LA THUILE 2024

ttX and tX

Peter Berta

Charles University

(on behalf of the ATLAS and CMS Collaborations)

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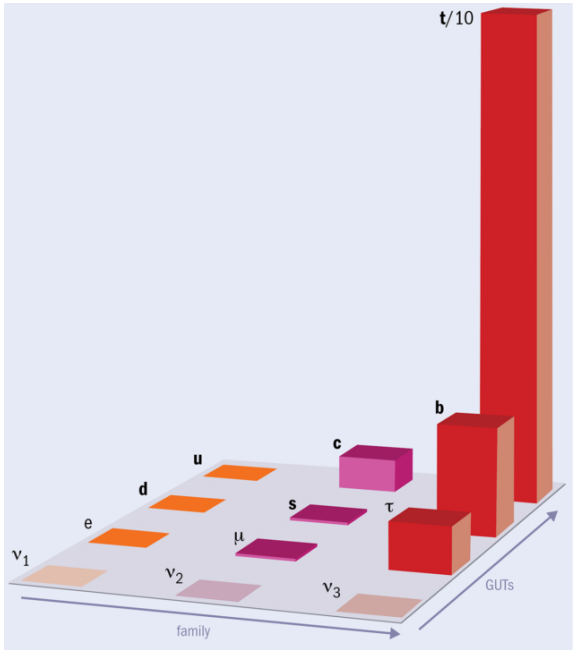
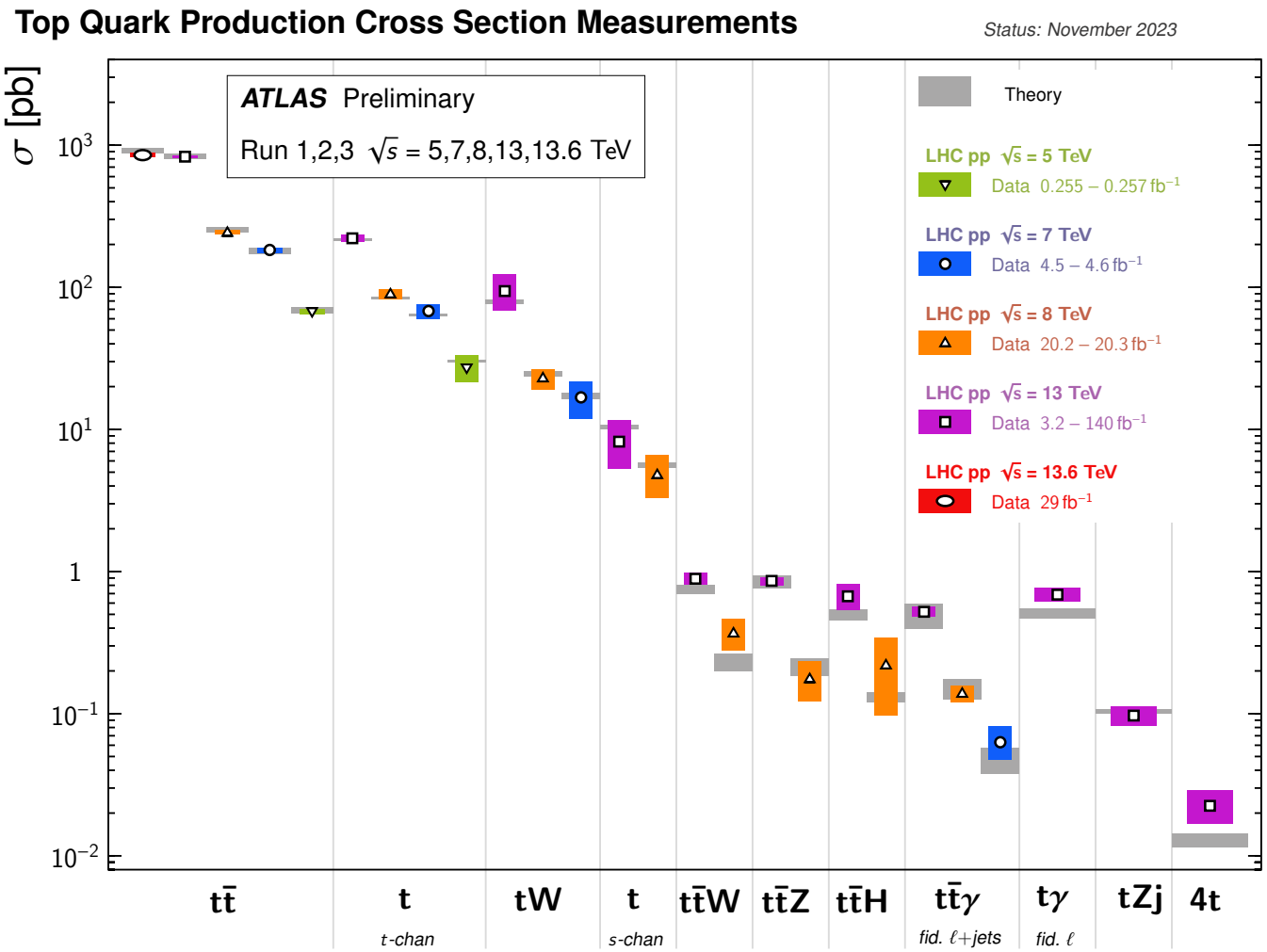
Top quark is special

- The heaviest known elementary particle
  - largest Yukawa coupling $y_t \approx 1$
  - unique properties from experimental and theoretical side
- Very short lifetime
  - the only quark which does not hadronize
  - properties studied via its decay products
- The main ingredient of many BSM scenarios



CERN Courier

Top quark production



ATL-PHYS-PUB-2023-038

- $t\bar{t}$ and single-top production presented by Louise Skinnari (Thursday 8:30)
- Focusing on rare top-production processes in this talk: ttX and tX

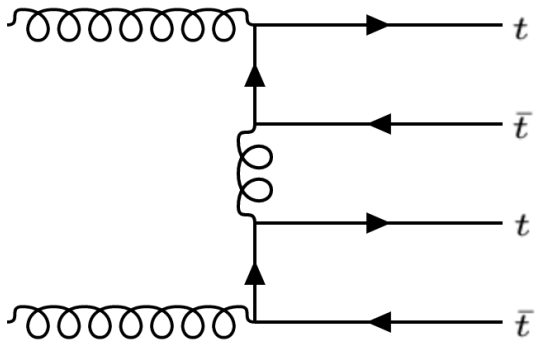
Recent ttX and tX results

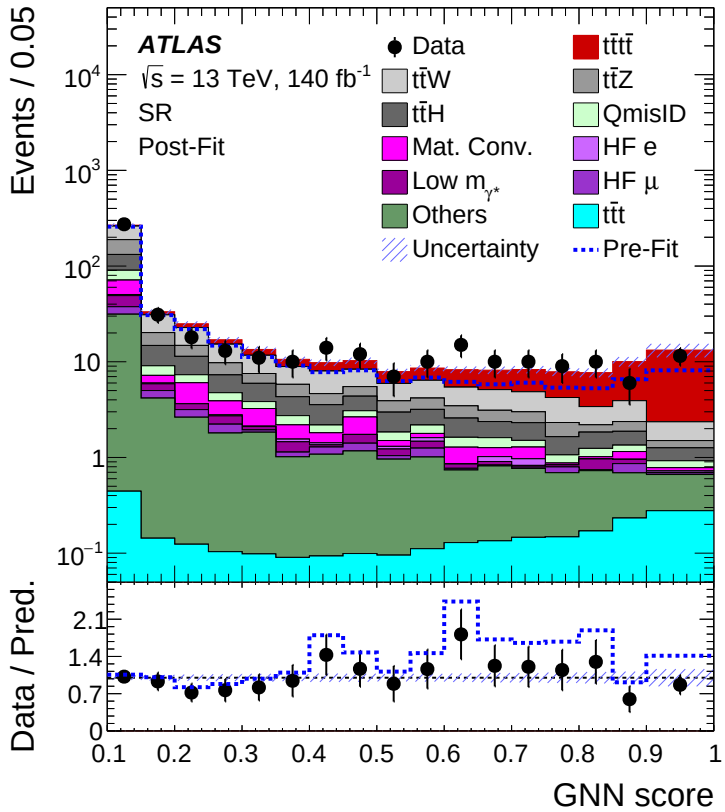
- **ATLAS Collaboration**:
  - Observation of four-top-quark production: Eur. Phys. J. C 83 (2023) 496
  - $t\bar{t}W$ inclusive and differential cross sections: arXiv:2401.05299
  - $t\bar{t}Z$ inclusive and differential cross sections: arXiv:2312.04450
  - Search for flavor-changing neutral tqH interaction: JHEP 12 (2023) 195
- **CMS Collaboration**:
  - Observation of four top quark production: Phys. Lett. B 847 (2023) 138290
  - Evidence for tWZ production: arXiv:2312.11668
  - Search for flavor changing neutral $tq\gamma$: arXiv:2312.08229
  - Search for flavor-changing neutral tqH interaction: CMS-PAS-TOP-22-002

ATLAS: Four-top-quark observation

- Eur. Phys. J. C 83 (2023) 496
- Two same-charge leptons or ≥ 3 leptons
- Graph Neural Network used to separate signal from background
- Observed (expected) sign.: 6.1 (4.3) σ
- Measured cross section: $22.5^{+6.6}_{-5.5}$ fb
  - 1.8 σ consistency with the SM prediction (12.0 ± 2.4 fb at NLO(QCD+EW))
- Constrained four-heavy-quark SMEFT operators

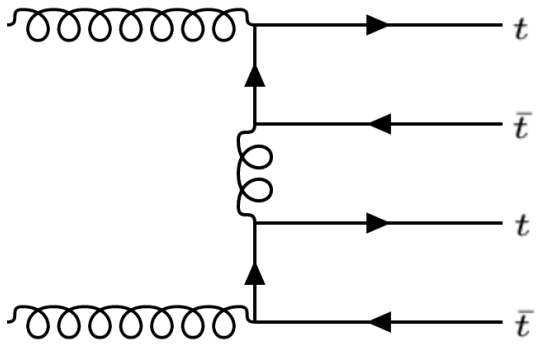
Operators	Expected C_i/Λ^2 [TeV $^{-2}$]	Observed C_i/Λ^2 [TeV $^{-2}$]
$\mathcal{O}^1_{QQ}$	$[-2.5, 3.2]$	$[-4.0, 4.5]$
$\mathcal{O}^1_{Qt}$	$[-2.6, 2.1]$	$[-3.8, 3.4]$
$\mathcal{O}^1_{tt}$	$[-1.2, 1.4]$	$[-1.9, 2.1]$
$\mathcal{O}^8_{Qt}$	$[-4.3, 5.1]$	$[-6.9, 7.6]$

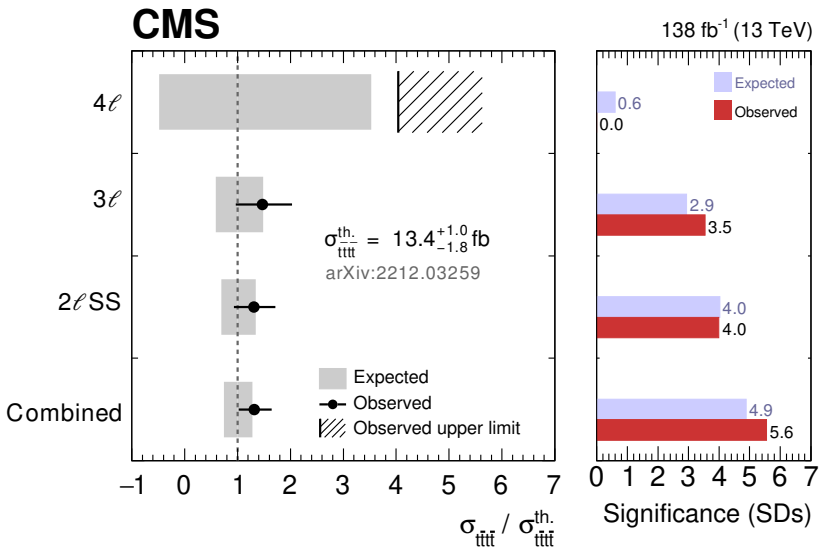


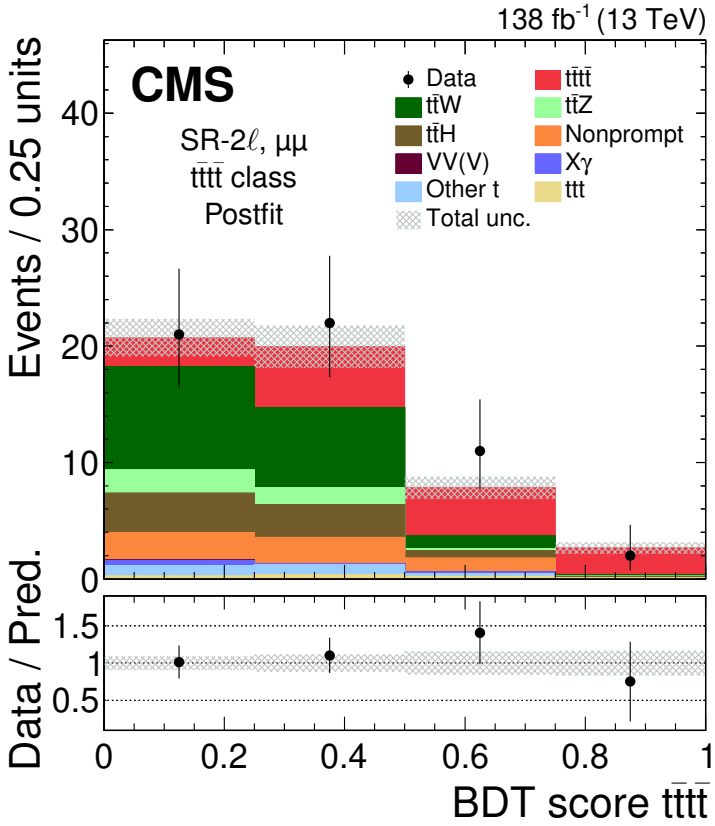


CMS: Four-top-quark observation

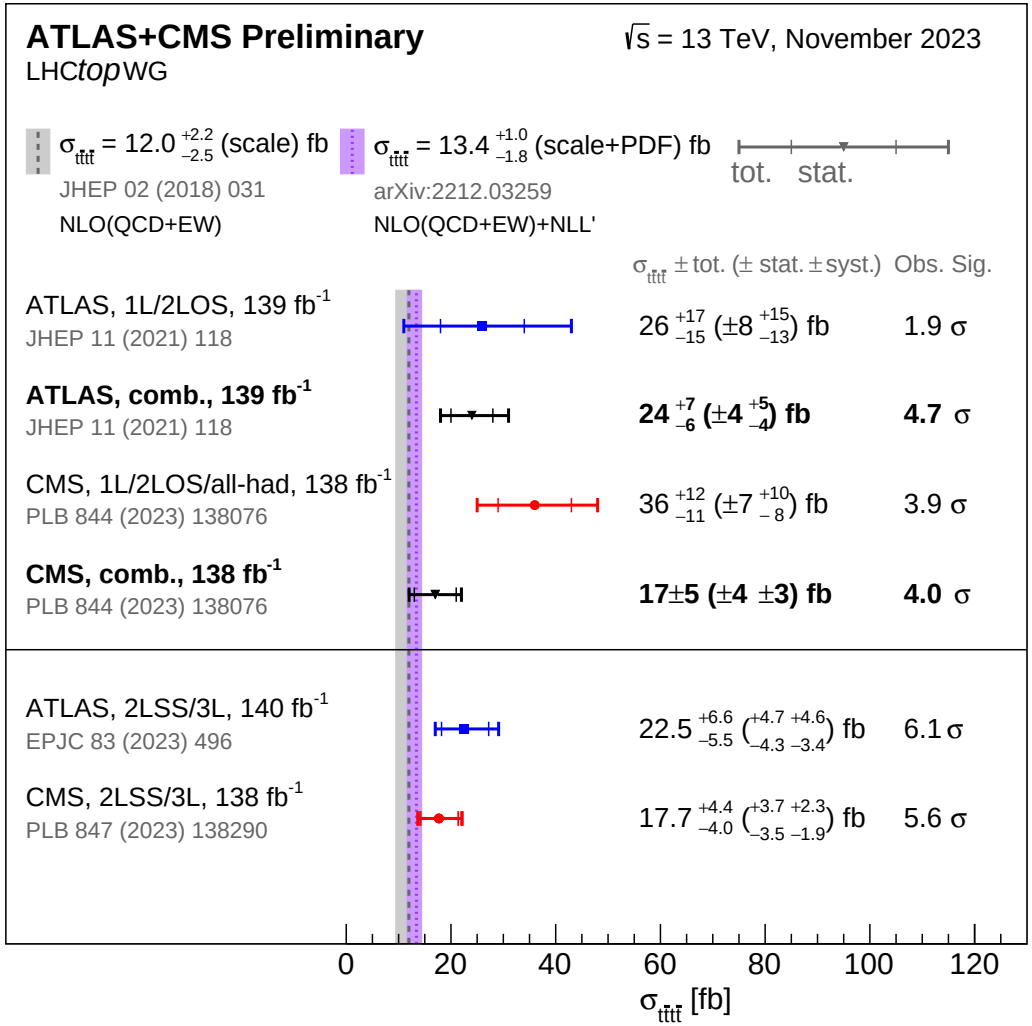
- Phys. Lett. B 847 (2023) 138290
- Two same-charge leptons or ≥ 3 leptons
- Multi-class Boosted Decision Tree to separate signal from background
- Observed (expected) sign.: 5.6 (4.9) σ
- Measured cross section: $17.7^{+3.7}_{-3.5}(\text{stat})^{+2.3}_{-1.9}(\text{syst})$ fb
  - consistent with the SM prediction







Cross section measurements of four-top-quark production



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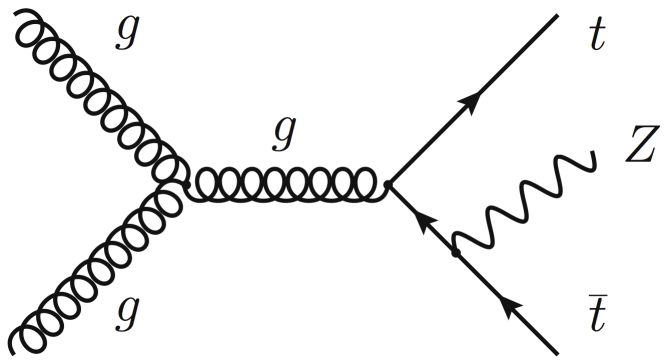
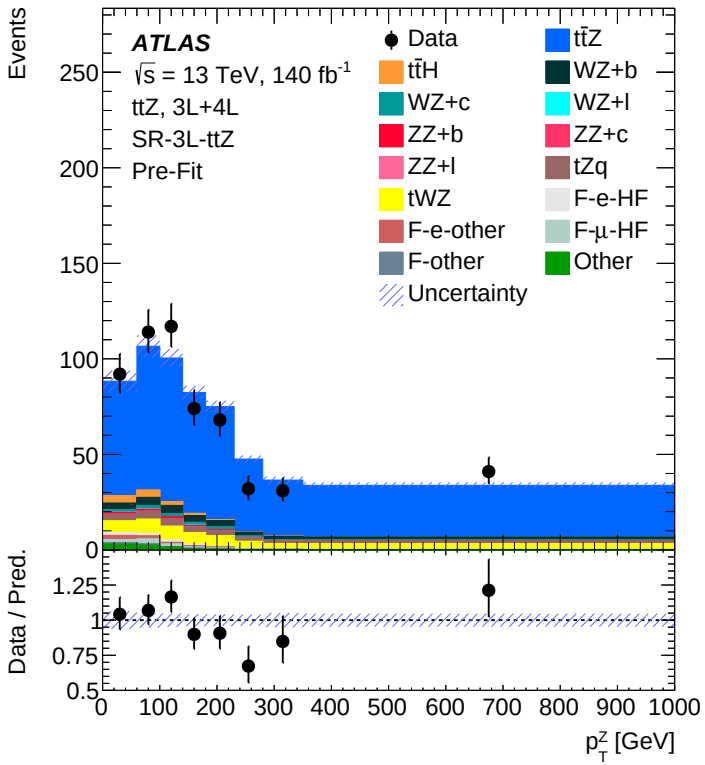
ATLAS: $t\bar{t}Z$

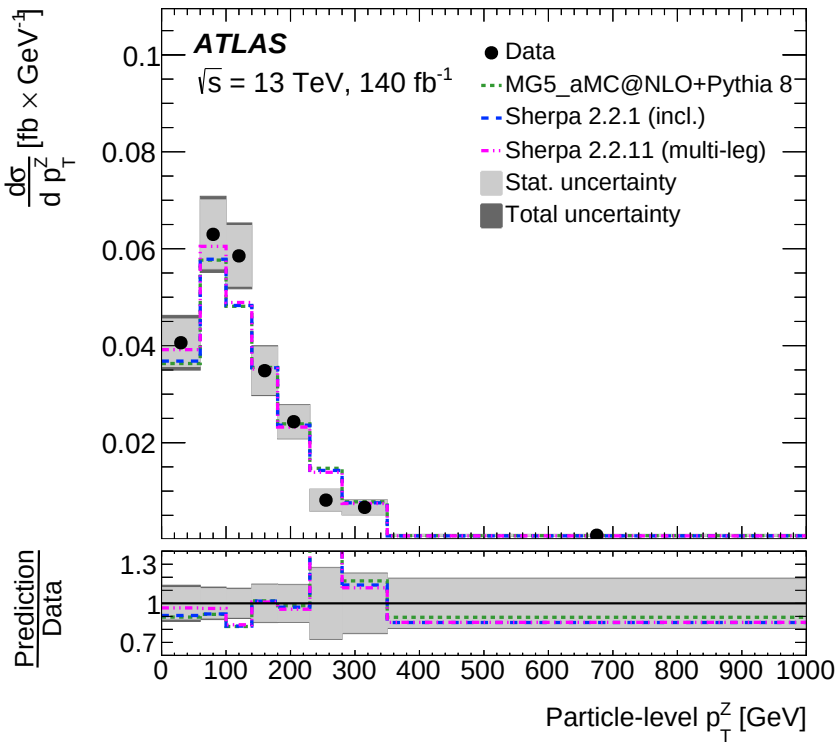
- arXiv:2312.04450
- Selections with 2, 3, and 4 leptons
- Deep Neural Networks used to separate signal from background
- Measured cross section:
  $0.86 \pm 0.04(\mathrm{stat}) \pm 0.04(\mathrm{syst})$ pb
  - consistent with the SM prediction (0.86 ± 0.09 pb at NLO(QCD+EW)+NNLL)
- Spin correlations of the top quarks
  - consistent with the SM prediction
  - 1.8 σ difference from the hypothesis of no spin correlations

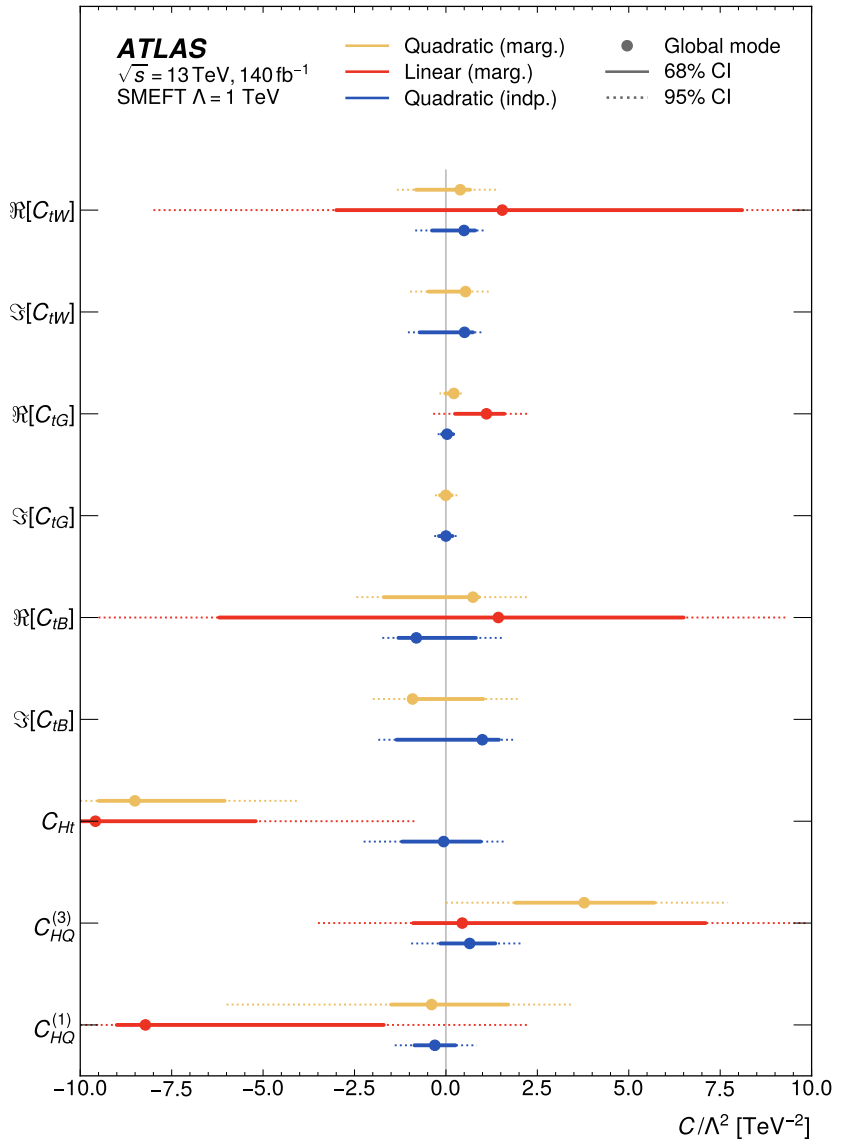




ATLAS: $t\bar{t}Z$, cont.

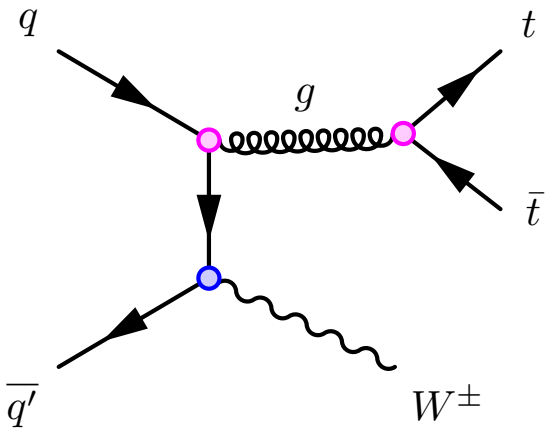
- Differential cross sections
  - Many observables (N_{jets}, H_T^{ℓ}, p_T^t,...)
  - Unfolded to parton and particle level in fiducial phase spaces
  - Measured spectra consistent with SM
- Constrained top–electroweak and four-quark SMEFT operators

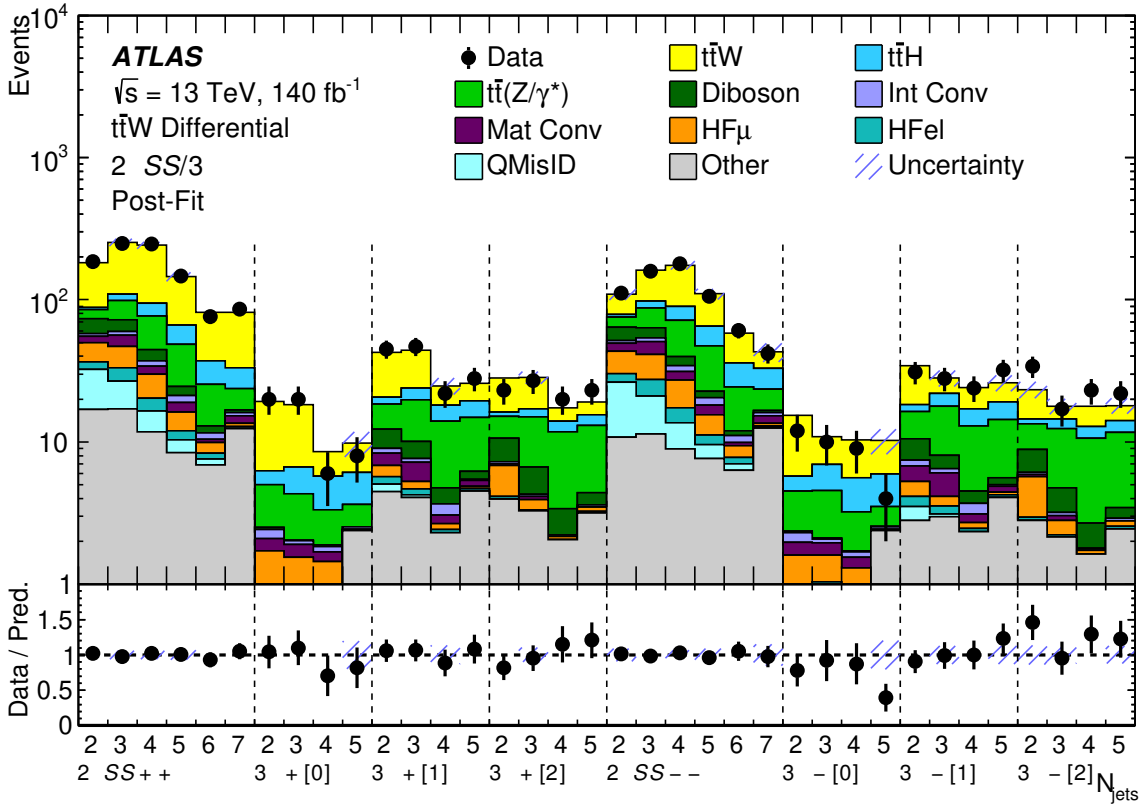




ATLAS: $t\bar{t}W$

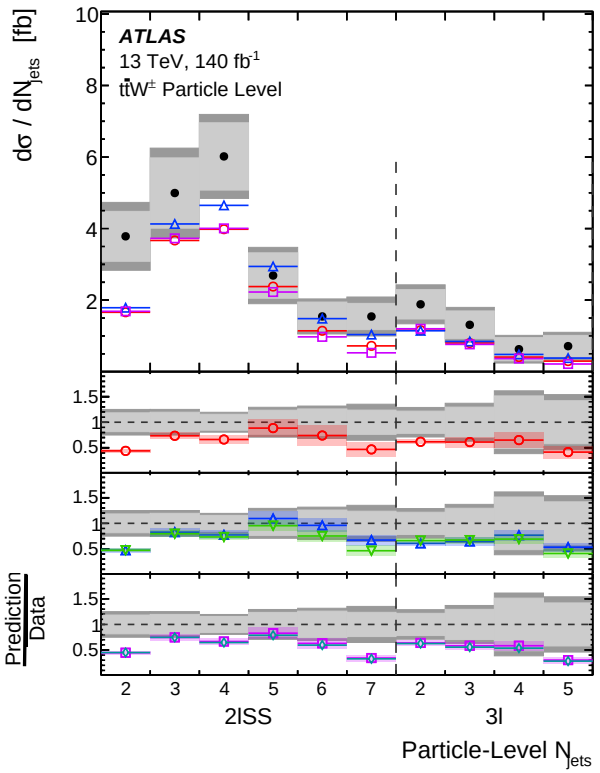
- arXiv:2401.05299
- Two same-charge or three leptons
- Measured cross section: 0.88 ± 0.08 pb
  - consistent with the SM prediction (0.75 ± 0.05 pb at NNLO(QCD)+NLO(EW))

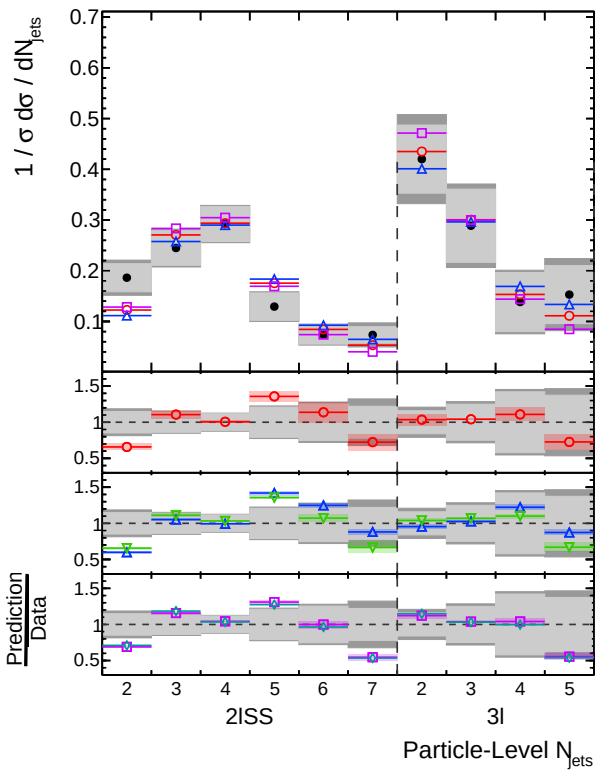


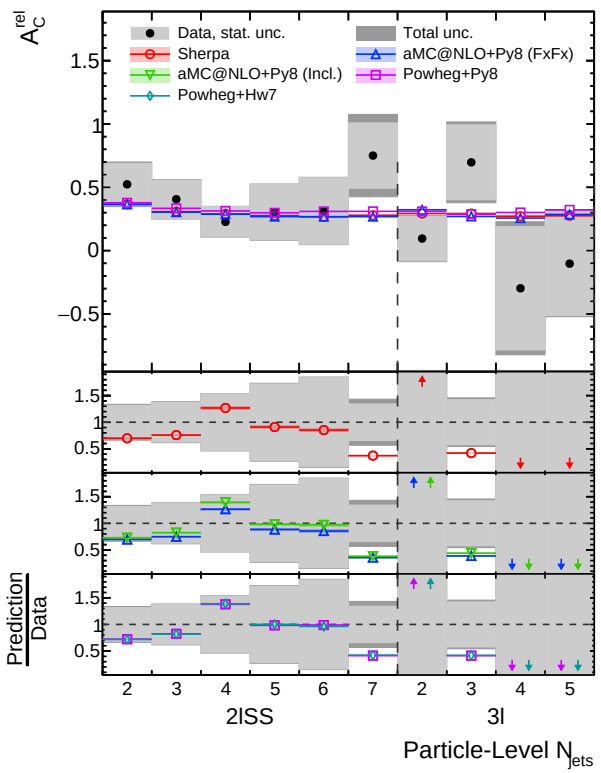


ATLAS: $t\bar{t}W$, cont.

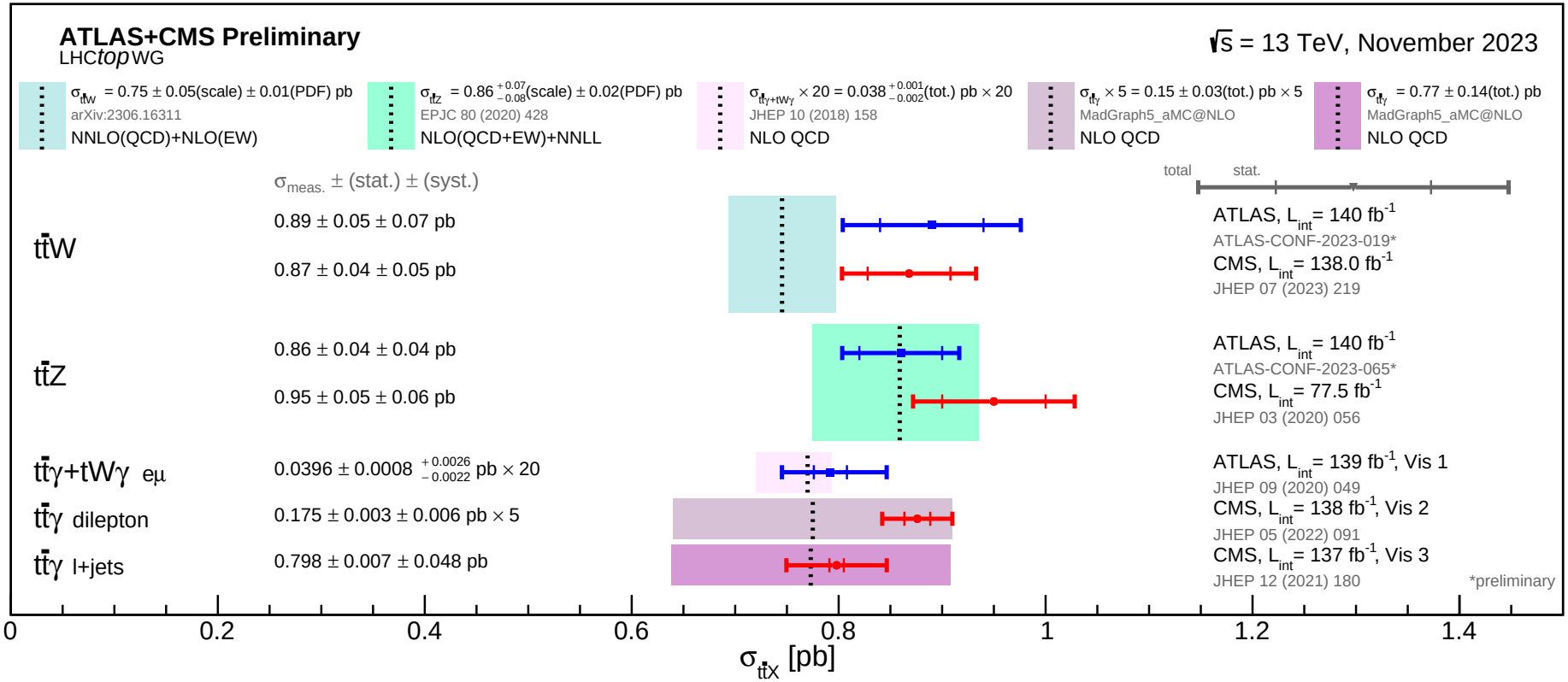
- Differential cross sections
  - First such measurement in this topology
  - Jet and lepton observables (N_{jets}, H_T^{jet}, $\Delta\Phi_{\ell\ell}$,...)
  - Unfolded to particle level in a fiducial phase space
  - Measurements consistent with SM
- Measured $t\bar{t}W^+$ vs $t\bar{t}W^-$ charge asymmetry







Cross section measurements of associated $t\bar{t}$ production



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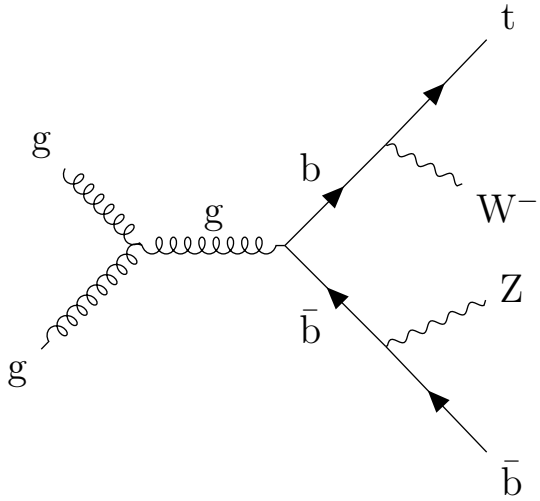
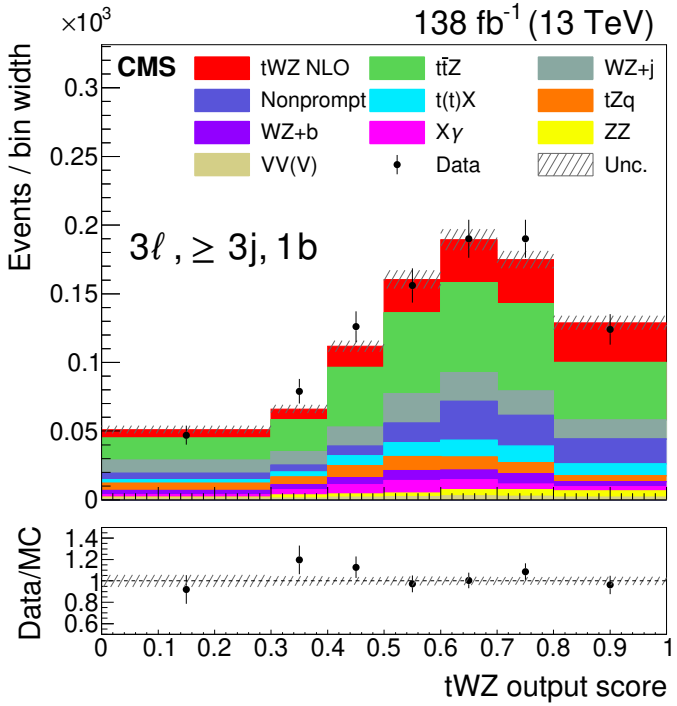
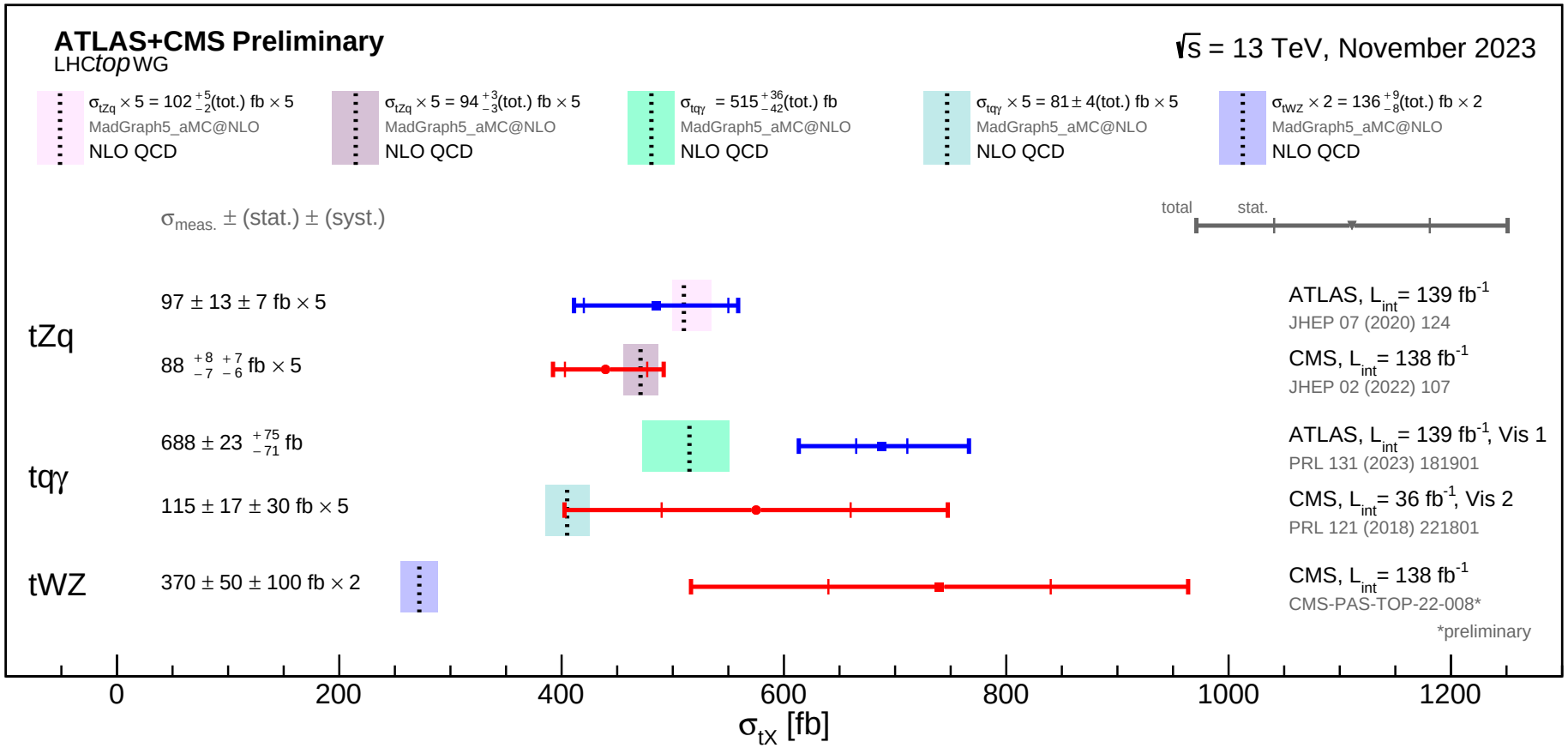
CMS: *tWZ*

- arXiv:2312.11668
- Selections with 3 and 4 leptons
- $t\bar{t}Z$ is the main background
- Deep Neural Network used to separate signal from background
- The first evidence
  - observed significance: 3.4σ
  - expected significance: 1.4σ
- Measured cross section:
  $354 \pm 54(\mathrm{stat}) \pm 95(\mathrm{syst})$ fb
  - 2σ above the SM prediction
    (136 ± 9 fb at NLO(QCD))





Cross section measurements of associated top production



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CMS: Search for flavor changing neutral current $t\gamma q$

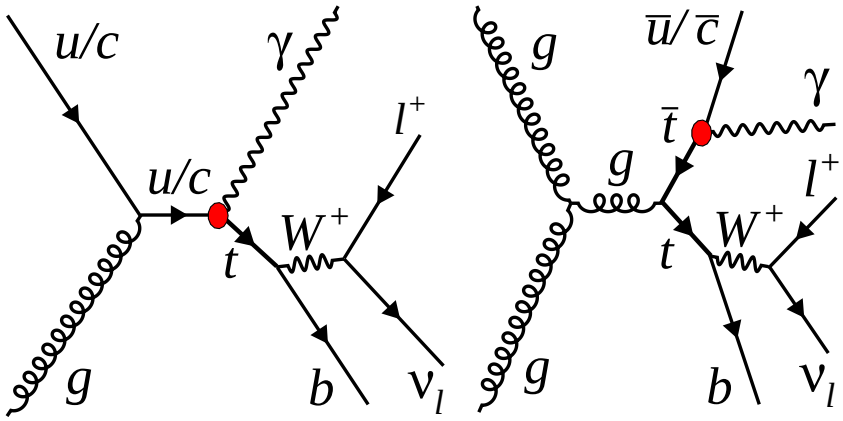
- arXiv:2312.08229
- FCNC:
  - single top produced in association with a photon
  - $t\bar{t}$ pair where one of the top quarks decays $t \to u\gamma$
- Selection: 1 lepton and 1 γ
- Boosted Decision Trees used to separate signal from background
- No excess from FCNC contributions is observed
- Obtained limits:

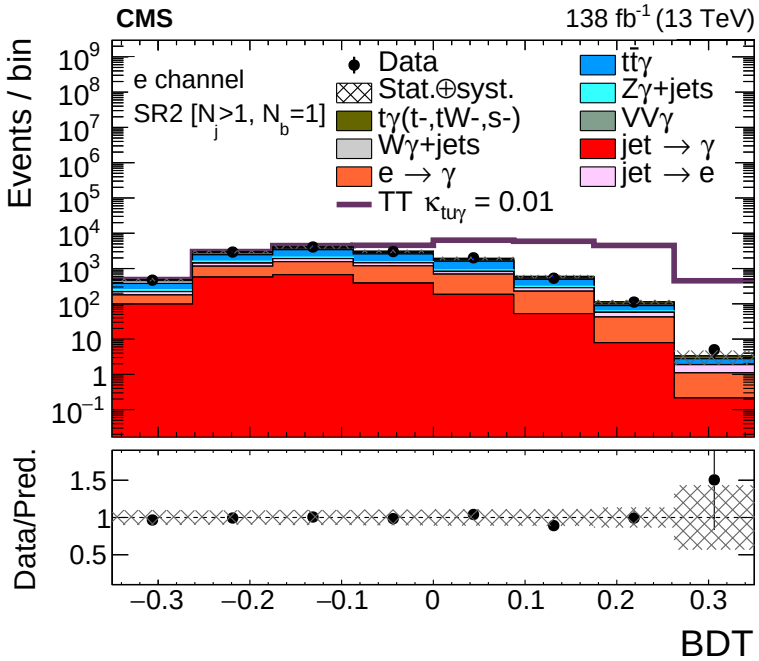
$\kappa_{tu\gamma} < 6.2 \cdot 10^{-3}$ (exp. $6.9 \cdot 10^{-3}$)

$\kappa_{tc\gamma} < 7.7 \cdot 10^{-3}$ (exp. $7.8 \cdot 10^{-3}$)

$BR(t \to u\gamma) < 0.95 \cdot 10^{-5}$

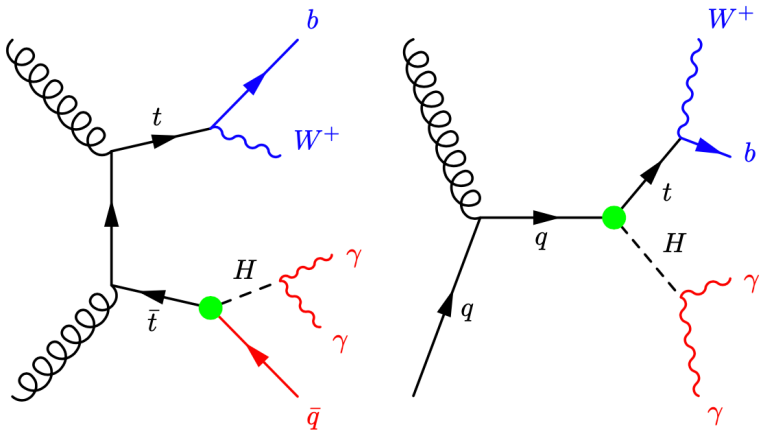
$BR(t \to c\gamma) < 1.51 \cdot 10^{-5}$

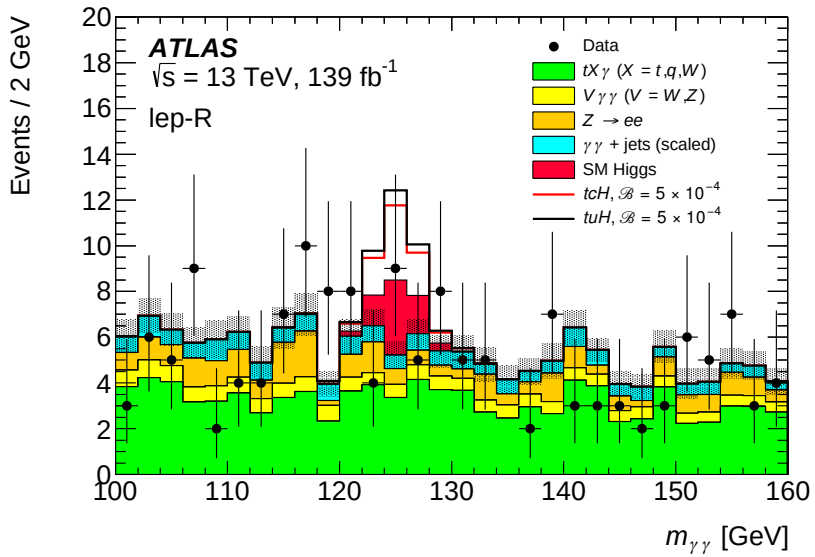




ATLAS: Search for flavor-changing neutral tqH

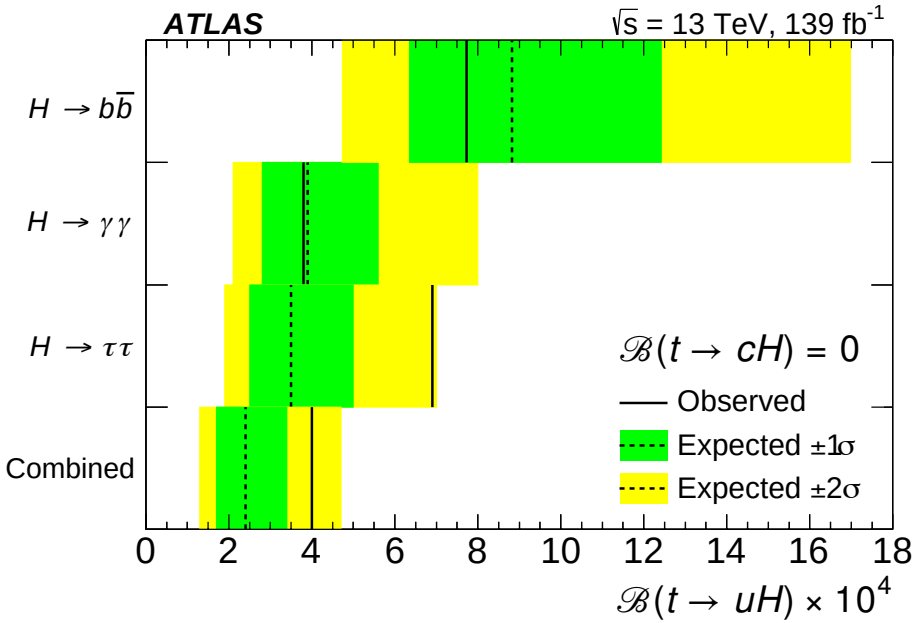
- JHEP 12 (2023) 195
- FCNC:
  - single top produced in association with a Higgs boson
  - $t\bar{t}$ pair where one of the top quarks decays $t \to qH$
- Target decay $H \to \gamma\gamma$
- Boosted Decision Trees used to separate signal from background
- Exploiting the diphoton invariant mass
- No excess from FCNC contributions is observed



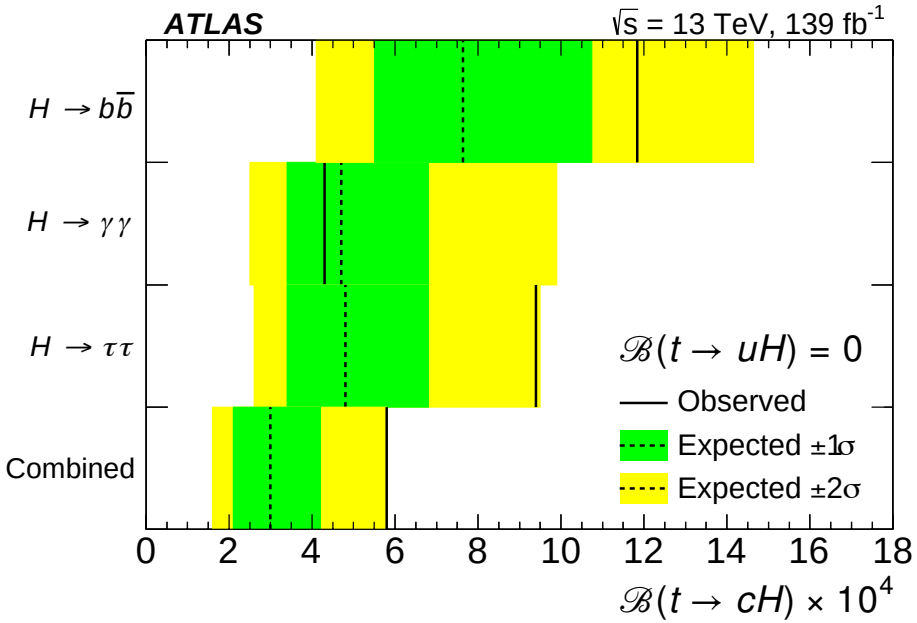


ATLAS: Search for flavor-changing neutral tqH, cont.

- Combination with earlier searches targeting $H \to \tau\tau$ and $H \to b\bar{b}$



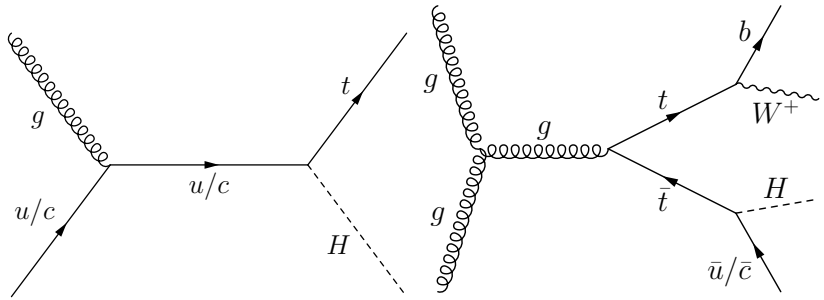
BR($t \to uH$)

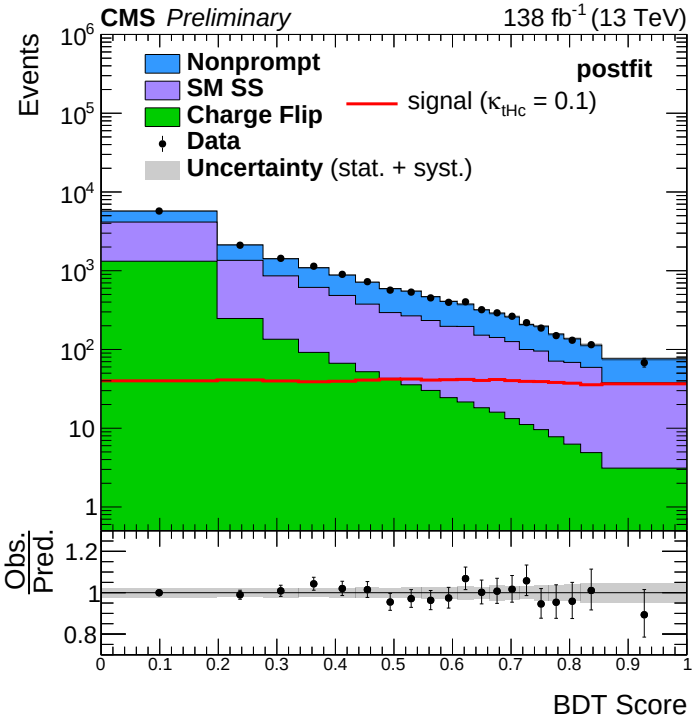


BR($t \to cH$)

CMS: Search for flavor-changing neutral tqH

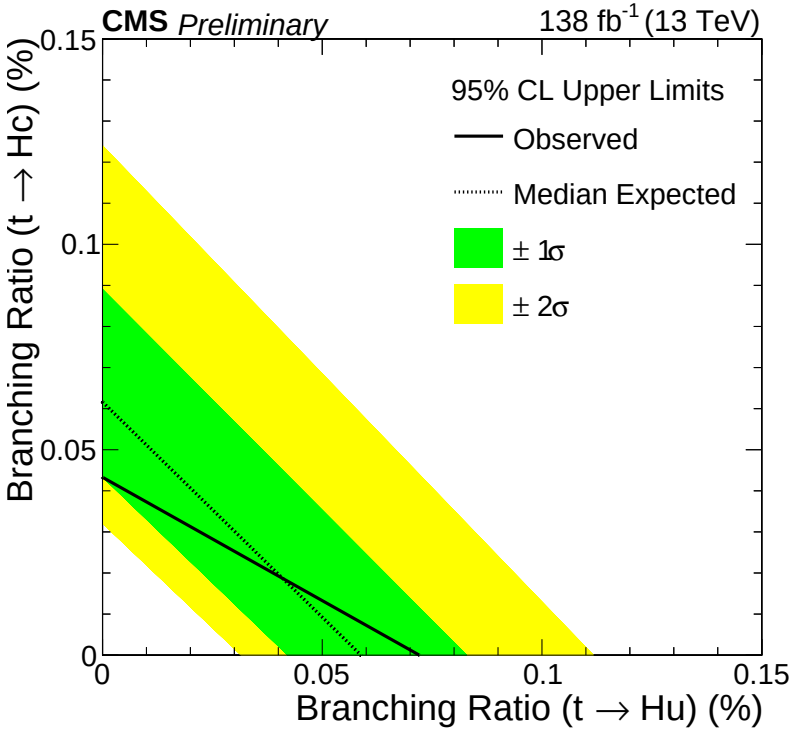
- CMS-PAS-TOP-22-002
- FCNC:
  - single top produced in association with a Higgs boson
  - $t\bar{t}$ pair where one of the top quarks decays $t \to qH$
- Target decays $H \to \tau\tau$, $H \to WW$, or $H \to ZZ$
  - Two same-charge leptons
- Boosted Decision Trees used to separate signal from background
- No excess from FCNC contributions is observed

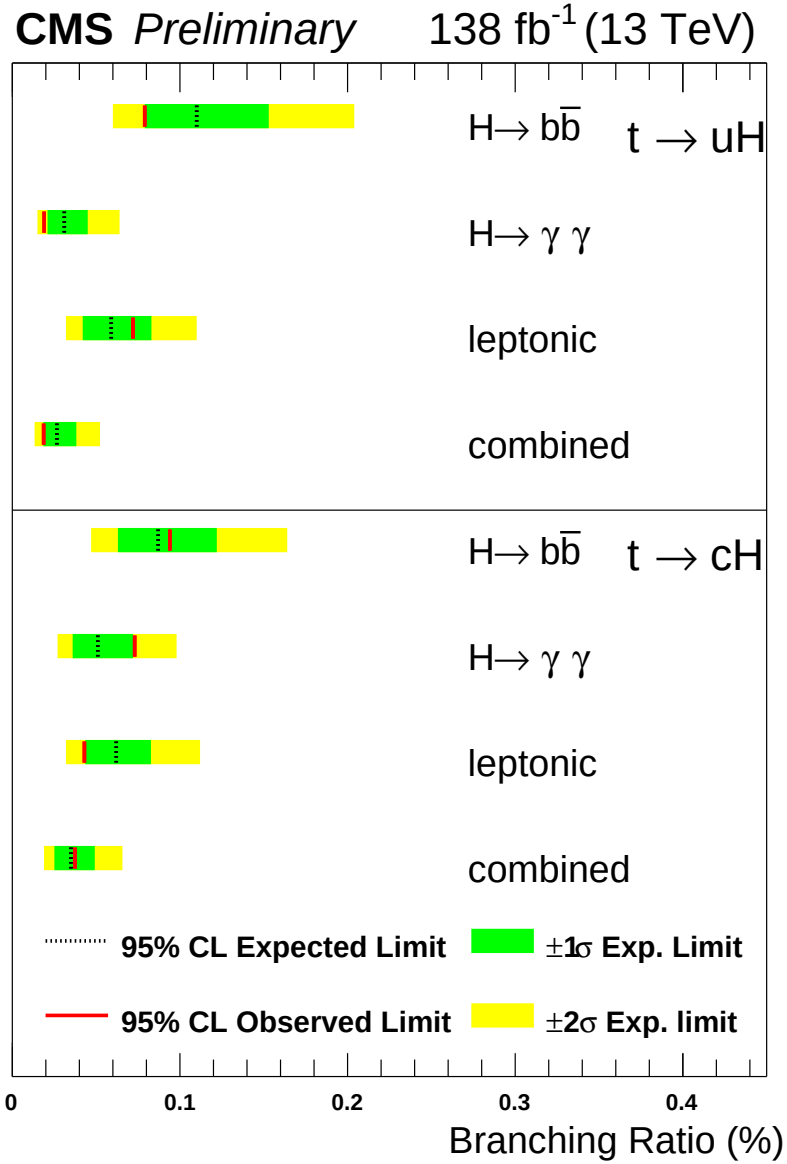




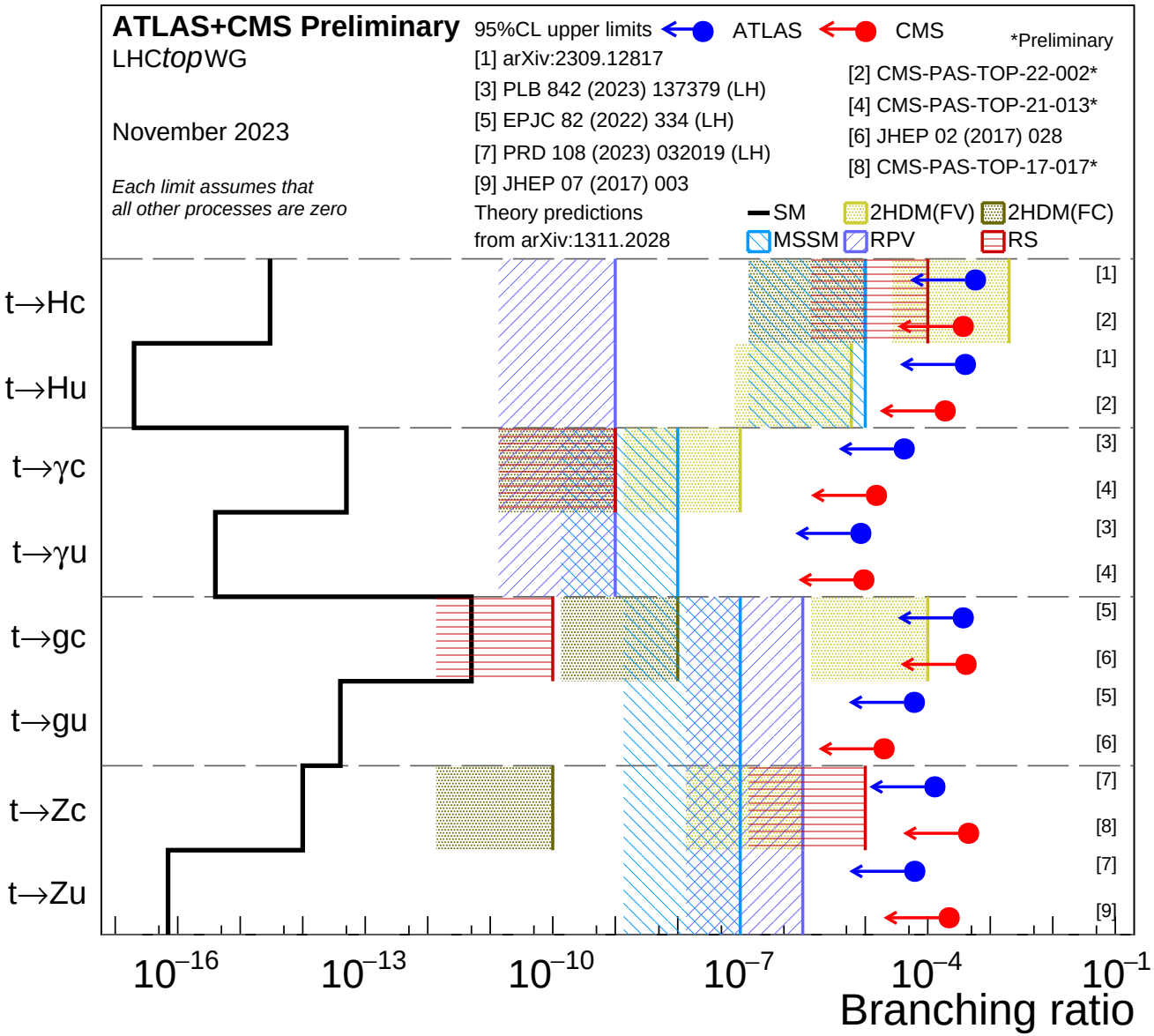
CMS: Search for flavor-changing neutral tqH, cont.

- Combination with earlier searches targeting $H \to \gamma\gamma$ and $H \to b\bar{b}$





Constraints to FCNC couplings



ATL-PHYS-PUB-2023-035

Summary

- ATLAS and CMS experiments have an extensive physics program to target ttX and tX processes
- Recent highlights presented:
  - Observation of four-top-quark production from both collaborations
  - $t\bar{t}W$ and $t\bar{t}Z$ inclusive and differential cross section measurements from the ATLAS Collaboration
  - Evidence for tWZ process from the CMS Collaboration
  - FCNC tqH and $tq\gamma$ searches
    - Improvement in the limits with respect to previous searches