Searches for rare top quark production and decay processes with the ATLAS experiment

Jiri Hejbal (Institute of Physics in Prague)

on behalf of the ATLAS Collaboration

Pheno 2022, Pittsburgh

10/05/2022

Introduction

Flavour Changing Neutral Currents (FCNC)

- FCNC processes are forbidden at tree level and highly suppressed at higher order in the Standard Model (SM)
  - Branching ratios of top quark decay ~ 10^{-12} to 10^{-17}
- Observation of enhanced rates would be a clear evidence for new physics
  - Several extensions to the SM include additional sources of FCNCs

FCNC couplings can be described by an EFT:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda_{\text{NP}}^2} \sum_k C_k O_k$$

Λ_{NP} ... scale of new physics

O_k ... dimension-6 operator

We present result of searches for FCNC processes involving top quarks

- tqg, tqγ, tqZ and tqH

Finally, we focus on results of rare SM processes involving top quarks

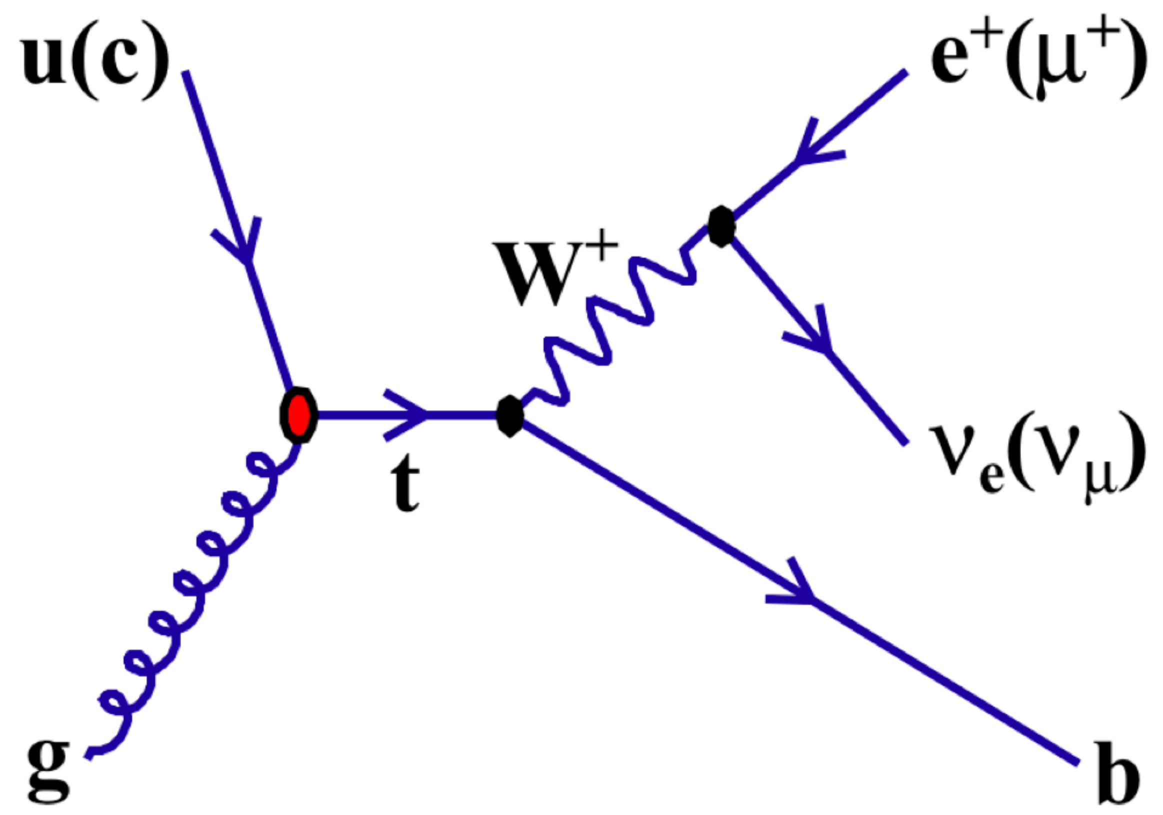
- $t\bar{t}t\bar{t}$ and tγ

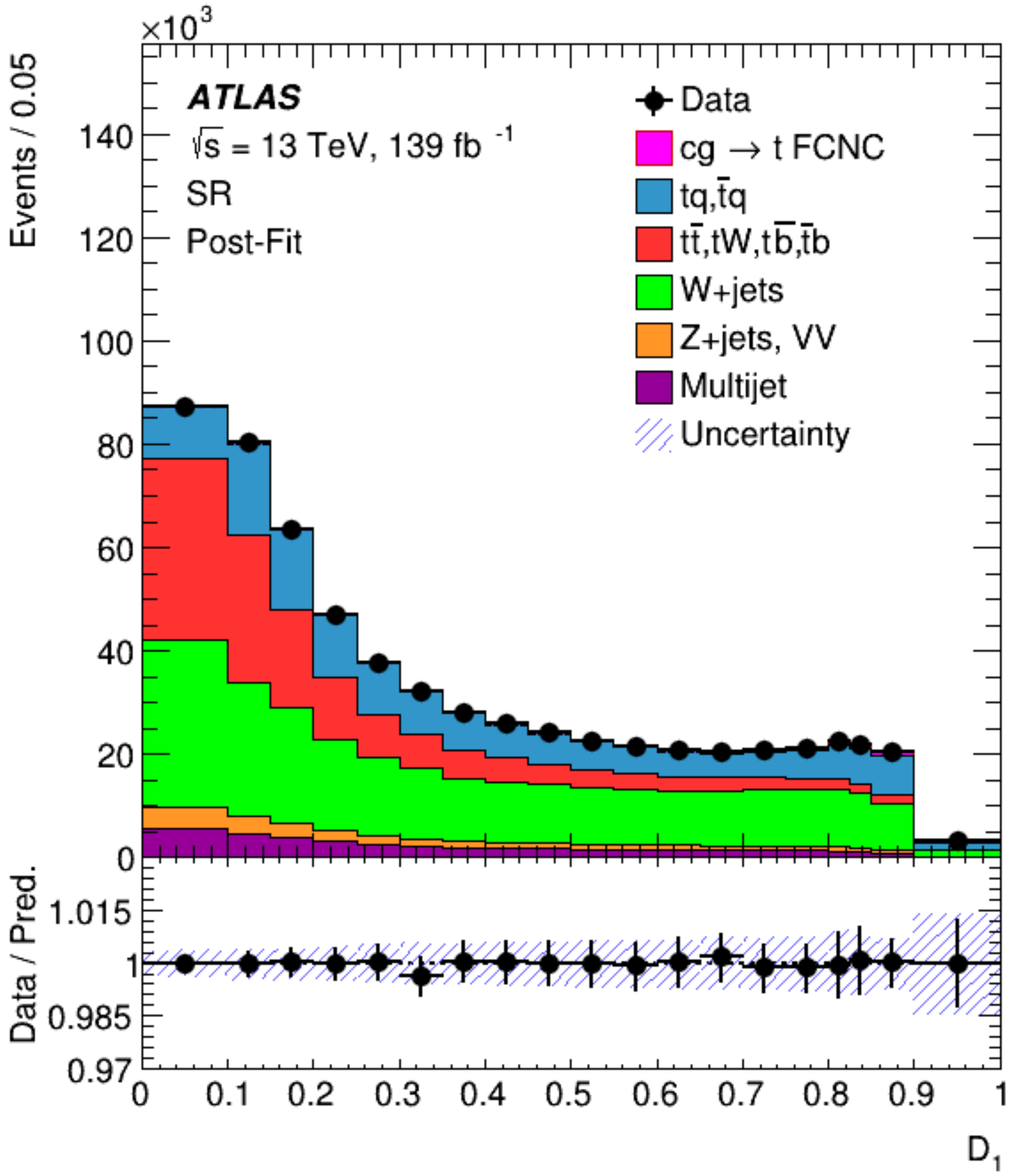
For more top quark related results see Pavol's talk

FCNC tqg

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

- Probes single top quark production via FCNC
- Reconstruct top in $t \to e/\mu\, \nu b$ final states, where $t \to \tau \nu b$ may also contribute
  - =1 lepton, ≥1 b-jet, ETmiss > 30 GeV, $m_T(W) > 50$ GeV
  - Nr. of b-jet to define validation region, in signal region =1 b-jet





- The analysis targets separate contributions from tgu and tgc
  - Separate contributions from valence quark vs. sea quark
  - Two neural networks trained to target different signals from background
    - Target tgc (sea quark) signal ⇒ D1 discriminant
    - Target tgu (valence quark) signal ⇒ D2 discriminant

FCNC tqg

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

- Upper limits on the production

$$\sigma(ugt) \times \mathcal{B}(t \to Wb) \times \mathcal{B}(W \to \ell\nu) < 3.0\ \text{pb}$$ 2.4 pb expected

$$\sigma(cgt) \times \mathcal{B}(t \to Wb) \times \mathcal{B}(W \to \ell\nu) < 4.7\ \text{pb}$$ 2.5 pb expected

$$\mathcal{B}(W \to \ell\nu) = 0.325$$

- The cross-section limits are interpreted in an EFT and converted to limits on EFT coefficients and BR

$$\frac{|C_{uG}^{ut}|}{\Lambda^2} < 0.057\ \text{TeV}^{-2} \quad \text{and} \quad \frac{|C_{uG}^{ct}|}{\Lambda^2} < 0.14\ \text{TeV}^{-2}$$

$$\mathcal{B}(t \to u + g) < 0.61 \times 10^{-4} \quad \text{and} \quad \mathcal{B}(t \to c + g) < 3.7 \times 10^{-4}$$

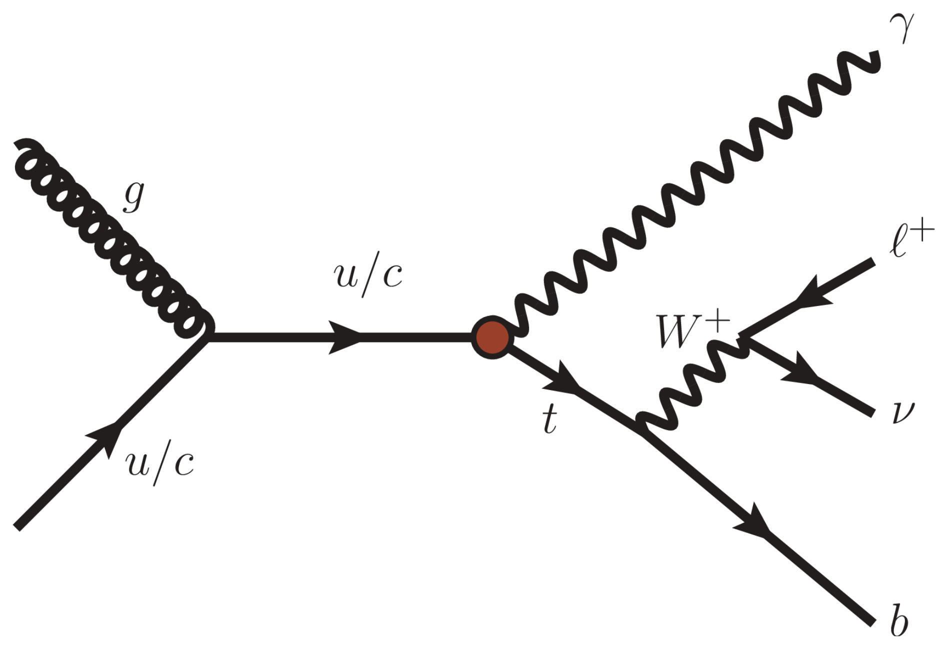
- A factor of 2 improvement wrt the ATLAS 8 TeV results

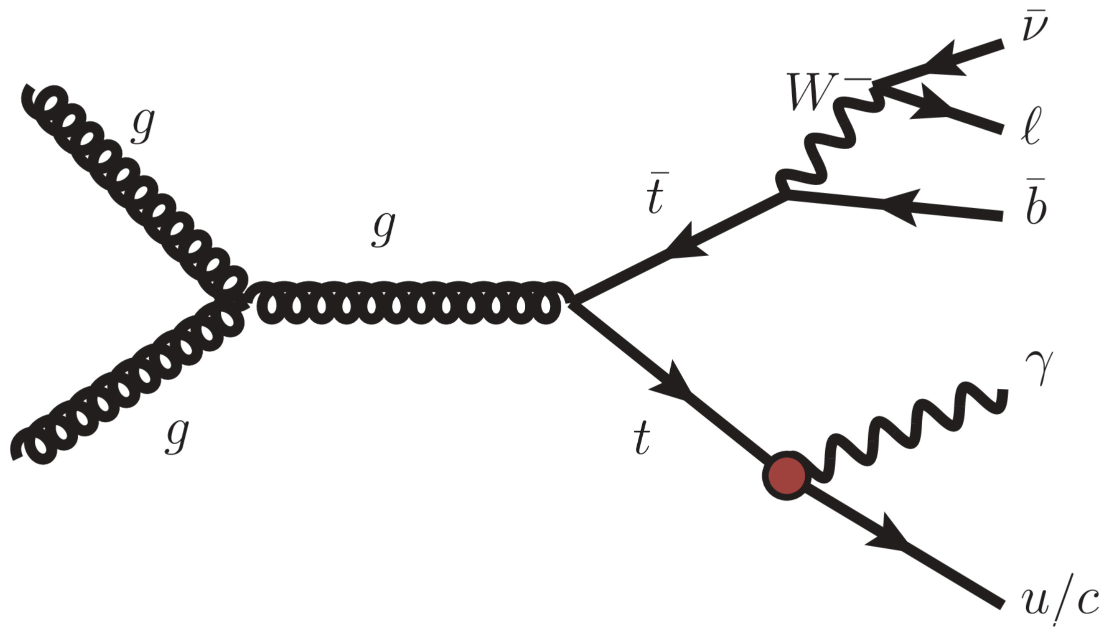
- Leading systematics: tug: related to W+jets process
  tgc: modelling of the parton shower

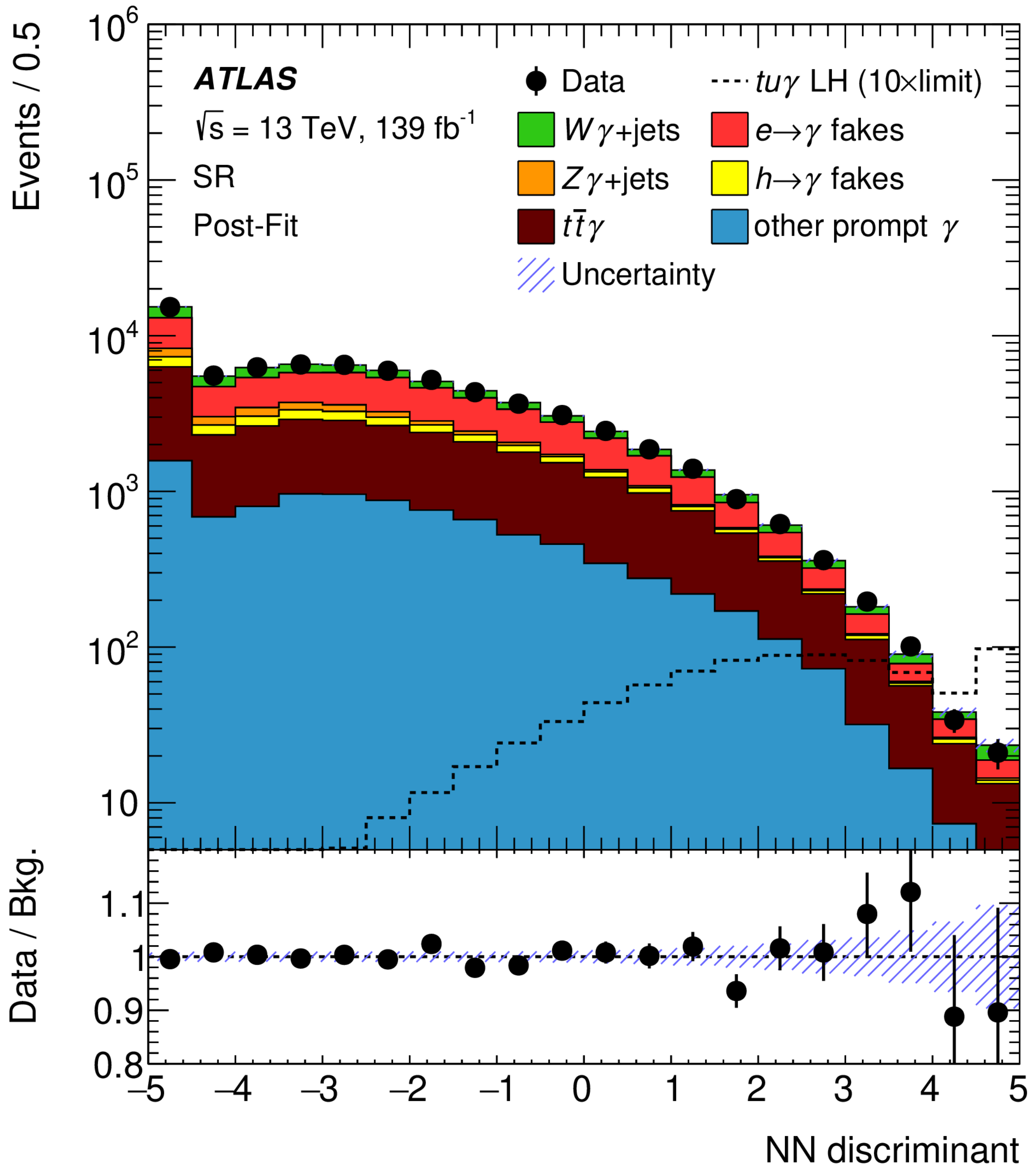
FCNC tqγ

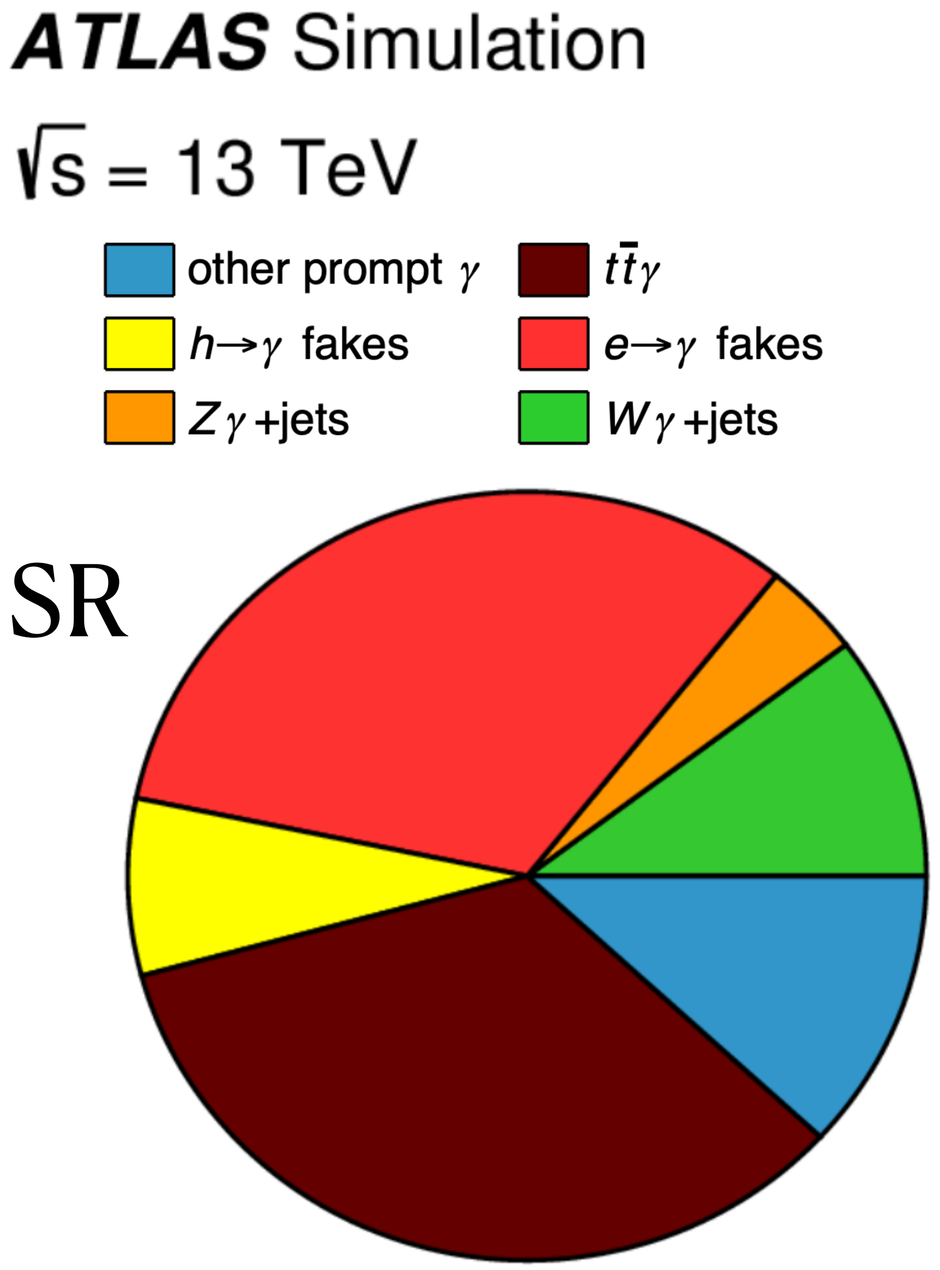
arXiv:2205.02537
submitted to Phys. Lett. B

- Target both production and decay of FCNC tγq vertices
- Background estimation
  - e→γ: estimate a fake factor to correct simulation
  - h→γ: transfer factor from control region
- Two neural network targeting tuγ and tcγ signal separately







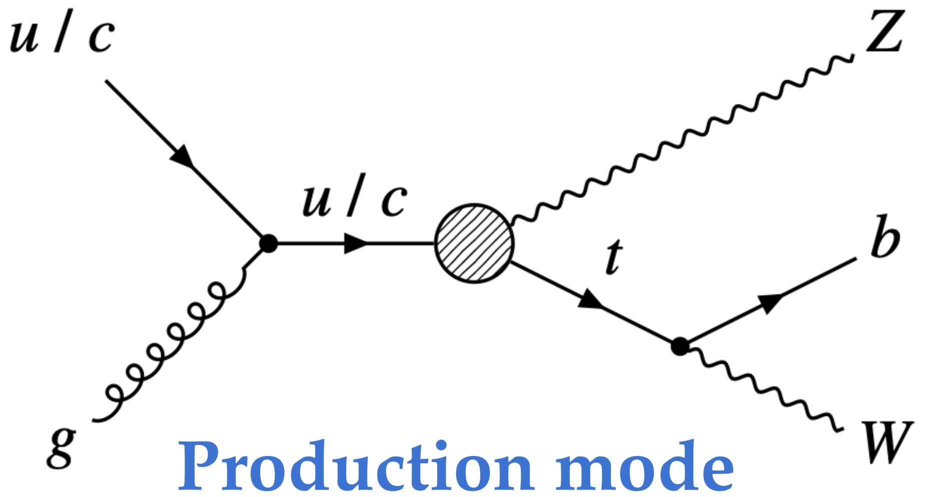


- Upper limits of BR

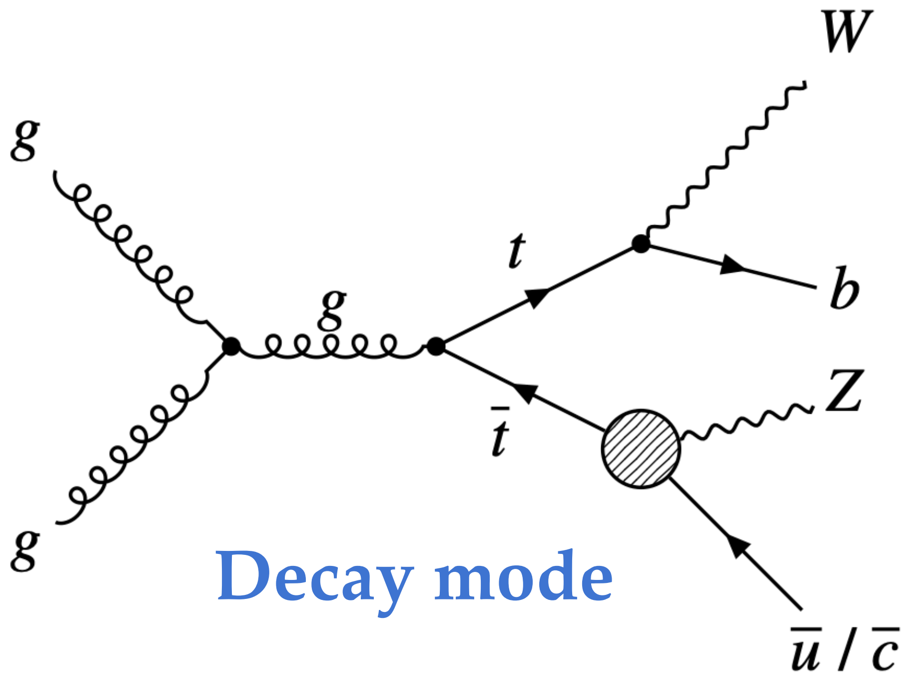
Effective coupling	Coefficient limits: Expected	Coefficient limits: Observed	Coupling	BRs $[10^{-5}]$: Expected	BRs $[10^{-5}]$: Observed
$\lvert C_{uW}^{(13)*} + C_{uB}^{(13)*} \rvert$	$0.104^{+0.020}_{-0.016}$	0.103	$t \to u\gamma$ LH	$0.88^{+0.37}_{-0.25}$	0.85
$\lvert C_{uW}^{(31)} + C_{uB}^{(31)} \rvert$	$0.122^{+0.023}_{-0.018}$	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

- Major systematic: statistical uncertainty
- Factor of 3.3 – 5.4 improvement wrt ATLAS 13 TeV 81 fb^{-1} results
  - More signal region, more optimised analysis and higher luminosity

- Target both production and decay of FCNC tqZ vertices:
  - Z→ ll, semi-leptonic top decay ⇒ tri- leptons

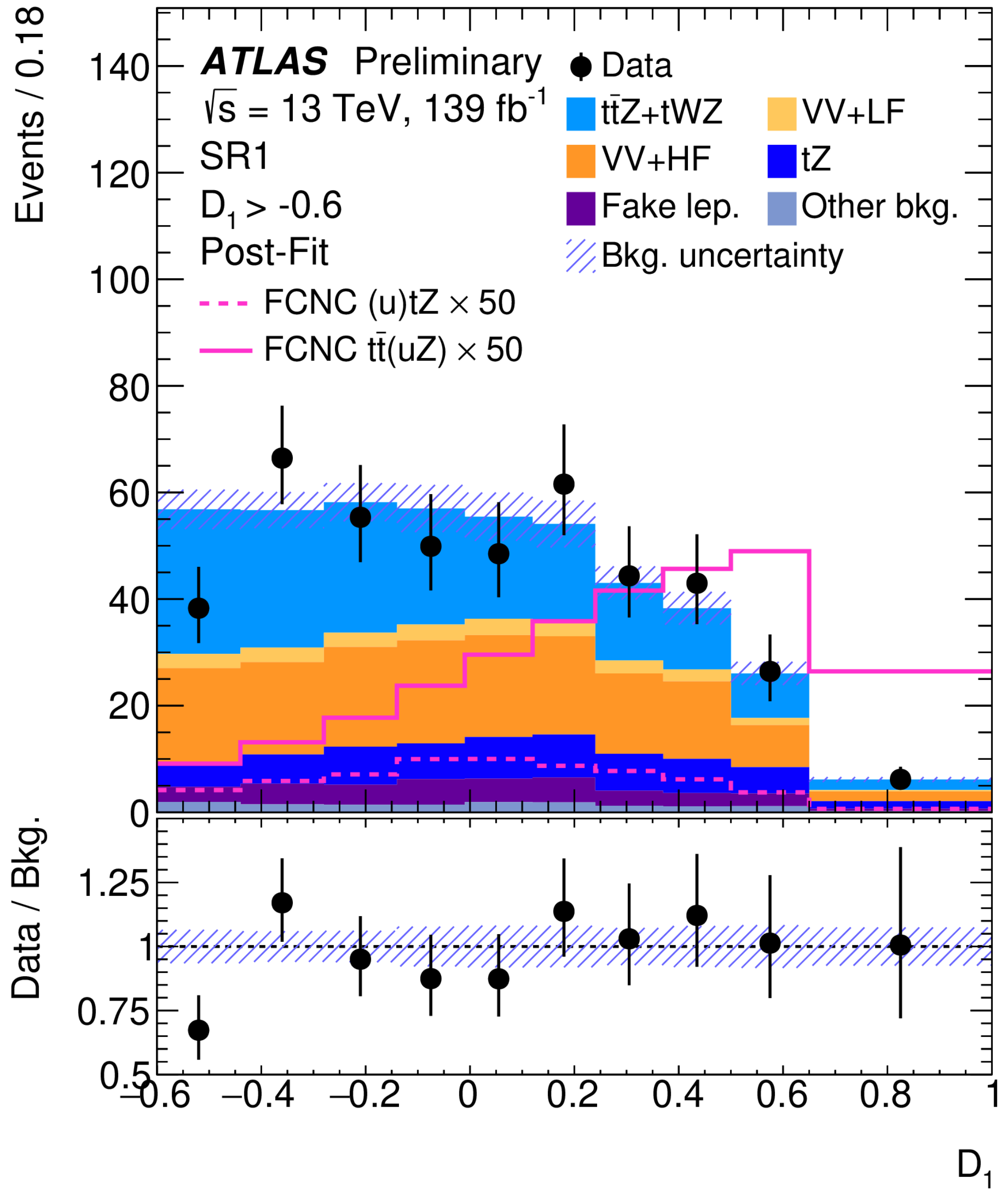


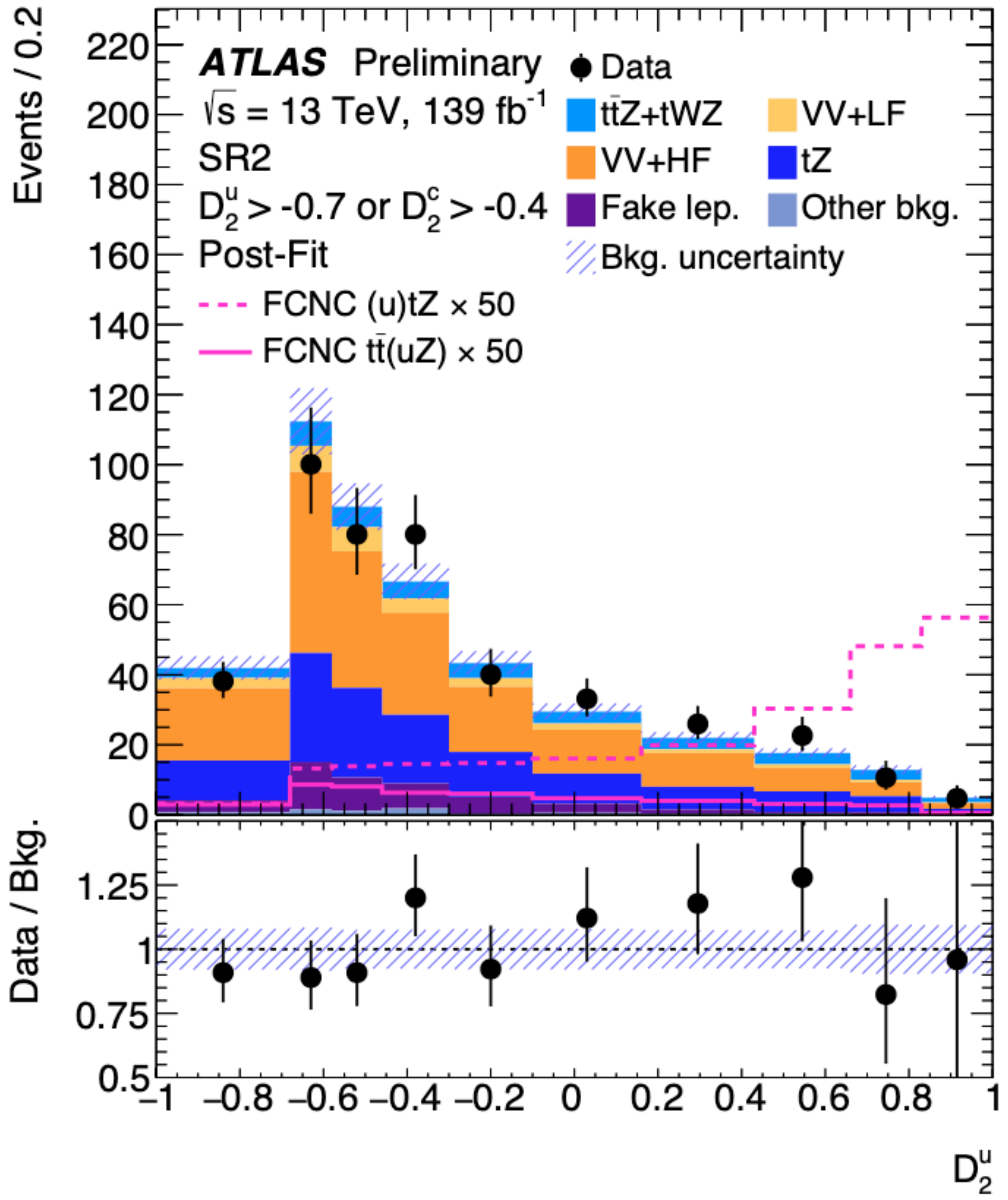
Production mode



Decay mode

- Analysis regions
  - Orthogonality cut applied on reconstructed top mass
  - ≥2 jets, 1 b-jet (SR1) targeting decay mode or ≥1 jet, 1 b-jet (SR2) targeting production mode





- Background estimation
  - $t\bar{t}$, $t\bar{t}Z$ yields estimated in control regions
  - VV+heavy flavour estimated in sideband regions
  - Others from MC simulation
- Separate signal against all bkg
  - BDT_1: SR1 tZu and tZc decay mode
  - BDT_2^u: SR2 tZu in production mode
  - BDT_2^c: SR2 tZc in both modes

FCNC tqZ

ATLAS-CONF-2021-049

Observable	Vertex	Coupling	Observed	Expected
		SR1+CRs		
$\mathcal{B}(t \to Zq)$ $[10^{-5}]$	tZu	LH	9.7	$8.6^{+3.6}_{-2.4}$
$\mathcal{B}(t \to Zq)$ $[10^{-5}]$	tZu	RH	9.5	$8.2^{+3.4}_{-2.3}$
		SR2+CRs		
$\mathcal{B}(t \to Zq)$ $[10^{-5}]$	tZu	LH	7.8	$6.1^{+2.7}_{-1.7}$
$\mathcal{B}(t \to Zq)$ $[10^{-5}]$	tZu	RH	9.0	$6.6^{+2.9}_{-1.8}$
		SRs+CRs		
$\mathcal{B}(t \to Zq)$ $[10^{-5}]$	tZu	LH	6.2	$4.9^{+2.1}_{-1.4}$
$\mathcal{B}(t \to Zq)$ $[10^{-5}]$	tZu	RH	6.6	$5.1^{+2.1}_{-1.4}$
$\mathcal{B}(t \to Zq)$ $[10^{-5}]$	tZc	LH	13	11^{+5}_{-3}
$\mathcal{B}(t \to Zq)$ $[10^{-5}]$	tZc	RH	12	10^{+4}_{-3}
$\lvert C_{uW}^{(13)*}\rvert$ 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	$0.19^{+0.04}_{-0.03}$

LH: left hand

RH: right hand

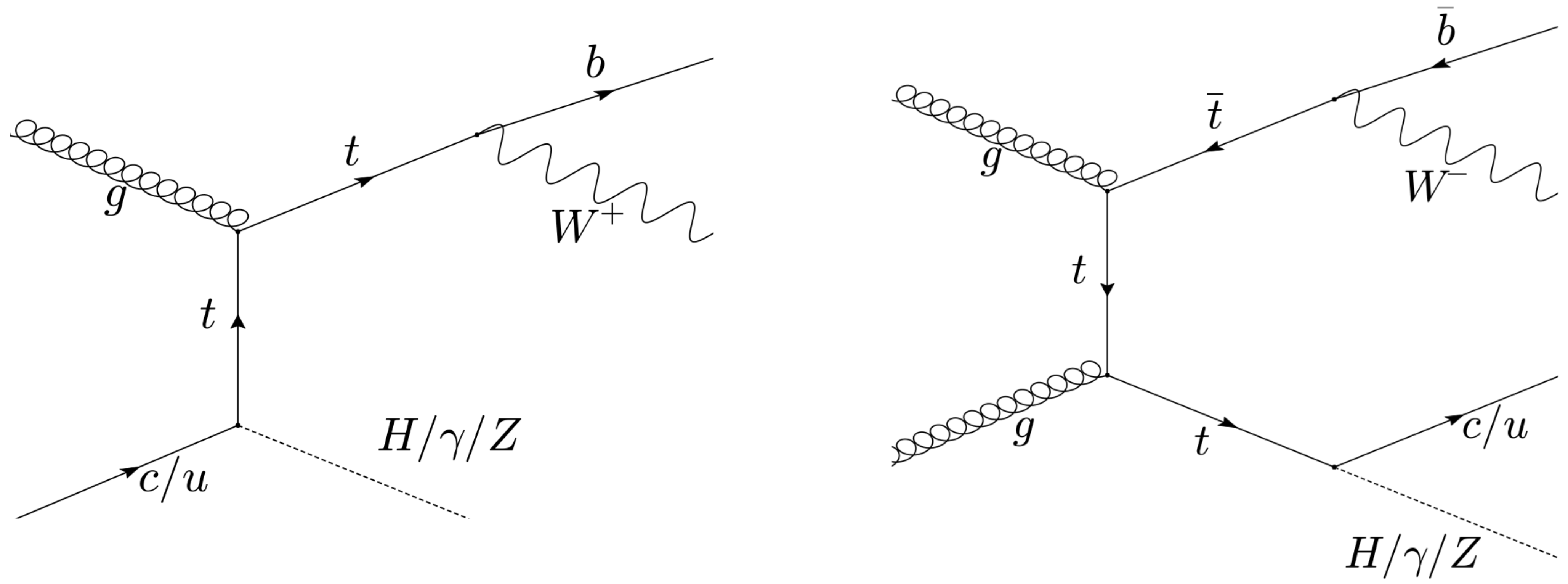
← Higher sensitivity from SR2

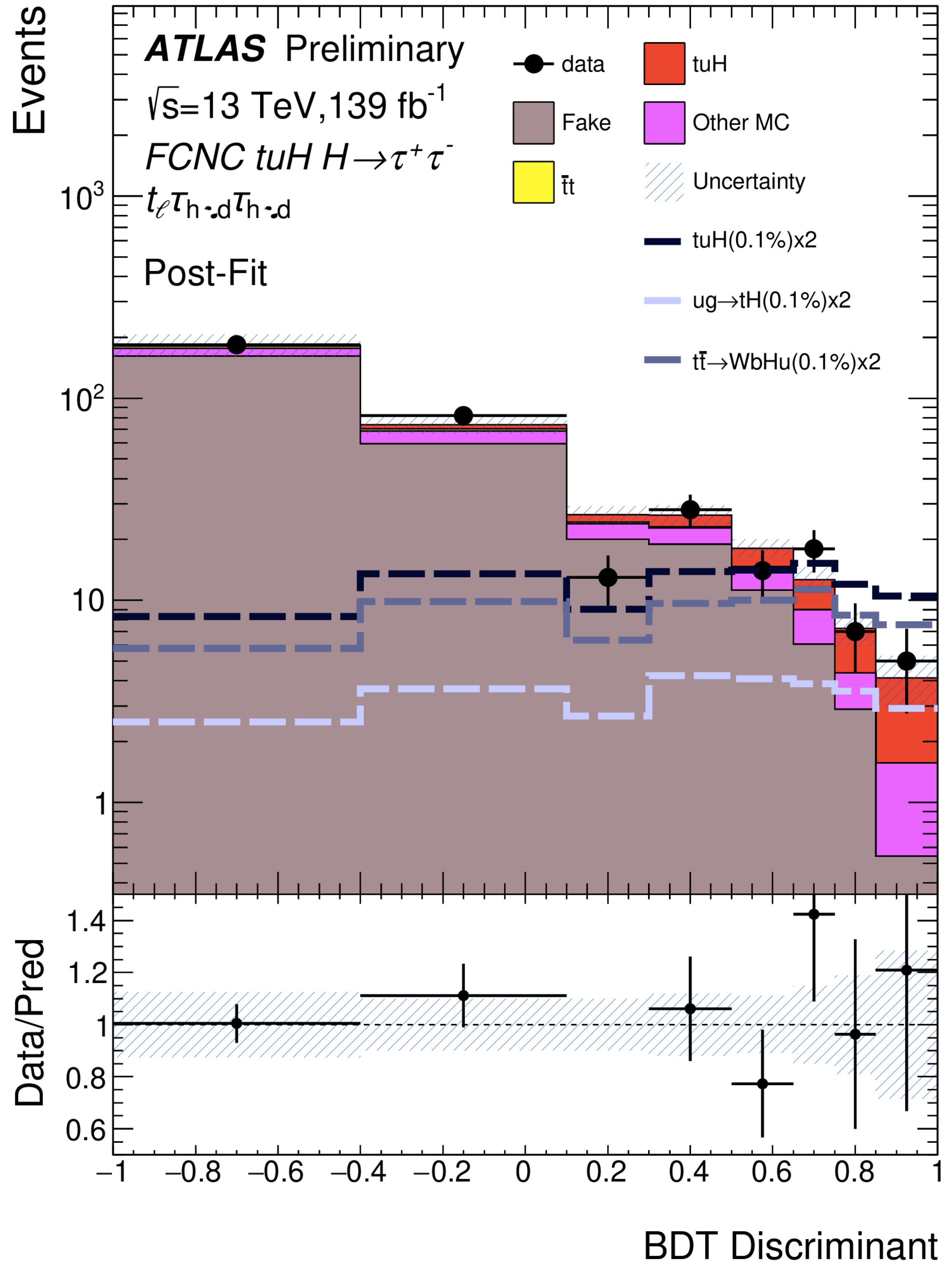
- Upper limits on branching ratios, were improved with respect to the previous results
  - by factors of 5 (3): LH expected BR limits for $t \to Zu$ ($t \to Zc$)
  - by factors of 3 (2): LH observed BR limits for $t \to Zu$ ($t \to Zc$)
  - Inclusion of prod. mode, MVA technique, and higher lumi.

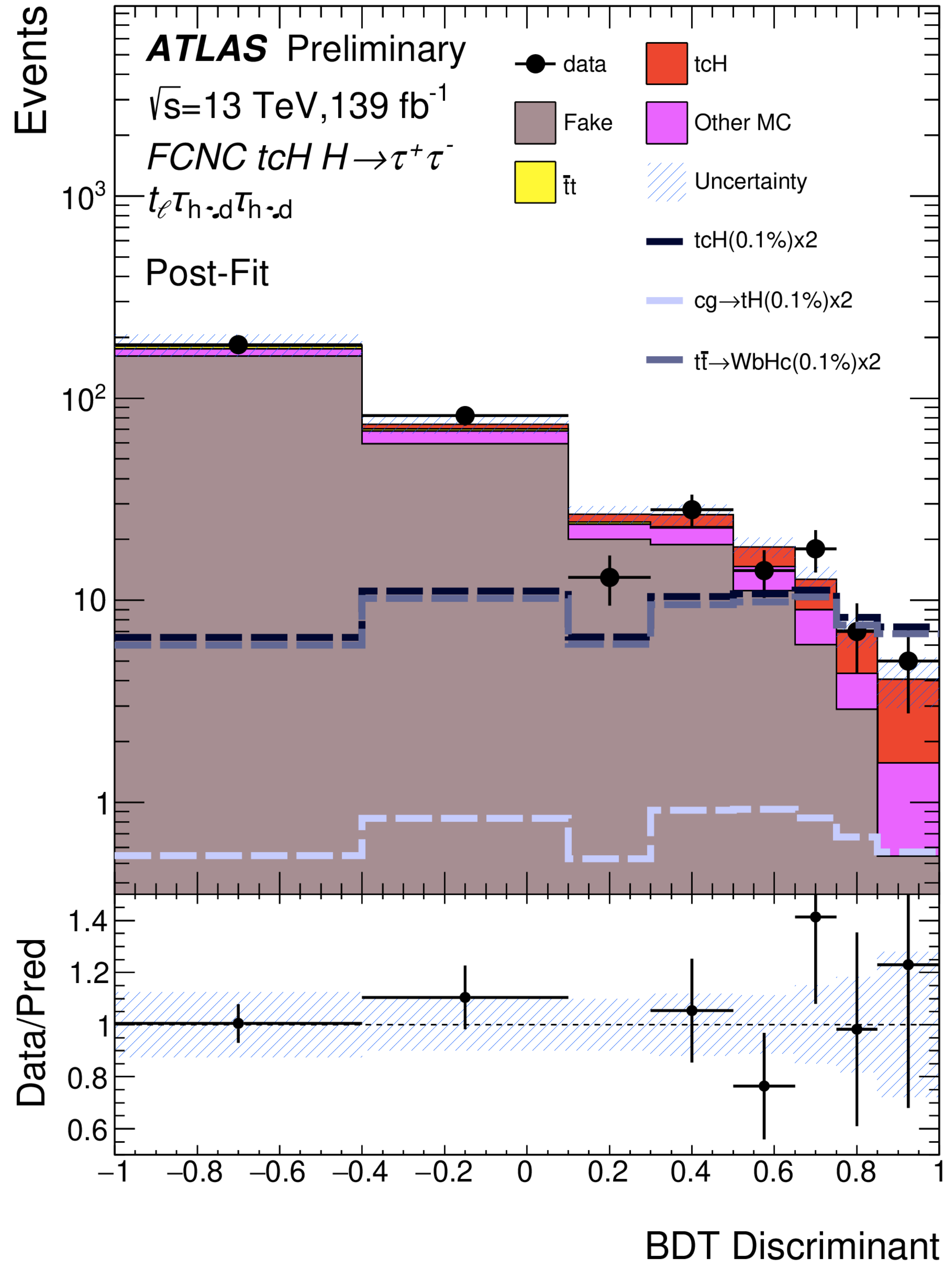
FCNC $H \to \tau^+\tau^-$

ATLAS-CONF-2022-014

- Explored both production and decay of FCNC tqH vertices
  - Top quark: leptonic or hadronic decay
  - $H \to \tau\tau$: $\tau_{had}\,\tau_{had}$ or $\tau_{lep}\,\tau_{had}$ (depending on τ-lepton decay)







- Analysis regions
  - Employ seven signal regions in a combination of top and di-tau decay, and additional jets
  - BDT is trained in each of the SR to separate signal from SM background
- Background estimation
  - Fake τ: estimate a transfer factor in CR
  - Others: Monte-Carlo simulation

FCNC $H \to \tau^+ \tau^-$

ATLAS-CONF-2022-014

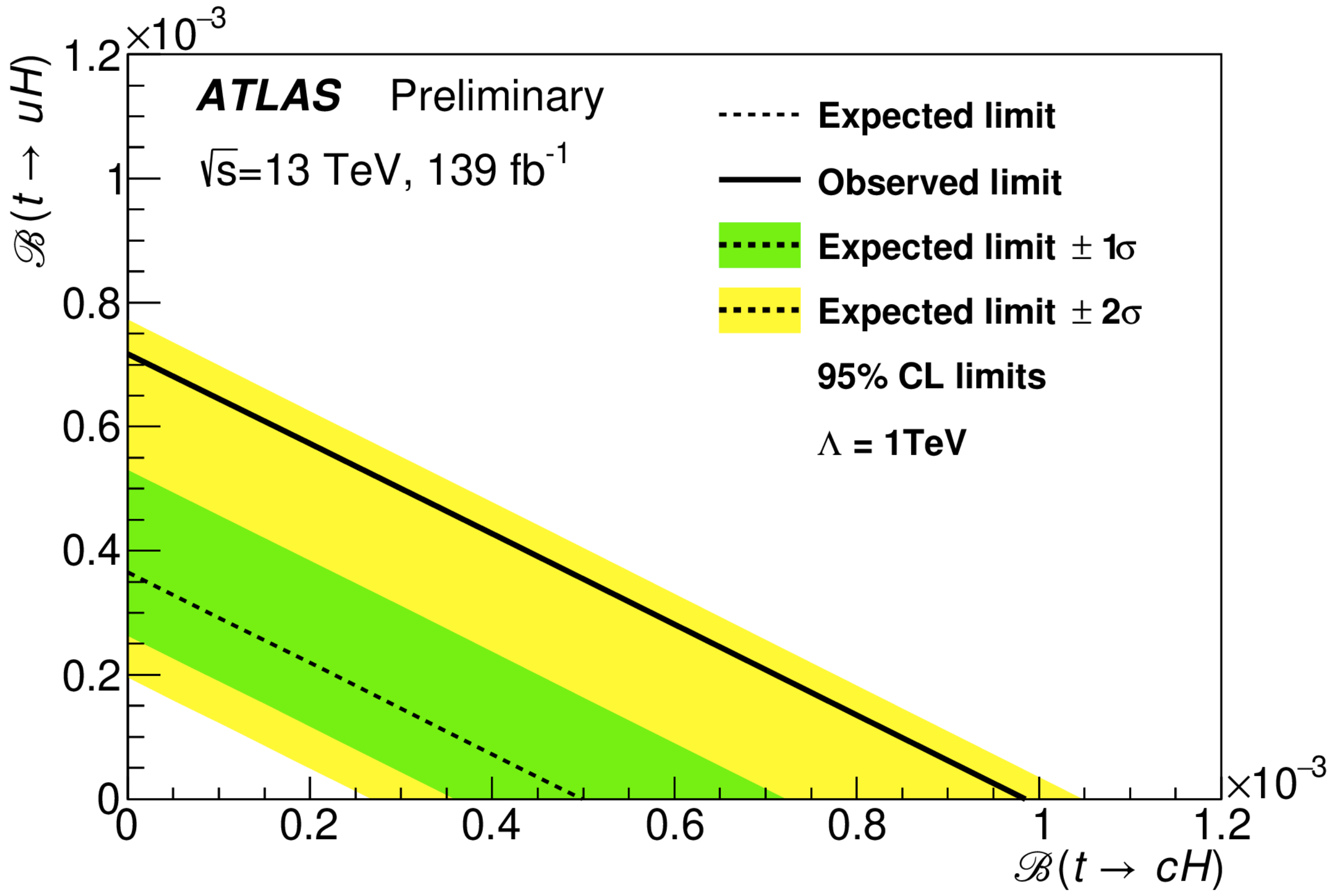
- Upper limits of BR:

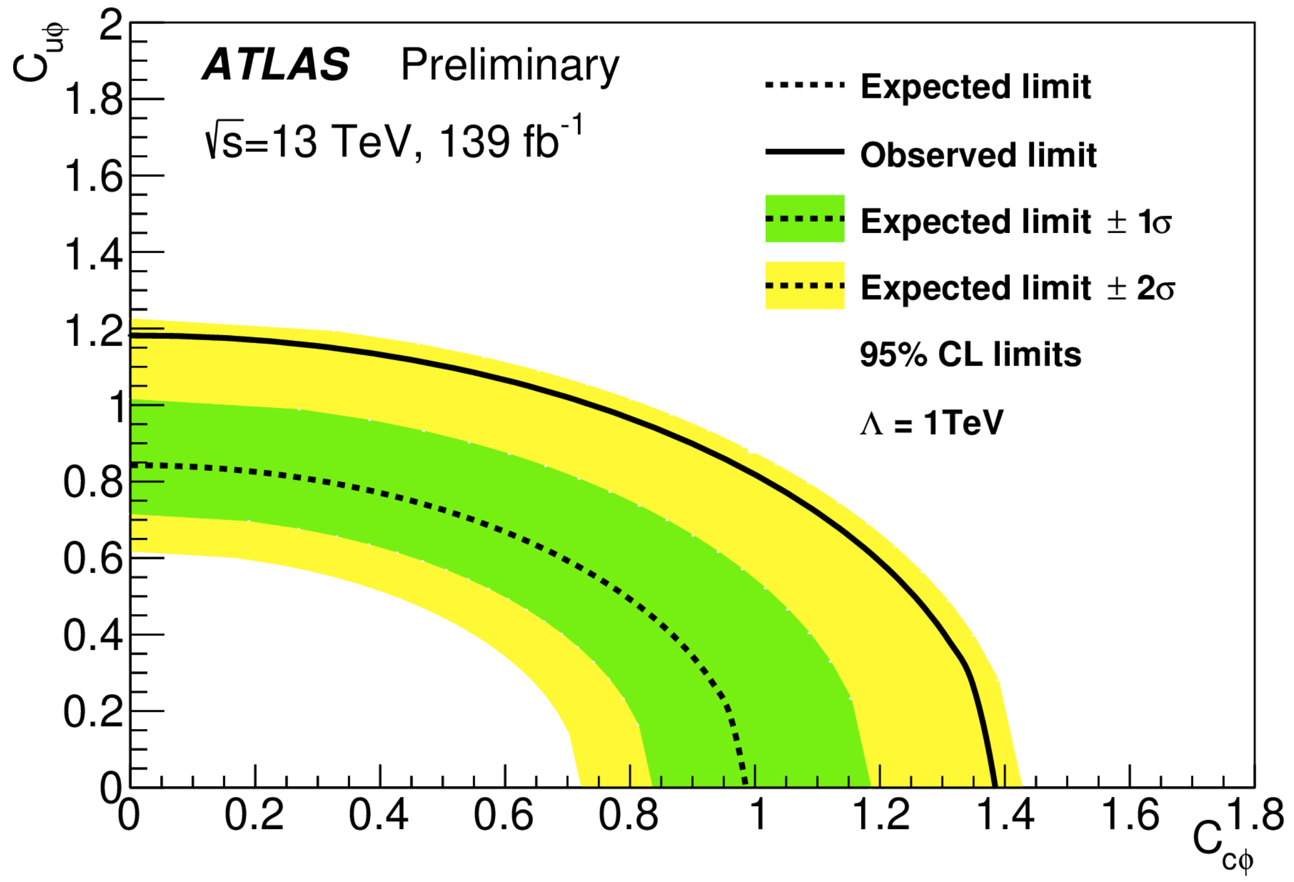
$$\mathcal{B}(t \to cH) < 9.9 \times 10^{-4}\,(5.0^{+2.2}_{-1.4} \times 10^{-4}), \text{ assuming } \mathcal{B}(t \to uH) = 0$$

$$\mathcal{B}(t \to uH) < 7.2 \times 10^{-4}\,(3.6^{+1.7}_{-1.0} \times 10^{-4}), \text{ assuming } \mathcal{B}(t \to cH) = 0$$

- Limits translate to tqH Wilson coefficients: $C_{c\phi} < 1.38\,(0.97)$ and $C_{u\phi} < 1.18\,(0.83)$

- 2D contours:

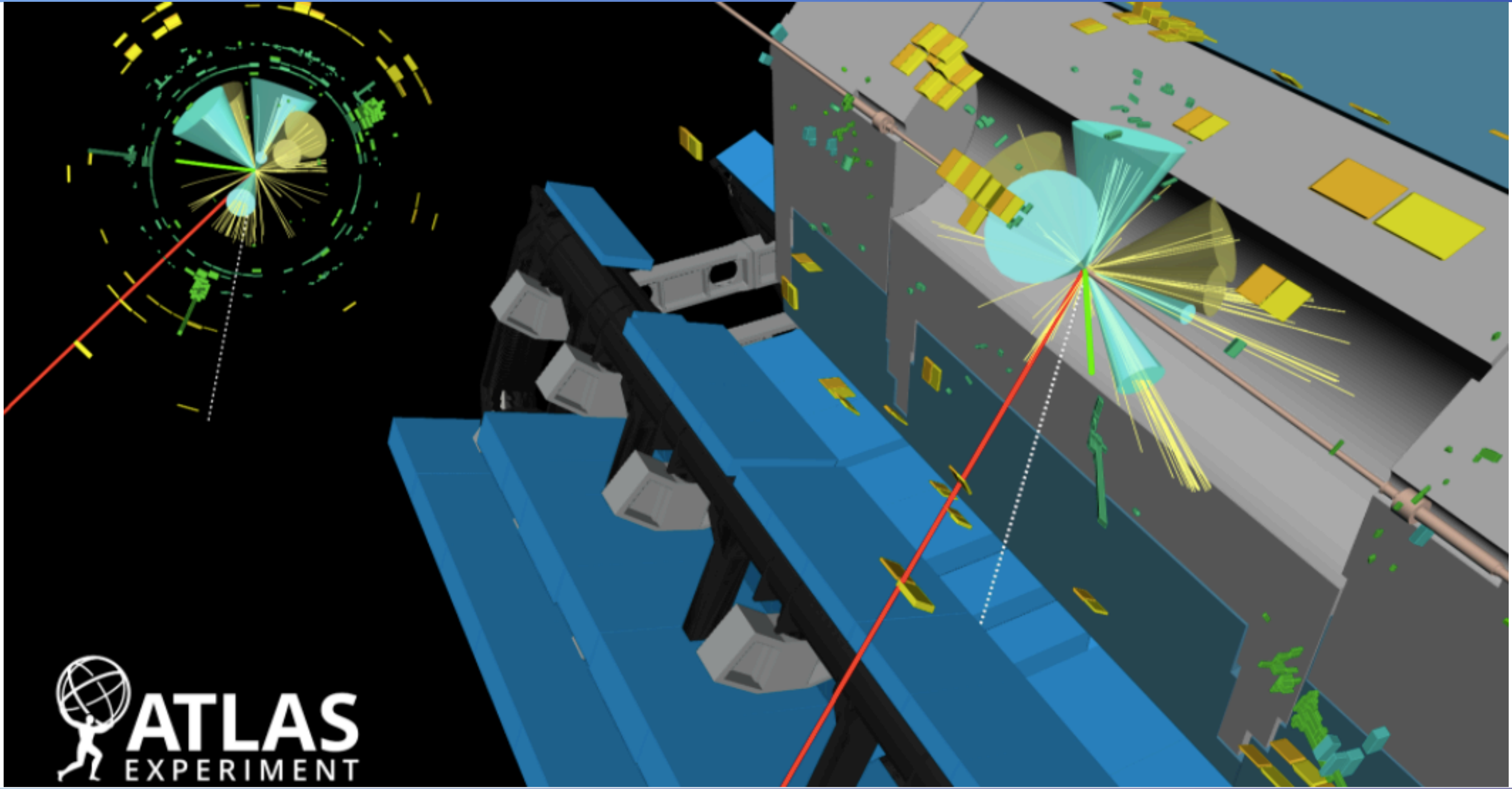




- Major systematic: statistical uncertainty
- A slight excess of data is observed above background with a significance of 2.3 σ
- A factor of 5 improvement wrt ATLAS 13 TeV 36 fb^{-1} results

$t\bar{t}t\bar{t}$ production

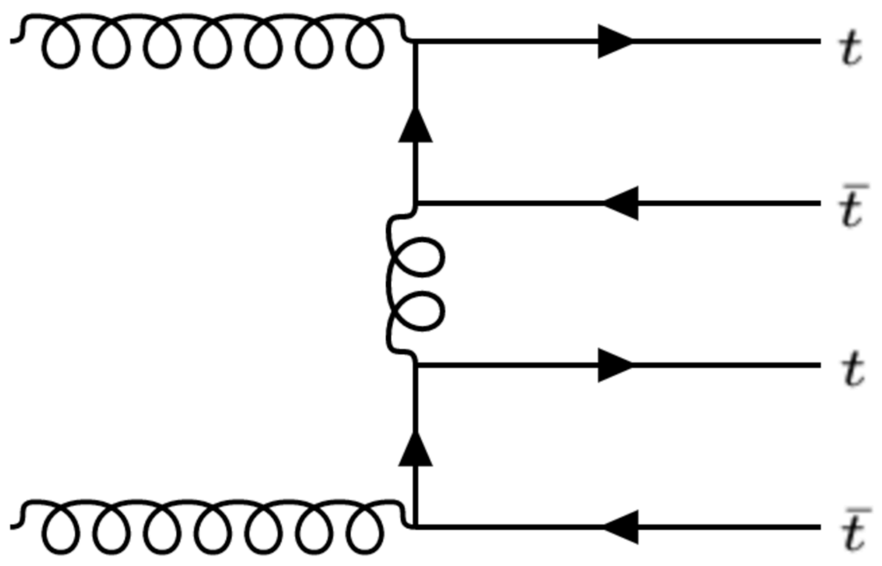
JHEP 11 (2021) 118

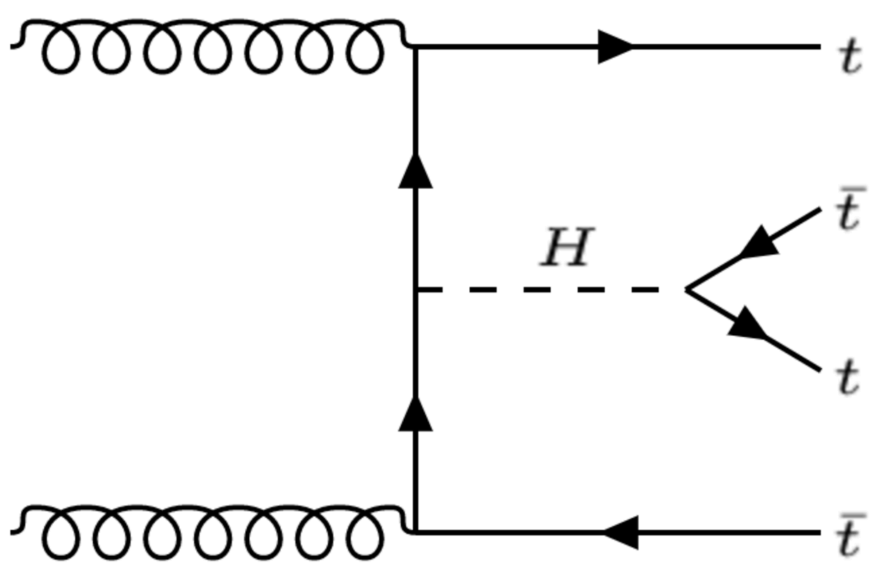


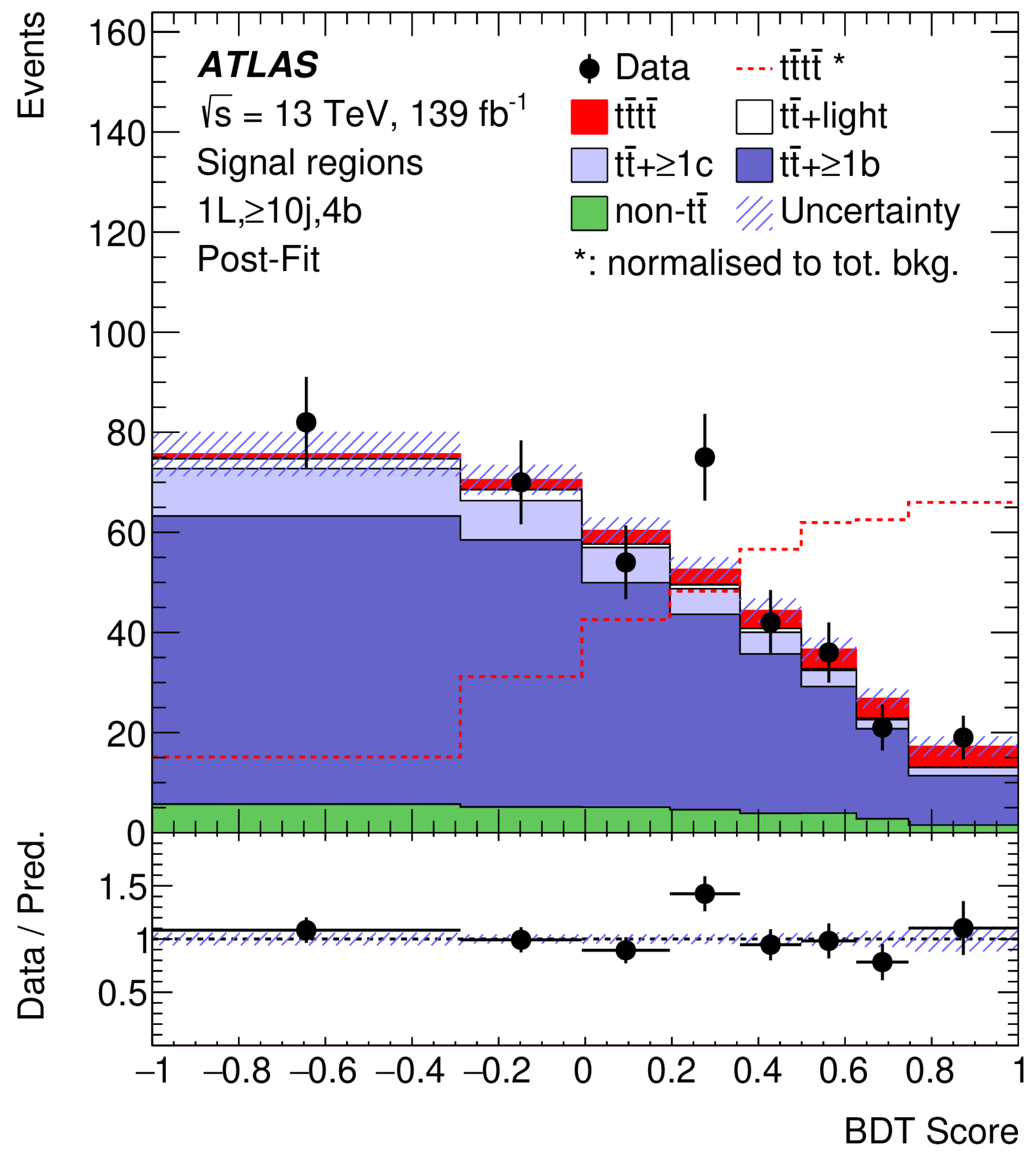
$t\bar{t}t\bar{t}$ production

JHEP 11 (2021) 118

- Measurements done in the all of the leptonic final states
  - SS dilepton and multi-lepton channel (**2LSS/ML**) -> Eur. Phys. J. C 80 (2020)
  - single-lepton and OS dilepton channel (**1L/2LOS**) -> this talk
- Never observed by ATLAS or CMS yet
- Sensitive to the magnitude and CP properties of the Yc of top-quark to Higgs boson



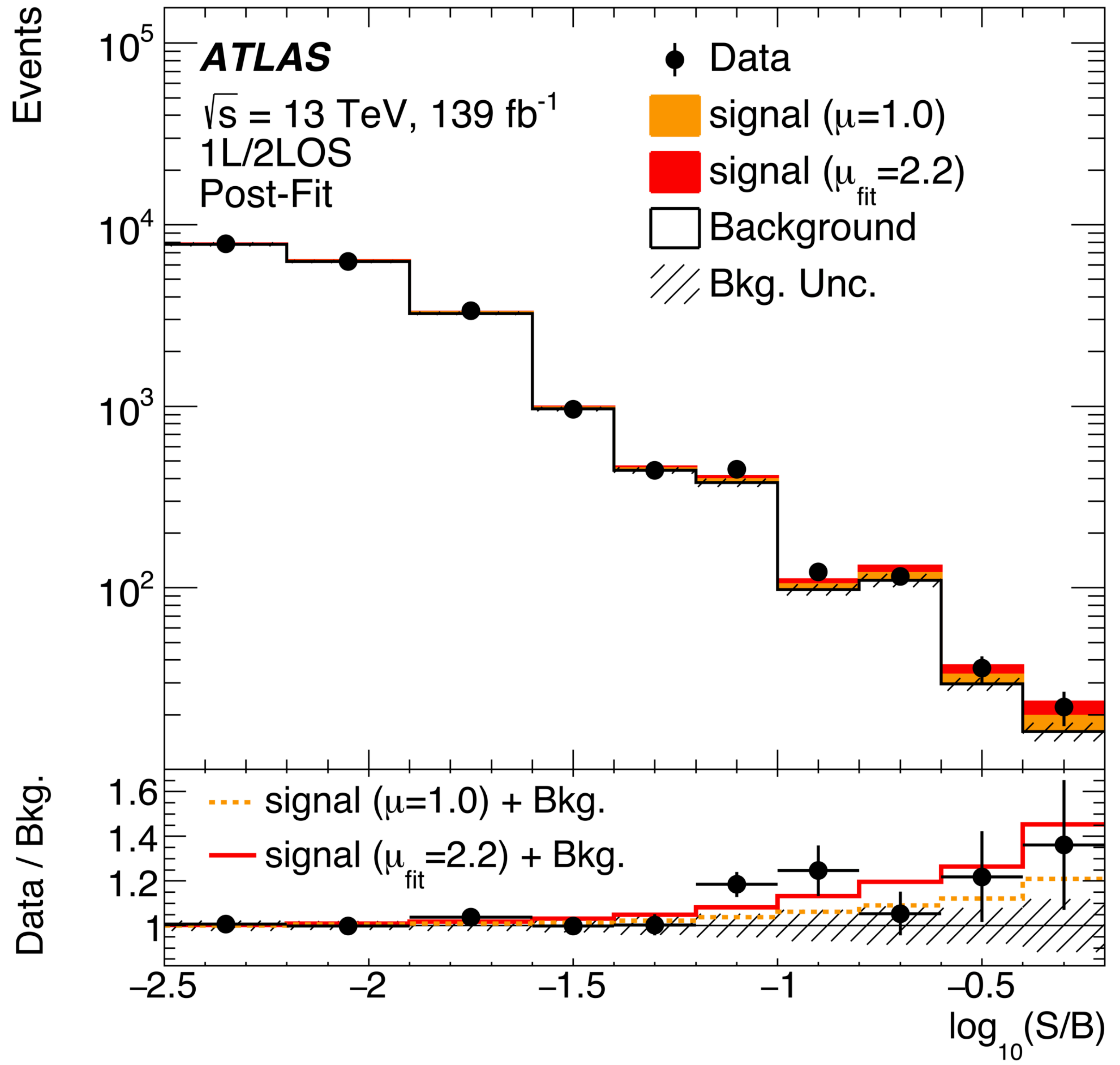


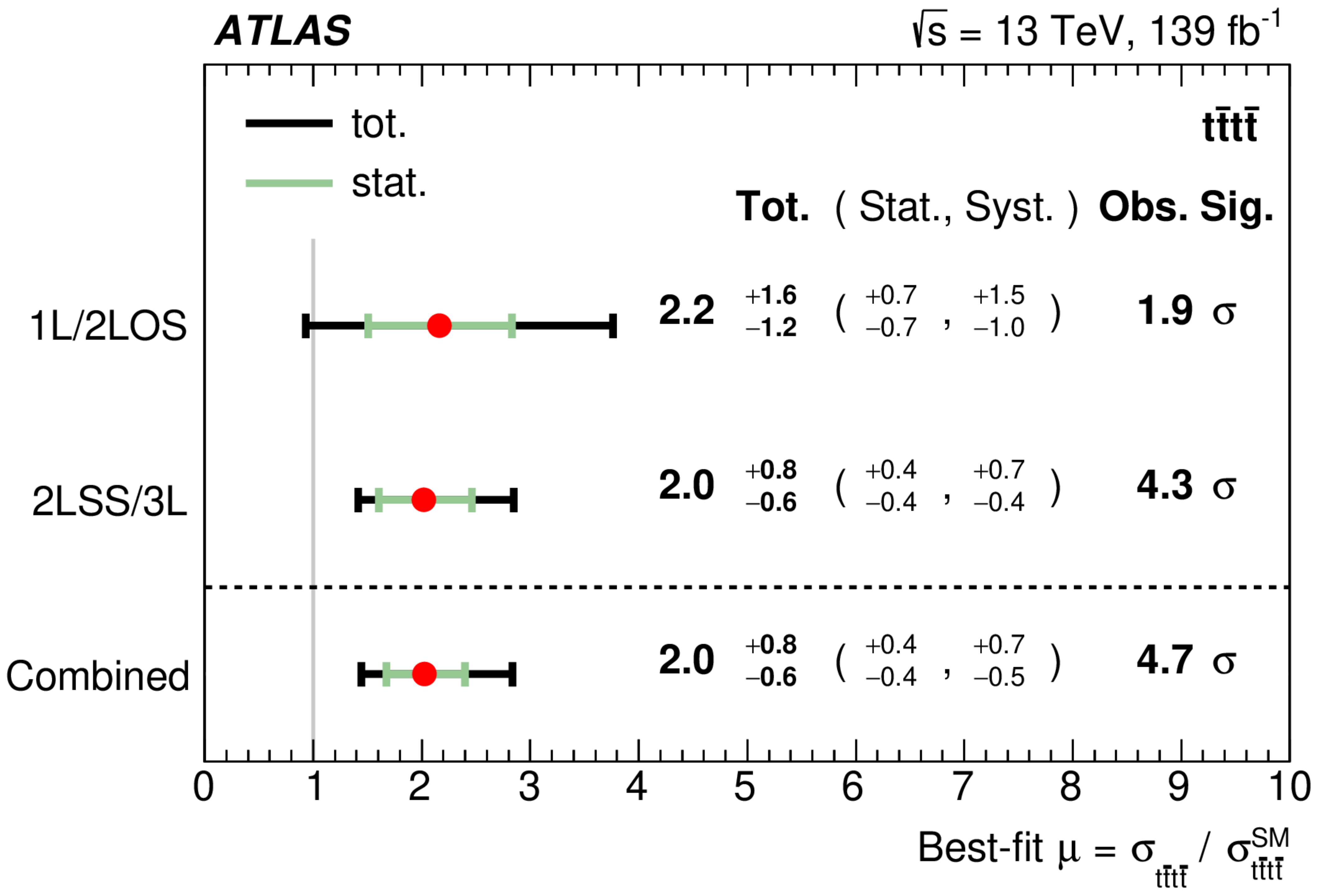


- Targeting events with high jet and b-jet multiplicities
  - 4-top final state features 10 (8) jets in 1L (2LOS) and 4 b-jets at truth level
- Pre-selected events are orthogonal to 2LSS/3L
  - 1L channel: One lepton (>28 GeV) and at least 7 jets and at least 2 b-tagged jets
  - 2LOS channel: Two leptons (>28,10 GeV) with OS charge and at least 5 jets and at least 2 b-tagged jets
- $t\bar{t}$+jets background is estimated using corrected MC simulations
  - Corrections factors are derived in data, improving the $t\bar{t}$+jets modelling

$t\bar{t}t\bar{t}$ production

JHEP 11 (2021) 118



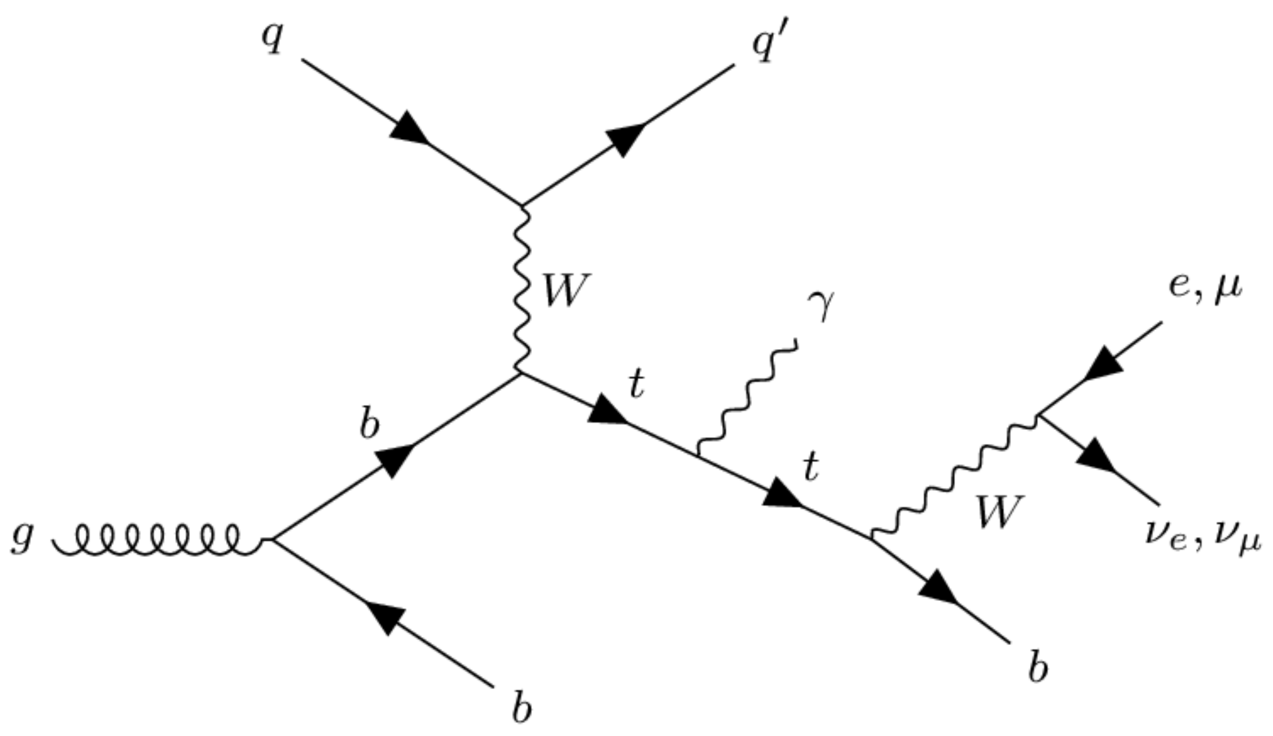


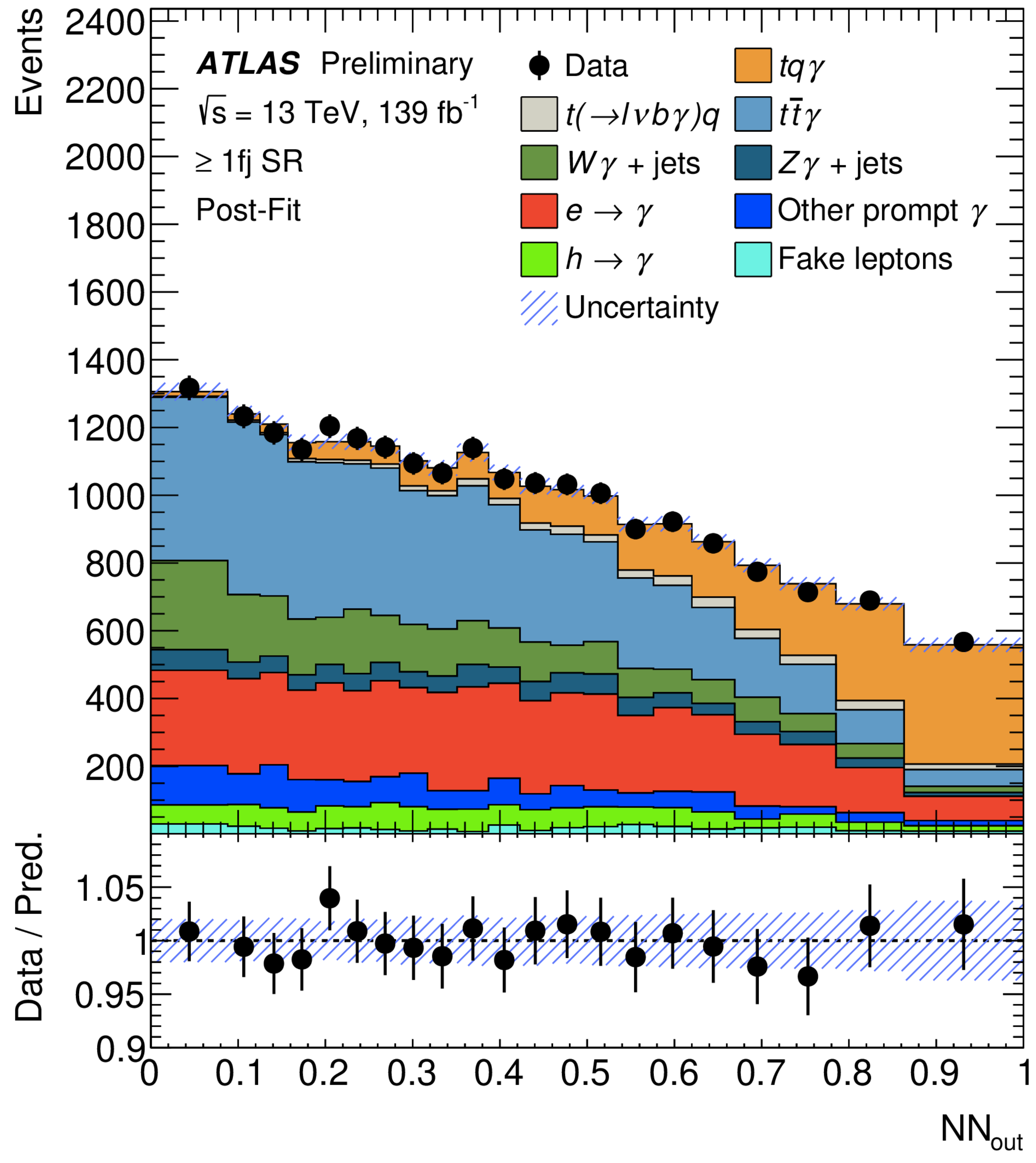
- Measured cross section for 1L/2LOS : $\sigma_{t\bar{t}t\bar{t}} = 26^{+17}_{-15}$ fb
  - With an observed (expected) significance of 1.9 (1.0) σ
  - Uncertainties dominated by 4-top and $t\bar{t}$+HF modelling uncertainties
- Combined cross section with 2LSS/3L analysis : 24^{+7}_{-6} fb
  - With an observed (expected) significance of **4.7** (2.6) **σ**
  - To be compared with the 4.3 σ observed significance from 2LSS/3L analysis

SM $tq\gamma$

ATLAS-CONF-2022-013

- First observation of *t*-channel single top quark production in association with a photon
  - $tq\gamma$ (prod) with observed (expected) significance: 9.1 (6.7) σ
- Sensitive to EW couplings of the top quark (esp. top-γ vertex)





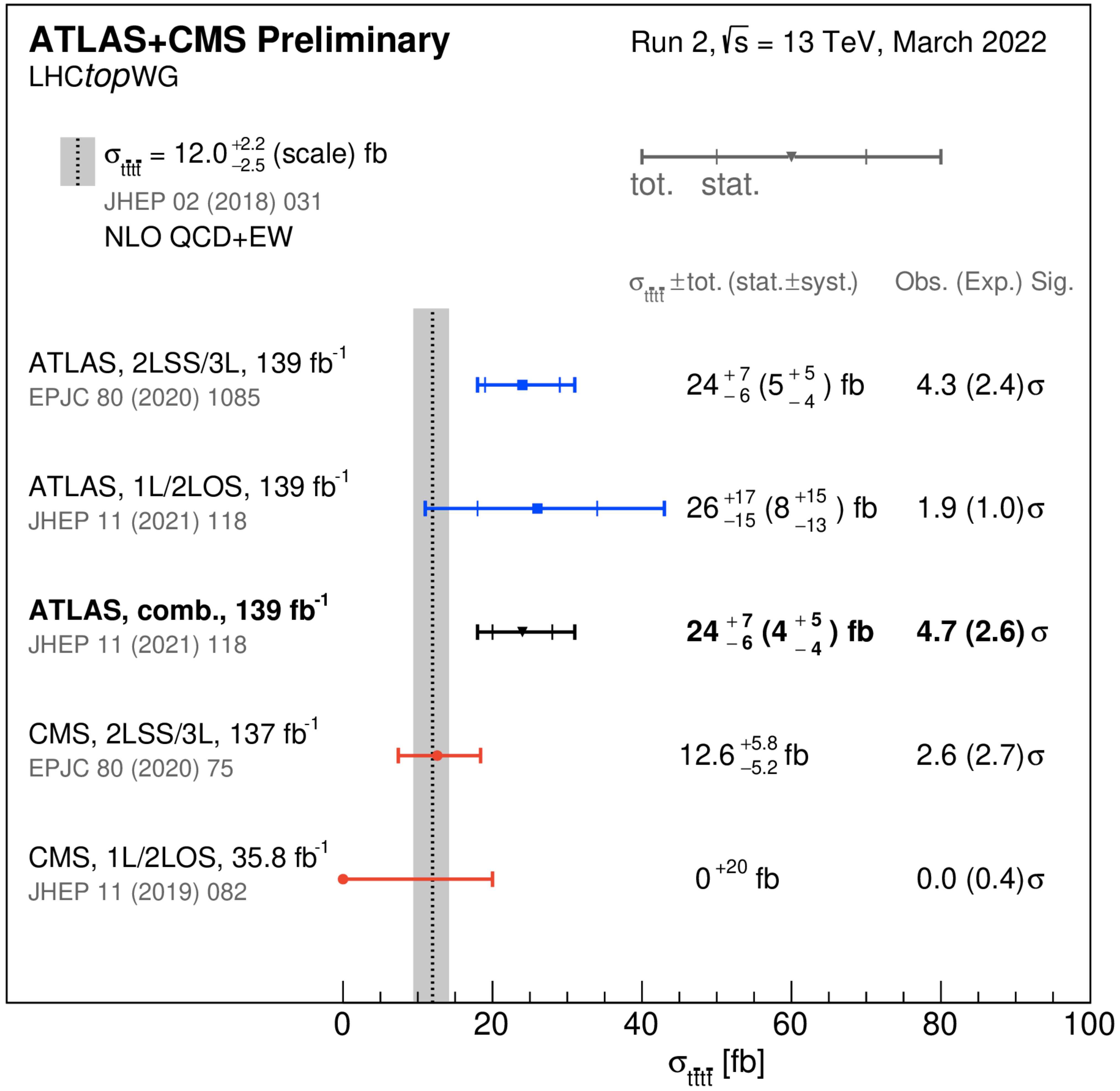
Cross section measurement

- Parton level: $\sigma_{tq\gamma} \times B(t \to l\nu b) = 580 \pm 19\,(\text{stat.}) \pm 63\,(\text{syst.})$ fb
- Particle level: $\sigma_{tq\gamma} \times B(t \to l\nu b) + \sigma_{t(\to l\nu b\gamma)q} = 287 \pm 8\,(\text{stat.}) \pm 31\,(\text{syst.})$ fb

- ATLAS measurements consistently higher than the prediction by ~ 40%
- Major systematic uncertainties come from
  - background modelling: $t\bar{t}\gamma$ ~ 6%; $t\bar{t}$ ~ 3%
  - MC statistics: $tq\gamma$ ~ 3%; all other processes ~ 3%

Summary

- Recent ATLAS measurements and searches in the associated production of top quarks were presented
- New results in the investigation of SM rare top processes:
  - **Strong evidence** for the $t\bar{t}t\bar{t}$ production
  - **Observation** of $t\gamma$ production
- Highlights of searches for FCNC processes involving top:
  - tqg, $tq\gamma$, tqZ and tqH
  - **Significant improvement** of the limits on the BR and the effective coupling strengths wrt previous results



Backup

Branching ratios of top FCNC decays

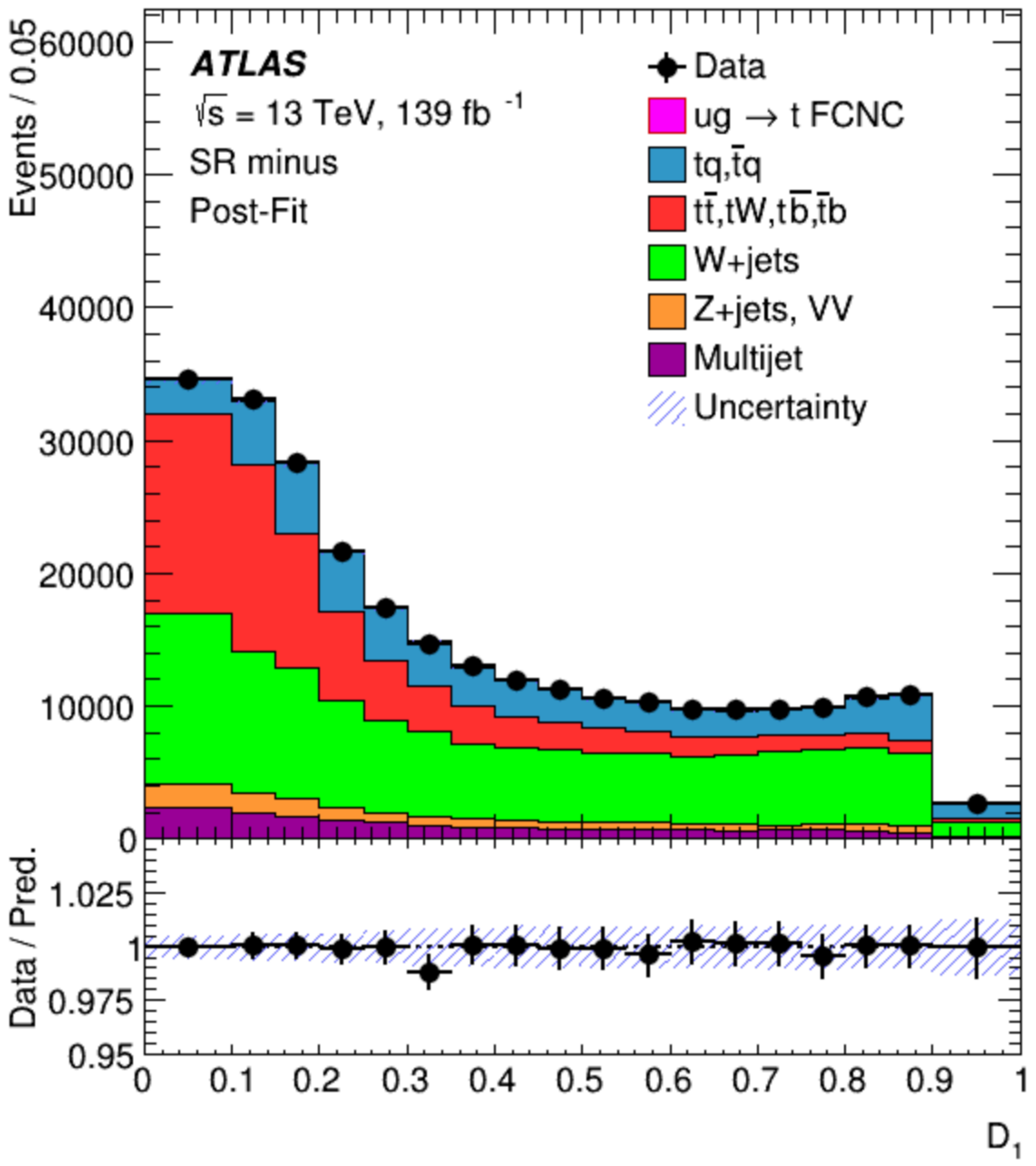
Process	SM	2HDM(FV)	2HDM(FC)	MSSM	RPV	RS
$t \to Zu$	7×10^{-17}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to Zc$	1×10^{-14}	$\leq 10^{-6}$	$\leq 10^{-10}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-5}$
$t \to gu$	4×10^{-14}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to gc$	5×10^{-12}	$\leq 10^{-4}$	$\leq 10^{-8}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-10}$
$t \to \gamma u$	4×10^{-16}	–	–	$\leq 10^{-8}$	$\leq 10^{-9}$	–
$t \to \gamma c$	5×10^{-14}	$\leq 10^{-7}$	$\leq 10^{-9}$	$\leq 10^{-8}$	$\leq 10^{-9}$	$\leq 10^{-9}$
$t \to hu$	2×10^{-17}	6×10^{-6}	–	$\leq 10^{-5}$	$\leq 10^{-9}$	–
$t \to hc$	3×10^{-15}	2×10^{-3}	$\leq 10^{-5}$	$\leq 10^{-5}$	$\leq 10^{-9}$	$\leq 10^{-4}$

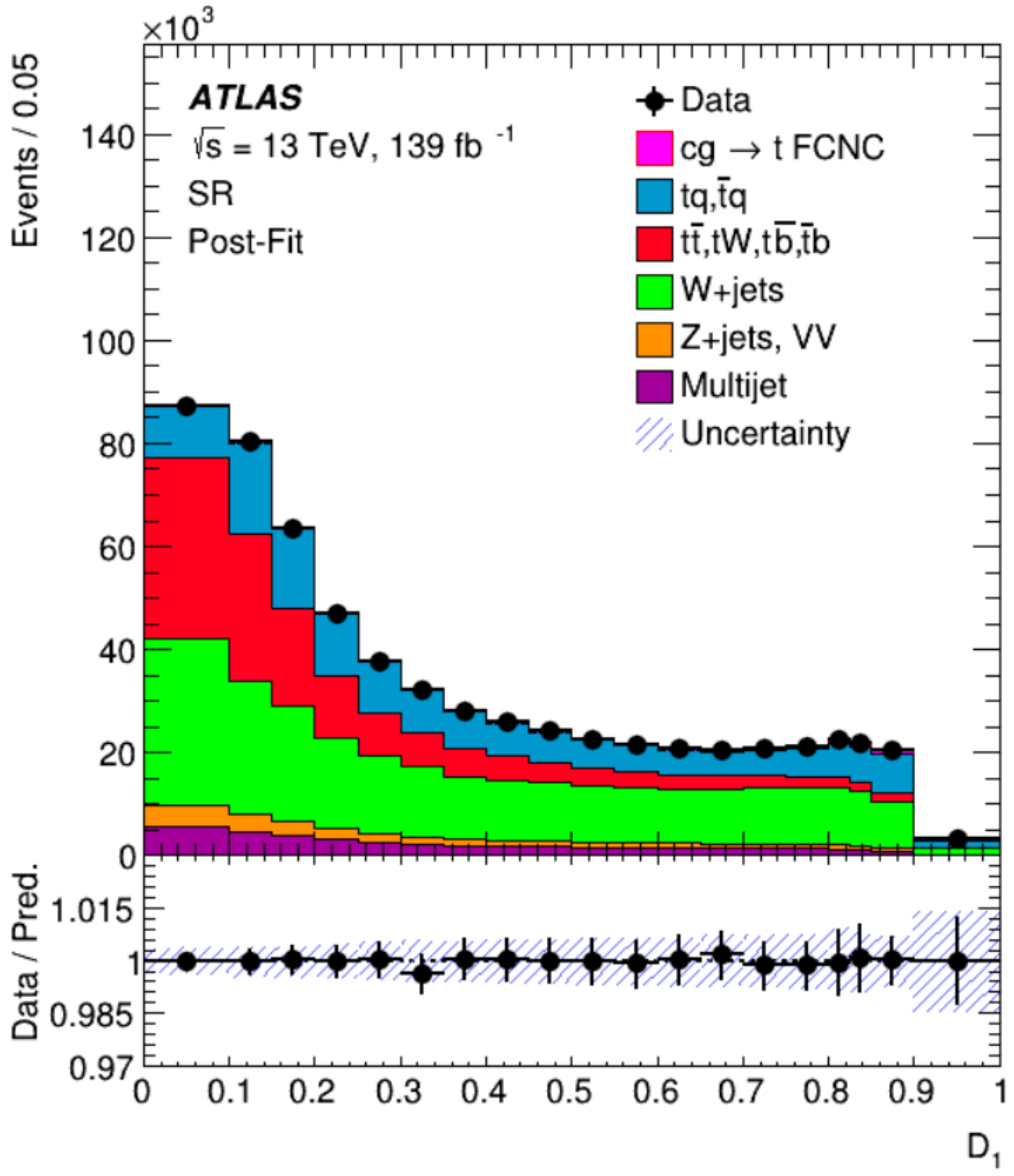
FCNC tqg - selection requirements

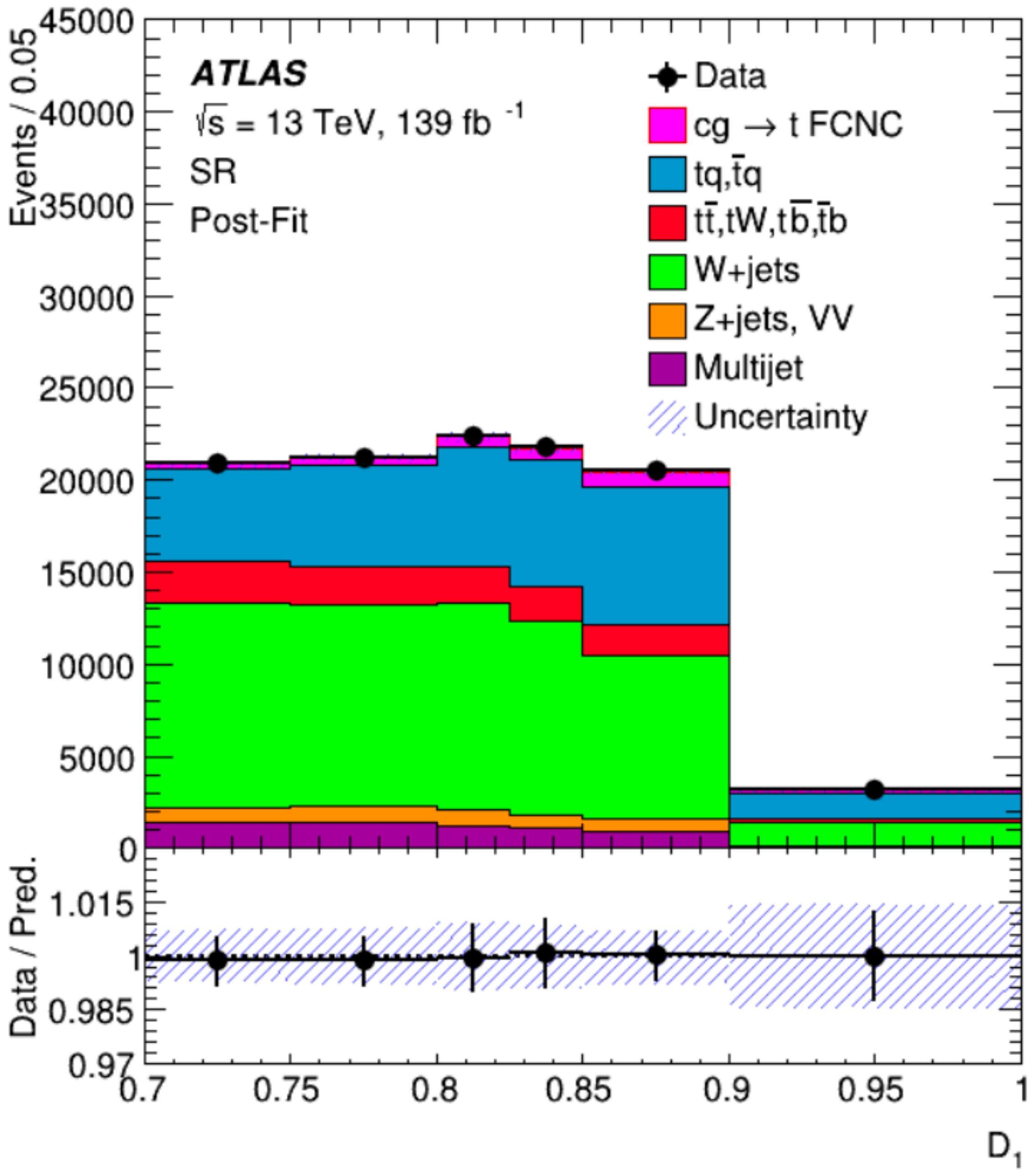
Observable	Common requirements
$n_{\text{Tight}}(e) + n_{\text{Medium}}(\mu)$	$= 1$
$n_{\text{Loose}}(e) + n_{\text{Loose}}(\mu)$	$= 1$
$E_{\text{T}}^{\text{miss}}$	$> 30\,\text{GeV}$
$m_{\text{T}}\,(W)$	$> 50\,\text{GeV}$
$n(j)$	≥ 1
$p_{\text{T}}\,(\ell)$	$> 50\,\text{GeV} \cdot \left(1 - \frac{\pi - \lvert\Delta\phi(j_1,\ell)\rvert}{\pi - 1}\right)$

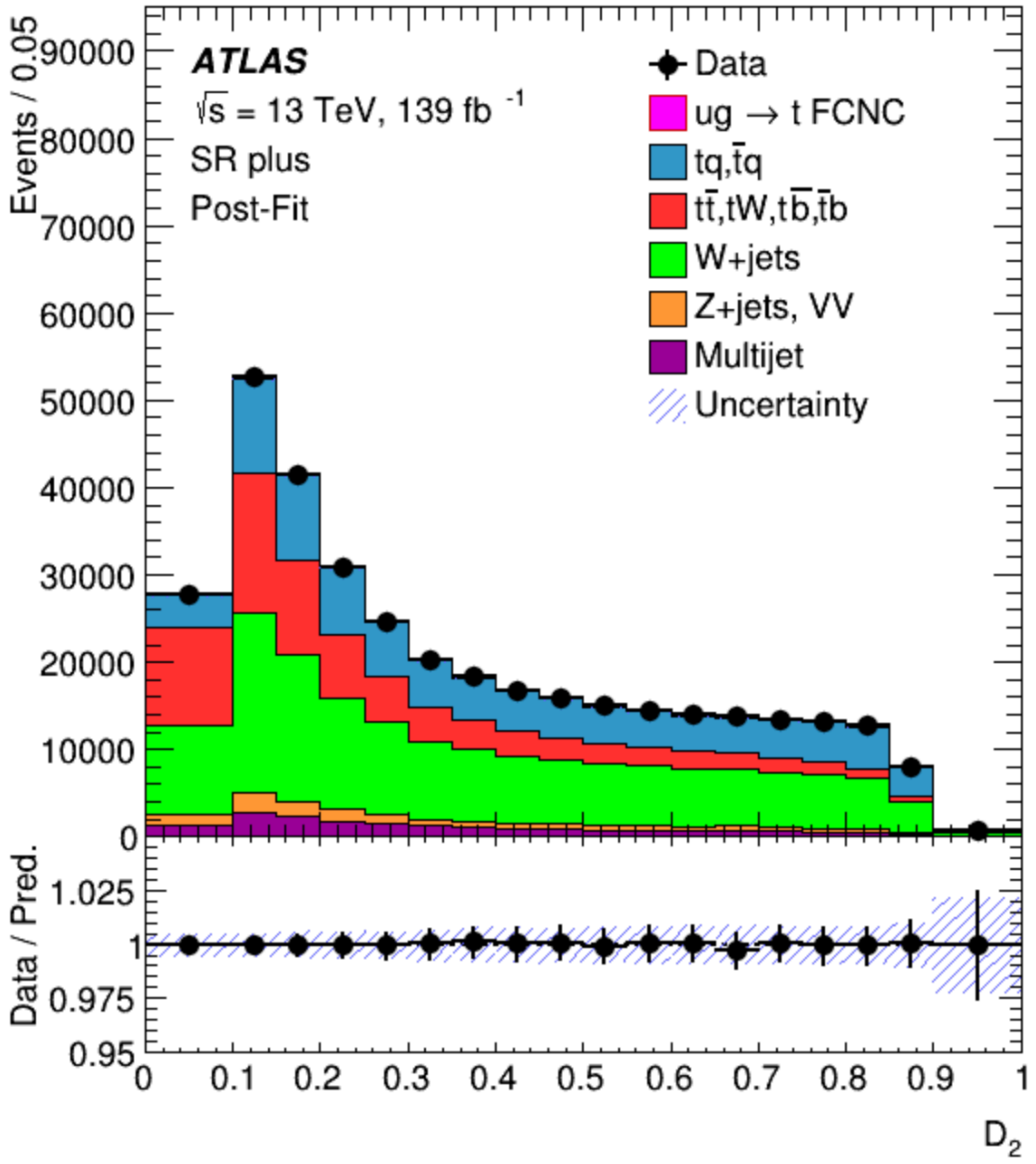
	Analysis regions			
	SR	W+jets VR	$t\bar{t}$ VR	tq VR
$n(\lvert\eta(j)\rvert < 2.5)$	$= 1$	$= 1$	$= 2$	$= 1$
$n(b)$	$= 1$	$= 1$	$= 2$	$= 1$
ϵ_b	30%	60% (veto 30%)	30%	30%
$n(\lvert\eta(j)\rvert > 2.5)$	≥ 0	≥ 0	≥ 0	$= 1$
$D_{1(2)}$	–	$0.3 < D_{1(2)} < 0.6$	–	$0.2 < D_{1(2)} < 0.4$

FCNC tqg - postfit discriminants

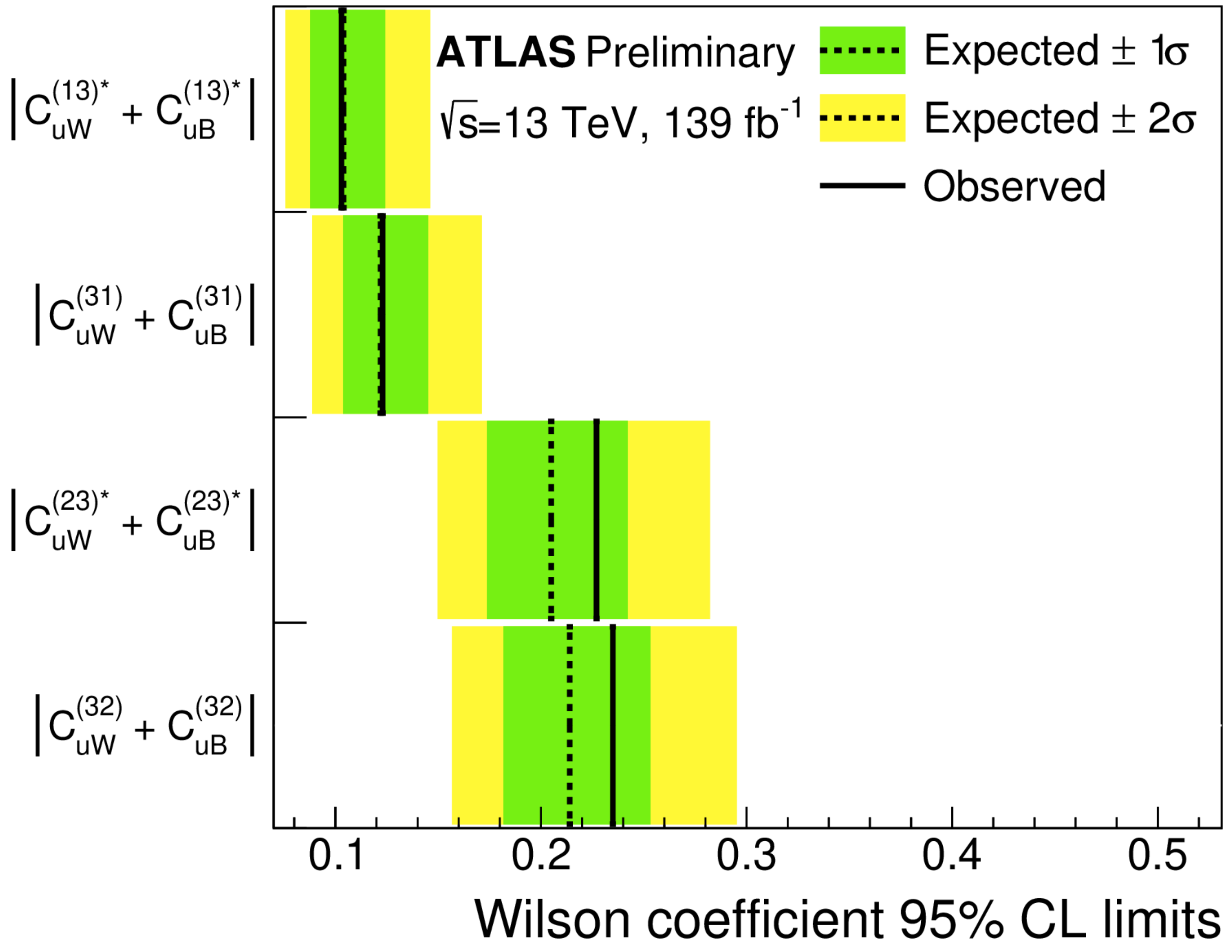


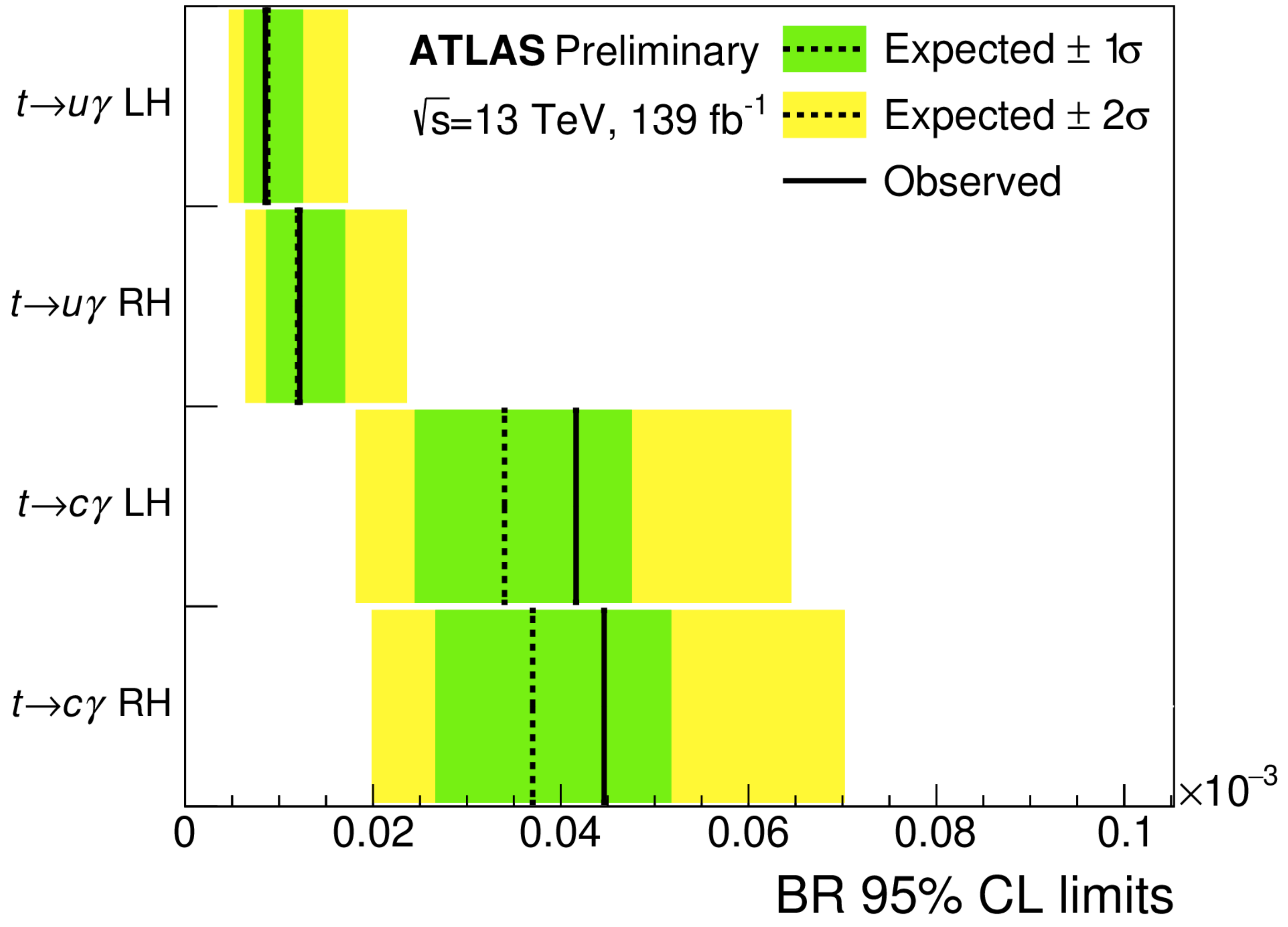






FCNC $tq\gamma$ - Wilson coeficient and BR limits





Effective coupling	Coefficient limits		Coupling	BRs $[10^{-5}]$	
	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

FCNC tqZ - predicted and observed yields in SR

	SR1 ($D_1 > -0.6$)	SR2 ($D_2^u > -0.7$ or $D_2^c > -0.4$)
$t\bar{t}Z + tWZ$	137 ± 12	36 ± 6
VV + LF	18 ± 7	24 ± 8
VV + HF	114 ± 19	162 ± 26
tZ	46 ± 7	108 ± 18
$t\bar{t} + tW$ fakes	14 ± 4	27 ± 8
Other fakes	7 ± 8	5 ± 6
$t\bar{t}W$	4.2 ± 2.1	3.1 ± 1.6
$t\bar{t}H$	4.8 ± 0.7	0.89 ± 0.17
Other bkg.	2.0 ± 1.0	2.5 ± 2.9
FCNC $(u)tZ$	0.9 ± 1.7	4 ± 8
FCNC $t\bar{t}(uZ)$	5 ± 9	0.8 ± 1.5
Total background	348 ± 15	369 ± 21
Data	345	380

FCNC tqZ - postfit discriminants

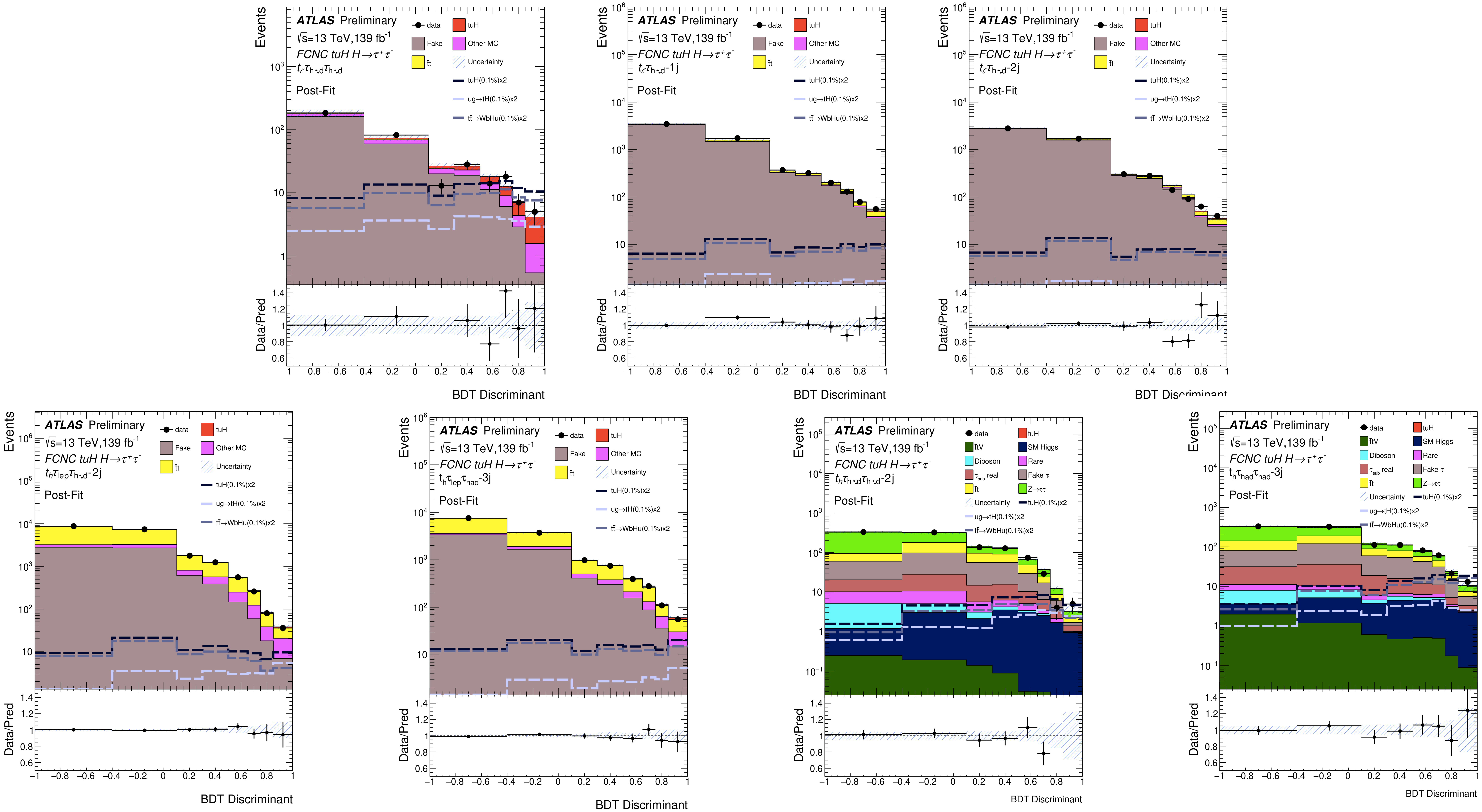
FCNC H → τ + τ - : overview of regions

Regions		b-jet	light flavour jets	lepton	hadronic taus	charge
SR	$t_\ell\tau_{\text{had}}\tau_{\text{had}}$	1	≥ 0	1	2	$\tau_{\text{had}}\tau_{\text{had}}$ OS
	$t_\ell\tau_{\text{had}}$-1j	1	1	1	1	$t_\ell\tau_{\text{had}}$ SS
	$t_\ell\tau_{\text{had}}$-2j	1	2	1	1	$t_\ell\tau_{\text{had}}$ SS
	$t_h\tau_{\text{lep}}\tau_{\text{had}}$-2j	1	2	1	1	$\tau_{\text{lep}}\tau_{\text{had}}$ OS
	$t_h\tau_{\text{lep}}\tau_{\text{had}}$-3j	1	≥ 3	1	1	$\tau_{\text{lep}}\tau_{\text{had}}$ OS
	$t_h\tau_{\text{had}}\tau_{\text{had}}$-2j	1	2	0	2	$\tau_{\text{had}}\tau_{\text{had}}$ OS
	$t_h\tau_{\text{had}}\tau_{\text{had}}$-3j	1	≥ 3	0	2	$\tau_{\text{had}}\tau_{\text{had}}$ OS
VR	$t_\ell\tau_{\text{had}}\tau_{\text{had}}$-SS	1	≥ 0	1	2	$\tau_{\text{had}}\tau_{\text{had}}$ SS
CRtt	$t_\ell t_\ell 1b\tau_{\text{had}}$	1	≥ 0	2	1	$t_\ell t_\ell$ OS
	$t_\ell t_\ell 2b\tau_{\text{had}}$	2	≥ 0	2	1	$t_\ell t_\ell$ OS
	$t_\ell t_h 2b\tau_{\text{had}}$-2jSS	2	2	1	1	$t_\ell\tau_{\text{had}}$ SS
	$t_\ell t_h 2b\tau_{\text{had}}$-2jOS	2	2	1	1	$t_\ell\tau_{\text{had}}$ OS
	$t_\ell t_h 2b\tau_{\text{had}}$-3jSS	2	≥ 3	1	1	$t_\ell\tau_{\text{had}}$ SS
	$t_\ell t_h 2b\tau_{\text{had}}$-3jOS	2	≥ 3	1	1	$t_\ell\tau_{\text{had}}$ OS

FCNC $H \to \tau + \tau -$: absolute uncertainties

Source of uncertainty	ΔB $[10^{-5}]$ $t \to uH$	ΔB $[10^{-5}]$ $t \to cH$
Lepton ID	0.6	1.0
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.7	0.8
Fake lepton modeling	0.9	1.1
JES and JER	2.4	3.2
Flavour tagging	2.7	3.7
$t\bar{t}$ modeling	2.9	4.3
Other MC modeling	2.1	2.9
Fake τ modeling	3.2	4.6
Signal modeling including $\mathrm{Br}(H \to \tau\tau)$	5.3	7.0
τ ID	3.3	4.4
Luminosity and Pileup	0.9	1.3
MC statistics	5.1	7.0
Total systematic uncertainty	11.2	15.5
Data statistical uncertainty	14.1	19.6
Total uncertainties	18	25

FCNC H → τ + τ - : tuH - BDT output distributions



FCNC H → τ + τ - : tcH - BDT output distributions