Universität Siegen

HEP Experimental High Energy Physics

CPPS Center for Particle Physics Siegen

ATLAS EXPERIMENT

GABRIEL GOMES, ON BEHALF OF THE ATLAS COLLABORATION

SEARCHES FOR BSM IN TOP FINAL STATES IN ATLAS

10 APRIL 2024

31ST INTERNATIONAL WORKSHOP ON DEEP INELASTIC SCATTERING

GRENOBLE

Introduction

Top-quark physics

- **Heaviest** known elementary particle
  - Large coupling to Higgs boson
  - Potential large couplings to BSM particles
- **ATLAS Run 2 data** (140 fb^{-1}): pp collisions at $\sqrt{s}$ = 13 TeV, collected during 2015–2018
  - Abundant sample of top-quark events
  - BSM searches + precision measurements in the top sector

In this talk

1. Search for **charged-lepton-flavour violating** $\mu\tau qt$ interactions in top-quark production and decay [arXiv:2403.06742] HOT
2. Search for **flavour-changing neutral-current** couplings between the top quark and Higgs boson in multi-lepton final states [arXiv:2404.02123] HOT
3. Precise test of **lepton flavour universality** in W boson decays into muons and electrons [arXiv:2403.02133] HOT

[arXiv:2403.06742]

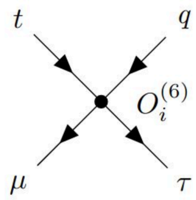
cLFV in $\mu\tau qt$ processes

[arXiv:2403.06742]

Introduction

Motivation

- SM: charged lepton flavour is conserved in weak interactions
- Observed neutrino oscillations permit LFV processes (highly suppressed)
- Experimental evidence of cLFV: clear sign of BSM physics
- cLFV is featured in several BSM models (leptoquarks, SUSY, 2HDM)



This search

- First direct probe on 4-fermion contact interaction for $\mu\tau q t$ processes
- Model-independent EFT search with additional leptoquark interpretation

Previous searches

$\mathscr{B}(t \rightarrow \ell\ell' q) < 1.86 \times 10^{-5}$

$\mathscr{B}(t \rightarrow e\mu q) < 6.6 \times 10^{-6}$ [ATLAS-CONF-2018-044]

$\mathscr{B}(t \rightarrow e\mu q) < 0.012 — 0.498 \times 10^{-6}$ [arXiv:2312.03199] **(CMS)**

EFT operators

$$O_{lq}^{1(ijkl)} = \left(\bar{l}_i \gamma^\mu l_j\right)\left(\bar{q}_k \gamma_\mu q_l\right)$$

$$O_{lq}^{3(ijkl)} = \left(\bar{l}_i \gamma^\mu \sigma^I l_j\right)\left(\bar{q}_k \gamma_\mu \sigma^I q_l\right)$$

$$O_{eq}^{(ijkl)} = \left(\bar{e}_i \gamma^\mu e_j\right)\left(\bar{q}_k \gamma_\mu q_l\right)$$

$$O_{lu}^{(ijkl)} = \left(\bar{l}_i \gamma^\mu l_j\right)\left(\bar{u}_k \gamma_\mu u_l\right)$$

$$O_{eu}^{(ijkl)} = \left(\bar{e}_i \gamma^\mu e_j\right)\left(\bar{u}_k \gamma_\mu u_l\right)$$

vector

$$O_{lequ}^{1(ijkl)} = \left(\bar{l}_i e_j\right) \varepsilon \left(\bar{q}_k u_l\right)$$

scalar

$$O_{lequ}^{3(ijkl)} = \left(\bar{l}_i \sigma^{\mu\nu} e_j\right) \varepsilon \left(\bar{q}_k \sigma_{\mu\nu} u_l\right)$$

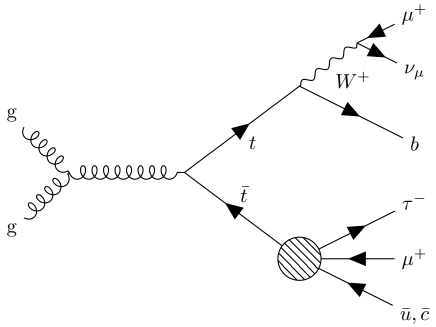
tensor

[arXiv:2403.06742]

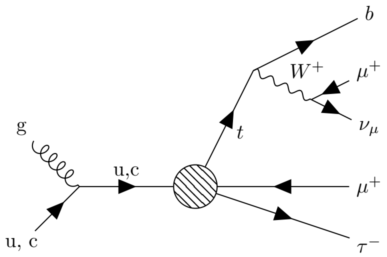
Signal and background

- **Signal modelling**:
  - **top-quark decay**: $t\bar{t} \to (\mu\tau q)(\mu\nu_\mu b)$
  - **single top-quark production**: $qg \to \mu\tau t \to (\mu\tau)(\mu\nu_\mu b)$
- **Background sources**:
  - non-prompt (NP) muons: $t\bar{t}$ heavy-flavour hadron decays inside jets
  - prompt leptons: $t\bar{t} + X$ ($t\bar{t}Z, t\bar{t}W, t\bar{t}H$) and diboson ($WZ, ZZ$)
  - fake τ_{had} candidates

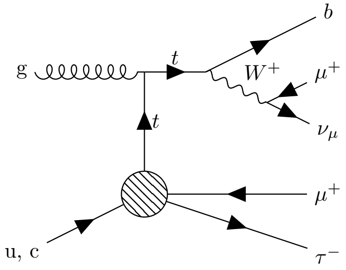
cLFV in top-quark decay



cLFV in top-quark production



s-channel



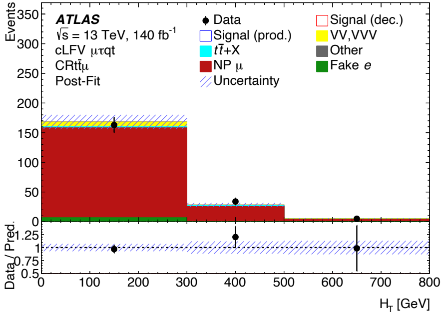
t-channel

[arXiv:2403.06742]

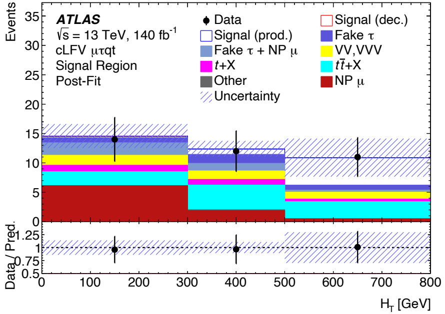
Analysis strategy

- **Signal Region** (SR):
  - $2\mu 1\tau_{\text{had}}$ (same-sign muons)
  - ≥ 1 jet (1 b-tagged)
- **Control Regions** (CRs):
  - CRτ: data-driven corrections to fake τ_{had}
  - CR$t\bar{t}\mu$: NP muon background normalisation
- **Binned profile-likelihood fit** over H_T across SR + CR$t\bar{t}\mu$ with systematic uncertainties

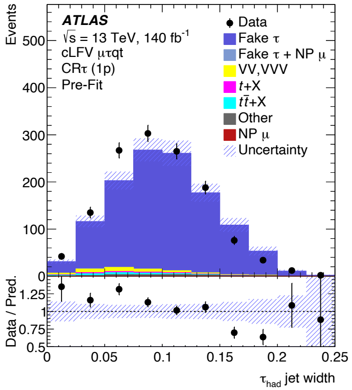
CR$t\bar{t}\mu$

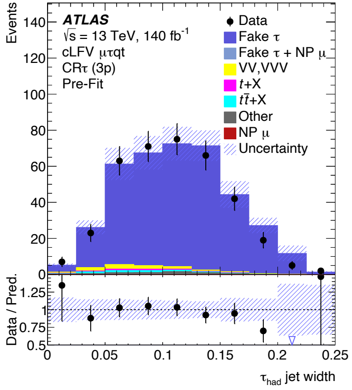


SR



CRτ





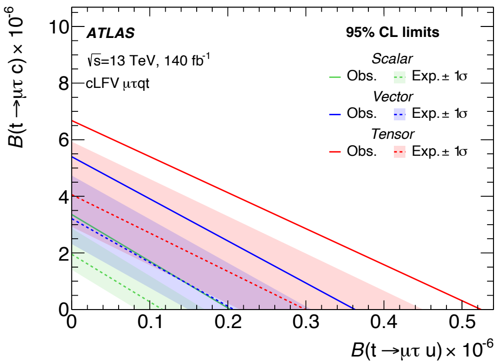
[arXiv:2403.06742]

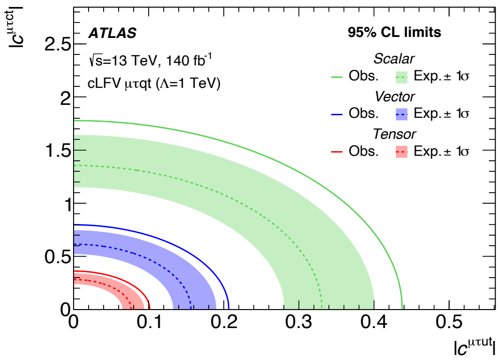
Results: EFT interpretation

– No significant excess above SM background
– Set first direct exclusion limit at 95% CL: $\mathcal{B}(t \to \mu\tau q) < 8.7 \times 10^{-7}$
– Improvement upon previous limits by up to a factor of 41

	95% CL upper limits on $\lvert c \rvert/\Lambda^2$ [TeV^{-2}]					
	$c^{*-(ijk3)}_{\mathrm{lq}}$	$c^{(ijk3)}_{\mathrm{eq}}$	$c^{(ijk3)}_{\mathrm{lu}}$	$c^{(ijk3)}_{\mathrm{eu}}$	$c^{1(ijk3)}_{\mathrm{lequ}}$	$c^{3(ijk3)}_{\mathrm{lequ}}$
Previous (u)	12	12	12	12	18	2.4
Expected (u)	0.33	0.31	0.3	0.32	0.33	0.08
Observed (u)	0.43	0.41	0.4	0.42	0.44	0.10
Previous (c)	14	14	14	14	21	2.6
Expected (c)	1.3	1.2	1.2	1.2	1.4	0.28
Observed (c)	1.6	1.6	1.6	1.6	1.8	0.36

$^{*}O_{\bar{l}q} = O^{1}_{lq} - O^{3}_{lq}$

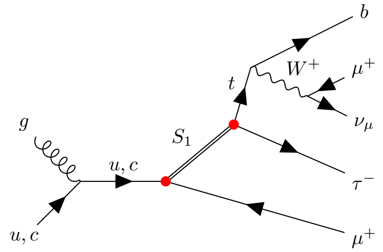




[arXiv:2403.06742]

Results: leptoquark interpretation

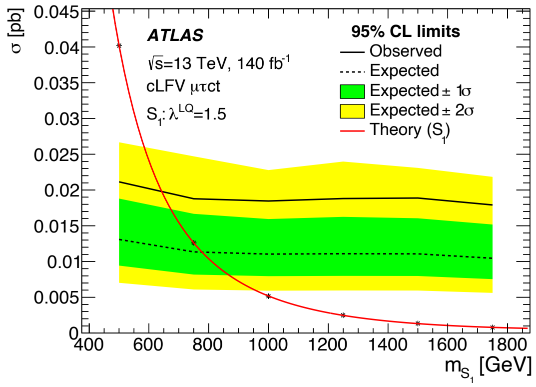
Resonant leptoquark production

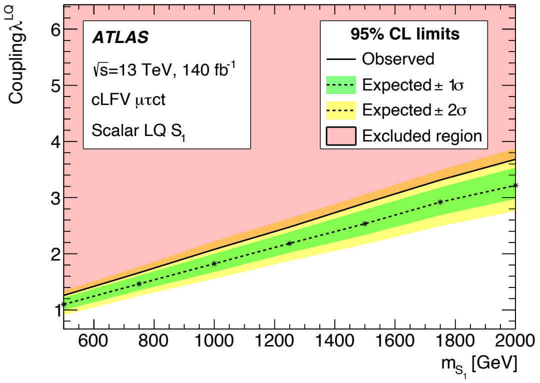


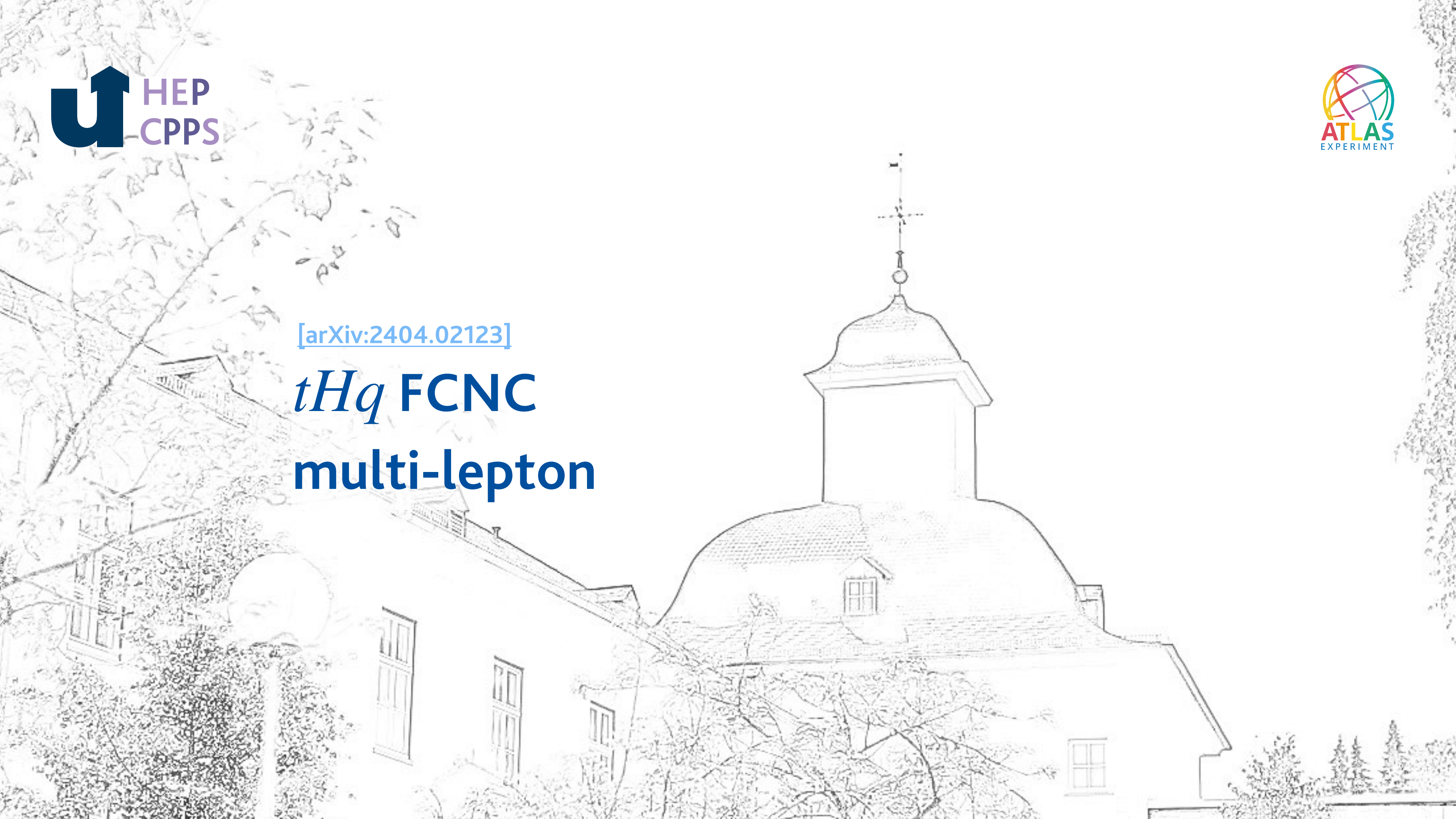
– Search for scalar leptoquark S_1 assuming fixed hierarchical couplings

$$\lambda_{ki} \in \begin{pmatrix} \lambda_{t\tau} & \lambda_{c\tau} & \lambda_{u\tau} \\ \lambda_{t\mu} & \lambda_{c\mu} & \lambda_{u\mu} \\ \lambda_{te} & \lambda_{ce} & \lambda_{ue} \end{pmatrix} \equiv \lambda^{\mathrm{LQ}} \begin{pmatrix} 10 & 1 & 0.1 \\ 1 & 0.1 & 0.01 \\ 0.1 & 0.01 & 0.001 \end{pmatrix}$$

– Upper limits on λ^{LQ}: 1.3 — 3.7 for masses between 0.5 and 2.0 TeV







[arXiv:2404.02123]

tHq FCNC multi-lepton

[arXiv:2404.02123]

Introduction

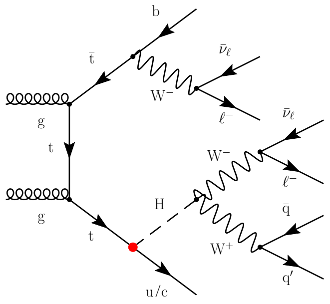
Motivation

- SM: FCNC interactions are forbidden at tree-level and highly suppressed at higher orders
- Branching ratios large enough to be measured in BSM models
- Experimental evidence of FCNC: clear sign of BSM physics

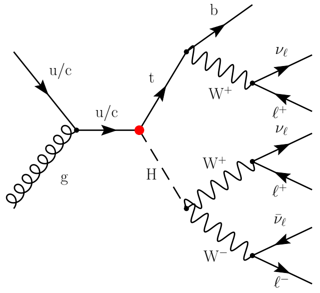
This search

- FCNC interactions of the top quark, the Higgs boson and a charm or up quark (tHq)
- Final states with 2 leptons of the same charge (2ℓSS) or with three leptons (3ℓ)
- Dominant Higgs decay in 2ℓSS and 3ℓ: $H \to VV^*$
- Model-independent EFT search
- Combination with other ATLAS Run 2 searches for tHq FCNC couplings in different final states
  - $H \to \tau^+\tau^-$ [JHEP 06 (2022) 155]
  - $H \to b\bar{b}$ [JHEP 07 (2023) 199]
  - $H \to \gamma\gamma$ [arXiv:2309.12817]

FCNC in top decay (2ℓSS final state)



FCNC in top production (3ℓ final state)



[arXiv:2404.02123]

Analysis strategy

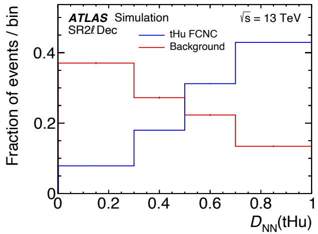
Definition of kinematic regions

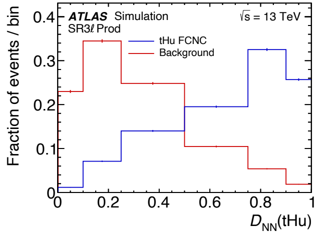
- 2 SRs for 2ℓSS and 2 SRs for 3ℓ focus on $t \rightarrow Hq$ decay or $q \rightarrow Ht$ production signal
- 3 CRs in 2ℓSS and 4 CRs in 3ℓ final state for various bkg. processes (HF decay leptons, $t\bar{t}V$)

Event reconstruction + NN in SRs

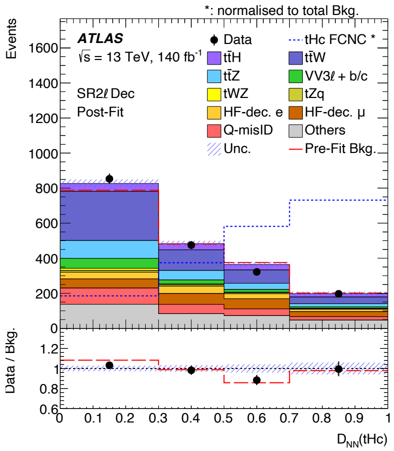
- **R**ecursive **J**igsaw **R**econstruction (2ℓSS and 3ℓ)
- **N**eutrino **I**ndependent **C**ombinatorics **E**stimator (3ℓ)
- Feed-forward **N**eural **N**etworks
  - Reconstructed object variables as input
- **Profile-Likelihood fit** (simultaneously in all CRs and SRs)

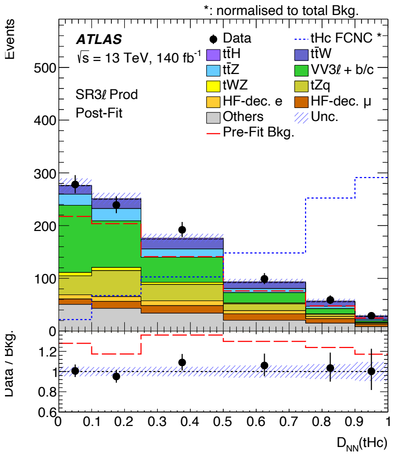
NN discriminants





Post-fit plots





[arXiv:2404.02123]

Results

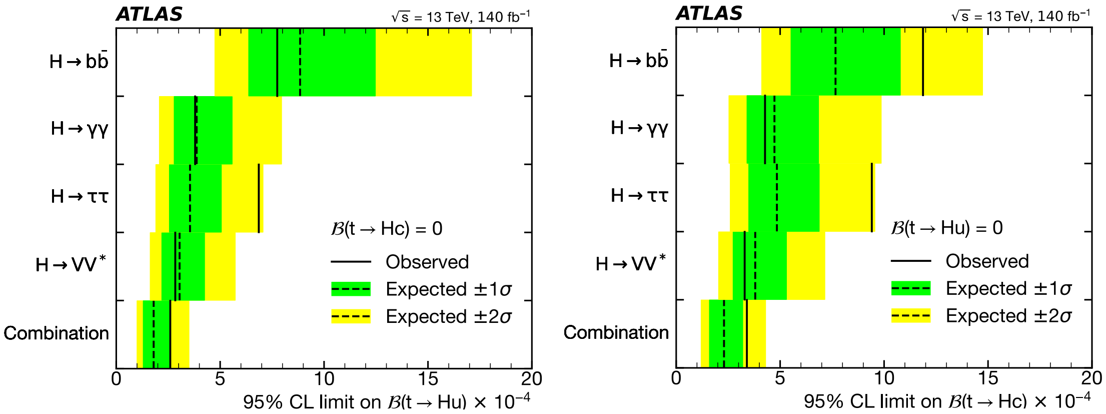
tHq results

- No observation of FCNC couplings
- Most stringent upper limits in multi-lepton final states

Signal	Observed (expected) 95% CL upper limits $\mathcal{B}(t \to Hq)$	$\lvert C_{u\phi}^{qt,tq} \rvert$
tHu	$2.8\,(3.0) \times 10^{-4}$	0.71 (0.73)
tHc	$3.3\,(3.8) \times 10^{-4}$	0.76 (0.82)

Combination

- $\mathcal{B}^{(\mathrm{comb})}(t \to Hu) < 2.6\ (1.8) \times 10^{-4}$
- $\mathcal{B}^{(\mathrm{comb})}(t \to Hc) < 3.4\ (2.3) \times 10^{-4}$
- $C_{u\phi}^{ut,tu} < 0.68(0.56)$
- $C_{u\phi}^{ct,tc} < 0.78(0.64)$



[arXiv:2403.02133]

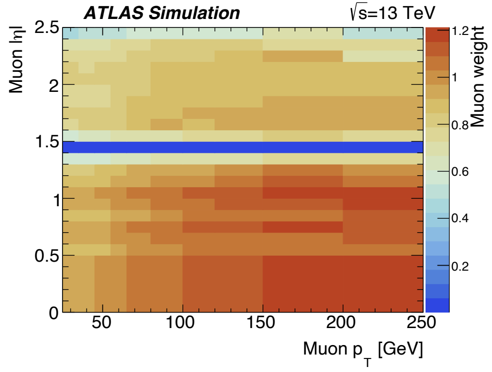
LFU test

[arXiv:2403.02133]

Introduction

Motivation

- SM axiom: equality of e, μ, τ couplings to W boson
- Previous tests:
    - Tested in τ, π, K decays to 0.1-0.2%
    - Tested in real W decays in $e^+e^- \to WW, pp \to W, t\bar{t} \to WbWb$ to % level
    - Flavour anomalies: some tensions in $B \to D^{(*)}\tau$ vs. $B \to D^{(*)}\mu$



This measurement

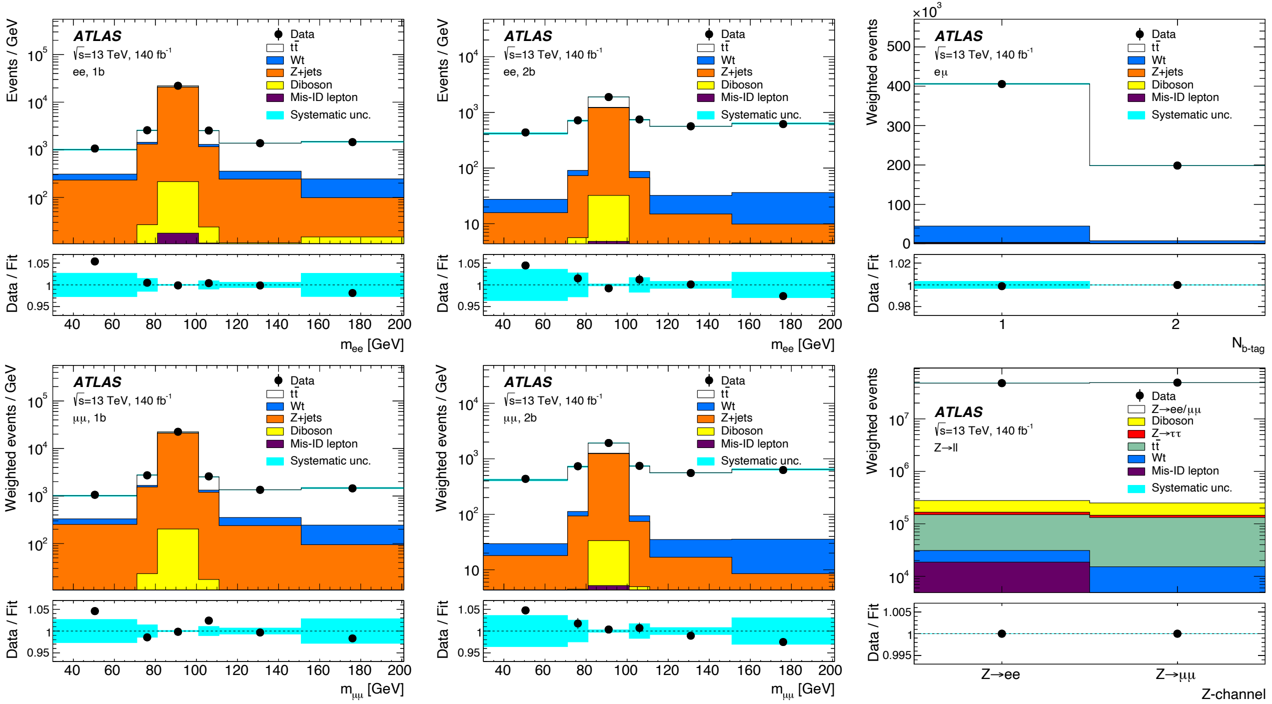
- Simultaneous measurement of $\sigma_{t\bar{t}}$ in ee, $e\mu$ and $\mu\mu$ final states gives sensitivity to $R_W^{\mu/e} = \dfrac{\mathcal{B}(W \to \mu\nu)}{\mathcal{B}(W \to e\nu)}$
- Strategy to reduce systematics:
    - Weight muons vs. (p_T, η) to give similar kinematic acceptance for ee and $\mu\mu$
    - Lepton isolation efficiency measured in data
    - Normalise $R_W^{\mu/e}$ using $\sqrt{R_Z^{\mu\mu/ee}}$ to reduce electron and muon efficiency systematics, measure $R_{WZ}^{\mu/e}$

$$R_{WZ}^{\mu/e} = \frac{R_W^{\mu/e}}{\sqrt{R_Z^{\mu\mu/ee}}} = \frac{\mathcal{B}(W \to \mu\nu)}{\mathcal{B}(W \to e\nu)} \cdot \sqrt{\frac{\mathcal{B}(Z \to ee)}{\mathcal{B}(Z \to \mu\mu)}}$$

[arXiv:2403.02133]

Analysis strategy

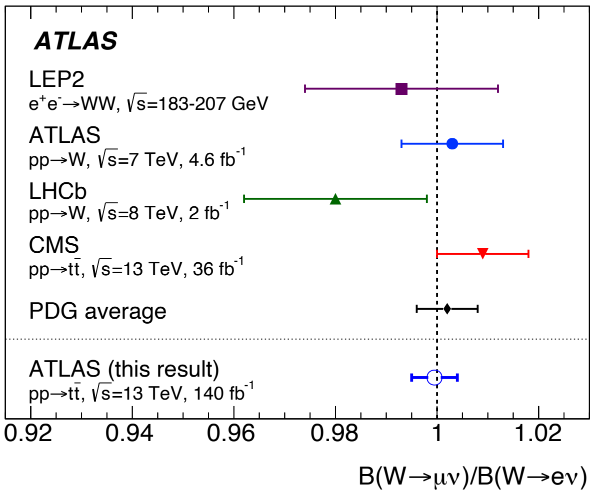
- Fit numbers of dilepton events with 1 or 2 b-jets, vs $m_{\ell\ell}$ in $ee/\mu\mu$ events
  - $m_{\ell\ell}$ exploited for Z+jets background separation
  - b-jet reconstruction and tagging are determined in data
- Fit number of inclusive $Z \to ee$ and $Z \to \mu\mu$ events to measure $R_Z^{\mu\mu/ee}$



[arXiv:2403.02133]

Results

- $\sigma_{t\bar{t}}$ measurement in agreement with previous results
- $R_Z^{\mu\mu/ee}$ = 0.9913 ± 0.0002 ± 0.0045
  - 1.9σ below unity, similar to trend seen in other 13 TeV Z measurements
- $R_{WZ}^{\mu/e}$ = 0.9990 ± 0.0022 ± 0.0036
- Using external value of $R_Z^{\mu\mu/ee}$ from e^+e^- (LEP+SLD):
  - $R_{Z-\mathrm{ext}}^{\mu\mu/ee}$ = 1.0009 ± 0.0028
  - Conversion: $R_W^{\mu/e} = R_{WZ}^{\mu/e}\sqrt{R_{Z-\mathrm{ext}}^{\mu\mu/ee}}$
- $R_W^{\mu/e}$ = 0.9995 ± 0.0022 (stat) ± 0.0036 (syst) ± 0.0014 (ext)
  - Total uncertainty: 0.0045
  - Most precise result to date (previous PDG average 1.002 ± 0.006)
  - No sign of lepton flavour violation



Conclusions

- ATLAS continues to take advantage of the LHC as top factory
- Full programme of ATLAS top physics results
- First direct search for cLFV $\mu\tau qt$ coupling
  - 2 interpretations: EFT and leptoquark
- Most stringent upper limits in tqH FCNC couplings in multi-lepton final states
  - Combination of several final states: $H \to VV^*, H \to \tau^+\tau^-, H \to b\bar{b}, H \to \gamma\gamma$
- Most precise $R_W^{\mu/e}$ measurement to date
- Overall no disagreement with SM

Thank you for your attention!

BACKUP

cLFV: Introduction

Top decay width

$$\Gamma\left(t \to \ell_i^+ \ell_j^- q_k\right) = \frac{m_t}{6144\pi^3}\left(\frac{m_t}{\Lambda}\right)^4 \left\{ 4\left|c_{\mathrm{lq}}^{-(ijk3)}\right|^2 + 4\left|c_{\mathrm{eq}}^{(ijk3)}\right|^2 + 4\left|c_{\mathrm{lu}}^{(ijk3)}\right|^2 + 4\left|c_{\mathrm{eu}}^{(ijk3)}\right|^2 + 2\left|c_{\mathrm{lequ}}^{1(ijk3)}\right|^2 + 96\left|c_{\mathrm{lequ}}^{3(ijk3)}\right|^2 \right\}$$

Cross-section for cLFV $t\bar{t}$ decay

$$\sigma_{\mathrm{CLFV}} = 2 \cdot \sigma_{t\bar{t}} \cdot \mathcal{B}(t \to W(\to \ell\nu)b) \cdot \frac{\Gamma(t \to \ell_i^+ \ell_j^- q_k)}{\Gamma_t}$$

Common lepton selection

Preselection:	
Number of leptons	$N_\ell = 3,\ p_{\mathrm{T}} > 10$ GeV, $\lvert\eta\rvert < 2.5$
Leading muon / electron p_{T}	$p_{\mathrm{T}} > 27$ GeV
Trigger matching	≥ 1 trigger-matched muon / electron
Sum of lepton charges	$\sum q_i = \pm 1$

Theoretical cross-sections

	Cross-section $\sigma^{+\mathrm{scale}}_{-\mathrm{scale}} \pm$ PDF [fb]		
	$c_{\mathrm{vector}}^{(ijk3)}$	$c_{\mathrm{lequ}}^{1(ijk3)}$	$c_{\mathrm{lequ}}^{3(ijk3)}$
Production $\ell\ell' ut$	$118^{+24}_{-19} \pm 1$	$101^{+21}_{-16} \pm 1$	$2150^{+410}_{-320} \pm 20$
Production $\ell\ell' ct$	$7.9^{+1.2}_{-1.0} \pm 1.6$	$6.1^{+1.0}_{-0.8} \pm 1.5$	$153^{+21}_{-18} \pm 29$
Decay $\ell\ell' q_k t$	$6.9^{+1.8}_{-1.3} \pm 0.1$	$3.46^{+0.90}_{-0.66} \pm 0.03$	$166^{+43}_{-32} \pm 2$

Region definitions

	SR	CRτ	CR$t\bar{t}\mu$
Lepton flavour	$2\mu 1\tau_{\mathrm{had}}$		$2\mu 1e$ $(\ell_3 = \mu)$
N_{jets}	≥ 1	≥ 2	≥ 1
$N_{b-\mathrm{tags}}$	1	1	≤ 2
τ_{had} p_{T}	> 20 GeV	> 20 GeV	–
Muon p_{T}	> 15 GeV	> 15 GeV	> 10 GeV
Higher p_{T} muon	Tight	Tight	Tight
Lower p_{T} muon	Tight	Tight	Loose
Muon charges	SS	OS	–
$m_{\mu\mu}^{\mathrm{OS}}$	–	–	>15 GeV
$\lvert m_{\mu\mu}^{\mathrm{OS}} - M_Z\rvert$	–	<10 GeV	>10 GeV
$3p_{\mathrm{T}}^{\mu_1} + \sum m_{\ell\ell}^{\mathrm{OS}}$	–	–	< 400 GeV

cLFV: Region yields

Process	CRτ (1p)			CRτ (3p)		
Fake τ	1150	±	80	364	±	28
Fake τ + NP μ	1.6	±	1.2	0.3	±	0.5
WZ	22	±	7	6.5	±	2.0
ZZ	11	±	4	3.1	±	1.0
t+X	12.0	±	0.9	3.41	±	0.28
$t\bar{t}Z$	16	±	7	4.8	±	2.3
$t\bar{t}W$	0.65	±	0.34	0.25	±	0.15
$t\bar{t}H$	0.84	±	0.12	0.26	±	0.04
VVV	0.12	±	0.06	0.027	±	0.014
$t\bar{t}$ + NP μ	1.0	±	0.8	0.16	±	0.24
Z + NP μ	0.022	±	0.009		–	
Other	17	±	9	6.1	±	3.1
Total	1230	±	90	389	±	30
Data	1324			373		

Process	SR			CR$t\bar{t}\mu$		
$t\bar{t}$ + NP μ	7.9	±	3.4	164	±	14
$t\bar{t}W$	3.5	±	1.8	1.2	±	0.6
$t\bar{t}H$	3.1	±	0.4	1.26	±	0.14
$t\bar{t}Z$	2.9	±	0.5	0.88	±	0.33
t+X	2.48	±	0.18		–	
WZ	3.6	±	1.3	7.3	±	2.4
ZZ	0.59	±	0.22	1.8	±	0.6
VVV	0.01	±	0.05	0.47	±	0.24
Fake electron		–		7	±	4
Fake τ	3.3	±	0.4		–	
Fake τ + NP μ	3.7	±	2.7		–	
t+X + NP μ	0.29	±	0.31	15	±	5
Z + NP μ	0.192	±	0.010	1.8	±	1.0
Other NP μ	0.051	±	0.010		–	
Other	0.23	±	0.11	1.1	±	0.6
Signal ($t\bar{t}$)	0.19	±	0.14	0.025	±	0.019
Signal (single-top)	6	±	4	0.022	±	0.023
Total	38	±	5	201	±	14
Data	37			202		

cLFV: More fit results

	95% CL upper limits on $\mathcal{B}(t \to \mu\tau q)$ $(\times 10^{-7})$					
	$c_{\mathrm{lq}}^{-(ijk3)}$	$c_{\mathrm{eq}}^{(ijk3)}$	$c_{\mathrm{lu}}^{(ijk3)}$	$c_{\mathrm{eu}}^{(ijk3)}$	$c_{\mathrm{lequ}}^{1(ijk3)}$	$c_{\mathrm{lequ}}^{3(ijk3)}$
Expected (u)	2.3	2.0	1.9	2.2	1.2	3.0
Observed (u)	4.0	3.6	3.3	3.8	2.0	5.2
Expected (c)	33	32	32	33	20	41
Observed (c)	56	54	53	54	34	67

	95% CL upper limits on $\mathcal{B}(t \to \mu\tau q)$	
	Stat. uncertainty	**Stat.+syst. uncertainties**
Expected	4.6×10^{-7}	5.0×10^{-7}
Observed	8.2×10^{-7}	8.7×10^{-7}

FCNC: Region definitions

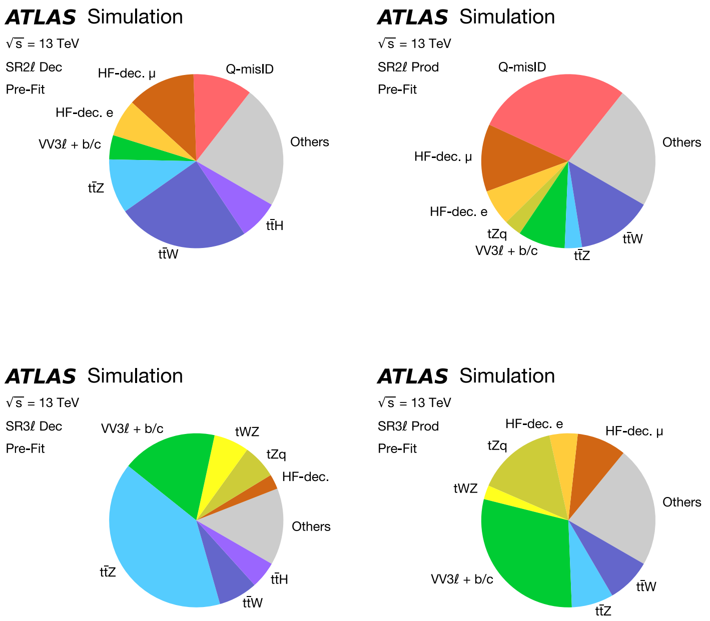
Preselection		
N_{jets}	≥ 1	
$N_{b\text{-tags}}$	≥ 1	
$p_{\text{T}}(\text{jet})$	≥ 20 GeV	
$p_{\text{T}}(\ell)$	≥ 10 GeV	
$p_{\text{T}}(\ell_0)$	≥ 28 GeV	
	2ℓSS	3ℓ
N_ℓ	$= 2$	$= 3$
$\sum q(\ell_i)$	$= \pm 2e$	$= \pm 1e$

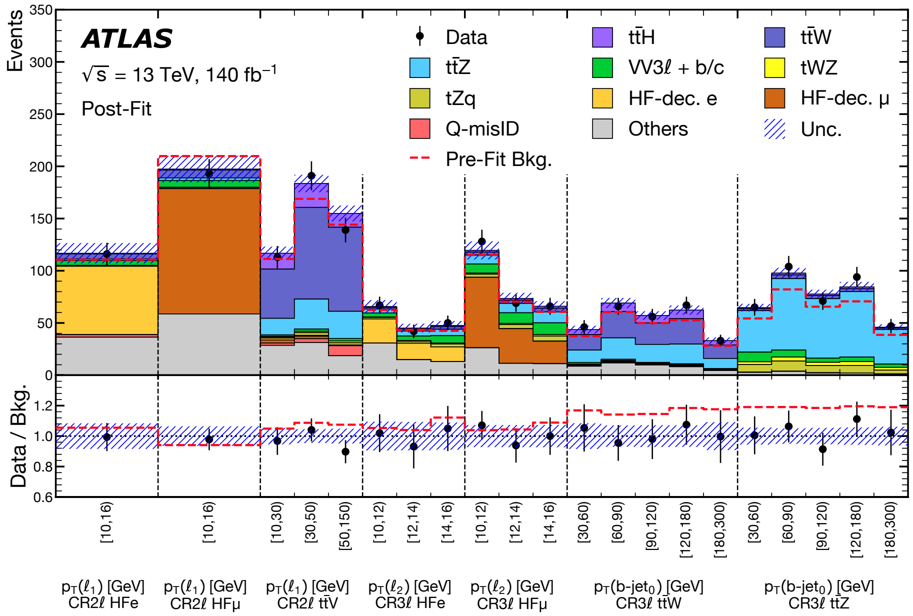
	SR2ℓDec	SR2ℓProd	SR3ℓDec	SR3ℓProd
N_{jets}	≥ 4	≤ 3	≥ 3	≤ 2
$N_{b\text{-tags}}$	$= 1$	$= 1$	$= 1$	$= 1$
$p_{\text{T}}(\ell_1)$	≥ 12 GeV	≥ 16 GeV	≥ 20 GeV	≥ 20 GeV
$p_{\text{T}}(\ell_2)$	–	–	≥ 16 GeV	≥ 16 GeV
$\lvert m(e,e) - m_Z \rvert$	≥ 10 GeV	≥ 10 GeV	–	–

	CR$2\ell t\bar{t}V$	CR$3\ell t\bar{t}W$	CR$3\ell t\bar{t}Z$
N_{jets}	≥ 4	≥ 2	≥ 2
$N_{b\text{-tags}}$	$= 2$	$= 2$	$= 2$
ℓ_0 flavour	μ	–	–
$p_{\text{T}}(\ell_1)$	≥ 18 GeV	≥ 20 GeV	≥ 20 GeV
$p_{\text{T}}(\ell_2)$	–	≥ 16 GeV	≥ 16 GeV
$\lvert m(\ell^+,\ell^-) - m_Z \rvert$	–	≥ 10 GeV	< 10 GeV

	CR2ℓHFe	CR2ℓHFμ	CR3ℓHFe	CR3ℓHFμ
N_{jets}	≤ 3	≤ 3	≥ 1	≥ 1
$N_{b\text{-tags}}$	≥ 1	≥ 1	$= 1$	$= 1$
ℓ_0 flavour	μ	μ	–	–
ℓ_1 flavour	e	μ	–	–
$p_{\text{T}}(\ell_1)$	< 16 GeV	< 16 GeV	≥ 20 GeV	≥ 20 GeV
ℓ_2 flavour	–	–	e	μ
$p_{\text{T}}(\ell_2)$	–	–	< 16 GeV	< 16 GeV

FCNC: Background composition





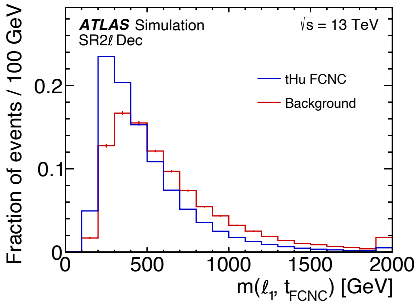
23

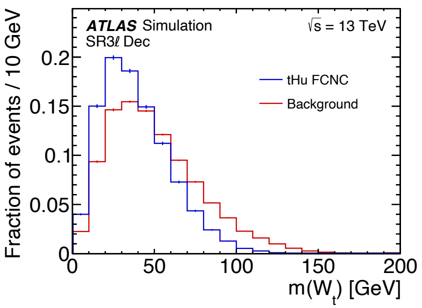
FCNC: Separation of signal and background

RJR

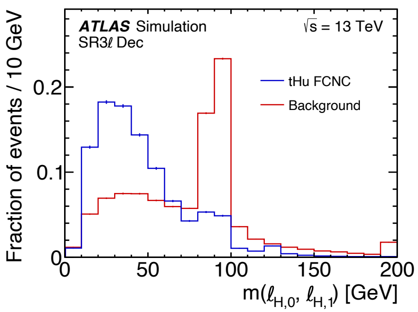
Regions	Particle name	Description
SR2ℓDec/ SR3ℓDec	t_{SM}	The top quark decaying via $t \to Wb$
	W_t	The W boson from the SM top-quark decay
	t_{FCNC}	The top quark decaying via $t \to Hq$
	H	The Higgs boson originating from th FCNC top-quark decay
SR2ℓDec	W_{had}	The hadronically decaying W boson from the $H \to WW^*$ decay
SR2ℓProd/ SR3ℓProd	t_{SM}	The top quark produced in the $gq \to Ht$ process
	W_t	The W boson from the top-quark decay
	H	The Higgs boson produced in the $gq \to Ht$ process

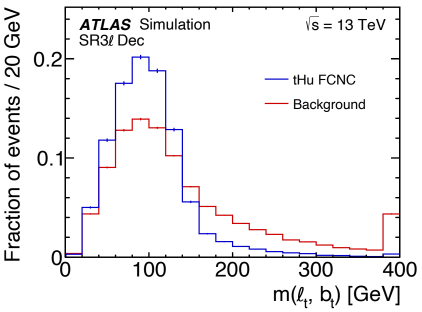
RJR





NICE





24

FCNC: Yields

2ℓ channel

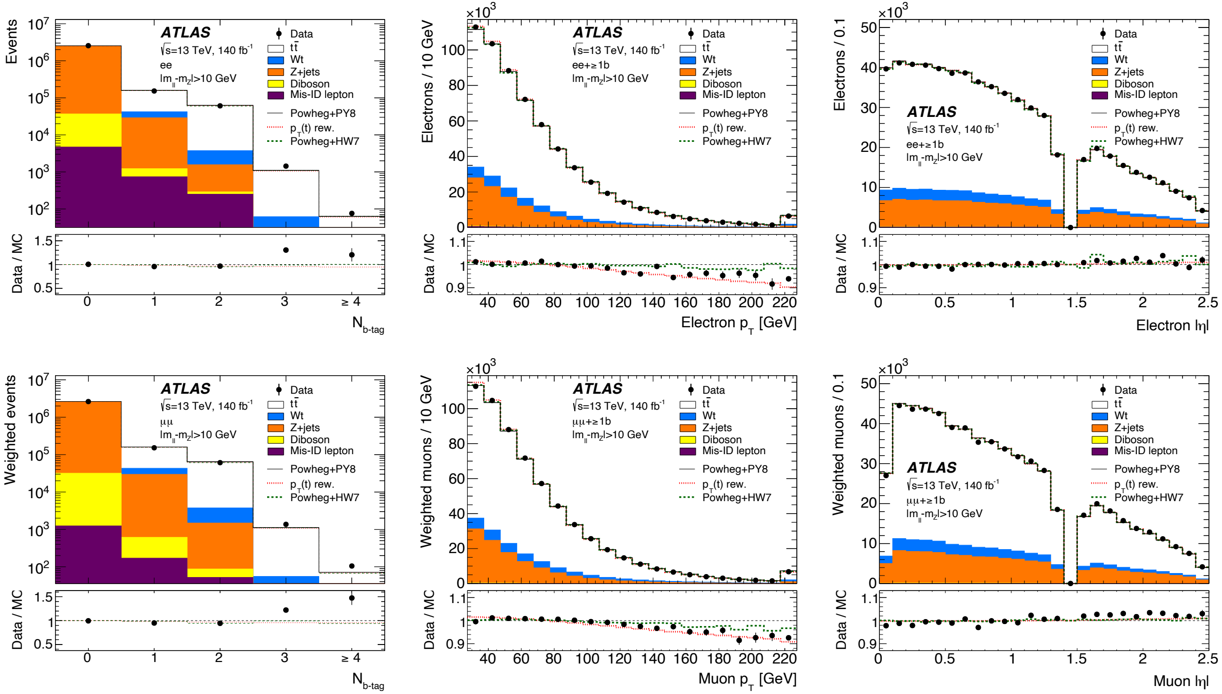
Process	SR2ℓDec	SR2ℓProd	CR2ℓHFe	CR2ℓHFμ	CR2ℓ$t\bar{t}V$
HF-decay e	122 ± 27	113 ± 25	66 ± 13	–	2.9 ± 0.9
HF-decay μ	201 ± 36	192 ± 35	0.1 ± 0.02	120 ± 22	5.6 ± 1.2
Q-misID	204 ± 16	457 ± 35	2.4 ± 0.2	–	15.5 ± 1.4
$t\bar{t}H$	132 ± 20	27 ± 5	0.6 ± 0.1	1.0 ± 0.2	51 ± 8
$t\bar{t}W$	512 ± 61	285 ± 42	4.8 ± 0.9	7.5 ± 1.4	216 ± 24
$t\bar{t}Z$	210 ± 21	66 ± 9	1.5 ± 0.2	2.4 ± 0.4	70 ± 6
VV 3ℓ+b/c	104 ± 20	192 ± 32	4.7 ± 1.0	6.6 ± 1.4	6.0 ± 1.2
tWZ	23 ± 7	12 ± 4	0.11 ± 0.04	0.17 ± 0.06	3.6 ± 1.1
tZq	26 ± 8	63 ± 18	0.7 ± 0.2	1.1 ± 0.3	5.8 ± 1.7
Others	340 ± 64	322 ± 46	36 ± 8	59 ± 20	79 ± 14
Pre-fit BG	1845 ± 91	1585 ± 70	111 ± 11	210 ± 32	424 ± 22
Post-fit BG	1874 ± 38	1729 ± 36	117 ± 10	198 ± 12	455 ± 17
$t\bar{t}(t\to Hu)$	207 ± 22	181 ± 10	3.4 ± 0.3	5.4 ± 0.7	6.8 ± 0.6
$ug\to Ht$	31 ± 4	68 ± 2	1.2 ± 0.1	2.1 ± 0.2	1.1 ± 0.1
$t\bar{t}(t\to Hc)$	196 ± 22	180 ± 10	3.5 ± 0.4	5.9 ± 0.7	13.4 ± 1.5
$cg\to Ht$	5 ± 1	11 ± 1	0.2 ± 0.1	0.4 ± 0.1	0.2 ± 0.1
Data	1847	1723	116	193	443

3ℓ channel

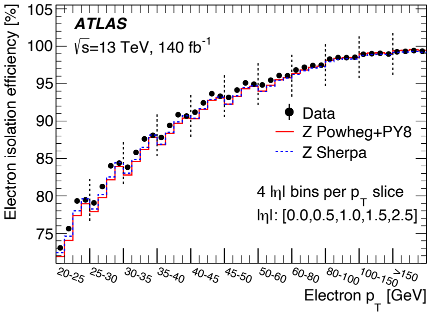
Process	SR3ℓProd	SR3ℓDec	CR3ℓ$t\bar{t}W$	CR3ℓ$t\bar{t}Z$	CR3ℓHFe	CR3ℓHFμ
HF-decay e	38 ± 9	14 ± 3	1.3 ± 0.3	0.28 ± 0.09	53 ± 11	–
HF-decay μ	63 ± 11	22 ± 4	1.6 ± 0.3	0.37 ± 0.08	0.2 ± 0.1	122 ± 19
Q-misID	–	–	–	–	–	–
$t\bar{t}H$	10 ± 2	47 ± 7	32 ± 5	6.7 ± 1.1	3.0 ± 0.5	5.2 ± 0.9
$t\bar{t}W$	77 ± 12	80 ± 10	98 ± 16	12.5 ± 1.6	5.8 ± 1.0	9.5 ± 1.4
$t\bar{t}Z$	75 ± 11	438 ± 40	78 ± 7	261 ± 20	14.7 ± 1.8	28 ± 3
VV 3ℓ+b/c	296 ± 49	215 ± 39	4.8 ± 0.9	27 ± 5	15 ± 3	30 ± 5
tWZ	19 ± 6	57 ± 18	2.9 ± 0.9	16 ± 5	1.9 ± 0.6	3.6 ± 1.1
tZq	134 ± 38	69 ± 20	3.5 ± 1.0	35 ± 10	6.1 ± 1.8	12 ± 3
Others	171 ± 32	119 ± 23	43 ± 7	11.7 ± 1.5	59 ± 8	48 ± 9
Pre-fit BG	710 ± 48	941 ± 42	228 ± 17	312 ± 19	148 ± 11	248 ± 16
Post-fit BG	882 ± 28	1061 ± 28	265 ± 14	371 ± 17	159 ± 10	258 ± 14
$t\bar{t}(t\to Hu)$	26 ± 2	39 ± 3	1.2 ± 0.2	0.7 ± 0.1	4.6 ± 0.5	8.0 ± 0.8
$ug\to Ht$	14 ± 1	7 ± 1	0.4 ± 0.1	0.2 ± 0.1	1.2 ± 0.1	2.1 ± 0.2
$t\bar{t}(t\to Hc)$	27 ± 2	37 ± 3	4.3 ± 0.4	1.5 ± 0.1	4.4 ± 0.5	7.8 ± 0.7
$cg\to Ht$	2 ± 1	1 ± 1	0.1 ± 0.1	0.1 ± 0.1	0.2 ± 0.1	0.4 ± 0.1
Data	896	1046	268	381	159	263

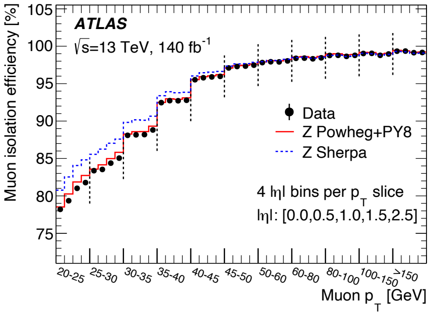
LFU: Event reconstruction and selection

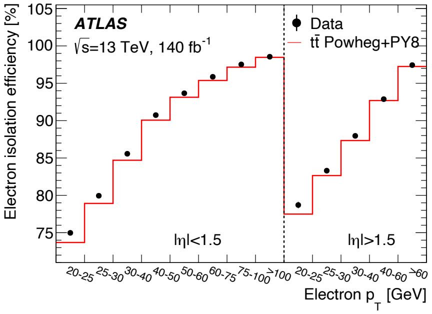
Object selection		
Electrons	$p_T > 27.3\,\text{GeV}$, $\lvert\eta\rvert < 1.37$ or $1.52 < \lvert\eta\rvert < 2.47$	
Muons	$p_T > 27.3\,\text{GeV}$, $\lvert\eta\rvert < 2.5$	
b-tagged jets	$p_T > 30.0\,\text{GeV}$, $\lvert\eta\rvert < 2.5$, b-tagging DL1r 70%	
Event selection	$t\bar{t} \to \ell\ell b\bar{b}\nu\bar{\nu}$	$Z \to \ell\ell$
Dilepton flavour ($\ell^+\ell^-$)	ee, $e\mu$, $\mu\mu$	ee, $\mu\mu$
Dilepton invariant mass	$m_{\ell\ell} > 30\,\text{GeV}$	$66\,\text{GeV} < m_{\ell\ell} < 116\,\text{GeV}$
b-tagged jet multiplicity	1 or 2	–

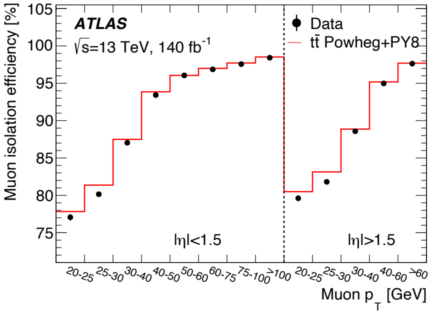


LFU: Lepton isolation efficiency measurements









LFU: Observed events in the dilepton channels

$t\bar{t}$ selection

Event counts	$N^{ee}_{1,\text{off}-Z}$	$N^{ee}_{1,\text{on}-Z}$	$N^{e\mu}_{1}$	$N^{\mu\mu}_{1,\text{off}-Z}$	$N^{\mu\mu}_{1,\text{on}-Z}$
Data	222304	442108	405437	223085	448105
$t\bar{t}$	154800 ± 1700	24830 ± 850	361000 ± 4200	152500 ± 1800	24070 ± 860
Wt	17500 ± 1600	2770 ± 240	41500 ± 3800	17800 ± 1700	2730 ± 250
Z+jets	46880 ± 400	410700 ± 2000	859 ± 21	51010 ± 780	418000 ± 2000
Diboson	770 ± 160	3940 ± 840	790 ± 280	770 ± 160	3880 ± 830
Mis-ID leptons	1300 ± 500	360 ± 260	1740 ± 610	390 ± 150	172 ± 87
Total prediction	221280 ± 550	442600 ± 1100	405900 ± 1800	222390 ± 670	448900 ± 1100

Event counts	$N^{ee}_{2,\text{off}-Z}$	$N^{ee}_{2,\text{on}-Z}$	$N^{e\mu}_{2}$	$N^{\mu\mu}_{2,\text{off}-Z}$	$N^{\mu\mu}_{2,\text{on}-Z}$
Data	85936	37704	198502	86169	38512
$t\bar{t}$	79750 ± 920	13340 ± 480	191000 ± 1800	79770 ± 830	13180 ± 450
Wt	2860 ± 760	400 ± 110	6700 ± 1600	2940 ± 740	423 ± 90
Z+jets	2675 ± 68	23610 ± 590	78 ± 2	3095 ± 87	24110 ± 600
Diboson	67 ± 23	550 ± 110	29 ± 8	71 ± 30	570 ± 110
Mis-ID leptons	400 ± 290	96 ± 59	720 ± 520	350 ± 160	104 ± 56
Total prediction	85760 ± 360	38000 ± 190	198510 ± 440	86230 ± 300	38380 ± 210

Inclusive $Z \to \ell\ell$ selection

Event counts	$Z \to ee$	$Z \to \mu\mu$
Data	47898836	49016812
$Z \to \ell\ell$	47621000 ± 33000	48767000 ± 29000
Diboson	111000 ± 22000	104000 ± 21000
$Z \to \tau\tau$	16850 ± 140	13780 ± 110
$t\bar{t}$	119000 ± 14000	117000 ± 14000
Wt	12380 ± 890	12390 ± 880
Mis-ID leptons	19000 ± 18000	3000 ± 13000
Total prediction	47898800 ± 6900	49016800 ± 6200

LFU: Statistical and systematic uncertainties

Uncertainty [%]	$\sigma_{t\bar{t}}$	$\sigma_{Z\to\ell\ell}$	$R^{\mu/e}_{WZ}$	$R^{\mu\mu/ee}_{Z}$
Data statistics	0.13	0.01	0.22	0.02
$t\bar{t}$ modelling	1.68	0.03	0.10	0.00
Top-quark p_T modelling	1.42	0.00	0.06	0.00
Parton distribution functions	0.67	0.68	0.15	0.03
Single-top modelling	0.65	0.00	0.05	0.00
Single-top/$t\bar{t}$ interference	0.54	0.00	0.09	0.00
Z(+jets) modelling	0.06	0.73	0.13	0.20
Diboson modelling	0.05	0.04	0.01	0.00
Electron energy scale/resolution	0.05	0.06	0.10	0.11
Electron identification	0.10	0.07	0.04	0.13
Electron charge misidentification	0.06	0.06	0.01	0.13
Electron isolation	0.09	0.02	0.08	0.04
Muon momentum scale/resolution	0.04	0.02	0.06	0.04
Muon identification	0.18	0.12	0.11	0.23
Muon isolation	0.09	0.01	0.07	0.01
Lepton trigger	0.09	0.12	0.01	0.23
Jet energy scale/resolution	0.08	0.00	0.03	0.00
b-tagging efficiency/mistag	0.14	0.00	0.00	0.00
Misidentified leptons	0.17	0.02	0.15	0.05
Simulation statistics	0.04	0.00	0.06	0.00
Integrated luminosity	0.93	0.83	0.00	0.00
Beam energy	0.23	0.09	0.00	0.00
Total uncertainty	2.66	1.32	0.42	0.45

LFU: More fit results

Cross-section results

- $\sigma_{t\bar{t}} = 809.5 \pm 1.1 \pm 20.1 \pm 7.5 \pm 1.9$ pb
- $\sigma_{Z\to\ell\ell} = 2019.4 \pm 0.2 \pm 20.7 \pm 16.8 \pm 1.8$ pb
- $\sigma^{\mathrm{fid}}_{Z\to\ell\ell} = 774.7 \pm 0.1 \pm 1.8 \pm 6.4 \pm 0.7$ pb

Ratio of the number of events