Top quark charged-lepton flavour violation arXiv:2403.06742

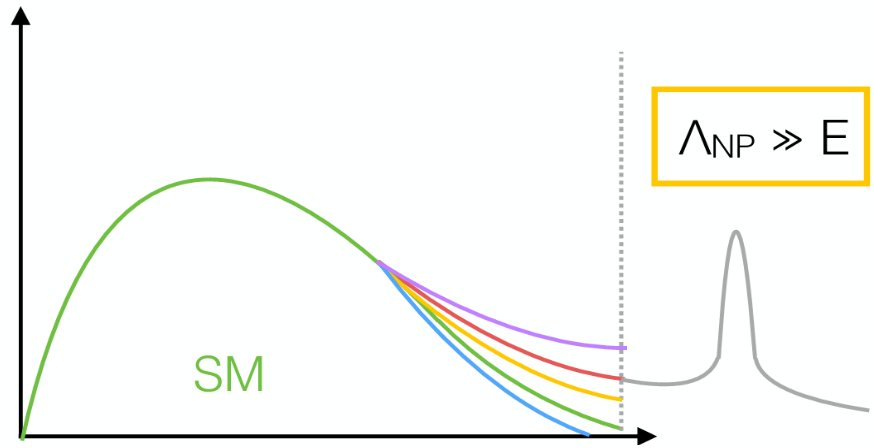
Jacob Kempster on behalf of ATLAS

LHC EFT + Top Working Groups: Joint Meeting

24 April 2024

Effective Field Theory (EFT)

Maybe New Physics (NP) exists at a significantly higher energy scale (Λ_{NP}) than LHC can reach…



K. Mimasu, EFTforTop

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{i,n} \frac{c_i^{(n)}}{\Lambda^{n-4}} \mathcal{O}_i^{(n)}$$

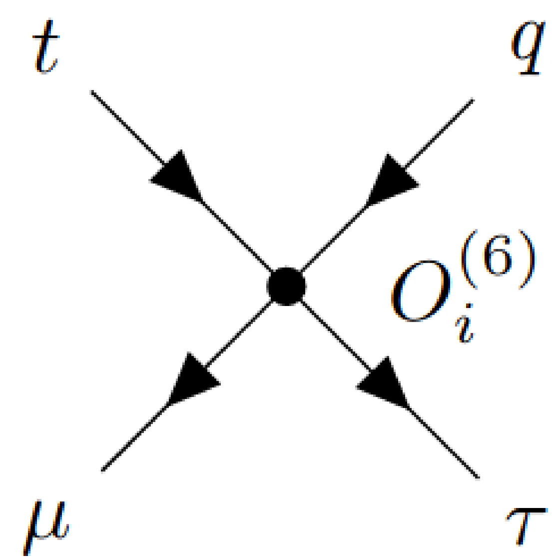
Standard Model

Coupling Strength

Operators introducing new interactions

Target 2Q2L EFT operators

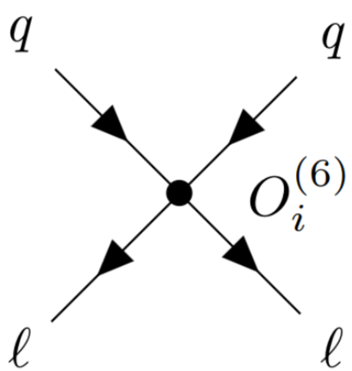
Operator	Interaction	Lorentz Structure
$O_{\mathrm{lq}}^{1(ijkl)}$	$(\bar{\mathrm{l}}_i\gamma^\mu \mathrm{l}_j)(\bar{\mathrm{q}}_k\gamma_\mu \mathrm{q}_l)$	Vector
$O_{\mathrm{lq}}^{3(ijkl)}$	$(\bar{\mathrm{l}}_i\gamma^\mu\sigma^I \mathrm{l}_j)(\bar{\mathrm{q}}_k\gamma_\mu\sigma_I \mathrm{q}_l)$	Vector
$O_{\mathrm{eq}}^{(ijkl)}$	$(\bar{\mathrm{e}}_i\gamma^\mu \mathrm{e}_j)(\bar{\mathrm{q}}_k\gamma_\mu \mathrm{q}_l)$	Vector
$O_{\mathrm{lu}}^{(ijkl)}$	$(\bar{\mathrm{l}}_i\gamma^\mu \mathrm{l}_j)(\bar{\mathrm{u}}_k\gamma_\mu \mathrm{u}_l)$	Vector
$O_{\mathrm{eu}}^{(ijkl)}$	$(\bar{\mathrm{e}}_i\gamma^\mu \mathrm{e}_j)(\bar{\mathrm{u}}_k\gamma_\mu \mathrm{u}_l)$	Vector
$O_{\mathrm{lequ}}^{1(ijkl)}$	$(\bar{\mathrm{l}}_i \mathrm{e}_j)\varepsilon(\bar{\mathrm{q}}_k \mathrm{u}_l)$	Scalar
$O_{\mathrm{lequ}}^{3(ijkl)}$	$(\bar{\mathrm{l}}_i\sigma^{\mu\nu} \mathrm{e}_j)\varepsilon(\bar{\mathrm{q}}_k\sigma_{\mu\nu} \mathrm{u}_l)$	Tensor



(Same family that enter into the B-anomalies e.g. $b \to sll$)

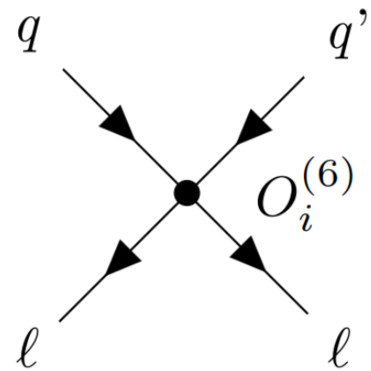
Top 2Q2L operator effects

$t\bar{t}Z$-like (diagonal)



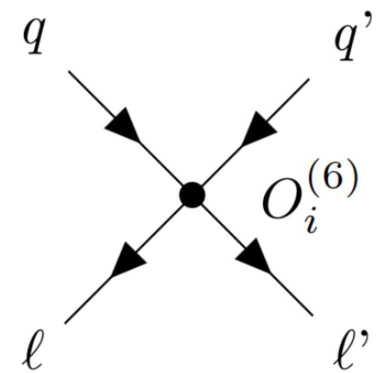
$t\bar{t}ll$

FCNC (semi-diagonal)



$tqll$

CLFV (fully off-diagonal)



$tqll'$

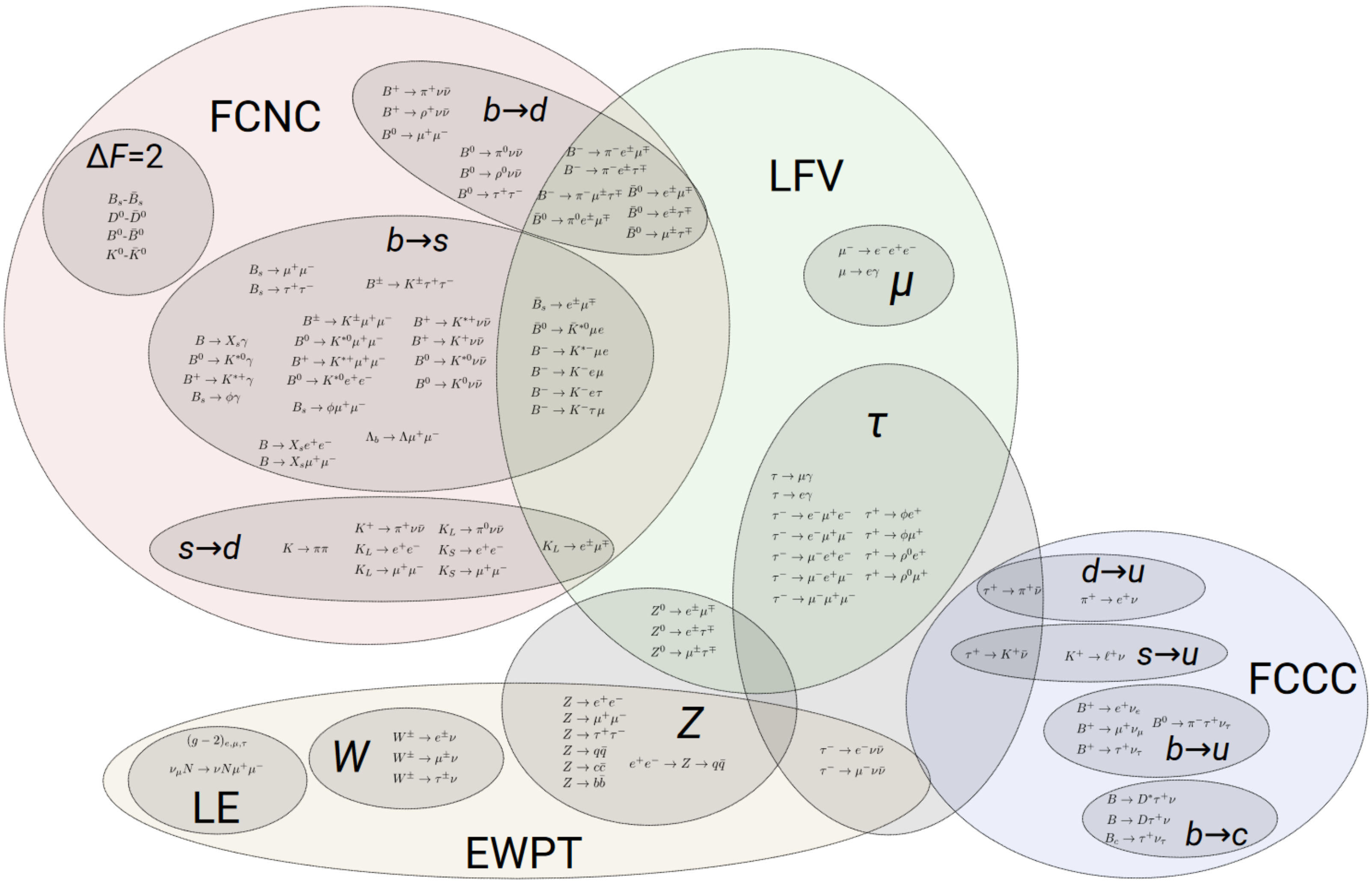
Four-fermion / 2-quark-2-lepton (2Q2L) operator 'family' in context

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu} u_t)$		

Four-fermion operators

Larger picture



[D. Straub](https://arxiv.org/)

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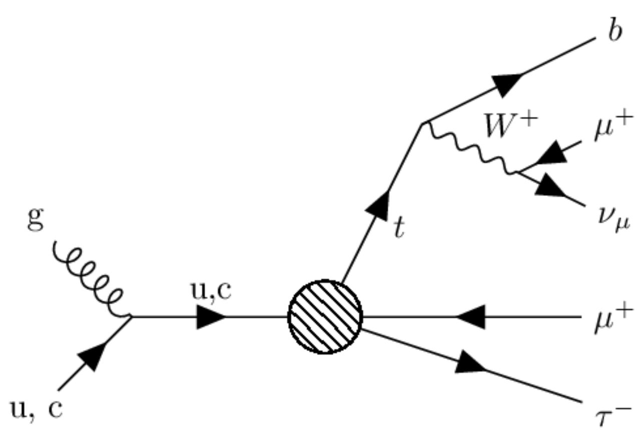
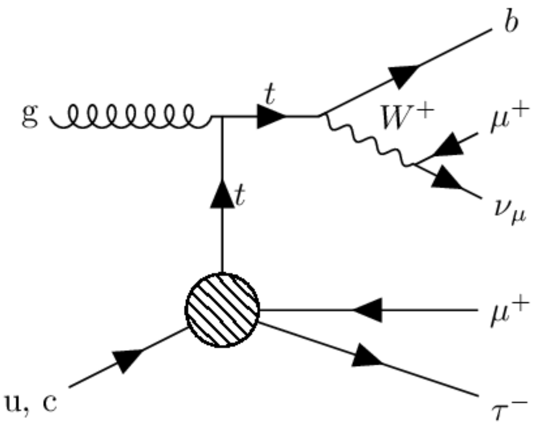
Charged Lepton Flavour Violation

Production

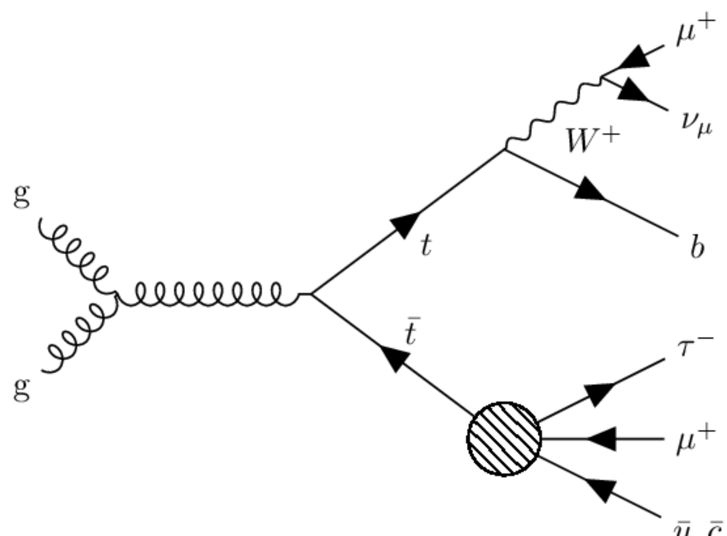
$qg \rightarrow tll'$





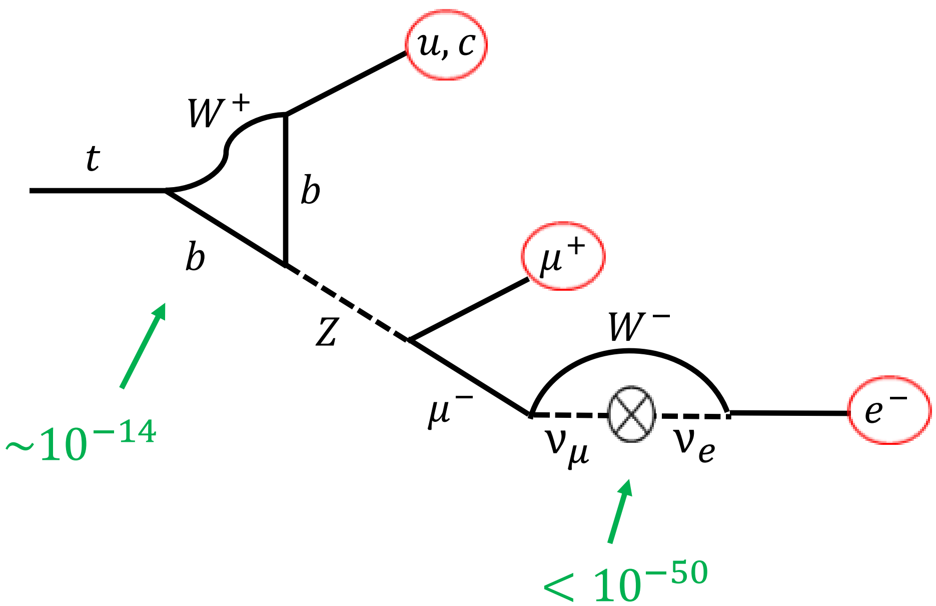
Decay

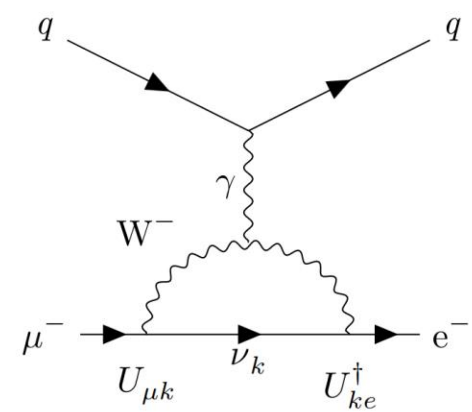
$t\bar{t} \rightarrow (ll'q)(lvb)$

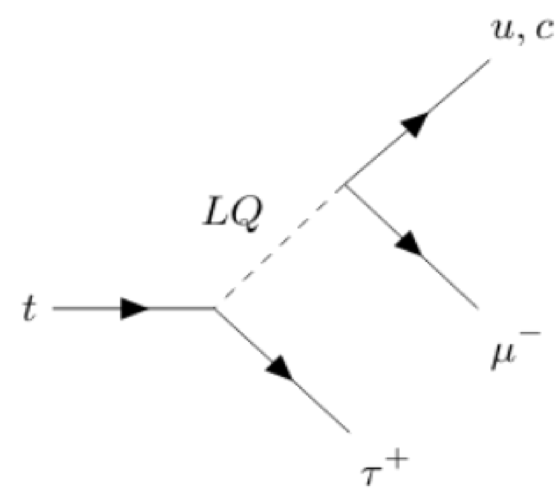


Neutrino Oscillations / New Physics

Neutrino oscillations → LFV in lepton sector but far beyond any experimental sensitivity







New physics which introduces additional terms involving lepton fields in Lagrangian can lead to LFV, e.g. SUSY, leptoquarks, 2HDMs

Recent history

Limits on CLFV branching ratio of top (95% CL):

$B(t \to ll'q) < 1.86 \times 10^{-5}$

$B(t \to e\mu q) < 6.6 \times 10^{-6}$

ATLAS-CONF-2018-044
(3-lepton final state, $80\ \mathrm{fb}^{-1}$)

$B(t \to e\mu q) < 0.009 - 0.258 \times 10^{-6}$

CMS-PAS-TOP-22-005
(3-lepton final state , $138\ \mathrm{fb}^{-1}$)

This analysis is first direct search for CLFV $\mu\tau qt$ coupling.

BSM models predicting CLFV with electrons/muons also apply to taus, often additionally enhanced due to larger mass

Charged Lepton Flavour Violation

	Cross-section $\sigma^{+\text{scale}}_{-\text{scale}} \pm$ PDF [fb]		
	$c^{(ijk3)}_{\text{vector}}$	$c^{1(ijk3)}_{\text{lequ}}$	$c^{3(ijk3)}_{\text{lequ}}$
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 $\ell\ell' q_k t$	$6.9^{+1.8}_{-1.3} \pm 0.1$	$3.46^{+0.90}_{-0.66} \pm 0.03$	$166^{+43}_{-32} \pm 2$

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

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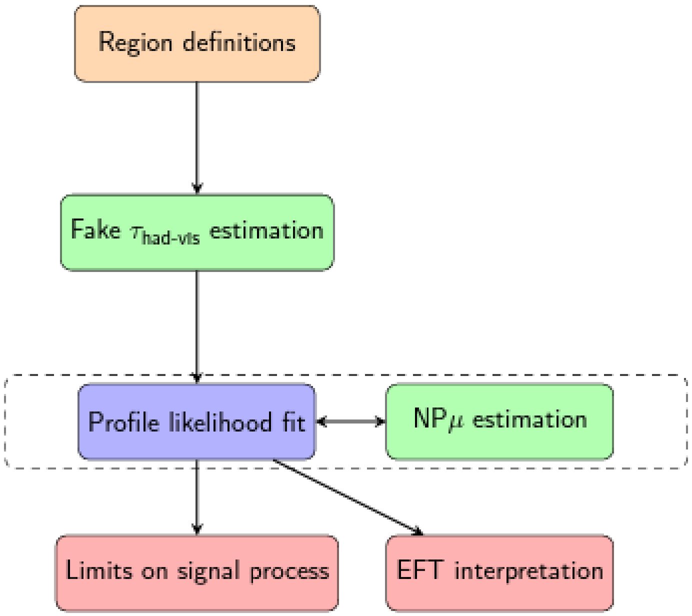
Using dim6top, found to agree with SMEFTsim 3.0

Charged Lepton Flavour Violation

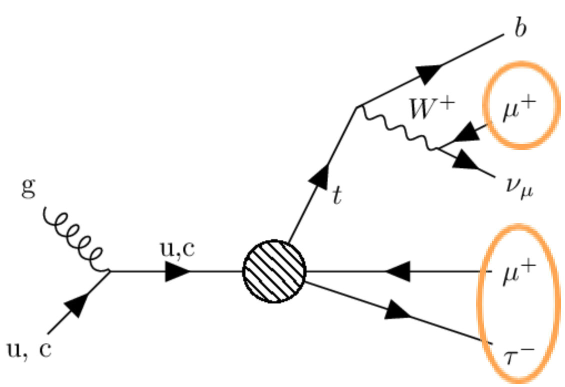
- Single lepton triggers
- Definition of analysis regions including dedicated CRs for fake backgrounds
  - → Select events with electrons, muons and *hadronically-decaying* tau leptons ($\tau_{\text{had-vis}}$)
  - → **Trilepton** selection: $\mu\mu\tau_{\text{had-vis}}$/ $e\mu\mu$
- Prompt/real backgrounds estimated in MC ($t\bar{t}V$, diboson, tW)
- Data-driven estimation of fake lepton backgrounds (CRs)
  - → Fake $\tau_{\text{had-vis}}$ (+ 2 prompt μ): scale factor method
  - → Non-prompt muons: template fit method (*takes place in PL fit*)
- Profile likelihood fit to SRs and non-prompt muon CR
- EFT interpretation

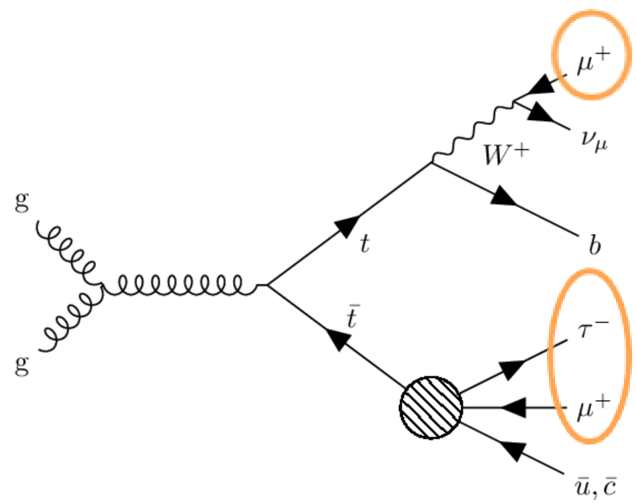


Event selection with $139\ \text{fb}^{-1}$

- Top quark decay and production diagrams differ by 1-jet
- Trilepton event selection including hadronic taus
- Same-sign muons produce significant background reduction

	SR	**CRτ**	**CR$t\bar{t}\mu$**
Lepton flavour	$2\mu 1\tau_{\text{had}}$		$2\mu 1e\ \ (\ell_3 = \mu)$
N_{jets}	≥ 1	≥ 2	≥ 1
$N_{b\text{-tags}}$	1	1	≤ 2
$\tau_{\text{had}}\ p_{\text{T}}$	> 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	–
$m_{\mu\mu}^{\text{OS}}$	–	–	>15 GeV
$\lvert m_{\mu\mu}^{\text{OS}} - M_Z \rvert$	–	<10 GeV	>10 GeV
$3p_{\text{T}}^{\mu_1} + \sum m_{\ell\ell}^{\text{OS}}$	–	–	< 400 GeV





Yields

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		

Post-fit yields

Fake-tau estimation

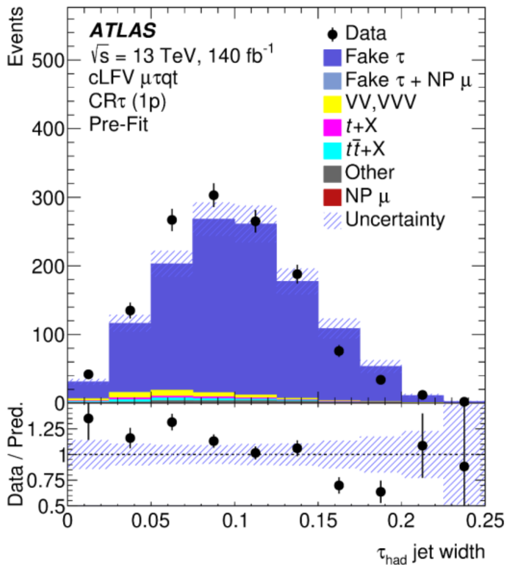
Fakes are usually due to mis-identified jets

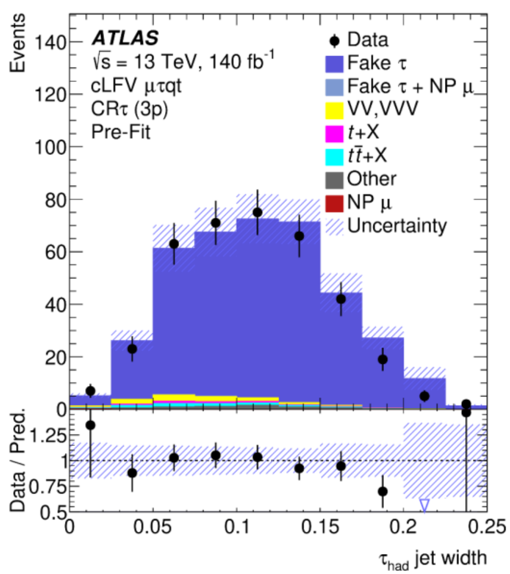
Dedicated CR (does not enter the fit)

Scale factors (SF) are used to correct the rate of the fake-tau background

SFs are parameterised by:

- Track multiplicity (1-prong / 3-prong)
- Tau-jet width
  - This is a good proxy for the quark-gluon fractions which may differ slightly between SR/CR and between data and MC
- Systematics for SM backgrounds are propagated to the SFs and correlated appropriately in the fits



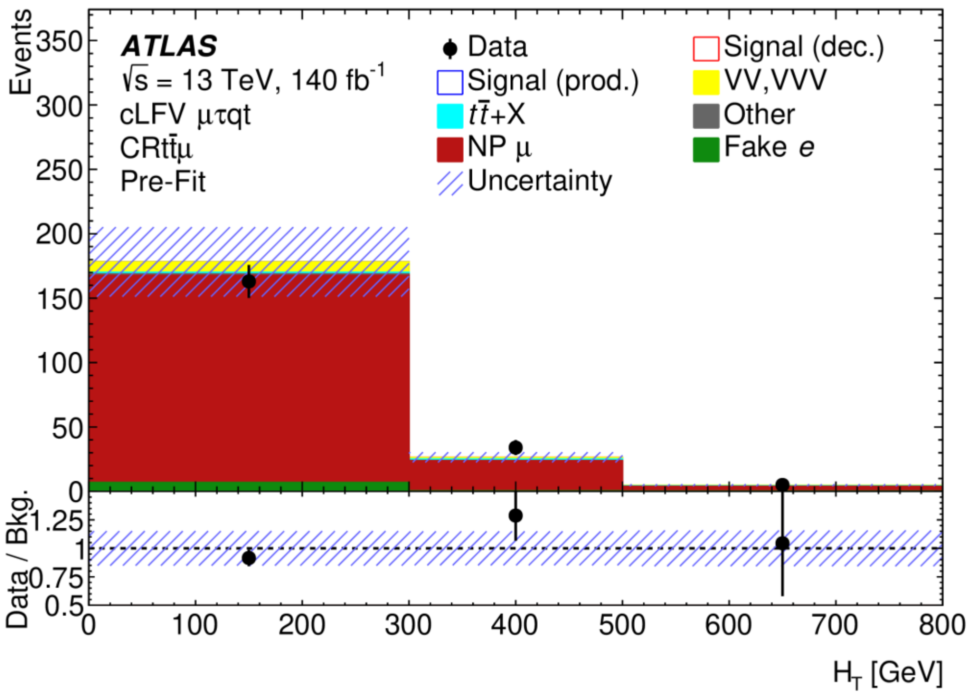


Fake/Non-prompt (NP) muon estimation

Dedicated CR (enters the fit)

Targeting non-prompt muons from b-jets in $t\bar{t}$ events

Normalisation is controlled by a profile-likelihood fit (next slides)



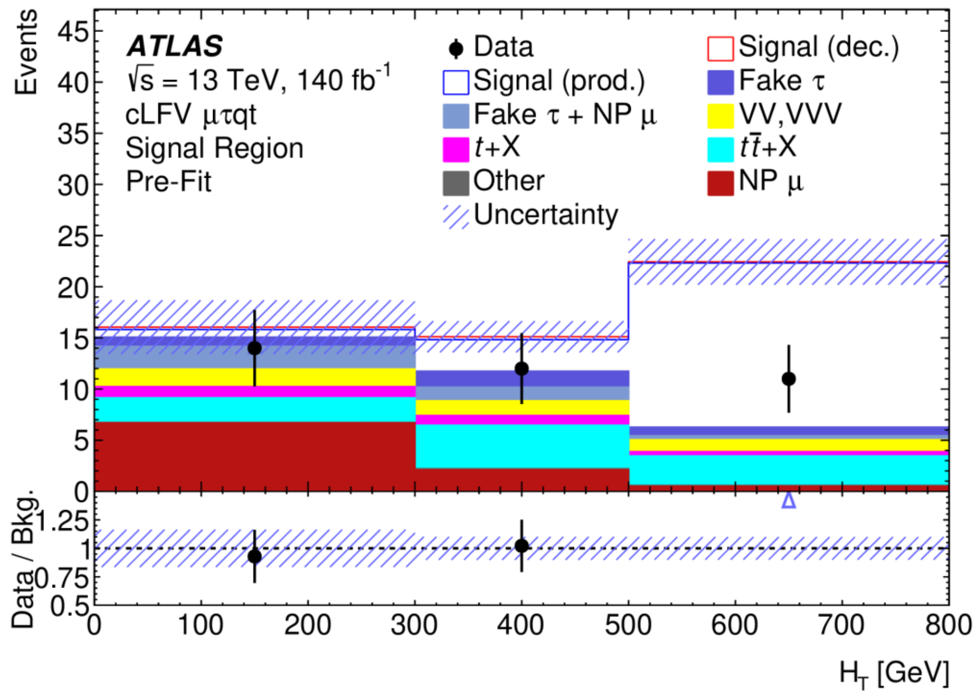
Signal region

Binned in HT to capture energy growth behaviour of EFT operators

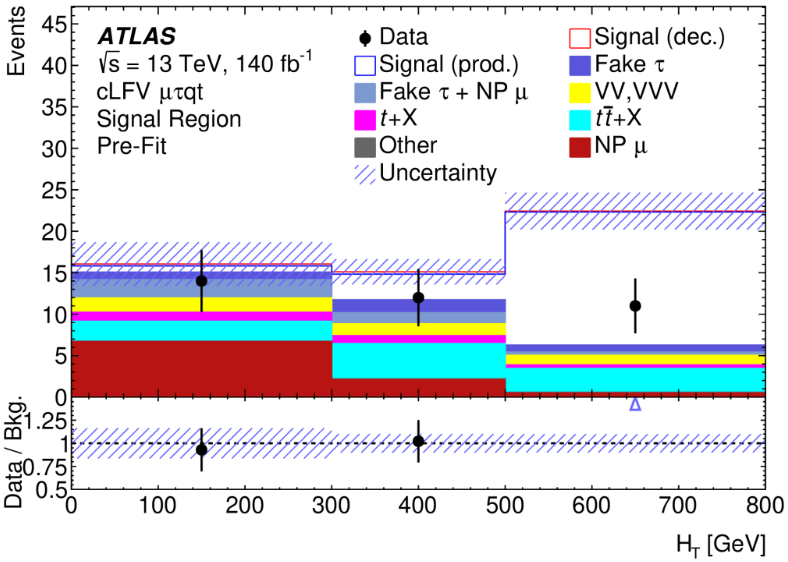
Signal shown is inclusive EFT (up-initiated, charm-initiated, all operators)

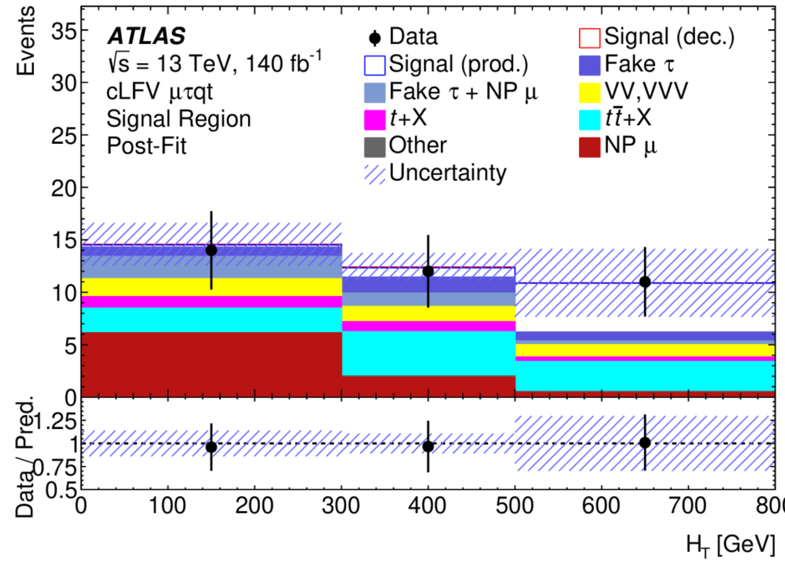
For up-quark operators, the production mode (blue) dominates the cross-section and sensitivity

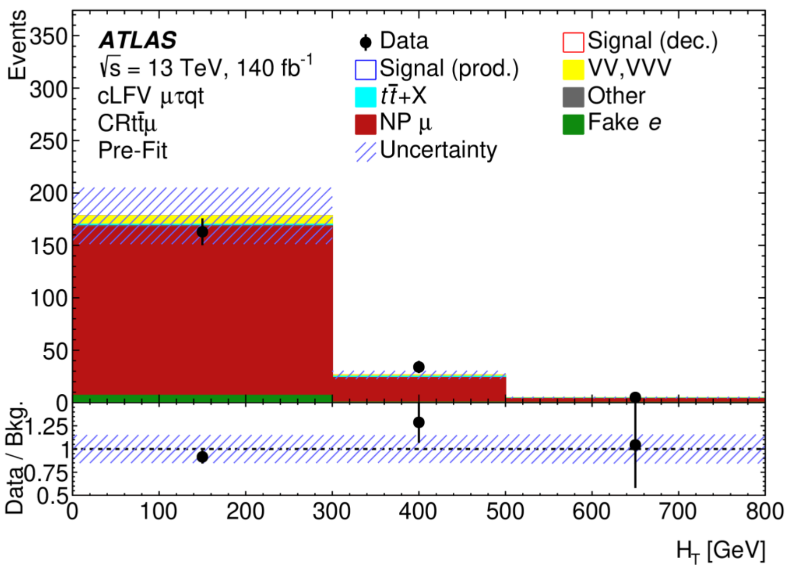
For charm-quark operators, the production and decay modes are more balanced

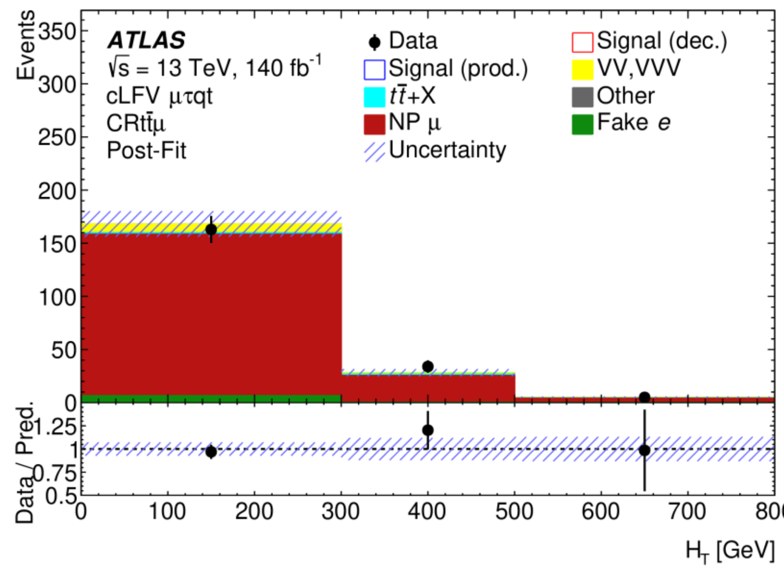


Profile-likelihood fit





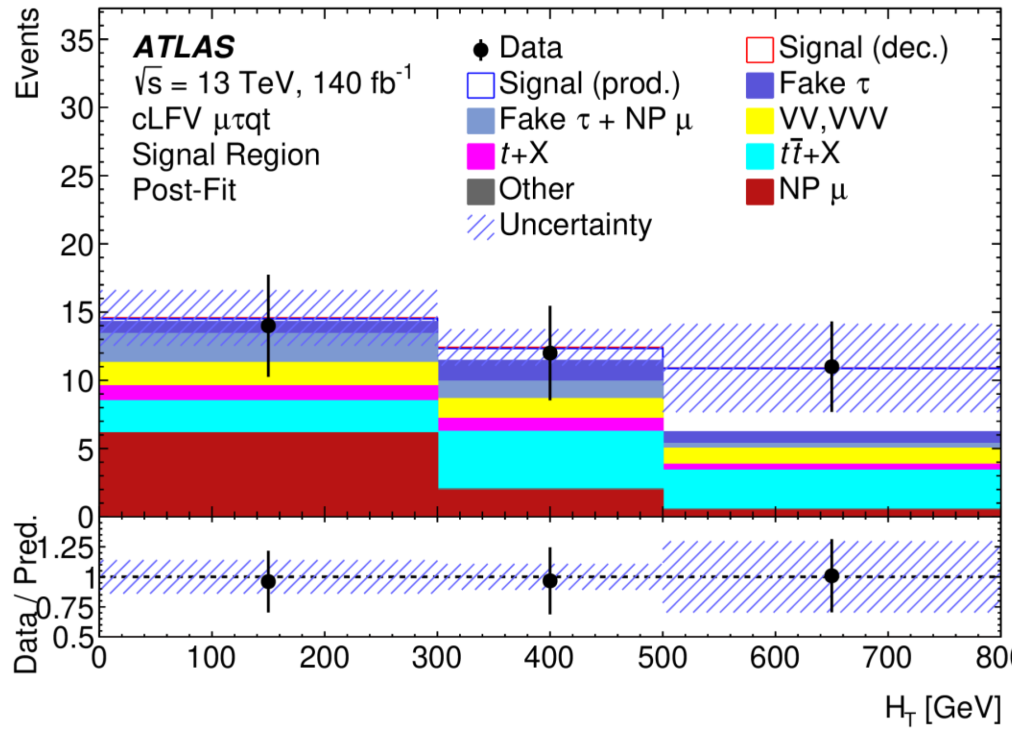




Profile-likelihood fit

Good agreement between data and background-only model

Statistically limited result
Largest systematics are signal, $t\bar{t}W$ and diboson modelling



'Inclusive' BR limits set assuming all EFT operators are of equal magnitude

	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}

EFT Result breakdown

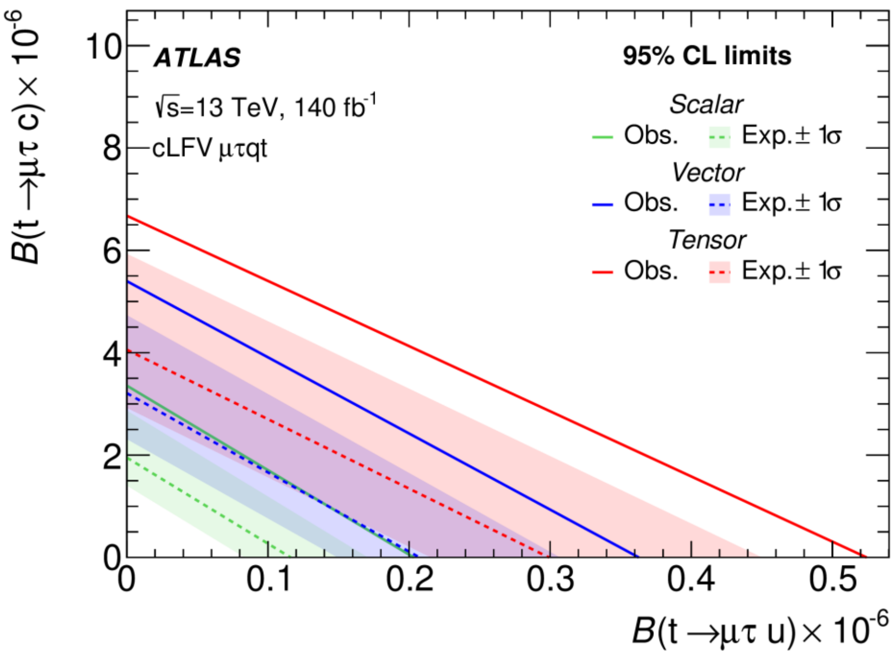
	95% CL upper limits on $\mathcal{B}(t \to \mu\tau q)$ $(\times 10^{-7})$					
	$c_{\text{lq}}^{-(ijk3)}$	$c_{\text{eq}}^{(ijk3)}$	$c_{\text{lu}}^{(ijk3)}$	$c_{\text{eu}}^{(ijk3)}$	$c_{\text{lequ}}^{1(ijk3)}$	$c_{\text{lequ}}^{3(ijk3)}$
Expected (u)	2.3	2.0	1.9	2.2	1.2	3.0
Observed (u)	4.0	3.6	3.3	3.8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

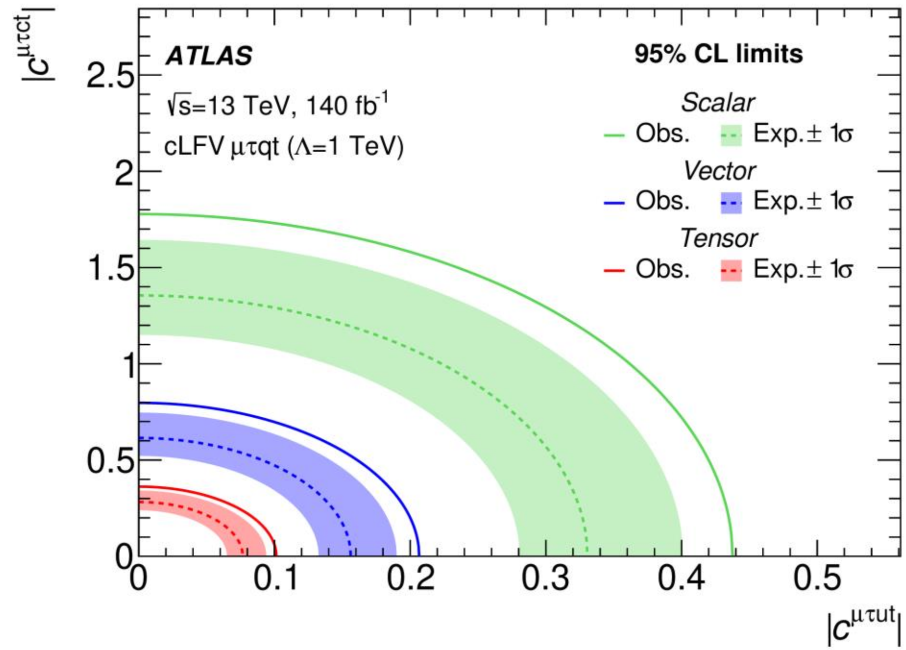
	95% CL upper limits on $\lvert c\rvert/\Lambda^2$ [TeV^{-2}]					
	$c_{\text{lq}}^{-(ijk3)}$	$c_{\text{eq}}^{(ijk3)}$	$c_{\text{lu}}^{(ijk3)}$	$c_{\text{eu}}^{(ijk3)}$	$c_{\text{lequ}}^{1(ijk3)}$	$c_{\text{lequ}}^{3(ijk3)}$
Previous (u)	12	12	12	12	18	2.4
Expected (u)	0.33	0.31	0.3	0.32	0.33	0.08
Observed (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

EFT limits improve upon previous results (re-interpretation of ATLAS FCNC tZq analysis):

- From factors of 7.2 for $c_{lequ}^{3(2323)}$ (for $\mu\tau ct$) to 41 for $c_{lequ}^{1(2313)}$ (for $\mu\tau ut$).

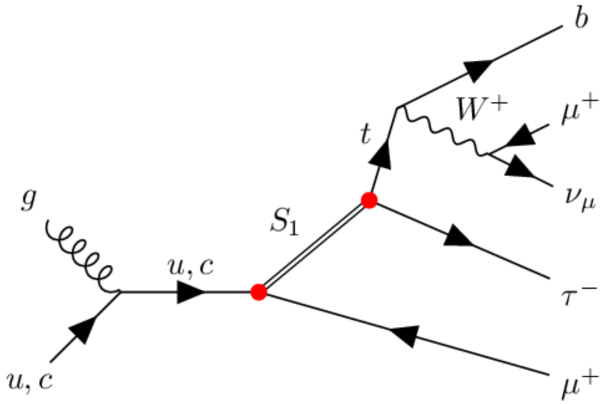
EFT Result breakdown

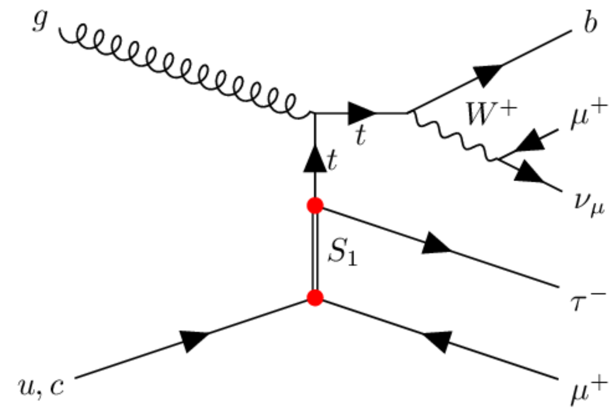


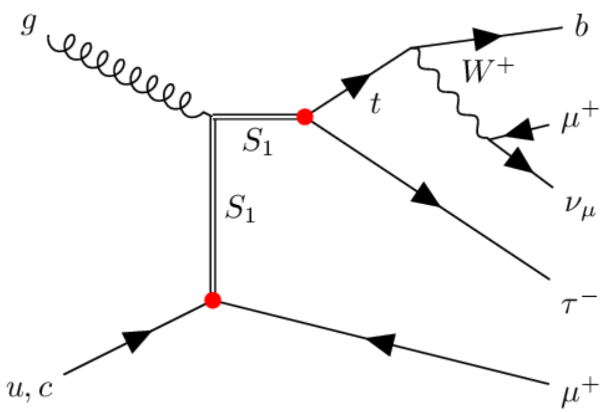


Leptoquark interpretation

Scalar leptoquark with cross-generational couplings could produce CLFV processes.







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

Leptoquark interpretation

Cross-generational couplings introduce many degrees of freedom, which may be simplified with a hierarchical modal:

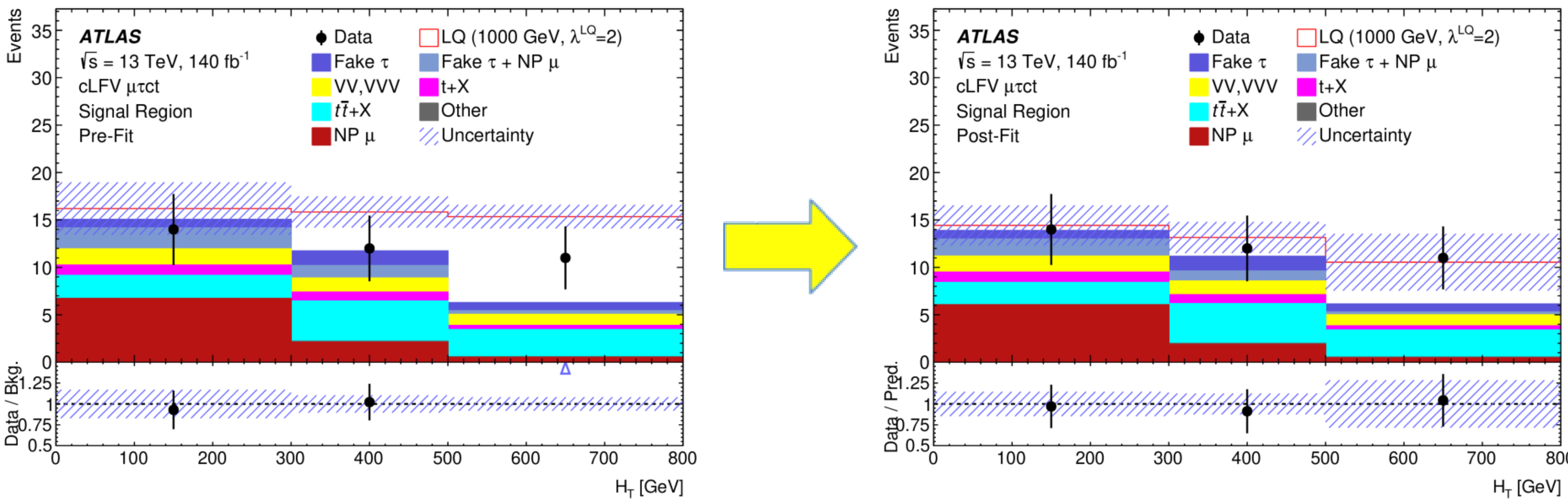
$$\lambda_{ki} \in \begin{pmatrix} \lambda_{t\tau} & \lambda_{c\tau} & \lambda_{u\tau} \\ \lambda_{t\mu} & \lambda_{c\mu} & \lambda_{u\mu} \\ \lambda_{te} & \lambda_{ce} & \lambda_{ue} \end{pmatrix} \equiv \lambda^{\mathrm{LQ}} \begin{pmatrix} 10 & 1 & 0.1 \\ 1 & 0.1 & 0.01 \\ 0.1 & 0.01 & 0.001 \end{pmatrix}$$

This reduces 10 degrees of freedom (9 coupling, 1 mass) into 2 (1 coupling, 1 mass).

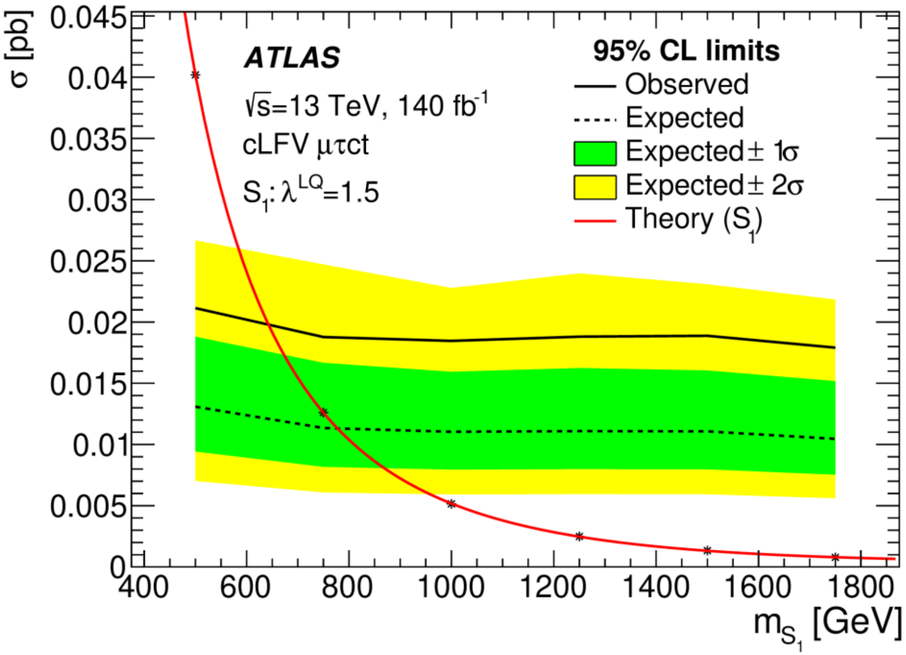
Various theory papers apply hierarchical coupling models, with different magnitudes spanning steps of $\sqrt{2}$ to $\frac{1}{16}$ [1,2,3,4,5]

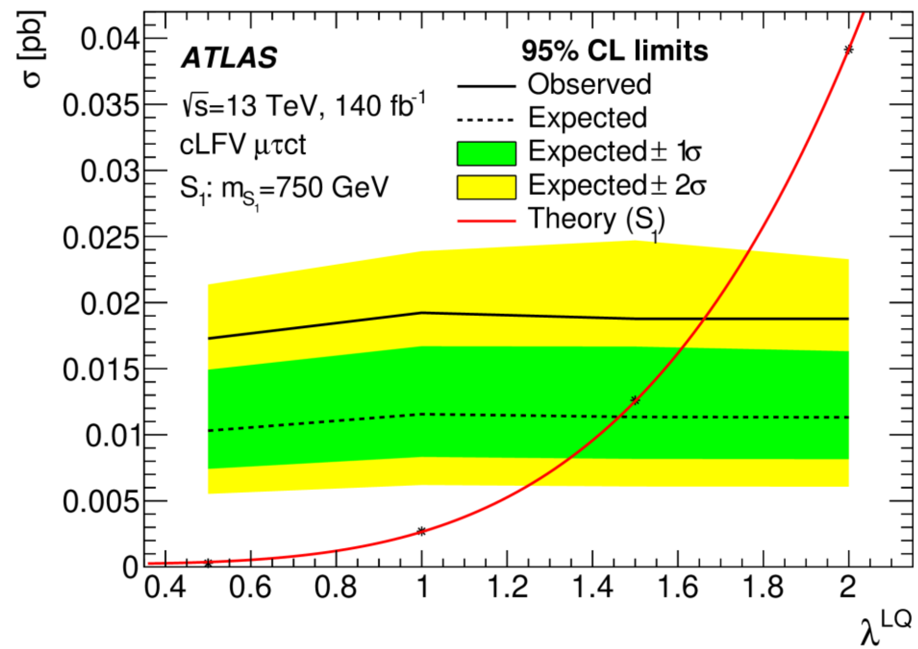
Leptoquark interpretation

Analysis is not re-optimised for LQ signal, but HT is already a very good discriminating variable. Signals $0.5 < m_{\mathrm{LQ}} < 2.5$ TeV, and $0.5 < \lambda^{\mathrm{LQ}} < 3.5$ are fit independently:

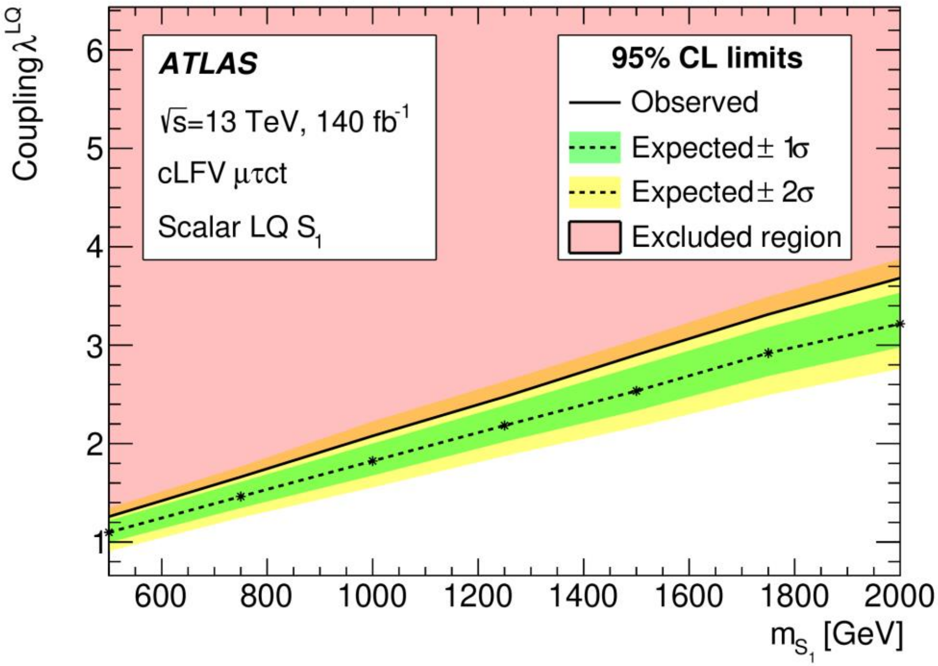


Leptoquark interpretation





Leptoquark interpretation



m_{S_1} [GeV]	Limit on λ^{LQ} (95% CL) Observed	Expected
500	1.3	1.1
750	1.7	1.5
1000	2.1	1.8
1250	2.5	2.2
1500	2.9	2.5
1750	3.3	2.9
2000	3.7	3.2

Summary

- Top CLFV search with muons and tau-leptons
  - Optimised beyond previous CONF note (ATLAS-CONF-2023-001) improving sensitivity by a factor of two
  - LQ interpretation added

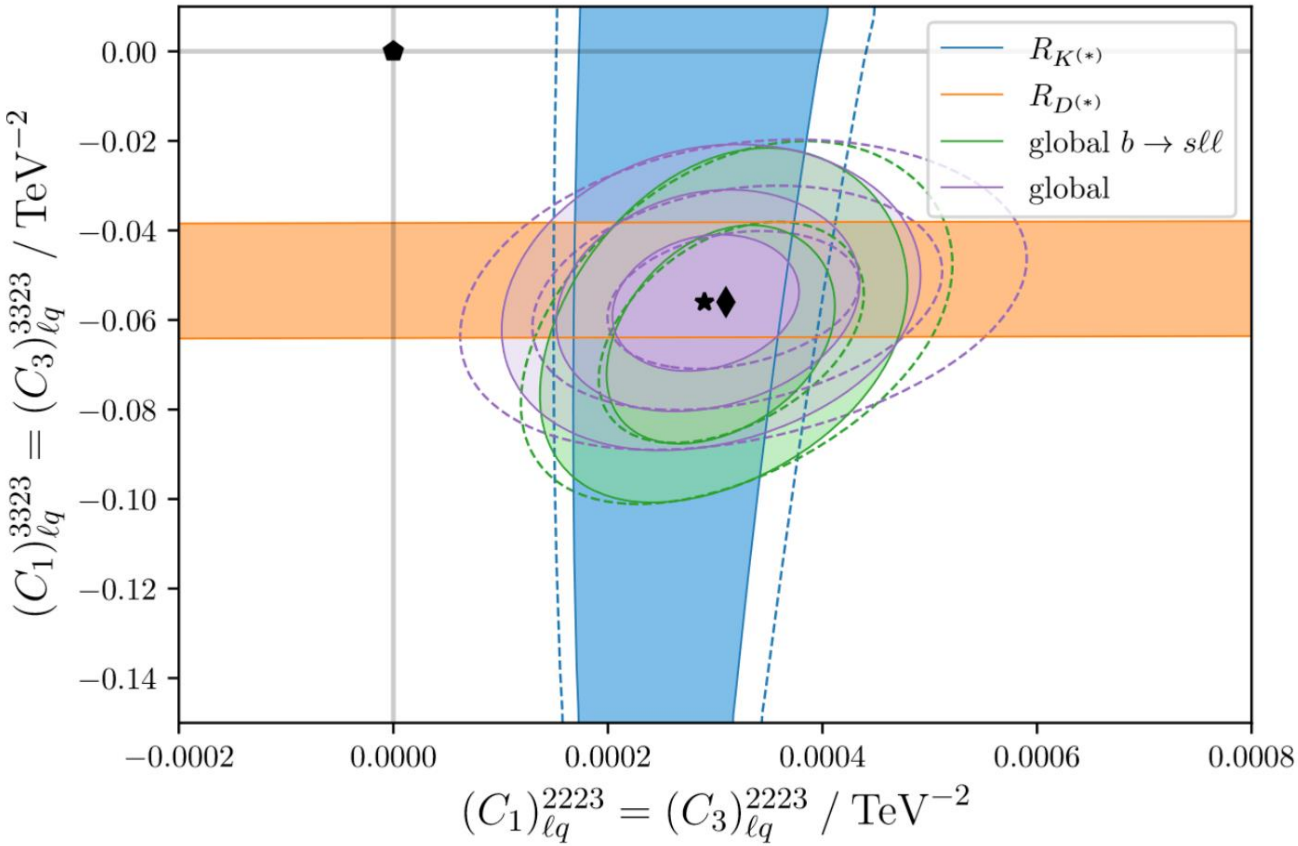
- Results are consistent with SM within 1.6σ – small deviation in highest HT bin

- First direct limits set on relevant EFT couplings with muon and tau flavour indices

- Analysis is heavily statistically limited

- Leptoquark Interpretation – first attempted at setting limits on single-LQ production for a model with multi-generational couplings
  - Coupling hierarchy utilised to simplify interpretation
  - Limits set as a function of leptoquark mass and coupling strength

BACKUP



SM prediction

Best fit 2021 R_K (LHCb arXiv:2103.11769 , 3.1σ)

- But remember **2022** result (LHCb arXiv:2212.09152) brought this **inline with SM**

Best fit pre-2021 R_K

arXiv:2104.00015

Top-EFT and the B-anomalies (quick aside)

$$\bar{s}_L\gamma_\mu b_L \bar{\mu}_L \gamma^\mu \mu_L \Rightarrow \begin{array}{l} O_{lq}^{(1)} = \bar{Q}\gamma_\mu Q \bar{L}\gamma^\mu L, \\ O_{lq}^{(3)} = \bar{Q}\gamma_\mu \tau^I Q \bar{L}\gamma^\mu \tau^I L \end{array}$$

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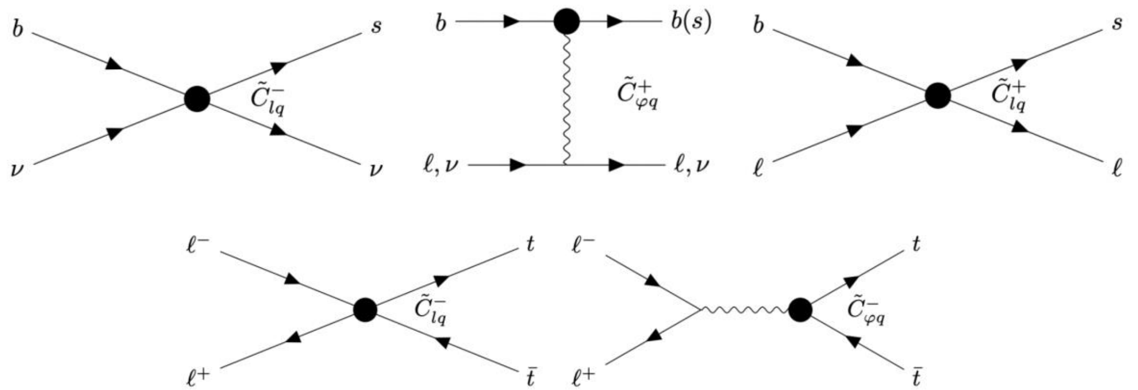
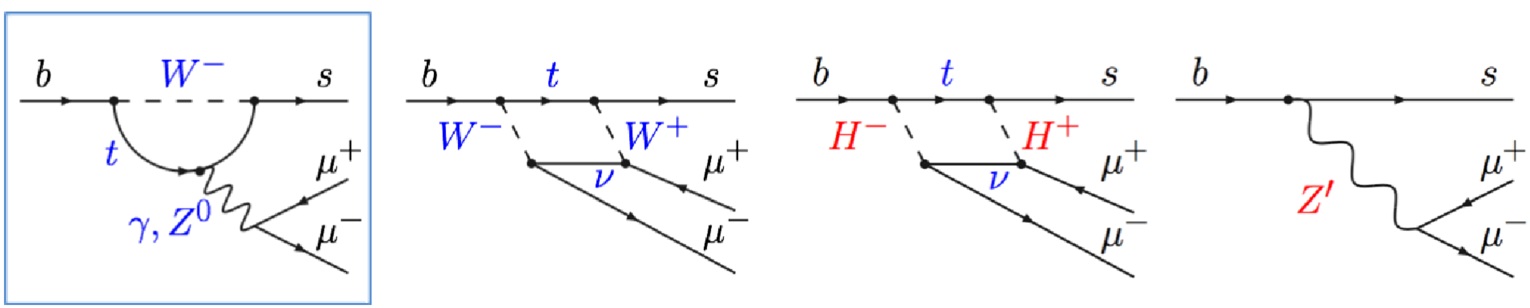


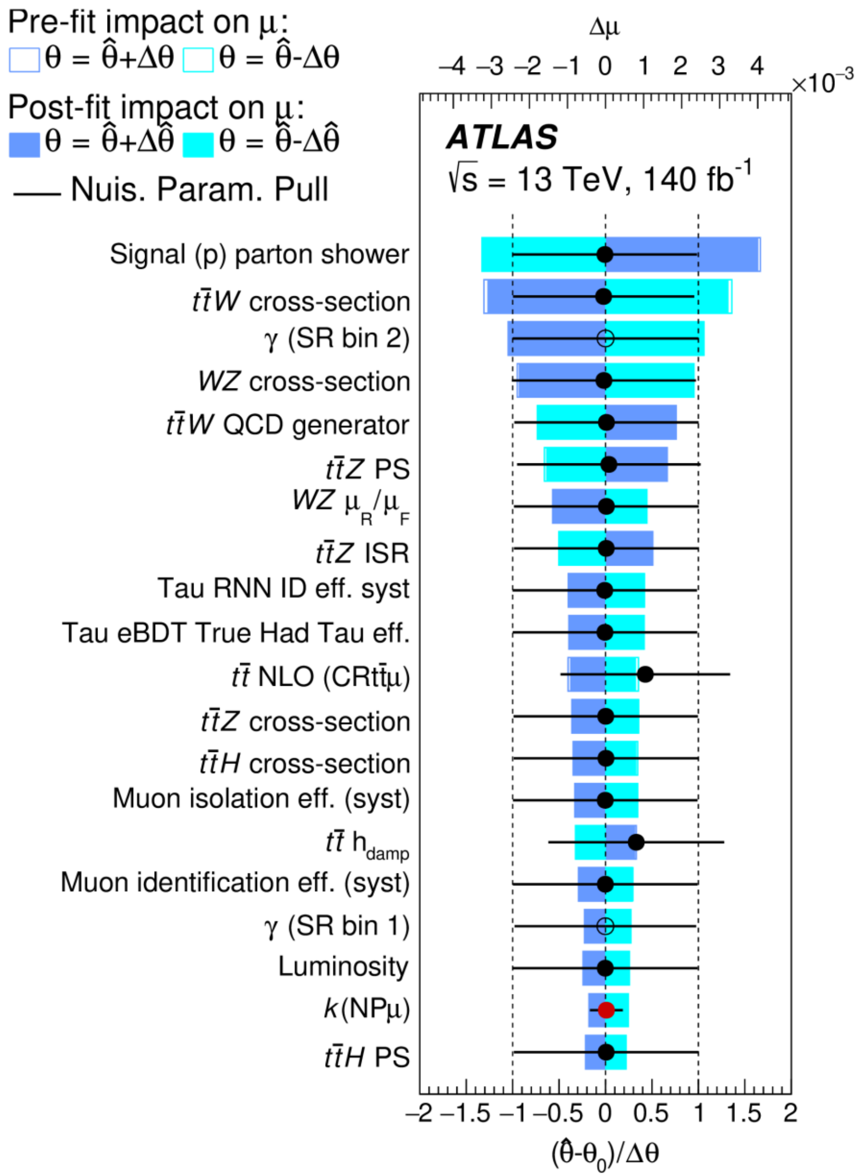
$b \to s\ell\ell$ transitions

- Flavour Changing Neutral Current (FCNC) $b \to s(d)l^+l^-$ decays, such as $B^0 \to K^{*0}\mu^+\mu^-$, are forbidden at tree level in the SM

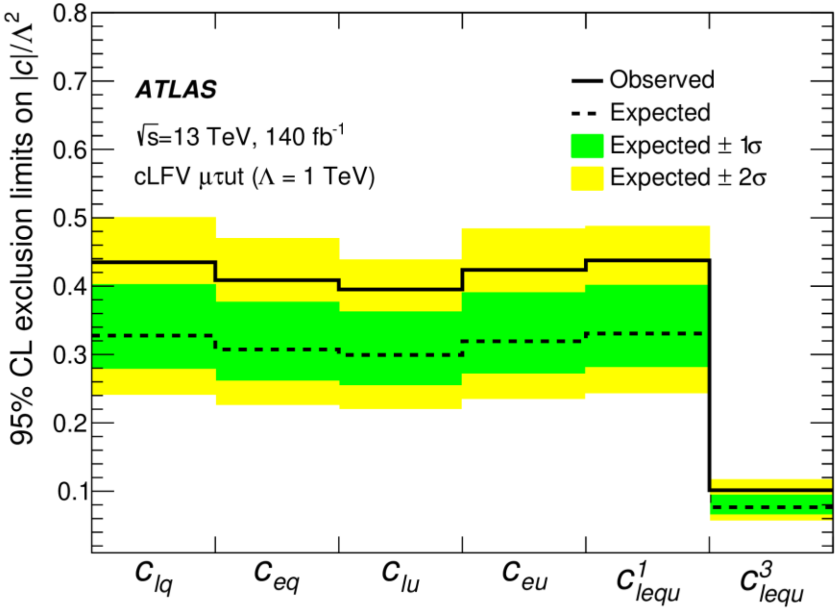


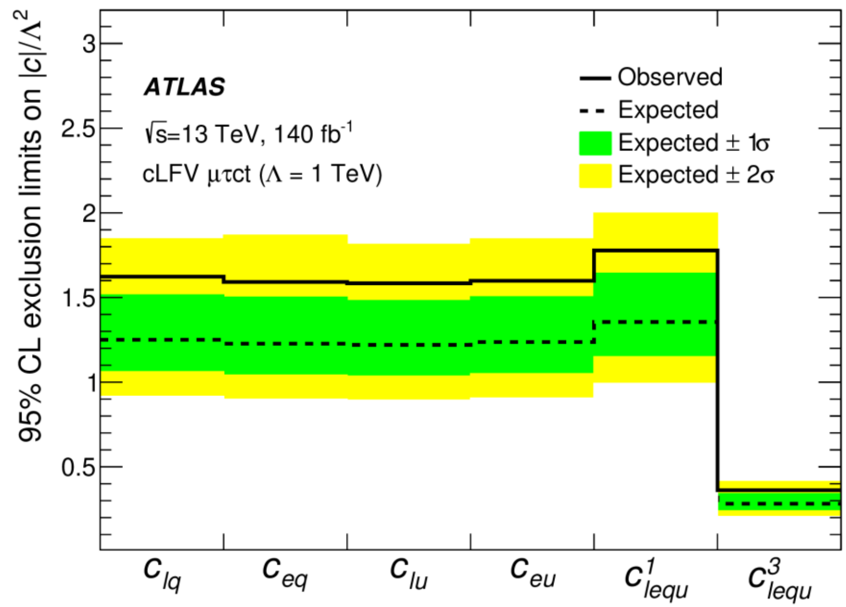
P. Cartelle

EFT Result breakdown



EFT Result breakdown





Fake tau estimation region

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