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Search for lepton flavor violation in top quark production and decay

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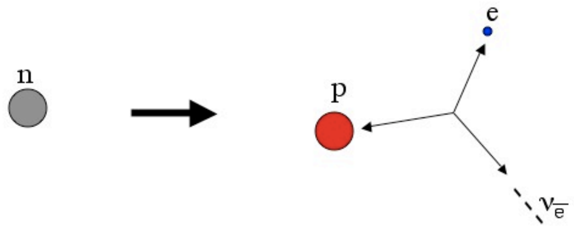
Introduction

Theory Motivations

Lepton flavor violation (LFV) processes are forbidden within the Standard Model (SM)

$$n \rightarrow p + e + \nu_{\bar{e}}$$

- Baryon Number: (+1) → (+1) + 0 + 0
- Charge: 0 → (+1) + (-1) + 0
- Lepton Flavor: 0 → 0 + (e) + (-e)

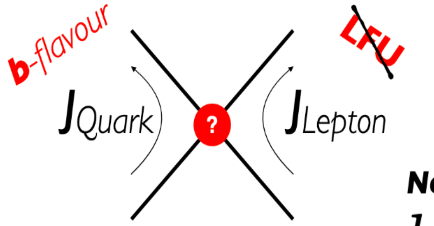


Non-zero mass for neutrinos leads to lepton flavour violation in the leptons

Many new physics models predict sizable LFV (neutrino mass models, multi-Higgs doublet models,…)

Experimental Motivations

❖ Recent LHCb measurements exhibit anomalous B→K(∗) transitions
❖ Hints for the violation of the lepton flavor universality in b-quark sector
❖ Any departure from lepton flavor universality imply LFV
❖ Many models that explain the B-anomaly predict the existence of the similar interactions in the top sector



Neutral currents

$b \rightarrow s\mu\bar{\mu}$ > 4σ *Global fits

$$R_K^{\mu/e} = \frac{\mathcal{B}(B \rightarrow K\mu^+\mu^-)}{\mathcal{B}(B \rightarrow Ke^+e^-)}$$

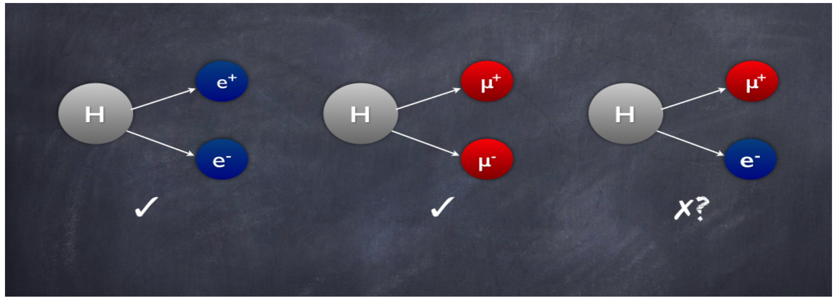
Search for LFV

Experimental searches for LFV can be divided into low-energy and high-energy categories.

- Low energy channels $\mu \longrightarrow e\gamma$, $\mu \longrightarrow eee, \mu \longrightarrow e$

- High energy channels (Atlas and CMS) $Z \longrightarrow e\mu, \mu\tau, e\tau$
$H \longrightarrow e\mu, \mu\tau, e\tau$

No significance excess of events over the background expectation

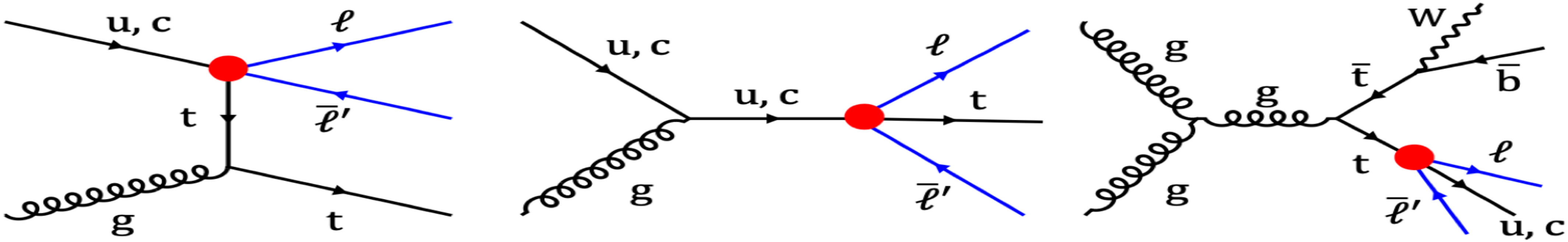


Process	limit	Experiment	Year
$Z \to \mu e$	$< 7.5 \times 10^{-7}$	ATLAS	2014
$Z \to \tau e$	$< 9.8 \times 10^{-6}$	OPAL	1995
$Z \to \tau\mu$	$< 1.2 \times 10^{-5}$	DELPHI	1997
$H \to e\mu$	$< 3.5 \times 10^{-4}$	CMS	2016
$H \to \tau\mu$	$< 2.5 \times 10^{-3}$	CMS	2017
$H \to \tau e$	$< 6.1 \times 10^{-3}$	CMS	2017

- In https://arxiv.org/abs/1507.07163 LFV in top quark decays at the LHC is studied
By recasting CMS search for $t \to Zq$ using 20/fb of data at 8 TeV, $B(t \to qe\mu) < 6 \times 10^{-5}$ is obtained.

Signal Modeling

- ❖ Top quark decay to ueμ (pp$\rightarrow t\bar{t} \rightarrow te\mu u$)
- ❖ Top quark decay to ceμ (pp$\rightarrow t\bar{t} \rightarrow te\mu c$)
- ❖ Single top via u-quark ST (pp$\longrightarrow te\mu$)
- ❖ Single top via c-quark ST (pp$\longrightarrow te\mu$)



An effective Lagrangian originated from dimension-six operators (O_x) weighted by the Wilson coefficients (C_x) over powers of the new physics scale (Λ) is used for LFV definition

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

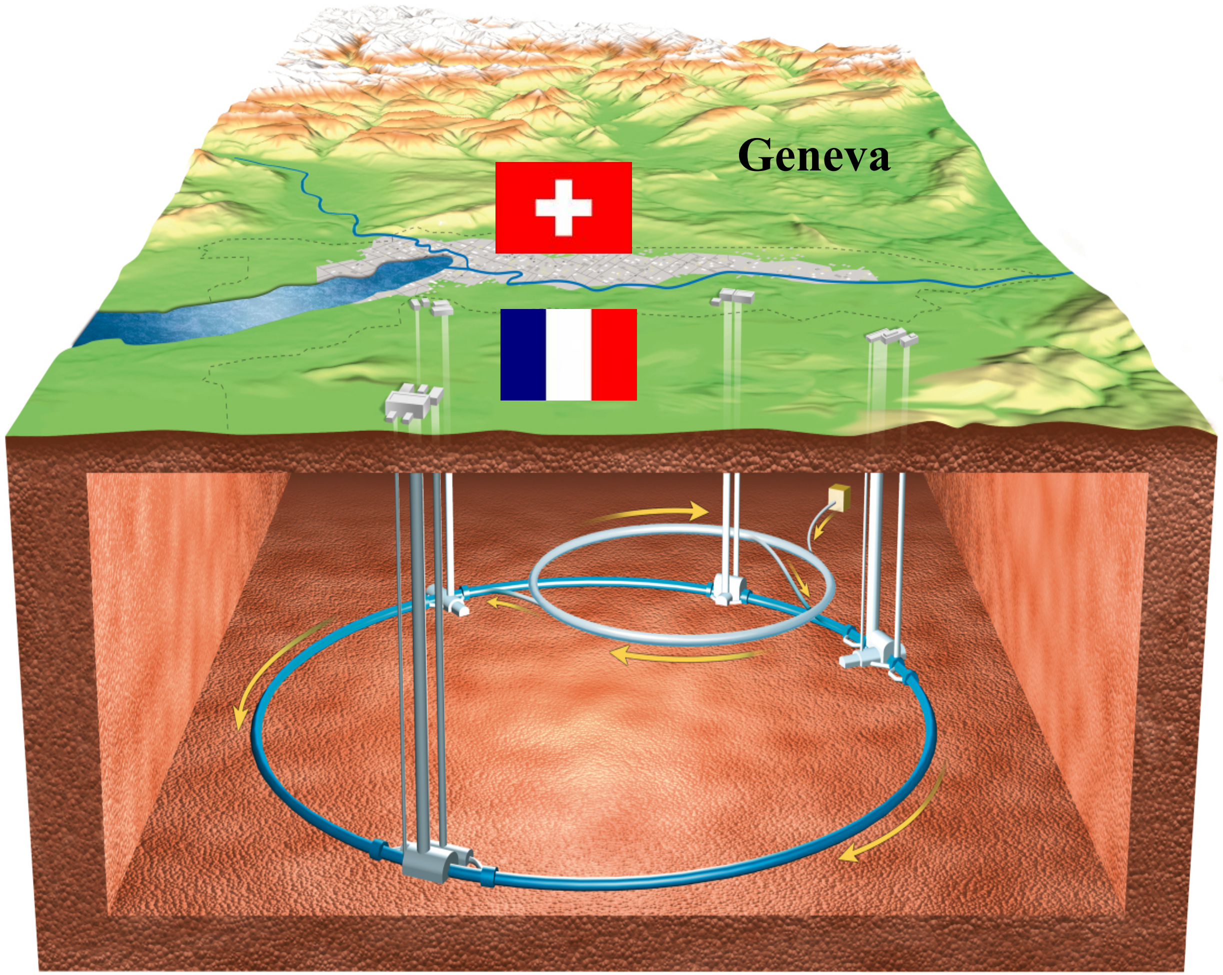
Base on Lorentz structures operators divided to: O_{vector} , O_{scalar}, O_{tensor}

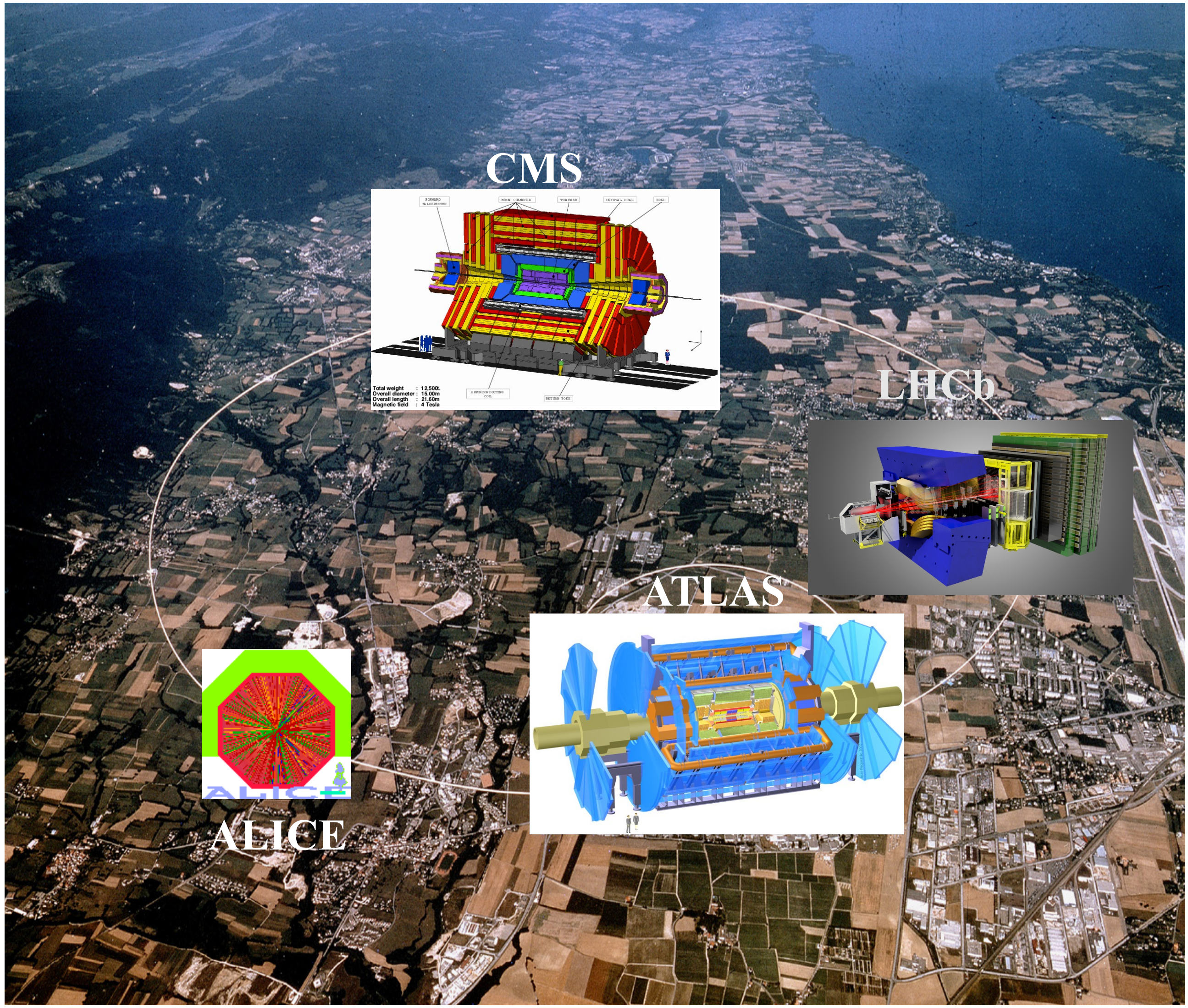
Our aim is to search for the three Wilson coefficients corresponding to operators C_{vector} , C_{scalar}, C_{tensor}

The Large Hadron Collider (LHC) and CMS Detector

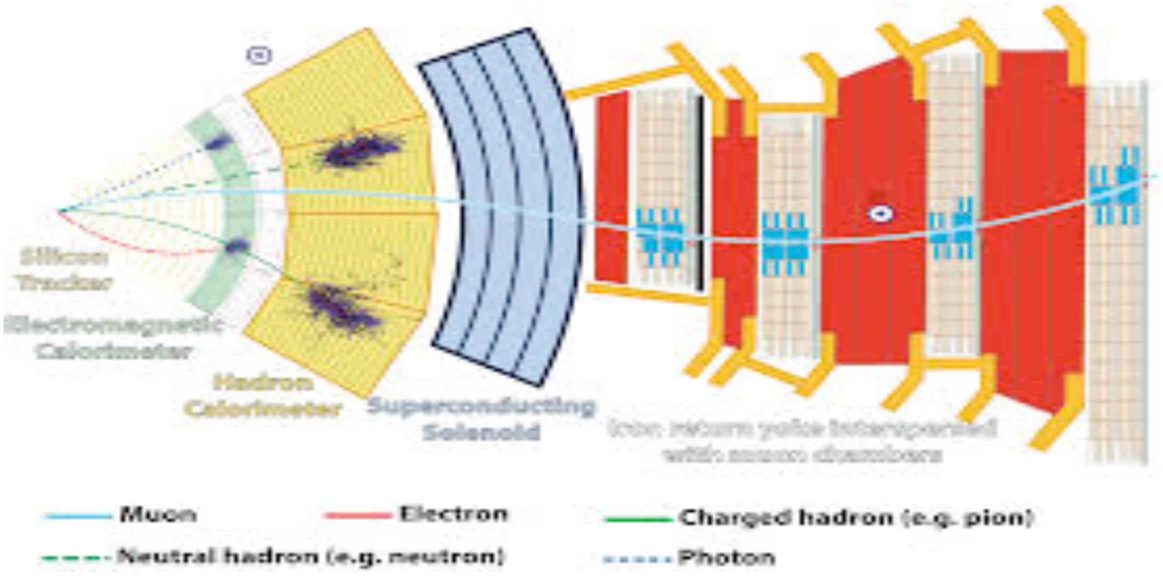
The LHC is installed in a tunnel 3.8 m in diameter, buried 50 to 175 m below ground.

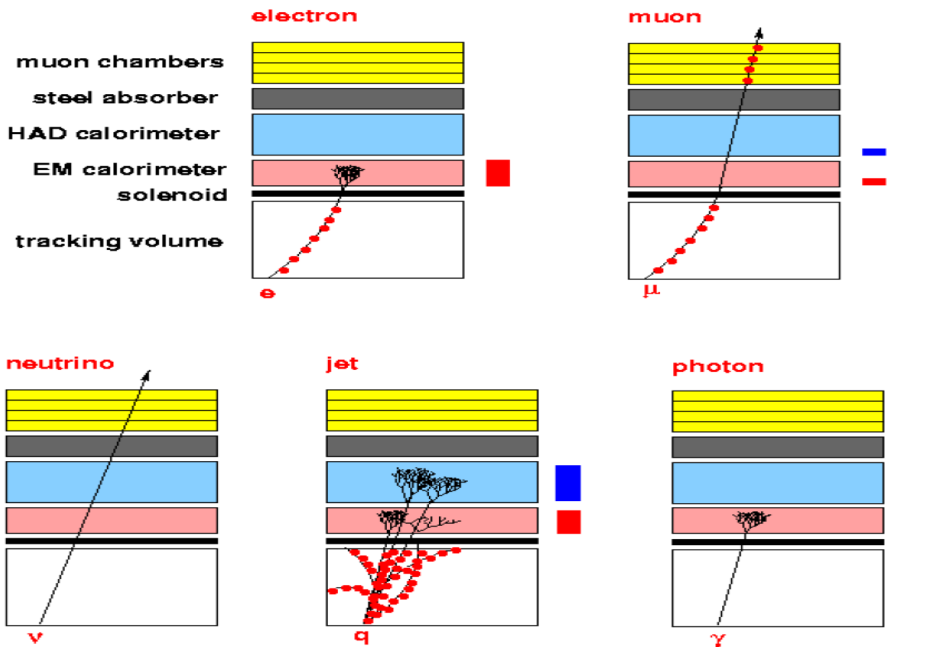
Designed and built over last two decades





Reconstruction and Identification





Electrons: Deposit all their energy in the electromagnetic calorimeter, matched to a track

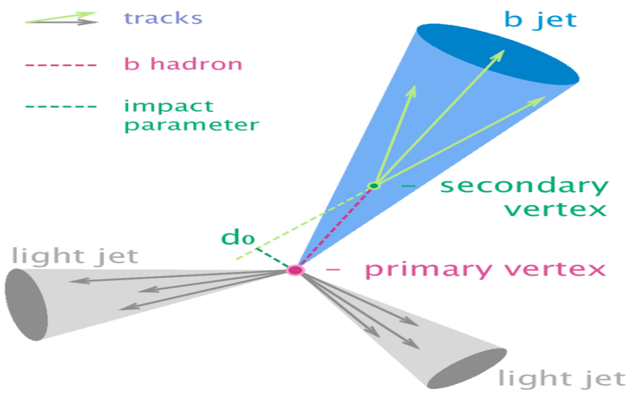
Photons: Same as above but no track

Muons: Match signal in muon chambers to track

Jets: Quarks fragment into many particles energy in both calorimeters matched to track(s)

Neutrinos: Pass through all material measured indirectly by imbalance of energy in calorimeters

b-quark jets: Jets originating from the hadronization of bottom quarks are identified ("b-tagged") using deep machine learning algorithms



Data and MC Simulation

Data: Stored by CMS in the 2016-2017-2018 years.

SM backgrounds:

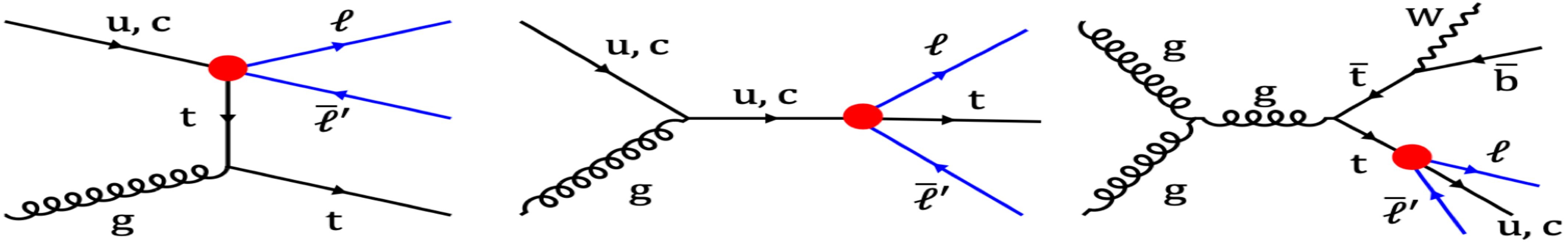
❖ The $t\bar{t}$, single top quark production in association with a W boson (tW), and diboson processes (including WW, WZ, and ZZ) are simulated using the POWHEG event generator.

❖ All other background processes including Z/γ^* bosons produced with additional jets (DY+jets), W boson production with additional jets (W+jets), and W/Z bosons produced in association with $t\bar{t}$ are simulated using the MADGRAPH5 aMC@NLO generator.

Signal:

❖ The top LFV effective Lagrangian is implemented into the FEYNRULES program.
❖ The MADGRAPH aMC@NLO program is used for the cross section calculation and event generation.

Event Selection



- ❖ Exactly one electron and one muon with opposite charge (p_T >20GeV, $|\eta|$<2.4)
- ❖ Number of jets(p_T >30GeV, $|\eta|$<2.4 and $\Delta R(beteen\ leptons\ and\ jets) > 0.4$)
- ❖ At least one b-tag jet
- ❖ leading lepton p_T > 25GeV
- ❖ Lepton need to pass offline triggers (Triggers are applied on both data and MC)
- ❖ In order to reduce the instrumental noise in the detector, MET filters are applied
- ❖ To reduce Z+jets bg Invariant mass for $e\mu$ > 20GeV

- ❖ After event selection, $t\bar{t}$ is dominant (more than 90% of total SM backgrounds)
- ❖ Our signal events have at most one b jet while ttbar events can be have more than one bjet
- ❖ So we categorize events with number of b-tagged jets
  - ❖ Exactly one b-tag jet (signal region)
  - ❖ More than one b-tag jet (control region)

Systematics uncertainties

Various sources of systematic uncertainty affect the final signal and background yields and distributions

The systematic uncertainties are categorized into two classes:

- ❖ Experimental uncertainties arising from modeling of the detector response

For Example: Lepton reconstruction, identification, and isolation efficiencies and scale factors (SF) are applied to all MC simulations to correct any discrepancies between data and simulation

- ❖ Theoretical uncertainties arising from the modeling of the signal and background processes in the MC simulation

Estimated by repeating analysis or using dedicated samples with altered parameters or by changing the reference simulation using the related weights

For Example: The uncertainty related to the choice of PDF, uncertainties in initial- and final-state QCD radiation (ISR and FSR)

Event Counting

Number of expected signal and background events, compared to the event yields in the data, after various selection steps.

Channel			1 b tagged	>1 b tagged
$t\bar{t}$			477800 ± 7900	265000 ± 7100
tW			49100 ± 1300	7710 ± 250
Other			7950 ± 670	850 ± 70
Total background prediction			534900 ± 8000	273600 ± 7100
Data			537236	268781
$e\mu tu$	Vector	t decay	604 ± 2	45.2 ± 0.4
		t production	17103 ± 29	1557 ± 9
	Scalar	t decay	78.2 ± 0.2	6.1 ± 0.1
		t production	3670 ± 6	336 ± 2
	Tensor	t decay	3499 ± 9	266 ± 2
		t production	61011 ± 107	5567 ± 33
$e\mu tc$	Vector	t decay	596 ± 2	90.4 ± 0.5
		t production	1711 ± 3	166 ± 1
	Scalar	t decay	77.7 ± 0.2	11.4 ± 0.1
		t production	294 ± 1	28.5 ± 0.2
	Tensor	t decay	3467 ± 8	534 ± 3
		t production	6329 ± 13	621 ± 4

Signal extraction

BDT approach to separate signal from BG events

- After event selection more than 90% of total SM backgrounds is $t\bar{t}$

- Several differences between the signal events and the SM $t\bar{t}$ events can be used to construct a discriminating observable.

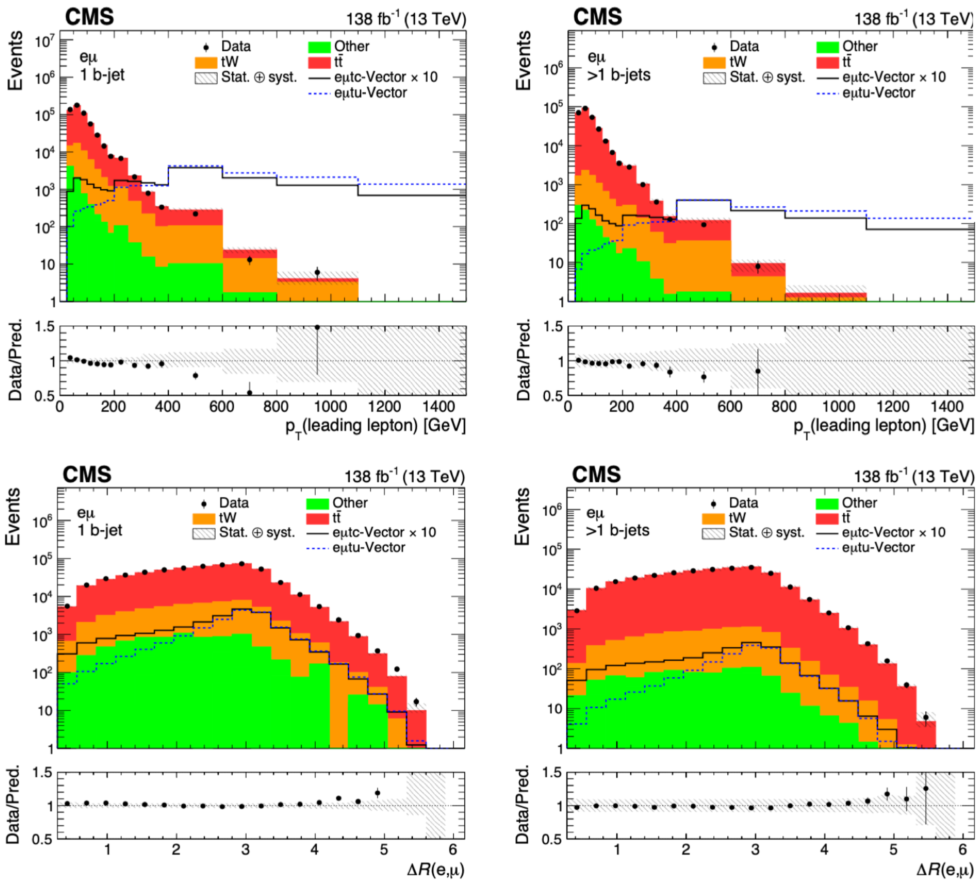
For example:

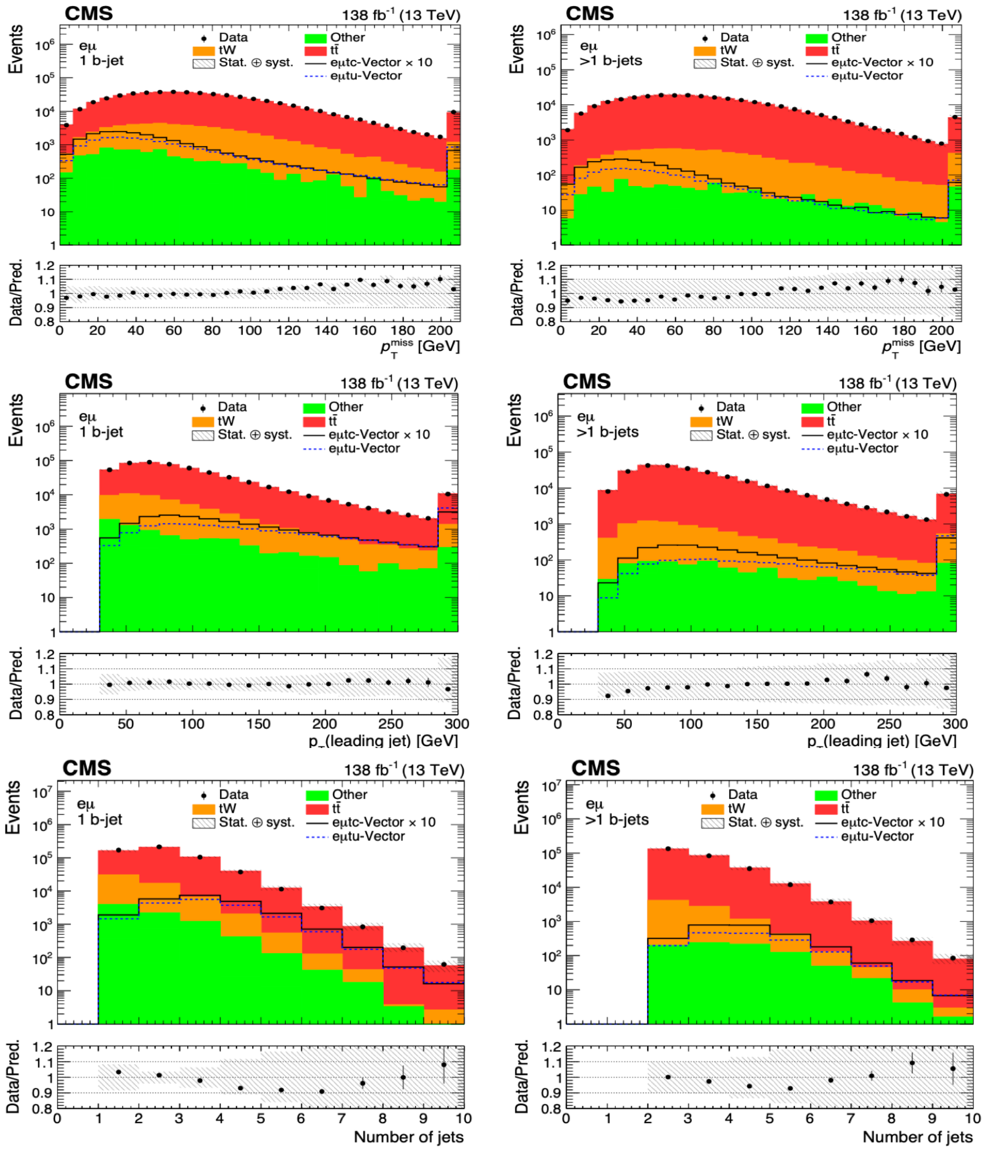
- The sources of missing transverse energy of the signal events are from detector resolutions while $t\bar{t}$ events have genuine missing transverse energy produced by neutrinos from the W boson decays.
- Leptons in $t\bar{t}$ events come from the decay of W bosons and have different angular separations and energy spectra compared to the signal dilepton events.
- Signal events have a higher number of light quark jets since the top quark decays hadronically in the signal samples.

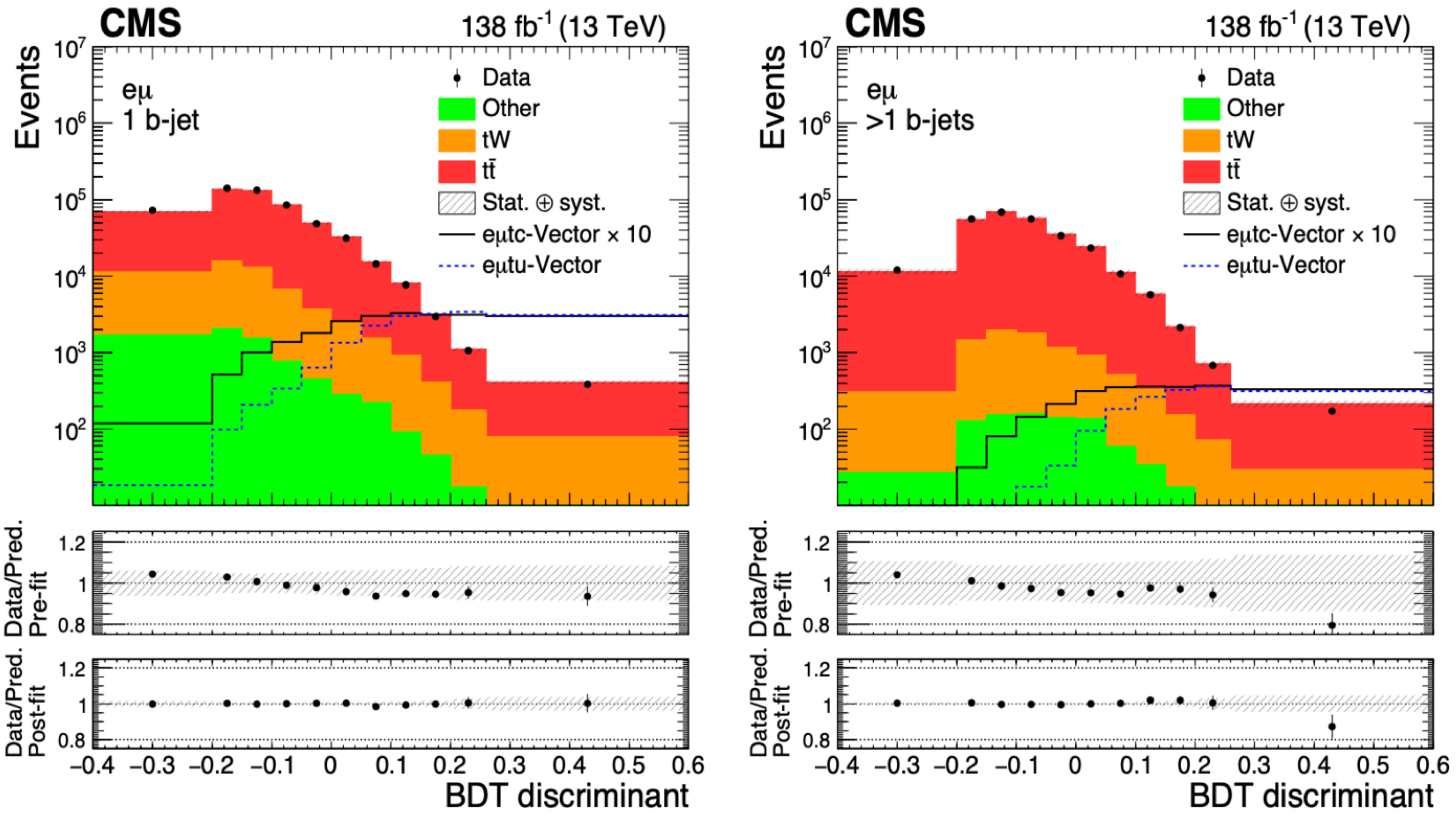
Signal extraction

In order to maximize the sensitivity of the search, a boosted decision tree (BDT) that combines several discriminating variables in the TMVA framework is used to distinguish signal events from the $t\bar{t}$ events .

Input Variables for BDT







CMS
138 fb^{-1} (13 TeV)
eμ
1 b-jet
Data
Other
tW
$t\bar{t}$
Stat. ⊕ syst.
eμtc-Vector × 10
eμtu-Vector
Events
Data/Pred. Pre-fit
Data/Pred. Post-fit
BDT discriminant
CMS
138 fb^{-1} (13 TeV)
eμ
>1 b-jets
Data
Other
tW
$t\bar{t}$
Stat. ⊕ syst.
eμtc-Vector × 10
eμtu-Vector
Events
Data/Pred. Pre-fit
Data/Pred. Post-fit
BDT discriminant

Results

- The data are found to be consistent with expectations of the SM in the absence of signal.
- Upper limits on the production cross section for signal are set at 95% confidence level (CL) using the modified frequentist CLs method with a likelihood ratio as a test statistic
- The limit setting procedure is performed for a given individual Wilson coefficient (C_{vector}, C_{scalar}, or C_{tensor})
- Upper limits on the Wilson coefficients are translated to limits on the related top quark CLFV branching fractions

The resulting limits are the most restrictive bounds to date.

Vertex	Int. type	Cross section [fb] Exp	Cross section [fb] Obs	$C_{e\mu tq}/\Lambda^2$ [TeV $^{-2}$] Exp	$C_{e\mu tq}/\Lambda^2$ [TeV $^{-2}$] Obs	$\mathcal{B}(10^{-6})$ Exp	$\mathcal{B}(10^{-6})$ Obs
$e\mu tu$	Vector	7.02	6.78	0.12	0.12	0.14	0.13
	Scalar	5.63	6.25	0.23	0.24	0.06	0.07
	Tensor	10.01	9.18	0.07	0.06	0.27	0.25
$e\mu tc$	Vector	11.21	9.73	0.39	0.37	1.49	1.31
	Scalar	9.11	8.88	0.87	0.86	0.91	0.89
	Tensor	21.02	17.22	0.24	0.21	3.16	2.59

Thanks for your attention