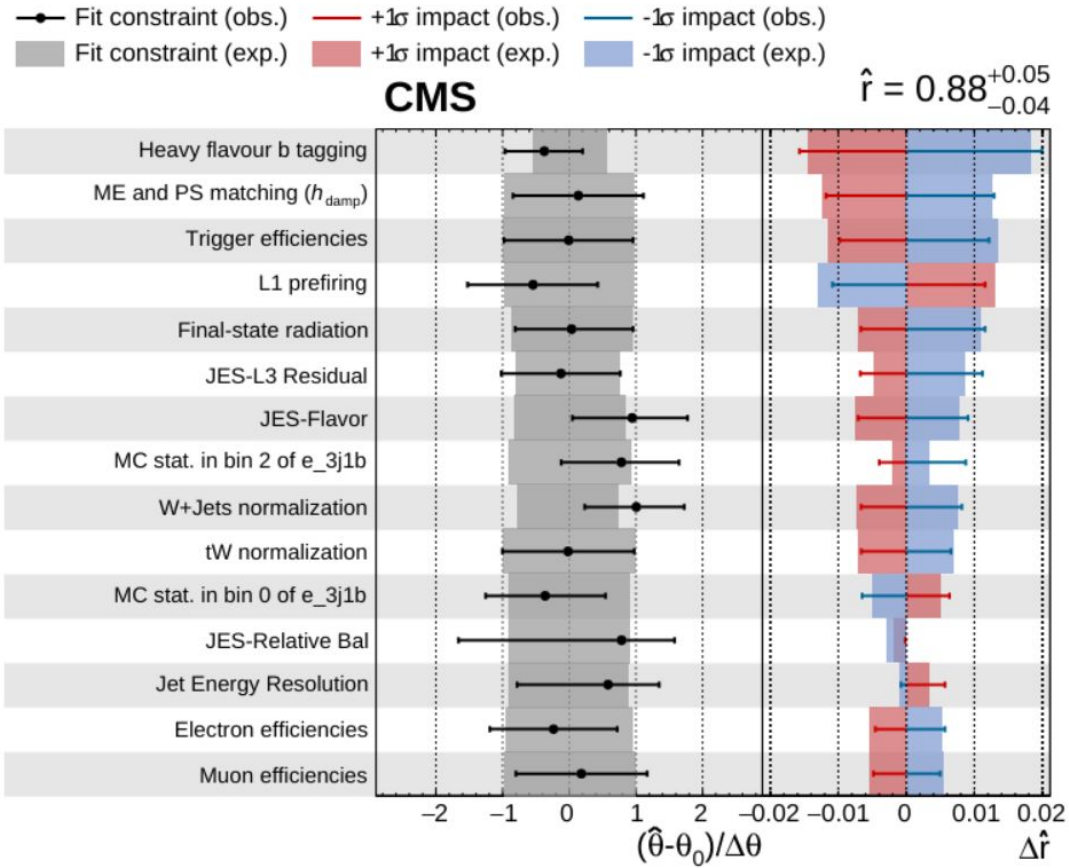
CMS $t\bar{t}$(+1jet) differential - uncertainties



tW Run 3, CMS - NP ranking

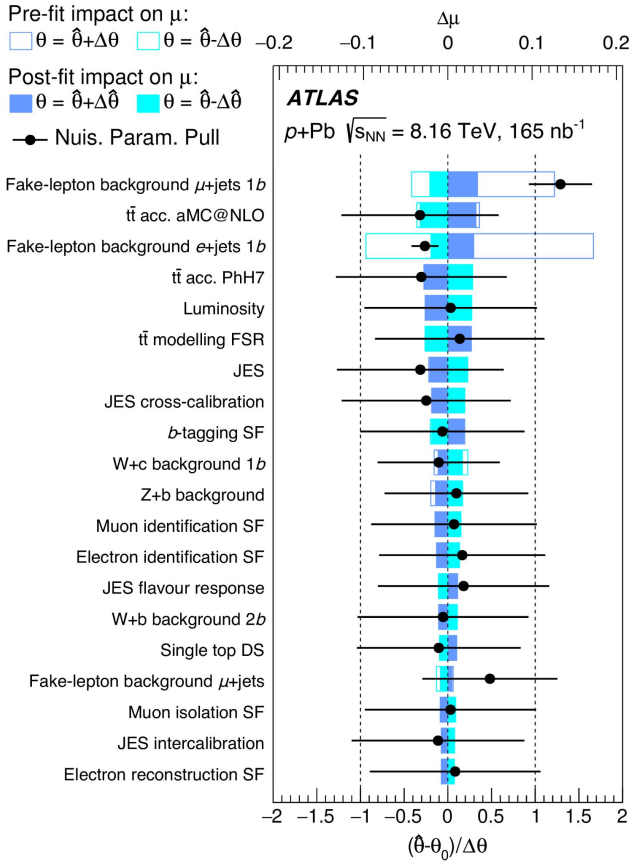


CMS 5.02 TeV $t\bar{t}$ cross-section - NP ranking



Observation of $t\bar{t}$ in p-Pb, ATLAS

- NP ranking
- Conservative fake lepton estimate
- Dominant uncertainties
  - Fake leptons
  - Ttbar modelling
  - Lumi
  - JES

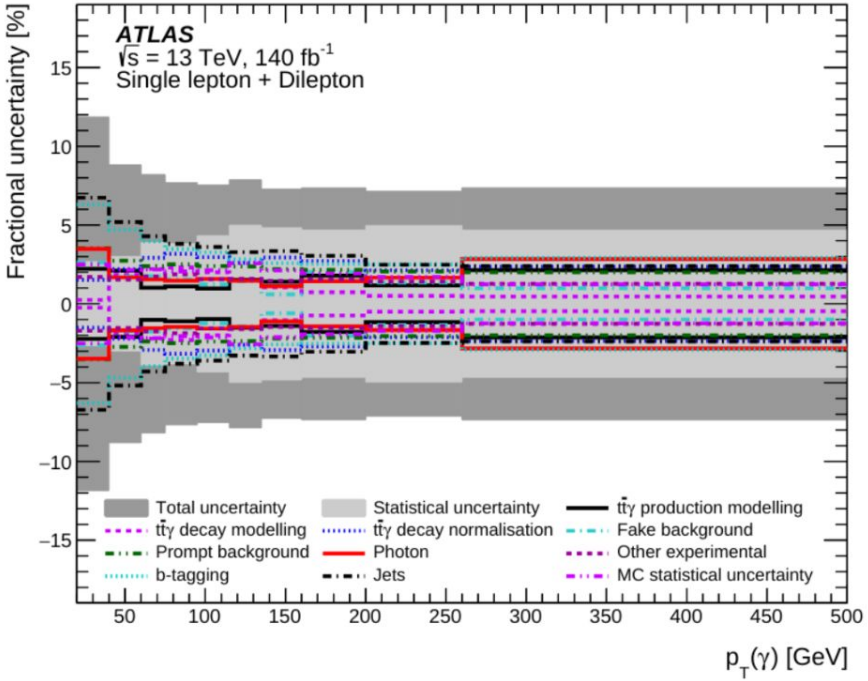


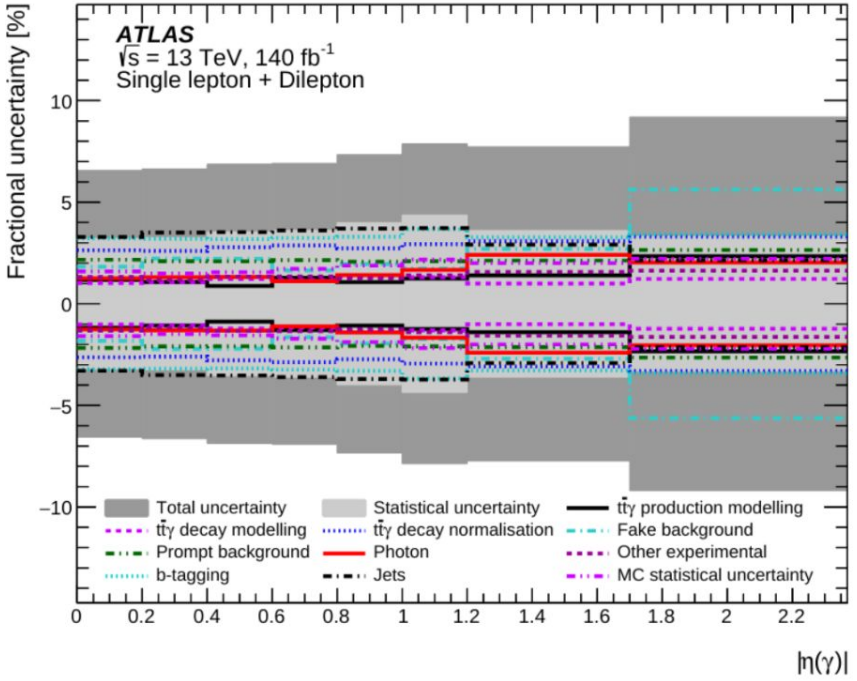
$t\bar{t}Z$ (ATLAS) systematic impact

- Background modelling
- Jet energy + reconstruction
- Flavour tagging
- $t\bar{t}Z$ modelling

Uncertainty Category	$\Delta\sigma_{t\bar{t}Z}/\sigma_{t\bar{t}Z}$ [%]
Background normalisations	2.0
Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$	1.9
b-tagging	1.7
$t\bar{t}Z$ μ_{f} and μ_{r} scales	1.6
Leptons	1.6
Z+jets modelling	1.5
tWZ modelling	1.1
$t\bar{t}Z$ showering	1.0
$t\bar{t}Z$ A14 tune	1.0
Luminosity	1.0
Diboson modelling	0.8
tZq modelling	0.7
PDF (signal & backgrounds)	0.6
MC statistical	0.5
Other backgrounds	0.5
Fake leptons	0.4
Pile-up	0.3
Data-driven $t\bar{t}$	0.1

$t\bar{t}\gamma$, ATLAS - uncertainties decomposition





$t\bar{t}W$ ATLAS - NP ranking