(t)tX (X = anything but H) Production on ATLAS

Kenneth Johns

University of Arizona

On Behalf of the ATLAS Collaboration

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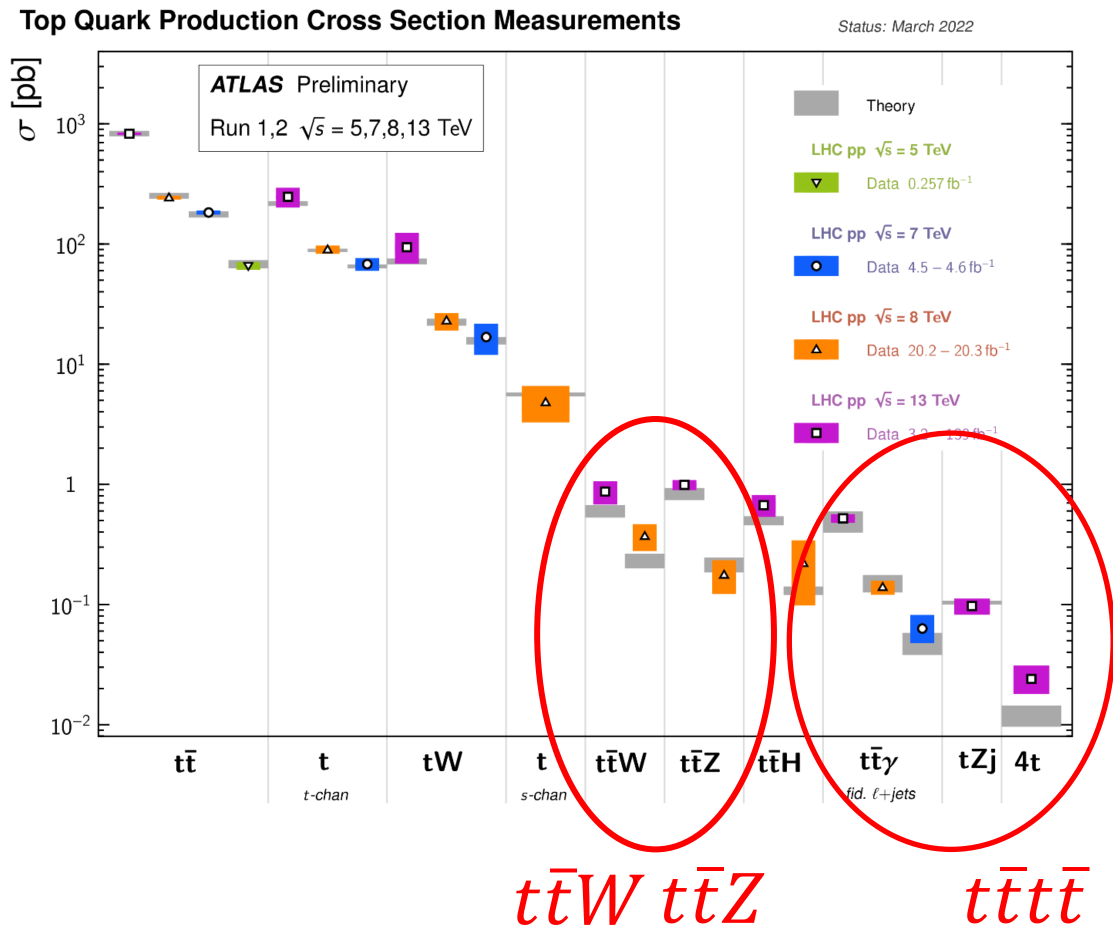
Associated $t\bar{t}$ Production

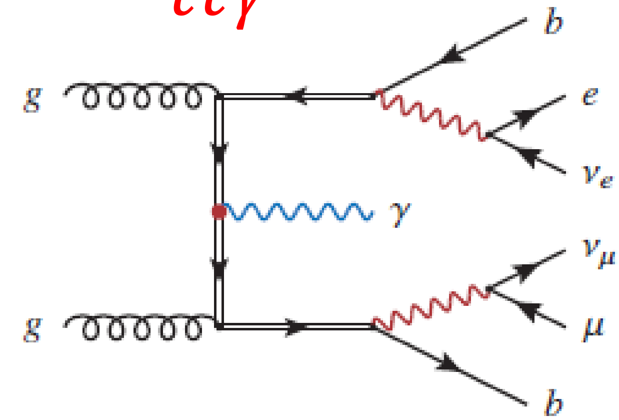
- Small production cross sections but important for
  - Sensitivity to beyond the standard model (BSM) contributions
  - Searches for anomalous tV couplings
  - As input for constraining SM effective field theory (EFT) coefficients, …



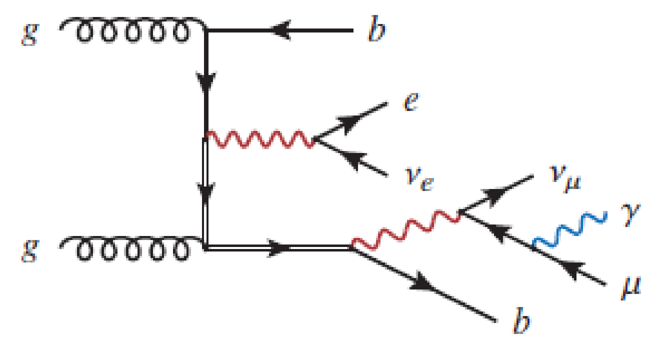
$t\bar{t}\gamma$ and $tW\gamma$ Cross-Sections

- Probe of the $t\gamma$ electroweak coupling and sensitivity to anomalous dipole moments of the top quark
- With 139 fb^{-1}, measurements of the inclusive and differential cross-sections are made
  - $e\mu$ channel only
  - Plus photon, $\geq 2\ jets, \geq 1\ b-jet$
- Full NLO calculation available including resonant and non-resonant diagrams, interferences and off-shell effects

$t\bar{t}\gamma$



$tW\gamma$



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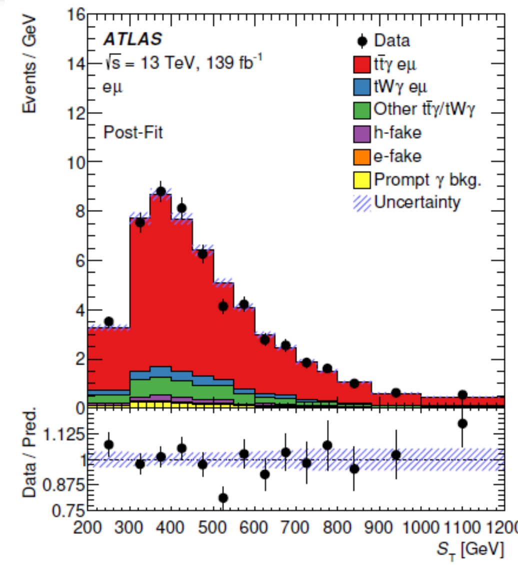
$t\bar{t}\gamma$ and $tW\gamma$ Inclusive Cross-Section

- A binned profile likelihood fit to the S_T distribution is used to extract the number of events
  - S_T is the scalar sum of all p_T in the event (leptons, photons, jets, MET)
  - The fiducial cross-section σ_{fid} is the parameter of interest in the fit
  - Signal and background modelling uncertainties dominate the systematic errors



S_T

$$\sigma_{fid}^{meas} = 39.6 \pm 0.8\,(stat)^{+2.6}_{-2.3}(syst)\text{fb}$$

$$\sigma_{fid}^{NLO} = 39.6^{+0.56}_{-2.18}\,(scale)^{+1.04}_{-1.18}(PDF)\text{fb}$$

Category	Uncertainty
$t\bar{t}\gamma/tW\gamma$ modelling	3.8%
Background modelling	2.1%
Photons	1.9%
Luminosity	1.8%
Jets	1.6%
Pile-up	1.3%
Leptons	1.1%
Flavour-tagging	1.1%
MC statistics	0.4%
Soft term E_T^{miss}	0.2%
$tW\gamma$ parton definition	2.8%
Total syst.	6.3%

- Good agreement with full NLO calculation

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$t\bar{t}\gamma$ and $tW\gamma$ Differential Cross-Sections

- Both absolute and normalized
- The data are corrected for the detector response and acceptance to the parton level using an iterative Bayesian unfolding procedure (RooUnfold)
- Photon and lepton variables

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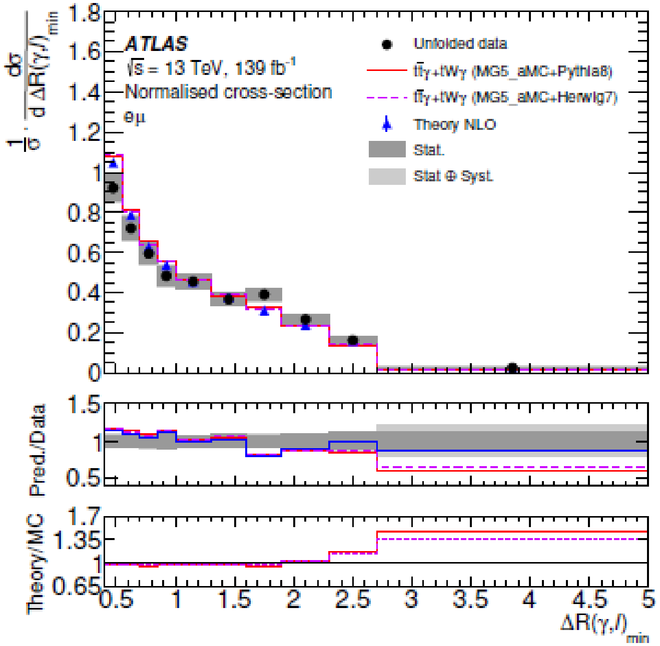
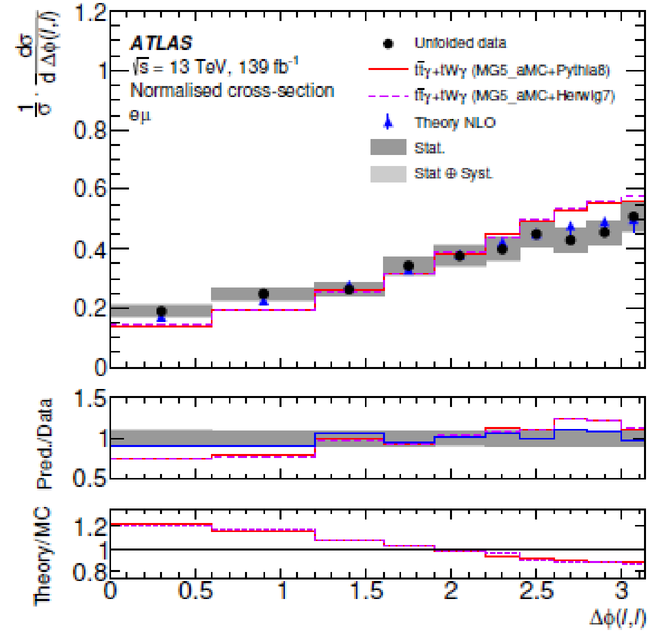
Variable	Sensitivity
p_T^γ	NLO prediction
$\|\eta^\gamma\|$	NLO prediction
$\Delta R(\gamma,\ell)_{min}$	$t\gamma$ coupling
$\Delta\varphi(\ell,\ell)$	$t\bar{t}$ spin correlation
$\|\Delta\eta(\ell,\ell)\|$	$t\bar{t}$ spin correlation

$t\bar{t}\gamma$ and $tW\gamma$ Differential Cross-Section



$\Delta R(\gamma,\ell)_{min}$



$\Delta\varphi(\ell,\ell)$

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- For these two variables, the full NLO prediction describes the data slightly better than MadGraph5_aMC@NLO
- All absolute differential measurements are found to be in good agreement with NLO predictions

$t\bar{t}Z$ Cross-Sections

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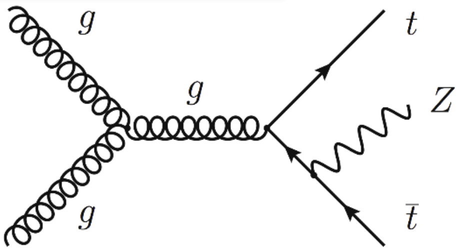
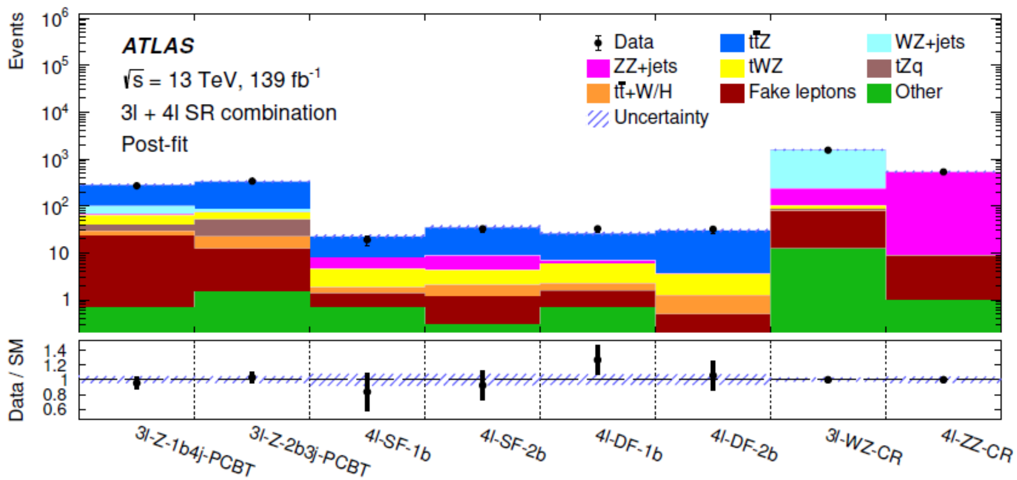
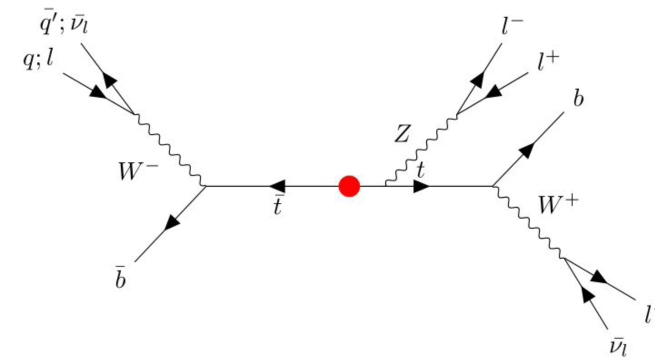


- Probe of the tZ electroweak coupling
  - Can be used to set constraints on SM EFT operator coefficients
  - Important to understand as an irreducible background in several SM and BSM searches
  - Important as input for Monte Carlo tuning
- Now with 139 fb^{-1}, new measurements of the inclusive and differential cross-sections are produced

$t\bar{t}Z$ Inclusive Cross-Section

- Uses final state with 3 or 4 isolated leptons (e or μ), ≥ 3 jets, ≥ 1 b-jet, Z mass
- Six signal regions and two control regions for WZ and ZZ background





Uncertainty	$\Delta\sigma_{t\bar{t}Z}/\sigma_{t\bar{t}Z}$ [%]
$t\bar{t}Z$ parton shower	3.1
tWZ modelling	2.9
b-tagging	2.9
$WZ/ZZ+$jets modelling	2.8
tZq modelling	2.6

- Profile likelihood fit to the number of events all regions
  - $\sigma(pp \rightarrow t\bar{t}Z) = 0.99 \pm 0.05\ (stat) \pm 0.08\ (syst)$ pb
  - $\sigma^{NLO}(pp \rightarrow t\bar{t}Z) = 0.84^{+0.09}_{-0.10}$ pb

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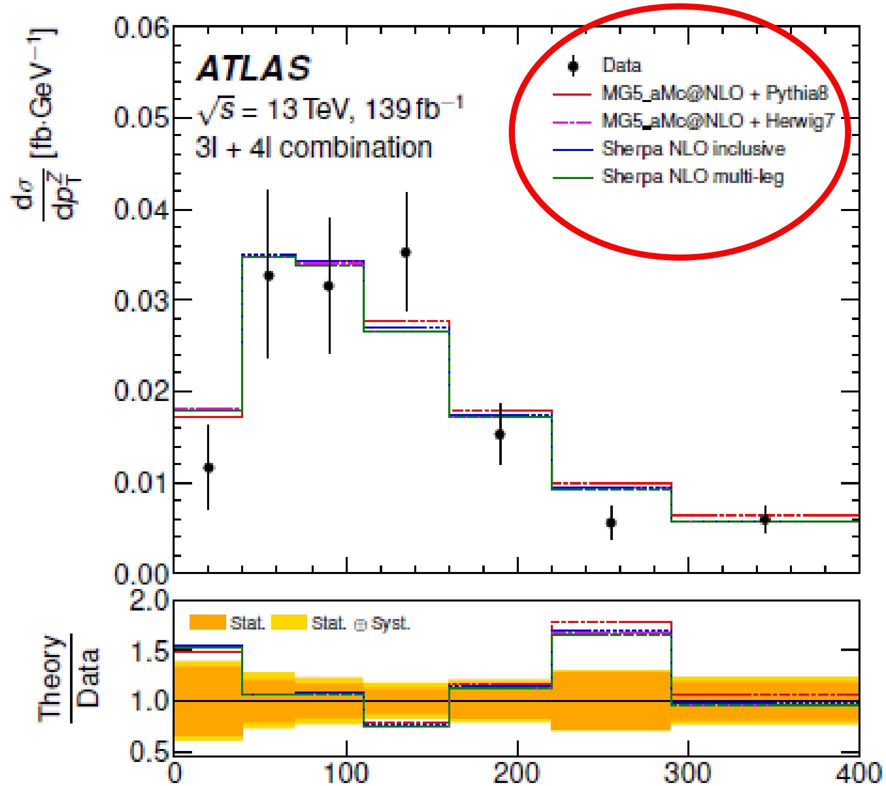
$t\bar{t}Z$ Differential Cross-Sections

- Both absolute and normalized EPJC 81 (2021) 737
- Both parton and particle levels, after correction for detector response using an iterative Bayesian unfolding procedure (RooUnfold)
- 10 variables

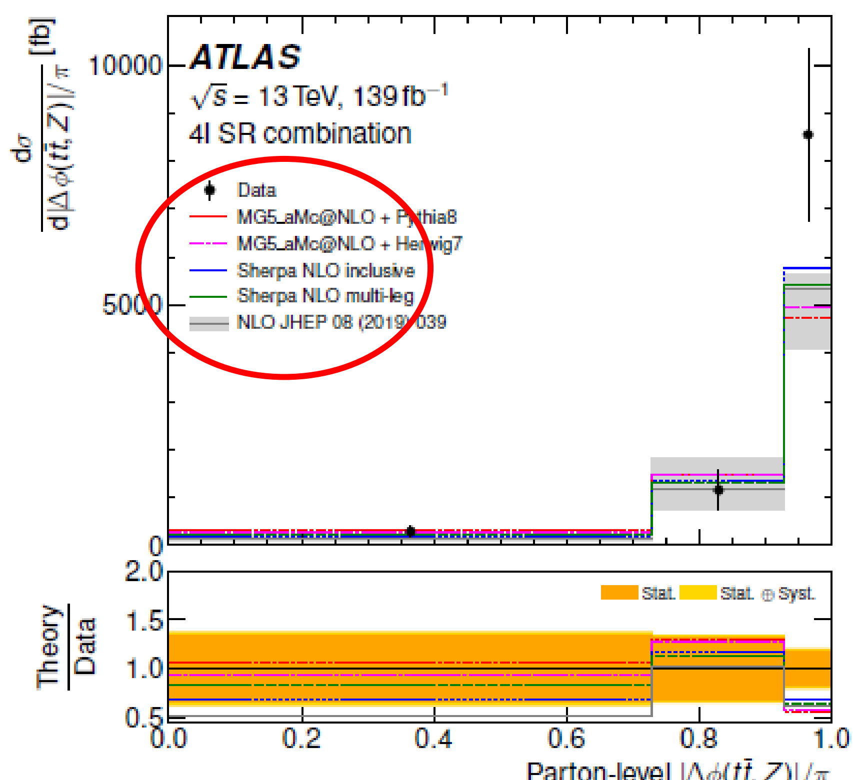
$3\ell + 4\ell$	Transverse momentum of the Z boson	$t\bar{t}Z$ generator modelling and BSM effects
	Absolute value of the rapidity of the Z boson	
3ℓ	Number of selected jets with $p_T > 25$ GeV and $\|\eta\| < 2.5$	QCD modelling in MC
	Transverse momentum of the lepton which is not associated with the Z boson	Top quark modelling
	Azimuthal separation between the Z boson and the top quark (antiquark) featuring the $W \to \ell\nu$ decay	tZ coupling
	Absolute rapidity difference between the Z boson and the top quark (antiquark) featuring the $W \to \ell\nu$ decay	
4ℓ	Number of selected jets with $p_T > 25$ GeV and $\|\eta\| < 2.5$	QCD modelling in MC
	Azimuthal separation between the two leptons from the $t\bar{t}$ system	BSM effects on $t\bar{t}$ spin
	Azimuthal separation between the Z boson and the $t\bar{t}$ system	tZ coupling
	Transverse momentum of the $t\bar{t}$ system	Hard scatter and QCD modelling in MC

$t\bar{t}Z$ Differential Cross-Sections

- BSM effects and $t\bar{t}Z$ coupling



p_T^Z



$|\Delta\varphi(t\bar{t}, Z)|/\pi$

- In general, good agreement between data and predictions everywhere

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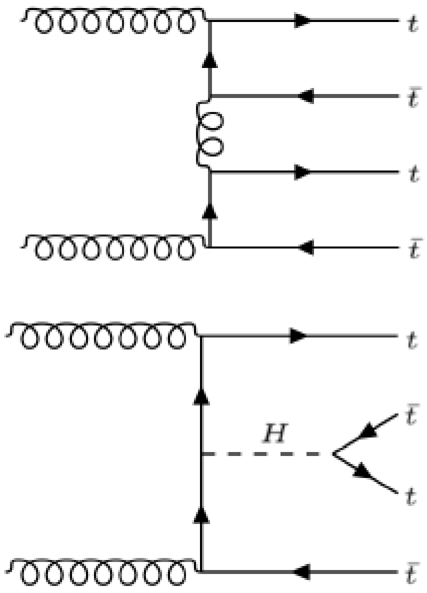
$t\bar{t}t\bar{t}$ Cross-Section



- Rare but potentially impactful process
  - SM prediction at NLO $12.0^{+2.0}_{-2.5}$ fb
  - Several possible BSM contributions
  - Sensitive to tH Yakawa coupling
  - Sensitive to 4-fermion EFT operators
- Measurements using leptonic final states
  - Evidence for using 2LSS / ML
  - New results using 1L/2LOS

[EPJC 80 (2020) 1085](#)

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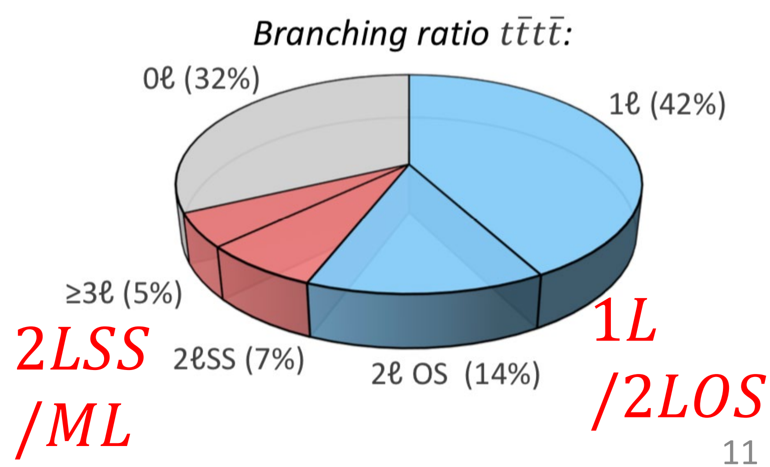
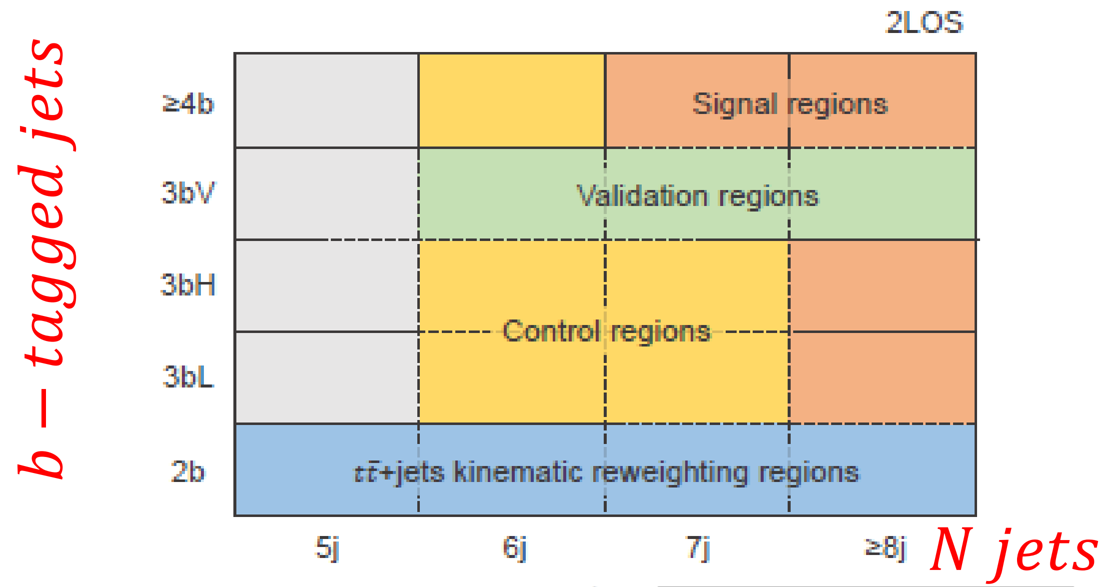
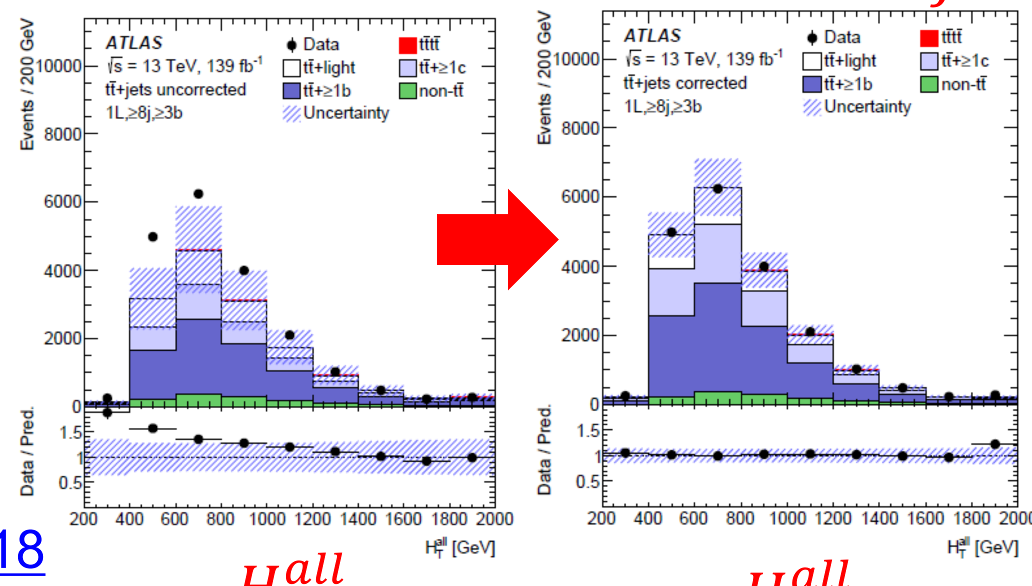


$t\bar{t}t\bar{t}$ Cross-Sections (1L/2LOS)

- Events are categorized by the number of jets and b-tagging requirements
- Significant attention to $t\bar{t} + jets$ modelling
  - $t\bar{t} + jets$ flavor rescaling using dedicated profile likelihood
  - Sequential kinematic reweighting for N_{jets}, $N_{LR-jets}$, ΔR^{jj}_{avg}, and H_T^{all}





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$t\bar{t}t\bar{t}$ Cross-Sections (1L/2LOS)

- A boosted decision tree (BDT) is used to discriminate the $t\bar{t}t\bar{t}$ signal from the large background
  - 14 input variables including global event variables, kinematic properties of reconstructed objects and pairs of objects, multiplicity and substructure variables of large-R jets, missing E_T, and pseudo-continuous b-tagging score
- A binned profile likelihood fit is used to extract the $t\bar{t}t\bar{t}$ signal strength
  - BDT distribution for signal regions
  - H_T^{all} for the control regions

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$t\bar{t}t\bar{t}$ Cross-Sections (1L/2LOS)

- Post-fit predictions

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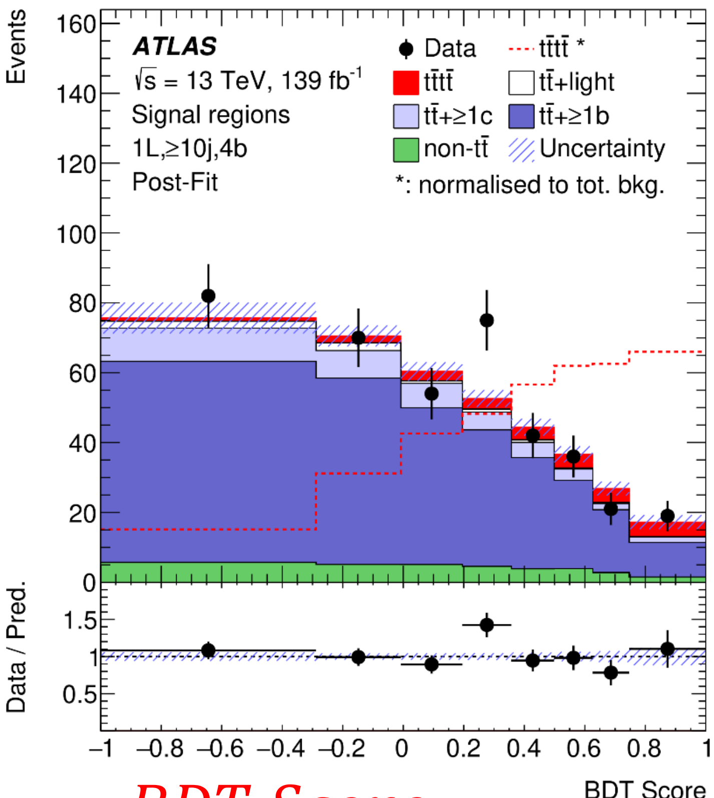
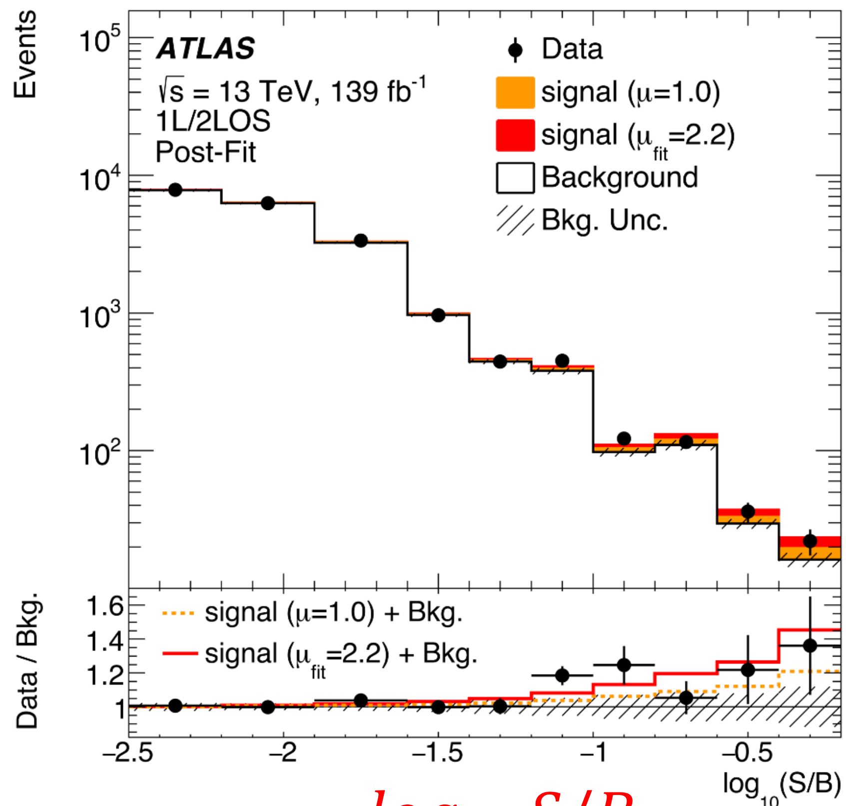


BDT Score

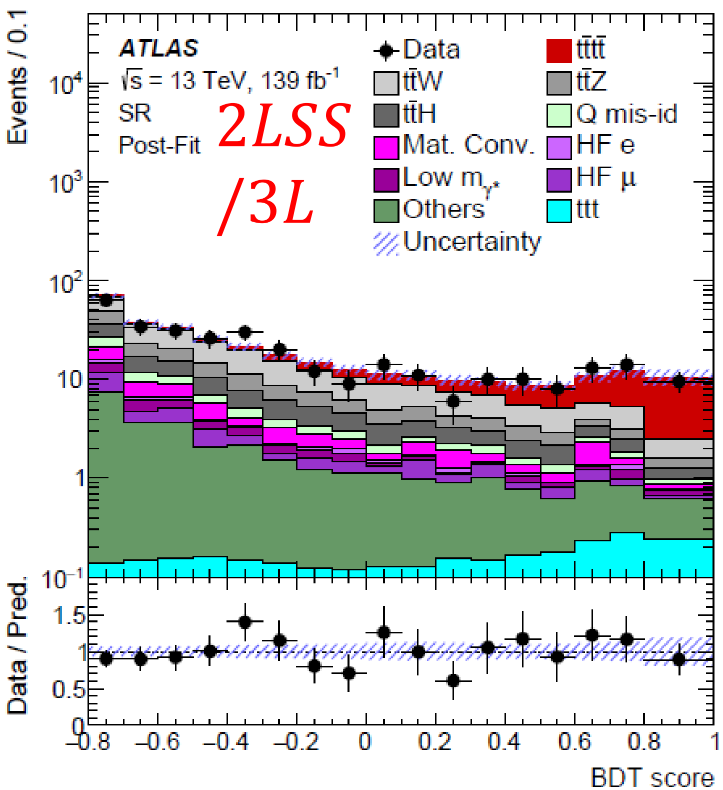


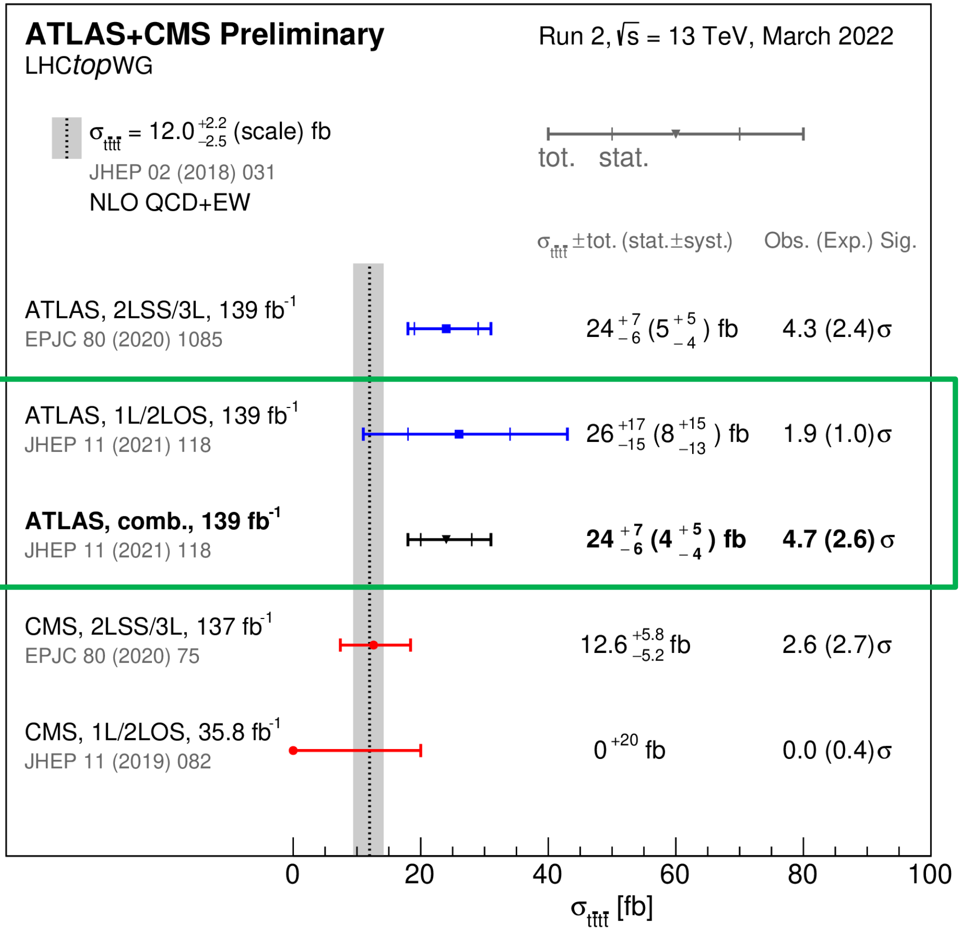
$log_{10}\, S/B$

- Largest systematic errors on $\sigma_{t\bar{t}t\bar{t}}$ are $t\bar{t}t\bar{t}$ and $t\bar{t}+1b/1c$ modeling and jet energy scale uncertainties

$t\bar{t}t\bar{t}$ Cross-Section

➢ 1L/2LOS and Combination (with 2LSS/3L)





[Four top production summary]

$t \to qX\ (q = u, c)\ with\ X \to b\bar{b}$

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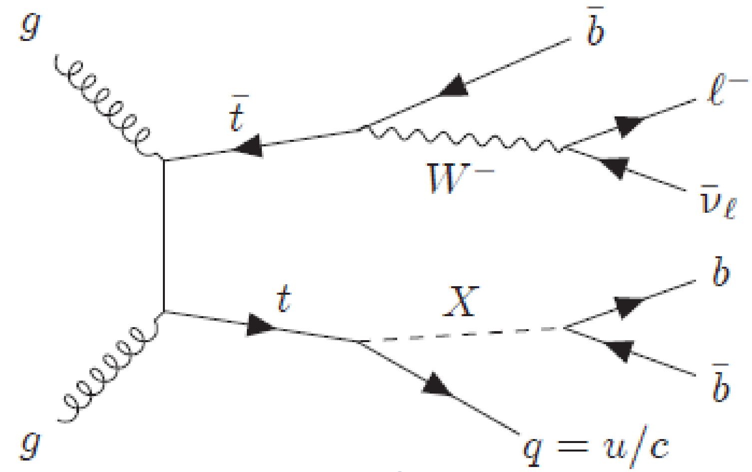
- Search for strongly suppressed FCNC
  - Several BSM theories predict large FCNC enhancements in top decays



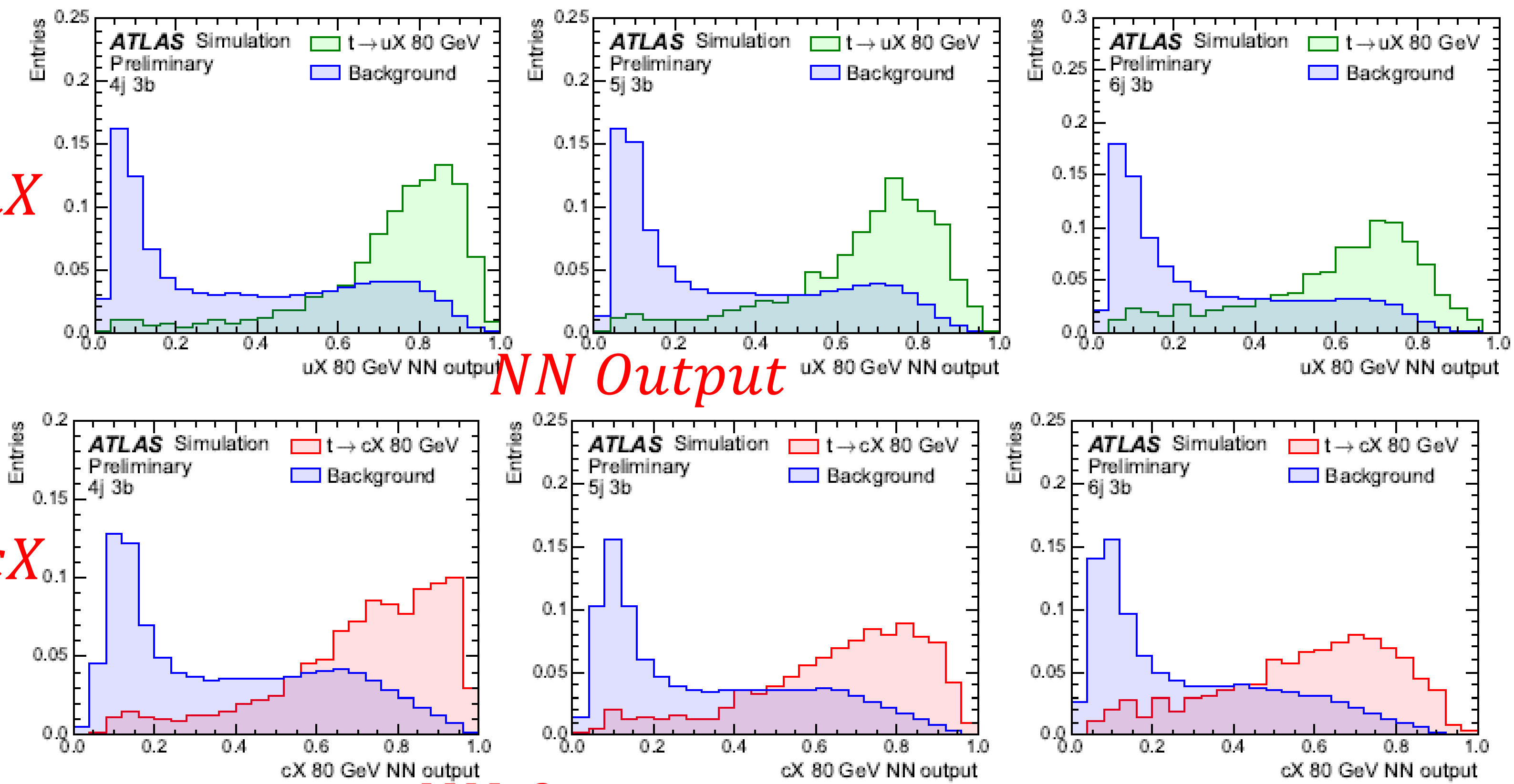
- Event selection is one e or μ, plus $\geq$ 4 jets, at least three of which are b-tagged
  - Also, $E_T^{miss} > 20$ GeV and $E_T^{miss} + m_T^W > 60$ GeV
- Three signal regions (4j3b, 5j3b, 6j3b)
  - Three control regions ($\geq 4b$) and three reweighting regions ($2b + 1$ looser b) are also used

$t \rightarrow qX\ (q = u, c)\ with\ X \rightarrow b\bar{b}$

- NN (5 hidden layers) is used to separate signal from background, mainly $t\bar{t} + jets$
  - 32 input variables including m_X and b-tagging scores

$t \rightarrow uX$

$t \rightarrow cX$



NN Output

NN Output

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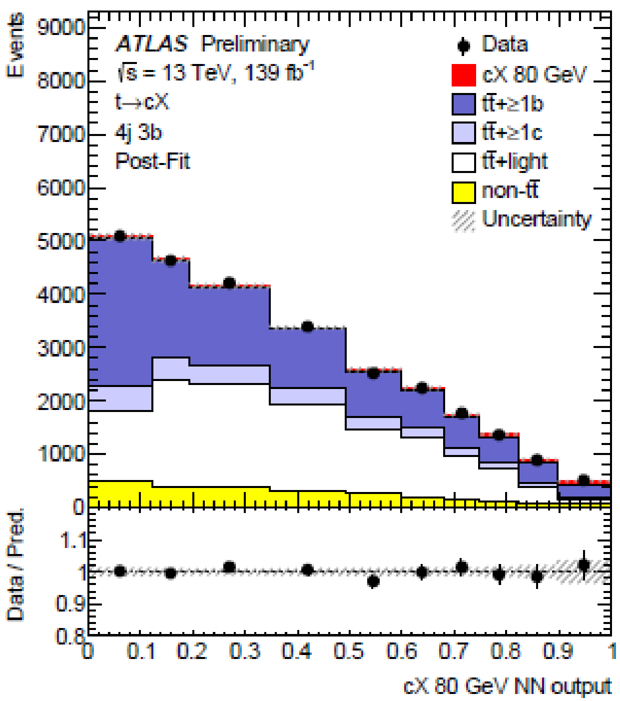
$t \to qX\ (q = u, c)\ with\ X \to b\bar{b}$

- A binned maximum likelihood fit to the NN output distribution in the three signal regions and yields in the three control regions is used
- Similar procedure to $t\bar{t}t\bar{t}$ measurement is used to reweight $t\bar{t}$ + jets distributions



NN output

μ is the signal strength

Uncertainty source	$\Delta\mu(uX_{30})$	$\Delta\mu(uX_{80})$	$\Delta\mu(uX_{120})$
$t\bar{t}$+≥1b modelling	0.040	0.060	0.098
$t\bar{t}$+≥1c modelling	0.033	0.055	0.091
$t\bar{t}$+light modelling	0.034	0.058	0.040
$t\bar{t}$+≥1b normalisation	0.012	0.011	0.039
$t\bar{t}$+≥1c normalisation	0.017	0.036	0.087
$W \to cb$ modelling	0.001	0.010	0.017
Reweighting	0.005	0.013	0.017
Other backgrounds	0.008	0.026	0.023
Luminosity, JVT, pile-up	0.002	0.006	0.012
Lepton trigger, identification, isolation	0.001	0.004	0.007
Jet energy scale and resolution	0.008	0.037	0.040
b-tagging efficiency for b-jets	0.007	0.008	0.041
b-tagging efficiency for c-jets	0.014	0.027	0.079
b-tagging efficiency for light jets	0.007	0.008	0.010

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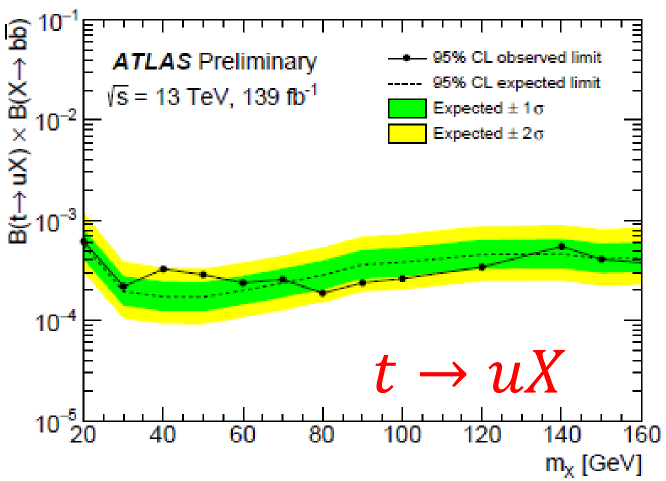
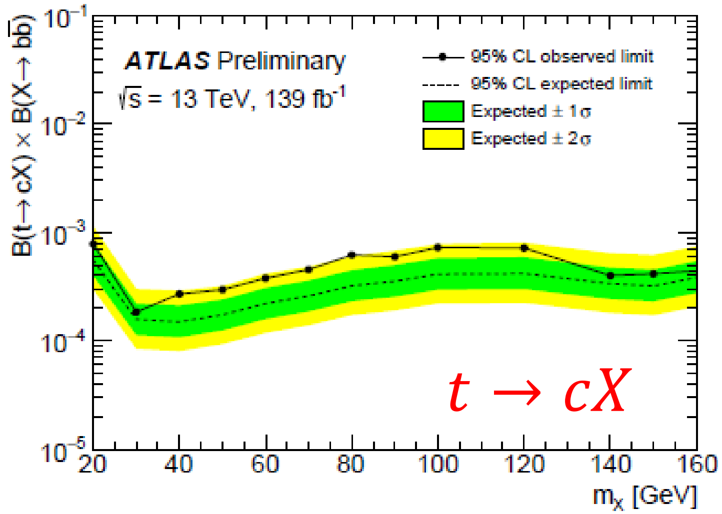
$t \to qX\ (q = u, c)\ with\ X \to b\bar{b}$

- Expected and observed 95% limits





- No significant excess is observed
  - $t \to uX\ UL\ (\%): 0.019\ (0.017) - 0.062\ (0.056)$
  - $t \to cX\ UL\ (\%): 0.018\ (0.015) - 0.078\ (0.056)$
- Expected limits are 3x better compared with previous ATLAS $t \to qH$ search results scaled to the same integrated luminosity

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Conclusions

- Highlights of $t\bar{t}X$ production
  - New inclusive and differential cross-section measurements in $t\bar{t}\gamma, tW\gamma$, and $t\bar{t}Z$ channels
  - Improved significance (4.7σ) for $t\bar{t}t\bar{t}$ production upon combining 1L/2LOS results with previous 2LSS/3L
  - New results on $t \rightarrow qX, X \rightarrow b\bar{b}$ FCNC searches
- Looking forward to even more rare top physics with 200 fb^{-1} at 13.6 TeV in LHC Run 3