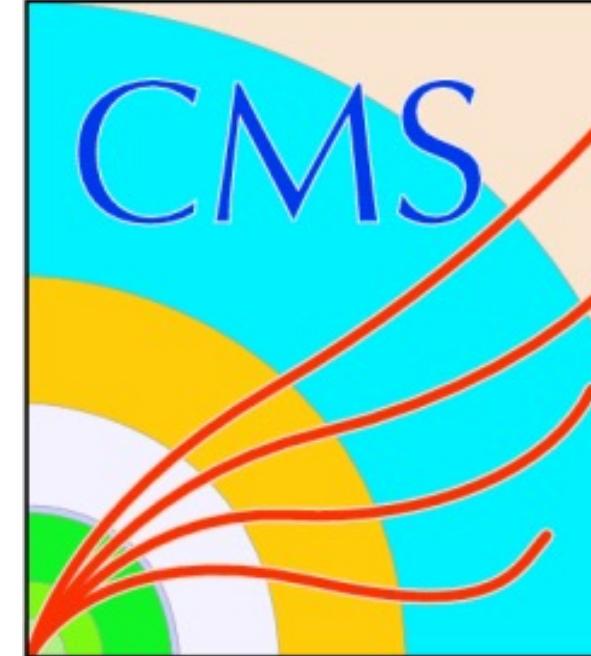


LFU/LFV IN PRECISION MEASUREMENT (EW, TOP)

REZA GOLDOUZIAN

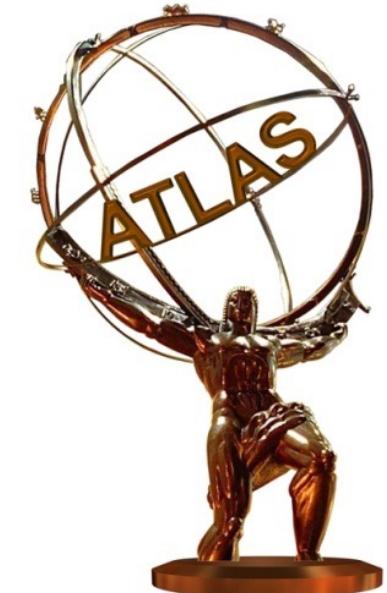


UNIVERSITY OF
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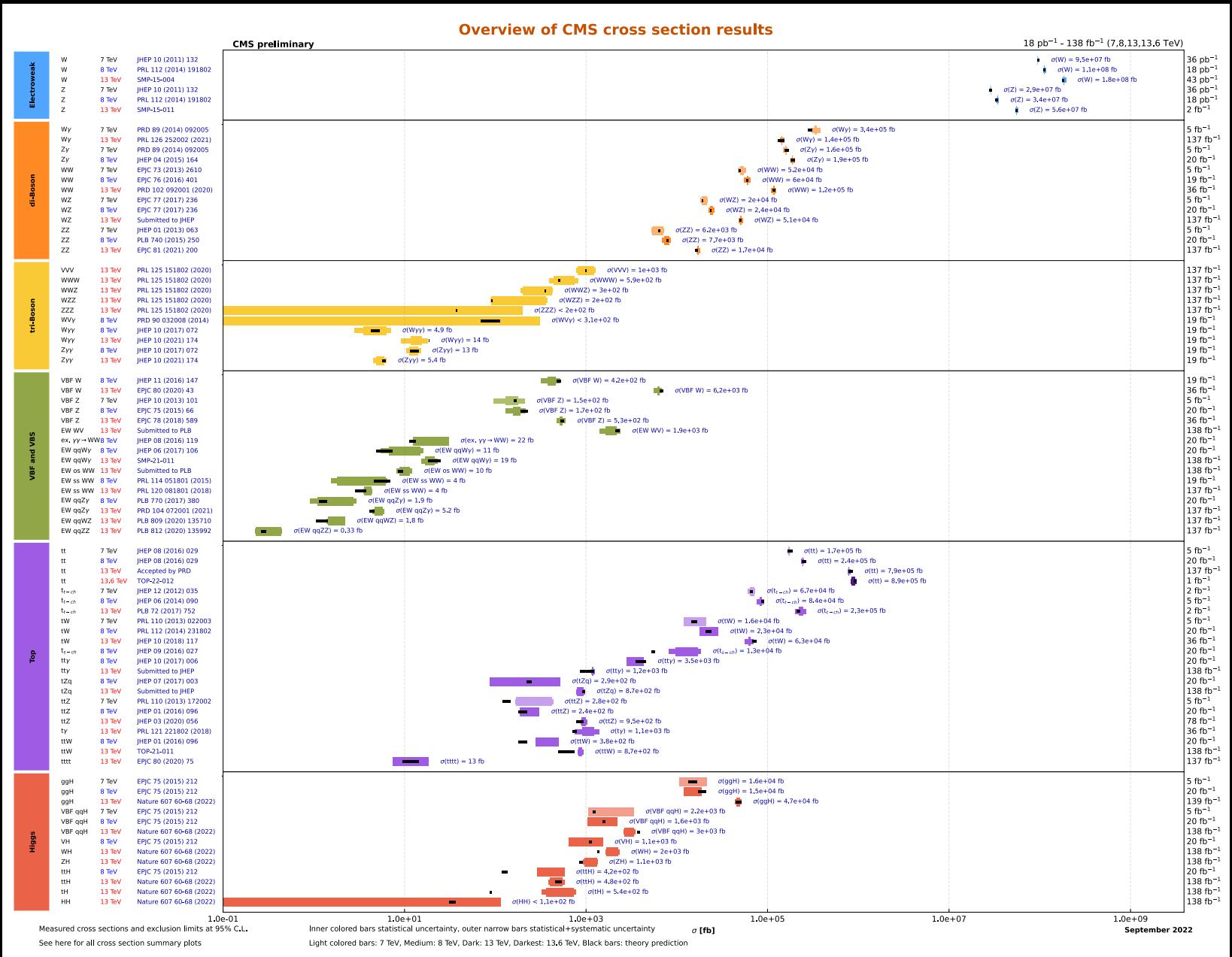
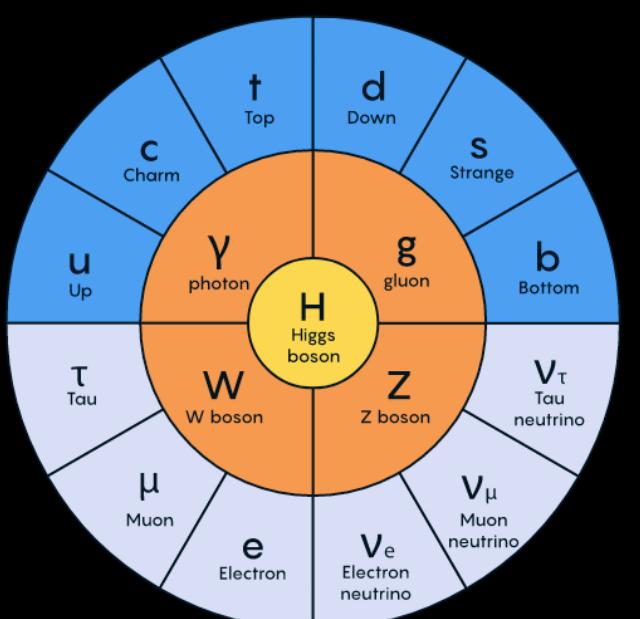
On behalf of the
ATLAS and CMS
Collaborations

FPCP 2023
29 May- 2 Jun



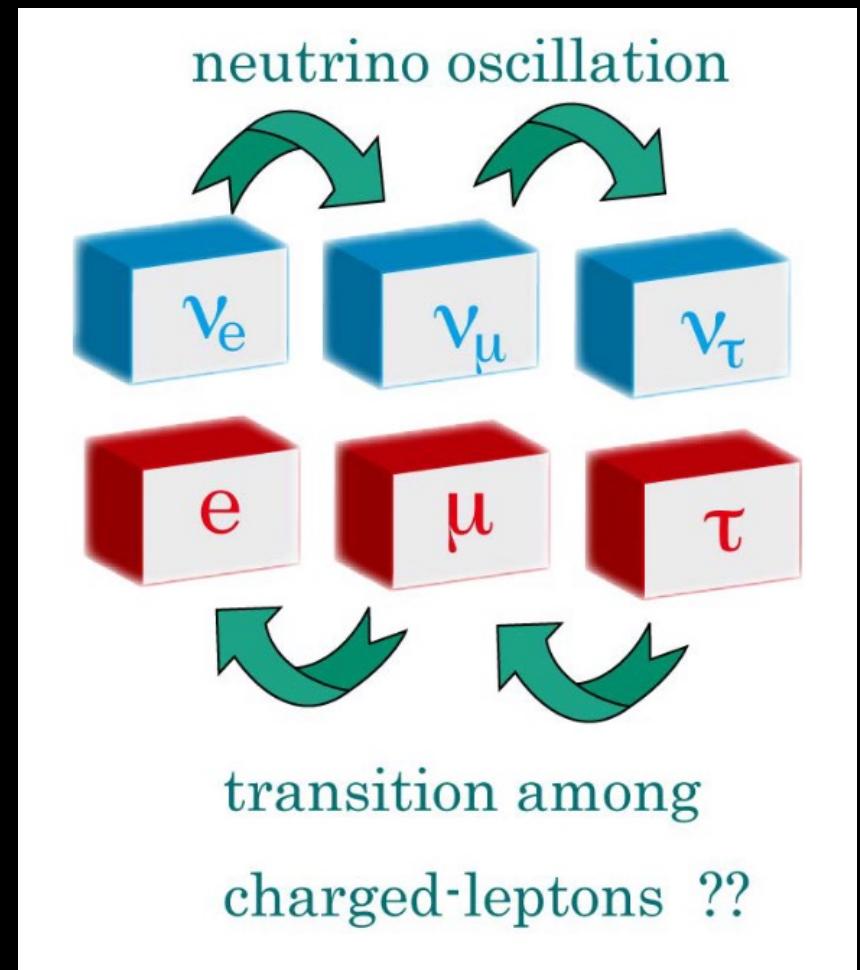
The SM

- SM confirmed by the data...so far
- Good agreement over 10 orders of magnitude
- Despite its success, the SM has unresolved problems (hierarchy problem, neutrino masses, DM, dark energy, etc.)



Lepton flavors

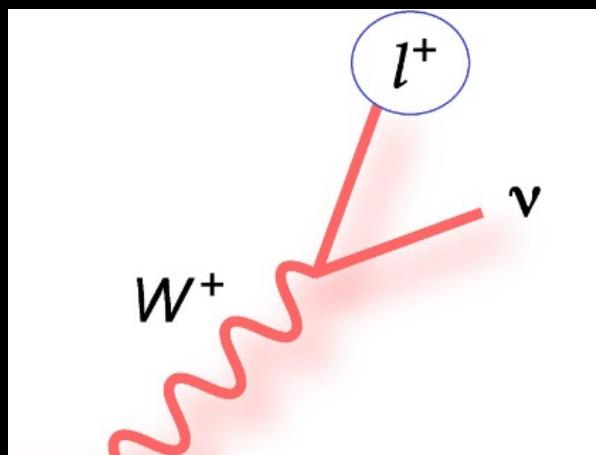
- In the SM, leptons of different flavours have identical properties (except for their mass)
 - The leptons coupling to gauge boson are flavour-independent
- The lepton flavour symmetries in the Standard Model are accidental
 - Testing them is a very sensitive to theories beyond the SM
- Neutral lepton flavour is violated through neutrino oscillations
 - No charged LFV process observed yet
- Measurements at the LHCb exhibit anomalous $B \rightarrow K^*$ transitions
 - hints for lepton flavor universality violation
- Some symmetries of interest
 - Lepton Flavour Universality (**LFU**)
 - Lepton Flavour Violation (**LFV**)
 - Lepton Number Violation (LNV)



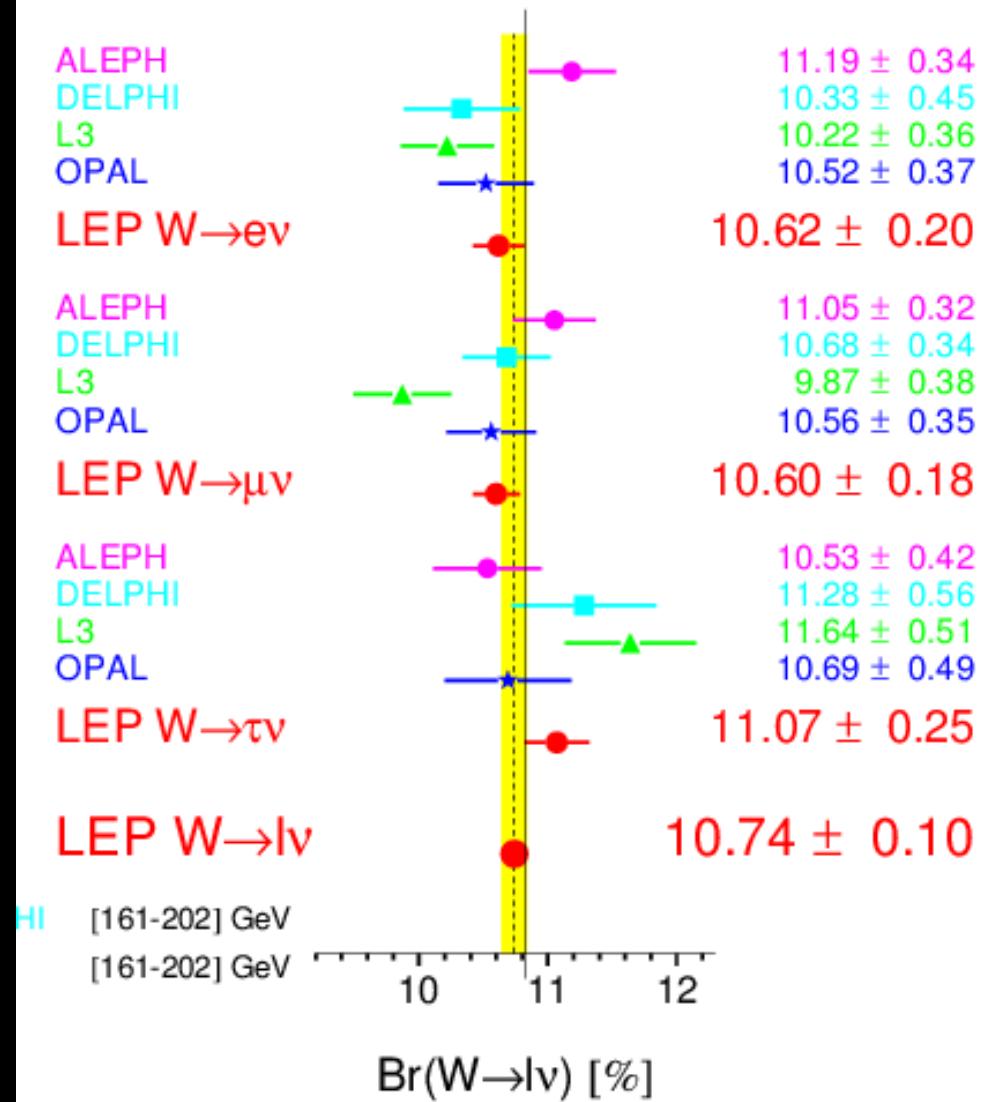
Measurements of the W branching fractions

- Precise measurement of the W boson leptonic branching fractions would be a test of lepton universality
- Precise measurements of $B(W \rightarrow l\nu)$ from LEP has 2.6σ deviation from LFU (PR 532, 119-244 (2013))
 - Agreement between $W \rightarrow e \nu$ and $W \rightarrow \mu \nu$ branching fractions, but $W \rightarrow \tau \nu$ is above the average

$$R_{\tau/\ell} = \frac{2 \mathcal{B}(W \rightarrow \tau \bar{\nu}_\tau)}{\mathcal{B}(W \rightarrow e \bar{\nu}_e) + \mathcal{B}(W \rightarrow \mu \bar{\nu}_\mu)} = 1.066 \pm 0.025$$



W Leptonic Branching Ratios

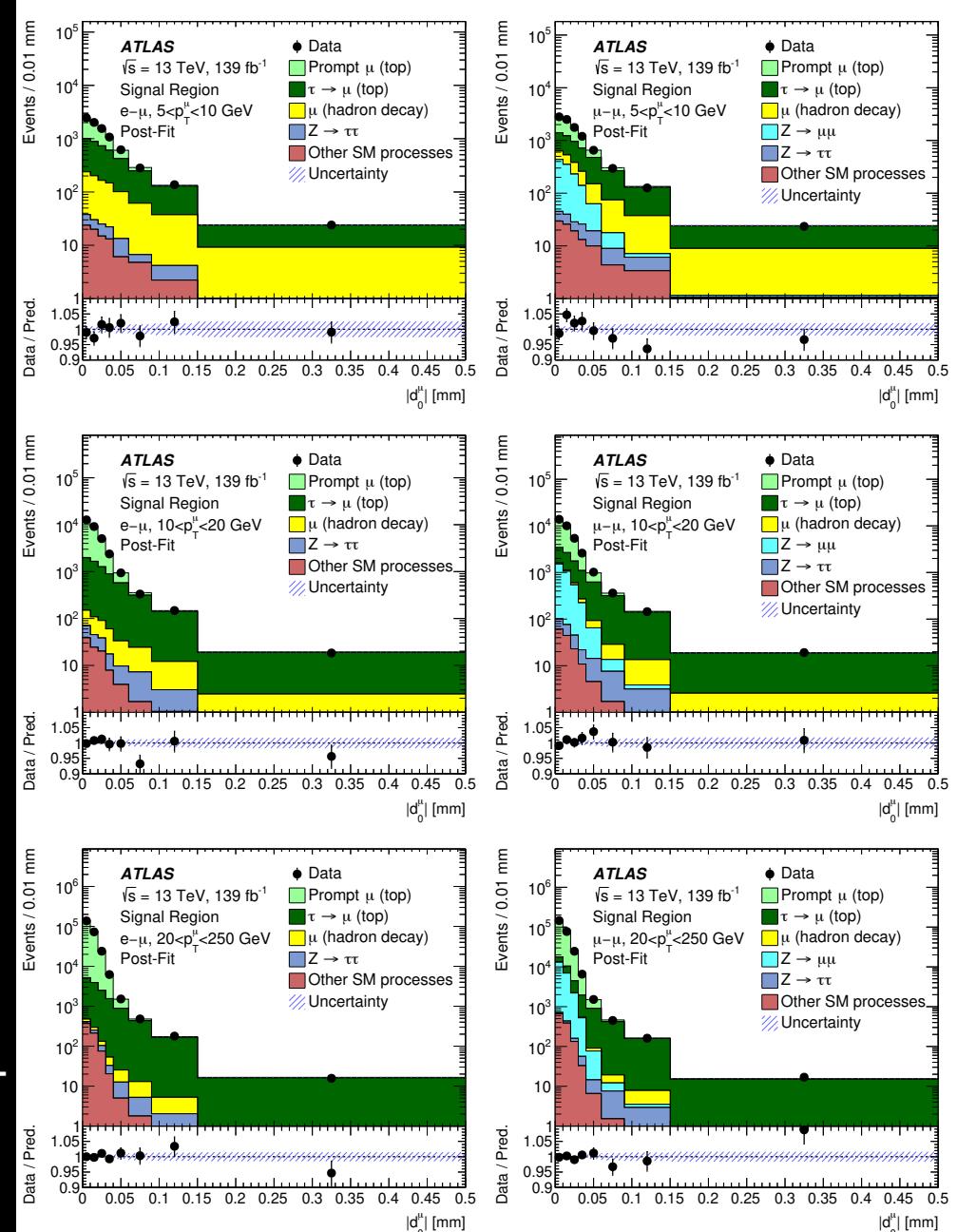




- Precise measurement of the ratio of the rate decay of W bosons to τ -leptons and muons

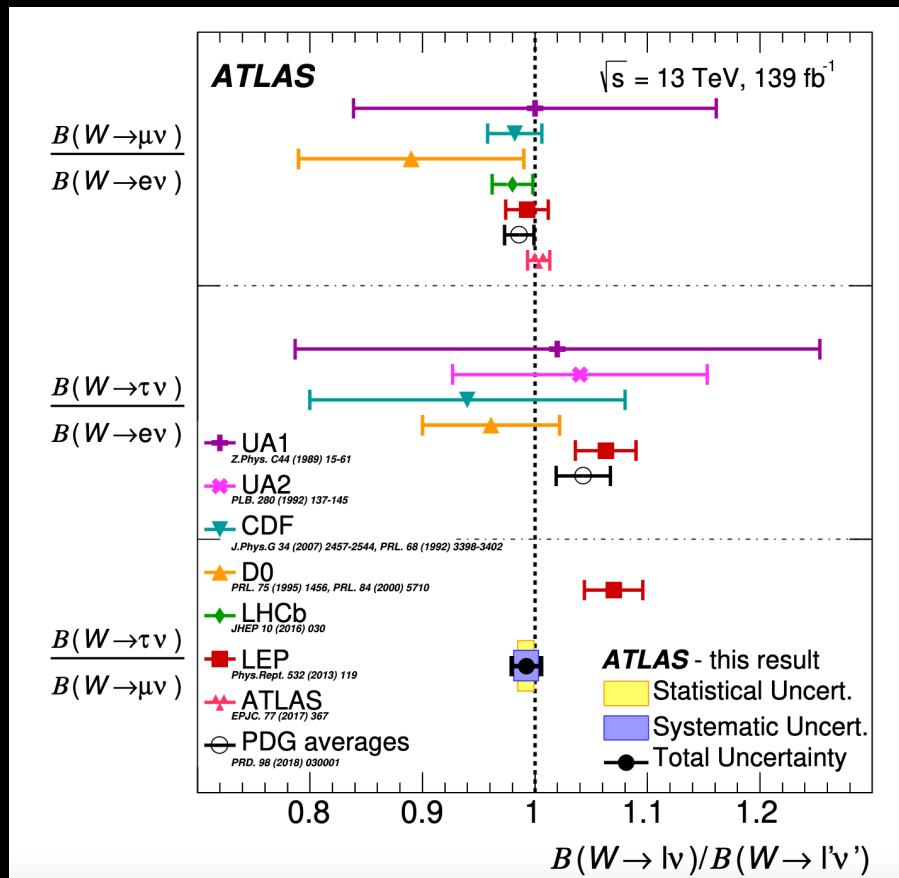
$$R(\tau/\mu) = B(W \rightarrow \tau\nu)/B(W \rightarrow \mu\nu)$$

- $t\bar{t}$ dilepton events are selected using tag and probe approach
 - One of the W decays is selected through the muon or electron decay (tag lepton);
 - Second W decays is selected through the muon (probed lepton)
- The analysis focuses on the leptonic τ decay
- Muons from intermediate τ -leptons are distinguished from prompt muons by their different p_T and different transverse impact parameter ($|d_0^\mu|$)
- $|d_0^\mu|$ is the distance of closest approach of a track to the beam-line

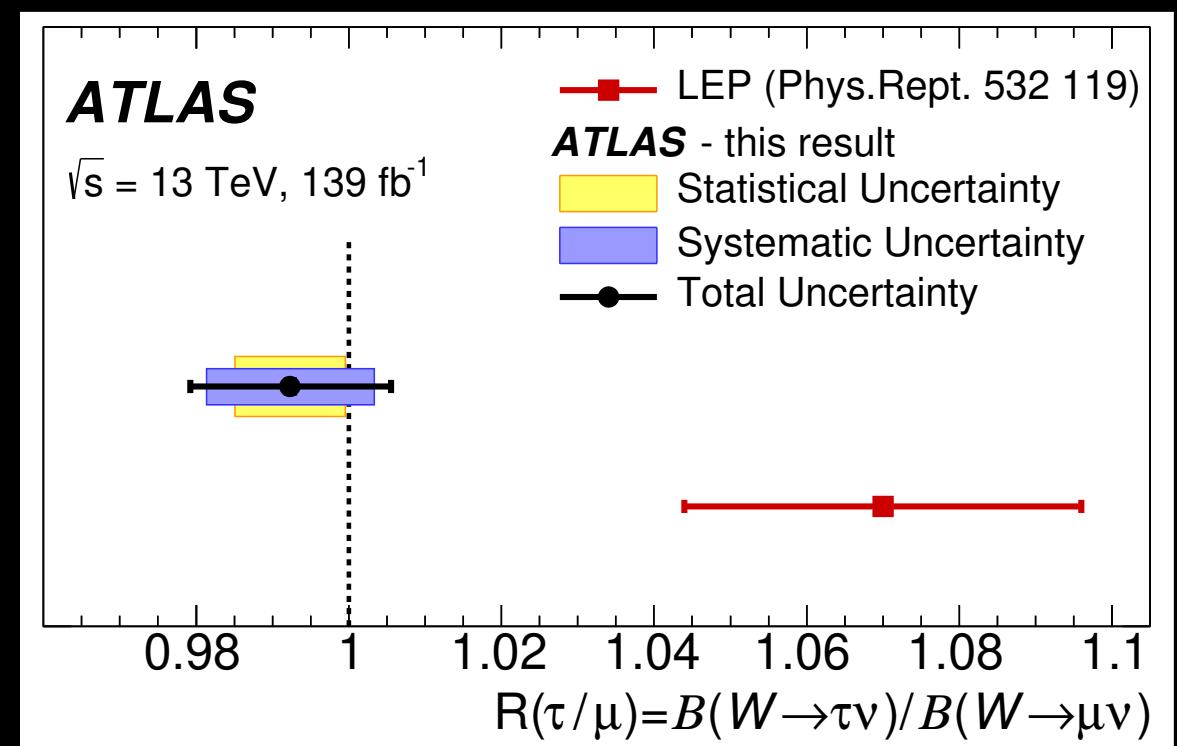




- To extract $R(\tau/\mu)$ a 2-D fit is performed in the probe muon p_T and $|d\mu_0|$
- Many systematic uncertainties cancelled in the ratio measurements
- A precision two times better than LEP is achieved
- The Standard Model survives this stringent test of Lepton Flavour Universality!



$$R(\tau/\mu) = 0.992 \pm 0.013 [\pm 0.007 \text{ (stat)} \pm 0.011 \text{ (syst)}].$$





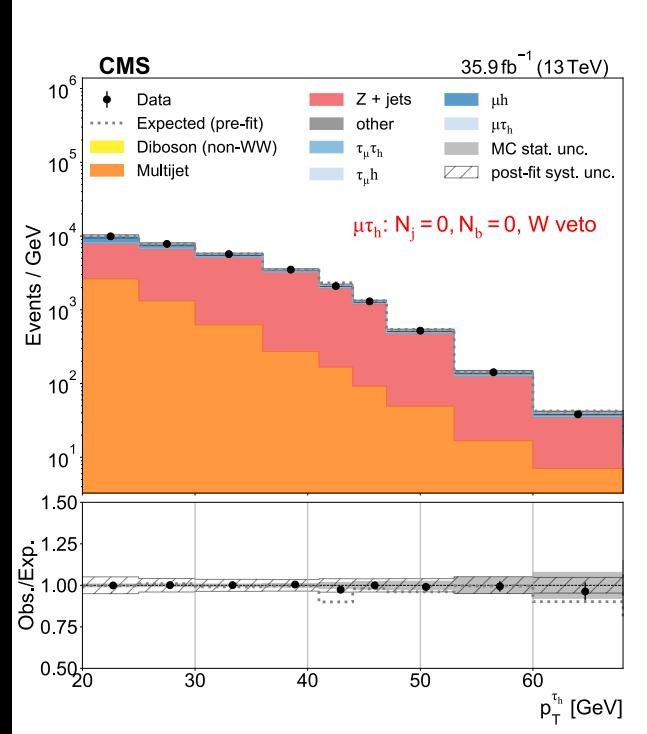
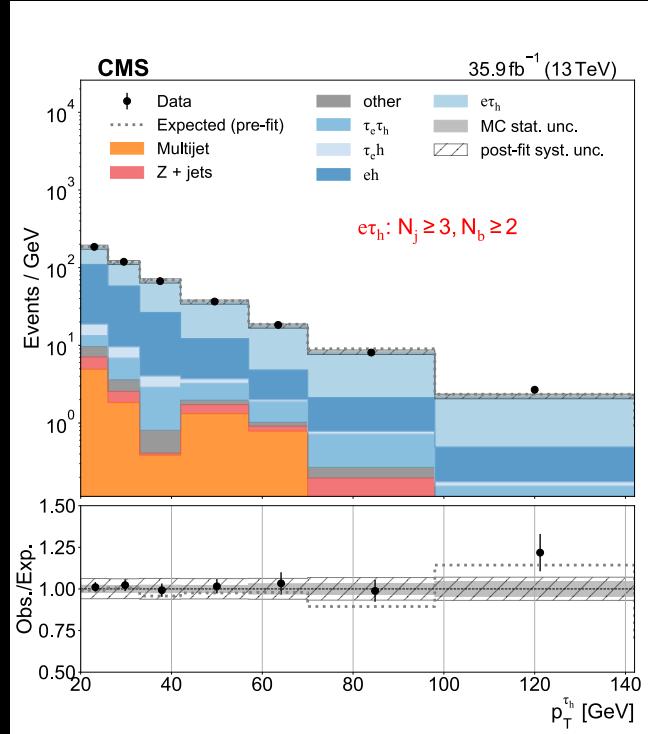
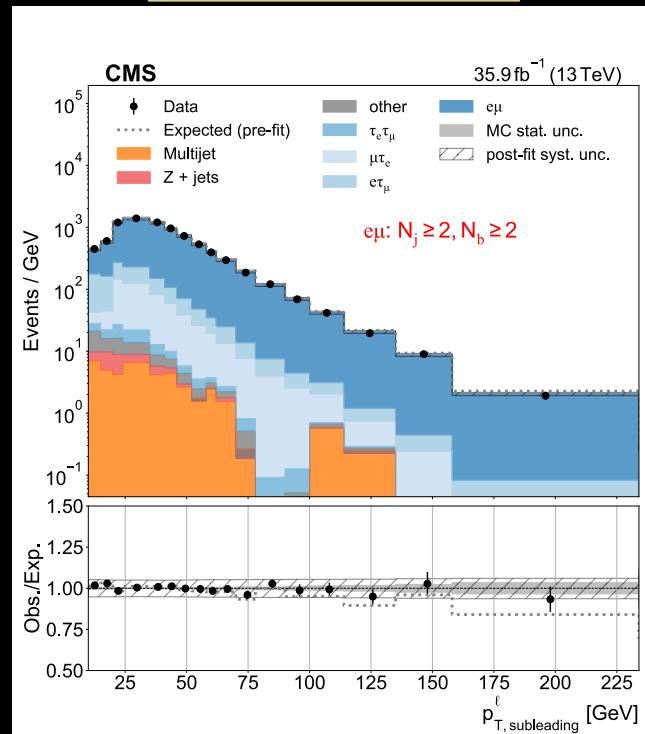
- Measurements of leptonic and inclusive hadronic decay branching fractions of the W ($+ \alpha_S(m^2_W)$) and V_{ij})
- Use $t\bar{t}$ production as primary source (tW , W are also included)
- τ vs. light ℓ driven by p_T spectrum (different wrt ATLAS, uses vertex)

	$N_j = 0$	$N_j = 1$	$N_j = 2$	$N_j = 3$	$N_j \geq 4$
$N_b = 0$	$e\tau_h, \mu\tau_h$ $e\mu$	$e\tau_h, \mu\tau_h$ $e\mu$	$e\tau_h, \mu\tau_h$ $e\mu$		
$N_b = 1$		$e\tau_h, \mu\tau_h$ $e\mu$	$e\tau_h, \mu\tau_h$ $ee, \mu\mu, e\mu$	$e\tau_h, \mu\tau_h$ $ee, \mu\mu, e\mu$	$eh, \mu h$
$N_b \geq 2$			$e\tau_h, \mu\tau_h$ $ee, \mu\mu, e\mu$	$e\tau_h, \mu\tau_h$ $ee, \mu\mu, e\mu$	$eh, \mu h$

p_T to differentiate $\tau \rightarrow e, \mu$ from prompt e, μ

Important contribution from τh

Z CR for constraining
 τ reco. unc.



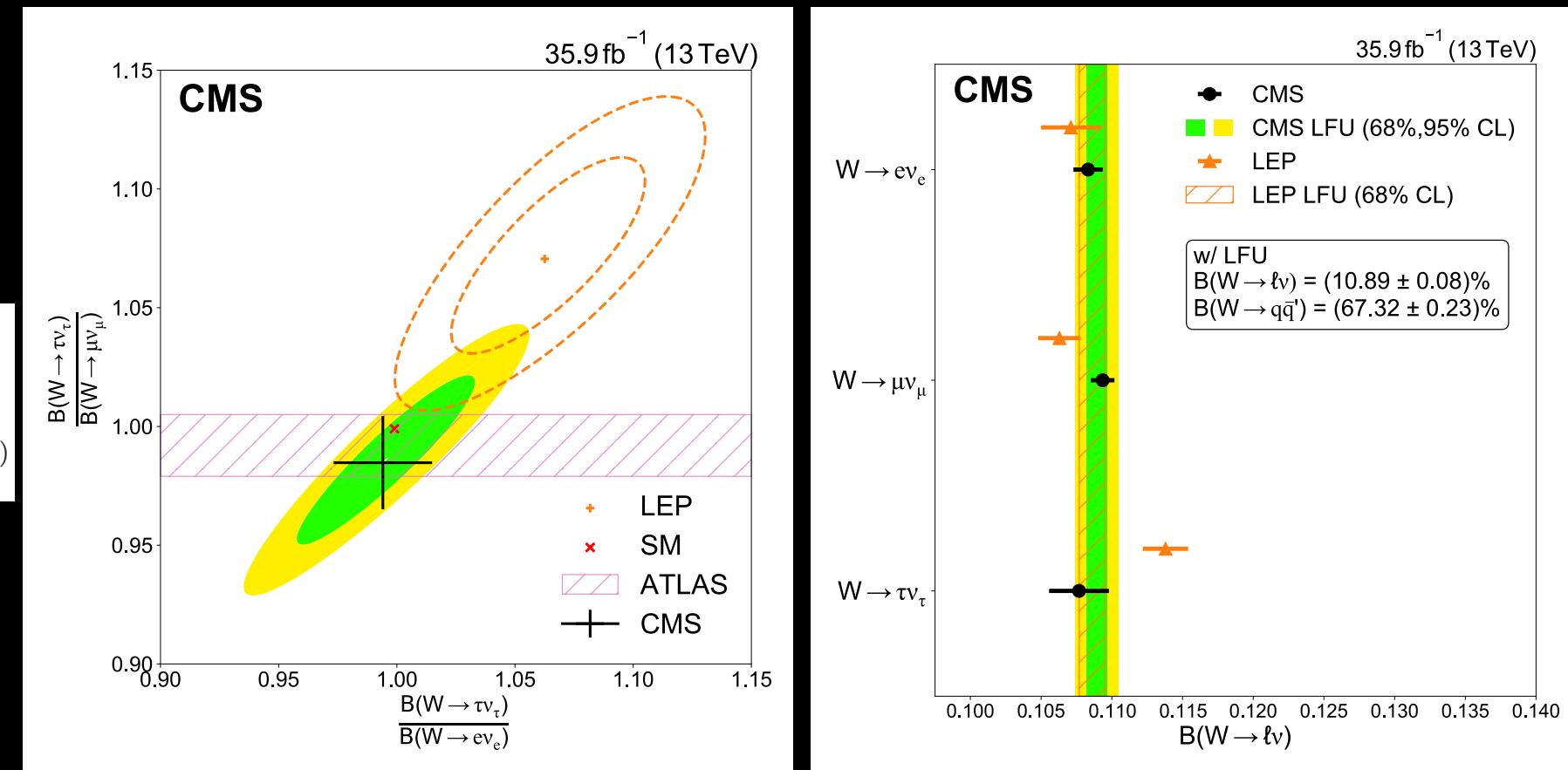
- The measured branching fractions are consistent with the LFU and ATLAS measurement

	CMS	LEP	ATLAS	LHCb	CDF	D0
$R_{\mu/e}$	1.009 ± 0.009	0.993 ± 0.019	1.003 ± 0.010	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	—	—	—	—

- More precise than the LEP results
- Extraction of the V_{cs} and $\alpha_S(m^2_W)$

$$\Gamma(W \rightarrow q\bar{q}') = \frac{\sqrt{2}G_F N_c}{12\pi} m_W^3 \sum_{i,j} |V_{ij}|^2 \left[1 + \sum_{k=1}^4 c_{\text{QCD}}^{(i)} \left(\frac{\alpha_S}{\pi}\right)^k + \delta_{\text{EW}}(\alpha) + \delta_{\text{mix}}(\alpha\alpha_S) \right], \quad (2)$$

$\alpha_S(m_W^2)$	$ V_{cs} $	$\sum_{ij} V_{ij} ^2$
0.095 ± 0.033	0.967 ± 0.011	1.984 ± 0.021

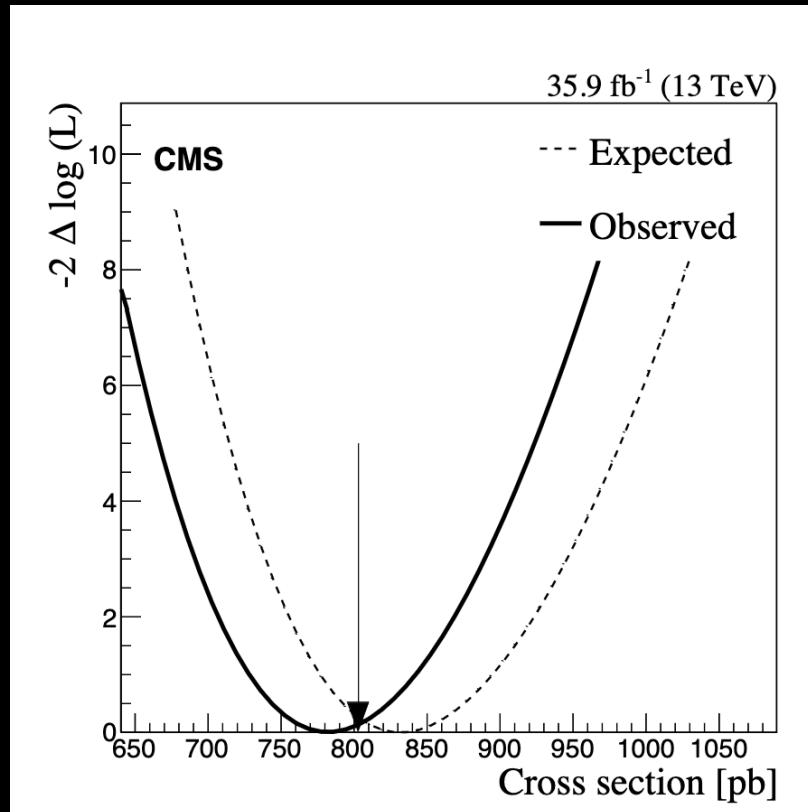
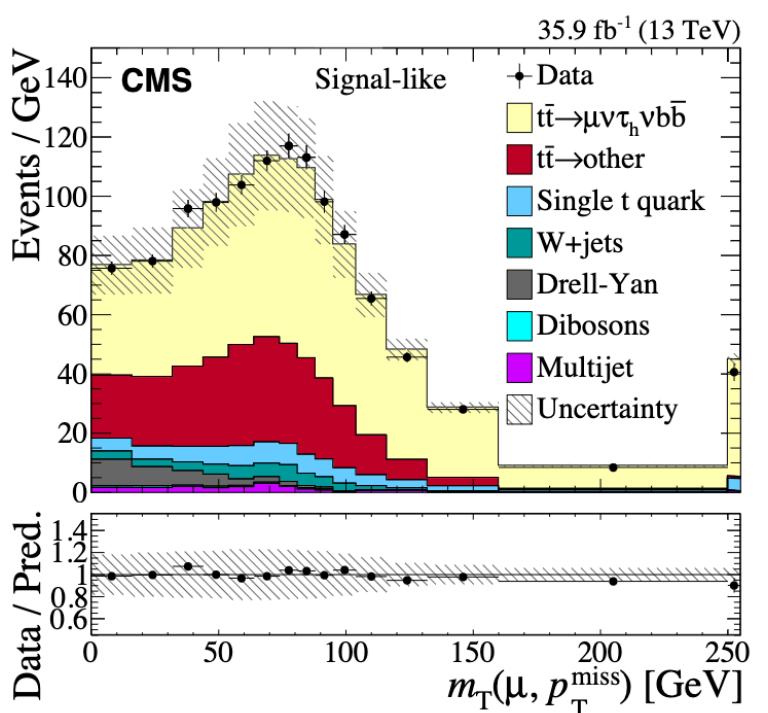
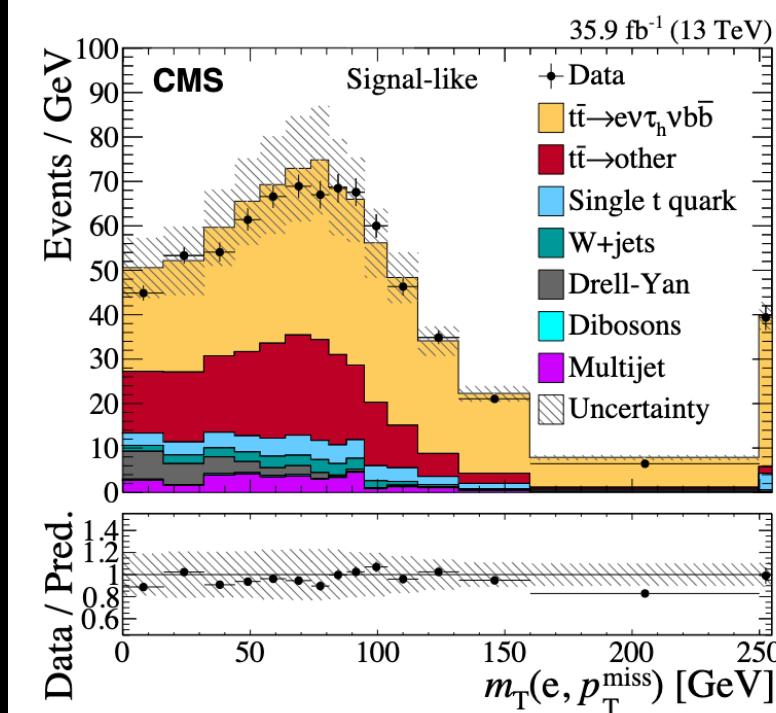


- First measurement of the $t\bar{t}$ cross section with at least one τ (hadronic)
- Selection: 1 lepton (e or μ) and ≥ 3 jets (≥ 1 b-jet + one is identified as a τ (hadronic))
- Main background coming from semi-leptonic $t\bar{t}$ decays
- Observable: m_T of the lepton and p_T^{miss}
- Measured cross section in agreement to the SM prediction
- The ratio of the τl cross section to ll cross section is consistent with LFU

$$\sigma_{t\bar{t}}(\ell\tau_h) = 781 \pm 7 (\text{stat}) \pm 62 (\text{syst}) \pm 20 (\text{lumi}) \text{ pb}$$

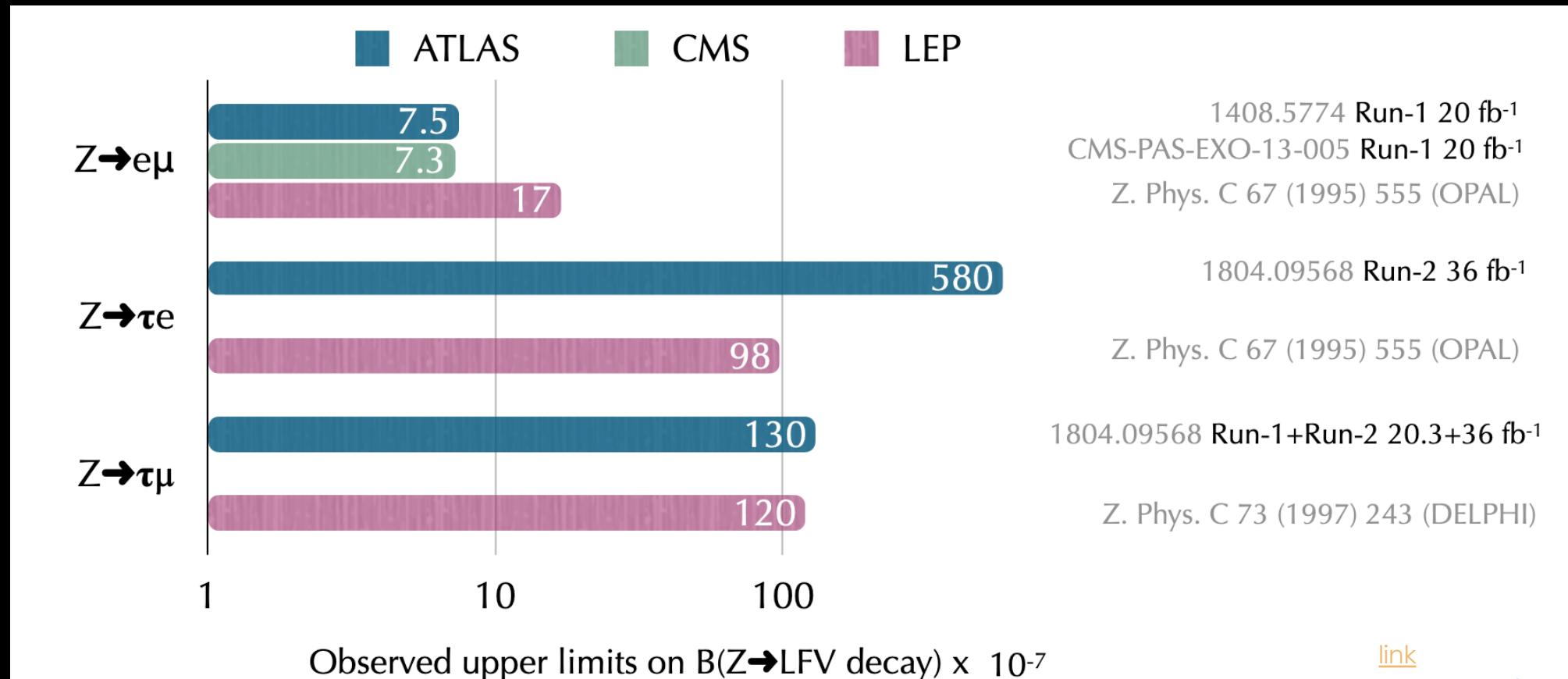
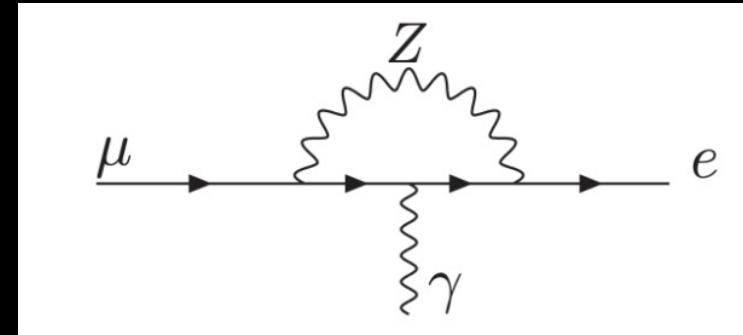
$$R_{\ell\tau_h/\ell\ell} = 0.973 \pm 0.009 (\text{stat}) \pm 0.066 (\text{syst}),$$

$$\Gamma(t \rightarrow \tau\nu_\tau b)/\Gamma_{\text{total}} = 0.1050 \pm 0.0009 (\text{stat}) \pm 0.0071 (\text{syst})$$



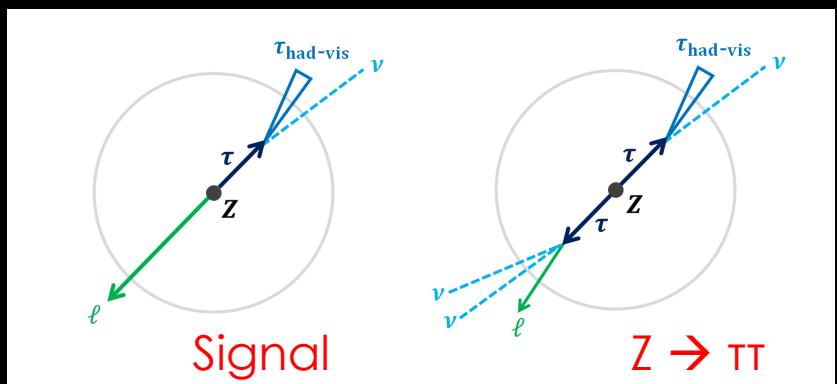
LFV in Z boson decays

- Stringent direct constraints from LEP and indirect constraints on $B(Z \rightarrow e\mu) \lesssim 10^{-10}$ from low energy experiments ($\mu \rightarrow e\gamma$)
- Many Z events produced at the LHC (8 billion Z events in 139 fb^{-1})



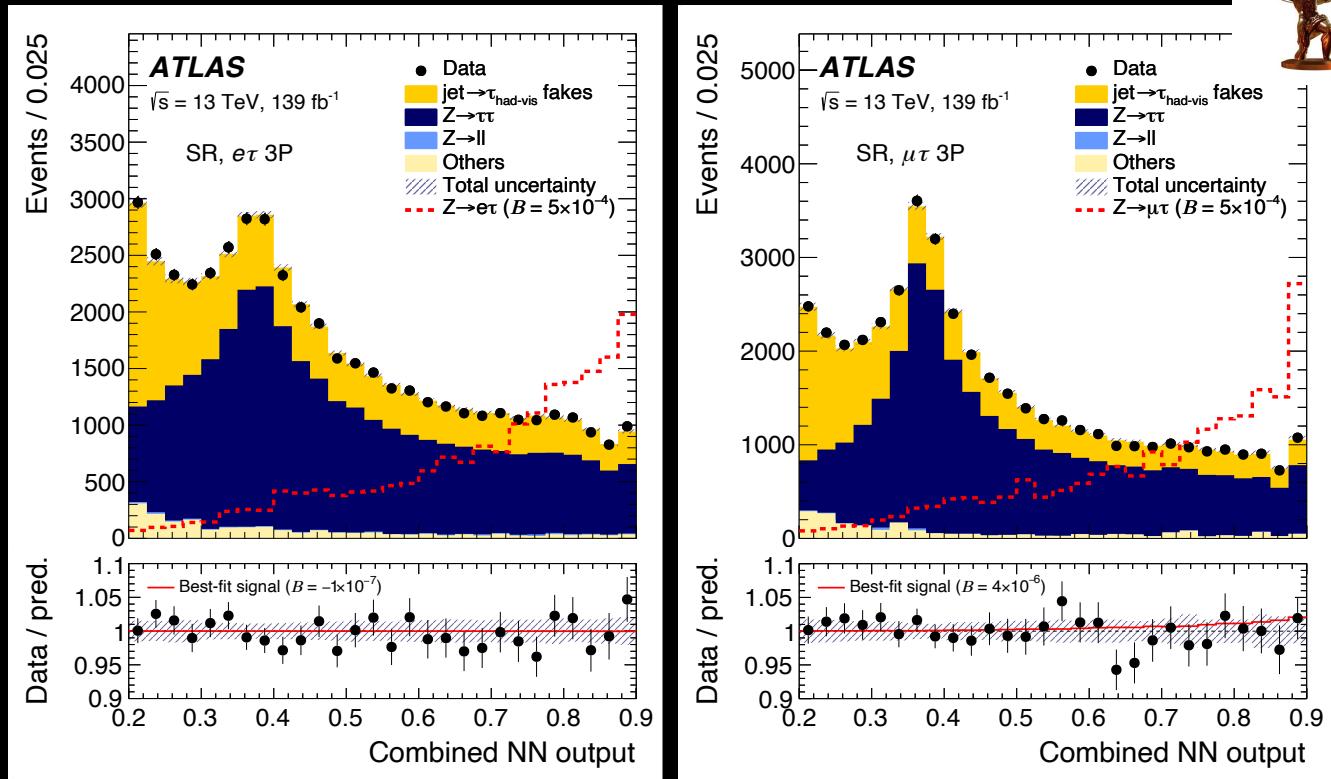
LFV in Z boson decays

- Search for Z LFV decays in $e\tau$ and $\mu\tau$ modes
- Exploit unique signal topology (1l, 1 τ) and Z resonance
- Five neural networks trained in each channel
- No significant excess over the SM background observed
- First limits for polarised (left- or right-handed) τ hypotheses
- New results supersede the most stringent constraints by LEP



13 TeV (139/fb)

Nature Phys. 17(2021) 819

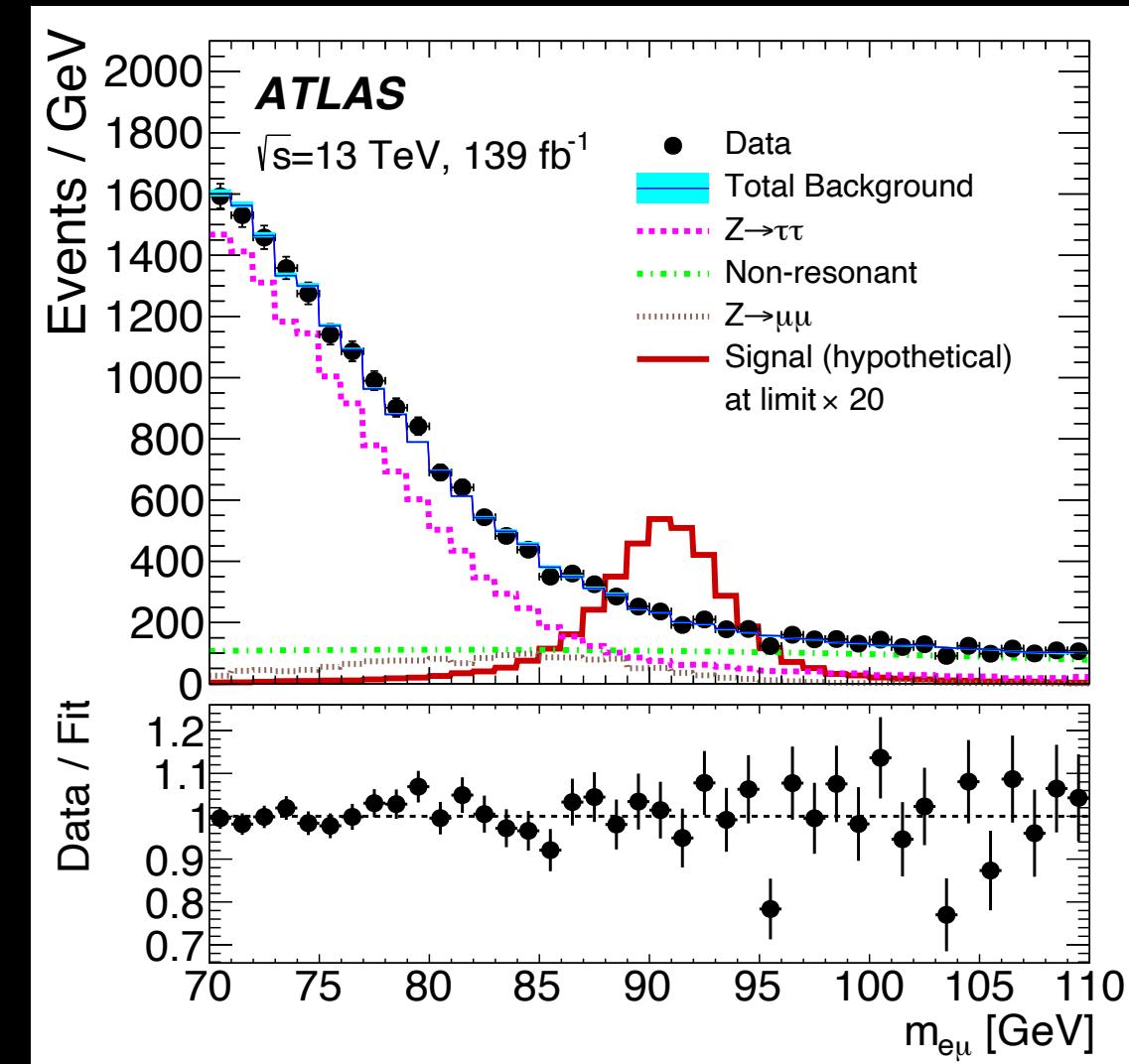
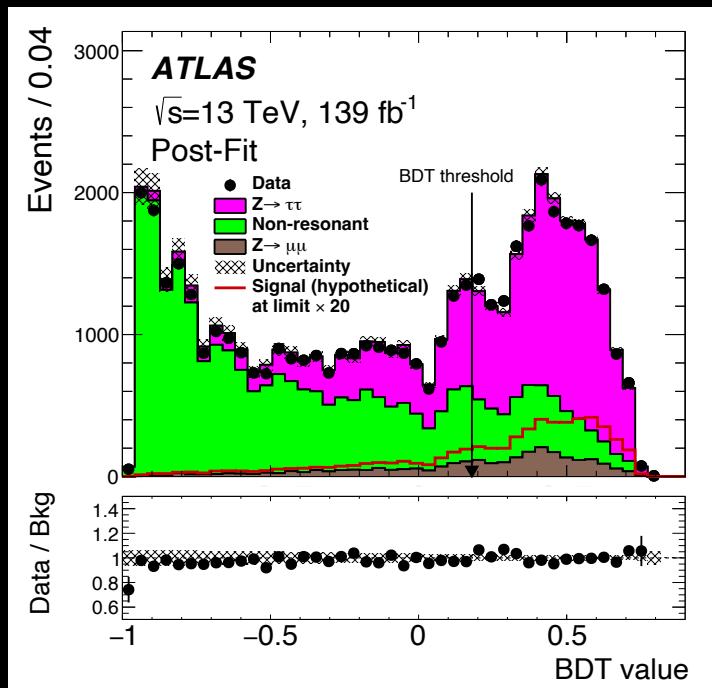


Experiment, polarization assumption	Observed (expected) upper limit on $\mathcal{B}(Z \rightarrow \ell\tau) [\times 10^{-6}]$	
	$e\tau$	$\mu\tau$
ATLAS Run 2, unpolarized τ	8.1 (8.1)	9.9 (6.3)
ATLAS Run 2, left-handed τ	8.2 (8.6)	9.5 (6.7)
ATLAS Run 2, right-handed τ	7.8 (7.6)	10 (5.8)
ATLAS Run 1, unpolarized τ [17]		17 (26)
ATLAS Run 1+Run 2 combination, unpolarized τ		9.5 (6.1)
LEP OPAL, unpolarized τ [10]	9.8	17
LEP DELPHI, unpolarized τ [11]	22	12



- Search for Z LFV decays in $e\mu$ modes
- Easy signature: Look for bump in $e\mu$ inv. Mass distribution (70 $< m_{e\mu} < 110$ GeV)
- A BDT is trained to suppress the background
- No significant excess over the SM background observed
- 95% CL branching fraction limit using 7.9×10^9 Z decays

$$\mathcal{B}(Z \rightarrow e\mu) < 2.62 \times 10^{-7}$$

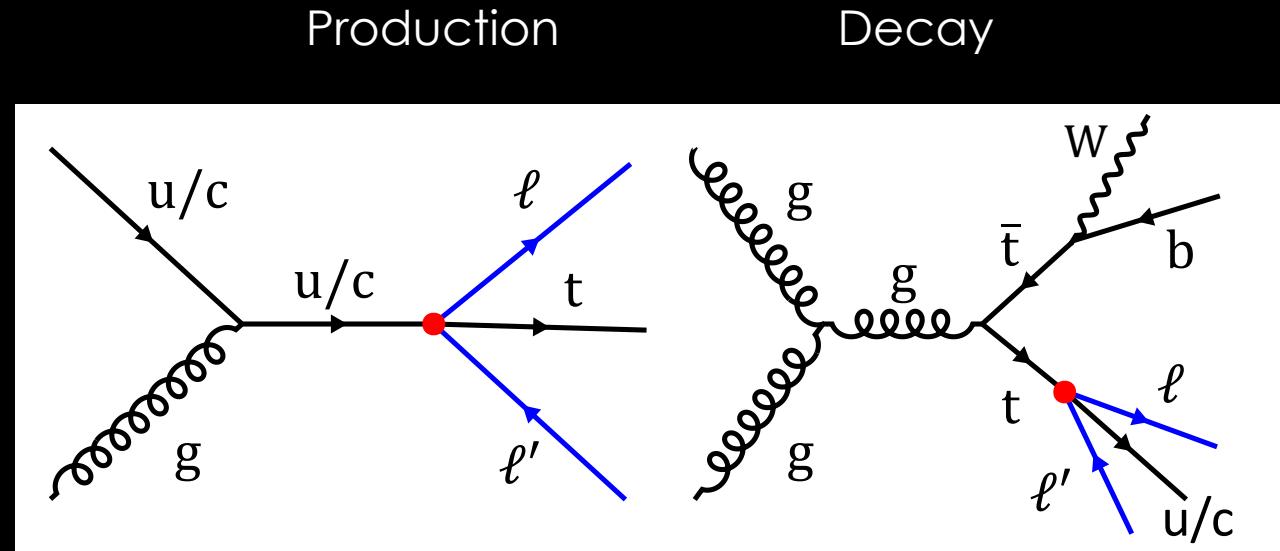


LFV in top quark production and decay

- If the new physics responsible for the CLFV is at scales beyond what the LHC can directly probe, the SM Lagrangian can be extended by dimension-6 operators

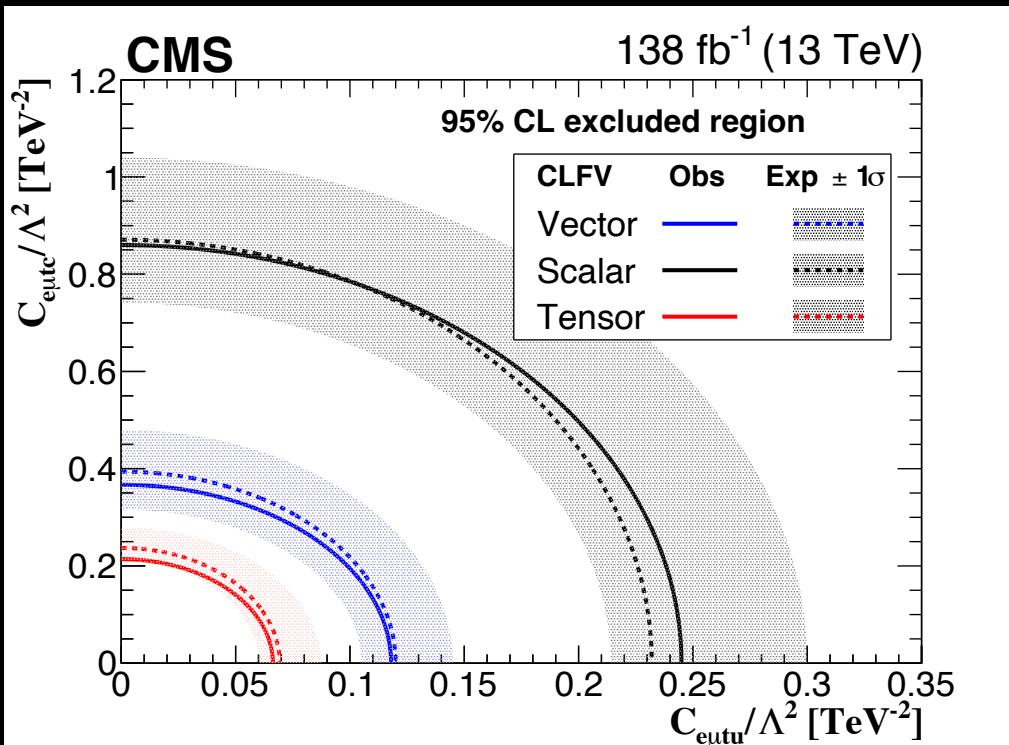
$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_x \frac{C_x}{\Lambda^2} O_x + \dots ,$$

- Two-lepton two-quark operator with one top quark leg contribute to top quark production and decay
 - Top quark production mode is dominant

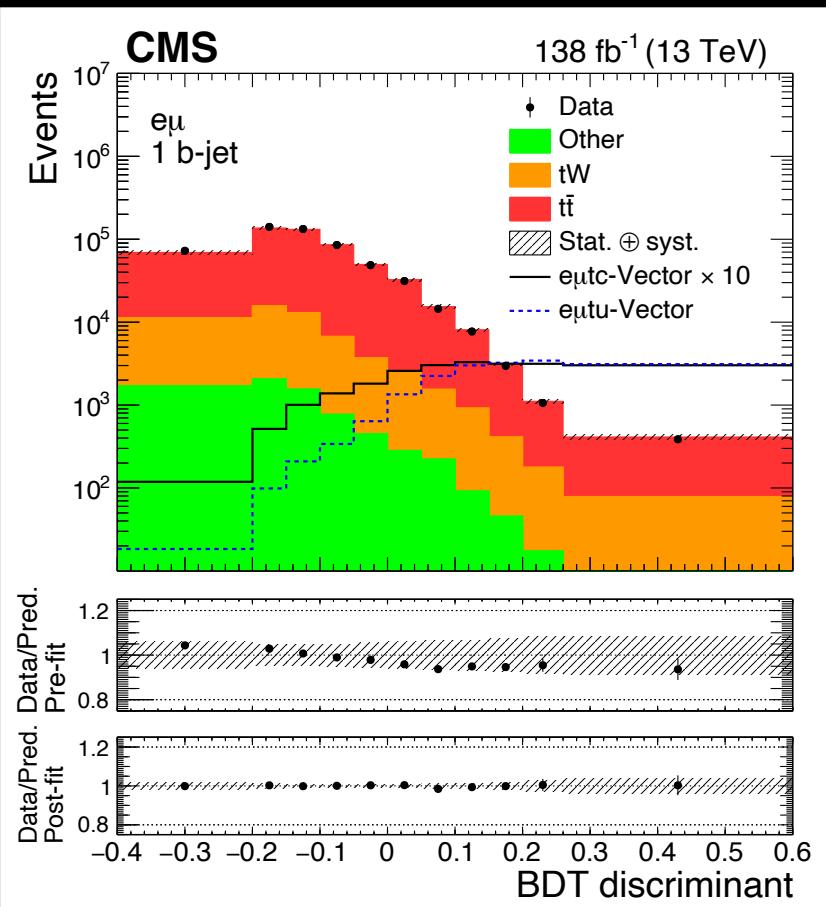


Vector	$O_{lq}^{(3)ijkl} = (\bar{l}_i \gamma^\mu \tau^I l_j)(\bar{q}_k \gamma^\mu \tau^I q_l),$
Vector	$O_{lq}^{(1)ijkl} = (\bar{l}_i \gamma^\mu l_j)(\bar{q}_k \gamma^\mu q_l),$
Vector	$O_{lu}^{ijkl} = (\bar{l}_i \gamma^\mu l_j)(\bar{u}_k \gamma^\mu u_l),$
Vector	$O_{eq}^{ijkl} = (\bar{e}_i \gamma^\mu e_j)(\bar{q}_k \gamma^\mu q_l),$
Vector	$O_{eu}^{ijkl} = (\bar{e}_i \gamma^\mu e_j)(\bar{u}_k \gamma^\mu u_l),$
Scalar	$O_{lequ}^{(1)ijkl} = (\bar{l}_i e_j) \epsilon (\bar{q}_k u_l),$
Tensor	$O_{lequ}^{(3)ijkl} = (\bar{l}_i \sigma^{\mu\nu} e_j) \epsilon (\bar{q}_k \sigma_{\mu\nu} u_l),$

- Search for CLFV in $e\mu$ final state
- Production & decay
- Signal: CLFV vector, scalar and tensor
- BDT is used to discriminate signal from BG events
- Data consistent with SM expectation
 - Upper limits are set at 95% CL

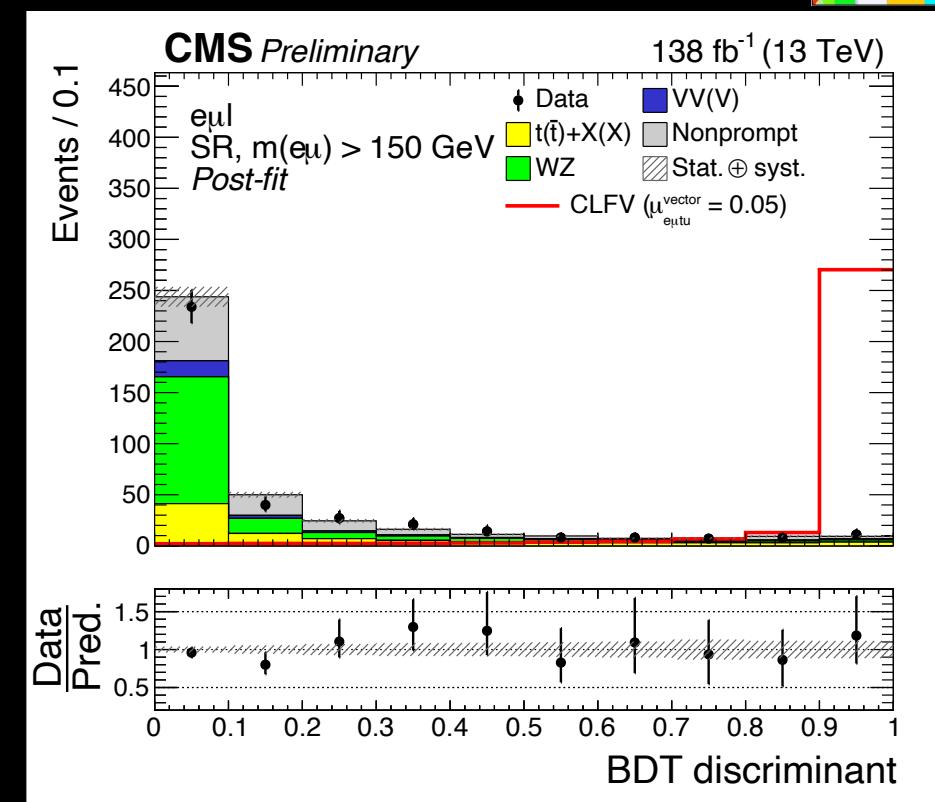
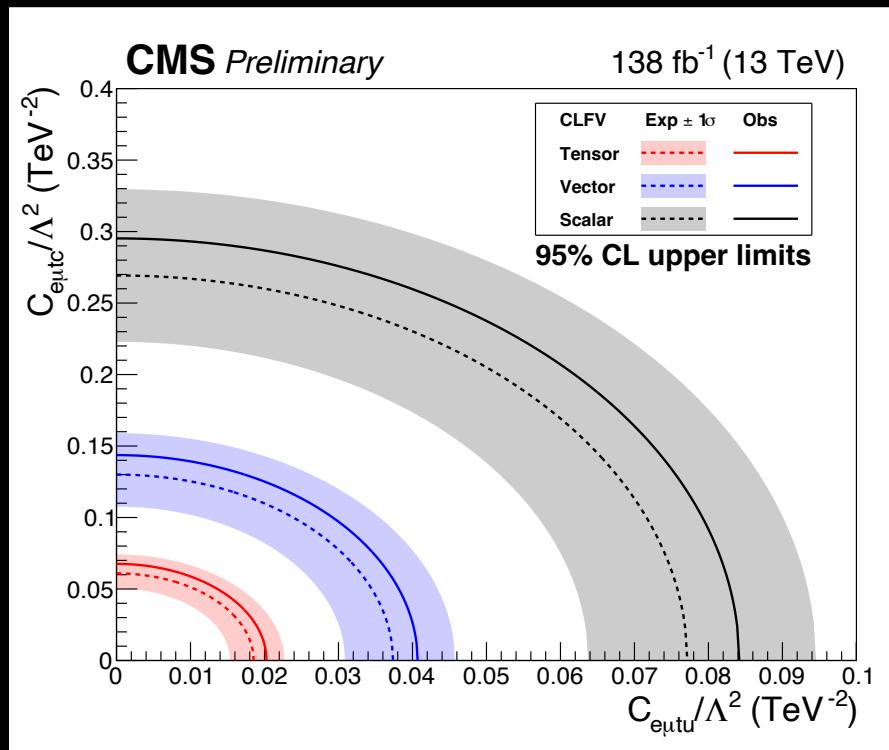


Vertex	Int. type	$\mathcal{B}(10^{-6})$	
		Exp	Obs
$e\mu tu$	Vector	0.14	0.13
	Scalar	0.06	0.07
	Tensor	0.27	0.25
$e\mu tc$	Vector	1.49	1.31
	Scalar	0.91	0.89
	Tensor	3.16	2.59





- Search for CLFV in three lepton final states
- Signal region (SR)
 - $m_{e\mu} < 150\text{GeV}$ top decay enriched
 - $m_{e\mu} > 150\text{GeV}$ top production enriched
- BDT is used to discriminate signal from BG events
- The most stringent limits are set on top LFV BRs

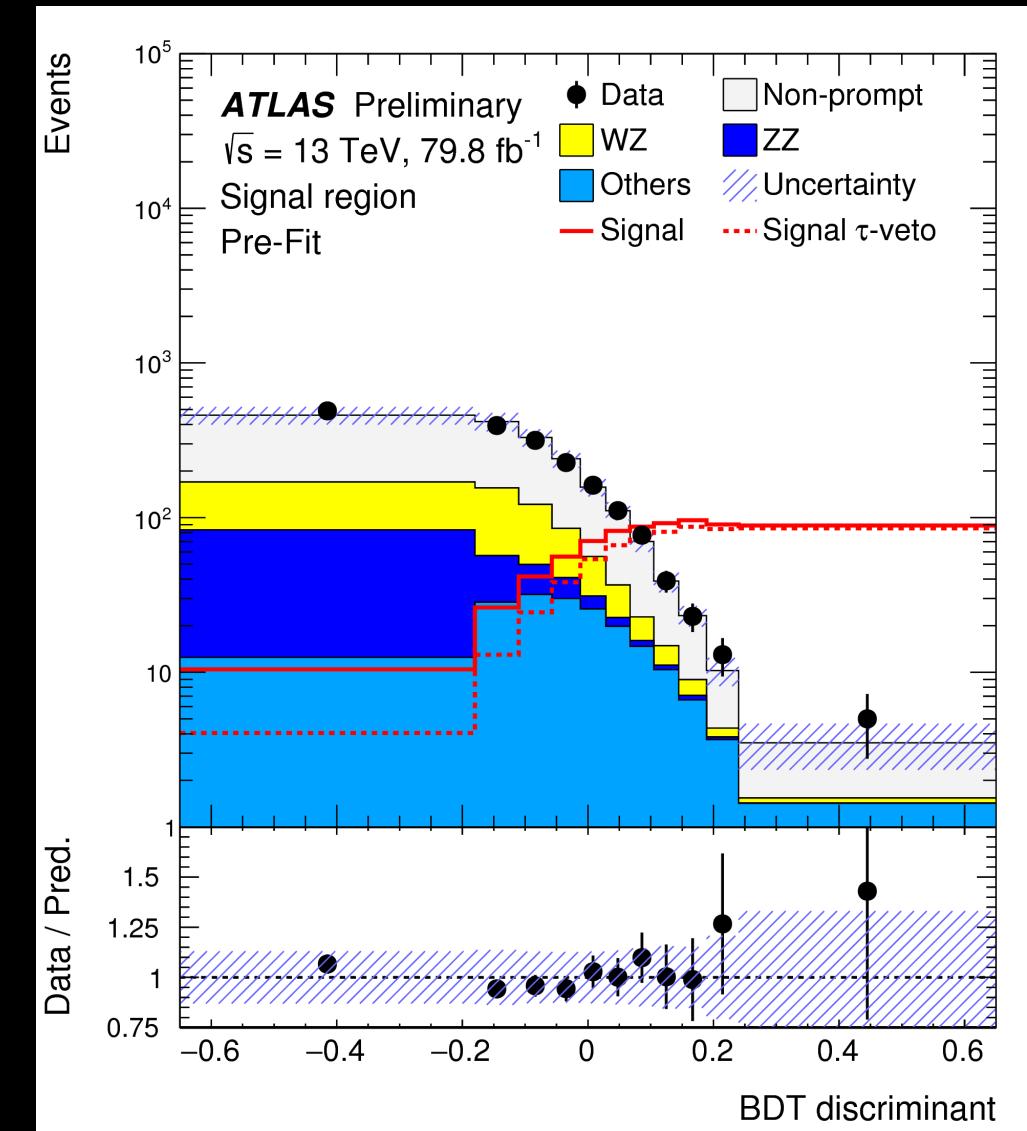
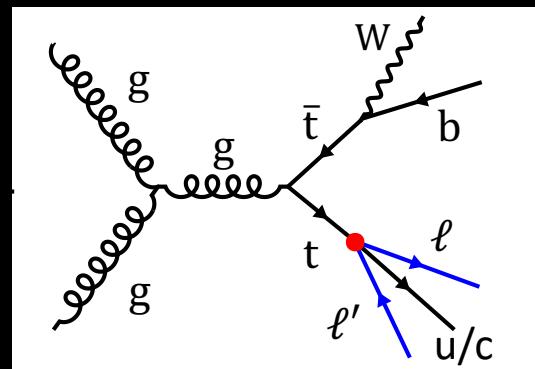


CLFV coupling	Lorentz structure	$\mathcal{B}(t \rightarrow e\mu q) \times 10^{-6}$	exp ($-\sigma, +\sigma$)	obs
$e\mu tu$	tensor	0.019 (0.013, 0.029)	0.023	
	vector	0.013 (0.009, 0.020)	0.016	
	scalar	0.007 (0.005, 0.011)	0.009	
$e\mu tc$	tensor	0.209 (0.143, 0.311)	0.258	
	vector	0.163 (0.111, 0.243)	0.199	
	scalar	0.087 (0.060, 0.130)	0.105	



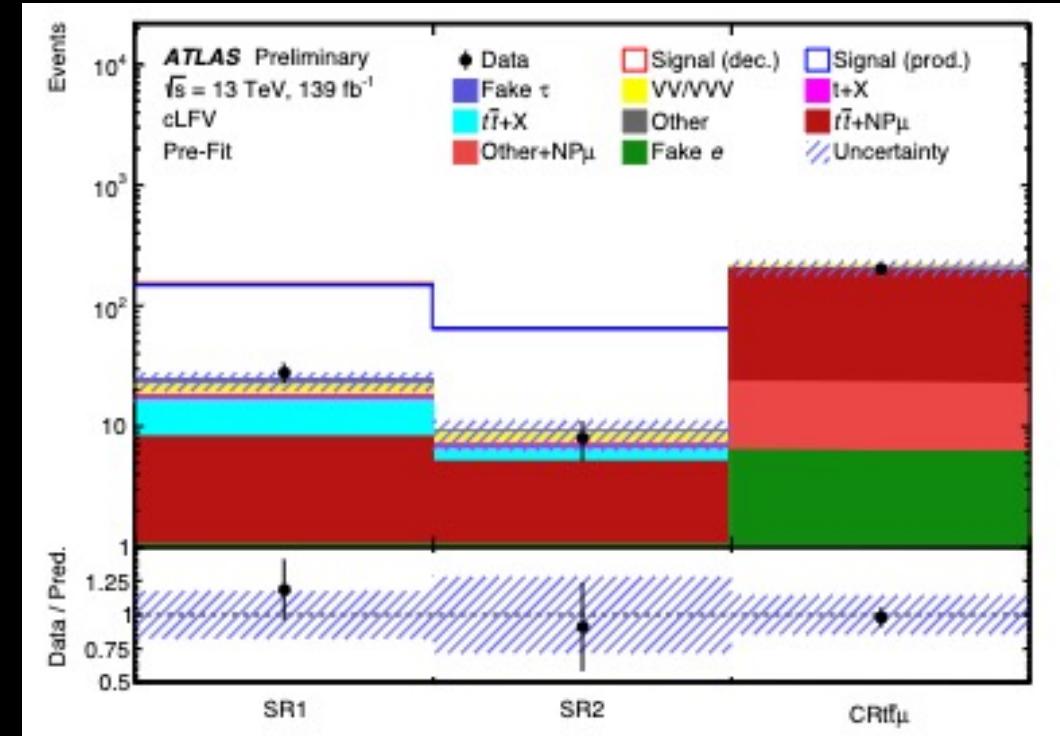
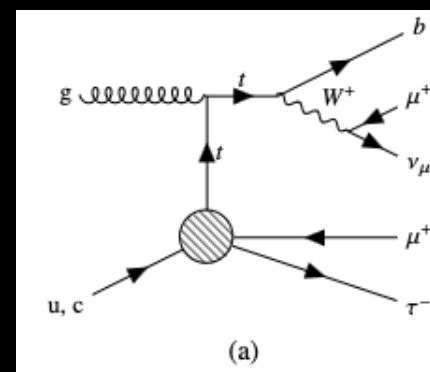
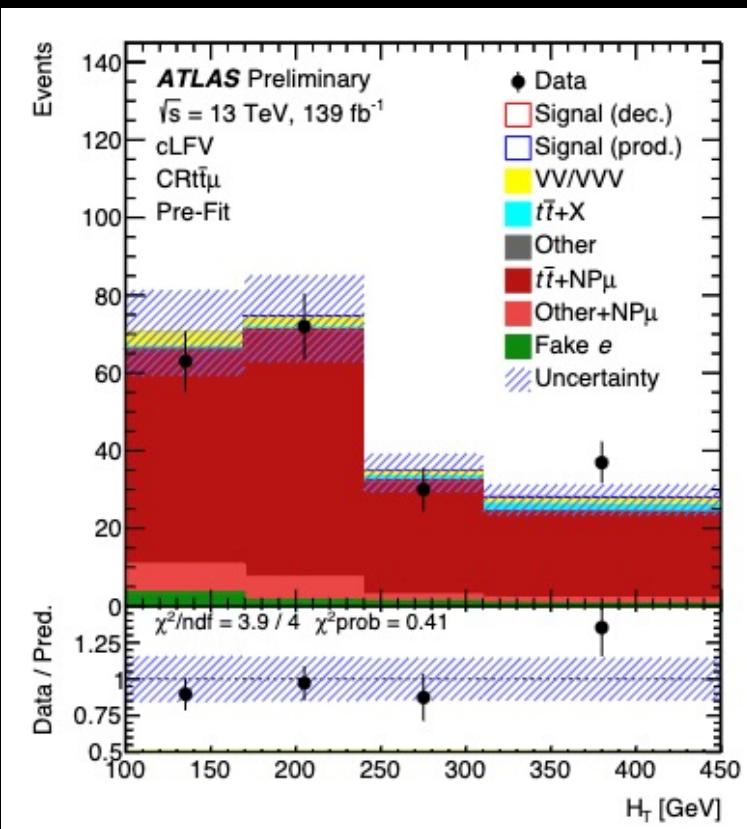
- Search for CLFV in final states with three isolated charged leptons
- Decay only
- CLFV top reconstructed from two opposite sign different-flavour leptons and a jet
- BDT is used to discriminate signal from BG events
- Data consistent with SM expectation
 - Upper limits are set at 95% CL

$B(t \rightarrow \ell\ell'q) < 1.86(1.36) \times 10^{-5}$ obs (exp)
$B(t \rightarrow e\mu q) < 6.6(4.8) \times 10^{-6}$ obs (exp)





- First search for $tq\mu\tau$ LFV interactions
- Production & decay
- Signal region: two same sign muons and one hadronic tau
- Control region: two opposite sign muons and one hadronic tau
- Data consistent with SM expectation, 95% CL limits are set



	95% CL upper limits on $\text{BR}(t \rightarrow \mu\tau q) (\times 10^{-7})$							
	$c_{lq}^{-(ijk3)}$	$c_{eq}^{(ijk3)}$	$c_{lu}^{(ijk3)}$	$c_{eu}^{(ijk3)}$	$c_{lequ}^{1(ijk3)}$	$c_{lequ}^{1(ijk3)}$	$c_{lequ}^{3(ijk3)}$	$c_{lequ}^{3(ijk3)}$
Expected (u)	4.6	4.2	4.0	4.5	2.5	2.5	5.8	5.8
Observed (u)	5.1	4.6	4.4	5.0	2.8	2.8	6.4	6.4
Expected (c)	54	51	51	52	35	35	61	61
Observed (c)	60	56	56	57	38	38	68	68

Summary

- The LHC, ATLAS and CMS, have proven to be precision tools, competitive with measurements of fundamental parameters at LEP
 - All published results agree with the LFU hypothesis
- Multiple search is done for the LFV in connection with the heavy particles accessible at the LHC (Z-boson, top quark,...)
 - No evidence of the LFV is observed
- More searches are performed with full run-2 data and will be published soon, stay tuned!

Thanks for your attention