

**SEARCH FOR CHARGED-LEPTON FLAVOR VIOLATION IN  
THE PRODUCTION AND DECAY OF TOP QUARKS AT  
 $\sqrt{s} = 13$  TEV WITH THE CMS DETECTOR**

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## Abstract

A search for charged-lepton flavor violation has been performed in the top quark sector through both top quark production and decay signal processes. The data were collected by the CMS experiment from proton-proton collisions at a center-of-mass energy of 13 TeV and correspond to an integrated luminosity of  $138 \text{ fb}^{-1}$ . The selected events are required to contain one opposite-sign electron-muon pair, a third charged lepton (electron or muon), at least one jet, and at most one jet associated with a bottom quark. The analysis utilizes boosted decision trees to separate background processes from a possible signal, exploiting differences in the kinematics of the final state particles. The data are found to be consistent with the standard model expectation. Upper limits at 95% confidence level are placed on the branching fractions involving up (charm) quarks,  $t \rightarrow e\mu u$  ( $t \rightarrow e\mu c$ ), of  $0.032 \times 10^{-6}$  ( $0.498 \times 10^{-6}$ ),  $0.022 \times 10^{-6}$  ( $0.369 \times 10^{-6}$ ), and  $0.012 \times 10^{-6}$  ( $0.216 \times 10^{-6}$ ) for tensor, vector, and scalar interactions, respectively.

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## List of Acronyms

<b>AR</b>	application region
<b>ATLAS</b>	A Toroidal LHC Apparatus
<b>BDT</b>	Boosted Decision Tree
<b>CL</b>	confidence-level
<b>CLFV</b>	Charged-Lepton Flavor Violation
<b>CMS</b>	Compact Muon Solenoid
<b>EFT</b>	Effective Field Theory
<b>HLT</b>	High Level Trigger
<b>HL-LHC</b>	High Luminosity-LHC
<b>JES</b>	jet energy scale
<b>JER</b>	jet energy resolution
<b>LHC</b>	Large Hadron Collider
<b>LO</b>	leading order
<b>L1</b>	Level-1
<b>MC</b>	Monte-Carlo
<b>ME</b>	matrix-element
<b>MET</b>	missing transverse momentum
<b>MR</b>	measurement region
<b>MVA</b>	multivariate analysis
<b>NLO</b>	next-to-leading order
<b>NN</b>	neural network
<b>NNLO</b>	next-to-next-to-leading order
<b>OSDF</b>	opposite-sign and different-flavor
<b>OSSF</b>	opposite-sign and same-flavor

- 
- PD** Primary Dataset
- PDF** Parton Distribution Function
- PF** particle flow
- PS** parton shower
- PU** pile-up
- PV** primary vertex
- QCD** quantum chromodynamics
- ROC** receiver operating characteristic curve
- SM** Standard Model
- SR** signal region
- SSSF** same-sign and same-flavor
- SV** secondary vertex
- VR** validation region
- WC** Wilson Coefficient



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**8.3 Tau**

**8.4 Jets**

**8.5 Energy Sums**

# CHAPTER 9

## **Run-3 Operation of the CMS detector**

### **9.1 The CMS Run Organisation**

### **9.2 Central Shifting Crew**

### **9.3 Detector On-call Expert**

# CHAPTER 10

## **The Phase-2 Upgrade of the CMS Detector**

### **10.1 Overview of the Upgrade**

### **10.2 Leve-1 Track Finder**

### **10.3 Leve-1 Electron Trigger Algorithm**

## **Part III**

# **Search for Flavor-Violating $e\mu\tau q$ Interactions**

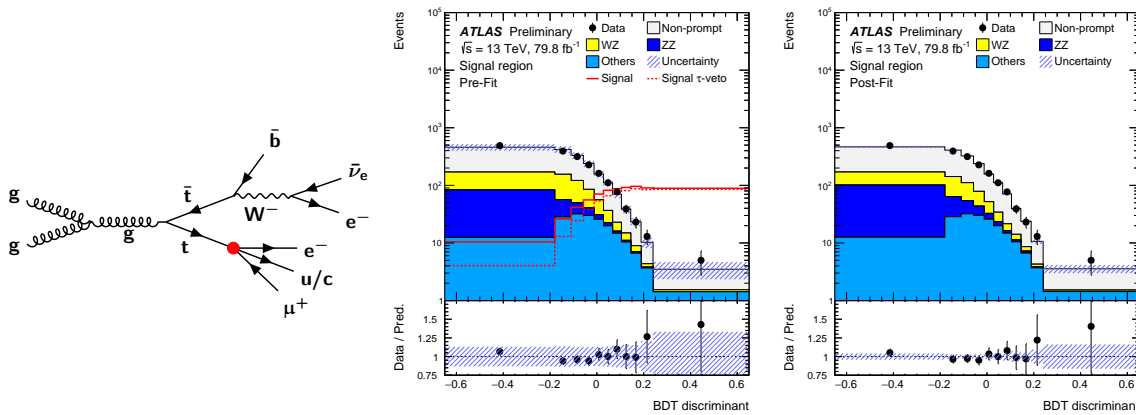
# CHAPTER 11

## Previous searches

**CLFV** search involving top quarks is an active area of research at the Large Hadron Collider (LHC) experiments. So far, no significant excess over the **SM** predictions has been reported, and the observations from the A Toroidal LHC Apparatus (**ATLAS**) and Compact Muon Solenoid (**CMS**) experiments are both interpreted using the framework of Effective Field Theory (**EFT**). Two existing **ATLAS** analyses are described in section 11.1 and one existing **CMS** analysis is described in section 11.2.

### 11.1 ATLAS

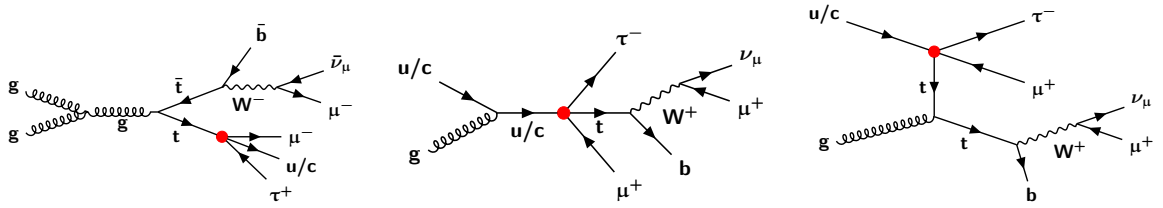
The flavor-violating  $e\mu tq$  interactions were first studied by the **ATLAS** Collaboration [1] using data collected during 2015-2017 with an integrated luminosity of  $79.8 \text{ fb}^{-1}$ . In addition to three leptons, this analysis targets final states with two or more jets. Only the top quark decay signal mode is considered. Lorentz structures of dimension-6 operators are not probed separately. Discriminating variables, such as the  $p_T$  of the leptons, are combined into a **BDT**, which is used to interpret the observation. A representative Feynman diagram targeted by this analysis and the distributions of the **BDT** discriminator are shown in Figure 11.1.



**Figure 11.1:** Representative Feynman diagram for the **CLFV** top quark decay processes that are targeted by [1] (left). The **CLFV** interaction vertex is shown as a solid red circle to indicate that it is not allowed in the **SM**. The middle (right) histogram shows the distribution of the pre-fit (post-fit) **BDT** discriminator targeting the **CLFV** top quark decay.

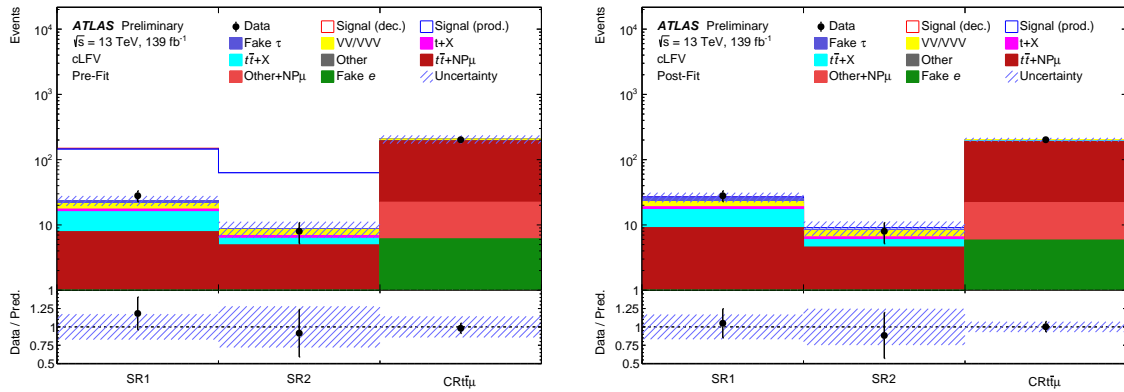
Data is found to be compatible with the **SM** predictions, and an upper limit on the branching fraction of  $\mathcal{B}(t \rightarrow e\mu q) < 6.6 \times 10^{-6}$  is set at 95% confidence-level (**CL**) [4]. This result improves a previous bound established in an indirect search [5] by three orders of magnitude.

The **ATLAS** Collaboration also studied the  $\mu\tau tq$  interactions using data corresponds to  $140 \text{ fb}^{-1}$  [2]. This analysis targets final states with two same-sign muons, one hadronic tau, and one or more jets. Both top quark production and decay signals are considered by this analysis. Operators with different Lorentz structures are considered separately. Representative Feynman diagrams are shown in Figure 11.2.



**Figure 11.2:** Representative Feynman diagrams for the signal processes that are targeted by [2]. Both top quark decay (left) and production (middle and right) CLFV processes are shown.

Due to limited statistics, event yields of the **SRs** are directly used to interpret the observation, which are shown in Figure 11.3. An upper limit at 95% **CL** is placed on the branching fraction of  $\mathcal{B}(t \rightarrow \mu\tau q) < 1.1 \times 10^{-6}$ . The corresponding constraint on the Wilson Coefficient (**WC**) improves the previous bound [6] by nearly a factor of 30.

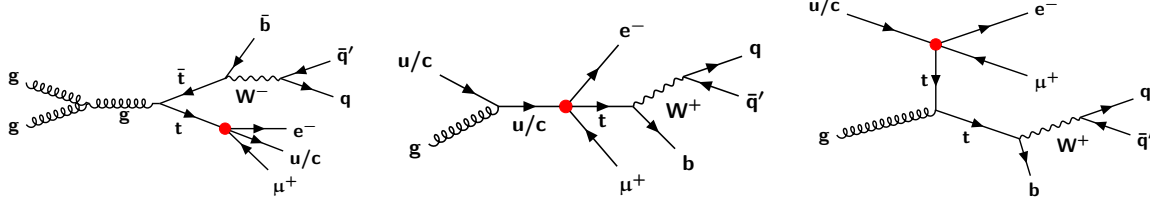


**Figure 11.3:** The left (right) histogram shows the pre-fit (post-fit) event yields of various regions studied by [2].

## 11.2 CMS

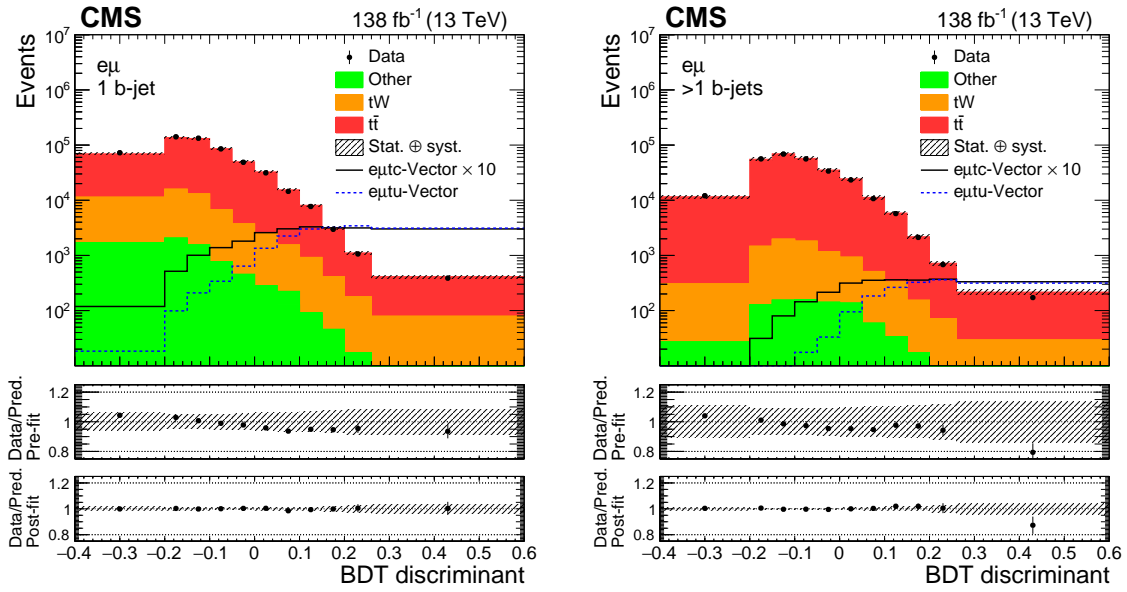
The **CMS** Collaboration followed up with a search for  $e\mu tq$  interactions using data corresponds to  $138 \text{ fb}^{-1}$  [3]. Unlike the previous ATLAS analysis [1], this **CMS** analysis targets final states with two leptons and a hadronically decaying top quark. Both top quark production and decay

signals are considered by this analysis. Operators with different Lorentz structures are considered separately. Representative Feynman diagrams are shown in Figure 11.4.



**Figure 11.4:** Representative Feynman diagrams for the signal processes that are targeted by [3]. Both top quark decay (left) and production (middle and right) CLFV processes are shown.

A **BDT** using multiple discriminating variables is trained to further enhance the sensitivity. Distributions of the **BDT** discriminator are shown in Figure 11.5. An upper limit at 95% **CL** is placed on the branching fraction of  $\mathcal{B}(t \rightarrow \mu\tau q) < 7 \times 10^{-8}$ , which improves the previous bound established by the **ATLAS** Collaboration [1] by two orders of magnitude.



**Figure 11.5:** The left (right) histogram shows the distribution of the **BDT** discriminator in regions with exactly (more than) one b-tagged jet.



# CHAPTER 12

## Datasets, Simulated Samples and Triggers

This analysis is based on data collected by the CMS experiment in 2016-2018 from  $pp$  collisions at a center-of-mass energy of 13 TeV corresponding to an integrated luminosity of  $138 \text{ fb}^{-1}$ . There were approximately 30 simultaneous  $pp$  collisions occurring per 25 ns. Based on online selection criteria, fully reconstructed collision data that contain high-level physics objects are divided into “Primary Datasets (PDs)”. The PDs that make use of lepton information for selection include “DoubleEG”, “DoubleMu”, “MuonEG”, “SingleElectron”, and “SingleMuon” for 2016 and 2017 data taking era. In 2018, “SingleElectron”, “DoubleEG” are replaced by “EGamma”. The names of these PDs reflect the selection criteria. In addition to these PDs, MC samples are also generated to model both signal and background processes, which are described in section 12.1 and section 12.2, respectively. To account for the different data taking conditions across the years, all MC samples are generated separately for each year. HLT triggers are used to select events offline, which is described in section 12.3.

### 12.1 Signal Samples

In this analysis, New Physics is described by Dimension-6 EFT operators,

$$\mathcal{L} = \mathcal{L}_{\text{SM}}^{(4)} + \frac{1}{\Lambda^2} \sum_a C_a^{(6)} O_a^{(6)} + O\left(\frac{1}{\Lambda^4}\right). \quad (12.1)$$

Among many of the Dimension-6 operators in Warsaw basis [7], a total of 6 operators are considered, which are summarized in Table 12.1. To reduce the number of free parameters, the permutations of fermion flavors are combined. Taking  $e\mu\tau u$  vertex as an example, the WCs are parameterized in the following way:

$$C_{lq} = C_{lq}^{(1)1213} + C_{lq}^{(1)2113} + C_{lq}^{(1)1231} + C_{lq}^{(1)1213}, \quad (12.2)$$

$$C_{lu} = C_{lu}^{1213} + C_{lu}^{2113} + C_{lu}^{1231} + C_{lu}^{1213}, \quad (12.3)$$

$$C_{eq} = C_{eq}^{1213} + C_{eq}^{2113} + C_{eq}^{1231} + C_{eq}^{1213}, \quad (12.4)$$

$$C_{eu} = C_{eu}^{1213} + C_{eu}^{2113} + C_{eu}^{1231} + C_{eu}^{1213}, \quad (12.5)$$

**Table 12.1:** Summary of relevant dimension-6 operators considered in this analysis. Here,  $\varepsilon$  is the two dimensional Levi-Civita symbol,  $\gamma^\mu$  the gamma matrix, and  $\sigma^{\mu\nu} = \frac{i}{2}[\gamma^\mu, \gamma^\nu]$ . The  $l$  and  $q$  denote left-handed doublets, whereas  $u$  and  $e$  denote right-handed singlets. The indices  $i$  and  $j$  are lepton flavor indices that run from 1 to 2 with  $i \neq j$ ;  $m$  and  $n$  are quark flavor indices with the condition that one of them is 3 and the other one is 1 or 2.

Lorentz Structure	Operator
vector	$O_{lq}^{(1)ijmn} = (\bar{l}_i \gamma^\mu l_j)(\bar{q}_m \gamma_\mu q_n)$
	$O_{lu}^{ijmn} = (\bar{l}_i \gamma^\mu l_j)(\bar{u}_m \gamma_\mu u_n)$
	$O_{eq}^{ijmn} = (\bar{e}_i \gamma^\mu e_j)(\bar{q}_m \gamma_\mu q_n)$
	$O_{eu}^{ijmn} = (\bar{e}_i \gamma^\mu e_j)(\bar{u}_m \gamma_\mu u_n)$
scalar	$O_{lequ}^{(1)ijmn} = (\bar{l}_i e_j) \varepsilon (\bar{q}_m u_n)$
tensor	$O_{lequ}^{(3)ijmn} = (\bar{l}_i \sigma^{\mu\nu} e_j) \varepsilon (\bar{q}_m \sigma_{\mu\nu} u_n)$

$$C_{lequ}^{(1)} = C_{lequ}^{(1)1213} + C_{lequ}^{(1)2113} + C_{lequ}^{(1)1231} + C_{lequ}^{(1)1213}, \quad (12.6)$$

$$C_{lequ}^{(3)} = C_{lequ}^{(3)1213} + C_{lequ}^{(3)2113} + C_{lequ}^{(3)1231} + C_{lequ}^{(3)1213}. \quad (12.7)$$

Additionally, all vector-like operators are combined,

$$O_{e\mu tu}^{\text{vector}} = O_{lq} + O_{lu} + O_{eq} + O_{eu}, \quad (12.8)$$

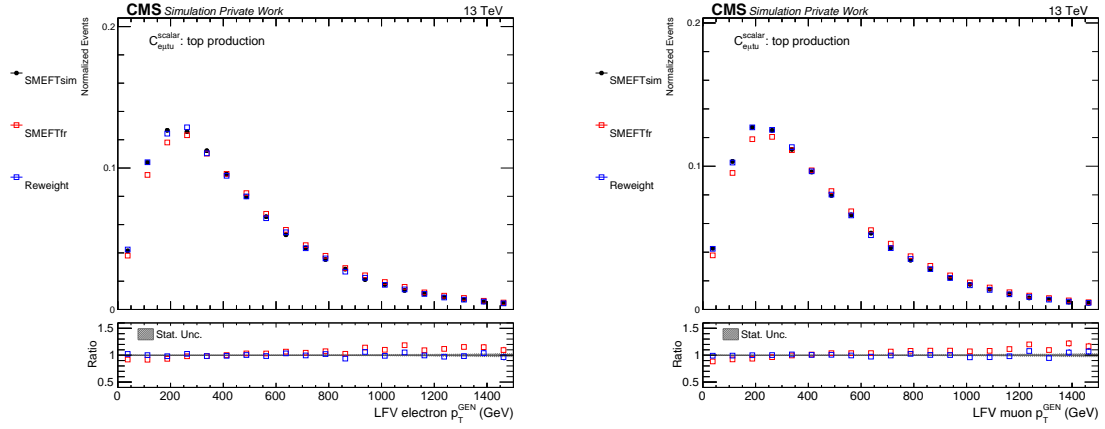
$$O_{e\mu tu}^{\text{scalar}} = O_{lequ}^{(1)} + \text{h.c.}, \quad (12.9)$$

$$O_{e\mu tu}^{\text{tensor}} = O_{lequ}^{(3)} + \text{h.c.}, \quad (12.10)$$

which results in 6 independent **WCs**:  $C_{e\mu tu}^{\text{vector}}$ ,  $C_{e\mu tu}^{\text{scalar}}$ ,  $C_{e\mu tu}^{\text{tensor}}$ ,  $C_{e\mu tc}^{\text{vector}}$ ,  $C_{e\mu tc}^{\text{scalar}}$ ,  $C_{e\mu tc}^{\text{tensor}}$ .

To generate signal **MC** samples, the effective Lagrangian described above is implemented using the SmeftFR v2 [8] model, and saved in the “UFO” format [9]. Additionally, all the **WCs** are set to 1 with  $\Lambda = 1$  TeV in the UFO, which then interfaces with the FEYNRULES [10] package to calculate Feynman diagrams. The output of the FEYNRULES is used in **ME** event generator MADGRAPH5\_AMC@NLO v2.4.2 [11] to generate events at leading order (**LO**).

In general, the calculations done by the **ME** event generators are model-agnostic assuming the same **EFT** configurations. In other words, models like SmeftFR or SMEFTsim [12] are expected to give the same or very similar results in terms of cross sections and four-momenta of



**Figure 12.1:** Comparison of kinematic distributions at **ME**-level produced by different models: LFV electron  $p_T$  (left), LFV muon  $p_T$  (right). The “SmeftFR” samples (shown in red curve) and “SMEFTsim” samples (shown in black curve) are statistically independent of each other. The “Reweight” (shown in blue curve) are produced by applying weights calculated by Equation 12.11 to “SmeftFR” samples.

final-state particles. Nevertheless, visible differences in kinematics have been observed and shown in Figure 12.1. Furthermore, the cross sections predicted by SmeftFR v2 also yield more than 20% difference relative to SMEFTsim due to a bug that was later fixed in SmeftFR v3. In the light of these differences, the **CMS** and **ATLAS** Collaborations agreed to adopt the SMEFTsim model as the common standard. To quantify the impact of the choice of models on kinematics, the following ratio is calculated for each event  $i$ ,

$$R_{\text{reweight}}^i = \frac{\omega_{\text{SMEFTsim}}^i}{\omega_{\text{SmeftFR}}^i}, \quad (12.11)$$

where  $\omega_X^i$  is the per-event **ME** weight calculated by MADGRAPH5\_AMC@NLO using model  $X$ . Since SMEFTsim was not used by **CMS** at the time when the signal samples were generated,  $R_{\text{reweight}}$  are used to “reweight” the original samples generated using SmeftFR.

Due to the significant differences in kinematic distributions between top decay and production signals, **MC** samples are generated separately for these processes. The cross sections for top production signals are taken directly from MADGRAPH5\_AMC@NLO with SMEFTsim UFO as input. The event generation for top decay signals at the **ME**-level take two steps: (i) production of the SM  $t\bar{t}$ , and (ii) **CLFV** decay of one of the top quarks. Therefore, the  $t\bar{t}$  cross section at next-to-next-to-leading order (**NNLO**) precision [13] is used to normalize the top decay signals,

$$\sigma_{\text{CLFV}}^{\text{Top Decay}} = 2 \times \sigma_{\text{tt}}^{\text{NNLO}} \times \mathcal{B}(t \rightarrow e\mu q), \quad (12.12)$$

where  $q=\{u,c\}$ , and  $\mathcal{B}(t \rightarrow e\mu q)$  [14] can be expressed as,

$$\mathcal{B}(t \rightarrow e\mu q) = \frac{\frac{|C_{e\mu tq}^{\text{vector}}|^2}{\Lambda^4} \frac{m_t^5}{384\pi^3\Gamma_t^{\text{SM}}}}{\frac{|C_{e\mu tq}^{\text{scalar}}|^2}{\Lambda^4} \frac{m_t^5}{3072\pi^3\Gamma_t^{\text{SM}}} + \frac{|C_{e\mu tq}^{\text{tensor}}|^2}{\Lambda^4} \frac{m_t^5}{64\pi^3\Gamma_t^{\text{SM}}}} \quad (12.13)$$

where  $m_t$  and  $\Gamma_t^{\text{SM}}$  are taken to be 172.5 GeV and 1.33 GeV in this analysis, respectively. The choice of  $u$  or  $c$  quark in final states does not affect the cross sections of the top decay signals. The cross sections for all signal **MC** samples are summarized in Table 12.2. These cross sections are used as baseline to define the signal strength  $\mu$ , which is used to quantify the relative strength of the signals when their normalization change,

$$\mu(C/\Lambda^2) = \frac{\sigma_{\text{CLFV}}(C/\Lambda^2)}{\sigma_{\text{CLFV}}(1\text{TeV}^{-2})} \propto (C/\Lambda^2)^2. \quad (12.14)$$

**Table 12.2:** Theoretical cross sections for top production and decay for each **CLFV** coupling, calculated at  $C/\Lambda^2 = 1 \text{ TeV}^{-2}$ . Uncertainties related to PDF and QCD scale in **ME** calculation are given ( $\sigma_{-\text{scale}}^{+\text{scale}} \pm \text{PDF}$ ).

Lorentz Structure	Samples	XS (fb)
vector	top production via u quark	$460_{-64}^{+81} \pm 6$
	top production via c quark	$33_{-4}^{+5} \pm 6$
	top decay via u/c quark	$32_{-1.1}^{+0.8} \pm 1.3$
scalar	top production via u quark	$97_{-14}^{+18} \pm 1$
	top production via c quark	$6.3_{-0.8}^{+0.9} \pm 1.4$
	top decay via u/c quark	$4.0_{-0.1}^{+0.1} \pm 0.2$
tensor	top production via u quark	$2143_{-293}^{+368} \pm 31$
	top production via c quark	$164_{-18}^{+22} \pm 27$
	top decay via u/c quark	$187_{-6}^{+5} \pm 8$

Steps other than the **ME** calculation concerning signal **MC** generation follow the **CMS** standard, which is described in the following section.

## 12.2 Background Samples

Besides  $tZq$ ,  $tHq$ ,  $tHW$ , and  $tWZ$  processes, the next-to-leading order (NLO) Parton Distribution Function (PDF) set from NNPDF3.0 [15] is used in 2016 to generate background MC samples. The NNLO PDF set from NNPDF3.1 [16] is used for  $tZq$  while the LO PDF set from NNPDF3.0 is used for  $tHq$ ,  $tHW$ , and  $tWZ$  in 2016. In 2017 and 2018, the NNLO PDF set from NNPDF3.1 is used to generate all the samples.

The default choice of ME event generator is MADGRAPH5\_AMC@NLO v2.4.2 (v2.2.2 for 2016), which is used to generate all but ZZ,  $t\bar{t}H$ , and  $t\bar{t}$  samples. These three samples are generated with POWHEG v2 [17] instead. Samples with small contributions ( $tHq$ ,  $tWZ$ ,  $tHW$ , and low mass DY) are generated at LO while other samples are generated at NLO. Whenever possible and relevant, theoretical cross sections from high-order quantum chromodynamics (QCD) calculations are used. The references of these calculations are included in 12.3.

The PYTHIA v8.2 [18] is used to model parton shower and hadronization. The CUETP8M1 [19] is used in 2016 for underlying event tuning while the CP5 [20] is used in 2017 and 2018. The configurations of the MC samples are summarized in Table 12.3. The background processes are divided into two categories: (i) processes with three or more *prompt* leptons in the final states are classified as “*prompt* background”, and (ii) other processes are classified as “*nonprompt* background”. The *nonprompt* backgrounds in this analysis are modeled with a data-driven technique, which is discussed in chapter 15. The MC samples listed in “*nonprompt*” category in Table 12.3 are therefore only used for the purpose of validations.

## 12.3 Triggers

The target final states of this analysis contain three prompt leptons, which make lepton triggers the most optical choice to select events. To achieve the maximum acceptance, a combination of single-lepton, di-lepton and tri-lepton triggers are used. These triggers are summarized in Appendix A. Events in simulated samples are required to fire at least one of the triggers listed in Table A.1-A.3. Since multiple PDs are used to record data events and the orthogonality of these PDs are not guaranteed by the online selection criteria, the following trigger logic is implemented to remove the overlap between different PDs:

- Events in SingleMuon datasets are required to fire at least one of the triggers listed under “SingleMuon”.
- Events in DoubleMuon datasets are required to fire at least one of the triggers listed under “DoubleMu”. Events are removed if they also fire at least one of the triggers listed under “SingleMuon”.
- Events in MuonEG’ datasets are required to fire at least one of the triggers listed under “MuonEG”. Events are removed if they also fire at least one of the triggers listed under

**Table 12.3:** Summary of the configurations of the MC samples. DYM50 (DYM10to50) denote DY sample with a dilepton invariant mass greater than 50 GeV (between 10 and 50 GeV). V includes W and Z bosons. The cross sections for samples without a citation are taken directly from their event generators.

Category	Process	Event Generator	Perturbative QCD	Tune	XS precision
<i>prompt</i> background	WZ	MADGRAPH	NLO	CUETP8M1(CP5)	NLO [21]
	ZZ	POWHEG	NLO	CUETP8M1(CP5)	NLO [21]
	VVV	MADGRAPH	NLO	CUETP8M1(CP5)	NLO
	$t\bar{t}W$ , $t\bar{t}Z$	MADGRAPH	NLO	CUETP8M1(CP5)	NLO [22, 23]
	$t\bar{t}H$	POWHEG	NLO	CUETP8M1(CP5)	NLO [23]
	$tZq$	MADGRAPH	NLO	CP5	NLO
	$tHq$ , $tHW$ , $tWZ$	MADGRAPH	LO	CUETP8M1(CP5)	LO
<i>nonprompt</i> background	$t\bar{t}$	POWHEG	NLO	CUETP8M1(CP5)	NNLO [13]
	DYM50	MADGRAPH	NLO	CUETP8M1(CP5)	NNLO [24]
	DYM10to50	MADGRAPH	LO	CUETP8M1(CP5)	NLO [24]

“SingleMuon” or “DoubleMu”.

- Events in Single Electron datasets are required to fire at least one of the triggers listed under “SingleElectron”. Events are removed if they also fire at least one of the triggers listed under “SingleMuon” or “DoubleMu” or “MuonEG”.
- Events in DoubleEG datasets are required to fire at least one of the triggers listed under “DoubleEG”. Events are removed if they also fire at least one of the triggers listed under “SingleMuon” or “DoubleMu” or “MuonEG” or “SingleElectron”.
- Events in EGamma datasets are required to fire at least one of the triggers listed under “EGamma”. Events are removed if they also fire at least one of the triggers listed under “SingleMuon” or “DoubleMu” or “MuonEG”.

# CHAPTER 13

## Object Selection

Objects described in [chapter 8](#), referred to as “candidates”, are further selected with more stringent requirements with the goal of suppressing the contributions from background processes while maintaining a high signal acceptance. In particular, prompt electron and muon candidates are identified through a custom-trained [BDT](#) classifier, which is discussed in [section 13.1](#). Two jet identification algorithms are deployed to select jet candidates originating from hard collisions, which is discussed in [section 13.2](#). Furthermore, jet candidates that originate from b quarks are identified with a neural network ([NN](#)) based algorithm, which is discussed in [section 13.3](#).

### 13.1 Lepton Selection

The target final states of this analysis feature exactly three leptons that originate either from decays of electroweak bosons or from the [CLFV](#) interaction, which in this analysis is a contact interaction that involves four fermions. These leptons, referred to as *prompt* leptons, typically appear to be isolated and not far away from the primary vertex ([PV](#)). In contrast, *nonprompt* leptons are leptons that originate from decays of hadrons, or from photon conversions, or misidentified leptons. They often travel a noticeable distance away from the [PV](#) and appear to be less isolated due to nearby activities. Due to the high multiplicity of leptons in our selection, backgrounds with at least one *nonprompt* lepton outnumber any other [SM](#) processes that produce three or more *prompt* leptons. It is therefore crucial to exploit the differences between *nonprompt* and *prompt* leptons and bring the *nonprompt* background under control.

#### 13.1.1 TOP LeptonMVA

The TOP LEPTONMVA is an offline lepton identification algorithm that is originally developed for tZq analyses [[25](#), [26](#)]. It is based on Gradient [BDT](#) implemented using the TMVA package [[27](#)]. A total of 13 features are used as input to the [BDT](#). They can be categorised into four groups: (i) positions and momenta of the lepton candidates, (ii) isolation variables, (iii) variables associated to the closest jet, and (iv) a quality variable that is specific to electron or muon candidate. The version of TOP LEPTONMVA used by this analysis is the same as [[26](#)], where a detailed description of all input features can be found.

*Prompt* leptons from  $t\bar{t}W$ ,  $t\bar{t}Z$ , and  $tZq$  samples are used as signals in the **BDT** training while *nonprompt* leptons from  $t\bar{t}$  samples are used as backgrounds. The trained **BDT** outputs a single score for each lepton candidate ranging from -1 to 1 with -1 (1) being the most background- (signal-) like. The tight working point with a threshold of ( $>$ ) 0.9 is chosen as the selection criteria for both electron candidates and muon candidates, which corresponds to a signal(background) efficiency of 90%(1%). The strategy is to trade a small percentage ( $<10\%$ ) of signal efficiency for several factors of background rejection.

### 13.1.2 Full Selection

In addition to the TOP LEPTONMVA requirement, a set of common selection criteria are applied to both electron and muon candidates. The minimum  $p_T$  requirement is 38 GeV, 20 GeV, and 20 GeV for the leading, sub-leading, and trailing lepton in  $p_T$ , respectively. This requirement is driven by the  $p_T$  thresholds of the **HLT** triggers to avoid inefficiency at turn-on. Electron and muon candidates are required to be in the pseudorapidity range  $|\eta| < 2.4$ , which corresponds to the acceptance of **CMS** tracker and muon system in 2016-2018. The transverse (longitudinal) impact parameters with respect to the **PV**, denoted as  $d_{xy}$  ( $d_z$ ), is required to be in the range  $|d_{xy}| < 0.05$  cm ( $|d_z| < 0.05$  cm). The significance of the 3-dimensional impact parameter, denoted as  $SIP_3$ , is defined as the 3-dimensional impact parameter divided by its uncertainty. It is required that  $SIP_3 < 8$ . The three cuts on impact parameters are added due to the difference in distributions of these parameters between *prompt* and *nonprompt* leptons. Also, they are part of the pre-selection requirement in the **BDT** training.

Furthermore, all lepton candidates are required to be isolated. This is achieved by first defining a cone with a distance parameter of  $\Delta R$  around each lepton candidate, where  $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ . Only particles within  $\Delta R < R_{\max}$  can contribute to the isolation variable, where  $R_{\max}$  is referred to as the size of the cone. Secondly, a particle flow (**PF**) based isolation variable is defined as,

$$I_{\min}^{\text{rel}} = \frac{1}{p_T^\ell} \left\{ \sum_{\text{charged}} p_T + \max(0, \sum_{\text{neutral}} p_T - \rho \mathcal{A}[\frac{\Delta R}{0.3}]^2) \right\}, \quad (13.1)$$

where  $p_T^\ell$  is the  $p_T$  of the lepton candidate, the first term inside the curly braces is the scalar sum of all charged particles associated with the **PV** while the second term evaluates the contribution from neutral particles. This is done by first scalar-summing over  $p_T$  of all neutral particles associated to the **PV**. A correction term, known as effective area correction [28], is then subtracted. This term is used to mitigate the impact of pile-up (**PU**) interactions. The size of the cone scales with  $p_T^\ell$  as,

$$R_{\max} = \max(0.05, \min(0.2, \frac{10\text{GeV}}{p_T^\ell})). \quad (13.2)$$



This type of isolation variable is known as “mini” isolation, which maximises the signal efficiency at  $p_T^\ell$  by reducing the cone size. It is required that lepton candidates to have  $I_{\text{mini}}^{\text{rel}} < 0.12$ .

For electron specifically, candidates are required to have a GSF track with one of less missing inner hit. Electron candidates reconstructed in the transition region between ECAL barrel and endcap (i.e.  $1.44 < |\eta_{\text{SC}}| < 1.57$ ) are removed from consideration. For muon specifically, candidates are required to be **PF** muons and pass the medium working point discussed in [section 8.2](#).

Lepton candidates that pass all requirements stated above are referred to as “*tight*” leptons. Leptons selected with a separate set of criteria, known as “*loose*”, is used in estimating the *nonprompt* background, which is discussed in [chapter 15](#). Unless explicitly stated, all lepton objects presented in this search are *tight* leptons.

The energy of electron candidates are calibrated through. The moment scale of muon candidates are calibrated for muon candidates with  $p_T < 200$  GeV. Scale factors are applied to *tight* leptons to correct for the differences in reconstruction, isolation, and identification between data and **MC**. These scale factors are obtained using dilepton events in Z resonance window.

## 13.2 Jet Selection

Jet candidates are reconstructed from **PF** candidates using the anti- $k_T$  algorithm described in [section 13.2](#) with a cone size of 0.4. Charged hadrons that are not associated to the **PV** are removed. Jet candidates are required to have a minimum  $p_T$  of 30 GeV and in the pseudorapidity range  $|\eta| < 2.4$ , where b-tagging are still effective. It is further required that all jet candidates to be isolated from *tight* leptons. A cone of the size 0.4 around each jet candidate is defined and candidates will be removed if any *tight* leptons are found within such a cone. This procedure is implemented to remove the overlap between leptons and jets.

The two primary sources of background are (i) detector noise, and (ii) jets from **PU** interactions. To suppress detector noise, a set of cut-based selections are applied to jet candidates. This algorithm utilizes information from **PF** candidates, including: (i) fraction of charged (neutral) hadrons energy, (ii) fraction of charged (neutral) EM energy, (iii) fraction of muon energy, and (iv) object multiplicity. The “tightLepVeto” working point is chosen to select jet candidates, which corresponds to 98-99% signal efficiency.

The second algorithm is designed to reject jet candidates that originate from **PU** interactions. This algorithm is based on a **BDT** that utilizes: (i) the trajectories of tracks associated to the jets, (ii) the topology of the jet shape, and (iii) object multiplicity. The *loose* working point is chosen to select jet candidates with  $p_T < 50$  GeV, which corresponds to 99% signal efficiency. Applying this algorithm to jet candidates with  $p_T > 50$  GeV is both ineffective and unnecessary as **PU** jets mostly reside in low  $p_T$  spectrum. The overall effect of this algorithm on this analysis is small as **PU** jets constitute only a small fraction of all jet candidates in the phase space of this analysis.

As discussed in [section 8.4](#), the energy scale for all jet candidates (data and [MC](#)) are calibrated. One extra correction is applied to simulated jets to recreate the jet energy resolution as measured in data.

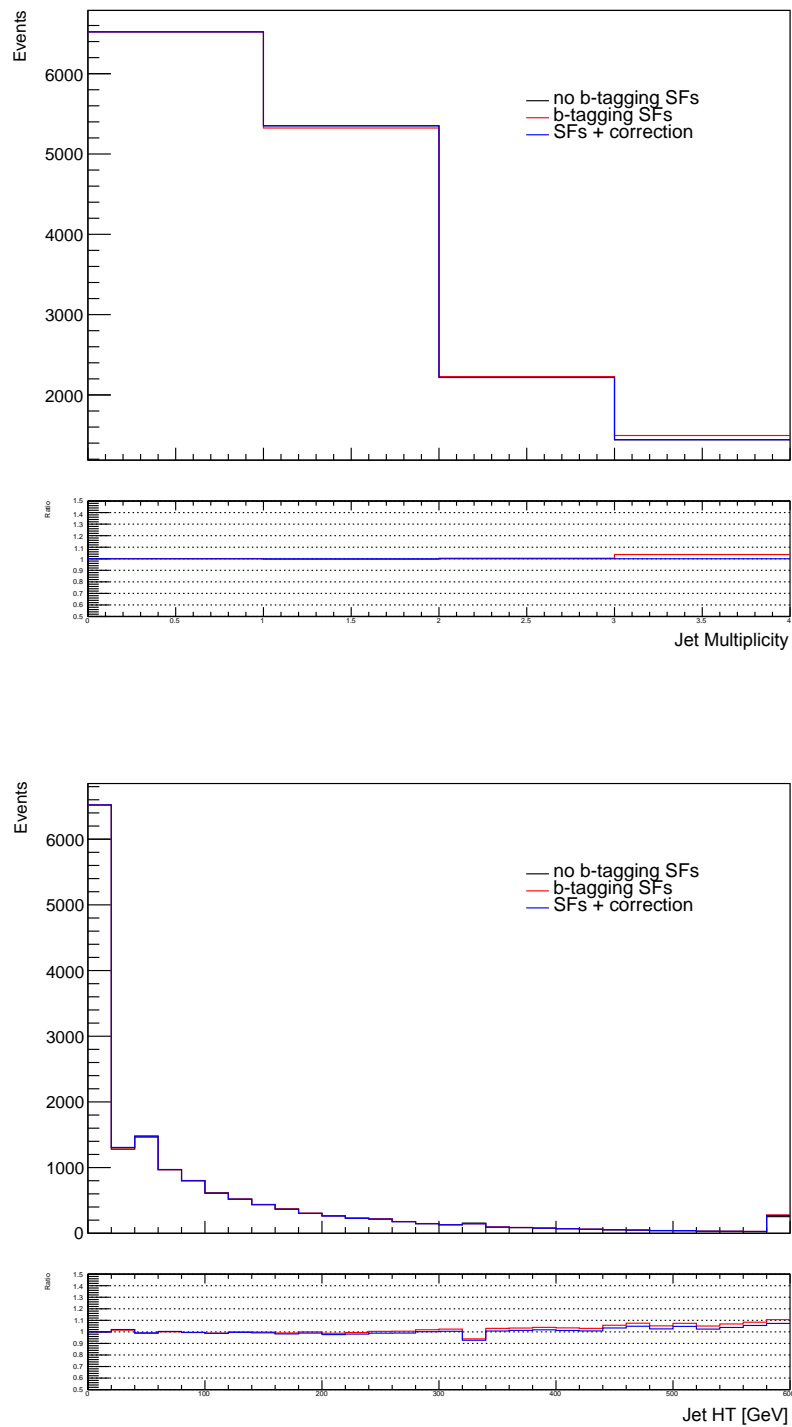
### 13.3 Identification of b jets

The DEEPJET algorithm [\[29\]](#) is used to identify jets that originate from b quark. The core strategy of this algorithm is to minimise information. This is achieved by removing entirely the selection of jet constituents, which limits the number of jet constituents considered. Additionally, an effort is made to use as many low-level features as possible, which further further deepens the feature space. Approximately a total of 650 input features are used, which can be categorized into four groups: (i) global variables, (ii) charged PF candidate features, (iii) neutral PF candidate features, (iv) and secondary vertex ([SV](#)) features associated with the jet. When compared to the existing DEEPCSV algorithm [\[30\]](#), DEEPJET algorithm delivers up to 20% improvement in signal efficiency while maintaining the same background efficiency.

The DEEPJET algorithm outputs a score ranging between 0 and 1, with 0 (1) being the most background- (signal-) like. The medium working point is chosen to tag b jet candidate, which corresponds to 70%-80% signal efficiency. The shape of the DEEPJET output distribution is corrected for the differences between data and [MC](#) in signal and background efficiencies. The per-event correction weight  $\omega$  is defined as,

$$\omega = \prod_i^{N_{\text{jets}}} \text{SF}(p_{T_i}, \eta_i, F_i, D_i), \quad (13.3)$$

where SF is the ratio of efficiency in data to efficiency to [MC](#) parameterized as a function of  $p_T$ ,  $\eta$ , (MC truth) flavor F, as well as DEEPJET output  $D$  of each jet in the event.  $\omega$  is applied to all [MC](#) events, and additional scale factors are also applied to remove the normlization effect of  $\omega$ . These scale factors are measured using [MC](#) in  $e\mu\ell$  channel described in [chapter 14](#). The effect of these scale factors are shown in [Figure 13.1](#).



**Figure 13.1:** Simulated events in  $e\mu\ell$  channel: jet multiplicity (top) and  $H_T$  (bottom).

# CHAPTER 14

## Event Selection

Events are required to contain exactly three *tight* leptons described in [section 13.1](#). Furthermore, events are selected with [HLT](#) triggers discussed in [section 12.3](#). Events with different lepton flavor composites are further categorized into three exclusive channels:  $eee$ ,  $\mu\mu\mu$ ,  $e\mu\ell$ . In all three channels, the sum of the electric charges of the selected leptons are required to be 1 or -1. The leading leptons in all selected events are required to be matched with trigger objects within  $\Delta R < 0.2$ . Within each channel, different regions are defined to further understand signal and background.

$e\mu\ell$  is the channel where close to 100% of the simulated signal events reside. This channel is divided into signal-enriched [SRs](#) and signal-depleted [VRs](#), which are discussed in [section 14.1](#) and [section 14.2](#), respectively. Due to the lack of different flavors, the  $eee$  and  $\mu\mu\mu$  channels are signal-depleted by definition. Therefore, events found in these two channels are only used to study background processes, which are discussed in [section 14.2](#). The kinematic reconstruction of heavy particles, such as the top quark, is described in [section 14.3](#).

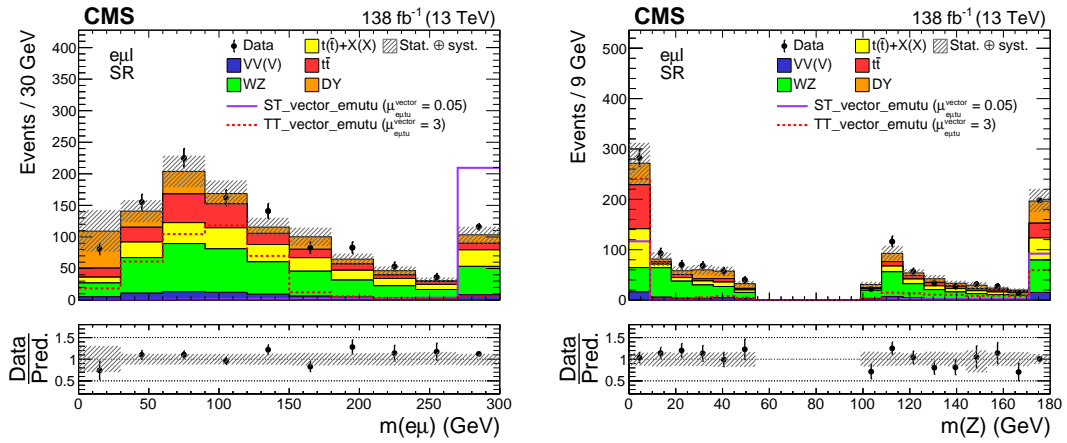
### 14.1 Signal Region

The core feature of the signal events is the presence of the “LFV  $e\mu$ ” pair, which consists of a pair of opposite-sign and different-flavor ([OSDF](#)) leptons. It is guaranteed that there is at least one [OSDF](#) pair in all events residing in  $e\mu\ell$  channel due to the requirement on electric charges. The [OSDF](#) pair is immediately labelled as the LFV  $e\mu$  pair if it is only possible to reconstruct one [OSDF](#) pair. In events where a pair of same-sign and same-flavor ([SSSF](#)) leptons are present, a kinematic reconstruction is used to determine which one of two leptons form the LFV  $e\mu$  pair with the third lepton, which is detailed in [section 14.3](#). Leptons that form the LFV  $e\mu$  pair are referred to as the LFV electron or muon as it is assumed that they originate from the [CLFV](#) interaction. Based on the event topology of the signal process, further selection criteria are applied to define the [SR](#). These selection criteria help achieve an optimal signal to background ratio by removing majority of the background events present in  $e\mu\ell$  channel.

At tree-level, signal events are expected to contain one or two jets, which motivates a requirement of at least one jet in [SR](#). Furthermore, it is required that there is no more than one b-tagged

jet to suppress the contribution from  $t\bar{t}$  events. Another prominent background is Drell-Yan production that features an  $OSSF$  pair. To suppress Drell-Yan processes in  $SR$ , events that contain an  $OSSF$  lepton pair with an invariant mass between 50 GeV and 106 GeV are removed. The lower bound of this veto is lower than the typical value (e.g. 75 GeV) because the mass range between 50 GeV and 75 GeV has very few signal events and is dominated by *nonprompt* background from photon conversion. Additionally, a modest threshold of 20 GeV is applied to  $MET$  due to the presence of neutrinos in the signal events.

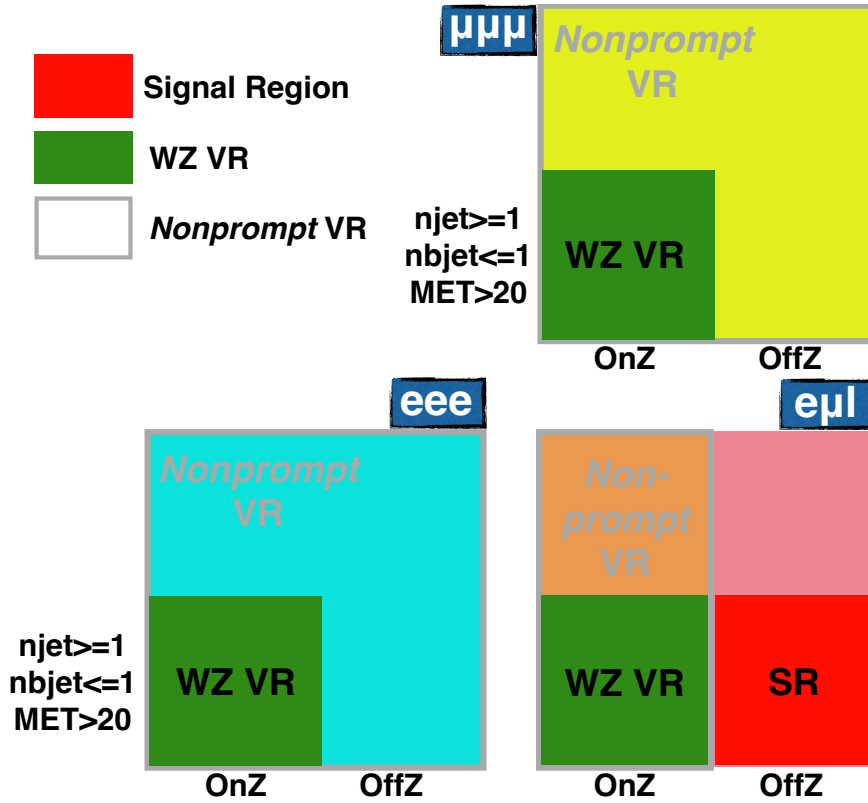
Distributions of the LFV  $e\mu$  mass and the Z boson mass are shown in Figure 14.1. All backgrounds in Figure 14.1 are estimated using MC simulation even though strategy is to use a data-driven method to estimate the *nonprompt* background. This serves as a preliminary check to understand the components of different backgrounds in  $SR$ . Distributions of more variables in  $SR$  are included in Appendix B.



**Figure 14.1:** Distributions of the LFV  $e\mu$  mass (left) and the Z boson mass (right) in  $SR$ . The data are shown as filled points and the  $SM$  background predictions as histograms. The  $VV(V)$  background includes  $ZZ$  and triboson production, while the  $t\bar{t} + X(X)$  component includes  $t\bar{t}W$ ,  $t\bar{t}Z$ ,  $t\bar{t}H$ ,  $tZq$ , and smaller backgrounds containing one or two top quarks plus a boson or quark. All backgrounds are estimated using MC simulation. The hatched bands indicate statistical and systematic uncertainties for the  $SM$  background predictions. The normalisation of the signal processes is chosen arbitrarily for improved visualisation. The last bin of both histograms includes the overflow events.

Using the LFV  $e\mu$  mass, the  $SR$  is further divided into two subsets to create top production and decay enriched regions:

- $SR1$ ,  $m_{e\mu} < 150$  GeV: top decay enriched.
- $SR2$ ,  $m_{e\mu} > 150$  GeV: top production enriched.



**Figure 14.2:** Illustration of selection criteria used to define different regions. “OnZ” means the presence of at least one  $OSSF$  pair with an invariant mass between 50 GeV and 106 GeV. Events are labelled as “OffZ” when they fail “OnZ” criteria.

## 14.2 Validation Region

There are two types of signal-depleted **VR** defined across three channels: *nonprompt VR* and *WZ VR*. The purpose of these two types of **VR** is only limited to the validation of the background modelling as neither of them enter the final fit. It is expected that the *nonprompt VR* has a significant fraction of *nonprompt* background while *WZ VR* production is responsible for most of the backgrounds in the *WZ VR*. Distributions of leading lepton  $p_T$  and leading lepton  $\eta$  in *WZ VR* control region can be found in Figure 14.3. The *nonprompt VR*s are further discussed in chapter 15.

Selection criteria used to define different regions are illustrated in Figure 14.2 and is summarized in Table 14.1.

## 14.3 Kinematic Reconstruction

As mentioned, the LFV  $e\mu$  pair is assumed to be the product of the  $CLFV$  interaction, while the third lepton, referred to as the standalone lepton, is assumed to originate from the leptonically

Channel	Region	OnZ	OffZ	MET > 20 GeV	njet>=1	nbjet<=1
eee	VR	-	-	-	-	-
	WZ VR	✓	-	✓	✓	✓
eμℓ	SR	-	✓	✓	✓	✓
	Nonprompt VR	✓	-	-	-	-
	WZ VR	✓	-	✓	✓	✓
μμμ	Nonprompt VR	-	-	-	-	-
	WZ VR	-	✓	✓	✓	✓

**Table 14.1:** Summary of the selection criteria used to define different event regions. “OnZ” means the presence of at least one **OSSF** pair with an invariant mass between 50 GeV and 106 GeV. Events are labelled as “OffZ” when they fail “OnZ” criteria.

decaying top quark. To distinguish this top quark ( $t \rightarrow \ell \nu b$ ) with the top quark that decays via the **CLFV** interaction ( $t \rightarrow e \mu q$ ), the former is referred to as the **SM** top quark while the latter is referred to as the LFV top quark.

Jet with the highest b-tagging score, regardless of whether or not it crosses the medium working point threshold, is assumed to originate from bottom quark decay. Therefore, it is combined with **MET** and to build the **SM** top quark. The x and y component of **MET** are taken as measurements of neutrino  $p_x$  and  $p_y$ . The z component of neutrino momentum is calculated by imposing the constraint that the invariant mass of the combined object (standalone lepton + neutrino) must be equal to W boson mass. If there is no real solution, the real part of the complex solution is taken. If there is more than one real solution, the solution that is the closest to the  $p_z$  of the standalone lepton is taken. In events where there is more than one candidate of standalone lepton (i.e. the presence of the **SSSF** pair), the lepton that gives a top mass that is the closest to the **SM** top quark mass ( $m_t = 172.5$  GeV) is taken as the standalone lepton.

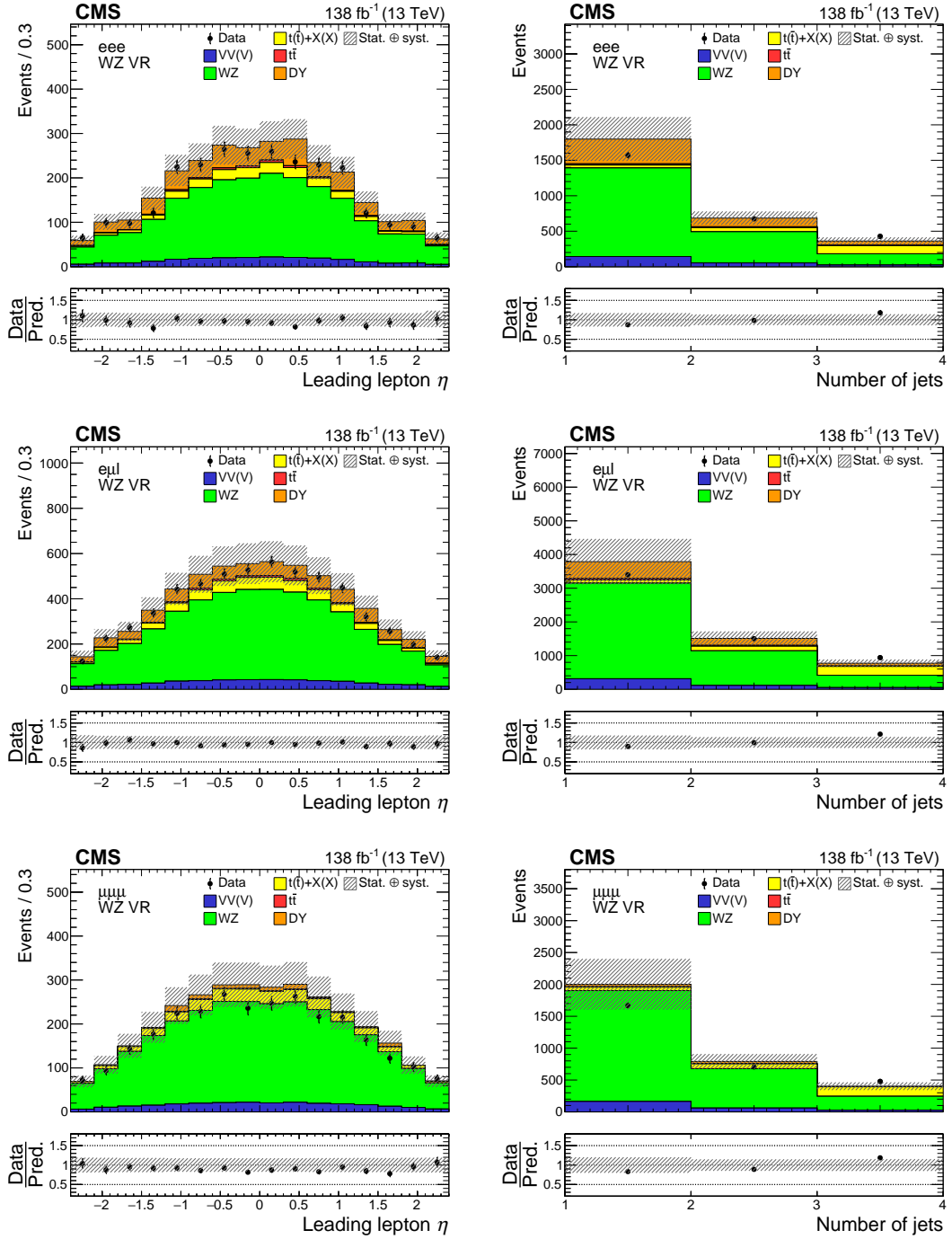
Once the standalone lepton has been determined, the remaining two leptons are labelled as the LFV  $e\mu$  pair and is combined with each selected jet to reconstruct the LFV top quark candidates. Jet with the highest b-tagging score is excluded from this reconstruction since it is assumed to be from the decay of the **SM** top quark. Out of all the LFV top quark candidates, the candidate that gives a top mass that is the closest to the **SM** top quark mass is taken. The LFV top quark mass is set to 0 in events where there are less than two jets.

Z boson candidate is reconstructed using the **OSSF** pair, which is not guaranteed to be present in the  $e\mu\ell$  channel. The Z boson mass ( $m_Z$ ) is set to 0 in events where the **OSSF** is absent. Z boson candidate is the only heavy particle reconstructed in the eee and  $\mu\mu\mu$  channels. Since

there are always two ways to form the **OSSF** pair, the **OSSF** pair with an invariant mass that is closer to the Z boson mass ( $m_Z = 91.2$  GeV) is taken.

Jets with high b-tagging scores are combined with leptons to form so called “ $m_{b\ell}$ ” systems. The first  $m_{b\ell}$  system takes the jet with the highest b-tagging score and combine it with each *tight* lepton in events. Out of the three  $m_{b\ell}$  system candidates, the one with the lowest  $m_{b\ell}$  is taken, the two constitutes are excluded from the consideration of the second  $m_{b\ell}$  system. If additional jets exist, the second  $m_{b\ell}$  system takes jet with the highest b-tagging score and combine it with two of the remaining leptons separately. Out of the two candidates, the one with lowest  $m_{b\ell}$  is taken.  $m_{b\ell}$  is set to 0 if no additional jet exists after the formation of the first  $m_{b\ell}$  system.





**Figure 14.3:** Distributions of the leading lepton  $\eta$  (left column) and the jet multiplicity (right column) in the WZ VRs. Events in the eee,  $e\mu\ell$ , and  $\mu\mu\mu$  WZ VRs are shown in the upper, middle, and lower row, respectively. The data are shown as filled points and the background predictions as histograms. All backgrounds are estimated with MC simulation. The hatched bands indicate statistical and systematic uncertainties for the background predictions. The last bin of the right column histograms includes the overflow events.

# CHAPTER 15

## Nonprompt Background Estimation

In this analysis, the term *prompt* leptons refers to leptons that originate from the CLFV vertex, the Drell-Yan process, or an electroweak boson decay, including leptons from  $\tau$  decays if the  $\tau$  lepton originates from the latter two processes. *Nonprompt* leptons refer to leptons that originate from hadron decays and photon conversions, as well as particles misidentified as leptons. *Nonprompt* leptons are suppressed through isolation requirements and a multivariate analysis (MVA)-based identification specifically trained to reject them.

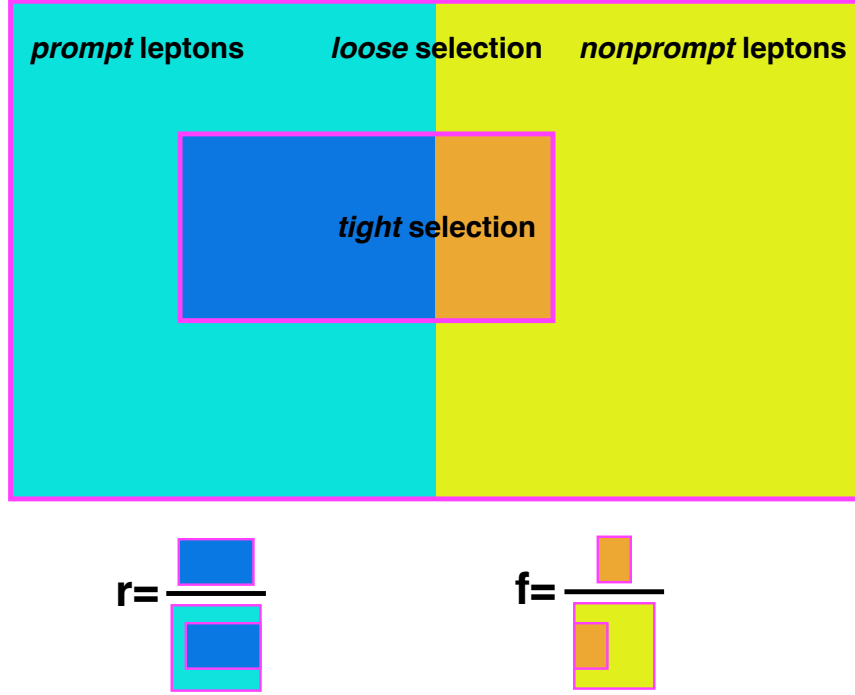
*Nonprompt* backgrounds are defined to be backgrounds with at least one *nonprompt* lepton passing the *tight* selection criteria, in this case generally dominated by Drell-Yan and  $t\bar{t}$  production. An accurate estimation of *nonprompt* backgrounds is difficult to achieve through MC modelling. Therefore, a data-driven technique called the “*matrix method*” [31] is used to estimate the *nonprompt* backgrounds.

A brief description of the *matrix method* in its simplest form is given in section 15.1 followed by its generalization and implementation in section 15.2. This method is validated using three VRs and is described in section 14.2. Lastly, the *nonprompt* estimation in the SR is presented in section 15.4.

### 15.1 The Matrix Method

The *matrix method* is a data driven technique used to estimate the fraction of *nonprompt* leptons that pass a given lepton selection, referred to as “*tight*”. The *tight* selection usually incorporates tight lepton identification and isolation requirements and corresponds to the full lepton selection used in an analysis. The *loose* selection is obtained by loosening the *tight* selection. The *loose* selection is used as a baseline such that any *loose* leptons fall into one of the two exclusive categories: *tight* or *not tight*. The *matrix method* deals with *prompt* and *nonprompt* leptons separately. As a result, *prompt* and *nonprompt* efficiencies are introduced, as is illustrated in Figure 15.1.

In a simplified scenario with only one lepton in the final state, the *prompt* efficiency  $r$  measures the probability of *prompt* leptons pass *tight* selection. It is treated as an observable that can be obtained through measurement,



**Figure 15.1:** Illustration of the *prompt* efficiency  $r$  and the *nonprompt* efficiency  $f$ .

$$r = \frac{n_P^T}{n_P^T + n_P^{\bar{T}}}, \quad (15.1)$$

in which  $n_P^T/n_P^{\bar{T}}$  denotes the number of events with a *prompt* lepton that is *tight/not tight*.

Similarly, *nonprompt* efficiency  $f$  can be expressed as,

$$f = \frac{n_N^T}{n_N^T + n_N^{\bar{T}}}, \quad (15.2)$$

in which  $n_N^T/n_N^{\bar{T}}$  denotes the number of events with a *nonprompt* lepton that is *tight/not tight*.

The measurement of  $r/f$  is often performed in dedicated control regions, where high purity of *prompt/nonprompt* leptons is expected. These regions are referred to as the **MR**. It is assumed that  $r/f$  is a universal property of *prompt/nonprompt* leptons that is independent of physics processes. Therefore,  $r/f$  extracted from **MR** can be used to estimate the contamination of *nonprompt* leptons in a different region (e.g. **SR**) even though these two regions are orthogonal to each other.

In this simplified scenario, the total number of events in the region of interest (e.g. **SR/VR**) with a *tight/not tight* lepton can be expressed in a system of equations,

$$\begin{aligned} N^T &= N_P^T + N_N^T \\ N^{\bar{T}} &= N_P^{\bar{T}} + N_N^{\bar{T}}, \end{aligned} \quad (15.3)$$

in which capital letter “ $N$ ” is used to indicate that these numbers are referring to events in a region that is different from **MR**.  $N_P^{\bar{T}}/N_N^{\bar{T}}$  can be expressed in terms of  $r/f$  and  $N_P^T/N_N^T$  according to Equation 15.1/15.2 and the assumption that  $r/f$  remains the same across different regions,

$$\begin{aligned} N^T &= r \frac{N_P^T}{r} + f \frac{N_N^T}{f} \\ N^{\bar{T}} &= (1-r) \frac{N_P^T}{r} + (1-f) \frac{N_N^T}{f}. \end{aligned} \quad (15.4)$$

Equation 15.4 can also be expressed in the form of matrix,

$$\begin{pmatrix} N^T \\ N^{\bar{T}} \end{pmatrix} = \begin{pmatrix} r & f \\ 1-r & 1-f \end{pmatrix} \begin{pmatrix} N_P^T/r \\ N_N^T/f \end{pmatrix}. \quad (15.5)$$

Regions that correspond to the two numbers that appear in the righthand side vector of Equation 15.5 are referred to as the “application regions (**ARs**)”, which can be constructed using experimental data. The estimation of *nonprompt* background, denoted by  $N_N^T$ , can be obtained by a simple matrix inversion.

## 15.2 Generalization and Implementation of the Matrix Method

The description in previous section deals with a scenario where only one lepton is studied. This analysis uses a generalized version of the *matrix method*, where all three *tight* leptons are considered to be possibly *nonprompt*. Equation 15.5 is generalized as,

$$\begin{pmatrix} N^{TTTT} \\ N^{TTT\bar{t}} \\ N^{TT\bar{t}t} \\ N^{T\bar{t}t\bar{t}} \\ N^{\bar{t}t\bar{t}t} \\ N^{\bar{t}t\bar{t}\bar{t}} \\ N^{\bar{t}t\bar{t}t} \\ N^{\bar{t}t\bar{t}\bar{t}} \end{pmatrix} = \begin{pmatrix} r_1 r_2 r_3 & r_1 r_2 \bar{f}_3 & r_1 \bar{f}_2 r_3 & r_1 \bar{f}_2 \bar{f}_3 & \bar{f}_1 r_2 r_3 & \bar{f}_1 r_2 \bar{f}_3 & \bar{f}_1 \bar{f}_2 r_3 & \bar{f}_1 \bar{f}_2 \bar{f}_3 \\ r_1 r_2 (1-r_3) & r_1 r_2 (1-\bar{f}_3) & r_1 \bar{f}_2 (1-r_3) & r_1 \bar{f}_2 (1-\bar{f}_3) & \bar{f}_1 r_2 (1-r_3) & \bar{f}_1 r_2 (1-\bar{f}_3) & \bar{f}_1 \bar{f}_2 (1-r_3) & \bar{f}_1 \bar{f}_2 (1-\bar{f}_3) \\ r_1 (1-r_2) r_3 & r_1 (1-r_2) \bar{f}_3 & r_1 (1-\bar{f}_2) r_3 & r_1 (1-\bar{f}_2) \bar{f}_3 & \bar{f}_1 (1-r_2) r_3 & \bar{f}_1 (1-r_2) \bar{f}_3 & \bar{f}_1 (1-\bar{f}_2) r_3 & \bar{f}_1 (1-\bar{f}_2) \bar{f}_3 \\ r_1 (1-r_2)(1-r_3) & r_1 (1-r_2)(1-\bar{f}_3) & r_1 (1-\bar{f}_2)(1-r_3) & r_1 (1-\bar{f}_2)(1-\bar{f}_3) & \bar{f}_1 (1-r_2)(1-r_3) & \bar{f}_1 (1-r_2)(1-\bar{f}_3) & \bar{f}_1 (1-\bar{f}_2)(1-r_3) & \bar{f}_1 (1-\bar{f}_2)(1-\bar{f}_3) \\ (1-r_1) r_2 r_3 & (1-r_1) r_2 \bar{f}_3 & (1-r_1) \bar{f}_2 r_3 & (1-r_1) \bar{f}_2 \bar{f}_3 & (1-\bar{f}_1) r_2 r_3 & (1-\bar{f}_1) r_2 \bar{f}_3 & (1-\bar{f}_1) \bar{f}_2 r_3 & (1-\bar{f}_1) \bar{f}_2 \bar{f}_3 \\ (1-r_1) r_2 (1-r_3) & (1-r_1) r_2 (1-\bar{f}_3) & (1-r_1) \bar{f}_2 (1-r_3) & (1-r_1) \bar{f}_2 (1-\bar{f}_3) & (1-\bar{f}_1) r_2 (1-r_3) & (1-\bar{f}_1) r_2 (1-\bar{f}_3) & (1-\bar{f}_1) \bar{f}_2 (1-r_3) & (1-\bar{f}_1) \bar{f}_2 (1-\bar{f}_3) \\ (1-r_1)(1-r_2) r_3 & (1-r_1)(1-r_2) \bar{f}_3 & (1-r_1)(1-\bar{f}_2) r_3 & (1-r_1)(1-\bar{f}_2) \bar{f}_3 & (1-\bar{f}_1)(1-r_2) r_3 & (1-\bar{f}_1)(1-r_2) \bar{f}_3 & (1-\bar{f}_1)(1-\bar{f}_2) r_3 & (1-\bar{f}_1)(1-\bar{f}_2) \bar{f}_3 \\ (1-r_1)(1-r_2)(1-r_3) & (1-r_1)(1-r_2)(1-\bar{f}_3) & (1-r_1)(1-\bar{f}_2)(1-r_3) & (1-r_1)(1-\bar{f}_2)(1-\bar{f}_3) & (1-\bar{f}_1)(1-r_2)(1-r_3) & (1-\bar{f}_1)(1-r_2)(1-\bar{f}_3) & (1-\bar{f}_1)(1-\bar{f}_2)(1-r_3) & (1-\bar{f}_1)(1-\bar{f}_2)(1-\bar{f}_3) \end{pmatrix} \begin{pmatrix} N_{PPP}^{TTTT}/r_1 r_2 r_3 \\ N_{PPN}^{TTTT}/r_1 r_2 \bar{f}_3 \\ N_{PNP}^{TTTT}/r_1 \bar{f}_2 r_3 \\ N_{PNN}^{TTTT}/r_1 \bar{f}_2 \bar{f}_3 \\ N_{NPP}^{TTTT}/\bar{f}_1 r_2 r_3 \\ N_{NPN}^{TTTT}/\bar{f}_1 r_2 \bar{f}_3 \\ N_{NNP}^{TTTT}/\bar{f}_1 \bar{f}_2 r_3 \\ N_{NNN}^{TTTT}/\bar{f}_1 \bar{f}_2 \bar{f}_3 \end{pmatrix}. \quad (15.6)$$

All but the first number that appear in the righthand side vector correspond to events with at least one *nonprompt* lepton that pass *tight* selection criteria. Therefore, the overall *nonprompt* background is expressed as,

$$N_{Nonprompt}^{TTTT} = N_{PPN}^{TTTT} + N_{PNP}^{TTTT} + N_{PNN}^{TTTT} + N_{NPP}^{TTTT} + N_{NPN}^{TTTT} + N_{NNP}^{TTTT} + N_{NNN}^{TTTT}, \quad (15.7)$$

which can be obtained by first constructing 8 **ARs** to form the lefthand side vector. Secondly, the  $8 \times 8$  matrix is constructed and inverted. Lastly, the righthand side vector can be obtained by multiplying the lefthand side vector to the inverted matrix.

Only two **PDs** “SingleElectron” and “SingleMuon” are used in the construction of **MR** in 2016 and 2017 while “SingleElectron” is replaced with “EGamma” in 2018. In addition to **PDs**, the measurements of  $r/f$  also utilize the  $t\bar{t}$  sample and all **MC** samples listed under the “prompt background” category in Table 12.3. Depending on the flavor of the leading lepton in **MC**, events are selected with either a single-electron or a single-muon trigger, which is summarized in Table 15.1. Data events are selected with the same **HLT** triggers as well but events in “SingleMuon” (“SingleElectron” or “EGamma”) **PD** are only accepted if the leading lepton is a muon (electron).

Channel	Path	Dataset	2016	2017	2018
Electron	HLT_Ele27_WPTight_Gsf	Data & MC	✓	-	-
	HLT_Ele35_WPTight_Gsf	Data & MC	-	✓	✓
Muon	HLT_IsoMu27	Data & MC	✓	✓	✓

**Table 15.1:** Summary of the **HLT** triggers used in the measurement of  $r$  and  $f$ .

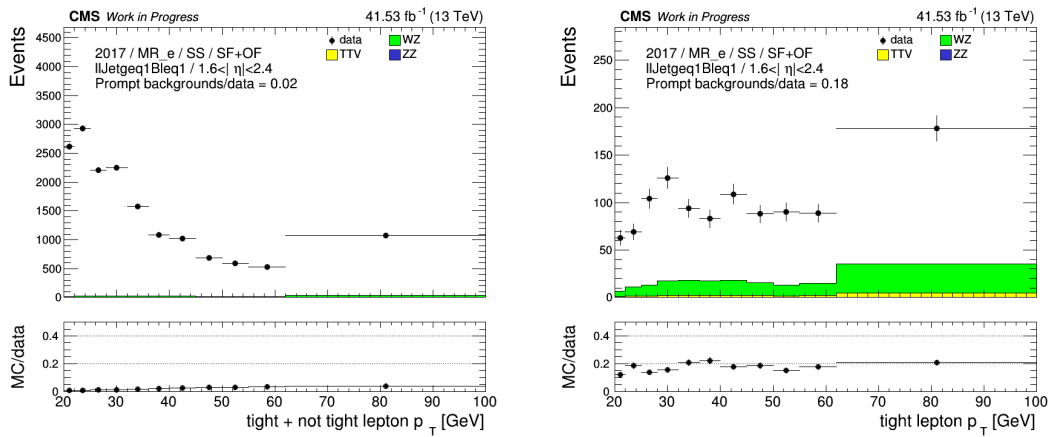
Both  $r$  and  $f$  are parameterized in bins of lepton  $p_T$ ,  $|\eta|$ , and jet multiplicity. The bin range is optimized to retain sufficient statistics for each bin:

- Electron  $p_T$  bin range:  $\{20.0, 24.6, 28.8, 33.0, 37.2, 41.4, 46.1, 52.1, 59.3, 68.3, 82.7, 110.6\}$  GeV,
- Muon  $p_T$  bin range:  $\{20.0, 23.8, 27.7, 31.3, 35.0, 38.9, 42.8, 45.6, 50.7, 59.5, 72.9, 94.3\}$  GeV,
- $|\eta|$  bin range:  $\{0, 0.8, 1.6, 2.4\}$ ,
- Jet multiplicity:  $\{0 \text{ jet}, \geq 1 \text{ jet}\}$ .

The jet multiplicity bin is a proxy for variation of the composition of physics processes. In addition to requiring at least one jet, the **MR** corresponds to the second jet multiplicity bin requires no more than one b-tagged jet as this is also required in the **SR**.

The *nonprompt* efficiency is measured in same-sign dilepton regions, in which the leading lepton in  $p_T$ , used as a *tag*, is required to be matched with trigger objects within  $\Delta R < 0.2$ . The sub-leading lepton is required to pass the *loose* selection and is taken as the *probe*. Events that have two same-sign electrons with an invariant mass between 76 GeV and 106 GeV are removed from **MR** to suppress the backgrounds that originate from charge misidentification. No such requirement has been introduced to the muon **MR** due to its negligible rate of charge misidentification.

The contribution from *prompt* backgrounds, estimated from **MC** simulation, are subtracted from data. A representative composition of backgrounds in **MR** is shown in Figure 15.2.



**Figure 15.2:** Distribution of lepton  $p_T$  in a representative electron *nonprompt* efficiency **MR**. In this particular example, both ee and  $\mu e$  flavor composites are considered. At least one jet and at most one b-tagged jet are required (the second jet multiplicity bin). *Probe* electron is required to have  $1.6 < |\eta| < 2.4$  (the third  $\eta$  bin). Contamination from *prompt* backgrounds are estimated with **MC** simulation, and are shown as histograms. The data are shown as filled points. From left to right: *loose* (i.e. *tight + not tight*) electron  $p_T$ , *tight* electron  $p_T$ .

The fake efficiency  $f$  is calculated as:

$$f = \frac{n_{data}^{tag+tight} - n_{MC(prompt)}^{tag+tight}}{n_{data}^{tag+loose} - n_{MC(prompt)}^{tag+loose}}, \quad (15.8)$$

where the numerator is selected with one *tag* and one *tight* lepton while the denominator is selected with one *tag* and one *loose* lepton. The selection criteria for *tag*, *loose*, and *tight* lepton is summarised in Table 15.3.

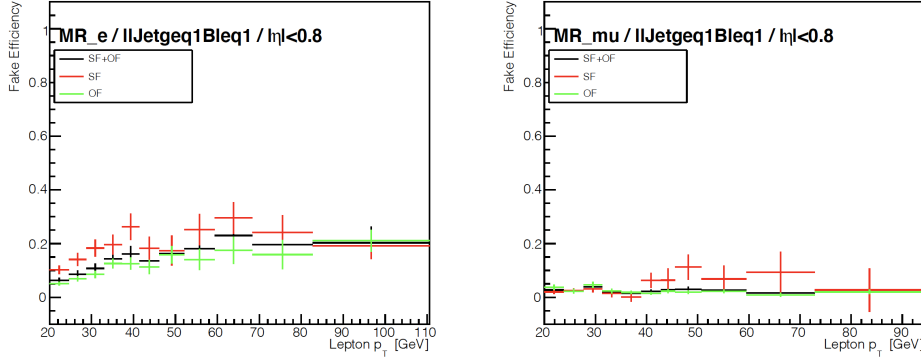
Lepton	Selection	<i>loose</i>	<i>tag</i>	<i>tight</i> <sup>ii</sup>
Electron	$p_T$	> 20 GeV	> 38 GeV <sup>i</sup>	> 20 GeV
	$I_{mini}^{rel}$	<0.4	<0.1	<0.12
	TOP LEPTONMVA	>-0.9	>0.95	>0.9
	Match with trigger objects	-	✓	-
Muon	$p_T$	> 20 GeV	> 30 GeV	> 20 GeV
	$I_{mini}^{rel}$	<0.4	<0.1	<0.12
	Cut-based ID	-	Medium WP	Medium WP
	TOP LEPTONMVA	>0.5	>0.9	>0.9
	Match with trigger objects	-	✓	-

**Table 15.2:** Summary of the lepton selections needed for the measurement of  $r$  and  $f$ . Please note: (i) the minimum  $p_T$  cut for *tag* electron in 2016 dataset is reduced to 30 GeV to adjust for the trigger threshold, and (ii) the *tight* selection here is the same as the *tight* lepton selection described in section 13.1.

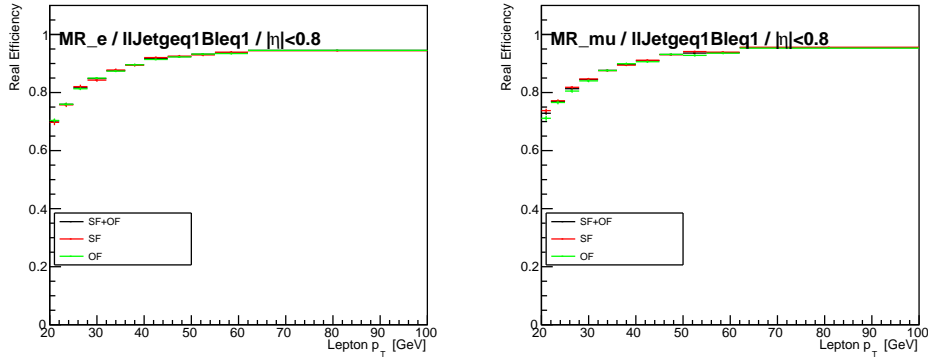
The measured *nonprompt* efficiency  $f$  exhibits a dependency on flavor composition, as is shown in Figure 15.3. This dependency is treated as a source of the systematic uncertainties of the *nonprompt* estimation and is further discussed in section 17.2.

The *prompt* efficiency  $r$  is measured in simulated  $t\bar{t}$  events in opposite-sign dilepton regions. The same lepton selection listed in Table 15.2 is used to perform the *Tag-and-Probe*. The leading lepton in  $p_T$  is used as a *tag* while the oppositely charged sub-leading lepton is taken as a *probe*. The variation of  $r$  between different flavor composition is negligible, as is shown in Figure 15.4. Therefore, only  $e\mu$  events are used to measure *prompt* efficiency in order to minimise the contamination of *nonprompt* leptons.

The selection criteria for various MRs is summarised in Table 15.3.



**Figure 15.3:** Representative *nonprompt* electron efficiency measured in data events. From left to right: electron  $f$ , muon  $f$ . Events with a same-flavor lepton pair are shown in red points while events selected with a different-flavor lepton pair are shown in green points. Events with a same-flavor or different-flavor lepton pair is shown in black points. These plots correspond to the first  $|\eta|$  bin ( $|\eta| < 0.8$ ) and the second jet multiplicity bin. Events selected Error bars displayed in these plots include statistical uncertainty only.



**Figure 15.4:** Representative *prompt* efficiency measured in simulated  $t\bar{t}$  events. From left to right: electron  $r$ , muon  $r$ . Events with a same-flavor lepton pair are shown in red points while events selected with a different-flavor lepton pair are shown in green points. Events with a same-flavor or different-flavor lepton pair is shown in black points. These plots correspond to the first  $|\eta|$  bin ( $|\eta| < 0.8$ ) and the second jet multiplicity bin. Error bars displayed in these plots include statistical uncertainty only.

### 15.3 Validation of the Matrix Method

The performance of the *matrix method* is validated using three regions that are tangential to the **SR**, referred to as **VRs**. In these **VRs**, *prompt* backgrounds are estimated using **MC** simulation while *nonprompt* background is estimated with the *matrix method*. A summary of the selections



Observable	jet bin	# of selected leptons	lepton flavor composite	$ \sum_i C_i $	OffZ	njet	nbjet
$f$	0 jet	2	any	2	same-sign ee	= 0	= 0
	1 or more jet	2	any	2	same-sign ee	$\geq 1$	$\leq 1$
$r$	0 jet	2	e $\mu$ only	0	-	= 0	= 0
	1 or more jet	2	e $\mu$ only	0	-	$\geq 1$	$\leq 1$

**Table 15.3:** Summary of the cuts applied to the  $r/f$  measurement region.

applied to these VRs is given in [chapter 14](#).

Distribution of the leading lepton  $\eta$  and jet multiplicity are shown in [Figure 15.5](#). Good agreement between data and background estimate has been observed in all three [VRs](#).

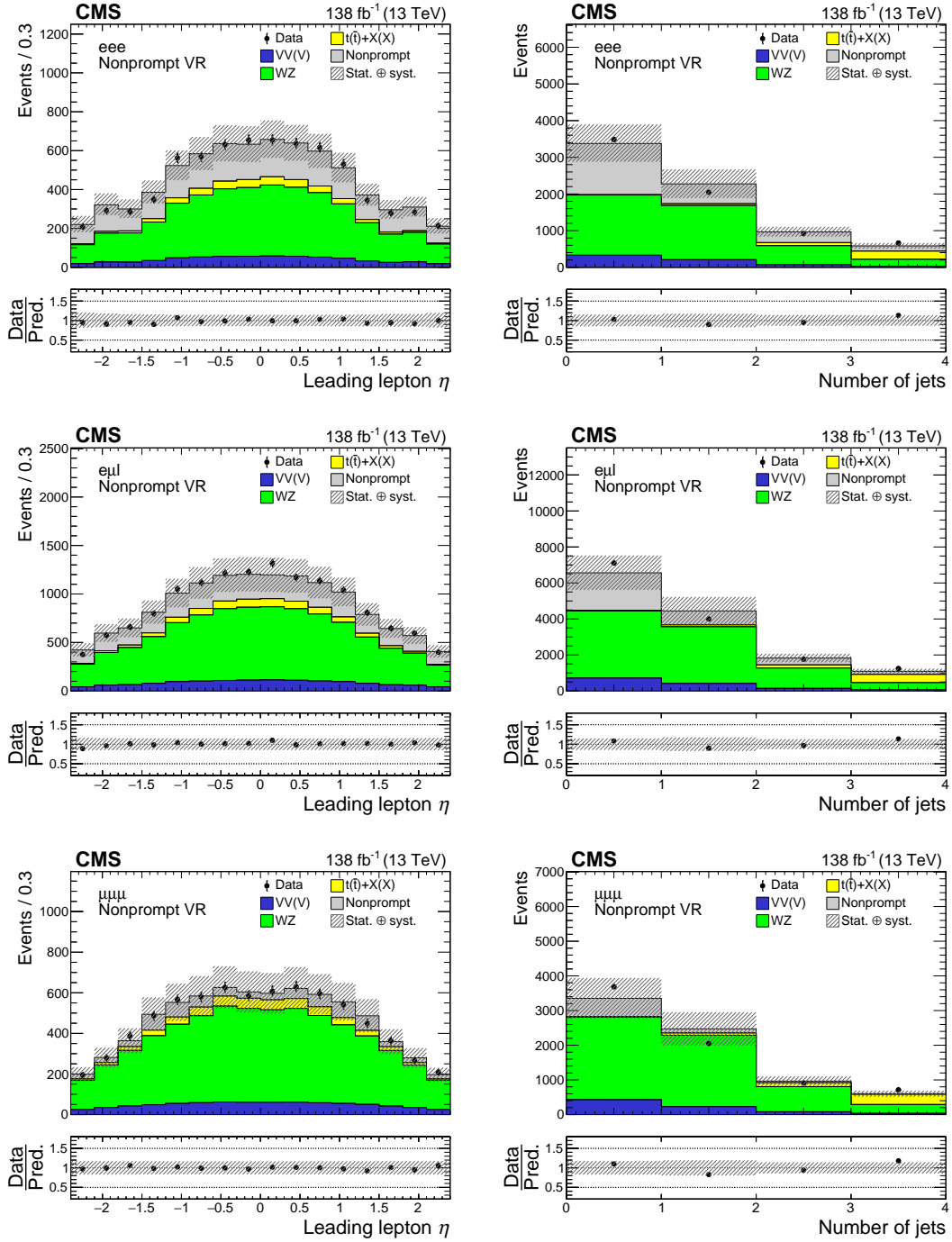
## 15.4 Nonprompt Estimate in SR

The *matrix method* is used to estimate *nonprompt* background in the [SR](#). Distributions of the LFV e $\mu$  mass and the Z boson mass are shown in [Figure 15.6](#). When compared to background estimate from pure [MC](#) simulation ([Figure 14.1](#)), the updated background template is smoother with lower statistical uncertainties.

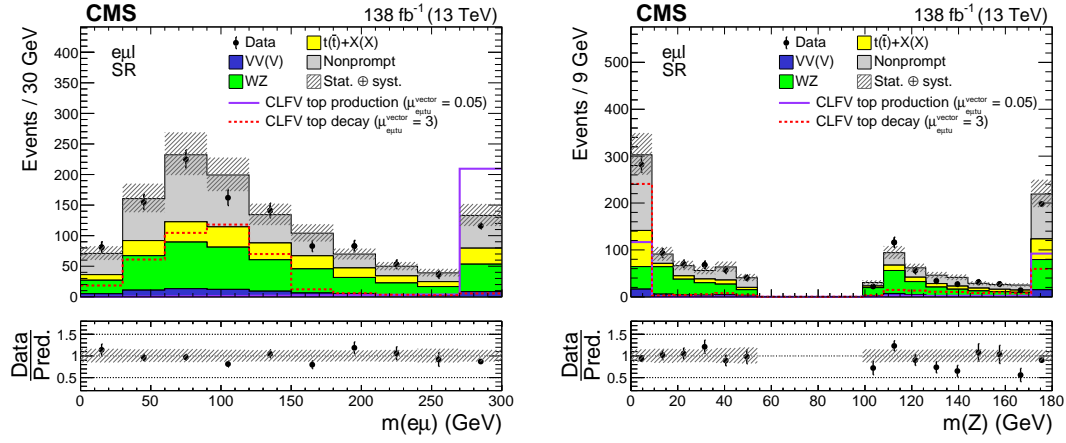
The number of expected events from various kinds of backgrounds are shown in [Table 15.4](#).

**Table 15.4:** Expected background contributions and the number of events observed in data collected during 2016–2018. The statistical and systematic uncertainties are added in quadrature. The category “other backgrounds” includes smaller background contributions containing one or two top quarks plus a boson or quark. The CLFV signal, generated with  $C_{\text{e}\mu\text{t}\text{u}}^{\text{vector}}/\Lambda^2 = 1\text{TeV}^{-2}$ , is also listed for reference. The signal yields include contributions from both top production and decay modes.

Process	$m(e\mu) < 150 \text{ GeV}$	$m(e\mu) > 150 \text{ GeV}$
Nonprompt	$351 \pm 92$	$146 \pm 38$
WZ	$275 \pm 64$	$145 \pm 35$
ZZ	$33.2 \pm 6.5$	$13.1 \pm 2.6$
VVV	$17.0 \pm 8.5$	$12.0 \pm 6.0$
$t\bar{t}W$	$47.6 \pm 10.0$	$40.0 \pm 9.1$
$t\bar{t}Z$	$39.1 \pm 7.9$	$25.8 \pm 5.4$
$t\bar{t}H$	$28.2 \pm 4.5$	$10.0 \pm 1.6$
$tZq$	$5.5 \pm 1.1$	$2.5 \pm 0.5$
Other	$7.3 \pm 3.7$	$4.5 \pm 2.3$
Total expected	$805 \pm 123$	$398 \pm 57$
Data	783	378
CLFV	$207 \pm 15$	$4440 \pm 215$



**Figure 15.5:** Distributions of the leading lepton  $\eta$  (left column) and the jet multiplicity (right column) in the *nonprompt VRs*. Events in the  $eee$ ,  $e\mu\ell$ , and  $\mu\mu\mu$  *nonprompt VRs* are shown in the upper, middle, and lower row, respectively. The data are shown as filled points and the **SM** background predictions as histograms. The *nonprompt* background is estimated using control samples in data, while other backgrounds are estimated using **MC** simulation. The hatched bands indicate statistical and systematic uncertainties for the **SM** background predictions. The last bin of the right histogram includes the overflow events.



**Figure 15.6:** Distributions of the LFV  $e\mu$  mass (left) and the Z boson mass (right) in **SR**. The data are shown as filled points and the **SM** background predictions as histograms. The *nonprompt* background is estimated using control samples in data, while other backgrounds are estimated using **MC** simulation. The hatched bands indicate statistical and systematic uncertainties for the **SM** background predictions. The normalisation of the signal processes is chosen arbitrarily for improved visualisation. The last bin of both histograms includes the overflow events.

# CHAPTER 16

## Signal Extraction with Boosted Decision Trees

A **MVA** is performed in **SR** to further separate the LFV signals from the backgrounds, and enhance the sensitivity of this analysis. More specifically, a dozen of discriminating variables, referred to as “features”, are selected and combined by a gradient-**BDT**, which is implemented using the XGBOOST package [32]. There are several reasons why **BDT** is chosen: (i) the goal of the **MVA** is to achieve maximum separation between signals and backgrounds using a small number of already well-separated kinematic variables, instead of exploring some complicated structures hidden in event topology, (ii) under such a goal, the potential performance gain from a more sophisticated algorithm like a **NN** is limited, (iii) a **BDT**-based algorithm is straightforward to implement and consumes only a moderate amount of computational resources, and (iv) the interpretability of a **BDT**-based algorithm is excellent.

The top production and decay signals are longer distinguished by the **BDT**. They are combined into a single signal class, just like all backgrounds are combined into a single background class. The training of the **BDT** depends entirely on **MC** samples that are statistically orthogonal to the samples used in the actual background estimation. More details on the configurations of the **BDT** are described in section 16.1. The input features are described in section 16.2. The output of the **BDT** is presented in section 16.3.

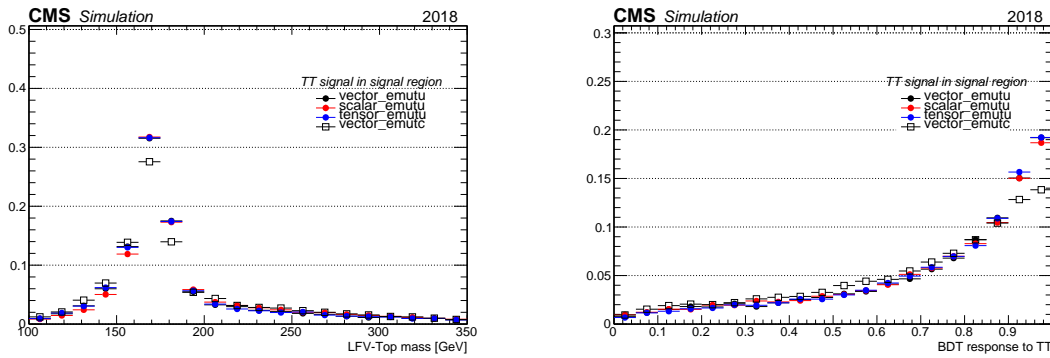
### 16.1 BDT Configuration

The LFV  $e\mu$  mass of the top decay signal is bounded by the **SM** top quark mass, as is shown in Figure 14.1. On the contrary, the LFV  $e\mu$  mass of the top production signal has no such restriction and often reaches TeV level. Therefore, a 150 GeV threshold is used to divide the **SR** into two **SRs** enriched in different signal modes. The **MVA** strategy is to combine two signal modes within each **SR** and train binary **BDTs** separately for each **SR**. In other words, only two signal datasets and two background datasets are needed.

Other aspects of the signal **MC** samples, such as the Lorentz structure and the flavor of the up-type quark involved in LFV interaction, are shown to have a relatively small impact on the kinematics of final state particles, as is shown in Figure 16.1. Therefore, they are not distinguished by the **BDT**. The selection criteria used to define **SR**, described in section 14.1, are used to

preselect events before the construction of both signal and background datasets.

The construction of the signal datasets take a few steps. Firstly, the cross sections of all top production signal samples, regardless of the Lorentz structure or the quark flavor, are set to the cross section of the vector-like top production signal with an  $e\mu$  vertex, which is shown in Table 12.2. This is done to remove potential bias towards the signals with higher cross sections. Similarly, the cross sections of all top decay signal samples are set to the cross section of the vector-like top decay signal. For each sample, a normalisation weight is calculated and is used to replace the original normalisation component of the MC weights. These updated MC weights are eventually passed on to the BDT to weight each signal event. Secondly, all top production and decay signal samples are combined into a single dataset, which is then sub-divided into two datasets using a 150 GeV threshold on LFV  $e\mu$ . The last step is to adjust the overall normalisation (i.e. sum of the MC weights) of each of the two signal datasets to match the overall normalisation of the corresponding background dataset.



**Figure 16.1:** Normalized distribution in SR1. From left to right: LFV top mass, BDT shape

The *prompt* background dataset is constructed by combining all MC samples listed under the “prompt” category listed in Table 12.3. Cross sections referenced Table 12.3 are directly used to normalise the *prompt* backgrounds. The construction of the *nonprompt* background dataset is different since the *nonprompt* backgrounds are modelled with the *matrix method*, which is itself constructed from 8 ARs. Therefore, 8 ARs are constructed to collect simulated  $t\bar{t}$  and Drell-Yan events. These events used to form the *nonprompt* dataset. Each event in the *nonprompt* dataset is then “weighted” using the output of the *matrix method*. Finally, the *nonprompt* dataset is combined with the *prompt* dataset and then divided into two datasets using a 150 GeV threshold on LFV  $e\mu$  mass.

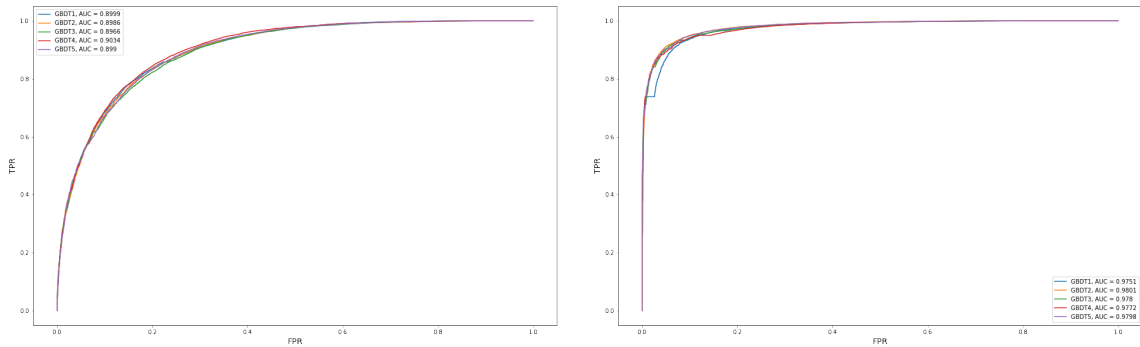
A technique known as the “ $k$ -fold cross validation” is used to minimise the loss of statistics when partitioning datasets into training, validation, and test sets. For each targeted SR, the corresponding signal/background set is divided evenly into five subsets. Three out of the five subsets are used in the training while a fourth subset is used as a validation set. The fifth set is used to test the performance of the trained BDT. A second BDT is trained using a different combination of subsets to form training, validation, and test sets. This process is repeated five

times until a unique test set no longer exists, which is illustrated in Figure 16.2. This technique ensures that the test set is always statistically independent of the process of parameters tuning, which serves as the basis for the bias-free evaluation after training: when evaluating each event using the trained model, it is always possible to pick one of the five BDTs where this particular event was not included in the training or validation.

**Figure 16.2:** Illustration of a 5-fold cross validation.

Signal / background set				
training set			validation set	test set
BDT 1	BDT 1	BDT 1	BDT 1	BDT 1
BDT 2	BDT 2	BDT 2	BDT 2	BDT 2
BDT 3	BDT 3	BDT 3	BDT 3	BDT 3
BDT 4	BDT 4	BDT 4	BDT 4	BDT 4
BDT 5	BDT 5	BDT 5	BDT 5	BDT 5

The same set of hyper parameters are used for all BDTs, which are optimised using a randomised grid search algorithm. The number of estimators is set to 1000 with a max depth of 5. Standard loss function implemented in [32] is used as the evaluation metric. The performance of the BDT is visualised using a metric known as “receiver operating characteristic curve (ROC)”, which is shown in Figure 16.3. In general, the BDTs trained in SR2 (i.e.  $m_{e\mu} > 150$  GeV) are much more performant due to the high  $p_T$  objects in the final states.



**Figure 16.3:** ROC curve with 5-fold cross validation. From left to right: BDT targeting TT (SR1), BDT targeting ST (SR2).

## 16.2 BDT Features

The discriminating variables used as input in training are referred to as "features" in this analysis. A total of 14 features are used for BDT trained in SR1 and SR2. The names and descriptions of these 14 features are summarized in Table 16.1. Many of these features are derived from reconstructed heavy objects which are described in section 14.3.

**Table 16.1:** Features shared by BDTs trained in both SR1 and SR2.

Name	Description
MVA_Memu	invariant mass of the LFV- $e\mu$ pair
MVA_LFVePt	$p_T$ of the LFV electron
MVA_LFVmuPt	$p_T$ of the LFV muon
MVA_LFVTopmass	invariant mass of the LFV top quark candidate
MVA_Zmass	invariant mass of Z boson candidate
MVA_Jet2Btag	b-tagging score of the jet with the second highest b-tagging score
MVA_Mbl2	invariant mass of the second $m_{b\ell}$ system
MVA_njet	number of jets
MVA_nbjet	number of b-tagged jets
MVA_tM	transverse mass of the W boson candidate (from the SM top quark)
MVA_lIDr	$\Delta R$ between LFV electron and LFV muon
MVA_SSee_Zmass	invariant mass of a Same-Sign di-electron pair
MVA_Topmass	invariant mass of the SM top quark candidate
MVA_Met	missing transverse momentum (MET)

Four additional features are added to the BDT trained in SR1. The "MVA\_JeDr" and "MVA\_JeDr" variables are defined by using the jet that forms the LFV top quark candidate and calculate the opening angle between this jet and the LFV leptons. It is expected that this angle is smaller in the LFV decay mode than LFV production mode. Two additional features are added to the BDT trained in SR2. Description on how the standalone lepton is determined can be found in section 14.3.

Distributions of selected features are shown in Figure 16.4-16.8. Distributions of the full list of features can be found in Appendix B. The relative importance of these feature is extracted using the "gain" method and is shown in Figure 16.9. The correlation between different features are shown in Figure 16.10-16.11.

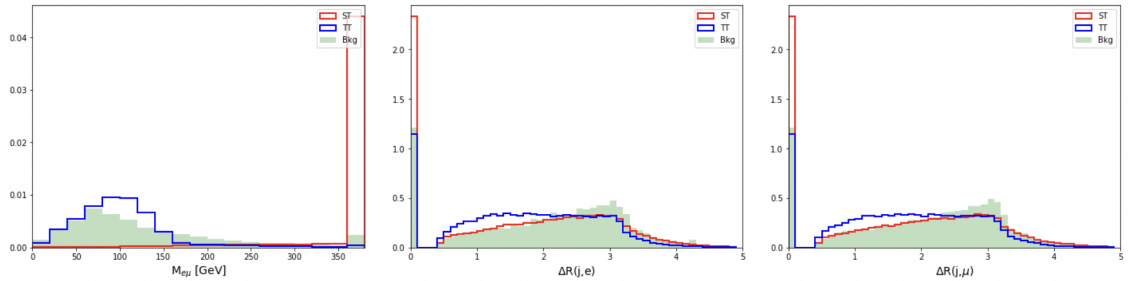


**Table 16.2:** Features only used by **BDT** trained in **SR1**

Name	Description
MVA_Ht	scalar sum of the $p_T$ of all jets and leptons
MVA_Mbl1	invariant mass of the second $m_{b\ell}$ system
MVA_JeDr	$\Delta R$ between LFV electron and a light jet (non b jet)
MVA_JmuDr	$\Delta R$ between LFV muon and a light jet (non b jet)

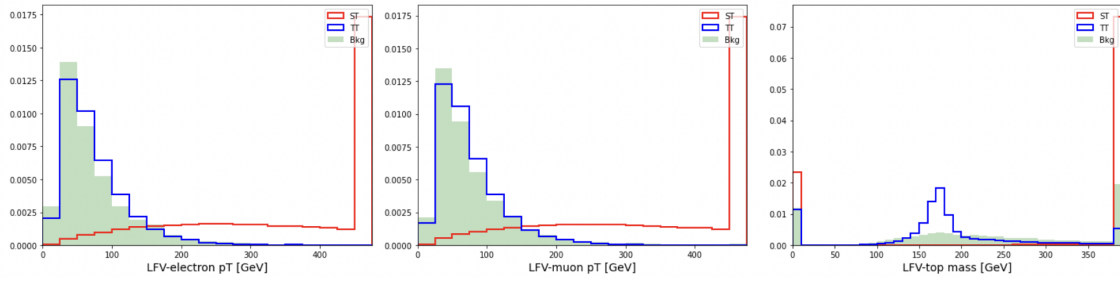
**Table 16.3:** Features only used by **BDT** trained in **SR2**

Name	Description
MVA_BaPt	$p_T$ of the standalone lepton
MVA_JetHt	scalar sum of the $p_T$ of all jets

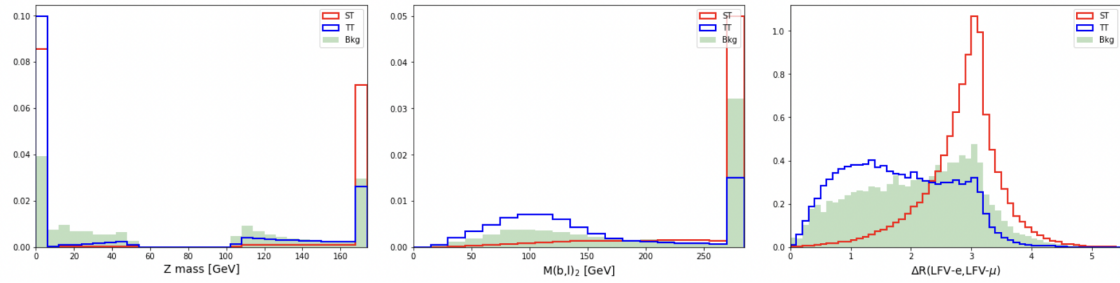
**Figure 16.4:** Normalized distribution of various features in SR. From to left to right: MVA\_  $M_{e\mu}$ , MVA\_  $\Delta R(j,e)$ , MVA\_  $\Delta R(j,\mu)$ .

### 16.3 BDT Output

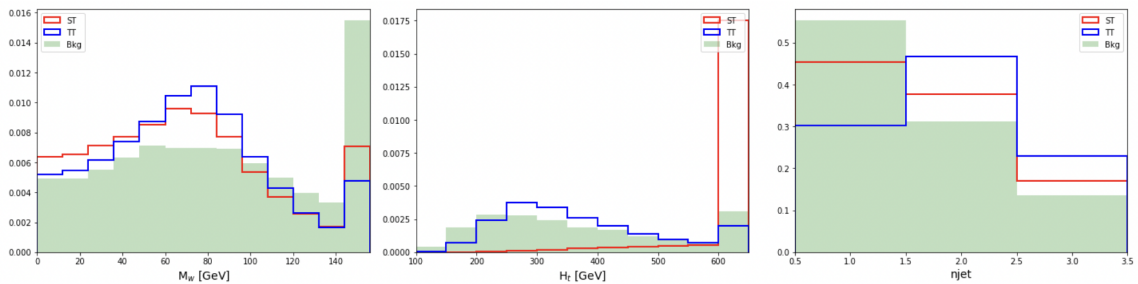
The output of the **BDTs** in **SRs** are shown in Figure 16.12. The *nonprompt* background is estimated with the matrix method. Other backgrounds are estimated with **MC** simulation.



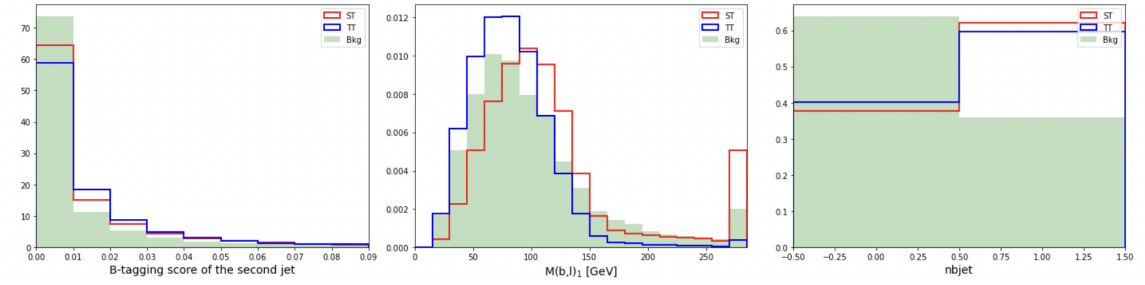
**Figure 16.5:** Normalized distribution of additional features in SR. From to left to right: MVA\_LFVePt, MVA\_LFVmuPt, MVA\_LFVTopmass.



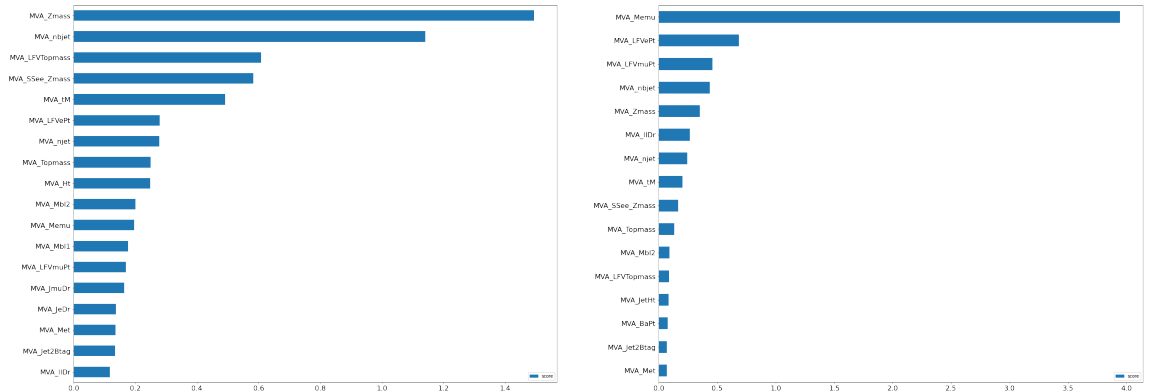
**Figure 16.6:** Normalized distribution of additional features in SR. From to left to right: MVA\_Zmass, MVA\_Mbl2, MVA\_IIDr.



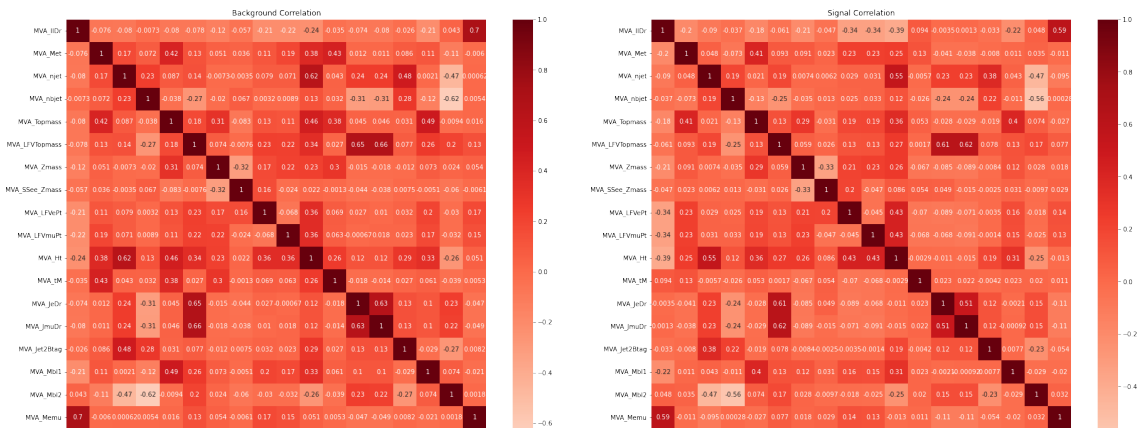
**Figure 16.7:** Normalized distribution of additional features in SR. From to left to right: MVA\_tM, MVA\_Ht, MVA\_njet.



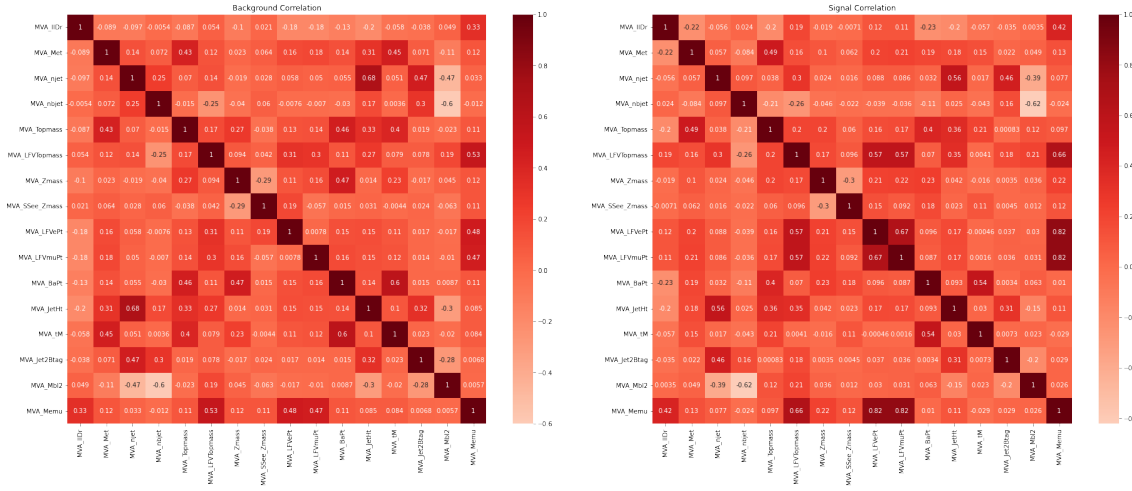
**Figure 16.8:** Normalized distribution of additional features in SR. From left to right: MVA\_Jet2Btag, MVA\_Mbl1, MVA\_nbjet.



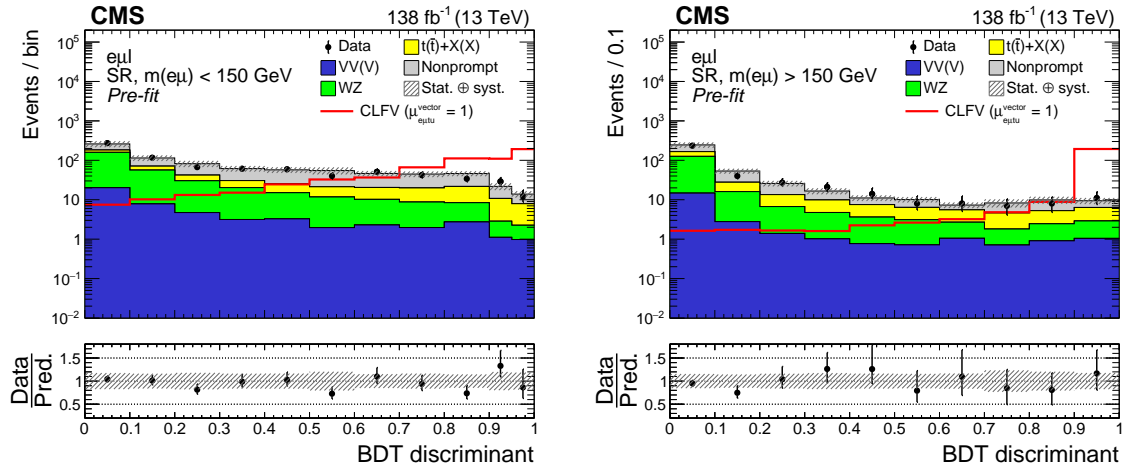
**Figure 16.9:** List of features ranked by their relative importance. From left to right: BDT targeting TT (SR1), BDT targeting ST (SR2)



**Figure 16.10:** Correlation matrices (SR1), from left to right: background correlation, signal correlation.



**Figure 16.11:** Correlation matrices (SR2), from left to right: background correlation, signal correlation.



**Figure 16.12:** Distributions of the BDT discriminator targeting the CLFV top quark decay (left) and production (right) signal. Contributions from the two signal modes (production and decay) are combined within each SR and are shown as the solid red line. The pre-fit signal strength ( $\mu_{\text{e}^+\mu^-}^{\text{vector}} = 1$ ), corresponding to  $C_{\text{e}^+\mu^-}^{\text{vector}}/\Lambda^2 = 1 \text{ TeV}^{-2}$ , is used to normalise the signal cross sections. The hatched bands indicate statistical and systematic uncertainties for the background predictions.

# CHAPTER 17

## Systematic Uncertainties

Different sources of systematic uncertainty contribute to the estimation of background events and modeling of the signal. The chapter is organized as follows. Theoretical uncertainties concerning signals and major backgrounds are discussed in [section 17.1](#). Uncertainties concerning the *nonprompt* background is discussed in [section 17.2](#). Uncertainties concerning the modeling of the diboson processes are discussed in [section 17.3](#). Finally, other systematic uncertainties are discussed in [section 17.4](#).

### 17.1 Theoretical Uncertainties

Variations on theoretical cross sections for *prompt* backgrounds are introduced to cover the uncertainties in perturbative [QCD](#) calculations. A 6% normalization uncertainty is assigned to WZ and ZZ processes [\[21\]](#). A 15% normalization uncertainty is assigned to  $t\bar{t}W$ ,  $t\bar{t}Z$ , and  $t\bar{t}H$  processes [\[22, 23\]](#). A 20% normalization uncertainty is assigned to  $tZq$  process, which is a conservative estimate taken from the MC generator. A conservative 50 % normalization uncertainty is assigned to other smaller *prompt* backgrounds. All normalization uncertainties are considered uncorrelated between different processes but correlated across the years.

Uncertainties associated to the [PDF](#) are evaluated by using 100 replicas of the NNPDF sets [\[15, 16\]](#). The procedure described in [\[33\]](#) is followed. Firstly, the sum of the generator weights of each replica is normalized to the nominal sum of the generator weights. This is done before any event selection to ensure no additional normalization effect is introduced. After previous step, the bin-by-bin variations of the [BDT](#) templates are obtained by calculating the bin-by-bin difference of the [BDT](#) templates when switching from nominal [PDF](#) to each [PDF](#) replica. Finally, [PDF](#) uncertainty for each bin is assigned by taking the root mean square value of the 100 variations of the corresponding bin. This uncertainty is treated as uncorrelated between different processes but correlated across the years. We consider this uncertainty for all the signals and major prompt backgrounds (i.e. WZ,  $t\bar{t}W$ ,  $t\bar{t}Z$ , and  $t\bar{t}H$ ).

[QCD](#) scale uncertainties are evaluated by varying the renormalization scale  $\mu_R$  and factorization scales  $\mu_F$  in [ME](#). A total of six variations are considered: varying  $\mu_R$  by a factor of 2 and 0.5, varying  $\mu_F$  by a factor of 2 and 0.5, and varying  $\mu_R$  and  $\mu_F$  simultaneously by a factor of 2 and

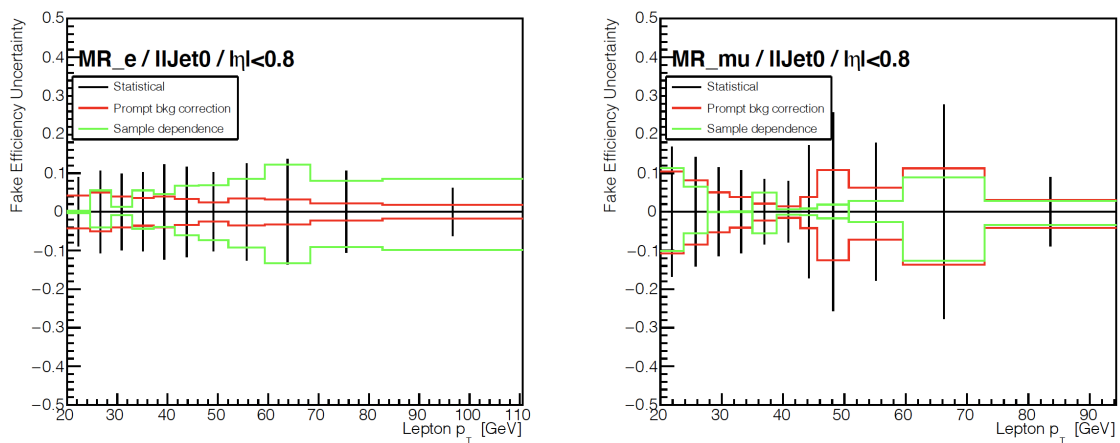
0.5. Similar to PDF uncertainty, normalization effects of each variation is removed. An envelope that covers all six variations is used to represent the scale uncertainty. This uncertainty is treated as uncorrelated between different processes but correlated across the years. We consider this uncertainty for all the signals and major prompt backgrounds (i.e. WZ,  $t\bar{t}W$ ,  $t\bar{t}Z$ , and  $t\bar{t}H$ ).

Uncertainties associated to the parton shower (PS) are evaluated by varying the renormalization scale  $\mu_R$  in the initial and final state radiations, which effectively changes the strong coupling constant in the PS. Similarly,  $\mu_R$  is varied by a factor of 2 and 0.5, and normalization effects of each variation is removed. This uncertainty is treated as uncorrelated between different processes but correlated across the years. We consider this uncertainty for all the signals and major prompt backgrounds (i.e. WZ,  $t\bar{t}W$ ,  $t\bar{t}Z$ , and  $t\bar{t}H$ ).

## 17.2 Nonprompt Uncertainties

There are several sources of uncertainties associated to the determination of the *nonprompt* efficiency  $f$ . One of these uncertainties comes from the estimate of *prompt* contamination in MR. As is discussed in chapter 15, *prompt* backgrounds (estimated with MC) are subtracted from total event yields measured in data. A flat 20 % uncertainty ( $\alpha$  in Equation 17.1) is assigned to the event yields of the *prompt* background and the resulting variation of  $f$  is taken as the uncertainty.

$$f = \frac{n_{data}^{tag+tight} - (1 + \alpha)n_{MC(prompt)}^{tag+tight}}{n_{data}^{tag+loose} - (1 + \alpha)n_{MC(prompt)}^{tag+loose}}. \quad (17.1)$$



**Figure 17.1:** Comparison of different components of the uncertainties associated to the *nonprompt* efficiency measured in 2017 dataset ( $n_{jet}=0$  bin,  $|\eta| < 0.8$  bin). From left to right: electron  $f$  uncertainty, muon  $f$  uncertainty.

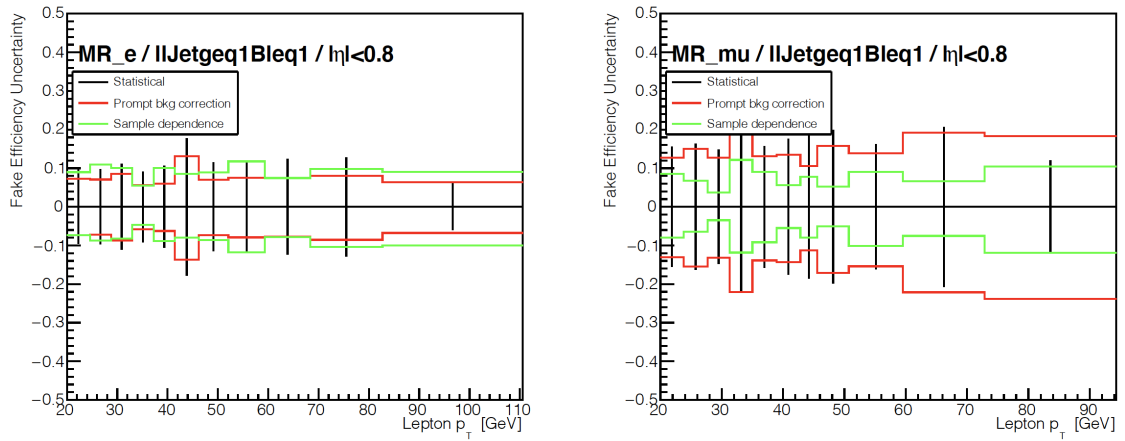
Another source of uncertainty associated to the determination of *nonprompt* efficiency  $f$  is concerned with the observation that  $f$  exhibits a flavor-dependency, as is shown in Figure 15.3.

This can happen when different physics processes enter **MRs** with different lepton flavor composites, which lead to differences in *nonprompt* lepton behaviors. This type of uncertainty, referred to as “sample dependence”, is estimated by introducing a variation factor  $\beta$  between the proportions of same-flavor and different-flavor pairs in **MR**. For example, electron  $f$  can be calculated as (prompt background correction is ignored from the equation),

$$f_e = \frac{(1 + \beta)n_{e+e}^{tag+tight} + (1 - \beta)n_{e+\mu}^{tag+tight}}{(1 + \beta)n_{e+e}^{tag+loose} + (1 - \beta)n_{e+\mu}^{tag+loose}}. \quad (17.2)$$

A 20% variation ( $\beta$ ) is assigned the resulting variation of  $f$  is taken as the uncertainty.

Statistical uncertainty is also considered when determining  $f$ . A comparison of different sources of uncertainties are shown in Figure 17.1 and Figure 17.2. All sources of uncertainties are added in quadrature to form the final uncertainty on  $f$ .



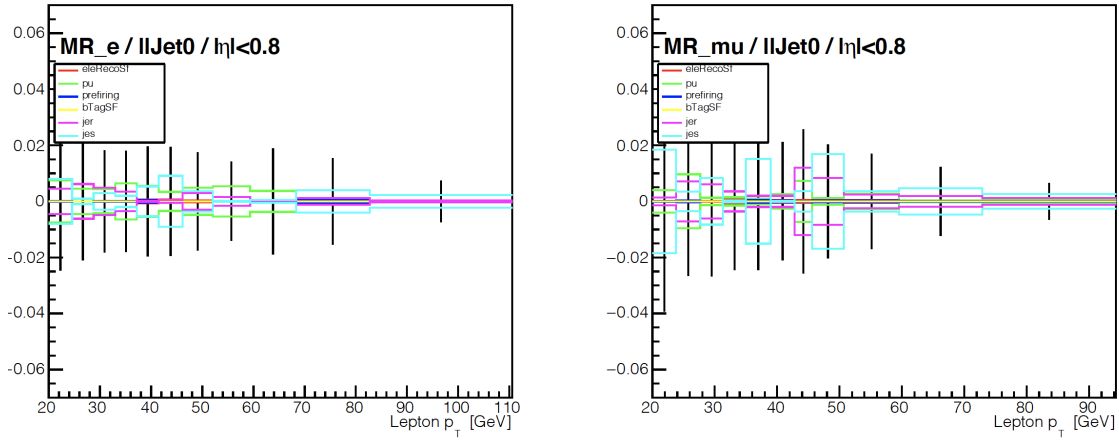
**Figure 17.2:** Comparison of different components of the uncertainties associated to the *non-prompt* efficiency measured in 2017 dataset ( $n_{jet}>0$  bin,  $|\eta| < 0.8$  bin). From left to right: electron  $f$  uncertainty, muon  $f$  uncertainty.

Since the *prompt* efficiency  $r$  is measured in simulated  $t\bar{t}$  events, **MC** uncertainties described in section 17.4 are propagated to  $r$  as the uncertainties. Additionally, statistical uncertainty is added in quadrature to the MC uncertainties to form the final uncertainty on  $r$ .

The uncertainties associated to the *prompt* efficiency are relatively small when compared to the *nonprompt* efficiency uncertainties. A comparison of different sources of *prompt* efficiency uncertainties are shown in Figure 17.3.

Uncertainties associated to  $r$  and  $f$  are determined separately for electron and muon. Therefore, there are four independent uncertainties:  $r_e$ ,  $r_\mu$ ,  $f_e$  and  $f_\mu$ .

A fifth uncertainty is considered that accounts for the potential bias caused by the way the generalized matrix method is implemented. Four out of the eight **ARs** that appear on the lefthand



**Figure 17.3:** Comparison of different components of the uncertainties associated to the *prompt* efficiency measured in 2017 dataset ( $n_{\text{jets}}=0$  bin,  $|\eta| < 0.8$  bin). From left to right: electron  $r$  uncertainty, muon  $r$  uncertainty.

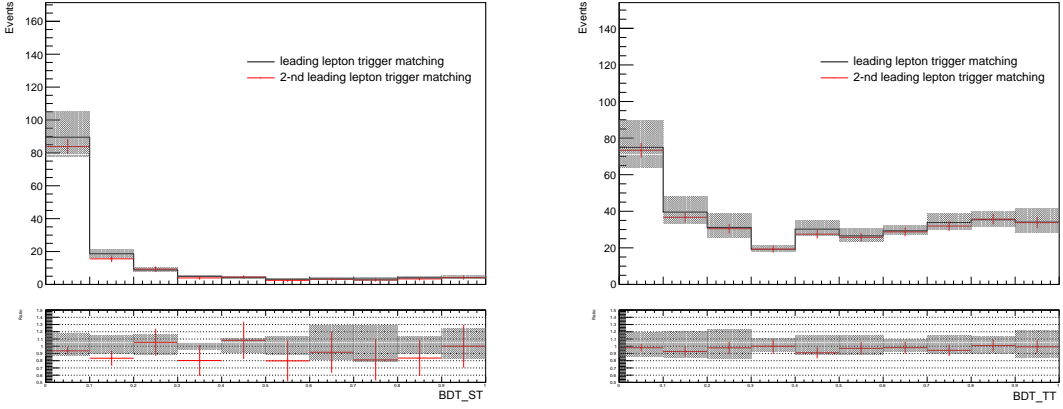
side of the Equation 15.6 (i.e.  $N^{\overline{T}TTT}$ ,  $N^{\overline{T}T\overline{T}T}$ ,  $N^{\overline{T}T\overline{T}T}$ ,  $N^{\overline{T}T\overline{T}T}$ ) are selected by requiring the leading lepton in  $p_T$  to fail the *tight* criteria described in Table 15.2. Effectively this means that the isolation requirement is reversed for leading lepton that enter these four ARs. Selecting the leading lepton by a loose requirement is not ideal since the leading lepton is required to match with iso-triggers. To account for this bias, a 50 % uncertainty is assigned to the  $f_1$  (*nonprompt* efficiency associated to the leading lepton) for events that enter these four ARs. The variation of the *nonprompt* estimate due to trigger matching is largely covered by this uncertainty, as is shown in Figure 17.4.

The five components of the uncertainties discussed in this section are propagated through the matrix inversion. The resulting variations of the *nonprompt* estimates are taken as the uncertainties, which contain both normalization and differential effects to the BDT templates. These uncertainties are treated uncorrelated between different components but correlated across the years. In addition to these five uncertainties, an overall normalization uncertainty of 10% is assigned to cover any other potential variations of the *nonprompt* backgrounds.

### 17.3 Diboson Uncertainties

Mismodeling of the jet multiplicity is observed in WZ control region, as is shown in Figure 14.3. This is largely due to the fact WZ process is modeled at LO with one extra parton in the ME. Any other extra jets are modeled by the parton shower, which is suboptimal when compared to the modeling from ME. To take this into account, a dedicated jet-dependent uncertainty is assigned to each event. This uncertainty is determined using diboson VR that has the same OnZ requirement as the WZ VR, no jet multiplicity requirement, a  $\text{MET} > 85$  GeV requirement,



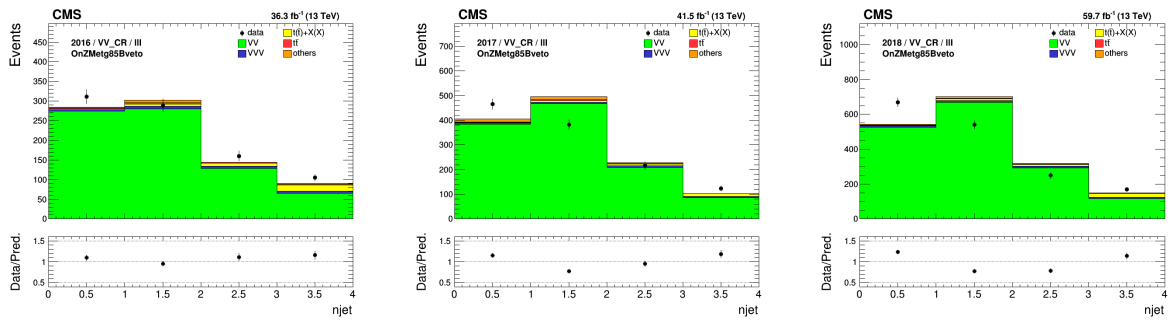


**Figure 17.4:** The impact of matching leptons to trigger objects on *nonprompt* estimate. From left to right: *nonprompt* estimate in top production enriched **SR**, *nonprompt* estimate in top decay enriched **SR**. The nominal configuration of the matrix method is to match the leading lepton with trigger objects. Matching the sub-leading with the trigger objects is taken as an alternative to evaluate the robustness of the *nonprompt* estimate. The uncertainty band only covers the variation of the *nonprompt* estimate as a result of varying leading lepton  $f$  by 50 %. Uncertainty bars only include statistical uncertainties.

and a requirement of no b-tagged jets with  $p_T > 20$  GeV. Unlike for the WZ **VR**, events with different lepton flavor compositions are combined.

The jet multiplicity distributions in diboson **VR** are shown in Figure 17.5. For each year, a scale factor parameterized as bins of jet multiplicity is derived,

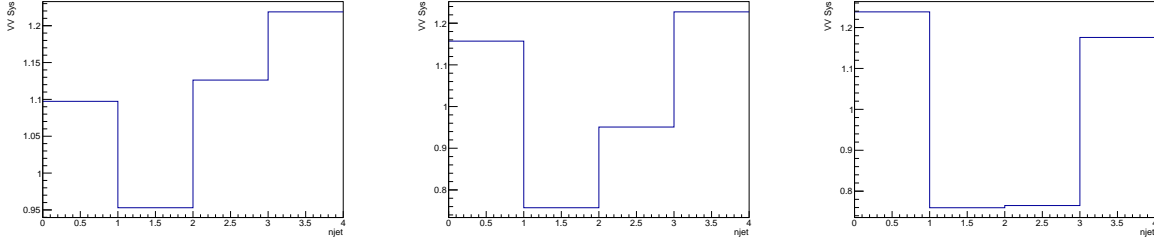
$$\epsilon = \frac{N_{data} - N_{VV} - N_{t\bar{t}+X(X)} - N_{t\bar{t}} - N_{others}}{N_{VV}}. \quad (17.3)$$



**Figure 17.5:** The diboson **VRs**, from left to right: 2016, 2017 and 2018 datasets.

The scale factor  $\epsilon$  is used to estimate the uncertainty, denoted by  $\Delta$ ,

$$\Delta = |1 - \epsilon| \quad (17.4)$$



**Figure 17.6:** Scale factors derived from the diboson **VRs**, from left to right: 2016, 2017 and 2018 datasets.

This uncertainty shifts the predictions of WZ and ZZ processes by up to 20%, as is shown in Figure 17.6.

## 17.4 Other Experimental Uncertainties

Uncertainties of 1.2, 2.3, and 2.5% are assigned to the integrated luminosity for 2016, 2017, and 2018, respectively [34, 35, 36]. These uncertainties affect the normalization of the **BDT** templates of all signals as well as *prompt* backgrounds. Correlation between these uncertainties are taken into account when combining 2016-2018 datasets together.

**PU** distributions of all signals and *prompt* backgrounds are reweighted using per-event scale factors to recreate the **PU** profile measured in data. The uncertainties associated with these scale factors are evaluated by varying the inelastic pp cross section by  $\pm 4.6$  [37]. These uncertainties are considered correlated across the years.

Calibrations of the reconstruction of electrons and muons are done centrally at **CMS** by using tag-and-probe approach in DY enriched dilepton events. Per-object scale factors are used to correct for the discrepancy between reconstruction efficiencies measured in data and **MC**. Limited sample size as well as the choice of fit models contribute to the uncertainties associated to these scale factors. These uncertainties are considered correlated across the years.

The TOP LEPTONMVA covers both identification and isolation of *prompt* leptons. Similar to lepton reconstruction, the calibration of TOP LEPTONMVA is done using tag-and-probe approach in DY enriched dilepton events. Per-object scale factors are used to correct for the discrepancy between reconstruction efficiencies measured in data and **MC**. Uncertainties of these scale factors are divided into two separate uncertainties: the statistical components of these uncertainties are treated as uncorrelated across the years while the other components are merged and treated as fully correlated across the years. For high  $p_T$  electrons and muons ( $p_T > 200$  GeV), an additional uncertainty, denoted by “eleIDHighPt/muIDHighPt”, is assigned and

it increases linearly from 0 to 10% (200 GeV-1000 GeV) and is capped at 10% after 1000 GeV. These additional uncertainties are introduced because the efficiency calibration is largely done in low  $p_T$  phase space. This additional uncertainty is considered correlated across the years.

Calibrations of energy scale and resolution of electrons are done centrally at CMS [38] and no uncertainties are considered as they are largely negligible. Calibrations of muon energy scale and resolution are done using the “Rochester algorithm” [39] for muons with  $p_T < 200$  GeV. “MuonScale” is used to denote the uncertainties associated to this correction, which comes primarily from limited sample size. For muons with  $p_T > 200$  GeV, no corrections are applied as there are not enough events for a robust correction from the “Rochester algorithm”. An additional uncertainty, also denoted by “MuonScale” is assigned to the momentum of these high  $p_T$  muons using the “Generalized Endpoint method” [40]. The “MuonScale” uncertainty is considered correlated across the years.

No calibration is done for trigger efficiency as they are generally close to 1 in both data and MC. A flat 2% uncertainty is assigned to all signals and *prompt* backgrounds to cover statistical fluctuations. This uncertainty is treated as uncorrelated across the years.

Calibrations of the DEEPJET scores are described in section 13.2. Uncertainties associated to the calibrations are divided into 8 different sources to properly account for the correlations, which are summarized in Table 17.1. For b and udsg jets, lf, hf, hfstats1/2, and lfstats1/2 uncertainties are applied. For c jets, cferr1/2 uncertainties are applied.

**Table 17.1:** A hyphen (–) denotes that a source is not correlated across the years.

Source	Correlated	Description
lf	✓	udsg+c jets in heavy flavor region
hf	✓	b+c jets in light flavor region
hfstats1	–	Linear fluctuations of c jets
hfstats2	–	Quadratic fluctuations of c jets
lfstats1	–	Linear fluctuations of udsg jets
lfstats2	–	Quadratic fluctuations of udsg jets
cferr1	✓	Linear fluctuations of c jets
cferr2	✓	Quadratic fluctuations of c jets

Calibrations of JES and JER are done centrally at CMS [41]. Uncertainties associated to the JES calibrations are divided into 27 sources to properly account for correlations, which are summarized in Table 17.2. Uncertainties associated to the calibrations of JER are considered as a separate uncertainty, which are uncorrelated across the years. Variations of JES and JER due to these uncertainties are propagated to the MET and calibrations of the DEEPJET scores: scale

factors used to correct DEEPJET scores and the MET vector are recomputed for each of the jet energy variation and treated as uncertainties that are fully correlated to the respective jet energy variation.

**Table 17.2:** Summary of the sources of uncertainty related to the JECs. A hyphen (–) denotes that a source is not correlated across the years.

Source	Correlated	Source	Correlated
AbsoluteStat	–	RelativePtHF	✓
AbsoluteScale	✓	RelativeBal	✓
AbsoluteMPFBias	✓	RelativeSample	–
Fragmentation	✓	RelativeFSR	–
SinglePionECAL	✓	RelativeStatFSR	✓
SinglePionHCAL	✓	RelativeStatEC	–
FlavorQCD	✓	RelativeStatHF	–
TimePtEta	–	PileUpDataMC	✓
RelativeJEREC1	–	PileUpPtRef	✓
RelativeJEREC2	–	PileUpPtBB	✓
RelativeJERHF	✓	PileUpPtEC1	✓
RelativePtBB	✓	PileUpPtEC2	✓
RelativePtEC1	–	PileUpPtHF	✓
RelativePtEC2	–		

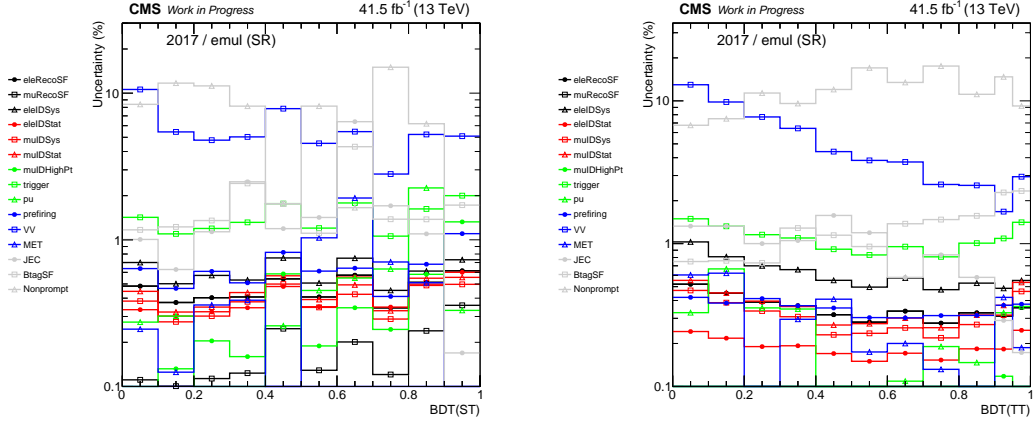
One additional uncertainty is assigned to the unclustered MET is considered [42], and is treated as uncorrelated across the years.

In the 2016 and 2017 runs, L1 ECAL triggers fired early [43] causing many uninteresting events to be recorded while the later interesting events were rejected. Since this effect is not present in the MC simulation, a correction is applied to all signals and *prompt* backgrounds. This correction is varied by 20% and the resulting change in per-event weight is taken as the uncertainty. This uncertainty is treated as correlated across the years.

In the 2018 runs, two HCAL modules whose power supply died in the middle of the data taking. This effected the measurement of jet energy and MET. No correction is applied as this effect is not well-understood and likely not significant relative to other corrections. Nevertheless, an uncertainty, denoted by “HEM”, is assigned to cover the variations of jet energy and MET caused by those two dead modules.

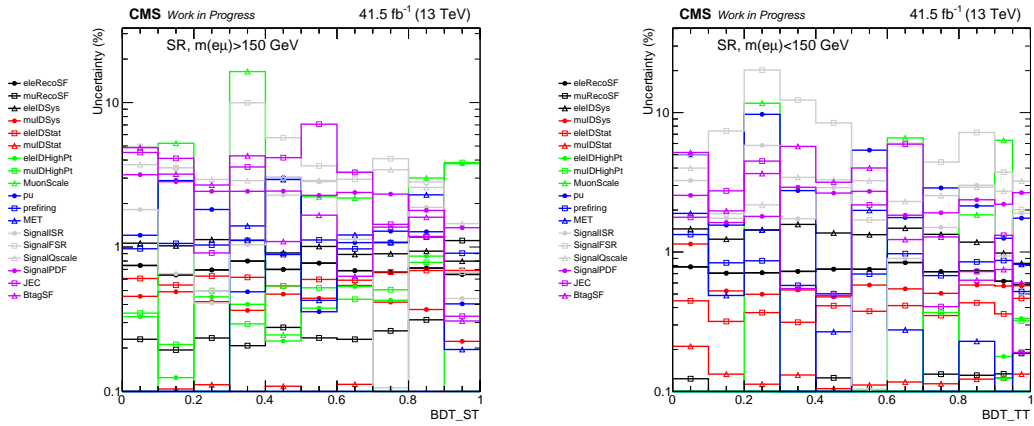
A comparison of different sources of systematic uncertainties of the background estimates in the

SRs is shown in Figure 17.7.



**Figure 17.7:** Distributions of relative uncertainties on total expected backgrounds as a function of BDT output in top production enriched SR (left), top decay enriched SR (right). Luminosity and cross section uncertainties are not included in these plots. JES, JER, and HEM are combined into “JEC”. Sources of b-tagging uncertainties listed in Table 17.1 are combined into “BtagSF”.

A comparison of different sources of systematic uncertainties of the signal estimates in the SRs is shown in Figure 17.8.



**Figure 17.8:** Distributions of relative uncertainties on signal ( $C_{\text{eutu}}^{\text{vector}}$  is used as an example) as a function of BDT output in top production enriched SR (left), top decay enriched SR (right). Luminosity and cross section uncertainties are not included in these plots. JES, JER, and HEM are combined into “JEC”. Sources of b-tagging uncertainties listed in Table 17.1 are combined into “BtagSF”.

Representative range of systematic uncertainties on  $t\bar{t}$  background and signal are summarized in Table 17.3. These uncertainties are extracted from pre-fit BDT templates shown in Figure 16.12.

**Table 17.3:** Representative range of systematic uncertainties extracted from 2017 dataset.

Sys. Unc.	BDT(TT)		BDT(ST)	
	t $\bar{t}$ W	LFV signal	t $\bar{t}$ W	LFV signal
eleRecoSF	0.5%-0.55%	0.6%-0.65%	0.59%-0.64%	0.64%-0.72%
muRecoSF	0.12%-0.16%	0.14%-0.23%	0.25%-0.35%	0.31%-1.13%
eleIDSys	0.72%-0.87%	0.82%-0.99%	0.73%-0.76%	0.79%-0.95%
eleIDStat	0.3%-0.32%	0.4%-0.49%	0.57%-0.62%	0.69%-0.73%
eleIDHighPt	0.03%-0.06%	0.17%-0.61%	0.46%-0.87%	0.89%-3.95%
mulDSys	0.68%-0.69%	0.54%-0.61%	0.37%-0.45%	0.22%-0.37%
mulDStat	0.15%-0.15%	0.12%-0.13%	0.08%-0.1%	0.05%-0.08%
mulDHighPt	0.06%-0.12%	0.09%-0.53%	0.43%-1.12%	0.84%-3.97%
MuonScale	0.09%-1.12%	0.1%-2.61%	1.04%-4.82%	0.01%-0.99%
pu	0.55%-1.89%	0.01%-0.53%	0.22%-0.72%	0.15%-0.57%
prefiring	0.65%-0.7%	0.66%-0.71%	0.86%-0.96%	0.88%-1.18%
MET	0.09%-1.18%	0.12%-0.89%	0.07%-1.9%	0.08%-0.14%
ISR	-	0.65%-1.11%	-	0.29%-0.66%
FSR	-	3.79%-4.87%	-	0.18%-2.58%
Qscale	11.16%-13.08%	2.88%-3.28%	14.82%-16.71%	1.35%-2.33%
PDF	0.07%-0.09%	2.33%-2.66%	0.18%-0.18%	1.28%-1.6%
VV	0.0%-0.0%	-	0.0%-0.0%	-
JEC	0.75%-1.74%	0.57%-1.83%	0.61%-2.28%	0.23%-1.08%
BtagSF	4.39%-5.65%	0.31%-1.2%	1.42%-2.29%	0.44%-0.83%

# CHAPTER 18

## Statistical Analysis

In absence of significant excess over the SM prediction, the observed distributions of the BDT discriminator are used to test various hypophyses, where coexistence of the CLFV signals and backgrounds are assumed. A statistical method called “profile likelihood” is used to move the focus on the cross sections of the CLFV signals while also keeping track of the systematic uncertainties. The profile likelihood fit performed on the distributions of the BDT discriminator is discussed in section 18.1. Upper limits on various WCs and branching fractions established by this analysis are presented in section 18.2.

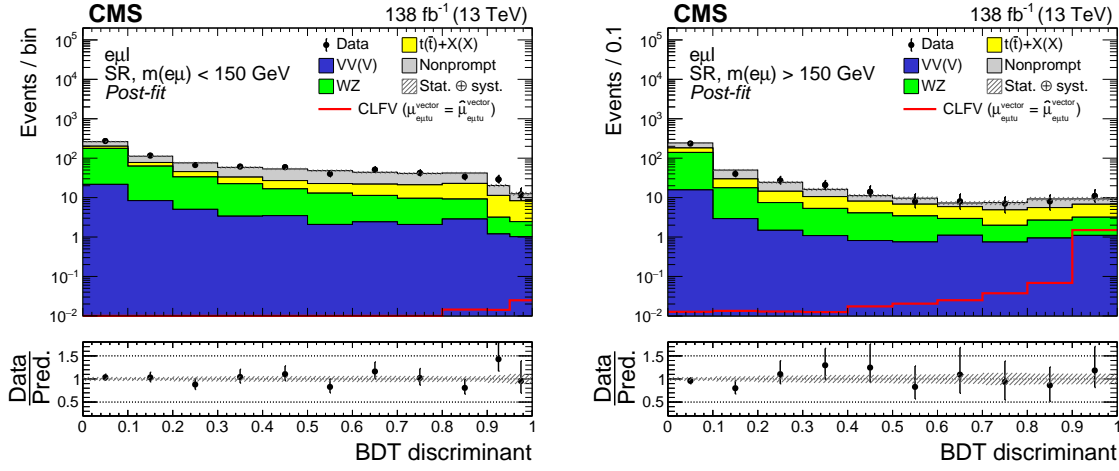
### 18.1 Profile Likelihood Fit

A binned likelihood function  $\mathcal{L}(\mu, \theta)$  is constructed to perform the statistical analysis using the BDT discriminator distributions. The top quark production and decay signal modes are combined. The signal strength  $\mu$ , defined previously in Equation 12.14, governs the cross section of the two signal modes simultaneously.

All systematic uncertainties are incorporated into the likelihood function as nuisance parameters, denoted by  $\theta$ . The uncertainties that affect the shape of the BDT discriminator distributions utilize Gaussian distributions while other uncertainties that only affect the normalizations utilize log-normal distributions. The “Barlow-Beeston lite” method [44] is used to incorporate the statistical uncertainties in the signal and background predictions.

A profile likelihood fit is performed simultaneously in six regions (three data-taking years and two SRs) by maximizing the likelihood function  $\mathcal{L}(\mu, \hat{\theta}_\mu)$ , where  $\hat{\theta}_\mu$  are the values of the nuisance parameters that maximize the likelihood for a specific signal strength. The post-fit distributions of the BDT discriminators are shown in Figure 18.1. The largest post-fit uncertainties are the statistical uncertainties from the limited number of simulated events.

The impacts of the nuisance parameters on the profile likelihood fit is quantified and a representative ranking of the impacts is shown in Figure 18.2. In general, the most prominent uncertainties affecting the likelihood fit are the statistical uncertainties that arise from limited sample size. A full collection of nuisance parameter impacts can be found in Appendix C.



**Figure 18.1:** Distributions of the post-fit BDT discriminator targeting the CLFV top quark decay (left) and production (right) signal. Contributions from the two signal modes (production and decay) are combined within each SR and are shown as the solid red line. The post-fit signal strength ( $\mu_{\text{e}\mu\text{t}}^{\text{vector}} = \hat{\mu}_{\text{e}\mu\text{t}}^{\text{vector}}$ ) is used to normalise the signal cross sections. The hatched bands indicate post-fit uncertainties (statistical and systematic) for the SM background predictions.

## 18.2 Upper Limits

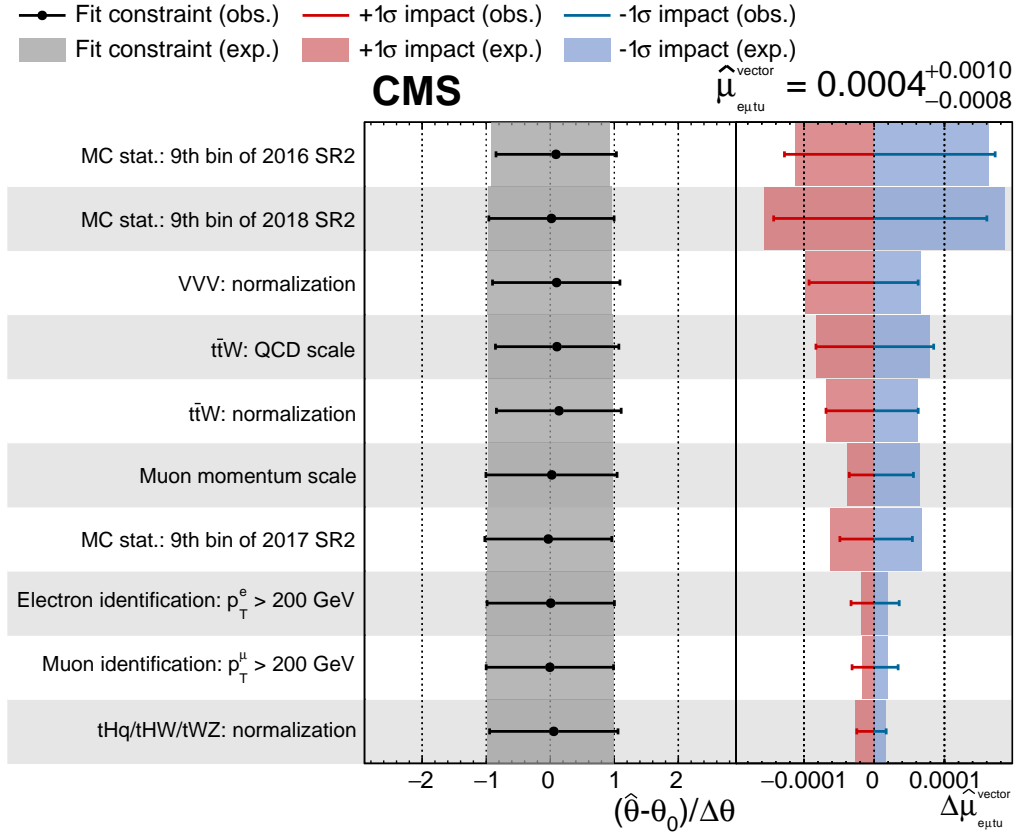
The compatibility between the data and the combined signal plus background expectation under the hypothesized value of the signal strength  $\mu$  is quantified by a test statistic that considers the profile likelihood ratio:

$$q(\mu) = -2 \ln \frac{\mathcal{L}(\mu, \hat{\theta}_\mu)}{\mathcal{L}(\hat{\mu}, \hat{\theta})}. \quad (18.1)$$

Using the asymptotic modified frequentist  $\text{CL}_s$  method [45, 4, 46] with the profile likelihood ratio as the test statistic, upper limits are placed on  $\mu$  at 95% confidence level (CL). The one-dimensional upper limits on a given Wilson coefficient,  $C_a/\Lambda^2$ , are obtained by taking the square root of the corresponding signal strength  $\mu_a$  while setting other Wilson coefficients to zero. The branching fractions,  $\mathcal{B}(t \rightarrow e\mu q)$  with  $q=u$  or  $c$ , are obtained assuming a top quark mass (width) of 172.5 (1.33) GeV in Equation 12.13 taken from [14].

The resulting one-dimensional limits are summarized in Table 18.1. Assuming a linear relationship between  $\mathcal{B}(t \rightarrow e\mu u)$  and  $\mathcal{B}(t \rightarrow e\mu c)$  in the case of nonvanishing signals, the two-dimensional limits can be obtained through interpolation and are shown in Figure 18.3.

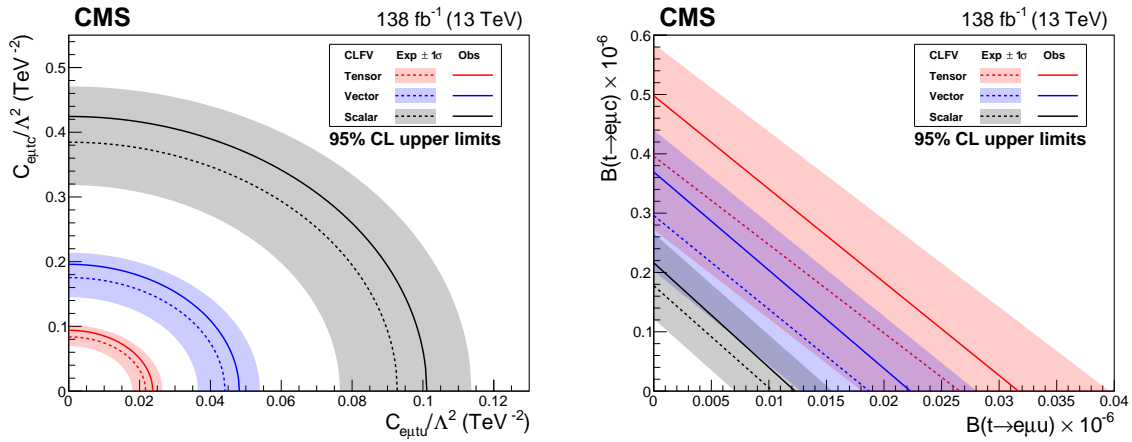




**Figure 18.2:** The nominal value of the observed signal strength  $\hat{\mu}$  and its uncertainty is shown in the top right corner. Ranking of the nuisance parameters according to their observed impacts on  $\hat{\mu}$  (represented with error bars) is shown in the right panel. Only the 10 nuisance parameters with the largest observed impacts are shown. The expected impacts (represented with red and blue rectangles) are derived using Asimov fits, where data is replaced by a background-only template (i.e. the nominal value of the expected  $\hat{\mu}$  is 0). The impact of each nuisance parameter,  $\Delta\hat{\mu}$ , is calculated as the difference between the nominal  $\hat{\mu}$  and the value of  $\hat{\mu}$  when the corresponding nuisance parameter is fixed to  $\hat{\theta} \pm \sigma$ , where  $\hat{\theta}$  ( $\sigma$ ) is its post-fit value (uncertainty). The left panel shows the pulls (represented with black dots) and uncertainties (represented with error bars and grey rectangles) of the nuisance parameters in units of the pre-fit uncertainties. The pulls are calculated as the difference between the nominal and the post-fit values of the nuisance parameters. The “SR2” quoted in the label corresponds to the top quark production enriched signal region.

**Table 18.1:** Upper limits at 95% CL on Wilson coefficients and the branching fractions. The expected and observed upper limits are shown in regular and bold fonts, respectively. The intervals that contain 68% of the distribution of the expected upper limits are shown in parentheses.

CLFV coupling	Lorentz structure	$C_{e\mu tq}/\Lambda^2$ ( $\text{TeV}^{-2}$ )		$\mathcal{B}(t \rightarrow e\mu q) \times 10^{-6}$	
		exp (68% range)	obs	exp (68% range)	obs
$e\mu tu$	tensor	0.022 (0.018–0.026)	<b>0.024</b>	0.027 (0.018–0.040)	<b>0.032</b>
	vector	0.044 (0.036–0.054)	<b>0.048</b>	0.019 (0.013–0.028)	<b>0.022</b>
	scalar	0.093 (0.077–0.114)	<b>0.101</b>	0.010 (0.007–0.016)	<b>0.012</b>
$e\mu tc$	tensor	0.084 (0.069–0.102)	<b>0.094</b>	0.396 (0.272–0.585)	<b>0.498</b>
	vector	0.175 (0.145–0.214)	<b>0.196</b>	0.296 (0.203–0.440)	<b>0.369</b>
	scalar	0.385 (0.318–0.471)	<b>0.424</b>	0.178 (0.122–0.266)	<b>0.216</b>



**Figure 18.3:** Two-dimensional 95% CL upper limits on the Wilson coefficients (left) and the branching fractions (right). The observed (expected) upper limits for tensor-, vector-, and scalar-like CLFV interactions are shown in red, blue, and black solid (dotted) lines, respectively. The shaded bands contain 68% of the distribution of the expected upper limits.

## **Part IV**

# **Outlook for CLFV Searches Using Top Quarks**

# CHAPTER 19

## **Inclusive Signal Generation**

### **19.1 UFO Model**

### **19.2 EFT Reweighting**

# CHAPTER 20

## **Object and Event Selection**

### **20.1 Object Selection**

### **20.2 Event Selection**

# CHAPTER 21

## **Expected Sensitivity**

### **21.1 Asimov Fit**

### **21.2 Expected Upper Limits**

# CHAPTER 22

## **Run-2 Combination**

### **22.1 Correlation Scheme**

### **22.2 Minimal Flavor Violation Interpretation**

# CHAPTER 23

## Summary and Conclusions



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# APPENDIX A

## List of Trigger Paths

**Table A.1:** Triggers used to record events during data taking in 2016.

Dataset	Trigger Path
SingleMuon	HLT_IsoMu22_eta2p1, HLT_IsoTkMu22_eta2p1
	HLT_IsoMu24, HLT_IsoTkMu24
	HLT_Mu50, HLT_TkMu50, HLT_Mu45_eta2p1
SingleElectron	HLT_Ele25_eta2p1_WPTight_Gsf
	HLT_Ele27_WPTight_Gsf
	HLT_Ele27_eta2p1_WPTight_Gsf
	HLT_Ele32_eta2p1_WPTight_Gsf
	HLT_Ele105_CaloldVT_GsfTrkIdT
	HLT_Ele115_CaloldVT_GsfTrkIdT
DoubleMuon	HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL
	HLT_Mu17_TrkIsoVVL_TkMu8_TrkIsoVVL
	HLT_TkMu17_TrkIsoVVL_TkMu8_TrkIsoVVL
	HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ
	HLT_Mu17_TrkIsoVVL_TkMu8_TrkIsoVVL_DZ
	HLT_TkMu17_TrkIsoVVL_TkMu8_TrkIsoVVL_DZ
	HLT_Mu30_TkMu11, HLT_TripleMu_12_10_5
DoubleEG	HLT_Ele23_Ele12_CaloldL_TrackIdL_IsoVL_DZ
	HLT_Ele16_Ele12_Ele8_CaloldL_TrackIdL
	HLT_DoubleEle33_CaloldL_MW
	HLT_DoubleEle33_CaloldL_GsfTrkIdVL
	HLT_DoubleEle33_CaloldL_GsfTrkIdVL_MW
MuonEG	HLT_Mu23_TrkIsoVVL_Ele8_CaloldL_TrackIdL_IsoVL
	HLT_Mu23_TrkIsoVVL_Ele8_CaloldL_TrackIdL_IsoVL_DZ
	HLT_Mu8_TrkIsoVVL_Ele23_CaloldL_TrackIdL_IsoVL
	HLT_Mu30_Ele30_CaloldL_GsfTrkIdVL
	HLT_Mu33_Ele33_CaloldL_GsfTrkIdVL
	HLT_DiMu9_Ele9_CaloldL_TrackIdL
	HLT_Mu8_DiEle12_CaloldL_TrackIdL

**Table A.2:** Triggers used to record events during data taking in 2017.

Dataset	Trigger Path
SingleMuon	HLT_IsoMu24_eta2p1
	HLT_IsoMu27
	HLT_Mu50
	HLT_OldMu100
	HLT_TkMu100
SingleElectron	HLT_Ele32_WPTight_Gsf_L1DoubleEG
	HLT_Ele35_WPTight_Gsf
	HLT_Ele115_CaloldVT_GsfTrkIdT
DoubleMuon	HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL
	HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ
	HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ_Mass8
	HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ_Mass3p8
	HLT_Mu19_TrkIsoVVL_Mu9_TrkIsoVVL_DZ_Mass3p8
	HLT_Mu37_TkMu27
	HLT_TripleMu_12_10_5
	HLT_TripleMu_10_5_5_DZ
	HLT_TripleMu_5_3_3_Mass3p8to60_DZ
DoubleEG	HLT_Ele23_Ele12_CaloldL_TrackIdL_IsoVL
	HLT_Ele16_Ele12_Ele8_CaloldL_TrackIdL
	HLT_DoubleEle25_CaloldL_MW
	HLT_DoubleEle33_CaloldL_MW
	HLT_DiEle27_WPTightCaloOnly_L1DoubleEG
MuonEG	HLT_Mu23_TrkIsoVVL_Ele12_CaloldL_TrackIdL_IsoVL
	HLT_Mu23_TrkIsoVVL_Ele12_CaloldL_TrackIdL_IsoVL_DZ
	HLT_Mu8_TrkIsoVVL_Ele23_CaloldL_TrackIdL_IsoVL_DZ
	HLT_Mu12_TrkIsoVVL_Ele23_CaloldL_TrackIdL_IsoVL_DZ
	HLT_Mu27_Ele37_CaloldL_MV
	HLT_Mu37_Ele27_CaloldL_MV
	HLT_DiMu9_Ele9_CaloldL_TrackIdL
	HLT_DiMu9_Ele9_CaloldL_TrackIdL_DZ
	HLT_Mu8_DiEle12_CaloldL_TrackIdL

**Table A.3:** Triggers used to record events during data taking in 2018.

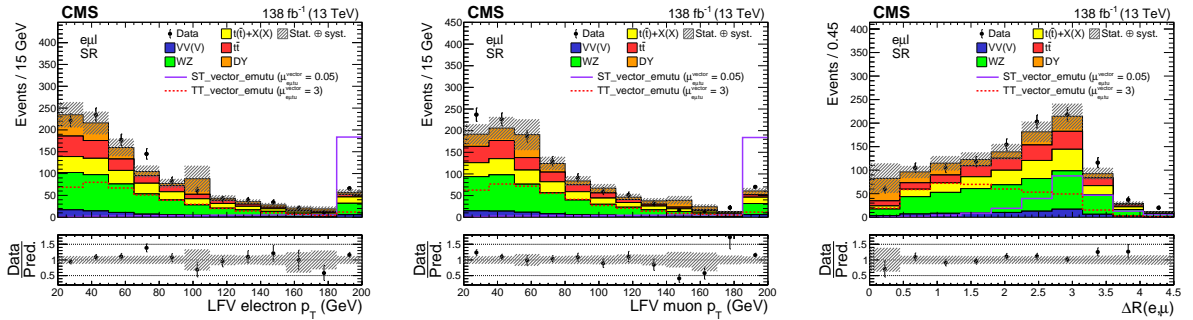
Dataset	Trigger Path
SingleMuon	HLT_IsoMu24
	HLT_IsoMu27
	HLT_Mu50
	HLT_OldMu100
	HLT_TkMu100
EGamma	HLT_Ele32_WPTight_Gsf
	HLT_Ele115_CaloldVT_GsfTrkIdT
	HLT_Ele23_Ele12_CaloldL_TrackIdL_IsoVL
	HLT_Ele16_Ele12_Ele8_CaloldL_TrackIdL
	HLT_DoubleEle25_CaloldL_MW
	HLT_DiEle27_WPTightCaloOnly_L1DoubleEG
DoubleMuon	HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ_Mass3p8
	HLT_Mu37_TkMu27
	HLT_TripleMu_12_10_5
	HLT_TripleMu_10_5_5_DZ
	HLT_TripleMu_5_3_3_Mass3p8to60_DZ
MuonEG	HLT_Mu23_TrkIsoVVL_Ele12_CaloldL_TrackIdL_IsoVL
	HLT_Mu23_TrkIsoVVL_Ele12_CaloldL_TrackIdL_IsoVL_DZ
	HLT_Mu8_TrkIsoVVL_Ele23_CaloldL_TrackIdL_IsoVL_DZ
	HLT_Mu12_TrkIsoVVL_Ele23_CaloldL_TrackIdL_IsoVL_DZ
	HLT_Mu27_Ele37_CaloldL_MV
	HLT_Mu37_Ele27_CaloldL_MV
	HLT_DiMu9_Ele9_CaloldL_TrackIdL_DZ
	HLT_Mu8_DiEle12_CaloldL_TrackIdL



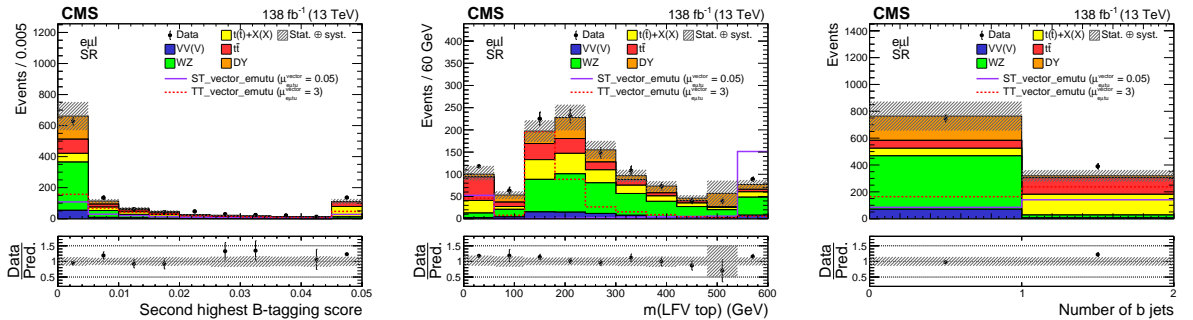
# APPENDIX B

## Signal Region Distributions with MC simulation

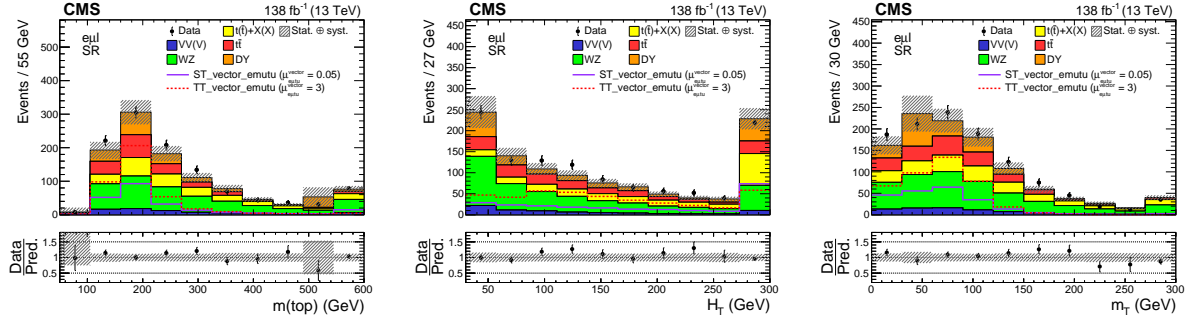
Distributions of various variables in **SR**, which are used in the **BDT** training. More details on these input features are described in [section 16.2](#). The data are shown as filled points and the **SM** background predictions as histograms. The VV(V) background includes ZZ and triboson production, while the  $t\bar{t} + X(X)$  component includes  $t\bar{t}W$ ,  $t\bar{t}Z$ ,  $t\bar{t}H$ ,  $tZq$ , and smaller backgrounds containing one or two top quarks plus a boson or quark. All backgrounds are estimated using **MC** simulation. The hatched bands indicate statistical and systematic uncertainties for the **SM** background predictions. The normalisation of the signal processes is chosen arbitrarily for improved visualisation.



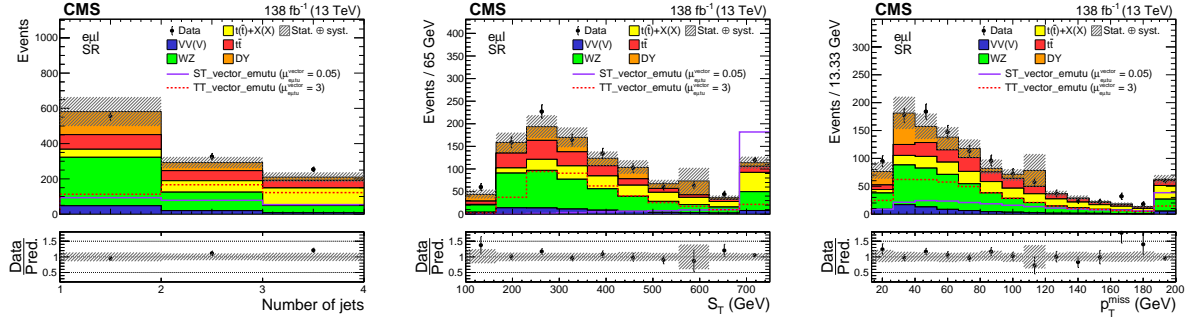
**Figure B.1:** Distributions of LFV electron  $p_T$  (left), LFV muon  $p_T$  (middle), and the opening angle between LFV electron and LFV muon (right).



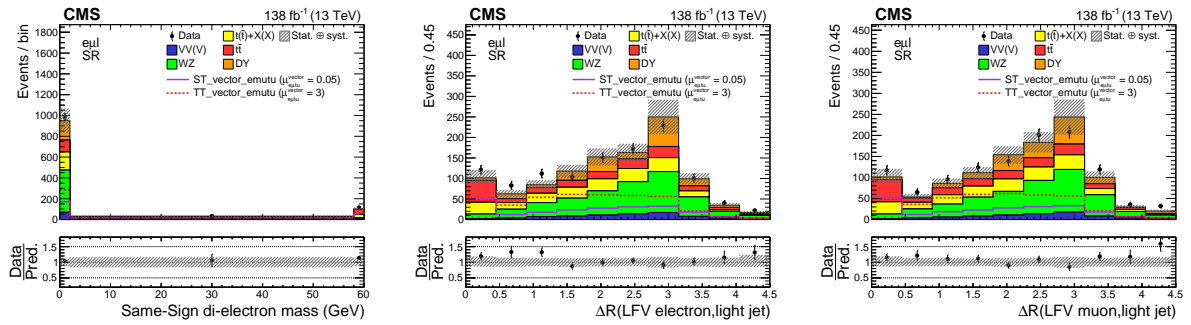
**Figure B.2:** Distributions of the second highest DEEPJET score (left), LFV top mass (middle), b jet multiplicity (right).



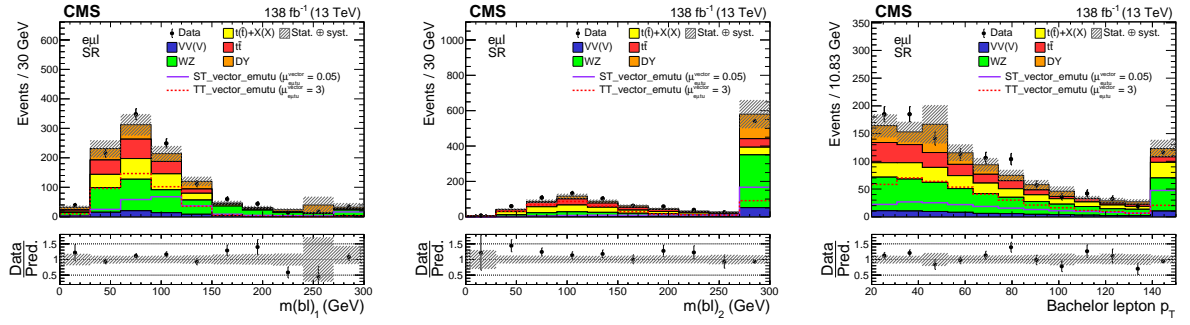
**Figure B.3:** Distributions of **SM** top quark mass (left), scalar sum of  $p_T$  of all jets (middle), and transverse mass of the W boson (right).



**Figure B.4:** Distributions of jet multiplicity (left), scalar sum of  $p_T$  of all jets and leptons (middle), and **MET** (right).



**Figure B.5:** Distributions of the same-sign di-electron mass (left), the opening angle between LFV electron and a light flavor jet (middle), and the opening angle between LFV muon and a light flavor jet (right).



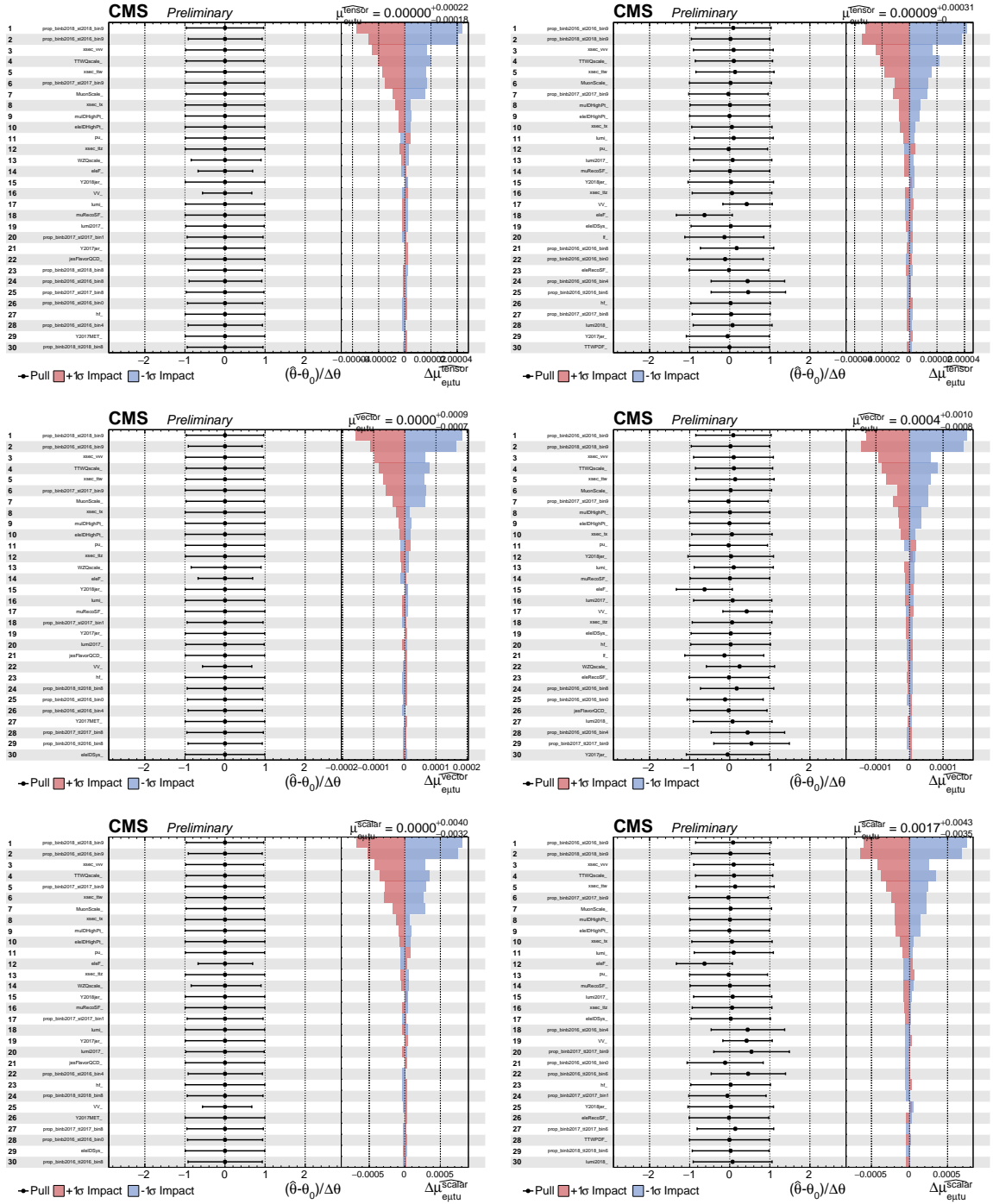
**Figure B.6:** Distributions of the mass of the first  $m_{b\ell}$  system (left), the mass of the second  $m_{b\ell}$  system (middle), and standalone lepton  $p_T$  (right).

# APPENDIX C

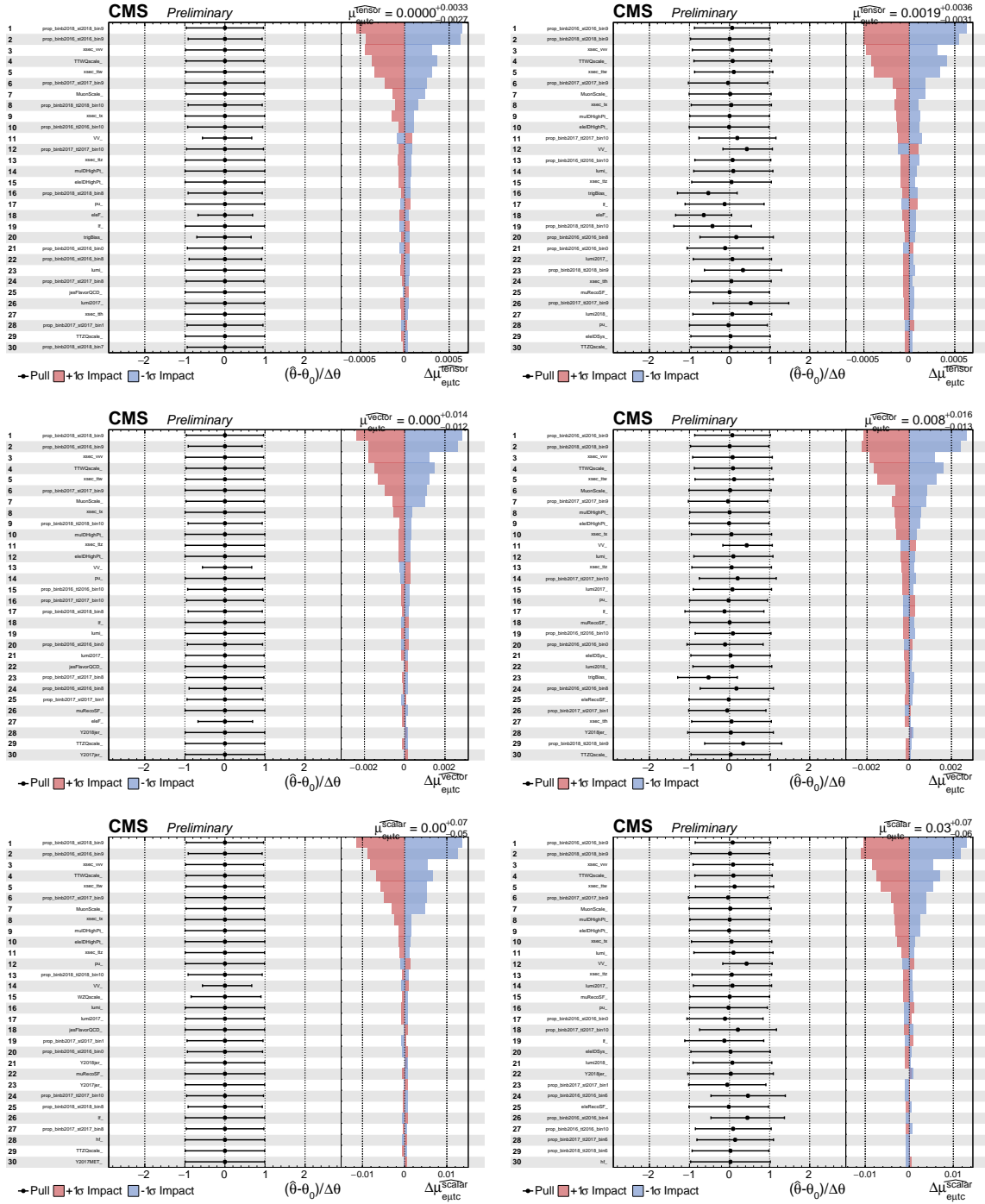
## Nuisance Parameter Impact

The observed and expected ( $\mu_{exp}=0$ ) impacts of the nuisance parameters on the profile likelihood fit are shown in Figure C.1-C.2. They were computed using the following commands and plotted below for full run 2.

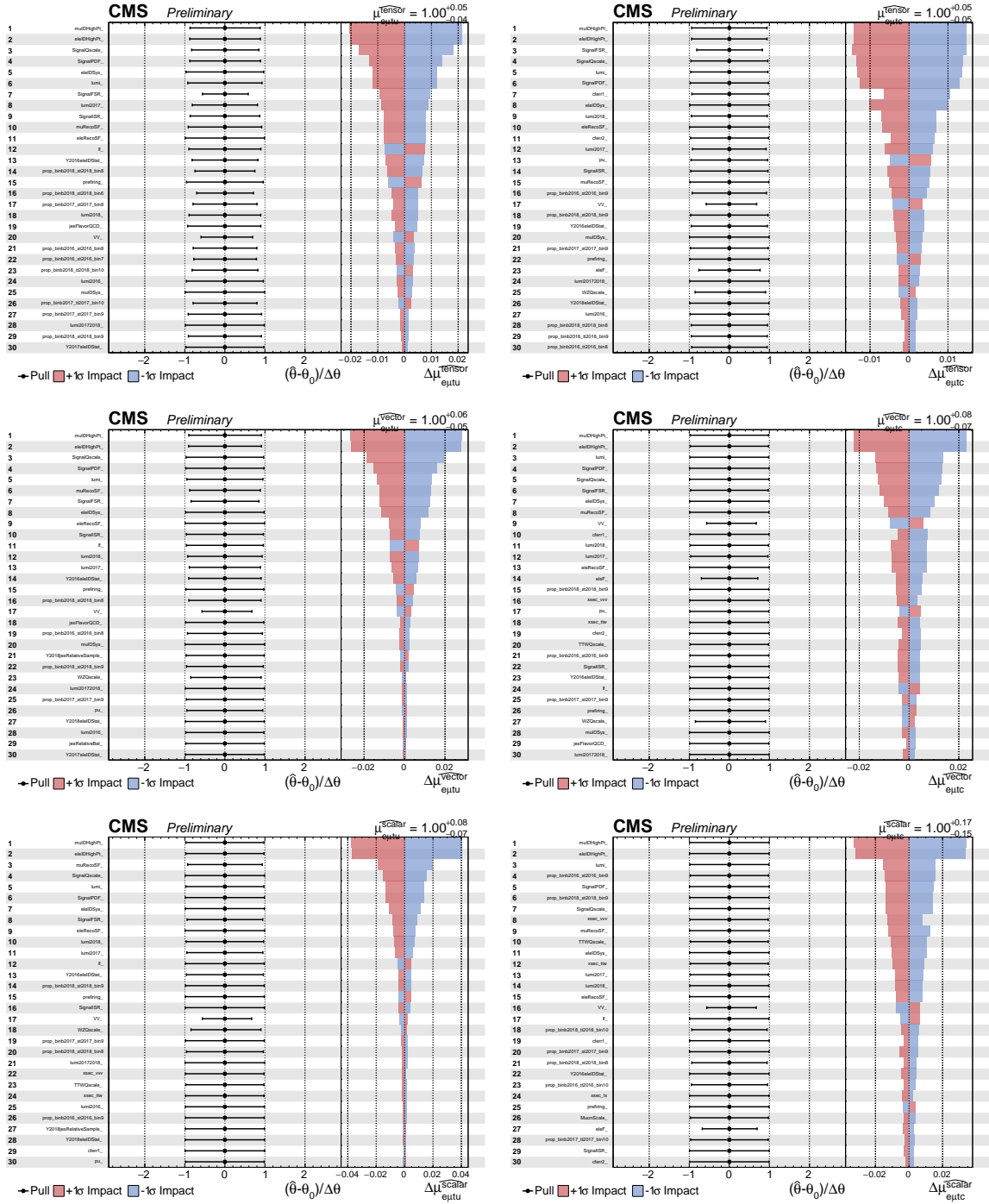
The expected ( $\mu_{exp}=1$ ) impacts of the nuisance parameters on the profile likelihood fit are shown in Figure C.3.



**Figure C.1:** Impacts of nuisance parameters for run II limit setting. From top to bottom:  $e\mu t u$ -tensor,  $e\mu t u$ -vector,  $e\mu t u$ -scalar. From left to right: expected impact (expected signal strength at 0), observed impact.



**Figure C.2:** Impacts of nuisance parameters for run II limit setting. From top to bottom:  $e\mu_{tc}$ -tensor,  $e\mu_{tc}$ -vector,  $e\mu_{tc}$ -scalar. From left to right: expected impact (expected signal strength at 0), observed impact.



**Figure C.3:** Expected impact with an expected signal strength at 1. From top to bottom: tensor, vector, scalar. From left to right:  $e\mu_{tu}$ ,  $e\mu_{tc}$ .