Recent results on associated top-quark production and searches for new top-quark phenomena with the ATLAS detector

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on behalf of the ATLAS Collaboration

Lake Louise Winter Institute, Alberta, Canada

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Top quarks in Run 2

- The top quark = the **heaviest** known fundamental particle – special role in BSM?
- **ATLAS Run 2 dataset** $(139\ \mathrm{fb}^{-1})$ enables exciting top-quark measurements:
  - Direct probes of top-quark couplings: tqZ, tqH, $tq\gamma$, …
  - Heavy final states (background to many direct searches): $t\bar{t}W$, $t\bar{t}H$, $t\bar{t}t\bar{t}$, …
  - Top-quark properties, for example **charge asymmetry** in pair production
    - Compared to $t\bar{t}$, enhanced in associated production modes: $t\bar{t}\gamma$, $t\bar{t}W$
  - Searches for BSM couplings of the top quark – **flavor-changing neutral currents:** tqH, $tq\gamma$, tqg, tqZ

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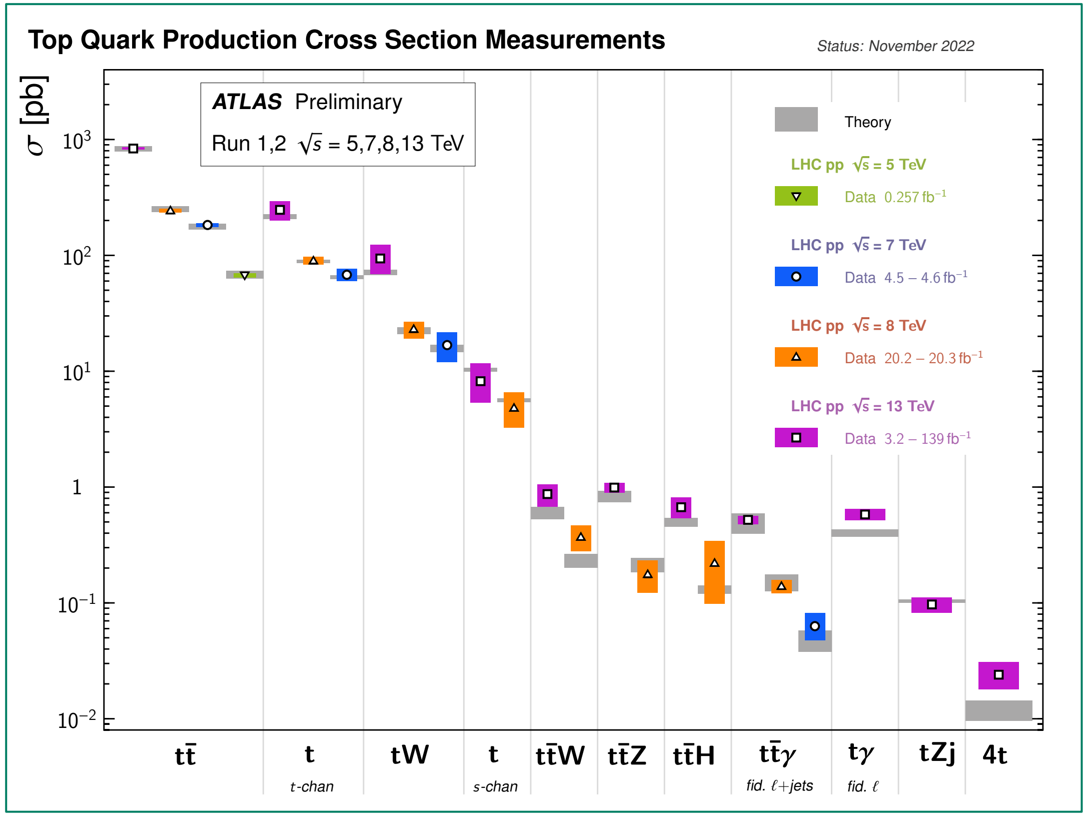

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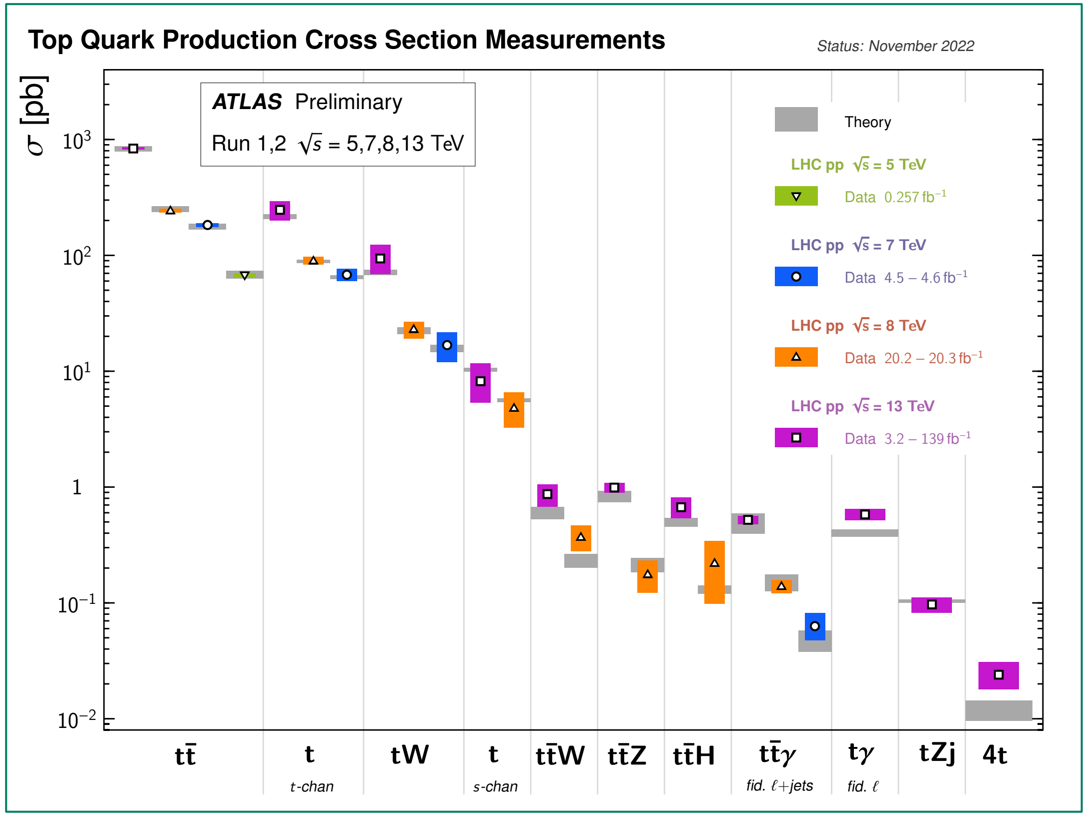
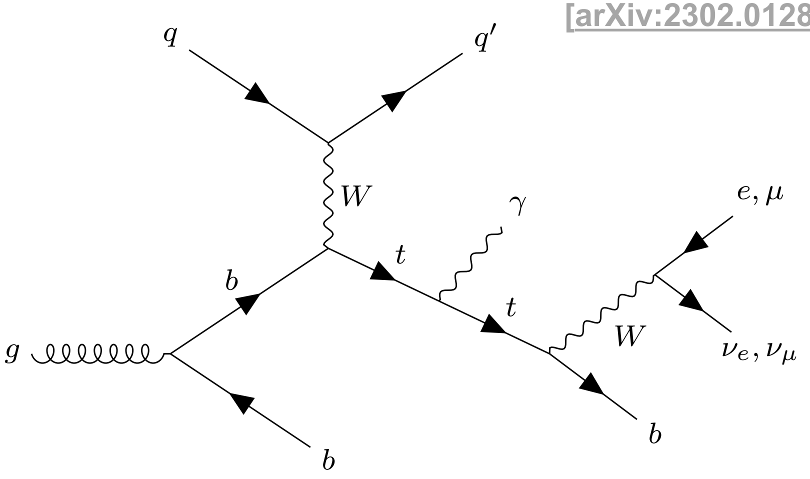
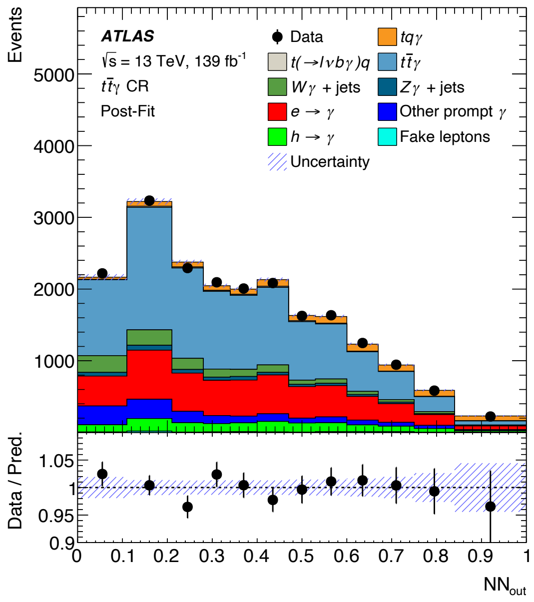


Submitted to Phys. Rev. Lett. (Feb 2023)
[arXiv:2302.01283]

Observation of $tq\gamma$



- Associated top–photon production through various diagrams:
  - Considered signal: $tq\gamma$ with semileptonic top-quark decays
  - Contamination from radiative top-quark decays $t \rightarrow l\nu b\gamma$
- **Two measurements in fiducial parton/particle phase spaces:**
  - $tq\gamma$ at parton level → direct comparison with fixed-order calculations possible
  - Combined $tq\gamma$ and $t(\rightarrow l\nu b\gamma)q$ measurement at particle level
- **Selection:** 1 e/μ, 1 γ, MET, 1 tight b-tag, 0/1 forward jets ($2.5 < |\eta| < 4.5$)
- Additional **control regions** for most dominant background processes:
  - $t\bar{t}\gamma$ (1 additional loose b-tag, inclusive in forward jets)
  - $W\gamma$ (1 loose b-tag, but no tight, inclusive in forward jets)



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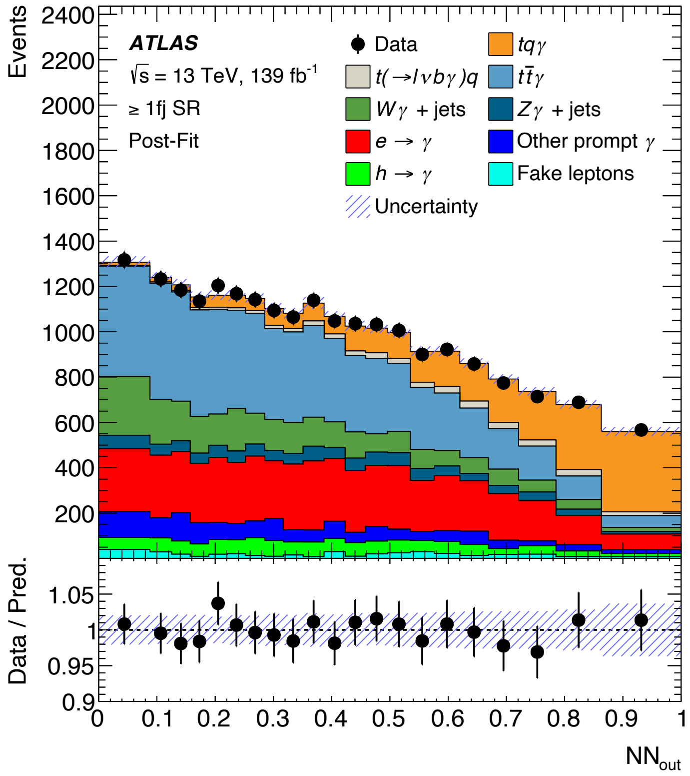
Observation of $tq\gamma$

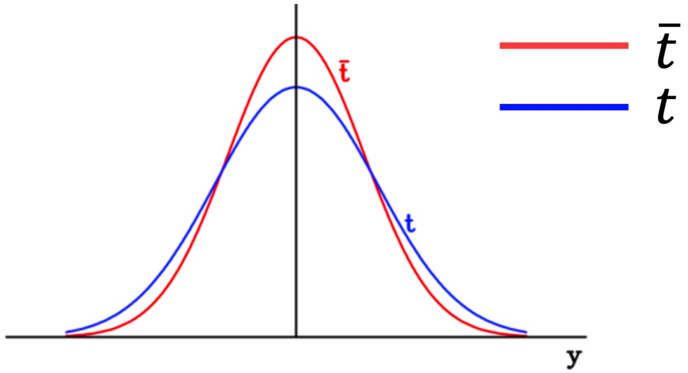
- **Estimates for fake-photon backgrounds:**
  - $e \to \gamma$ from dedicated $Z \to ee$ and $Z \to e\gamma$ control regions (for different photon reconstruction types and in bins of photon η)
  - $h \to \gamma$ through ABCD method (inverted photon isolation and identification criteria) in bins of η, p_{T} and reconstruction type
- NNs in the 0fj and ≥1fj regions to maximize S/B separation
- Simultaneous fit of the NN discriminant outputs in the 0fj and ≥1fj regions and the $t\bar{t}\gamma$ CR + event yields in the $W\gamma$ CR
- **Observation with** $\sigma_{tq\gamma} \times \mathcal{B}(t \to l\nu b) = 688 \pm 23(\mathrm{stat.})\,^{+75}_{-71}(\mathrm{syst.})\ \mathrm{fb}$
- Parton (particle) level results compatible with SM within 2.1σ (2.0σ)
  - CMS result using $36\ \mathrm{fb}^{-1}$ with ±28% (4.4σ) Phys. Rev. Lett. 121 (2018) 221802



Dominant systematic:
$t\bar{t}\gamma$ modelling

Charge asymmetry

At the LHC



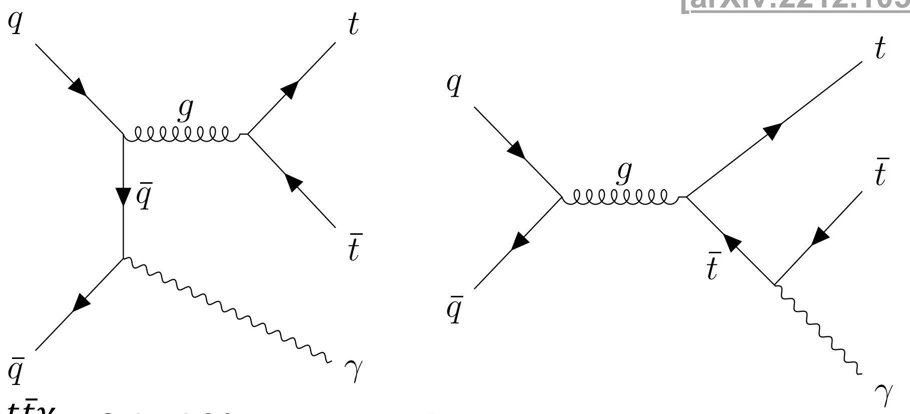
- **Difference in rapidity** of tops and antitops in pair production ($t\bar{t}$):

$$A_C^{t\bar{t}} = \frac{N(\Delta|y_{t\bar{t}}| > 0) - N(\Delta|y_{t\bar{t}}| < 0)}{N(\Delta|y_{t\bar{t}}| > 0) + N(\Delta|y_{t\bar{t}}| < 0)}$$

- Symmetric at LO in QCD, but interference effects at NLO predict $A_c > 0$
- Effect is "diluted" by dominant symmetric gg-initiated production mode at the LHC
- **Most recent ATLAS result:** $A_c^{t\bar{t}} = 0.0068 \pm 0.0015$ (incompatible with zero with 4.7σ!)
  - Consistent with SM predictions, also differentially in several observables
  - Sets **competitive bounds on several SMEFT Wilson coefficients**
  - Preliminary results shown at LLWI '22, now submitted to JHEP (arXiv:2208.12095)
- **Enhanced** in topologies with larger $q\bar{q}$-initiated production – for example $t\bar{t}\gamma$, $t\bar{t}W$

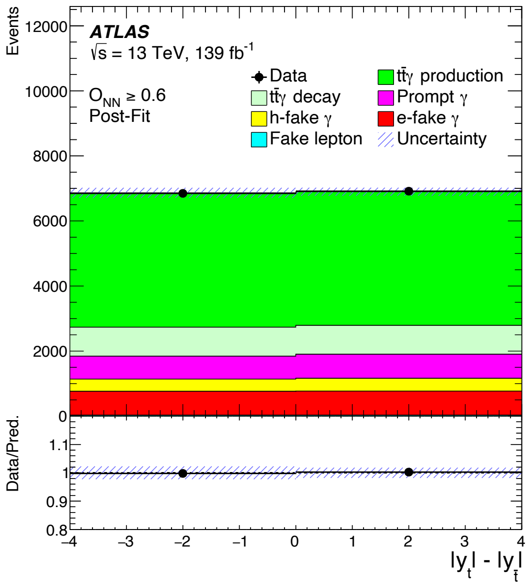
Submitted to Phys. Lett. B (Dec 2022)
[arXiv:2212.10552]

Charge asymmetry in $t\bar{t}\gamma$



- **Additional interference effects** present in $t\bar{t}\gamma$:
  - QED initial-state and final-state radiation + higher-order EW
  - Larger dominance of $q\bar{q}'$ initial state – Overall effect: negative $A_C^{t\bar{t}\gamma}$ of 1–2% expected
- Analysis only considers $t\bar{t}\gamma$ production as signal – photons from top decay = background
  - **Selection:** l+jets (≥4 jets, ≥1 b-tag), 1 photon, Z veto for $m(l,\gamma)$
  - **Fake photons** ($e \rightarrow \gamma$ and $h \rightarrow \gamma$) estimated as in $tq\gamma$ analysis
  - KLFitter-based reconstruction of $t\bar{t}$ system (top and W mass constraints)
  - NN output discriminant to construct signal-/background-enriched regions
- A_C extracted from unfolded $|y_t| - |y_{\bar{t}}|$ distribution **consistent with SM**

$$A_c = -0.003 \pm 0.024\,(\text{stat.}) \pm 0.017\,(\text{syst.})$$



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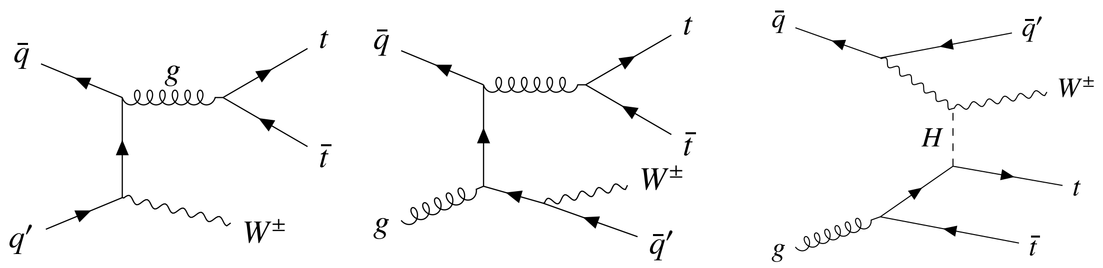
Submitted to JHEP (Jan 2023)
[arXiv:2301.04245]

Charge asymmetry in $t\bar{t}W$



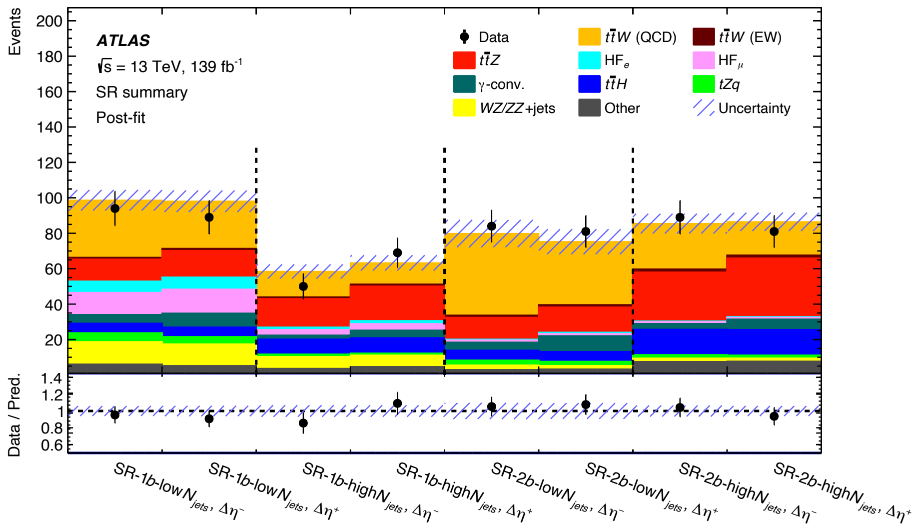
- **Two reasons** for charge asymmetry enhancement:
  - Larger dominance of $q\bar{q}'$ initial state
  - W boson radiated in initial state polarises $q\bar{q}'$ initial state – and in turn also the $t\bar{t}$ pair
- Best experimental handle on charge asymmetry is asymmetry in leptons ($t\bar{t}$ dilepton):

$$A_{\mathrm{c}}^{\ell} = \frac{N(\Delta\eta^{\ell} > 0) - N(\Delta\eta^{\ell} < 0)}{N(\Delta\eta^{\ell} > 0) + N(\Delta\eta^{\ell} < 0)}$$

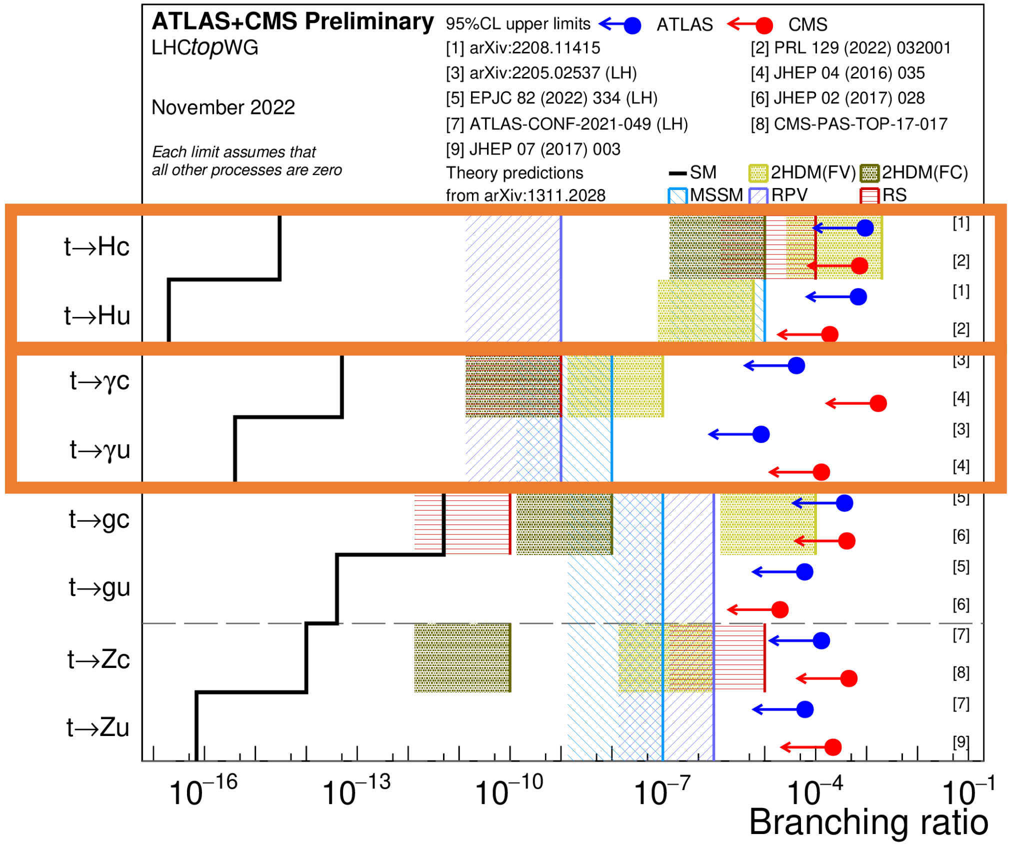
- Several signal and control regions included in the fit
- **Trilepton channel:** lepton-to-top assignment via BDT
- A_C^l extracted at reco. level, then **unfolded to particle level**

$$A_{\mathrm{c}}^{\ell}(t\bar{t}W)^{\mathrm{PL}} = -0.112 \pm 0.170\,(\mathrm{stat.}) \pm 0.054\,(\mathrm{syst.})$$

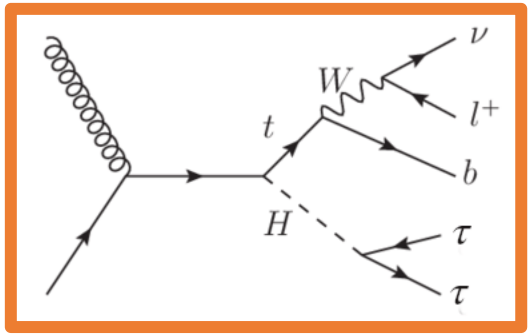
consistent with $A_{\mathrm{c}}^{\ell}(t\bar{t}W)^{\mathrm{PL}}_{\mathrm{SM}} = -0.063\,^{+0.007}_{-0.004}\,(\mathrm{scale}) \pm 0.004\,(\mathrm{MC\ stat.})$

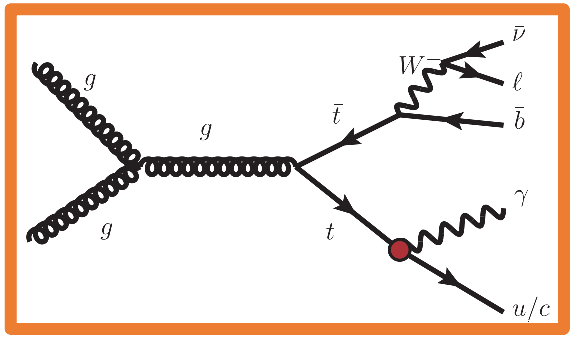


FCNC – introduction



- FCNC = **flavor-changing neutral currents** (H, γ, g, Z)
  - **Forbidden at tree level** in the Standard Model
  - Expressed as branching ratio (BR) with respect to $t \to Wb$
  - Heavily suppressed through GIM mechanism (BRs $\ll 10^{-10}$)
- Many BSM models predict **enhanced FCNC BRs**
  - Examples: 2HDM (flavor-conserving/violating), RPV SUSY, …
- Observation of FCNC would be an **indication for BSM!**
- FCNC measurable in both top-quark **production and decay** vertices





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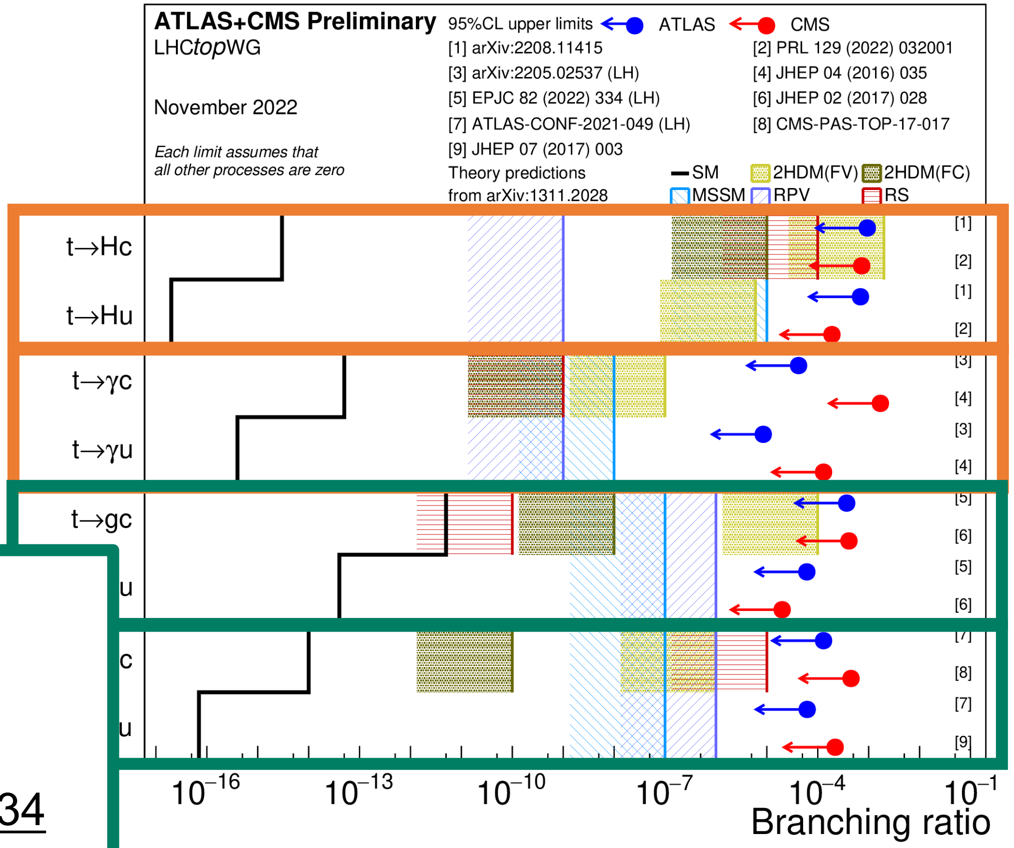
Updates since LLWI 2022:

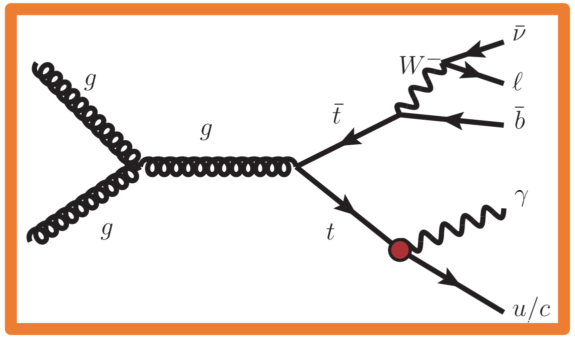
$t \rightarrow qg$

- Presented results now published as Eur. Phys. J. C 82 (2022) 334

$t \rightarrow qZ$

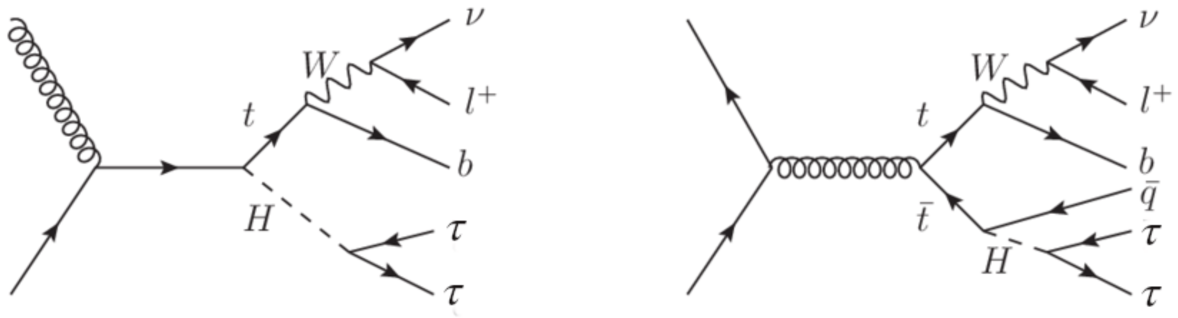
- Preliminary results shown at LLWI 2022
- Now submitted to Phys. Rev. D [arXiv:2301.11605]





Submitted to JHEP (Aug 2022)
[arXiv:2208.11415]

FCNC search for $tH(\tau\tau)$



- **Two processes** measured simultaneously:
  - tH **production**
  - **Decay** of top quark via H in pair production
  - Both probe FCNC tuH and tcH vertices – (one) top quark decays via SM vertex
- **Various analysis regions** based on W (t_l or t_h) and τ-lepton decay channels (τ_{lep}/τ_{had})
- Additional control regions for $t\bar{t}$ background with τ-fakes (difference: 2 leptons or 2 b-tags)
- **BDTs employed in all signal regions** for S/B discrimination:
  - Large list of input features used ($E_{\mathrm{T}}^{\mathrm{miss}}$, invariant masses, ...)
  - Among others: estimate of 4-momenta of invisible τ-lepton decay products through a kinematic χ^2 fit (Higgs mass constraint)
  - All signals combined: tH and $tt(qH)$ as well as tuH and tcH

Submitted to JHEP (Aug 2022)
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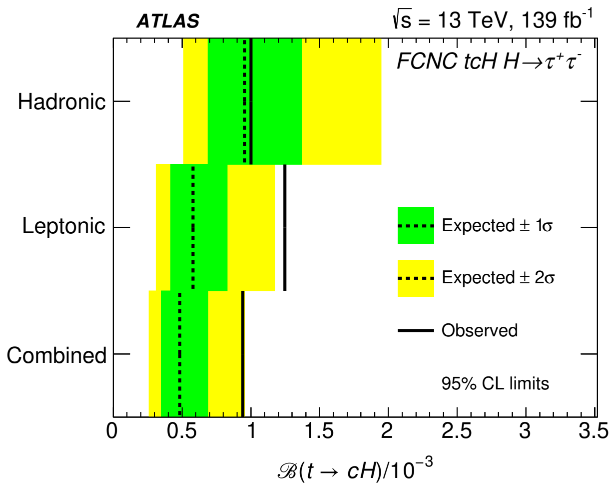
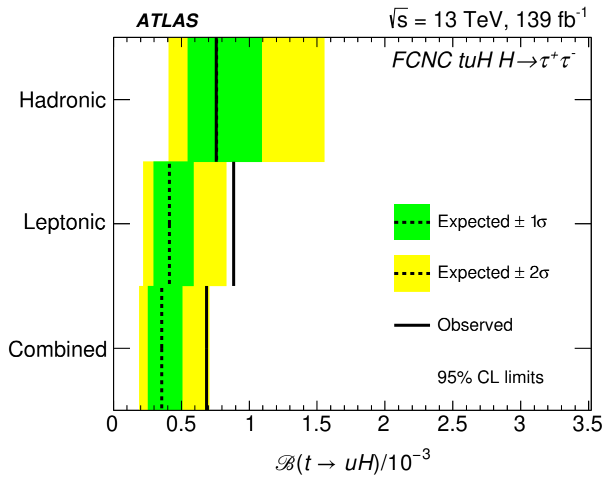
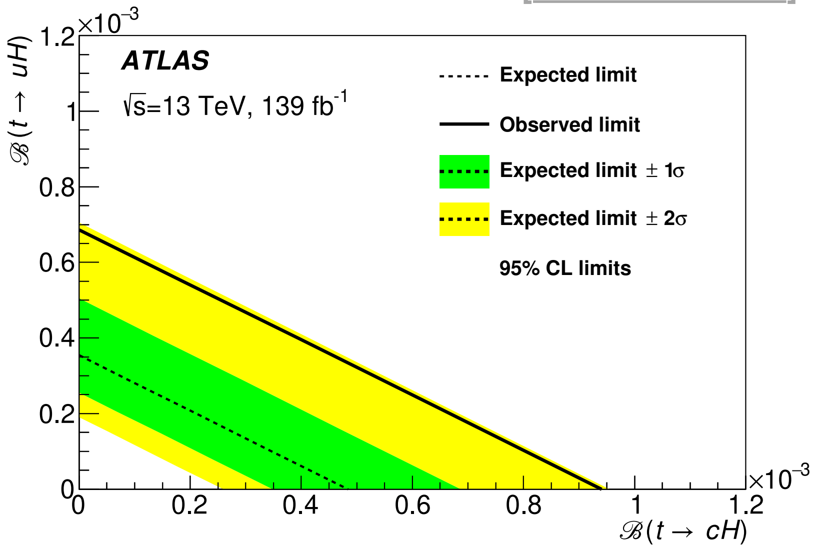
FCNC search for $tH(\tau\tau)$

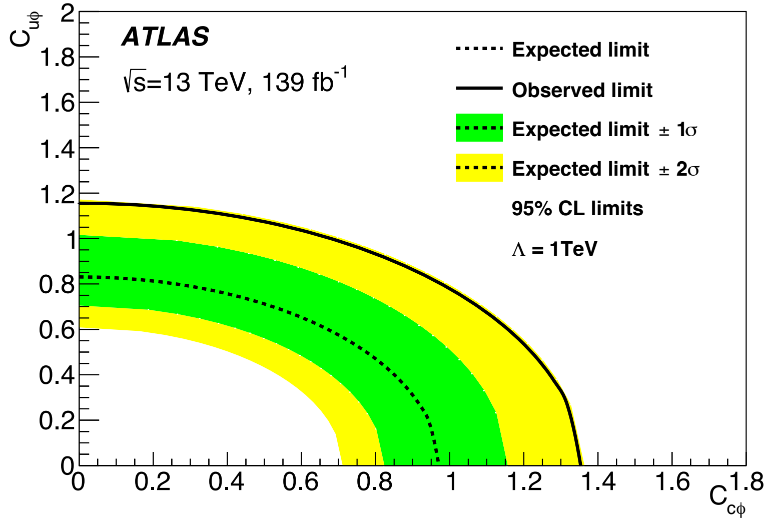
- Slight excess over data observed (2.3σ)
- **Dominant uncertainties:** stats, MC statistics, fake estimation
- Translatable into relevant SMEFT Wilson coefficients:

$$\mathcal{L}_{EFT} = \frac{C_{u\phi}^{i3}}{\Lambda^2}(\phi^\dagger\phi)(\bar{q}_i t)\tilde{\phi} + \frac{C_{u\phi}^{3i}}{\Lambda^2}(\phi^\dagger\phi)(\bar{t} q_i)\tilde{\phi}$$









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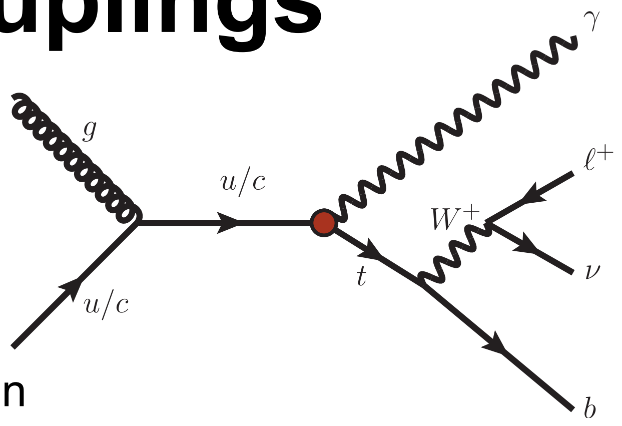
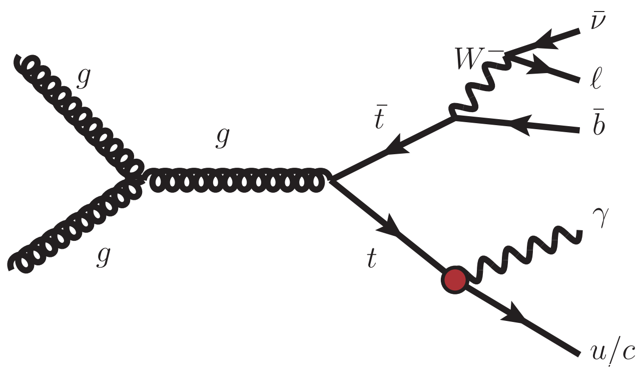
Submitted to Phys. Lett. B (May 2022)
[arXiv:2205.02537]

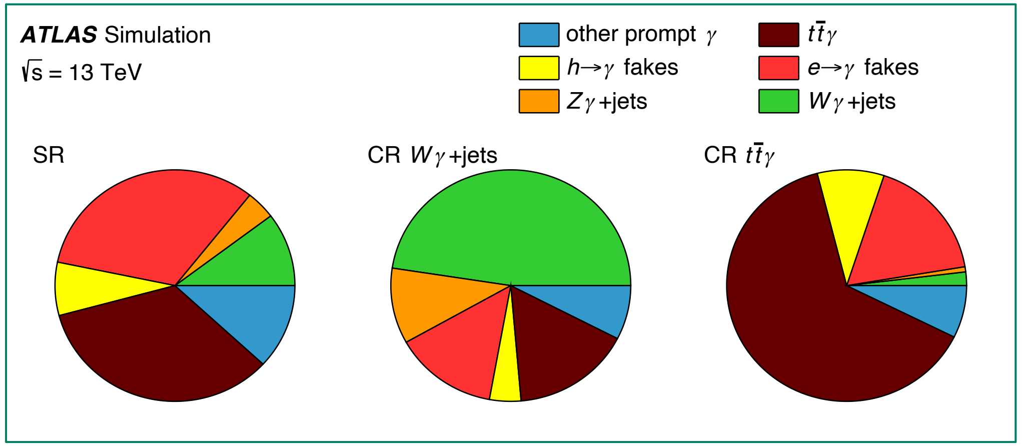
FCNC in top–photon couplings





- **Two processes** measured simultaneously:
  - Single-top + photon **production**
  - **Decay** of top quark via photon in pair production
  - Both probe FCNC $tu\gamma$ and $tc\gamma$ vertices – (one) top quark decays via SM vertex
- Event selection: high-p_T photon, lepton, MET > 30 GeV, ≥1 jet
- **Prompt photon backgrounds** controlled through:
  - CR $t\bar{t}\gamma$ (with ≥4 jets, b-tagging with ≥1b@70%, ≥2@77%)
  - CR $W\gamma + \mathrm{jets}$ (veto on b-tags (b@77%), Z veto for $m(e,\gamma)$)
- **Fake photons** ($e \to \gamma$ and $h \to \gamma$) estimated as

  in $tq\gamma$ analysis



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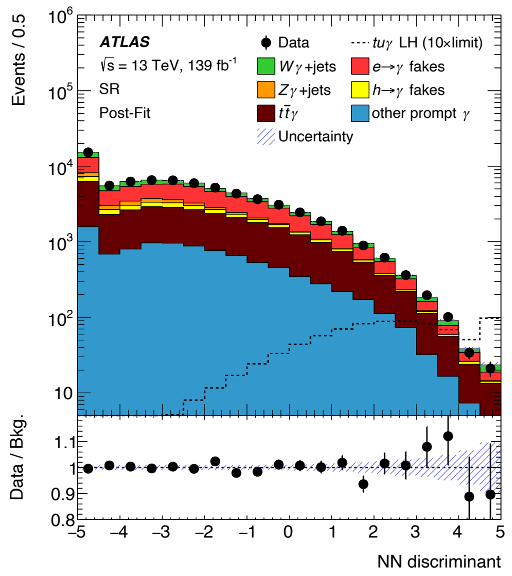
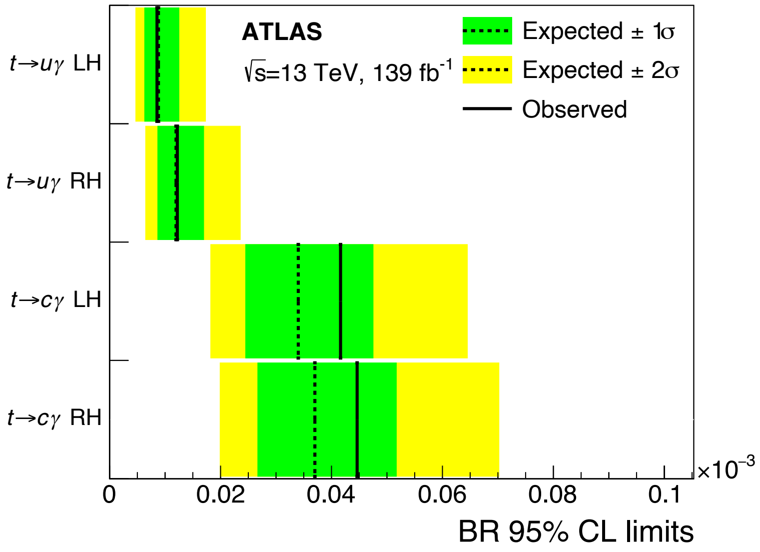


- **Multiclass NN** with output nodes for two signal types + background
  - Trained separately for $tu\gamma$ and $tc\gamma$ due to impact of different PDFs
  - Combine into single S vs. B discriminant with hyperparameter a

$$\mathcal{D} = \ln \frac{a \cdot y_{\text{prod}} + (1-a) \cdot y_{\text{dec}}}{y_{\text{bkg}}}$$

- **Agreement** between data and SM prediction within uncertainties
- **Limits on coupling parameters and BRs** calculated using CL_S method from 95% CL upper limit on the signal contribution
  - Dominant uncertainties: $tq\gamma$ theory cross-section, $h \to \gamma$ estimate ($tc\gamma$)

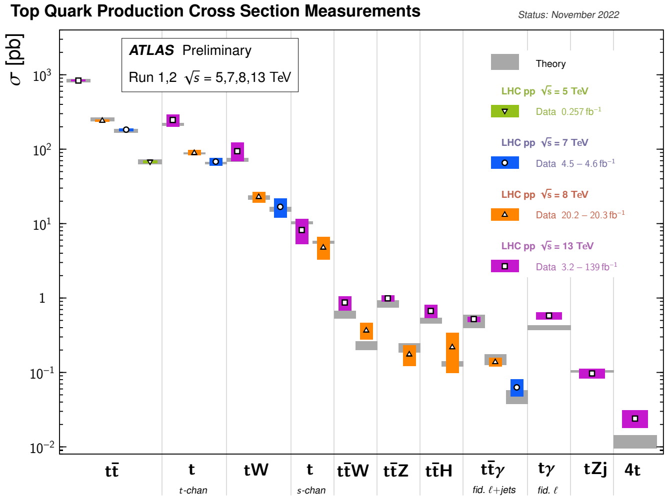


Conclusions

- LHC Run 2 has enabled **many exciting top-quark measurements!**
  - Expect further rapid improvements for statistically limited measurements in Run 3 and with the HL-LHC!
  - **Observation of $tq\gamma$ production** with high precision – this adds to the list of observed rare top-quark production modes
- Evidence for **charge asymmetry in $t\bar{t}$ pairs** seen by ATLAS
  - **Enhanced** in topologies with larger $q\bar{q}$-initiated production – for example $t\bar{t}\gamma$, $t\bar{t}W$
  - Measurements consistent with SM predictions – so far still **limited by statistics**
- **FCNC in top-quark production and decays** probed for various vertices
  - New ATLAS measurements for FCNC branching ratios $t \to qH$ and $t \to q\gamma$
  - Most stringent limits on these branching ratios observed by ATLAS to date

Full list of public ATLAS top physics results

ATL-PHYS-PUB-2022-051



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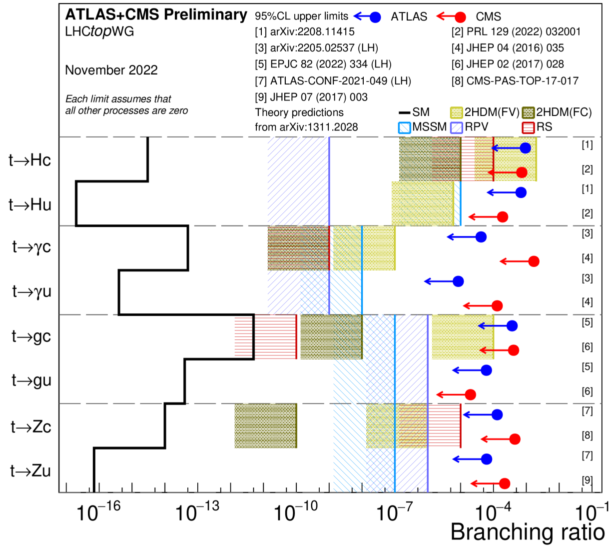

Backup

Backup – $tq\gamma$ observation

Left: parton level

Right: particle level

Uncertainty	$\Delta\sigma/\sigma$
$t\bar{t}\gamma$ modeling	±5.5%
Background MC statistics	±3.5%
$tq\gamma$ MC statistics	±3.3%
$t\bar{t}$ modeling	±2.4%
$tq\gamma$ modeling	±2.0%
$t\ (\rightarrow \ell\nu b\gamma)\ q$ modeling	±1.9%
Additional background uncertainties	±1.9%
$t\ (\rightarrow \ell\nu b\gamma)\ q$ MC statistics	±0.3%
$h \rightarrow \gamma$ photon fakes	±2.0%
Lepton fakes	±1.9%
$e \rightarrow \gamma$ photon fakes	±0.6%
Luminosity	±2.2%
Pileup	±1.2%
Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$	±3.6%
Photons	±2.5%
Leptons	±0.9%
b-tagging	±0.9%
Total systematic uncertainty	±10.6%

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Luminosity	±2.2%
Pileup	±1.3%
Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$	±3.5%
Photons	±2.5%
Leptons	±0.9%
b-tagging	±0.7%
Total systematic uncertainty	±10.7%

Submitted to Phys. Rev. Lett. (Feb 2023)
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Backup – $tq\gamma$ observation

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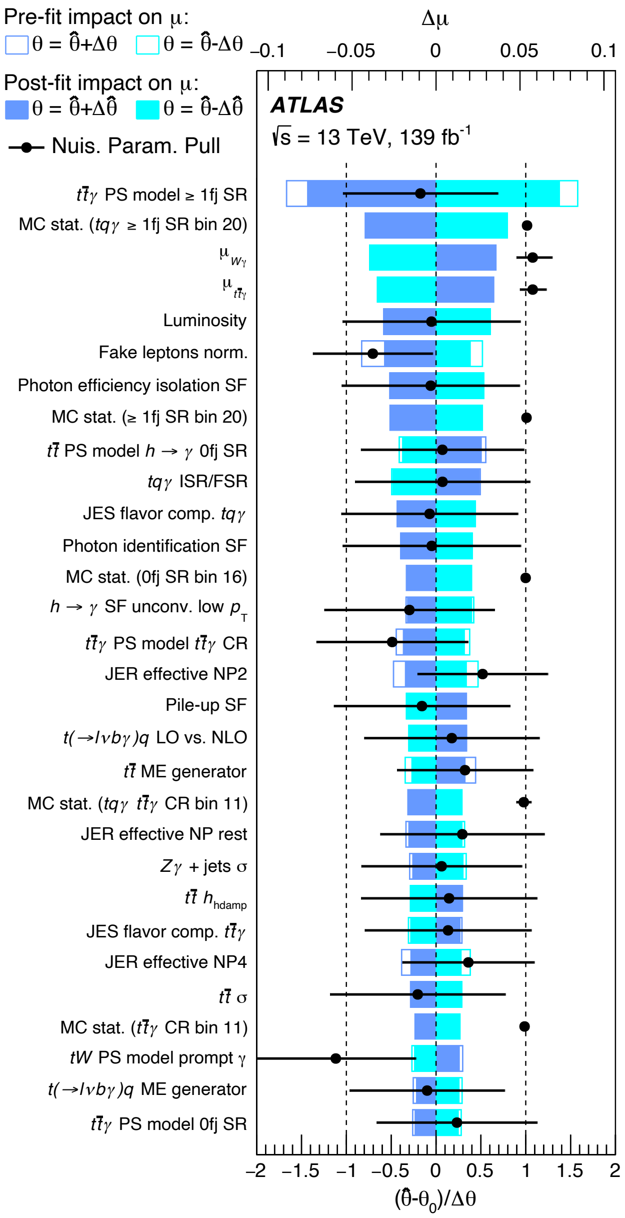
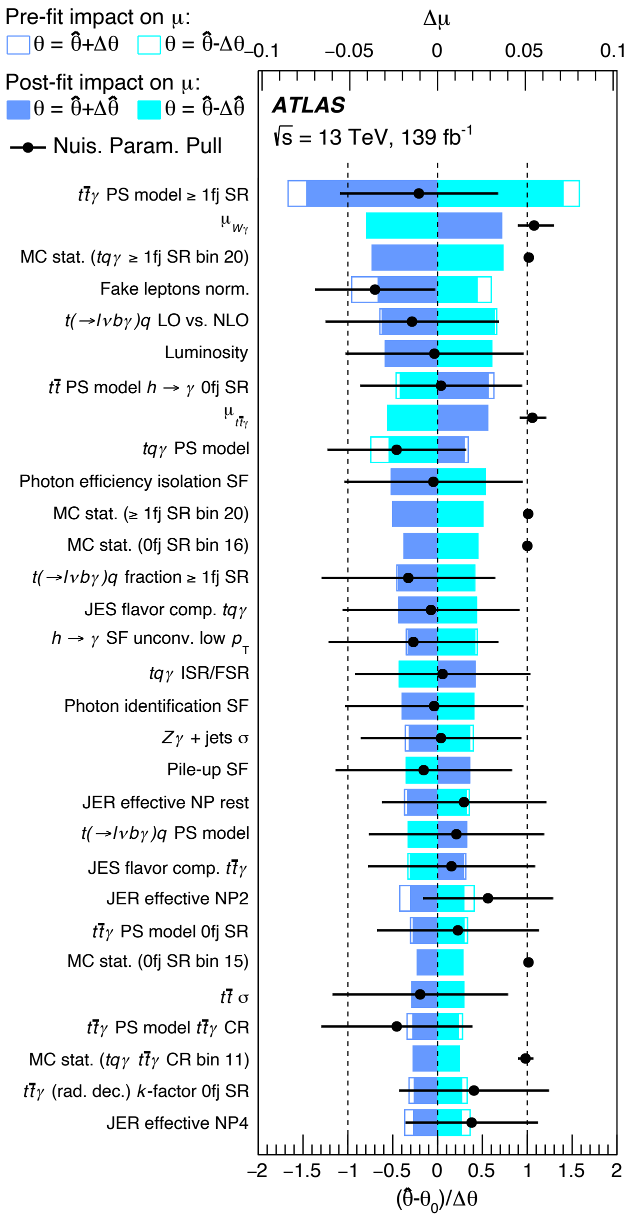
Right: particle level





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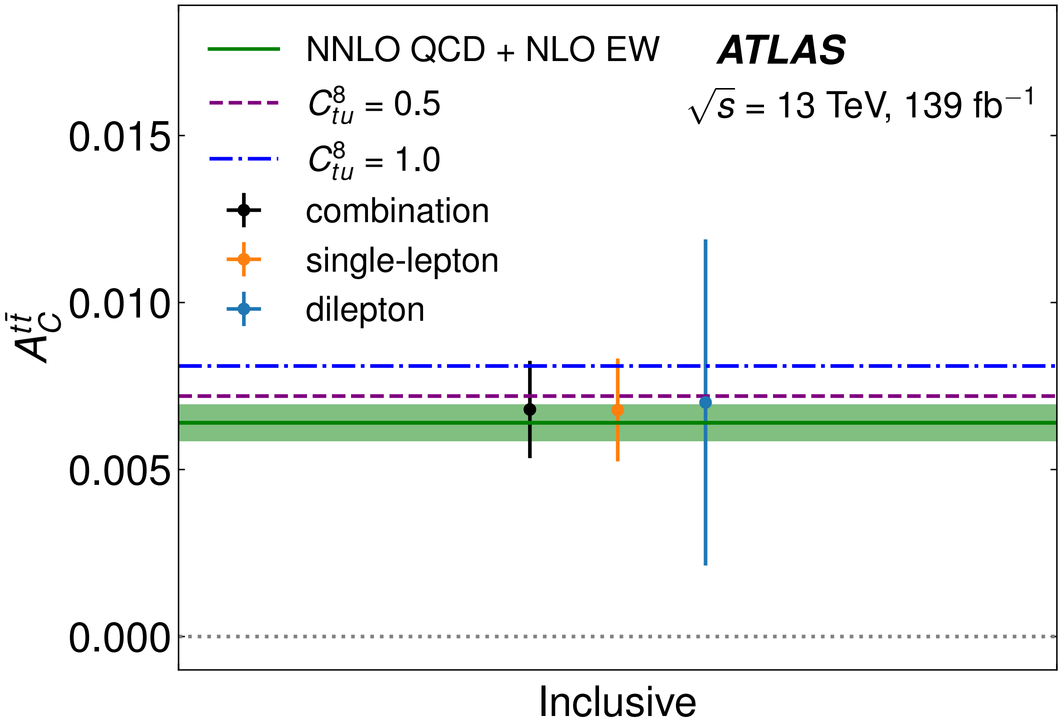

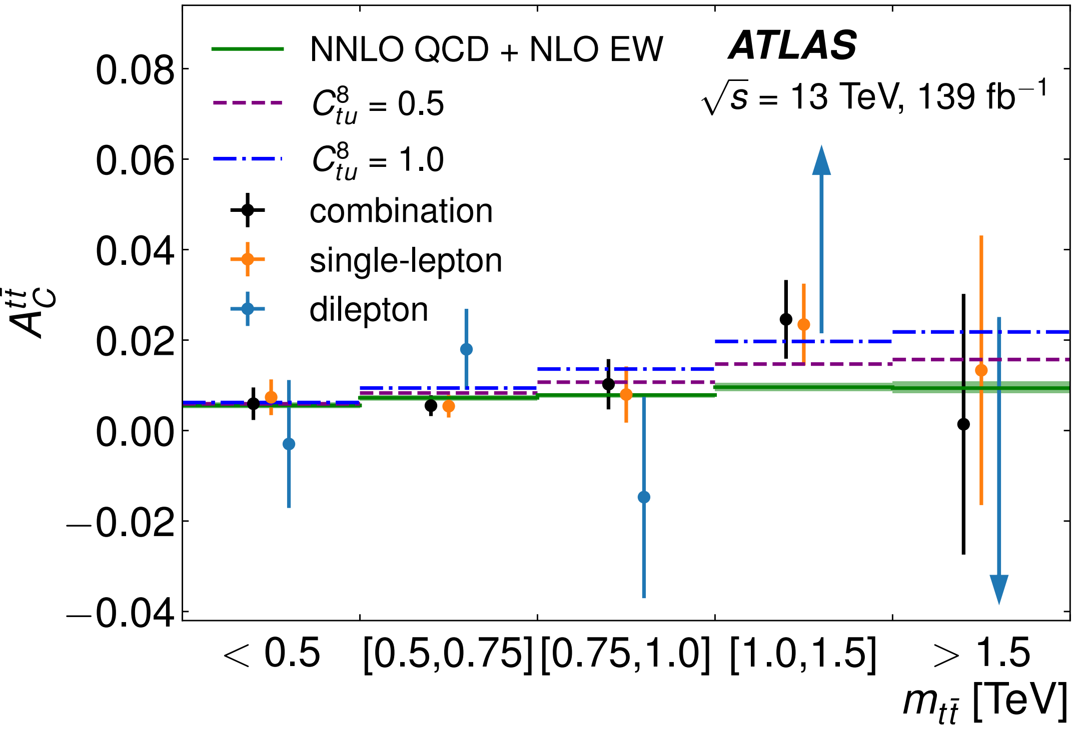

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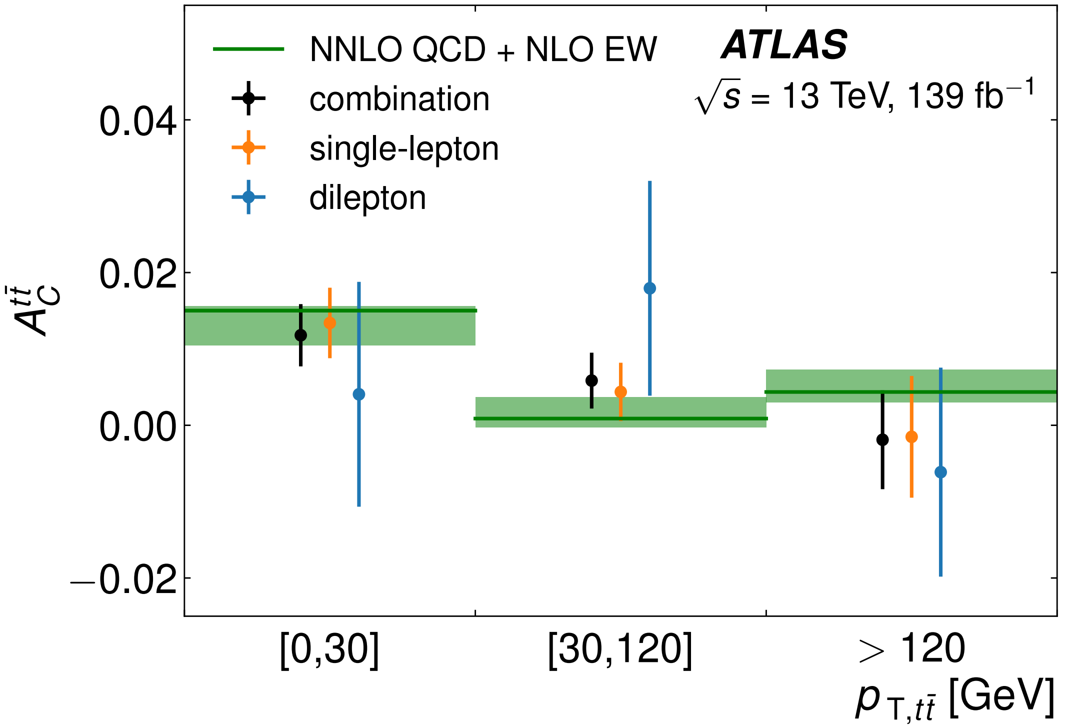

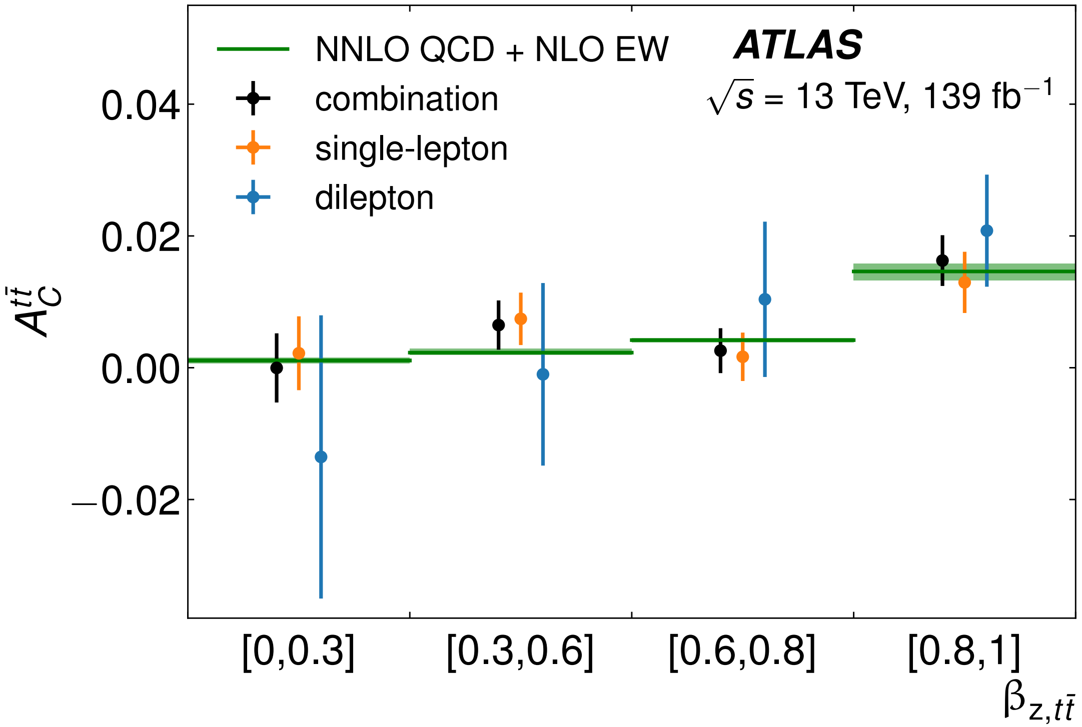

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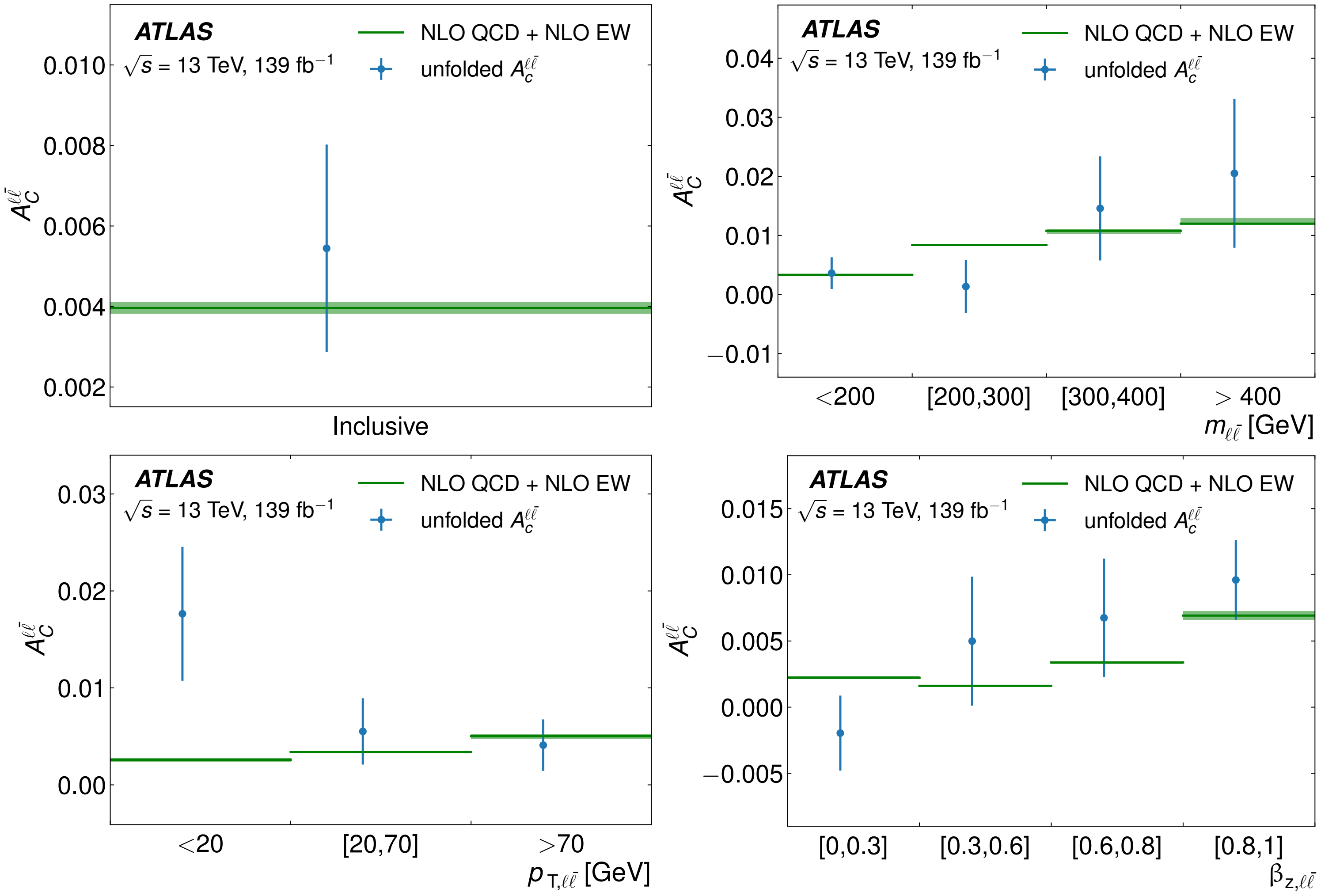

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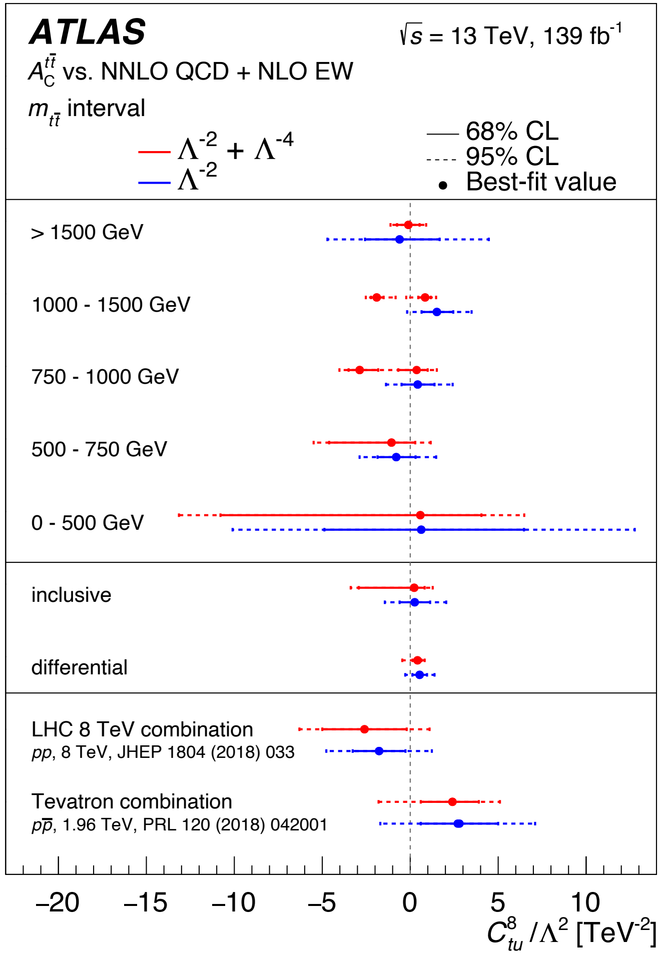
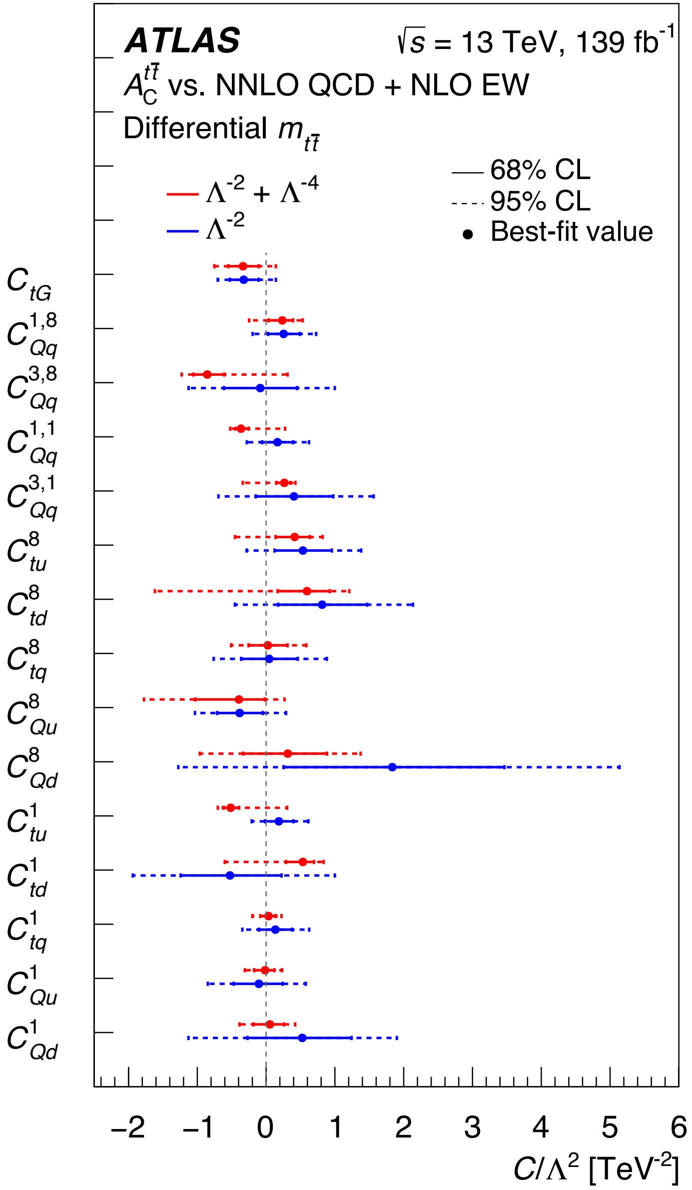
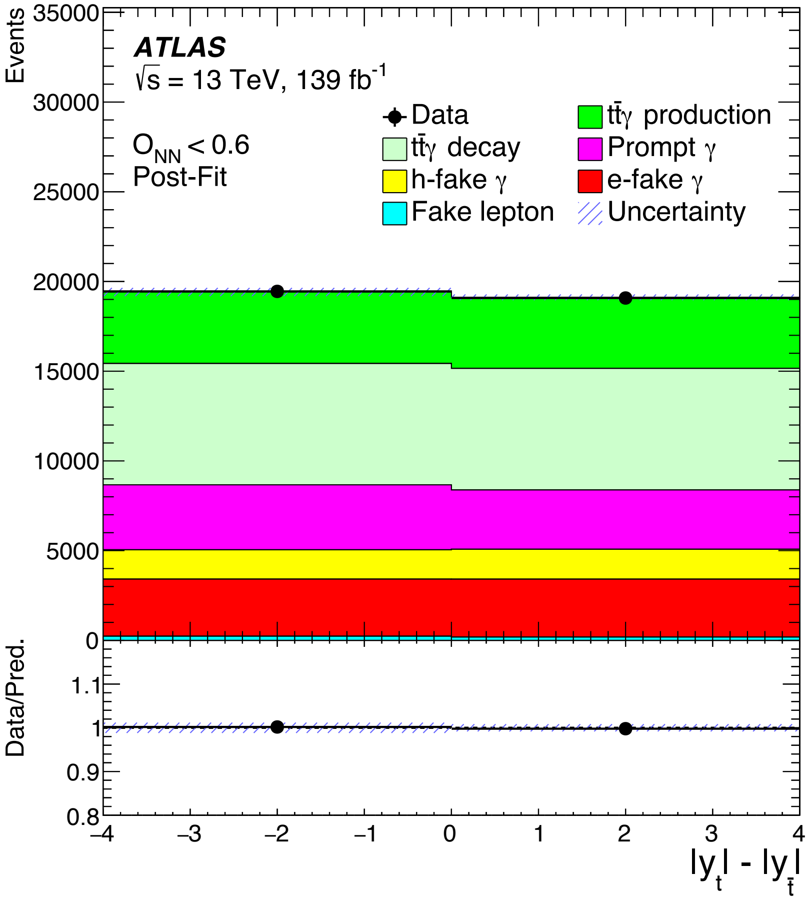
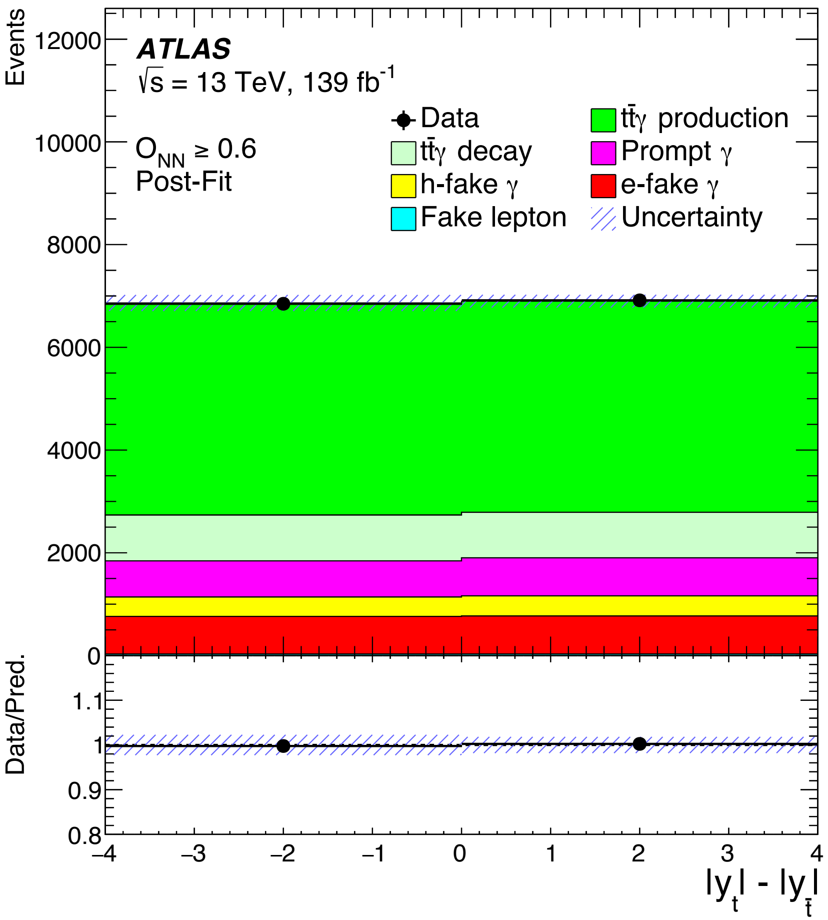




Submitted to Phys. Lett. B (Dec 2022)
[arXiv:2212.10552]

Backup – $t\bar{t}\gamma$ charge asymmetry





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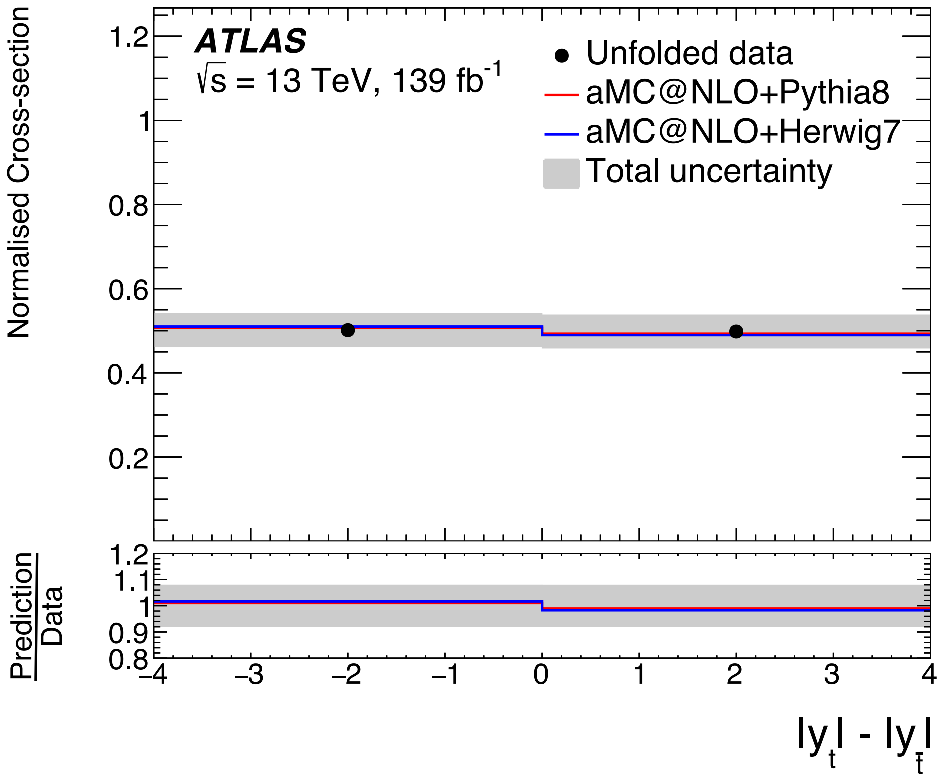
Backup – $t\bar{t}\gamma$ charge asymmetry

Total uncertainty	0.029
Statistical uncertainty	0.024
MC statistical uncertainties	
Background processes	0.008
$t\bar{t}\gamma$ production	0.004
Modelling uncertainties	
$t\bar{t}\gamma$ production modelling	0.003
Background modelling	0.002
Prompt background normalisation	0.002
Experimental uncertainties	
Jet	0.009
Fake-lepton background estimate	0.005
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.005
Fake-photon background estimates	0.003
Photon	0.001
b-tagging	0.001
Other experimental	0.004



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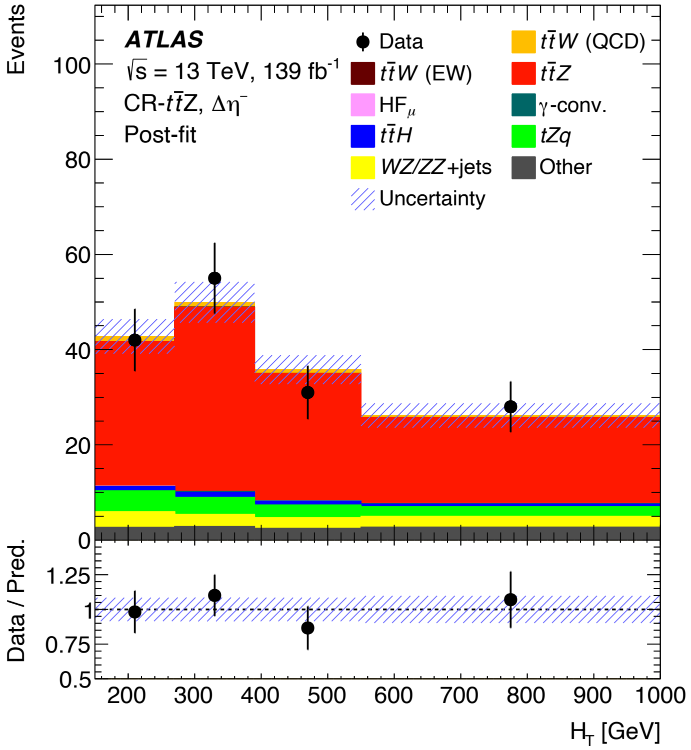
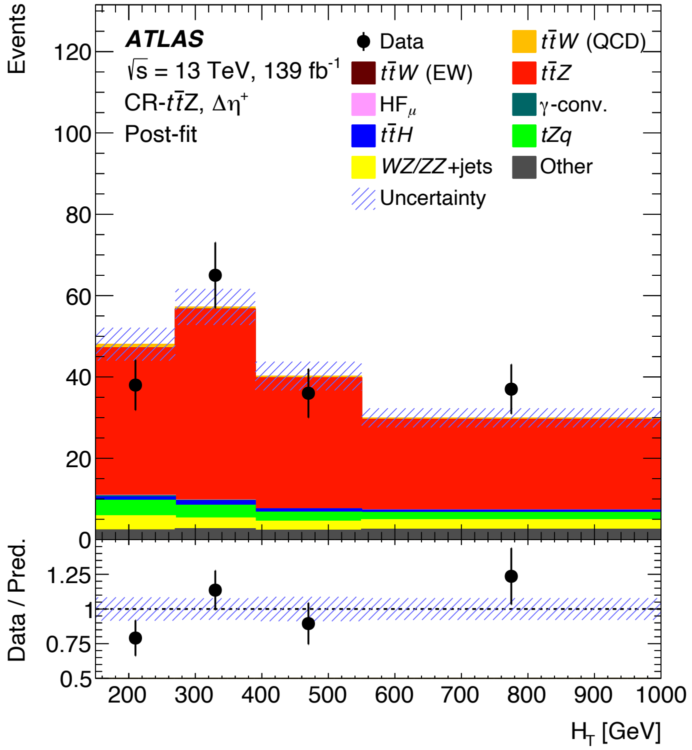
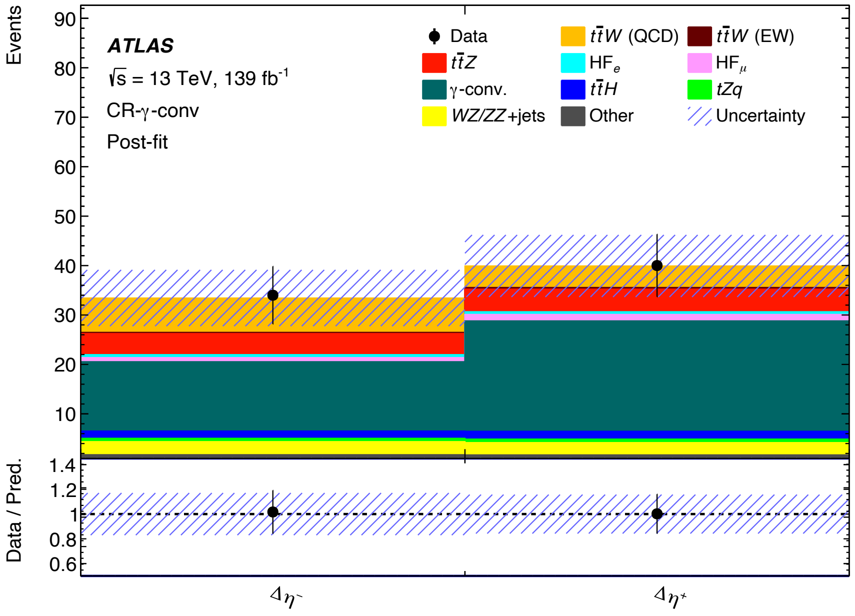
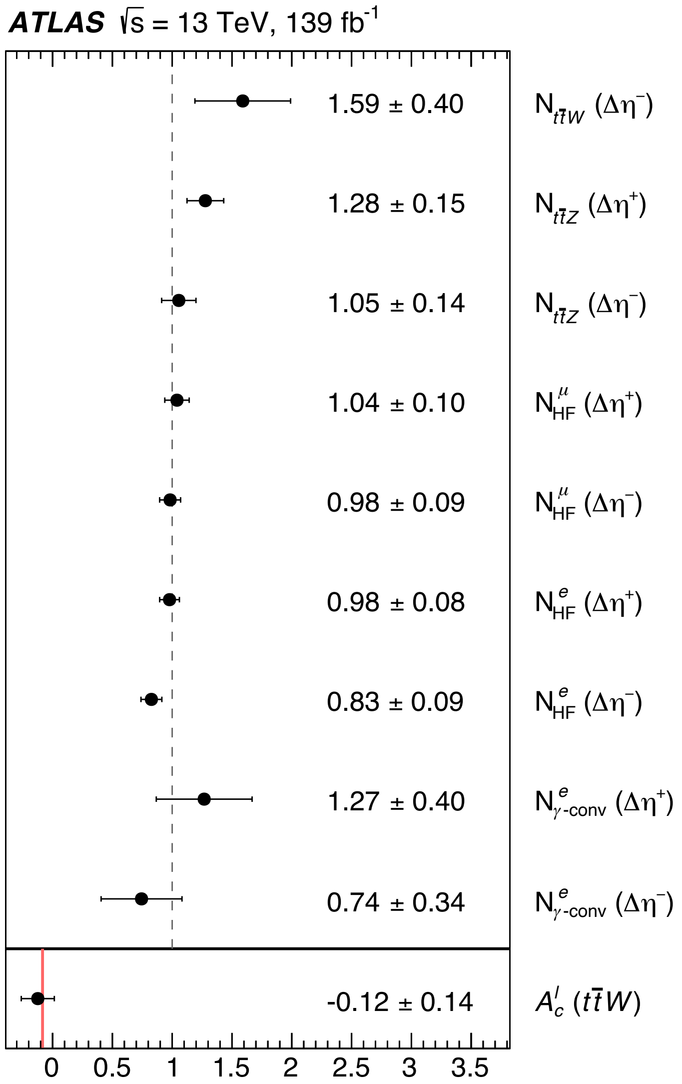
Backup – $t\bar{t}W$ charge asymmetry







Backup – $t\bar{t}W$ charge asymmetry



Submitted to JHEP (Jan 2023)
[arXiv:2301.04245]

Submitted to JHEP (Jan 2023)
[arXiv:2301.04245]

Backup – $t\bar{t}W$ charge asymmetry

Left: reconstr. level

Right: particle level

	$\Delta A_c^{\ell}(t\bar{t}W)$
Experimental uncertainties	
Jet energy resolution	0.013
Pile-up	0.007
b-tagging	0.005
Leptons	0.004
E_T^{miss}	0.004
Jet energy scale	0.003
Luminosity	0.001
MC modelling uncertainties	
$t\bar{t}W$ modelling	0.013
$t\bar{t}Z$ modelling	0.010
$HF_{e/\mu}$ modelling	0.006
$t\bar{t}H$ modelling	0.005
Other uncertainties	
$\Delta\eta^{\pm}$ CR-dependency	0.046
MC statistical uncertainty	0.019
Data statistical uncertainty	0.136
Total uncertainty	0.145

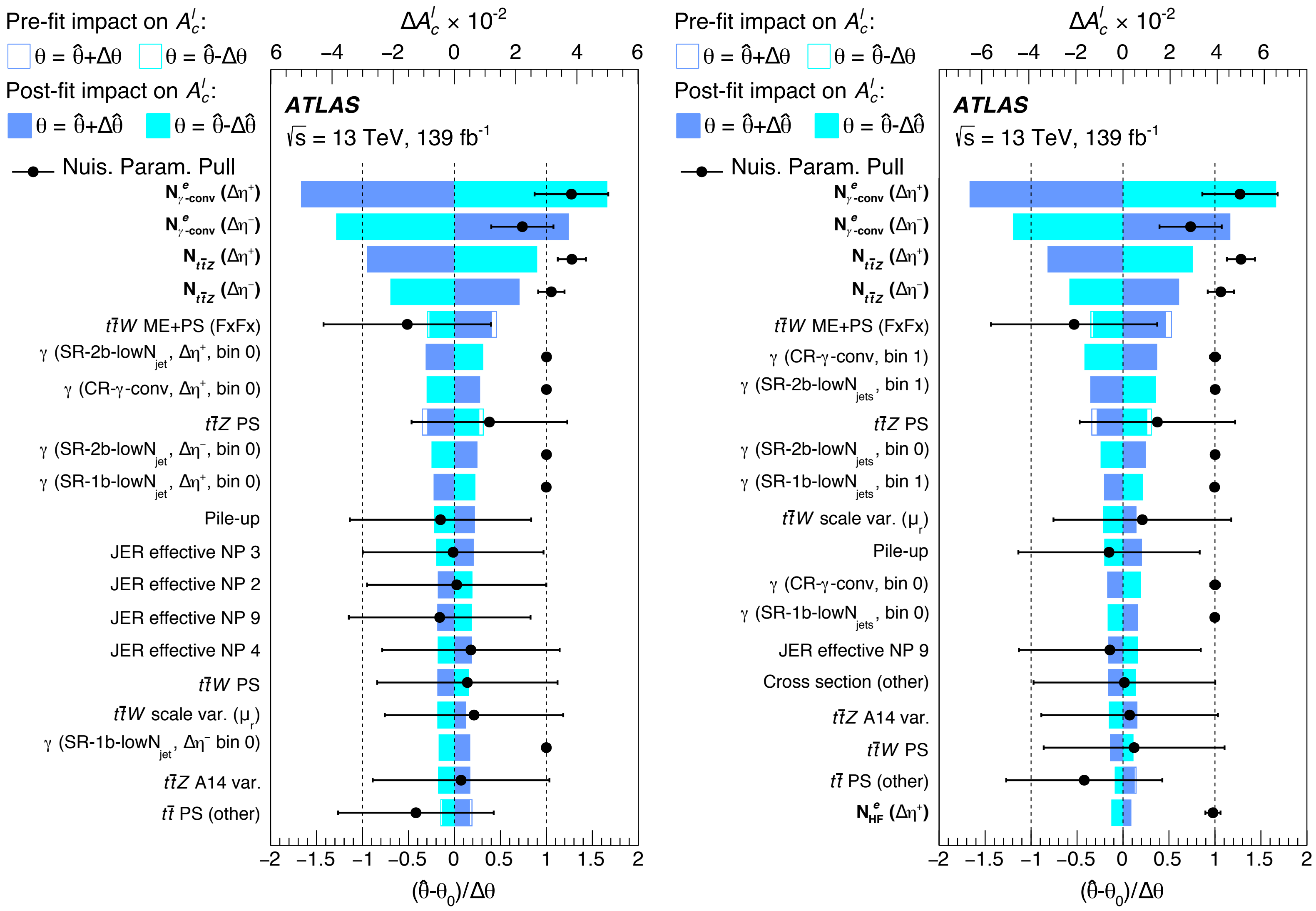
	$\Delta A_c^{\ell}(t\bar{t}W)^{PL}$
Experimental uncertainties	
Leptons	0.014
Jet energy resolution	0.011
Pile-up	0.008
Jet energy scale	0.004
E_T^{miss}	0.002
Luminosity	0.001
Jet vertex tagger	0.001
MC modelling uncertainties	
$t\bar{t}W$ modelling	0.022
$t\bar{t}Z$ modelling	0.017
$HF_{e/\mu}$ modelling	0.015
Others modelling	0.015
$WZ/ZZ+$jets modelling	0.014
$t\bar{t}H$ modelling	0.006
Other uncertainties	
Unfolding bias	0.004
$\Delta\eta^{\pm}$ CR-dependency	0.039
MC statistical uncertainty	0.027
Response matrix	0.009
Data statistical uncertainty	0.170
Total uncertainty	0.179

Backup – $t\bar{t}W$ charge asymmetry

Submitted to JHEP (Jan 2023)
[arXiv:2301.04245]

Left: reconstr. level

Right: particle level



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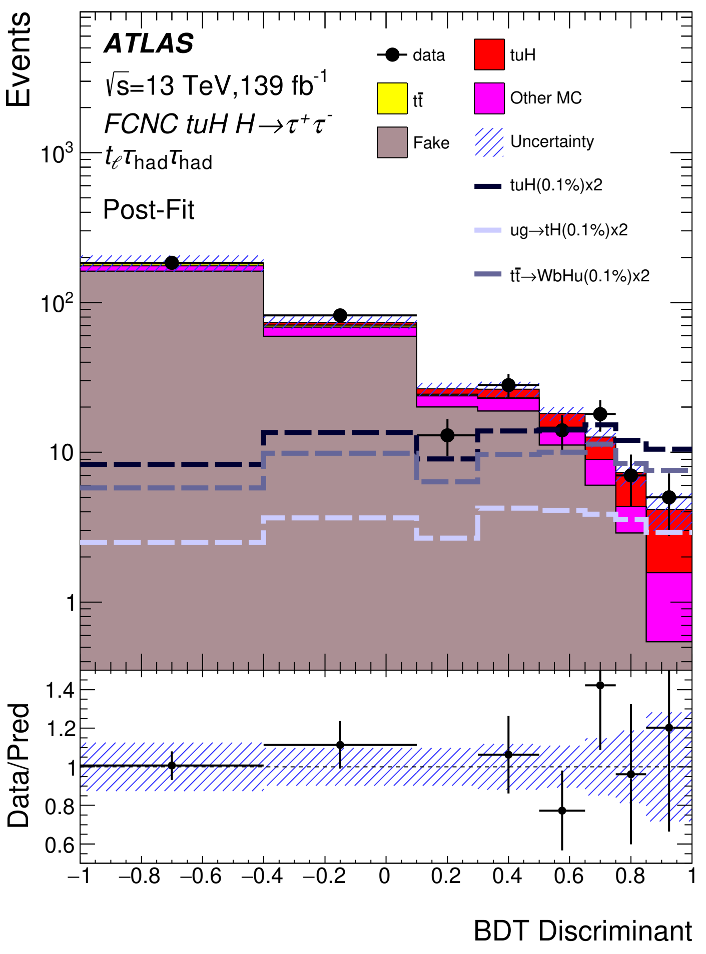
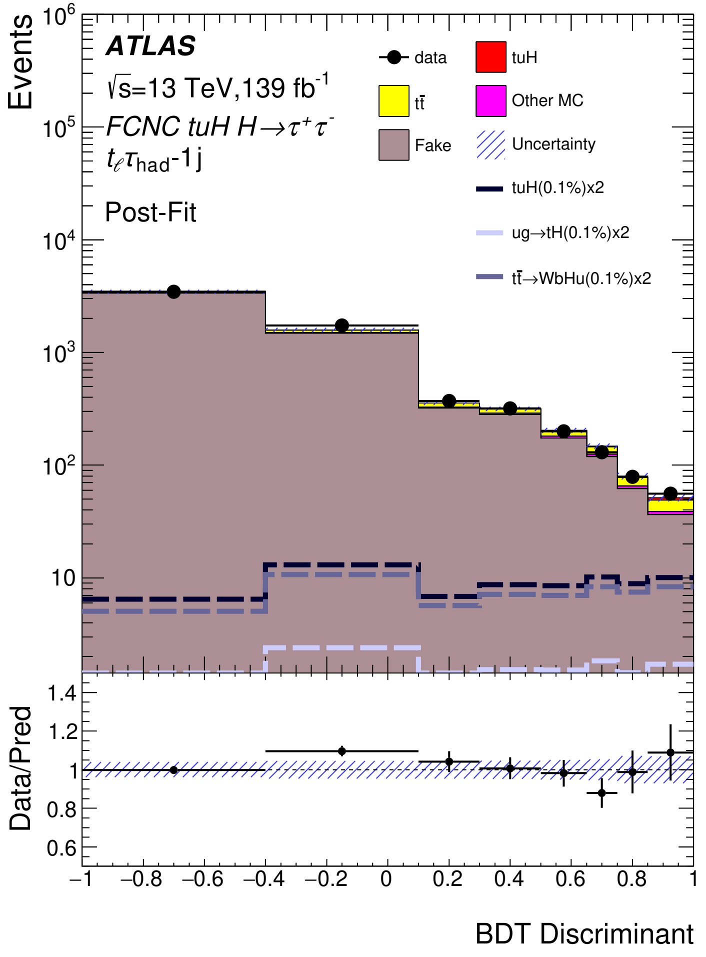
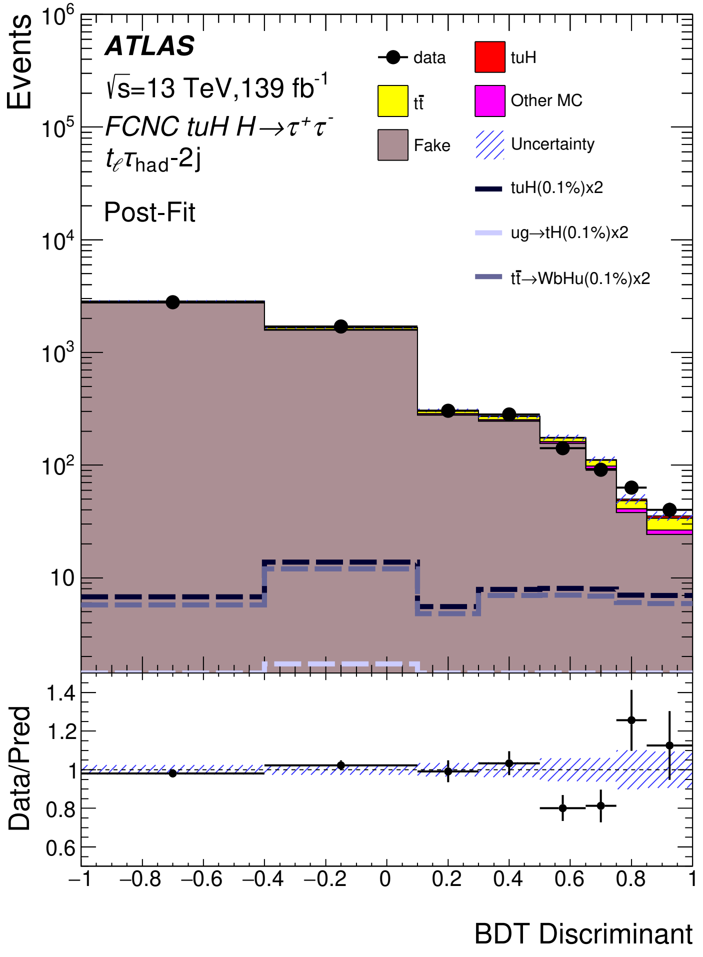
Backup – FCNC $tH(\tau\tau)$

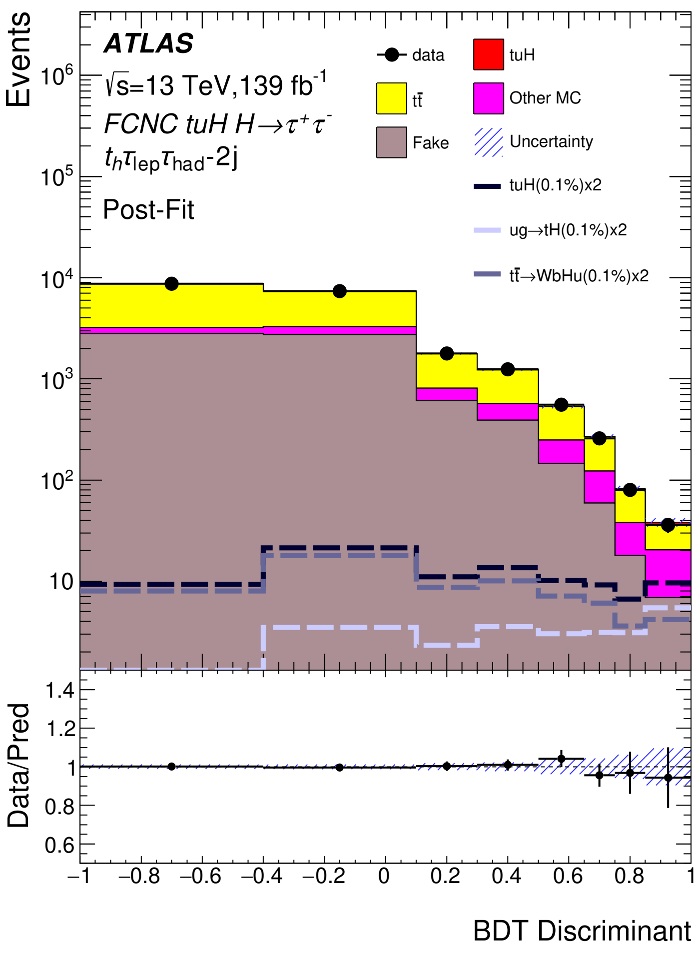


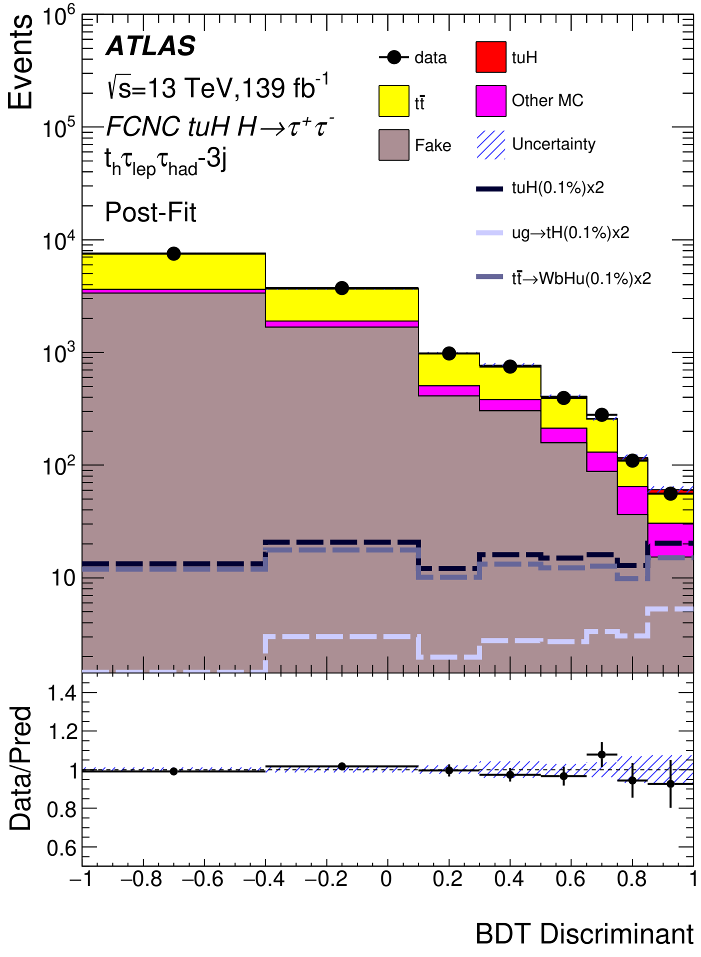


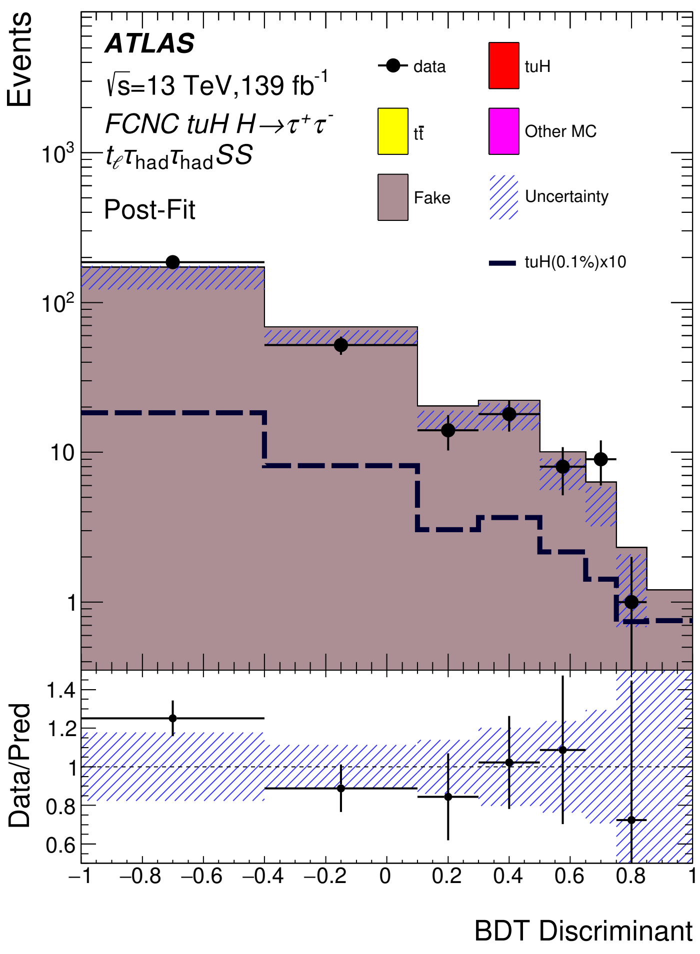


Submitted to JHEP (Aug 2022)
[arXiv:2208.11415]

Backup – FCNC $tH(\tau\tau)$







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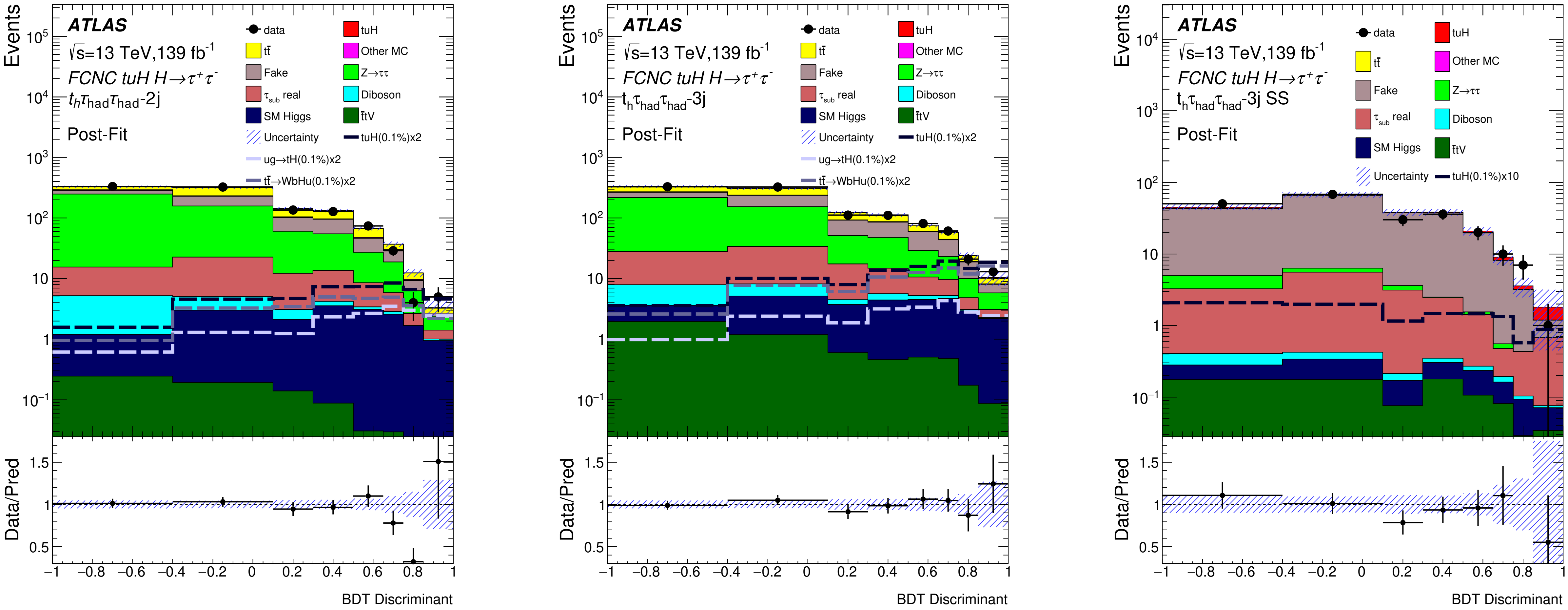
Backup – FCNC $tH(\tau\tau)$



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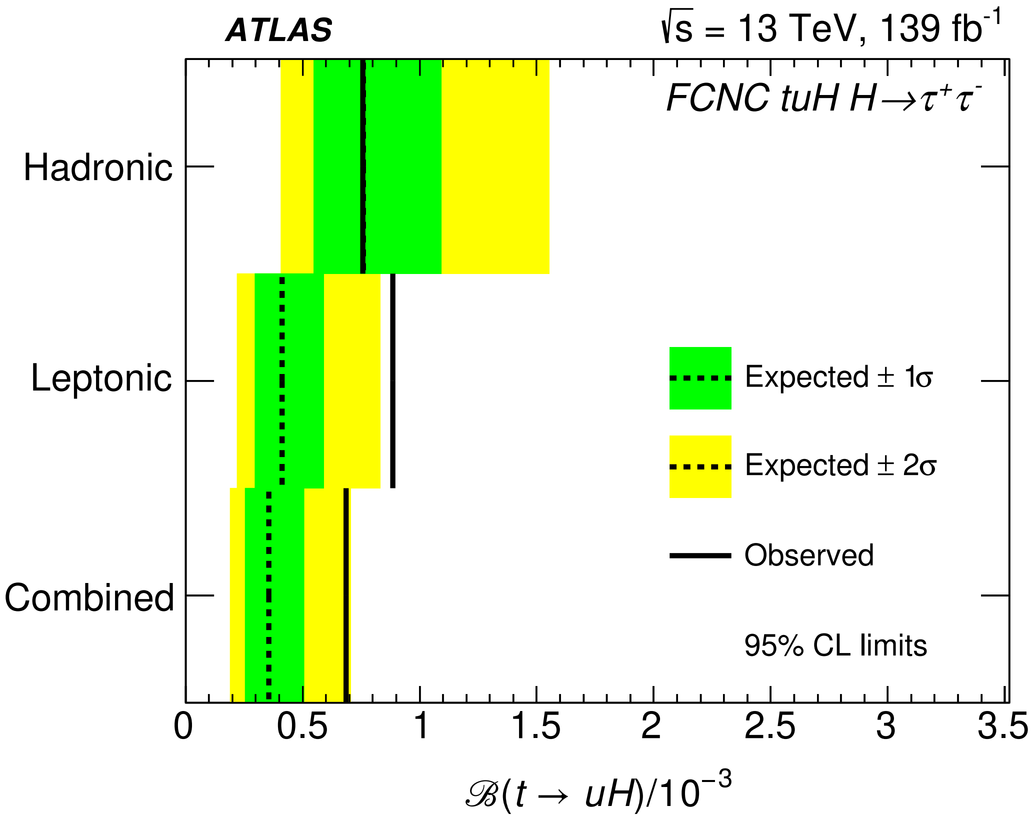
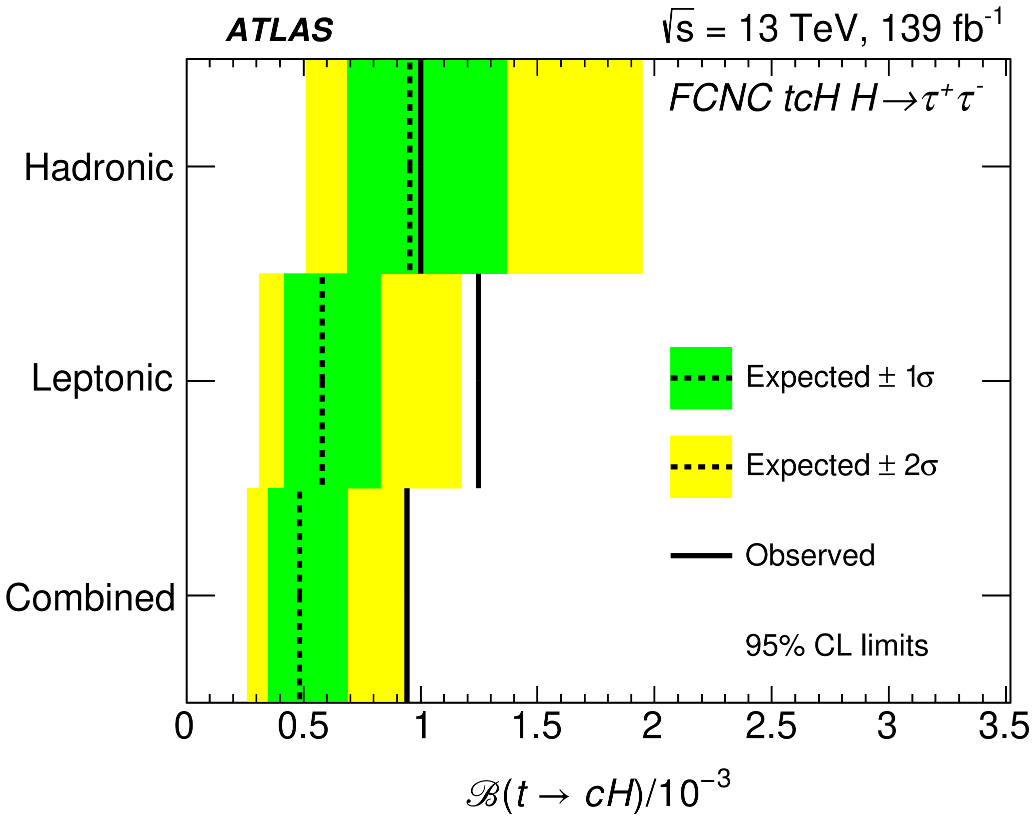
Backup – FCNC $tH(\tau\tau)$





Backup – FCNC $tH(\tau\tau)$

- Analysis regions:
  - $t_h \tau_{lep} \tau_{had}$ – (opposite charge) τ-lepton pair plus ≥ 3 jets with exactly 1 b-jet
  - $t_l \tau_{had} \tau_{had}$ – (opposite charge) τ-lepton pair plus exactly 1 lepton, ≥1 jets, exactly 1 b-jet
  - $t_l \tau_{had}$ – for events with failed τ_{had} reconstruction. Same-sign lepton–τ_{had} pair plus ≥2 jets, exactly 1 b-jet
  - $t_h \tau_{had} \tau_{had}$ – uses di-τ-lepton trigger. Plus ≥ 3 jets, exactly 1 b-jet

Submitted to JHEP (Aug 2022)
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Backup – FCNC $tH(\tau\tau)$

Regions		b-jets	Light-flavour jets	Leptons	Hadronic τ decays	Charge
SR	$t_\ell\tau_{\rm had}\tau_{\rm had}$	1	≥ 0	1	2	$\tau_{\rm had}\tau_{\rm had}$ OS
	$t_\ell\tau_{\rm had}$-1j	1	1	1	1	$t_\ell\tau_{\rm had}$ SS
	$t_\ell\tau_{\rm had}$-2j	1	2	1	1	$t_\ell\tau_{\rm had}$ SS
	$t_h\tau_{\rm lep}\tau_{\rm had}$-2j	1	2	1	1	$\tau_{\rm lep}\tau_{\rm had}$ OS
	$t_h\tau_{\rm lep}\tau_{\rm had}$-3j	1	≥ 3	1	1	$\tau_{\rm lep}\tau_{\rm had}$ OS
	$t_h\tau_{\rm had}\tau_{\rm had}$-2j	1	2	0	2	$\tau_{\rm had}\tau_{\rm had}$ OS
	$t_h\tau_{\rm had}\tau_{\rm had}$-3j	1	≥ 3	0	2	$\tau_{\rm had}\tau_{\rm had}$ OS
VR	$t_\ell\tau_{\rm had}\tau_{\rm had}$-SS	1	≥ 0	1	2	$\tau_{\rm had}\tau_{\rm had}$ SS
	$t_h\tau_{\rm had}\tau_{\rm had}$-3j SS	1	≥ 3	0	2	$\tau_{\rm had}\tau_{\rm had}$ SS
CRtt	$t_\ell t_\ell 1b\tau_{\rm had}$	1	≥ 0	2	1	$t_\ell t_\ell$ OS
	$t_\ell t_\ell 2b\tau_{\rm had}$	2	≥ 0	2	1	$t_\ell t_\ell$ OS
	$t_\ell t_h 2b\tau_{\rm had}$-2jSS	2	2	1	1	$t_\ell\tau_{\rm had}$ SS
	$t_\ell t_h 2b\tau_{\rm had}$-2jOS	2	2	1	1	$t_\ell\tau_{\rm had}$ OS
	$t_\ell t_h 2b\tau_{\rm had}$-3jSS	2	≥ 3	1	1	$t_\ell\tau_{\rm had}$ SS
	$t_\ell t_h 2b\tau_{\rm had}$-3jOS	2	≥ 3	1	1	$t_\ell\tau_{\rm had}$ OS

Submitted to JHEP (Aug 2022)
[arXiv:2208.11415]

Backup – FCNC $tH(\tau\tau)$

Source of uncertainty	$\Delta\mathcal{B}$ [10^{-5}] $t \to uH$	$\Delta\mathcal{B}$ [10^{-5}] $t \to cH$
Lepton ID	0.6	0.8
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.7	0.7
Fake lepton modeling	1.2	1.7
JES and JER	2.5	3.3
Flavour tagging	2.7	3.7
$t\bar{t}$ modeling	2.6	3.9
Other MC modeling	2.1	3.0
Fake τ modeling	3.3	4.7
Signal modeling including Br($H \to \tau\tau$)	1.8	1.5
τ ID	3.3	4.4
Luminosity and Pileup	1.7	2.4
MC statistics	5.1	7.1
Total systematic uncertainty	10.1	14.1
Data statistical uncertainty	14.9	19.4
Total uncertainties	18	24

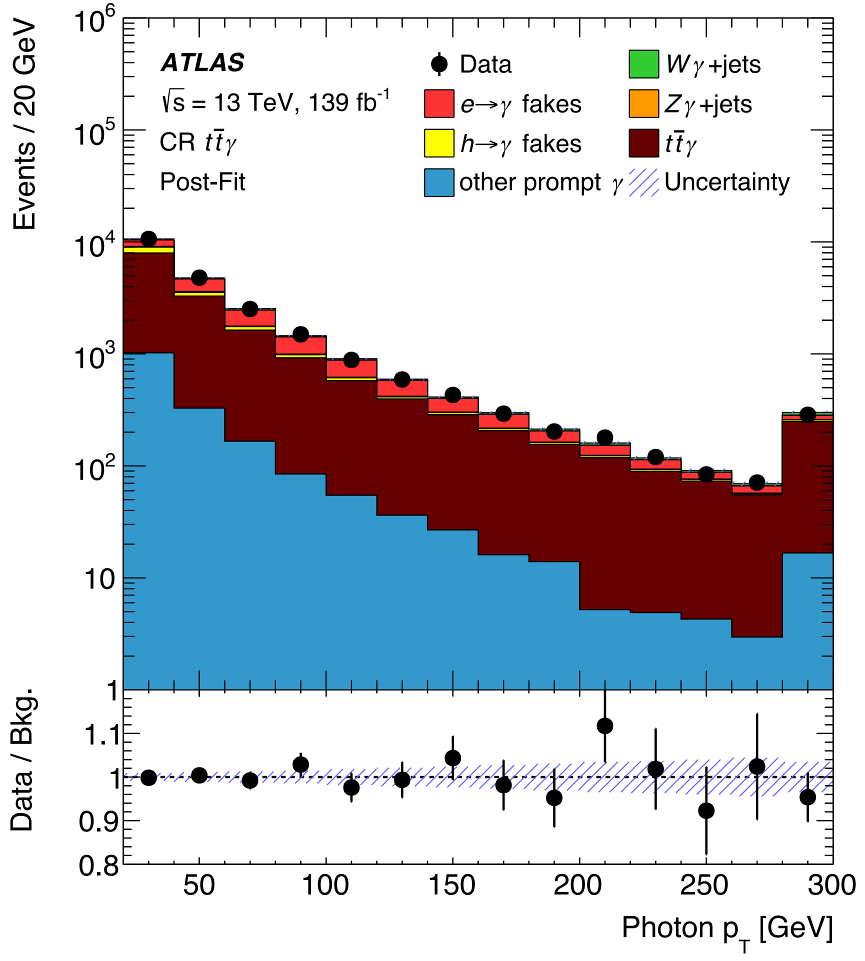
Submitted to JHEP (Aug 2022)
[arXiv:2208.11415]

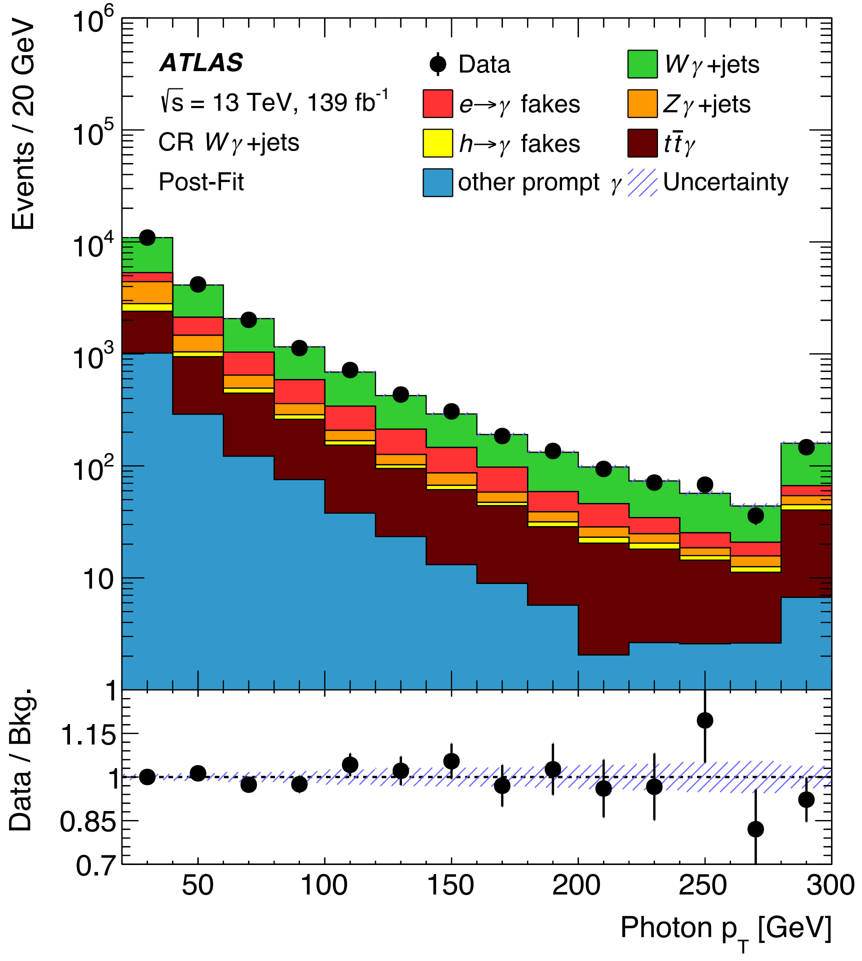
Backup – FCNC $tH(\tau\tau)$

Table 1: Summary of 95% CL upper limits on $\mathcal{B}(t \to cH)$ and $\mathcal{B}(t \to uH)$, significance and best-fit branching ratio in the signal regions with a benchmark branching ratio of $\mathcal{B}(t \to qH) = 0.1\%$. The expected significance is obtained from an Asimov fit with a signal injection corresponding to a branching ratio of 0.1%.

Signal Region	$t \to cH$ 95% CL upper limit [10^{-3}] Observed (Expected)	$t \to cH$ Significance	$t \to cH$ $\mathcal{B}$ [10^{-3}]	$t \to uH$ 95% CL upper limit [10^{-3}] Observed (Expected)	$t \to uH$ Significance	$t \to uH$ $\mathcal{B}$ [10^{-3}]
$t_h\tau_{\text{had}}\tau_{\text{had}}$-2j	$1.80\,(2.72^{+1.18}_{-0.76})$	$-0.96\,(0.78)$	$-1.03^{+1.03}_{-1.03}$	$1.07\,(1.60^{+0.71}_{-0.45})$	$-0.90\,(1.31)$	$-0.55^{+0.58}_{-0.58}$
$t_h\tau_{\text{had}}\tau_{\text{had}}$-3j	$1.14\,(1.02^{+0.45}_{-0.29})$	$0.34\,(1.87)$	$0.16^{+0.47}_{-0.47}$	$0.97\,(0.86^{+0.38}_{-0.24})$	$0.36\,(2.25)$	$0.14^{+0.40}_{-0.40}$
Hadronic combination	$1.00\,(0.95^{+0.42}_{-0.27})$	$0.26\,(1.99)$	$0.11^{+0.43}_{-0.43}$	$0.76\,(0.76^{+0.33}_{-0.21})$	$0.12\,(2.52)$	$0.04^{+0.34}_{-0.34}$
$t_\ell\tau_{\text{had}}$-2j	$4.77\,(4.23^{+1.72}_{-1.18})$	$0.41\,(0.47)$	$0.85^{+2.06}_{-2.06}$	$3.84\,(3.48^{+1.42}_{-0.97})$	$0.36\,(0.58)$	$0.61^{+1.68}_{-1.68}$
$t_\ell\tau_{\text{had}}$-1j	$3.80\,(3.56^{+1.51}_{-0.99})$	$0.22\,(0.58)$	$0.36^{+1.70}_{-1.70}$	$2.98\,(2.78^{+1.17}_{-0.78})$	$0.22\,(0.73)$	$0.29^{+1.33}_{-1.33}$
$t_h\tau_{\text{lep}}\tau_{\text{had}}$-2j	$4.71\,(5.71^{+2.68}_{-1.60})$	$-0.52\,(0.38)$	$-1.36^{+2.56}_{-2.56}$	$2.50\,(2.97^{+1.25}_{-0.83})$	$-0.47\,(0.70)$	$-0.66^{+1.38}_{-1.38}$
$t_h\tau_{\text{lep}}\tau_{\text{had}}$-3j	$2.71\,(2.71^{+1.25}_{-0.76})$	$-0.03\,(0.77)$	$-0.03^{+1.26}_{-1.26}$	$2.02\,(2.03^{+0.86}_{-0.57})$	$-0.05\,(0.99)$	$-0.03^{+0.98}_{-0.98}$
$t_\ell\tau_{\text{had}}\tau_{\text{had}}$	$1.35\,(0.61^{+0.27}_{-0.17})$	$2.64\,(3.31)$	$0.74^{+0.33}_{-0.33}$	$0.97\,(0.44^{+0.19}_{-0.12})$	$2.64\,(4.38)$	$0.53^{+0.24}_{-0.24}$
Leptonic combination	$1.25\,(0.58^{+0.25}_{-0.16})$	$2.61\,(3.46)$	$0.69^{+0.31}_{-0.31}$	$0.88\,(0.41^{+0.18}_{-0.11})$	$2.60\,(4.62)$	$0.49^{+0.22}_{-0.22}$
Combination	$0.94\,(0.48^{+0.20}_{-0.14})$	$2.34\,(4.02)$	$0.51^{+0.24}_{-0.24}$	$0.69\,(0.35^{+0.15}_{-0.10})$	$2.31\,(5.18)$	$0.37^{+0.18}_{-0.18}$

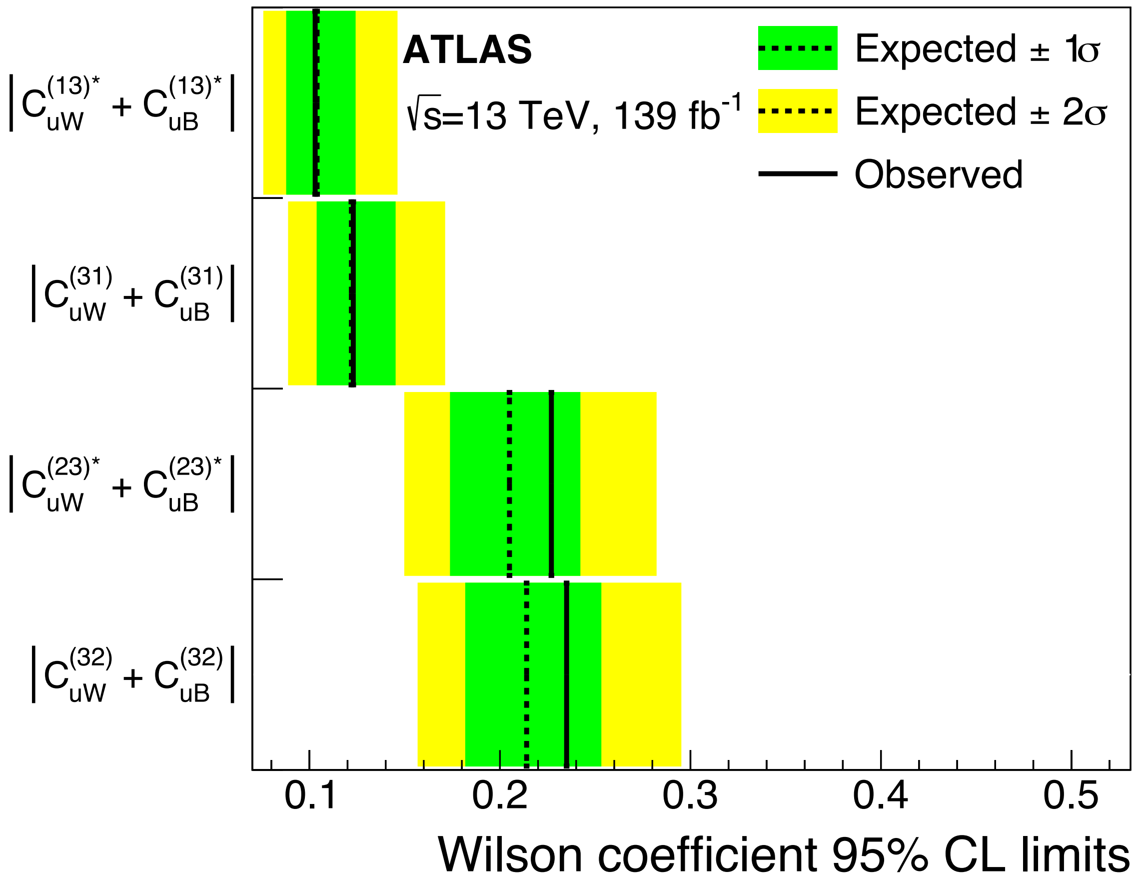
Backup – FCNC top–photon





Submitted to Phys. Lett. B (May 2022)
[arXiv:2205.02537]

Backup – FCNC top–photon



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Backup – FCNC top–photon

Effective coupling	Coefficient limits		Coupling	BR limits $[10^{-5}]$	
	Expected	Observed		Expected	Observed
$\lvert C_{uW}^{(13)*} + C_{uB}^{(13)*}\rvert$	$0.104^{+0.020}_{-0.016}$	0.103	$t \to u\gamma$ LH	$0.88^{+0.37}_{-0.25}$	0.85
$\lvert C_{uW}^{(31)} + C_{uB}^{(31)}\rvert$	$0.122^{+0.023}_{-0.018}$	0.123	$t \to u\gamma$ RH	$1.20^{+0.50}_{-0.33}$	1.22
$\lvert C_{uW}^{(23)*} + C_{uB}^{(23)*}\rvert$	$0.205^{+0.037}_{-0.031}$	0.227	$t \to c\gamma$ LH	$3.40^{+1.35}_{-0.95}$	4.16
$\lvert C_{uW}^{(32)} + C_{uB}^{(32)}\rvert$	$0.214^{+0.039}_{-0.032}$	0.235	$t \to c\gamma$ RH	$3.70^{+1.47}_{-1.03}$	4.46

Backup – FCNC top–photon

Submitted to Phys. Lett. B (May 2022)
[arXiv:2205.02537]