Rare Decays of Top Quark

Ece ASILAR
Hanyang University,
on behalf of the ATLAS and CMS Collaborations

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Introduction

In Standard Model (SM), top quark decays to b W "almost" with a branching ratio ~1.

Rare top quark decays such as flavour changing neutral current (FCNC) are highly suppressed, due to Glashow-Iliopoulos-Maiani mechanism

SM has been successful for many years, but recently several excesses are reported.

- Lepton flavour violation: Combined result of R(D) and R(D*) anomalies, 3.3σ deviation from SM [1]
- W boson mass measurement from CDF II [2] reported 7.0σ of deviation
- Muon g-2 measurement [3] recently showed 5.0σ discrepancy

[1] HFLAV, Semileptonic B decay, 2023 (link)
[2] CDF Collaboration, Science 376 (2022) 6589, 170-176
[3] Muon g-2 Collaboration, arxiv:2308.06230

This talk covers …

Flavour-changing neutral currents (FCNC)

- tqZ ATLAS TOPQ-2019-06 $L=139\ fb^{-1}$
- tqγ CMS TOP-21-013. $L=138\ fb^{-1}$

Charged lepton flavour violation (cLFV)

- $\mu\tau$tq ATLAS-CONF-2023-001 $L=139\ fb^{-1}$
- $e\mu$tq CMS TOP-22-005 $L=138\ fb^{-1}$

not covers …

See talk from Robert Orr

Measurement of Higgs FCNCs and anomalous couplings

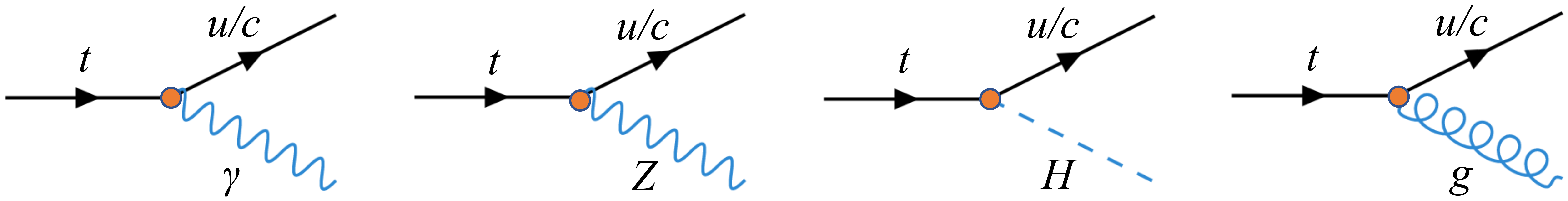
- tqH (H->$\tau\tau$) (ATLAS)

See talk from Maria Moreno Llacer

Single top measurements including CKM measurements

- All signal models based on EFT with dim-6 operators

FCNC involving a top quark



- Branching fractions in SM ~ 10^{-12} -10^{-17}
- Any excess is a hint for Beyond the SM

Search for tqZ FCNC

Phys. Rev. D 108 (2023) 032019.

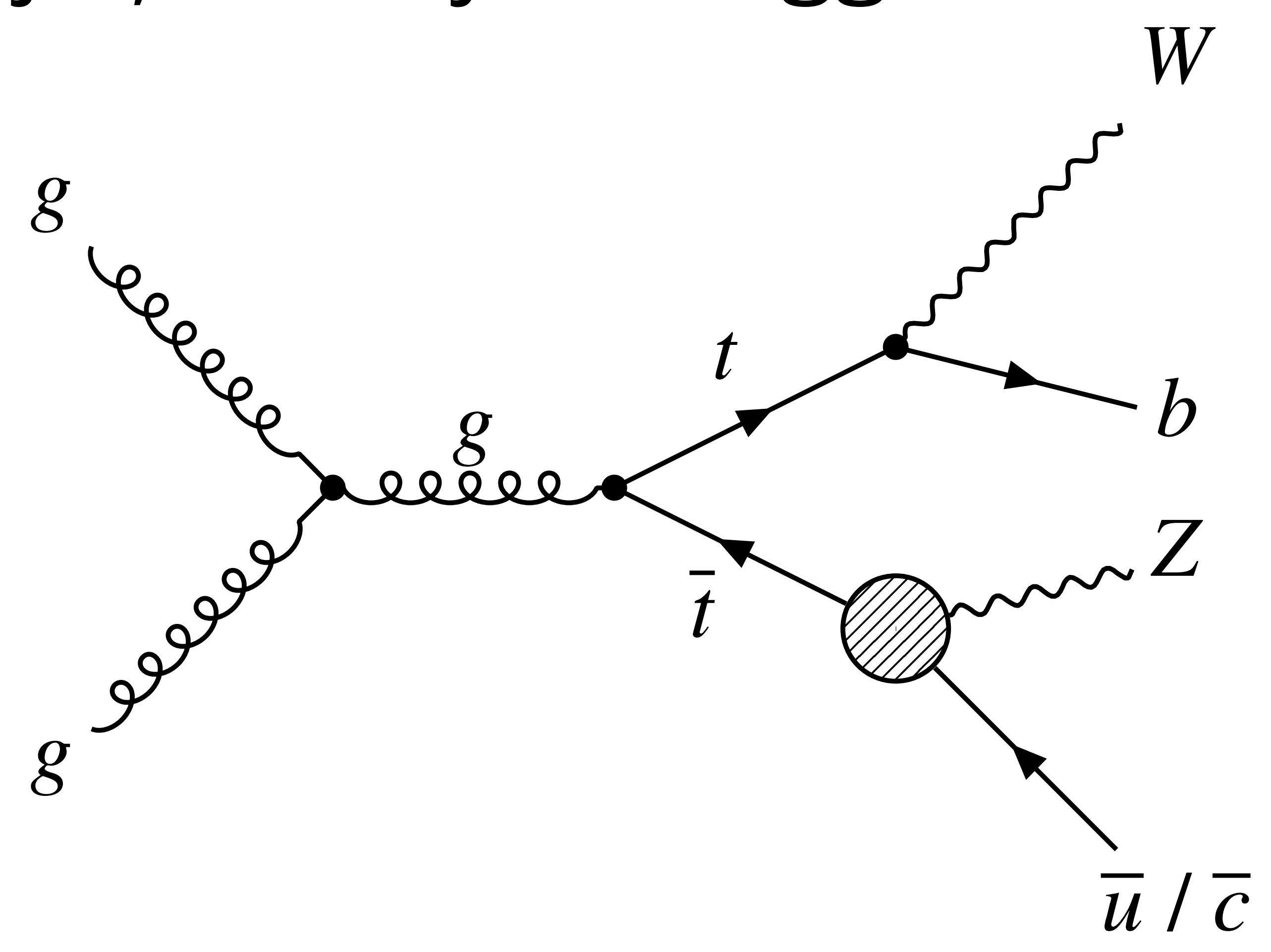
TOPQ-2019-06

L=139 fb^{-1}

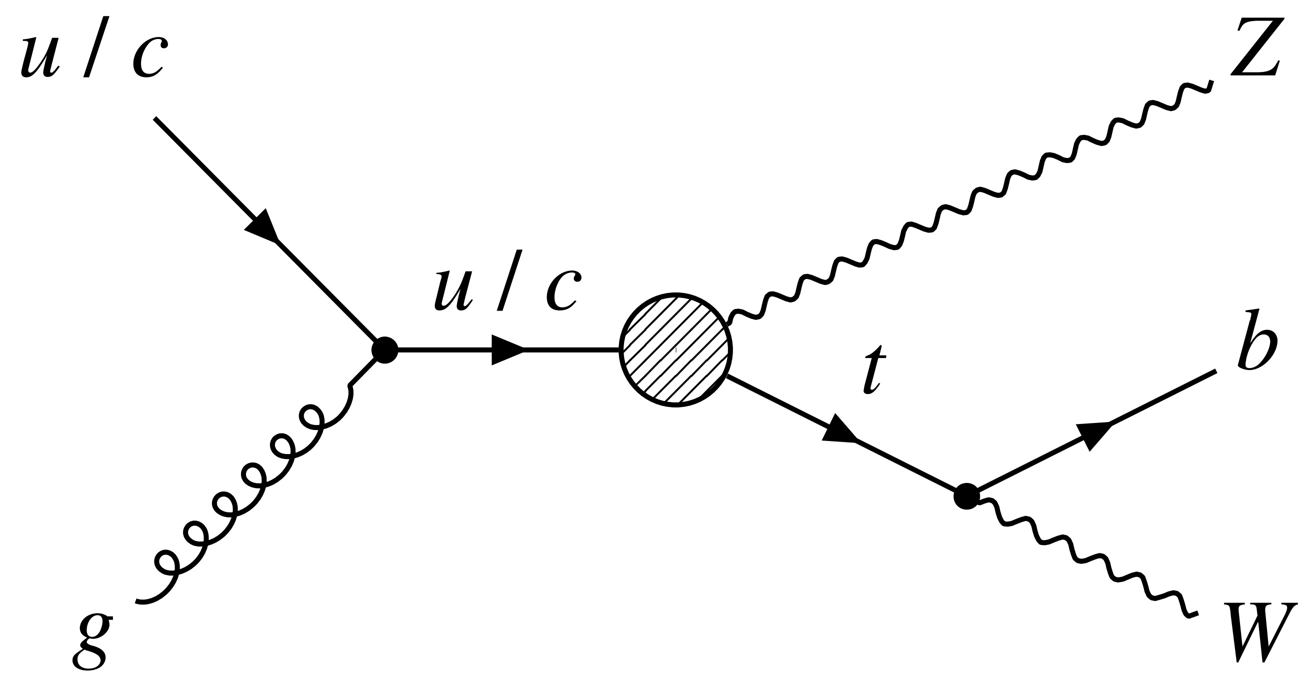
ATLAS EXPERIMENT

- 3 leptons, invariant mass of the opposite-sign leptons is within the Z mass window, jets, and b-tagging with DL1r algorithm
- top quarks and W boson are reconstructed by χ^2 minimization
- Reconstructed top quark masses are required to be within 172.5 GeV +/- 2 resolution
- Backgrounds are estimated by MC prediction
- CR and side bands to handle normalization and systematic uncertainties
  - $t\bar{t}$ (OSOF), $t\bar{t}Z$ ($\geq$ 4 jet, == 2 b-jet), and two side bands by inverting constraints on reconstructed mass

- SR1 : Targeting FCNC process in $t\bar{t}$ decays
  $\geq$ 2 jet, exactly 1 b-tagged



- SR2 : Targeting single top production
  1 or 2 jets, exactly 1 b-tagged



Search for tqZ FCNC

Phys. Rev. D 108 (2023) 032019.

TOPQ-2019-06

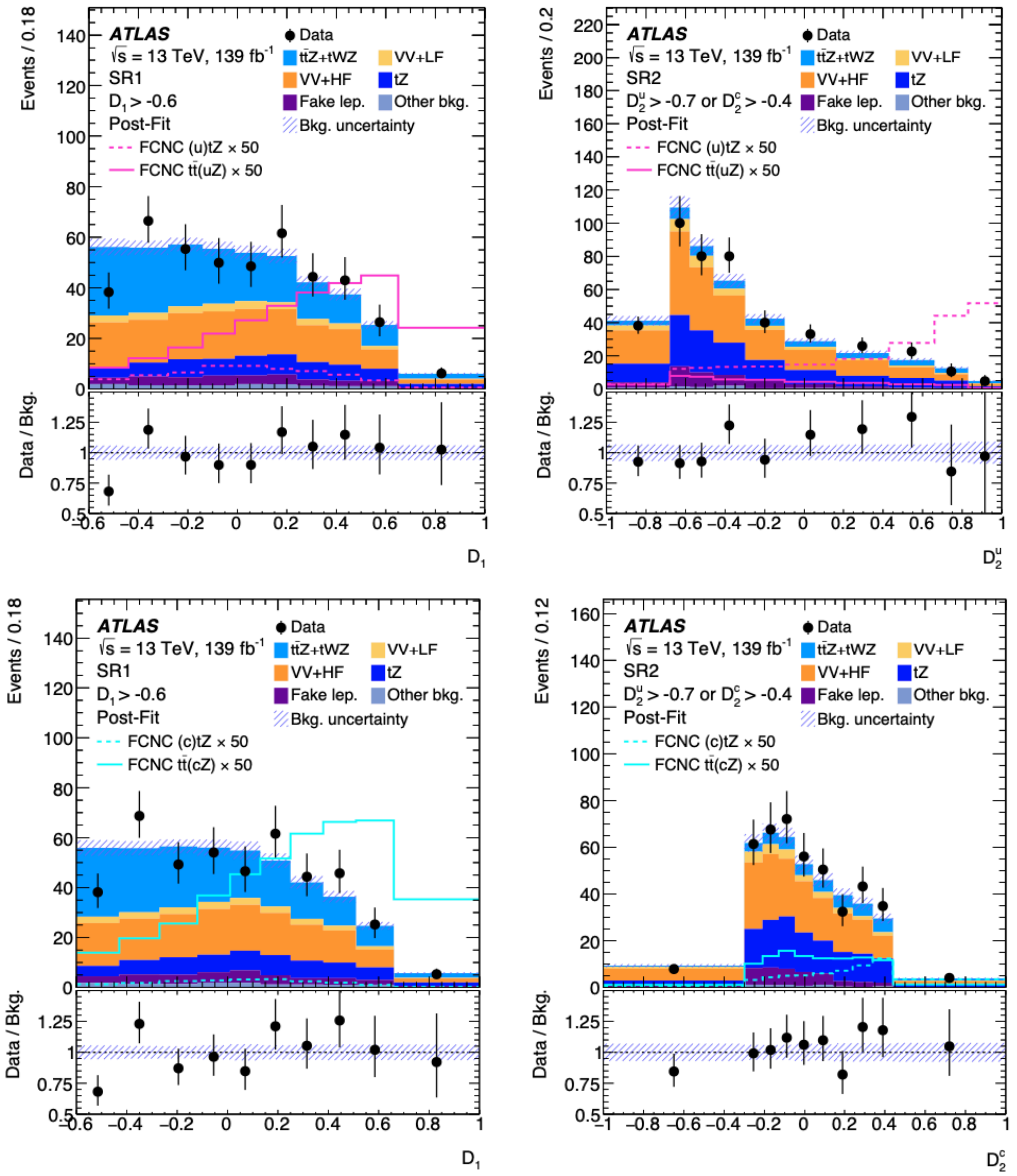
L=139 fb^{-1}

MVA (GBDT) are used to better separate signal from background events in the SRs

The data are in good agreement with the SM expectations, and no evidence of a signal is found.

These results for $t \to Zu$ ($t \to Zc$) improve on the previous observed limits from ATLAS by a factor of 3 (2), and on the previous expected limits by a factor of 5 (3).

Observable	Vertex	Coupling	Observed	Expected
		SRs+CRs		
$\mathcal{B}(t \to Zq)$	tZu	LH	6.2×10^{-5}	$4.9^{+2.1}_{-1.4} \times 10^{-5}$
$\mathcal{B}(t \to Zq)$	tZu	RH	6.6×10^{-5}	$5.1^{+2.1}_{-1.4} \times 10^{-5}$
$\mathcal{B}(t \to Zq)$	tZc	LH	13×10^{-5}	$11^{+5}_{-3} \times 10^{-5}$
$\mathcal{B}(t \to Zq)$	tZc	RH	12×10^{-5}	$10^{+4}_{-3} \times 10^{-5}$
$\lvert C_{uW}^{(13)*}\rvert$ and $\lvert C_{uB}^{(13)*}\rvert$	tZu	LH	0.15	$0.13^{+0.03}_{-0.02}$
$\lvert C_{uW}^{(31)}\rvert$ and $\lvert C_{uB}^{(31)}\rvert$	tZu	RH	0.16	$0.14^{+0.03}_{-0.02}$
$\lvert C_{uW}^{(23)*}\rvert$ and $\lvert C_{uB}^{(23)*}\rvert$	tZc	LH	0.22	$0.20^{+0.04}_{-0.03}$
$\lvert C_{uW}^{(32)}\rvert$ and $\lvert C_{uB}^{(32)}\rvert$	tZc	RH	0.21	$0.19^{+0.04}_{-0.03}$



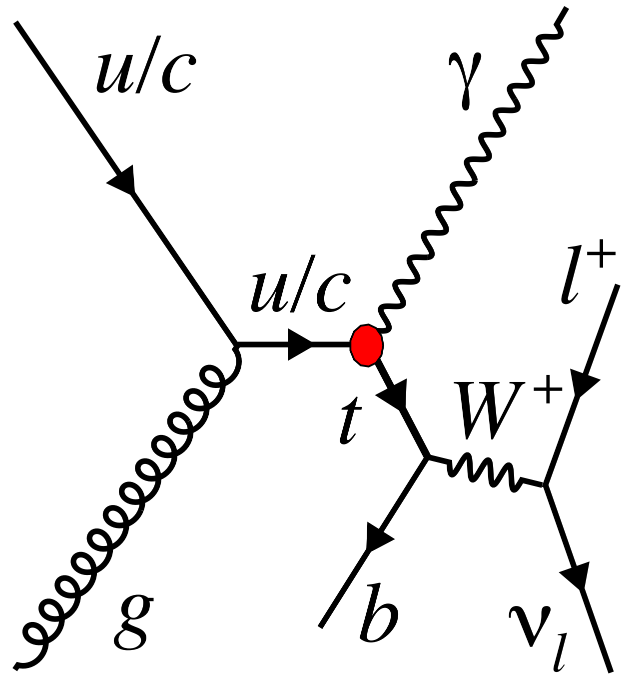
Search for tqγ FCNC

CMS PAS TOP-21-013

L=138 fb^{-1}

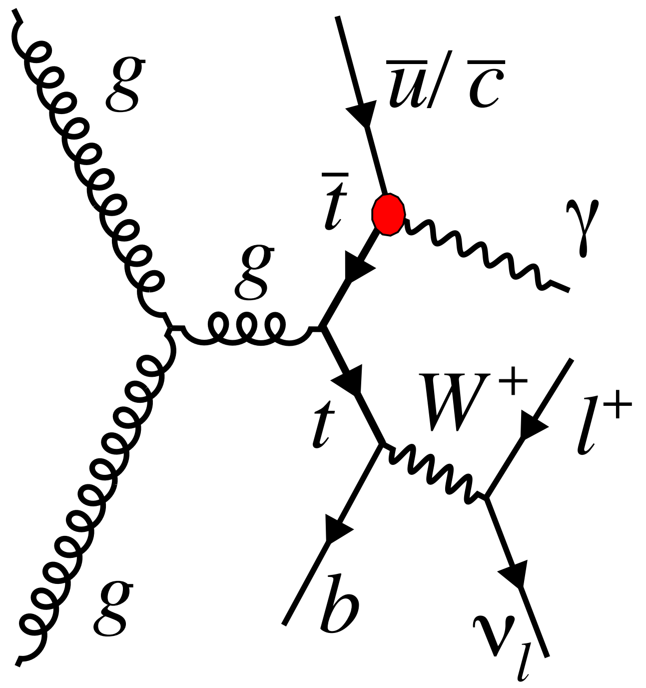
- Final states including the muon and electron

Single top production -> t + γ



SR1(Njets = 1;Nb = 1)

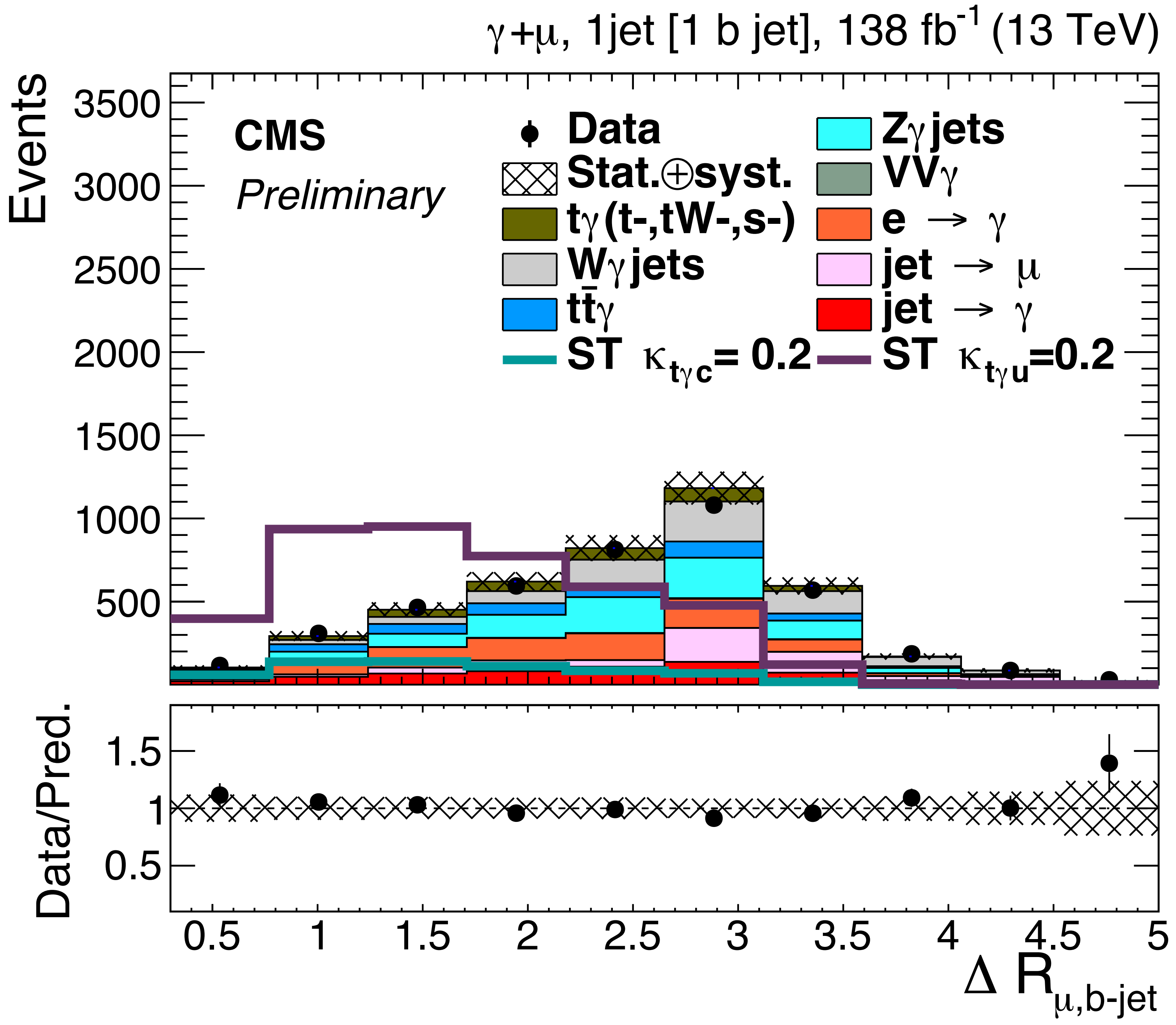
FCNC decay in top pair production ->t + γ + q

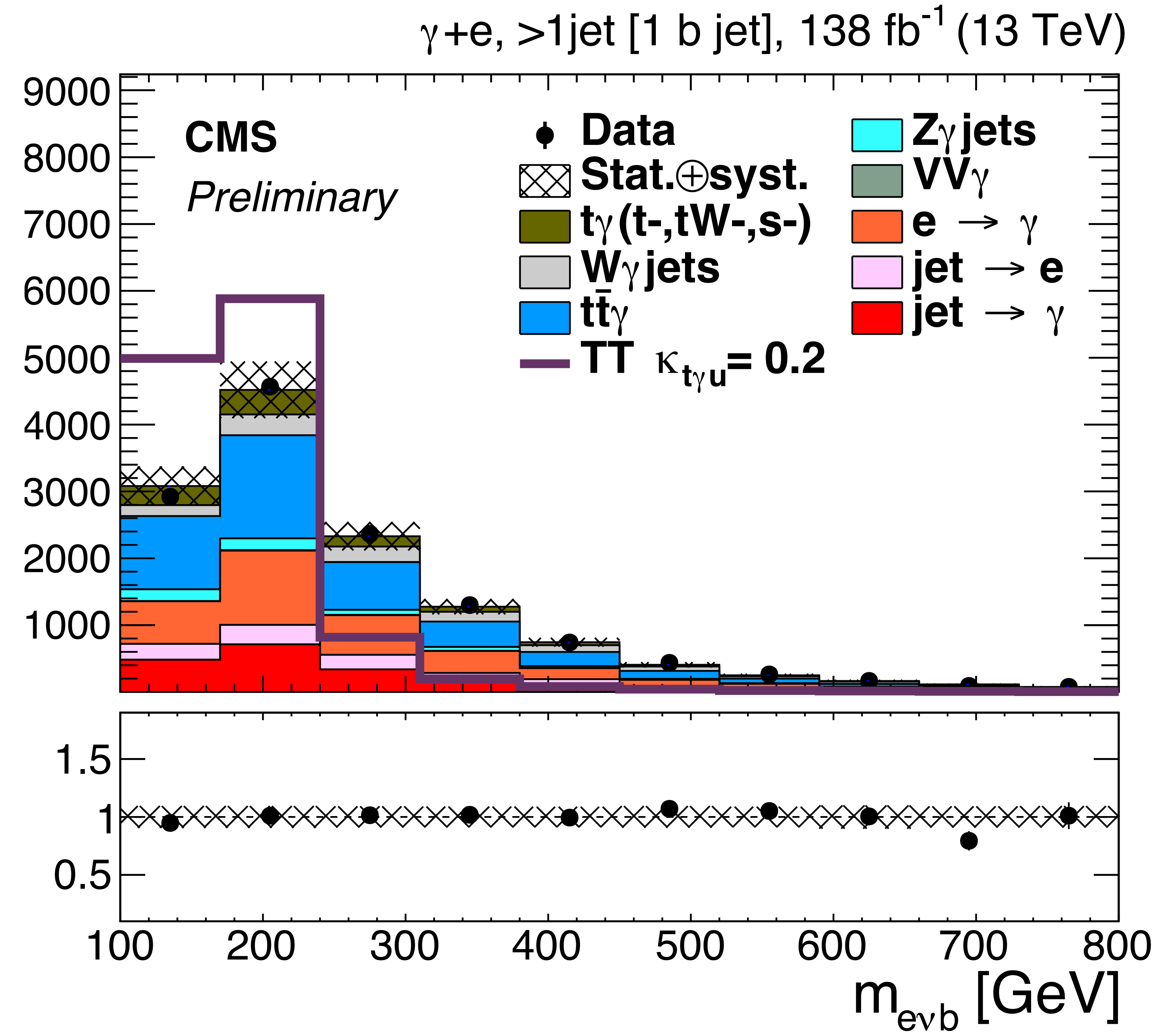


SR2 (Njets ≥ 2;Nb = 1)

Data based background estimation

- ttγ ($\geq$2 b-jet), Z/Wγ ($\geq$1 light jet) CR-> Fit to data gives normalization SF
- Jet-> γ fake: ABCD using photon isolation and shower shape
- Jet-> lepton fake: Fake rate using loose lepton identification
- e -> γ fake: Correction factors are calculated in CR with Z mass window

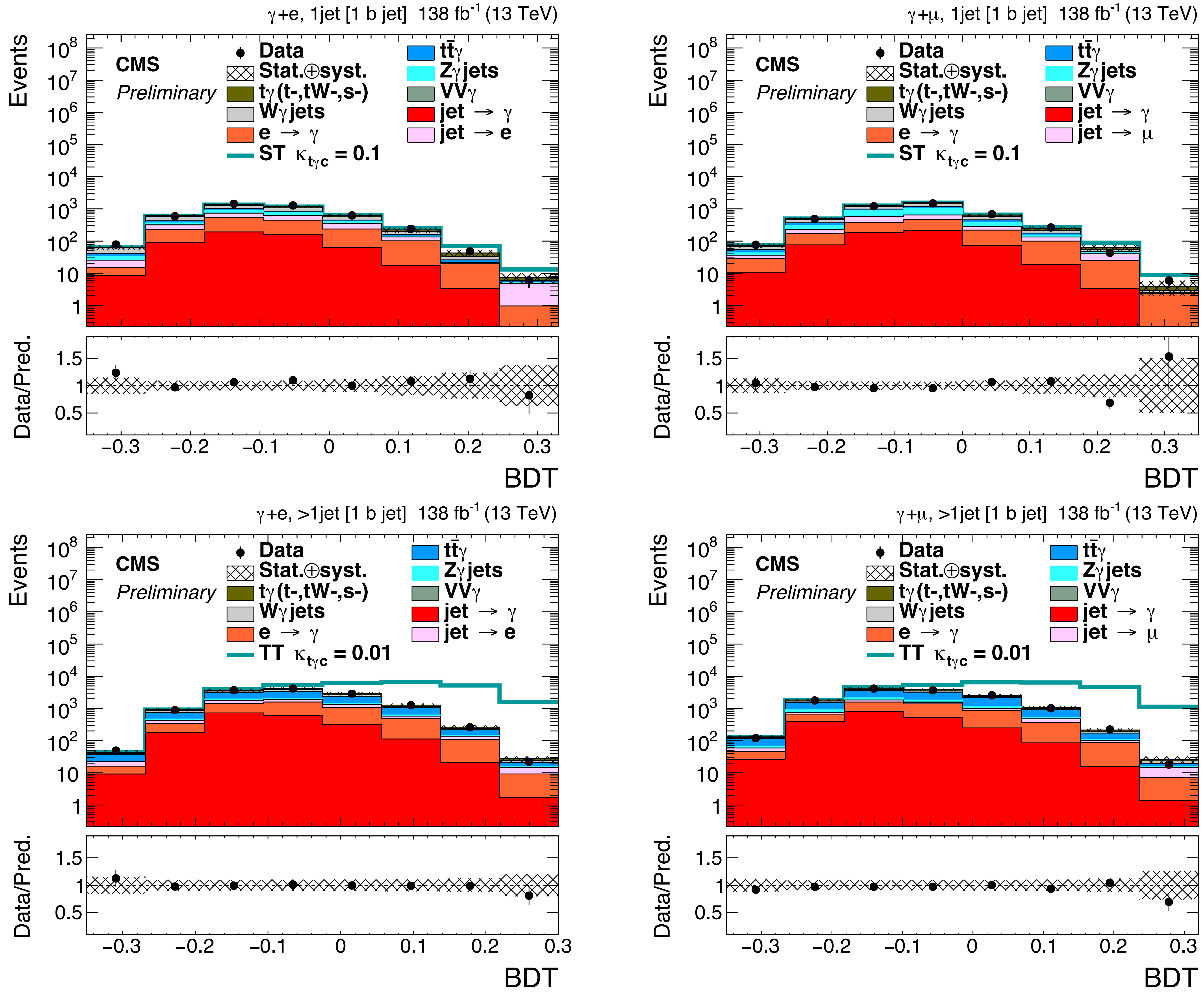




Search for tqγ FCNC

CMS PAS TOP-21-013

L=138 fb^{-1}



MVA (BDT) are used to better separate signal from background events in the SRs

- No significant deviation is observed over the predicted standard model background.
- Observed (expected) upper limits are set on the branching fractions of top quark decays.
- Limits obtained by combining two signal regions

Combined	Obs. limit	Exp. limit	$\pm 1\sigma$ (exp. limit)
$\kappa_{tu\gamma}$	6.2×10^{-3}	6.9×10^{-3}	$(5.9 - 8.4) \times 10^{-3}$
$\kappa_{tc\gamma}$	7.7×10^{-3}	7.8×10^{-3}	$(6.7 - 9.7) \times 10^{-3}$
$\mathcal{B}(t \to u + \gamma)$	0.95×10^{-5}	1.20×10^{-5}	$(0.89 - 1.78) \times 10^{-5}$
$\mathcal{B}(t \to c + \gamma)$	1.51×10^{-5}	1.54×10^{-5}	$(1.13 - 2.37) \times 10^{-5}$

★ Best limits

Summary of FCNC involving top quark results at LHC

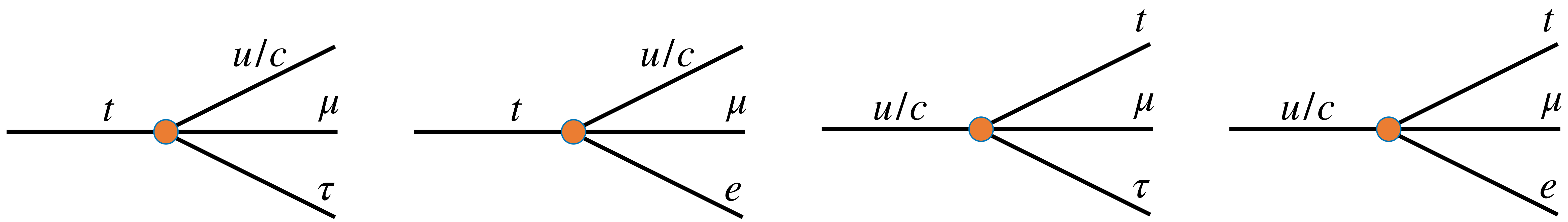
- Couplings: tqH, tqγ, tqZ, tqg (q = up or charm)
  - Results with Luminosity 138–139 fb^{-1} are presented
  - Only left-handed interactions are quoted
  - All observed limits approach the order of 10^{-4}–10^{-5}

Covered in this talk

Process	SM	ATLAS	CMS	ATLAS ref.	CMS ref.
t -> uH	2×10^{-17}	6.9×10^{-4} ($\tau\tau$) 7.7×10^{-4} (bb)	1.9×10^{-4} ($\gamma\gamma$) 7.9×10^{-4} (bb)	JHEP 06 (2023) 155 ($\tau\tau$) JHEP 07 (2023) 199 (bb)	Phys. Rev. Lett. 129 (2022) 032001 ($\gamma\gamma$) JHEP 02 (2022) 169 (bb)
t -> cH	3×10^{-15}	9.4×10^{-4} ($\tau\tau$) 12×10^{-4} (bb)	7.3×10^{-4} ($\gamma\gamma$) 9.4×10^{-4} (bb)		
t -> uZ	8×10^{-17}	6.2×10^{-5}	2.4×10^{-4} (36 fb^{-1})	Phys. Rev. D 108 (2023) 032019	CMS PAS-TOP-17-017
t -> cZ	1×10^{-14}	13×10^{-5}	4.5×10^{-4} (36 fb^{-1})		
t -> uγ	3.7×10^{-16}	0.85×10^{-5}	0.95×10^{-5}	Phys. Lett. B 842 (2023) 137379	CMS PAS-TOP-21-013
t -> cγ	4.6×10^{-14}	4.2×10^{-5}	1.51×10^{-5}		
t -> ug	3.7×10^{-14}	0.61×10^{-4}	0.2×10^{-4} (7+8 TeV)	Eur. Phys. J. C 82 (2022) 334	JHEP 02 (2017) 028
t -> cg	4.6×10^{-12}	3.7×10^{-4}	4.1×10^{-4} (7+8 TeV)		

- Table is taken from Jiwon Park's presentation

cLFV in top quark sector



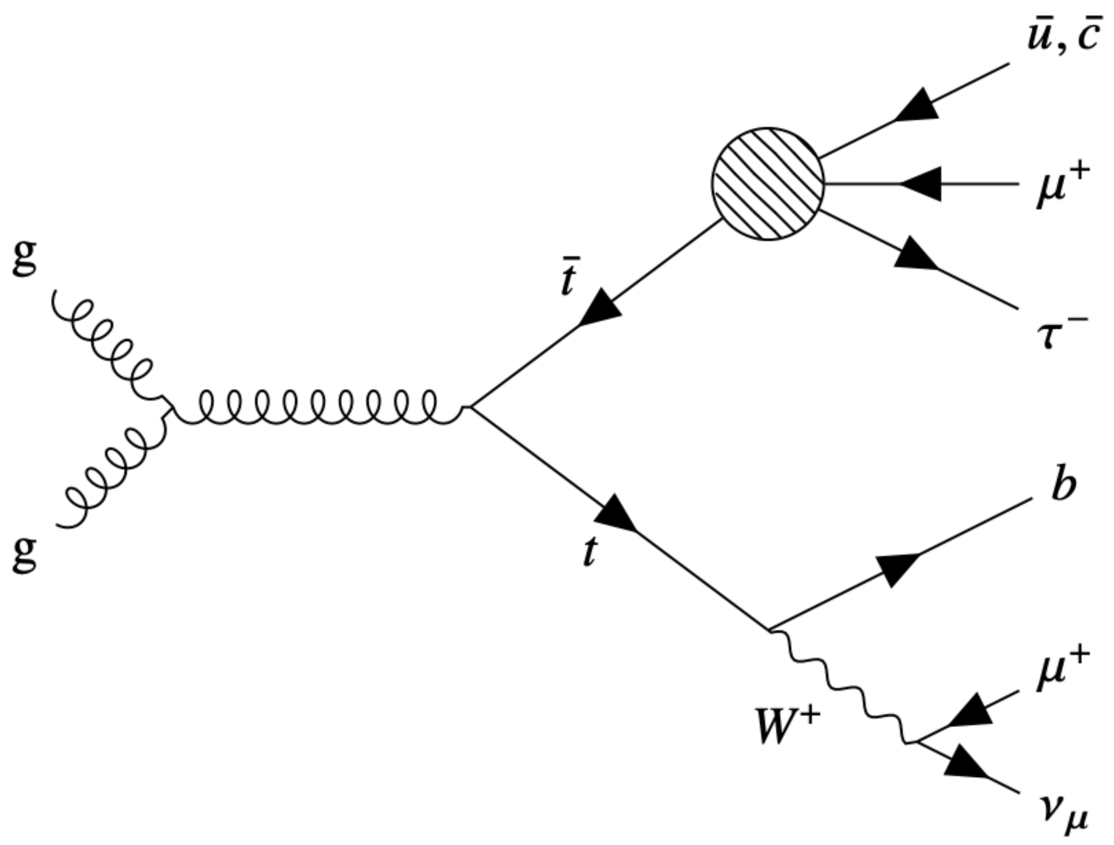
- Observation of Neutrino oscillations -> neutrino mass & neutral lepton flavour violation.
- The neutrino mass terms predict charged lepton flavour violation
- Branching fractions in SM ~ 10^{-55}, extended SM ~ 10^{-6}
- Any excess is a hint for Beyond the SM

Lepton flavor non-universality in B Physics [link]

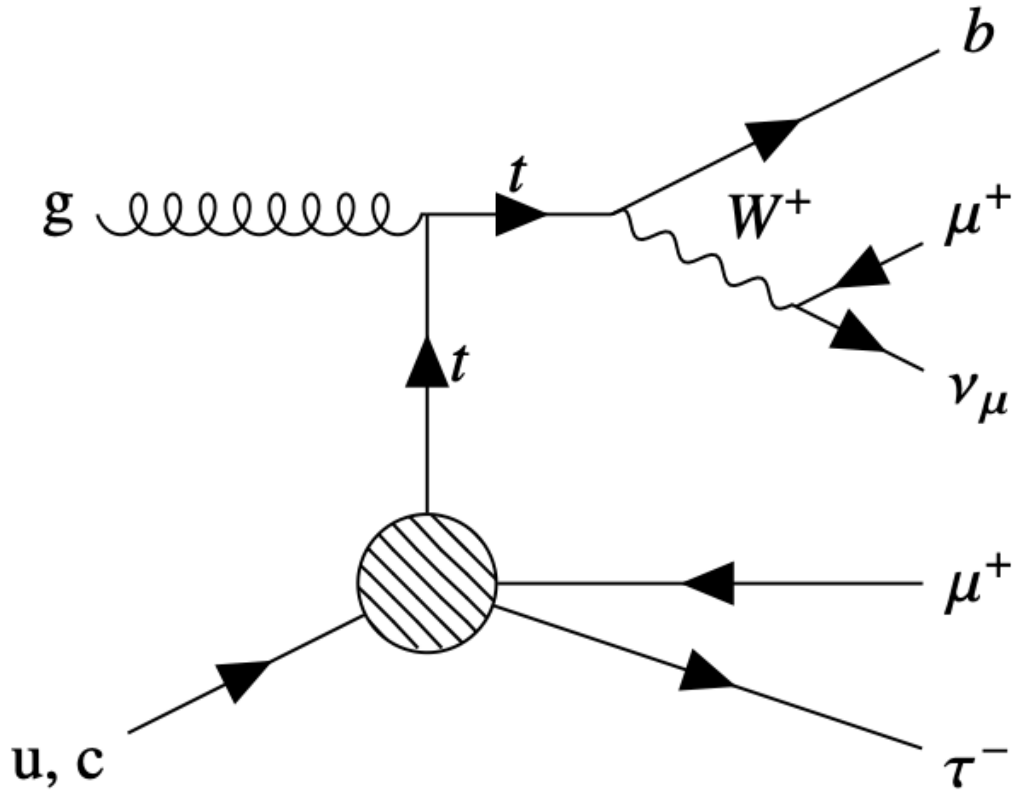
Interpretations of some flavor anomalies also predict a reachable CLFV rate in the top quark sector [link]

Search for cLFV: tq$\mu\tau$

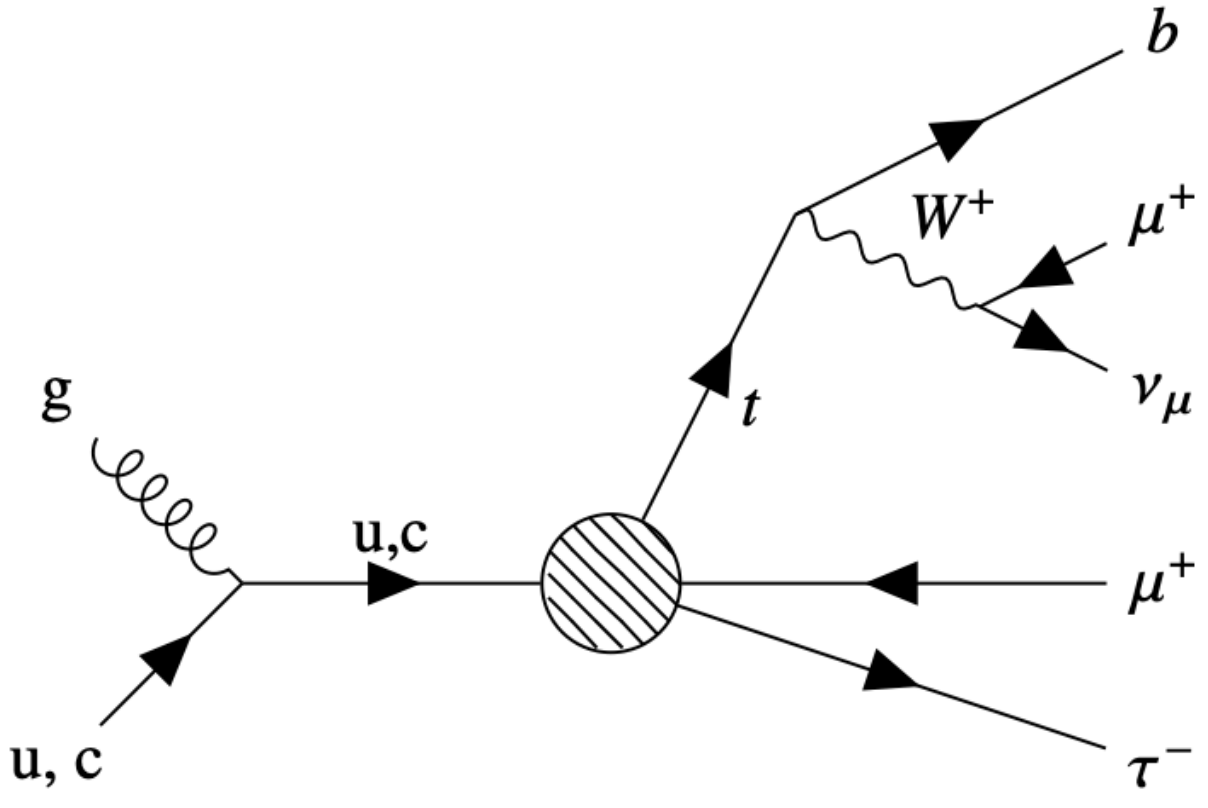
ATLAS-CONF-2023-001
L=139 fb^{-1}



top-quark pair production with a cLFV top-quark decay process



single-top-quark production with a cLFV process in the t-channel



single-top-quark production with a cLFV process in the s-channel

Operator	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
$^\ddagger O_{lequ}^{1(ijkl)}$	$(\bar{l}_i e_j)\varepsilon(\bar{q}_k u_l)$	Scalar
$^\ddagger O_{lequ}^{3(ijkl)}$	$(\bar{l}_i\sigma^{\mu\nu} e_j)\varepsilon(\bar{q}_k\sigma_{\mu\nu} u_l)$	Tensor

SR1

SS muons, 1 hadronic τ

exactly 1 b-jet

$>$ **1 jet**

SR2

SS muons, 1 hadronic τ

exactly 1 b-jet

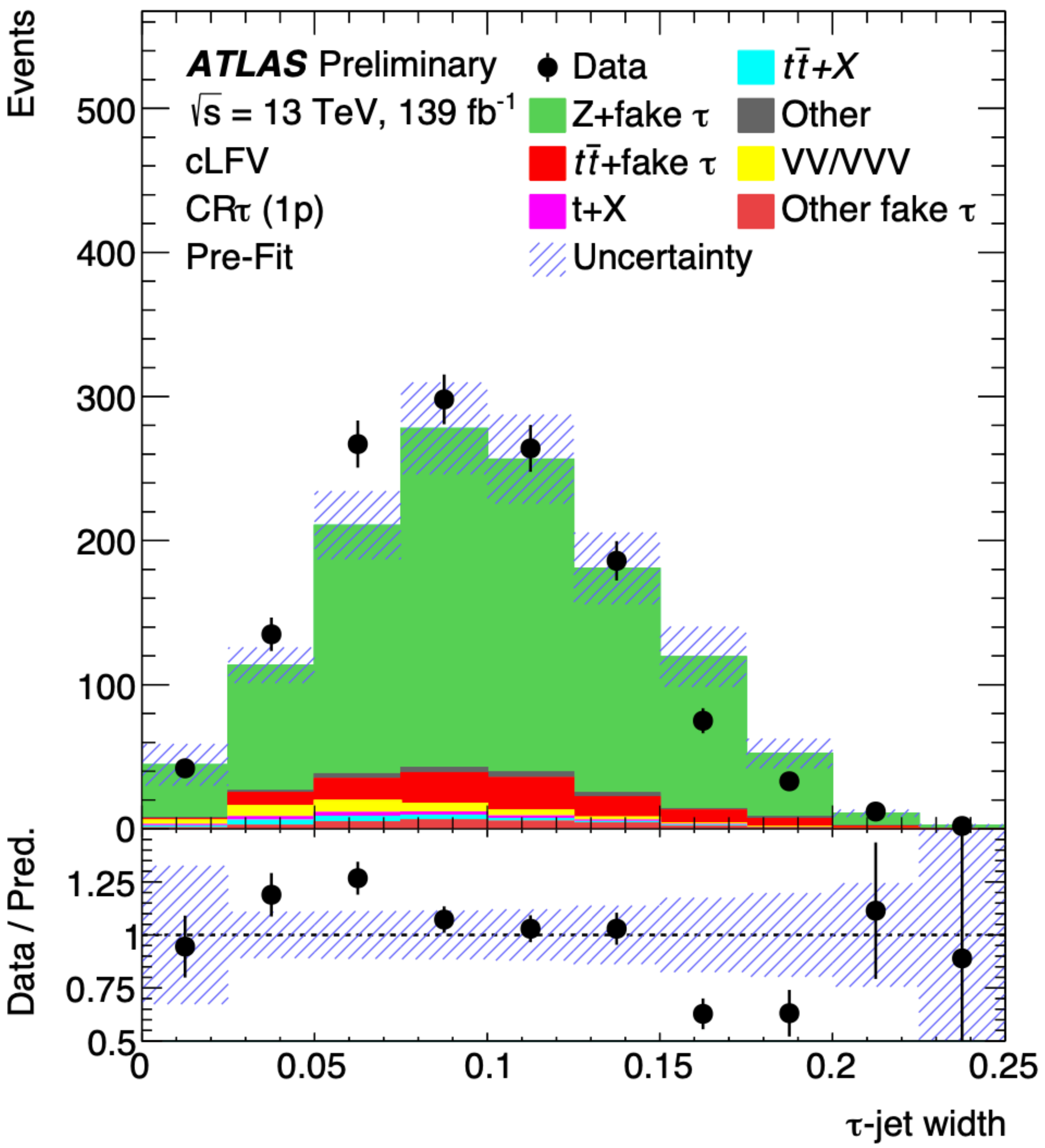
$=$ **1 jet**

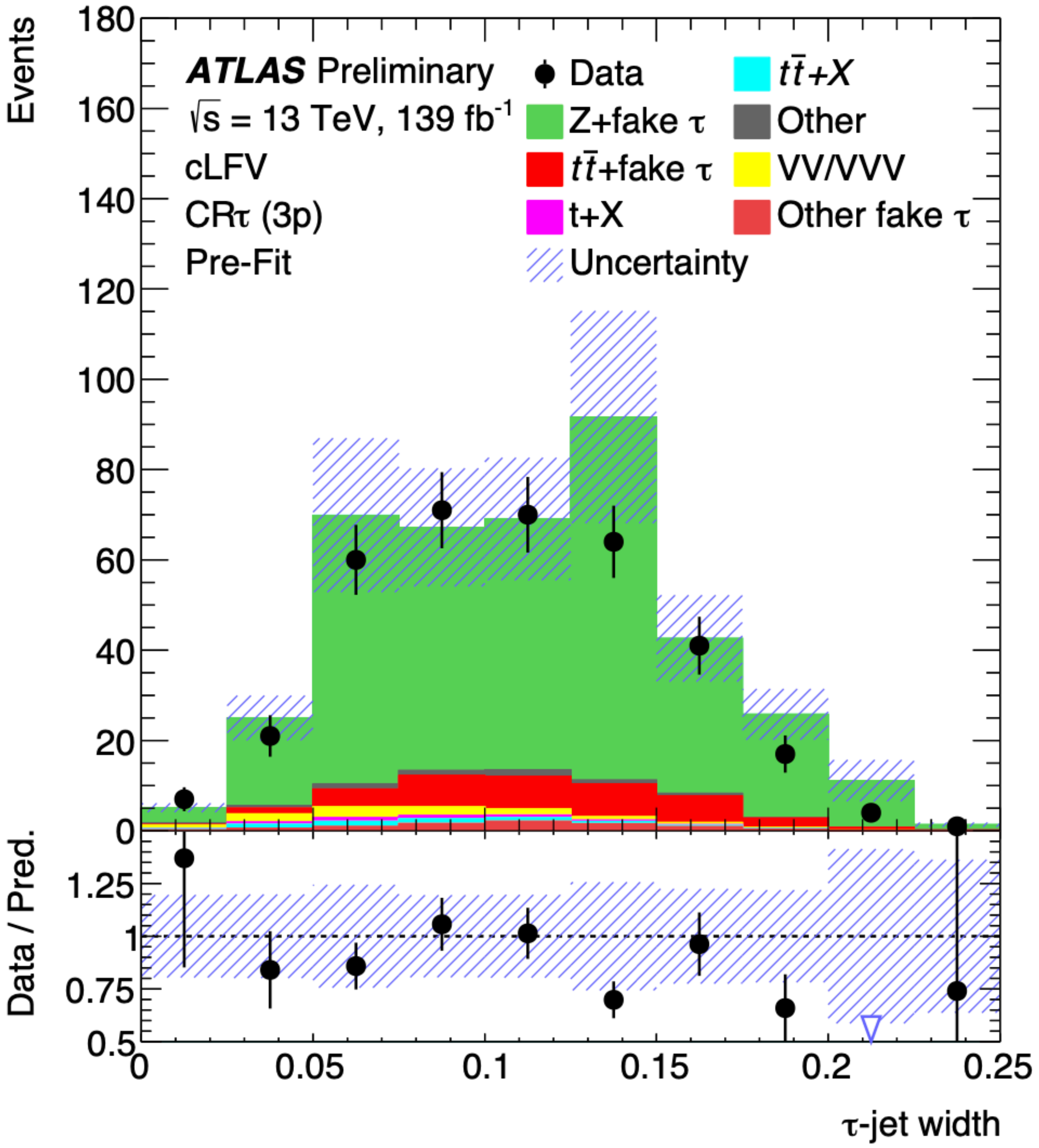
Search for cLFV: tq$\mu\tau$

ATLAS-CONF-2023-001
L=139 fb^{-1}

Data based background estimation

- Measured SF of fake tau events in CRτ (OS muon)
- Non-prompt muon contribution estimated by the fit in CRttμ ($e\mu\mu$)



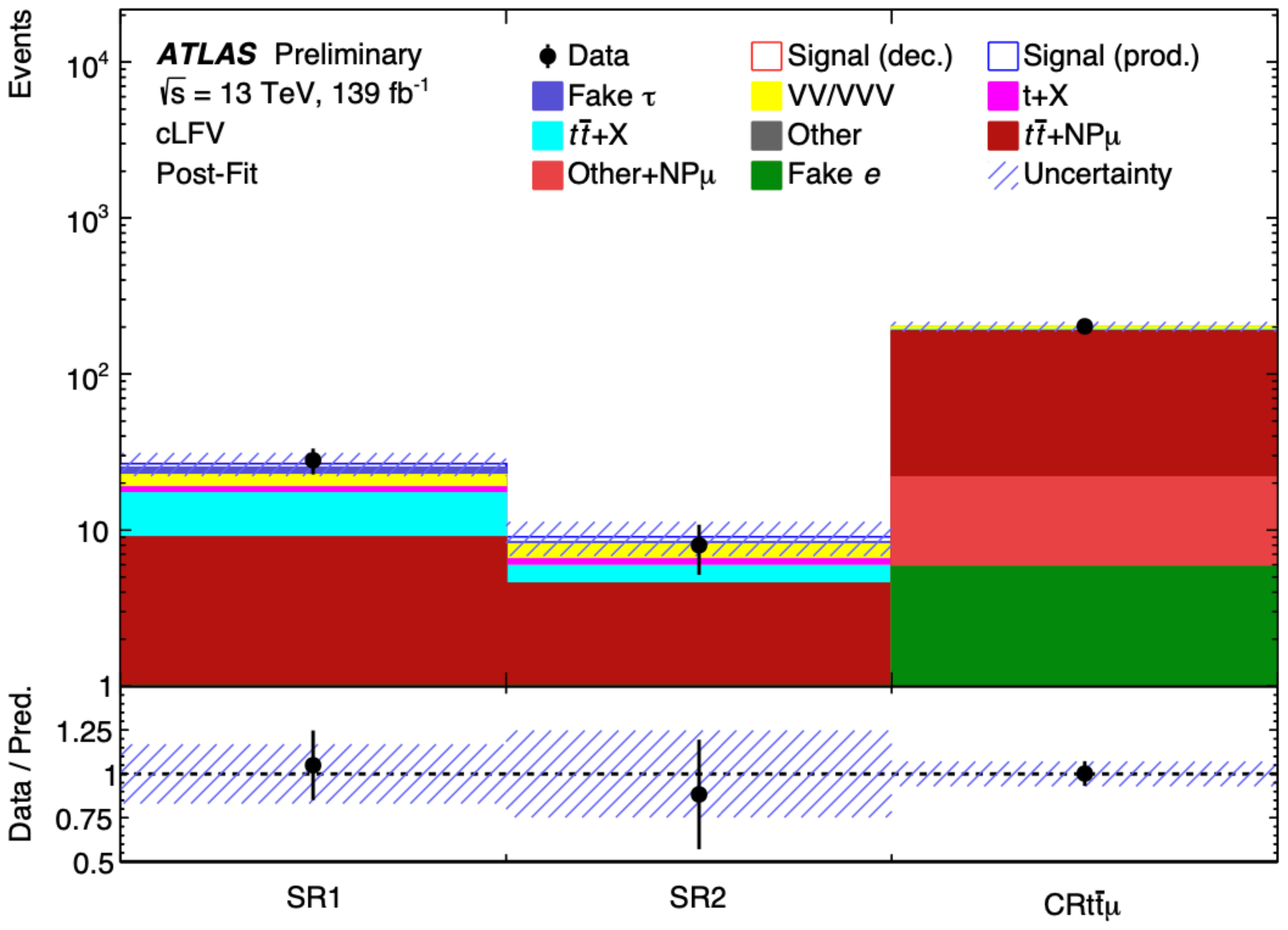


	CRτ	CR$tt\mu$
Lepton flavour		$2\mu 1e$ ($\ell_3 = \mu$)
N_{jets}	≥ 2	≥ 2
$N_{b-\text{tags}}$	1	≤ 2
Muon p_T cut	> 15 GeV	> 10 GeV
Lowest p_T muon selection	*Tight*	*Loose*
Muon charges	OS	-
$\lvert m_{\mu\mu}^{OS} - M_Z \rvert$	<10 GeV	>10 GeV

Search for cLFV: $\mu\tau$tq

ATLAS-CONF-2023-001
L=139 fb^{-1}

ATLAS EXPERIMENT



	95% CL upper limits on BR$(t \to \mu\tau q)$ $(\times 10^{-7})$							
	$c_{lq}^{-(ijk3)}$	$c_{eq}^{(ijk3)}$	$c_{lu}^{(ijk3)}$	$c_{eu}^{(ijk3)}$	$c_{lequ}^{1(ijk3)}$	$c_{lequ}^{1(ij3k)}$	$c_{lequ}^{3(ijk3)}$	$c_{lequ}^{3(ij3k)}$
Expected (u)	4.6	4.2	4.0	4.5	2.5	2.5	5.8	5.8
Observed (u)	5.1	4.6	4.4	5.0	2.8	2.8	6.4	6.4
Expected (c)	54	51	51	52	35	35	61	61
Observed (c)	60	56	56	57	38	38	68	68

	95% CL upper limits on BR$(t \to \mu\tau q)$	
	Stat. only	**All systematics**
Expected	8×10^{-7}	10×10^{-7}
Observed	9×10^{-7}	11×10^{-7}

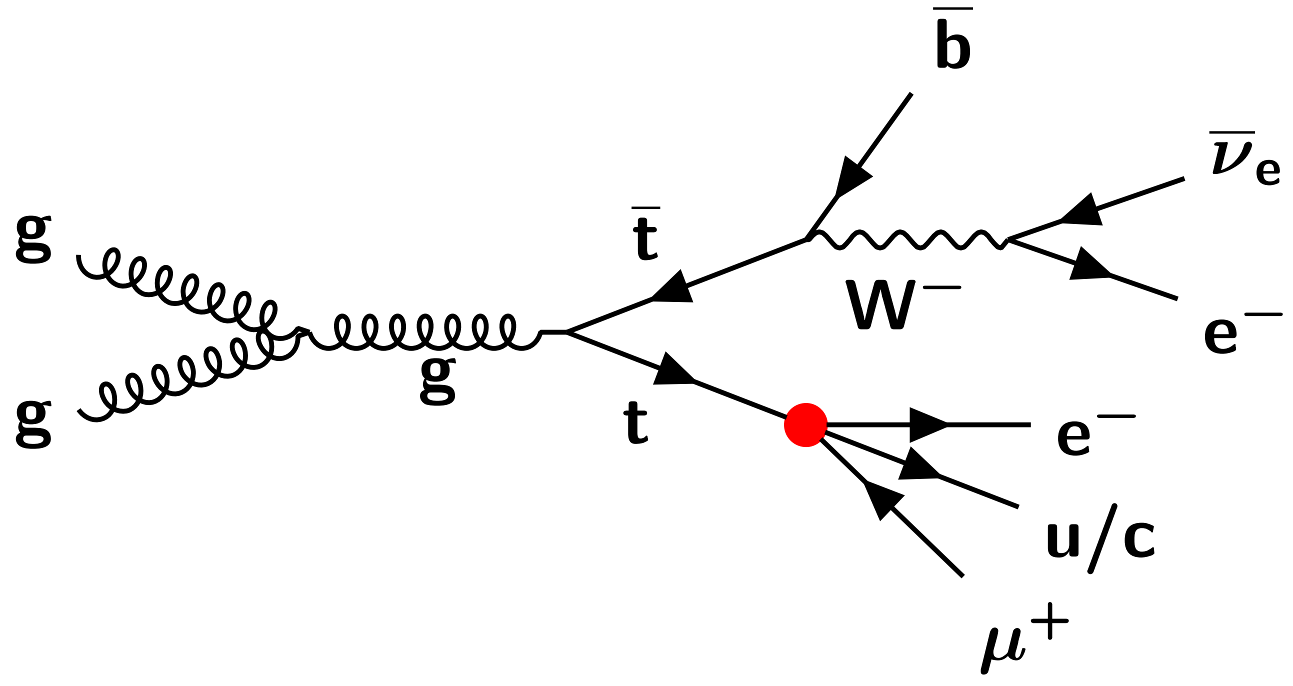
Observed event yields in SRs and CR$t\bar{t}\mu$ are compared to post-fit expectations from Monte Carlo simulations.

No evidence for a signal is found and tight limits on Wilson coefficients were achieved. The Wilson coefficient limits are translated into an observed upper limit on the $t \to \mu\tau q$ decay branching ratio, which is set at the 95% confidence level:

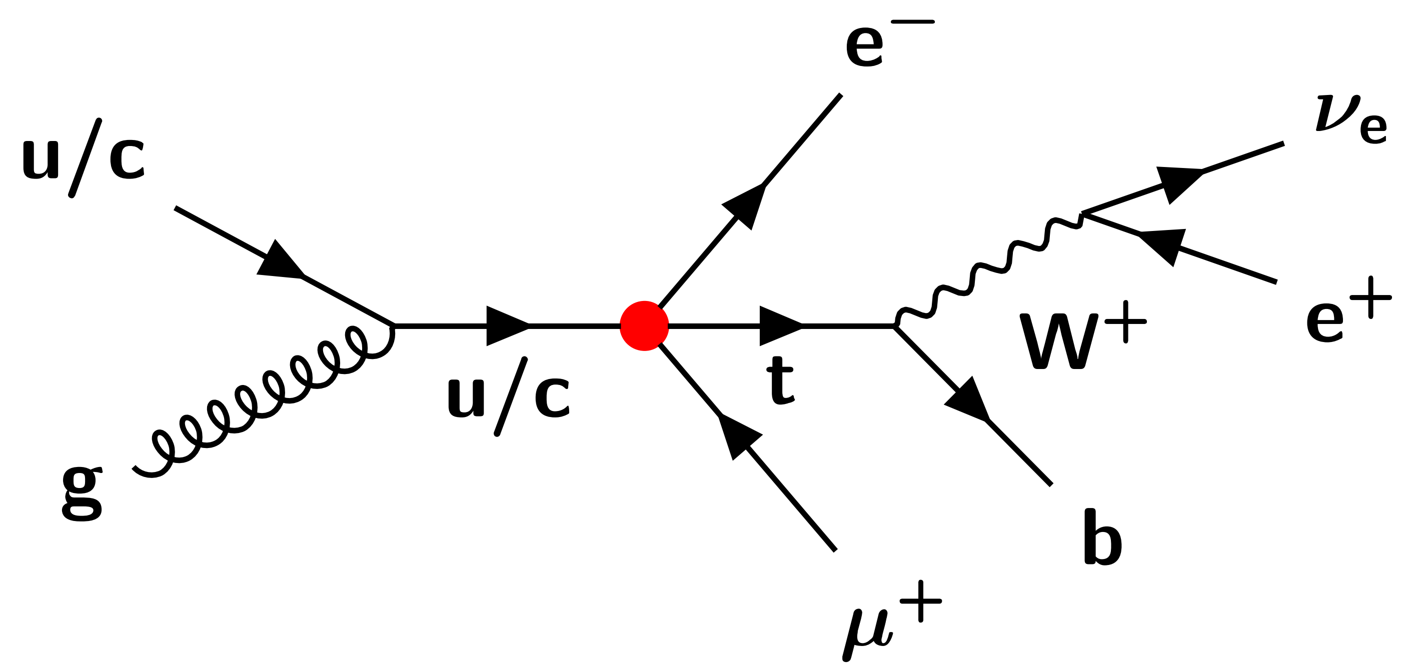
$$\text{BR}(t \to \mu\tau q) < 11\times10^{-7}$$

Search for cLFV: $e\mu$tq

CMS TOP-22-005
L=138 fb^{-1}



Decay



Production

Model-independent, effective field theory (EFT) approach

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}}^{(4)} + \frac{1}{\Lambda^2}\sum_a C_a^{(6)} Q_a^{(6)} + O\left(\frac{1}{\Lambda^4}\right)$$

Lorentz structure	Operator
vector	$O_{\mathrm{lq}}^{(1)ijkl} = (\bar{\mathrm{l}}_i\gamma^\mu \mathrm{l}_j)(\bar{\mathrm{q}}_k\gamma^\mu \mathrm{q}_l)$
	$O_{\mathrm{lu}}^{ijkl} = (\bar{\mathrm{l}}_i\gamma^\mu \mathrm{l}_j)(\bar{\mathrm{u}}_k\gamma^\mu \mathrm{u}_l)$
	$O_{\mathrm{eq}}^{ijkl} = (\bar{\mathrm{e}}_i\gamma^\mu \mathrm{e}_j)(\bar{\mathrm{q}}_k\gamma^\mu \mathrm{q}_l)$
	$O_{\mathrm{eu}}^{ijkl} = (\bar{\mathrm{e}}_i\gamma^\mu \mathrm{e}_j)(\bar{\mathrm{u}}_k\gamma^\mu \mathrm{u}_l)$
scalar	$O_{\mathrm{lequ}}^{(1)ijkl} = (\bar{\mathrm{l}}_i \mathrm{e}_j)\ \varepsilon\ (\bar{\mathrm{q}}_k u_l)$
tensor	$O_{\mathrm{lequ}}^{(3)ijkl} = (\bar{\mathrm{l}}_i\sigma^{\mu\nu} \mathrm{e}_j)\ \varepsilon\ (\bar{\mathrm{q}}_k\sigma_{\mu\nu} \mathrm{u}_l)$

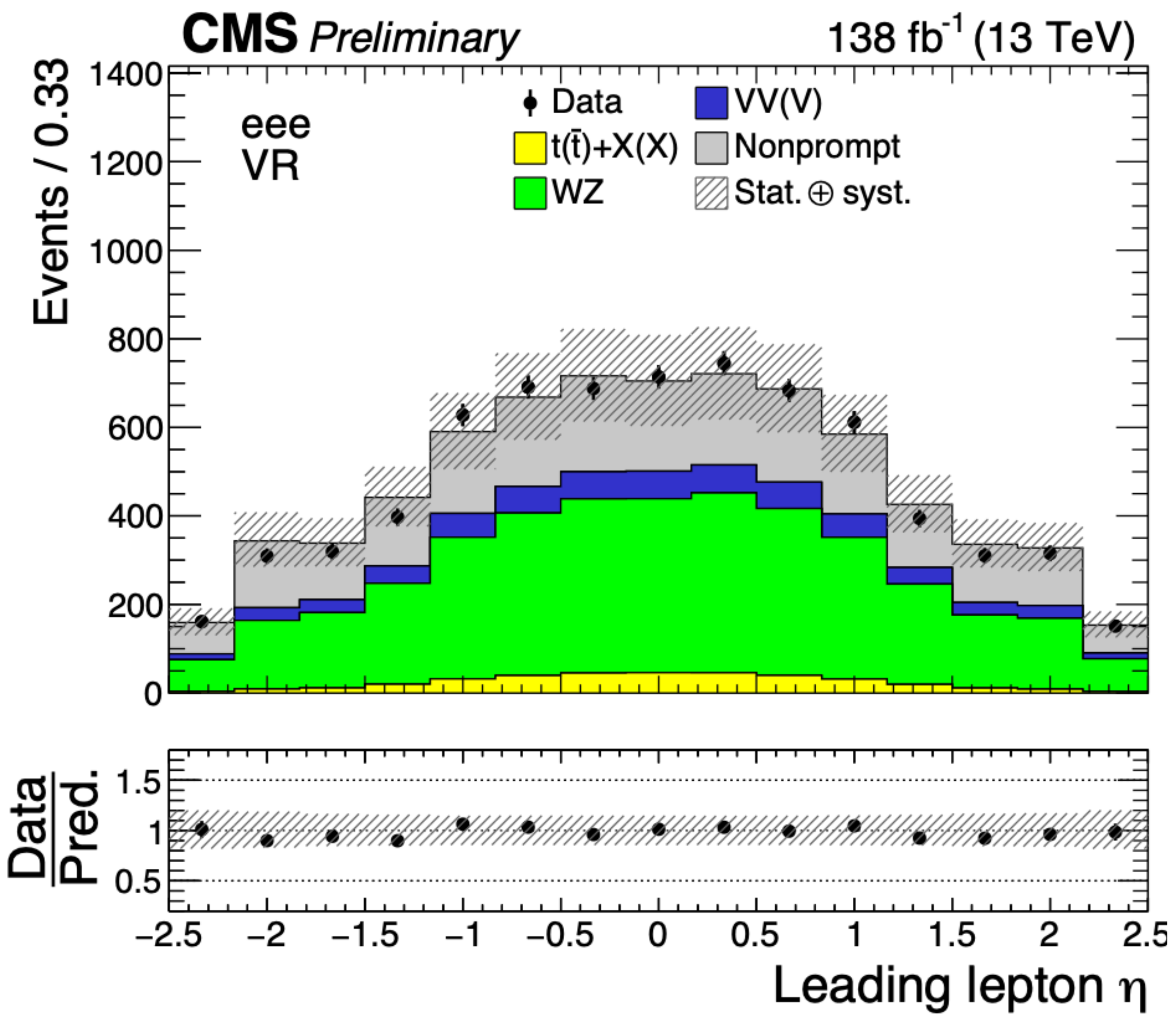
Analysis signature
Opposite-Charge eμ pair
Third lepton coming from leptonic top quark decay
One b-jet,
one/zero light jet (u/c)

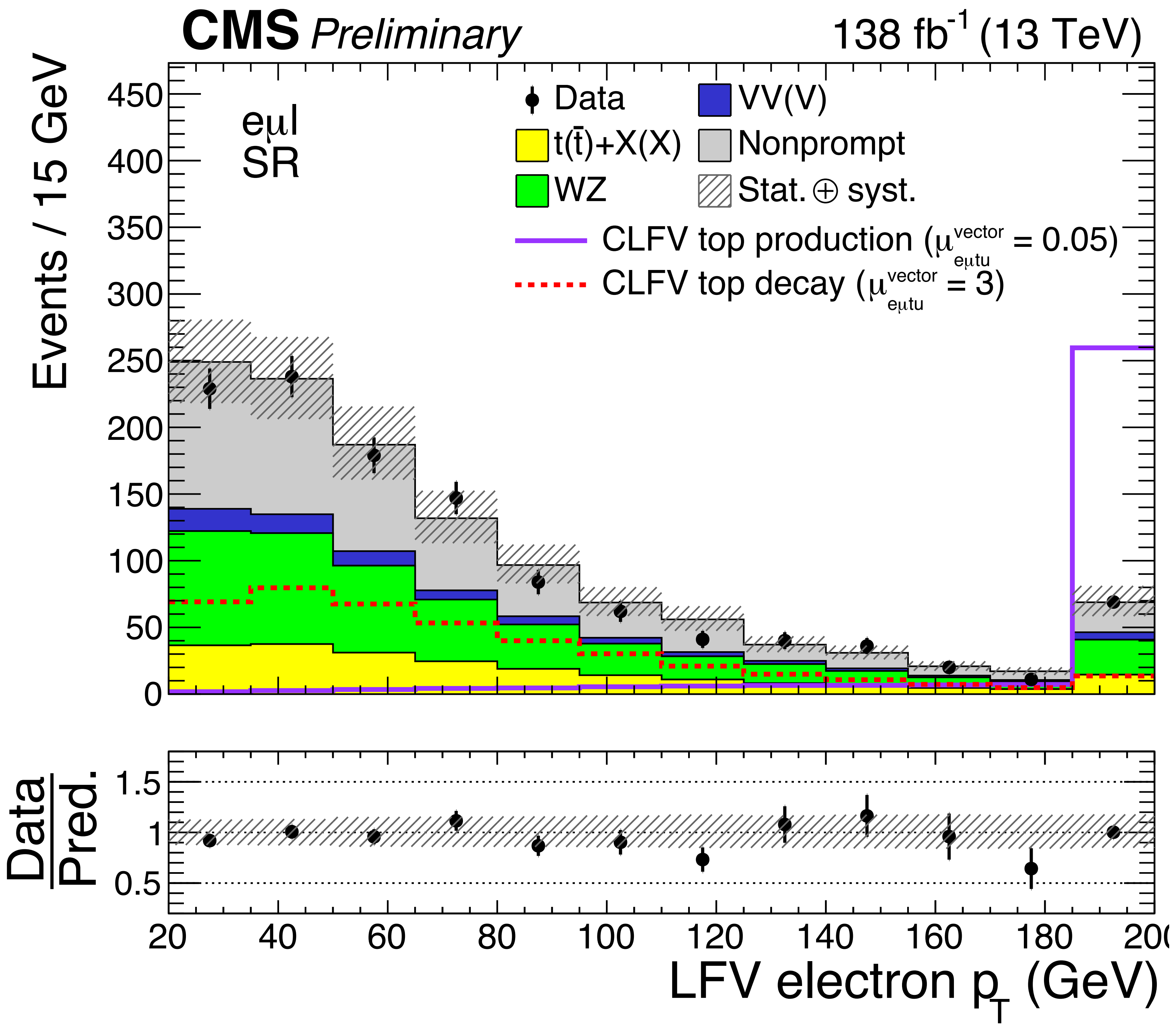
Search for cLFV: $e\mu$tq

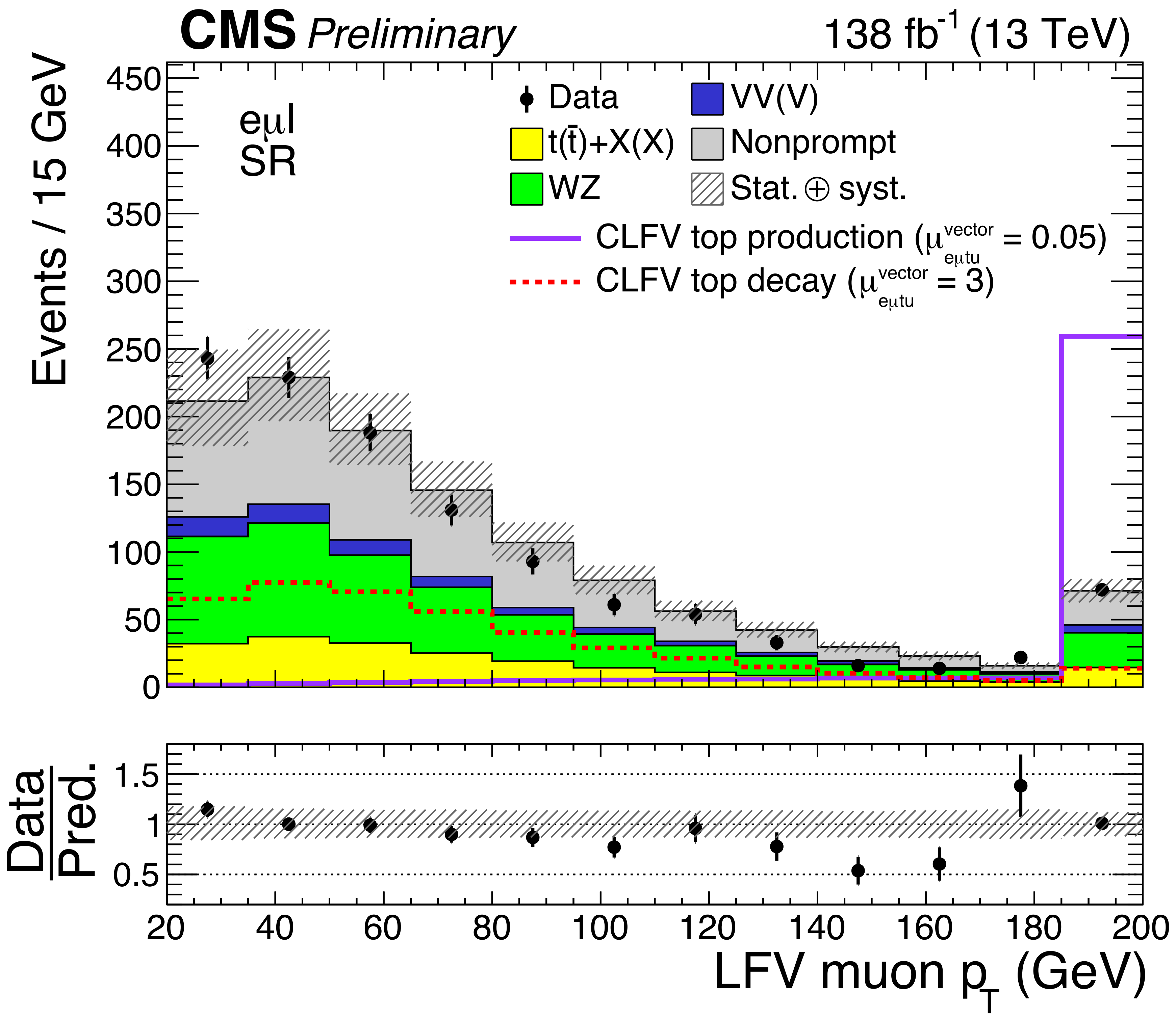
CMS TOP-22-005
L=138 fb^{-1}

Data based background estimation

- Prompt backgrounds rely on the simulation
- Nonprompt backgrounds estimated by data-driven “Matrix method”
- Estimated events are validated using control/validation regions







Search for cLFV: $e\mu$tq

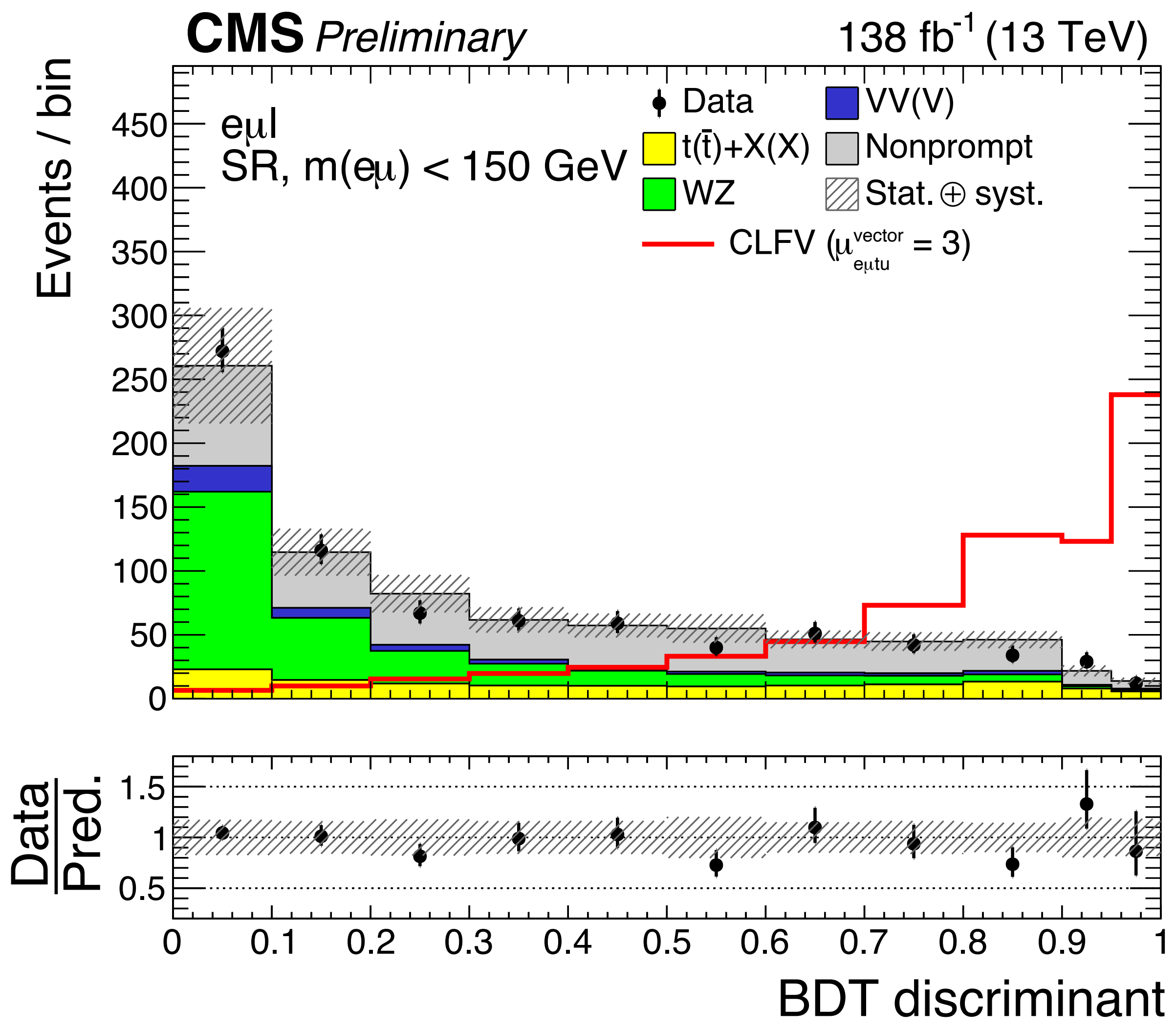
CMS TOP-22-005
L=138 fb^{-1}

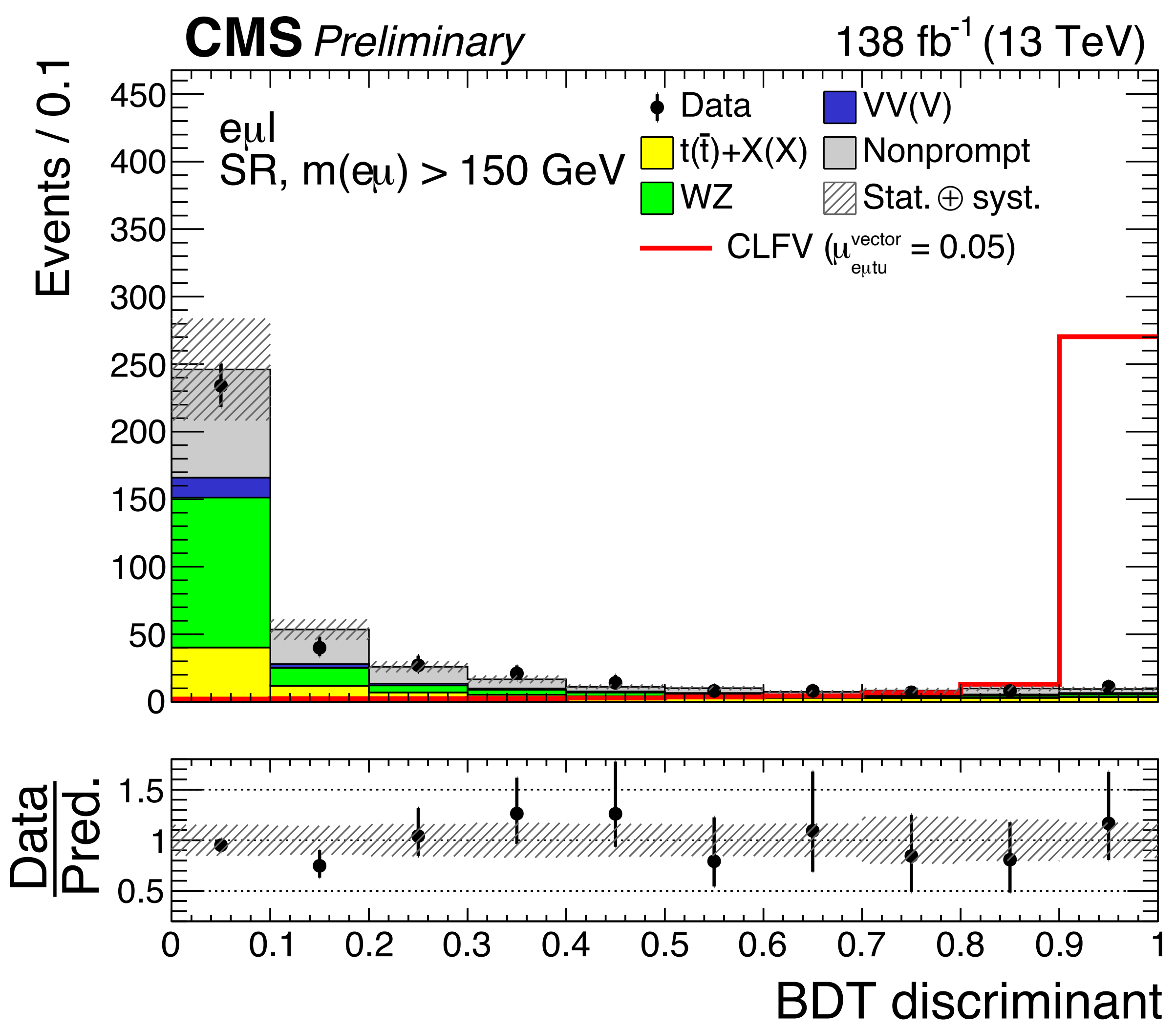
- The analysis utilizes boosted decision trees to separate background processes from a possible signal.
  - Separately trained for top decay (m($e\mu$) < 150 GeV) and production (m($e\mu$) > 150 GeV) enriched regions

The data are found to be consistent with the standard model expectation.

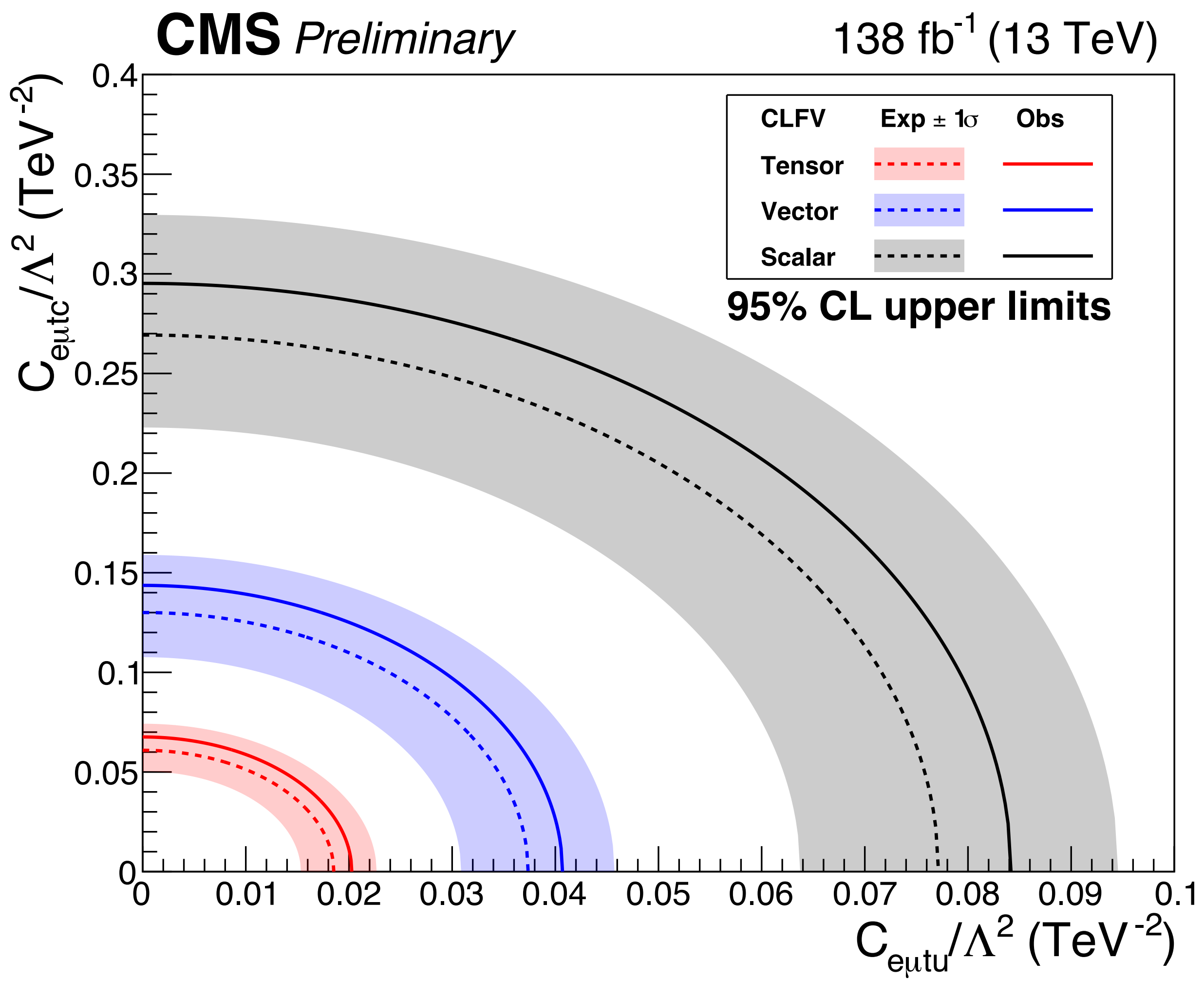
The one-dimensional limits

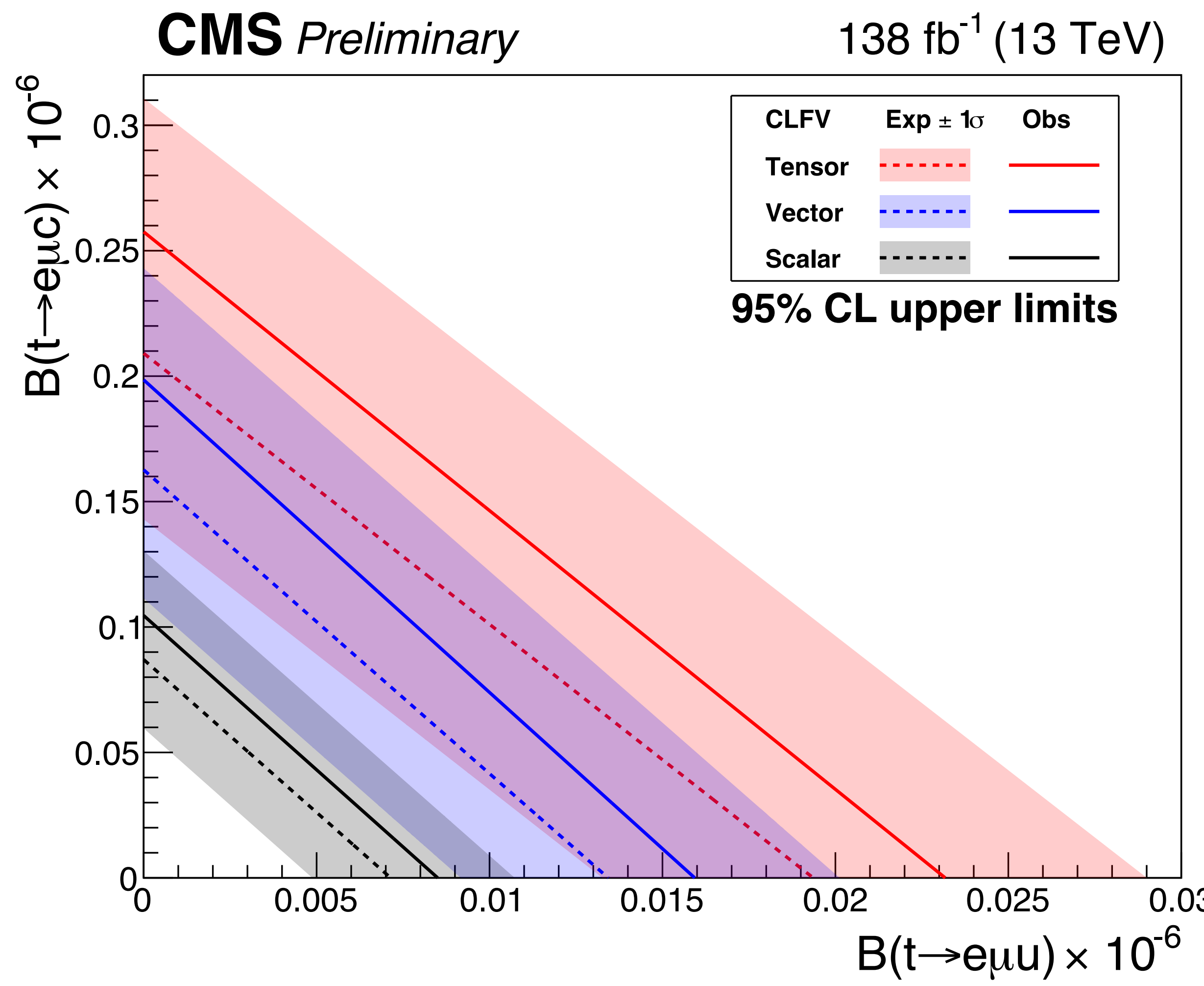
CLFV coupling	Lorentz structure	$C_{e\mu tq}/\Lambda^2$ (TeV^{-2}) Exp (68% range)	Obs	$\mathcal{B}(t \to e\mu q) \times 10^{-6}$ Exp (68% range)	Obs
$e\mu tu$	tensor	0.019 (0.015–0.023)	**0.020**	0.019 (0.013–0.029)	**0.023**
	vector	0.037 (0.031–0.046)	**0.041**	0.013 (0.009–0.020)	**0.016**
	scalar	0.077 (0.064–0.095)	**0.084**	0.007 (0.005–0.011)	**0.009**
$e\mu tc$	tensor	0.061 (0.050–0.074)	**0.068**	0.209 (0.143–0.311)	**0.258**
	vector	0.130 (0.108–0.159)	**0.144**	0.163 (0.111–0.243)	**0.199**
	scalar	0.269 (0.223–0.330)	**0.295**	0.087 (0.060–0.130)	**0.105**





The two-dimensional limits





Conclusion

LHC as a top quark factory provides excellent opportunity to search for rare top quark decays.

We searched for FCNC and cLFV, so far the results are in agreement with SM.

ATLAS and CMS collaborations continue analysing events with top quark production and decays.

There are still channels to be checked.

Stay tuned for up coming analysis !