

# *Highlights on top quark physics with the ATLAS experiment at the LHC.*



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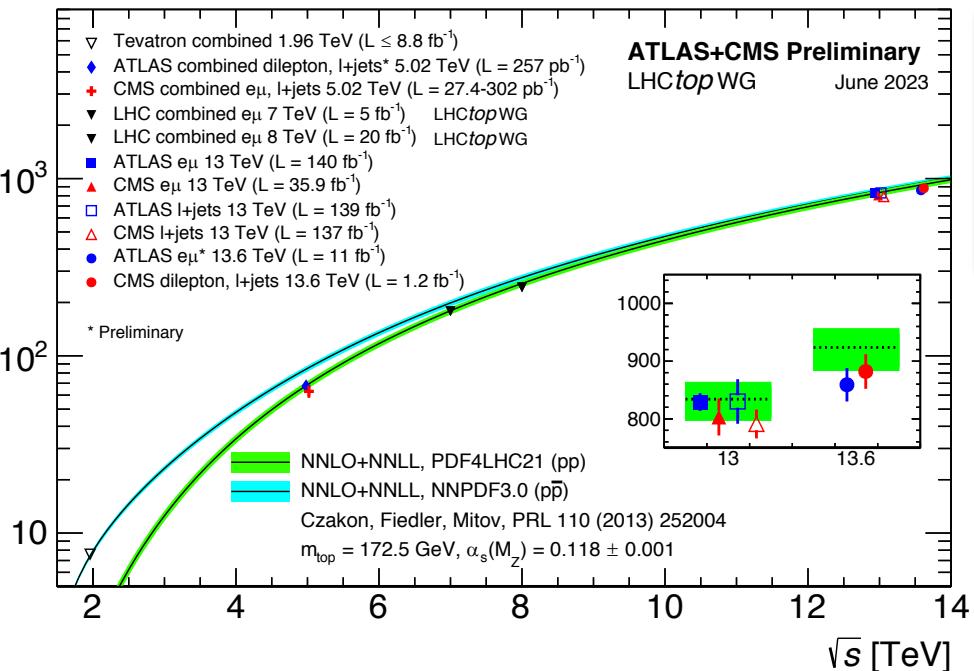


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- Review of most recent highlights of the ATLAS top quark physics program:
  - Selected from <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults>

ATL-PHYS-PUB-2023-014



## • FCNC: $tZq$

- Test new physics models:
  - Composite Higgs boson models, models from a warped extra dimension.
  - EFT interpretations.

## • Inclusive and differential $\sigma_{t\bar{t}}$

- Test MC models ( QCD NLO + LO PS + hadronization )
  - Boosted top-quark jets.
- Test NNLO+NNLL theoretical predictions.

## • $\sigma_{t\text{-chan}}, \sigma_{\bar{t}\text{-chan}}$

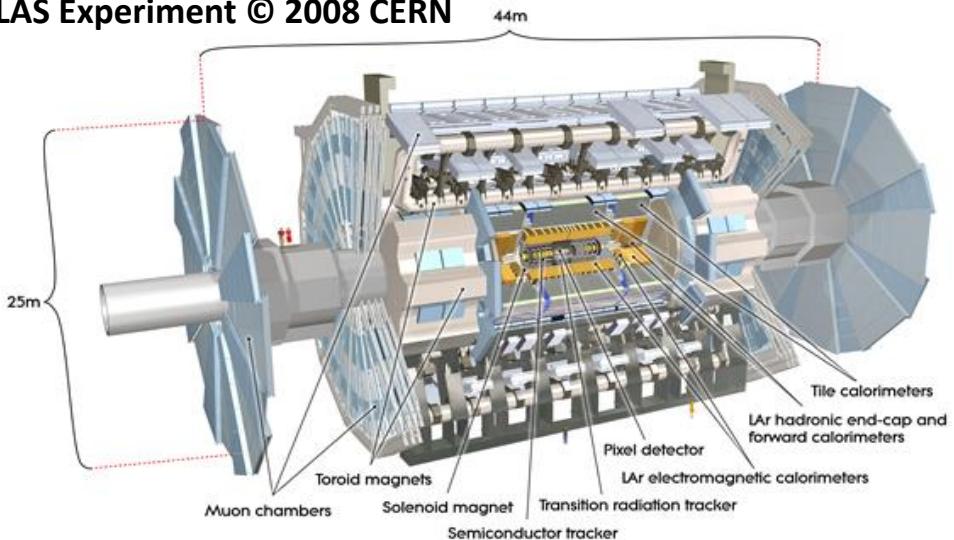
- Constrain PDFs and CKM matrix
- Test NNLO+NNLL theoretical predictions.
- EFT interpretations.

## • Top rare production processes: $tq\gamma$

- Complete top quark's electroweak couplings.

# THE FULL RUN-2 & THE ATLAS EXPERIMENT.

## ATLAS Experiment © 2008 CERN

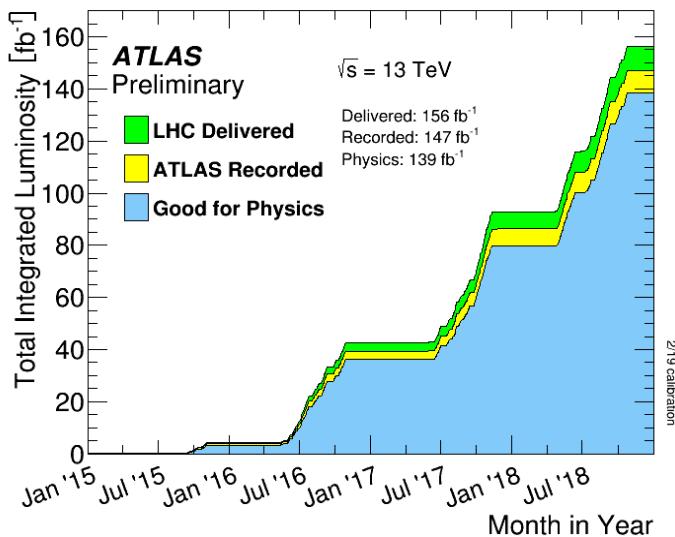


### ATLAS detector:

- Muon spectrometer.
- Calorimeters: electromagnetic and hadronic.
- Inner detector: main tracking system.
- Magnetic system: 2T
- Trigger system:
  - 2 levels: hardware and software based.

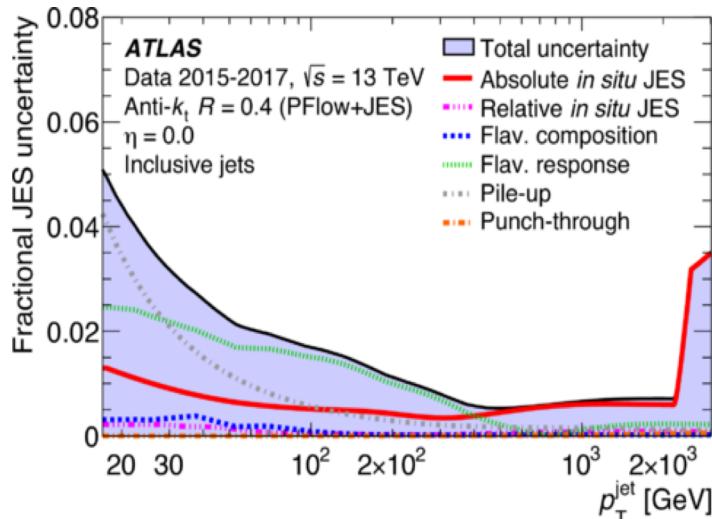
Excellent detector performance.

- Run 2 Data taking efficiency = 94%
- ATLAS pp RUN-2 Data quality fraction = 95.6%
- Precision object performance.
  - Energy scale for central jets ~1% for  $p_T \sim 250\text{--}2000\text{ GeV}$



[arXiv:2212.09379](https://arxiv.org/abs/2212.09379).

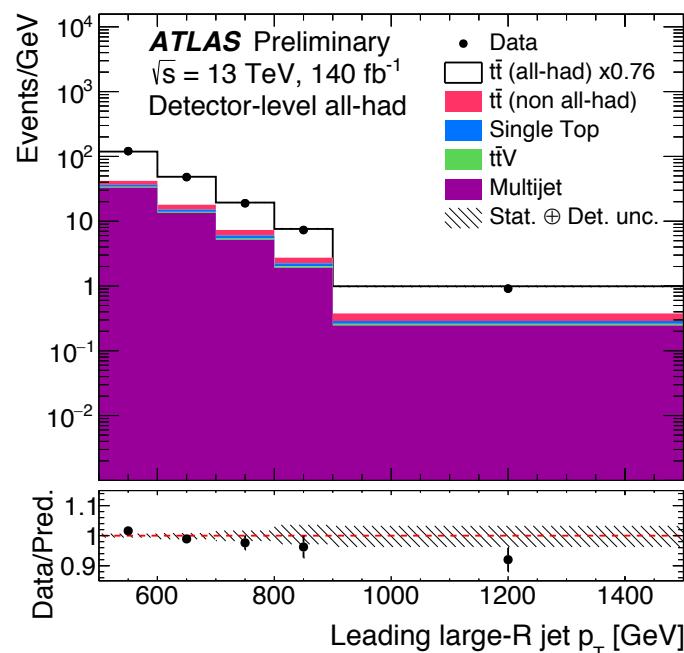
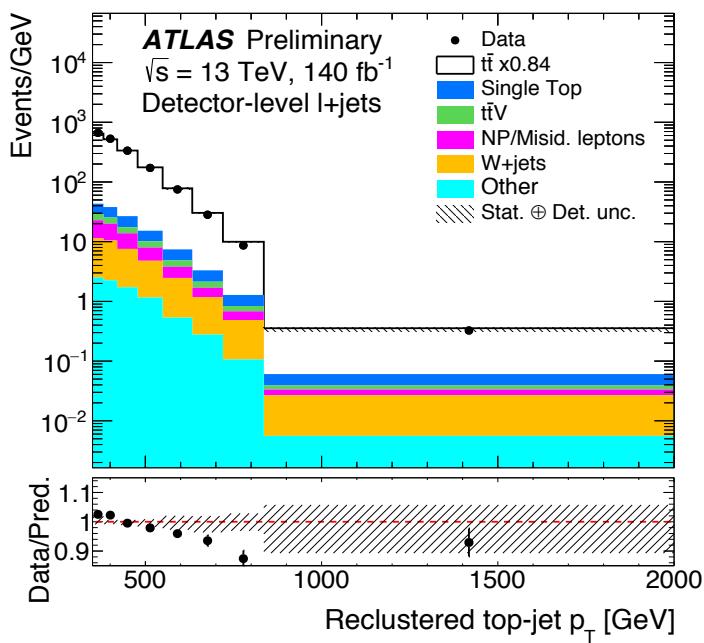
$$L_{\text{int}} = 140.1 \pm 1.2 \text{ fb}^{-1}, \text{ 0.83\% uncertainty}$$



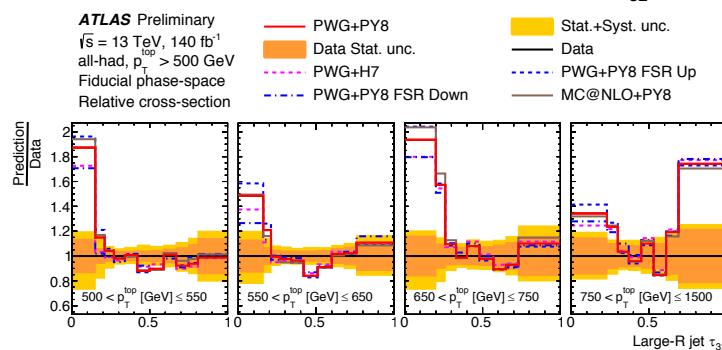
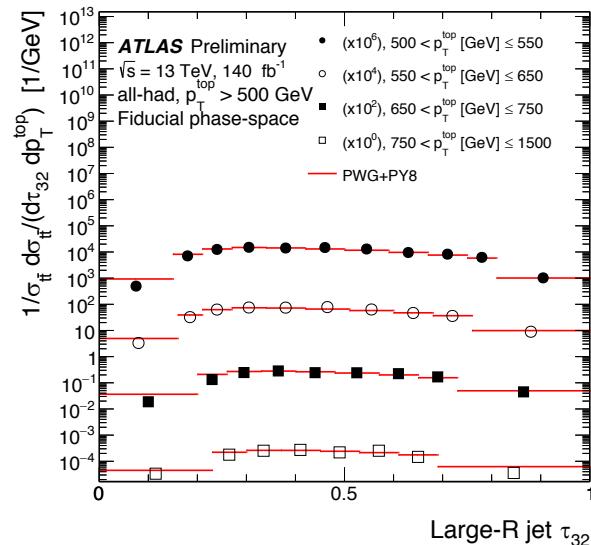
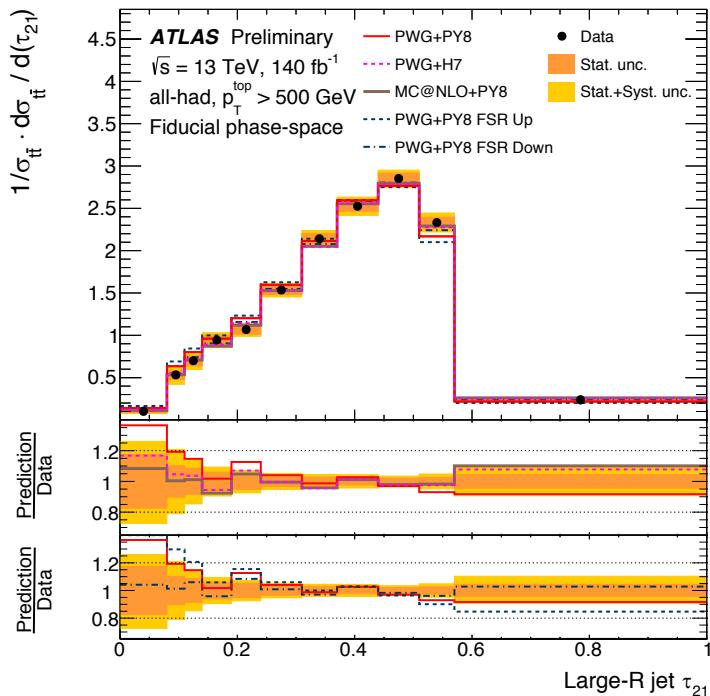
[Eur. Phys. J. C 81 \(2021\) 689](https://doi.org/10.1140/epjc/s10050-021-09689-0)

- MOTIVATION:

- Test MC models ( QCD NLO + LO PS + hadronization ) to predict the substructure of boosted top-quark jets.
- Beyond SM effects can modify the top-quark substructure:
  - Heavy particles decaying to top-quark pairs, di-boson resonances, dark matter candidates etc.
- Normalized differential  $\sigma_{t\bar{t}}$  measurements as a function of the substructure variables of the large radius jets.
  - Measurements in fiducial phase-spaces and unfolding detector effects to stable-particle level.
- Two independent channels:
  - L+jets: one single lepton ( e/ $\mu$  ), a top-quark jet with  $p_T > 350$  GeV, additional jets from b-quark hadronization.
    - Main backgrounds: single top ( MC driven) and misidentified leptons ( data driven )
  - All-Hadronic: no isolated leptons and two top-quark jets with  $p_T > 500$  GeV, 350 GeV.
    - Main background: Multijets (QCD) data driven.

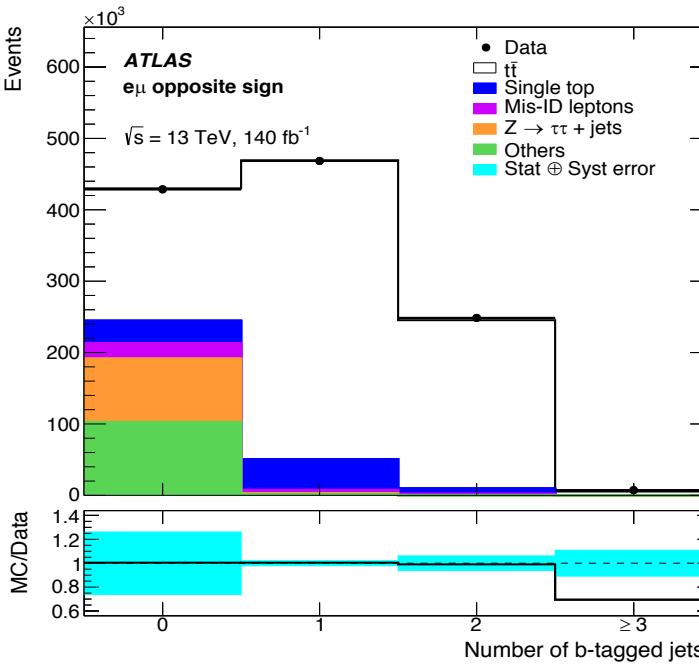
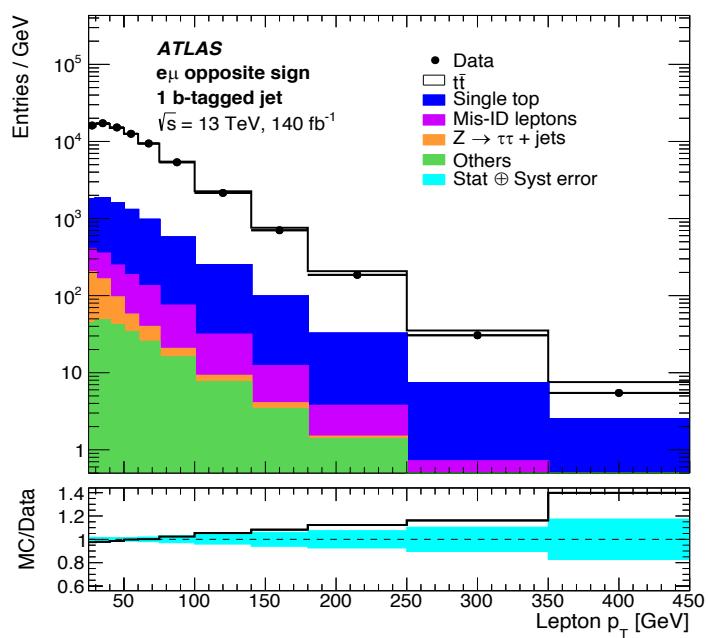


- Measurements of energy-flow and variables sensitive to the 3-body structure of the top quark jets:
  - Angularities, Energy Correlation Functions, N-subjettiness.
- Nominal Powheg+Pythia8 MC:  $\tau_{21}$ , ECF2 and  $D_2$  well described.  $\tau_{32}$ ,  $\tau_3$ ,  $C_3$ ,  $p_T$  dispersion, poorly described.
- Description of 3-body like substructure improves with: aMC@NLO+Pythia8, nominal FSR Up and PWG+herwig.



- SYSTEMATICS: From 5% till 40% in low and high bins.
- Signal modeling: FSR, PS and hadronization model
- Detector-level: JES/JER
- CONCLUSIONS:** Need for improvements in models used to predict the substructure of boosted top-quark jets.

- All differential cross section measurement in fiducial region:  $|\eta\ell| < 2.5$  and  $|p_T^\ell| < 27(25)$  GeV
  - Total cross section measurement also measured inclusively.
- Opposite-sign charge electron-muon ( $e\mu$ ) pairs.  $N_{\text{b-jets}}=1,2$ .
  - Main backgrounds: single top and misidentified leptons.
  - Same-sign  $e\mu$  pairs for misidentified lepton background estimation.



- Cross sections together with combined selection and b-tagging efficiencies from a log-likelihood fit solving two equations:

- $G_{e\mu}^i \rightarrow$  reconstruction efficiencies from simulation.
- $C_b^i \rightarrow$  b-tagging correlation coefficients from simulation.

$$N_1^i = \mathcal{L} \sigma_{t\bar{t}}^i G_{e\mu}^i 2\epsilon_b^i (1 - \epsilon_b^i C_b^i) + N_{1,\text{bkg}}^i$$

$$N_2^i = \mathcal{L} \sigma_{t\bar{t}}^i G_{e\mu}^i (\epsilon_b^i)^2 C_b^i + N_{2,\text{bkg}}^i$$

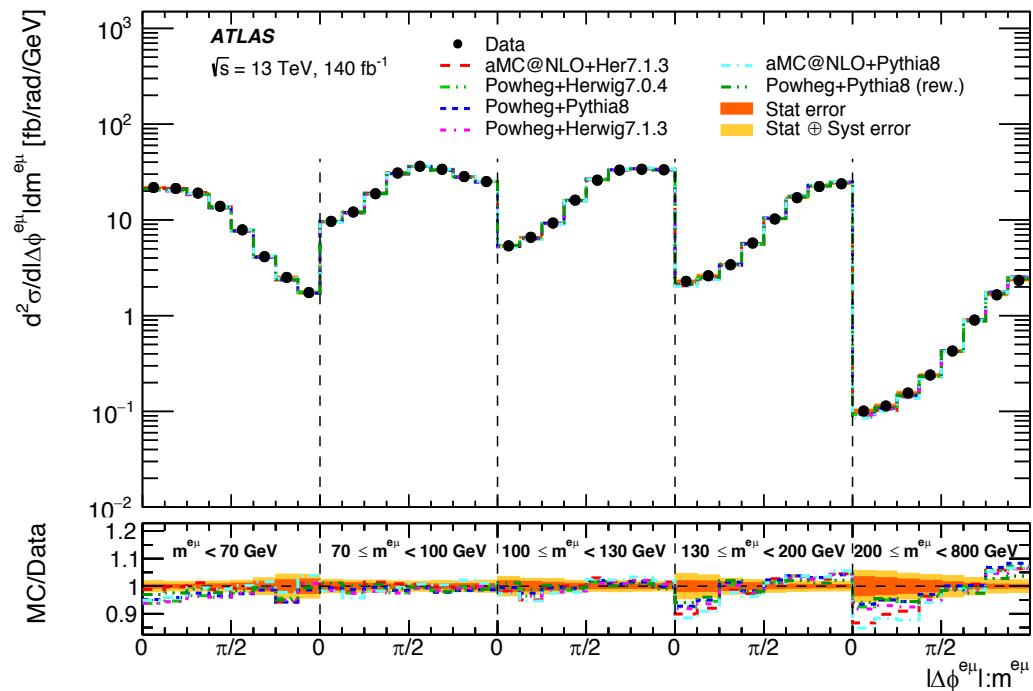
- Differential cross-section measured as a function of several lepton kinematic variables:
  - $p_T^\ell$ ,  $|\eta^\ell|$ ,  $m^{e\mu}$ ,  $p_T^{e\mu}$ ,  $|y^{e\mu}|$ ,  $E^e + E^\mu$ ,  $p_T^e + p_T^\mu$  and  $|\Delta\phi^{e\mu}|$
  - Luminosity uncertainty dominant in all bins.
  - Systematic uncertainties: modeling of signal and background processes and lepton reconstruction.
  - Statistical uncertainties important at increasing  $p_T$ ,  $E$ ,  $M \rightarrow$  overtaken by interference  $t\bar{t}/Wt$

### CONCLUSIONS:

- No model can described all measured distributions.
- Most precise measurement to date: inclusive  $\sigma_{t\bar{t}}$

$$A_{e\mu} = N_{e\mu}^{t\bar{t}, \text{fiducial}} / N_{t\bar{t}} = (1.2708 \pm 0.0004)\%$$

$$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}} [\%] = 1.8$$



$$\sigma_{t\bar{t}}^{\text{inclusive}} = 829 \pm 1(\text{stat}) \pm 13(\text{syst}) \pm 8(\text{lumi}) \pm 2(\text{beam}) \text{ pb}$$

Excellent agreement

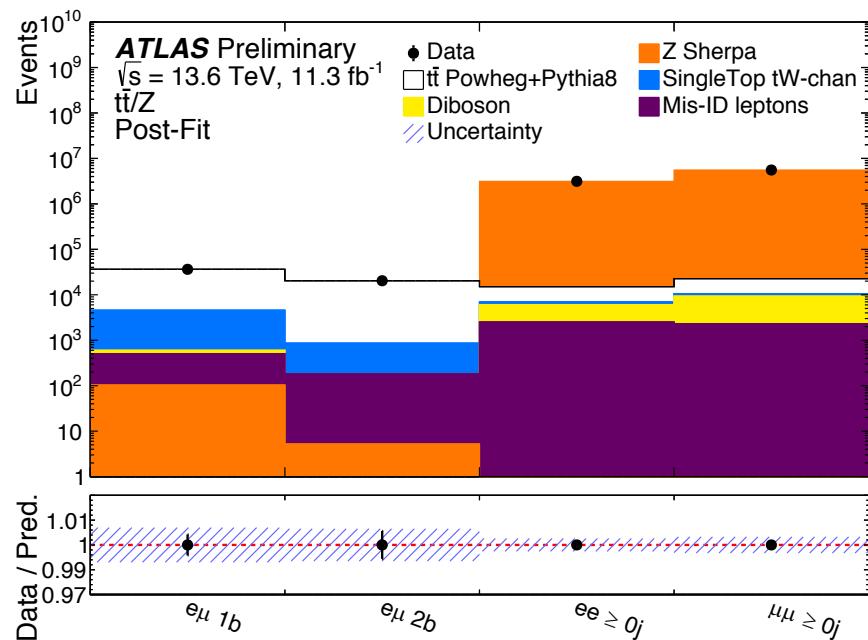
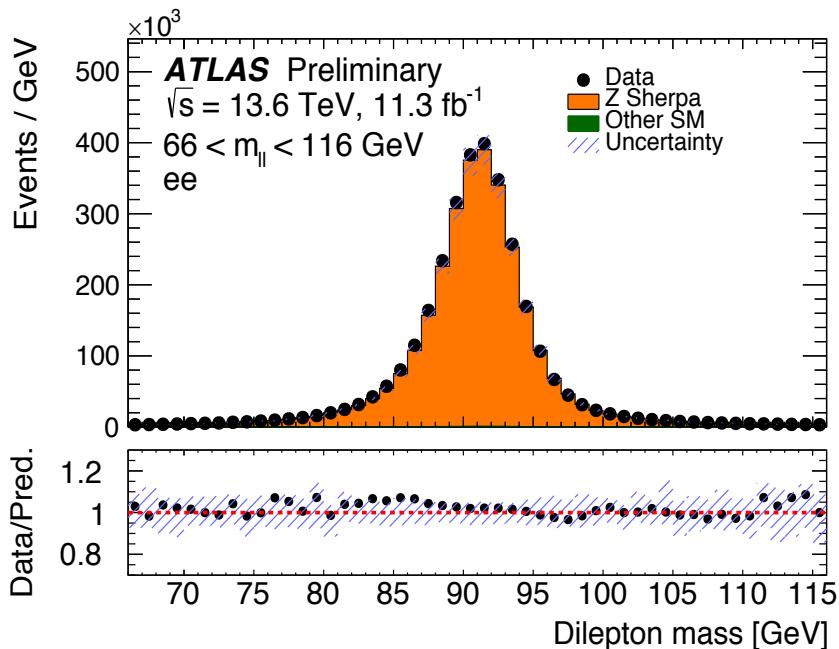
$$\text{NNLO+NNLL: } \sigma_{t\bar{t}, \text{pred}} = 832^{+20}_{-29}(\text{scale})^{+23}_{-23}(m_{\text{top}})^{+35}_{-35}(\text{PDF} + \alpha_s) \text{ pb}$$

- MOTIVATION:

- An increase of  $\sigma_{t\bar{t}}$  by about 12% is expected from 13 TeV and 13.6 TeV.
- The ratio  $R_{t\bar{t}/Z}$  has a significant sensitivity to the gluon-to-quark PDF.

- Analysis strategy:

- $\sigma_{t\bar{t}}$  : Opposite-sign electron-muon pairs selected:  $N_{1(2)}$  events with 1(2) b-tagged jets.
- $\sigma_{Z \rightarrow \ell\ell}^{fid.}$ : same flavor pairs ( $ee/\mu\mu$ ) with opposite electric charge,  $p_T^\ell > 27$  GeV,  $|\eta^\ell| < 2.5$  and  $66 < M_{\ell\ell} < 116$  GeV

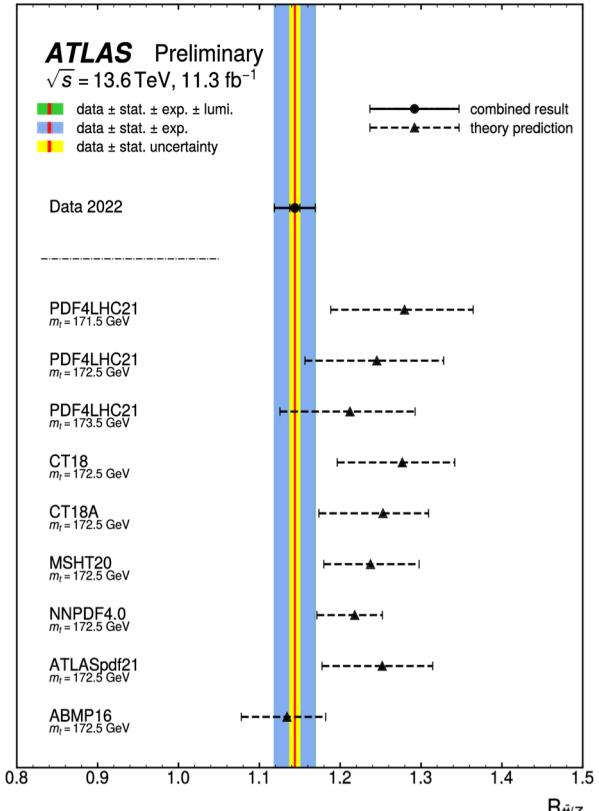
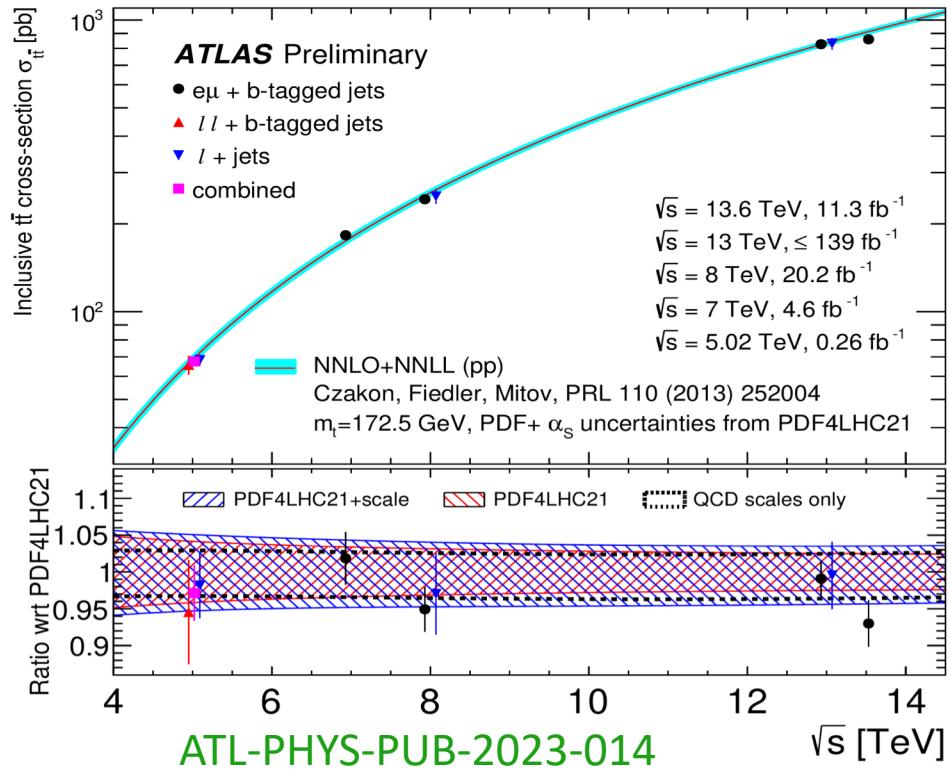


- Profile-likelihood technique with  $ee/\mu\mu/e\mu$  events:

- First fit: free parameters  $\sigma_{t\bar{t}}$ ,  $\sigma_{Z \rightarrow \ell\ell}^{fid.}$  and  $\epsilon_b$ ,
- Second fit:  $R_{t\bar{t}/Z}$ ,  $\sigma_{Z \rightarrow \ell\ell}^{fid.}$  and  $\epsilon_b$ .

$$N_1 = L\sigma_{t\bar{t}}\epsilon_{e\mu}2\epsilon_b(1 - C_b\epsilon_b) + N_1^{\text{bkg}},$$

$$N_2 = L\sigma_{t\bar{t}}\epsilon_{e\mu}C_b\epsilon_b^2 + N_2^{\text{bkg}},$$



$$\sigma_{t\bar{t}}^{inclusive} = 859 \pm 4(stat) \pm 22(syst) \pm 19(lumi) pb$$

$$\sigma_{Z \rightarrow \ell\ell}^{fid.} = 751 \pm 0.3(stat) \pm 15(syst) \pm 17(lumi) pb$$

$$\epsilon_b = 0.548 \pm 0.002(stat) \pm 0.004(syst) \pm 0.001(lumi)$$

$$R_{t\bar{t}/Z} = 1.144 \pm 0.006(stat) \pm 0.022(syst) \pm 0.003(lumi) pb$$

$$\sigma_{t\bar{t}}^{theory} = 924^{+32}_{-40} (scale + PDF) pb$$

$$\sigma_{Z \rightarrow \ell\ell}^{fid.theory} = 741 \pm 15 (scale + PDF) pb$$

$$\epsilon_b = 0.545$$

$$R_{t\bar{t}/Z} = 1.245 \pm 0.076 (scale + PDF) pb$$

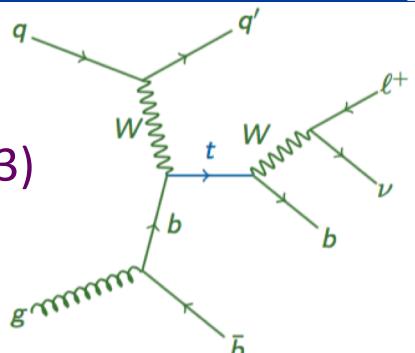
PDF set: PDF4LHC21

- New Run 3  $\sigma_{t\bar{t}}$  measurement slightly lower than SM predictions, compatible within  $1.3\sigma$   $\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}} [\%]=3.4$
- $\sigma_{Z \rightarrow \ell\ell}^{fid.}$  agrees within  $1\sigma$  and  $R_{t\bar{t}/Z}$  different level of compatibility depending on the PDF set.

## t-channel signature:

- 1 isolated and high-p<sub>T</sub> lepton.
- 1 high-p<sub>T</sub> and forward |η| jet (light jet).
- 1 high-p<sub>T</sub> and central |η| jet (b-jet).
- Missing transverse momentum from the neutrino.

## t-channel: LO 4FS (2 → 3)

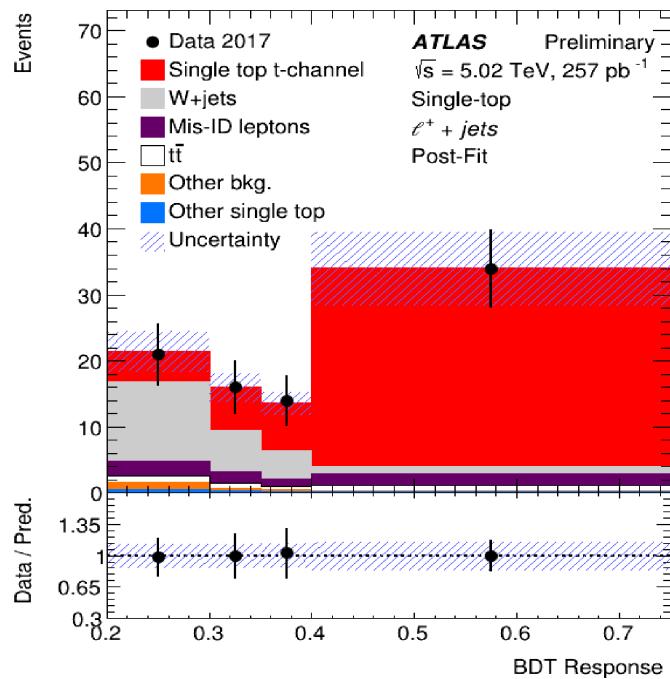


## MOTIVATION:

- Studies of unitarity of CKM matrix.
- Test higher-order corrections in QCD theoretical predictions.
- Constrains on PDFs.

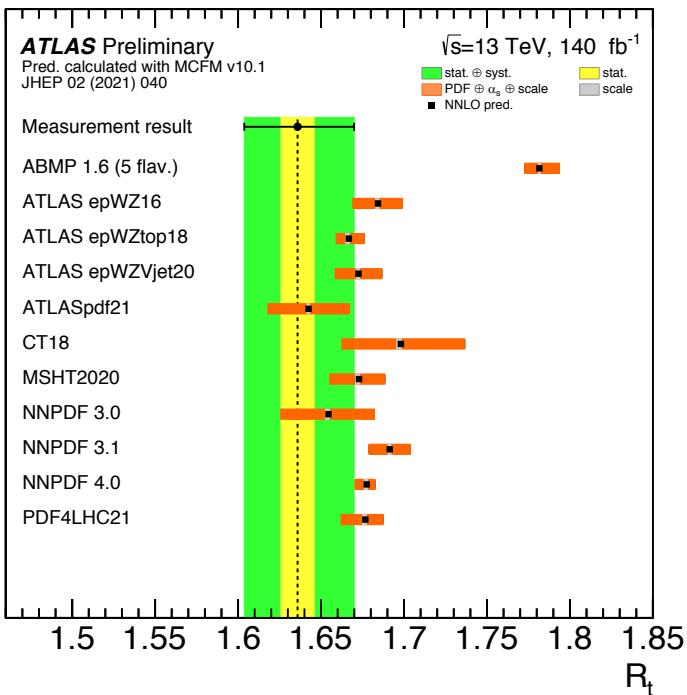
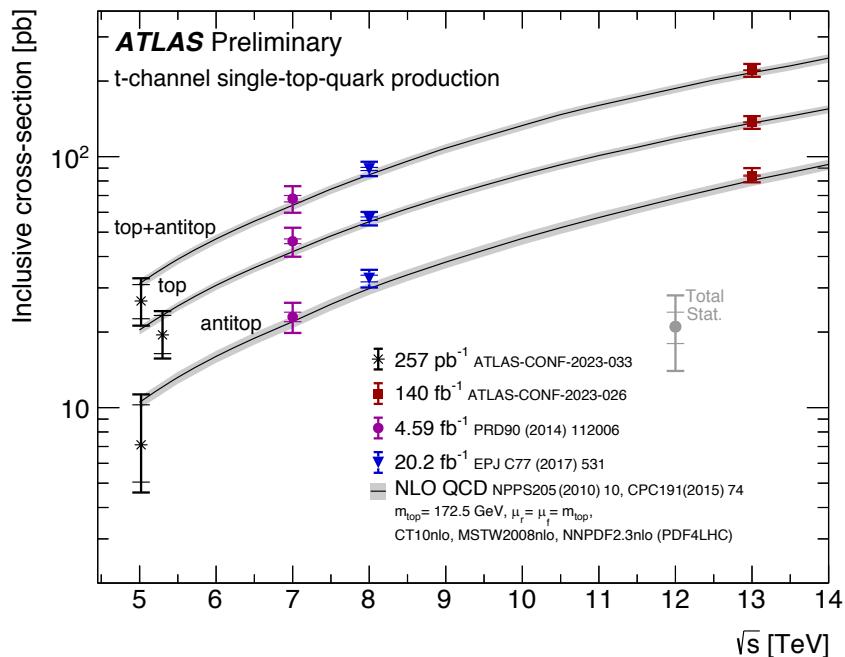
## Analysis strategy:

- BDT to enhance signal to background separation.
  - $H_T$  most discriminant variable.
- Profile maximum-likelihood fit on observed BDT distribution in two samples:  $\ell^+ \ell^-$
- Main backgrounds: W+jets, misidentified leptons.
- Main systematics: signal modelling and mis-ID lepton background



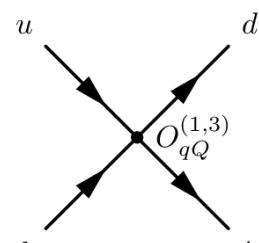
$$\begin{aligned} \sqrt{s} = 5.02 \text{ TeV}: \sigma(tq) &= 19.5^{+3.8}_{-3.1}(\text{stat})^{+2.9}_{-2.2}(\text{syst}) \text{ pb} & \sigma(\bar{t}q) &= 7.1^{+3.2}_{-2.1}(\text{stat})^{+2.8}_{-1.5}(\text{syst}) \text{ pb} \\ \sigma(tq + \bar{t}q) &= 26.6^{+4.3}_{-4.0}(\text{stat})^{+4.4}_{-3.6}(\text{syst}) \text{ pb} & \delta\sigma(tq + \bar{t}q)/\sigma(tq + \bar{t}q)[\%] &= 22 \\ R_t &= \sigma(tq)/\sigma(\bar{t}q) = 2.74^{+1.44}_{-0.83}(\text{stat})^{+2.8}_{-1.5}(\text{syst}) \end{aligned}$$

- Similar measurement as 5.02 TeV, but NN instead of BDT.
- Very different background composition w.r.t 5.02 TeV:  $t\bar{t}$  and W+HF are dominant.
- Main systematics: signal modelling, b-tagging and multijet background.

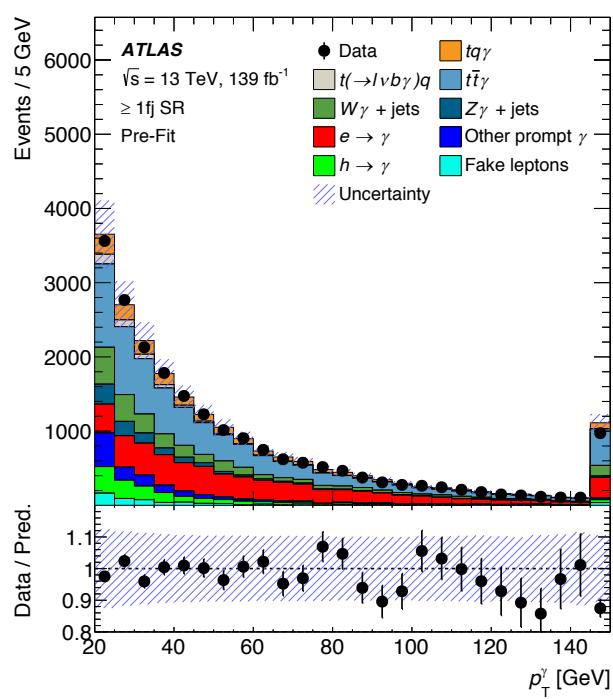
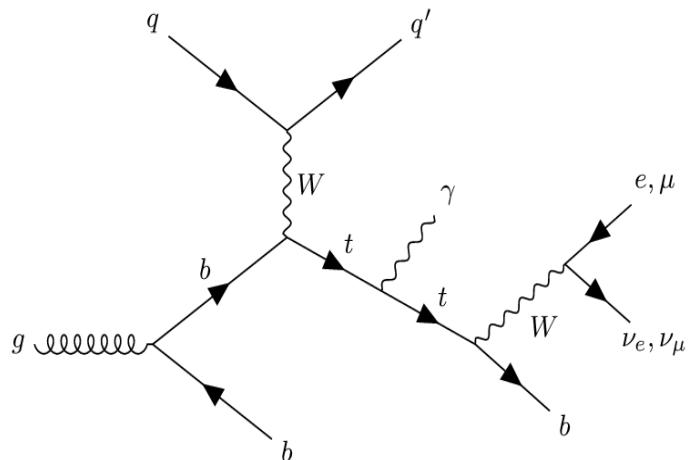


$\sqrt{s} = 13 \text{ TeV}: \sigma(tq) = 137 \pm 8 \text{ pb} \quad \sigma(\bar{t}q) = 84^{+6}_{-5} \text{ pb}$   
 $\sigma(tq + \bar{t}q) = 221 \pm 13 \text{ pb}, \delta\sigma(tq + \bar{t}q)/\sigma(tq + \bar{t}q)[\%] = 5\%$   
 $R_t = \sigma(tq)/\sigma(\bar{t}q) = 1.636^{+0.036}_{-0.034}$

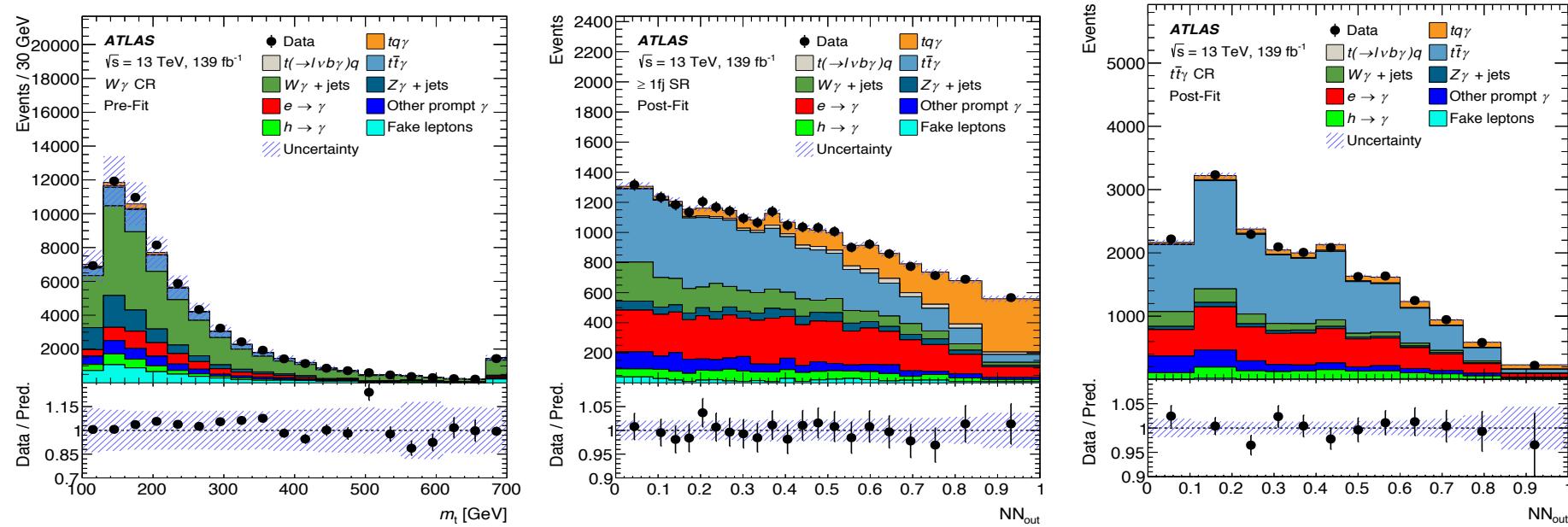
EFT: Limits to the strength of a 4-quark operator:  $-0.25 < C_{qQ}^{(1,3)} < 0.12$



- **MOTIVATION:** Complete top quark's electroweak couplings probed so far with observed processes:
  - Top pair production  $t\bar{t}(H, W, Z, \gamma)$  and single top  $t(W, Z)$ .
  - Constraining non-resonant contributions from physics beyond the SM parameterized with SMEFT.
  - Most recent analysis: [JHEP 02 \(2022\) 032](#) and [JHEP 02 \(2020\) 131](#).
- $\sigma_{t\bar{q}\gamma}$  measured in fiducial phase space at parton level
  - Excluding  $t(\rightarrow \ell\nu b\gamma)q$ .
  - Signature: t-channel production with a photon.
    - High  $p_T$  ( $e/\mu$ ) + high  $p_T \gamma + E_{miss}^T$  + one tight b-jet
    - Two SR: with zero and one forward jet.
    - Modelled with MadGraph5\_AMC@NLO
  - Main backgrounds:
    - Prompt photons:  $t\bar{t}\gamma$  and  $W\gamma$  :
      - MC estimate normalized to data in CRs
      - CR( $t\bar{t}\gamma$  : additional loose b-jet)
      - CR( $W\gamma$  : additional loose b-jet, no tight b-jets)
    - Fake photons: ( $e/\text{hadron} \rightarrow \gamma$ )
      - MC estimate adjusted with data-driven methods.



- ANALYSIS STRATEGY:** Profile-likelihood fit simultaneously in 2 SR and 2 CR:
  - NN outputs in  $0fj(\geq 1fj)$  SRs and  $t\bar{t}\gamma$  CR.
  - Inclusive event yields in  $W\gamma$  CR.
- Main uncertainties:  $\pm 5.5\% t\bar{t}\gamma$  modeling,  $\pm 3.5\%$  MC statistics for backgrounds,  $\pm 1.9\%(t \rightarrow \ell\nu b\gamma)q \pm 2.4\%(t\bar{t})$

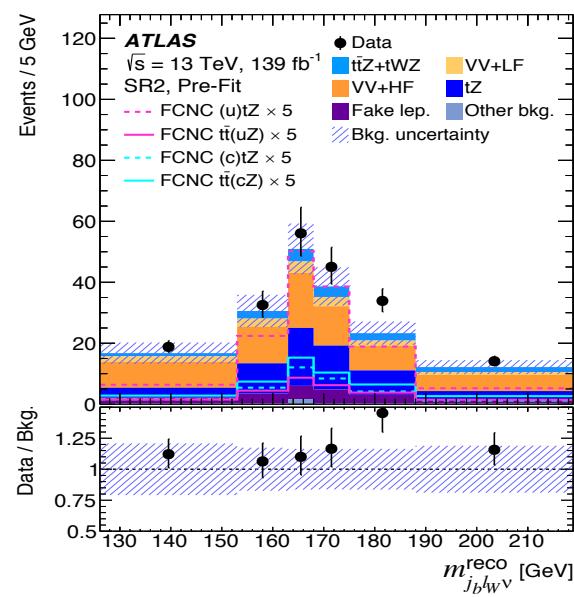
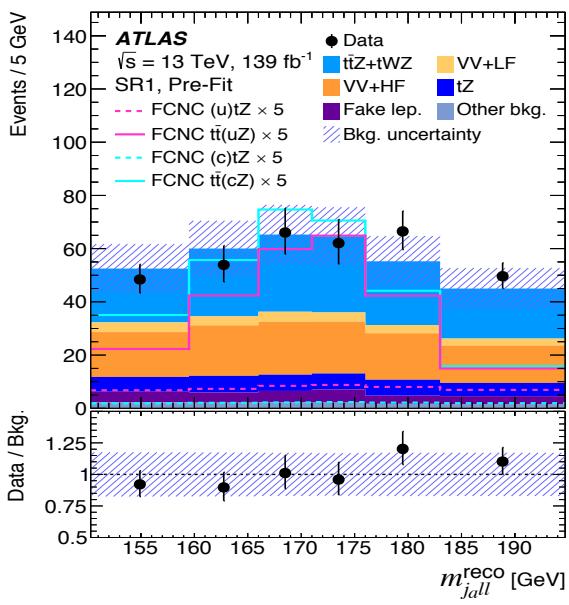
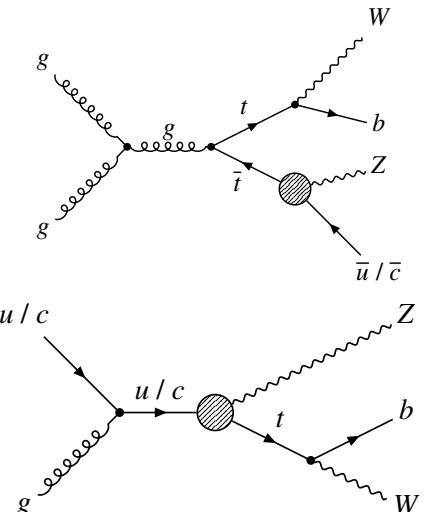


- Observed(expected) significance of  $tq\gamma$  signal:  $9.3\sigma$  ( $6.8\sigma$ ):
  - First experimental evidence by CMS:  $4.4\sigma$  observed ( $3\sigma$  expected)
  - Both experiments measured 30%-40% higher cross sections.

Fiducial ( $\gamma, p_T > 20$  GeV) parton level  $\sigma_{tq\gamma} \times \mathcal{B}(t \rightarrow \ell\nu b) = 688 \pm 23(\text{stat.})^{+75}_{-71}(\text{syst.}) \text{ fb}$

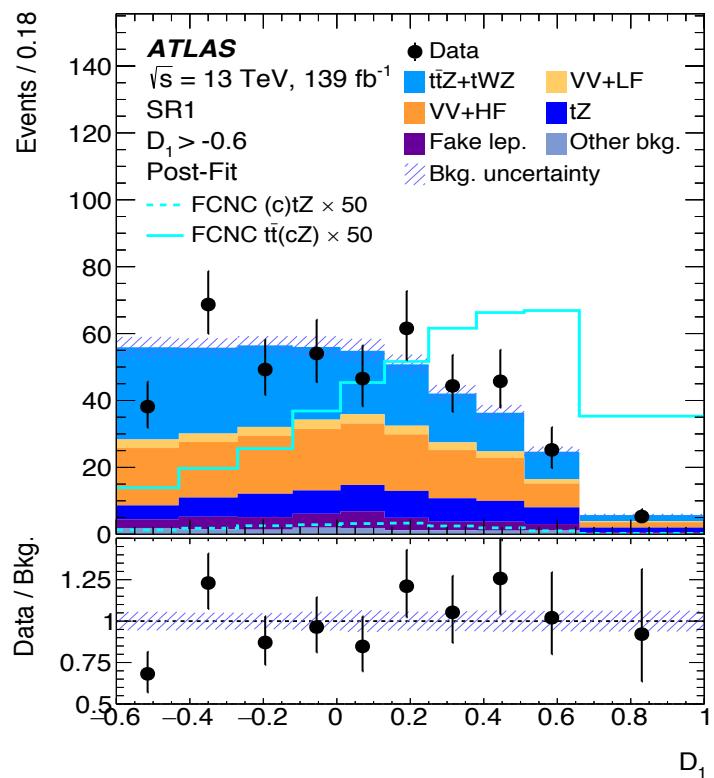
In agreement with SM NLO prediction:  $\sigma_{tq\gamma} \times \mathcal{B}(t \rightarrow \ell\nu b) = 515^{+36}_{-42} \text{ fb}$

- FCNC  $tZq$  highly suppressed in the SM by the GIM mechanism, order  $10^{-14}$
- Beyond SM extensions: **up to order  $10^{-4}$** 
  - Quark-singlet model ([Phys. Rev. D 67 \(2003\) 035003](#))
  - 2HDM ([Phys. Rev. D 55 \(1997\) 3156](#))
- Main backgrounds: di-boson,  $t\bar{t}Z$  and  $tZ$  production.
- Final states with 3 leptons ( $e/\mu$ ) or 1 OSSF pair with  $|m_{\ell\ell} - m_Z| < 15 \text{ GeV}$ :
  - SR1 (at least 2 jets, at least 1 b-jet)
    - Top pair production with  $t \rightarrow Zq$ : sensitive to both FCNC  $tZu$  and  $tZc$
  - SR2 (1 b-jet, up to one additional jet)
    - FCNC in s-channel single top production:  $gq \rightarrow tZ$  more sensitive to  $tZu$
- Kinematics of top quark candidates reconstructed by minimizing  $\chi^2$  functions with mass constraints.

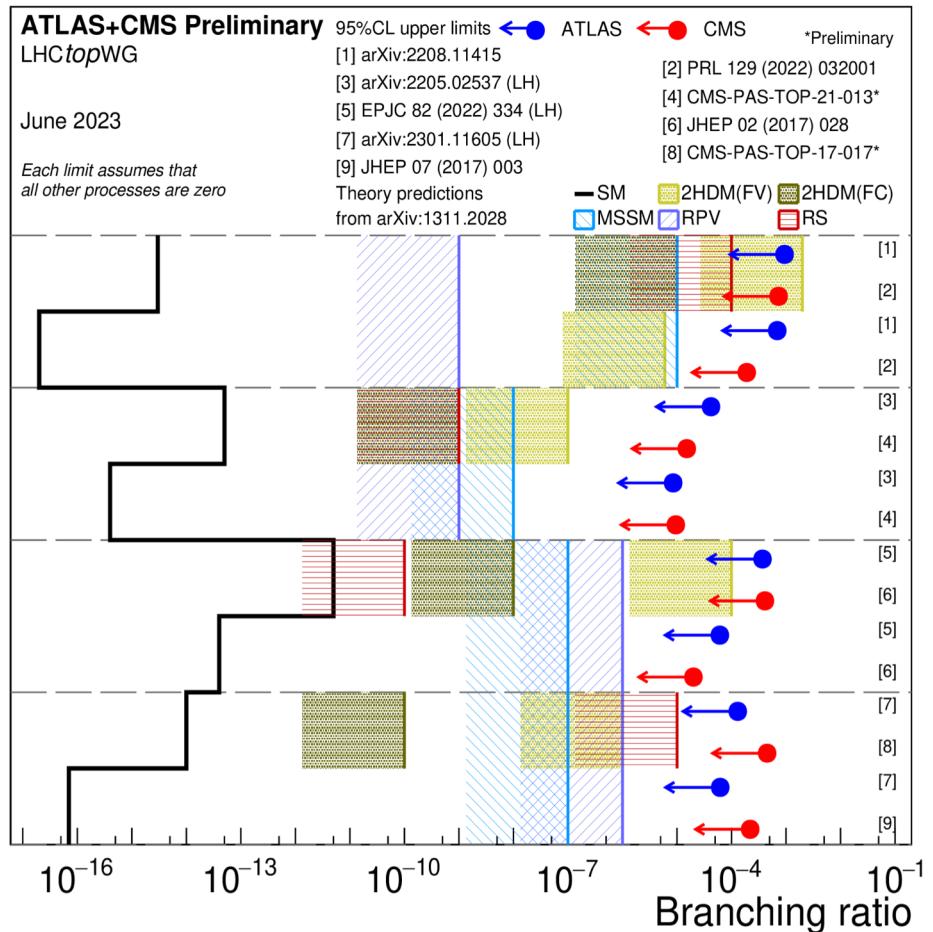


- Simultaneous binned profile likelihood fit to the data in SRs and CRs.
  - Binned distributions of two GBDT discriminants.
- Main systematics:
  - SM  $tZ$  background normalization and diboson modelling uncertainties.

Observable	Vertex	Coupling	Observed	Expected
SRs+CRs				
$\mathcal{B}(t \rightarrow Zq)$	$tZu$	LH	$6.2 \times 10^{-5}$	$4.9^{+2.1}_{-1.4} \times 10^{-5}$
$\mathcal{B}(t \rightarrow Zq)$	$tZu$	RH	$6.6 \times 10^{-5}$	$5.1^{+2.1}_{-1.4} \times 10^{-5}$
$\mathcal{B}(t \rightarrow Zq)$	$tZc$	LH	$13 \times 10^{-5}$	$11^{+5}_{-3} \times 10^{-5}$
$\mathcal{B}(t \rightarrow Zq)$	$tZc$	RH	$12 \times 10^{-5}$	$10^{+4}_{-3} \times 10^{-5}$
$ C_{uW}^{(13)*} $ and $ C_{uB}^{(13)*} $	$tZu$	LH	0.15	$0.13^{+0.03}_{-0.02}$
$ C_{uW}^{(31)} $ and $ C_{uB}^{(31)} $	$tZu$	RH	0.16	$0.14^{+0.03}_{-0.02}$
$ C_{uW}^{(23)*} $ and $ C_{uB}^{(23)*} $	$tZc$	LH	0.22	$0.20^{+0.04}_{-0.03}$
$ C_{uW}^{(32)} $ and $ C_{uB}^{(32)} $	$tZc$	RH	0.21	$0.19^{+0.04}_{-0.03}$
SR1+CRs				
$\mathcal{B}(t \rightarrow Zq)$	$tZu$	LH	$9.7 \times 10^{-5}$	$8.6^{+3.6}_{-2.4} \times 10^{-5}$
$\mathcal{B}(t \rightarrow Zq)$	$tZu$	RH	$9.5 \times 10^{-5}$	$8.2^{+3.4}_{-2.3} \times 10^{-5}$
SR2+CRs				
$\mathcal{B}(t \rightarrow Zq)$	$tZu$	LH	$7.8 \times 10^{-5}$	$6.1^{+2.7}_{-1.7} \times 10^{-5}$
$\mathcal{B}(t \rightarrow Zq)$	$tZu$	RH	$9.0 \times 10^{-5}$	$6.6^{+2.9}_{-1.8} \times 10^{-5}$



- Current limits entering in the sensitivity region to FCNC models from a warped extra dimension: **order  $10^{-5}$** 
  - K. Agashe et al. [Phys. Rev. D 75 \(2007\) 015002](#)



K.Agashe et al., [arXiv:1311.2028](https://arxiv.org/abs/1311.2028)

Process	SM	2HDM(FV)	2HDM(FC)	MSSM	RPV	RS
$t \rightarrow Zu$	$7 \times 10^{-17}$	—	—	$\leq 10^{-7}$	$\leq 10^{-6}$	—
$t \rightarrow Zc$	$1 \times 10^{-14}$	$\leq 10^{-6}$	$\leq 10^{-10}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-5}$
$t \rightarrow gu$	$4 \times 10^{-14}$	—	—	$\leq 10^{-7}$	$\leq 10^{-6}$	—
$t \rightarrow gc$	$5 \times 10^{-12}$	$\leq 10^{-4}$	$\leq 10^{-8}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-10}$
$t \rightarrow \gamma u$	$4 \times 10^{-16}$	—	—	$\leq 10^{-8}$	$\leq 10^{-9}$	—
$t \rightarrow \gamma c$	$5 \times 10^{-14}$	$\leq 10^{-7}$	$\leq 10^{-9}$	$\leq 10^{-8}$	$\leq 10^{-9}$	$\leq 10^{-9}$
$t \rightarrow hu$	$2 \times 10^{-17}$	$6 \times 10^{-6}$	—	$\leq 10^{-5}$	$\leq 10^{-9}$	—
$t \rightarrow hc$	$3 \times 10^{-15}$	$2 \times 10^{-3}$	$\leq 10^{-5}$	$\leq 10^{-5}$	$\leq 10^{-9}$	$\leq 10^{-4}$

arXiv:2301.11605	Observed	Expected
$t \rightarrow Zc$	$13(L)/12(R) \times 10^{-5}$	$11_{-3}^{+5}(L)/10_{-3}^{+4}(R) \times 10^{-5}$
$t \rightarrow Zu$	$6.2(L)/6.6(R) \times 10^{-5}$	$4.9_{-1.4}^{+2.1}(L)/5.1_{-1.4}^{+2.1}(R) \times 10^{-5}$

# CONCLUSIONS.

- The large top quark samples in the LHC Run 2 datasets have allowed new measurements of  $\sigma_{t\bar{t}}$  and the observation of new rare top production processes.
  - Most precise inclusive  $\sigma_{t\bar{t}}$  measurement to date with  $\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}} [\%]=1.8$  in agreement with the NNLO+NNLL prediction.
    - No MC model can described all measured differential distributions.
  - Normalized differential  $\sigma_{t\bar{t}}$  measurements as a function of jet substructure variables indicate the need for improvements in models used to predict the substructure of boosted top-quark jets.
  - New early Run 3  $\sigma_{t\bar{t}}$  measurement in agreement with the prediction at 13.6 TeV, current precision limited by luminosity uncertainty and lepton efficiency uncertainties.

$$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}} [\%]=3.4$$

- Observation of  $tqy$  with observed(expected) significance :  $9.3\sigma$  ( $6.8\sigma$ ).
- Recent searches have explored FCNC top-quark interactions  $tZq$ .
  - Multivariate methods and targeting not only FCNC decays but also FCNC production modes have allowed improving previous LHC limits.
  - Data in good agreement with the SM expectation: no evidence of an FCNC signal.

