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

FSP ATLAS
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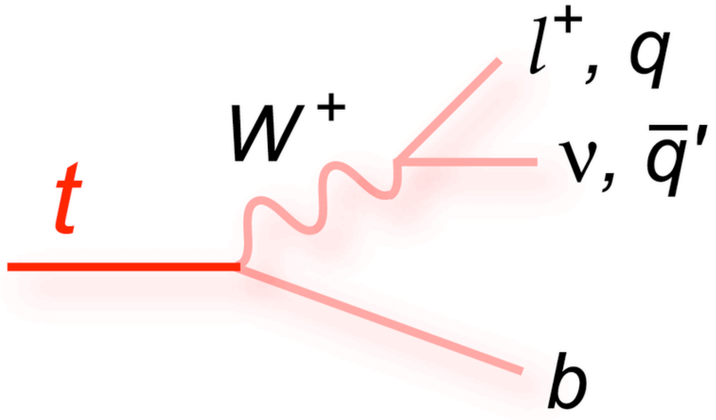
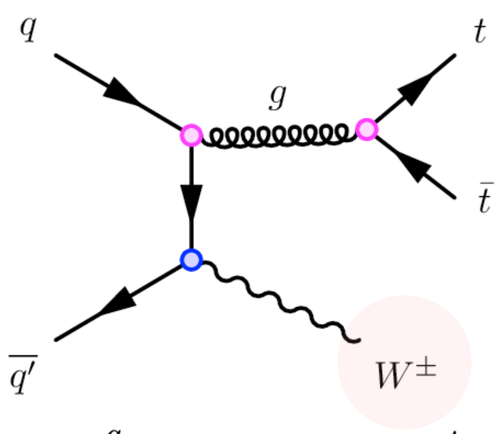
Overview



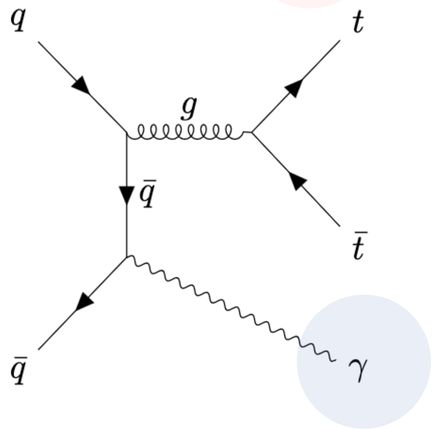
- **Top quark in association with bosons**
  - Essential for testing SM and probing new physics
  - New results: **Cross section** measurements and **charge asymmetry** studies in $t\bar{t}W$ and $t\bar{t}\gamma$
- **BSM searches with top quarks**
  - Top **plays integral part in multiple BSM due to heavy mass, highest coupling to Higgs**
  - Multiple analyses searching for **new particles with top quarks in final state**: search for **Vector-Like quarks**, **heavy resonances** such as Z' etc. (not a part of this talk)
  - Many BSM introduce **new particles that enhance FCNC interactions**; top decay processes excellent probe for such particles (New results on t→qZ, t→qX(bb), cLFV tμτq)
- General strategies involve **MVA techniques to improve signal sensitivity, profile-likelihood to constrain systematics, unfolding on reconstructed data for differential measurements**

Top Production with Bosons

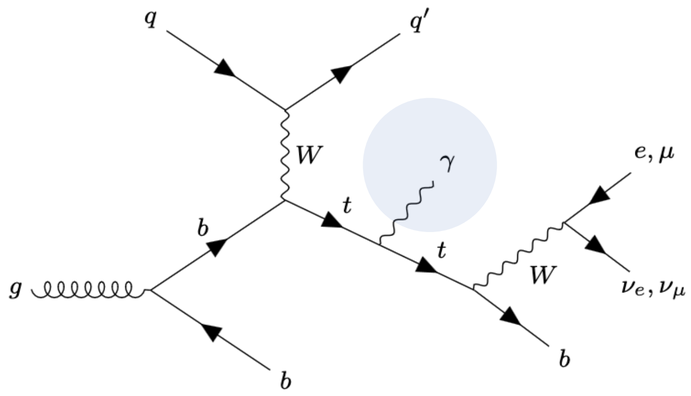


Rare processes that

- **test electroweak couplings** of top quarks with bosons as predicted by SM
- **probe anomalous couplings** for potential signs of new physics
- **test higher-order calculations and Monte Carlo simulations** for better modelling,
- are **irreducible background** to many BSM searches and to important SM measurements (such as $t\bar{t}H$)



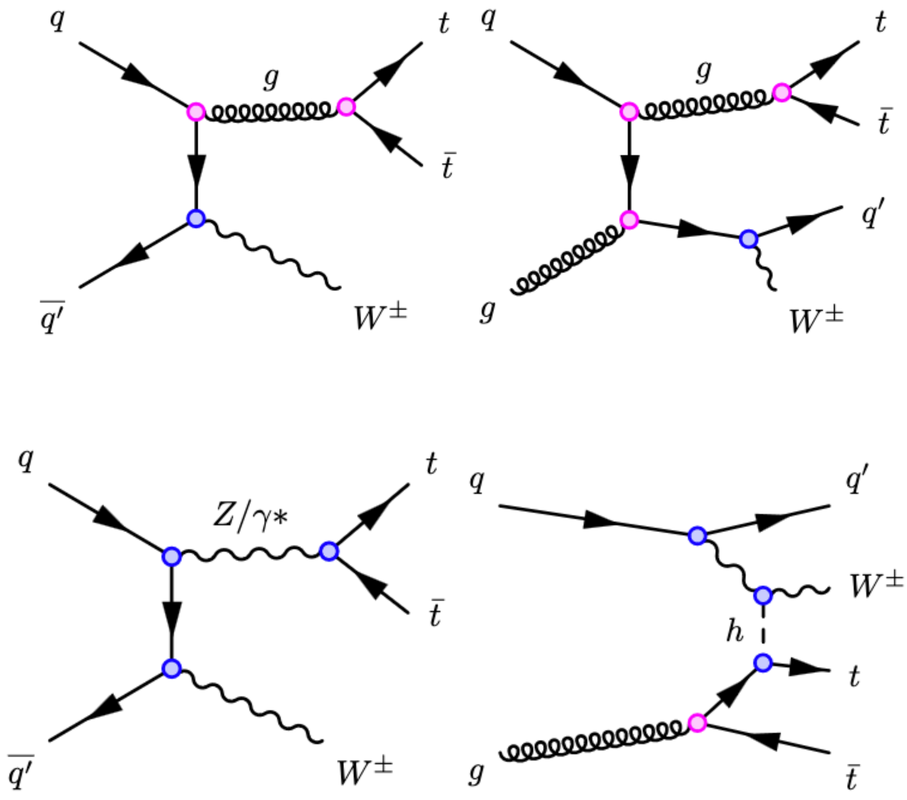
ATLAS collected **huge dataset (139 fb^{-1}) during Run 2 allowing for first measurements of very rare processes, perform differential measurements, study top-boson couplings to greater precision**



$t\bar{t}W$ Inclusive and Differential

[ATLAS-CONF-2023-019]

- Rich phenomenology from **charge-asymmetric production** and complex higher order QCD and EWK corrections
- Observed in Run 1; Run 2 makes precise measurements possible
- Irreducible source of same-sign dilepton pairs - **dominant background for other rare searches** (e.g $t\bar{t}H$ and $t\bar{t}t\bar{t}$)
- Measurement done on events with **3ℓ** or **same-sign 2ℓ**
- Signal and Control regions defined on basis of number of jets, b-tagged jets, lepton charge and flavour
- Major backgrounds:
  - **irreducible**: diboson, $t\bar{t}Z$
  - **reducible**: fake/non-prompt leptons mainly from $t\bar{t}$ production, electrons with charge misassignment (QMisID)



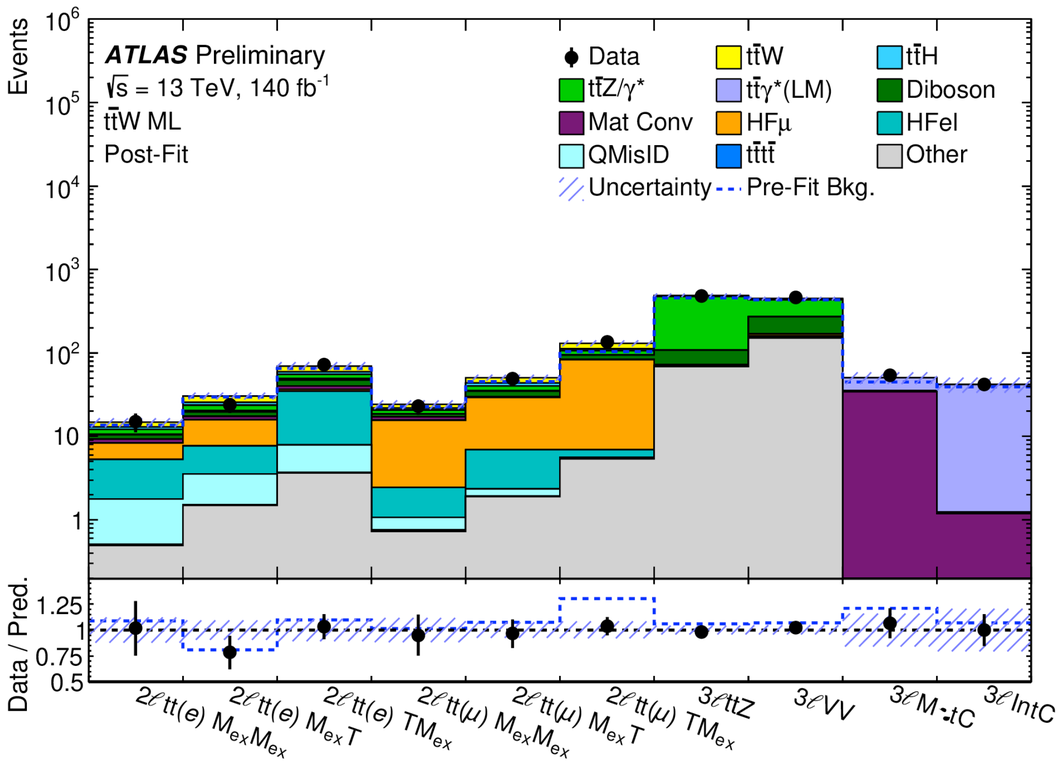
$t\bar{t}W$ Inclusive

[ATLAS-CONF-2023-019]

- Simultaneous profile-likelihood fit to data using event yields in 56 SRs and 10 CRs

$\sigma(t\bar{t}W) = 890 \pm 50$ (stat.) ± 70 (syst.) $= 890 \pm 80$ (tot.) fb

- **Consistent with SM at 1.5σ:** $722\ ^{+70}_{-78}$ (scale) ± 7 (PDF) fb (JHEP 11 (2021) 029)



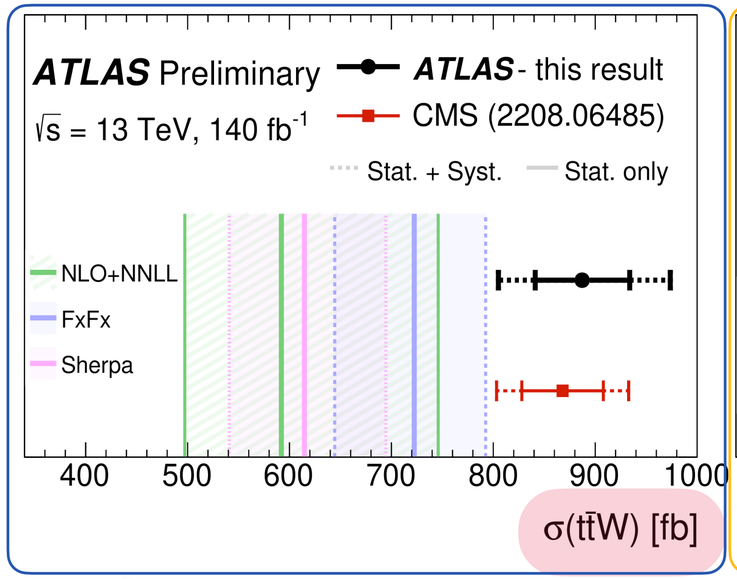
- Ratio ($t\bar{t}W^+/t\bar{t}W^-$) in good agreement with prediction

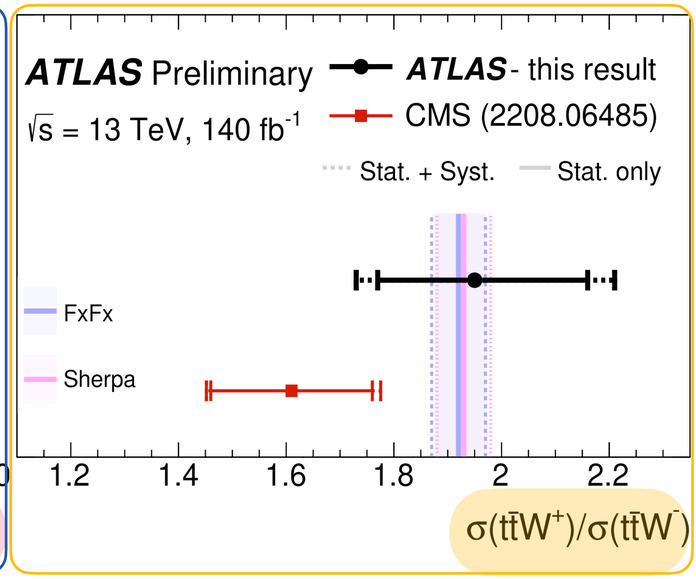
$R(t\bar{t}W) = 1.95^{+0.21}_{-0.18}$(stat.)$^{+0.16}_{-0.13}$(syst.)

$R(t\bar{t}W) = 1.92 \pm 0.02$ (scale) ± 0.04 (PDF) (FxFx, JHEP 11 (2021) 029)

- Relative charge asymmetry, A_c^{rel}, also in very good agreement with prediction

- **Major systematics - $t\bar{t}W$ modelling, prompt lepton background normalisation**

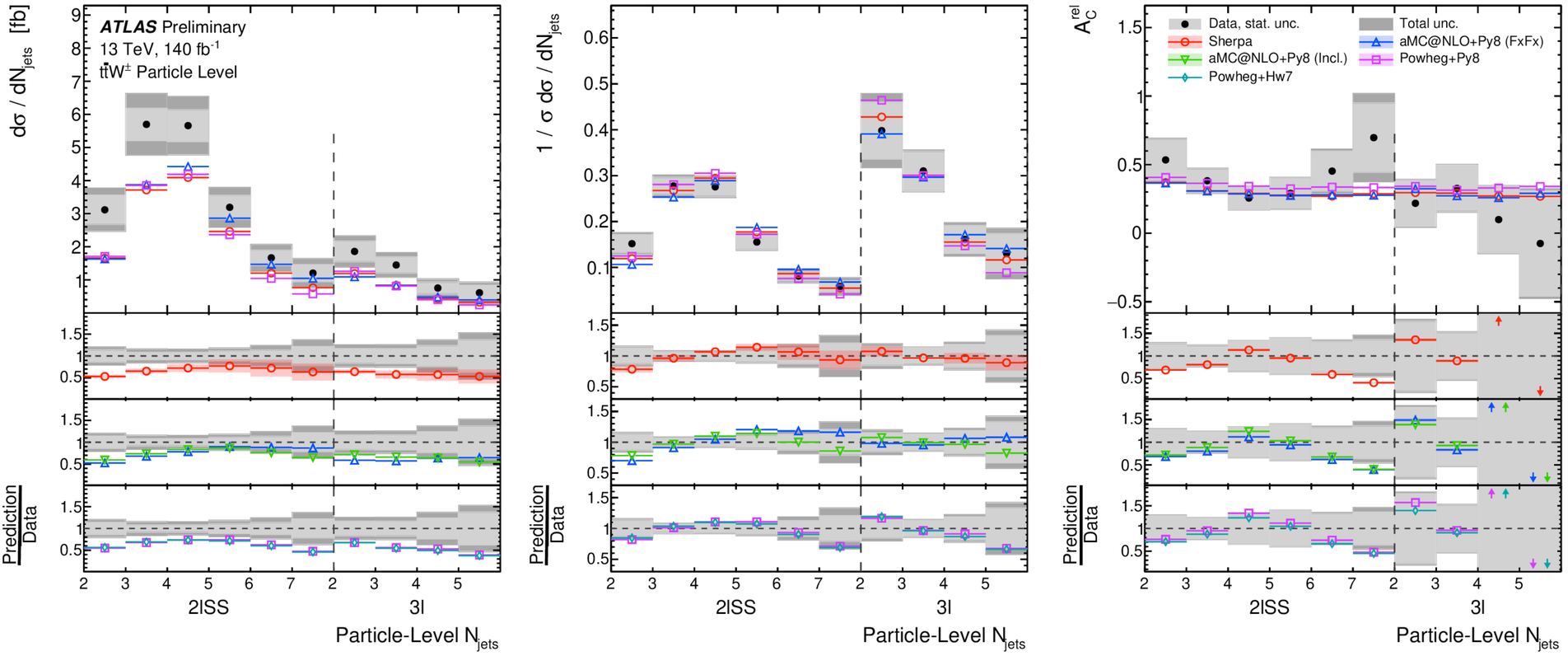




$t\bar{t}W$ Differential

[ATLAS-CONF-2023-019]

- Profile Likelihood Unfolding to measure differential absolute and normalised cross-sections at particle level - 7 unfolded observables (H_T, no. of jets, angular distance between lepton and b-jet, etc...)

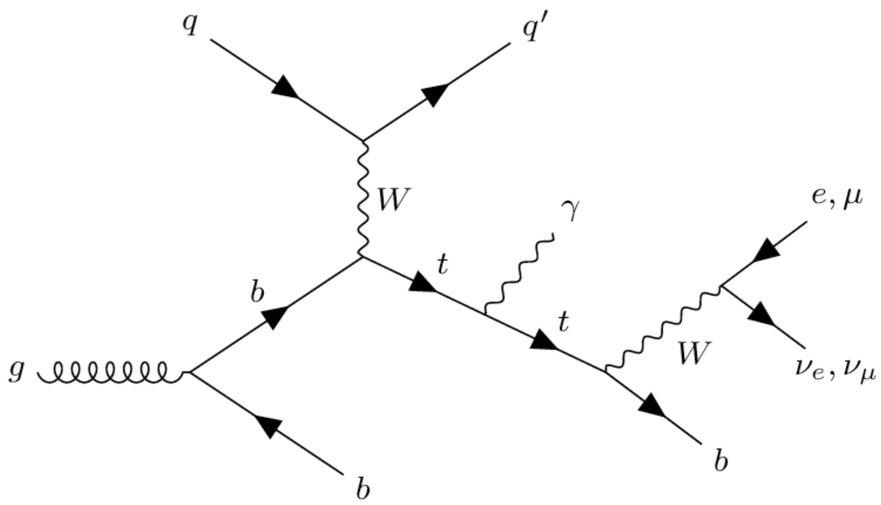


- Slight disagreement in absolute cross-section measurements
- Normalised cross-section in good agreement with data
- Differential uncertainties **dominated by low data statistics** and **$t\bar{t}W$ modelling**

Observation of tqγ

[arXiv:2302.01283]

- **Final state signature:** one lepton, one photon, one b-tagged jet, one forward-jet of t-channel production and missing transverse momentum
- Two SRs defined - w/o and w/ forward jets
- Largest background contribution: processes with prompt photons ($t\bar{t}\gamma$ and $W\gamma$)
- Dedicated control regions defined for $t\bar{t}\gamma$ and $W\gamma$
- Data-driven estimate of background processes with misidentified (fake) objects, e.g. e → γ, hadron → γ fakes
- Neural networks trained on 12 (15) variables in the region w/o forward jet (1 forward jet) to separate signal from the background



Observation of tqγ

[arXiv:2302.01283]

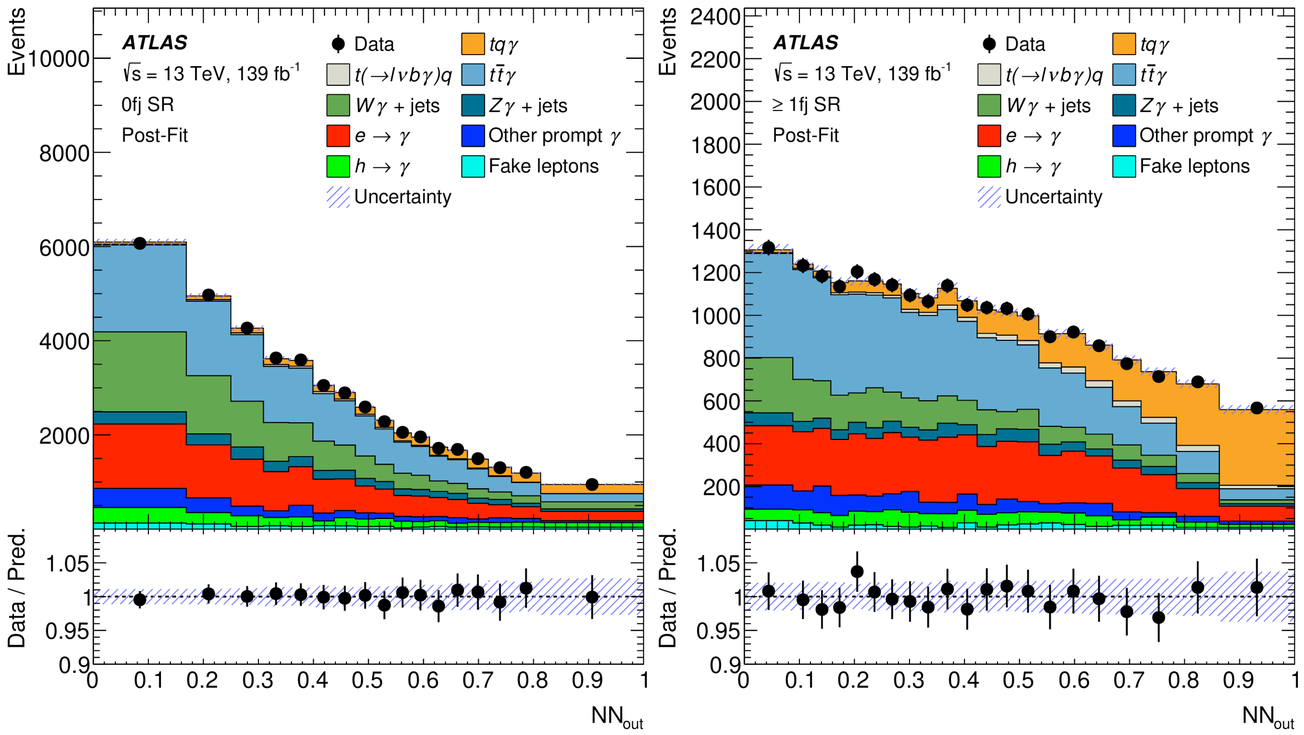
- Cross section measured in a fiducial phase space at parton level (only events with photons radiated from top) and at particle level (events where photons can be from production and decay) using a profile-likelihood unfolding

- **Parton level:** $\sigma_{tq\gamma} \times BR(t \to \ell\nu b) = 688 \pm 23(\text{stat})^{+75}_{-71}(\text{syst})$ fb

  ($\sigma_{tq\gamma}^{QCD+EW\ NLO} = 515^{+36}_{-42}$ fb) **agreement at 2.1σ**

- **Particle level:** $\sigma_{tq\gamma} \times BR(t \to \ell\nu b) + \sigma_{t\to\ell\nu b\gamma q} = 303 \pm 9(\text{stat})^{+33}_{-32}(\text{syst})$ fb

  ($\sigma_{tq\gamma}^{QCD+EW\ NLO} = 217^{+27}_{-15}$ fb) **agreement at 2.0σ**



- **First observation:** Observed (expected) significance: **9.3σ** (6.8σ)
- **Major systematics: $t\bar{t}\gamma$ and $t\bar{t}$ modelling, limited signal and background MC statistics**

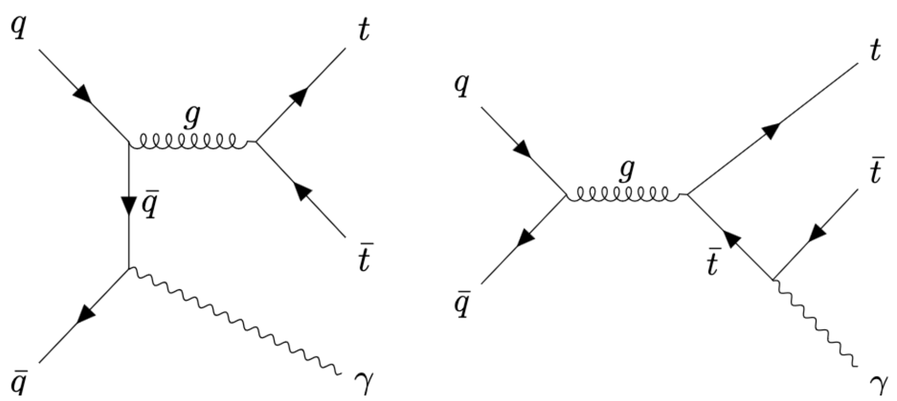
Charge Asymmetry: $t\bar{t}\gamma$

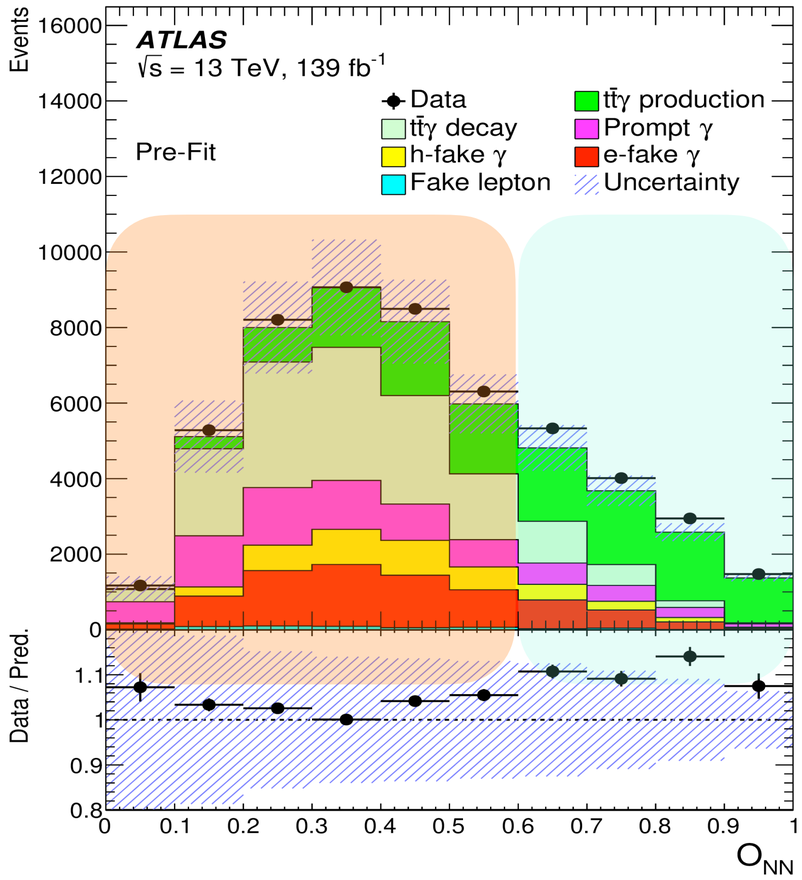
Phys. Lett. B 843 (2023) 137848

- Enhanced asymmetry in $t\bar{t}\gamma$ production compared to $t\bar{t}$
  - Larger fraction of $q\bar{q}$ initiated processes
  - Dominant LO EW contribution to A_C: interference between QED initial- and final-state radiation in $t\bar{t}\gamma$ production

$$A_C = \frac{N(|y_t| > |y_{\bar{t}}|) - N(|y_t| < |y_{\bar{t}}|)}{N(|y_t| > |y_{\bar{t}}|) + N(|y_t| < |y_{\bar{t}}|)},$$

- $t\bar{t}$ events with **exactly one additional high-p_T, isolated photon selected**
- Only **$t\bar{t}\gamma$ production chosen as signal** to overcome dilution from $t\bar{t}$ decays
- Data-driven estimate of background processes with fake objects (similar to $tq\gamma$ measurement)
- Neural network to discriminate signal from background ($O_{NN} <$ 0.6 background enriched and $O_{NN} \geq$ 0.6 for signal enriched)

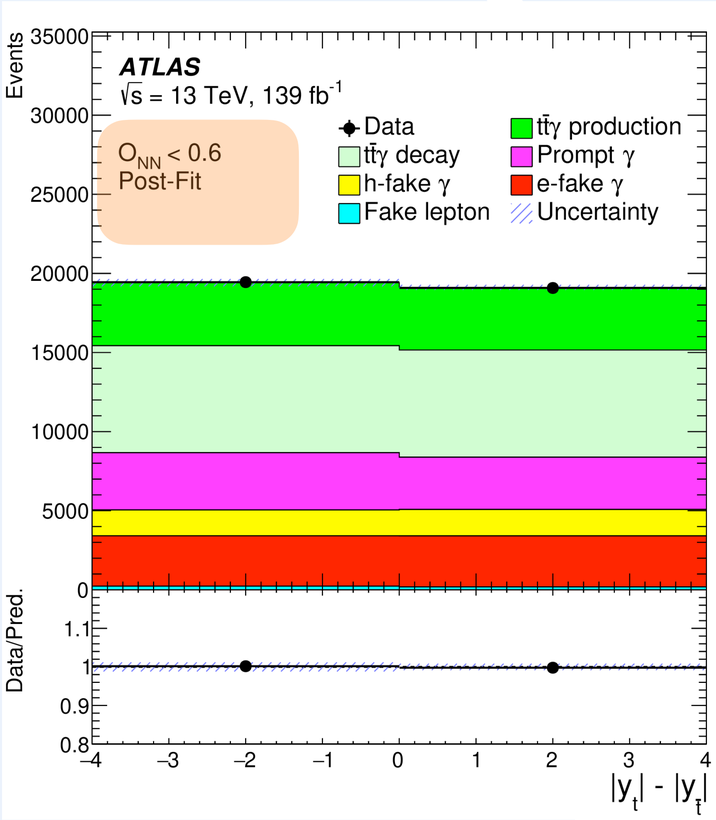


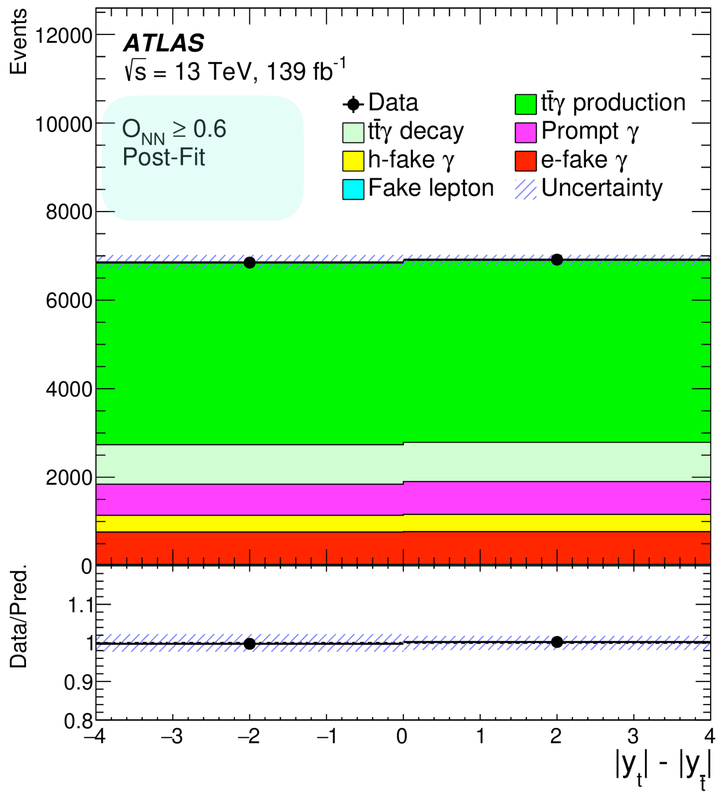


Charge Asymmetry: $t\bar{t}\gamma$

Phys. Lett. B 843 (2023) 137848

- Reconstruct top quark pairs using kinematic likelihood fit to define pseudorapidities y_t and $y_{\bar{t}}$
- Simultaneous maximum-likelihood unfolding of $|y_t| - |y_{\bar{t}}|$ performed in 2 regions defined by O_{NN}





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

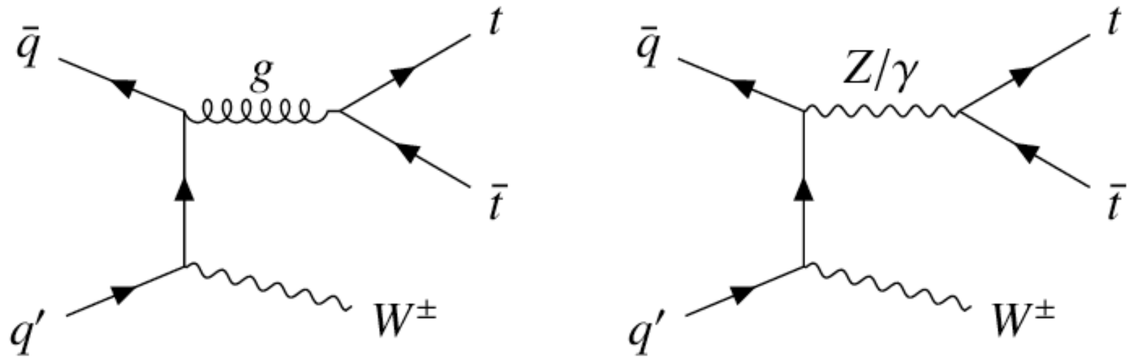
(SM at NLO: $A_c = -0.014 \pm 0.001(\text{ scale }))$

- **Dominated by data statistics**
- **Major systematics: MC statistics for prompt-photon background, experimental systematic sources related to jets and $\mathbf{E_T^{miss}}$**

Charge Asymmetry: $t\bar{t}W$

[arXiv:2301.04245], accepted by JHEP

- Enhanced asymmetry compared to $t\bar{t}$
  - $q\bar{q}$ initiated processes dominate
  - W emission from initial states polarises t and $\bar{t}$
  - Larger asymmetry in decay products

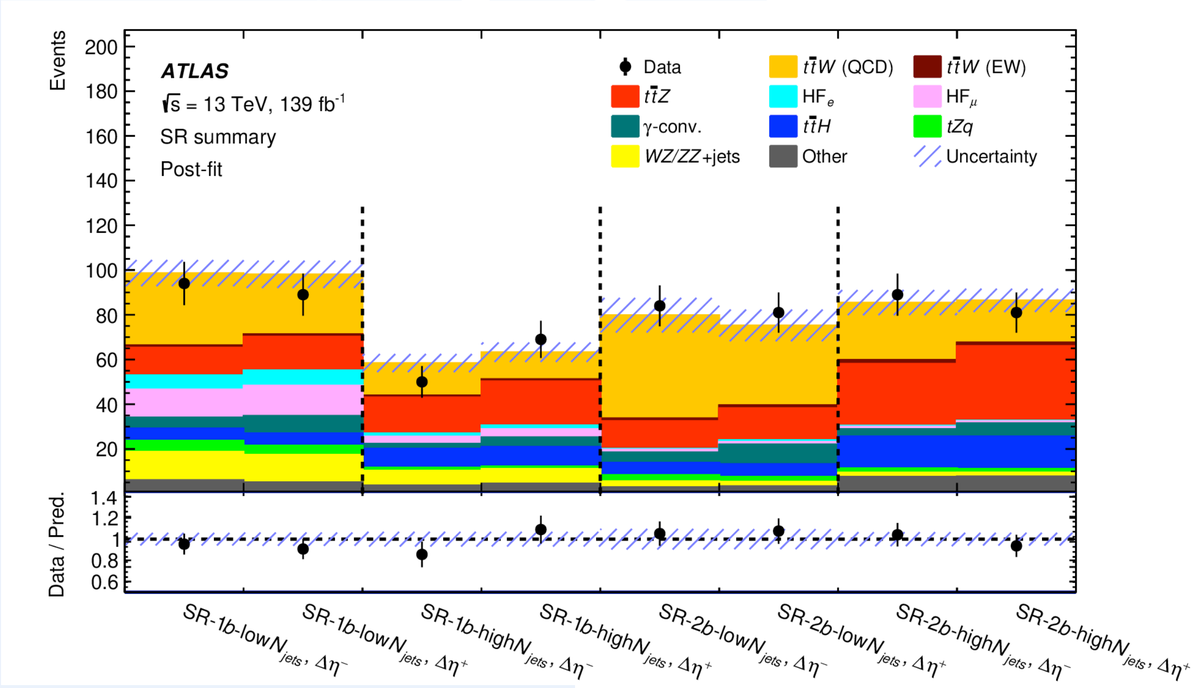


- First study in **3ℓ** final state with requirements on number of jets, b-tagged jets, missing transverse momentum imposed to define SR
- CRs defined to constrain major backgrounds ($t\bar{t}Z$, non-prompt leptons from heavy flavour hadron decays)
- 5-fold BDT trained to correctly match leptons to either t or $\bar{t}$ with 71% accuracy

Charge Asymmetry: $t\bar{t}W$

[arXiv:2301.04245], accepted by JHEP

- Simultaneous profile-likelihood fit performed to event yields in all SRs and CRs.



$$A_c^l = -0.123 \pm 0.136(\text{stat}) \pm 0.051(\text{syst})$$ [**Reconstruction** level]

(Sherpa: $A_c^l = -0.084^{+0.005}_{-0.003}(\text{scale}) \pm 0.006(\text{MC stat})$)

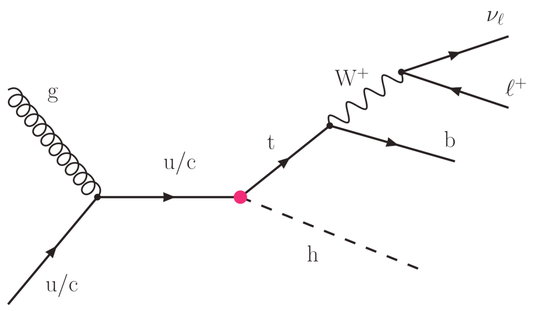
- Unfolding based on a profile-likelihood
- Measurement at particle level in a fiducial phase space close to the reco. level selection
- **Lepton-top association based on m_{lb}** discriminant with 65% efficiency to select correct leptons

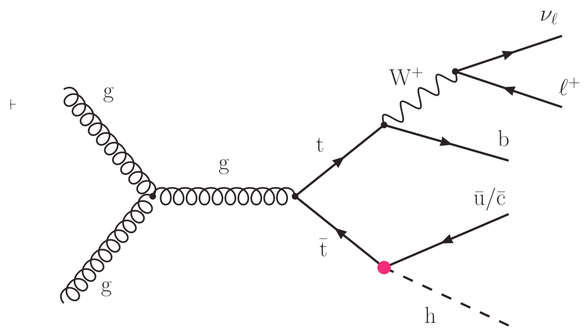
$$A_c^l = -0.112 \pm 0.170(\text{stat}) \pm 0.055(\text{syst})$$ [**Particle** level]

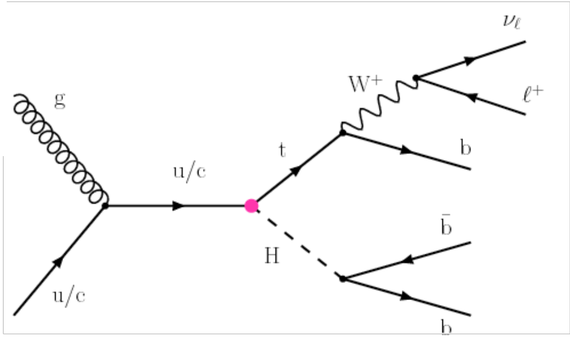
(Sherpa: $A_c^l = -0.063^{+0.007}_{-0.004}(\text{scale}) \pm 0.004(\text{MC stat})$)

FCNC Searches with Top

- **Highly suppressed in SM** because of GIM and forbidden tree level diagrams
- **Enhanced couplings in several BSM scenarios** (2HDM, SUSY, composite Higgs etc.)
- Observation of enhanced rates would be a clear evidence for new physics





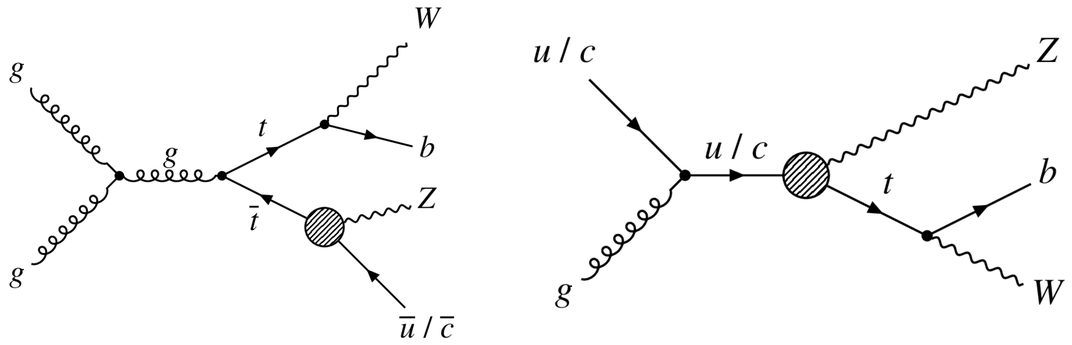


- **Multiple top FCNC couplings already measured in ATLAS in Run 2**

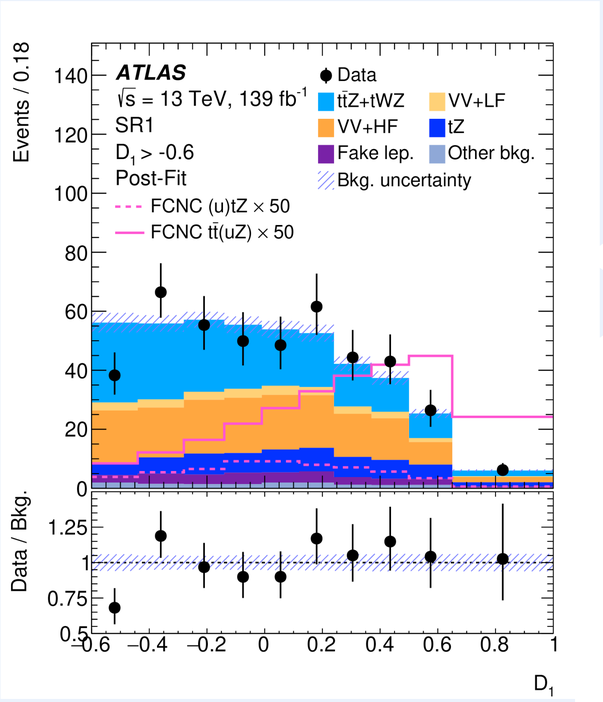
Process	SM	ATLAS **(Current limits on the BR)**	
$t \to u\gamma$	$4 \cdot 10^{-16}$	$0.85 \cdot 10^{-5}$	Phys. Lett. B 842 (2023) 137379
$t \to c\gamma$	$5 \cdot 10^{-14}$	$4.2 \cdot 10^{-5}$	
$t \to ug$	$4 \cdot 10^{-14}$	$0.61 \cdot 10^{-4}$	Eur. Phys. J. C 82 (2022) 334
$t \to cg$	$5 \cdot 10^{-12}$	$3.7 \cdot 10^{-4}$	
$t \to uZ$	$8 \cdot 10^{-17}$	$6.2 \cdot 10^{-5}$	arXiv:2301.11605 now accepted by PRD !!
$t \to cZ$	$1 \cdot 10^{-14}$	$13 \cdot 10^{-5}$	
$t \to uH$	$2 \cdot 10^{-17}$	$6.9 \cdot 10^{-4} (H \to \tau\tau)$	JHEP06(2023)155
		$7.6 \cdot 10^{-4} (H \to bb)$	
$t \to cH$	$3 \cdot 10^{-15}$	$9.4 \cdot 10^{-4} (H \to \tau\tau)$	arXiv:2301.03902
		$8.8 \cdot 10^{-4} (H \to bb)$	

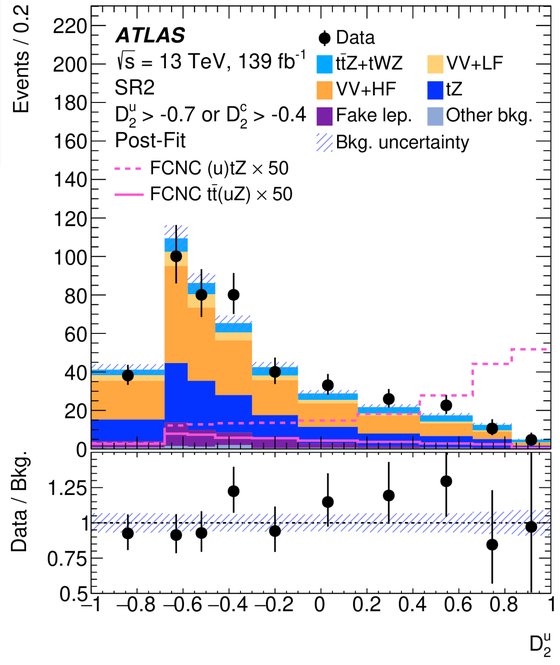
FCNC t→qZ

[arXiv:2301.11605], accepted by PRD



- Several BSM predict BR between 10^{-4} and 10^{-7} (SM at 10^{-14})
- Search for **tZu or tZc coupling** in **3ℓ** final states based on opposite sign, no. of jets and b-jets and missing transverse momentum
- Main backgrounds: prompt leptons from $t\bar{t}Z$ and diboson
- Gradient Boosted Decision Trees target separately tZu production, tZc production and the $t\bar{t}$ decay process
- Discriminators based on multiple variables - reconstructed SM and FCNC top masses, angular separation between top and leptons etc.





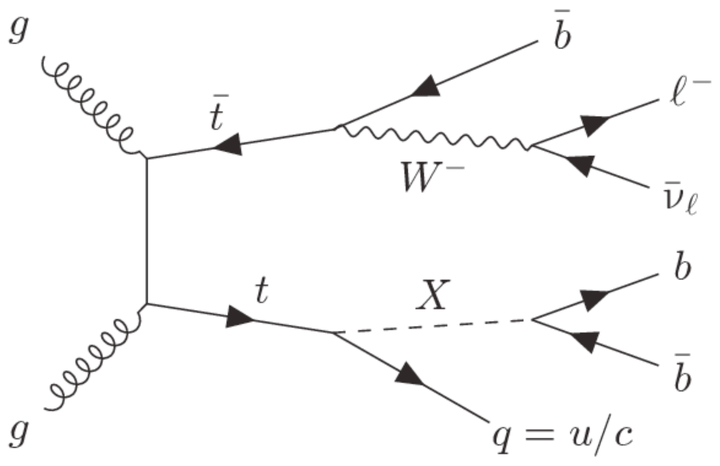
Observable	Vertex	Coupling	Observed	Expected
	SRs+CRs			
$\mathcal{B}(t \to Zq)$	tZu	LH	6.2×10^{-5}	$4.9\,^{+2.1}_{-1.4} \times 10^{-5}$
$\mathcal{B}(t \to Zq)$	tZu	RH	6.6×10^{-5}	$5.1\,^{+2.1}_{-1.4} \times 10^{-5}$
$\mathcal{B}(t \to Zq)$	tZc	LH	13×10^{-5}	$11\,^{+5}_{-3} \times 10^{-5}$
$\mathcal{B}(t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

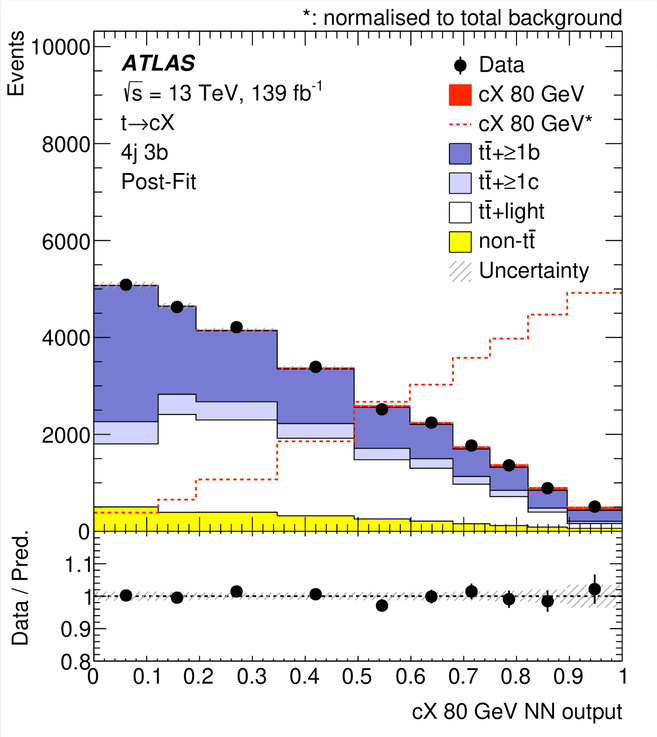
- Data in good agreement with SM expectations, no excess seen
- **Limits improved by x3 (x2) for tZu (tZc) from previous 36 fb^{-1} results**

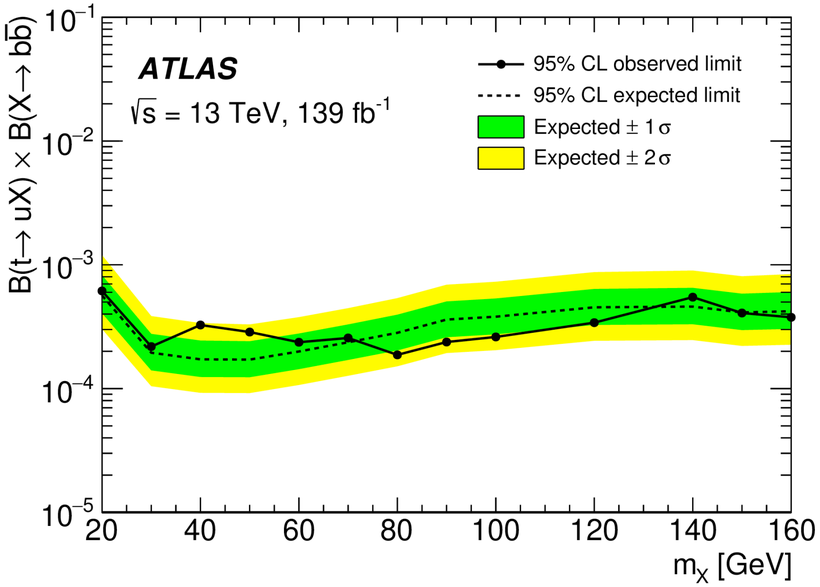
FCNC t→qX(bb)

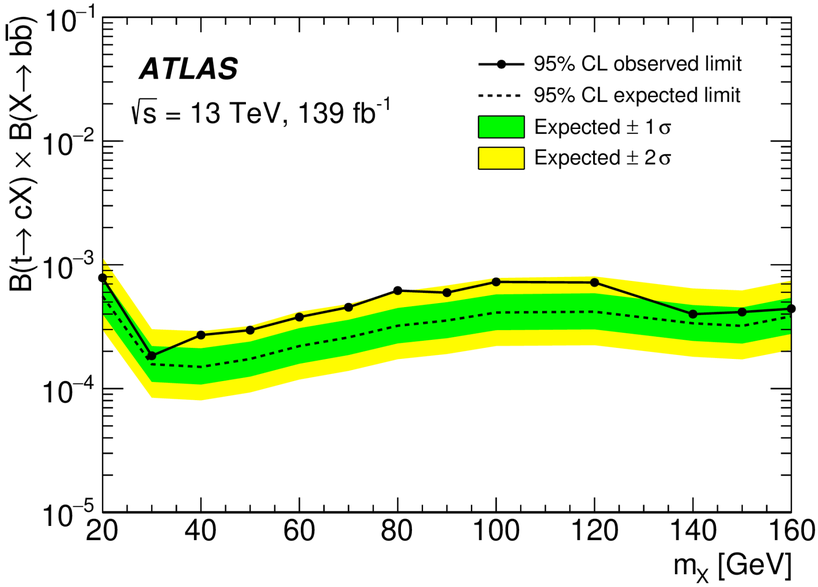
[arXiv:2301.03902]

- Non-SM Higgs field X with flavour charge (**flavon**) enhances FCNC couplings
- Search for the **light, neutral scalar X** in FCNC top decays in $t\bar{t}$ events
- Performed separately for **t→uX and t→cX with X→$b\bar{b}$**
- NN trained on jet and lepton kinematics and m_{bb} with m_X at 30, 80, 120 GeV







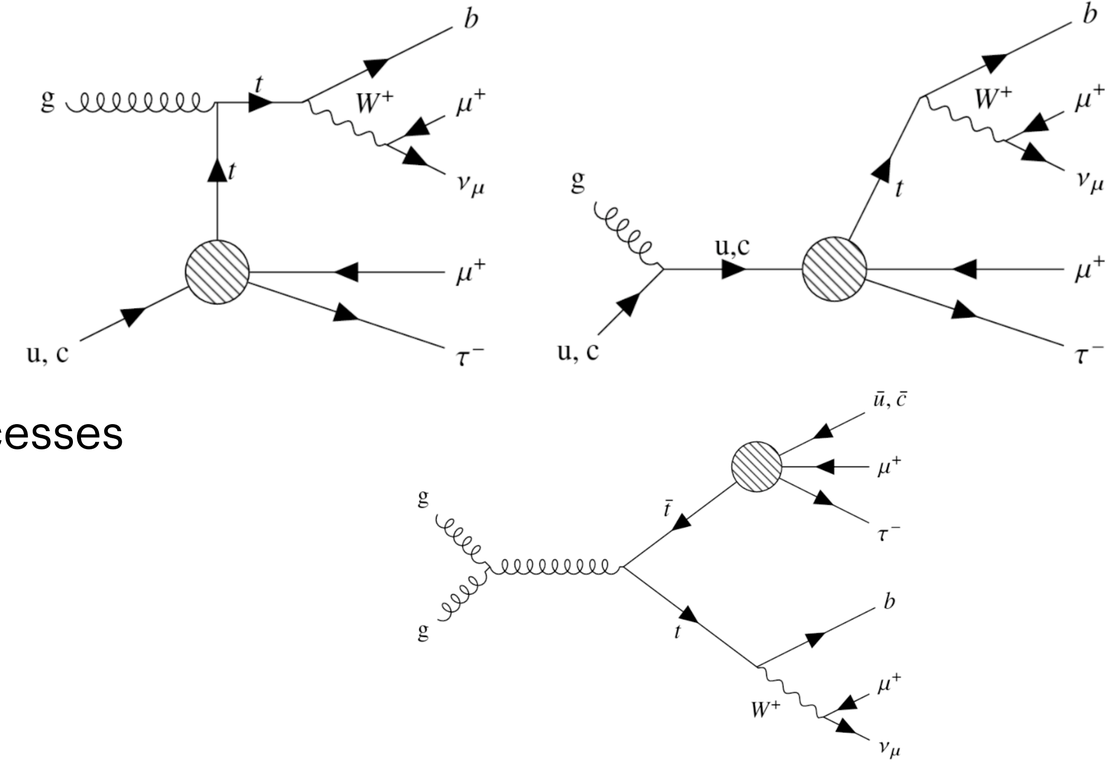


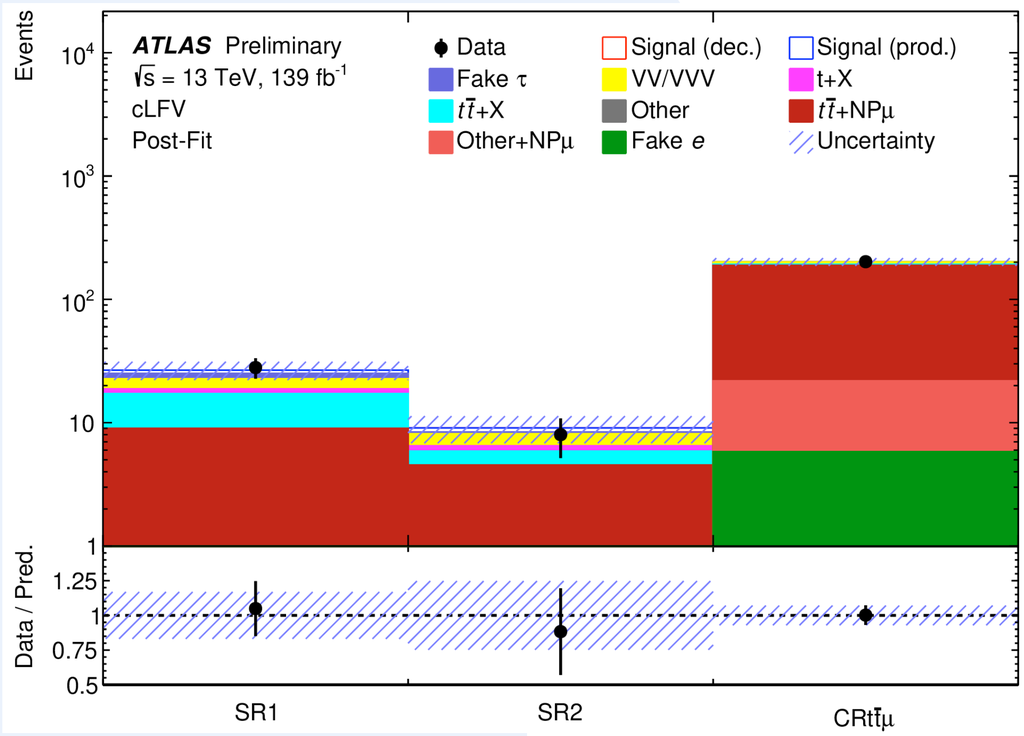
- No signal excess but upper limits on BR(t→uX) and BR(t→cX) of ~2×10^{-4}
- **Limits on BR(t→qH) on average x3 improved with respect to previous 36 fb^{-1} results**

cLFV tμτq

[ATLAS-CONF-2023-001]

- Charged lepton flavour violation in BSM (**leptoquarks**)
- Search for cLFV vertex in both production and decay processes
- Focus on **3ℓ** selection: $\mu\mu\tau_{\text{had-vis}}$ / μμμ / eμμ
- Dedicated fake $\tau_{\text{had-vis}}$ and non-prompt muon estimation





- No signal excess but upper limits on BR(t→uτq) derived from Wilson coefficients in EFT (better than ATLAS FCNC tZq)
- **Dominated by stat. uncert. in data**

	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}

Summary

- Presented recent results for:
  - Top production with associated boson

    $t\bar{t}W$ inclusive and differential >>

    Observation of $tq\gamma$ >>

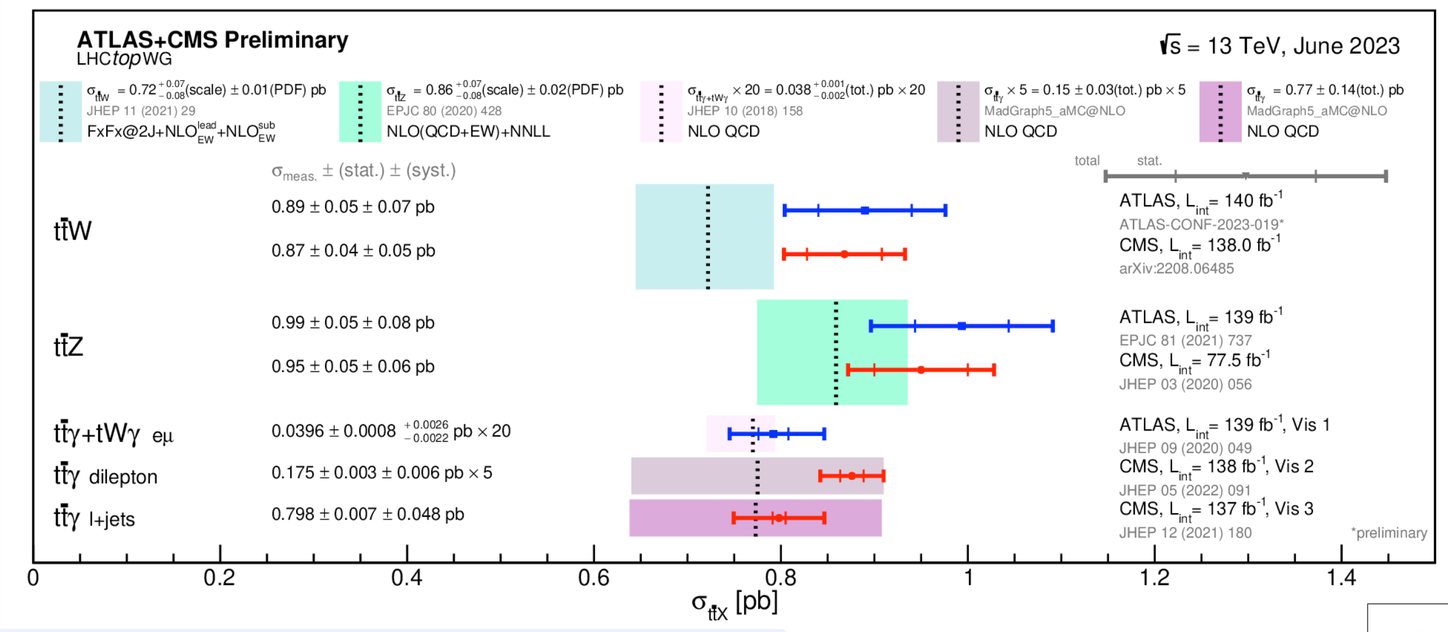
    Charge Asymmetry: $t\bar{t}\gamma$ >> and $t\bar{t}W$ >>
  - New Phenomena searches for BSM

    FCNC t→qZ >>

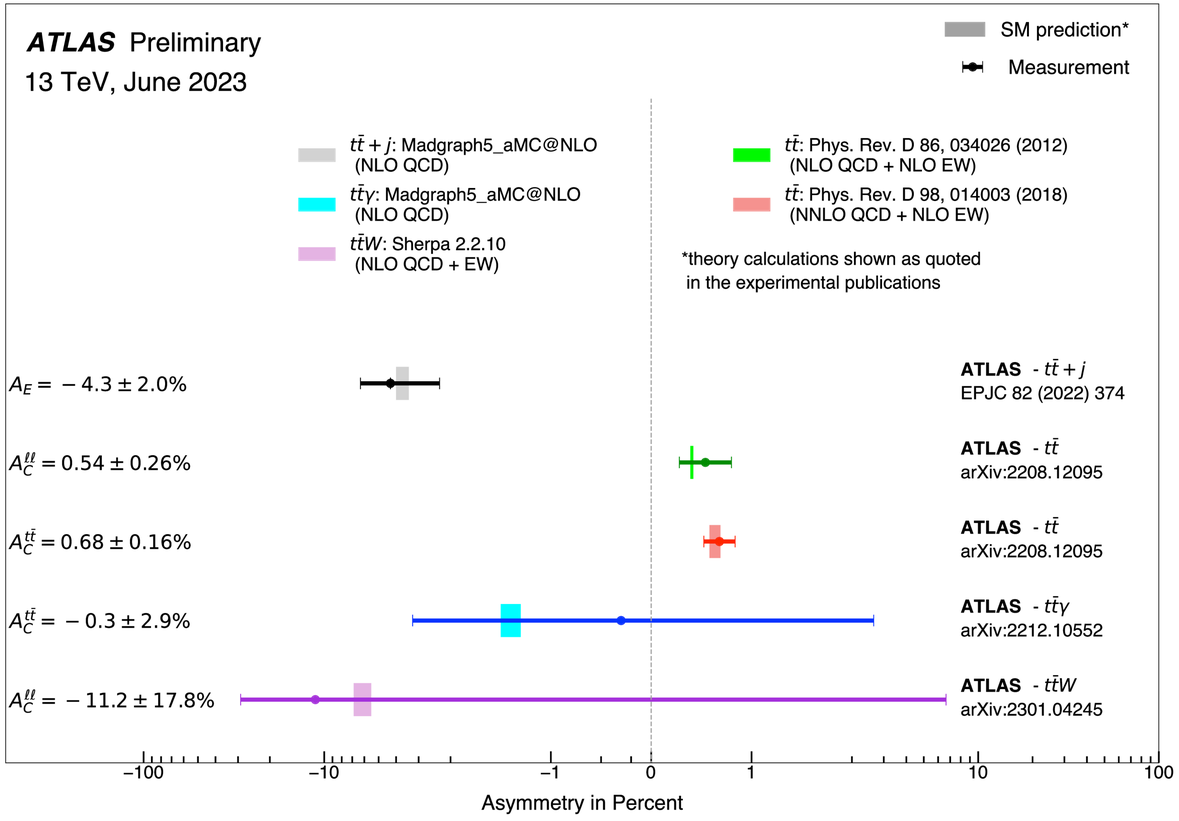
    FCNC t→qX(bb) >>

    cLFV tμτq >>

- Top sector remains an attractive testing ground for multiple BSM and new physics phenomena
- Extensive searches going on in ATLAS: **List of publications and conference notes**
- Run 3 data on the way - **more opportunity for precise measurements and searches in the top quark sector**



Summary of ATLAS and CMS measurements of $t\bar{t}$+X (X = W, Z or γ) cross sections at $\sqrt{s}$ = 13 TeV

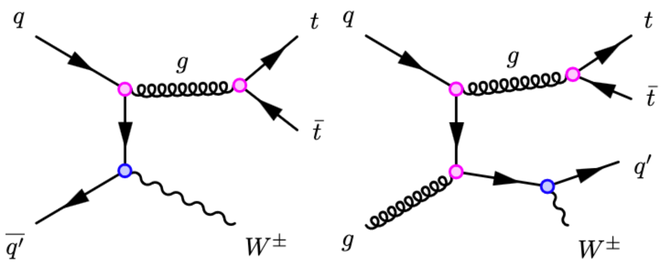


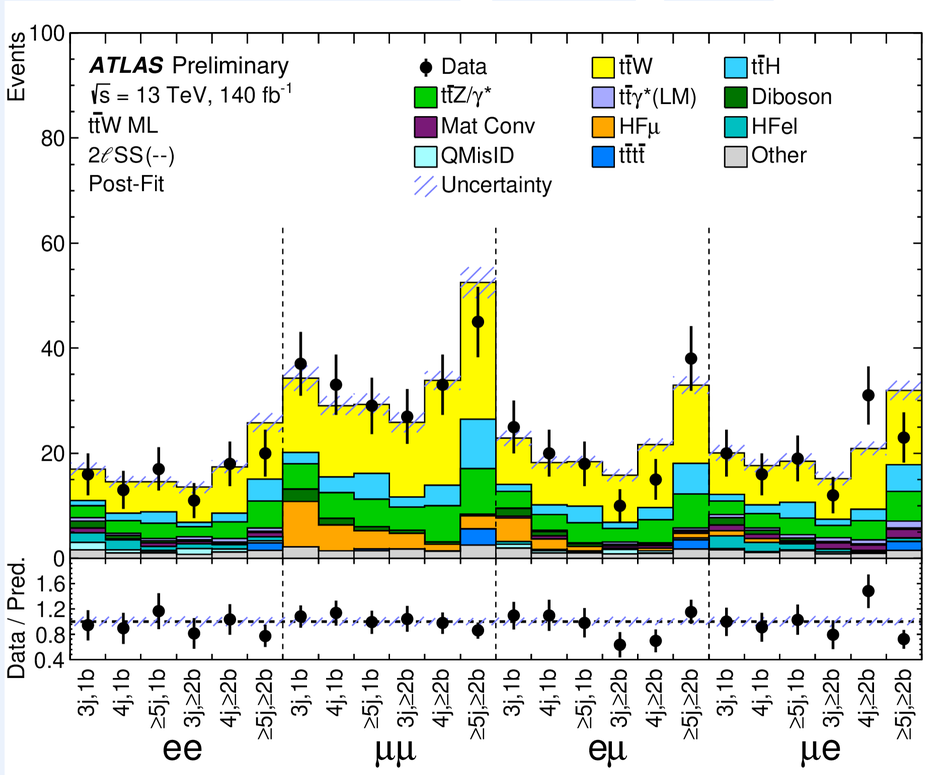
Summary of ATLAS measurements of the $t\bar{t}$ charge and energy asymmetry in inclusive $t\bar{t}$ final states, in $t\bar{t}$+j, and in $t\bar{t}\gamma$ and $t\bar{t}W$

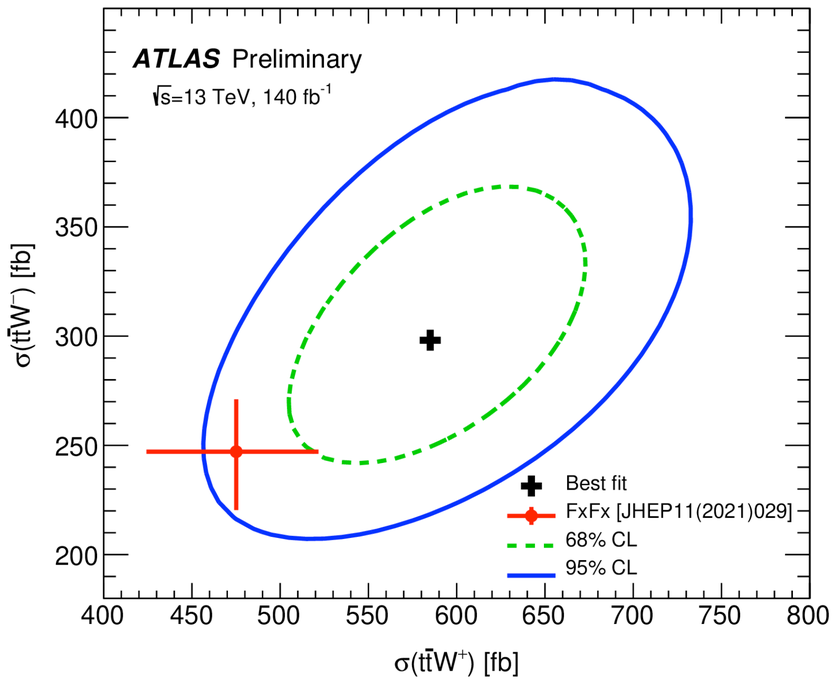
Backup

$t\bar{t}W$ inclusive and differential

[ATLAS-CONF-2023-019]



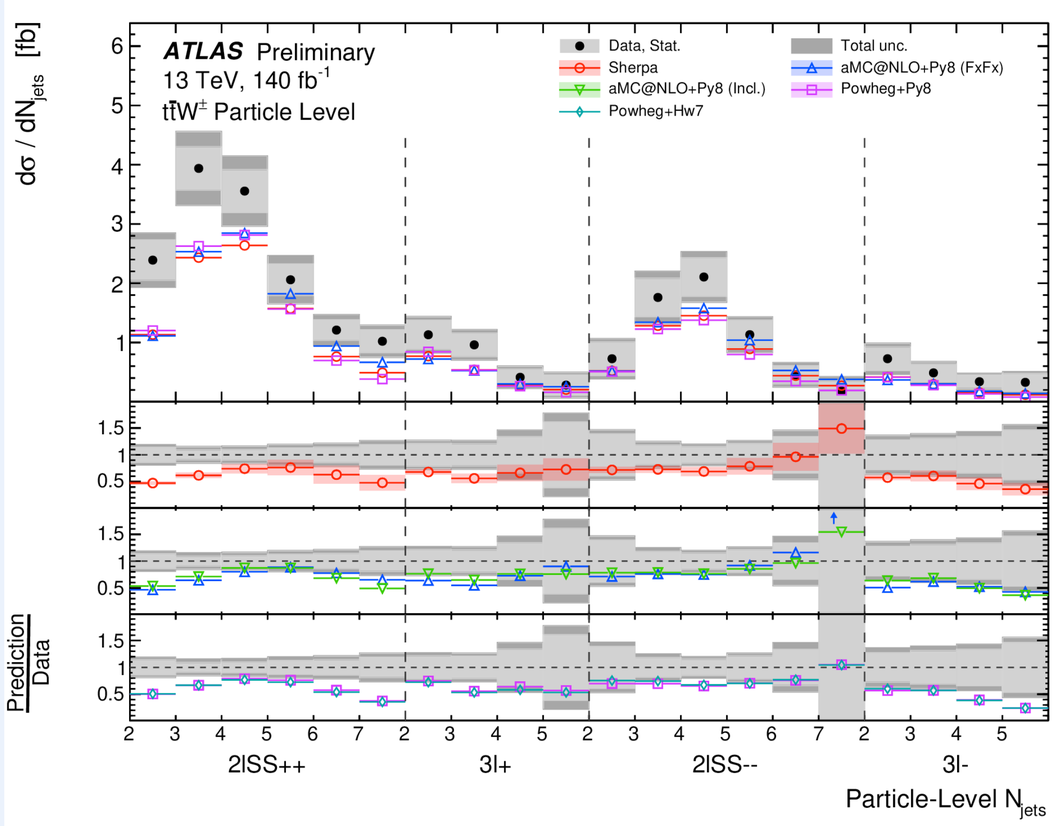


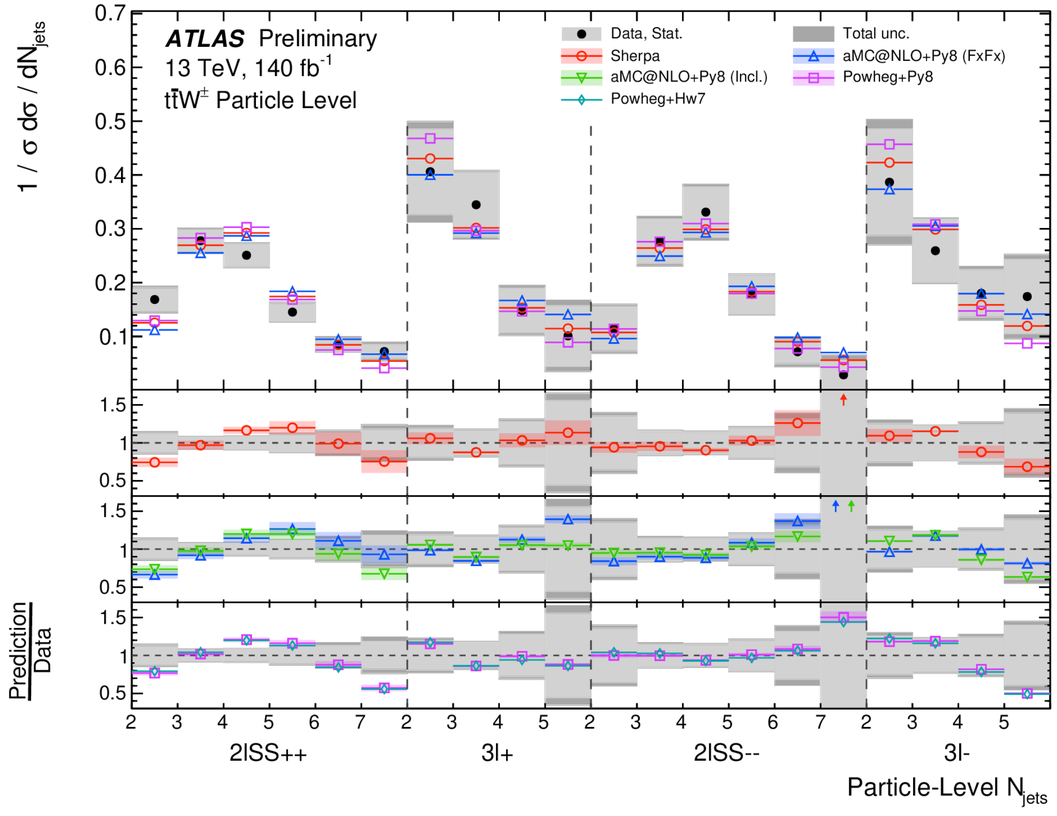


2-D likelihood scan of ttW^{+} and ttW^{-}

$t\bar{t}W$ differential

[ATLAS-CONF-2023-019]

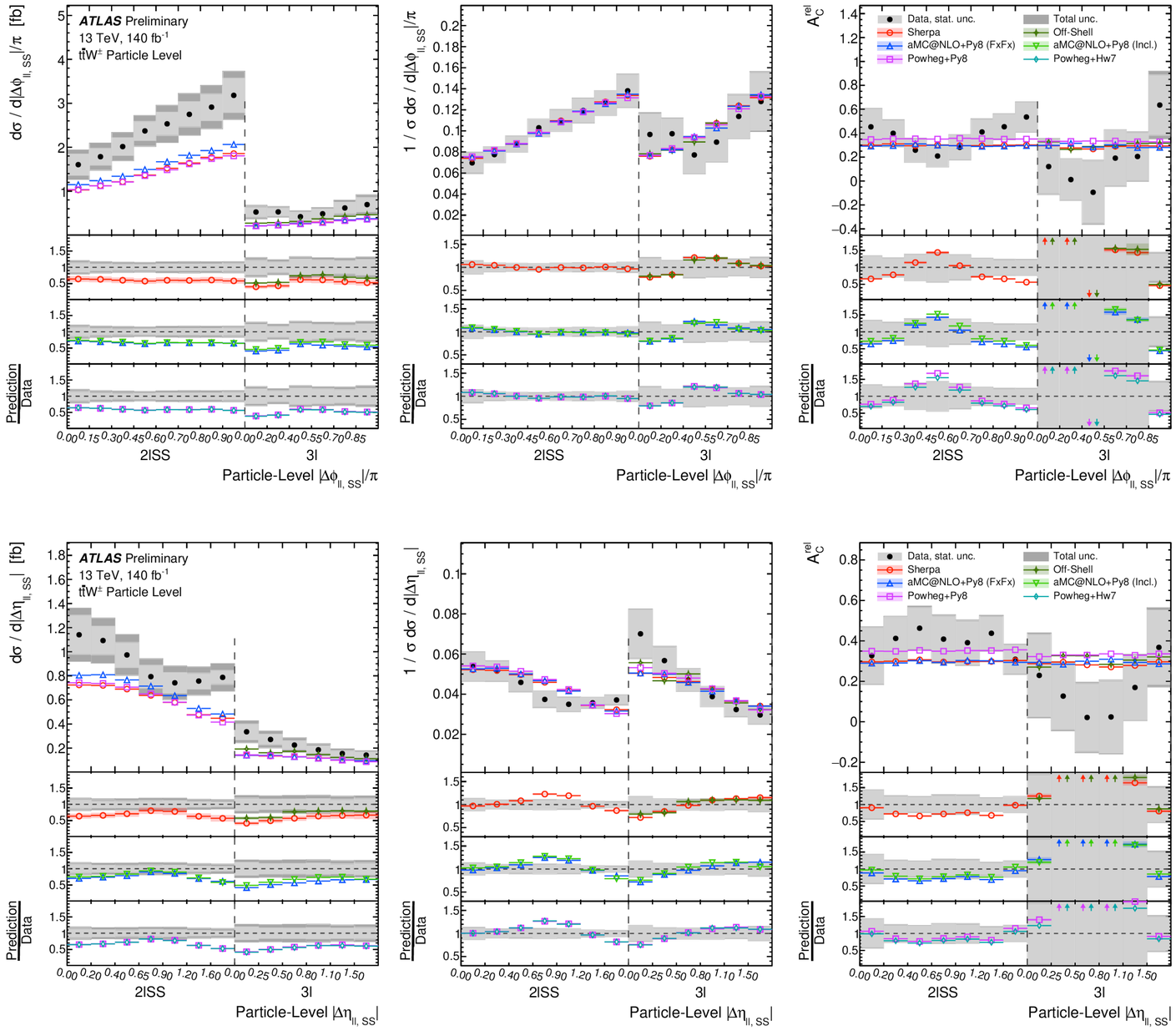




unfolded distributions of the lepton charge split absolute and normalised cross-sections, as a function of jet multiplicity.

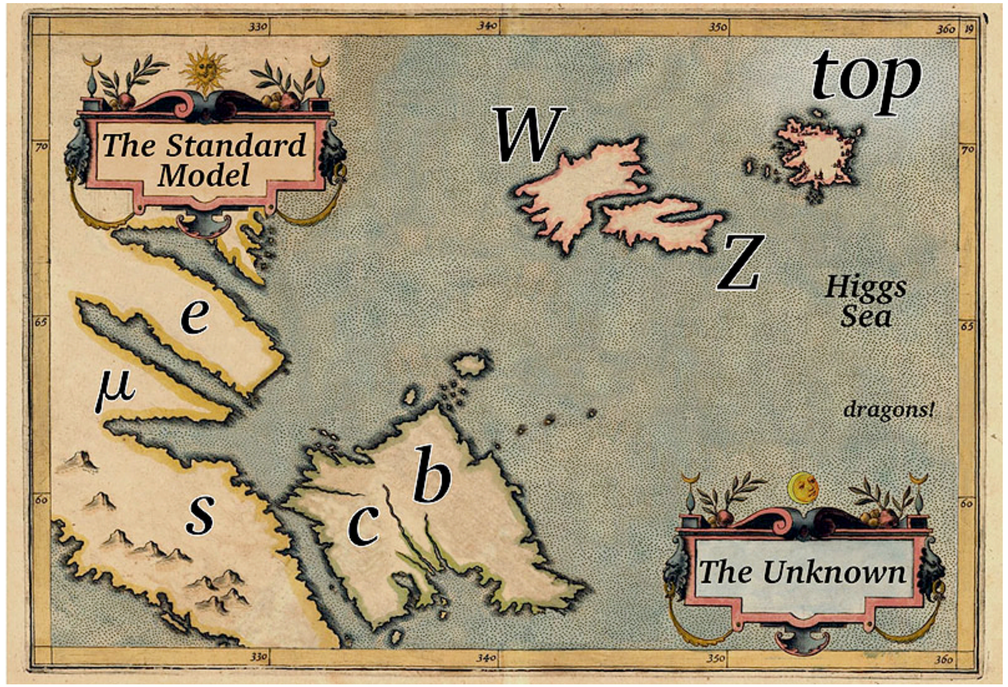
$t\bar{t}W$ differential

[ATLAS-CONF-2023-019]



BSM searches with Top

- Top quark plays important role in BSM
  - models predict new particles with possible interactions with top (can affect decays and couplings)
  - heavy mass, close to EW scale - lucrative for grand unification of gauge couplings
  - highest Yukawa coupling to Higgs boson

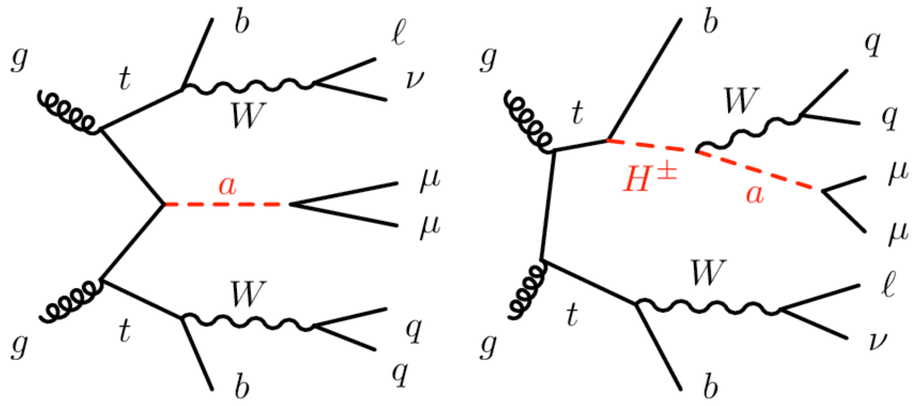


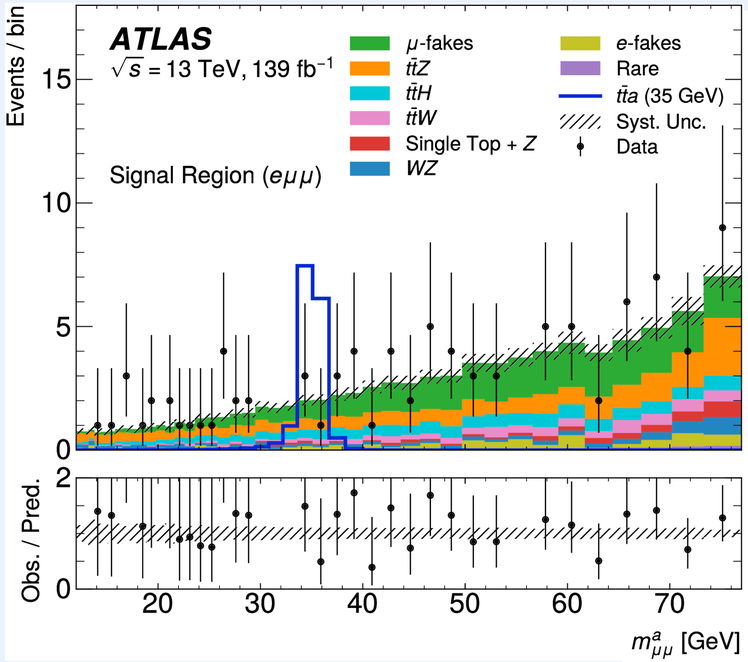
- Various BSM theories already proposed - dark matter, composite Higgs models, 2HDM, MSSM, Higgs triplet etc. ...
- Numerous ATLAS analyses already involved in BSM studies - light pseudoscalars that mix with fields in extended Higgs scenario, VLQs produced in pairs or singly at the LHC, FCNC and cLFV

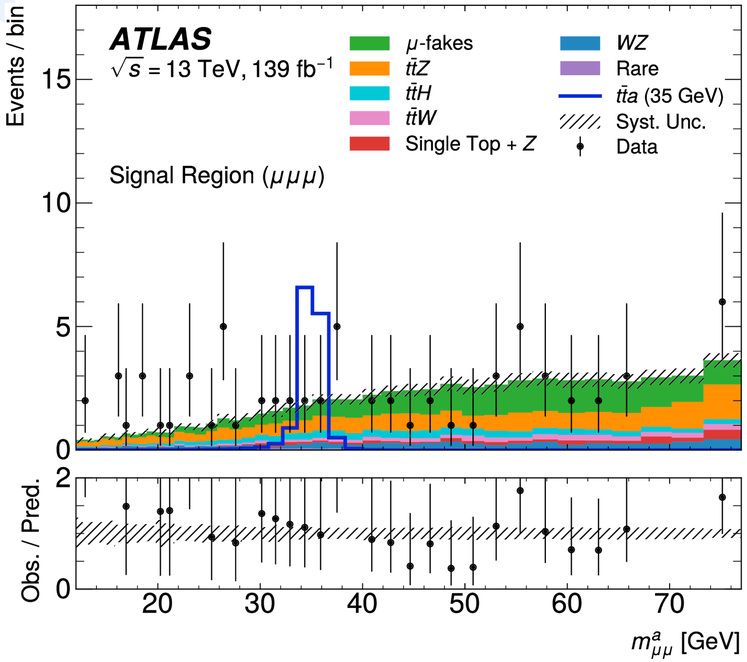
tta, a→μμ

[arXiv:2304.14247]

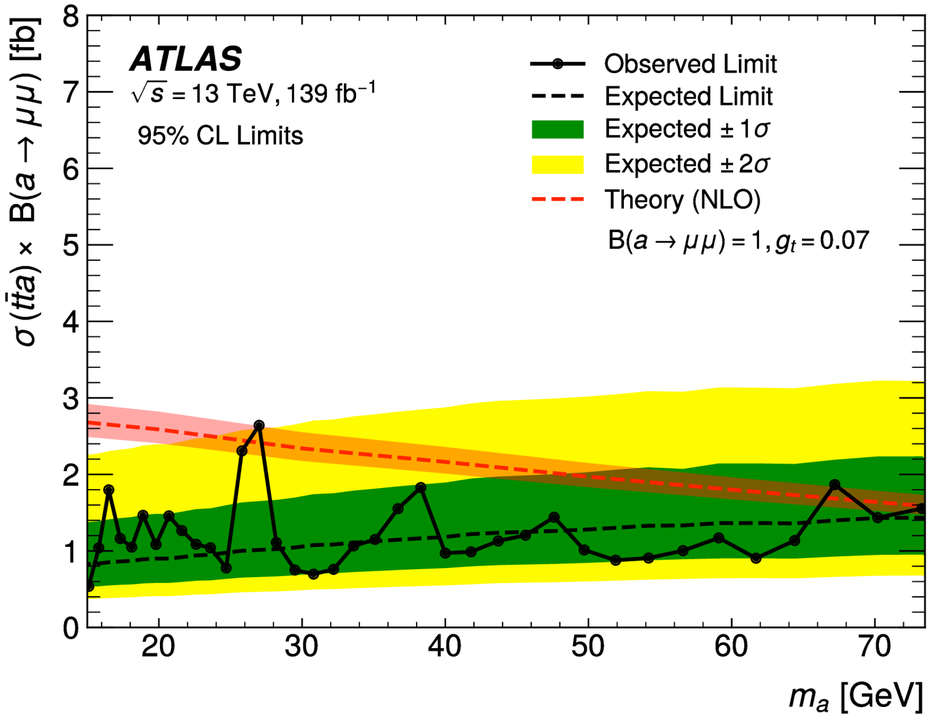
- Search for light pseudoscalars with large couplings to top quarks (predicted in 2HDM+a, NMSSM etc.) with $e\mu\mu$ or $\mu\mu\mu$ final states
- high mass resolution for muon pairs an excellent discriminator against most backgrounds
- Main backgrounds: prompt muons from $t\bar{t}Z$, non-prompt from $t\bar{t}$ and Z+jets







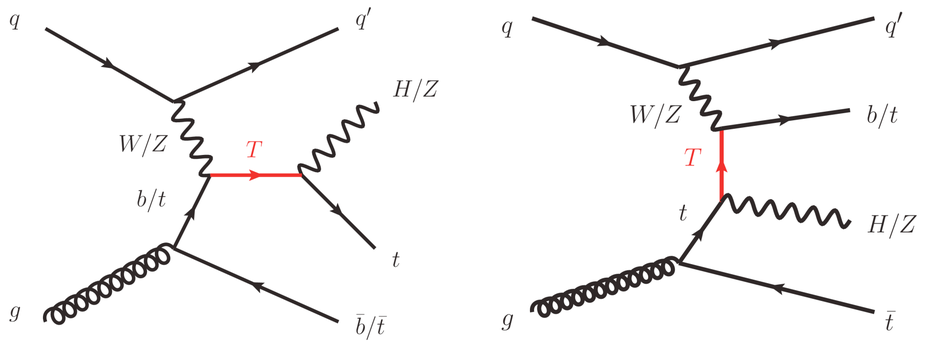
- Focus on mass ranges 15 GeV < m_a < 72 GeV and 120 GeV < $m_{H^\pm}$ < 160 GeV
- Data and background in good agreement - no signal observed at 95% CL.



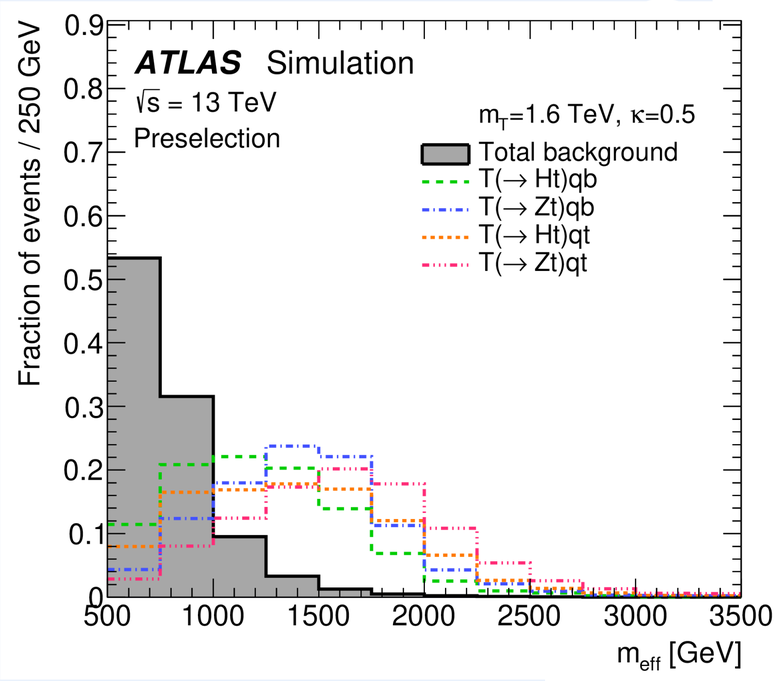
VLQ: Ht/Zt+X

[arXiv:2305.03401]

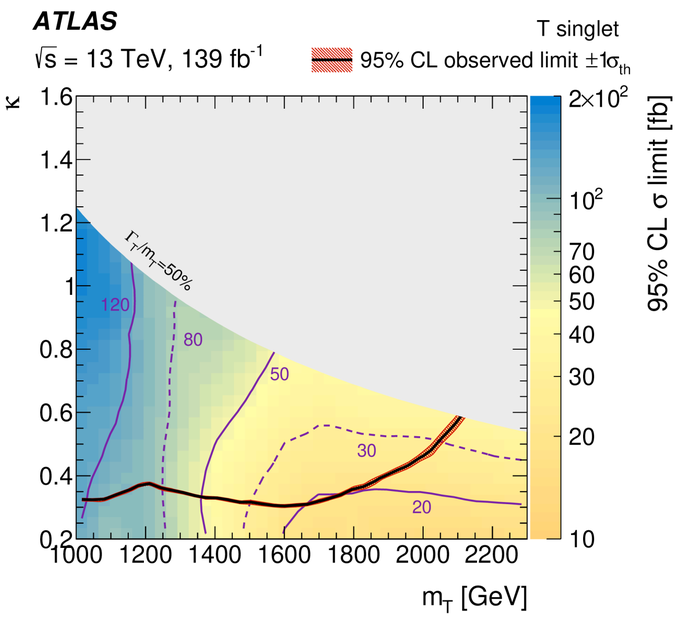
- Novel vector-like T quarks (VLQ) fermionic partners of the top quark in many BSM
- Search focused on T → Ht and T → Zt in singlet and doublet configurations
- Focus on single-lepton final state with requirements on multiplicity of jets, b-jets, forward jets and boosted tagged objects
- Regions defined to target different signal channels and to control $t\bar{t}$ and Wt (main backgrounds)
- Discriminating variable: Effective mass = $\sum_{\text{central jets}} p_{\mathrm{T}}^{j} + \sum_{\text{leptons}} p_{\mathrm{T}}^{\ell} + E_{\mathrm{T}}^{\mathrm{miss}}$

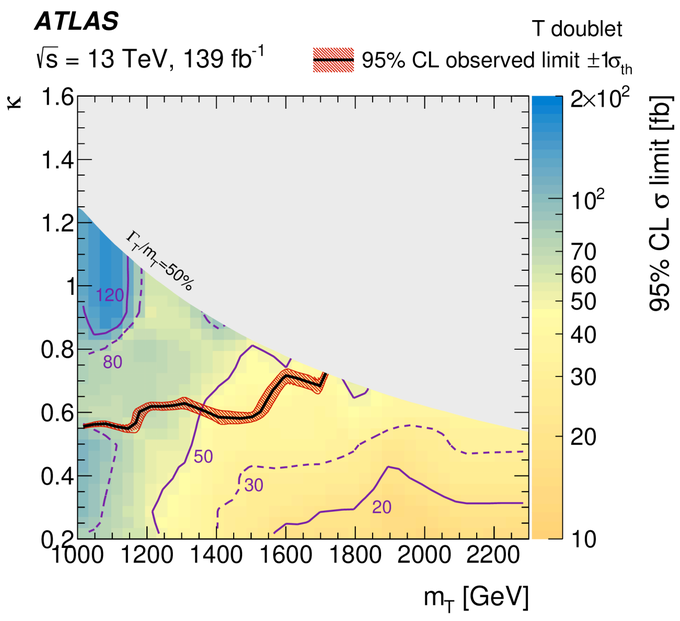


- Simultaneous likelihood-fit on 24 regions
- No significant excess above SM in background only fit



Observed limits on the $\sigma \times BR$ of single T-quark production: singlet and doublet

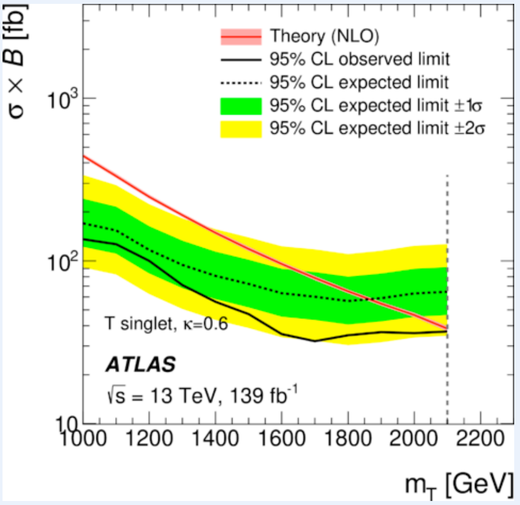


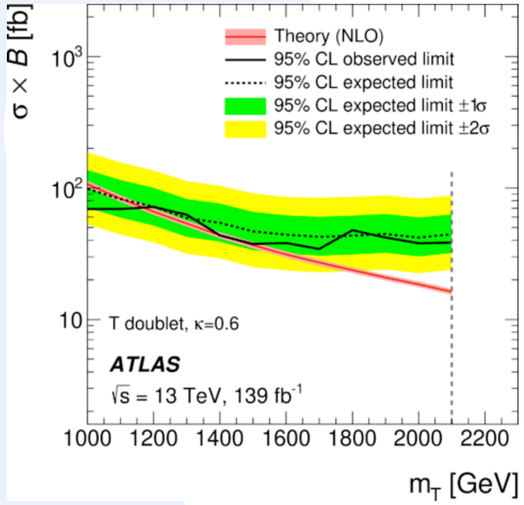


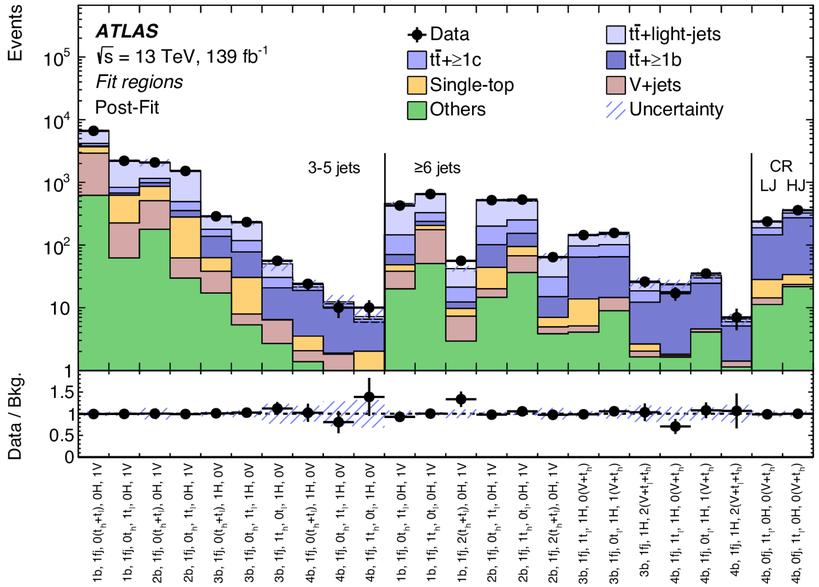
VLQ: Ht/Zt+X

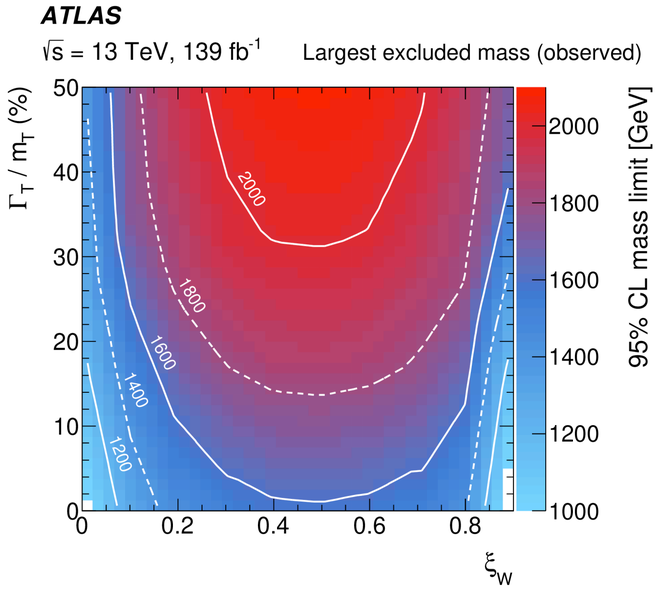
[arXiv:2305.03401]

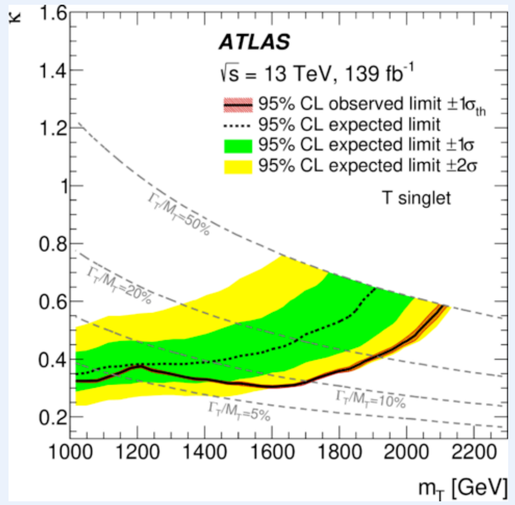
T-quark mass as a function of the relative resonance width (Γ_T/m_T) and the relative coupling parameter ξ_W

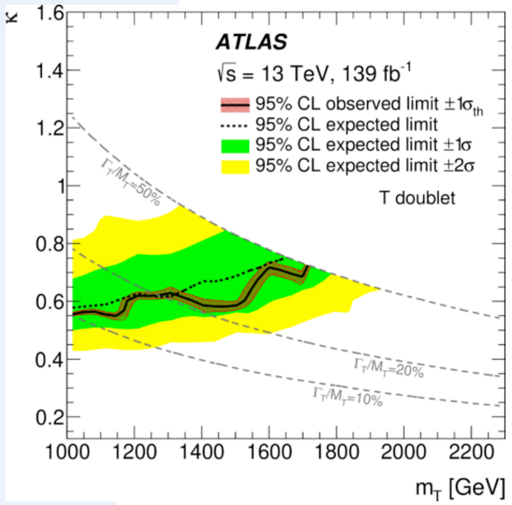


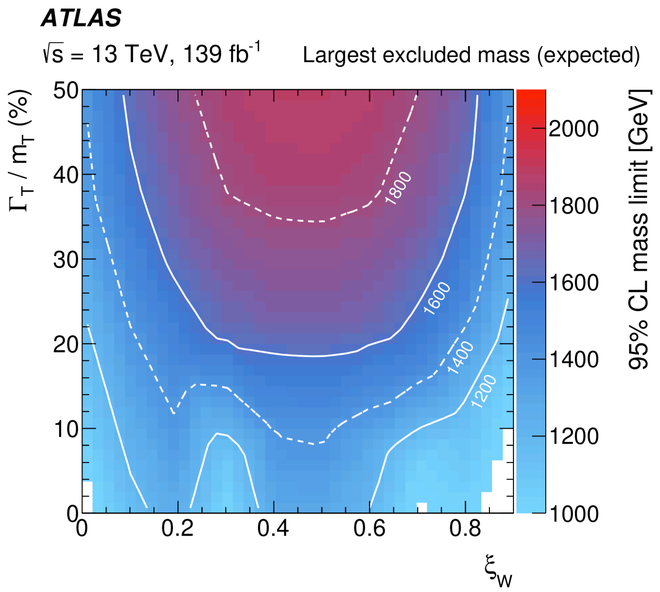






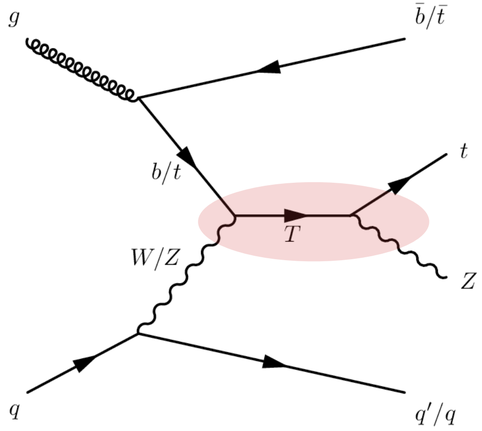




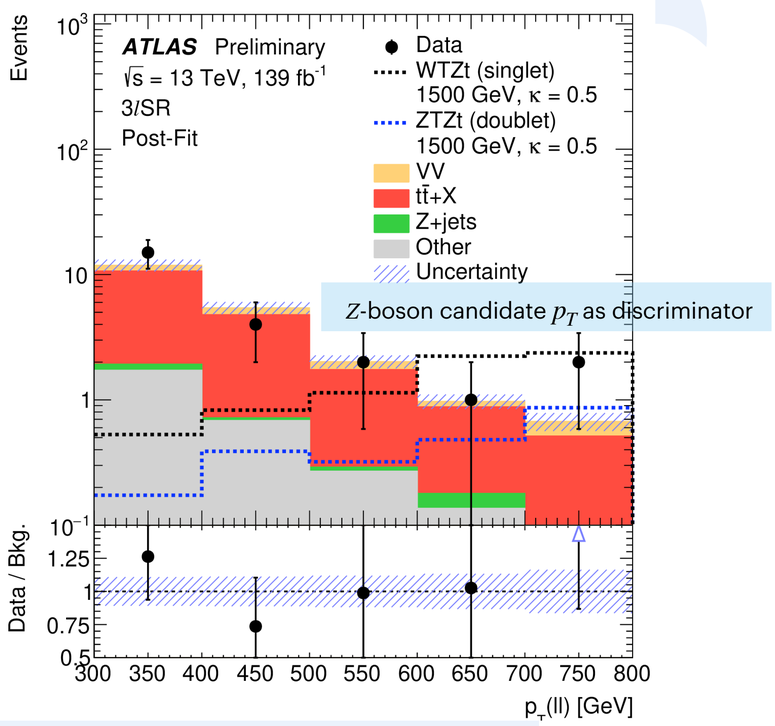


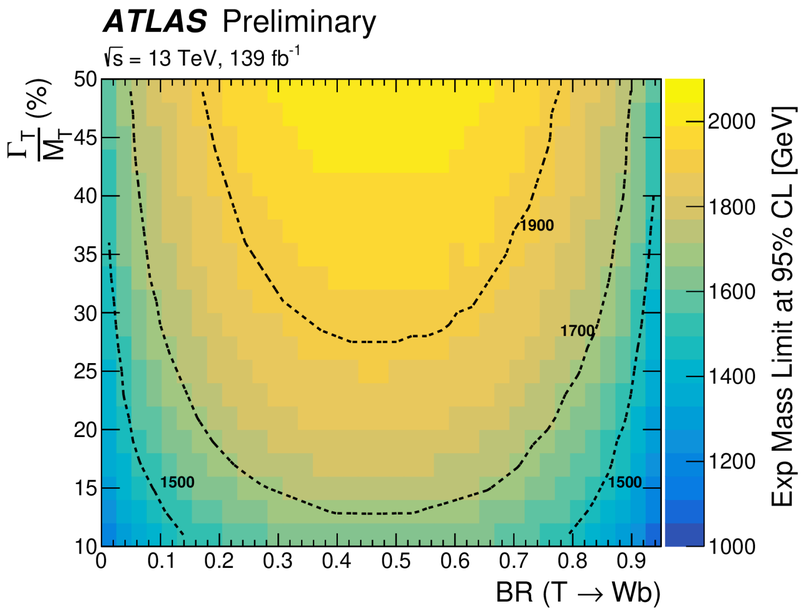
VLQ: Single VLQ in multilepton final states

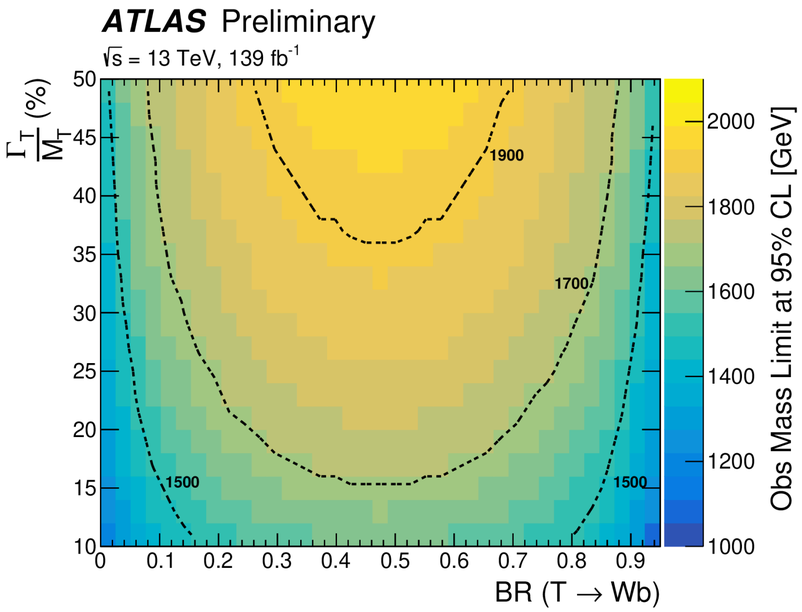
[ATLAS-CONF-2023-020]



- Very extensive VLQ-T search, 1 < m_T < 2.7 TeV and k ∈ [0.1,1]
- Focus on WTZt and ZTZt in singlet and doublet configurations
- Requirements on different multiplicity of jets, b-jets, forward jets and boosted tagged objects in multi-lepton selection for final states with Z decaying to lepton pairs
- 2ℓ regions dominated by Z+jets background, 3ℓ by diboson and $t\bar{t}$+Z



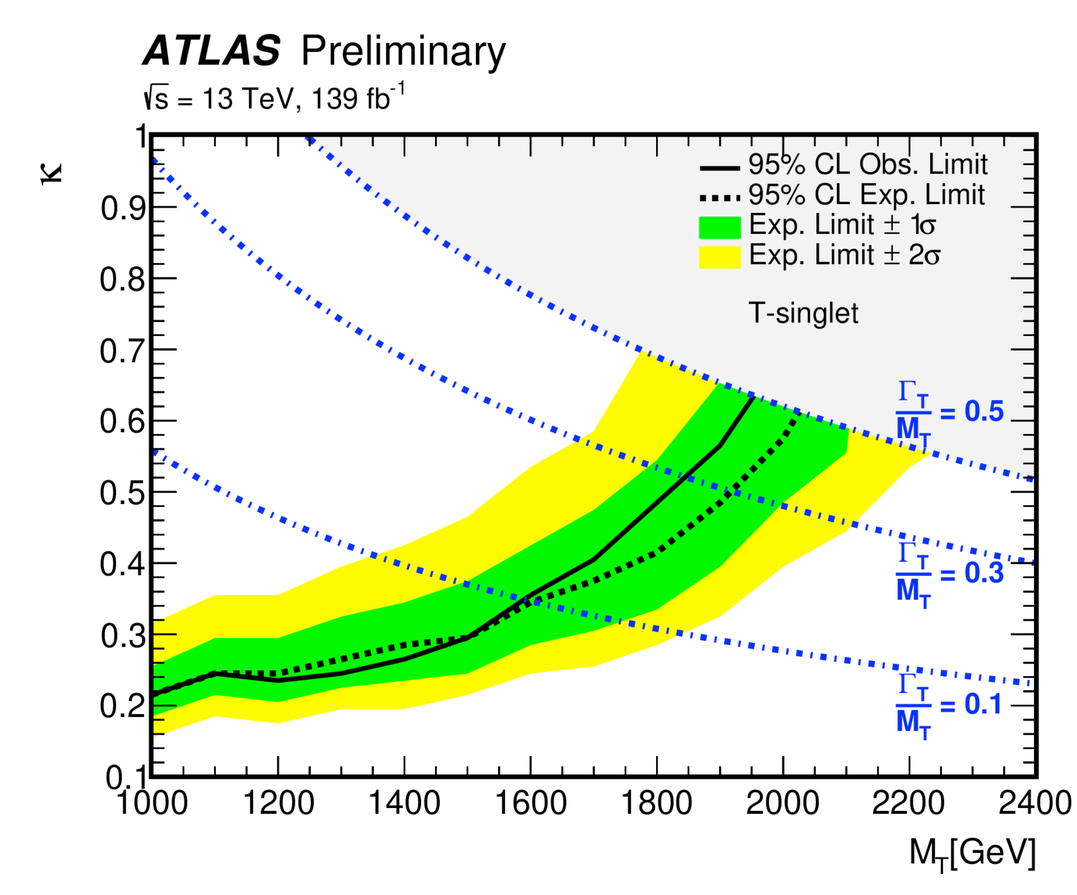


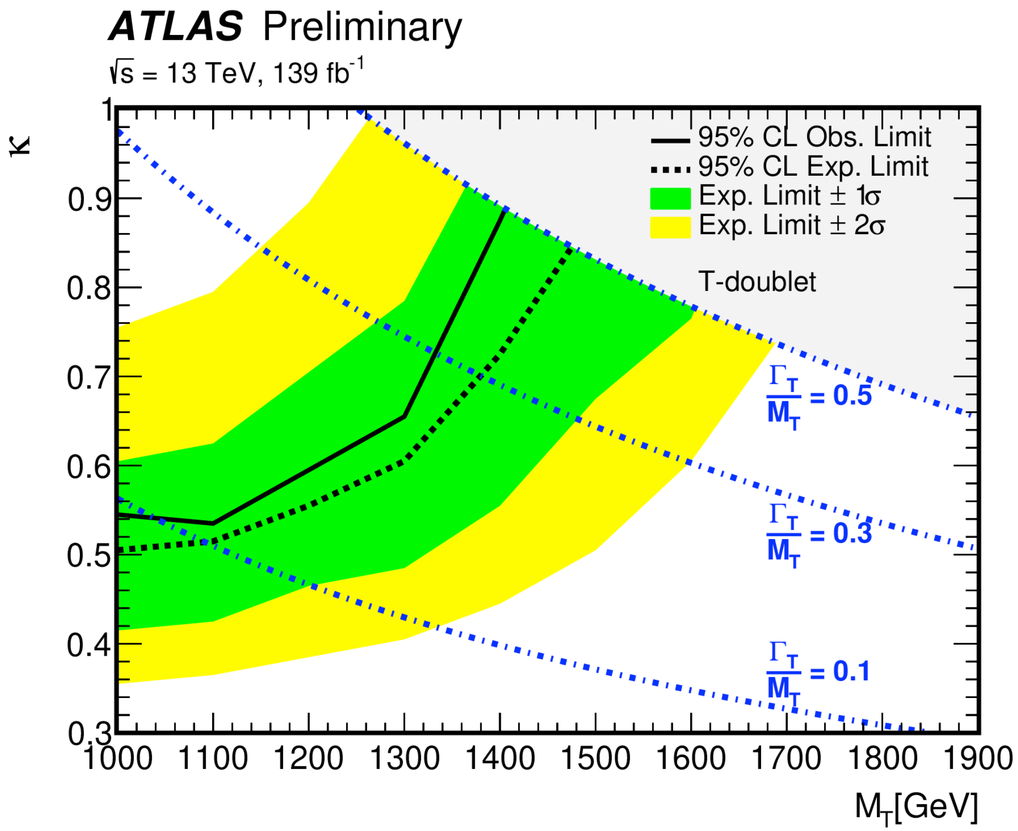


- No significant excess over background

VLQ: Single VLQ in multilepton final states

[ATLAS-CONF-2023-020]

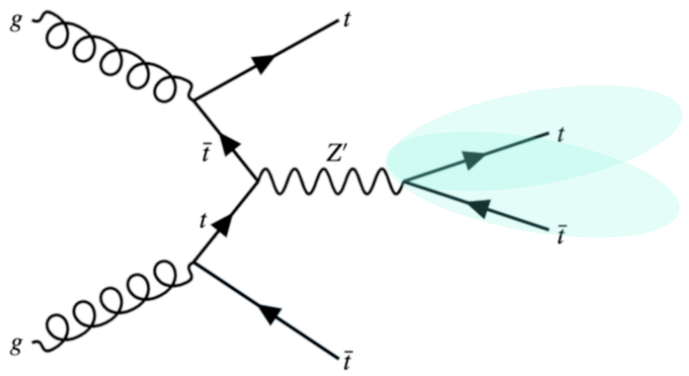


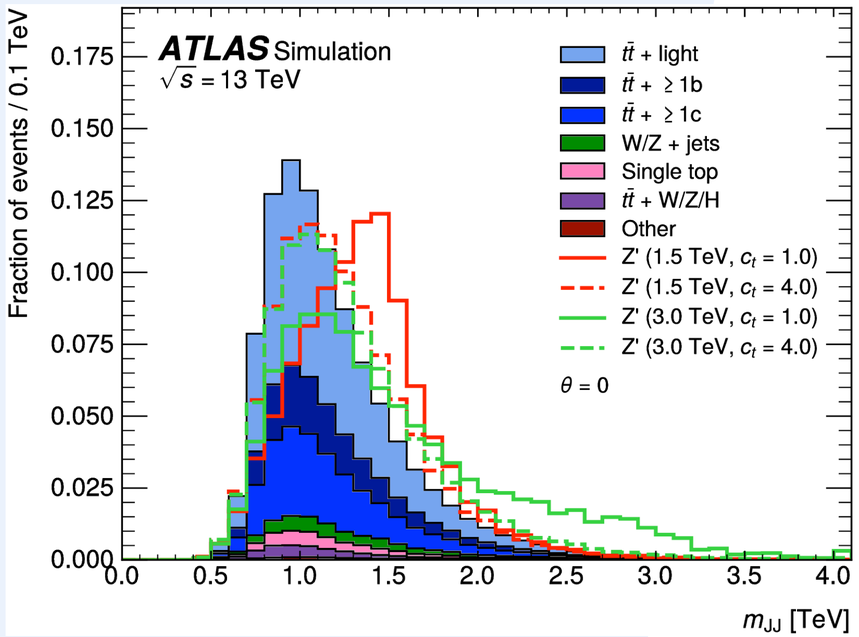


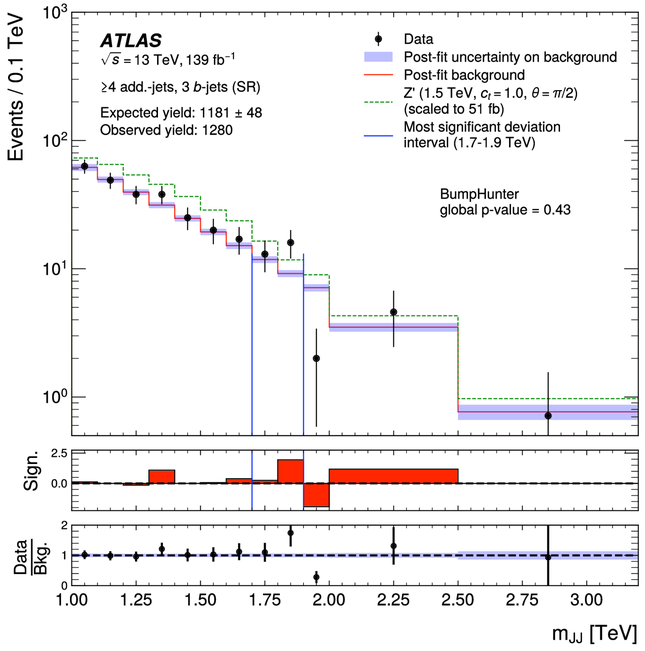
Top-philic heavy resonant search

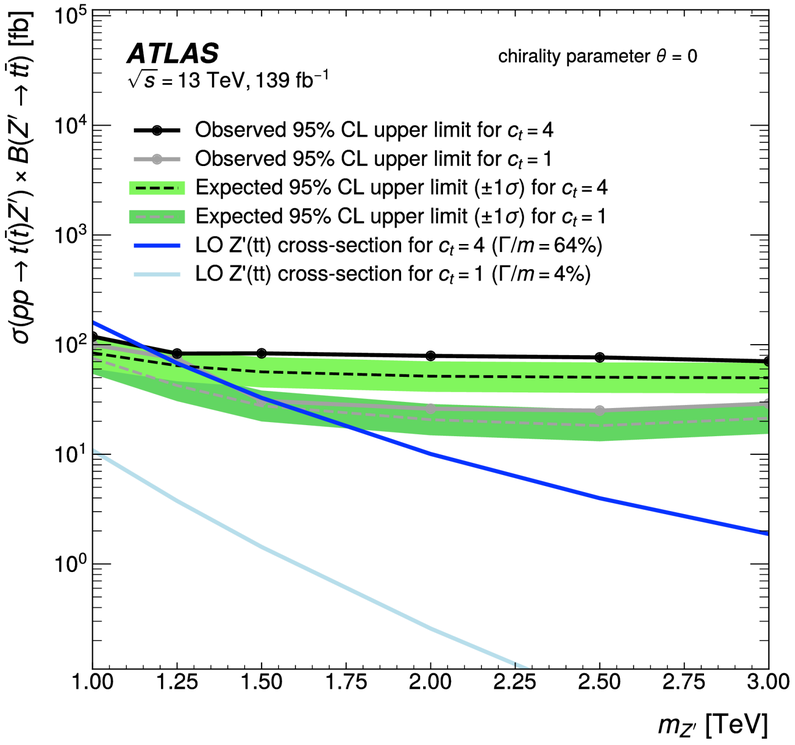
[arXiv:2304.01678]

- Heavy vector resonances that strongly couple to top predicted by many BSM
- Focus on resonance between 1 and 3.2 TeV in fully hadronic decay mode
- Large radius jets as proxies for two heavily-boosted top quarks from resonance to calculate invariant mass
- Dijet background estimated in low signal contamination region
- Bump hunt search with minimal model dependence and model-dependent likelihood fit performed





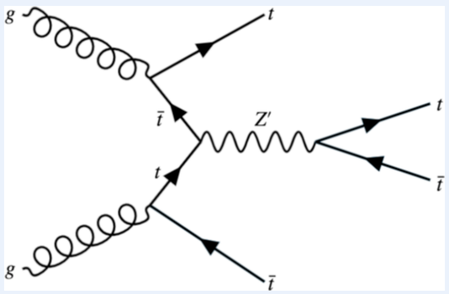


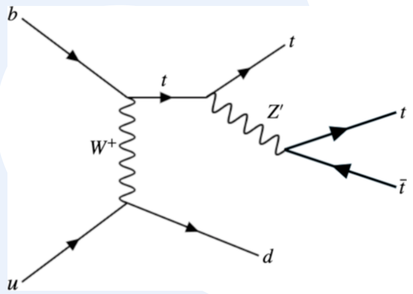


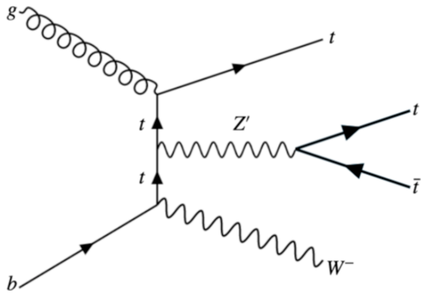
- Upper limits on Z′ production computed based on simplified model

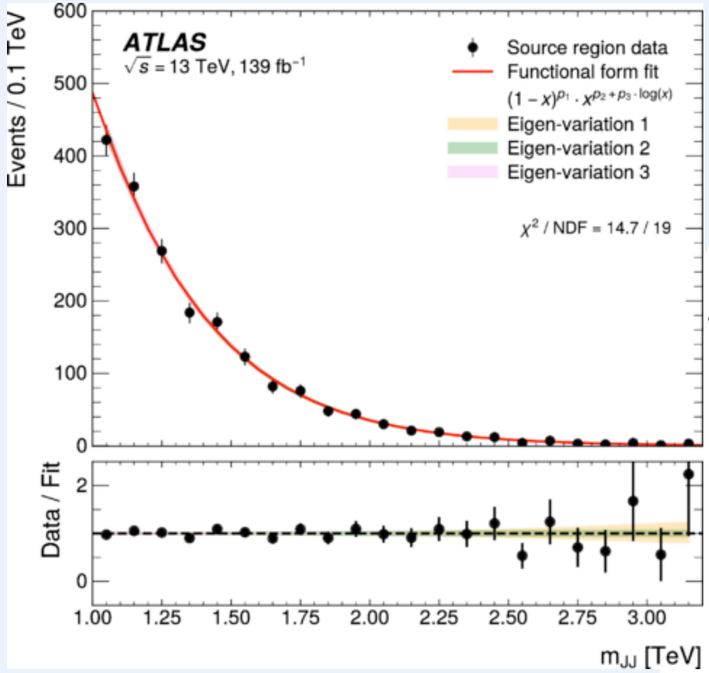
Top-philic heavy resonant search

[arXiv:2304.01678]







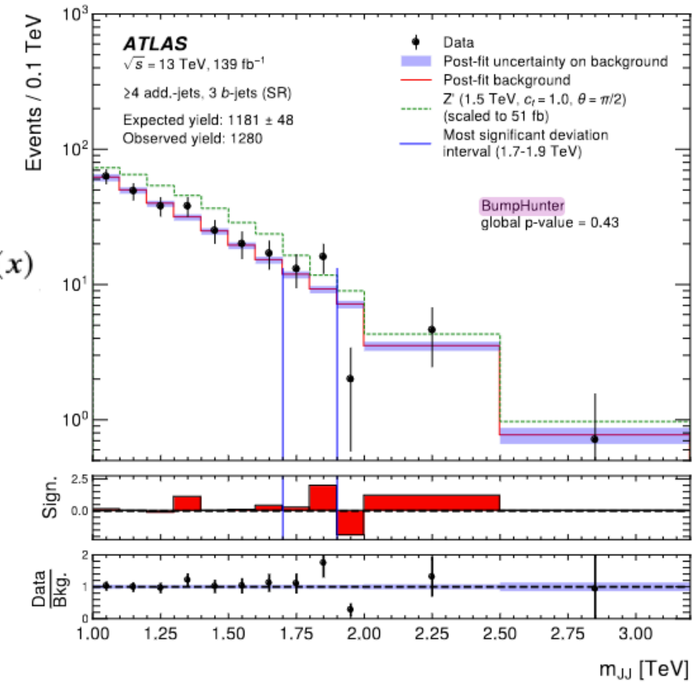


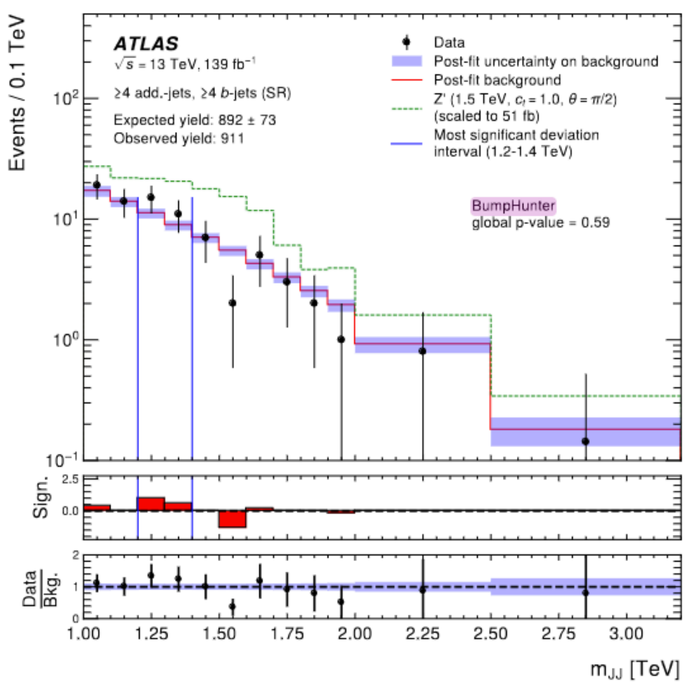
Data in source region along with fitted function in data

$$f(x) = (1-x)^{p_1} \cdot x^{p_2+p_3 \cdot \log(x)}$$

with $x = m_{JJ}/\sqrt{s}$

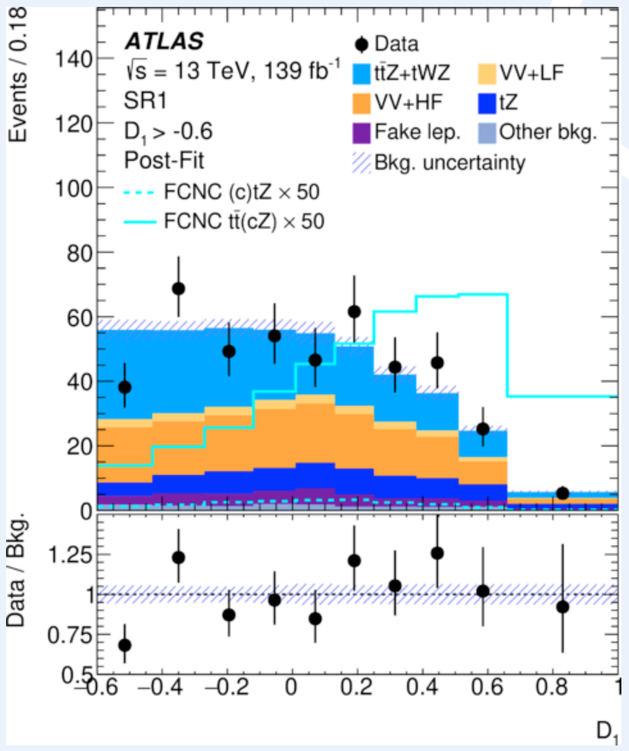
m_{JJ} under bkg-only hypothesis in 2 SRs

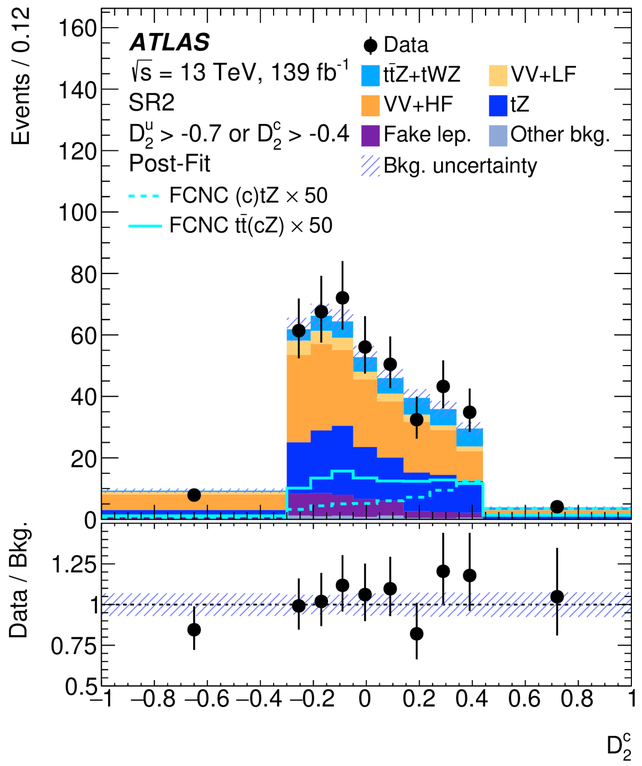




FCNC t→qZ

[arXiv:2301.11605]

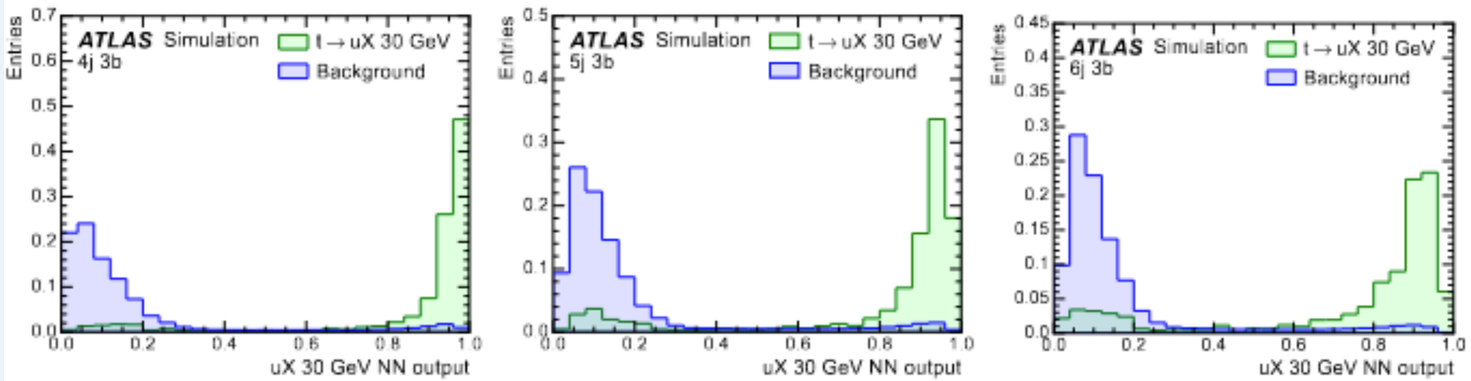




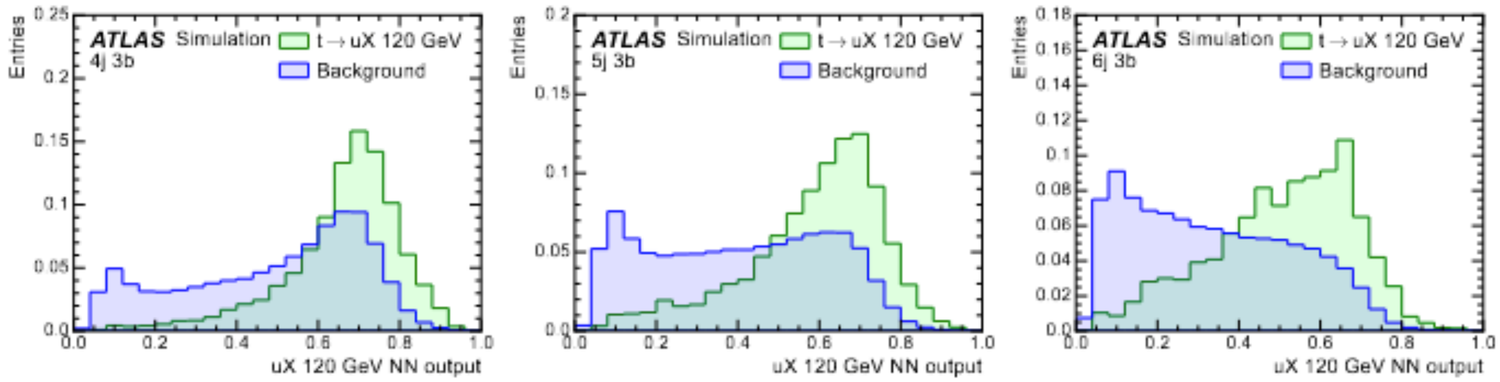
Observable	Vertex	Coupling	Observed	Expected
	SRs+CRs			
$\mathcal{B}(t \to Zq)$	tZu	LH	6.2×10^{-5}	$4.9\,^{+2.1}_{-1.4} \times 10^{-5}$
$\mathcal{B}(t \to Zq)$	tZu	RH	6.6×10^{-5}	$5.1\,^{+2.1}_{-1.4} \times 10^{-5}$
$\mathcal{B}(t \to Zq)$	tZc	LH	13×10^{-5}	$11\,^{+5}_{-3} \times 10^{-5}$
$\mathcal{B}(t \to Zq)$	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	$0.19\,^{+0.04}_{-0.03}$
	SR1+CRs			
$\mathcal{B}(t \to Zq)$	tZu	LH	9.7×10^{-5}	$8.6\,^{+3.6}_{-2.4} \times 10^{-5}$
$\mathcal{B}(t \to Zq)$	tZu	RH	9.5×10^{-5}	$8.2\,^{+3.4}_{-2.3} \times 10^{-5}$
	SR2+CRs			
$\mathcal{B}(t \to Zq)$	tZu	LH	7.8×10^{-5}	$6.1\,^{+2.7}_{-1.7} \times 10^{-5}$
$\mathcal{B}(t \to Zq)$	tZu	RH	9.0×10^{-5}	$6.6\,^{+2.9}_{-1.8} \times 10^{-5}$

FCNC t→qX(bb)

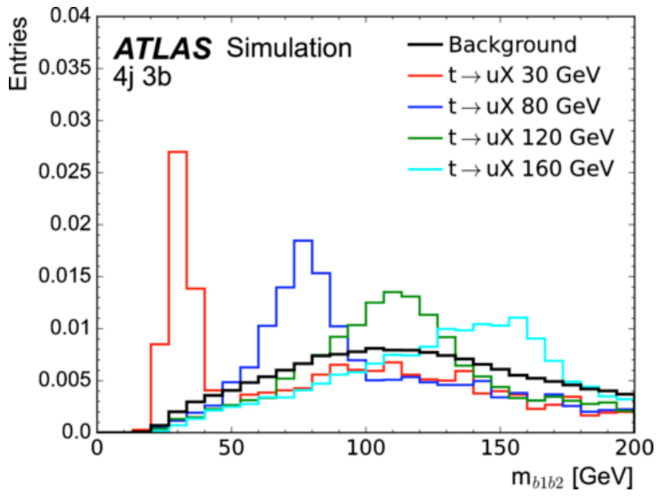
[arXiv:2301.03902]

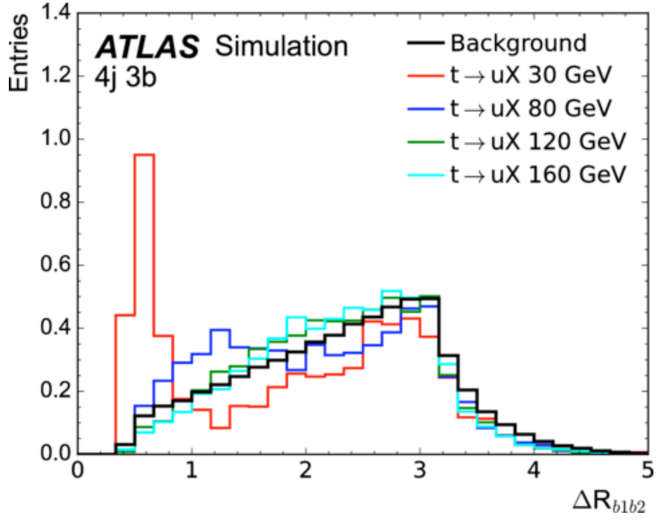


(a) m_X = 30 GeV, 4j 3b (b) m_X = 30 GeV, 5j 3b (c) m_X = 30 GeV, 6j 3b



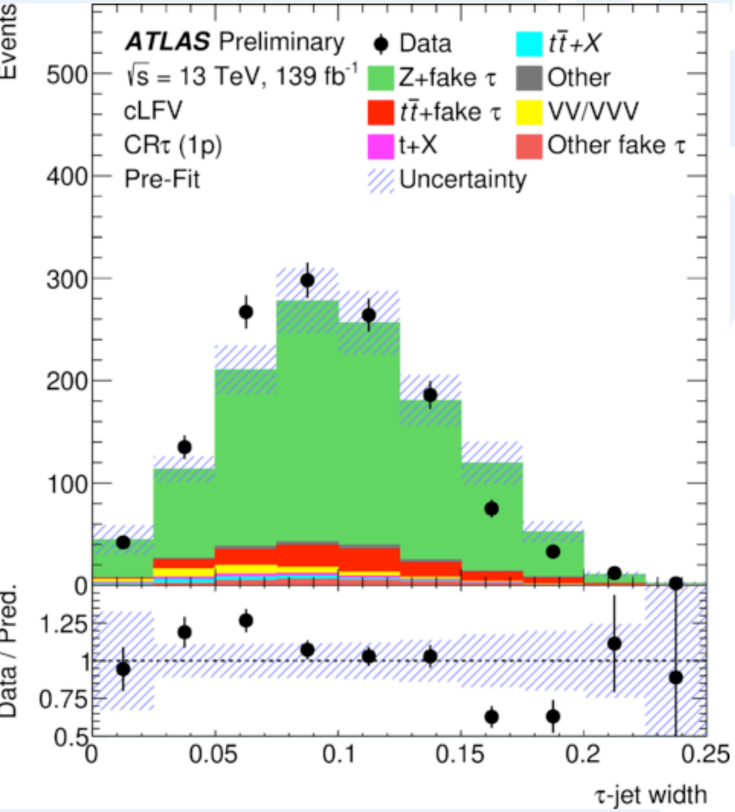
(g) m_X = 120 GeV, 4j 3b (h) m_X = 120 GeV, 5j 3b (i) m_X = 120 GeV, 6j 3b

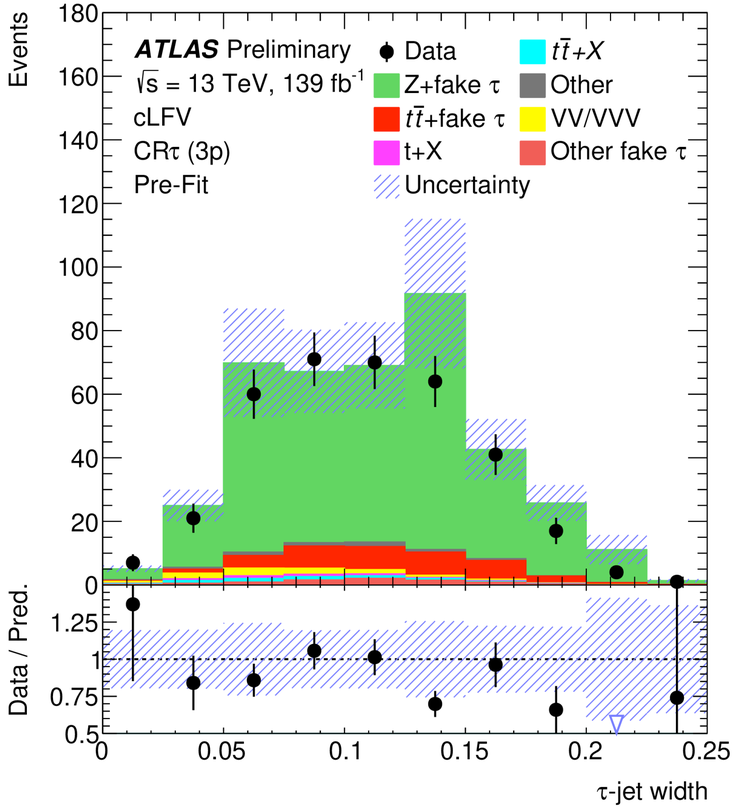




cLFV tμτq

[ATLAS-CONF-2023-001]





	95% CL upper limits on BR($t \to \mu\tau q$) ($\times 10^{-7}$)							
	$c_{lq}^{-(ijk3)}$	$c_{eq}^{(ijk3)}$	$c_{lu}^{(ijk3)}$	$c_{eu}^{(ijk3)}$	$c_{lequ}^{1(ijk3)}$	$c_{lequ}^{1(ij3k)}$	$c_{lequ}^{3(ijk3)}$	$c_{lequ}^{3(ij3k)}$
Expected (u)	4.6	4.2	4.0	4.5	2.5	2.5	5.8	5.8
Observed (u)	5.1	4.6	4.4	5.0	2.8	2.8	6.4	6.4
Expected (c)	54	51	51	52	35	35	61	61
Observed (c)	60	56	56	57	38	38	68	68