Lepton flavour universality and violation using top quarks

ATLAS Experiment

Jacob Kempster on behalf of the ATLAS Collaboration

18/07/2024

(Potentially) anomalous leptonic / flavour physics results

D0 – Like-sign dimuon asymmetry

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

Fermilab – Muon g-2

- PRL 131 (2023) 161802
- EPJC 80 (2020) 241

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

- PRD 108 (2023) 032002

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

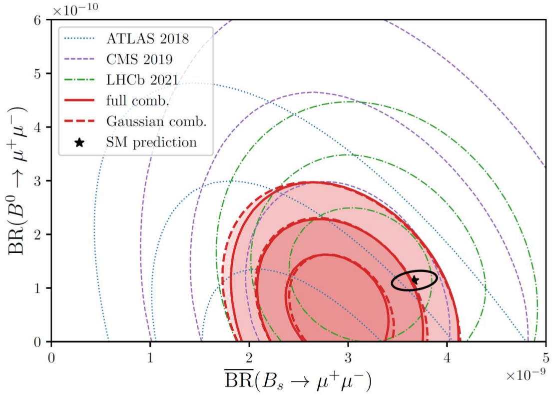
- EPJC 81 (2021) 952

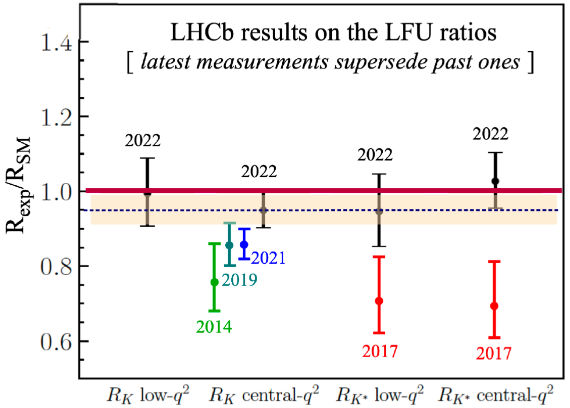
$R(D^{(*)})$

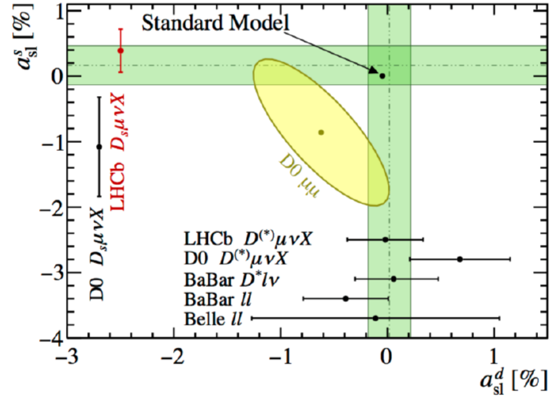
- LHCb-PAPER-2024-007 (in preparation)

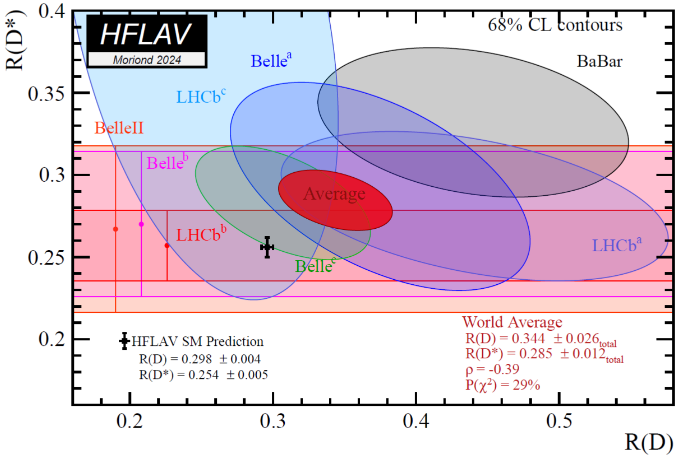
LEP - LFU

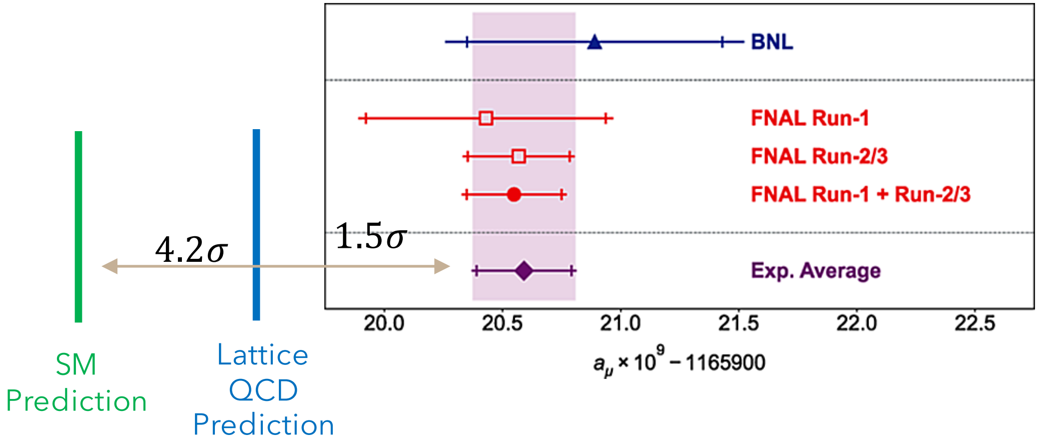
- J Phys Rep 532 (2013) 004

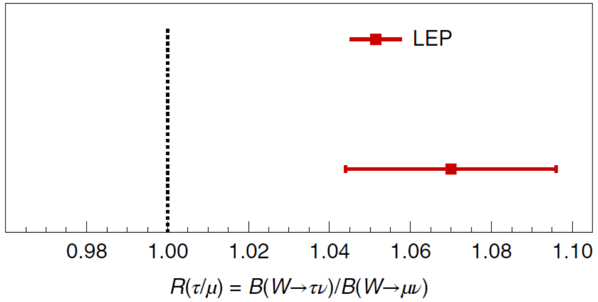






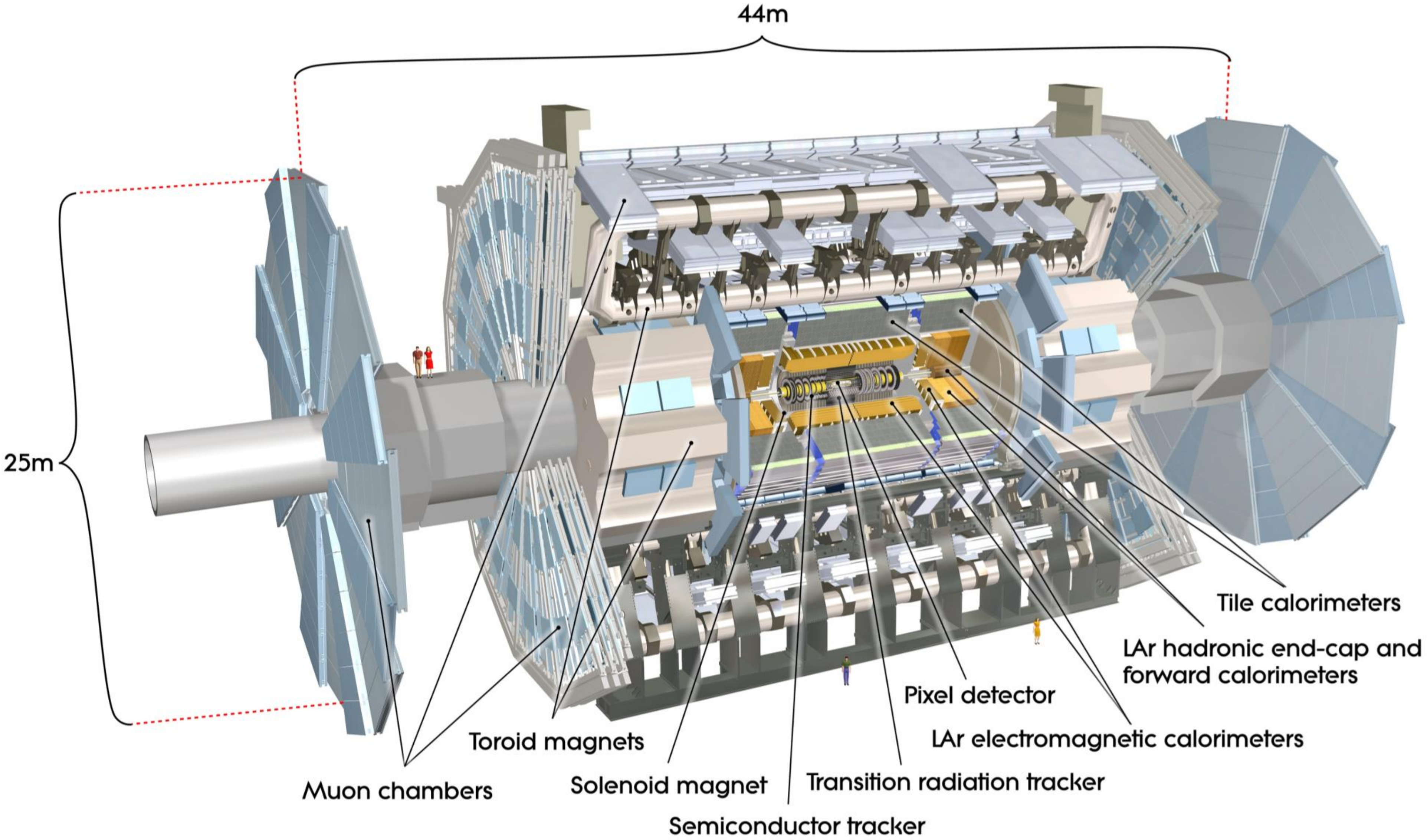






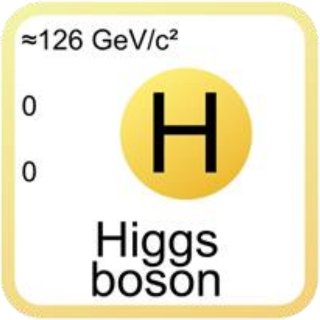
Lots of them!

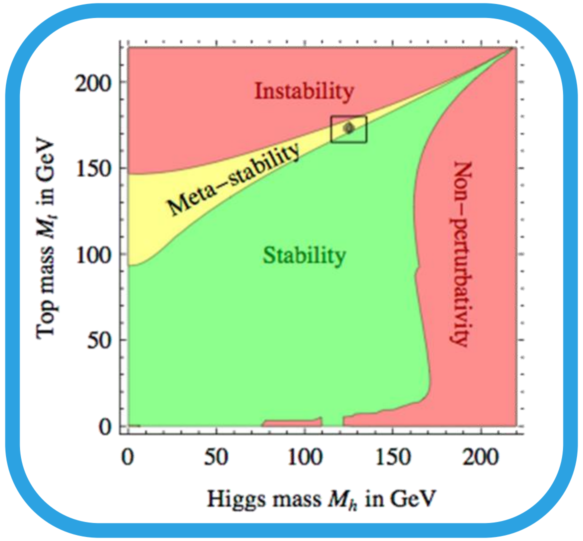
ATLAS

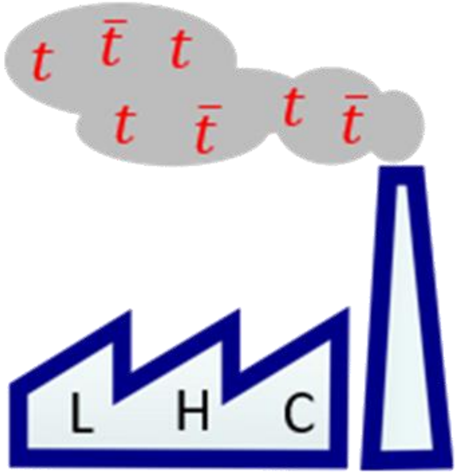

44m
25m
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker

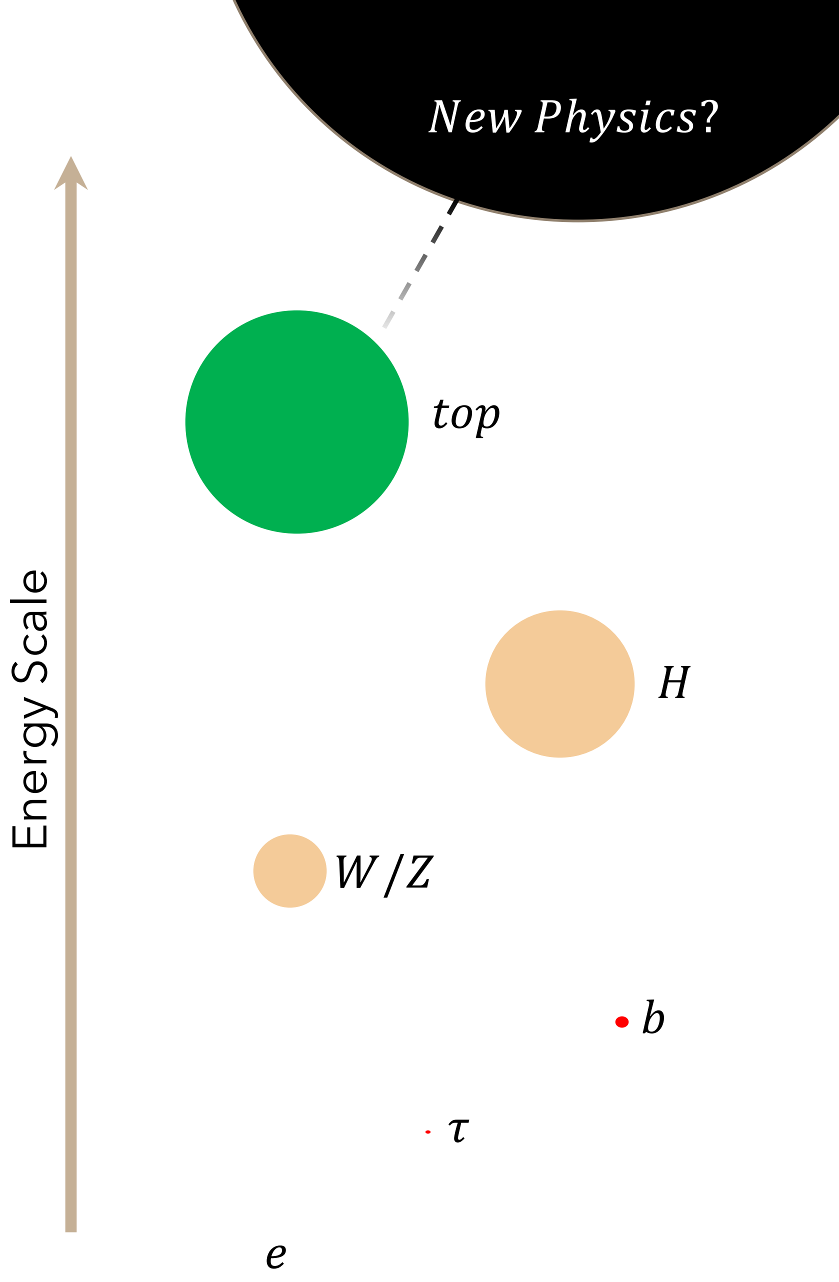
Top Methodology

- 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 $BR(t \to Wb) \sim 100\%$









Analyses (Full Run 2 dataset)

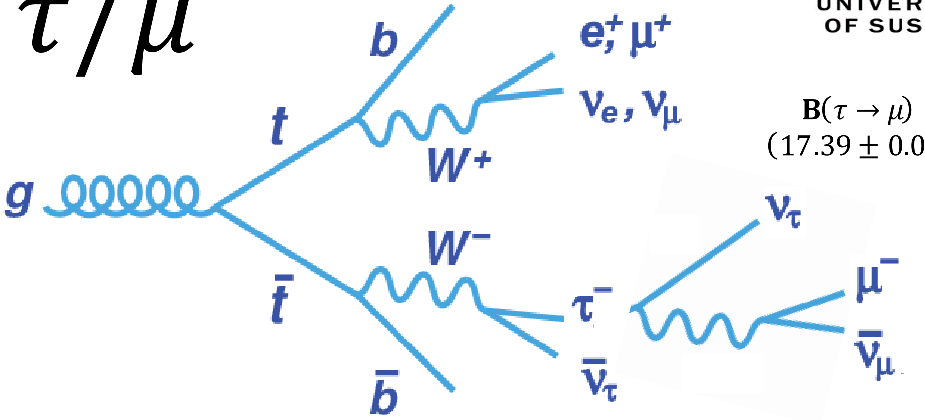
- Lepton Flavour Universality in Top decays (2021): τ/μ
  - Nat. Phys. 17 (2021) 813-818
- Lepton Flavour Universality in Top decays (2024): μ/e
  - arXiv:2403.02133 (Accepted by EPJC)
- Charged-lepton flavour violation: $\mu\tau qt$
  - arXiv:2403.06742 (Accepted by PRD)

Lepton Flavour Universality with Tops
τ/μ

Nat. Phys. 17 (2021) 813-818

Lepton Flavour Universality τ/μ

Fundamental axiom of the Standard Model that the couplings of W and Z-bosons to the charged leptons are independent of their mass.



$\mathbf{B}(\tau \to \mu) = (17.39 \pm 0.04)\%$

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

Di-leptonic $t\bar{t}$ decays

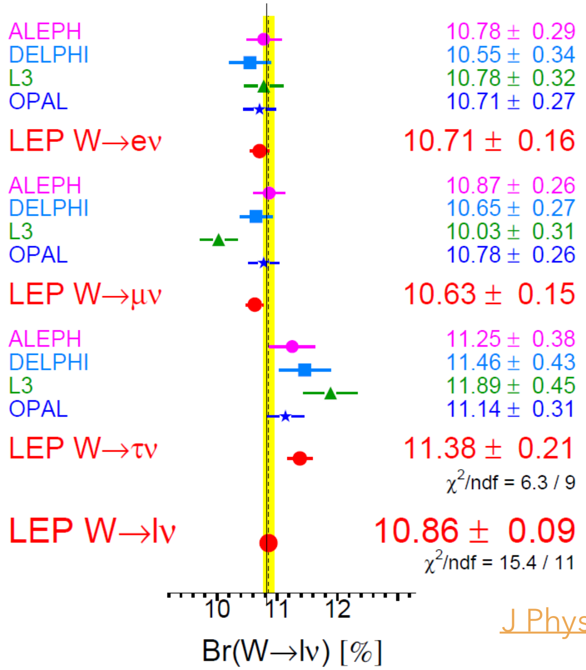
Using leptonic $\tau \to \mu$ decays = big challenge!

- Displaced τ decay vertex
- Low μ transverse momentum
- Kinematic overlap with prompt $W \to \mu$ decays
- Difficult to separate from hadronic decays to muons

Significant backgrounds to control:

- $Z \to \mu\mu$
- $b \to \mu$

W Leptonic Branching Ratios



J Phys Rep 532 (2013) 004

Designing the signal regions

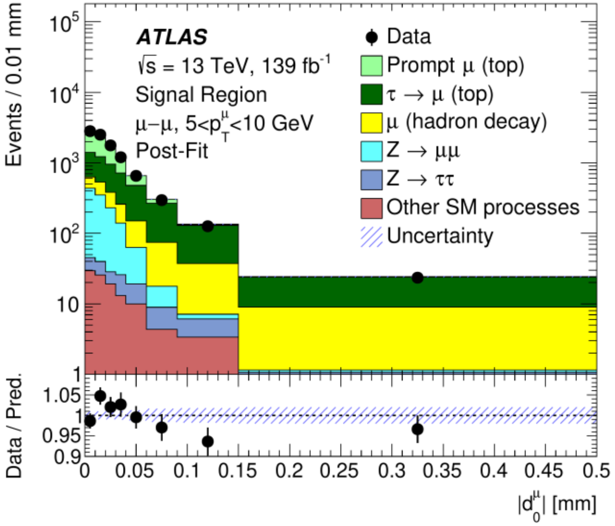
Double-differential binning to discriminate between $t \to W \to \mu$ and $t \to W \to \tau \to \mu$

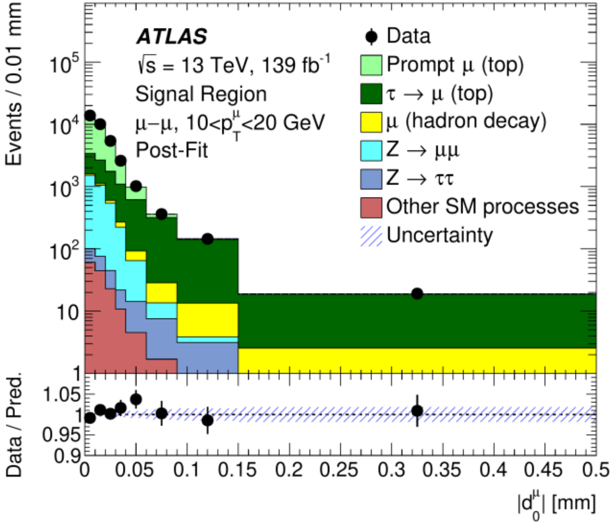
- Muon impact parameter $|d_0^\mu|$
  - Measure of the displacement caused by the lifetime of the parent particle
- Muon transverse momentum p_T^μ
  - Lower in $\tau \to \mu$ events due to energy loss via neutrinos

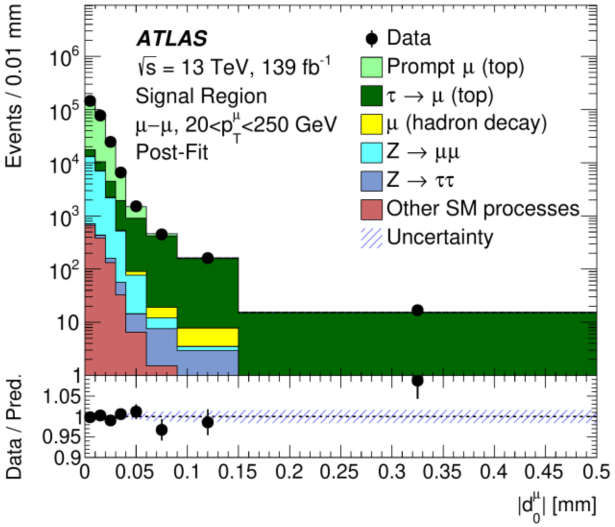
Utilise prompt $W \to l$ for event identification ($l = e, \mu$)

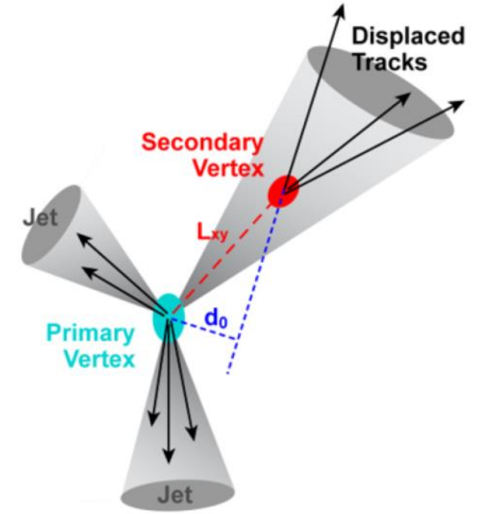
Suppress backgrounds:
Veto: $85 < m_{ll} < 95$ GeV
Veto: $m_{ll} < 15$ GeV
Require: $\mathrm{N_{b-jets}} \geq 2$

+ $e\mu$ channel equivalents







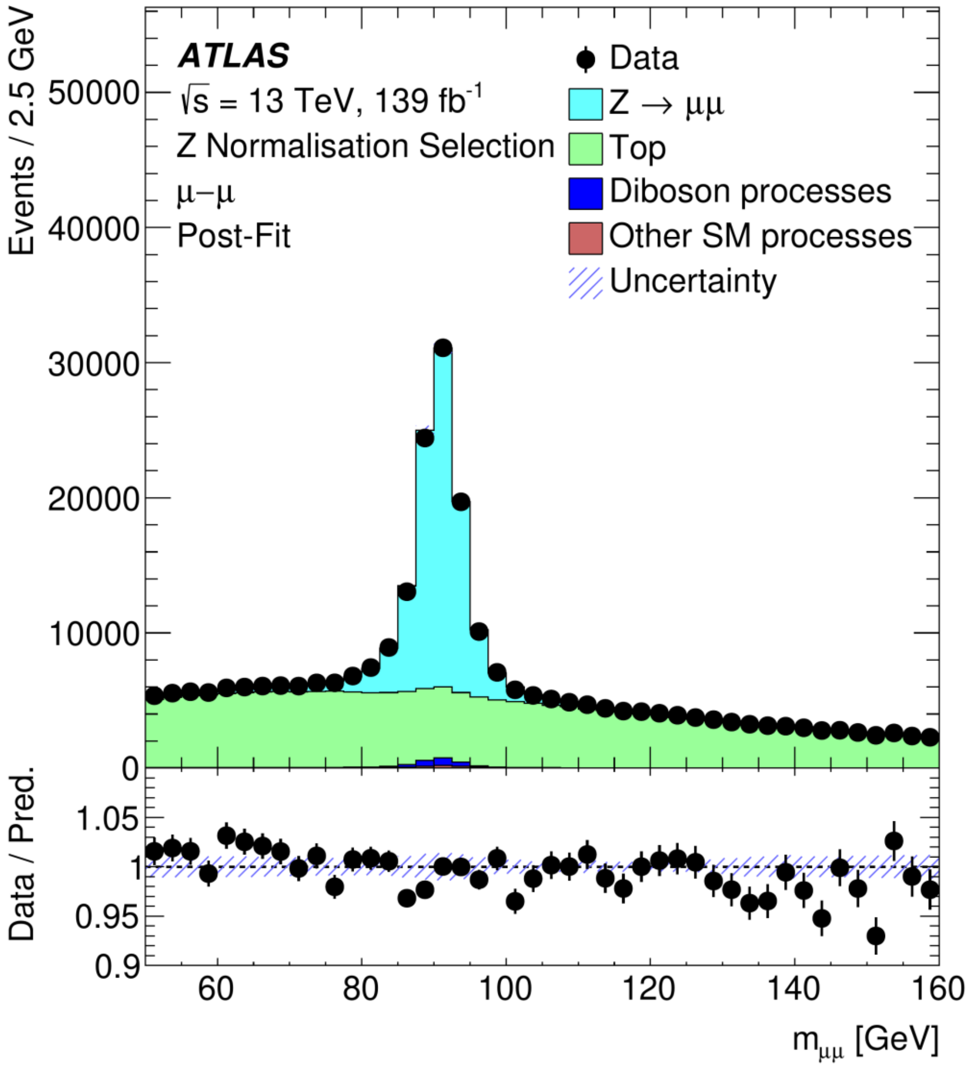


Dealing with $Z \rightarrow \mu\mu$

Important background for small values of $|d_0^\mu|$

Build control region enriched in $Z \rightarrow \mu\mu$

- Same as signal region selection except:
  - No veto on $85 < m_{ll} < 95$ GeV
  - No requirement on $\mathrm{N_{(b-)jets}}$
- Fit $m_{\mu\mu}$ distribution to understand normalisation
- Apply normalisation in signal region



Dealing with $b(c) \to \mu$

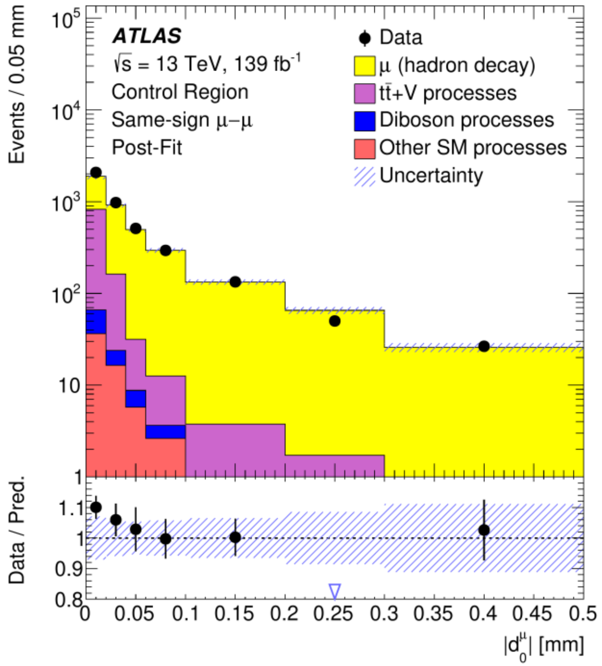
Important background for large values of $|d_0^{\mu}|$

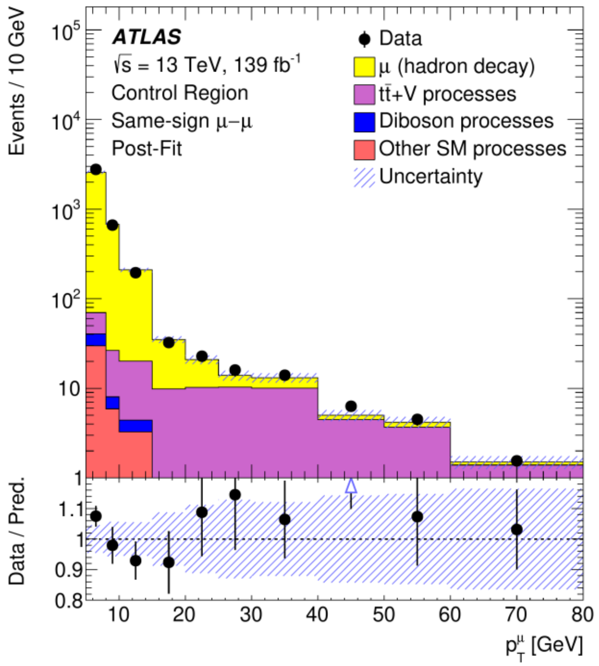
Build control region enriched in $b(c) \to \mu$

- Same as signal region selection except:
    - Same-charge leptons ($e\mu$ or $\mu\mu$)

- Higher p_T bins also used to control normalisation of $t\bar{t}V$ and $t\bar{t}$ with a charge-mis-ID lepton

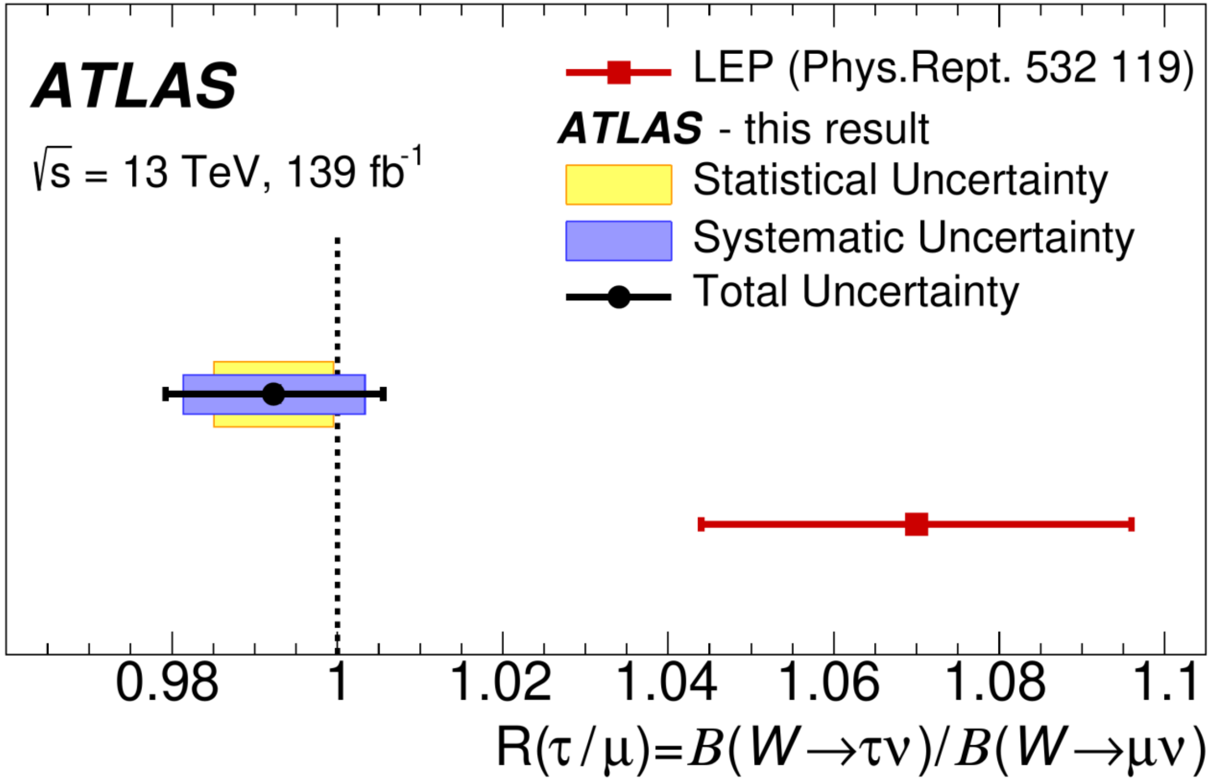
- Apply normalisations back to signal region





Lepton Flavour Universality τ/μ

Nat. Phys. 17 (2021) 813-818



$$R(\tau/\mu) = 0.992 \pm 0.007\ (\text{stat}) \pm 0.011\ (\text{syst})$$

~1.3% total uncertainty

- Imperfect $|d_0^{\mu}|$ modelling
- Parton shower
- Muon identification, selection and reconstruction efficiencies

- Consistent with assumption of lepton flavour universality

CMS: $R(\tau/\mu) = 0.985 \pm 0.020$
Phys. Rev. D 105 (2022) 072008

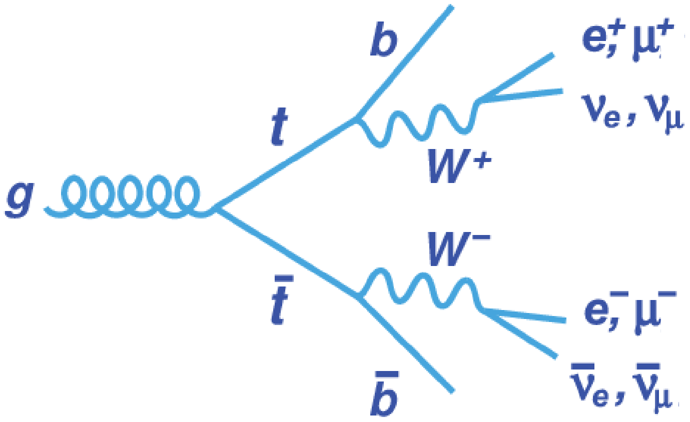
Lepton Flavour Universality with Tops

μ/e

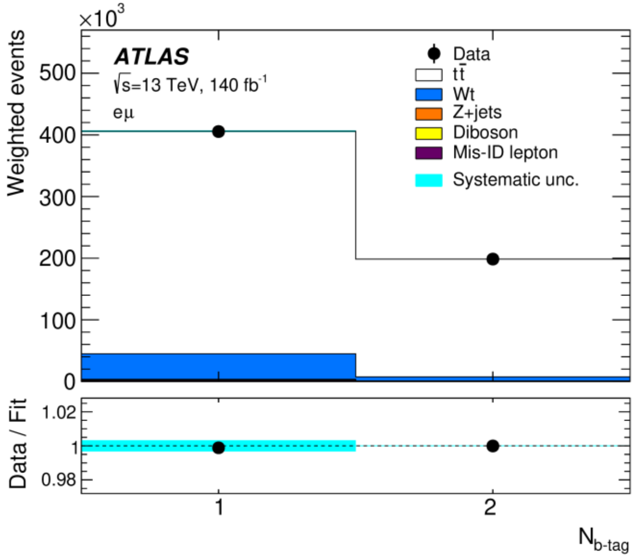
arXiv:2403.02133

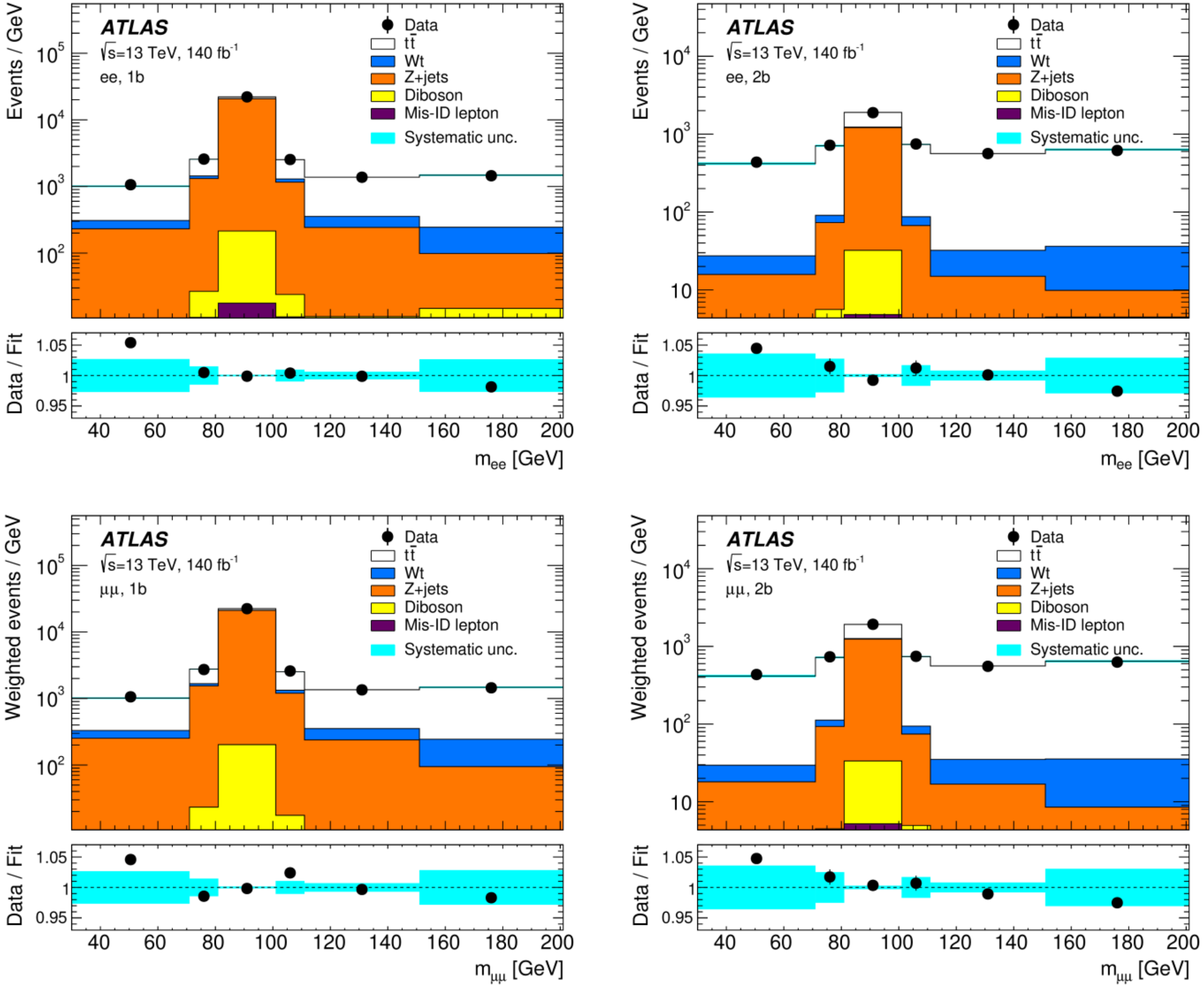
(Accepted by EPJC)

Lepton Flavour Universality μ/e



$$R_W^{\mu/e} = \frac{B(W \to \mu\nu)}{B(W \to e\nu)}$$





Lepton Flavour Universality μ/e

"B-tag counting method"

Describe the number of events with X-btags (N_X^{ll}) as a function of the luminosity, cross section, lepton (ϵ_{ll}) and b-tagging (ϵ_b^{ll}) efficiencies, b-tagging correlations (C_b^{ll}), branching ratio correlations $g_{ll}^{t\bar{t}}$ and background estimations.

$$N_{1,m}^{ll} = L\sigma_{t\bar{t}}\, \epsilon_{ll}\, g_{ll}^{t\bar{t}}\, 2\epsilon_b^{ll}\left(1 - C_b^{ll}\, \epsilon_b^{ll}\right) f_{1,m}^{ll,t\bar{t}} + \sum\nolimits_{k=\mathrm{bkg}}\left(s_1^k\, g_{ll}^k\, f_{1,m}^{ll,k}\, N_1^{ll,k}\right)$$

$$N_{2,m}^{ll} = L\sigma_{t\bar{t}}\, \epsilon_{ll}\, g_{ll}^{t\bar{t}}\, C_b^{ll}\left(\epsilon_b^{ll}\right)^2 f_{2,m}^{ll,t\bar{t}} + \sum\nolimits_{k=\mathrm{bkg}}\left(s_2^k\, g_{ll}^k\, f_{2,m}^{ll,k}\, N_2^{ll,k}\right)$$

$$\boxed{R_W^{\mu/e} = \frac{\mathcal{B}(W \to \mu\nu)}{\mathcal{B}(W \to e\nu)} = \frac{\overline{W}(1+\Delta_W)}{\overline{W}(1-\Delta_W)}}$$

$$\begin{aligned}
g_{ee}^{t\bar{t}} &= f_{0\tau}^{ee}(1-\Delta_W)^2 && + f_{1\tau}^{ee}(1-\Delta_W) && + f_{2\tau}^{ee} \\
g_{e\mu}^{t\bar{t}} &= f_{0\tau}^{e\mu}(1-\Delta_W)(1+\Delta_W) && + f_{1\tau}^{e\mu} && + f_{2\tau}^{e\mu} \\
g_{\mu\mu}^{t\bar{t}} &= f_{0\tau}^{\mu\mu}(1+\Delta_W)^2 && + f_{1\tau}^{\mu\mu}(1+\Delta_W) && + f_{2\tau}^{\mu\mu}
\end{aligned}$$

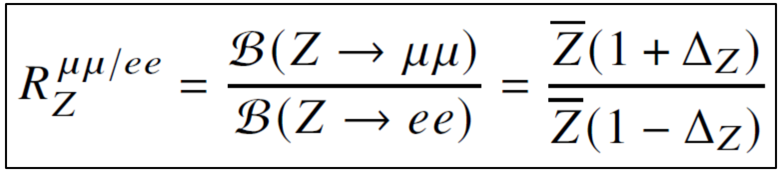
Lepton Flavour Universality μ/e

"B-tag counting method"

Describe the number of events with X-btags (N_X^{ll}) as a function of the luminosity, cross section, lepton (ϵ_{ll}) and b-tagging (ϵ_b^{ll}) efficiencies, b-tagging correlations (C_b^{ll}), branching ratio correlations $g_{ll}^{t\bar{t}}$ and background estimations.

$$N_Z^{ee} = L\sigma_{Z\to ll}\,\epsilon_{Z\to ee}\,g_{ee}^{Z+\text{jets}} + \sum_{k=\text{bkg}}\left(s_Z^k\,N_Z^{ee,k}\right)$$

$$N_Z^{\mu\mu} = L\sigma_{Z\to ll}\,\epsilon_{Z\to \mu\mu}\,g_{\mu\mu}^{Z+\text{jets}} + \sum_{k=\text{bkg}}\left(s_2^k\,N_Z^{\mu\mu,k}\right)$$



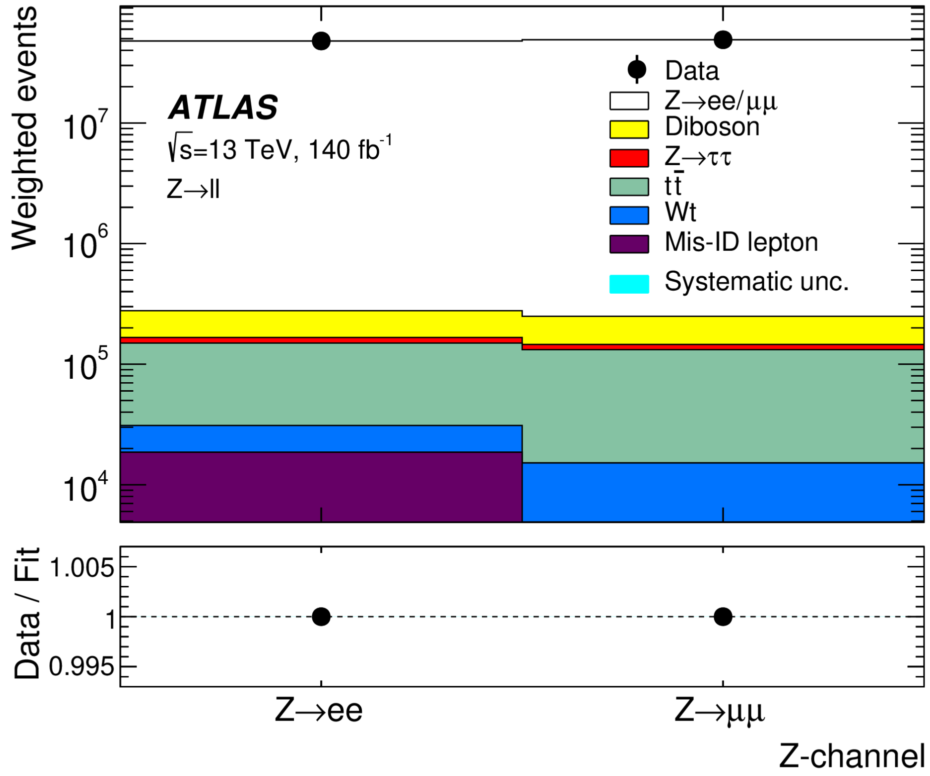
$$\boxed{R_Z^{\mu\mu/ee} = \frac{\mathcal{B}(Z\to\mu\mu)}{\mathcal{B}(Z\to ee)} = \frac{\overline{Z}(1+\Delta_Z)}{\overline{Z}(1-\Delta_Z)}}$$

$$g_{ee}^{Z+\text{jets}} = (1-\Delta_Z)(1-\Delta_{Z+b})$$
$$g_{e\mu}^{Z+\text{jets}} = 1$$
$$g_{\mu\mu}^{Z+\text{jets}} = (1+\Delta_Z)(1+\Delta_{Z+b})$$

Lepton Flavour Universality μ/e

Fitting 10 free parameters: $\sigma_{t\bar{t}}$, $\sigma_{Z\rightarrow ll}$, $R_{WZ}^{\mu/e}$, $R_{Z}^{\mu\mu/ee}$, $\epsilon_{b}^{ll'}$, Z+jets normalisation…
Measuring b-tagging and lepton efficiencies, lepton mis-ID and charge mis-ID in place…

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



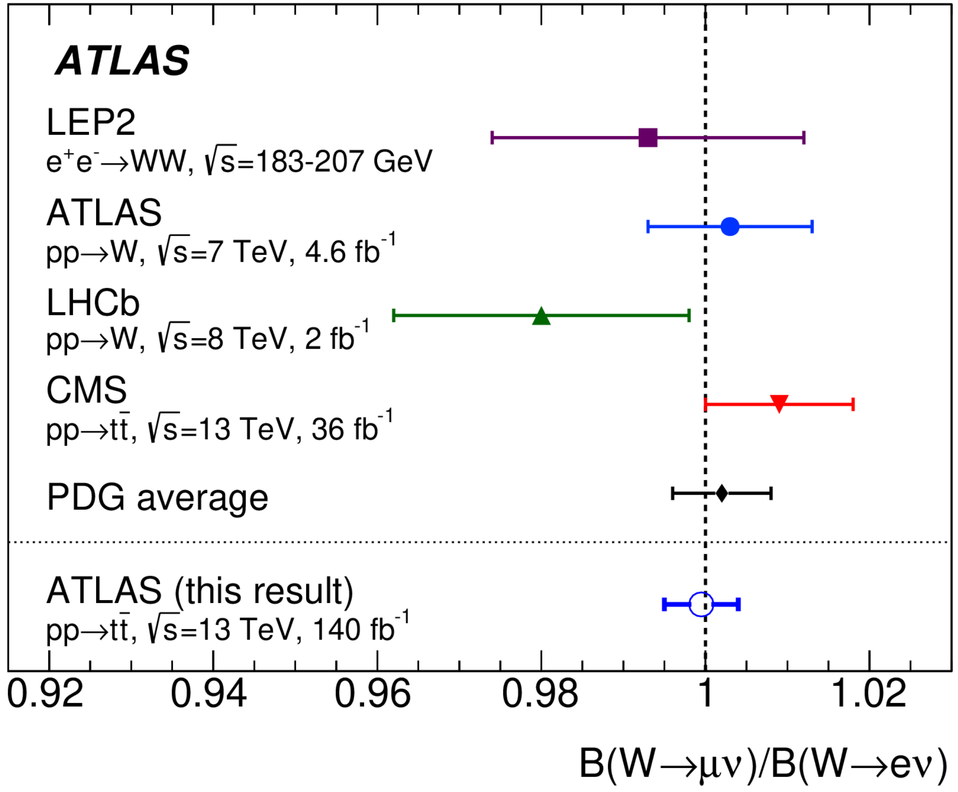
Tailored normalisation:

- Reduces sensitivity to uncertainties on electron and muon efficiencies through cancellations
- Exploits extremely precise external measurement of $R_{Z}^{\mu\mu/ee}$ from LEP and SLD:

$$R_{Z-\mathrm{ext}}^{\mu\mu/ee} = 1.0009 \pm 0.0028$$

Lepton Flavour Universality μ/e

arXiv:2403.02133 , ATLAS Briefing , CERN Courier



$$R_W^{\mu/e} = 0.9995 \pm 0.0022\ (\text{stat}) \pm 0.0036\ (\text{syst}) \pm 0.0014\ (\text{ext})$$

~0.45% total uncertainty

- Misidentified leptons
- PDFs
- $t\bar{t}$ and Z+jets modelling
- Lepton efficiencies

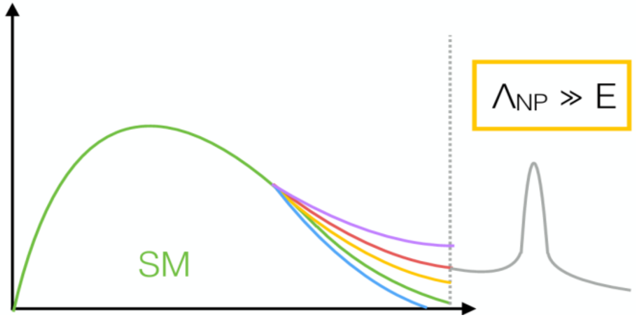
- Consistent with assumption of lepton flavour universality
- Smaller uncertainty than previous world average

Top Charged-Lepton Flavour-Violation $\mu\tau qt$

arXiv:2403.06742
(Accepted by PRD)

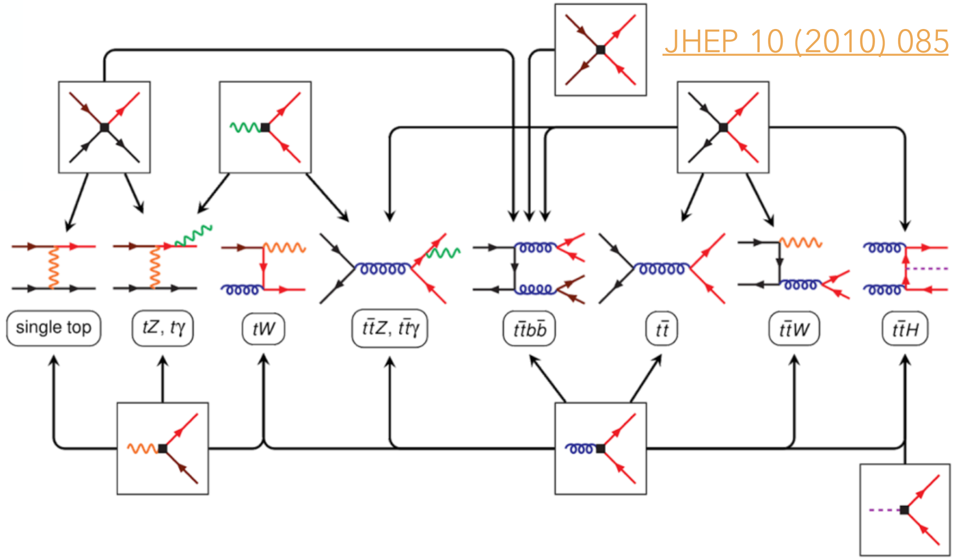
Effective Field Theory (EFT)

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



K. Mimasu, EFTforTop

JHEP 10 (2010) 085

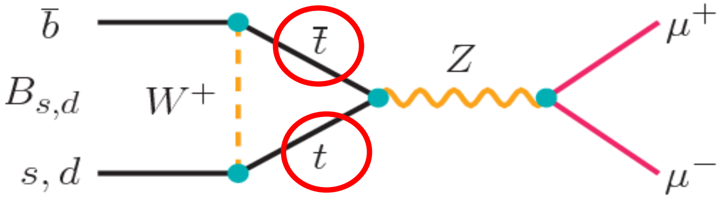


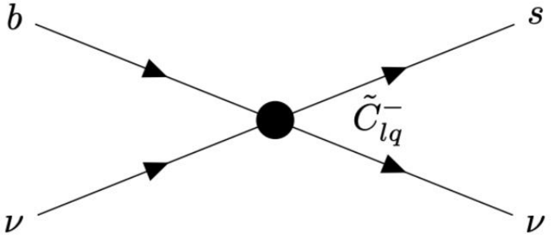
$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{i,n} \frac{c_i^{(n)}}{\Lambda^{n-4}} \mathcal{O}_i^{(n)}$$

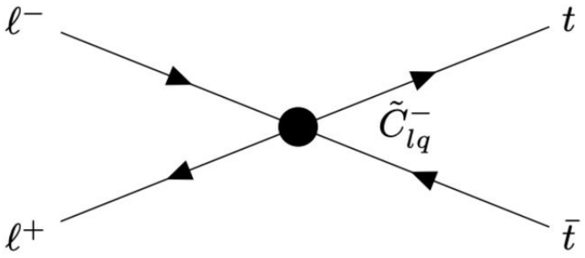
Standard Model

Coupling Strength

Operators introducing new interactions

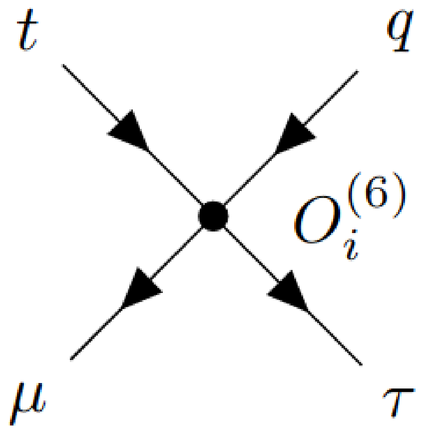






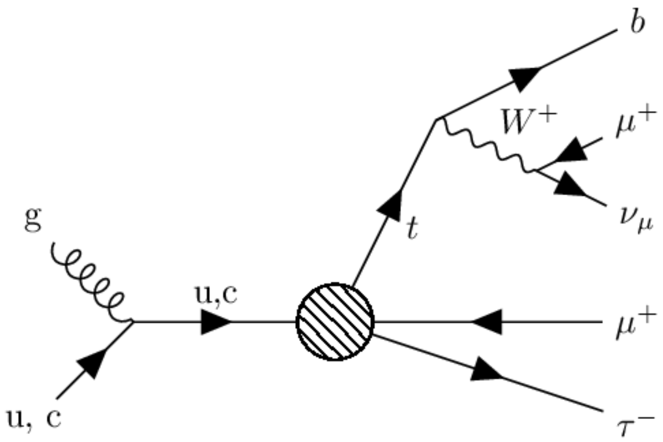
2Q2L EFT operators

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



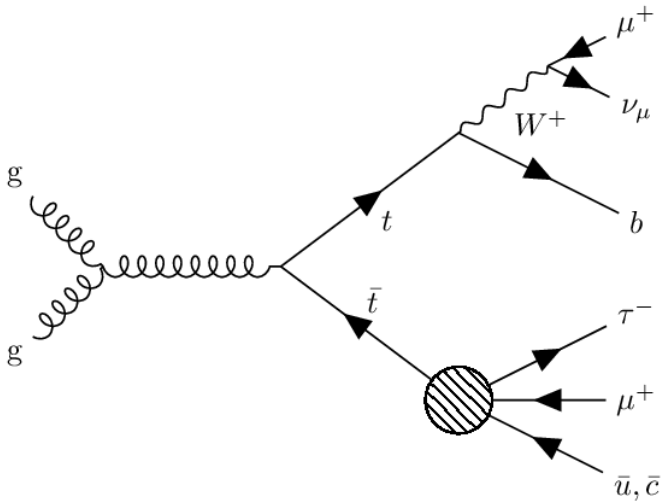
Production

$qg \rightarrow tll'$



Decay

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



Recent history

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

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

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

ATLAS-CONF-2018-044

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

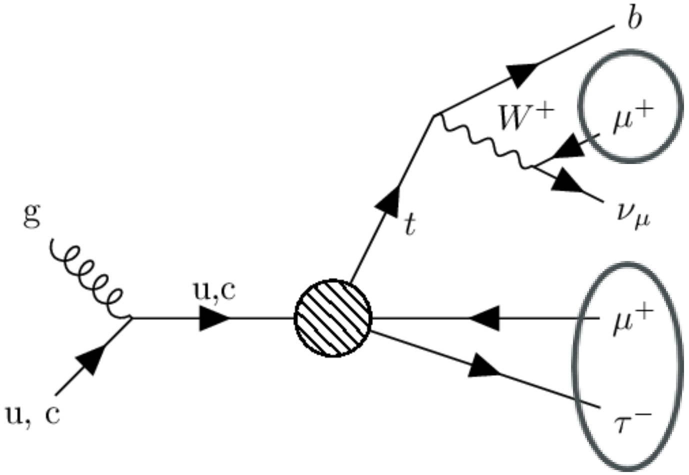
$$B(t \to e\mu q) < 0.009 - 0.258 \times 10^{-6}$$

CMS-PAS-TOP-22-005

(3-lepton final state , $138\ \mathrm{fb}^{-1}$)

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

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



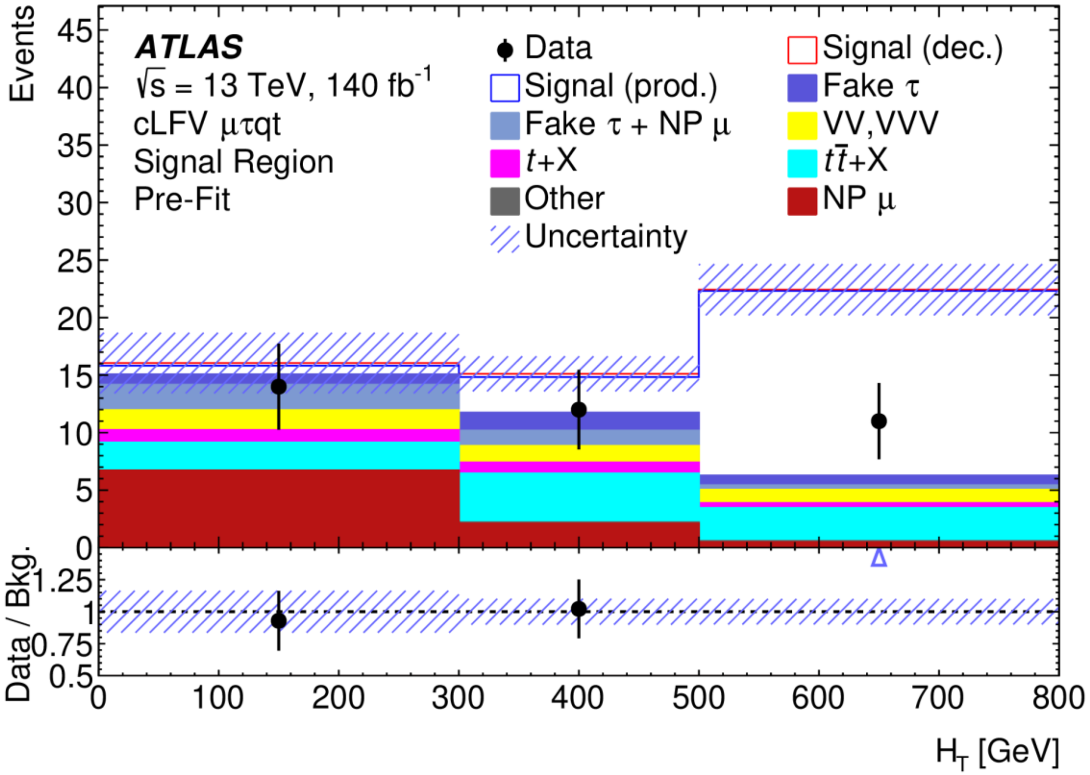
Signal region

Binned in H_T (sum of visible object transverse momenta) 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



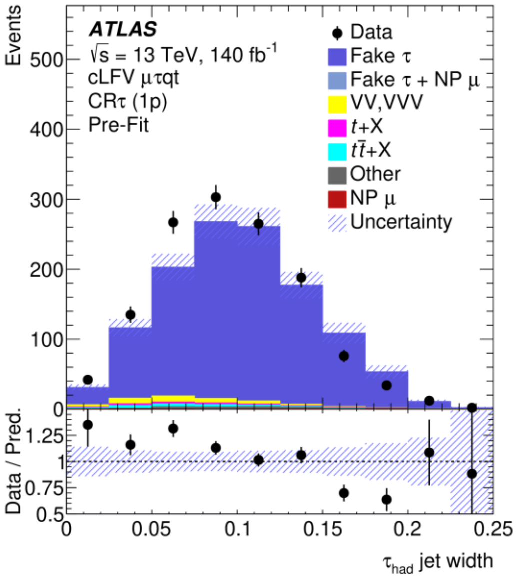
Fake and non-prompt estimations

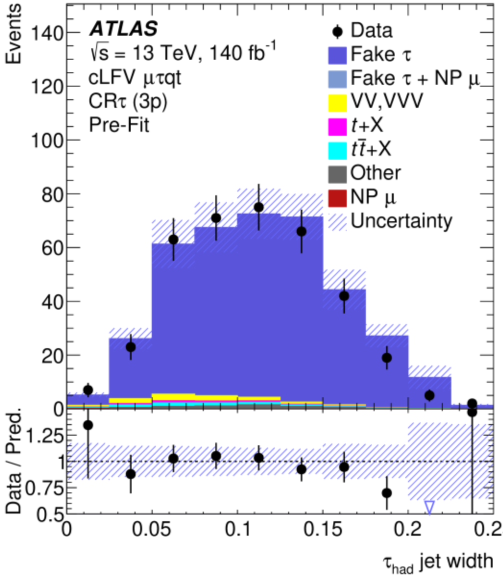
TAUS

- Fake hadronic taus are usually due to mis-identified jets
- Dedicated CRs (right, do 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



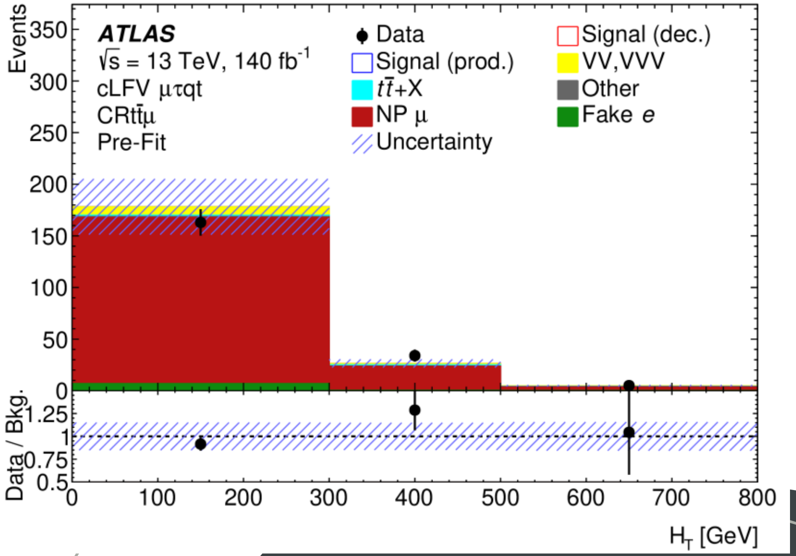


MUONS

Dedicated CR (right, 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)



Profile-likelihood fit

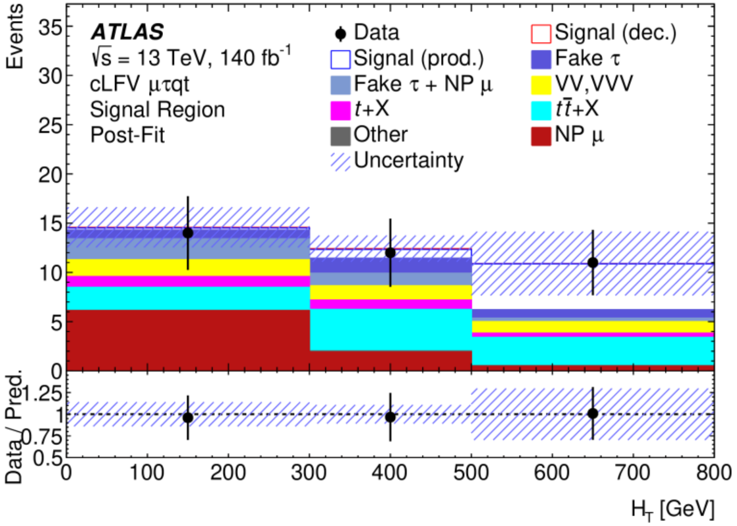
arXiv:2403.06742

Good agreement between data and background-only model

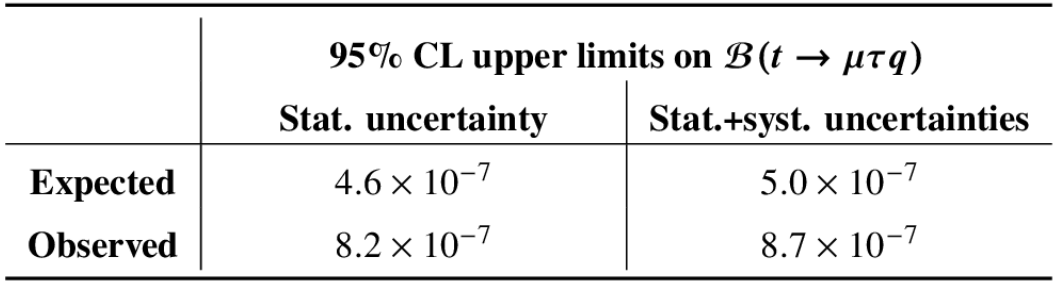
Statistically limited result

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

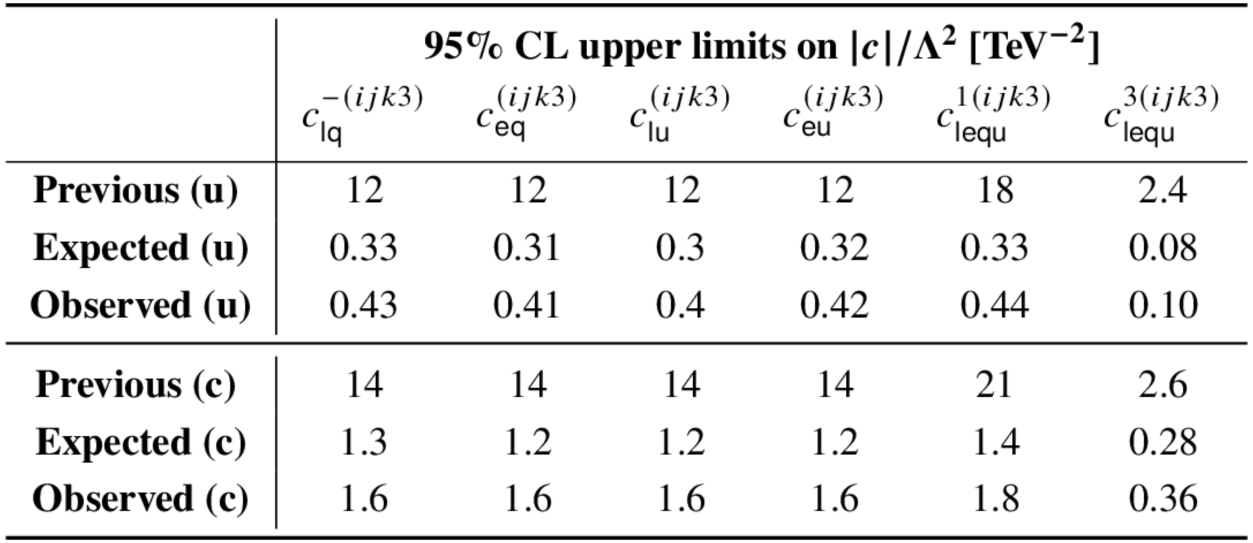
1.6σ tension



'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}



	95% CL upper limits on $\|c\|/\Lambda^2$ [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 $\mu\tau ut$).

Summary

- (Some) Lepton and Flavour physics anomalies persist
- Top quarks are a fantastic tool to search for new physics
- Effective Field Theory is valuable for model-independent BSM searches
- ATLAS is actively engaged in research for LFU and CLFV

Backup

D0 - Tevatron

Counting experiment – how many same-sign muon pairs?

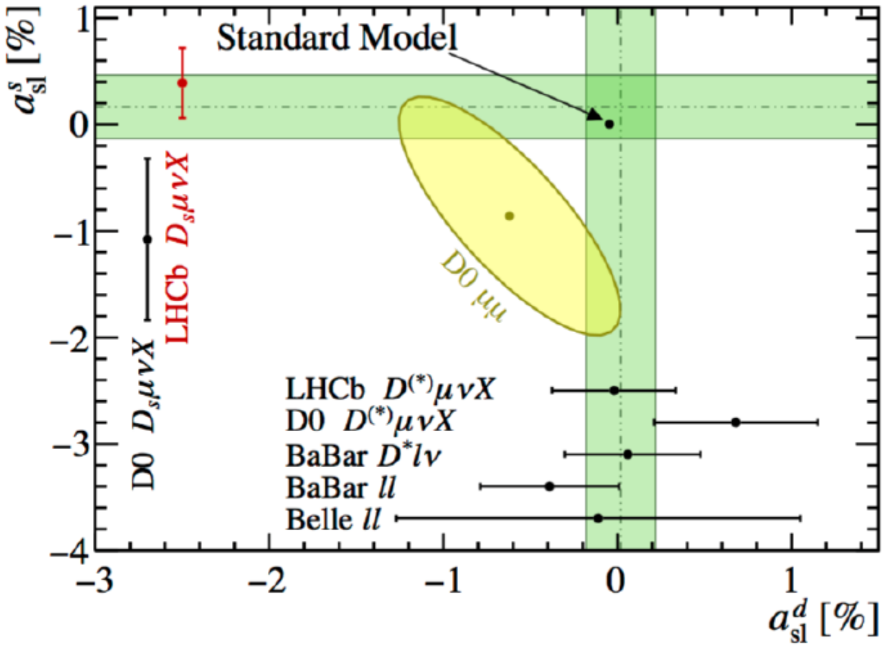
$$A = \frac{(N^{++} - N^{--})}{(N^{++} + N^{--})}$$

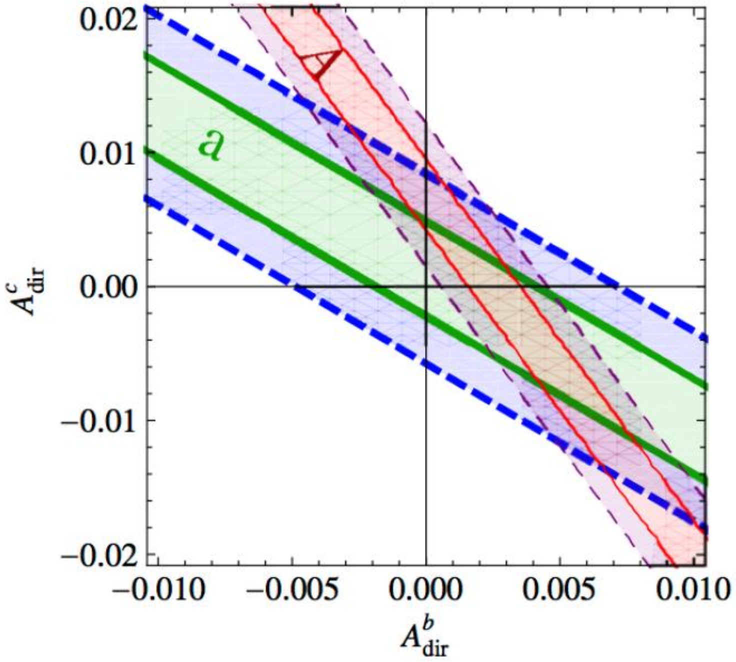
(2010-2013) Observed asymmetries up to $\mathbf{3.9\sigma}$ from SM expectation

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

$$a^q_{\rm sl} = \frac{\Gamma\left(\bar{B}^0_q \to B^0_q \to f\right) - \Gamma\left(B^0_q \to \bar{B}^0_q \to \bar{f}\right)}{\Gamma\left(\bar{B}^0_q \to B^0_q \to f\right) + \Gamma\left(B^0_q \to \bar{B}^0_q \to \bar{f}\right)},$$

$$a^q_{\rm dir} = \frac{\Gamma\left(b \to \mu^- X\right) - \Gamma\left(\bar{b} \to \mu^+ X\right)}{\Gamma\left(b \to \mu^- X\right) + \Gamma\left(\bar{b} \to \mu^+ X\right)},$$





Muon g-2 - Fermilab

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

g_μ = Muon gyromagnetic factor

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

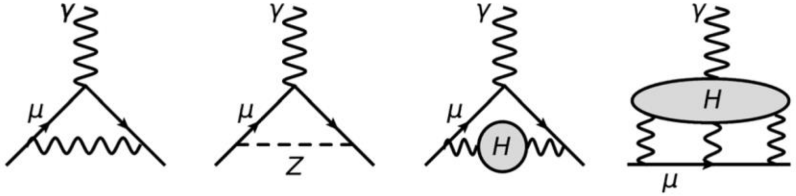
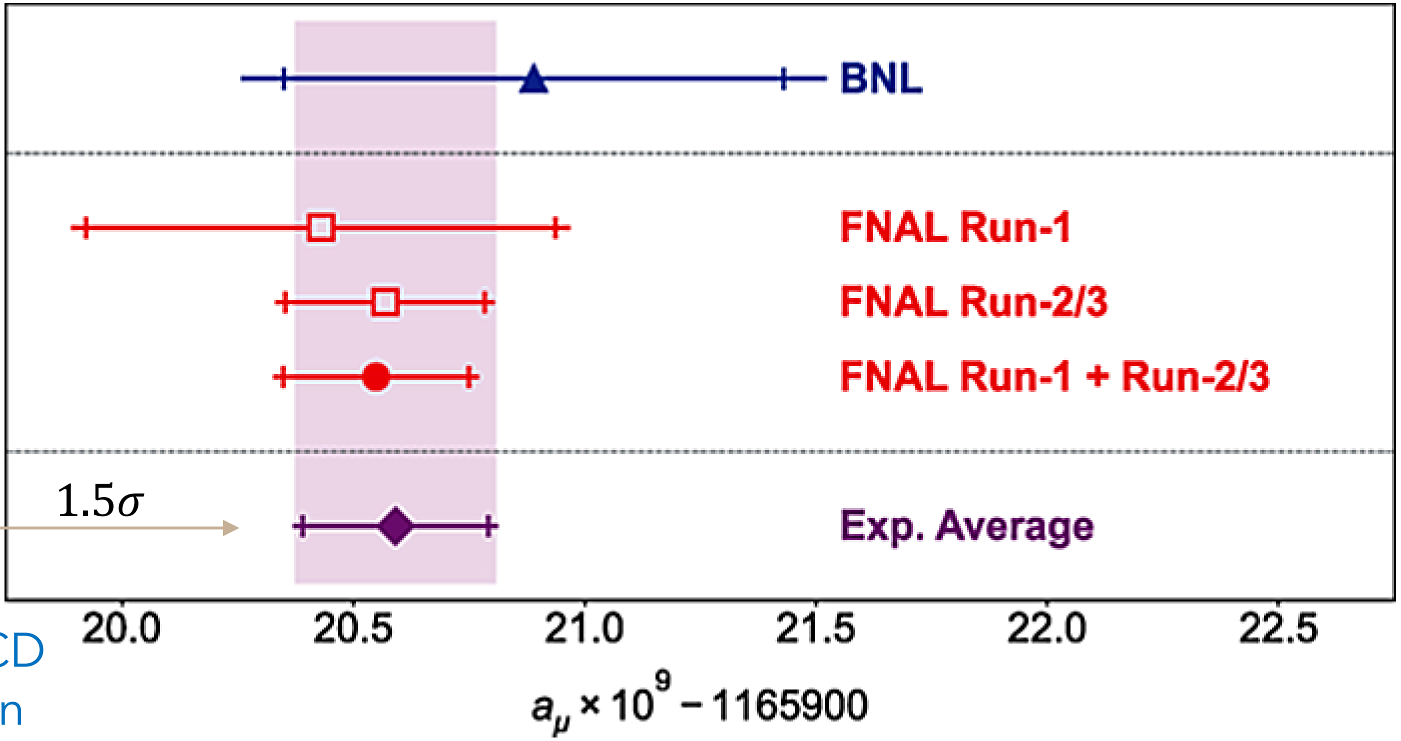
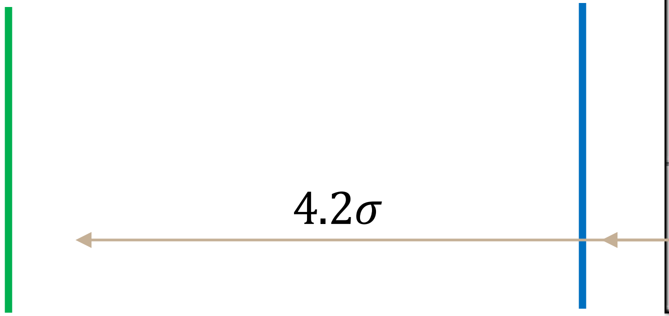


FIG. 1. Feynman diagrams of representative SM contributions to the muon anomaly. From left to right: first-order QED and weak processes, leading-order hadronic (H) vacuum polarization, and hadronic light-by-light contributions.

PRL 131 (2023) 161802





SM Prediction

Lattice QCD Prediction

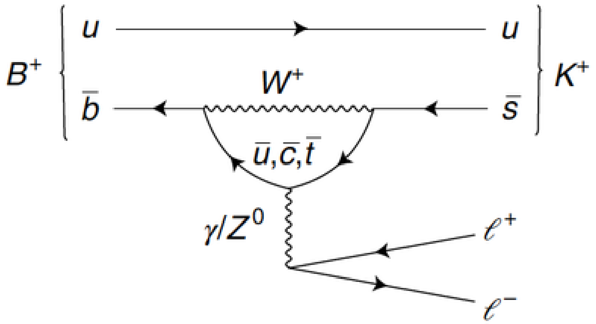
EPJC 80 (2020) 241

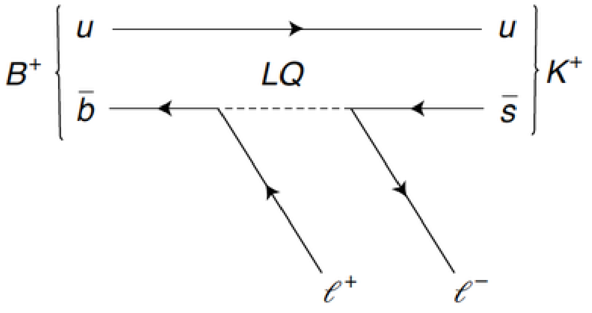
$\mathrm{R}(\mathrm{K}^{(*)})$

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

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

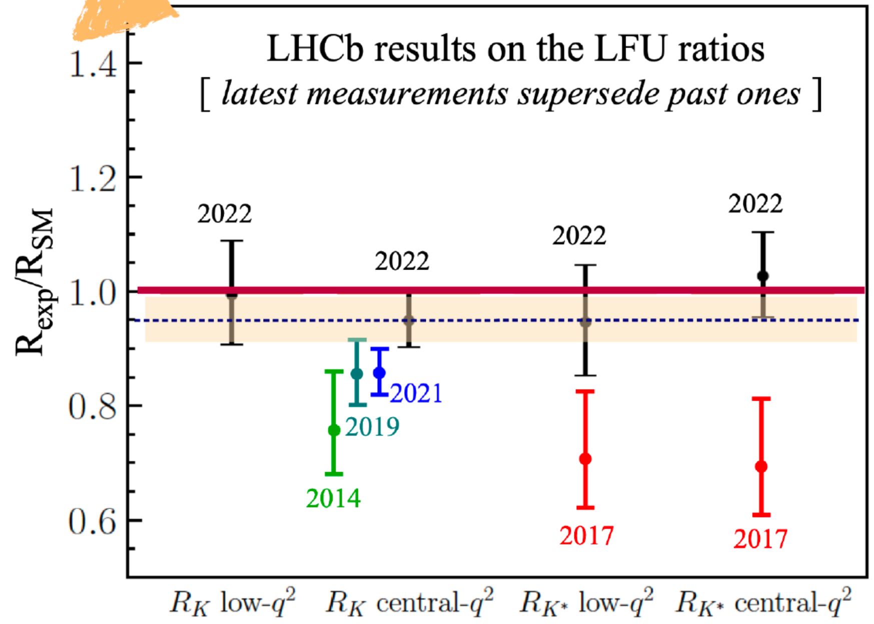
$$R_{K^*} = \frac{\mathrm{BR}(B \to K^*\mu^+\mu^-)}{\mathrm{BR}(B \to K^*e^+e^-)}.$$



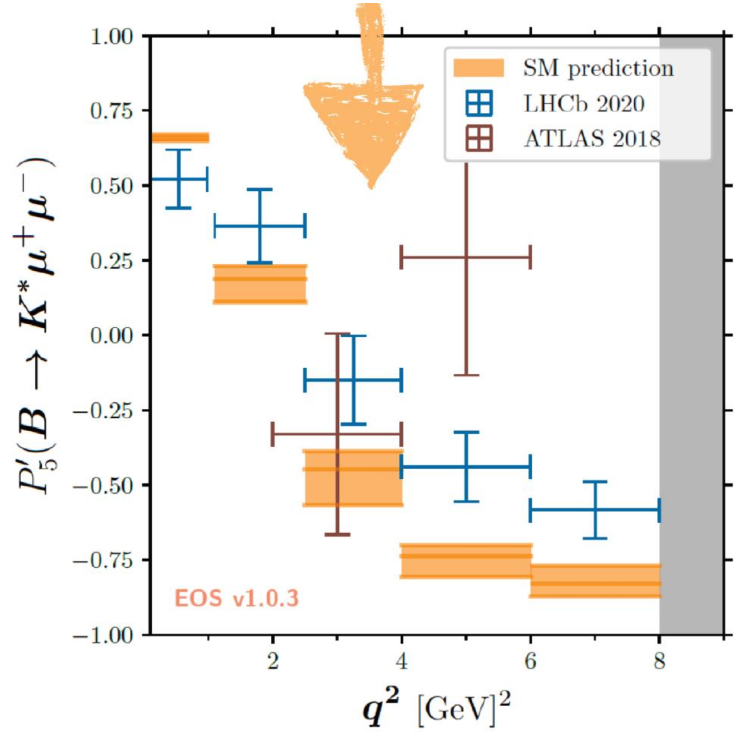


At one point this was up to 3.1σ away from the SM

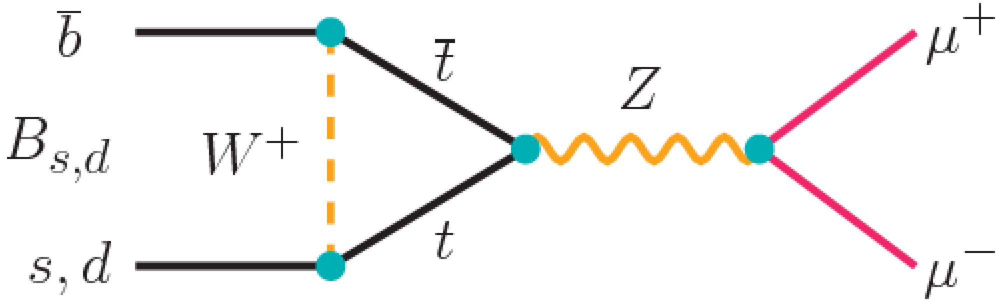
Now found to be in good agreement
PRD 108 (2023) 032002

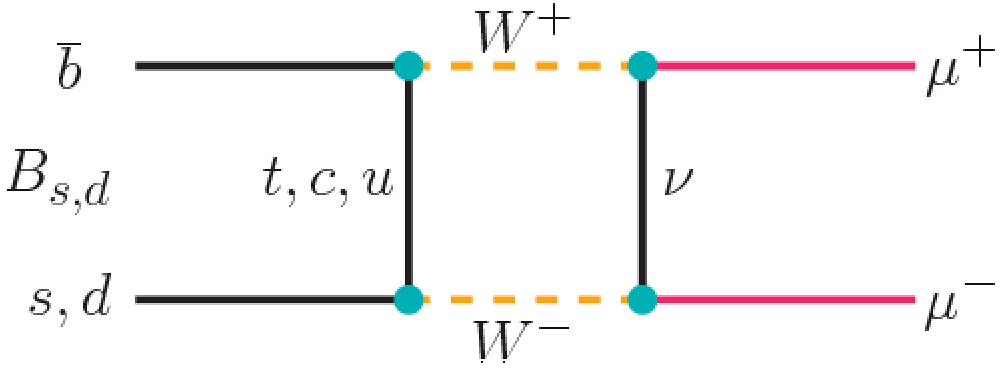


(However, some angular discrepancies remain!)



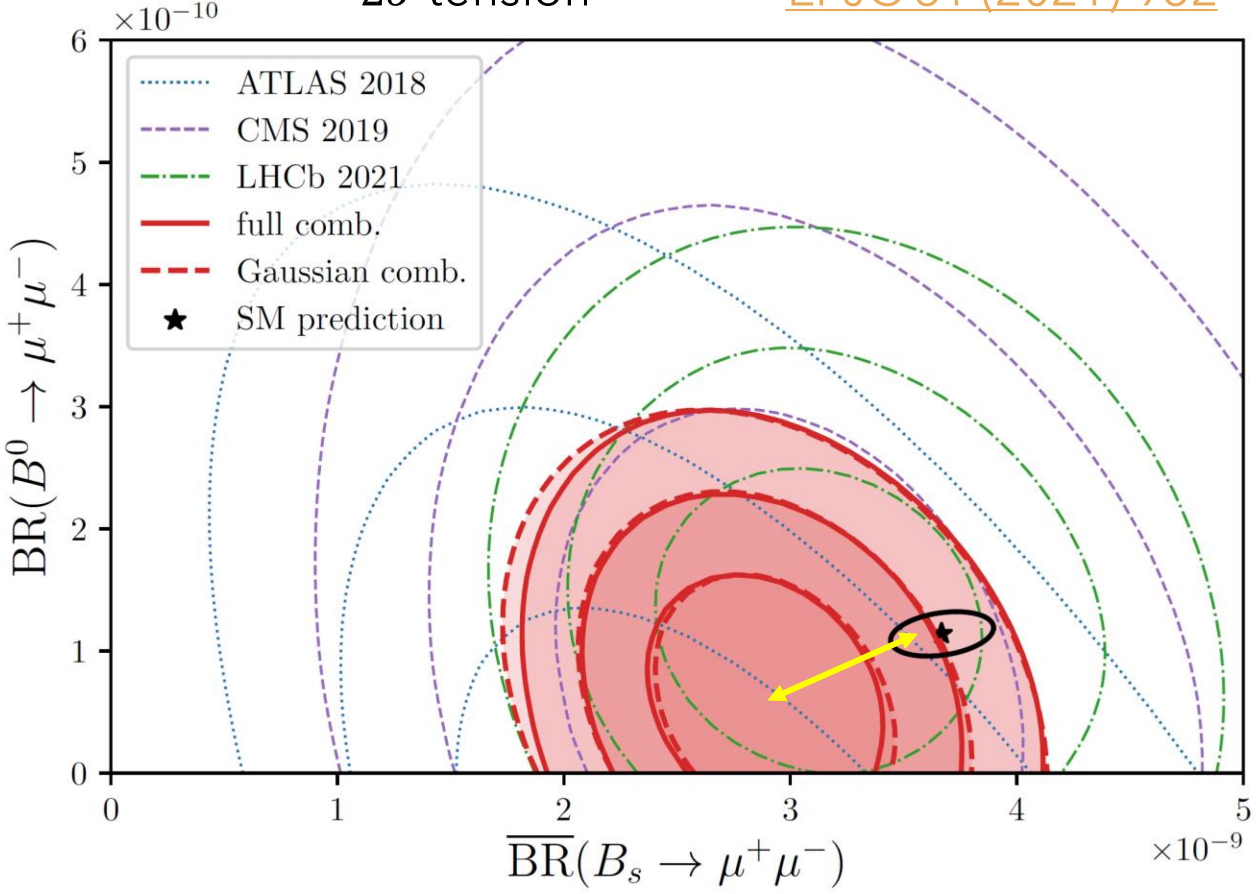
$B_s \to \mu^+\mu^-$





2σ tension

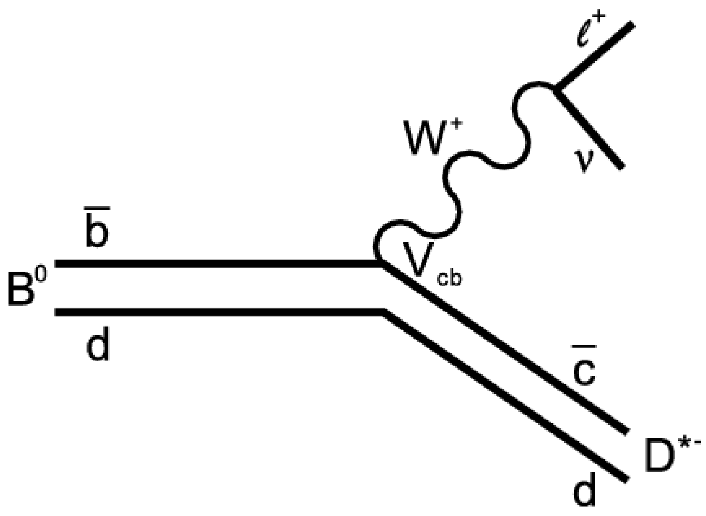
EPJC 81 (2021) 952



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

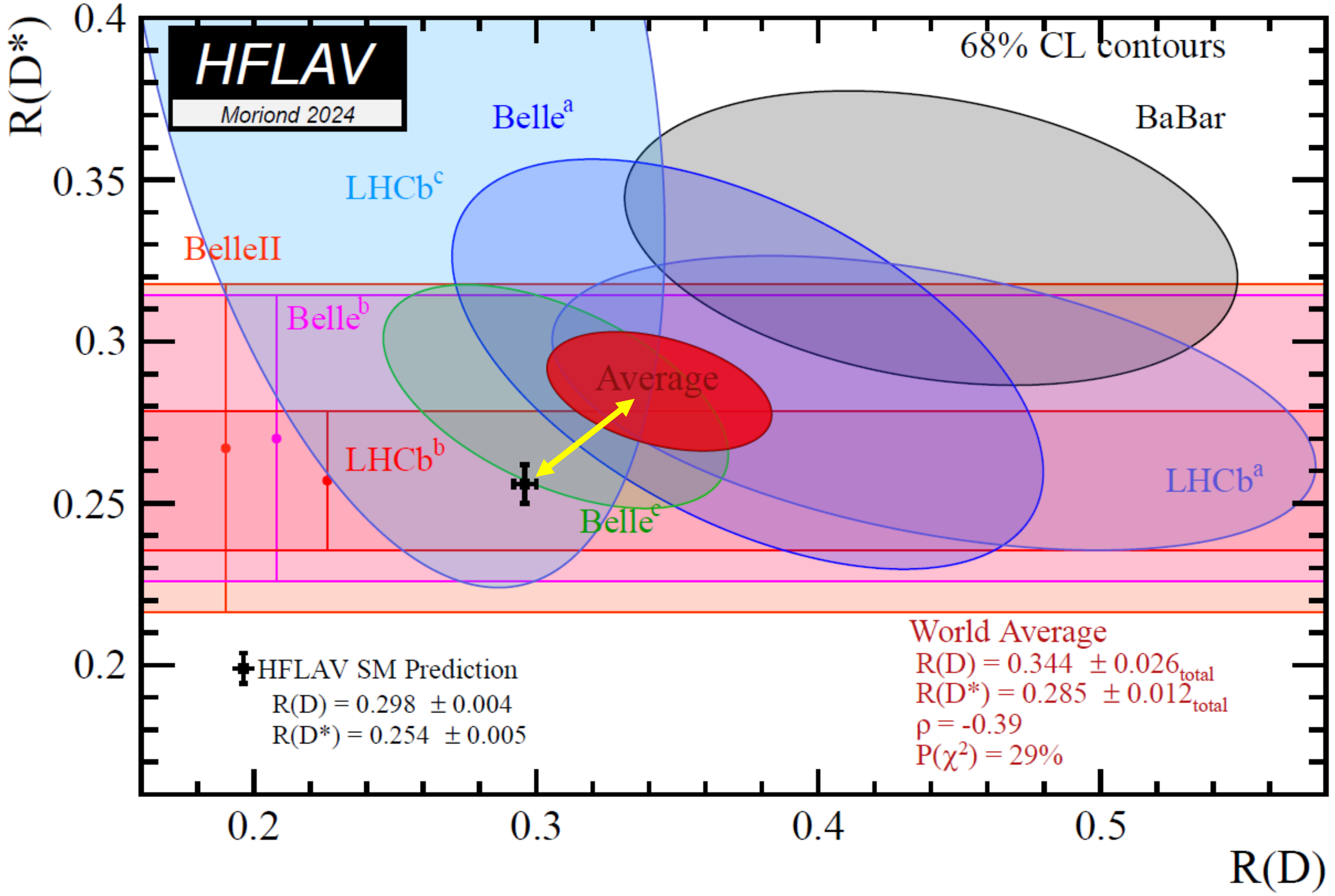
LHCb-PAPER-2024-007 (in preparation)

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

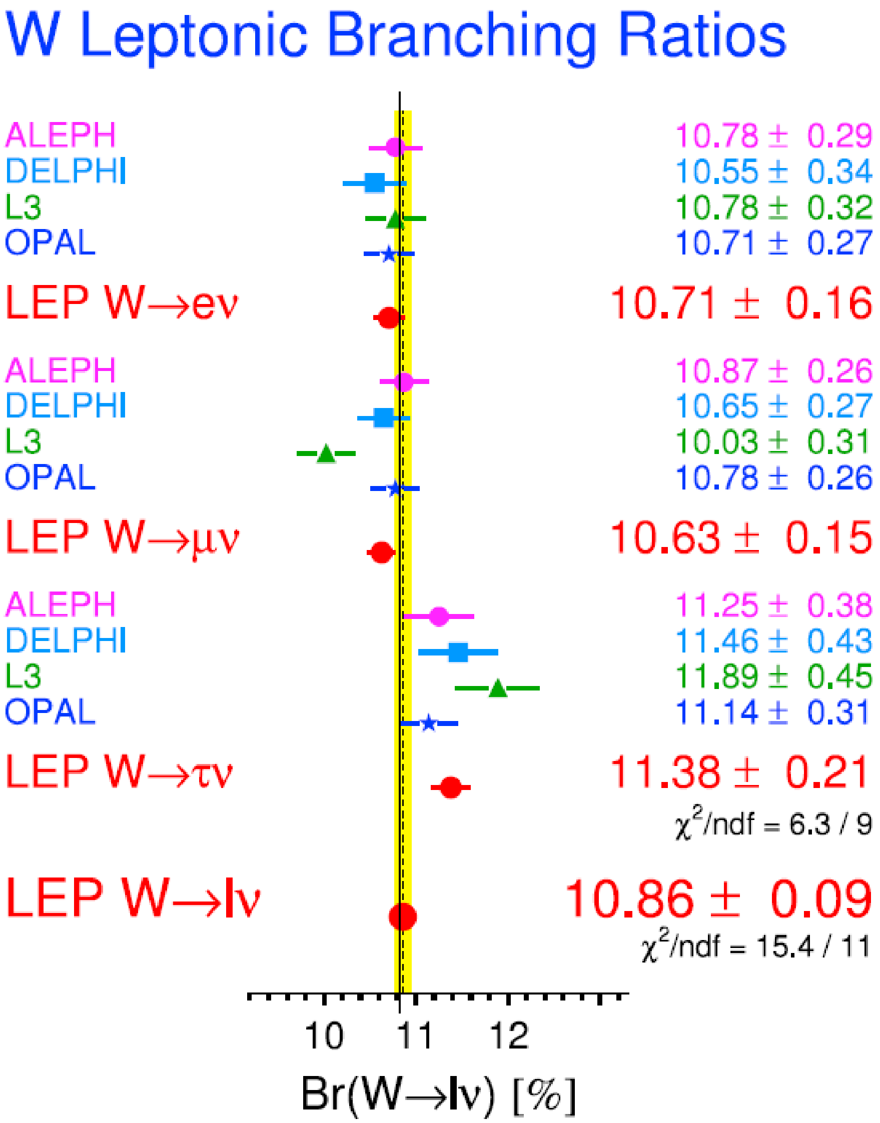


3.17σ tension

HFLAV (Moriond 2024)

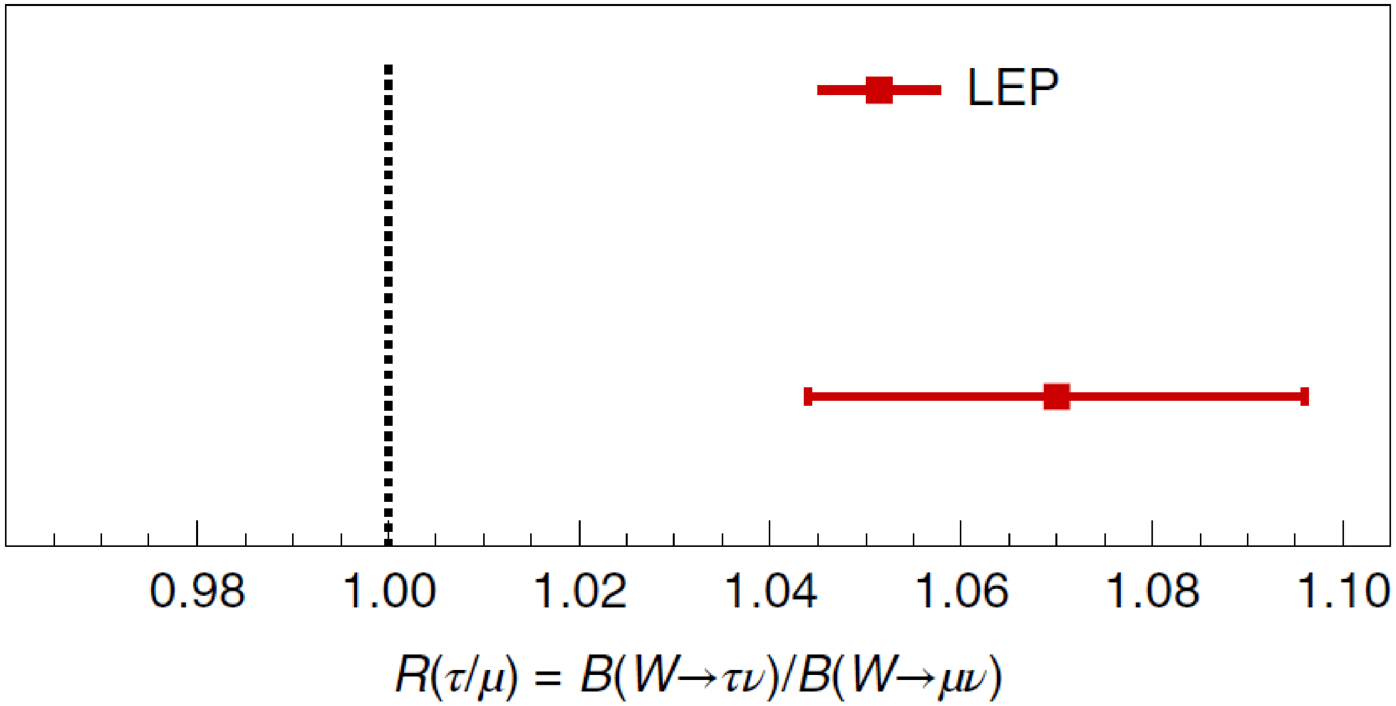


LEP (CERN) Lepton Flavour Universality



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!)

Lepton Flavour Universality μ/e

"B-tag counting method"

$$
\begin{aligned}
N_1^{e\mu} &= L\sigma_{t\bar{t}}\,\epsilon_{e\mu} g_{e\mu}^{t\bar{t}}\,2\epsilon_b^{e\mu}(1 - C_b^{e\mu}\epsilon_b^{e\mu}) &+ \sum_{k=\mathrm{bkg}} s_1^k g_{e\mu}^k\, N_1^{e\mu,k} \\
N_2^{e\mu} &= L\sigma_{t\bar{t}}\,\epsilon_{e\mu} g_{e\mu}^{t\bar{t}}\,C_b^{e\mu}(\epsilon_b^{e\mu})^2 &+ \sum_{k=\mathrm{bkg}} s_2^k g_{e\mu}^k\, N_2^{e\mu,k}
\end{aligned}
$$

$$
\begin{aligned}
N_{1,m}^{\ell\ell} &= L\sigma_{t\bar{t}}\,\epsilon_{\ell\ell}\, g_{\ell\ell}^{t\bar{t}}\,2\epsilon_b^{\ell\ell}(1 - C_b^{\ell\ell}\epsilon_b^{\ell\ell})\, f_{1,m}^{\ell\ell,t\bar{t}} &+ \sum_{k=\mathrm{bkg}} s_1^k g_{\ell\ell}^k\, f_{1,m}^{\ell\ell,k} N_1^{\ell\ell,k} \\
N_{2,m}^{\ell\ell} &= L\sigma_{t\bar{t}}\,\epsilon_{\ell\ell}\, g_{\ell\ell}^{t\bar{t}}\,C_b^{\ell\ell}(\epsilon_b^{\ell\ell})^2\, f_{2,m}^{\ell\ell,t\bar{t}} &+ \sum_{k=\mathrm{bkg}} s_2^k g_{\ell\ell}^k\, f_{2,m}^{\ell\ell,k} N_2^{\ell\ell,k}
\end{aligned}
$$

Lepton Flavour Universality μ/e

"B-tag counting method"

$$R_W^{\mu/e} = \frac{\mathcal{B}(W \to \mu\nu)}{\mathcal{B}(W \to e\nu)} = \frac{\overline{W}(1+\Delta_W)}{\overline{W}(1-\Delta_W)}$$

$$\begin{array}{lclll} g_{ee}^{t\bar{t}} & = & f_{0\tau}^{ee}(1-\Delta_W)^2 & +f_{1\tau}^{ee}(1-\Delta_W) & +f_{2\tau}^{ee} \\ g_{e\mu}^{t\bar{t}} & = & f_{0\tau}^{e\mu}(1-\Delta_W)(1+\Delta_W) & +f_{1\tau}^{e\mu} & +f_{2\tau}^{e\mu} \\ g_{\mu\mu}^{t\bar{t}} & = & f_{0\tau}^{\mu\mu}(1+\Delta_W)^2 & +f_{1\tau}^{\mu\mu}(1+\Delta_W) & +f_{2\tau}^{\mu\mu} \end{array}$$

$$R_Z^{\mu\mu/ee} = \frac{\mathcal{B}(Z \to \mu\mu)}{\mathcal{B}(Z \to ee)} = \frac{\overline{Z}(1+\Delta_Z)}{\overline{Z}(1-\Delta_Z)}$$

$$\begin{array}{lcl} g_{ee}^{Z+\text{jets}} & = & (1-\Delta_Z)(1-\Delta_{Z+b}) \\ g_{e\mu}^{Z+\text{jets}} & = & 1 \\ g_{\mu\mu}^{Z+\text{jets}} & = & (1+\Delta_Z)(1+\Delta_{Z+b}) \end{array} .$$

LFU Comparison to CMS and others

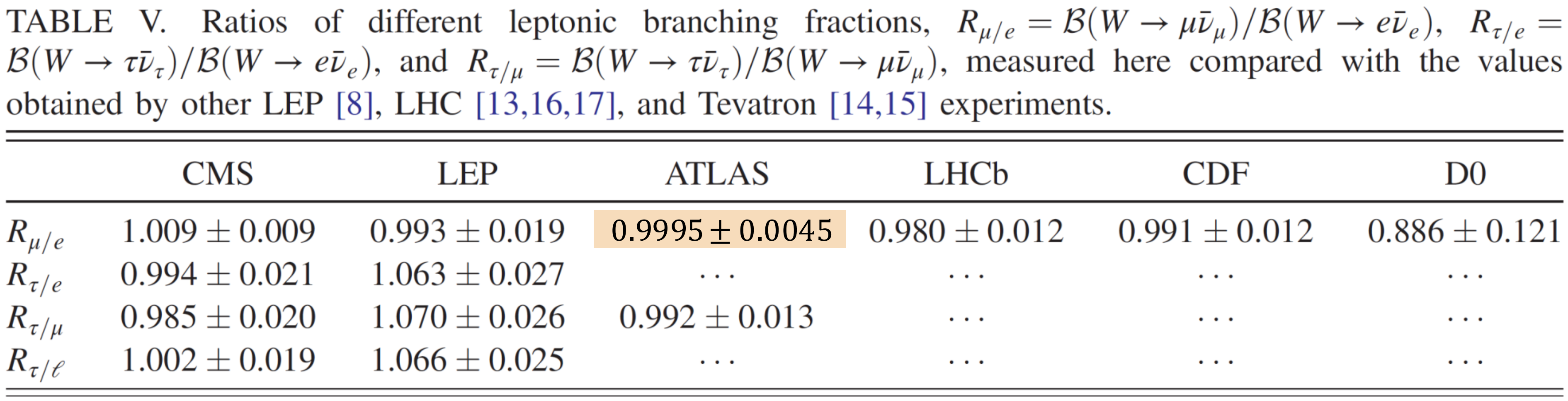


TABLE V. Ratios of different leptonic branching fractions, $R_{\mu/e} = \mathcal{B}(W \to \mu\bar{\nu}_\mu)/\mathcal{B}(W \to e\bar{\nu}_e)$, $R_{\tau/e} = \mathcal{B}(W \to \tau\bar{\nu}_\tau)/\mathcal{B}(W \to e\bar{\nu}_e)$, and $R_{\tau/\mu} = \mathcal{B}(W \to \tau\bar{\nu}_\tau)/\mathcal{B}(W \to \mu\bar{\nu}_\mu)$, measured here compared with the values obtained by other LEP [8], LHC [13,16,17], and Tevatron [14,15] experiments.

	CMS	LEP	ATLAS	LHCb	CDF	D0
$R_{\mu/e}$	1.009 ± 0.009	0.993 ± 0.019	0.9995 ± 0.0045	0.980 ± 0.012	0.991 ± 0.012	0.886 ± 0.121
$R_{\tau/e}$	0.994 ± 0.021	1.063 ± 0.027	...	...	...	...
$R_{\tau/\mu}$	0.985 ± 0.020	1.070 ± 0.026	0.992 ± 0.013	...	...	...
$R_{\tau/\ell}$	1.002 ± 0.019	1.066 ± 0.025	...	...	...	...

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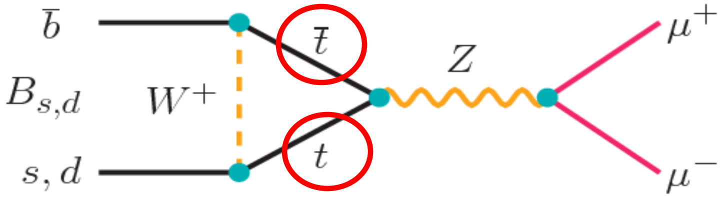
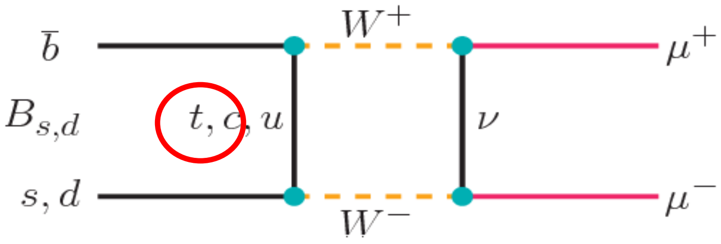
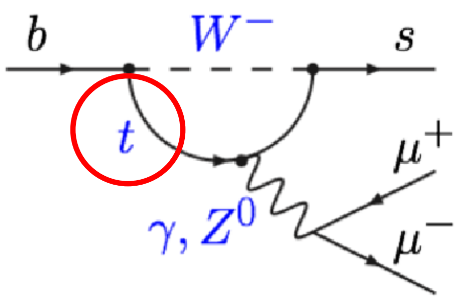
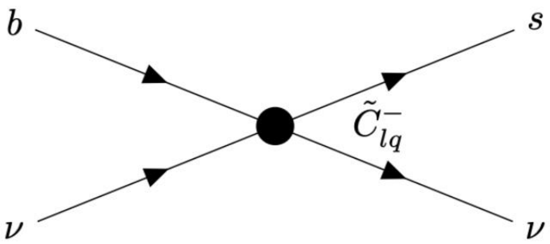
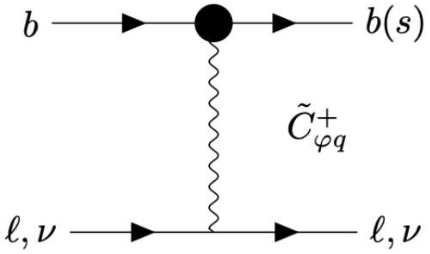
Top EFT and the B-anomalies

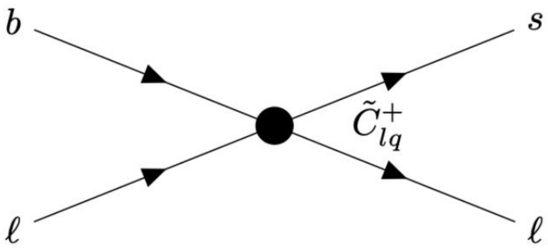


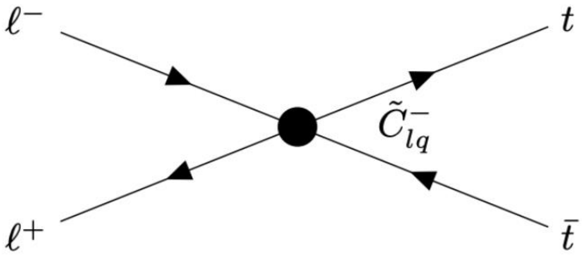


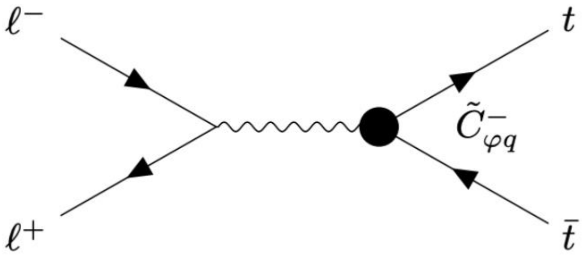


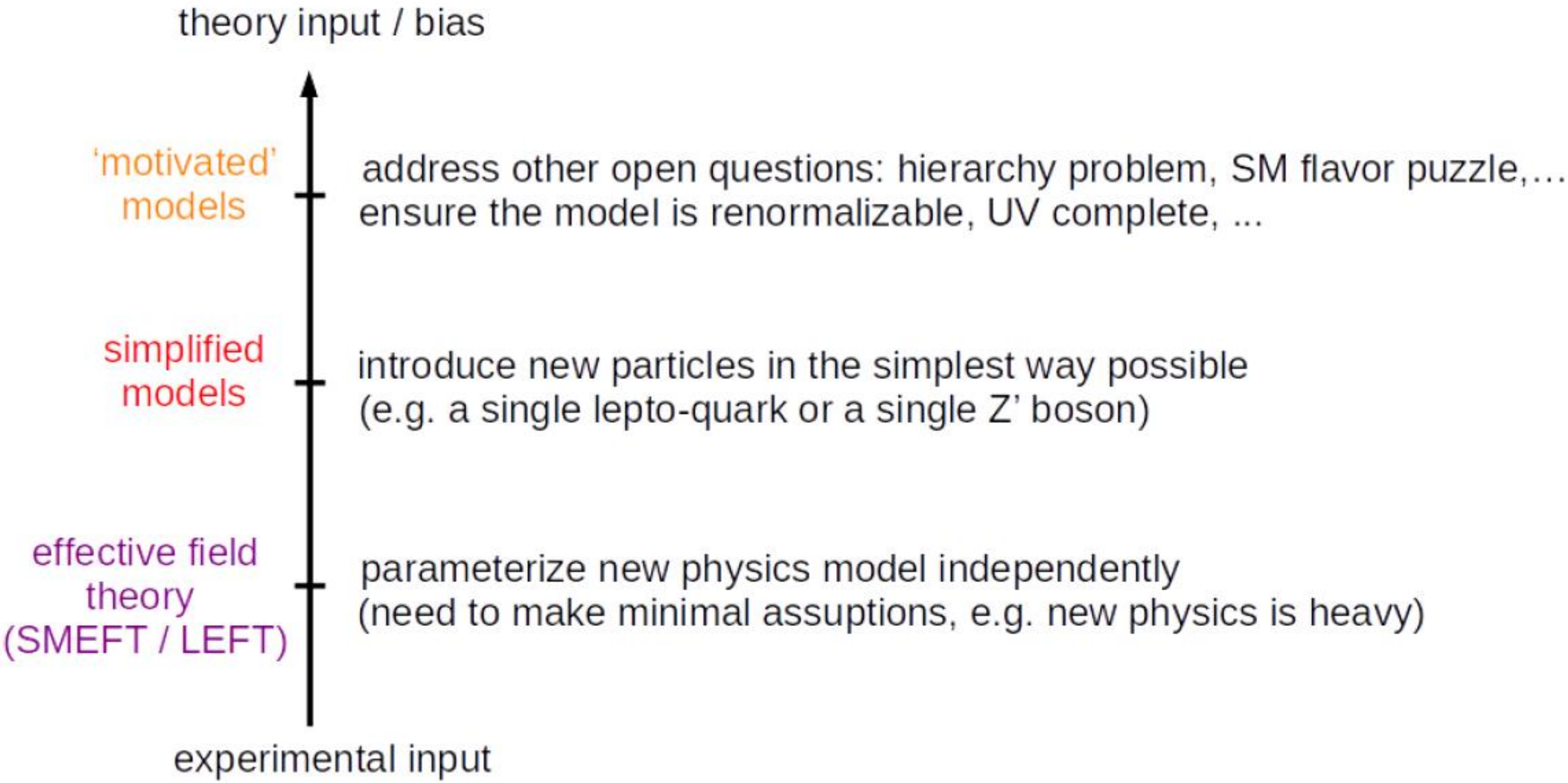












theory input / bias

'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)

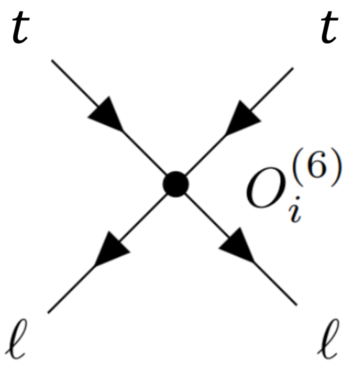
effective field theory (SMEFT / LEFT)

parameterize new physics model independently
(need to make minimal assuptions, e.g. new physics is heavy)

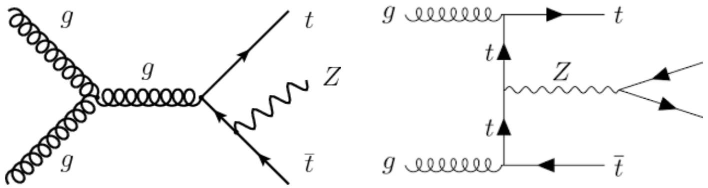
experimental input

Top 2Q2L operator effects

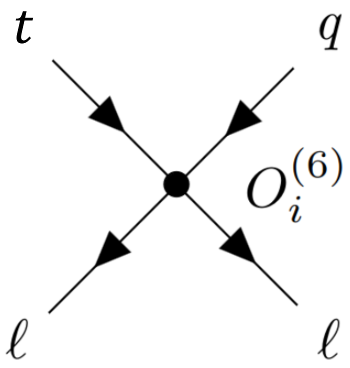
$t\bar{t}Z$-like (diagonal)



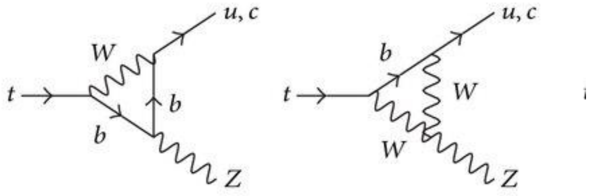
$t\bar{t}ll$



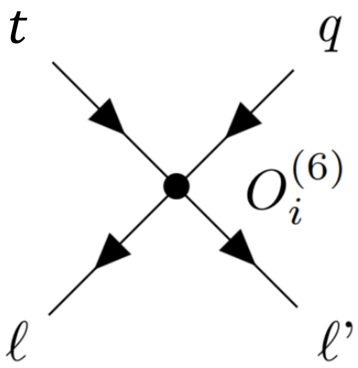
FCNC (semi-diagonal)



$tqll$



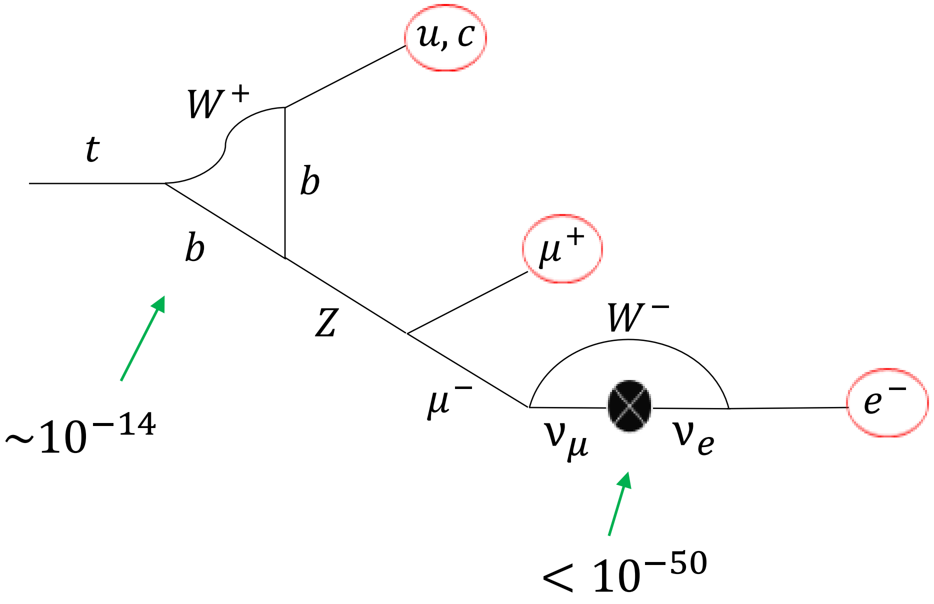
CLFV (fully off-diagonal)

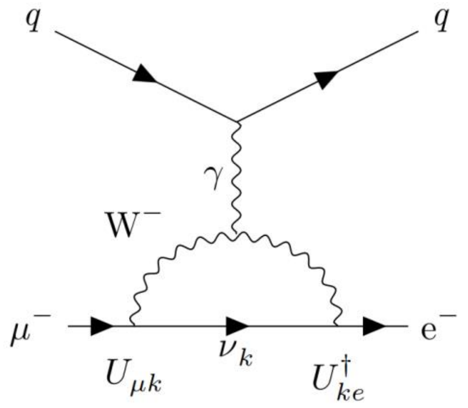


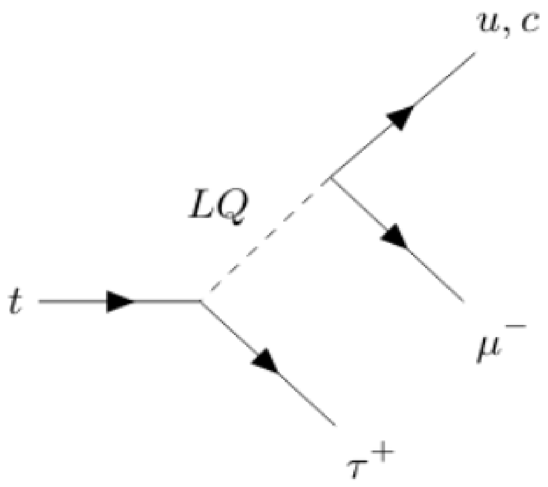
$tqll'$

CLFV and Neutrino Oscillations / New Physics

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



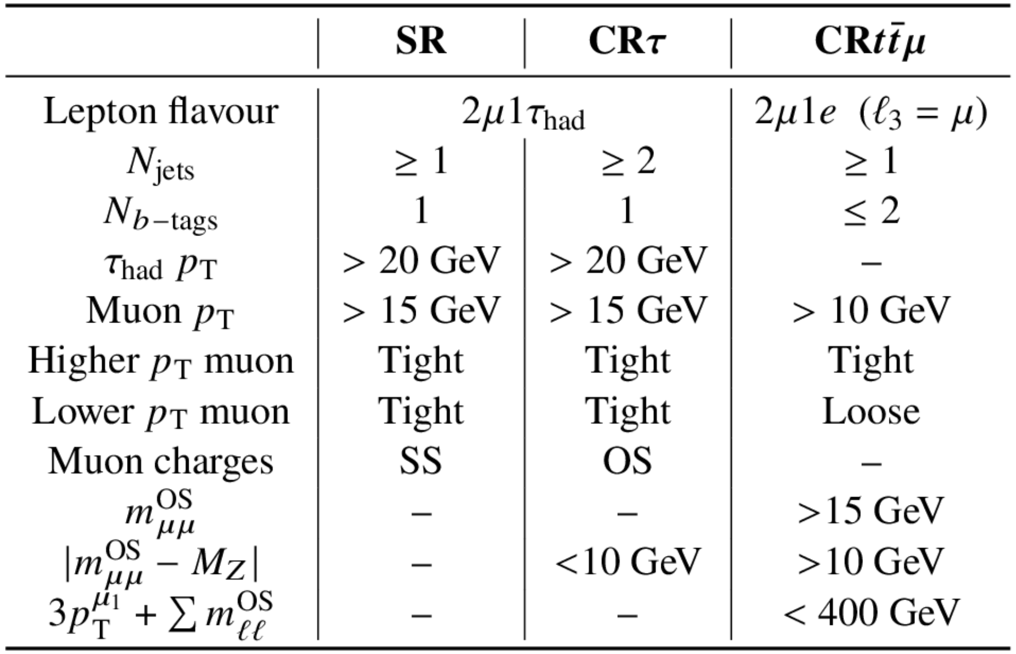




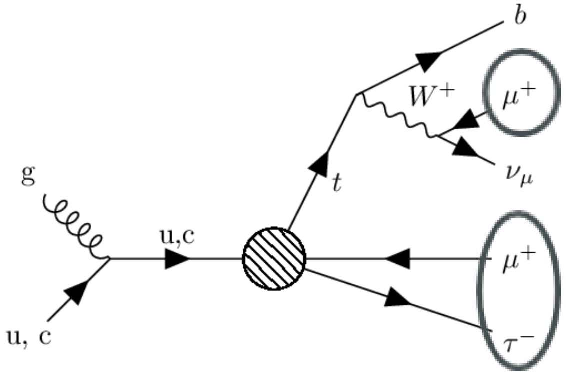
New physics which introduces additional terms involving lepton fields in Lagrangian can lead to LFV, e.g. SUSY, leptoquarks, 2HDMs

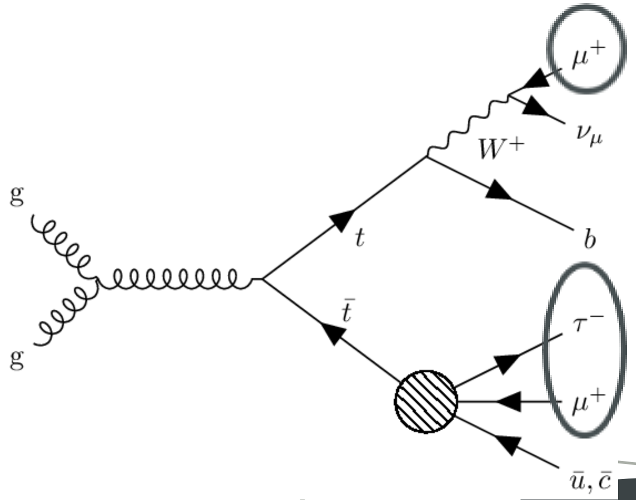
Event selection with 139 fb^{-1}

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





Charged Lepton Flavour Violation

Using dim6top, found to agree with SMEFTsim 3.0

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

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

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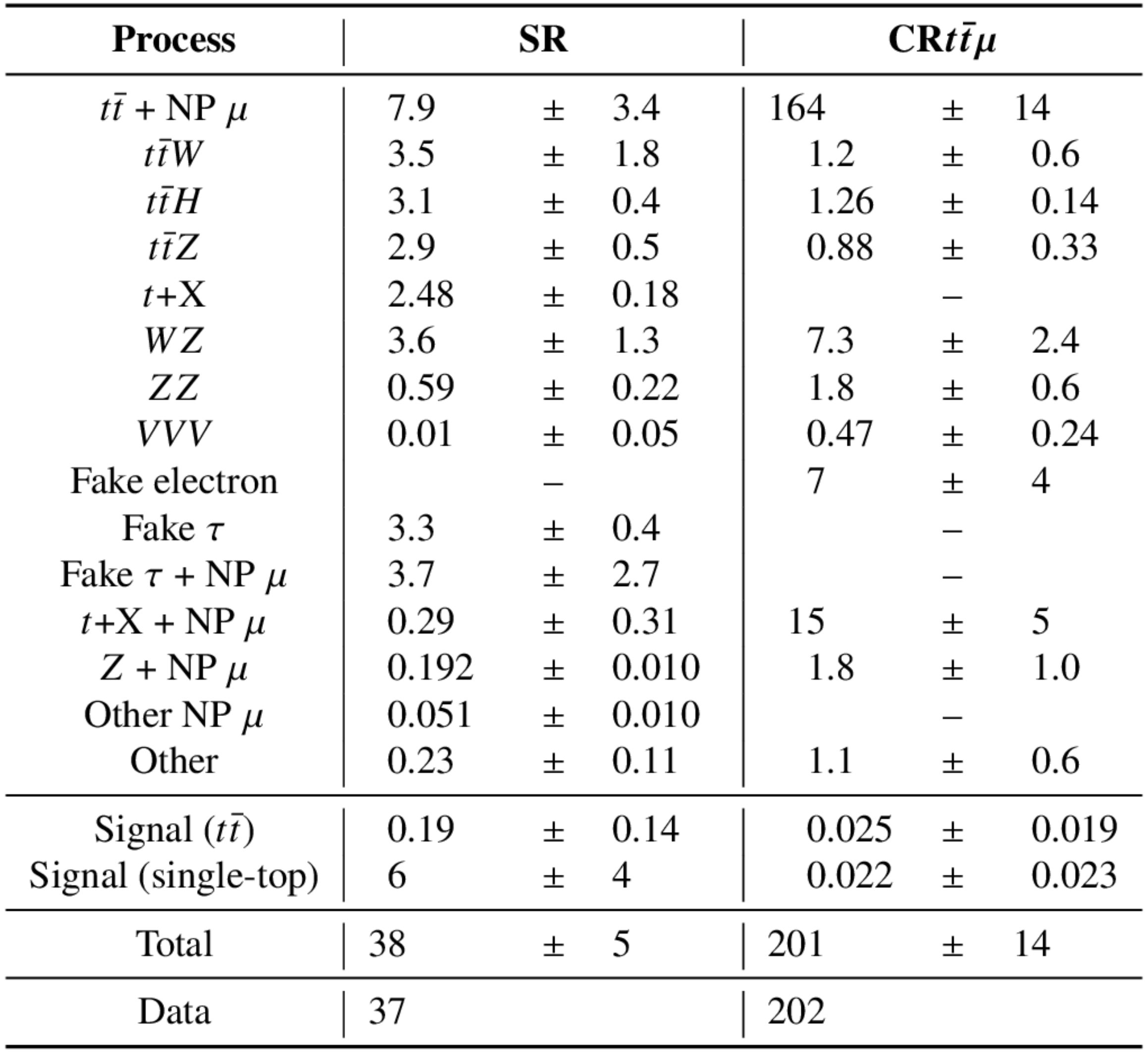
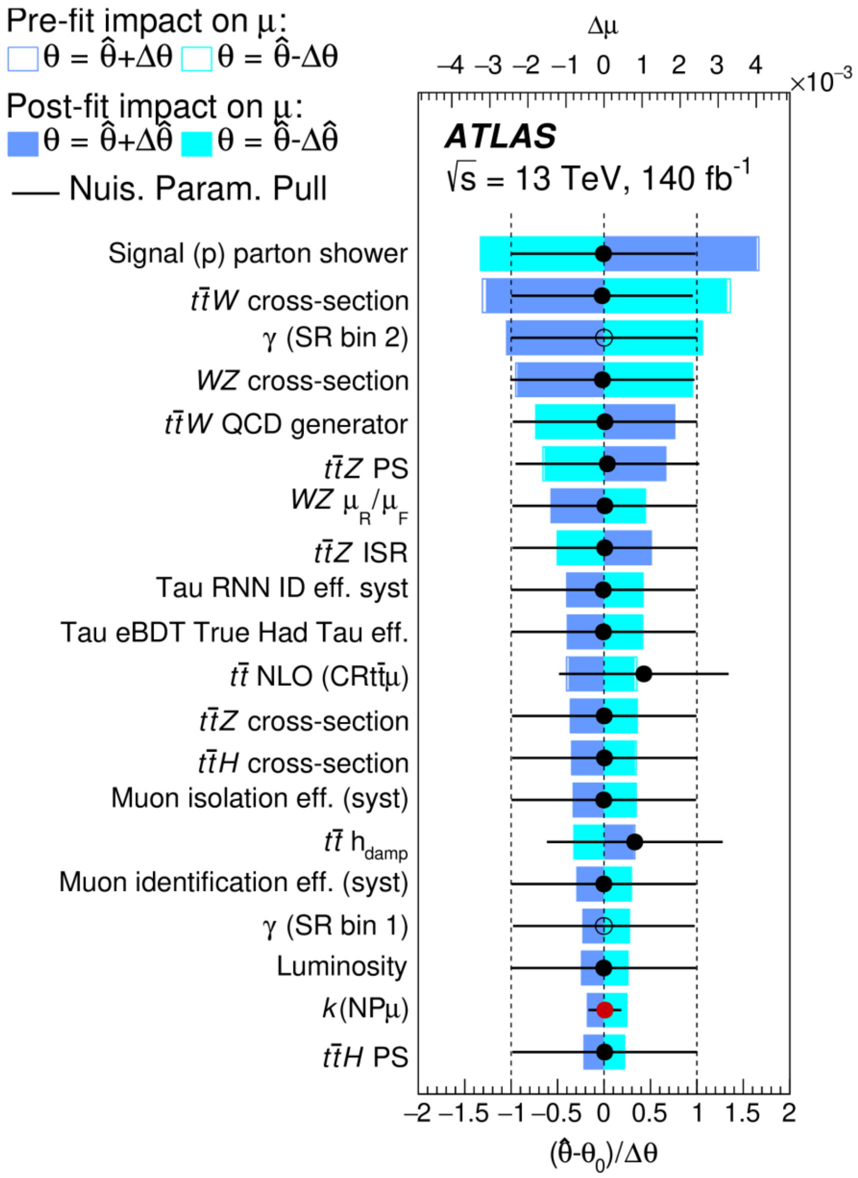
Yields

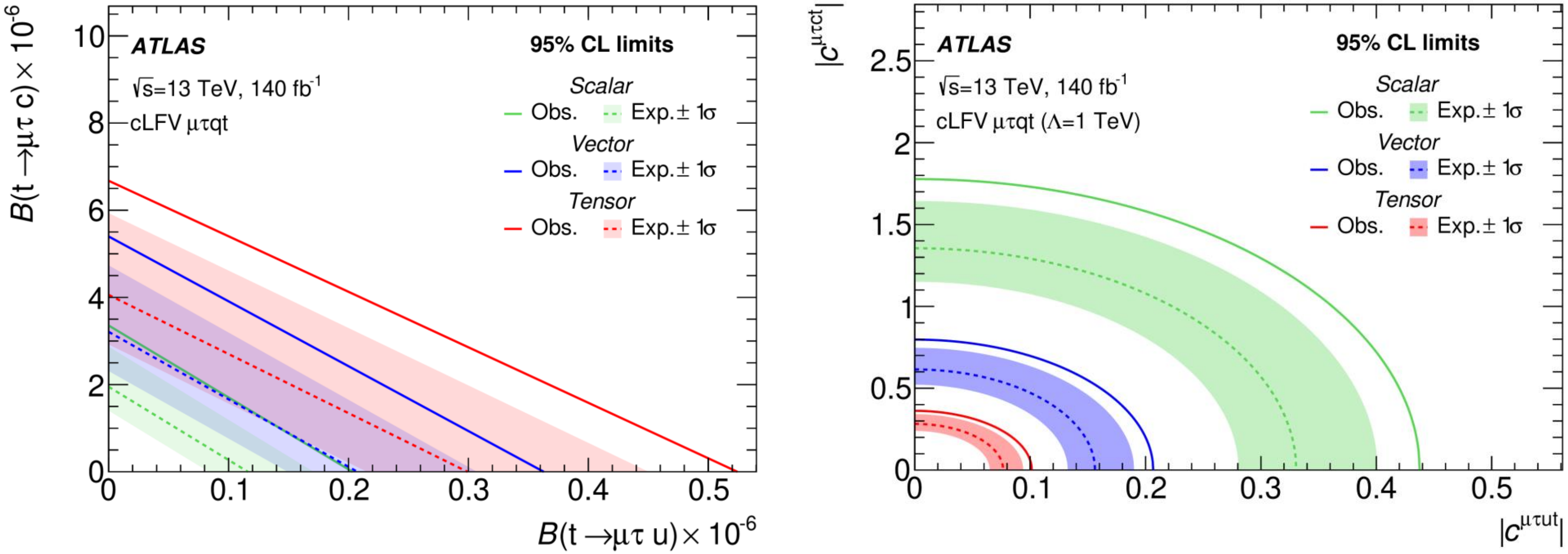


Process	**SR**	**CR$t\bar{t}\mu$**
$t\bar{t}$ + NP μ	7.9 ± 3.4	164 ± 14
$t\bar{t}W$	3.5 ± 1.8	1.2 ± 0.6
$t\bar{t}H$	3.1 ± 0.4	1.26 ± 0.14
$t\bar{t}Z$	2.9 ± 0.5	0.88 ± 0.33
t+X	2.48 ± 0.18	–
WZ	3.6 ± 1.3	7.3 ± 2.4
ZZ	0.59 ± 0.22	1.8 ± 0.6
VVV	0.01 ± 0.05	0.47 ± 0.24
Fake electron	–	7 ± 4
Fake τ	3.3 ±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

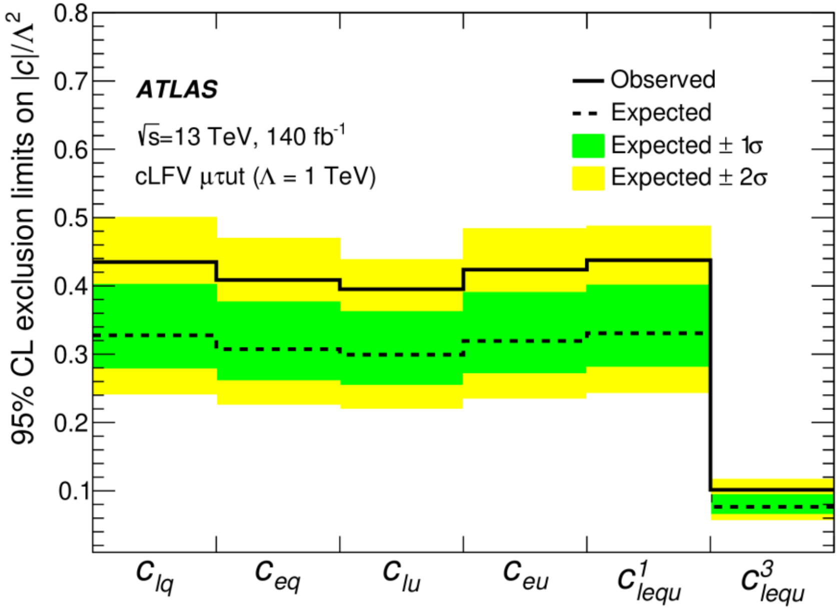
CLFV EFT Result breakdown

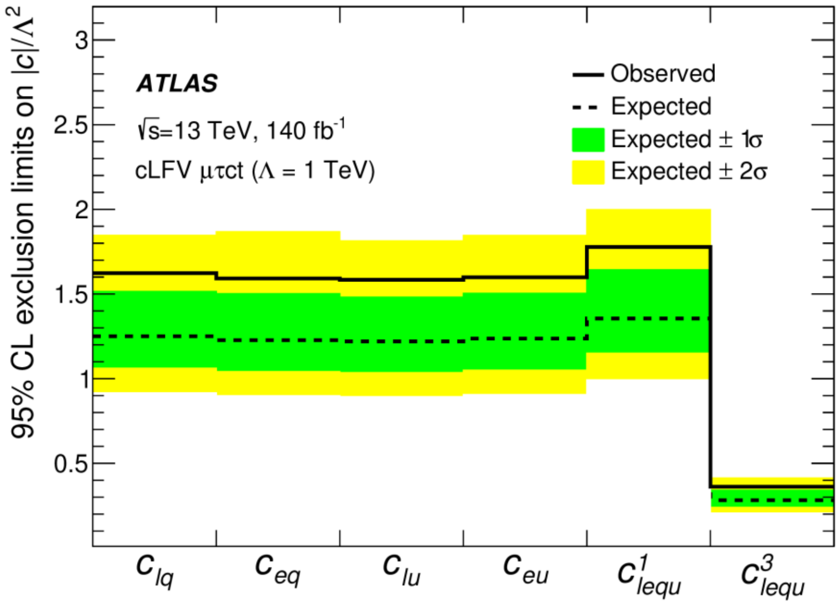


EFT Result breakdown



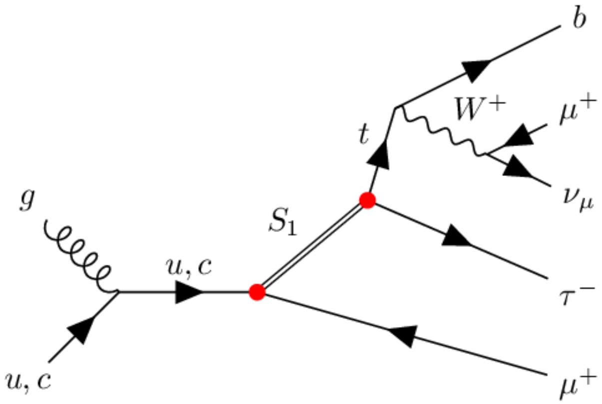
CLFV EFT Result breakdown

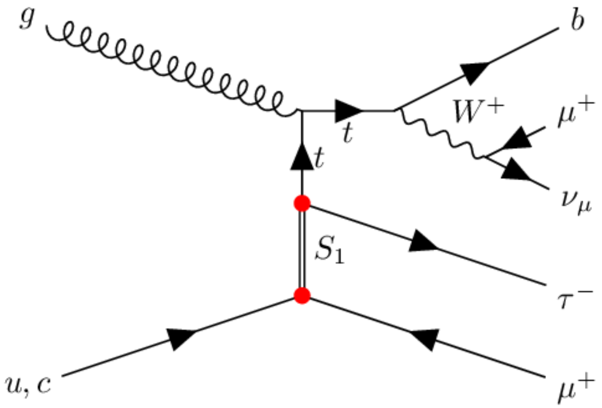


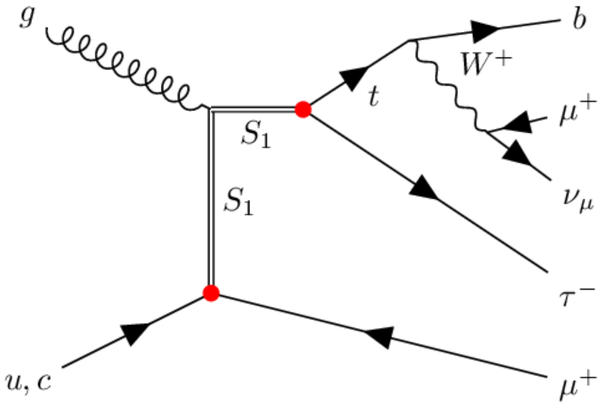


CLFV - Leptoquark interpretation

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:

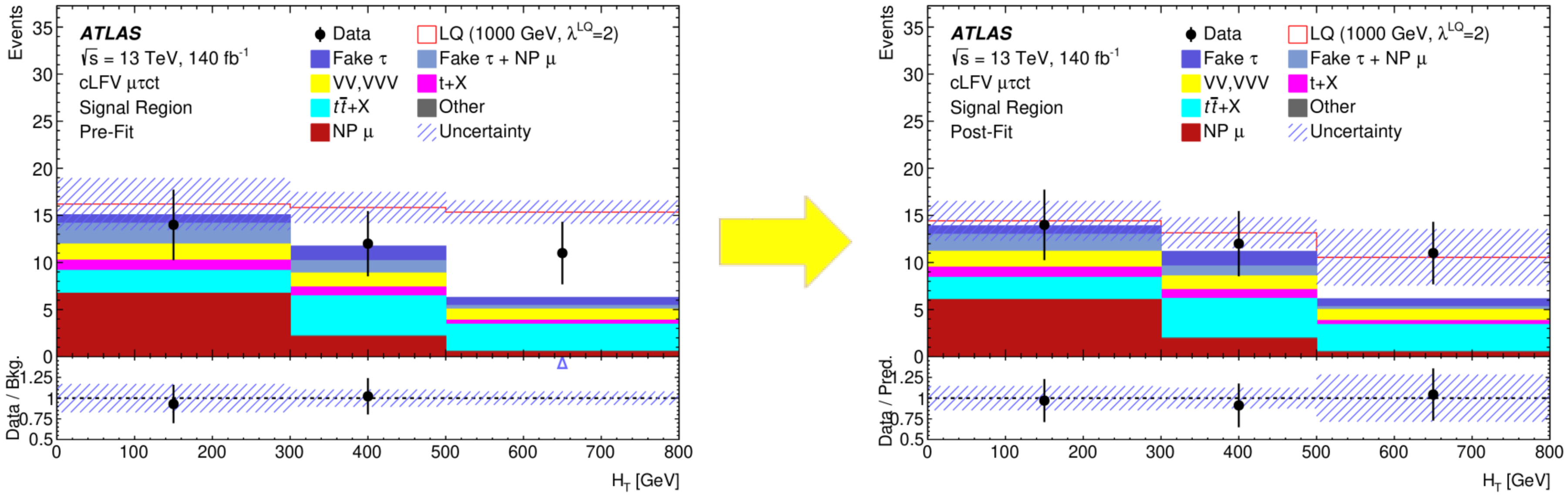
$$\lambda_{ki} \in \begin{pmatrix} \lambda_{t\tau} & \lambda_{c\tau} & \lambda_{u\tau} \\ \lambda_{t\mu} & \lambda_{c\mu} & \lambda_{u\mu} \\ \lambda_{te} & \lambda_{ce} & \lambda_{ue} \end{pmatrix} \equiv \lambda^{\mathrm{LQ}} \begin{pmatrix} 10 & 1 & 0.1 \\ 1 & 0.1 & 0.01 \\ 0.1 & 0.01 & 0.001 \end{pmatrix}$$

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

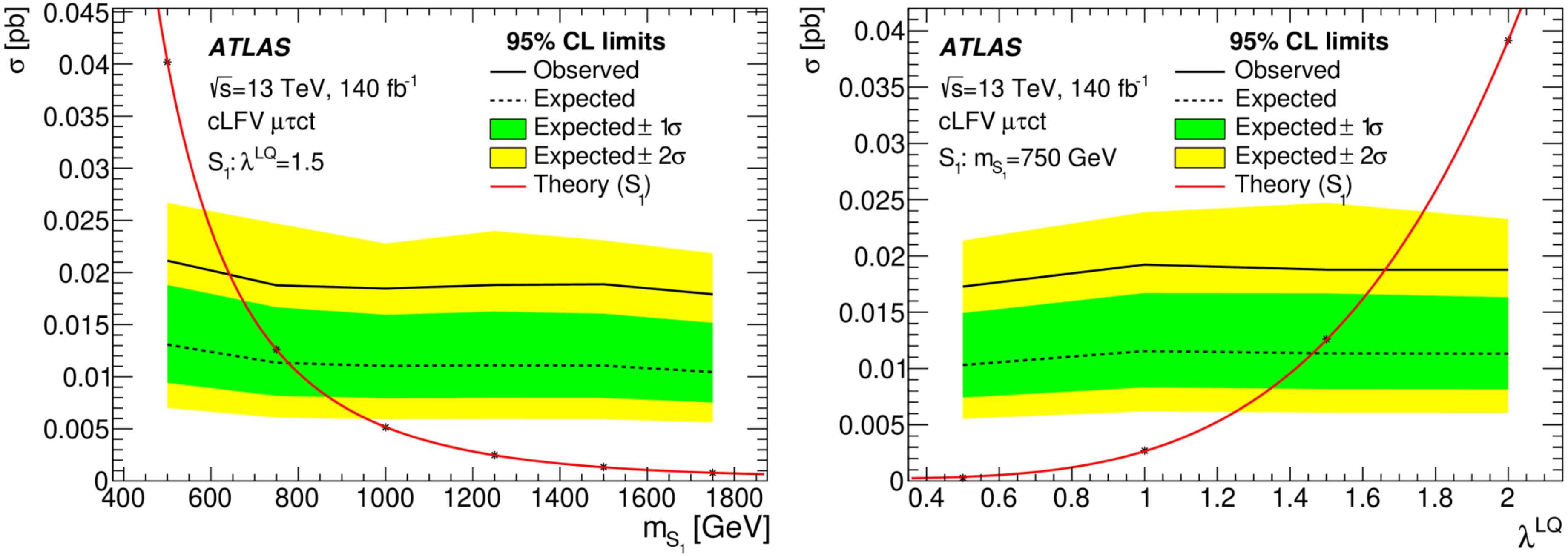
Various theory papers apply hierarchical coupling models, with different magnitudes spanning steps of $\sqrt{2}$ to $\frac{1}{16}$ [1,2,3,4,5]

CLFV - Leptoquark interpretation

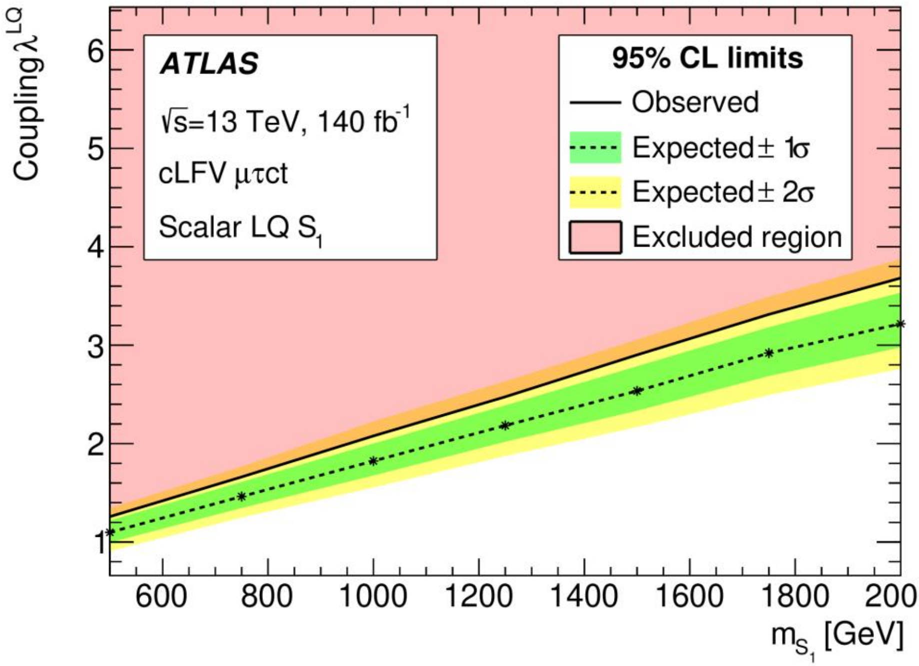
Analysis is not re-optimised for LQ signal, but HT is already a very good discriminating variable. Signals $0.5 < m_{\mathrm{LQ}} < 2.5$ TeV, and $0.5 < \lambda^{\mathrm{LQ}} < 3.5$ are fit independently:

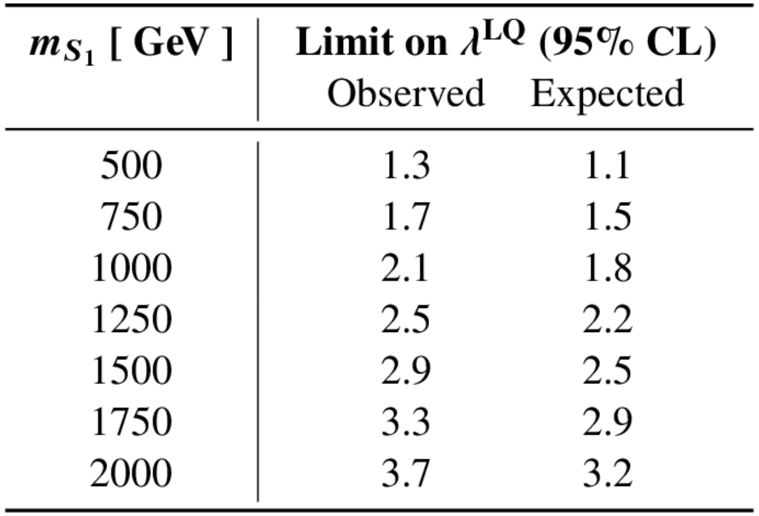


CLFV - Leptoquark interpretation



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