SMEFT in the TOP sector at ATLAS

Jacob Kempster on behalf of the ATLAS Collaboration

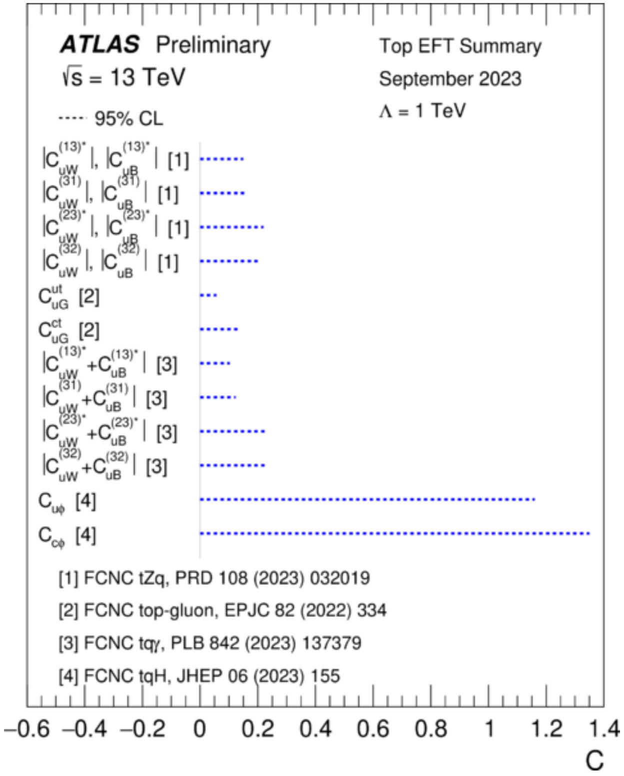
ATL-PHYS-PUB-2023-027

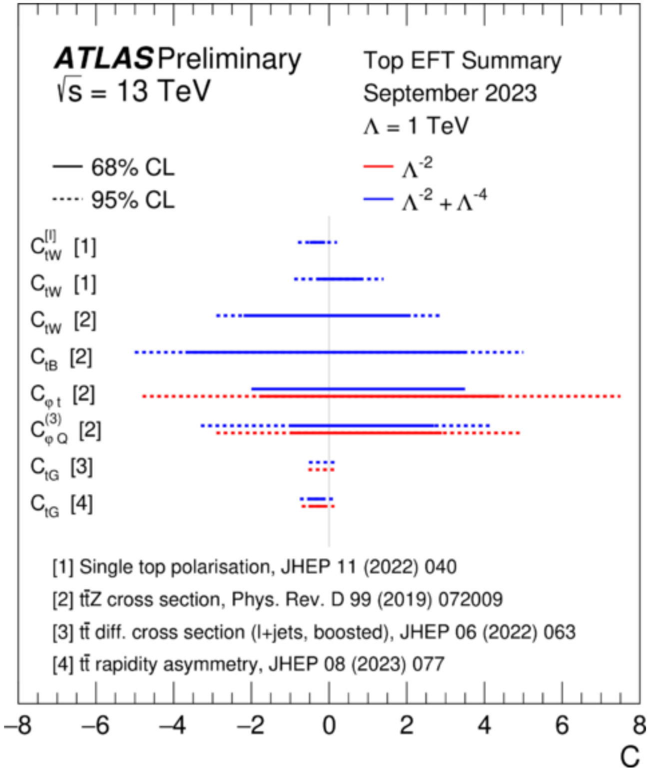
“A brief overview”

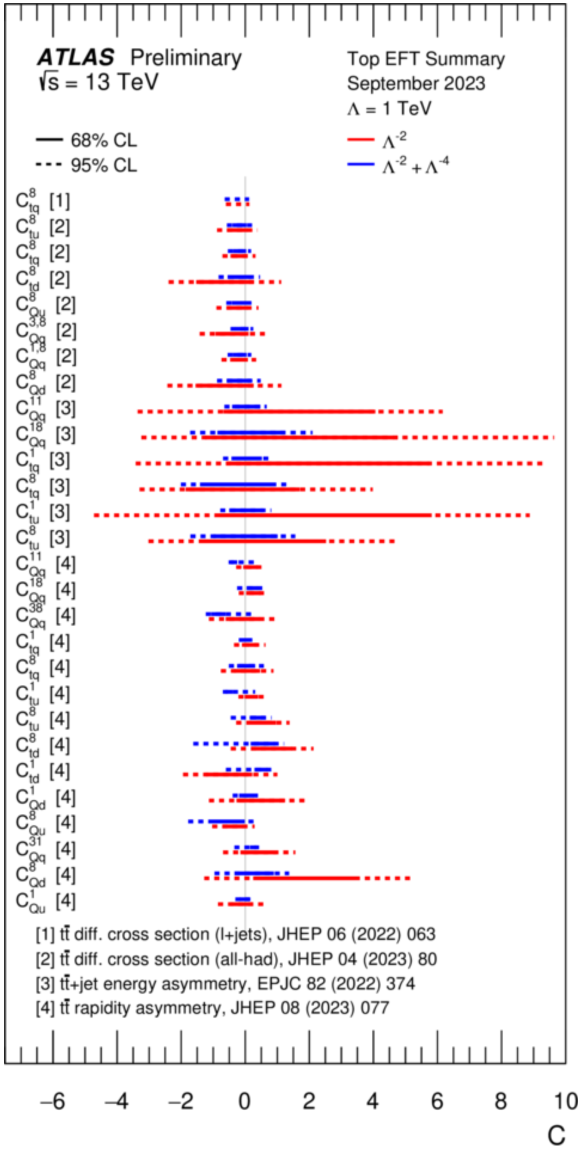
ATLAS Top EFT

ATL-PHYS-PUB-2023-027

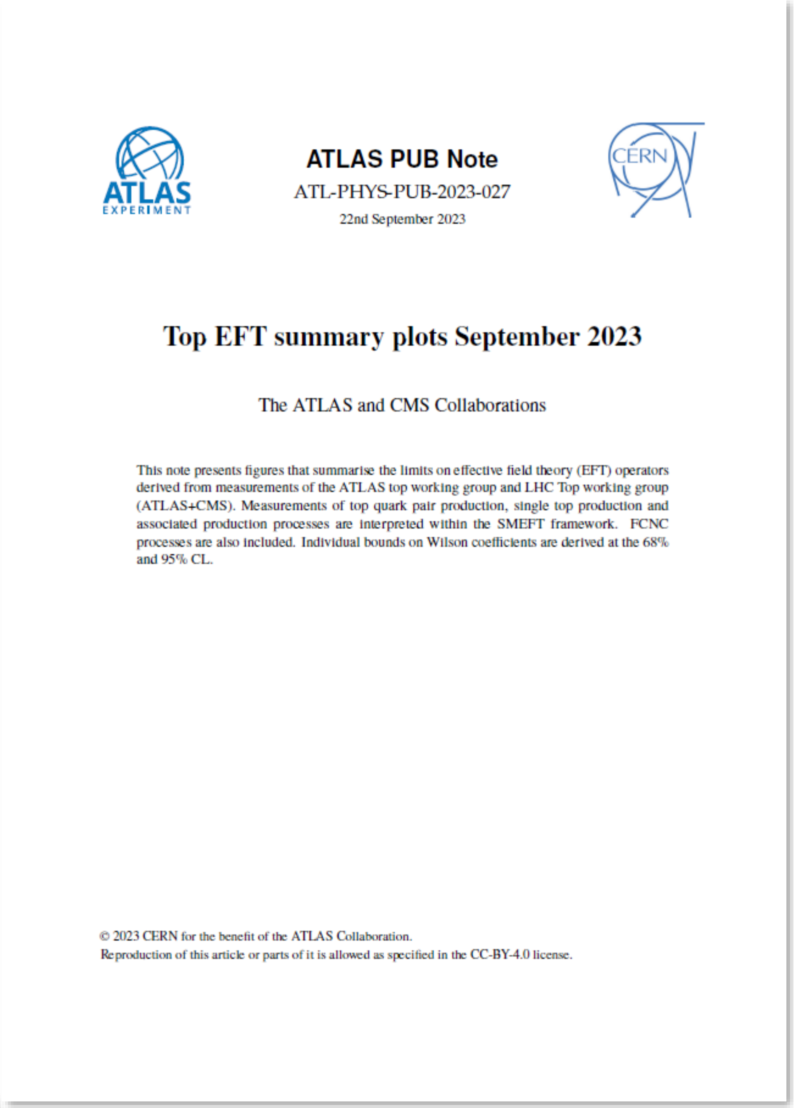
There are a lot of ATLAS Top SMEFT results







Summary Plots



ATLAS PUB Note

ATL-PHYS-PUB-2023-027

22nd September 2023

Top EFT summary plots September 2023

The ATLAS and CMS Collaborations

This note presents figures that summarise the limits on effective field theory (EFT) operators derived from measurements of the ATLAS top working group and LHC Top working group (ATLAS+CMS). Measurements of top quark pair production, single top production and associated production processes are interpreted within the SMEFT framework. FCNC processes are also included. Individual bounds on Wilson coefficients are derived at the 68% and 95% CL.

- For a full overview – please refer to the September summary plots (very soon to be updated again!)

- This talk will give a quick look into 3 of the new analyses this year (preliminary results only)
    - Charged lepton flavour violation
        - ATLAS-CONF-2023-001
    - Single-top t-channel cross-section
        - ATLAS-CONF-2023-026
    - $t\bar{t}Z$ differential cross section
        - ATLAS-CONF-2023-065

ATL-PHYS-PUB-2023-027

Charged Lepton Flavour Violation (CLFV)

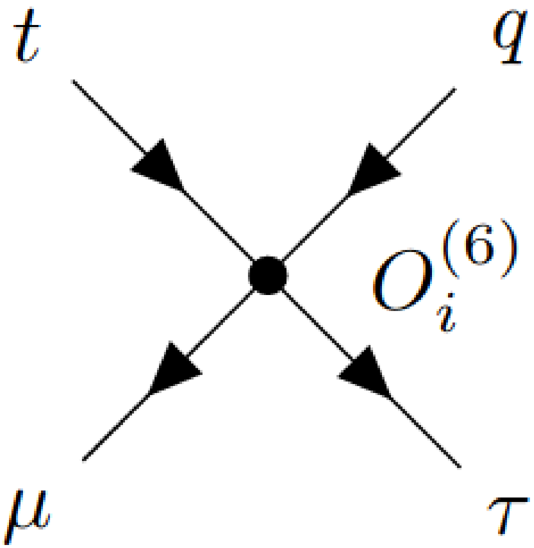
ATLAS-CONF-2023-001

Target 2-quark-2-lepton (2Q2L) EFT operators

Scalar $c_{lequ}^{1(ijk3)}$

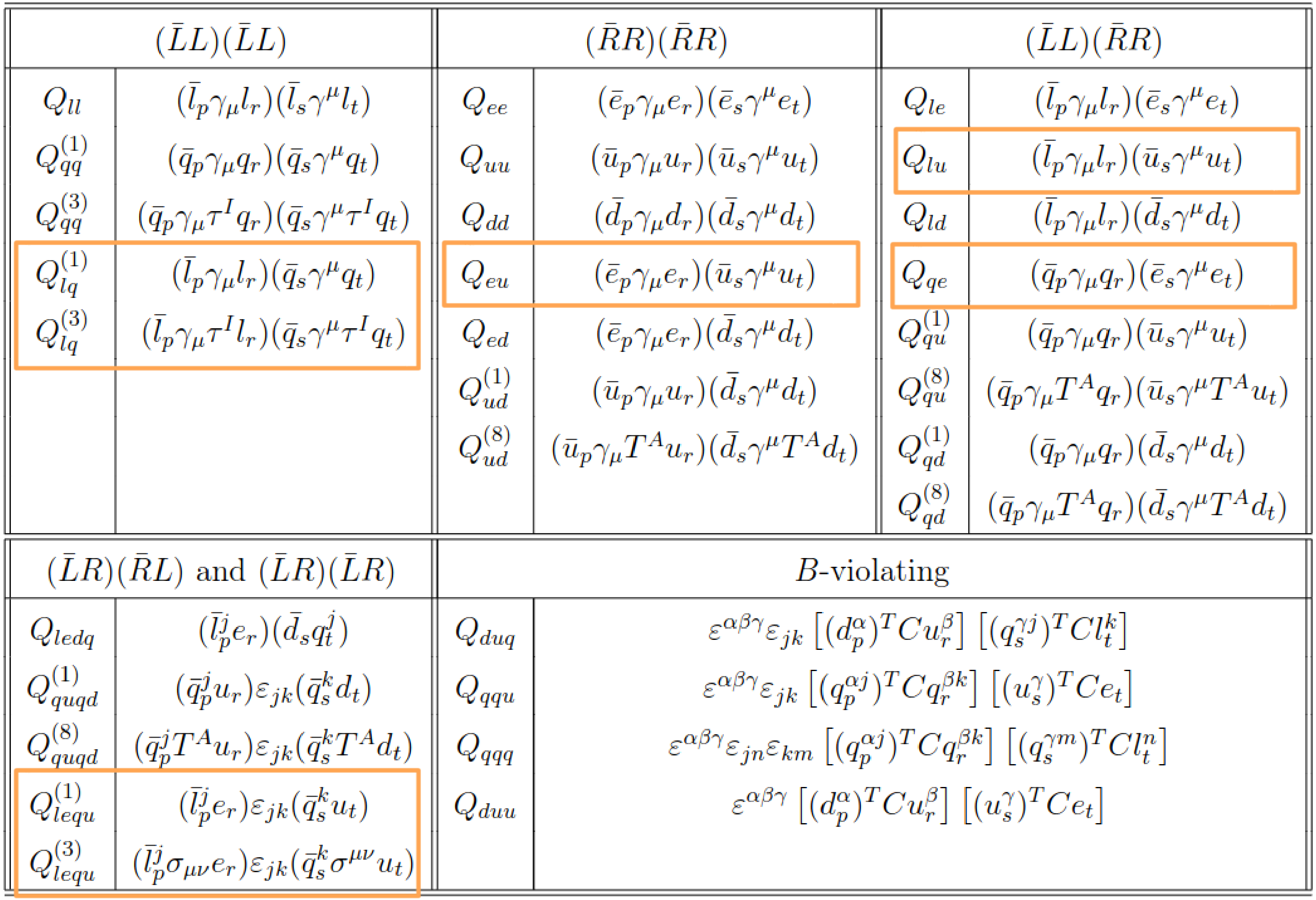
Vector $c_{lq}^{-(ijk3)}$ $c_{eq}^{(ijk3)}$ $c_{lu}^{(ijk3)}$ $c_{eu}^{(ijk3)}$

Tensor $c_{lequ}^{3(ij3k)}$



$$\Gamma(t \to \ell_i^+ \ell_j^- q_k) = \frac{m_t}{6144\pi^3}\left(\frac{m_t}{\Lambda}\right)^4 \Big\{4|c_{lq}^{-(ijk3)}|^2 + 4|c_{eq}^{(ijk3)}|^2 + 4|c_{lu}^{(ijk3)}|^2 + 4|c_{eu}^{(ijk3)}|^2$$
$$+|c_{lequ}^{1(jik3)}|^2 + |c_{lequ}^{1(ij3k)}|^2 + 48|c_{lequ}^{3(jik3)}|^2 + 48|c_{lequ}^{3(ij3k)}|^2\Big\}$$

Four-fermion / 2Q2L operator ‘family’ in context



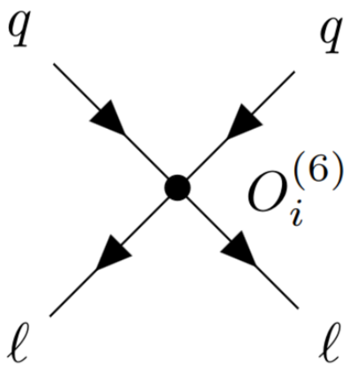
$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$	Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$	Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	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}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$

$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		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

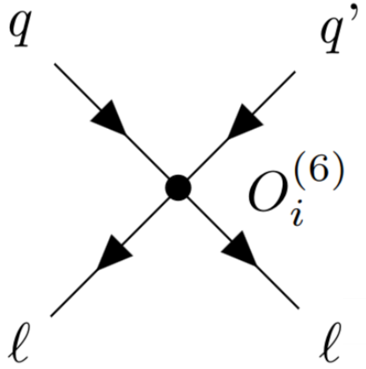
2Q2L operator 'family' in context

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



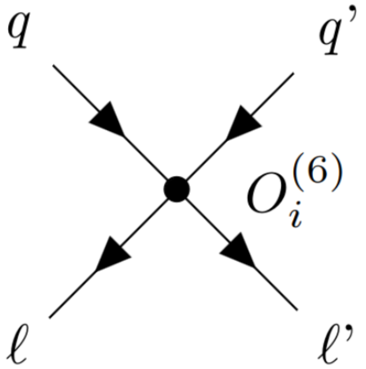
$t\bar{t}ll$

FCNC (semi-diagonal)



$tqll$

CLFV (fully off-diagonal)



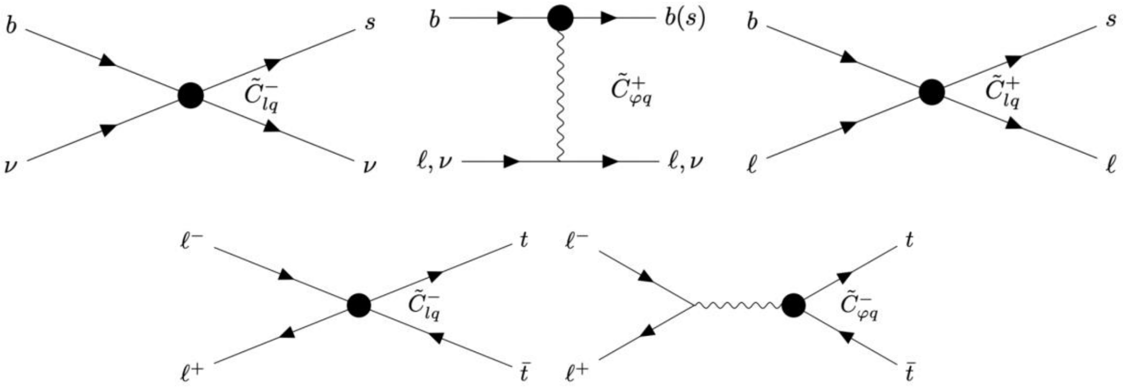
$tqll'$

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

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

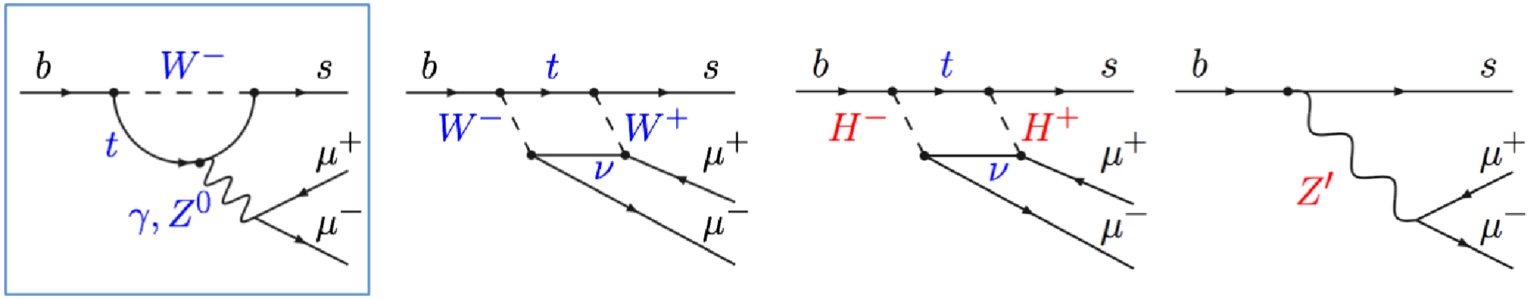
JHEP 06 (2021) 010

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



$b \to s\ell\ell$ 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

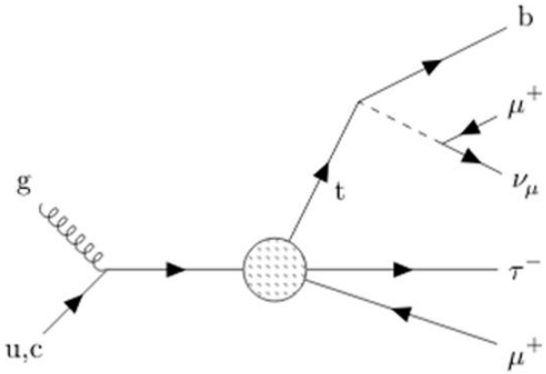


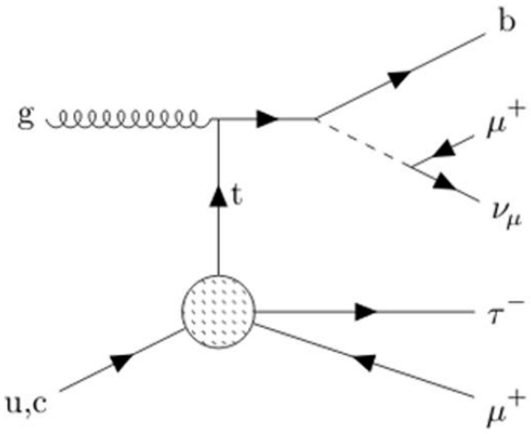
P. Cartelle

Charged Lepton Flavour Violation

Production

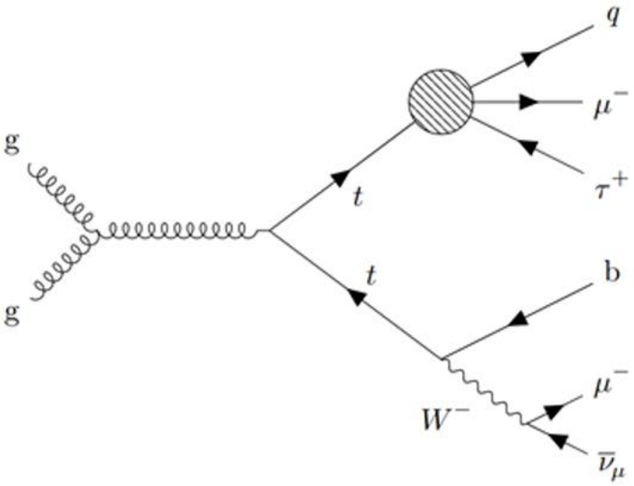
$qg \rightarrow tll'$





Decay

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

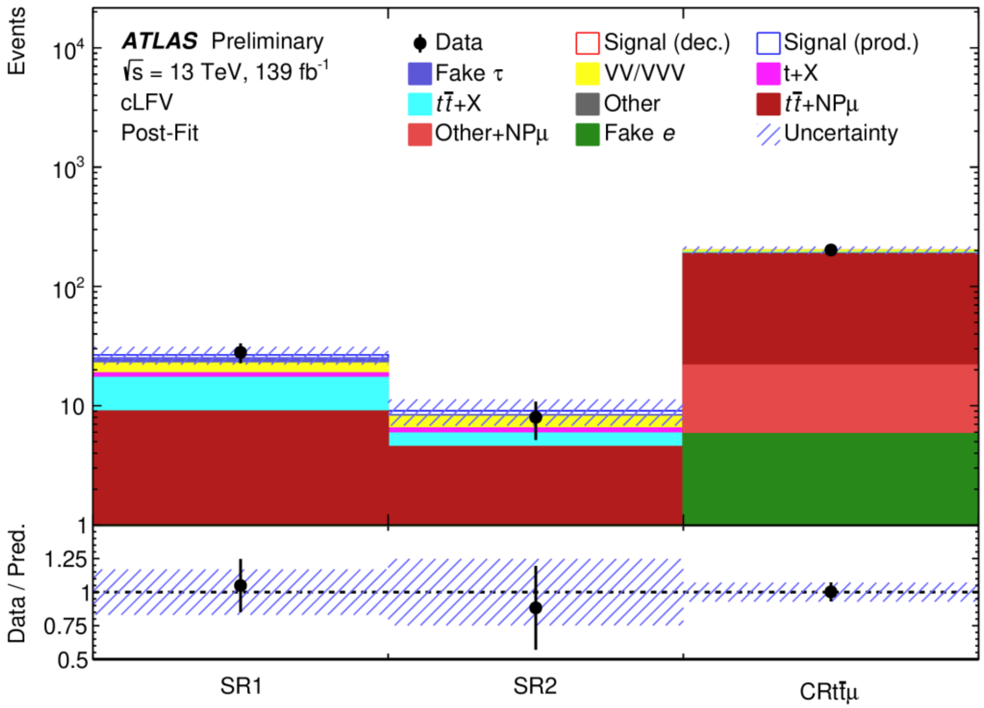


Profile-likelihood fit

Profile-likelihood fit across:
- Two SRs (single bins)
- Non-prompt muon CR (binned in H_T)

Good agreement between data and background-only model

Statistically limited result
Largest systematics related to top modelling and NP muon estimation



'Inclusive' BR limits set assuming all EFT operators have equal contributions

	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}

Result breakdown

	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

	95% CL upper limits on Wilson coefficients c/Λ^2 [TeV^{-2}]							
	$c_{lq}^{-(ijk3)}$	$c_{eq}^{(ijk3)}$	$c_{lu}^{(ijk3)}$	$c_{eu}^{(ijk3)}$	$c_{lequ}^{1(ijk3)}$	$c_{lequ}^{1(ij3k)}$	$c_{lequ}^{3(ijk3)}$	$c_{lequ}^{3(ij3k)}$
Previous (u) [22]	12	12	12	12	26	26	3.4	3.4
Expected (u)	0.47	0.44	0.43	0.46	0.49	0.49	0.11	0.11
Observed (u)	0.49	0.47	0.46	0.48	0.51	0.51	0.11	0.11
Previous (c) [22]	14	14	14	14	29	29	3.7	3.7
Expected (c)	1.6	1.6	1.5	1.6	1.8	1.8	0.35	0.35
Observed (c)	1.7	1.6	1.6	1.6	1.9	1.9	0.37	0.37

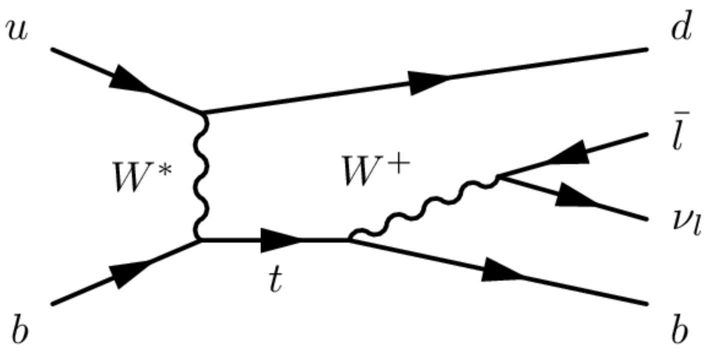
EFT limits improve upon previous results (re-interpretation of ATLAS FCNC tZq analysis):

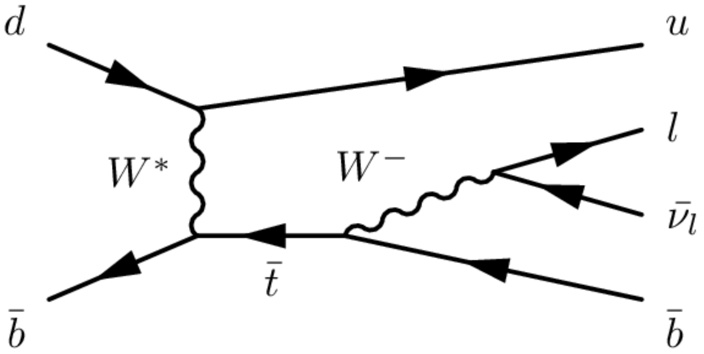
- From factors of 8 for $c_{lq}^{-(2323)}$ (for $\mu\tau ct$) to 51 for $c_{lequ}^{1(2313)}$ (for $\mu\tau ut$).

Single-top t-channel cross section

ATLAS-CONF-2023-026

Single-top t-channel

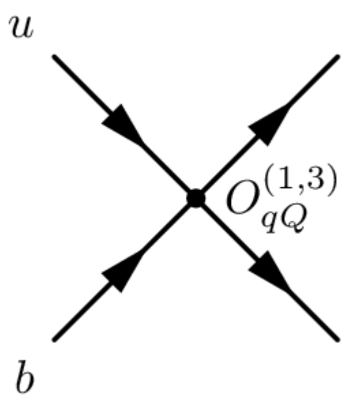




- Dominant single-top production mechanism at LHC
- Naturally charge-asymmetric due to proton PDFs

- Analysis provides measurements of $\sigma(tq)$, $\sigma(\bar{t}q)$, R_t and sets limits on f_{LV}, V_{tb}, V_{ts} and V_{td} - but not covering those here!

- Provides opportunities to constraint four-fermion operators (two-heavy-two-light, $tbqq'$) such as $\boldsymbol{C}_{\boldsymbol{qQ}}^{(\mathbf{1,3})}$



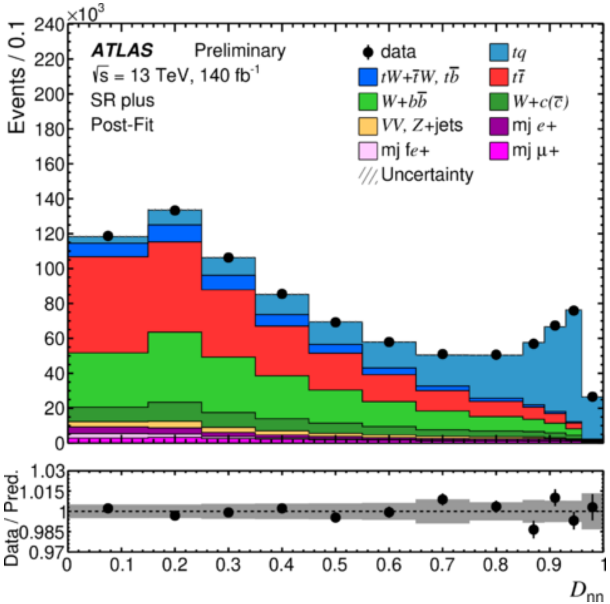
Single-top t-channel

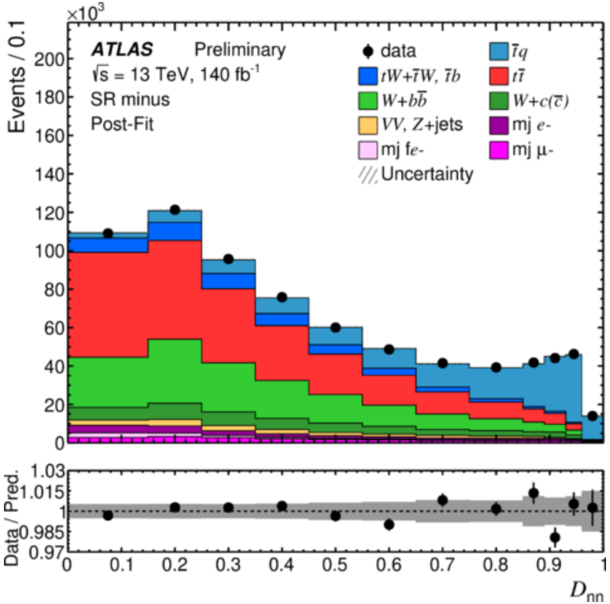
Event selection:

- 1 isolated el or mu ($p_T > 28$ GeV , |η| < 2.5)
- 2 jets ($p_T > 30$ GeV , |η| < 4.5)
- 1 b-tag jet (60% eff., |η| < 2.5)
- Additional selection on:
  - $E_{\mathrm{T}}^{\mathrm{miss}}$,$\mathrm{m}_{\mathrm{T}}(W)$,$p_T(l)$: Reduce multijet bkg
  - $\mathrm{m}(lb)$: Improve top decay modelling

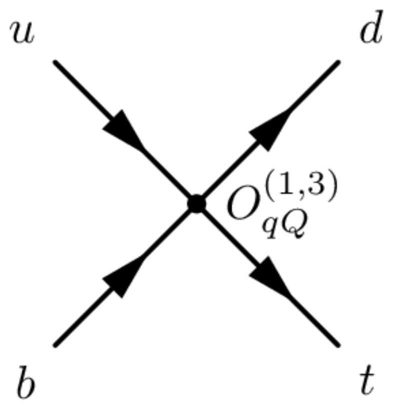
NN discriminant trained on 17 kinematic variables relating to top quark and W-boson

Process	SR plus	SR minus
tq	169 000 ± 6000	150 ± 150
$\bar{t}q$	90 ± 90	109 000 ± 5000
$tW + \bar{t}W, t\bar{b} + \bar{t}b$	50 700 ± 3400	48 800 ± 3400
$t\bar{t}$	264 000 ± 14 000	264 000 ± 13 000
$W+b\bar{b}$	202 000 ± 19 000	162 000 ± 16 000
$W+c(\bar{c})$	60 000 ± 13 000	49 000 ± 11 000
Z+jets, diboson	20 000 ± 4000	19 000 ± 4000
Multijet	48 000 ± 10 000	47 000 ± 10 000
Total	814 000 ± 2100	698 800 ± 2000
Observed	814 185	698 845





Single-top t-channel



	σ_t[pb]	$\sigma_{\bar{t}}$ [pb]	σ_{t-chan} [pb]	$R_t = \sigma_t/\sigma_{\bar{t}}$
Measured	137 ± 8	84^{+6}_{-5}	221 ± 13	$1.636^{+0.036}_{-0.034}$
Predicted	134.2 ± 2.2	80.0 ± 1.6	214.2 ± 3.4	$1.677^{+0.010}_{-0.014}$

Limited by top quark modelling systematic uncertainties

$$O_{qQ}^{(1,3)} = (\bar{q}^i \gamma_\mu \tau^I q^j)(\bar{Q}\gamma^\mu \tau^I Q)$$

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i}{\Lambda^2} O_i + \text{H.c.}$$

Normal parametrisation process, generated using MadGraph with SMEFTatNLO-NLO model in the five-flavour scheme, for multiple values of C

Maximum-likelihood scan (95% CL): $-0.25 < C_{qQ}^{(1,3)} < 0.12$

Compares to global fit results:

$[-0.088, 0.166]$ Higgs + diboson + top

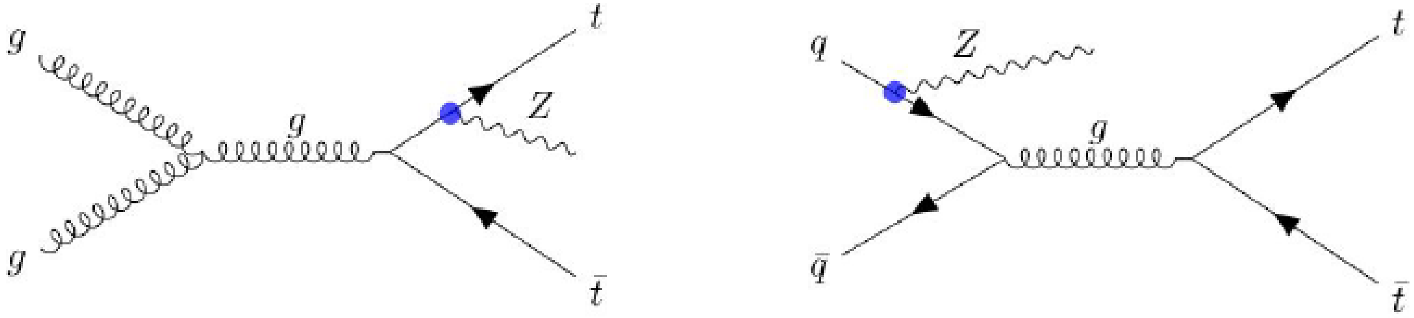
$[-0.043, 0.16]$ Higgs + diboson + top + EWK

$[-0.39, 0.11]$ Top-only

$t\bar{t}Z$ differential cross section

ATLAS-CONF-2023-065

$t\bar{t}Z$



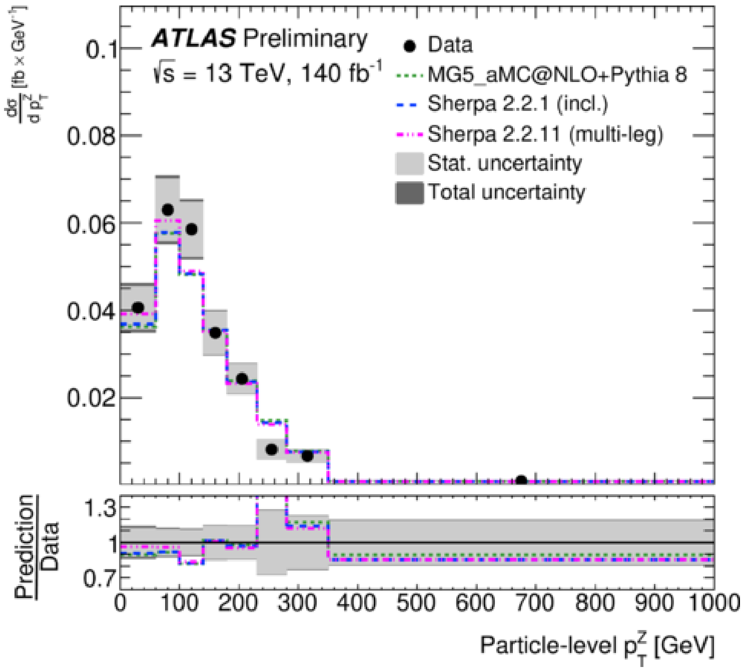
- Rare Standard Model process
- Direct probe of the neutral electroweak coupling of the top quark
- Important background for top processes $(tZq, t\bar{t}H, t\bar{t}W)$ and BSM searches
- Sensitivity to new physics

Huge CONF! Measures inclusive and differential cross sections, top quark spin correlations and sets limits on EFTS – I will only focus on the latter!

$t\bar{t}Z$

Channel	$\sigma_{t\bar{t}Z}$
Dilepton	$0.84 \pm 0.11\ \text{pb} = 0.84 \pm 0.06\ (\text{stat.}) \pm 0.09\ (\text{syst.})\ \text{pb}$
Trilepton	$0.84 \pm 0.07\ \text{pb} = 0.84 \pm 0.05\ (\text{stat.}) \pm 0.05\ (\text{syst.})\ \text{pb}$
Tetralepton	$0.97\,^{+0.13}_{-0.12}\ \text{pb} = 0.97 \pm 0.11\ (\text{stat.}) \pm 0.05\ (\text{syst.})\ \text{pb}$
Combination $(2\ell, 3\ell\ \&\ 4\ell)$	$0.86 \pm 0.06\ \text{pb} = 0.86 \pm 0.04\ (\text{stat.}) \pm 0.04\ (\text{syst.})\ \text{pb}$

SM cross section precision ~ 6.5%



The EFT fit uses 5 SRs (3-lepton + 4-lepton), dominated by WZ/ZZ backgrounds which are normalised using CRs, and 3 additional CRs for the normalisation of fake lepton signatures

Many distributions (p_T^Z, $|y^Z|$, $\cos\theta_Z^*$, p_T^t, $|\Delta\varphi(t\bar{t}, Z)|$, $|y^{t\bar{t}Z}|$) are unfolded to particle level, and **fit simultaneously** to increase the information used to constrain the EFTs. (Care must be taken in building correlation matrices to deal with statistical overlaps).

$t\bar{t}Z$

	Operator	Definition	
top-boson	Q_{tW}	$(\bar{Q}\sigma^{\mu\nu}t)\sigma^i\tilde{H}W^i_{\mu\nu}$	$(\star)$
	Q_{tB}	$(\bar{Q}\sigma^{\mu\nu}t)\tilde{H}B_{\mu\nu}$	$(\star)$
	Q_{tG}	$(\bar{Q}\sigma^{\mu\nu}T^a t)\tilde{H}G^a_{\mu\nu}$	$(\star)$
	$Q^{(1)}_{HQ}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{Q}\gamma^\mu Q)$	
	$Q^{(3)}_{HQ}$	$(H^\dagger i\overleftrightarrow{D}^i_\mu H)(\bar{Q}\sigma^i\gamma^\mu Q)$	
	Q_{Ht}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{t}\gamma^\mu t)$	
four-quark	$Q^{(1)}_{tu}$	$(\bar{t}\gamma_\mu t)(\bar{u}\gamma^\mu u)$	
	$Q^{(8)}_{tu}$	$(\bar{t}T^a\gamma_\mu t)(\bar{u}T^a\gamma^\mu u)$	
	$Q^{(1)}_{td}$	$(\bar{t}\gamma_\mu t)(\bar{d}\gamma^\mu d)$	
	$Q^{(8)}_{td}$	$(\bar{t}T^a\gamma_\mu t)(\bar{d}T^a\gamma^\mu d)$	
	$Q^{(1)}_{qt}$	$(\bar{q}\gamma_\mu q)(\bar{t}\gamma^\mu t)$	
	$Q^{(8)}_{qt}$	$(\bar{q}T^a\gamma_\mu q)(\bar{t}T^a\gamma^\mu t)$	
	$Q^{(1)}_{Qu}$	$(\bar{Q}\gamma_\mu Q)(\bar{u}\gamma^\mu u)$	
	$Q^{(8)}_{Qu}$	$(\bar{Q}T^a\gamma_\mu Q)(\bar{u}T^a\gamma^\mu u)$	
	$Q^{(1)}_{Qd}$	$(\bar{Q}\gamma_\mu Q)(\bar{d}\gamma^\mu d)$	
	$Q^{(8)}_{Qd}$	$(\bar{Q}T^a\gamma_\mu Q)(\bar{d}T^a\gamma^\mu d)$	
	$Q^{(1,1)}_{Qq}$	$(\bar{Q}\gamma_\mu Q)(\bar{q}\gamma^\mu q)$	
	$Q^{(3,1)}_{Qq}$	$(\bar{Q}\sigma^i\gamma_\mu Q)(\bar{q}\sigma^i\gamma^\mu q)$	
	$Q^{(1,8)}_{Qq}$	$(\bar{Q}T^a\gamma_\mu Q)(\bar{q}T^a\gamma^\mu q)$	
	$Q^{(3,8)}_{Qq}$	$(\bar{Q}\sigma^i T^a\gamma_\mu Q)(\bar{q}\sigma^i T^a\gamma^\mu q)$	

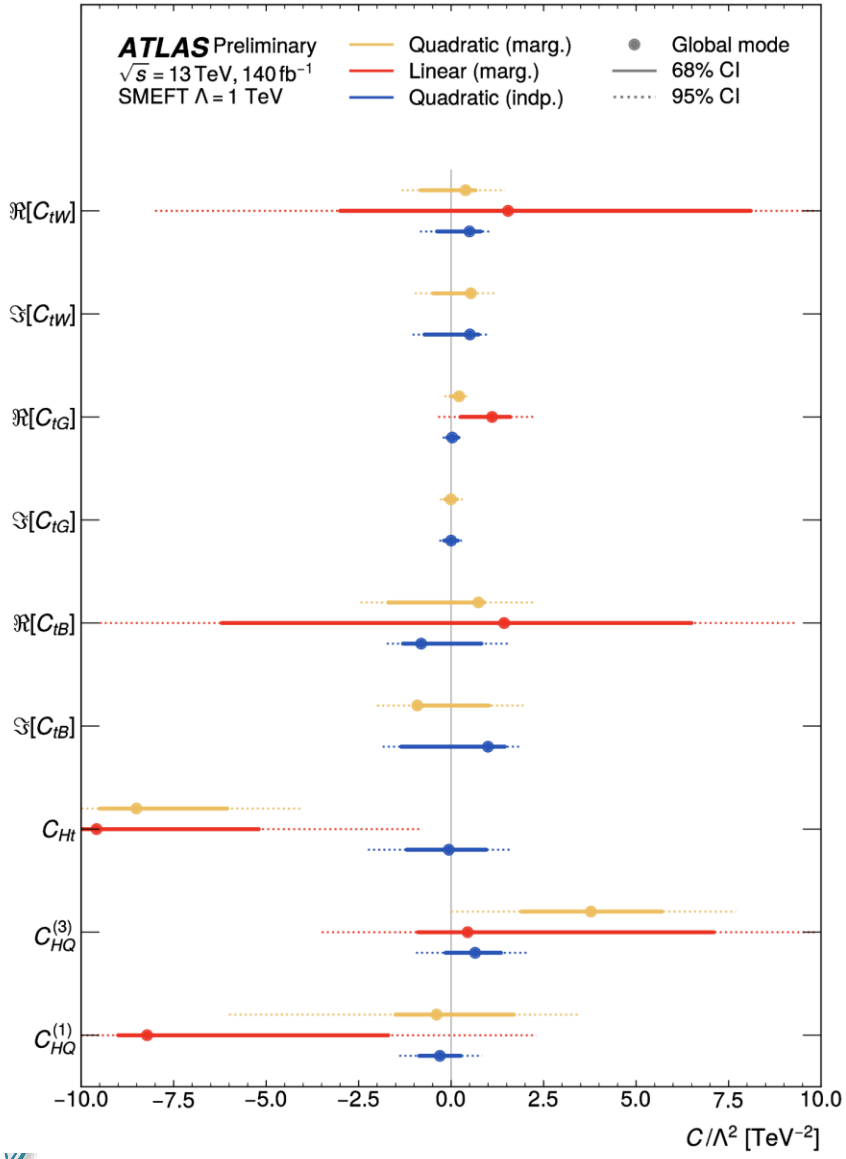
20 operators considered
(= 23 including imaginary terms)

MC samples generated using MadGraph5_aMC@NLO with SMEFTsim3.0 at LO

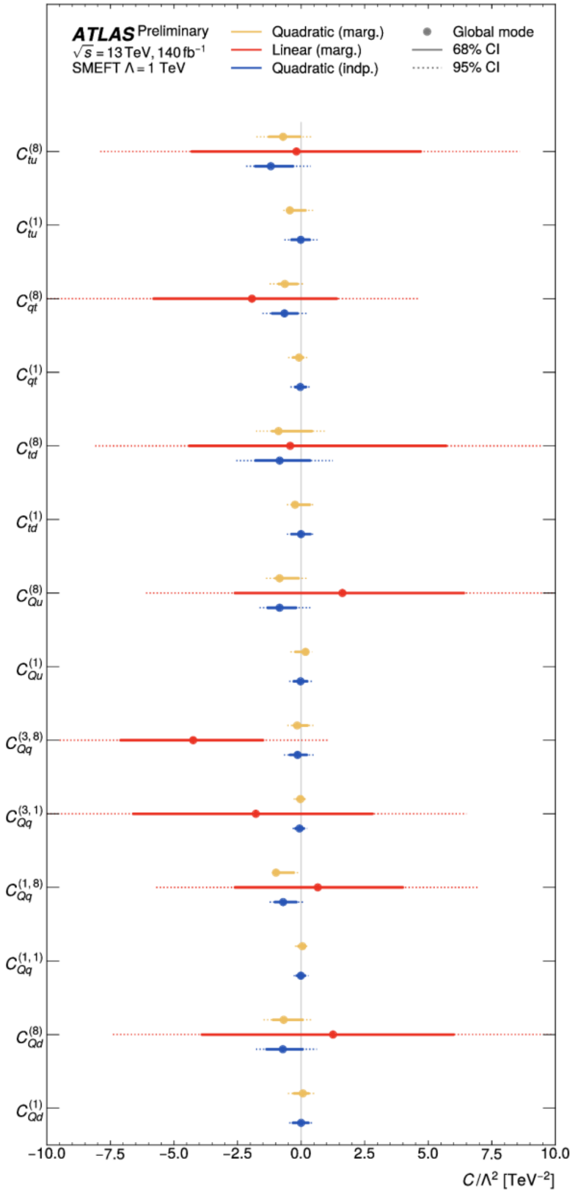
- 'top' flavour structure (fields split between gens 1+2 and gen 3)
- CKM matrix = unity
- Simple flavour diagonality in the lepton sector

Marginalised and individual, linear-only and linear+quadratic fits are performed.

$t\bar{t}Z$



ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 140 fb^{-1}
SMEFT Λ = 1 TeV
Quadratic (marg.)
Linear (marg.)
Quadratic (indp.)
Global mode
68% CI
95% CI
$\Re[C_{tW}]$
$\Im[C_{tW}]$
$\Re[C_{tG}]$
$\Im[C_{tG}]$
$\Re[C_{tB}]$
$\Im[C_{tB}]$
C_{Ht}
$C_{HQ}^{(3)}$
$C_{HQ}^{(1)}$
−10.0
−7.5
−5.0
−2.5
0.0
2.5
5.0
7.5
10.0
C/Λ^2 [TeV^{-2}]

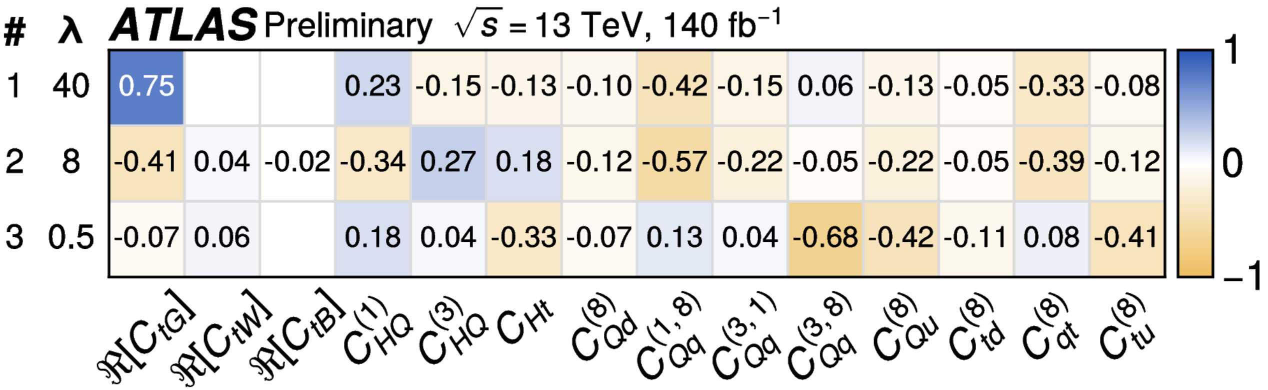


ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 140 fb^{-1}
SMEFT Λ = 1 TeV
Quadratic (marg.)
Linear (marg.)
Quadratic (indp.)
Global mode
68% CI
95% CI
$C_{tu}^{(8)}$
$C_{tu}^{(1)}$
$C_{qt}^{(8)}$
$C_{qt}^{(1)}$
$C_{td}^{(8)}$
$C_{td}^{(1)}$
$C_{Qu}^{(8)}$
$C_{Qu}^{(1)}$
$C_{Qq}^{(3,8)}$
$C_{Qq}^{(3,1)}$
$C_{Qq}^{(1,8)}$
$C_{Qq}^{(1,1)}$
$C_{Qd}^{(8)}$
$C_{Qd}^{(1)}$
−10.0
−7.5
−5.0
−2.5
0.0
2.5
5.0
7.5
10.0
C/Λ^2 [TeV^{-2}]

$t\bar{t}Z$

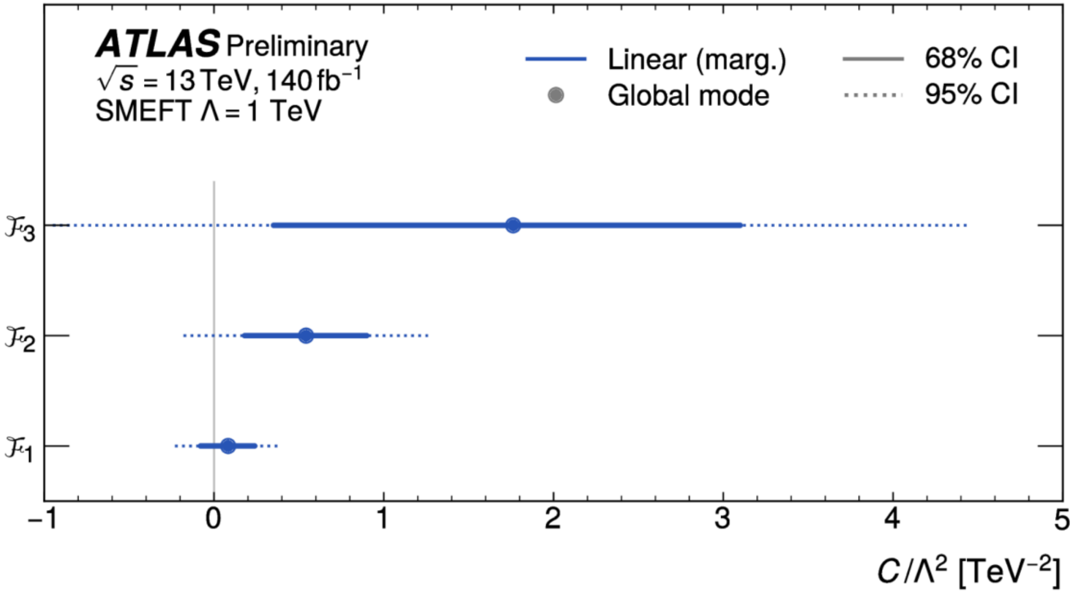
Principal Component Analysis applied to linear-only fit

- Measure of sensitivity along directions in Wilson Coefficient space

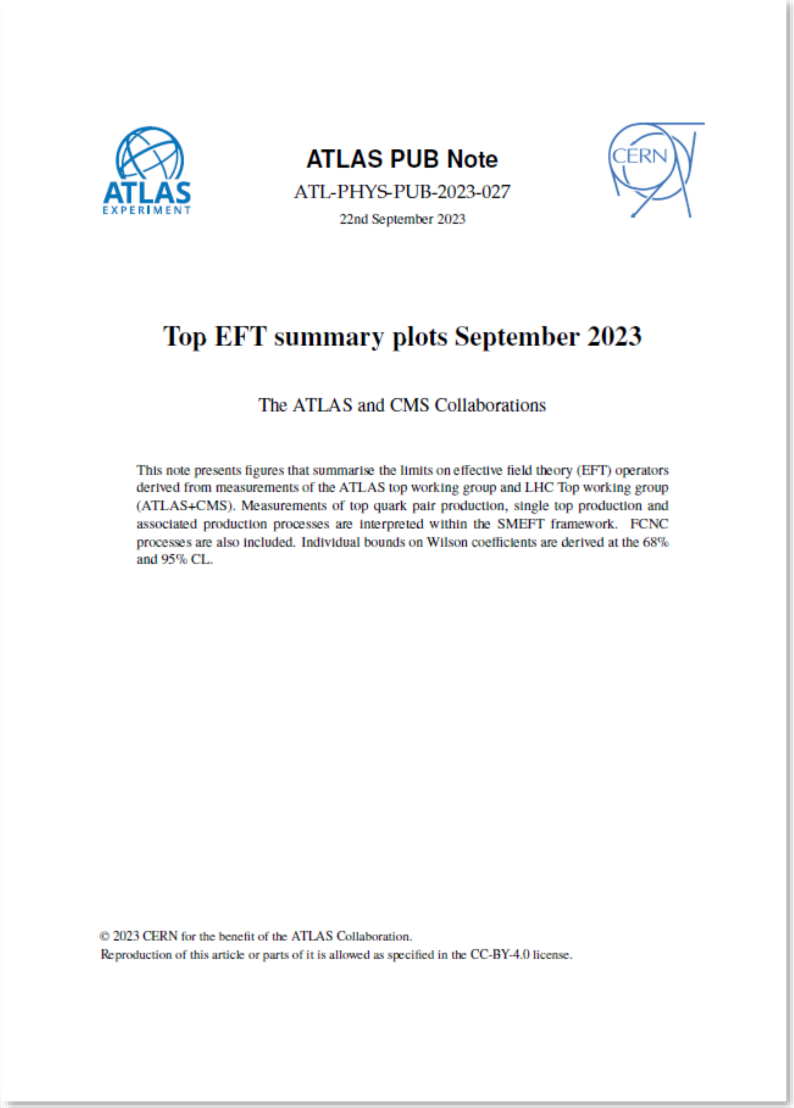


ATLAS Preliminary $\sqrt{s}$ = 13 TeV, 140 fb^{-1}

#	λ	$\Re[C_{tG}]$	$\Re[C_{tW}]$	$\Re[C_{tB}]$	$C_{HQ}^{(1)}$	$C_{HQ}^{(3)}$	C_{Ht}	$C_{Qd}^{(8)}$	$C_{Qq}^{(1,8)}$	$C_{Qq}^{(3,1)}$	$C_{Qq}^{(3,8)}$	$C_{Qu}^{(8)}$	$C_{td}^{(8)}$	$C_{qt}^{(8)}$	$C_{tu}^{(8)}$
1	40	0.75			0.23	-0.15	-0.13	-0.10	-0.42	-0.15	0.06	-0.13	-0.05	-0.33	-0.08
2	8	-0.41	0.04	-0.02	-0.34	0.27	0.18	-0.12	-0.57	-0.22	-0.05	-0.22	-0.05	-0.39	-0.12
3	0.5	-0.07	0.06		0.18	0.04	-0.33	-0.07	0.13	0.04	-0.68	-0.42	-0.11	0.08	-0.41



Summary('ish)



ATLAS PUB Note
ATL-PHYS-PUB-2023-027
22nd September 2023

Top EFT summary plots September 2023

The ATLAS and CMS Collaborations

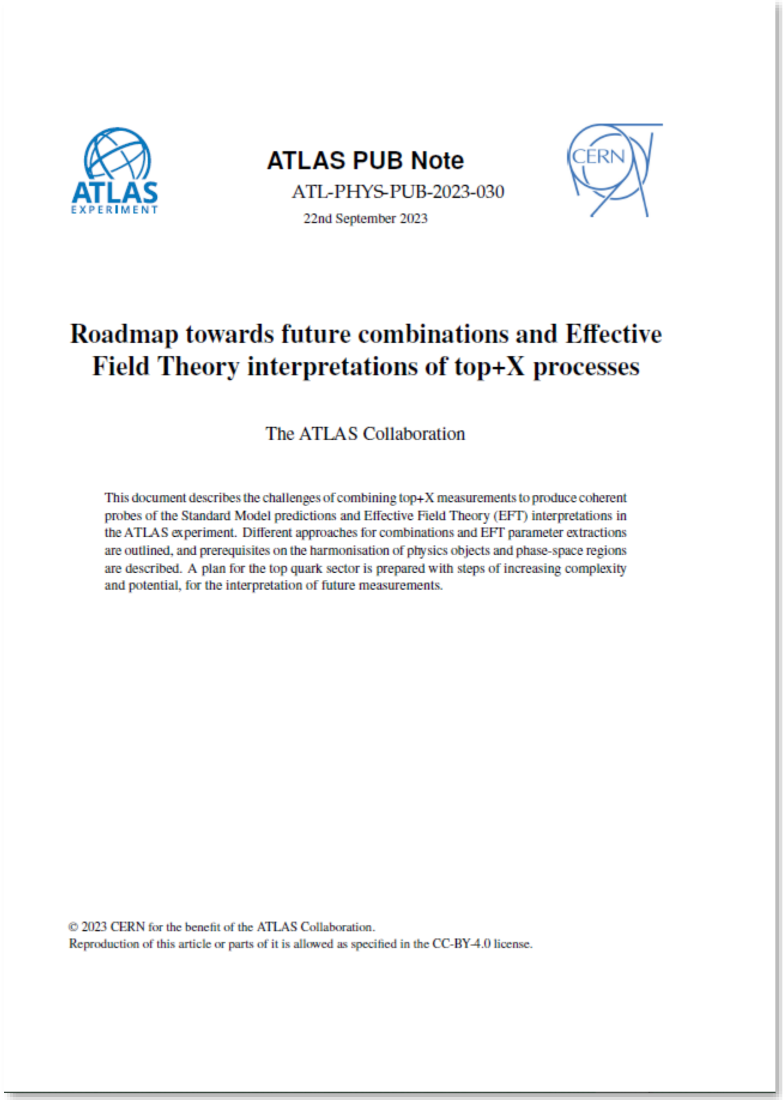
This note presents figures that summarise the limits on effective field theory (EFT) operators derived from measurements of the ATLAS top working group and LHC Top working group (ATLAS+CMS). Measurements of top quark pair production, single top production and associated production processes are interpreted within the SMEFT framework. FCNC processes are also included. Individual bounds on Wilson coefficients are derived at the 68% and 95% CL.

For a full overview – please refer to the September summary plots (very soon to be updated again!)

- Charged lepton flavour violation
  - EFT results in a novel channel sensitive to new physics related to flavour-anomalies and adjacent to FCNCs
- Single-top t-channel cross-section
  - Strong limits on a single operator with significant opportunity to enhance global fits
- $t\bar{t}Z$ differential cross section
  - Detailed study of many EFT operators with competitive limits
  - PCA gives insight into relative sensitivities of different directions

ATL-PHYS-PUB-2023-027

Sneaky plug



ATLAS PUB Note
ATL-PHYS-PUB-2023-030
22nd September 2023

Roadmap towards future combinations and Effective Field Theory interpretations of top+X processes

The ATLAS Collaboration

This document describes the challenges of combining top+X measurements to produce coherent probes of the Standard Model predictions and Effective Field Theory (EFT) interpretations in the ATLAS experiment. Different approaches for combinations and EFT parameter extractions are outlined, and prerequisites on the harmonisation of physics objects and phase-space regions are described. A plan for the top quark sector is prepared with steps of increasing complexity and potential, for the interpretation of future measurements.

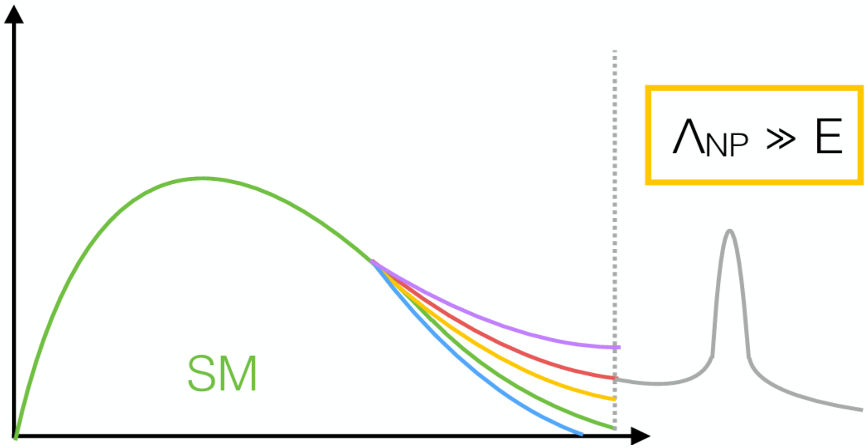
- Another talk later today on future ATLAS Top EFT studies

ATL-PHYS-PUB-2023-030

BACKUP

Effective Field Theory (EFT)

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



K. Mimasu, EFTforTop

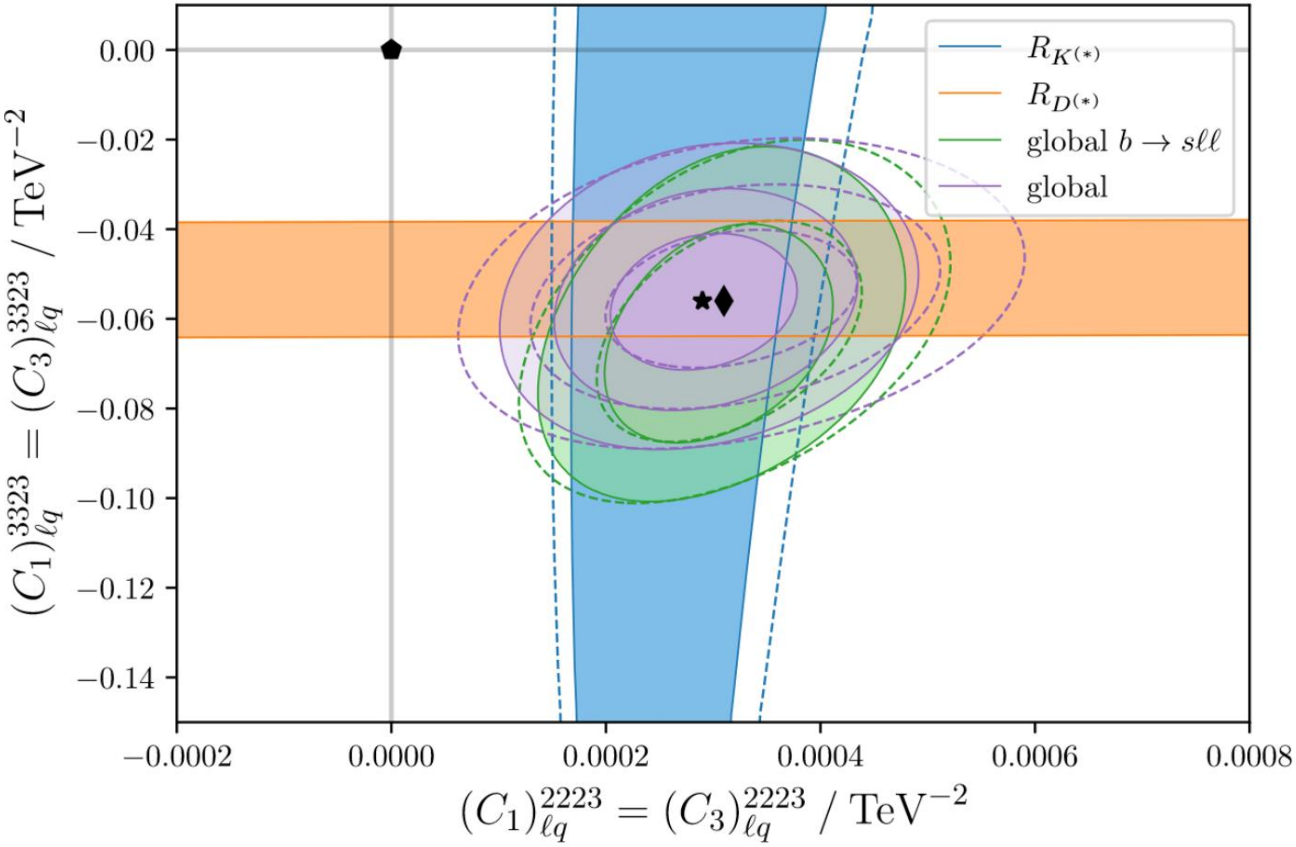
$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{i,n} \frac{c_i^{(n)}}{\Lambda^{n-4}} \mathcal{O}_i^{(n)}$$

Standard Model

Coupling Strength

Operators introducing new interactions

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



⬟ SM prediction

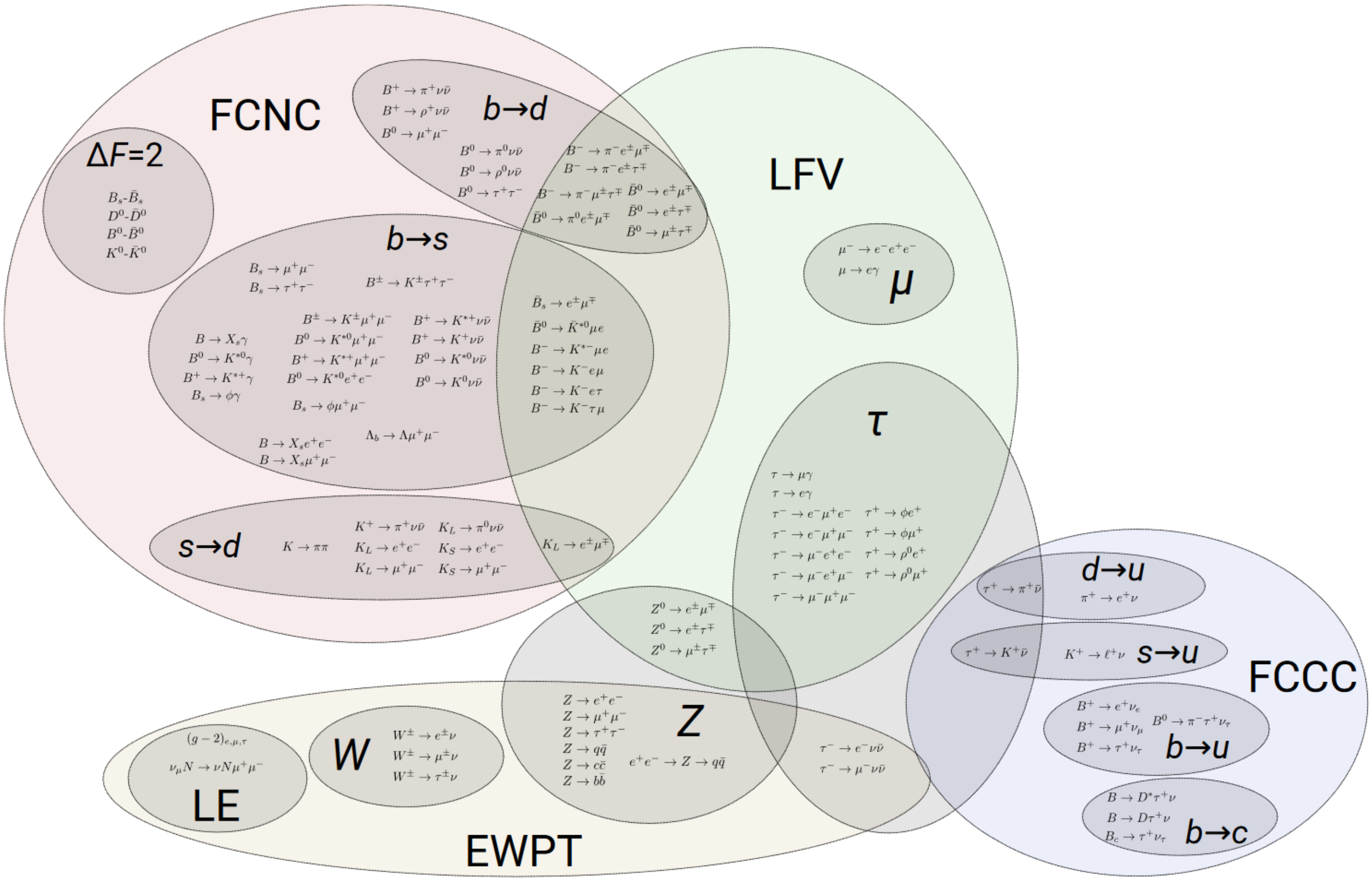
★ Best fit 2021 R_K (LHCb arXiv:2103.11769 , 3.1σ)

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

◆ Best fit pre-2021 R_K

arXiv:2104.00015

LFU and the B-anomalies (quick aside)

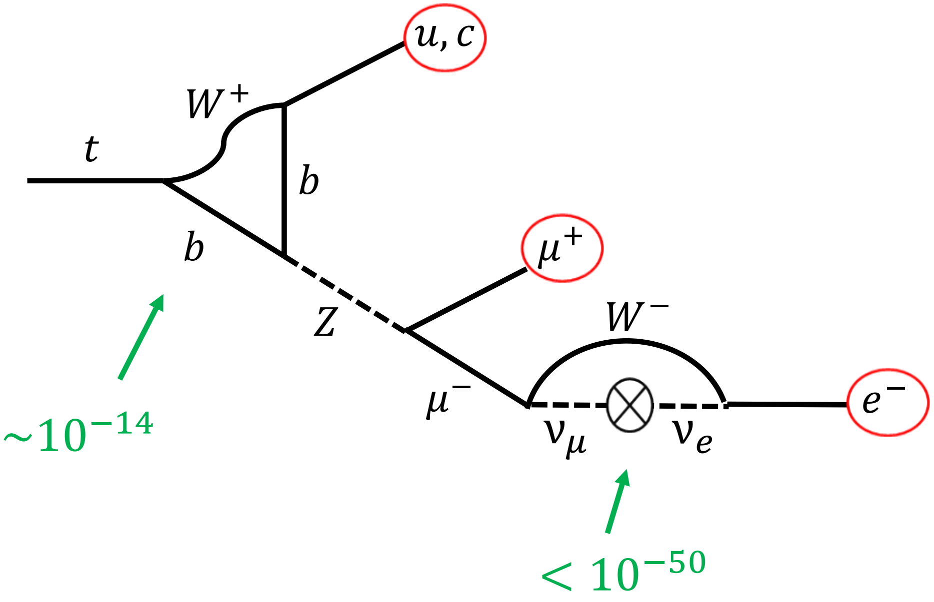


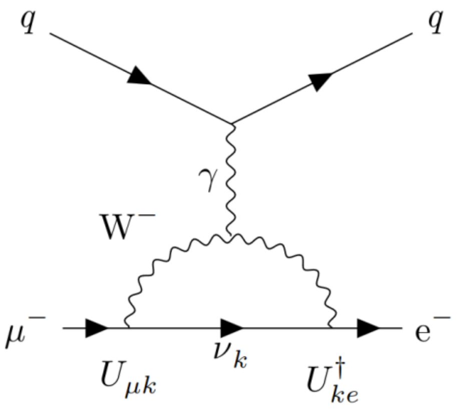
D. Straub

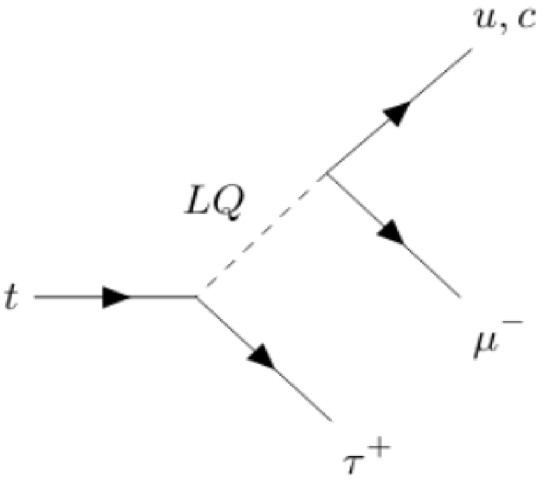
EPJC 79 (2019) 505

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, $80\ \mathrm{fb}^{-1}$)

$$B(t \to e\mu q) < 0.07 - 2.59 \times 10^{-6}$$

JHEP 06 (2022) 082 (CMS)
(2-lepton final state , $138\ \mathrm{fb}^{-1}$)

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

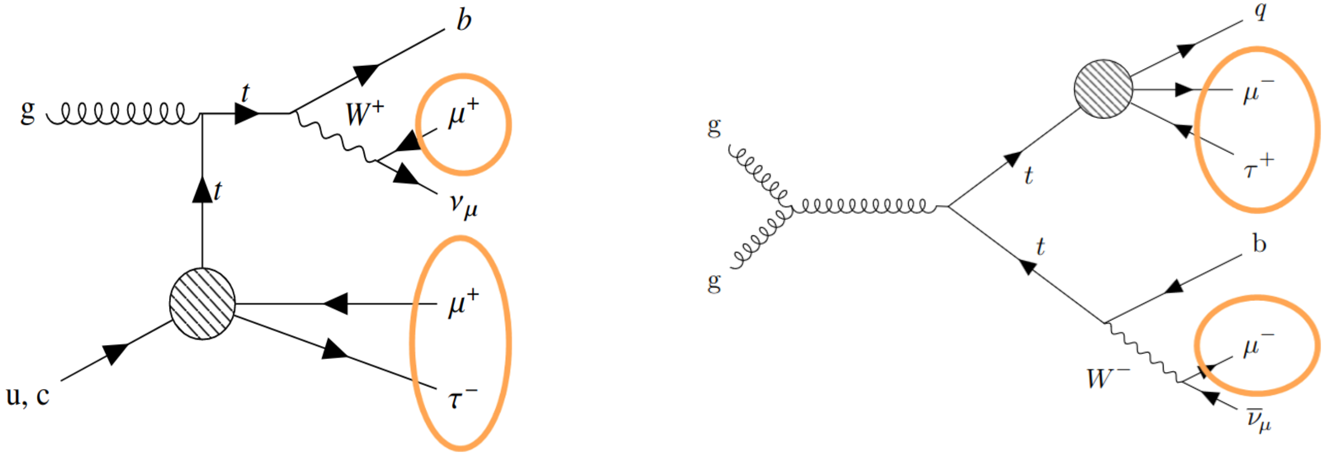
CMS-PAS-TOP-22-005
(3-lepton final state , $138\ \mathrm{fb}^{-1}$)

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

Event selection with 139 fb^{-1}

- Top quark decay and production diagrams differ by 1-jet (SR1 / SR2 below)
- Trilepton event selection including hadronic taus
- Same-sign muons produce significant background reduction
- Control regions for fake-tau and fake/non-prompt-muon backgrounds

	SR1	**SR2**	**CRτ**	**CR$tt\mu$**
Lepton flavour	$2\mu 1\tau_{\text{had-vis}}$			$2\mu 1e$ $(\ell_3 = \mu)$
N_{jets}	≥ 2	1	≥ 2	≥ 2
$N_{b-\text{tags}}$	1	1	1	≤ 2
Muon p_T cut	> 15 GeV	> 15 GeV	> 15 GeV	> 10 GeV
Lowest p_T muon selection	*Tight*	*Tight*	*Tight*	*Loose*
Muon charges	SS	SS	OS	-
$\lvert m_{\mu\mu}^{OS} - M_Z \rvert$	-	-	<10 GeV	>10 GeV



Backgrounds

Process	SR1	SR2	CR$tt\mu$
$t\bar{t}$ + NPμ	8.2 ± 3.3	4.0 ± 1.5	166 ± 15
Z + NPμ	0.20 ± 0.10	0.025 ± 0.013	1.80 ± 0.87
Fake $\tau_{\text{had-vis}}$	2.54 ± 0.54	0.288 ± 0.066	-
Fake electron	-	-	5.8 ± 3.0
$t\bar{t}H$	2.90 ± 0.75	0.179 ± 0.077	1.25 ± 0.18
$t\bar{t}W$	2.8 ± 2.0	0.92 ± 0.67	1.08 ± 0.54
$t\bar{t}Z$	2.43 ± 0.65	0.254 ± 0.054	0.88 ± 0.24
WZ	2.24 ± 0.81	0.91 ± 0.31	7.3 ± 2.3
ZZ	0.266 ± 0.095	0.222 ± 0.081	1.75 ± 0.55
t+X	1.58 ± 0.13	0.611 ± 0.070	-
W + jets	0.27 ± 0.14	-	-
VVV	1.35 ± 0.67	0.49 ± 0.25	0.47 ± 0.24
Other	0.080 ± 0.040	-	1.11 ± 0.55
Total	26.7 ± 4.5	9.1 ± 2.2	201 ± 14
Signal (production)	1.4 ± 5.4	0.6 ± 2.4	0.008 ± 0.030
Signal (decay)	0.05 ± 0.22	0.007 ± 0.028	0.009 ± 0.034
Data	28	8	202

Post-fit yields

Fake-tau estimation

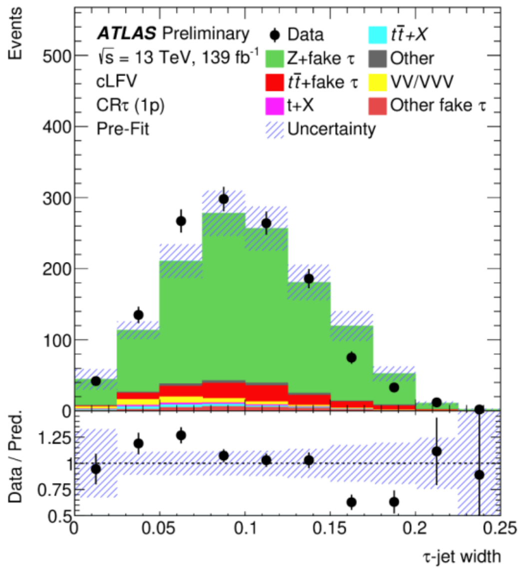
Dedicated CR (does not enter the fit)

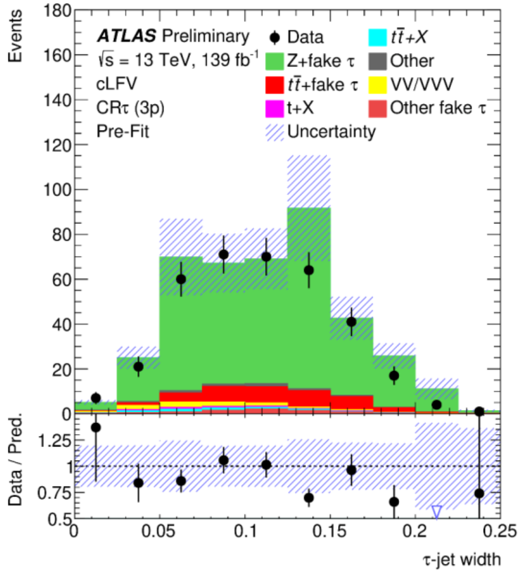
Scale factors (SF) are used to correct the rate of the fake-tau background

Fakes are usually due to mis-identified jets

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



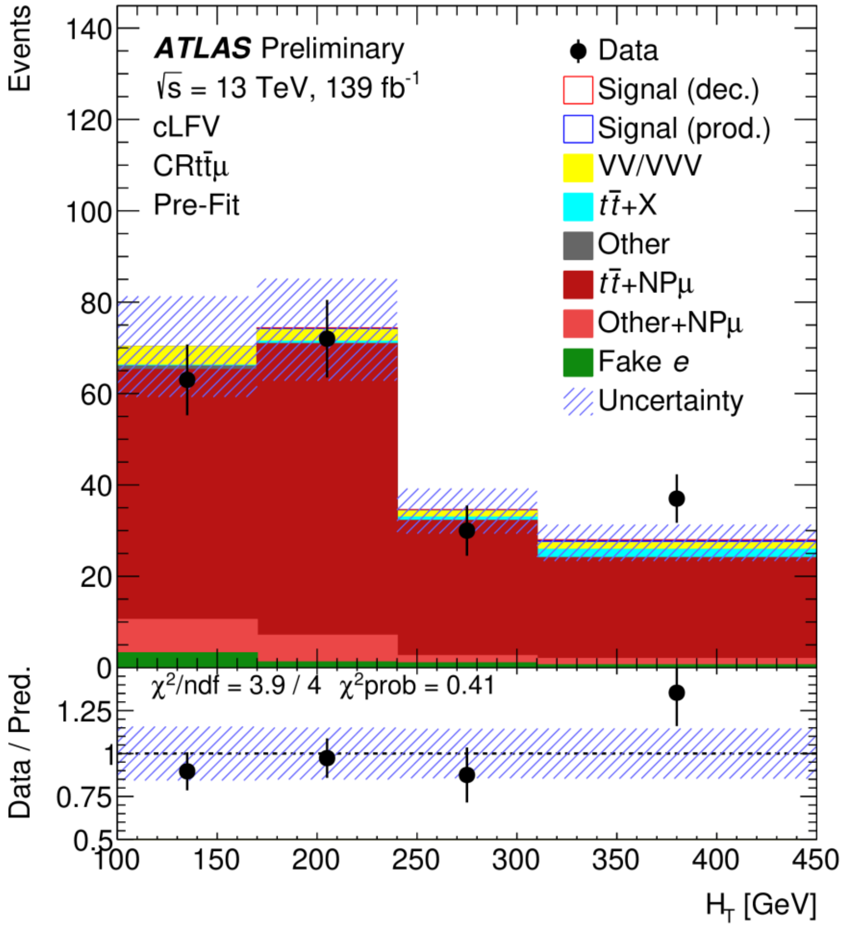


Fake/Non-prompt (NP) muon estimation

Dedicated CR (does enter the fit)

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

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



Comment on MC Models

Xsec value depends on WC, not on lepton flavours

Experiment	Publication	Channel	UFO	Tensor Xsec (lequ3)
CMS	JHEP , $138\ \mathrm{fb}^{-1}$	$gq \rightarrow te\mu\ ,\ t \rightarrow \mathrm{hadronic}$	SMEFTfr v2	2.9 pb
CMS	PAS , $138\ \mathrm{fb}^{-1}$	$gq \rightarrow te\mu\ ,\ t \rightarrow \mathrm{leptonic}$	SMEFTfr v2	2.9 pb
ATLAS	CONF , $139\ \mathrm{fb}^{-1}$	$gq \rightarrow t\mu\tau\ ,\ t \rightarrow \mathrm{leptonic}$	dim6top	2.1 pb

Differences in central values between ATLAS and CMS are larger than uncertainties – appear to be due to genuine differences in the UFO models

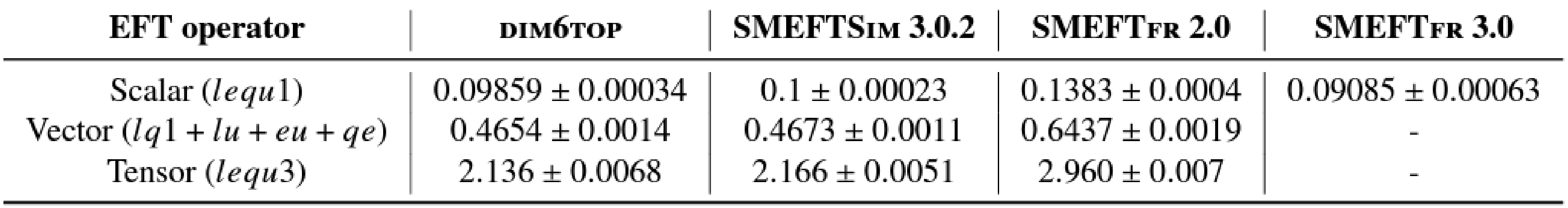
A 40% difference in cross-sections (up-quark couplings) means ~18% difference in EFT limits ($\sqrt{1.4}$)

A 100% difference in cross-sections (charm-quark couplings) means ~40% difference in EFT limits ($\sqrt{2.0}$)

SMEFTfr v2 and SMEFTfr v3

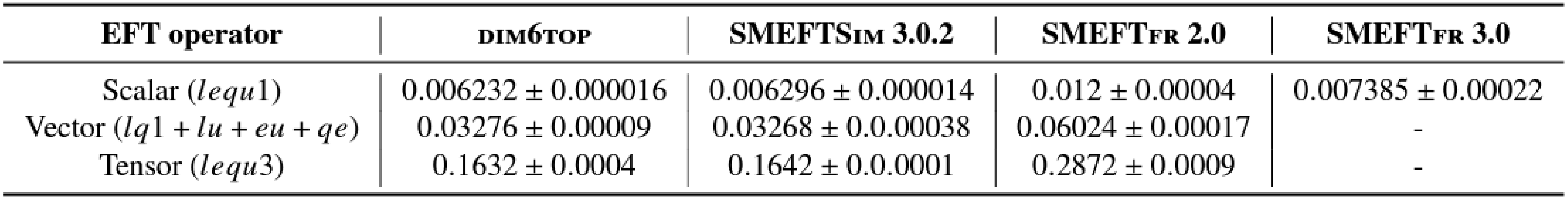
SMEFTfr v3 is quite different – normalisation reduces significantly to be in much better agreement with SMEFTSim and dim6top.
There remains a greater difference in charm than in up however.

up



EFT operator	DIM6TOP	SMEFTSim 3.0.2	SMEFTfr 2.0	SMEFTfr 3.0
Scalar ($lequ1$)	0.09859 ± 0.00034	0.1 ± 0.00023	0.1383 ± 0.0004	0.09085 ± 0.00063
Vector ($lq1 + lu + eu + qe$)	0.4654 ± 0.0014	0.4673 ± 0.0011	0.6437 ± 0.0019	-
Tensor ($lequ3$)	2.136 ± 0.0068	2.166 ± 0.0051	2.960 ± 0.007	-

charm



EFT operator	DIM6TOP	SMEFTSim 3.0.2	SMEFTfr 2.0	SMEFTfr 3.0
Scalar ($lequ1$)	0.006232 ± 0.000016	0.006296 ± 0.000014	0.012 ± 0.00004	0.007385 ± 0.00022
Vector ($lq1 + lu + eu + qe$)	0.03276 ± 0.00009	$0.03268 \pm 0.0.00038$	0.06024 ± 0.00017	-
Tensor ($lequ3$)	0.1632 ± 0.0004	$0.1642 \pm 0.0.0001$	0.2872 ± 0.0009	-

Flavour-difference (1)

SMEFTfr authors have tracked down flavour-behaviour to a convention difference – i.e. the **effects of Wilson Coefficients in each UFO do not mean the same thing**

In short: When defining the quark Yukawa matrices and determining a flavour basis you have a choice about diagonalising the up-type quark mass basis or the down-type quark mass basis
https://arxiv.org/pdf/2003.05432.pdf (see backup)

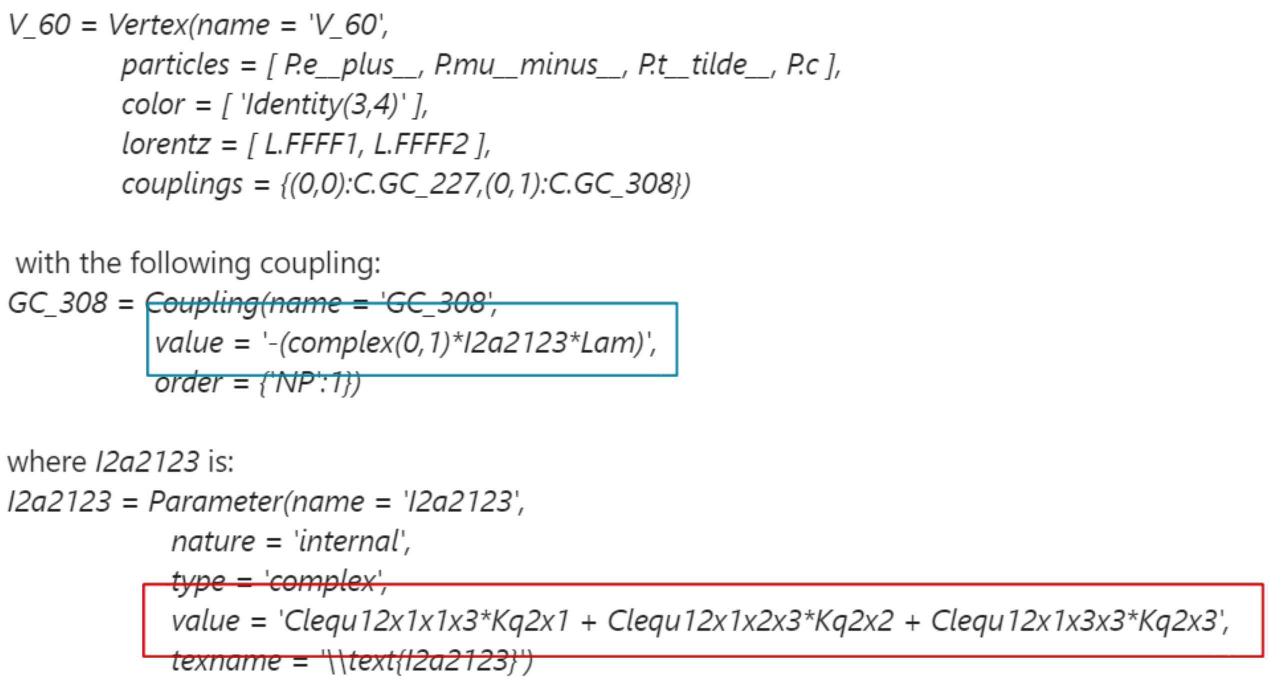
$$Y_u = \mathrm{diag}(y_u, y_c, y_t) \ , \quad Y_d = V_{\mathrm{CKM}} \cdot \mathrm{diag}(y_d, y_s, y_b)$$

It's a free decision, neither is more correct, but it means that one group of quarks will end up with CKM terms included.

SMEFTfr chooses to have diagonal Yd and non-diagonal Yu
SMEFTsim chooses to have diagonal Yu and non-diagonal Yd

Flavour-difference (2)

In practice, this means that the CKM matrix then enters into the definitions of the up-type EFT operators for SMEFTfr:



```
V_60 = Vertex(name = 'V_60',
              particles = [ P.e__plus__, P.mu__minus__, P.t__tilde__, P.c ],
              color = [ 'Identity(3,4)' ],
              lorentz = [ L.FFFF1, L.FFFF2 ],
              couplings = {(0,0):C.GC_227,(0,1):C.GC_308})
```

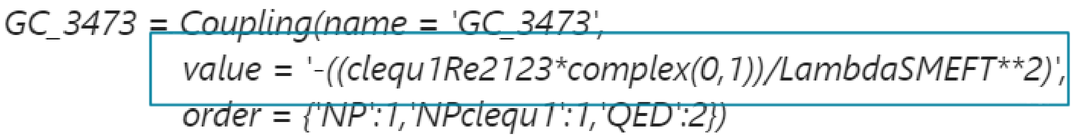
with the following coupling:

```
GC_308 = Coupling(name = 'GC_308',
                  value = '-(complex(0,1)*I2a2123*Lam)',
                  order = {'NP':1})
```

where *I2a2123* is:

```
I2a2123 = Parameter(name = 'I2a2123',
                    nature = 'internal',
                    type = 'complex',
                    value = 'Clequ12x1x1x3*Kq2x1 + Clequ12x1x2x3*Kq2x2 + Clequ12x1x3x3*Kq2x3',
                    texname = '\\text{I2a2123}')
```

Whereas for SMEFTsim this does not happen (for up-type):



```
GC_3473 = Coupling(name = 'GC_3473',
                   value = '-((clequ1Re2123*complex(0,1))/LambdaSMEFT**2)',
                   order = {'NP':1,'NPclequ1':1,'QED':2})
```