Lepton and Flavour Anomalies: Starting from the Top

Imperial College London, Particle Physics Seminar

Jacob Kempster

26/06/2024

Jacob Kempster

7 years postdoctoral experience

ATLAS Member for 13 years

Research Interests

- Experimental particle physicist
- ATLAS Experiment, Large Hadron Collider (LHC)
- Top quark physics and Effective Field Theory
- Flavour physics anomalies

Relevant Roles of Responsibility

- LHC Effective Field Theory Working Group Convener (ATLAS Top)
- ATLAS Top Group EFT Contact
- ATLAS HTop Combination Contact
- British Science Association Community Partner
- (Former) Top+X Working Group Convener
- (Former) Top UK Convener

Contact

- jacob.julian.kempster@cern.ch

UNIVERSITY OF SUSSEX

This talk

Overview of studies other people have done

↓ to justify

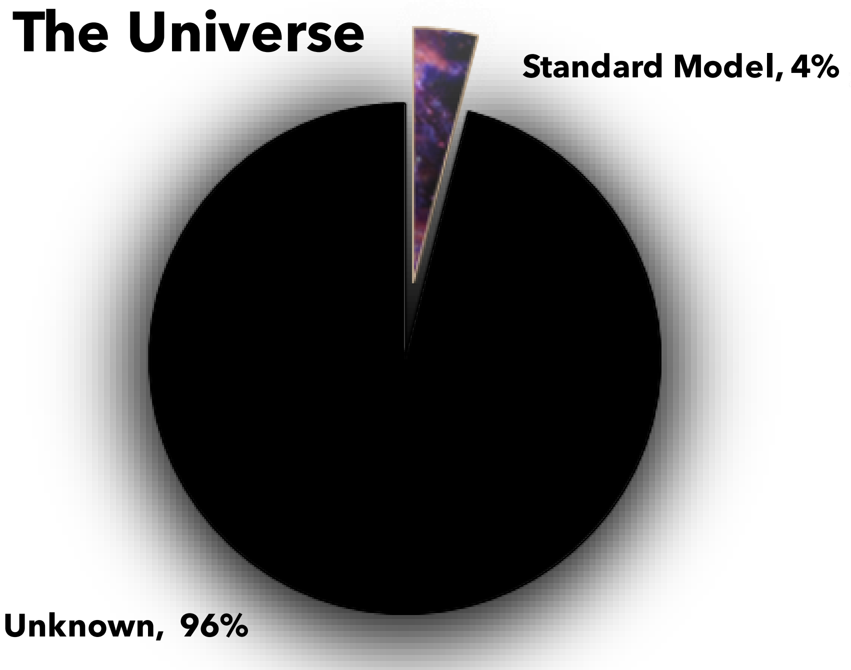
discussion of something I did

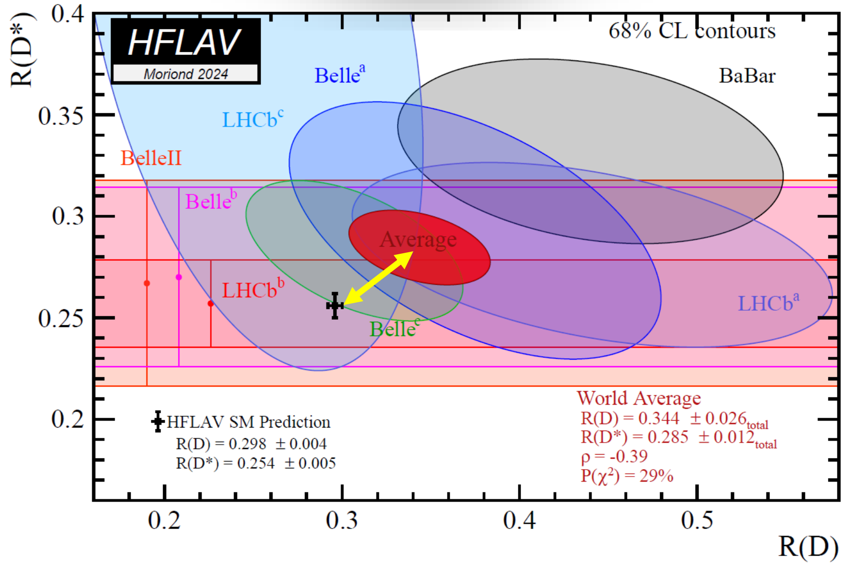
↓ to consider

what I think we should do next

The Problem(s)

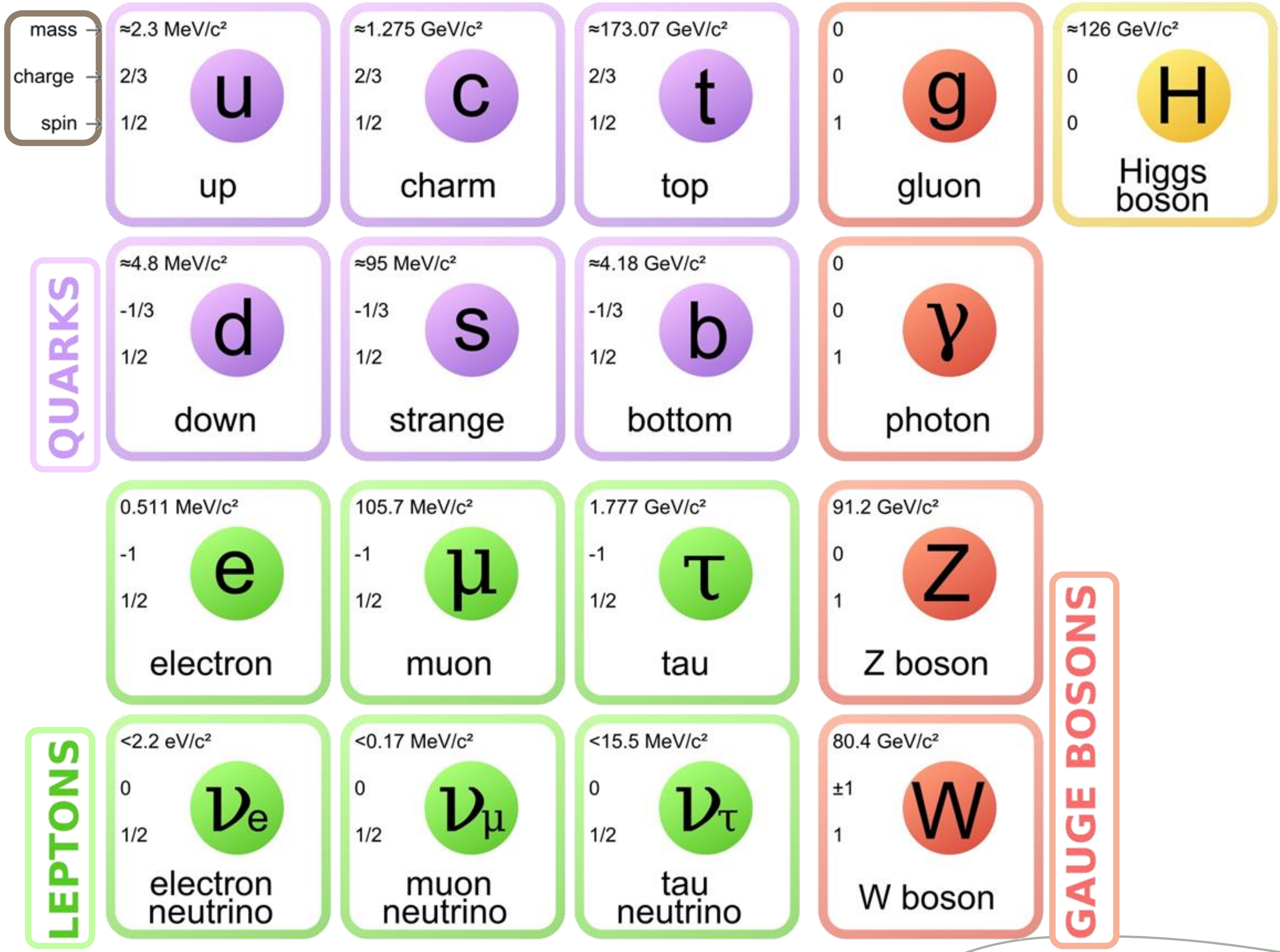
- New physics is elusive, but the Standard Model is incomplete!
- The next fundamental discovery may be outside of the direct energy reach of the Large Hadron Collider (LHC)
- We see hints of anomalous results in B-physics measurements, and now possibly beginning to appear in Top+X measurements





HFLAV

The Standard Model



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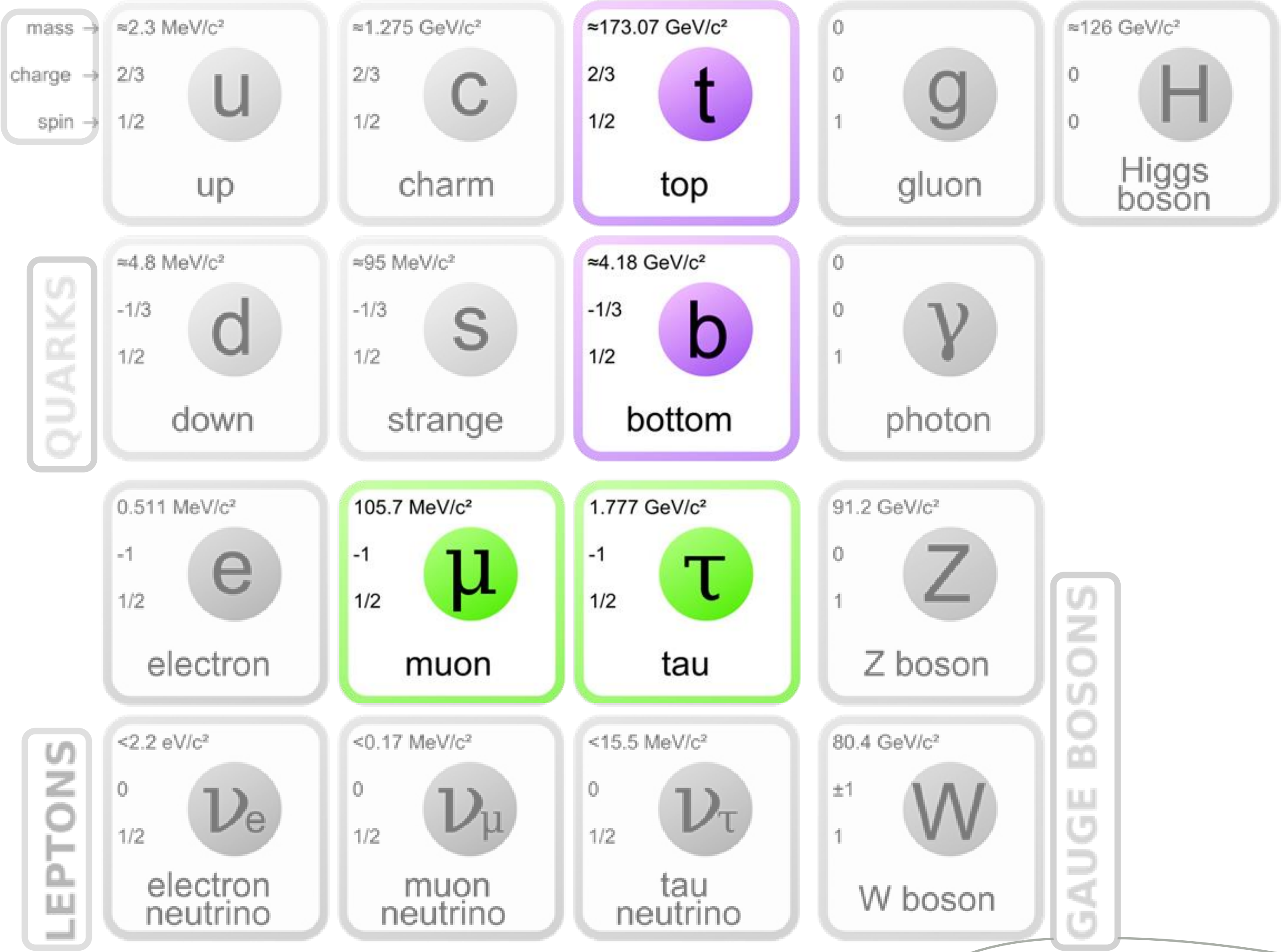


Muons behaving badly

D0 - Tevatron

Counting experiment – how many same-sign muon pairs?

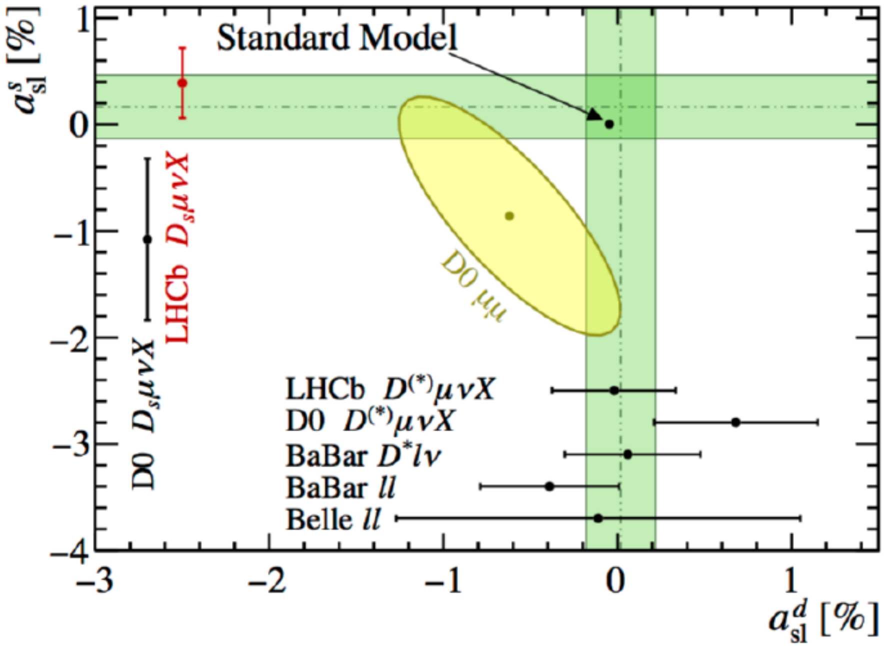
$$A = \frac{(N^{++} - N^{--})}{(N^{++} + N^{--})}$$

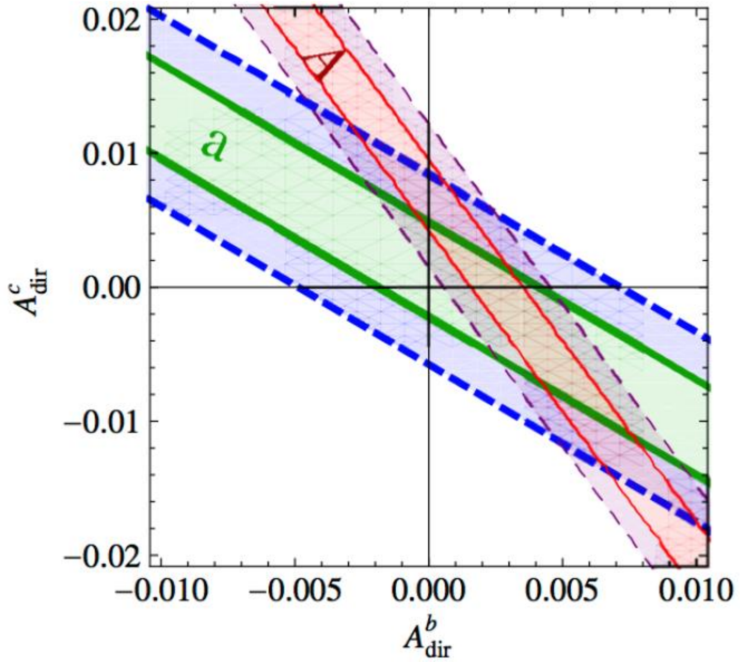
(2010-2013) Observed asymmetries up to $\mathbf{3.9\sigma}$ from SM expectation

- PRD 105 (2010) 081801
- PRD 84 (2011) 052007
- PRD 87 (2013) 074020

$$a_{\mathrm{sl}}^{q} = \frac{\Gamma\left(\bar{B}_q^0 \to B_q^0 \to f\right) - \Gamma\left(B_q^0 \to \bar{B}_q^0 \to \bar{f}\right)}{\Gamma\left(\bar{B}_q^0 \to B_q^0 \to f\right) + \Gamma\left(B_q^0 \to \bar{B}_q^0 \to \bar{f}\right)},$$

$$a_{\mathrm{dir}}^{q} = \frac{\Gamma(b \to \mu^- X) - \Gamma(\bar{b} \to \mu^+ X)}{\Gamma(b \to \mu^- X) + \Gamma(\bar{b} \to \mu^+ X)},$$





Muon g-2 - Fermilab

$a_\mu = (g_\mu - 2)/2$

g_μ = Muon gyromagnetic factor

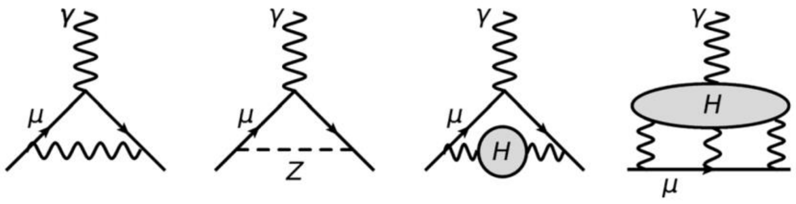
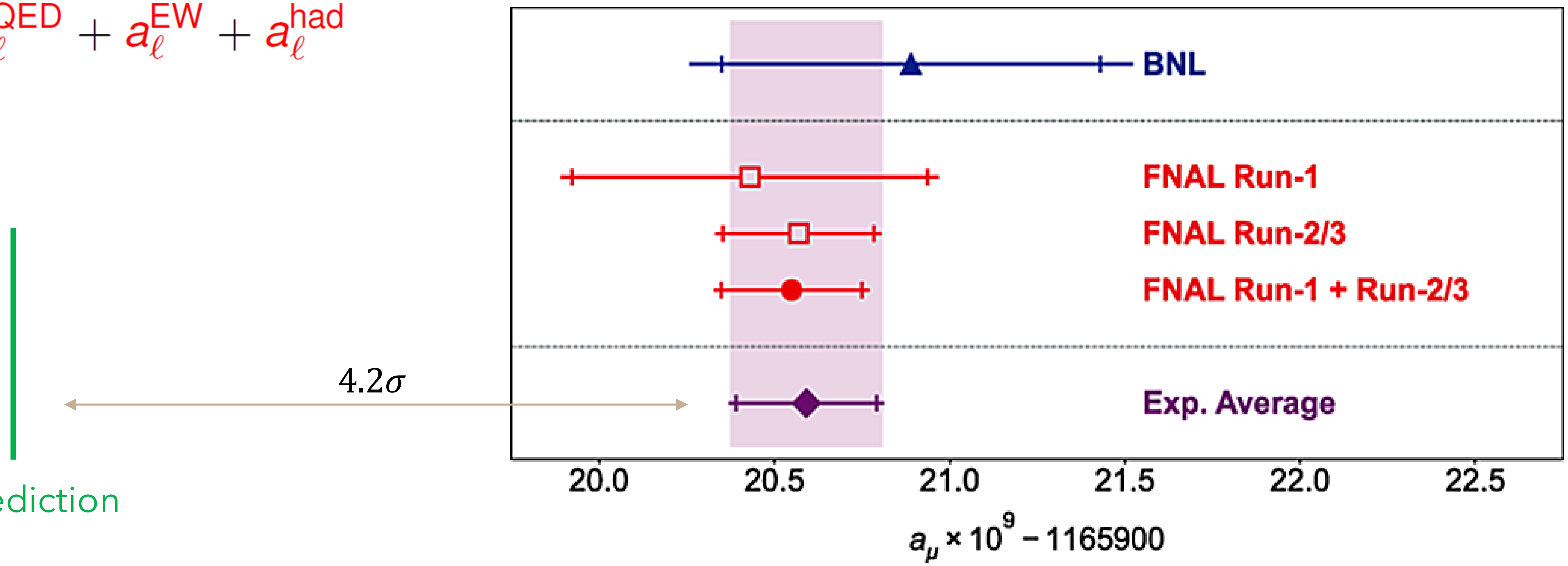


FIG. 1. Feynman diagrams of representative SM contributions to the muon anomaly. From left to right: first-order QED and weak processes, leading-order hadronic (H) vacuum polarization, and hadronic light-by-light contributions.

PRL 131 (2023) 161802

$a_\ell^{SM} = a_\ell^{QED} + a_\ell^{EW} + a_\ell^{had}$



SM Prediction

EPJC 80 (2020) 241

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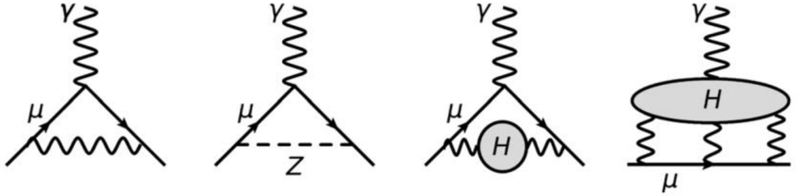

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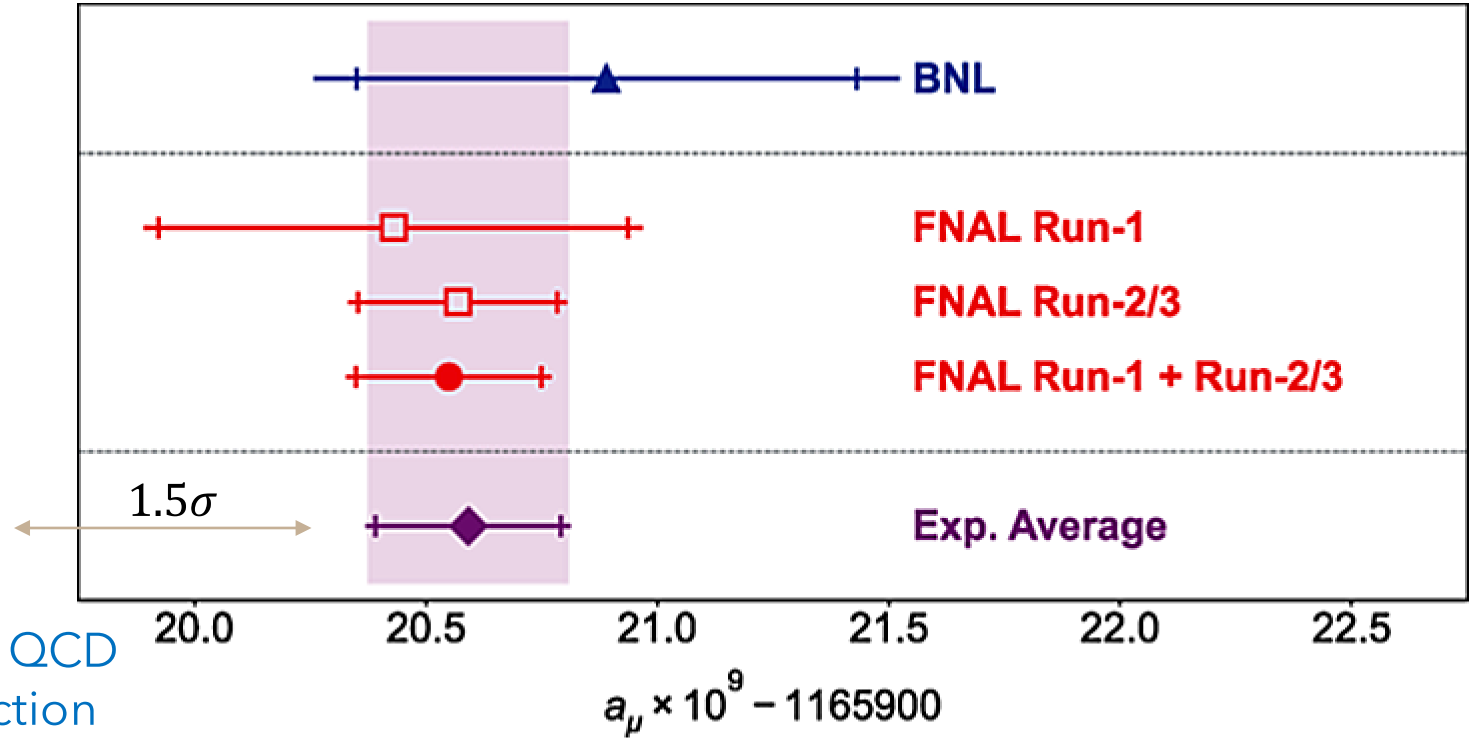


SM Prediction

Lattice QCD Prediction

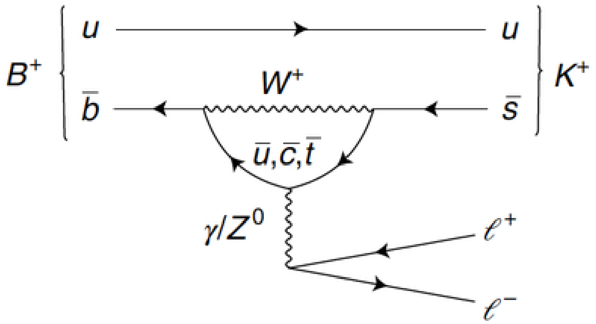
EPJC 80 (2020) 241

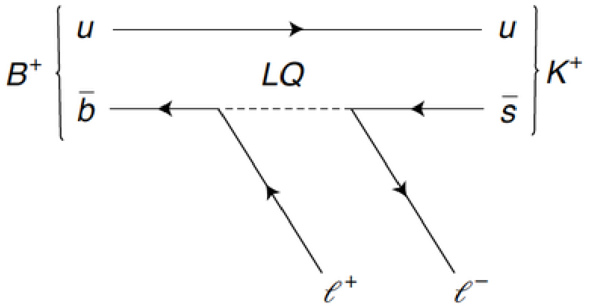
$R(K^{(*)})$

$B \to s\mu^+\mu^-$

$$R_K = \frac{BR(B \to K\mu^+\mu^-)}{BR(B \to Ke^+e^-)},$$

$$R_{K^*} = \frac{BR(B \to K^*\mu^+\mu^-)}{BR(B \to K^*e^+e^-)}.$$

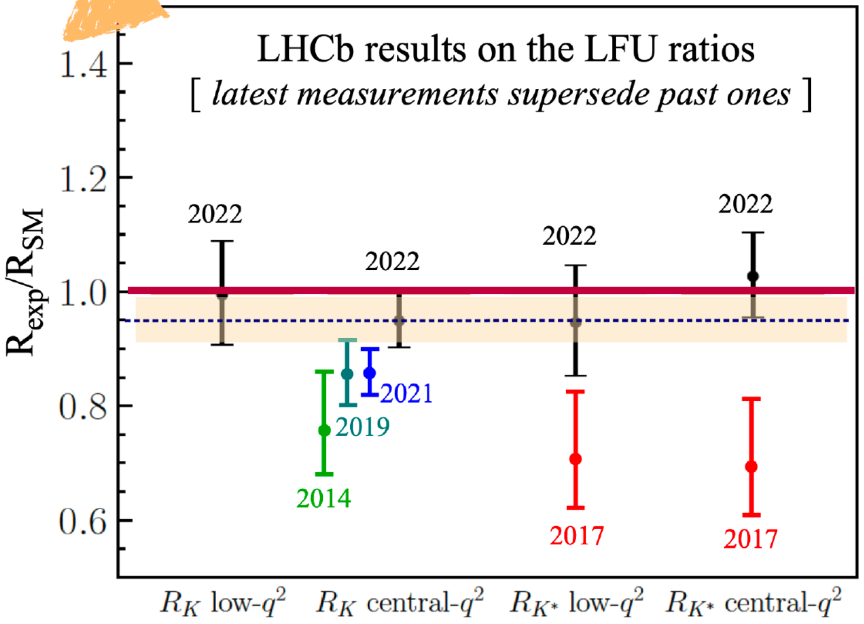


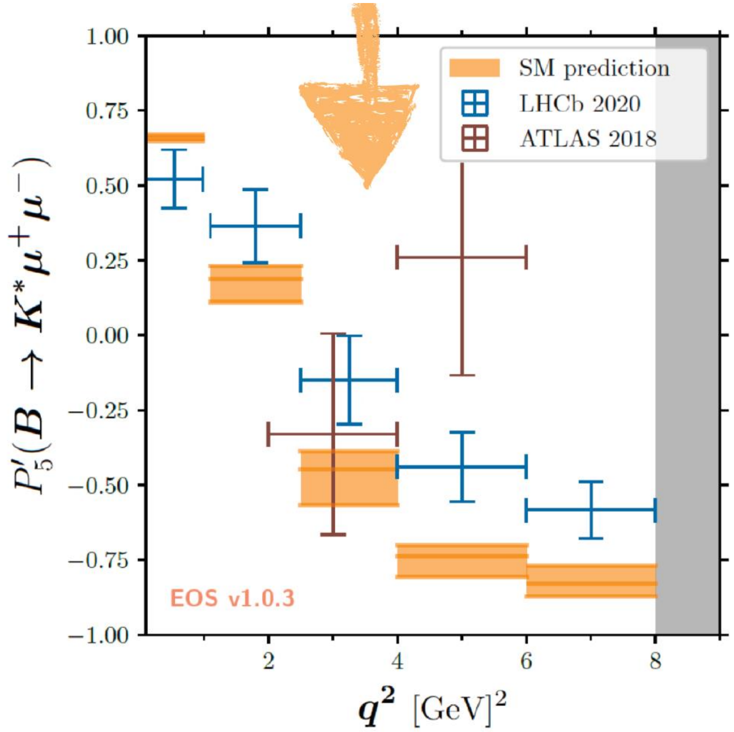


At one point this was up to 3.1σ away from the SM

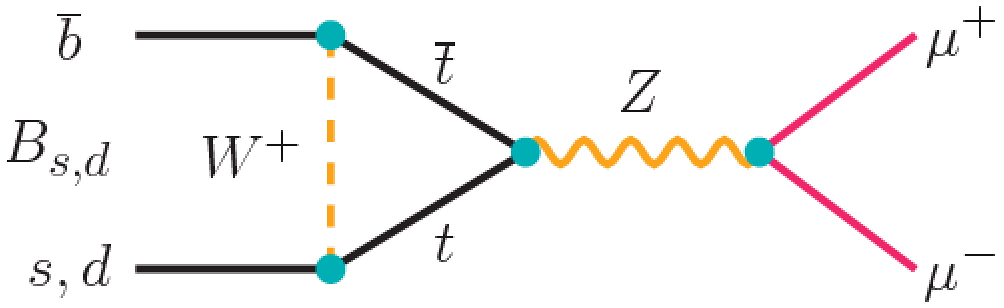
Now found to be in good agreement
PRD 108 (2023) 032002

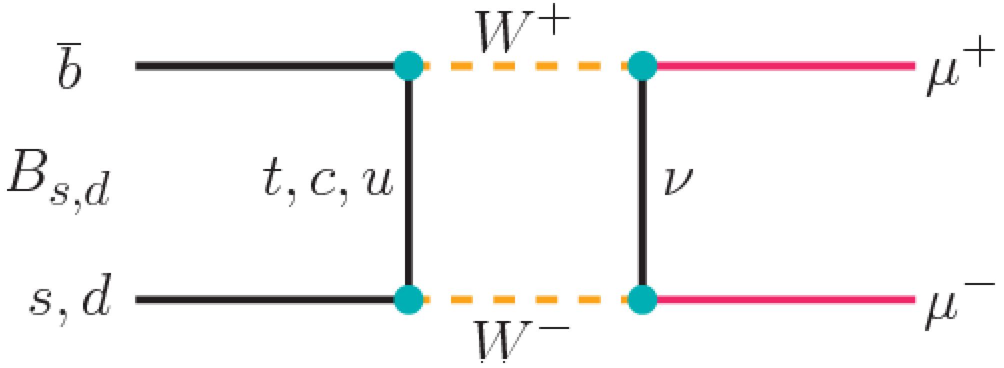
(However, some angular discrepancies remain!)





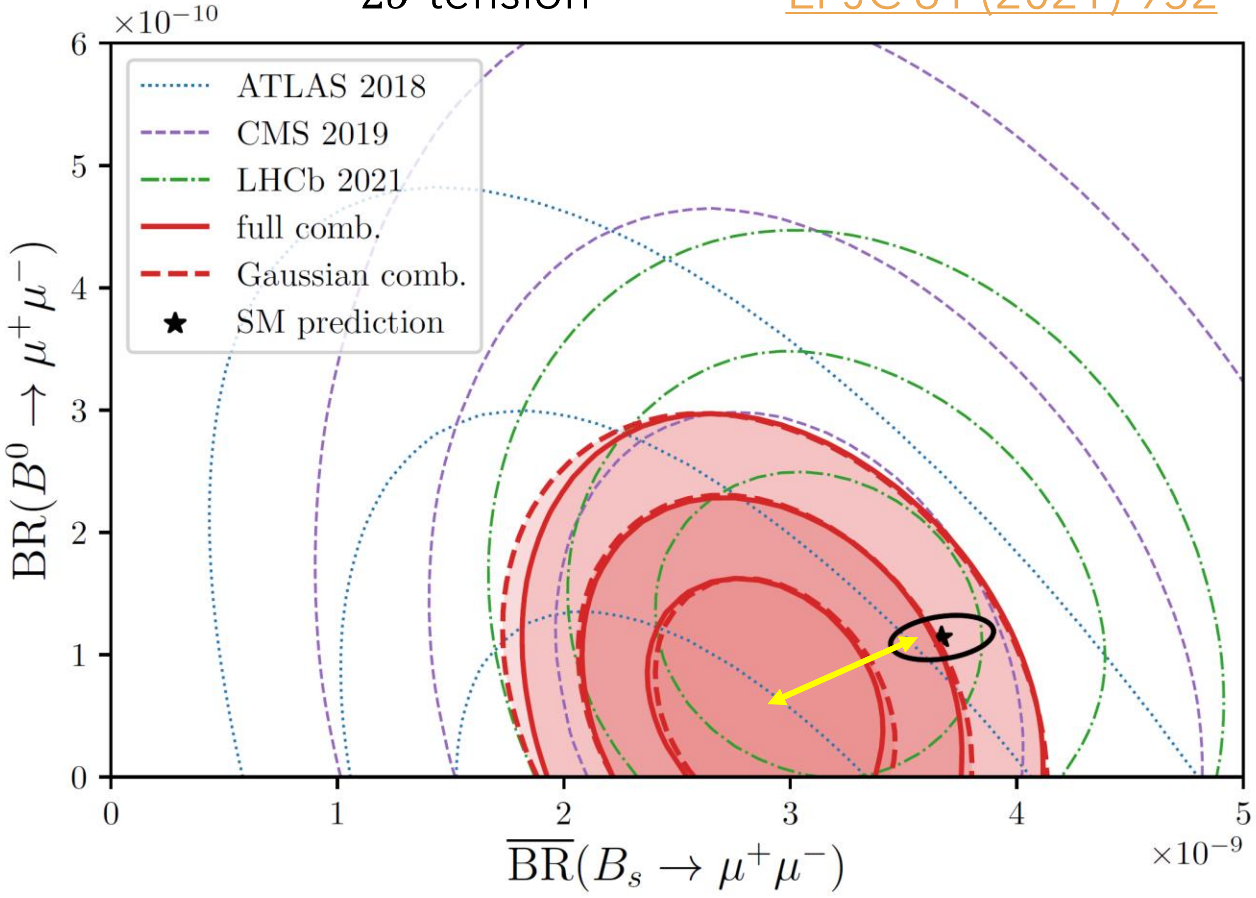
$B_s \to \mu^+\mu^-$





2σ tension

EPJC 81 (2021) 952

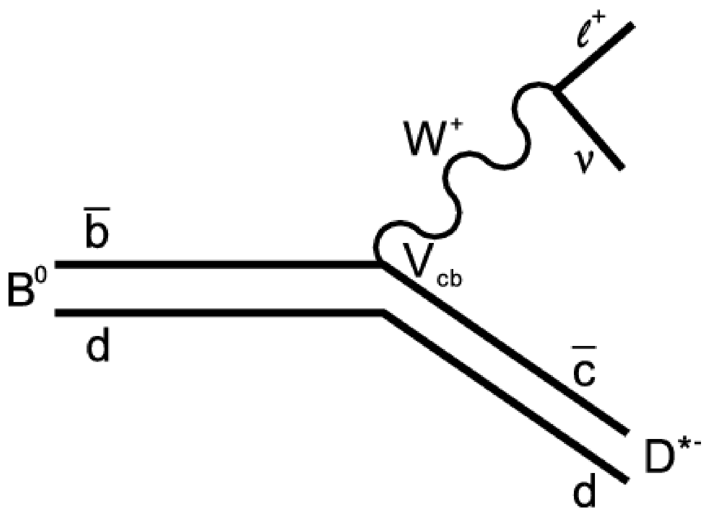


Taus behaving badly too?

$R(D^{(*)})$

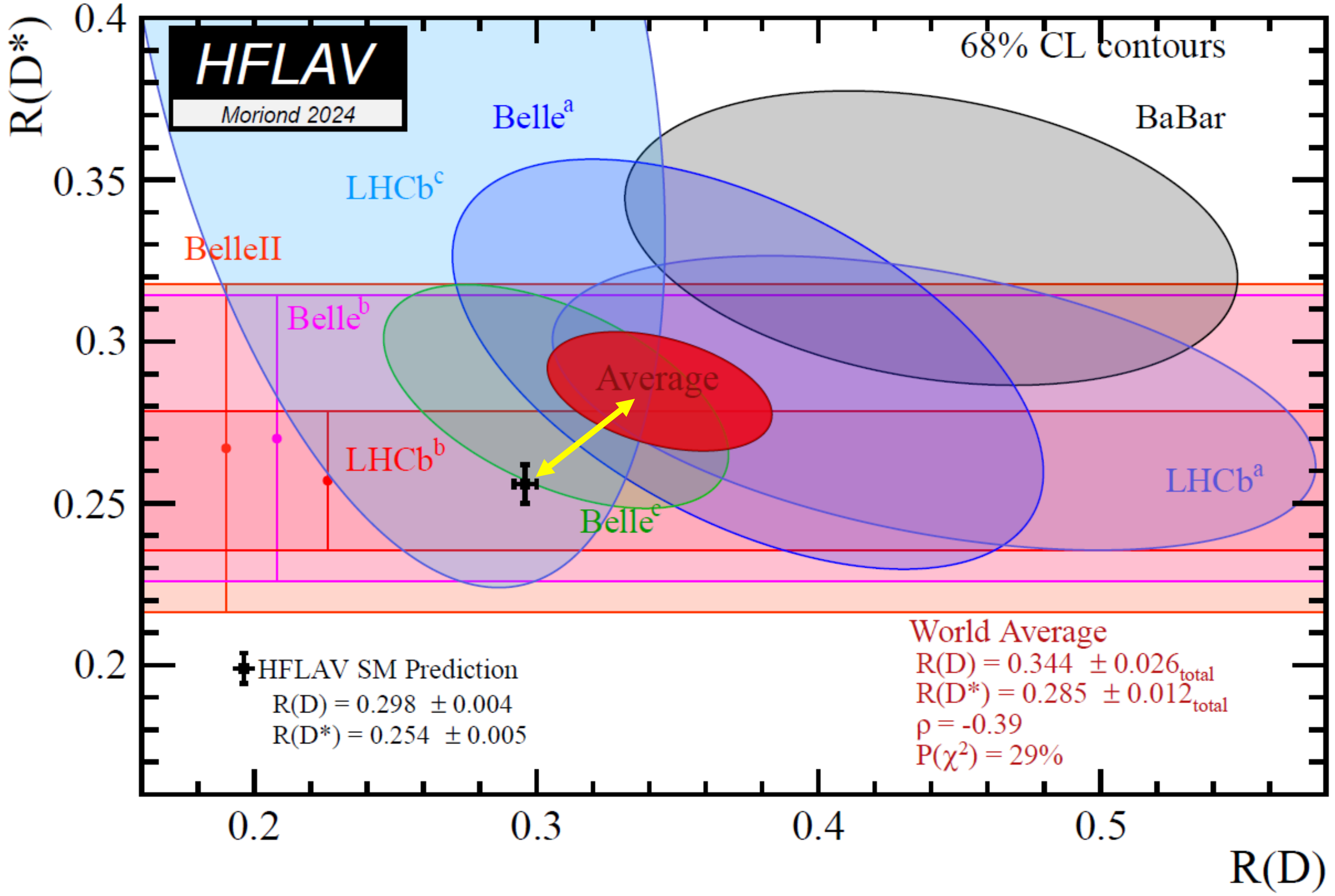
LHCb-PAPER-2024-007 (in preparation)

$$R(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)} l^- \bar{\nu}_l)}$$

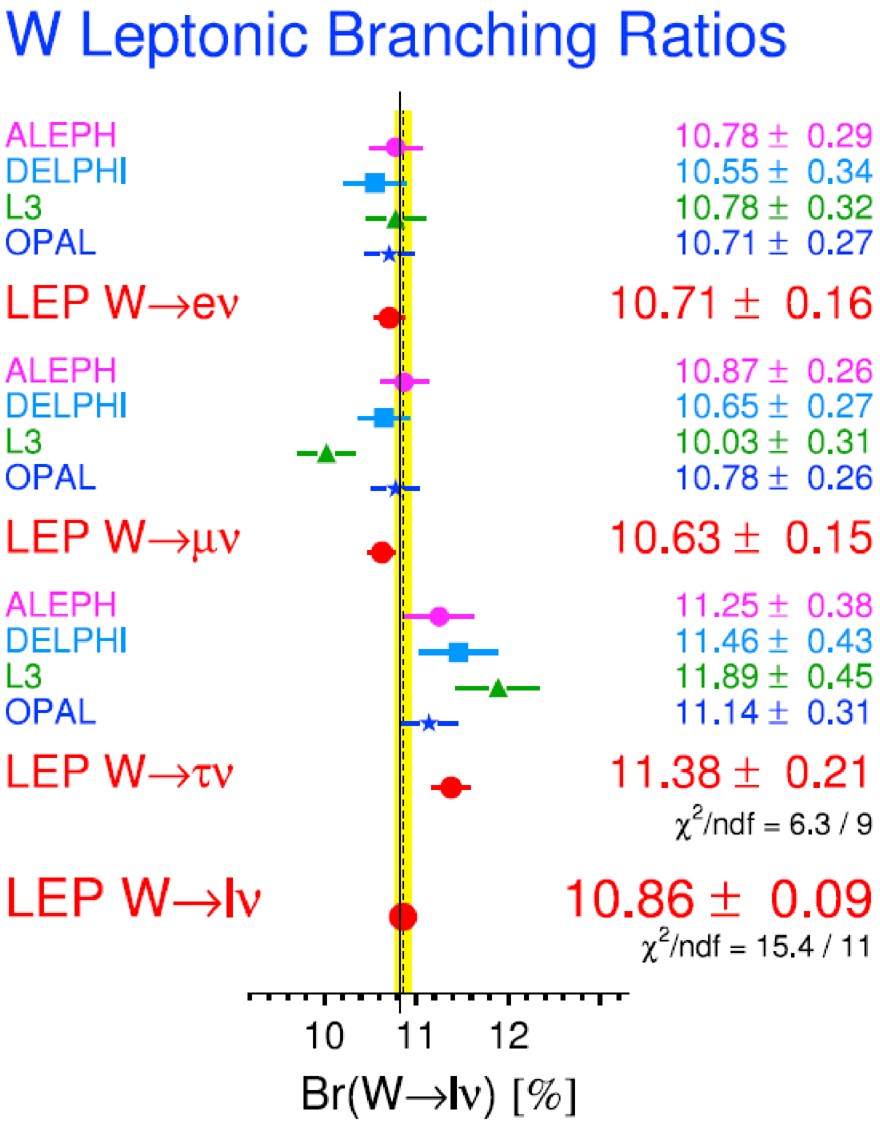


3.17σ tension

HFLAV (Moriond 2024)

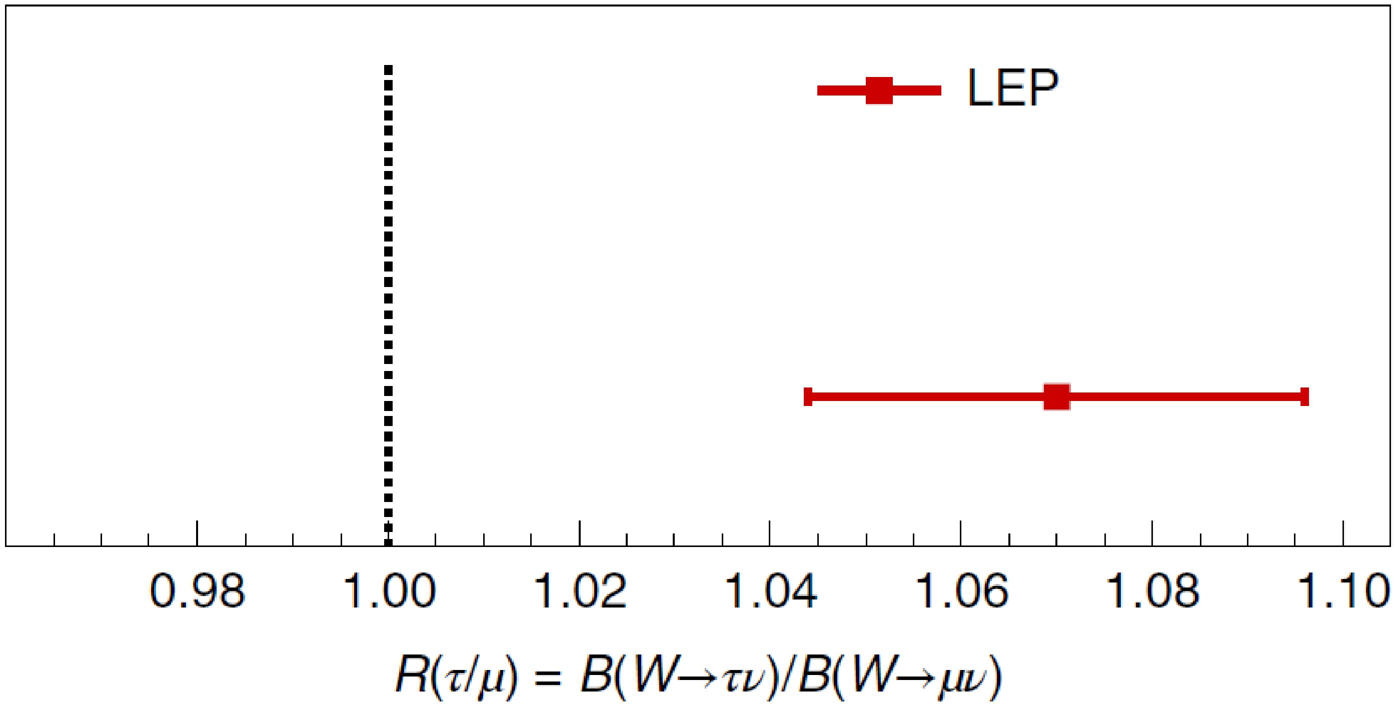


LEP (CERN) Lepton Flavour Universality



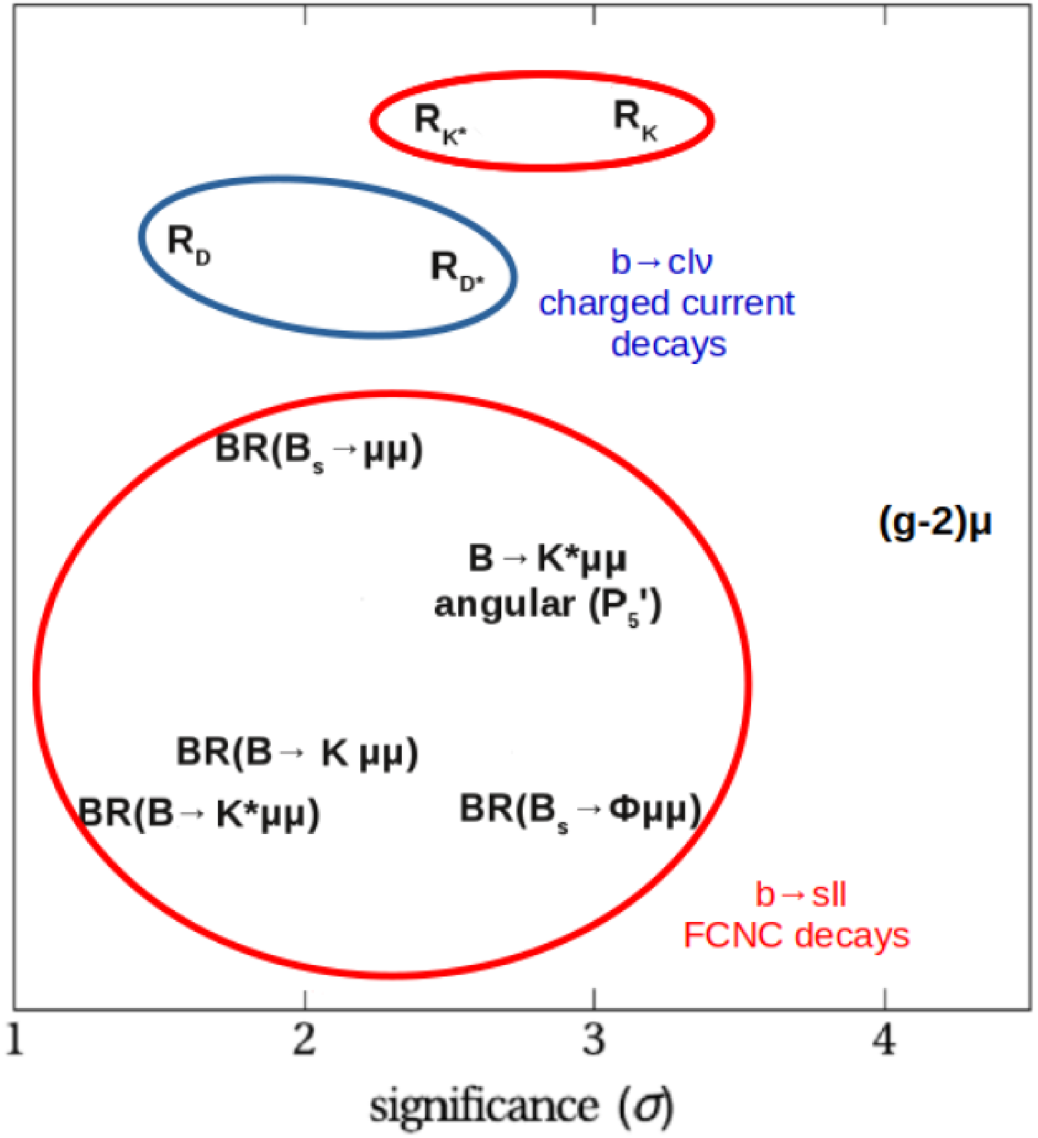
2.6σ tension

J Phys Rep 532 (2013) 004

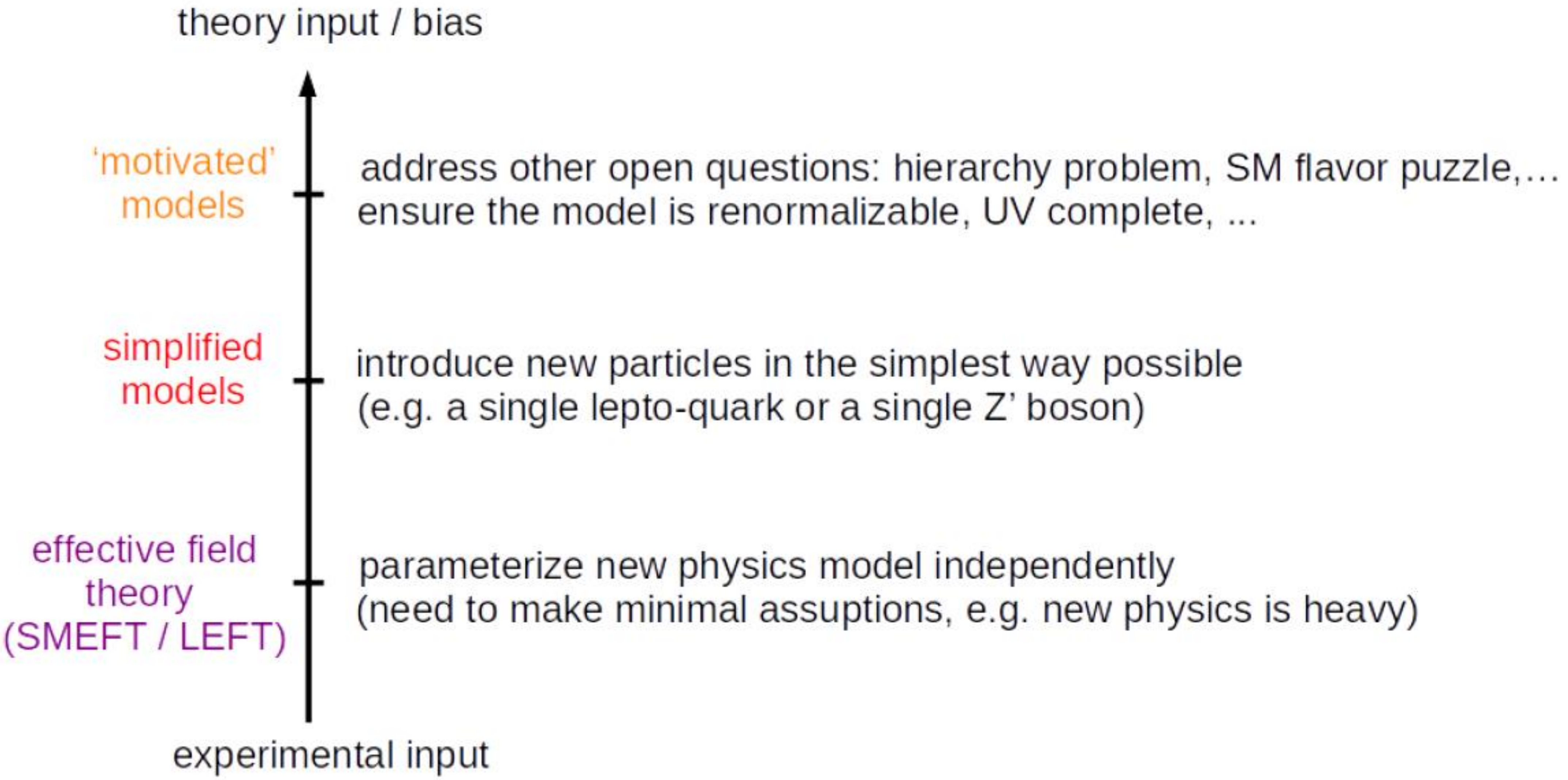


(This is prompt lepton behaviour – i.e. unlikely to be same anomalous physics, but still interesting!)

W. Altmannshofer (2022)

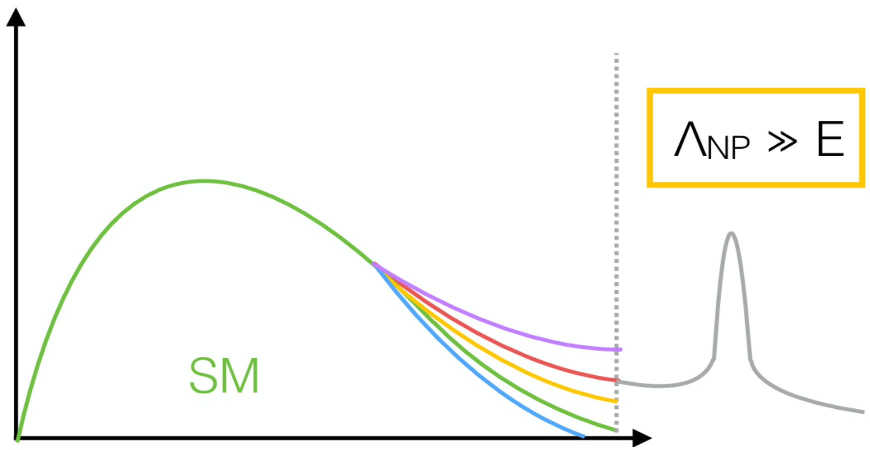


Effective Field Theory


theory input / bias
'motivated' models
address other open questions: hierarchy problem, SM flavor puzzle,…
ensure the model is renormalizable, UV complete, ...
simplified models
introduce new particles in the simplest way possible
(e.g. a single lepto-quark or a single Z' boson)
effective field theory (SMEFT / LEFT)
parameterize new physics model independently
(need to make minimal assuptions, e.g. new physics is heavy)
experimental input

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

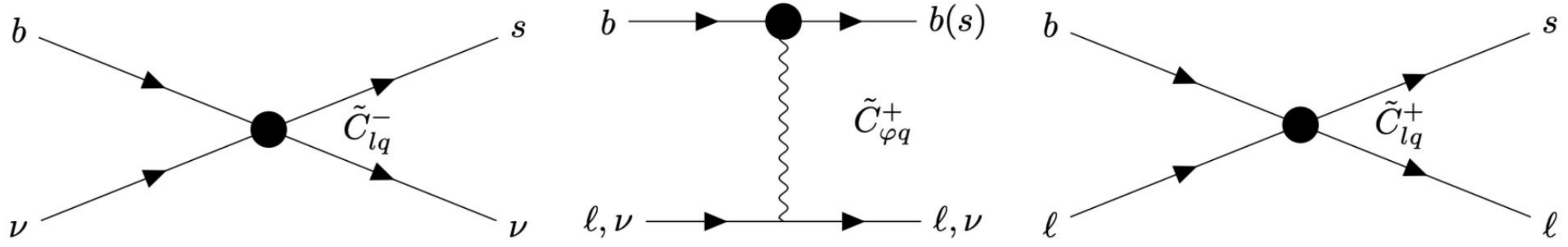
Coupling Strength

Operators introducing new interactions

EFT and the B-anomalies

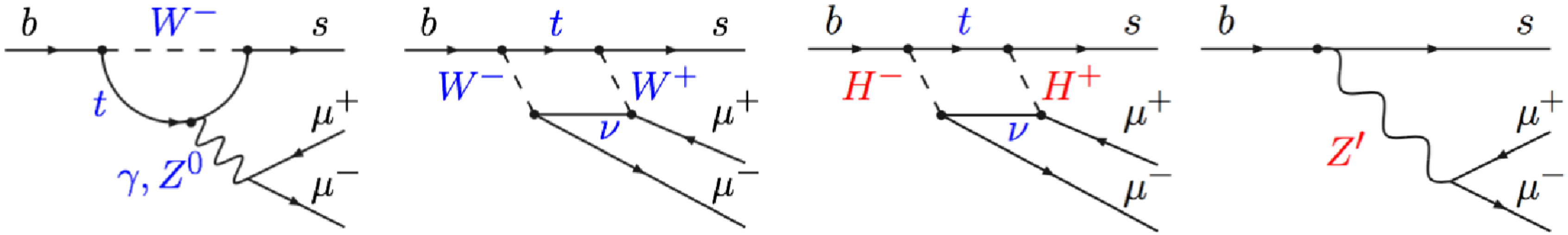
$$\bar{s}_L\gamma_\mu b_L\bar{\mu}_L\gamma^\mu\mu_L \Rightarrow \begin{aligned} O_{lq}^{(1)} &= \bar{Q}\gamma_\mu Q\bar{L}\gamma^\mu L, \\ O_{lq}^{(3)} &= \bar{Q}\gamma_\mu\tau^I Q\bar{L}\gamma^\mu\tau^I L \end{aligned}$$

JHEP 06 (2021) 010



$b \to s\ell\ell$ transitions

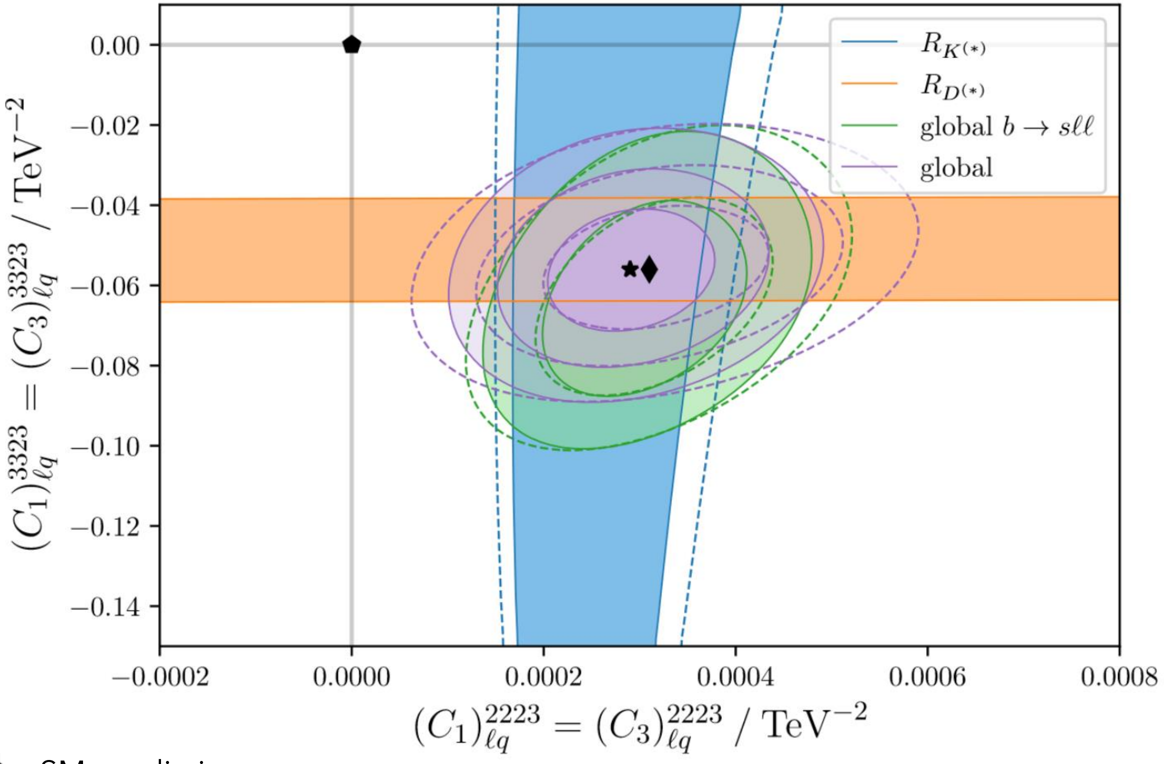
- Flavour Changing Neutral Current (FCNC) $b \to s(d)l^+l^-$ decays, such as $B^0 \to K^{*0}\mu^+\mu^-$, are forbidden at tree level in the SM



P. Cartelle

EFT and the B-anomalies

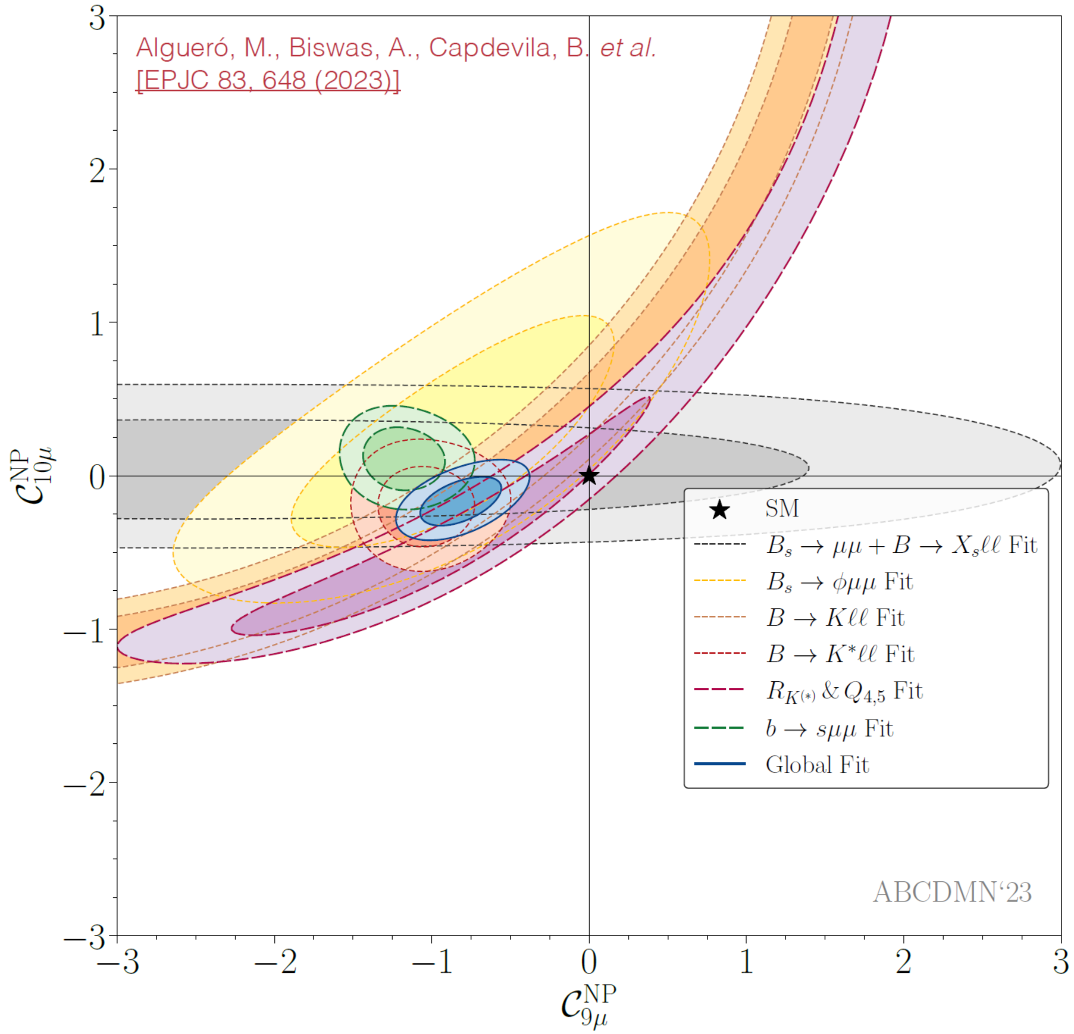
arXiv:2104.00015



SM prediction

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

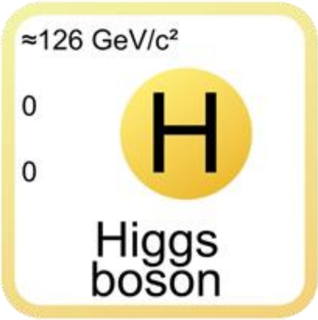
Best fit pre-2021 R_K

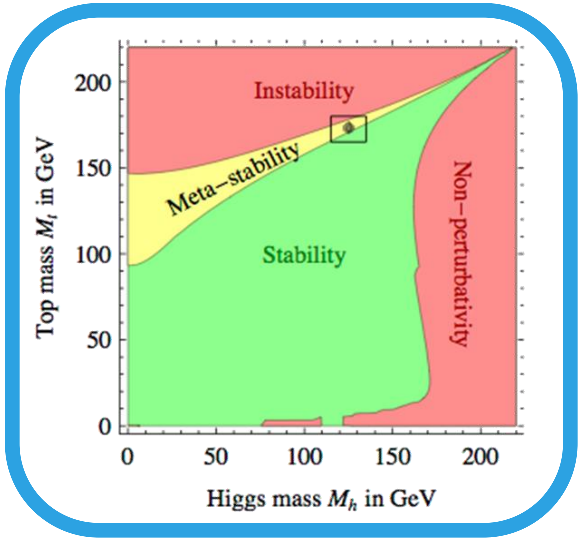


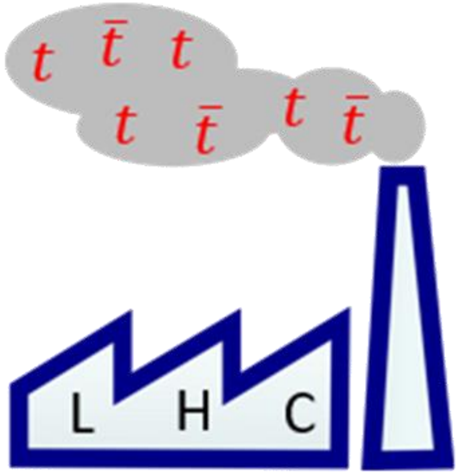
Why Top quarks?

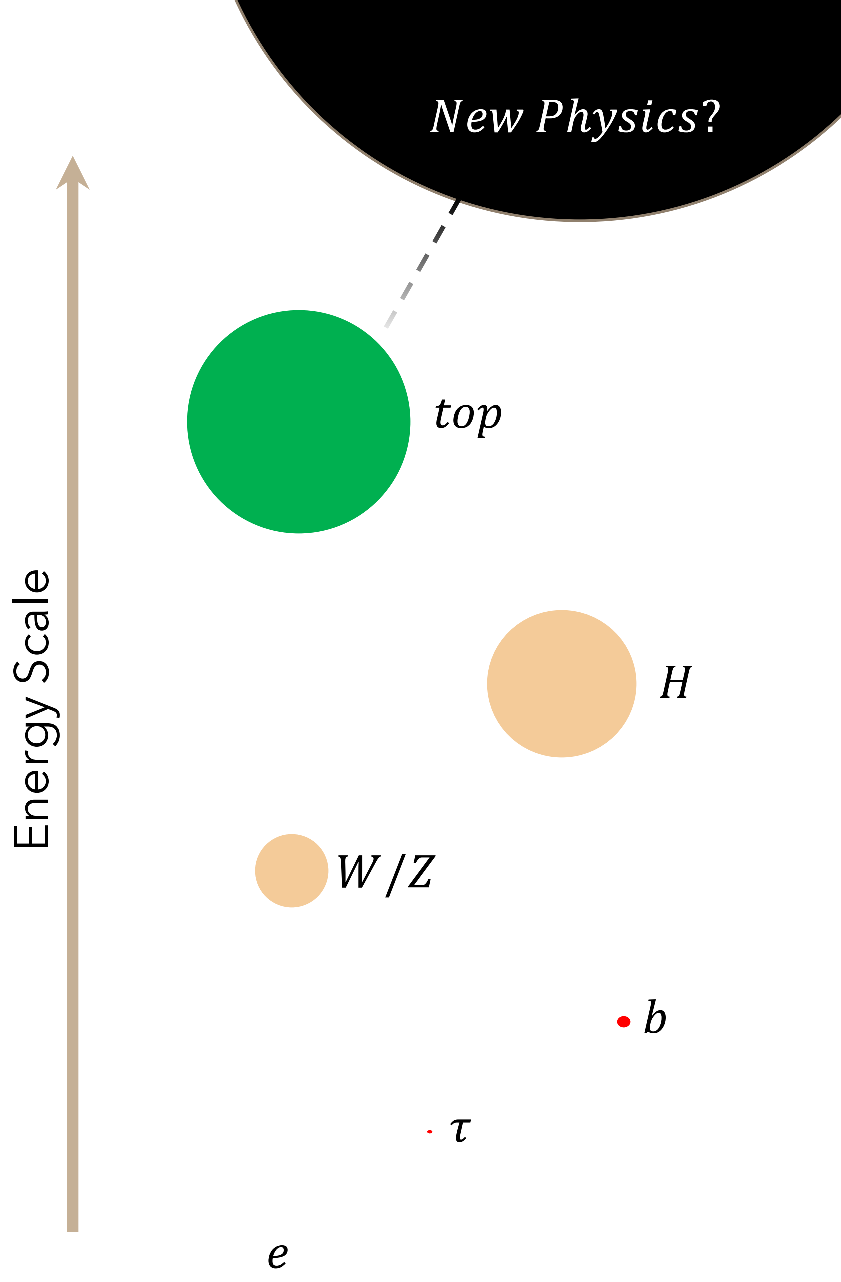
Top Methodology

- Use the top quark – it is the most massive particle and the closest to the scale of new physics – it's vulnerable!
- Very short lifetime (does not hadronise) – opportunity to study a 'bare' quark
- Very selective about decay channels $BR(t \to Wb) \sim 100\%$



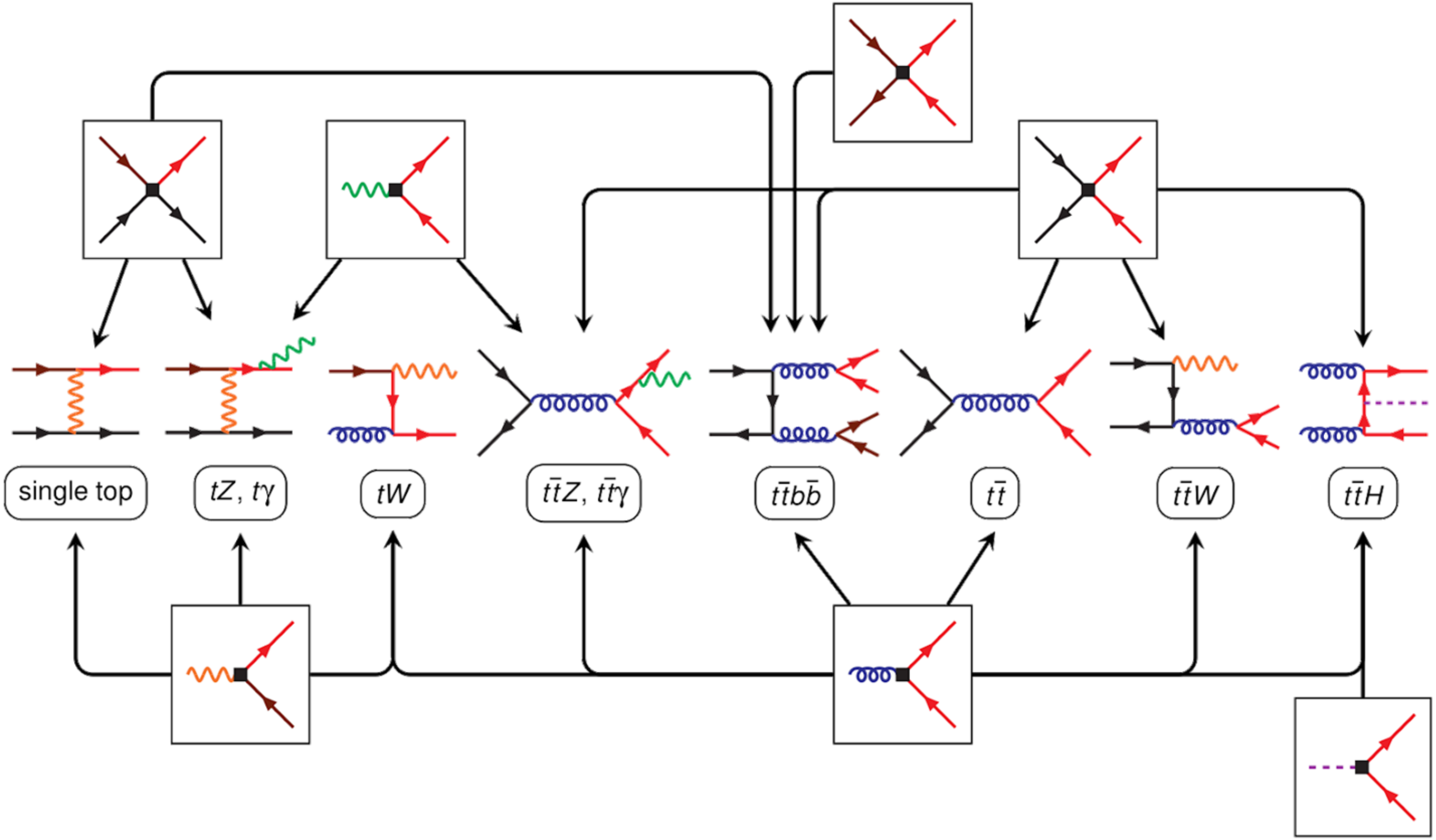






Top EFT

arXiv:1008.4484



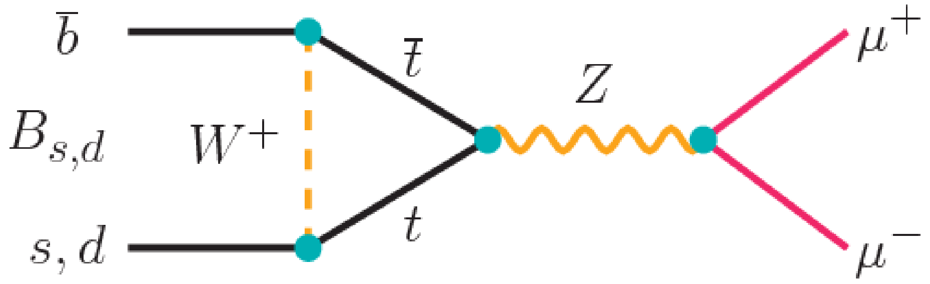
Top EFT

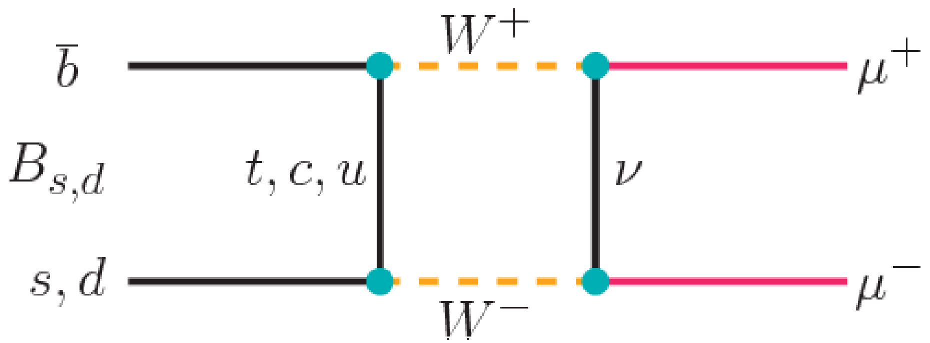
arXiv:1008.4484

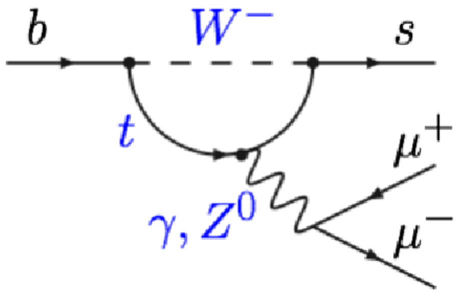
parameter	$t\bar{t}$	single t	tW	tZ	t decay	$t\bar{t}Z$	$t\bar{t}W$
$C_{Qq}^{1,8}$	Λ^{-2}	–	–	–	–	Λ^{-2}	Λ^{-2}
$C_{Qq}^{3,8}$	Λ^{-2}	Λ^{-4} $[\Lambda^{-2}]$	–	Λ^{-4} $[\Lambda^{-2}]$	Λ^{-4} $[\Lambda^{-2}]$	Λ^{-2}	Λ^{-2}
C_{tu}^{8}, C_{td}^{8}	Λ^{-2}	–	–	–	–	Λ^{-2}	–
$C_{Qq}^{1,1}$	Λ^{-4} $[\Lambda^{-2}]$	–	–	–	–	Λ^{-4} $[\Lambda^{-2}]$	Λ^{-4} $[\Lambda^{-2}]$
$C_{Qq}^{3,1}$	Λ^{-4} $[\Lambda^{-2}]$	Λ^{-2}	–	Λ^{-2}	Λ^{-2}	Λ^{-4} $[\Lambda^{-2}]$	Λ^{-4} $[\Lambda^{-2}]$
C_{tu}^{1}, C_{td}^{1}	Λ^{-4} $[\Lambda^{-2}]$	–	–	–	–	Λ^{-4} $[\Lambda^{-2}]$	–
C_{Qu}^{8}, C_{Qd}^{8}	Λ^{-2}	–	–	–	–	Λ^{-2}	–
C_{tq}^{8}	Λ^{-2}	–	–	–	–	Λ^{-2}	Λ^{-2}
C_{Qu}^{1}, C_{Qd}^{1}	Λ^{-4} $[\Lambda^{-2}]$	–	–	–	–	Λ^{-4} $[\Lambda^{-2}]$	–
C_{tq}^{1}	Λ^{-4} $[\Lambda^{-2}]$	–	–	–	–	Λ^{-4} $[\Lambda^{-2}]$	Λ^{-4} $[\Lambda^{-2}]$
$C_{\phi Q}^{-}$	–	–	–	Λ^{-2}	–	Λ^{-2}	–
$C_{\phi Q}^{3}$	–	Λ^{-2}	Λ^{-2}	Λ^{-2}	Λ^{-2}	Λ^{-2}	–
$C_{\phi t}$	–	–	–	Λ^{-2}	–	Λ^{-2}	–
$C_{\phi tb}$	–	Λ^{-4}	Λ^{-4}	Λ^{-4}	Λ^{-4}	–	–
C_{tZ}	–	–	–	Λ^{-2}	–	Λ^{-2}	–
C_{tW}	–	Λ^{-2}	Λ^{-2}	Λ^{-2}	Λ^{-2}	–	–
C_{bW}	–	Λ^{-4}	Λ^{-4}	Λ^{-4}	Λ^{-4}	–	–
C_{tG}	Λ^{-2}	$[\Lambda^{-2}]$	Λ^{-2}	–	$[\Lambda^{-2}]$	Λ^{-2}	Λ^{-2}

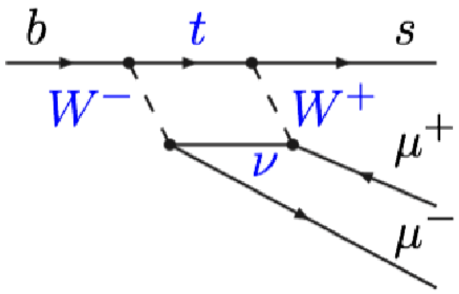
Example contributions of Wilson coefficients to top-quark observables via SM-interference (Λ^{-2}) and via dimension-6 squared terms only (Λ^{-4})

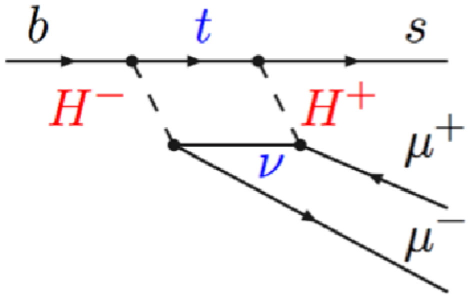
Top EFT and the B-anomalies



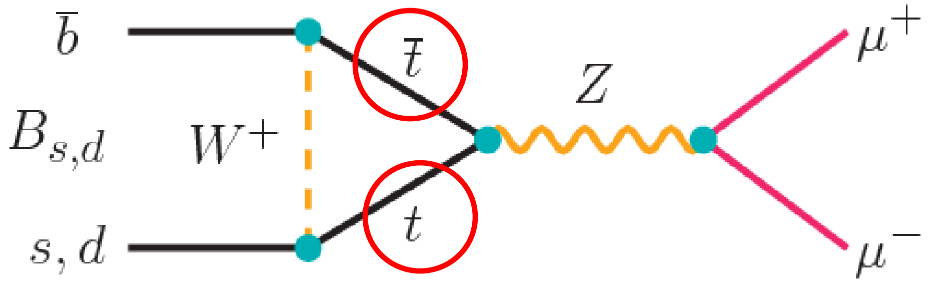


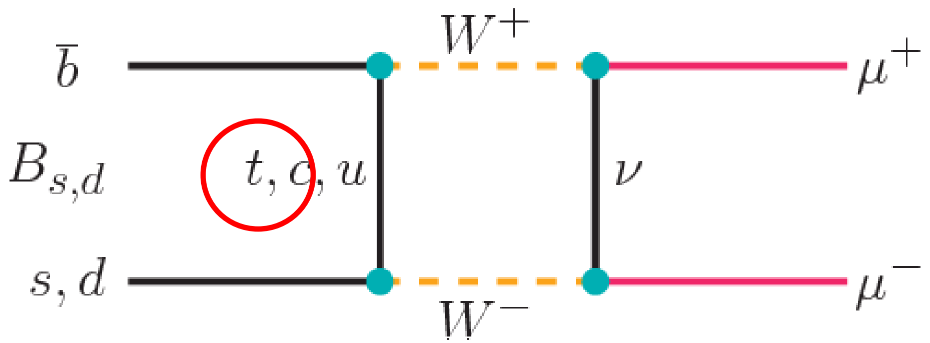


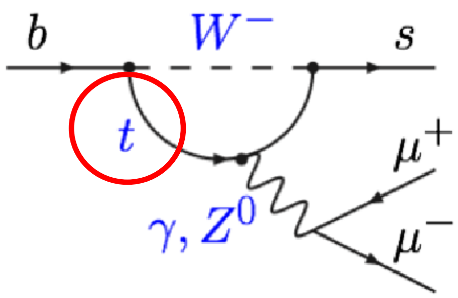


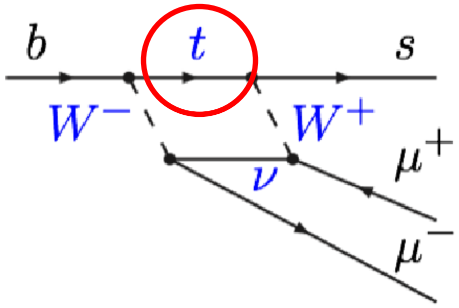


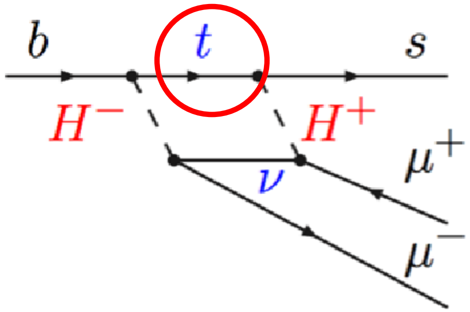
Top EFT and the B-anomalies



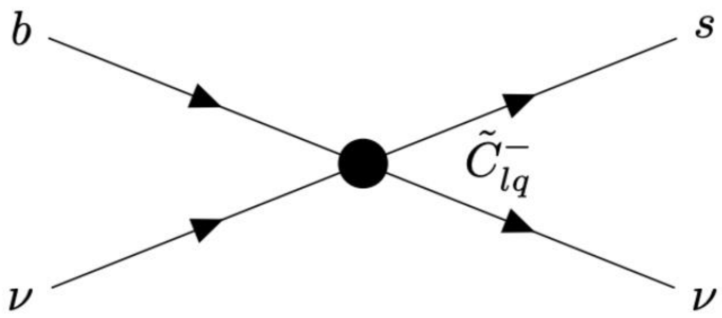


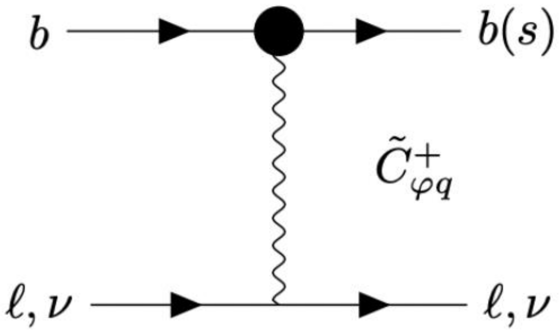


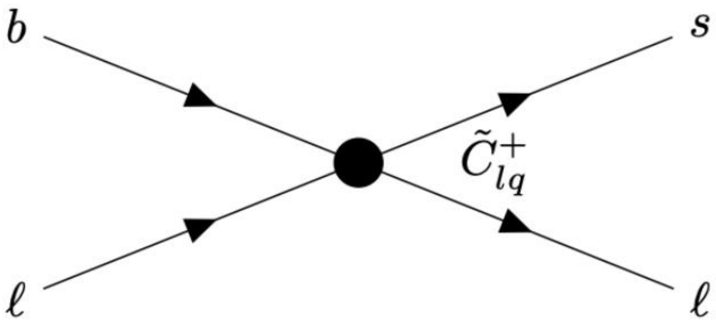


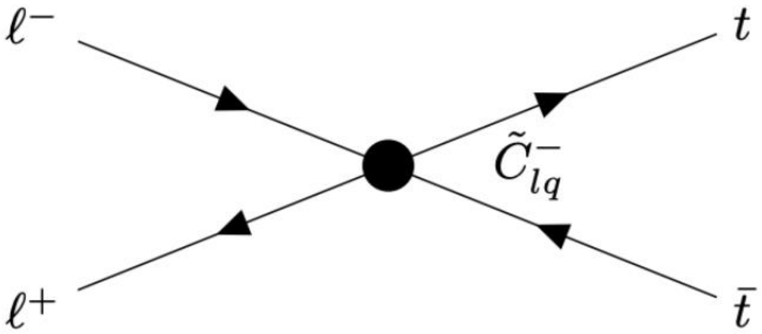


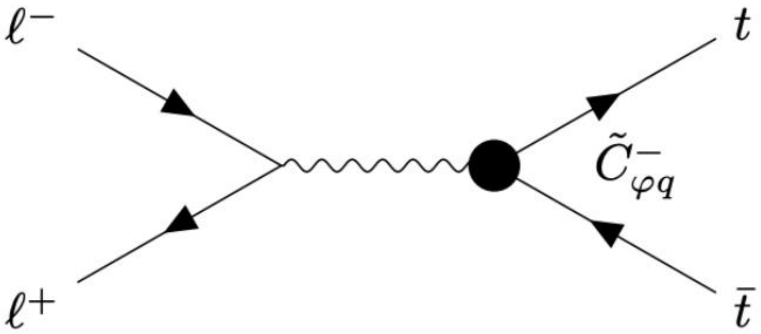
Top EFT and the B-anomalies











Four-fermion operators

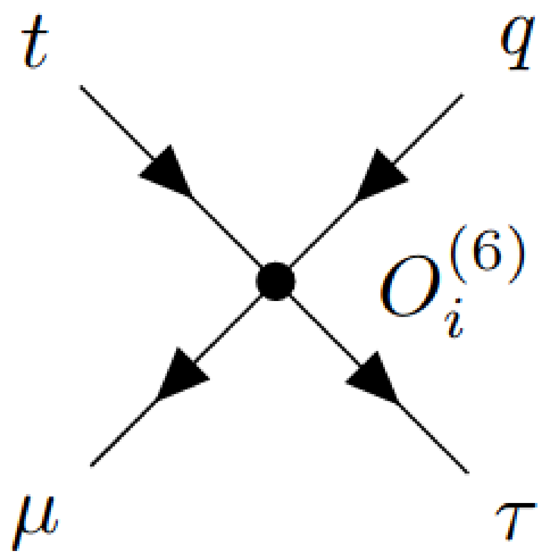
Four-fermion / 2-quark-2-lepton (2Q2L) operator ‘family’ in context

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
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}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu} u_t)$		

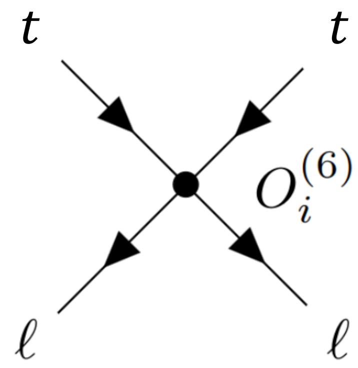
2Q2L EFT operators

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

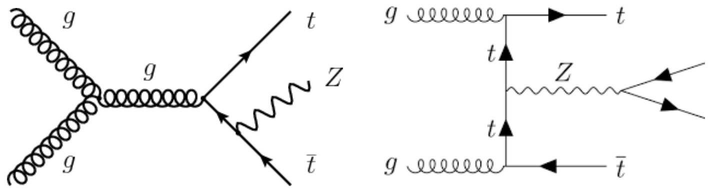


Top 2Q2L operator effects

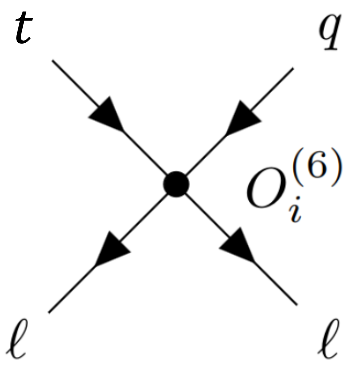
$t\bar{t}Z$-like (diagonal)



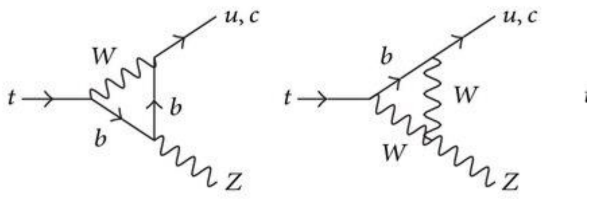
$t\bar{t}ll$



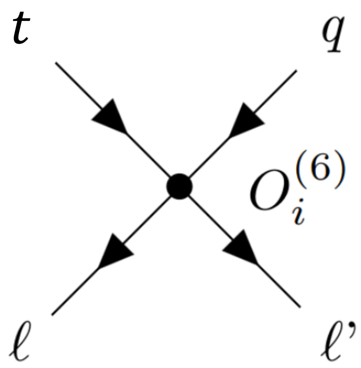
FCNC (semi-diagonal)



$tqll$



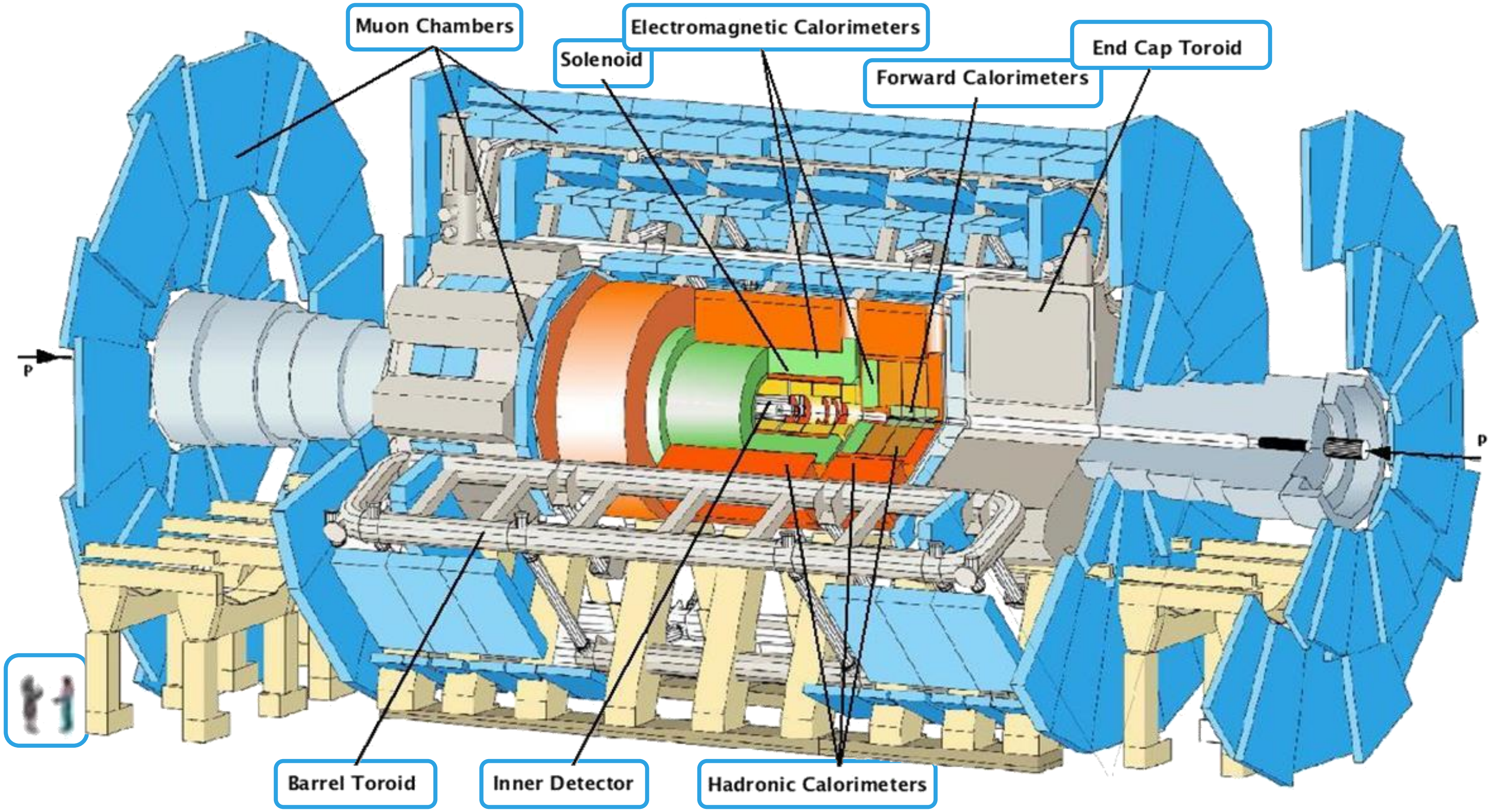
CLFV (fully off-diagonal)



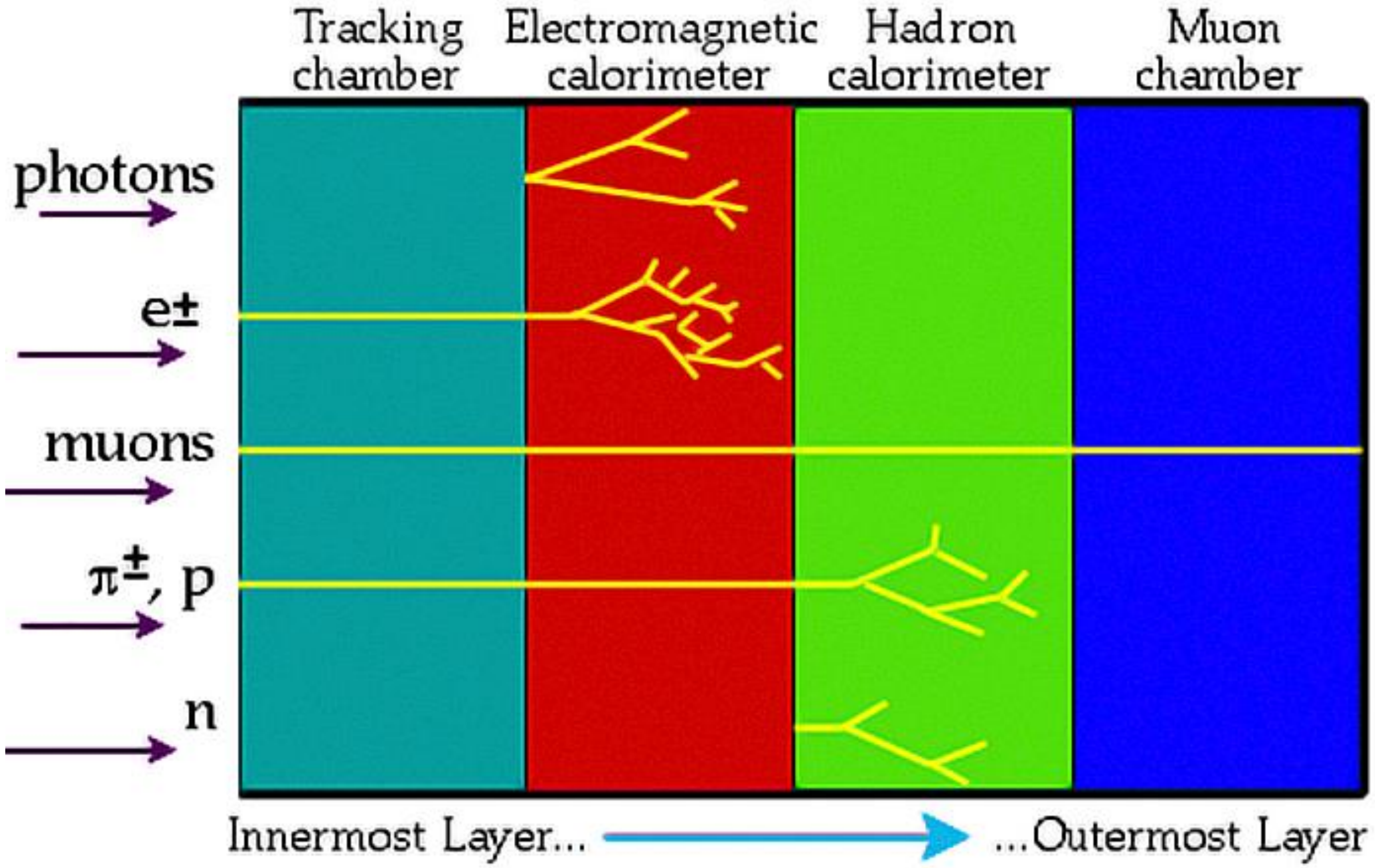
$tqll'$

ATLAS and Top

ATLAS


Muon Chambers
Solenoid
Electromagnetic Calorimeters
Forward Calorimeters
End Cap Toroid
P
P
Barrel Toroid
Inner Detector
Hadronic Calorimeters

ATLAS


Tracking chamber
Electromagnetic calorimeter
Hadron calorimeter
Muon chamber
photons
e±
muons
π±, p
n
Innermost Layer...
...Outermost Layer

Analyses

- B-physics CP violation with Soft Muon Tagging — JHEP 02 (2017) 071
- Lepton Flavour Universality in Top decays — Nat. Phys. 17 (2021) 813-818
- Top FCNC $t \to qH(\to \tau\tau)$ — JHEP 06 (2023) 155
- Top CLFV $\mu\tau qt$ — (Accepted by PRD) arXiv:2403.06742

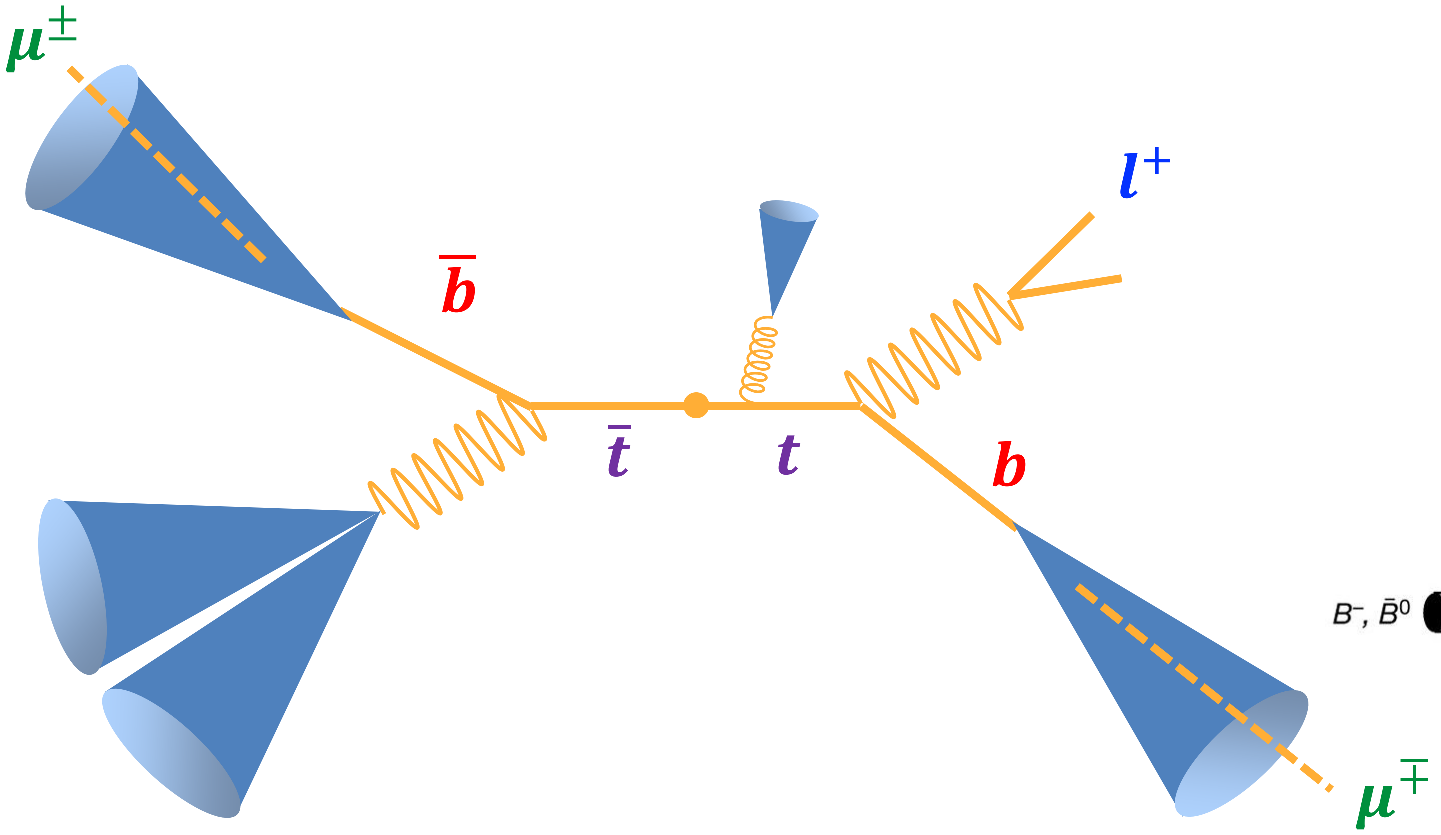
What's in the future?

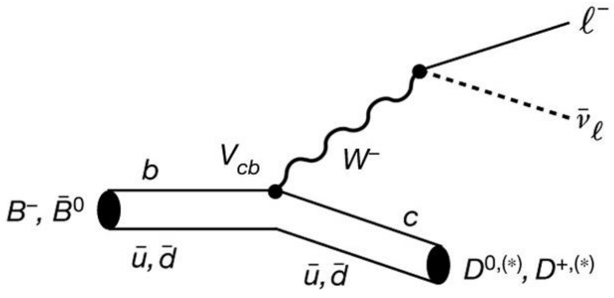
B-physics CP violation with Soft Muon Tagging

(vs D0 dimuon asymmetry)

B-physics CP violation with Soft Muon Tagging

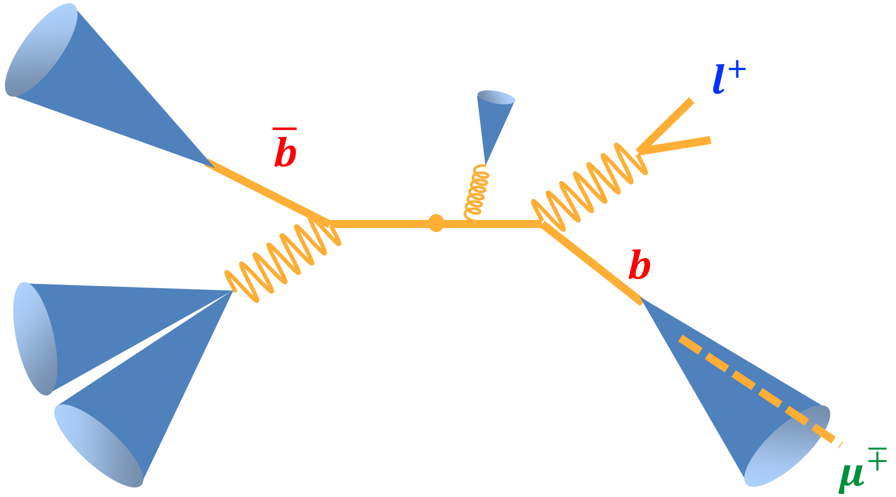
Lots of tops **lots of b** **lots of information**



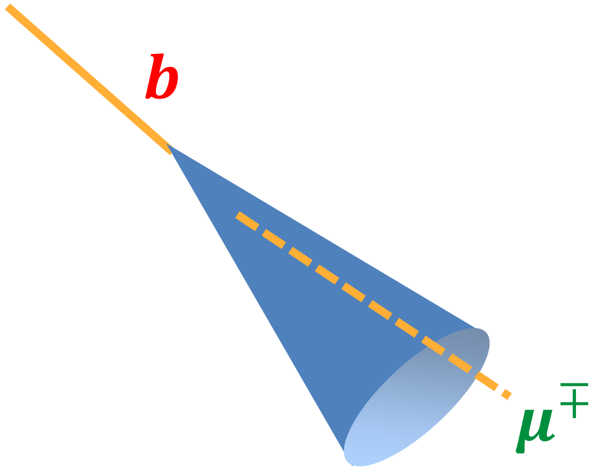


Unlike $gg \to b\bar{b}$, we know which b we are dealing with!

The charge of the W, tagged with a lepton, tells you the charge of the associated b-quark at **production**



$$l^+ \Rightarrow b \qquad\qquad l^- \Rightarrow \bar{b}$$

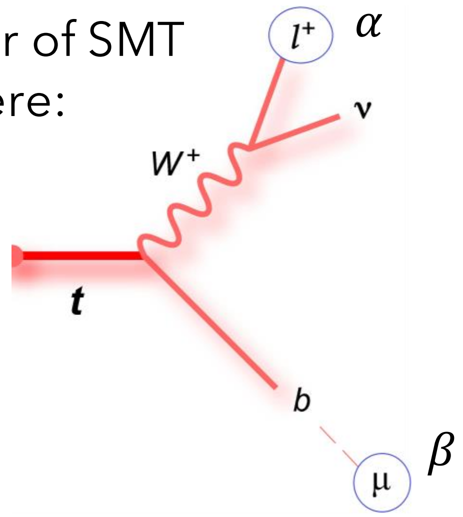


$$\mathbf{BR}(b \to (\ldots) \to \mu) \sim 20\%$$

The charge of the soft muon, tells you the charge of the associated b-quark at **decay**

Charge asymmetries

Consider number of SMT muons, $N^{\alpha\beta}$, where:



$$A^{ss} = \frac{P(b \to l^+) - P(\bar{b} \to l^-)}{P(b \to l^+) + P(\bar{b} \to l^-)} = \frac{\left(\frac{N^{++}}{N^+}\right) - \left(\frac{N^{--}}{N^-}\right)}{\left(\frac{N^{++}}{N^+}\right) + \left(\frac{N^{--}}{N^-}\right)}$$

$$A^{os} = \frac{P(b \to l^-) - P(\bar{b} \to l^+)}{P(b \to l^-) + P(\bar{b} \to l^+)} = \frac{\left(\frac{N^{+-}}{N^+}\right) - \left(\frac{N^{-+}}{N^-}\right)}{\left(\frac{N^{+-}}{N^+}\right) + \left(\frac{N^{-+}}{N^-}\right)}$$

CP asymmetries

- CP asymmetries can be extracted from A^{ss}, A^{os}
- As defined in **PRL 110,232002 (2013)**:

$$A^{ss} = r_b A^{bl}_{\text{mix}} + r_{c\bar{c}} A^{bc}_{\text{mix}} + r_c A^{bc}_{\text{dir}} - (r_c + r_{c\bar{c}}) A^{cl}_{\text{dir}}$$

$$A^{os} = \tilde{r}_c A^{bc}_{\text{mix}} + \tilde{r}_b A^{bl}_{\text{dir}} + (\tilde{r}_c + \tilde{r}_{c\bar{c}}) A^{cl}_{\text{dir}}$$

$$A^{bl}_{\text{mix}} = \frac{\Gamma(b\to\bar{b}\to l^+X)-\Gamma(\bar{b}\to b\to l^-X)}{\Gamma(b\to\bar{b}\to l^+X)+\Gamma(\bar{b}\to\bar{b}\to l^-X)} \quad \overset{A^{b}_{\text{mix}}}{\longleftrightarrow} \quad A^{bc}_{\text{mix}} = \frac{\Gamma(b\to\bar{b}\to\bar{c}X)-\Gamma(\bar{b}\to b\to cX)}{\Gamma(b\to\bar{b}\to cX)+\Gamma(\bar{b}\to\bar{b}\to cX)}$$

$$A^{bl}_{\text{dir}} = \frac{\Gamma(b\to l^-X)-\Gamma(\bar{b}\to l^+X)}{\Gamma(b\to l^-X)+\Gamma(\bar{b}\to l^+X)} \qquad A^{cl}_{\text{dir}} = \frac{\Gamma(\bar{c}\to l^-X_L)-\Gamma(c\to l^+X_L)}{\Gamma(\bar{c}\to l^-X_L)+\Gamma(c\to l^+X_L)}$$

$$A^{bc}_{\text{dir}} = \frac{\Gamma(b\to cX_L)-\Gamma(\bar{b}\to\bar{c}X_L)}{\Gamma(b\to cX_L)+\Gamma(\bar{b}\to\bar{c}X_L)}$$

Results	Data (10^{-2})	Existing limits (2σ) (10^{-2})	SM (10^{-2})
A^{ss}	-0.7 ± 0.8	–	$< 10^{-2}$ [1]
A^{os}	0.4 ± 0.5	–	$< 10^{-2}$ [1]
A^{b}_{mix}	-2.5 ± 2.8	< 0.1 [3]	$< 10^{-3}$ [2,3]
A^{bl}_{dir}	0.5 ± 0.5	< 1.2 [4]	$< 10^{-5}$ [1]
A^{cl}_{dir}	1.0 ± 1.0	< 6.0 [4]	$< 10^{-9}$ [1]
A^{bc}_{dir}	-1.0 ± 1.1	–	$< 10^{-7}$ [5]

At 2σ the constraints made by this analysis are stronger than the existing limit on A^{cl}_{dir}
This the first direct experimental constraint on A^{bc}_{dir}.

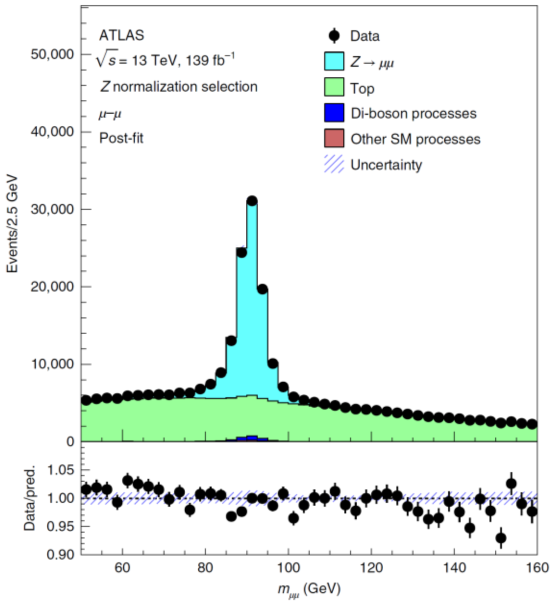
[1] PRL 110, 232002 (2013) [2] arXiv:1511.09466v1 [3] arXiv:1412.7515v1 (HFAG) [4] PRD 87, 074036 (2015) [5] PLB 694, 374 (2011)

Lepton Flavour Universality with Tops

(vs LEP LFU)

Lepton Flavour Universality

$$R(\tau/\mu) = \frac{\mathcal{B}(t \to bW(\to \tau\nu))}{\mathcal{B}(t \to bW(\to \mu\nu))}$$

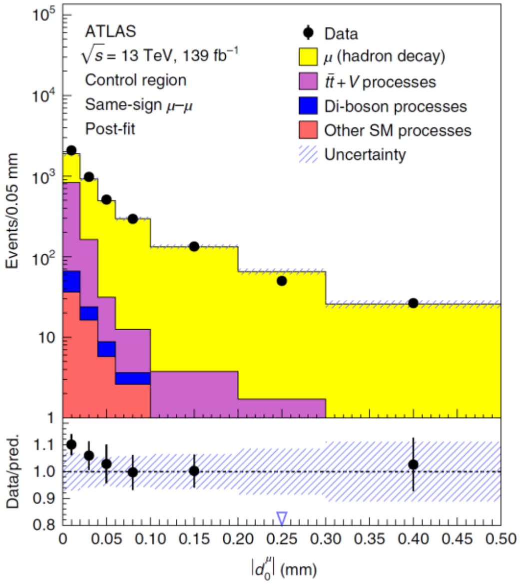


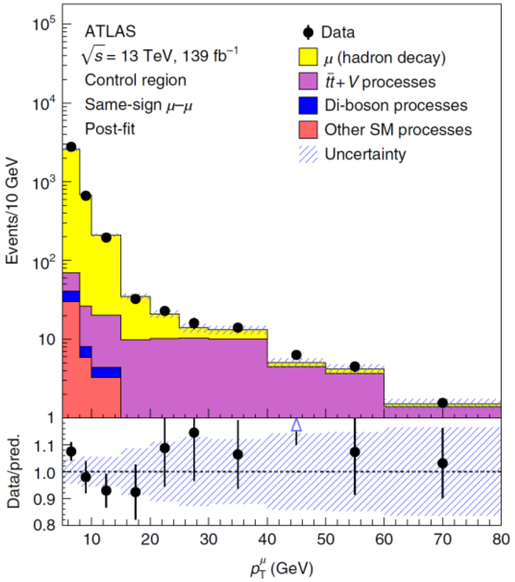
Opposite-sign dimuon events

- Big backgrounds from $Z \to \mu\mu$

Using leptonic $\tau \to \mu$ decays = big challenge!

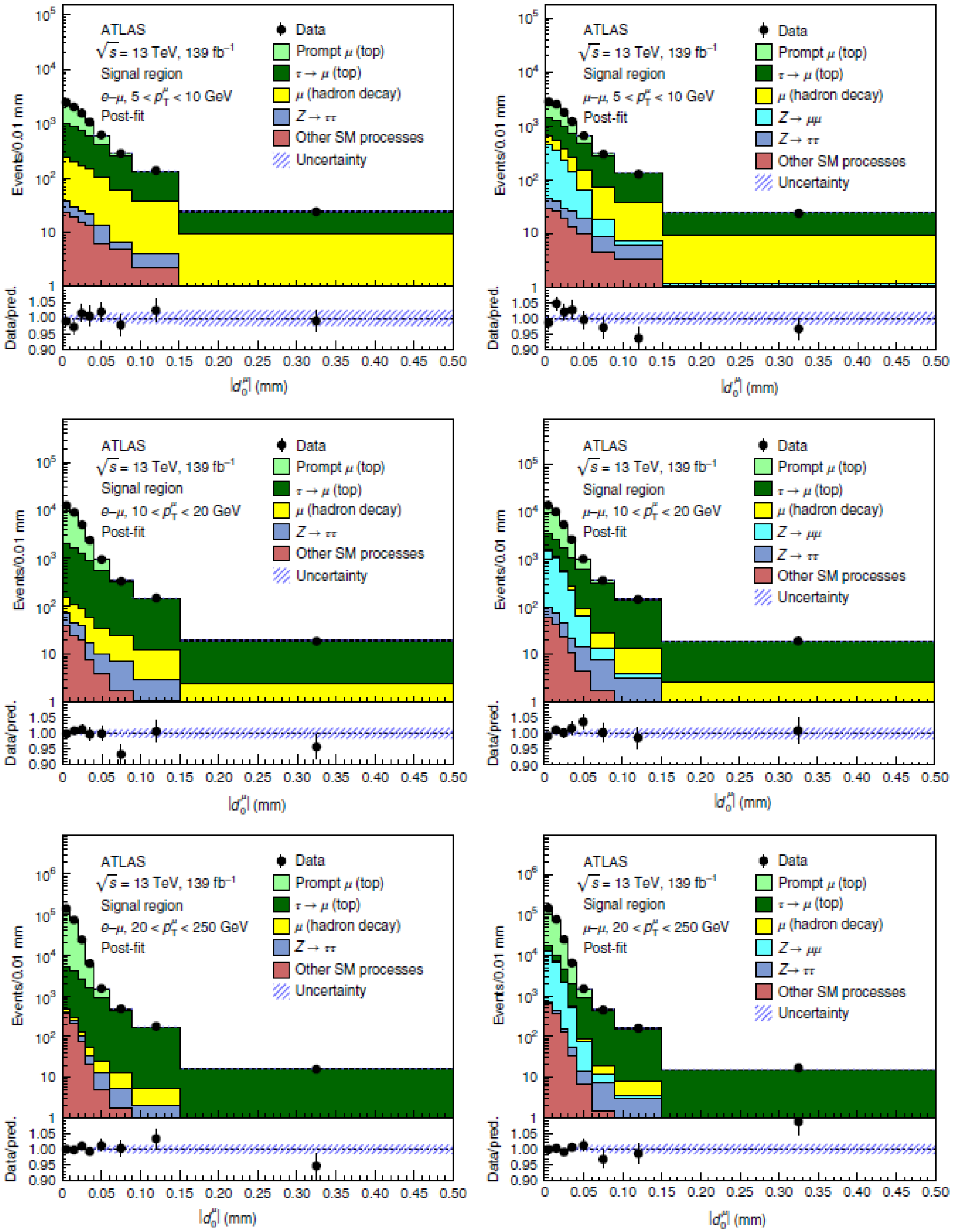
- Difficult to separate from soft muons (hadron decays)

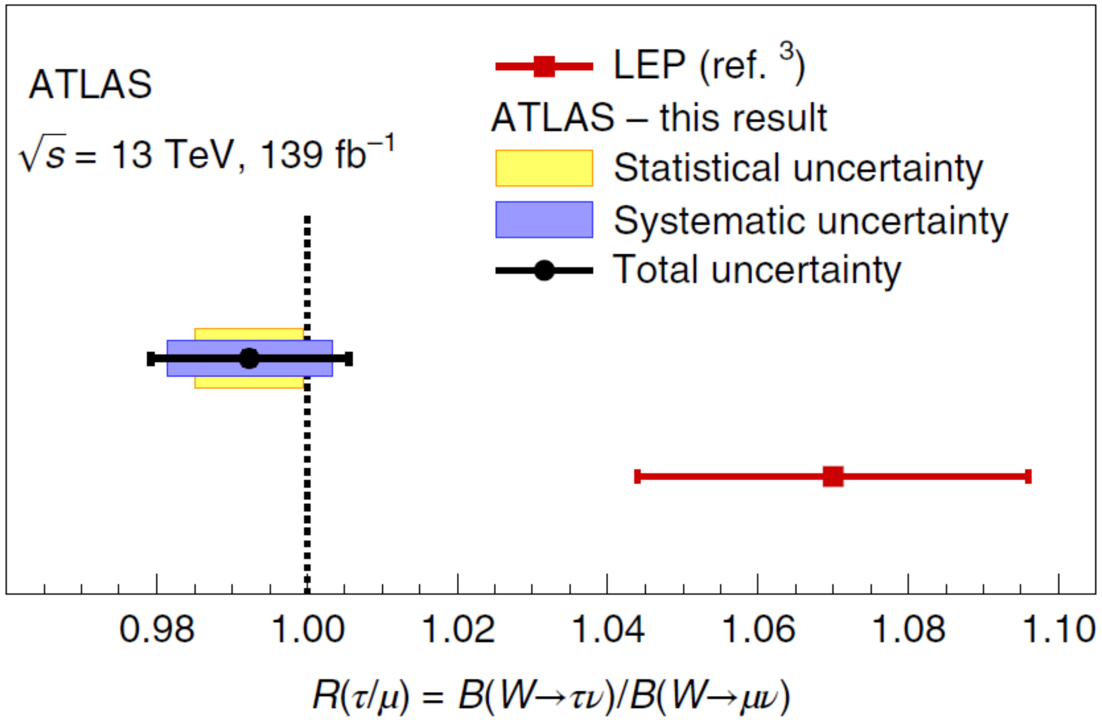




(This is prompt lepton behaviour – i.e. unlikely to be same anomalous physics, but still interesting!)

Lepton Flavour Universality





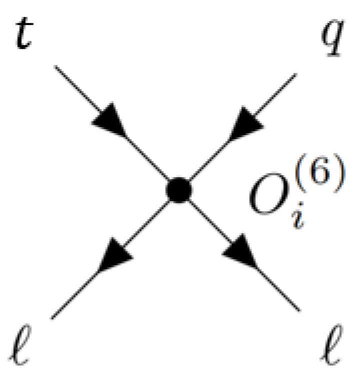
Top FCNC

(vs $b \to sll$)

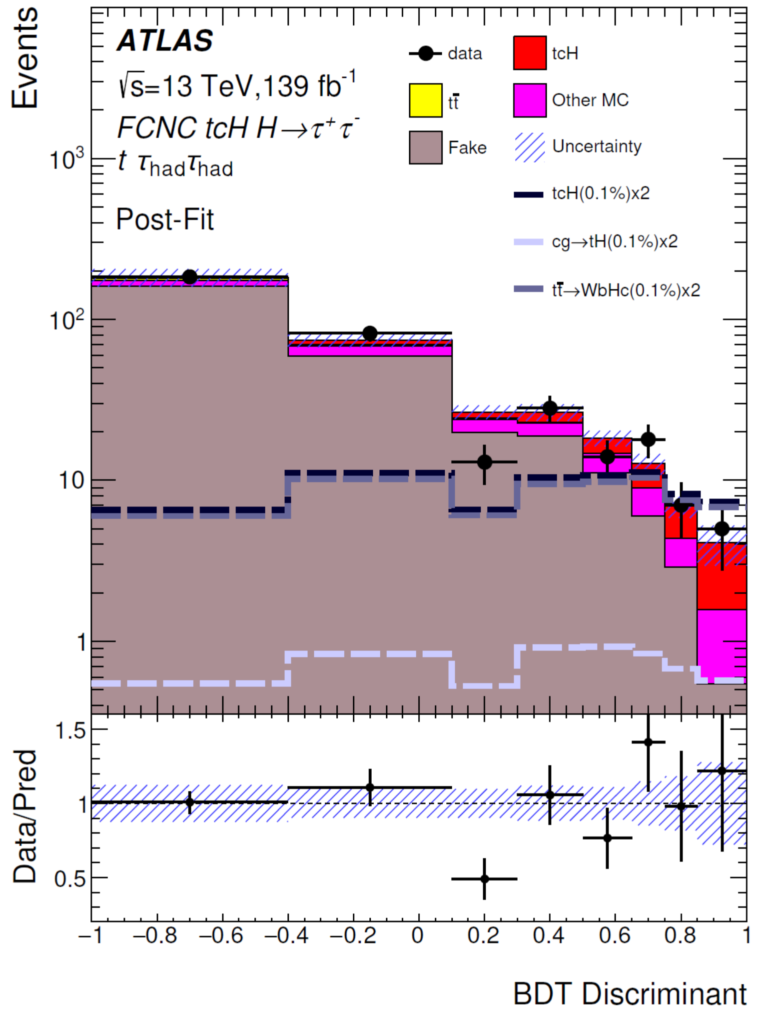
Top FCNC $t \to qH(\to \tau\tau)$

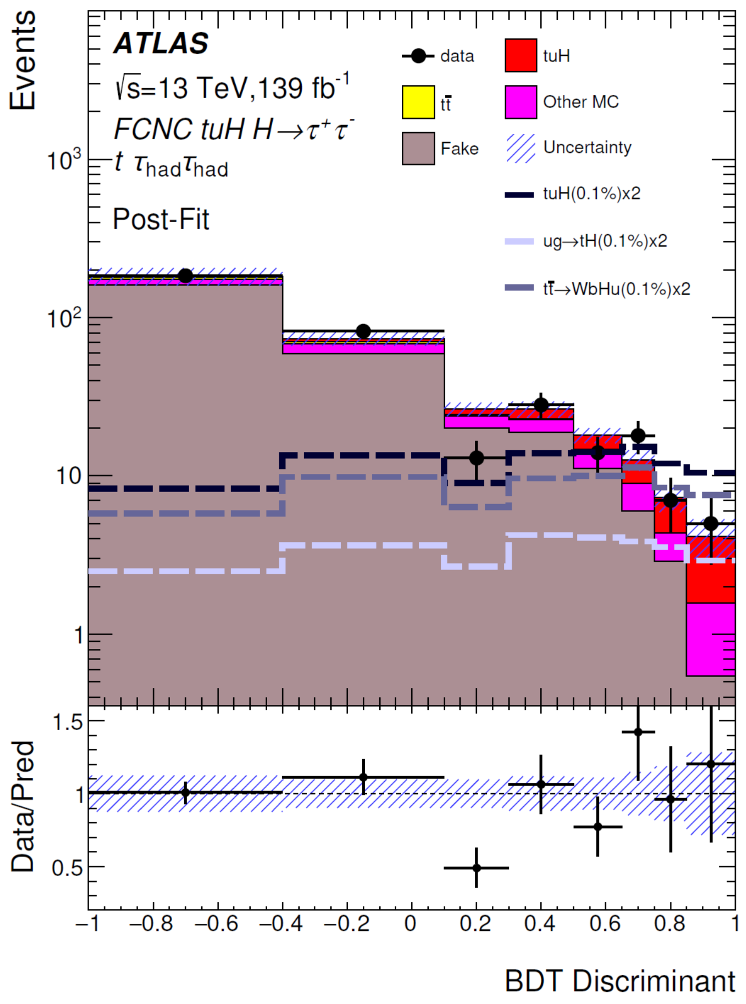
JHEP 06 (2023) 155

FCNC (semi-diagonal)



$tqll$

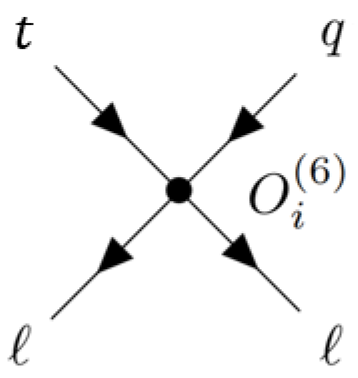




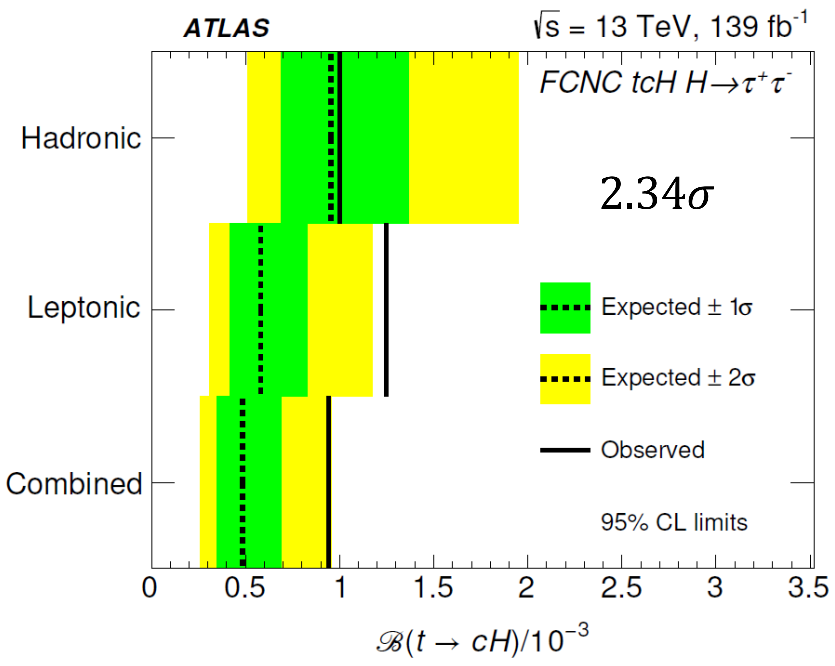
Top FCNC $t \to qH(\to \tau\tau)$

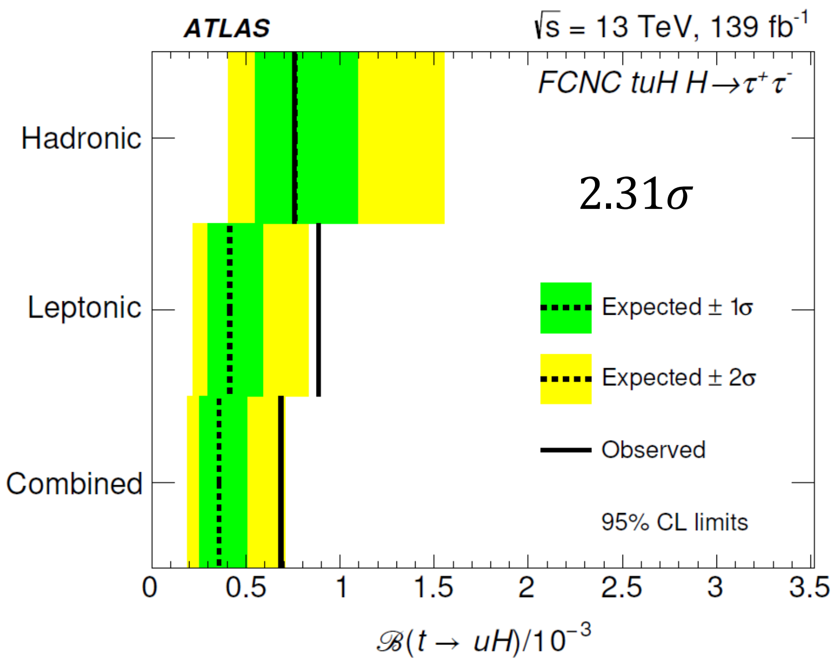
JHEP 06 (2023) 155

FCNC (semi-diagonal)



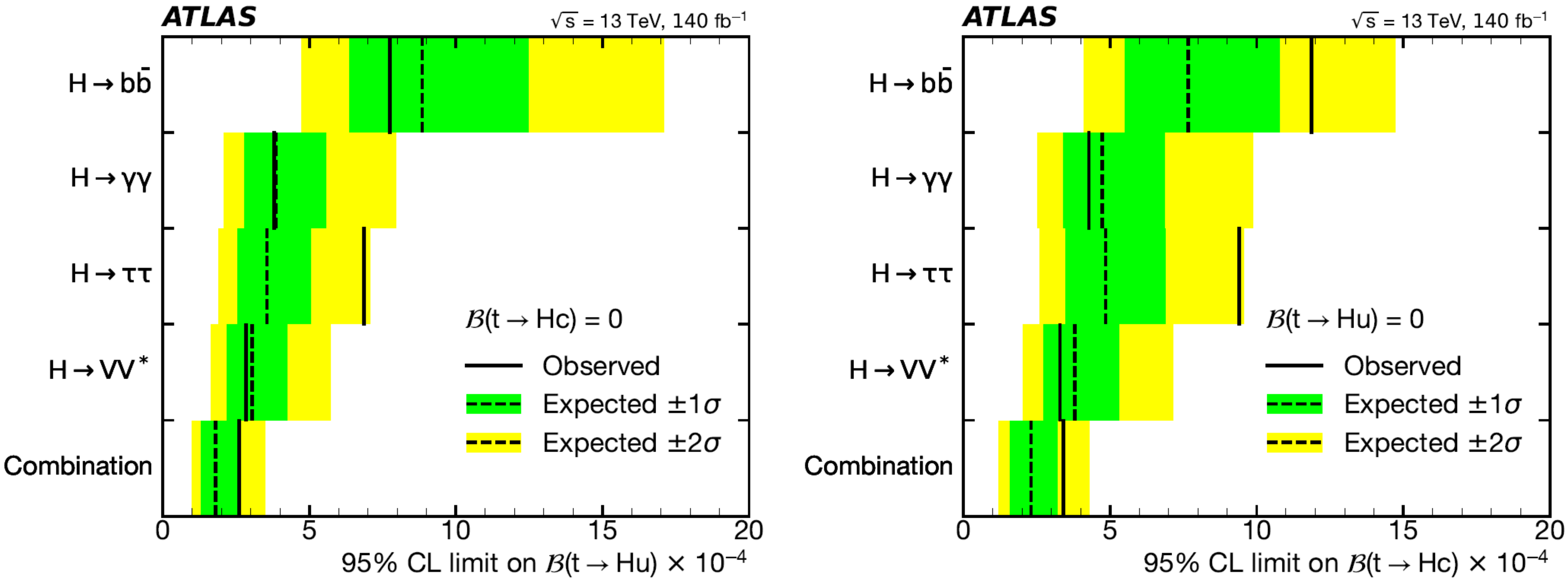
$tqll$





Top FCNC $t \to qH(\to XX)$

arXiv:2404.02123



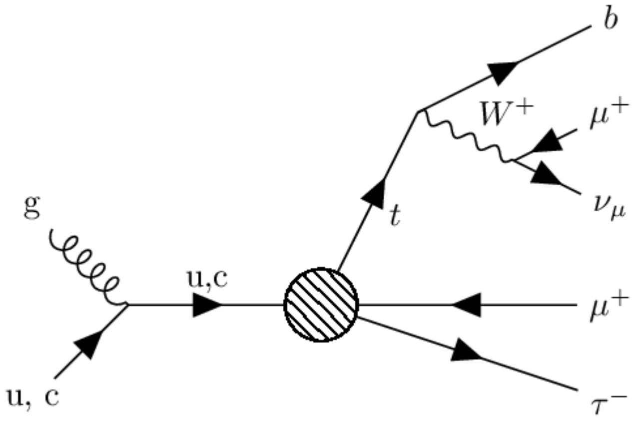
Top Charged-Lepton Flavour-Violation

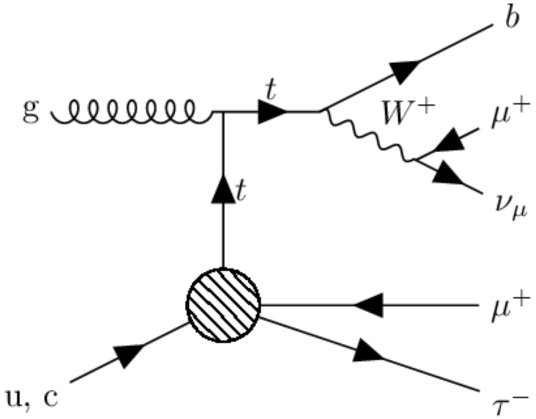
(vs B / Lep flavour anomalies)

Top CLFV

Production

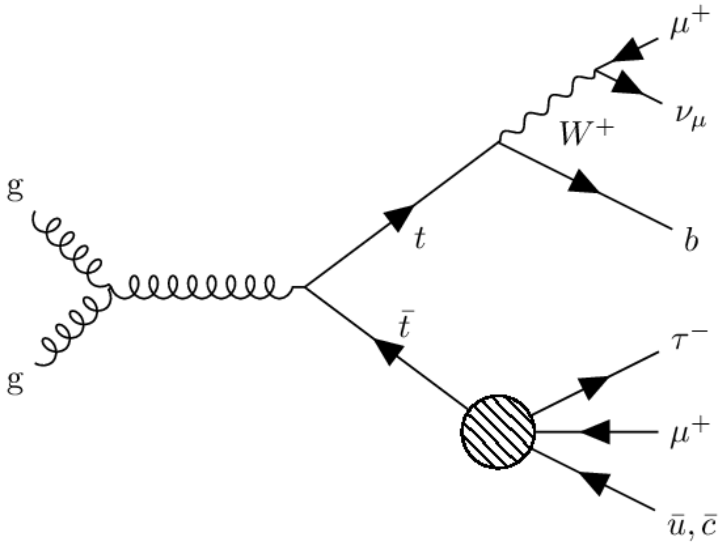
$qg \to tll'$





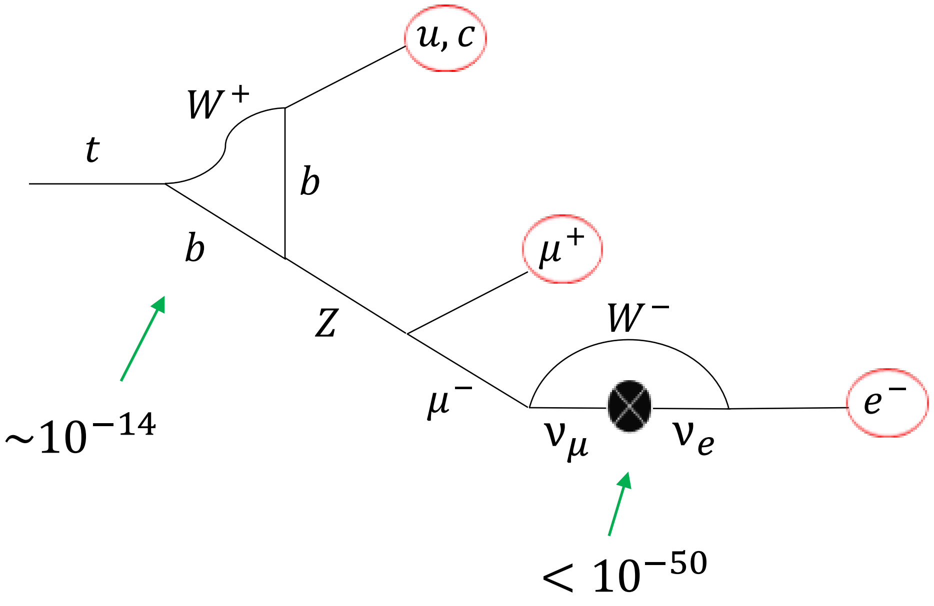
Decay

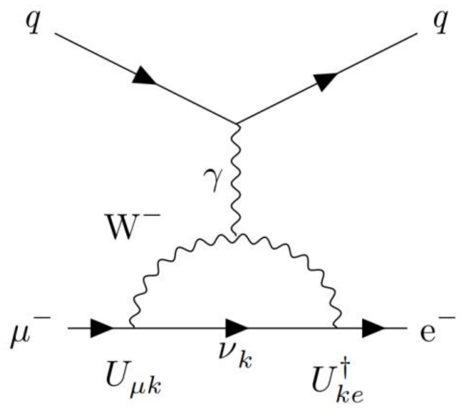
$t\bar{t} \to (ll'q)(l\nu b)$

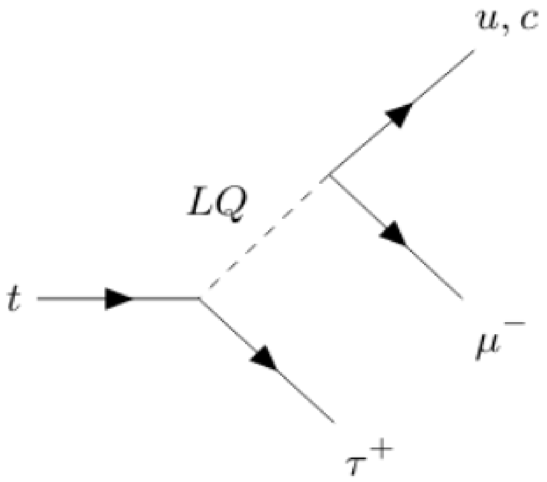


CLFV and Neutrino Oscillations / New Physics

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



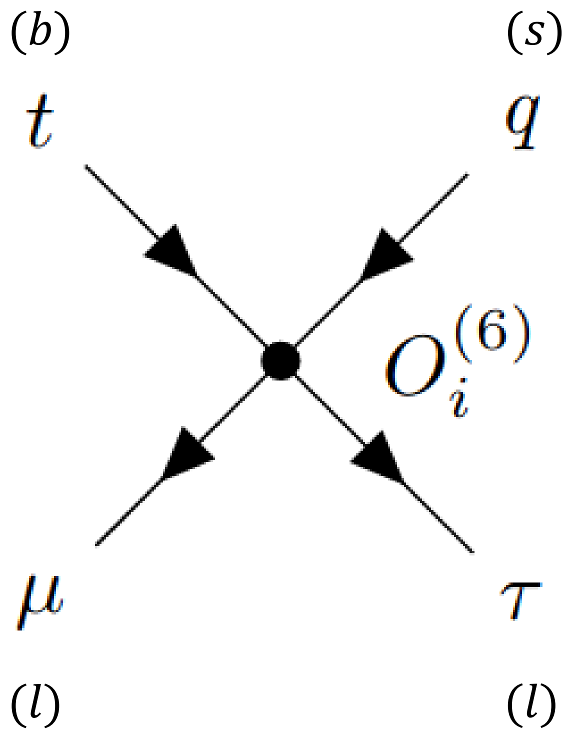




New physics which introduces additional terms involving lepton fields in Lagrangian can lead to LFV, e.g. SUSY, leptoquarks, 2HDMs

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



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 $\mu\tau q t$ coupling.

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

Charged Lepton Flavour Violation

Using dim6top, found to agree with SMEFTsim 3.0

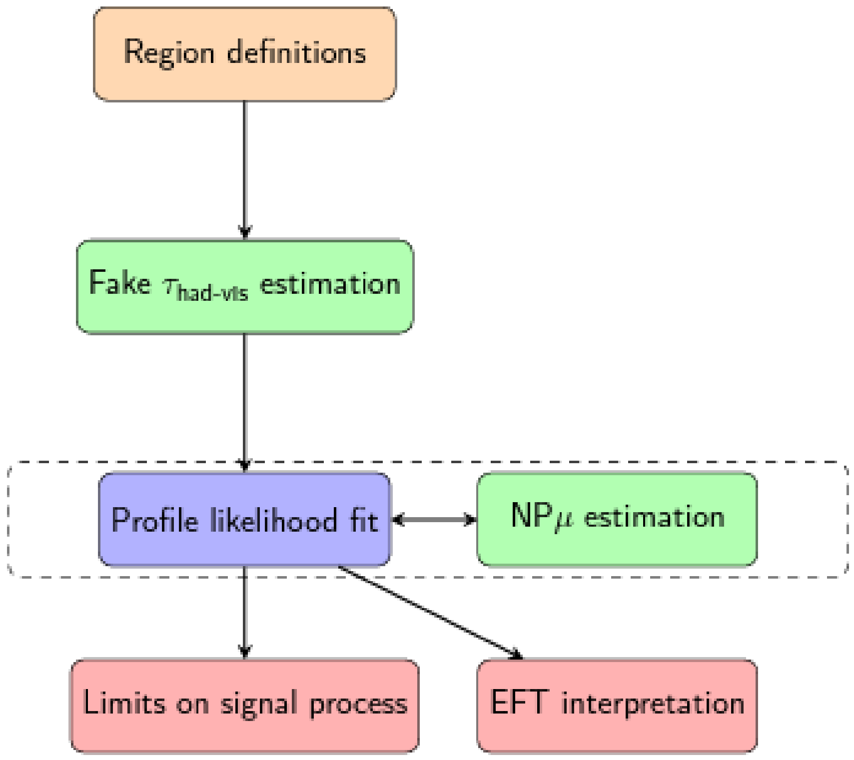
	Cross-section $\sigma^{+\text{scale}}_{-\text{scale}} \pm$ PDF [fb]		
	$c_{\text{vector}}^{(ijk3)}$	$c_{\text{lequ}}^{1(ijk3)}$	$c_{\text{lequ}}^{3(ijk3)}$
Production $\ell\ell' ut$	$118^{+24}_{-19} \pm 1$	$101^{+21}_{-16} \pm 1$	$2150^{+410}_{-320} \pm 20$
Production $\ell\ell' ct$	$7.9^{+1.2}_{-1.0}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

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

JHEP04 (2019) 014

Charged Lepton Flavour Violation

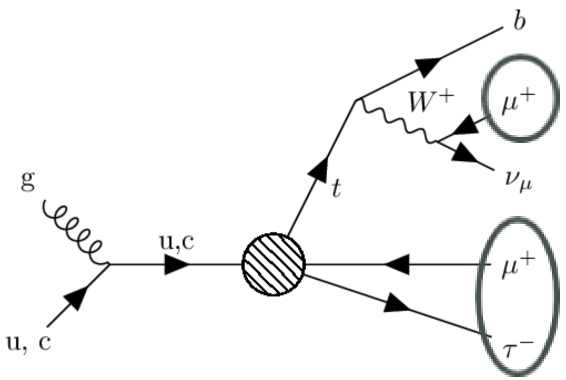
- Single lepton triggers
- Definition of analysis regions including dedicated CRs for fake backgrounds
  - → Select events with electrons, muons and *hadronically-decaying* tau leptons ($\tau_{\text{had-vis}}$)
  - → **Trilepton** selection: $\mu\mu\tau_{\text{had-vis}}/\ e\mu\mu$
- Prompt/real backgrounds estimated in MC ($t\bar{t}V$, diboson, tW)
- Data-driven estimation of fake lepton backgrounds
  - → 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

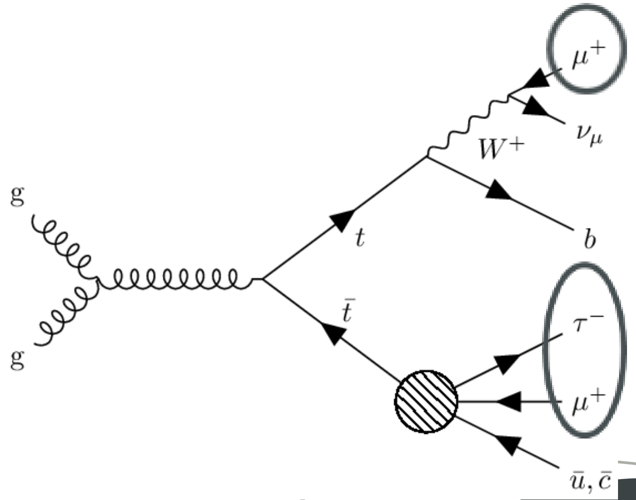


Event selection with 139 fb^{-1}

- 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	$2\mu 1\tau_{had}$		$2\mu 1e$ $(\ell_3 = \mu)$
N_{jets}	≥ 1	≥ 2	≥ 1
N_{b-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	–
$m_{\mu\mu}^{OS}$	–	–	>15 GeV
$\lvert m_{\mu\mu}^{OS} - M_Z \rvert$	–	<10 GeV	>10 GeV
$3p_T^{\mu_1} + \sum m_{\ell\ell}^{OS}$	–	–	< 400 GeV





Yields

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Process	SR			$\text{CR}t\bar{t}\mu$		
$t\bar{t}$ + 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		

Fake-tau estimation

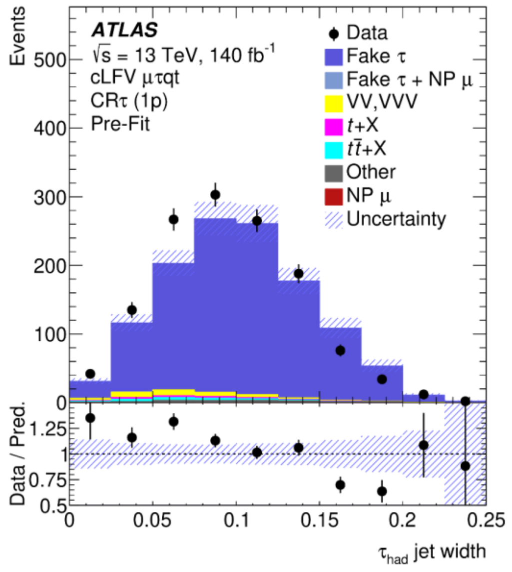
Fakes are usually due to mis-identified jets

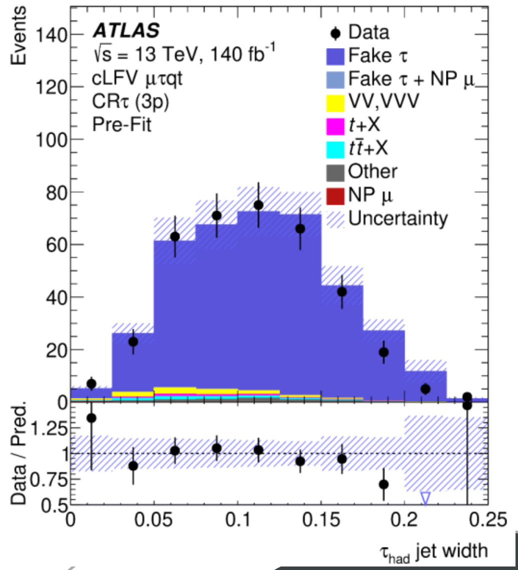
Dedicated CR (does not enter the fit)

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



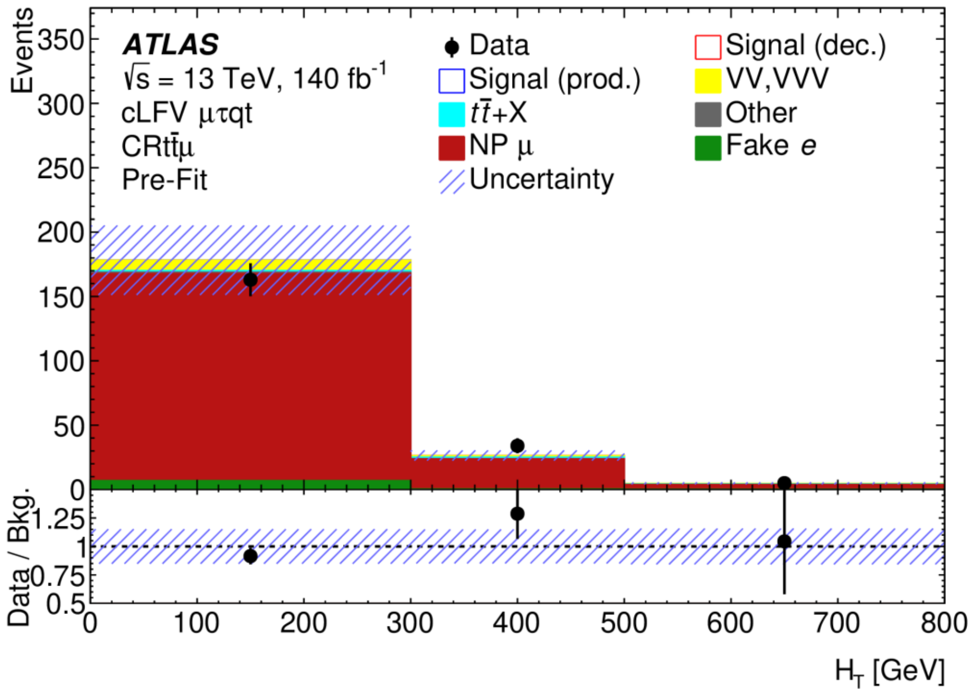


Fake/Non-prompt (NP) muon estimation

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)



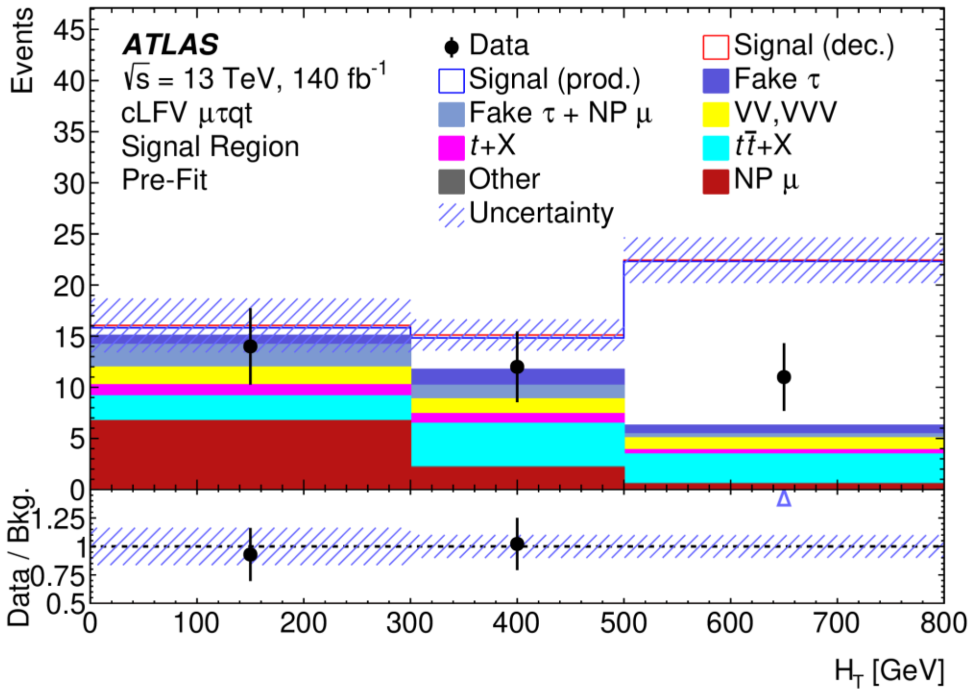
Signal region

Binned in HT to capture energy growth behaviour of EFT operators

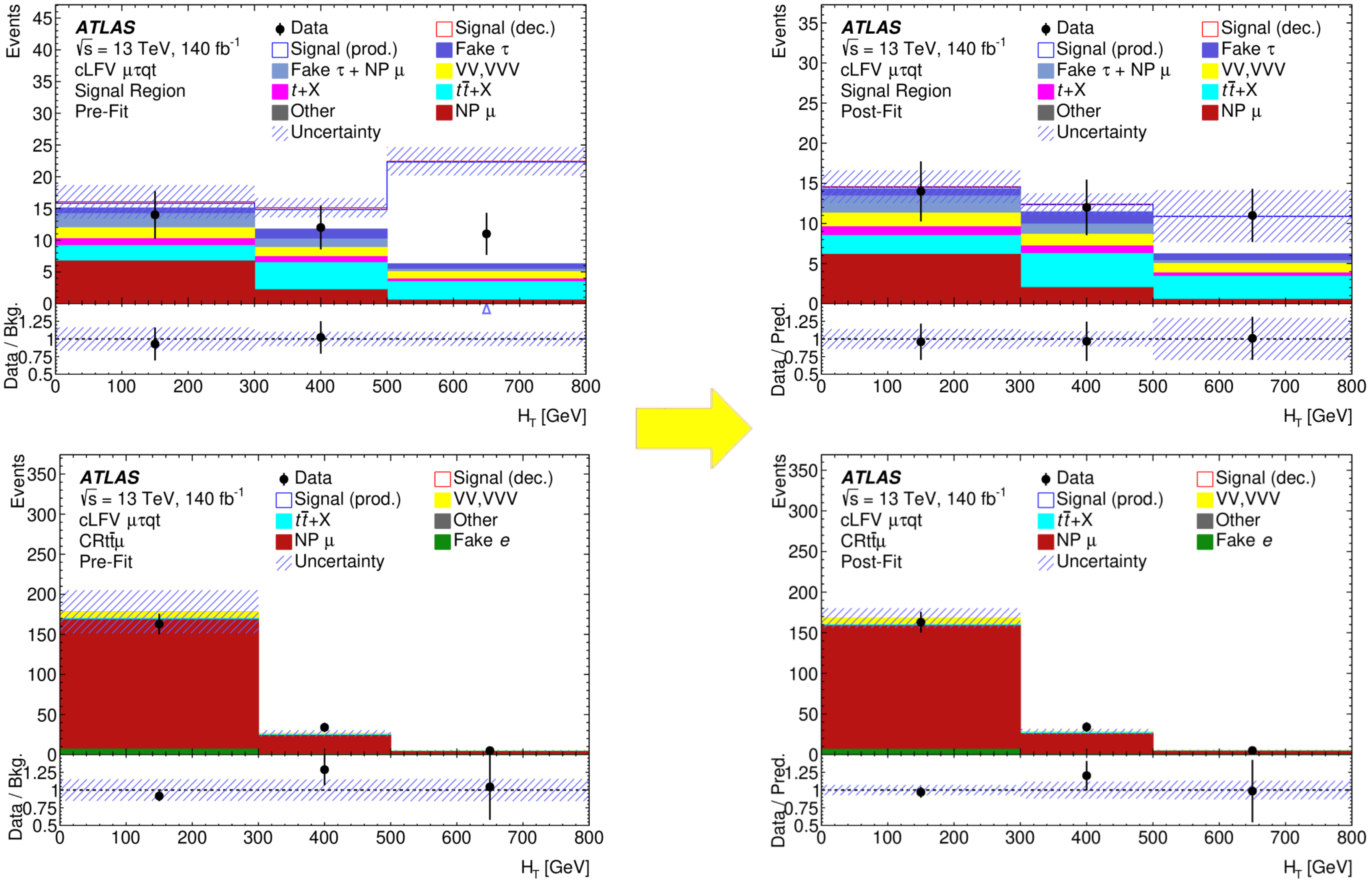
Signal shown is inclusive EFT (up-initiated, charm-initiated, all operators)

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

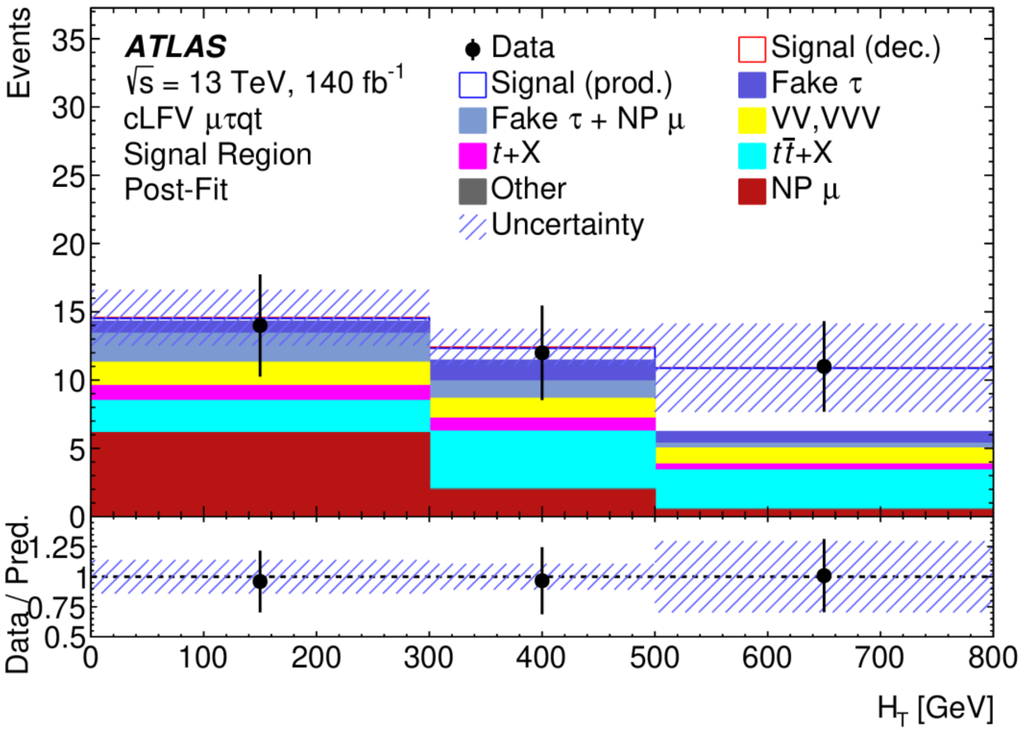


Profile-likelihood fit

Good agreement between data and background-only model

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

1.6σ tension



'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

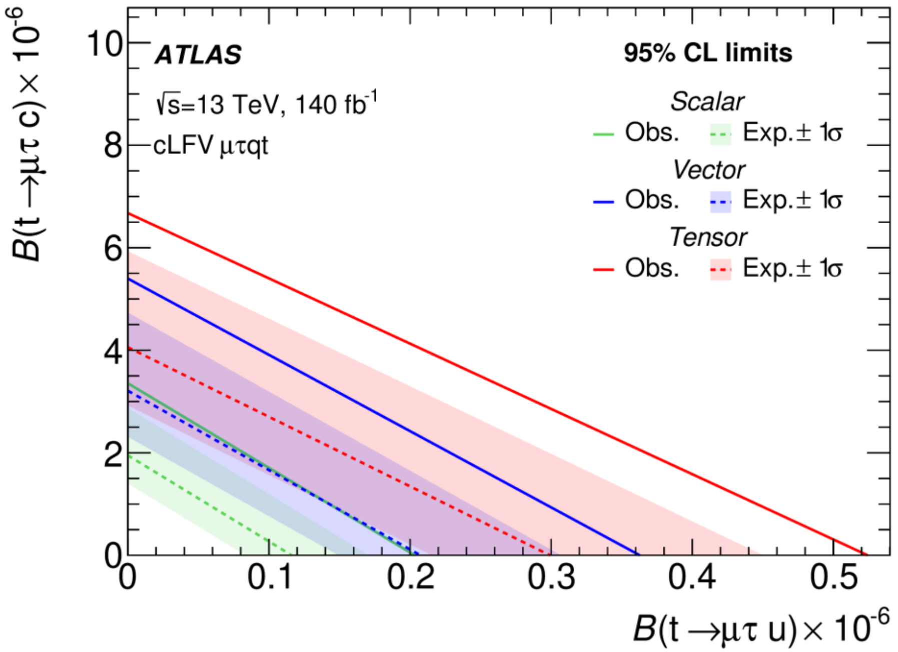
	95% CL upper limits on $\mathcal{B}(t \to \mu\tau q)$ $(\times 10^{-7})$					
	$c_{\mathrm{lq}}^{-(ijk3)}$	$c_{\mathrm{eq}}^{(ijk3)}$	$c_{\mathrm{lu}}^{(ijk3)}$	$c_{\mathrm{eu}}^{(ijk3)}$	$c_{\mathrm{lequ}}^{1(ijk3)}$	$c_{\mathrm{lequ}}^{3(ijk3)}$
Expected (u)	2.3	2.0	1.9	2.2	1.2	3.0
Observed (u)	4.0	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

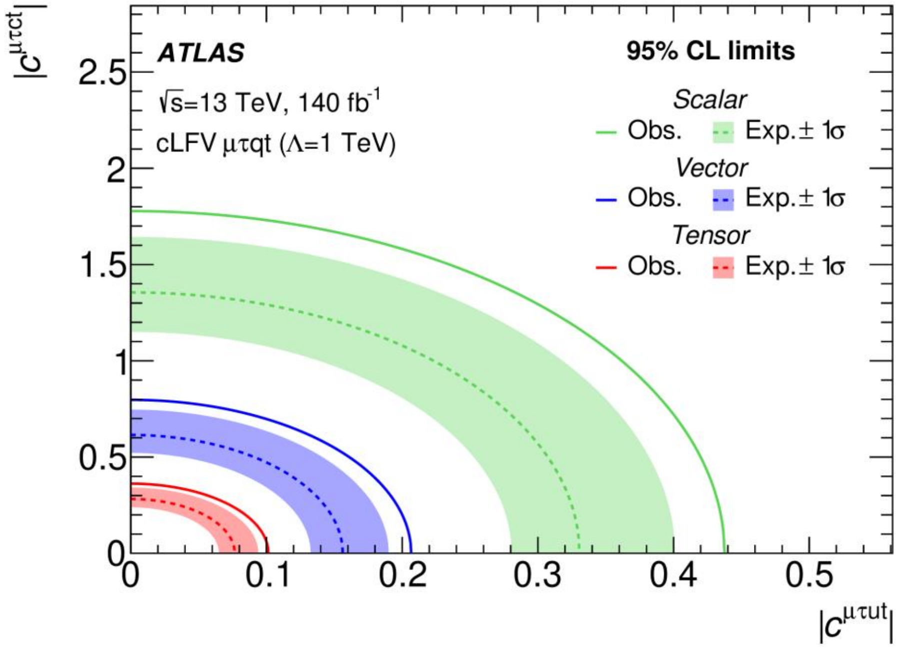
	95% CL upper limits on $\lvert c\rvert/\Lambda^2$ [TeV^{-2}]					
	$c_{\mathrm{lq}}^{-(ijk3)}$	$c_{\mathrm{eq}}^{(ijk3)}$	$c_{\mathrm{lu}}^{(ijk3)}$	$c_{\mathrm{eu}}^{(ijk3)}$	$c_{\mathrm{lequ}}^{1(ijk3)}$	$c_{\mathrm{lequ}}^{3(ijk3)}$
Previous (u)	12	12	12	12	18	2.4
Expected (u)	0.33	0.31	0.3	0.32	0.33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



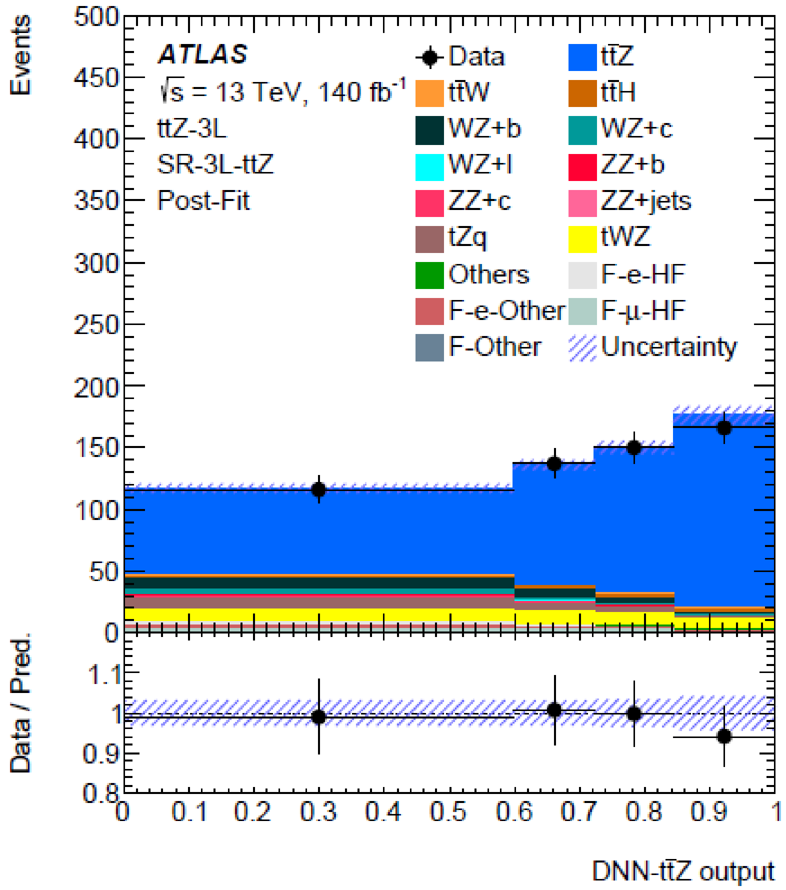


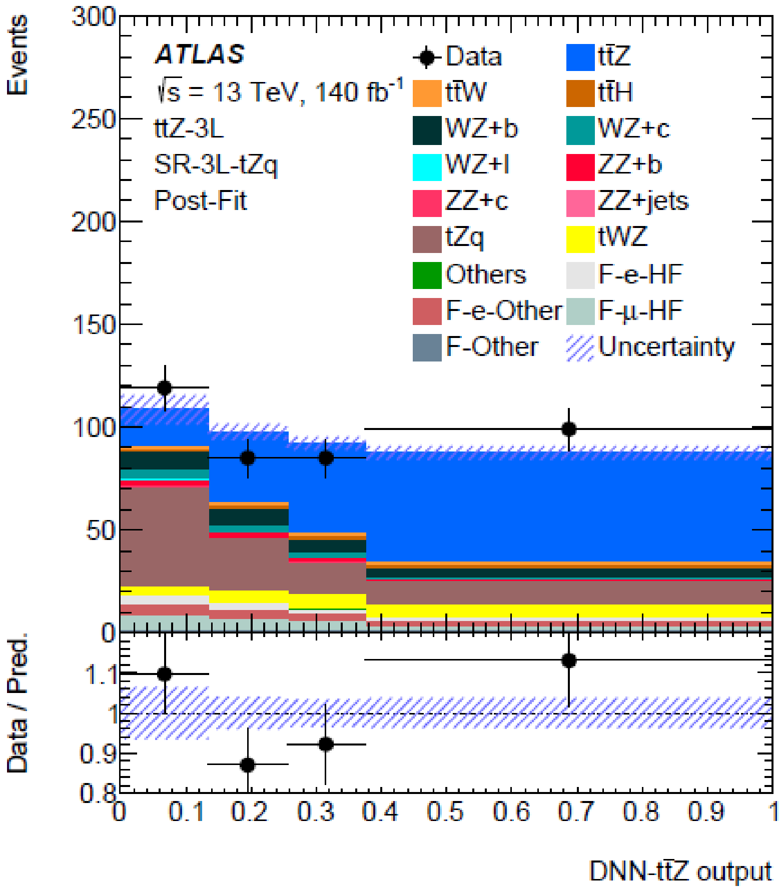
What's next?

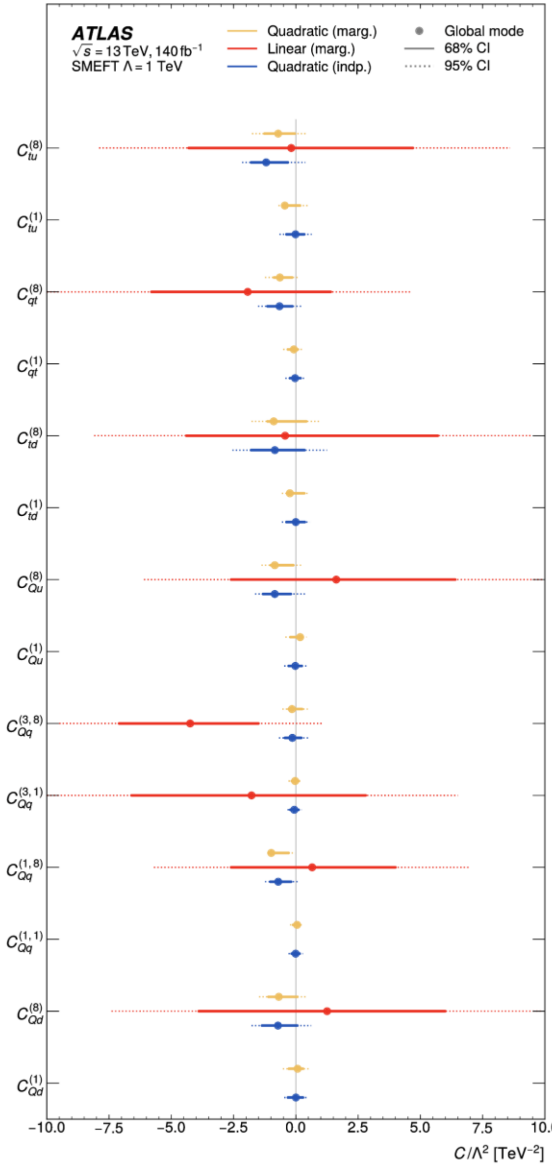
Off-shell $t\bar{t}Z$ $(t\bar{t}ll)$ and tZq $(tqll)$

Going off-shell

arXiv:2312.04450

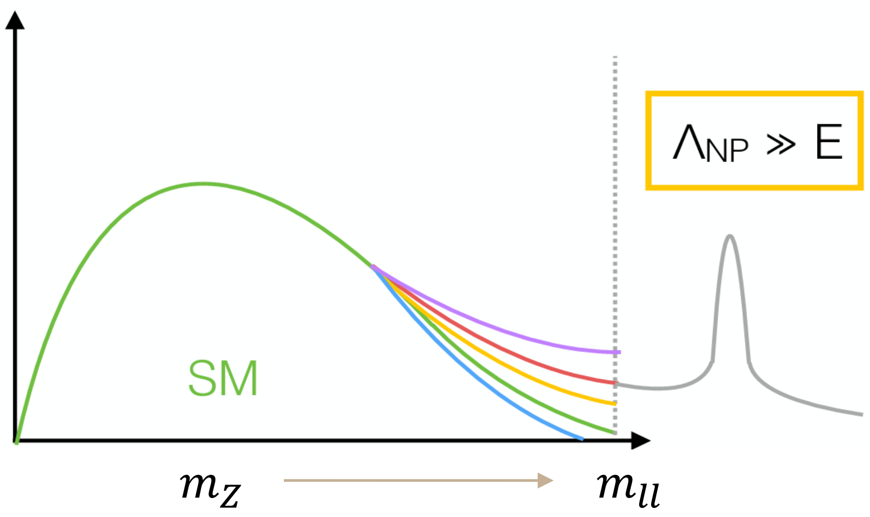






Going off-shell

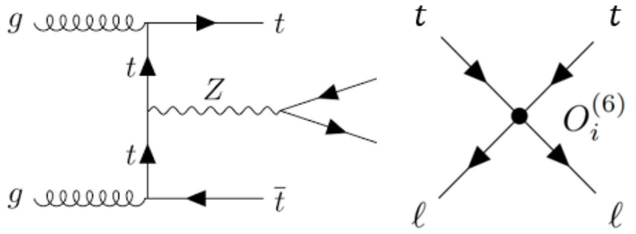
arXiv:2312.04450



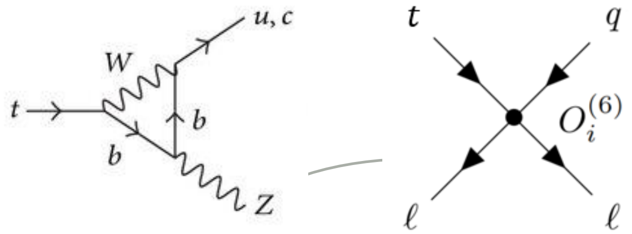
Taking a $t\bar{t}Z$ style analysis and going off shell has benefits for NP searches:

- Massively reduce SM backgrounds
- Enhance sensitivity to EFT operators (which exhibit energy growth)

$t\bar{t}Z$ search becomes $t\bar{t}ll$ search above Z peak



tZq search becomes $tqll$ search above Z peak

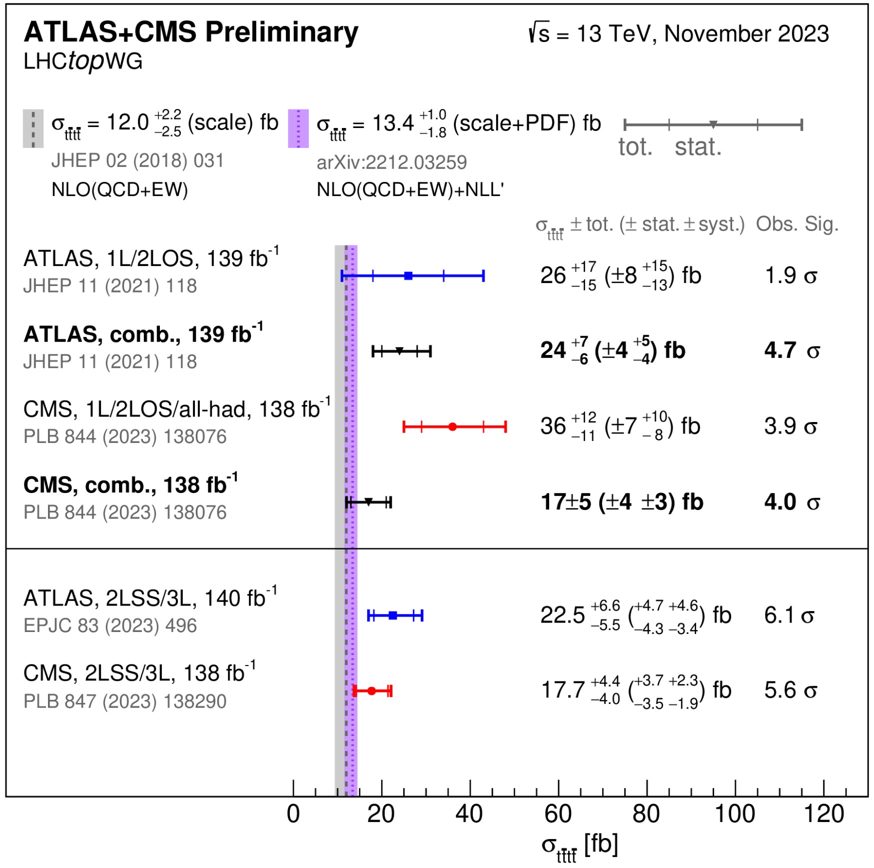


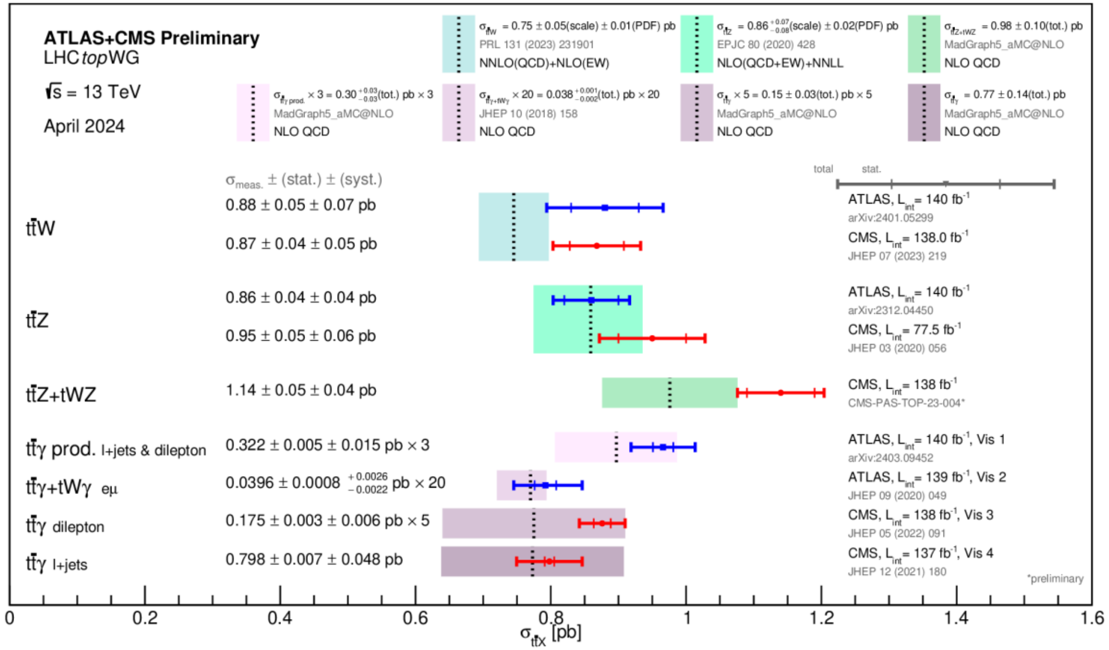
What's next?

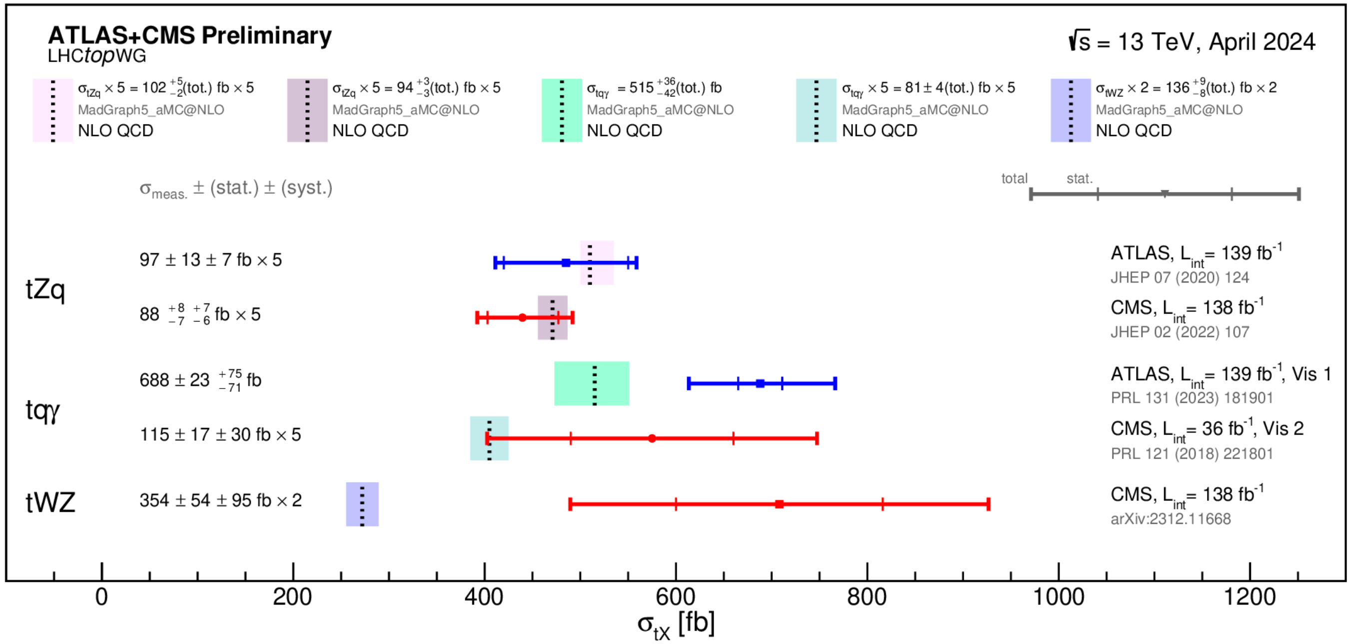
Future Top+X EFT

Top+X ATL-PHYS-PUB-2024-005

There are a lot of individual high-precision Top+X measurements!



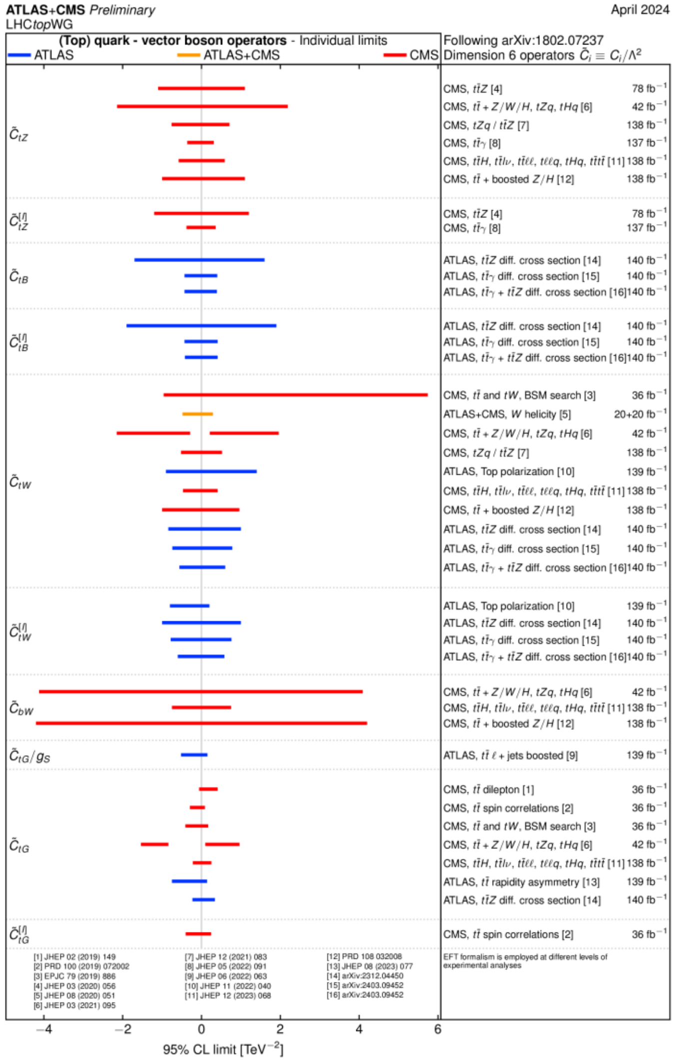


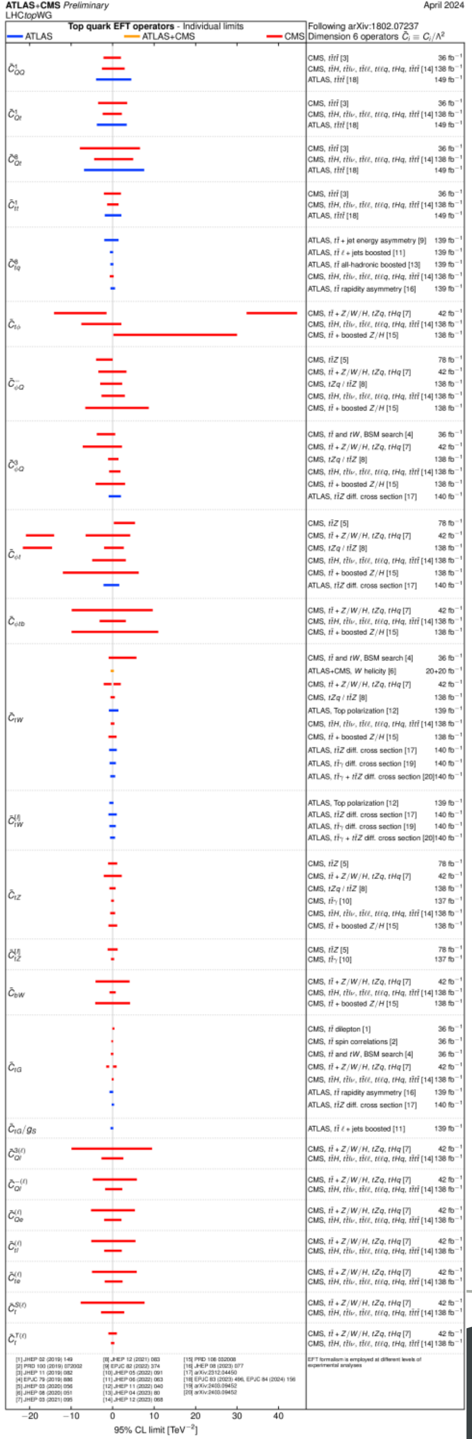


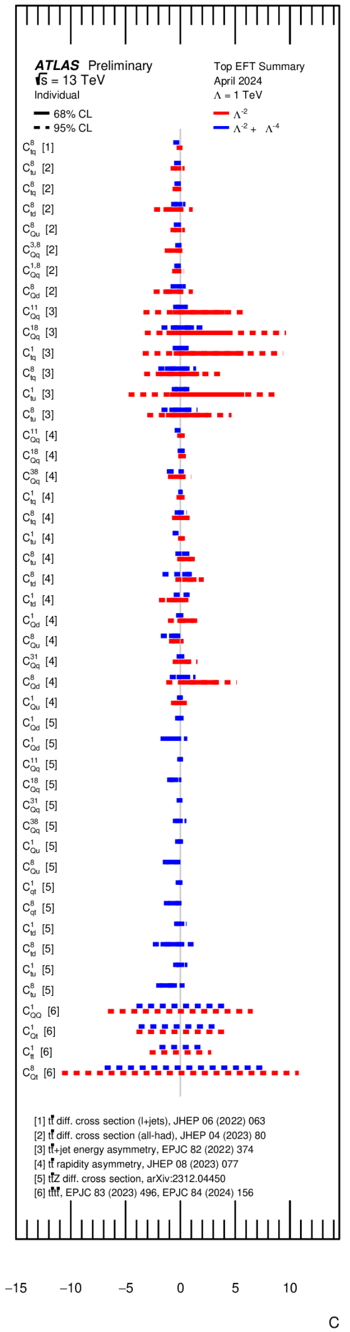
Top EFT

ATL-PHYS-PUB-2024-004

There are a lot of individual high-precision Top EFT measurements!







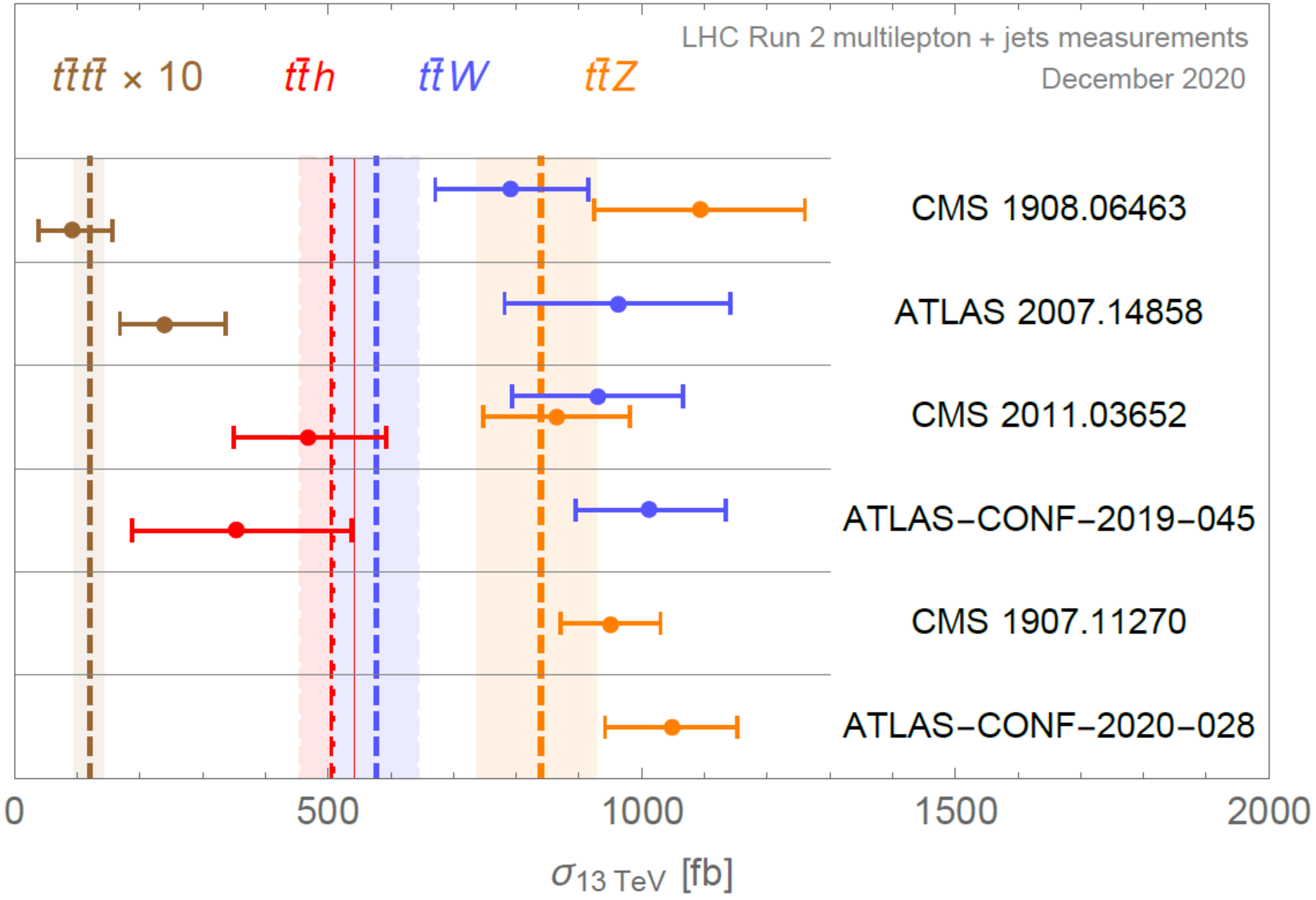
Top+X (EFT) Combinations

There are also some hints of disagreement with SM predictions – especially in $t\bar{t}W$ and potentially $t\bar{t}t\bar{t}$

How to understand these effects in the most robust way?

- In a Top+X measurement, every other Top+X process is the main background
- Many Top+X processes are sensitive to the same EFT couplings
- Impossible to disentangle them while measuring one at a time

(Plot not up to date, just exemplar)

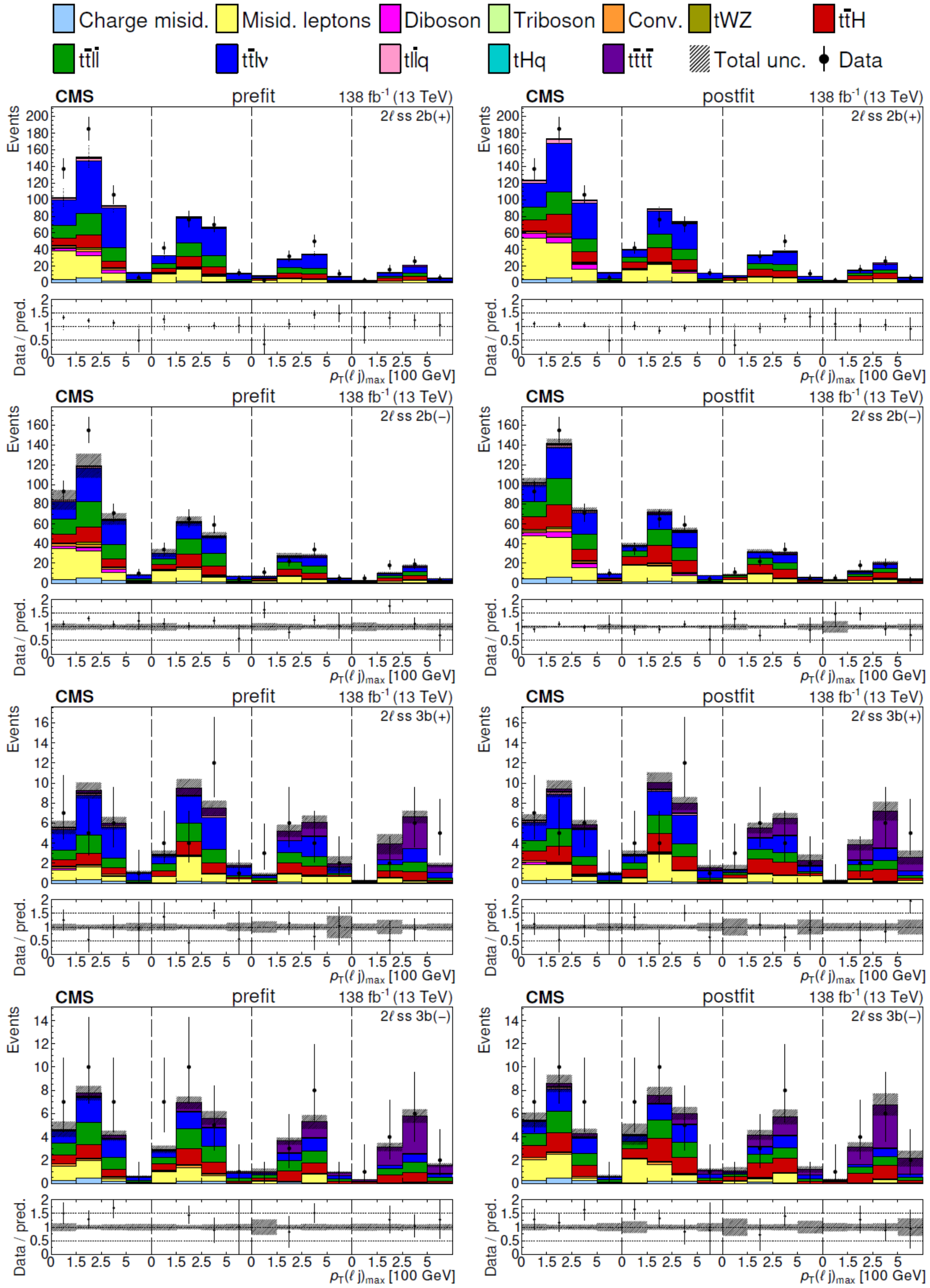


JHEP 02 (2021) 043

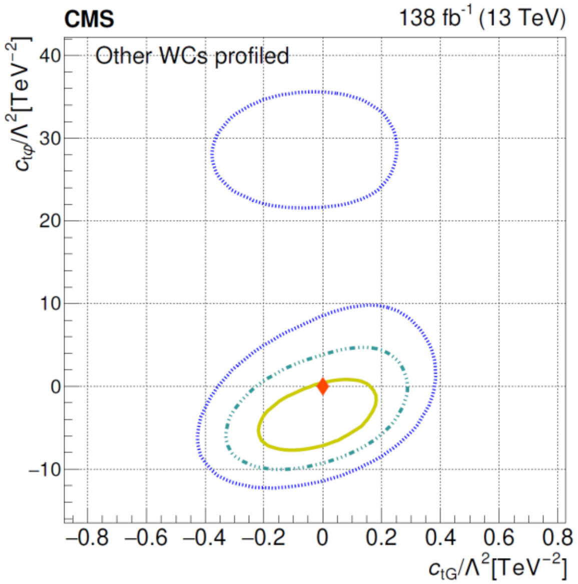
CMS JHEP 12 (2023) 068

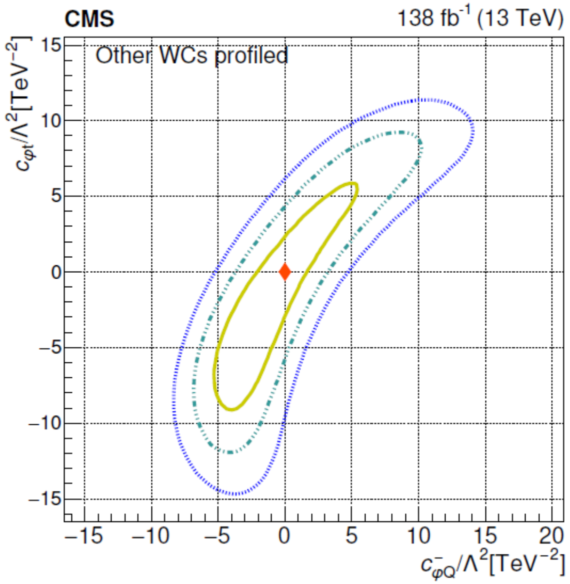
Event category	Leptons	$m_{\ell\ell}$	b tags	Lepton charge sum	Jets	Kinematical variable
2ℓss 2b	2	No requirement	2	>0, <0	4, 5, 6, ≥7	$p_T(\ell j)_{max}$
2ℓss 3b	2	No requirement	≥3	>0, <0	4, 5, 6, ≥7	$p_T(\ell j)_{max}$
3ℓ off-Z 1b	3	$\lvert m_Z - m_{\ell\ell}\rvert > 10\,\mathrm{GeV}$	1	>0, <0	2, 3, 4, ≥5	$p_T(\ell j)_{max}$
3ℓ off-Z 2b	3	$\lvert m_Z - m_{\ell\ell}\rvert > 10\,\mathrm{GeV}$	≥2	>0, <0	2, 3, 4, ≥5	$p_T(\ell j)_{max}$
3ℓ on-Z 1b	3	$\lvert m_Z - m_{\ell\ell}\rvert < 10\,\mathrm{GeV}$	1	No requirement	2, 3, 4, ≥5	$p_T(Z)$
3ℓ on-Z 2b	3	$\lvert m_Z - m_{\ell\ell}\rvert < 10\,\mathrm{GeV}$	≥2	No requirement	2, 3, 4, ≥5	$p_T(Z)$ or $p_T(\ell j)_{max}$
4ℓ	≥4	No requirement	≥2	No requirement	2, 3, ≥4	$p_T(\ell j)_{max}$

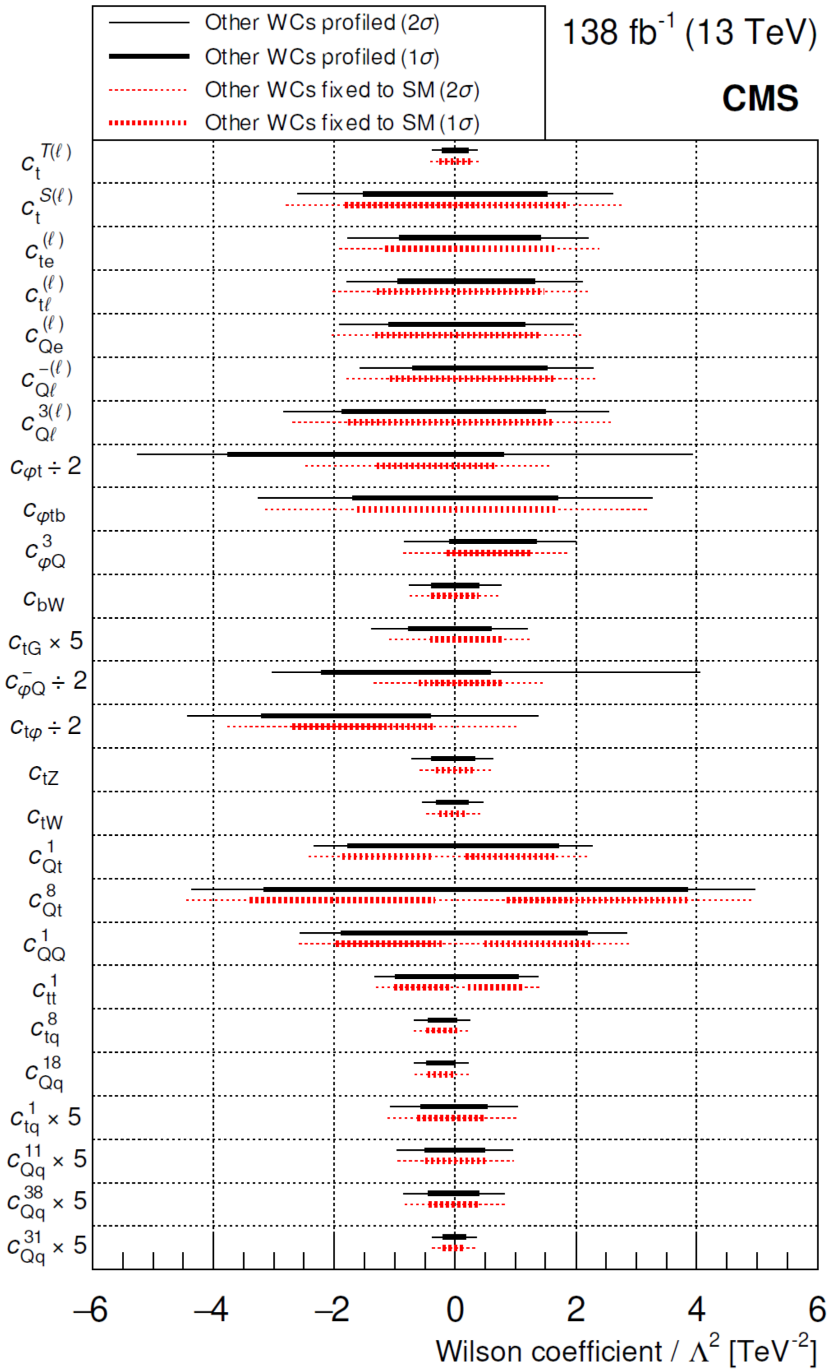
Grouping of WCs	WCs	Lead categories
$2hq2\ell$	$c_{Q\ell}^{3(\ell)}, c_{Q\ell}^{-(\ell)}, c_{Qe}^{(\ell)}, c_{t\ell}^{(\ell)}, c_{te}^{(\ell)}, c_{t}^{S(\ell)}, c_{t}^{T(\ell)}$	3ℓ off-Z
4hq	$c_{QQ}^{1}, c_{Qt}^{1}, c_{Qt}^{8}, c_{tt}^{1}$	2ℓss
2hq2lq "$t\bar{t}\ell\nu$-like"	$c_{Qq}^{11}, c_{Qq}^{18}, c_{tq}^{1}, c_{tq}^{8}$	2ℓss
2hq2lq "$t\ell\bar{\ell}q$-like"	c_{Qq}^{31}, c_{Qq}^{38}	3ℓ on-Z
2hqV "$t\bar{t}\ell\bar{\ell}$-like"	$c_{tZ}, c_{\varphi t}, c_{\varphi Q}^{-}$	3ℓ on-Z and 2ℓss
2hqV "tXq-like"	$c_{\varphi Q}^{3}, c_{\varphi tb}, c_{bW}$	3ℓ on-Z
2hqV (significant impacts on many processes)	$c_{tG}, c_{t\varphi}, c_{tW}$	3ℓ and 2ℓss



CMS JHEP 12 (2023) 068







ATLAS Top+X Roadmap

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.

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- **Describe:**
  - Challenges of combining Top+X measurements to coherently probe SM + EFTs
  - Available MC generators and UFOs
- **Discuss:**
  - Harmonisation of physics objects
  - Harmonisation of phase-space regions
- **Deliberate:**
  - Options for optimal observables
- **Develop:**
  - Incremental roadmap with increasing complexity, towards maximising the potential of Run-3 ATLAS data

ATL-PHYS-PUB-2023-030

ATLAS Top+X Roadmap

ATL-PHYS-PUB-2023-030

EFT for Monte Carlo

Generators:

- Madgraph
  - Predominant recommendation
  - Highly compatible with UFO models
  - 'Simple' user interface
  - Extension enabling computation of NLO in QCD and NLO EW corrections
  - (NLO generators often introduce more negative weights which can be difficult to deal with experimentally)

- Powheg:
  - Better modelling of SM ttbar process at NLO in QCD
  - Still requires reweighting according to MG5 EFT predictions
  - Resulting approximations would require extensive validation studies

- Pythia
  - Does not retain spin correlations
  - Problems associated to EFT operators which generate gluons and interaction with the parton shower

UFO models:

- SMEFTSim3.0
  - Current recommendation used widely in ATLAS
  - 'top' flavour assumption – treats operators with lepton-flavour indices as individual entities
  - LO accuracy only
  - Distinguishes between EFT insertions in vertices or in corrections to widths of propagators

- SMEFTatNLO
  - Both LO and NLO QCD precision
  - No implementation of CP violating operators, or operators with b-quarks in the initial state, or FCNC interactions
  - Extensive upgrades planned over the next ~5 years

Other topics discussed:

- Coupling orders
- Decomposition of EFT contributions
- Internal reweighting vs dedicated generation
- Higher-order corrections
- EFT effects in top decay

ATLAS Top+X Roadmap

ATL-PHYS-PUB-2023-030

Harmonisation

Object definitions proposals:

- Harmonise object definitions between all combinable analyses apriori
- Design lepton working points which support (pseudo)-continuous calibrations
- Adopt common-denominator systematic reduction schemes for different processes, according to the sensitivity of each

Phase-space regions proposals:

- Harmonise region definitions between all combinable analyses apriori
- Design common ML algorithms to separate heavily overlapping processes ($t\bar{t}H$, $t\bar{t}H$, $t\bar{t}t\bar{t}$)
- Adopt common fakes control regions between analyses

ATLAS Top+X Roadmap

ATL-PHYS-PUB-2023-030

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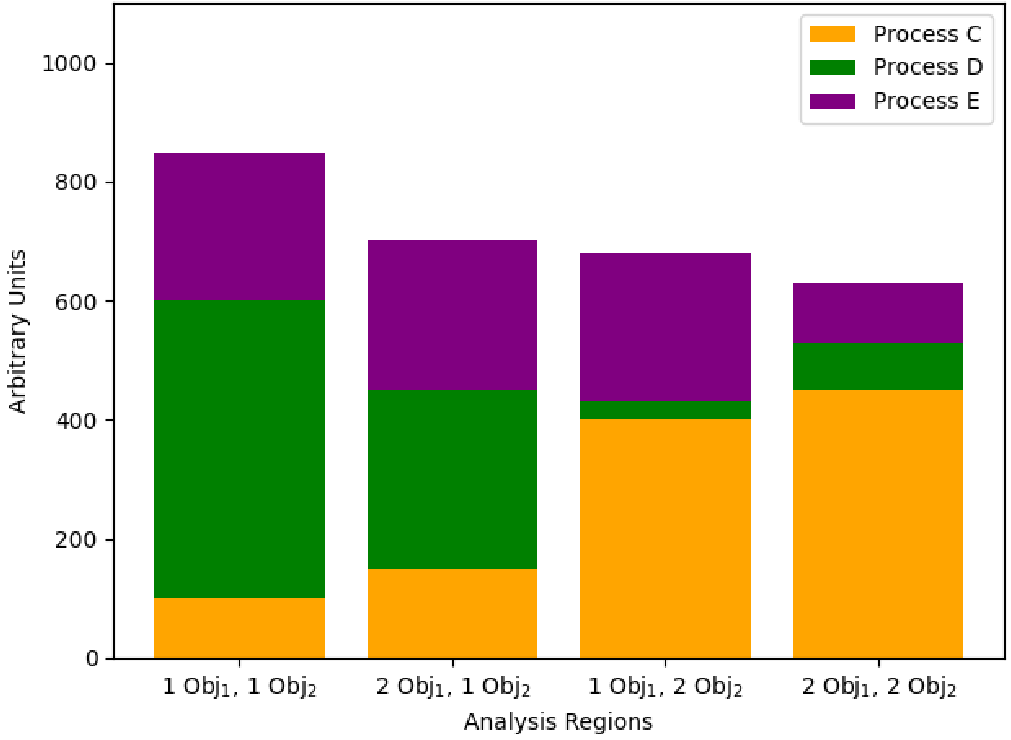
Region definitions and fitting tactics:

1. **Object-based (OB) fit:** The regions are broken down by lepton/jet/b-tag multiplicity, lepton charge etc. (à la CMS!)
   - Clean and simple to implement
   - Object + region harmonisation are automatic
   - Fakes treatment is coherent

- Some processes easy to distinguish – e.g. $t\bar{t}\gamma$
- Other processes difficult to separate this way – e.g. $t\bar{t}W, t\bar{t}H, t\bar{t}t\bar{t}$

- Principal Component Analysis will identify sensitive directions

- **Need to be clear what you are optimising for!**



ATLAS Top+X Roadmap

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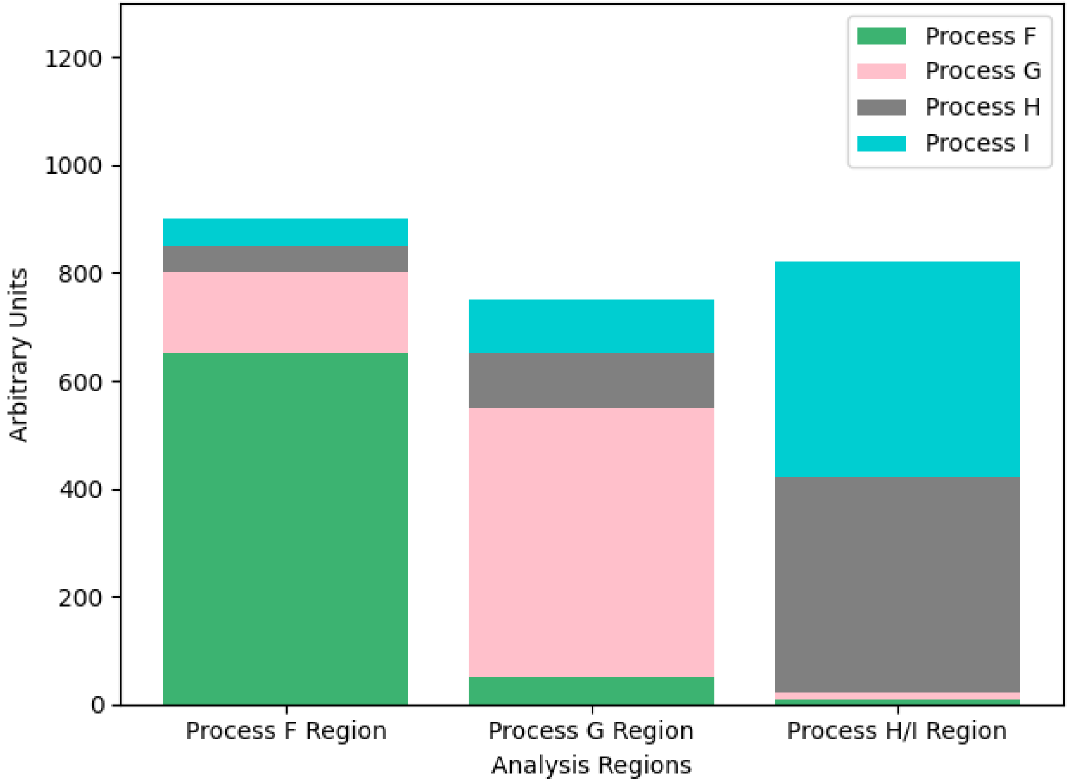
2. **Process-based (PB) fit:** The regions are defined with specific Top+X processes individually targeted in each.
    - Potential to re-use dedicated cross section analyses to minimise work duplication
    - Object + Region harmonisation and fakes treatment all require careful consideration if starting from separate analyses

- Some processes 'easy' to distinguish – e.g. $t\bar{t}Z$, tZq, $t\bar{t}\gamma$, $t\bar{t}H$
- Other processes remain difficult to separate this way – e.g. $t\bar{t}W$, $t\bar{t}H$, $t\bar{t}t\bar{t}$
- Principal Component Analysis will identify sensitive directions
- **Need to be clear what you are optimising for!**



ATLAS Top+X Roadmap

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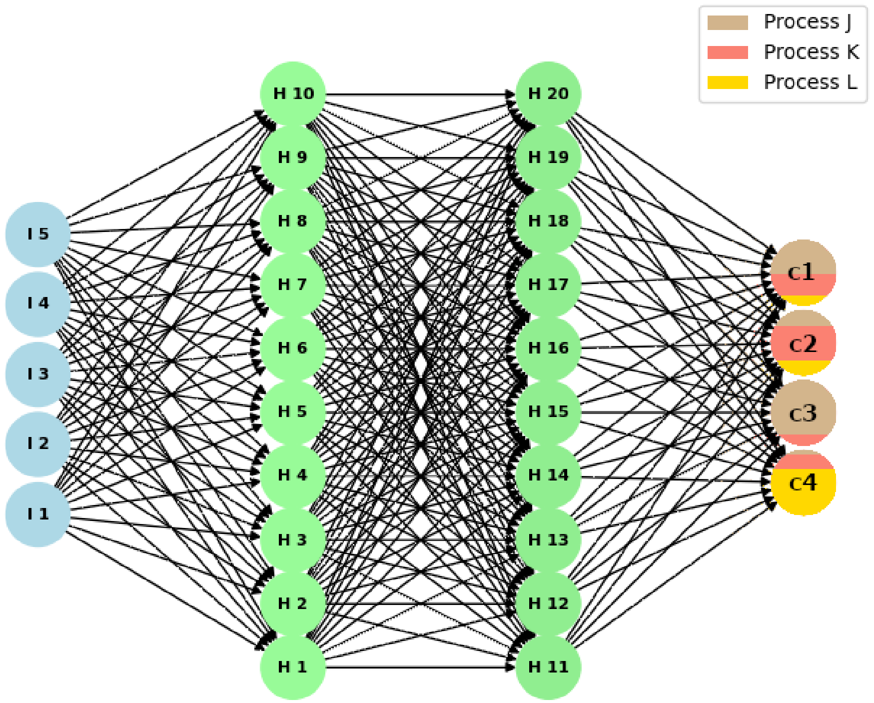
3. **EFT-optimised (EO) fit:** The regions are defined by ML algorithms to select events with the highest sensitivity to particular EFT operators. [Lots of freedom here to define your targets, but lots of complications too].
   - Object + region harmonisation are automatic
   - Fakes treatment is coherent
   - Higher dependency on EFT model
   - Is it easily reinterpretable? How about surrogate networks?

- This methodology may provide the opportunities to separate $t\bar{t}W, t\bar{t}H, t\bar{t}t\bar{t}$
  - (Or can determine whether it is even necessary)
- Principal Component Analysis will identify sensitive directions
- **Need to be clear what you are optimising for!**



ATLAS Top+X Roadmap

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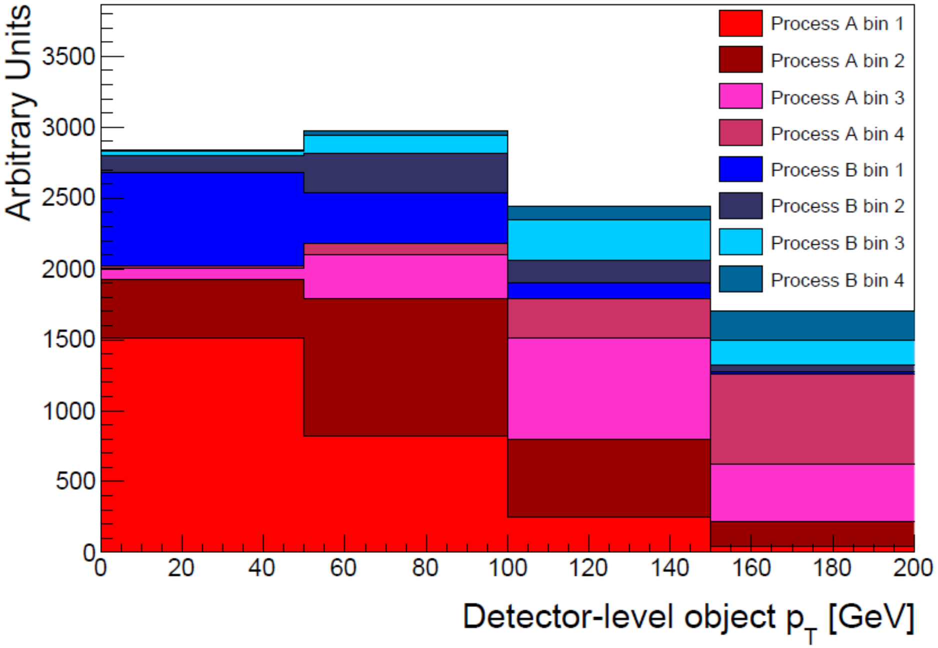
4. Fully differential multi-process unfolding:

- An extension of **(1)** or **(2)** (or technically **(3)**, with adjustments)
- Best reinterpretations and reusability
  - Unbiased unfolding retains reliable results even under updated SM or EFT predictions
  - Simple to compare to new theories
- Profile-likelihood unfolding with multiple signals reduces assumptions about EFT contributions compared to methods subtracting fixed SM backgrounds

- Truth-level binning optimisation required for EFT sensitivity
- Multi-signal unfolding is useful when dealing with largely inseparable processes



Summary

- Lepton and Flavour physics anomalies are persistent
- Top quarks are a fantastic tool to search for new physics
- Effective Field Theory is a highly active area of research for model-independent BSM searches
- Put it all together – maybe we'll get magic

Backup

LHC EFT WG https://lpcc.web.cern.ch/lhc-eft-wg

The LHC EFT WG's mandate is to provide a framework for the interpretation of LHC data in the context of effective field theories

- Study physics requirements needed to facilitate an interpretation commensurate with the available measurements, including Higgs bosons, top quarks, and electroweak bosons.
- Provide recommendations for the use of EFTs by the experiments to interpret their data
- Provide recommendations on theory setups and Monte Carlo simulations, as well as other tools.
- Provide a forum for theoretical discussions of EFT issues, such as constraints, higher-order corrections, and BSM interpretations.
- Discuss common uncertainties and combination procedures.
- Coordinate between the existing experimental WGs, to allow global EFT analyses inside and outside of experimental collaborations.

Conveners:

ATLAS:

- Sarah Heim (Higgs WG contact)
- Jacob Kempster (Top WG contact)
- Karolos Potamianos (EW WG contact)
- Sandra Kortner

CMS:

- Matteo Presilla (EW WG contact)
- Nadjieh Jafari
- Robert Schoefbeck (Top WG contact)
- Nicholas Wardle (Higgs WG contact)

LHCb:

- Greg Ciezarek and Christoph Langenbruch

Theory:

- Ilaria Brivio
- Anke Biekoetter (Higgs WG contact)
- Shankha Banerjee (EW WG contact)
- Gauthier Durieux
- Ken Mimasu (Top WG contact)
- Peter Stangl

LHC EFT WG

TWiki: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCEFT
Indico: https://indico.cern.ch/category/12374/
Documents: CDS

7th General Meeting of the LHC EFT Working Group

https://indico.cern.ch/event/1384135

(Recordings available)

Area 1: EFT Formalism – Higher-order corrections in SMEFT, Positivity Constraints, SMEFT vs HEFT

Area 2: Predictions and Tools – Common toolchain for SMEFT parameterisations, Common methodology for EFT MC production (reweighting vs direct) – PUB note under development

Area 3: Measurements and Observables – Optimal observables, complementarities, Machine learning opportunities (and challenges) for EFTs - dedicated discussion , Reinterpretability

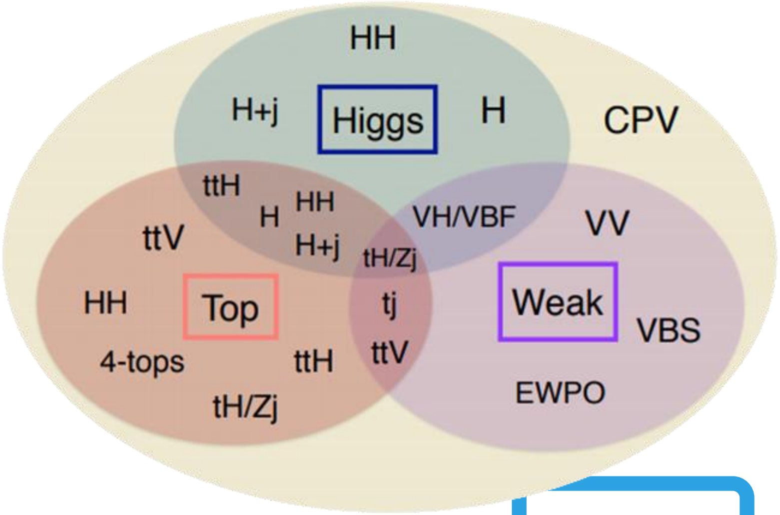
Area 4: Fits and Related Systematics – "Fitting exercise" (for study only!)

Area 5: Benchmark Scenarios from UV Models – Mapping BSM to SMEFT (database, framework)

Area 6: Flavour – Connecting flavour physics (and anomalies) to global EFT fits

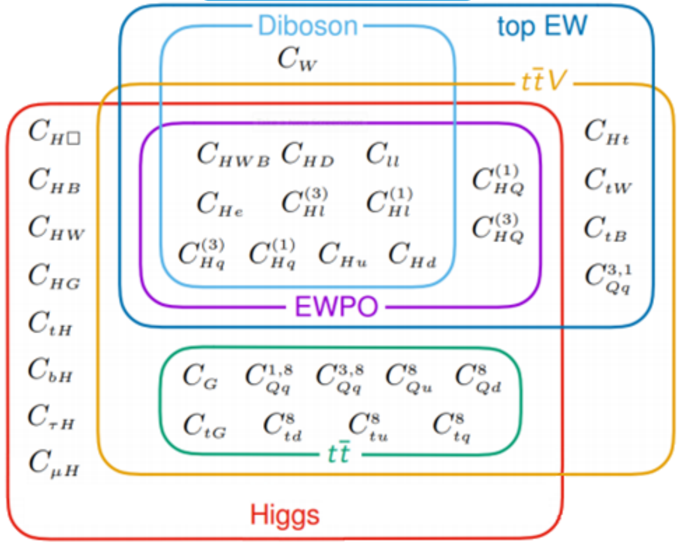
Top EFT

arXiv:1008.4484



Adapted from K. Mimasu

Warsaw basis



J. Ellis et al, JHEP 04 (2021) 279

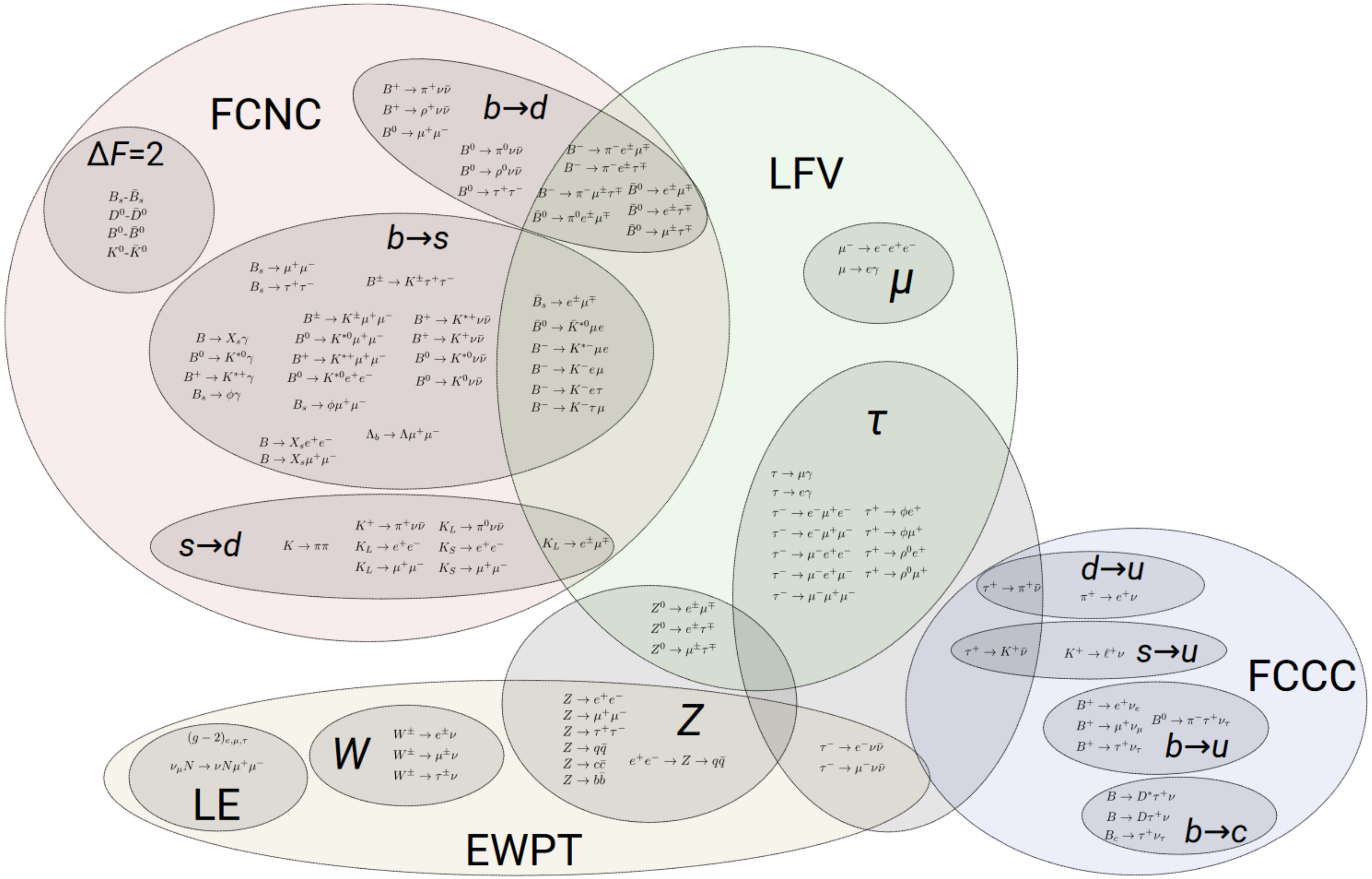
Grzadkowski,Iskrzynski,Misiak,Rosiek 1008.4884

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC}\widetilde G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^\star(\varphi^\dagger D_\mu\varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK}\widetilde W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar l_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar l_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p\sigma^{\mu\nu}T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar e_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p\sigma^{\mu\nu}u_r)\tau^I\widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar q_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar q_p\sigma^{\mu\nu}u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar q_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar q_p\sigma^{\mu\nu}T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar u_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar d_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p\gamma^\mu d_r)$

Grzadkowski,Iskrzynski,Misiak,Rosiek 1008.4884

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
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}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$		
$Q_{lequ}^{(3)}$	$(\bar l_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar q_s^k\sigma^{\mu\nu}u_t)$				

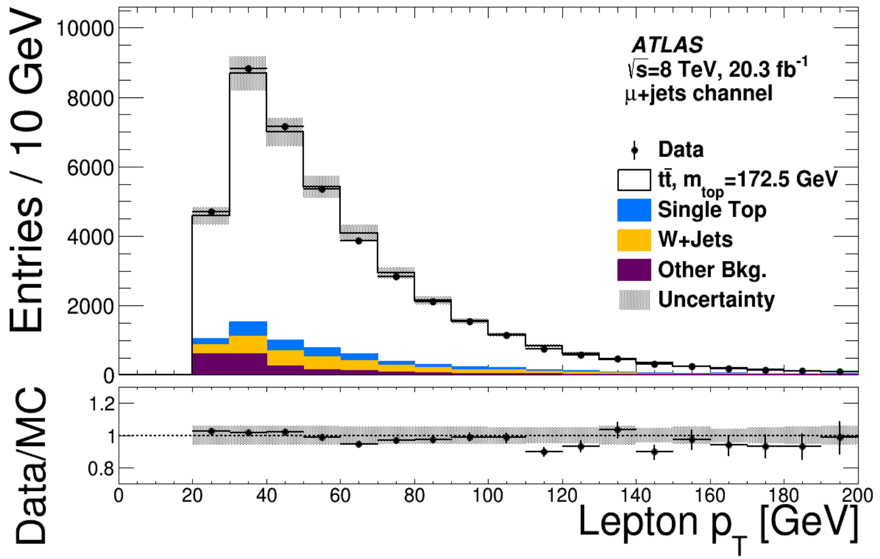
Larger picture



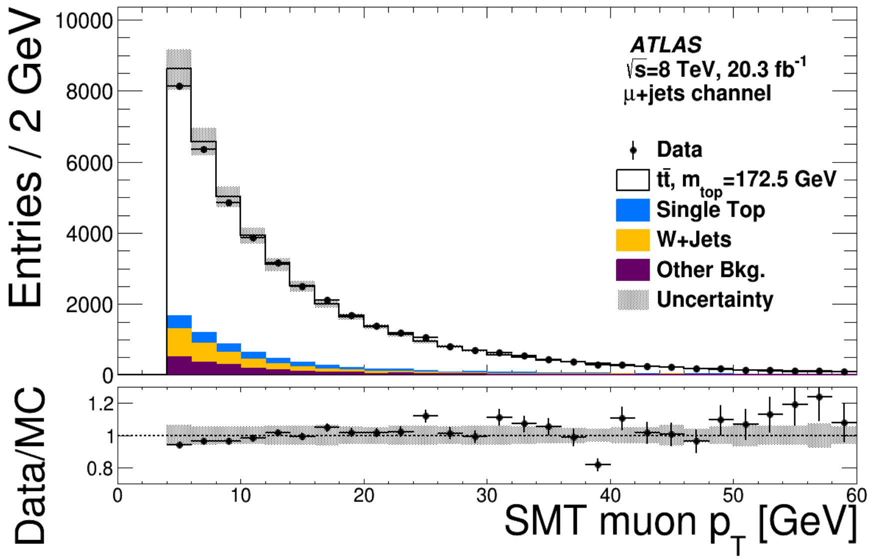
D. Straub

EPJC 79 (2019) 505

"Soft" muon



"Hard-lepton"
"W-lepton"



"Soft Muon"

Decay modes

- **Opposite Sign (OS)**
- $t \to l^+\nu\, b \to l^+l^-X$ ~55%
- $t \to l^+\nu\, (b \to \bar{b} \to \bar{c}) \to l^+l^-X$ ~4%
- $t \to l^+\nu\, (b \to c\bar{c}) \to l^+l^-X$ ~3%

- **Same Sign (SS)**
- $t \to l^+\nu\left(b \to \bar{b}\right) \to l^+l^+X$ ~7%
- $t \to l^+\nu\, (b \to c) \to l^+l^+X$ ~28%
- $t \to l^+\nu\left(b \to \bar{b} \to c\bar{c}\right) \to l^+l^+X$ ~3%

Comparing these processes with their charge conjugates allows for building of inclusive asymmetries sensitive to CP violation:

- Consider number of SMT muons, $N^{\alpha\beta}$, where:

$$P(b \to l^-) = \frac{N(b \to l^-)}{N(b \to l^-) + N(b \to l^+)} = \frac{N^{+-}}{N^{+-} + N^{++}} = \frac{N^{+-}}{N^+}$$

$$P(\bar{b} \to l^+) = \frac{N(\bar{b} \to l^+)}{N(\bar{b} \to l^-) + N(\bar{b} \to l^+)} = \frac{N^{-+}}{N^{--} + N^{-+}} = \frac{N^{-+}}{N^-}$$

$$P(b \to l^+) = \frac{N(b \to l^+)}{N(b \to l^-) + N(b \to l^+)} = \frac{N^{++}}{N^{+-} + N^{++}} = \frac{N^{++}}{N^+}$$

$$P(\bar{b} \to l^-) = \frac{N(\bar{b} \to l^-)}{N(\bar{b} \to l^-) + N(\bar{b} \to l^+)} = \frac{N^{--}}{N^{--} + N^{-+}} = \frac{N^{--}}{N^-}$$

PRL 110,232002 (2013)

Decay chain fractions (Obtained from simulation)

Same Sign

$$N_{r_b} = N\left[t \to \ell^+\nu\left(b \to \overline{b}\right) \to \ell^+\ell^+X\right],$$
$$N_{r_c} = N\left[t \to \ell^+\nu\,(b \to c) \to \ell^+\ell^+X\right],$$
$$N_{r_{c\overline{c}}} = N\left[t \to \ell^+\nu\left(b \to \overline{b} \to c\overline{c}\right) \to \ell^+\ell^+X\right],$$

$$r_b = \frac{N_{r_b}}{N_{r_b} + N_{r_c} + N_{r_{c\overline{c}}}},$$
$$r_c = \frac{N_{r_c}}{N_{r_b} + N_{r_c} + N_{r_{c\overline{c}}}},$$
$$r_{c\overline{c}} = \frac{N_{r_{c\overline{c}}}}{N_{r_b} + N_{r_c} + N_{r_{c\overline{c}}}},$$

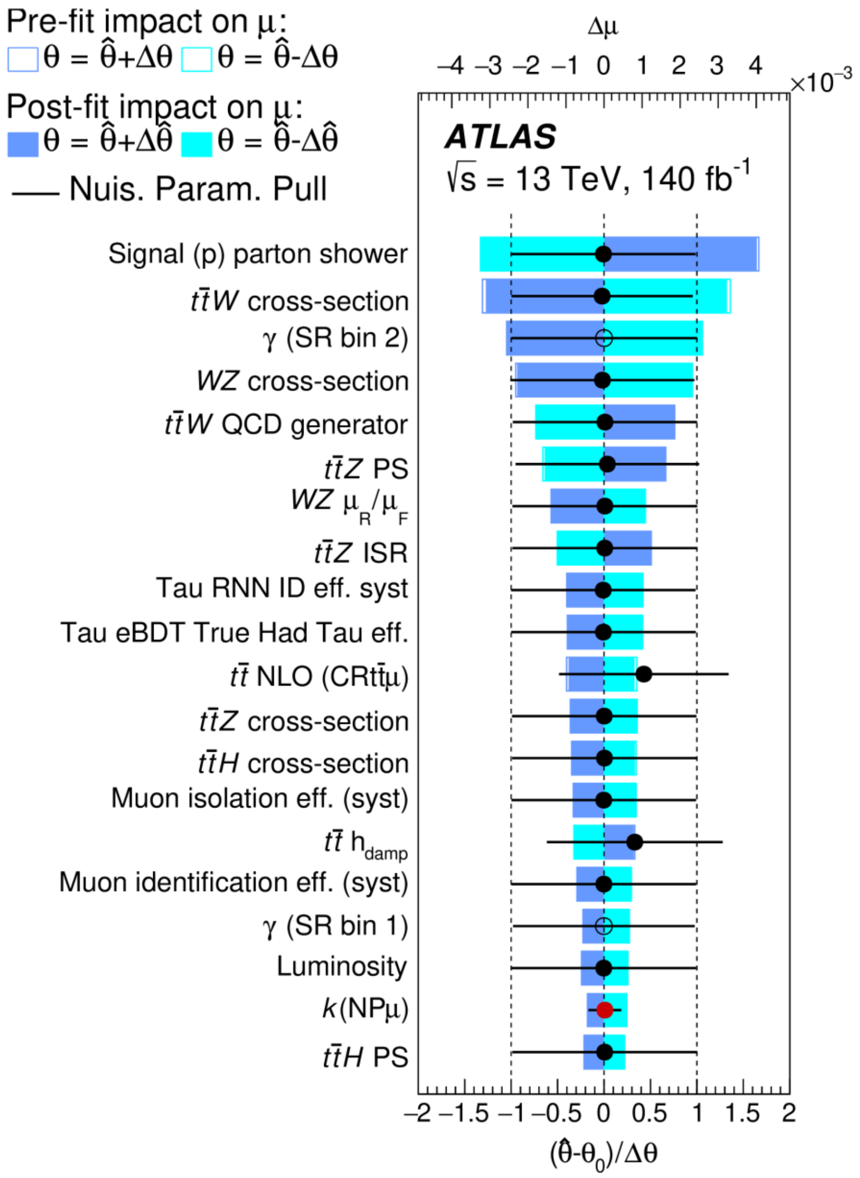
Opposite Sign

$$N_{\widetilde{r}_b} = N\left[t \to \ell^+\nu b \to \ell^+\ell^-X\right],$$
$$N_{\widetilde{r}_c} = N\left[t \to \ell^+\nu\left(b \to \overline{b} \to \overline{c}\right) \to \ell^+\ell^-X\right],$$
$$N_{\widetilde{r}_{c\overline{c}}} = N\left[t \to \ell^+\nu\,(b \to c\overline{c}) \to \ell^+\ell^-X\right].$$

$$\widetilde{r}_b = \frac{\widetilde{N}_{r_b}}{\widetilde{N}_{r_b} + \widetilde{N}_{r_c} + \widetilde{N}_{r_{c\overline{c}}}},$$
$$\widetilde{r}_c = \frac{\widetilde{N}_{r_c}}{\widetilde{N}_{r_b} + \widetilde{N}_{r_c} + \widetilde{N}_{r_{c\overline{c}}}},$$
$$\widetilde{r}_{c\overline{c}} = \frac{\widetilde{N}_{r_{c\overline{c}}}}{\widetilde{N}_{r_b} + \widetilde{N}_{r_c} + \widetilde{N}_{r_{c\overline{c}}}}.$$

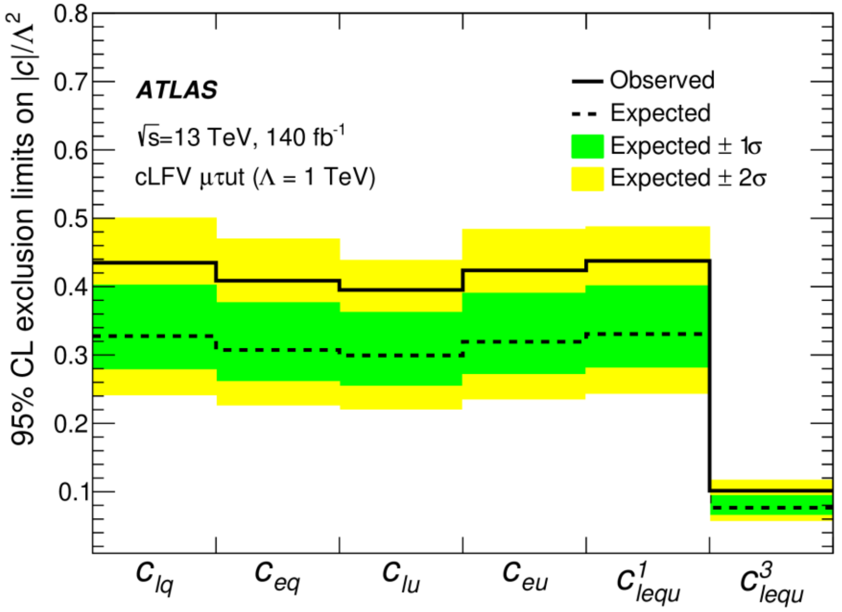
(Best measured in a well-defined fiducial volume)

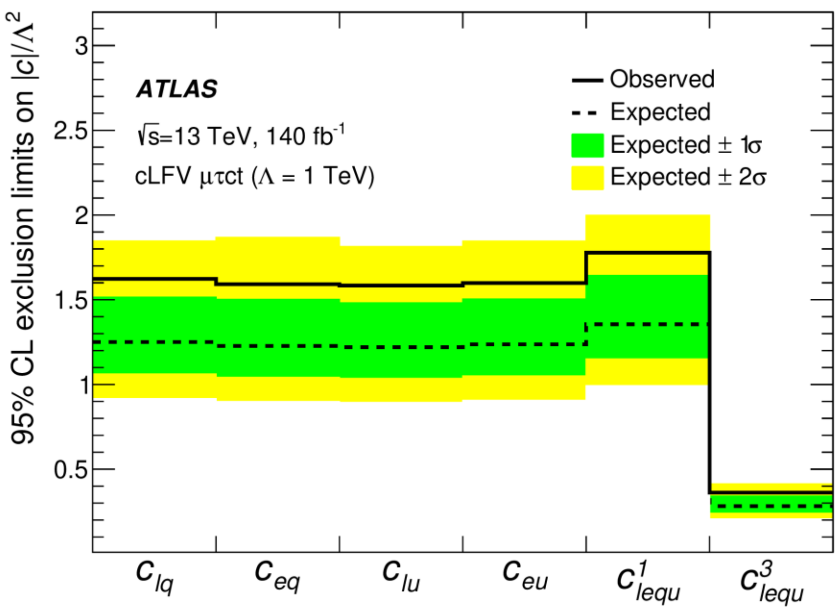
CLFV EFT Result breakdown



CLFV EFT Result breakdown

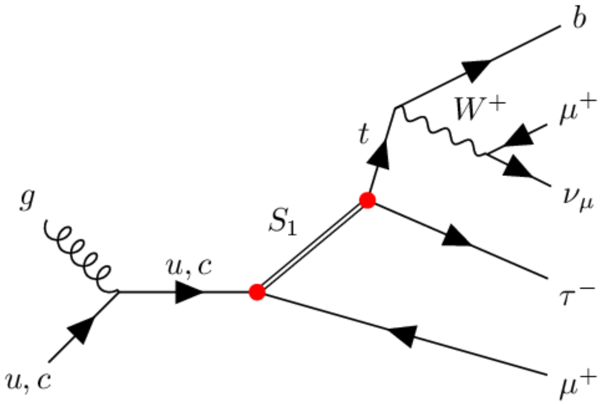
UNIVERSITY OF SUSSEX

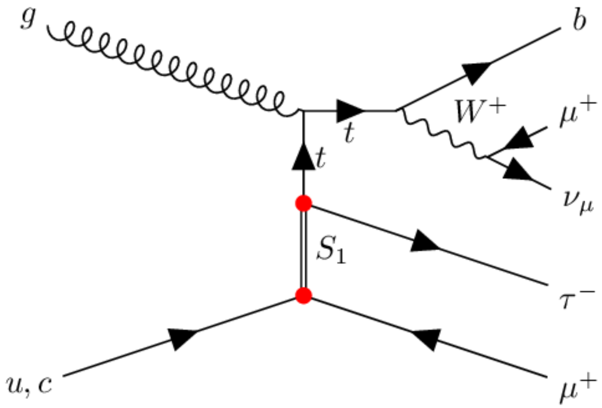


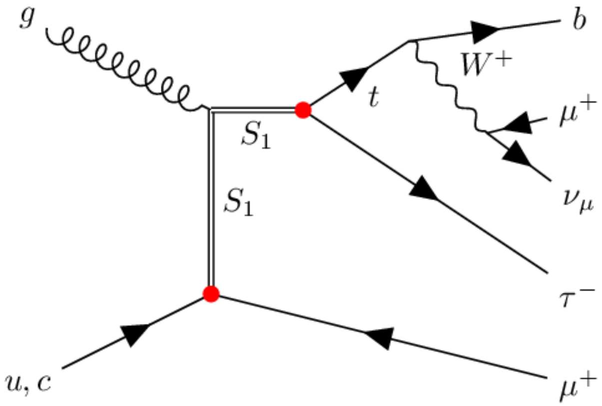


CLFV - Leptoquark interpretation

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







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

CLFV - Leptoquark interpretation

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

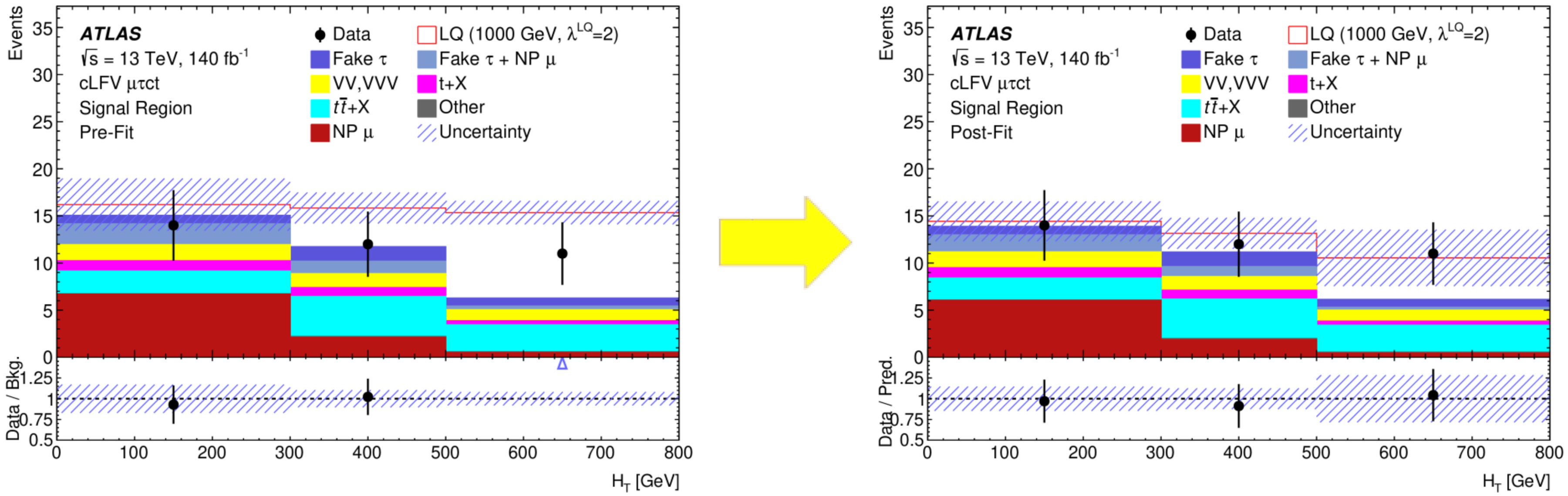
$$\lambda_{ki} \in \begin{pmatrix} \lambda_{t\tau} & \lambda_{c\tau} & \lambda_{u\tau} \\ \lambda_{t\mu} & \lambda_{c\mu} & \lambda_{u\mu} \\ \lambda_{te} & \lambda_{ce} & \lambda_{ue} \end{pmatrix} \equiv \lambda^{\mathrm{LQ}} \begin{pmatrix} 10 & 1 & 0.1 \\ 1 & 0.1 & 0.01 \\ 0.1 & 0.01 & 0.001 \end{pmatrix}$$

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

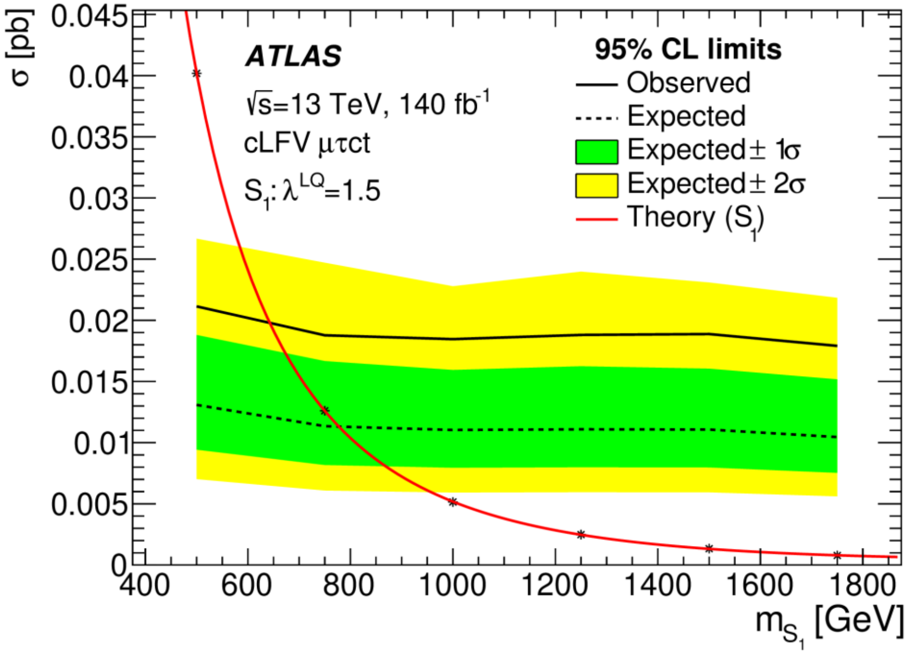
Various theory papers apply hierarchical coupling models, with different magnitudes spanning steps of $\sqrt{2}$ to $\frac{1}{16}$ [1,2,3,4,5]

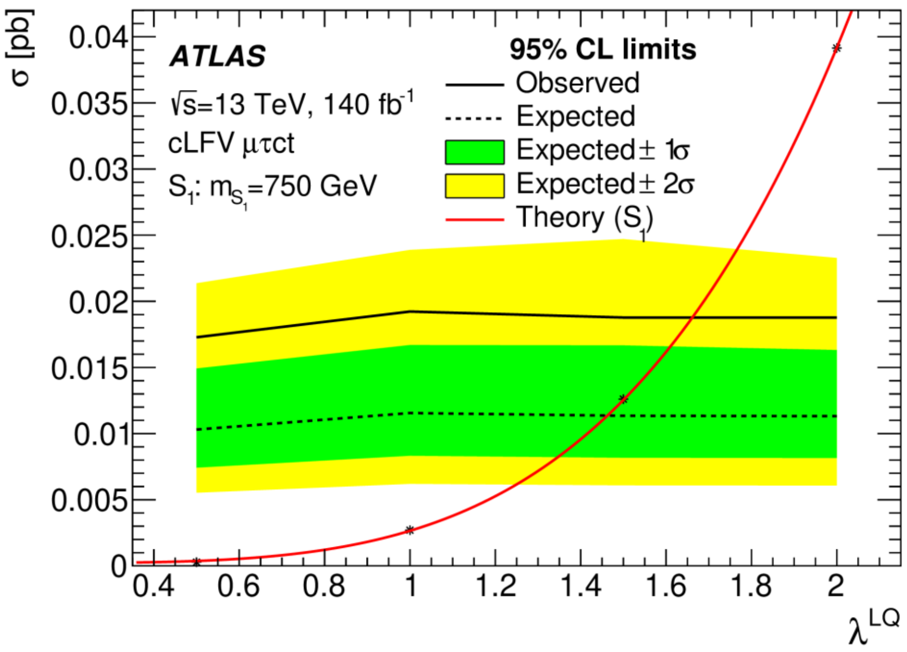
CLFV - Leptoquark interpretation

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:

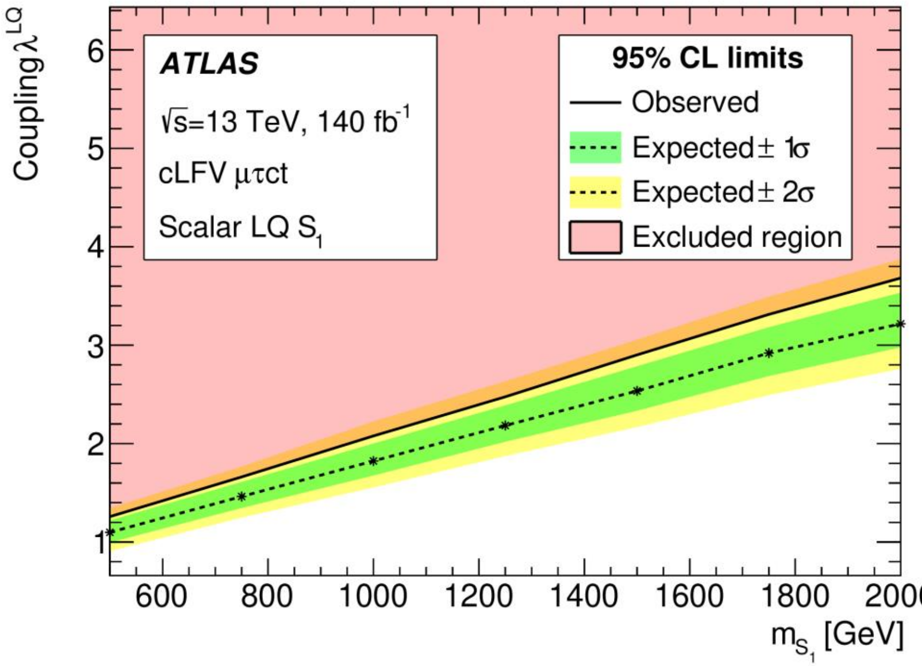


CLFV - Leptoquark interpretation

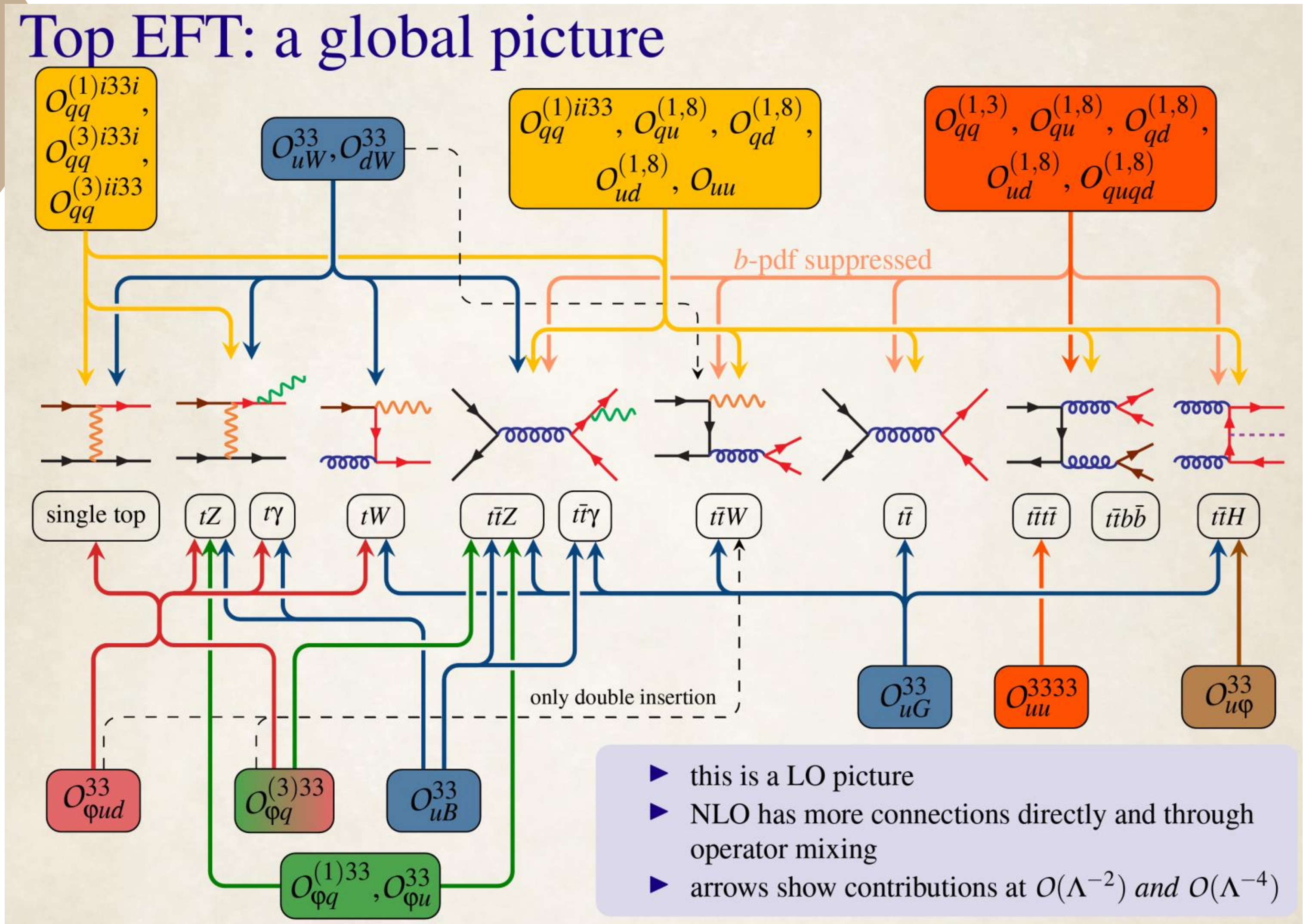




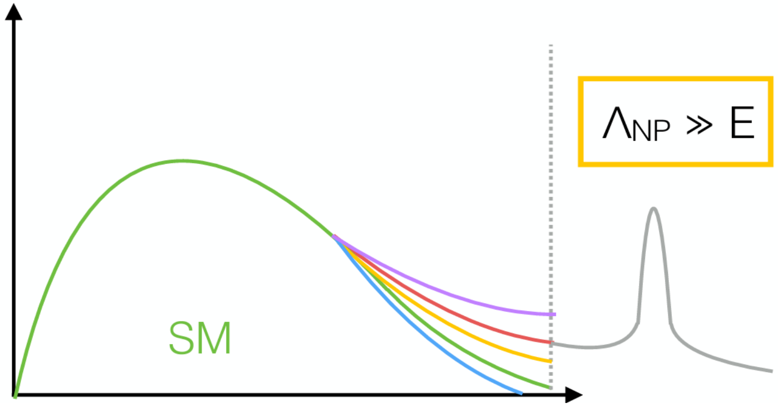
CLFV - Leptoquark interpretation



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



P. Galler, TopFitter, ICHEP 2020



parameter	$t\bar{t}$	single t	tW	tZ	t decay	$t\bar{t}Z$	$t\bar{t}W$
$C_{Qq}^{1,8}$	Λ^{-2}	–	–	–	–	Λ^{-2}	Λ^{-2}
$C_{Qq}^{3,8}$	Λ^{-2}	Λ^{-4} [Λ^{-2}]	–	Λ^{-4} [Λ^{-2}]	Λ^{-4} [Λ^{-2}]	Λ^{-2}	Λ^{-2}
C_{tu}^{8}, C_{td}^{8}	Λ^{-2}	–	–	–	–	Λ^{-2}	–
$C_{Qq}^{1,1}$	Λ^{-4} [Λ^{-2}]	–	–	–	–	Λ^{-4} [Λ^{-2}]	Λ^{-4} [Λ^{-2}]
$C_{Qq}^{3,1}$	Λ^{-4} [Λ^{-2}]	Λ^{-2}	–	Λ^{-2}	Λ^{-2}	Λ^{-4} [Λ^{-2}]	Λ^{-4} [Λ^{-2}]
C_{tu}^{1}, C_{td}^{1}	Λ^{-4} [Λ^{-2}]	–	–	–	–	Λ^{-4} [Λ^{-2}]	–
C_{Qu}^{8}, C_{Qd}^{8}	Λ^{-2}	–	–	–	–	Λ^{-2}	–
C_{tq}^{8}	Λ^{-2}	–	–	–	–	Λ^{-2}	Λ^{-2}
C_{Qu}^{1}, C_{Qd}^{1}	Λ^{-4} [Λ^{-2}]	–	–	–	–	Λ^{-4} [Λ^{-2}]	–
C_{tq}^{1}	Λ^{-4} [Λ^{-2}]	–	–	–	–	Λ^{-4} [Λ^{-2}]	Λ^{-4} [Λ^{-2}]
$C_{\phi Q}^{-}$	–	–	–	Λ^{-2}	–	Λ^{-2}	–
$C_{\phi Q}^{3}$	–	Λ^{-2}	Λ^{-2}	Λ^{-2}	Λ^{-2}	–	–
$C_{\phi t}$	–	–	–	Λ^{-2}	–	Λ^{-2}	–
$C_{\phi tb}$	–	Λ^{-4}	Λ^{-4}	Λ^{-4}	Λ^{-4}	–	–
C_{tZ}	–	–	–	Λ^{-2}	–	Λ^{-2}	–
C_{tW}	–	Λ^{-2}	Λ^{-2}	Λ^{-2}	Λ^{-2}	–	–
C_{bW}	–	Λ^{-4}	Λ^{-4}	Λ^{-4}	Λ^{-4}	–	–
C_{tG}	Λ^{-2}	[Λ^{-2}]	Λ^{-2}	–	[Λ^{-2}]	Λ^{-2}	Λ^{-2}

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