Recent results in **top quark physics** from the ATLAS experiment

Brendon Bullard

on behalf of the ATLAS Collaboration

SLAC National Accelerator Laboratory

Phenomenology Symposium

May 8, 2023

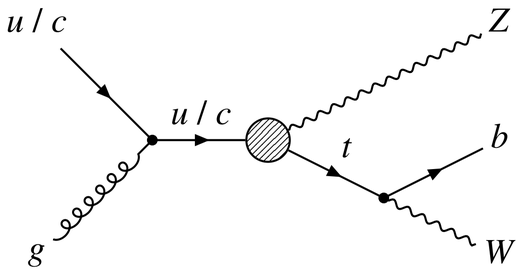
ATLAS EXPERIMENT

SLAC NATIONAL ACCELERATOR LABORATORY

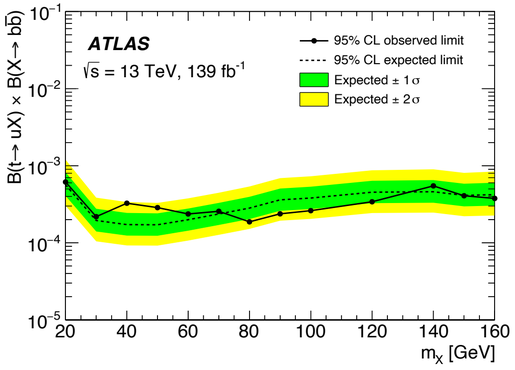
Overview of top quark measurements

- Top quark is most massive SM particle
  - Large coupling to Higgs boson
  - Can couple strongly to new physics
- Run 2 ATLAS dataset of 140 fb^{-1} gives maximal sensitivity to rare processes
  - Testing forbidden SM phenomena with $t\bar{t}$ production
  - Measure rare SM $t\bar{t} + X$ processes inclusively and differentially
- Presenting latest results from the ATLAS experiment

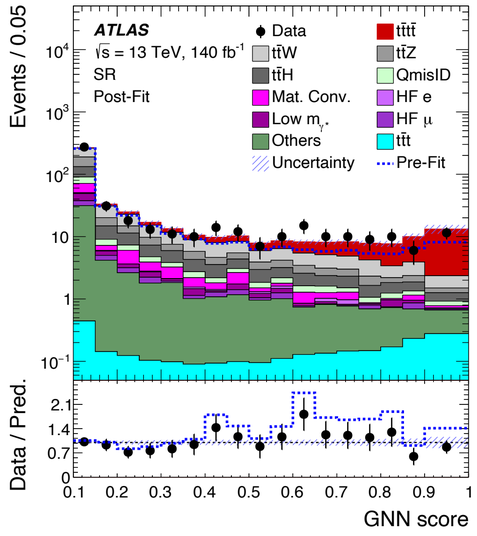
Flavor Changing Neutral Currents (FCNC)



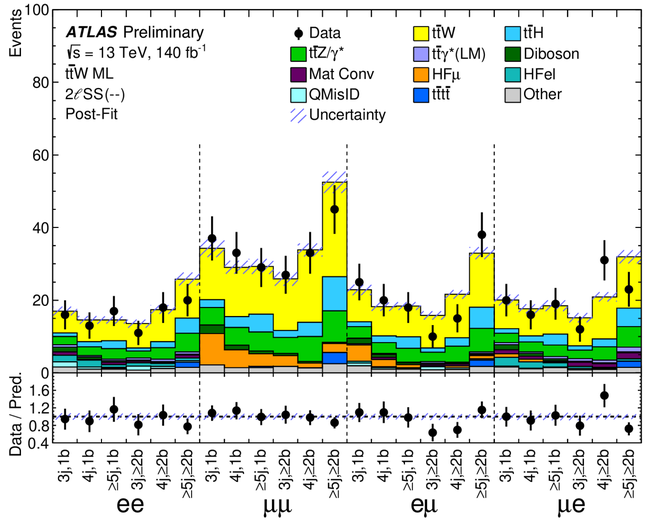
Searches for BSM physics



Observations of SM final states



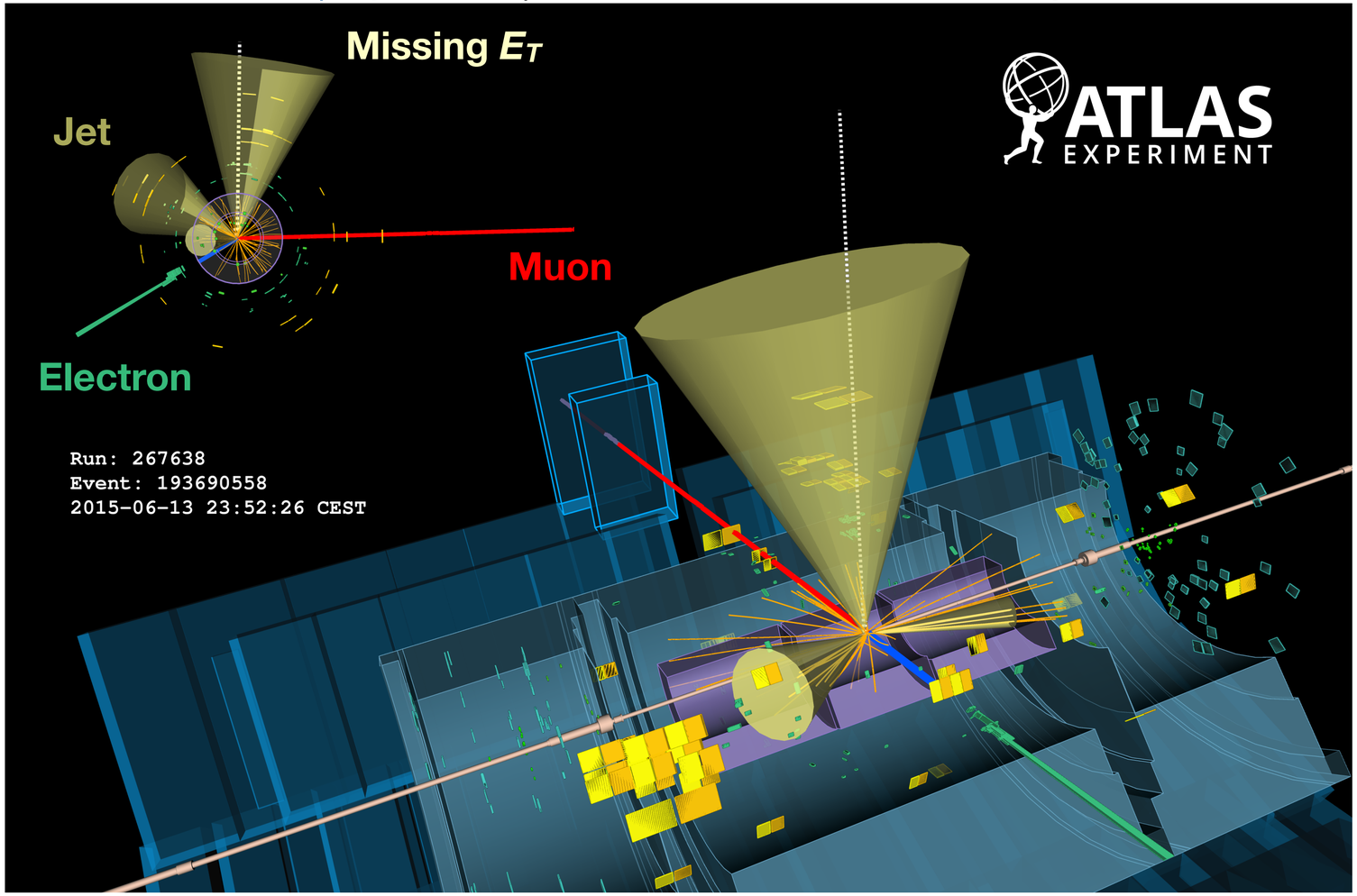
Measurements of rare Top+X processes



Reconstruction and systematics

- Top quark signatures rely on quality reconstruction multiple objects
  - Jets and flavor tagging
  - Muons, electrons (trigger, isolation)
  - Leptonic and hadronic taus
  - Missing energy (from neutrinos)
  - Sometimes photons
- Main systematic uncertainties
  - Luminosity, object reconstruction
  - Theory uncertainties of fixed order calculation (μ_R/μ_F variations)
  - Showering/hadronization modeling (variation of parton shower algorithm, MC parameters)

Event display for dileptonic $t\bar{t}$ candidate recorded by ATLAS



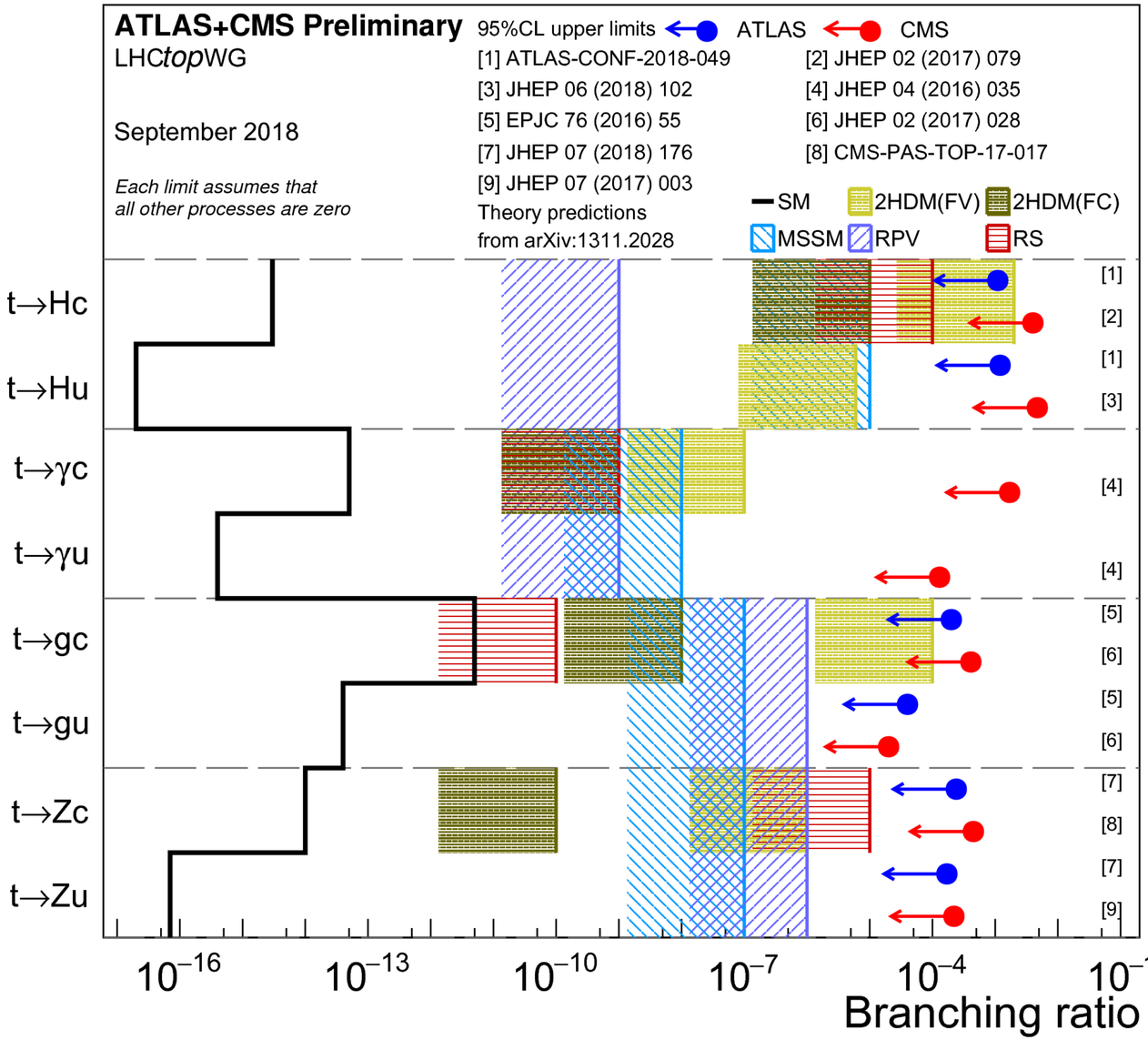
Tests of SM with top quarks

Overview of FCNC

All ATLAS measurements are improved since 2018!

- **Flavor changing neutral currents** (FCNC) forbidden at tree level and suppressed at loop level by GIM mechanism in SM
- Can be probed in many different decays of the top quark!
  - Top decays via FCNC ~10^{-14}, can be 10^{-7} - 10^{-4} in BSM (SUSY, 2HDM)
- Rates of FCNC top decays can be used to constrain Wilson coefficients in the SMEFT interpretation framework

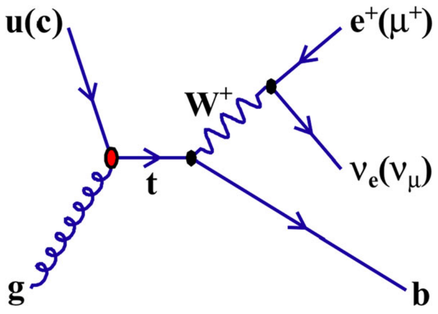
$$\mathscr{L}_{eff} = \mathscr{L}_{SM} + \frac{1}{\Lambda^2_{NP}} \sum_k C_k \mathcal{O}_k$$



Search for $u/c + g \rightarrow t$

Eur. Phys. J. C 82 (2022) 334

- Search for FCNC ugt and cgt with single-top production instead of decay
  - Distinct single top decay features help discriminate against **W+jets and multi-jet backgrounds**
- Trigger on lepton, use BDT-based b-tagging algorithm with 30% efficiency
  - Significantly reduces mis-tag backgrounds
- Neural net discriminants trained to target sea (D_1) and valence (D_2) quarks
- Expected limits improved, but less than expected by scaling 8 TeV result by luminosity and cross section
  - Faster increase in top quark background cross section with $\sqrt{s}$ than for FCNC signal



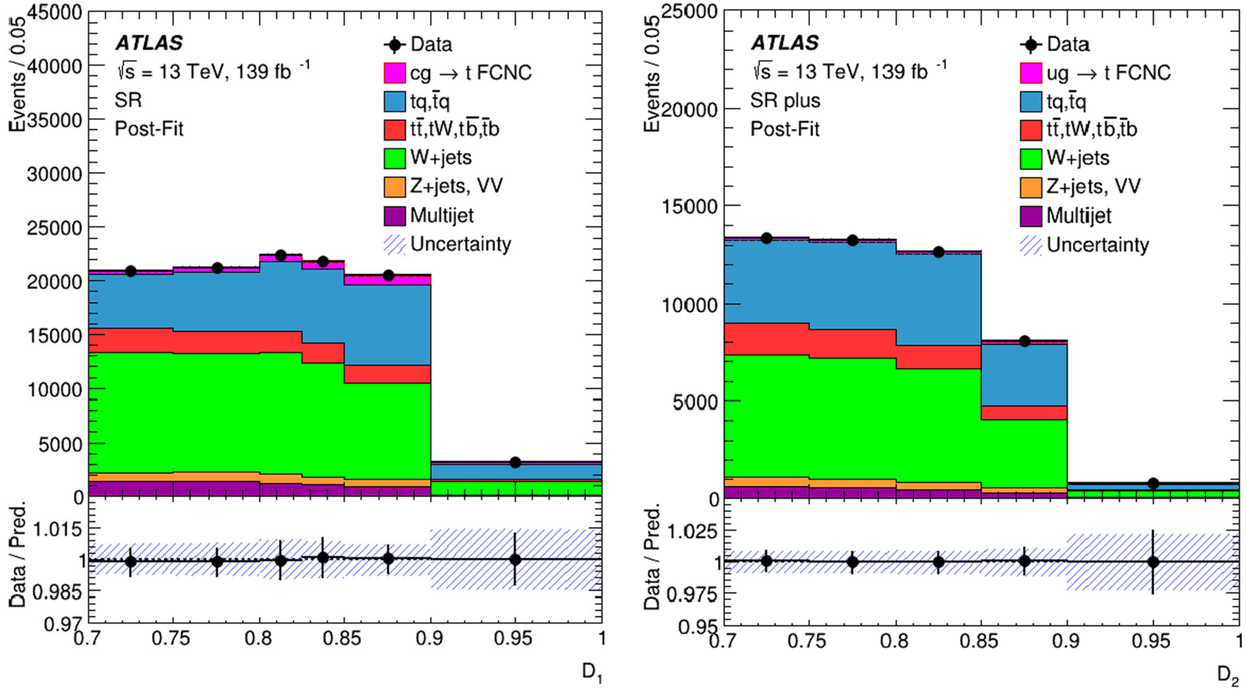
1 lepton, ≥1 jet, E_T^{miss} > 30 GeV

SR: 1 b-jet @ 30 %, (exactly 1 central jet)

W+jets VR: 1 b-jet @ 60% (veto 30%)

$t\bar{t}$ **VR:** 2 central jets, 2 b-jet @30%

tq **VR:** exactly 1 forward jet and 1 central jet



$$\sigma(ugt) \times \mathcal{B}(t \rightarrow Wb) \times \mathcal{B}(W \rightarrow \ell\nu) < 3.0\,\text{pb}$$

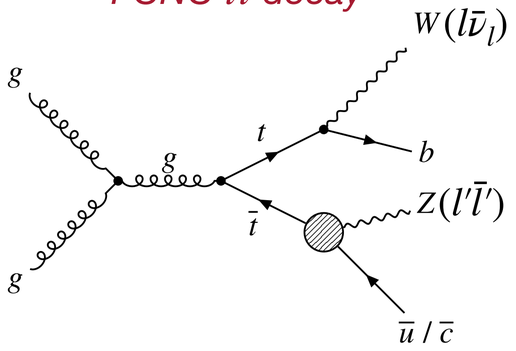
$$\sigma(cgt) \times \mathcal{B}(t \rightarrow Wb) \times \mathcal{B}(W \rightarrow \ell\nu) < 4.7\,\text{pb}$$

Search for $t \to Zu/Zc$ and $u/c \to tZ$

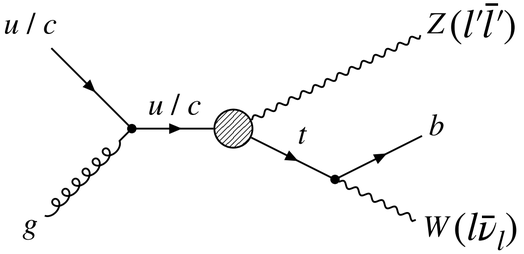
arXiv:2301.11605

- Search for FCNC uZt and cZt with single-top production **and** decay
  - Biggest improvement over 36 fb^{-1} analysis
- Dominant backgrounds from VV+heavy flavor, $t\bar{t}Z$ and tZ
- Neural networks for S/B discrimination
  - Consider uZt and cZt together in decays, separately for production (u/c from valence/sea quarks)
- Observed limits on $t \to Zu/Zc$ better by factor 3/2 over 36 fb^{-1} result
  - **Most stringent limits** to date!

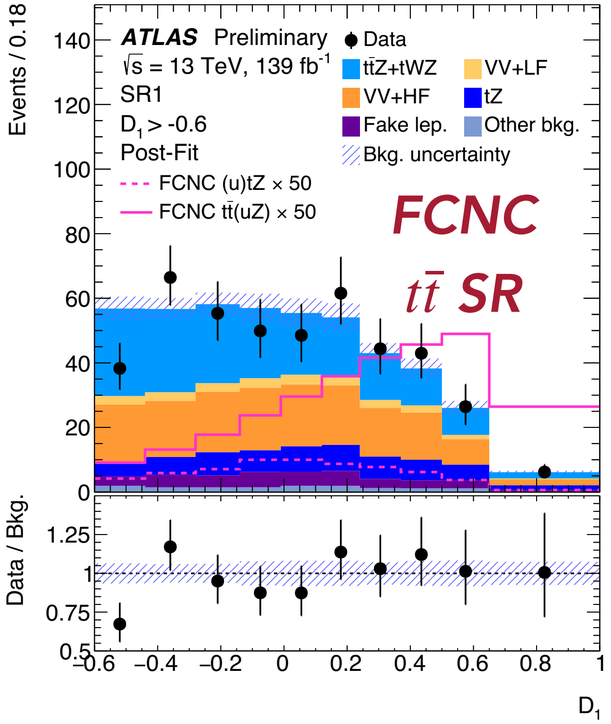
FCNC $t\bar{t}$ decay



FCNC tZ production



Select exactly **3 leptons**, **1 b-tagged jet** with DL1r NN tagger



Results

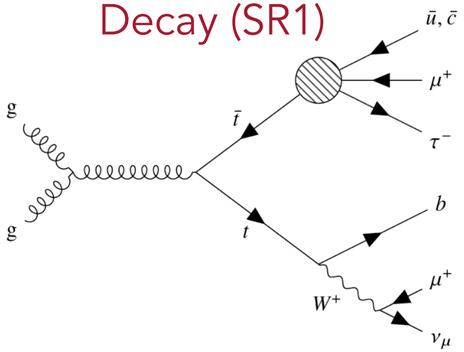
Observable	Vertex	Coupling	Observed	Expected
	SRs+CRs			
$\mathcal{B}(t \to Zq)$	tZu	LH	6.2×10^{-5}	$4.9\,^{+2.1}_{-1.4} \times 10^{-5}$
$\mathcal{B}(t \to Zq)$	tZu	RH	6.6×10^{-5}	$5.1\,^{+2.1}_{-1.4} \times 10^{-5}$
$\mathcal{B}(t \to Zq)$	tZc	LH	13×10^{-5}	$11\,^{+5}_{-3} \times 10^{-5}$
$\mathcal{B}(t \to Zq)$	tZc	RH	12×10^{-5}	$10\,^{+4}_{-3} \times 10^{-5}$
$\lvert C_{uW}^{(13)*}\rvert$ 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	$0.19\,^{+0.04}_{-0.03}$

Search for $\tau\mu$ cLFV with top quarks

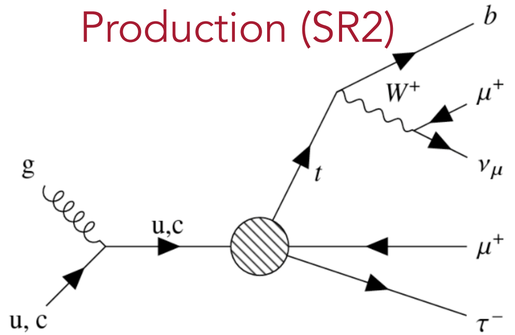
ATLAS-CONF-2023-001

- Charged lepton flavor violation (cLFV) is extremely suppressed
  - Possible in the SM via neutrino mixing at loop level, $\mathrm{BF_{SM}}(\mu \to e\gamma) < 10^{-55}$!
  - Any observation indicates new physics
- Main backgrounds from $t\bar{t}$ + non-prompt μ ($t\bar{t}$+NPμ), $t\bar{t}V/t\bar{t}H$, jets mis-ID'd as τ
  - Data-driven fake τ estimation in dedicated control region ($\mu^+\mu^- + \tau_{\mathrm{had}}$ i.e. Z+jets)
- Single bin in SRs, CR binned in H_T (scalar sum of jet p_T)
- Stringent limits on BR($t \to \mu\tau q$) obtained and interpreted in SMEFT

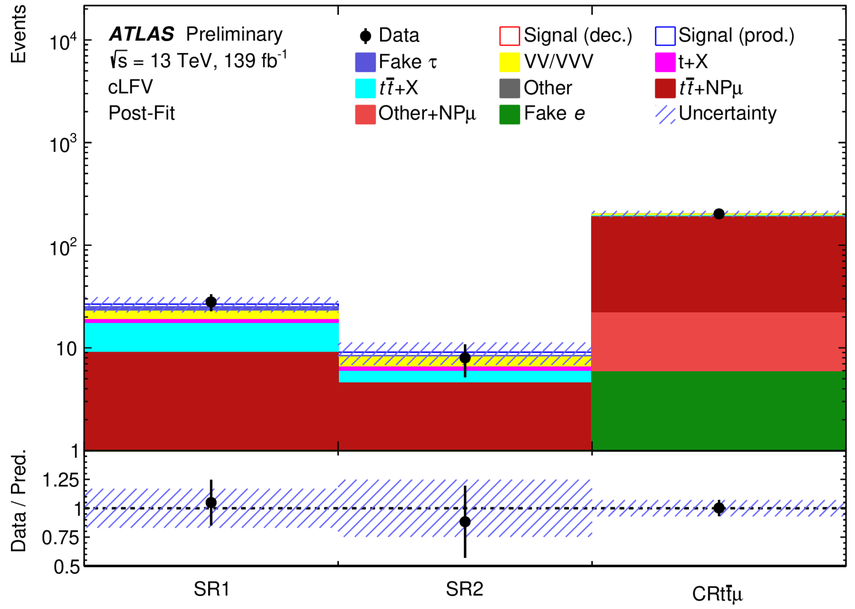
Decay (SR1)



Production (SR2)



	SR1	SR2	CR$tt\mu$
Lepton flavour		$2\mu 1\tau_{\text{had-vis}}$	$2\mu 1e$ ($\ell_3 = \mu$)
N_{jets}	≥ 2	1	≥ 2
$N_{b-\text{tags}}$	1	1	≤ 2
Muon p_T cut	> 15 GeV	> 15 GeV	> 10 GeV
Lowest p_T muon selection	*Tight*	*Tight*	*Loose*
Muon charges	SS	SS	-
$\lvert m^{OS}_{\mu\mu} - M_Z \rvert$	-	-	>10 GeV



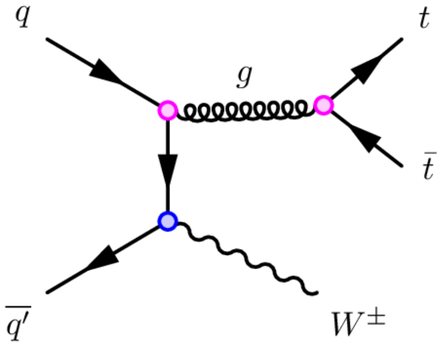
	95% CL upper limits on BR($t \to \mu\tau q$)	
	Stat. only	All systematics
Expected	8×10^{-7}	10×10^{-7}
Observed	9×10^{-7}	11×10^{-7}

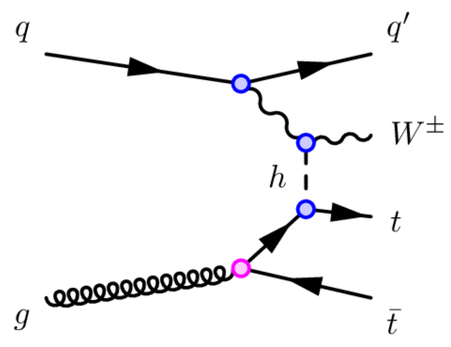
Top+X production

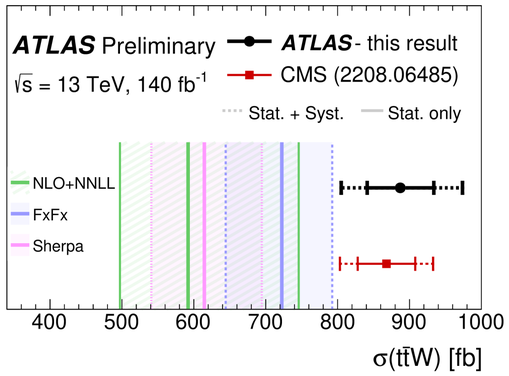
ttW inclusive and differential Cross Section

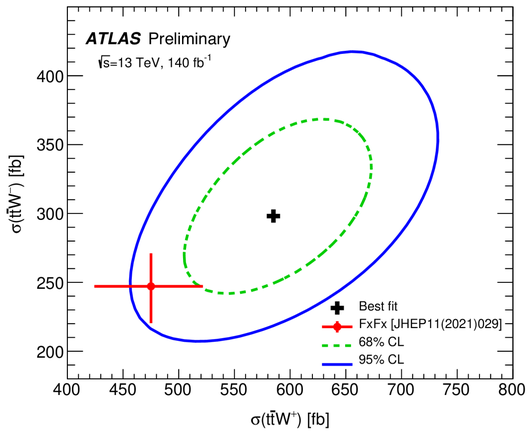
ATLAS-CONF-2023-019

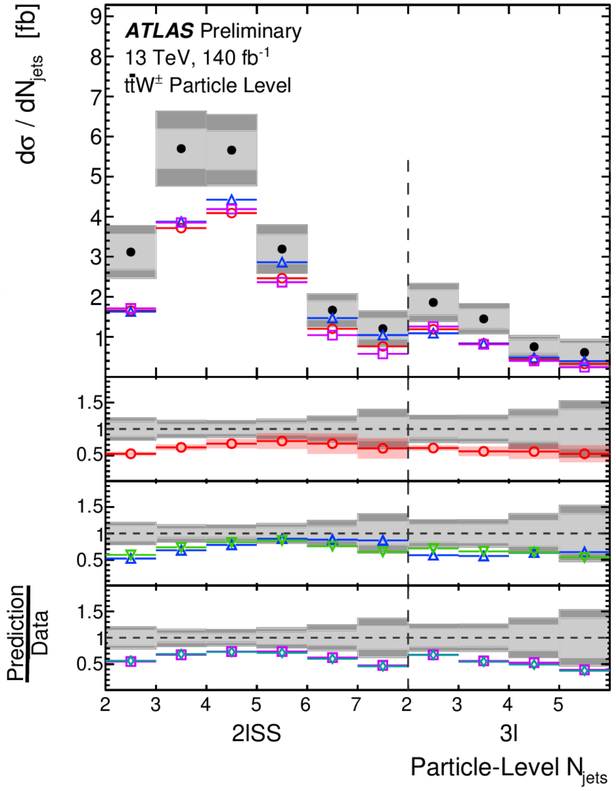
- $\sigma(t\bar{t}W)$ measured 20-50% larger than prediction (consistently by both ATLAS and CMS)
  - Large background for $t\bar{t}H$ and $t\bar{t}t\bar{t}$!
- Use di-lepton triggers, select $2\ell SS/3\ell$ channels + ≥2 jets, ≥1 b-tagged
  - Bkgs from $t\bar{t}Z/H$, VV, non-prompt leptons, $t\bar{t}t\bar{t}$ at high N_{jet}
  - Semi data-driven template fit method using CRs defined with lepton isolation BDT
- Inclusive cross section remains larger than theory predictions (1.5σ tension with FxFx)
- Perform first differential measurement of $t\bar{t}W$ in 9 observables using profile likelihood unfolding (PLU)
  - Shapes consistent between various MC and data







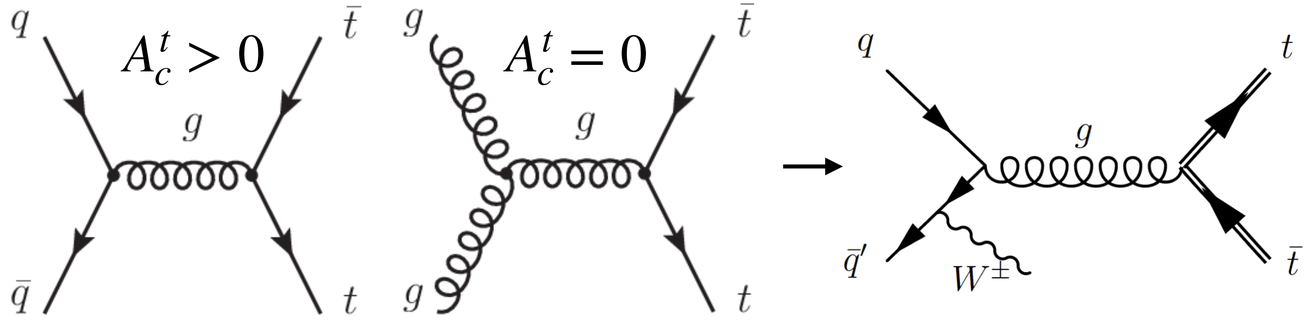




ttW leptonic charge asymmetry

arXiv:2301.04245

- $t\bar{t}$ forward-central asymmetry can probe NLO QCD effects, test of SM
  - Symmetry of pp beams reduces sensitivity!
  - Emission of W removes symmetric gg contribution, polarizes quark line



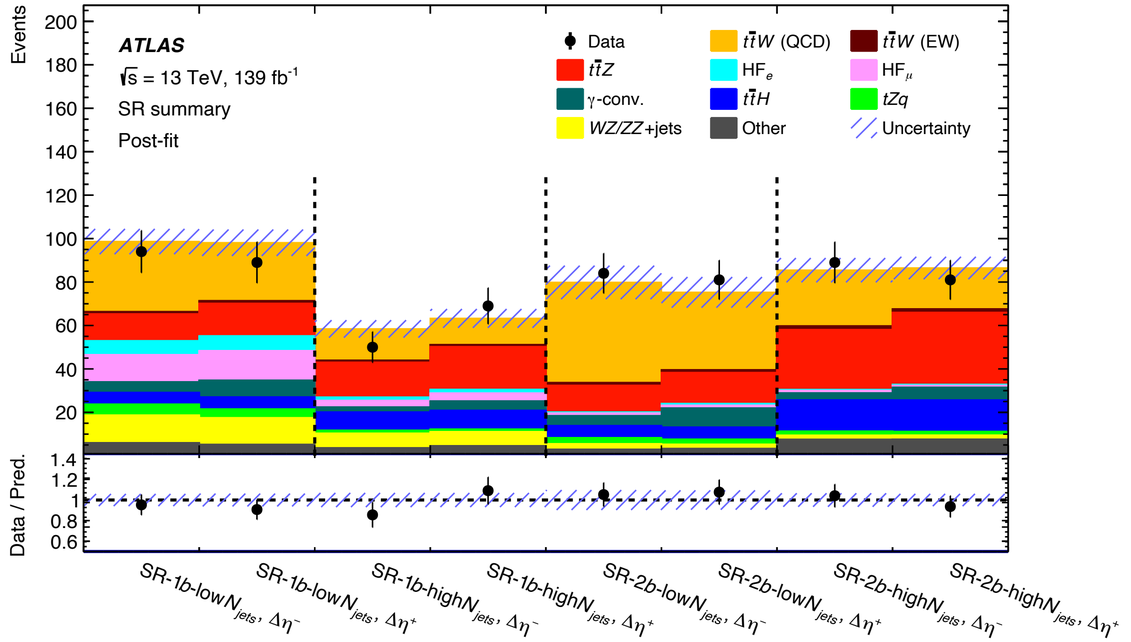
Leptonic Charge Asymmetry

$$A_c^{\ell} = \frac{N(\Delta_y^{\ell} > 0) - N(\Delta_y^{\ell} < 0)}{N(\Delta_y^{\ell} > 0) + N(\Delta_y^{\ell} < 0)}, \quad \Delta_y^{\ell} = |y_{\ell^+}| - |y_{\ell^-}|$$

- Similar strategy as for ttW incl.+diff.
  - Target only 3l channel, train BDT to identify which same-sign lepton came from top
  - Use PLU for particle-level measurement

- Dominant systematics from uncorrelated background NFs in $\Delta\eta^{\pm}$ bins

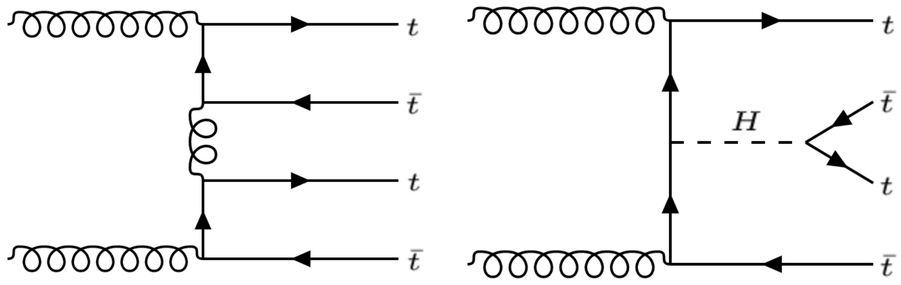
$$A_c^{\ell}(t\bar{t}W) = -0.123 \pm 0.136\,(\text{stat.}) \pm 0.051\,(\text{syst.})$$



Observation of four top quark production

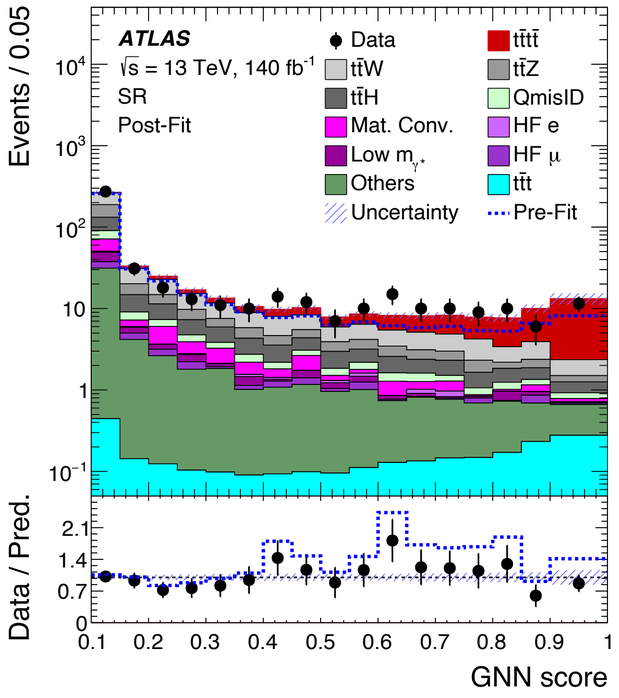
arXiv:2303.15061

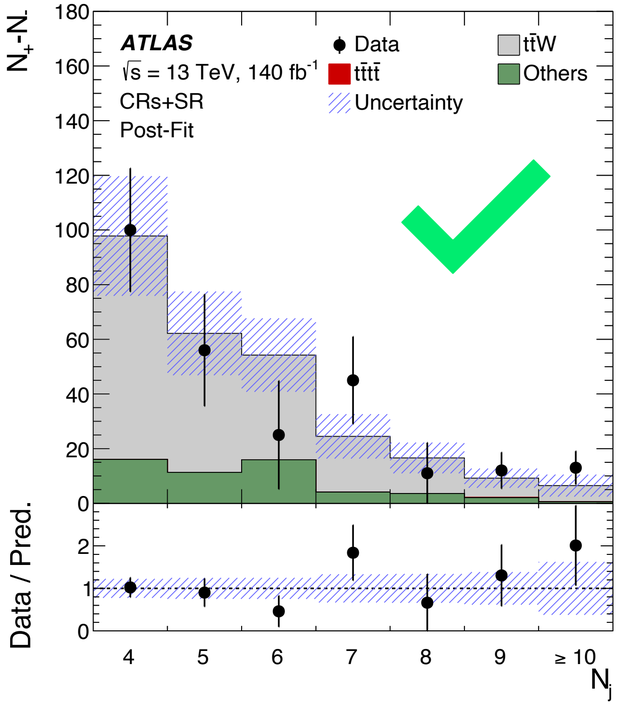
- $t\bar{t}t\bar{t}$ is one of the most massive SM signatures that can be probed at the LHC
  - Cross section of ~12 fb @NLO in SM, can be enhanced in BSM that couples to top quark
  - High multiplicities in the final state (≥6 jets, ≥2 leptons, H_T≥500 GeV in SR)
- Most sensitive channels $2\ell SS$/multi-lepton
- Perform data-driven estimation of dominant $t\bar{t}W$ background w/ ≥7 jets
- Observed (expected) sig. of 6.1σ (4.3σ)
  - Interpretations with 4-fermion EFT operator, Higgs oblique parameter, CP-structure of top Yukawa coupling, $t\bar{t}t$ cross section



Data Driven ttW estimate:

$$\mathrm{NF}_{t\bar{t}W(j)} = \mathrm{NF}_{t\bar{t}W^+(4\mathrm{jet})} \times \Pi_{j'=4}^{j'=j-1}\left[a_0 + \frac{a_1}{1+(j'-4)}\right] + \mathrm{NF}_{t\bar{t}W^-(4\mathrm{jet})} \times \Pi_{j'=4}^{j'=j-1}\left[a_0 + \frac{a_1}{1+(j'-4)}\right]$$

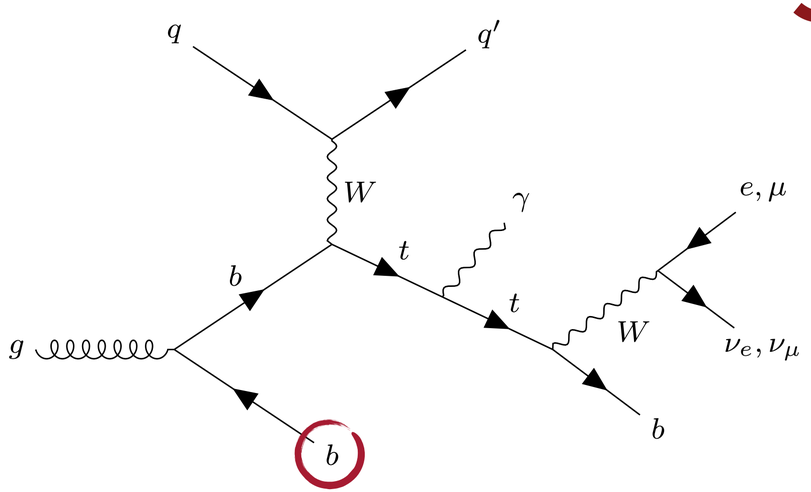




Observation of $t\gamma$ production

arXiv:2302.01283

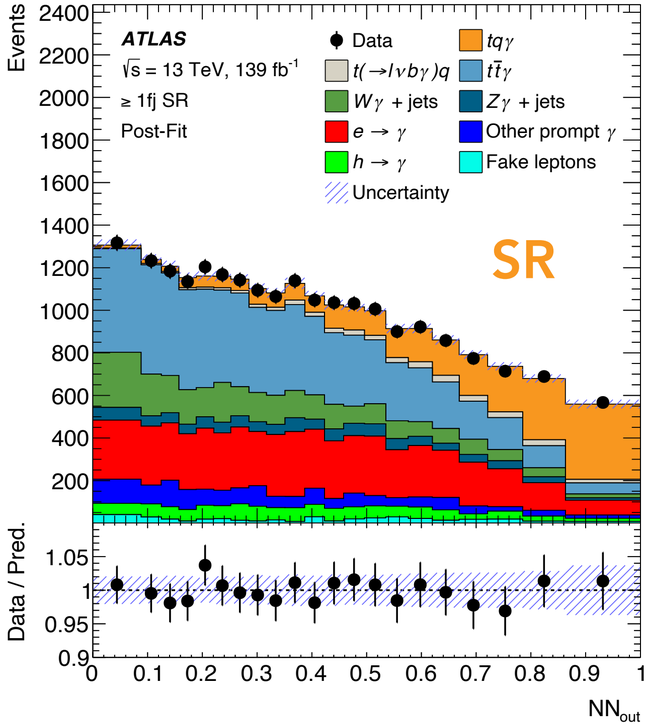
- Rare t+X measurements probe EW couplings
  - $t\bar{t}+H, W, Z, \gamma$ all observed, but only $t+W, Z$
  - Target t-channel $tq\gamma$, distinct signature of forward b-jet that is not tagged (outside tracker coverage)!

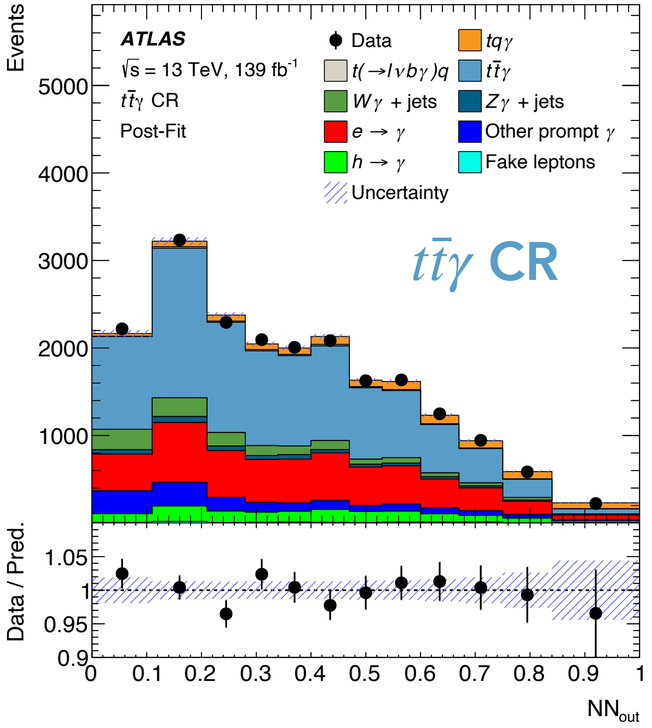


- Backgrounds from $t\bar{t}\gamma$, $W\gamma$ (define CR), fake γ
  - Veto on $m(\ell\gamma)$ in m_Z window to reduce $e \to \gamma$
  - ABCD method for $h \to \gamma$ estimation

- Observed (expected) sig. of 9.3σ (6.8σ)

- Parton-level fiducial cross section of
  $\sigma_{tq\gamma} \times B(t \to \ell\nu b) = 688 \pm 23\,(\text{stat}) \pm 73\,(\text{syst})$ fb
  - Compatible with SM predictions!



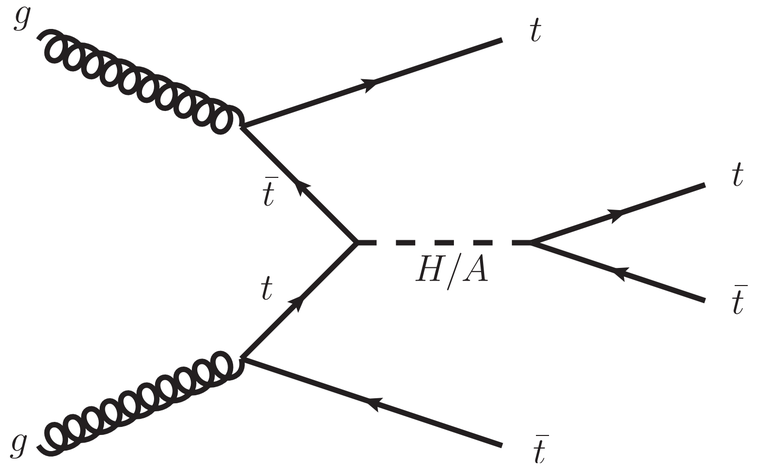


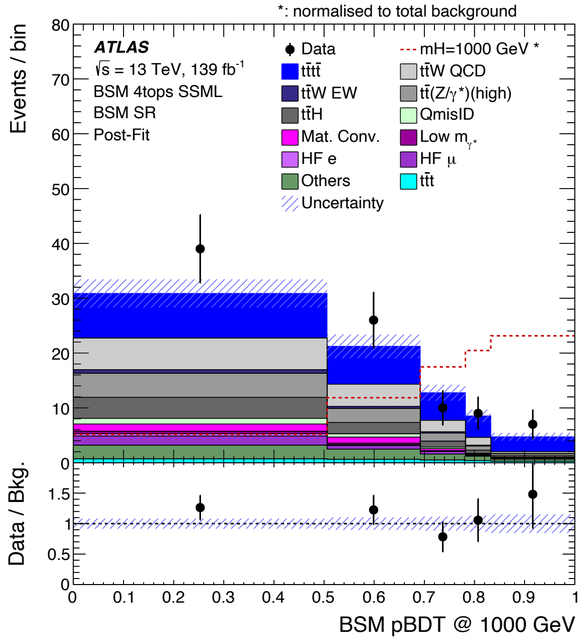
BSM searches

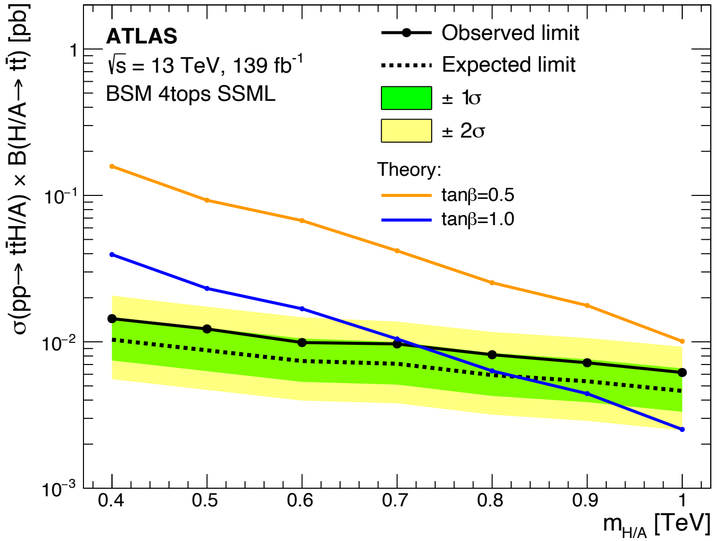
Search for $t\bar{t}H/A \rightarrow t\bar{t}t\bar{t}$

arXiv:2211.01136

- Search for associated production of heavy (pseudo-)scalar Higgs decay to $t\bar{t}$ (2HDM)
  - Most dominant decay for $m_{H/A} > 2m_{top}$
  - Search for masses between 400 and 1000 GeV
- Target 2lSS/3l channels, similar challenges as SM $t\bar{t}t\bar{t}$ (ttV/ttH, non-prompt backgrounds)
  - Template fit background estimation
- Signal ID using 2 BDT classifiers:
  - *SM BDT*: separates SM $t\bar{t}t\bar{t}$ from other bkgs
  - *BSM mass-parameterized. BDT*: BSM $t\bar{t}t\bar{t}$ vs. all
- 4x better exclusion limits over previous result with 36 fb^{-1}!



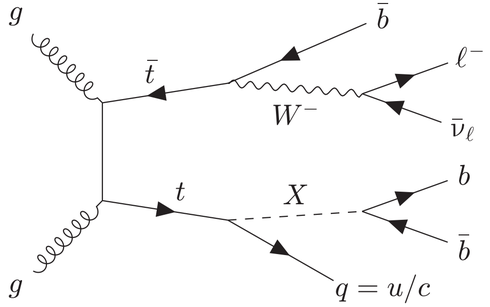




$t \to qX(b\bar{b})$ scalar resonance search

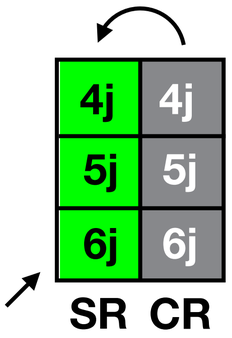
arXiv:2301.03902

- Froggatt-Nielson mechanism: broken U(1) flavor symmetry w/ BSM Higgs X
  - $M_X < 200$ GeV, $X \to b\bar{b}$ leads decay
- Main background $t\bar{t}$+jets, use data-driven correction in **control regions**
  - Use **pseudo-continuous b-tagging!**
    - b_{60}-jet (60% tag efficiency working point) and b_{70}-jet (looser: pass 70%, fail 60%)
    - SR = $3b_{60}$; CR = $2b_{60}+1b_{70}$
- 3x better than previous analyses! (adjusted for different luminosity)
  - Better b-tagging, using neural net training vs. likelihood discriminant, $t\bar{t}$+jets modeling improvement

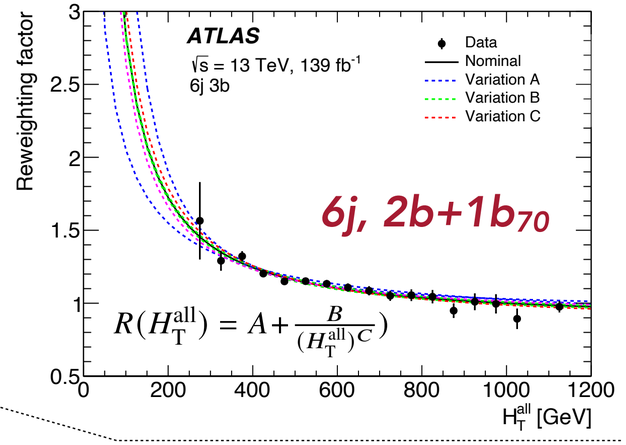


Trigger on lepton, select events with 4, 5, or 6 jets + 3 b_{70}-tagged jets

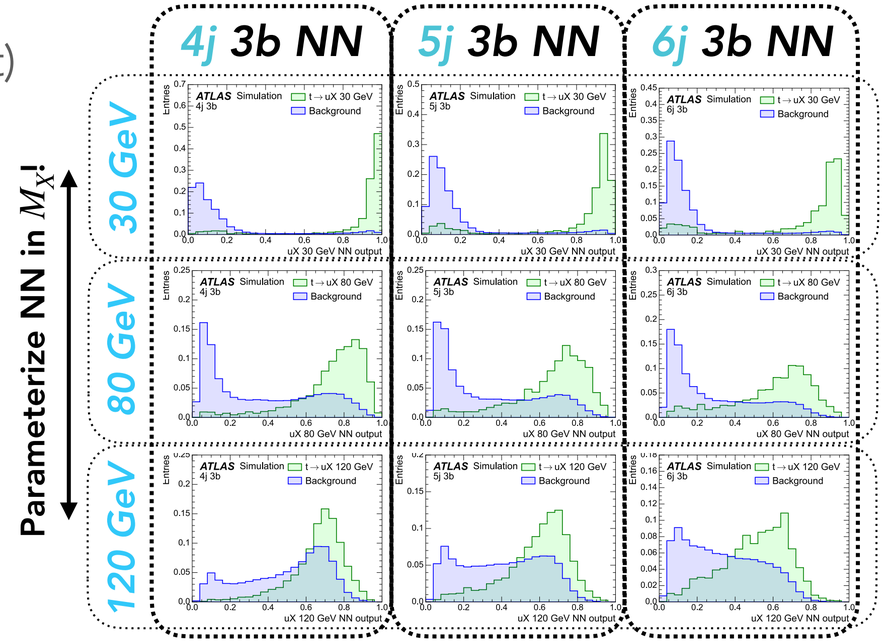
Reweight $t\bar{t}$ bkg



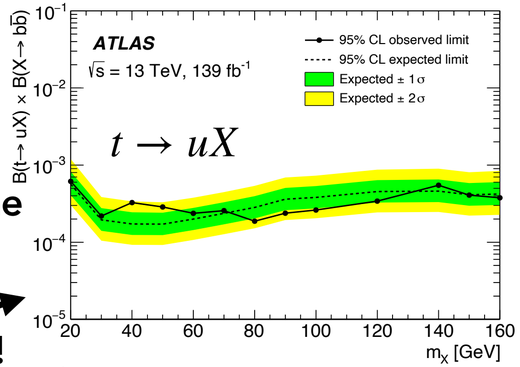
$$R(H_T^{all}) = \frac{N_{Data}(H_T^{all}) - N_{MC}^{non\text{-}t\bar{t}}(H_T^{all})}{N_{MC}^{t\bar{t}}(H_T^{all})}$$

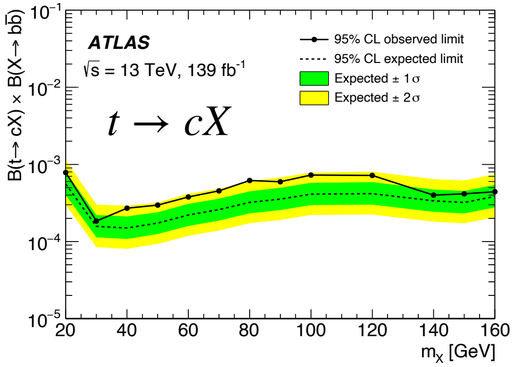


Train on three M_X signals + all backgrounds separately for 4j,5j,6j and *uX/cX*



Run some fits in the SRs!





Summary and Conclusions

- ATLAS is pursuing **rich program of top quark physics** using the full Run 2 dataset
- Many improved searches for **FCNC**, **limits improved by up to 5x** over previous measurements
- Nearly all measurements and searches interpreted in SMEFT framework
- ATLAS has **observed two new top-associated processes**: $t\gamma$ and $t\bar{t}t\bar{t}$
- **First and only** differential cross section and charge asymmetry measurements of $t\bar{t}W$
- Searches for BSM signals giving unique detector signatures

Thank you for your attention!

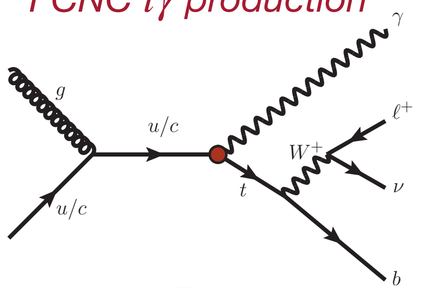
Backup

Search for $t \to \gamma u/\gamma c$ and $u/c \to t\gamma$

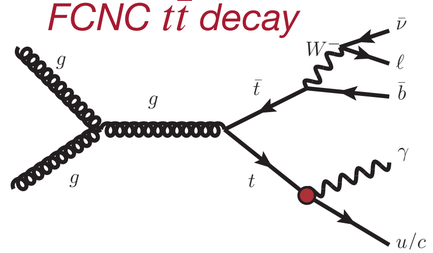
arXiv:2205.02537

- Search for FCNC $u\gamma t$ and $c\gamma t$ with single-top production **and** decay
- Backgrounds from $t\bar{t}\gamma$, $W\gamma$+jets, and misidentified electrons or hadrons
  - CR for prompt photon backgrounds
  - $\gamma \to e$ fake rate estimated with $e\gamma$ near m_Z
  - $\gamma \to h$ estimated with ABCD method
- Train a multi-class neural net to classify:
  - Production mode vs. decay mode vs. bkg
- Most stringent limits to date!
  - Improved by 3.3-5.4x over previous limit from including >1 jet events and increased luminosity

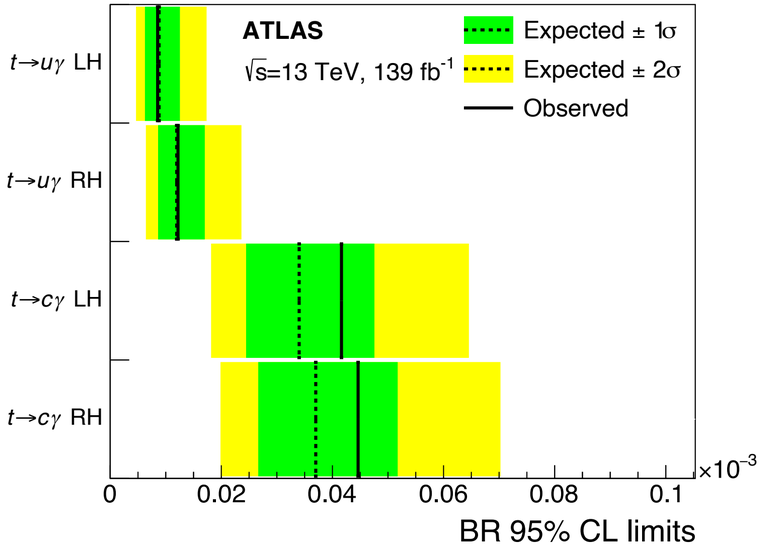
FCNC $t\gamma$ production

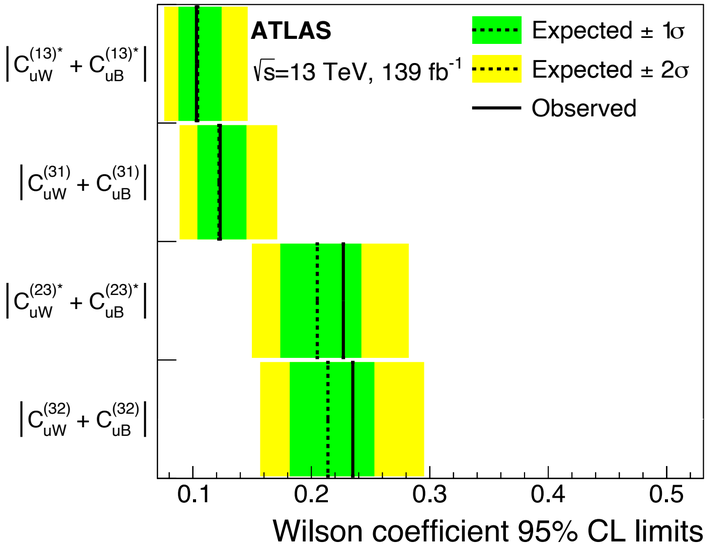


FCNC $t\bar{t}$ decay



Object	SR	CR $t\bar{t}\gamma$	CR $W\gamma$+jets
Photon ($p_T > 20$ GeV)	= 1		
Lepton ($p_T > 27$ GeV)	= 1		
E_T^{miss}	> 30 GeV		
Jets ($p_T > 25$ GeV)	≥ 1	≥ 4	≥ 1
b-tagged jets (60% WP)	= 1	–	= 0
b-tagged jets (70% WP)	= 1	≥ 1	= 0
b-tagged jets (77% WP)	= 1	≥ 2	= 1
$m(e,\gamma)$	–	–	$\notin$ [80, 100] GeV





Search for u/cHt, $H \to \tau^+\tau^-$

arXiv:2208.11415

- Target FCNC through production and decays of top quarks
  - Target several channels depending on decay of taus ($t_\ell\tau_{\text{had}}\tau_{\text{had}}$ most sensitive)
- Perform kinematic fit to reconstruct invisible tau decay products
- Dominant background is $t\bar{t}$+jets and fake τ - train BDT to discriminate S/B
- Exclusion limits improve by factor 2.5 from analysis improvements
  - Lepton channels, tH production, etc.

$$\chi^2 = \left(\frac{m_{\tau\tau,\text{fit}} - m_H}{\sigma_{\tau\tau}}\right)^2 + \left(\frac{E_{x,\text{fit}}^{\text{miss}} - E_x^{\text{miss}}}{\sigma_{E_x^{\text{miss}}}}\right)^2 + \left(\frac{E_{y,\text{fit}}^{\text{miss}} - E_y^{\text{miss}}}{\sigma_{E_y^{\text{miss}}}}\right)^2$$