UNIVERSITY OF BIRMINGHAM

ATLAS EXPERIMENT

Search for charged Lepton Flavour Violation in Top quark decays: eμ channel

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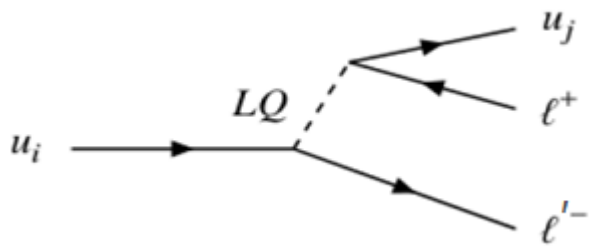
Theoretical motivation

- **Standard Model** (SM) of Particle Physics:
  - **Lepton family** (or flavour) is a conserved quantum number

Leptons	e ν_e	μ ν_μ	τ ν_τ
Lepton numbers	$L_e=1$ $L_{\mu,\tau}=0$	$L_\mu=1$ $L_{e,\tau}=0$	$L_\tau=1$ $L_{e,\mu}=0$

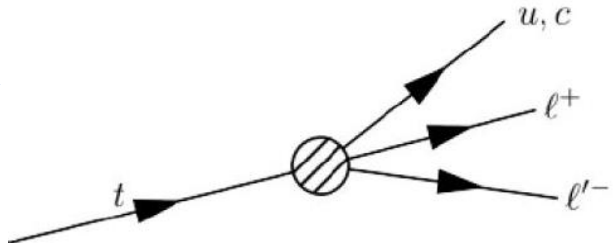
- **Charged Lepton Flavour Violation** (cLFV) predicted by many **Beyond Standard Model** (BSM) theories:
  - minimal extensions:
    - *Inclusion of neutrino masses*
    - *2 Higgs Doublet models* (2HDM)
  - *Grand Unified Theories* (GUTs)
  - *Supersymmetry* (SUSY)
  - *Seesaw Models*

prediction of leptoquarks (LQ)



- SM extension in *model-independent way* → **Effective Field Theory** (EFT):

$$\mathcal{L}^{eff} = \mathcal{L}_{SM}^{(4)} + \mathcal{L}^{(5)} + \mathcal{L}^{(6)} + \cdots = \mathcal{L}_{SM}^{(4)} + \frac{1}{\Lambda}\sum_k C_k^{(5)} O_k^{(5)} + \frac{1}{\Lambda^2}\sum_k C_k^{(6)} O_k^{(6)} + \cdots$$



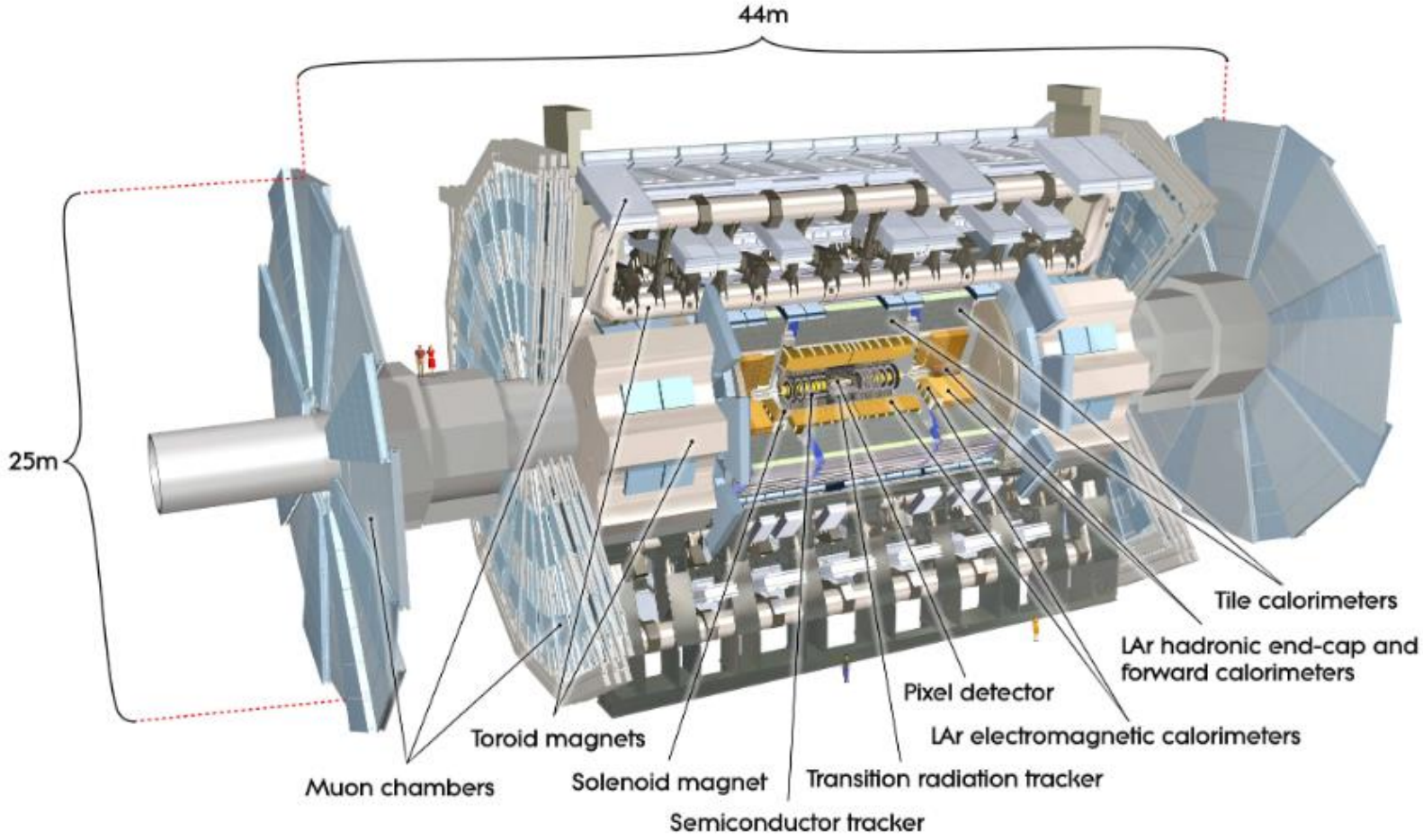
Λ : scale of New Physics. $O_k^{(n)}$: EFT operators, $C_k^{(n)}$: "Wilson" coefficients, of dimension n.

EFT operators must respect the SM gauge symmetries (*SU(3)×SU(2)×U(1)* invariance).

Seven dim-6 operators (depending on the operator basis used) involving 2q2l exist and are relevant to our analysis.

References: Grzadkowski , Calibbi , Teixeira , Vicente , Davidson

ATLAS Detector overview



Placed around one of CERN's Large Hadron Collider (LHC) interaction points, **ATLAS detector** comprises several subsystems:

- **Inner Detector** (ID): semi-conducting silicon sensors to extract tracking information about charged particles, placed inside the magnetic field of a solenoid magnet.
- **Calorimeters**: combination of lead/Liquid Argon (LAr) and steel/tile scintillator technology to extract information about the energy of particles passing through.
- **Muon Spectrometer:** gaseous detectors placed inside the magnetic field of large toroidal magnets.

Signal, Data and Background

The *signal process* we are in search of consists of ***$t\bar{t}$* events**, with:

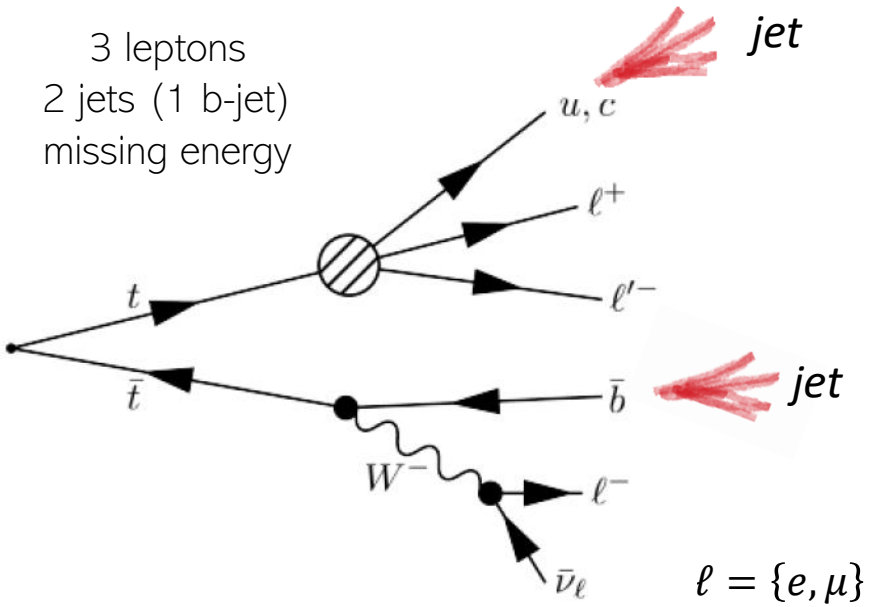
- one top decaying in the cLFV mode: $t \rightarrow \ell^{\pm}\ell'^{\mp}q$, $q = \{u, c\}$, $\ell = \{e, \mu\}$
- the second top decaying via SM: $\bar{t} \rightarrow W^{-}\bar{b}$, in the W leptonic decay mode

the conjugates being: $\bar{t} \rightarrow \ell^{\pm}\ell'^{\mp}\bar{q}$, $t \rightarrow W^{+}b$

We are using **data from proton-proton collisions**, at centre of mass energy $\sqrt{s} = 13\ TeV$, collected by the ATLAS detector during the LHC Run 2 period (2015-2018), corresponding to a total integrated luminosity $\int \mathcal{L}dt = 139\ fb^{-1}$.

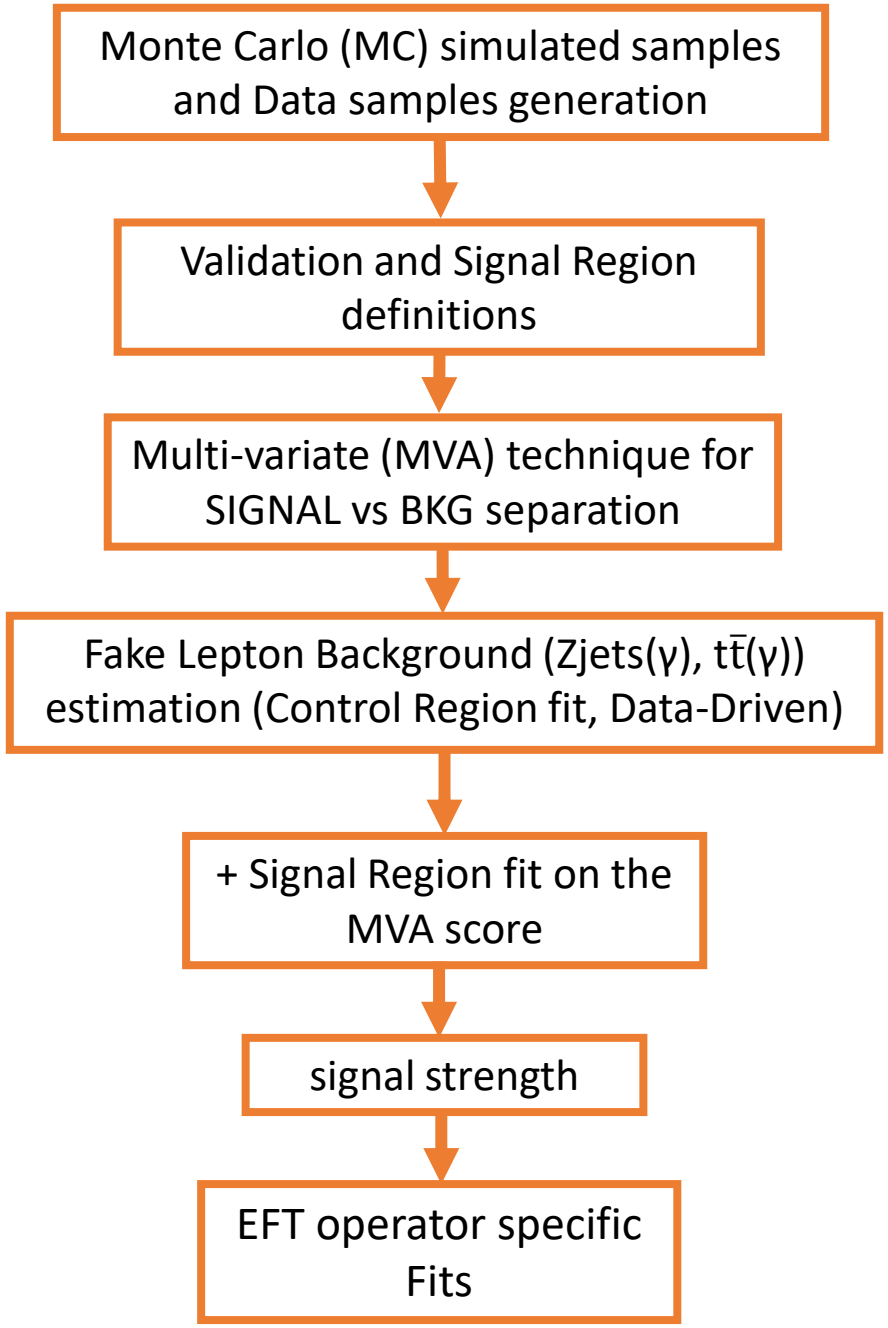
This analysis follows closely the previous study performed with 80 fb^{-1}, described in ATLAS-CONF-2018-044 .

Main Backgrounds are: (SM) $t\bar{t}$, $t\bar{t} + \gamma$, $Z + jets$, $Z + \gamma$,
$WZ\ (\rightarrow 3l\nu)$, $ZZ\ (\rightarrow 4l)$
with smaller contributions from : $t\bar{t}V, tV, t\bar{t}H$, VVV
(V: vector boson W or Z. H: SM Higgs)



*Quarks appear in the detector inside **jets** due to a Quantum Chromodynamics (QCD) property called confinement, which makes quarks appear in bound states (as hadrons).*
*A **b-jet** is a jet containing a b-hadron.*
***B-tagging** exploits the "secondary" decay of the b-hadron inside the jet.*
***Missing energy** is "carried" by the invisible neutrino.*

Analysis Overview



Event Selection – Regions Definition

Validation Regions (VRs):
Very low (<0.5%) signal contamination. Validation of background simulation and estimation via data-driven techniques.

Signal Region (SR): high signal acceptance, while retaining enough background acceptance for MVA method to be trained with high statistics.

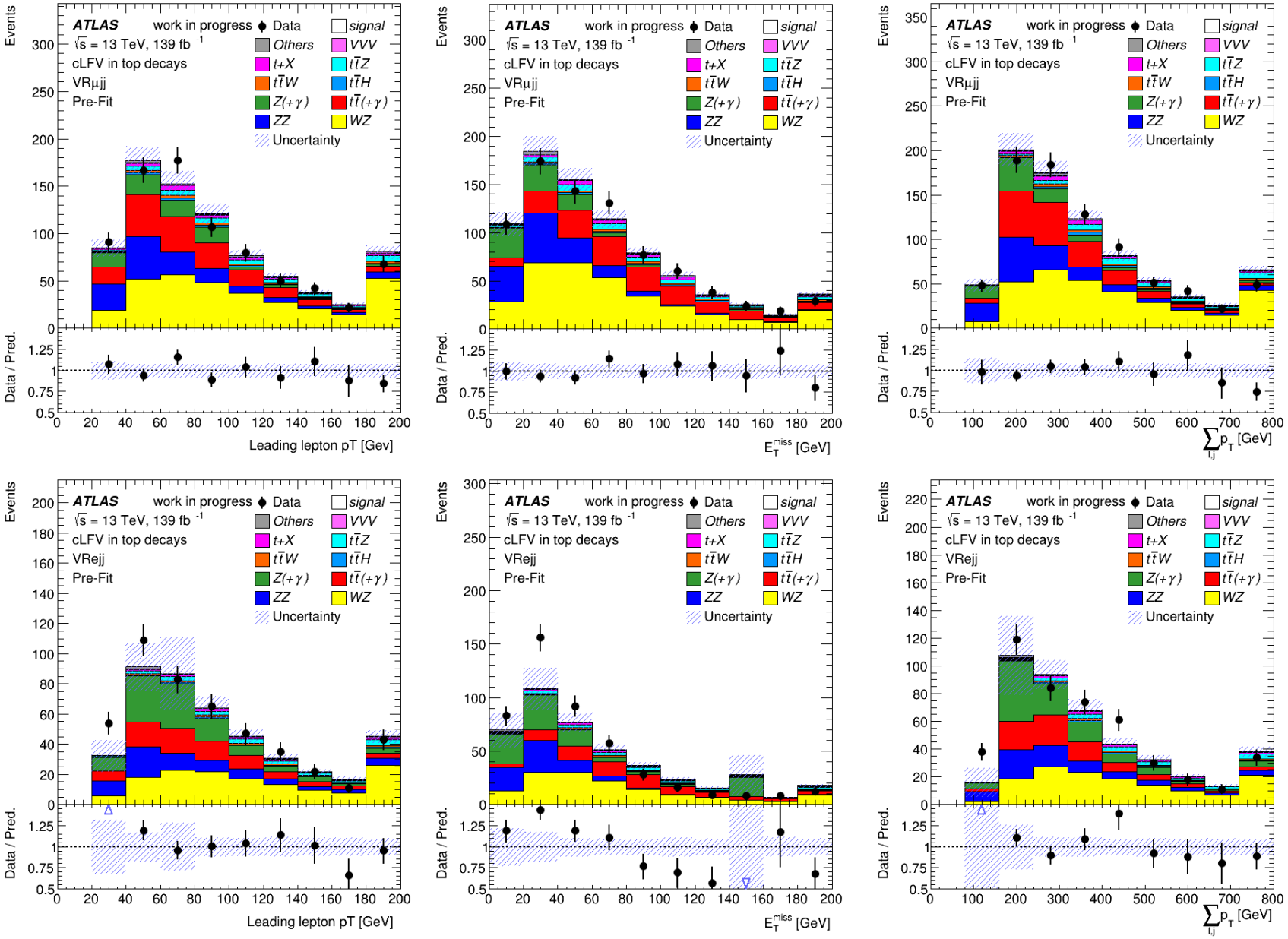
Description	Value
Preliminary cuts	
baseline lepton definition	$p_T > 10$ GeV, $\lvert\eta\rvert < 2.5$
baseline jet definition	$p_T > 25$ GeV, $\lvert\eta\rvert < 2.5$
number of leptons	$N_{lep} = 3$
number of jets	$N_{jets} \geq 2$
number of b-jets	$N_{bjets} \leq 1$
leading lepton p_T	$p_T > 27$ GeV
sum of leptons charge	$\Sigma q_i = \pm 1$
OSSF lepton pairs mass	any $m_{ll} > 15$ GeV
Z veto on OSSF pair with invariant mass closest to m_Z	20 GeV wide window
Signal Region additional cuts	
number of muons	$N_\mu \geq 1$
number of electrons	$N_e \geq 1$
VRμjj additional cuts	
number of muons	$N_\mu = 3$
VRejj additional cuts	
number of electrons	$N_e = 3$

quantities labelled with subscript T are called transverse: measured transversely to the proton beam axis

OSSF: Opposite Sign (OS) Same Flavour (SF)

"leading", "sub-leading" etc.: according to transverse momentum, p_T

Validation Region plots



Distribution of

- leading lepton p_T
- missing transverse energy
- scalar sum of p_T of all leptons and jets in the event

in the

- 3 muon VR (VRμjj), top row
- 3 electron VR (VRejj), bottom row

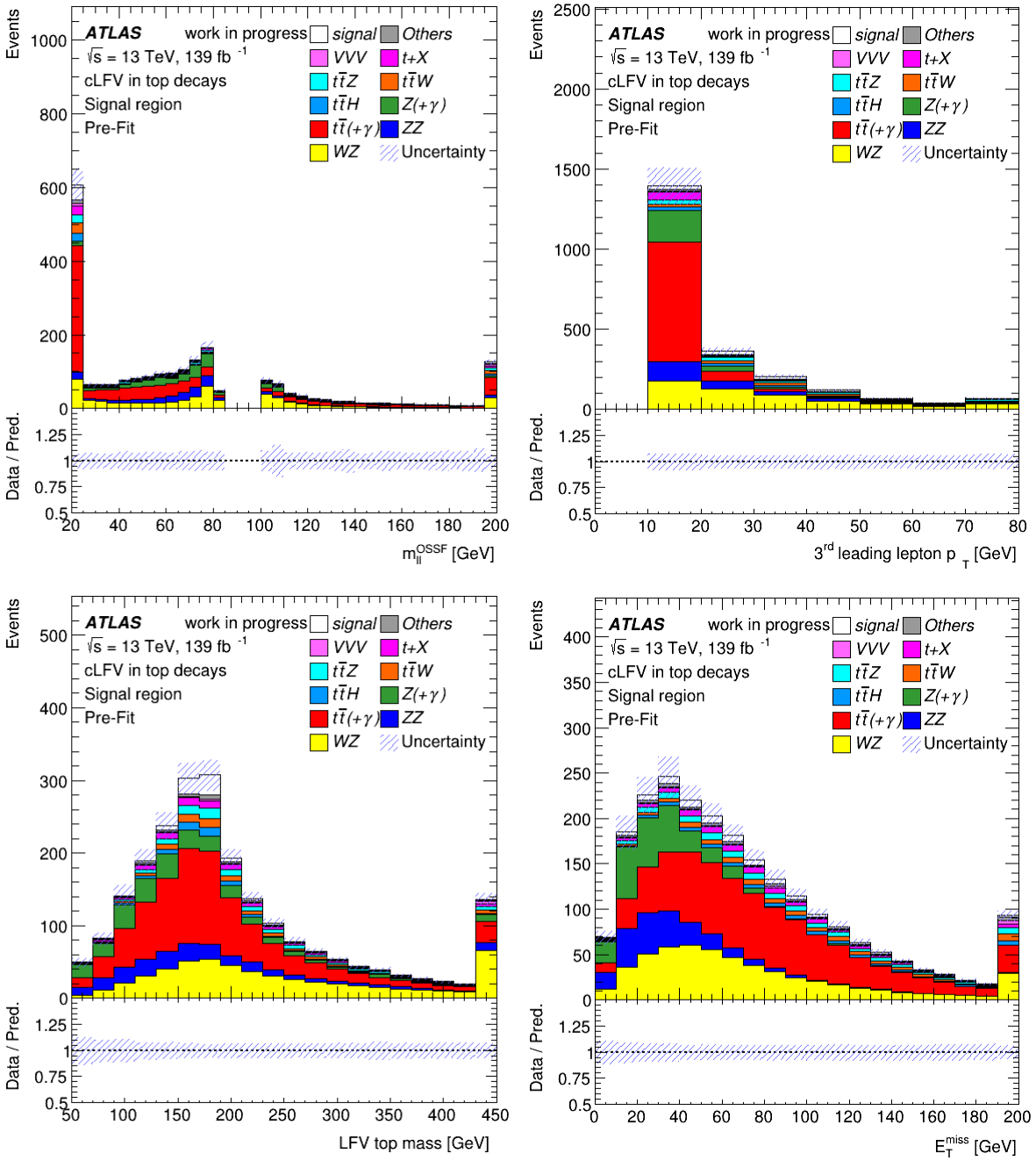
Data/MC agreement is better in the VRμjj.

Uncertainty includes:
MC statistical uncertainty +
a subset of instrumentation-related systematic uncertainties

Z(+γ) denotes the inclusive Z+jets and Z+γ sample

Multivariate Analysis

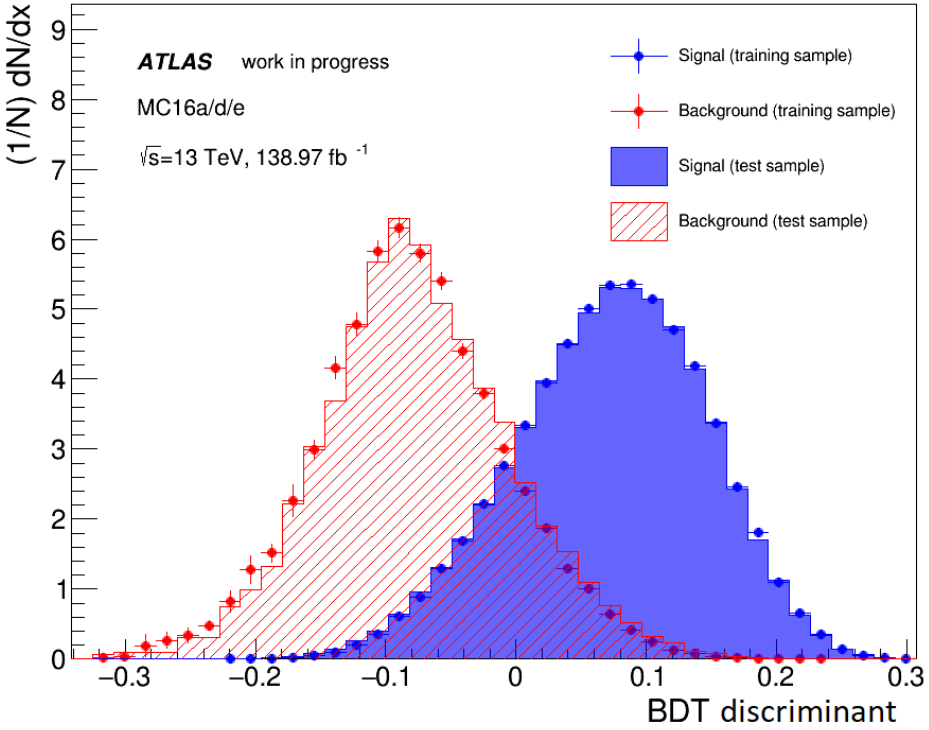
- **Boosted Decision Tree** (BDT) method for signal/background separation
- BDT trained with MC simulated samples, in the ***Signal Region***
- A set of 17 variables has been chosen as input, based on the discriminator performance. The 4 most discriminating variables:
  - OSSF lepton pair invariant mass
  - 3rd leading lepton transverse momentum
  - LFV top mass
  - missing transverse momentum
- ***Reconstruction*** of the top quarks provides us with the LFV top mass, and other useful variables.

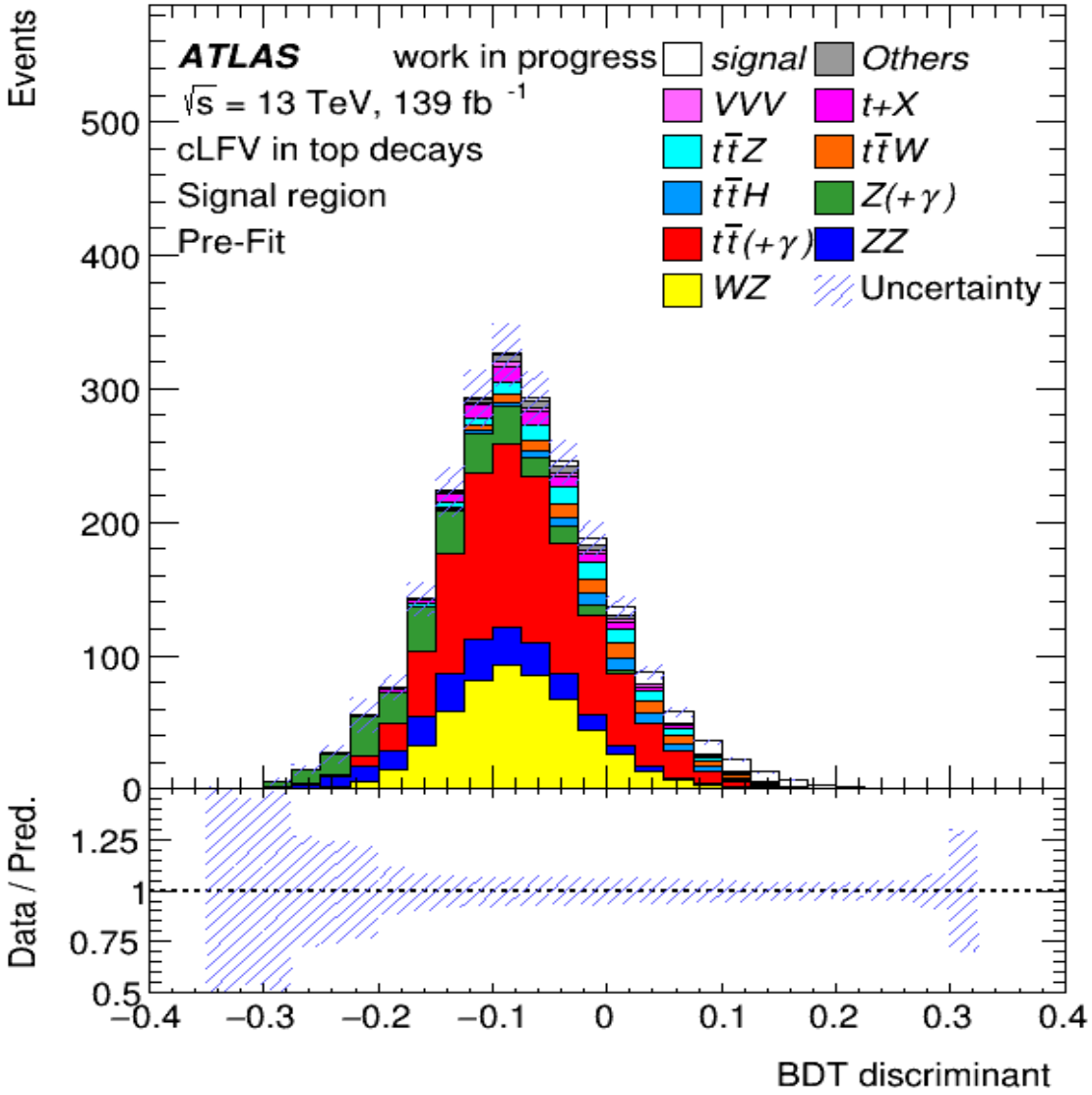


Multivariate Analysis (2)

Optimizing and testing the performance of the BDT for various configurations, leads to a signal vs background separation as shown in the plots.

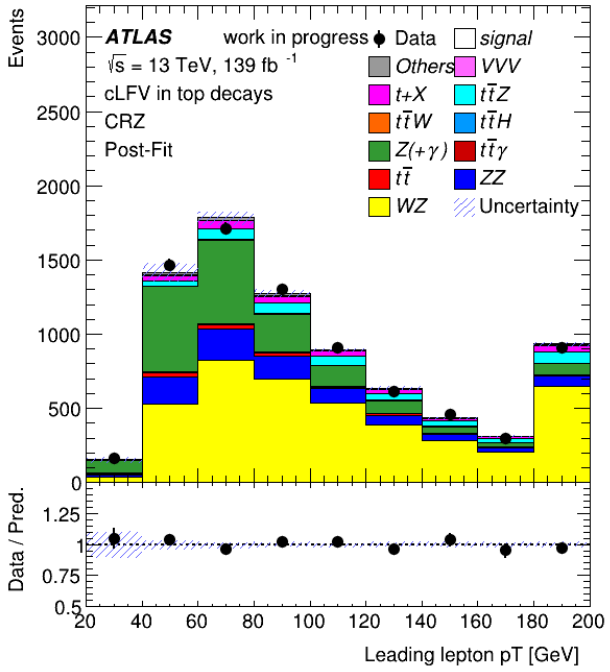
- Bottom plot: signal, bkg. distributions normalized to the total event yield.

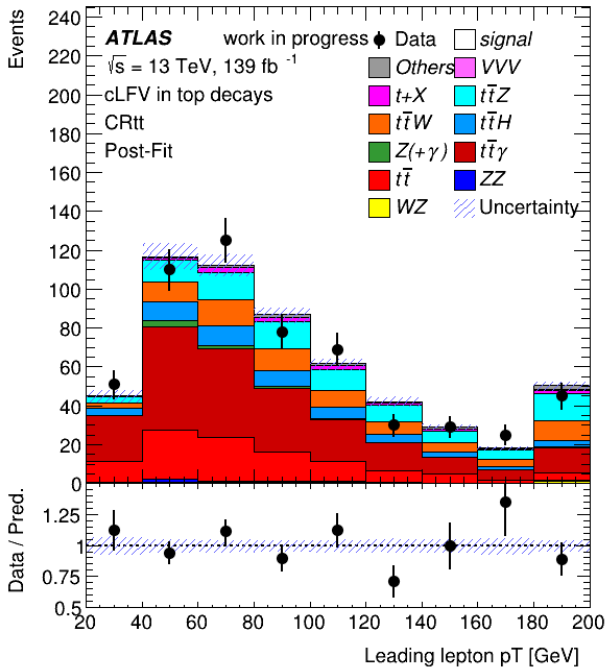




Fake Lepton background estimation

- $\boldsymbol{t\bar{t}(+\gamma)}$ and $\boldsymbol{Z+jets(+\gamma)}$ backgrounds contain:
  - fake leptons
    - photons converting to e^+e^-, mis-identification of light-jets as leptons
  - non-prompt leptons
    - e.g. from B meson decays
- MC simulation not sufficient
  - data-driven approach adopted
- Binned maximum-likelihood fit in ***2 Control Regions*** (CRs – signal depleted):
  - **CRZ**: OSSF lepton pair invariant mass inside Z mass window: $Z(\gamma)$ enhanced
  - **CRtt**: 2 b-tagged jets are required: $t\bar{t}(\gamma)$ enhanced
- The post-fit distributions of leading lepton p_T are shown on the right:
  - Fit successful with Normalization Factors (NF) for $Z(\gamma)$ and $t\bar{t}\gamma$ only
  - Further studies for additional CR definitions and NF application





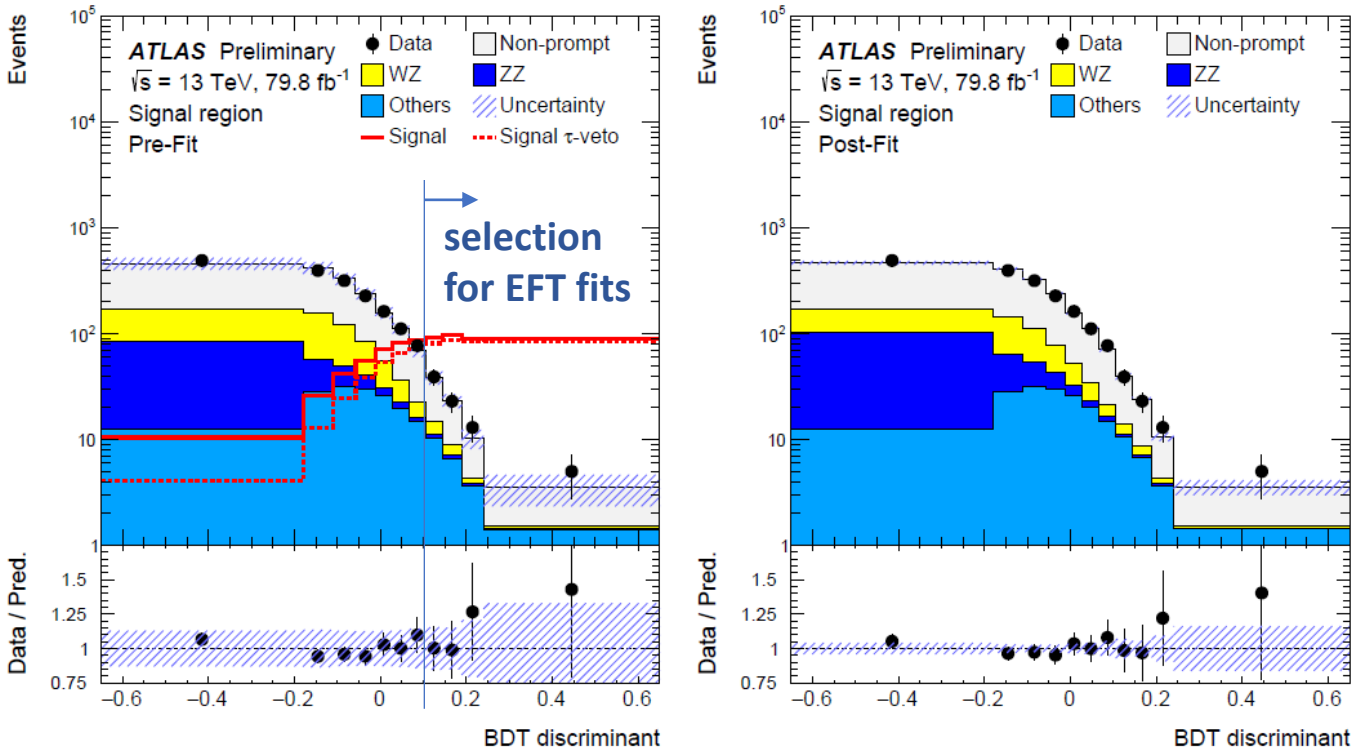
Previous Results and Plans on EFT fits

- Binned maximum-likelihood fit on BDT discriminant in SR, places bounds on the Branching Ratio (BR) of the top cLFV decay.
- The 80 fb^{-1} analysis results:

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

  $BR(t \to e\mu q) < 6.6 \times 10^{-6}$ (no τ in the event)

  at 95% confidence level
- Use of LHC Full Run 2 dataset, and refinement of the Fake Lepton background estimation is promising for improving these values.



Figures taken from ATLAS-CONF-2018-044

- Seven *2l2q EFT operators* contribute to the cLFV decay rate.
- EFT fits:
  - Cut on BDT discriminant
  - Simultaneous fit of regions targeting the different operators
  - ➢ Constraints on the Wilson coefficients

Summary

- We have presented an overview of the search for charged Lepton Flavour violation in top quark decays.
- The signature that we are after is
  - $t \longrightarrow e\mu q$, with e, μ of OS and q = u, c
- A multi-variate technique for Signal/Background separation in conjunction with a dedicated treatment of the Fake Lepton background provides us with a distribution that we can fit in order to place upper limits on the cLFV Branching Ratio.
- Further fits in regions targeting different contributing EFT operators, may result in placing bounds on the relevant EFT coefficients.

Thank you for your attention