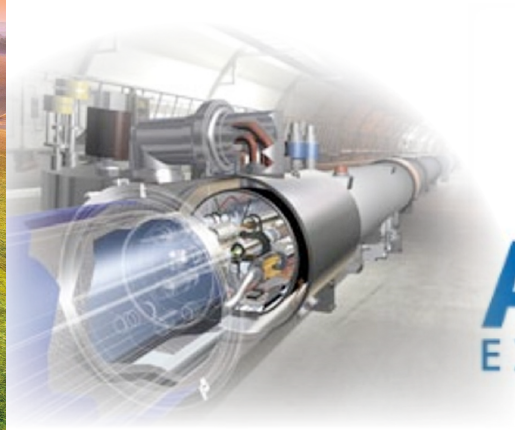
Highlights on top quark physics with the ATLAS experiment at the LHC.



ATLAS EXPERIMENT

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IFIC INSTITUT DE FÍSICA CORPUSCULAR

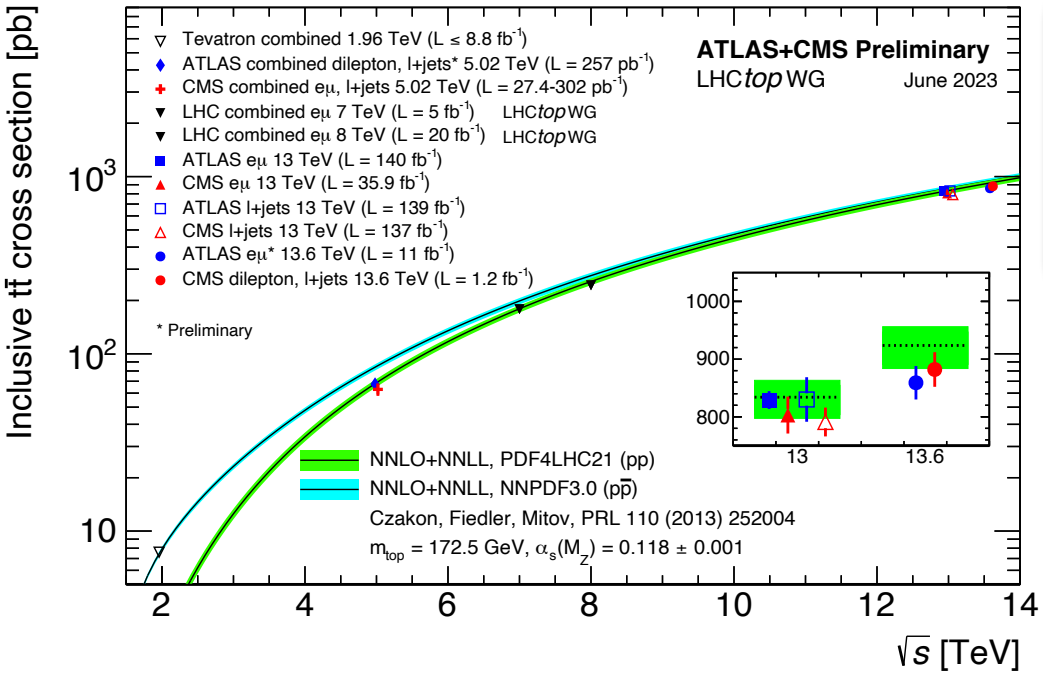
CSIC Consejo Superior de Investigaciones Científicas

Universitat de València

OUTLINE & INTRODUCTION/MOTIVATION

- 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



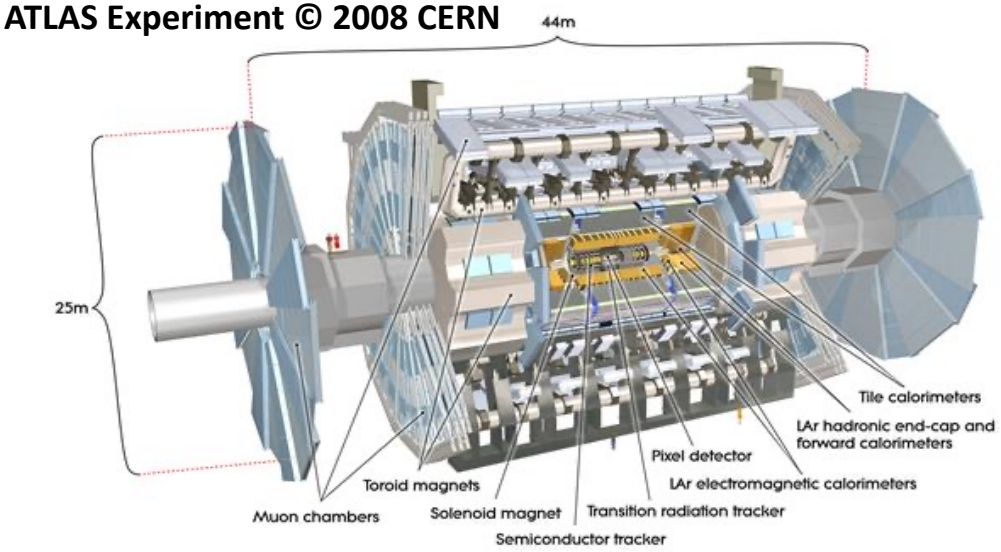
- Inclusive and differential $\sigma_{t\bar{t}}$
  - Test MC models (QCD NLO + LO PS + hadronization)
    - Boosted top-quark jets.
  - Test NNLO+NNLL theoretical predictions.

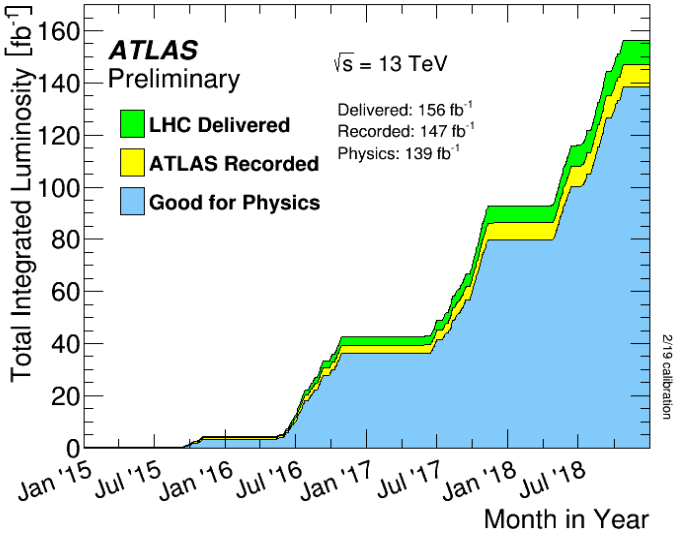
- σ_{t-chan}, $\sigma_{\bar{t}-chan}$
  - Constrain PDFs and CKM matrix
  - Test NNLO+NNLL theoretical predictions.
  - EFT interpretations.

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

- Top rare production processes: $tq\gamma$
  - Complete top quark's electroweak couplings.

THE FULL RUN-2 & THE ATLAS EXPERIMENT.





arXiv:2212.09379.

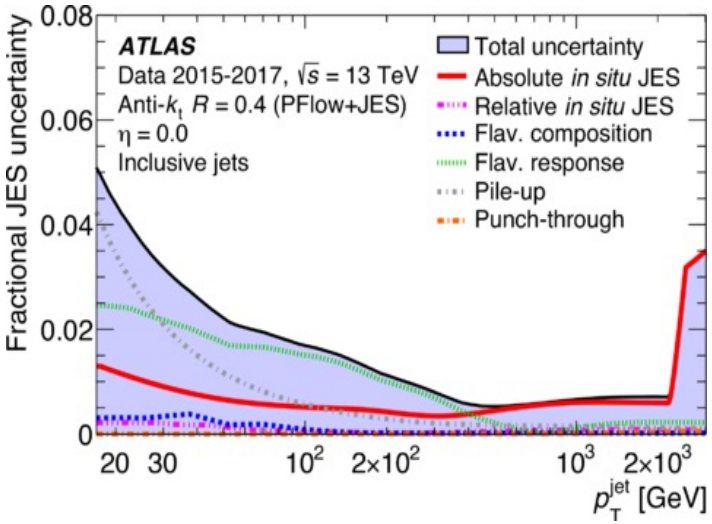
L_{int}=140.1 ± 1.2 fb^{-1}, 0.83% uncertainty

ATLAS detector:

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

Excellent detector performance.

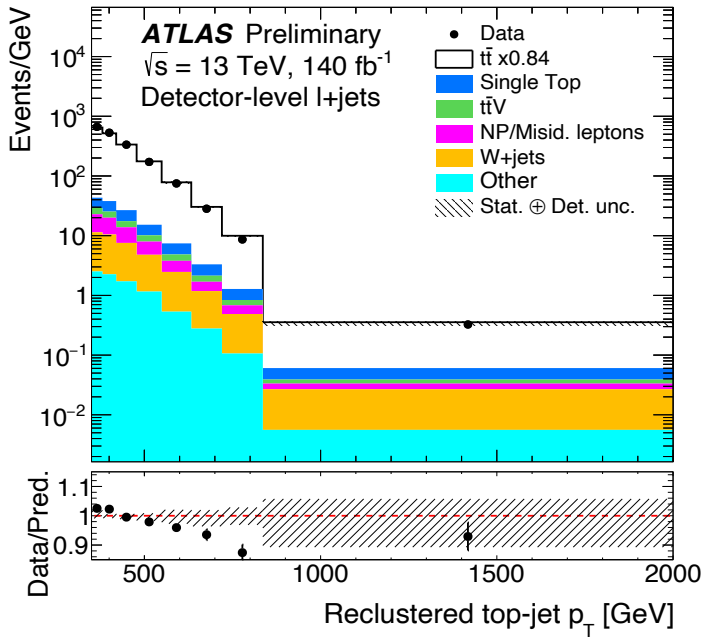
- Run 2 Data taking efficiency = 94%
- ATLAS pp RUN-2 Data quality fraction = 95.6%
- Precision object performance.
  - Energy scale for central jets ~1% for p_T ~ 250-2000 GeV

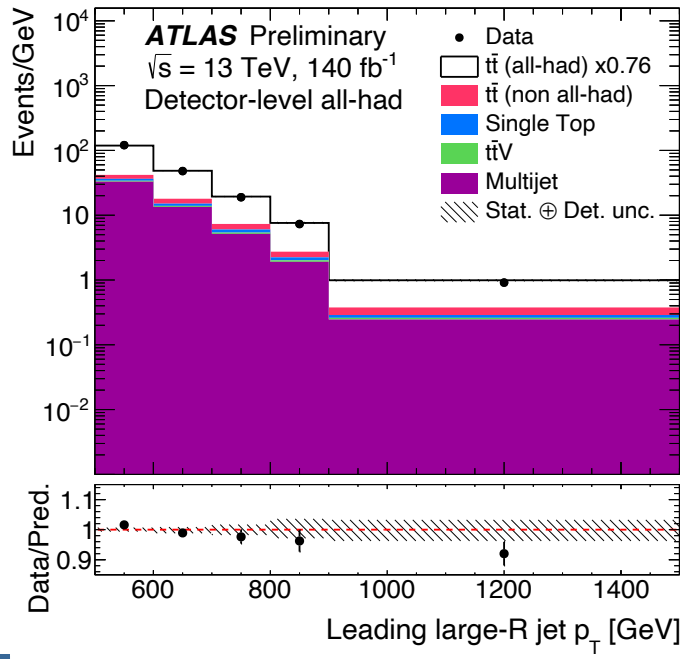


Eur. Phys. J. C 81 (2021) 689

Jet substructure in boosted $t\bar{t}$: $\sqrt{s}$=13 TeV $\mathcal{L}_{int}$ = 140 fb^{-1} ATLAS-CONF-2023-02

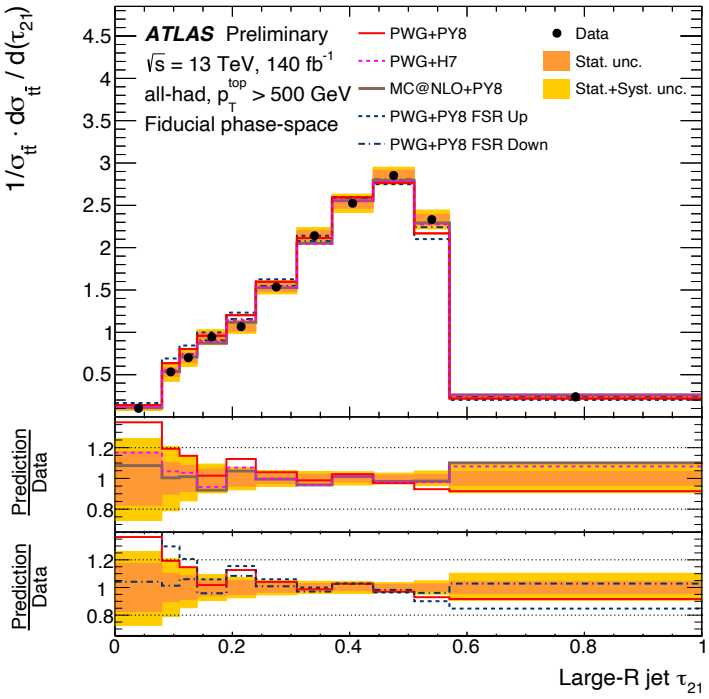
- MOTIVATION:
  - Test MC models (QCD NLO + LO PS + hadronization) to predict the substructure of boosted top-quark jets.
  - Beyond SM effects can modify the top-quark substructure:
    - Heavy particles decaying to top-quark pairs, di-boson resonances, dark matter candidates etc.
- Normalized differential $\sigma_{t\bar{t}}$ 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/μ), 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.

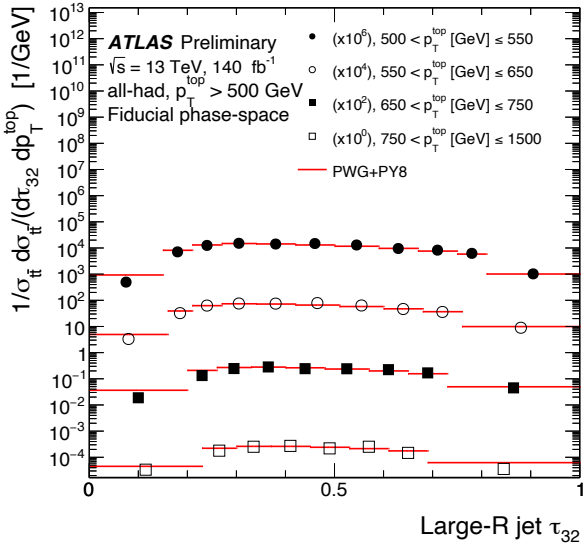


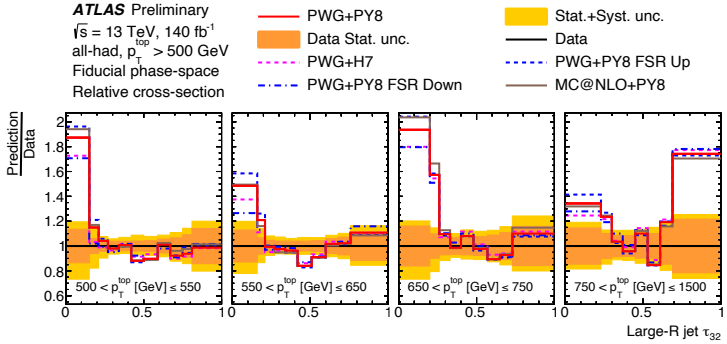


Jet substructure in boosted $t\bar{t}$: $\sqrt{s}$=13 TeV $\mathcal{L}_{int}$ = 140 fb^{-1} ATLAS-CONF-2023-02

- 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: τ_{21}, ECF2 and D_2 well described. τ_{32}. τ_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.





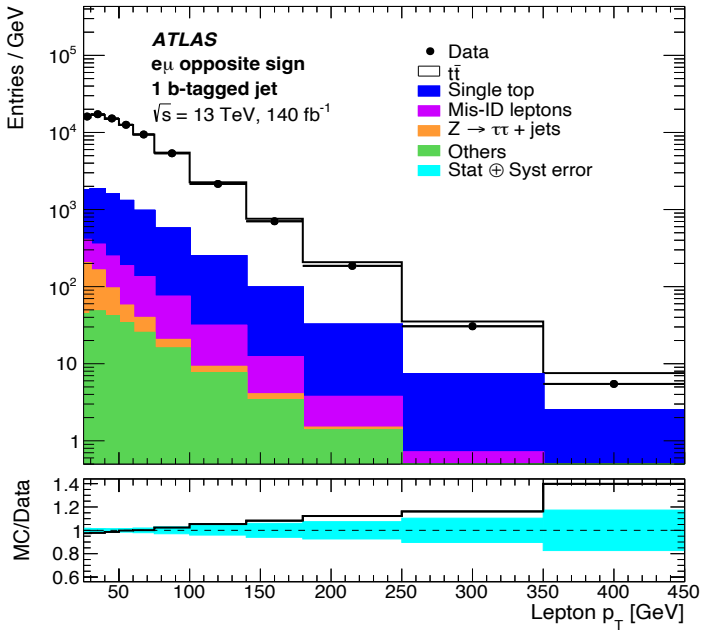


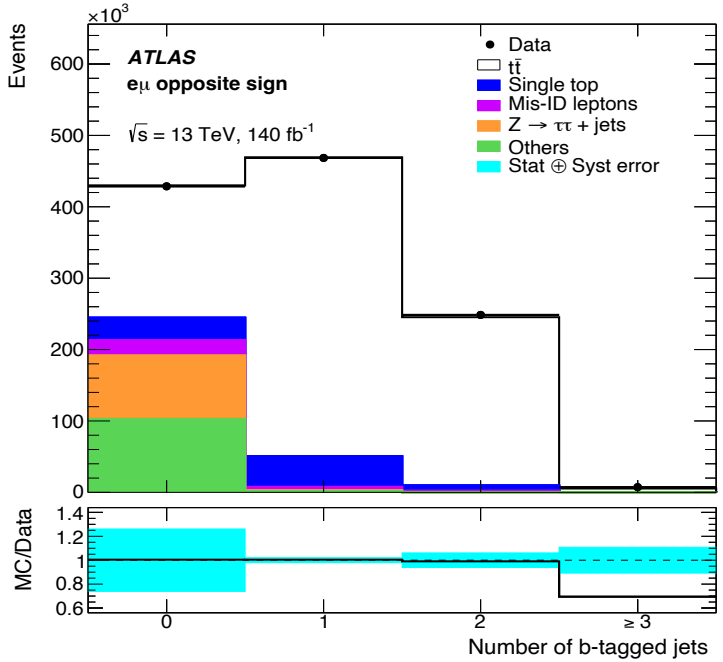
- SYSTEMATICS: From 5% till 40% in low and high bins.
- Signal modeling: FSR,PS and hadronization model
- Deterctor-level: JES/JER

- CONCLUSIONS: Need for improvements in models used to predict the substructure of boosted top-quark jets.

Inclusive and differential $\sigma_{t\bar{t}}$: $\sqrt{s}$=13 TeV $\mathcal{L}_{int}$ = 140 fb^{-1} arXiv:2303.15340

- 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 (eμ) pairs. $N_{b\text{-jets}}$=1,2.
  - Main backgrounds: single top and misidentified leptons.
  - Same-sign eμ pairs for misidentified lepton background estimation.





- Cross sections together with combined selection and b-tagging efficiencies from a log-likelihood fit solving two equations:
  - $G^{i}_{e\mu}$ → reconstruction efficiencies from simulation.
  - C^{i}_{b} → b-tagging correlation coefficients from simulation.

$$N^{i}_{1} = \mathcal{L}\sigma^{i}_{t\bar{t}} G^{i}_{e\mu} 2\epsilon^{i}_{b}(1 - \epsilon^{i}_{b} C^{i}_{b}) + N^{i}_{1,\text{bkg}}$$
$$N^{i}_{2} = \mathcal{L}\sigma^{i}_{t\bar{t}} G^{i}_{e\mu} (\epsilon^{i}_{b})^{2} C^{i}_{b} + N^{i}_{2,\text{bkg}}$$

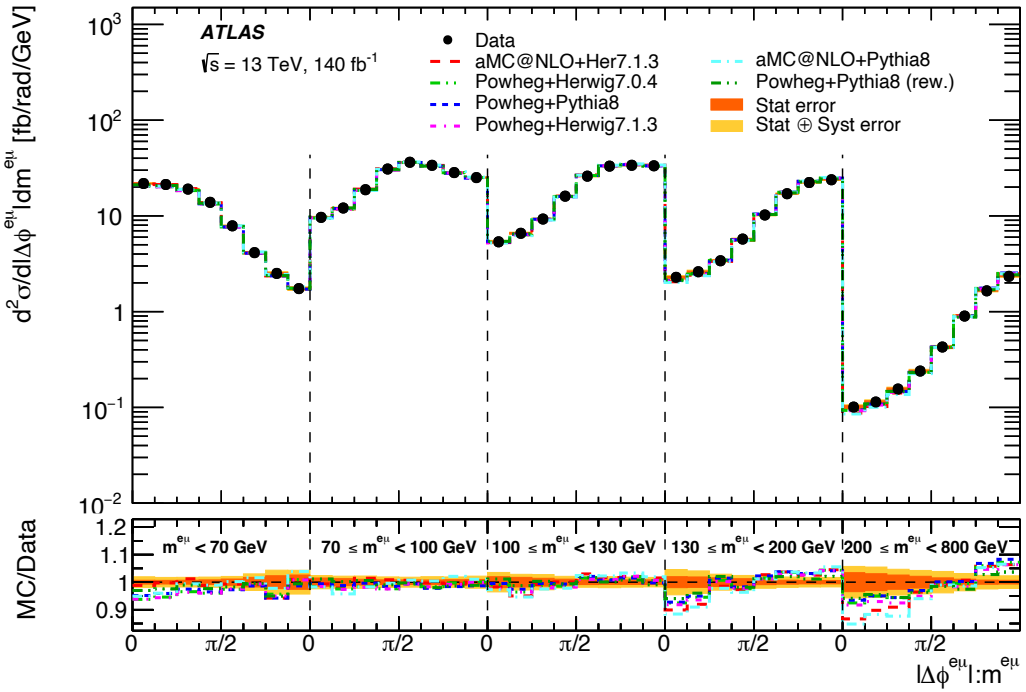
Inclusive and differential $\sigma_{t\bar{t}}$: $\sqrt{s}$=13 TeV $\mathcal{L}_{int}$ = 140 fb^{-1} arXiv:2303.15340

- Differential cross-section measured as a function of several lepton kinematic variables:
  - p_T^{ℓ}, $|\eta^{\ell}|$, $m^{e\mu}$, $p_T^{e\mu}$, $|y^{e\mu}|$, $E^e + E^\mu$, $p_T^e + p_T^\mu$ 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 → overtaken by interference $t\bar{t}/Wt$

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

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

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



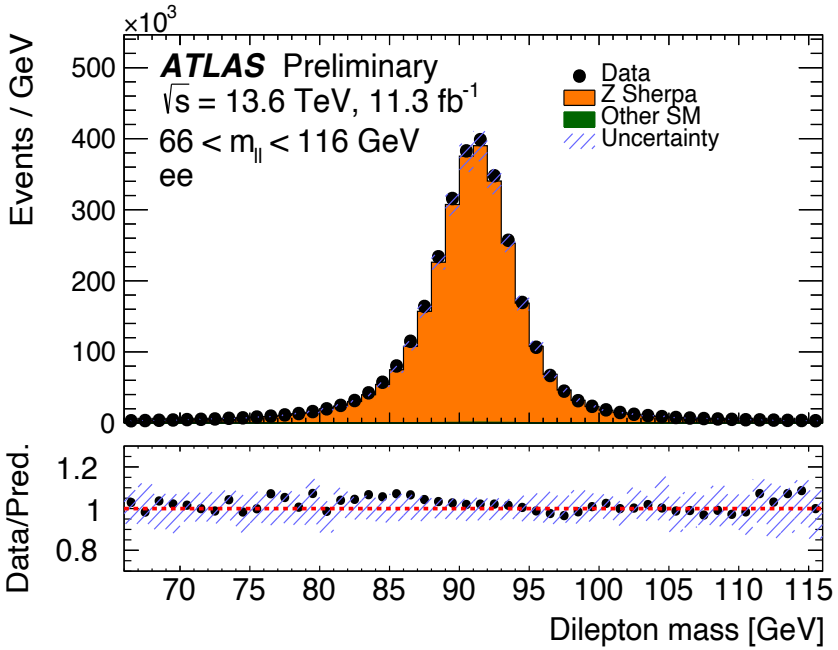
$$\sigma_{t\bar{t}}^{inclusive} = 829 \pm 1(stat) \pm 13(syst) \pm 8(lumi) \pm 2(beam)pb$$

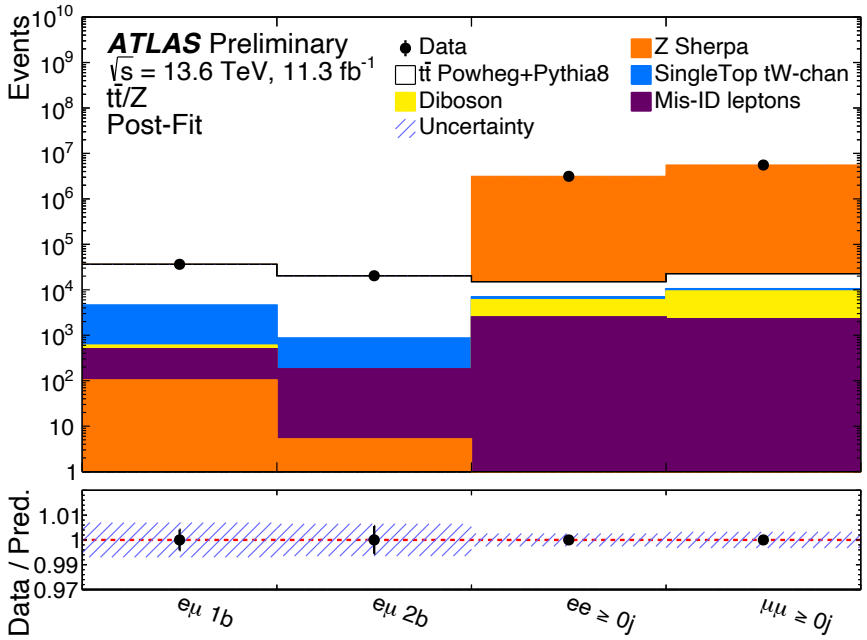
Excellent agreement

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

Inclusive $\sigma_{t\bar{t}}$, $\sigma^{fid.}_{Z\to\ell\ell}$, $R_{t\bar{t}/Z}$: $\sqrt{s}$=13.6 TeV $\mathcal{L}_{int}$ = 11.3 fb^{-1} ATLAS-CONF-2023-006

- 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.
  - $\sigma^{fid.}_{Z\to\ell\ell}$: same flavor pairs (ee/$\mu\mu$) with opposite electric charge, p_T^{ℓ}>27 GeV, $|\eta^{\ell}|$ <2.5 and 66 < $M_{\ell\ell}$<116 GeV

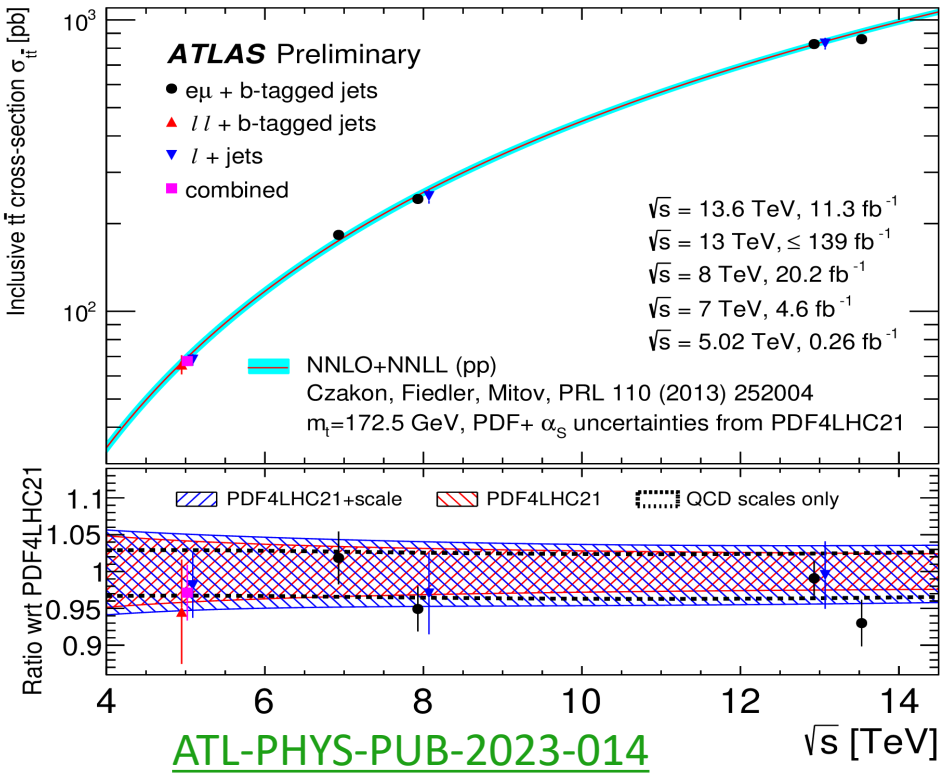




- Profile-likelihood technique with ee/$\mu\mu$/eμ events:
  - First fit: free parameters $\sigma_{t\bar{t}}$, $\sigma^{fid.}_{Z\to\ell\ell}$ and ϵ_b,
  - Second fit: $R_{t\bar{t}/Z}$, $\sigma^{fid.}_{Z\to\ell\ell}$ and ϵ_b.

$$N_1 = L\sigma_{t\bar{t}}\epsilon_{e\mu}2\epsilon_b\,(1 - C_b\epsilon_b) + N_1^{\mathrm{bkg}},$$
$$N_2 = L\sigma_{t\bar{t}}\epsilon_{e\mu}C_b\epsilon_b^2 + N_2^{\mathrm{bkg}},$$

Inclusive $\sigma_{t\bar{t}}$, $\sigma^{fid.}_{Z\to\ell\ell}$, $R_{t\bar{t}/Z}$: $\sqrt{s}$=13.6 TeV $\mathcal{L}_{int}$ = 11.3 fb^{-1} ATLAS-CONF-2023-006



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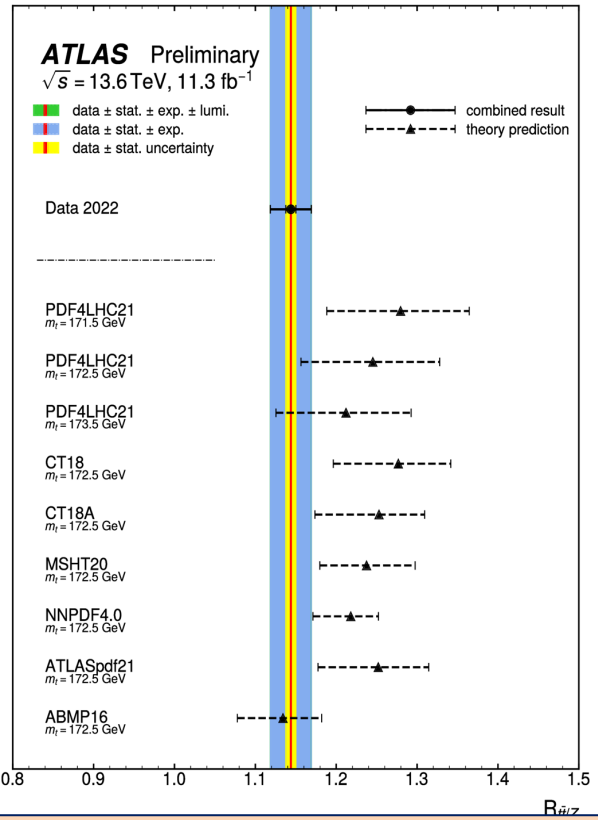


$$\sigma_{t\bar{t}}^{inclusive} = 859 \pm 4(stat) \pm 22(syst) \pm 19(lumi)pb$$
$$\sigma_{Z\to\ell\ell}^{fid.} = 751 \pm 0.3(stat) \pm 15(syst) \pm 17(lumi)pb$$
$$\epsilon_b = 0.548 \pm 0.002(stat) \pm 0.004(syst) \pm 0.001(lumi)$$
$$R_{t\bar{t}/Z} = 1.144 \pm 0.006(stat) \pm 0.022(syst) \pm 0.003(lumi)pb$$

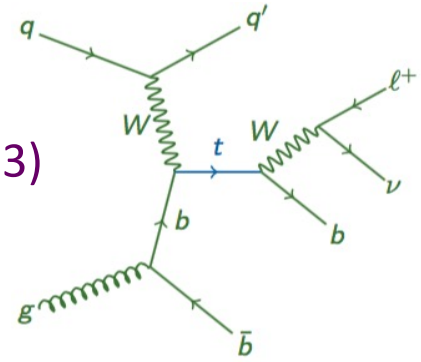
$$\sigma_{t\bar{t}}^{theory} = 924^{+32.}_{-40.}(scale + PDF)pb$$
$$\sigma_{Z\to\ell\ell}^{fid.theory} = 741 \pm 15(scale + PDF)pb$$
$$\epsilon_b = 0.545$$
$$R_{t\bar{t}/Z} = 1.245 \pm 0.076(scale + PDF)pb$$
PDF set: PDF4LHC21

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

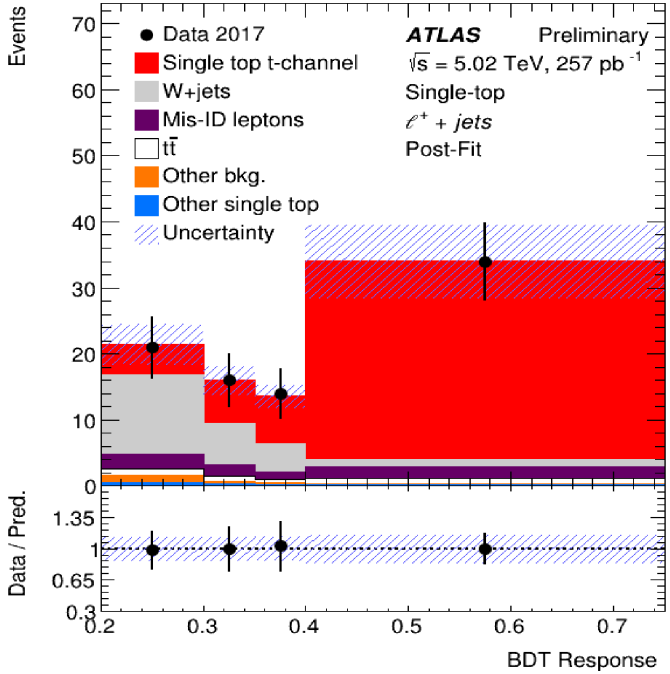
t-channel signature:

- 1 isolated and high-pT lepton.
- 1 high-pT and forward |η| jet (light jet).
- 1 high-pT 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

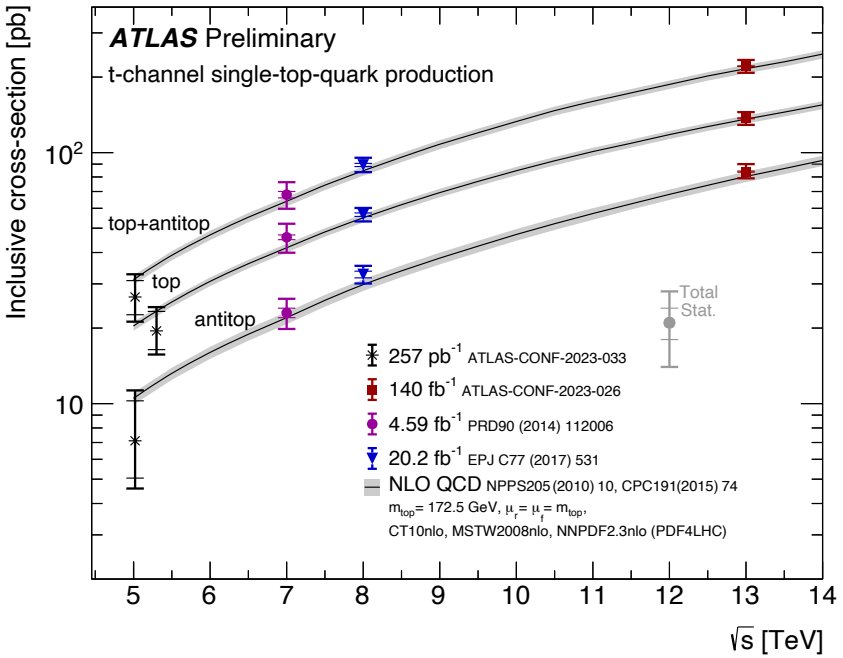


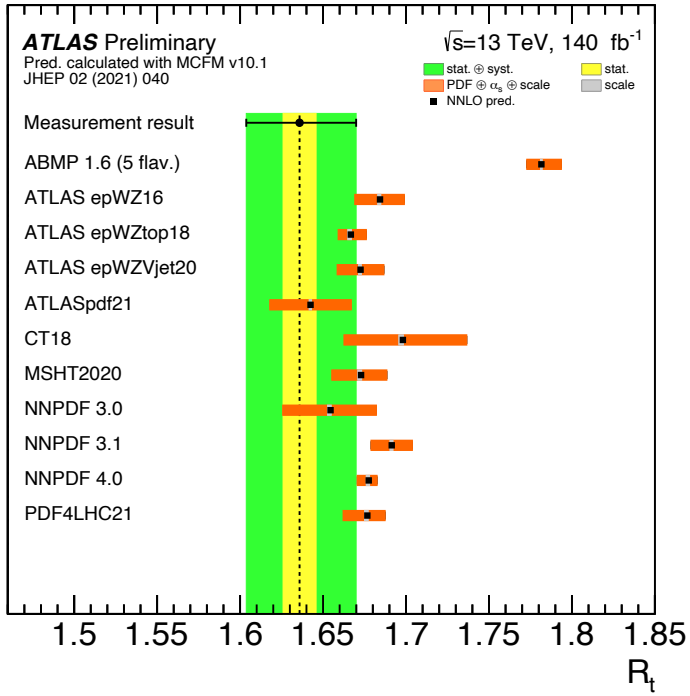
$\sqrt{s} = 5.02\,TeV$: $\sigma(tq) = 19.5^{+3.8}_{-3.1}(stat)^{+2.9}_{-2.2}(syst)\,pb$ $\sigma(\bar{t}q) = 7.1^{+3.2}_{-2.1}(stat)^{+2.8}_{-1.5}(syst)\,pb$

$\sigma(tq + \bar{t}q) = 26.6\,^{+4.3}_{-4.0}(stat)^{+4.4}_{-3.6}(syst)\,pb$ $\delta\sigma(tq + \bar{t}q)/\sigma(tq + \bar{t}q)[\%] = 22$

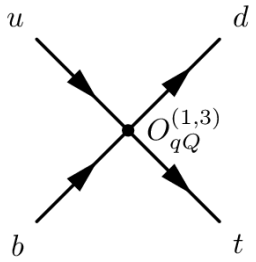
$R_t = \sigma(tq)/\sigma(\bar{t}q) = 2.74^{+1.44}_{-0.83}(stat)^{+2.8}_{-1.5}(syst)$

- 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.





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

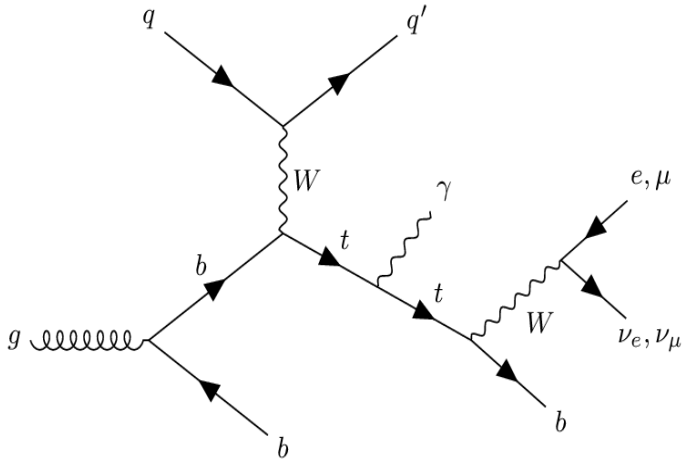


EFT: Limits to the strengh of a 4-quark operator: **-0.25 < $C_{qQ}^{(1,3)}$ <0.12**

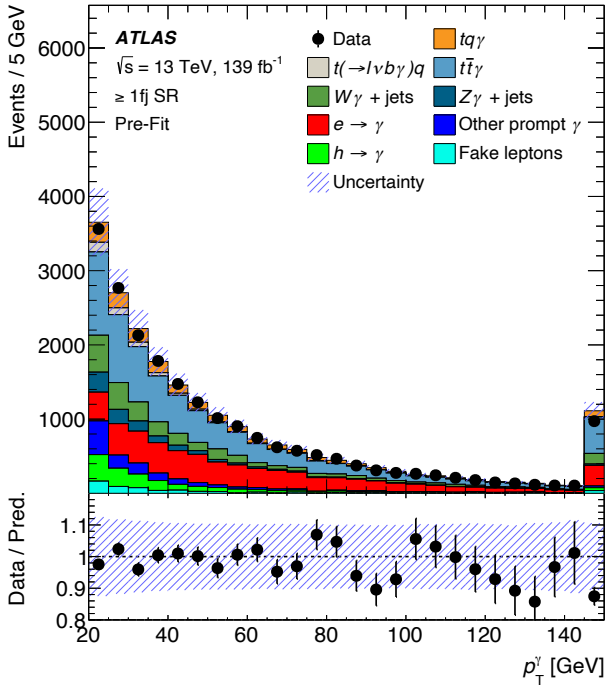
Observation of $tq\gamma$: $\sqrt{s}$=13 TeV $\mathcal{L}_{int}$ = 139 fb^{-1}

arXiv:2302.01283

- 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.



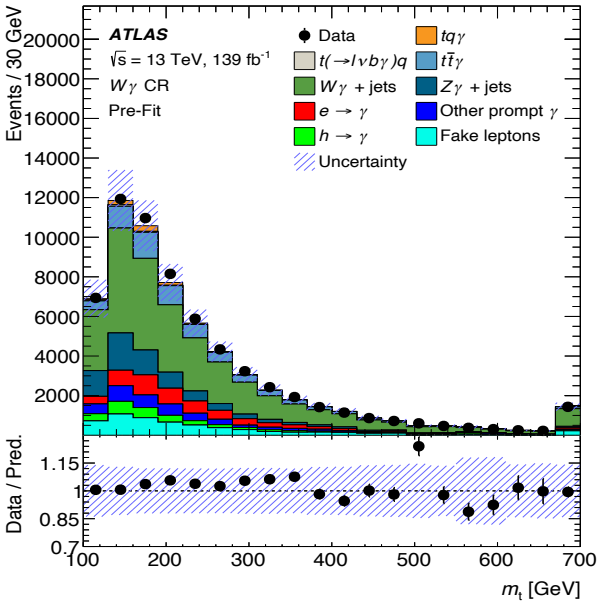
- $\sigma_{tq\gamma}$ measured in fiducial phase space at parton level
  - Excluding $t(\rightarrow \ell\nu b\gamma)q$.
  - Signature: t-channel production with a photon.
    - High p_T (e/μ) + high p_T γ + E_{miss}^T + one tight b-jet
    - Two SR: with zero and one forward jet.
    - Modelled with MadGraph5_AMC@NLO
  - Main backgrounds:
    - Prompt photons: $t\bar{t}\gamma$ and Wγ :
      - MC estimate normalized to data in CRs
      - CR($t\bar{t}\gamma$: additional loose b-jet)
      - CR(Wγ : additional loose b-jet, no tight b-jets)
    - Fake photons: (e/hadron →γ)
      - MC estimate adjusted with data-driven methods.

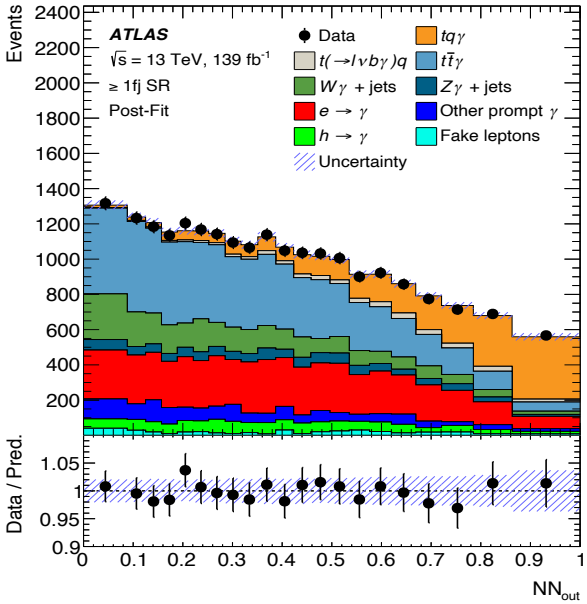


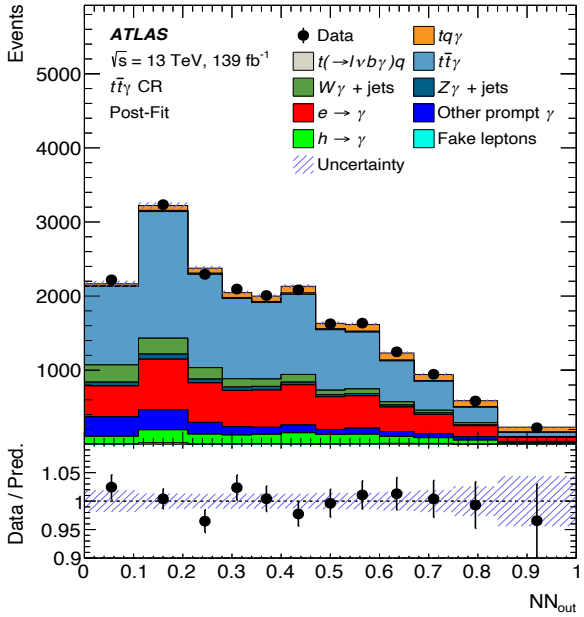
Observation of $tq\gamma$: $\sqrt{s}$=13 TeV $\mathcal{L}_{int}$ = 139 fb^{-1}

arXiv:2302.01283

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







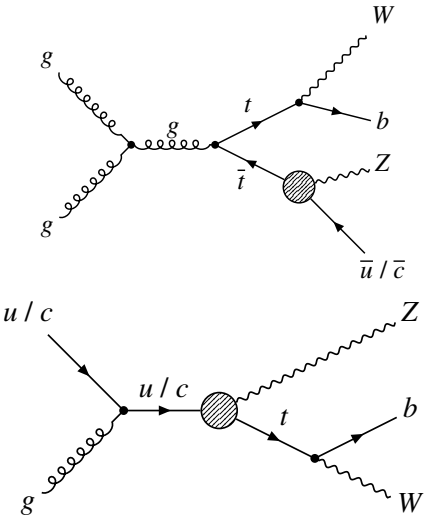
- Observed(expected) significance of $tq\gamma$ signal: 9.3σ (6.8σ):
  - First experimental evidence by CMS: 4.4σ observed (3σ expected)
  - Both experiments measured 30%-40% higher cross sections.

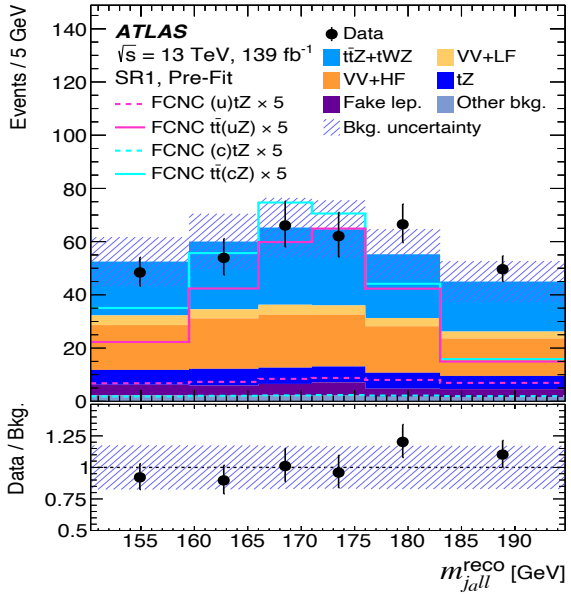
Fiducial (γ, p_T>20 GeV)parton level $\sigma_{tq\gamma} \times \mathcal{B}(t \rightarrow \ell\nu b) = 688 \pm 23(stat.)^{+75}_{-71}(syst.)fb$

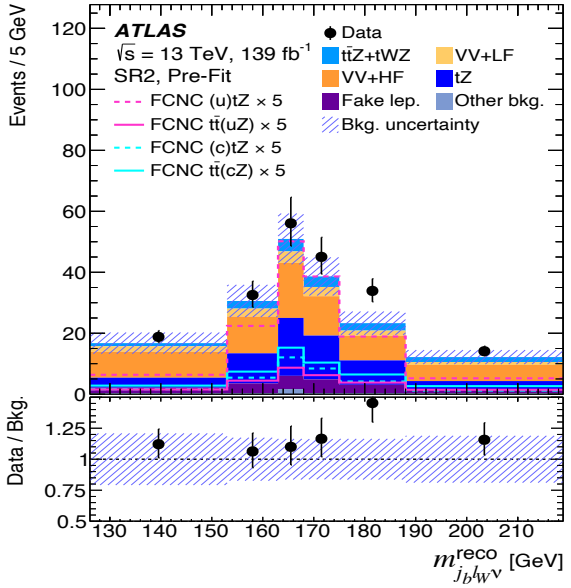
In agreement with SM NLO prediction: $\sigma_{tq\gamma} \times \mathcal{B}(t \rightarrow \ell\nu b) = 515^{+36}_{-42}fb$

Search for FCNC tZq: $\sqrt{s}$=13 TeV $\mathcal{L}_{int}$ = 139 fb^{-1} arXiv:2301.11605

- 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/μ) or 1 OSSF pair with $|m_{\ell\ell} - m_Z|$<15 GeV:
  - SR1 (at least 2 jets, at least 1 b-jet)
    - Top pair production with t→Zq: sentitive to both FCNC tZu and tZc
  - SR2 (1 b-jet, up to one additional jet)
    - FCNC in s-cannel single top production: $gq \rightarrow tZ$ more sentitive to tZu
  - Kinematics of top quark candidates reconstructed by minimizing χ^2 functions with mass constraints.



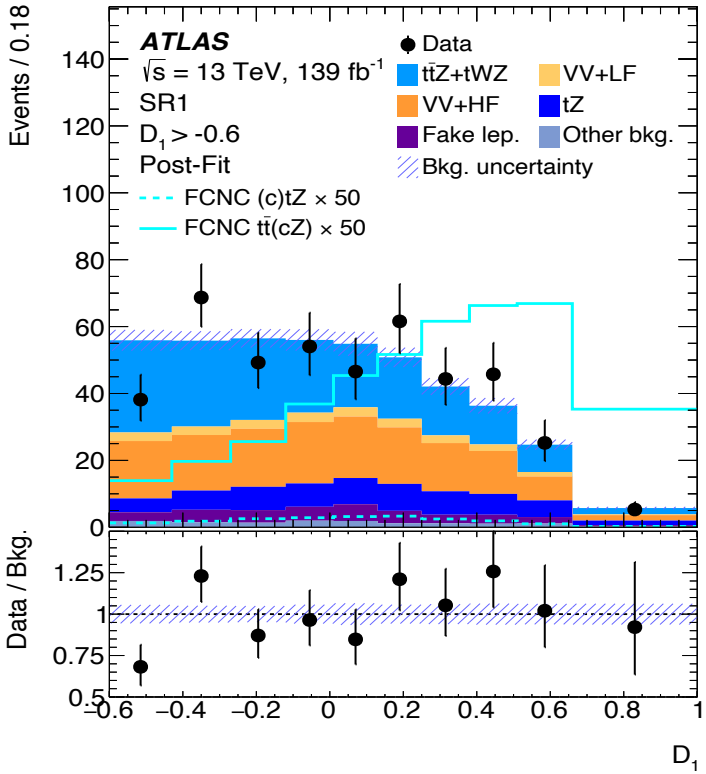




Search for FCNC tZq : $\sqrt{s}$=13 TeV $\mathcal{L}_{int}$ = 139 fb^{-1} arXiv:2301.11605

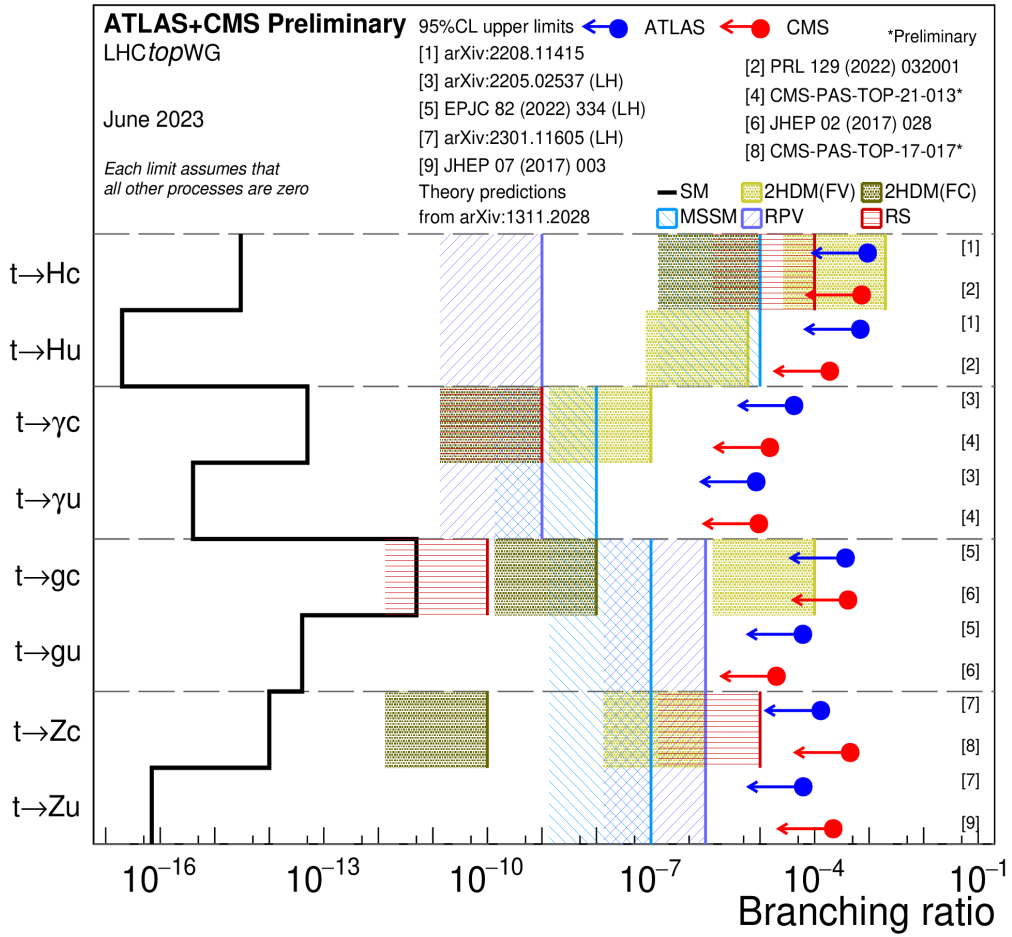
- Simultaneous binned profile likelihood fit to the data in SRs and CRs.
  - Binned distributions of two GBDT discriminants.
- Main systematics:
  - SM *tZ* background normalization and diboson modelling uncertainties.

Observable	Vertex	Coupling	Observed	Expected
	SRs+CRs			
$\mathcal{B}(t \to Zq)$	tZu	LH	6.2×10^{-5}	$4.9\,^{+2.1}_{-1.4}\times10^{-5}$
$\mathcal{B}(t \to Zq)$	tZu	RH	6.6×10^{-5}	$5.1\,^{+2.1}_{-1.4}\times10^{-5}$
$\mathcal{B}(t \to Zq)$	tZc	LH	13×10^{-5}	$11\,^{+5}_{-3}\times10^{-5}$
$\mathcal{B}(t \to Zq)$	tZc	RH	12×10^{-5}	$10\,^{+4}_{-3}\times10^{-5}$
$\lvert C_{uW}^{(13)*}\rvert$ and $\lvert C_{uB}^{(13)*}\rvert$	tZu	LH	0.15	$0.13\,^{+0.03}_{-0.02}$
$\lvert C_{uW}^{(31)}\rvert$ and $\lvert C_{uB}^{(31)}\rvert$	tZu	RH	0.16	$0.14\,^{+0.03}_{-0.02}$
$\lvert C_{uW}^{(23)*}\rvert$ and $\lvert C_{uB}^{(23)*}\rvert$	tZc	LH	0.22	$0.20\,^{+0.04}_{-0.03}$
$\lvert C_{uW}^{(32)}\rvert$ and $\lvert C_{uB}^{(32)}\rvert$	tZc	RH	0.21	$0.19\,^{+0.04}_{-0.03}$
	SR1+CRs			
$\mathcal{B}(t \to Zq)$	tZu	LH	9.7×10^{-5}	$8.6\,^{+3.6}_{-2.4}\times10^{-5}$
$\mathcal{B}(t \to Zq)$	tZu	RH	9.5×10^{-5}	$8.2\,^{+3.4}_{-2.3}\times10^{-5}$
	SR2+CRs			
$\mathcal{B}(t \to Zq)$	tZu	LH	7.8×10^{-5}	$6.1\,^{+2.7}_{-1.7}\times10^{-5}$
$\mathcal{B}(t \to Zq)$	tZu	RH	9.0×10^{-5}	$6.6\,^{+2.9}_{-1.8}\times10^{-5}$



- 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

SUMARY FCNC



K.Agashe et al., arXiv:1311.2028

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

arXiv:2301.11605	Observed	Expected
t→Zc	13(L)/12(R) × 10^{-5}	11^{+5}_{-3}(L)/10^{+4}_{-3} (R) ×10^{-5}
t→Zu	6.2(L)/6.6(R) × 10^{-5}	$4.9^{+2.1}_{-1.4}$(L)/$5.1^{+2.1}_{-1.4}$ (R) ×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 $tq\gamma$ with observed(expected) significance : 9.3σ (6.8σ).
- 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.

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