Flavor Violation at ATLAS and CMS

Le Rencontres de Physique de la Vallée d’Aoste

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Outline

- **Search for Higgs LFV decay $H \to e\mu$** NEW! CMS
- **Search for Higgs LFV decays $H \to e\tau$ and $H \to \mu\tau$** NEW! ATLAS

- **Search for CLFV in top quark sector in trilepton final states** NEW! CMS
- **Search for CLFV $\mu\tau qt$ interactions in top-quark production and decay** NEW! ATLAS

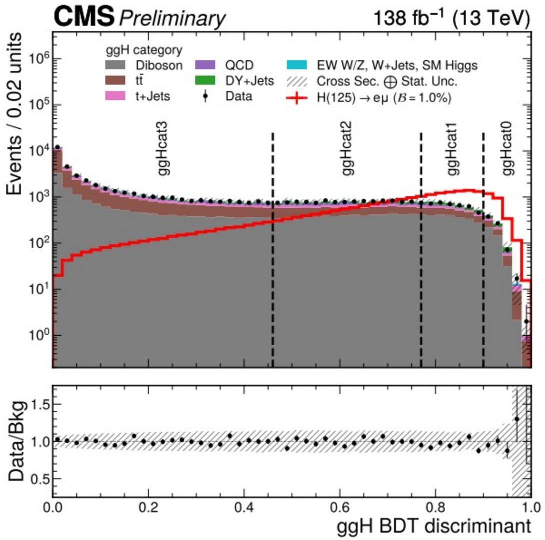
- **Search for heavy resonances and QBH in $e\mu$, $e\tau$, $\mu\tau$ final states** CMS

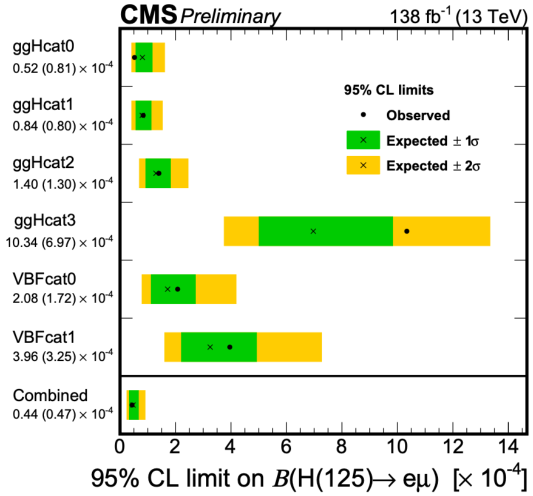
Introduction – Lepton Flavor Violation

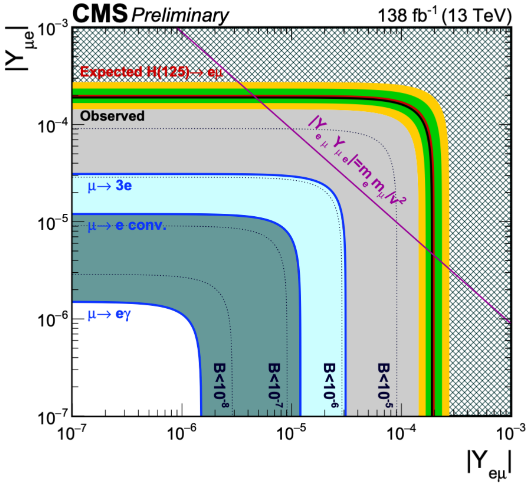
- Three lepton families (flavors) exist in the standard model (SM) of particle physics, and the number of leptons of each family is conserved in their interactions.

- Nevertheless, this conservation is not postulated by any fundamental principle of the theory (is an *accidental symmetry*), and neutrino oscillations indicate that processes violating this conservation do occur in nature.

- According to current knowledge, lepton-flavor-violating (LFV) processes in charged-lepton interactions can occur via neutrino mixing but are too rare to be detected by current experiments.
    - An observation of these would be an unambiguous sign of physics beyond the SM!







Search for Higgs LFV decay H→$e\mu$

Search for LFV decay H→$e\mu$: introduction and state of the art

PAS HIG-22-002

$\mathcal{L} = 138\ fb^{-1}$
$\sqrt{s} = 13$ TeV

- LFV Higgs decays forbidden in SM but arise in several BSM theories (with more than one Higgs boson doublet, models with flavor symmetries, the Randall–Sundrum model, composite Higgs models, certain susy models, etc.)
- In BSM theories, **LFV decays** can occur **through *off-diagonal LFV Yukawa couplings*** $\Upsilon_{e\mu}$, $\Upsilon_{e\tau}$, $\Upsilon_{\mu\tau}$ (*coupling Higgs with leptons of different flavor*)

✓ **ATLAS search** ($\mathcal{L} = 139\ \text{fb}^{-1}$ at $\sqrt{s} = 13$ TeV), set observed (expected) limit *

$$\mathcal{B}(H \to e\mu) < 6.2\ (5.9) \cdot 10^{-5}$$ @95% C.L.

In this CMS analysis: search for **LFV decay** of **SM Higgs** or **BSM Higgs boson** (X) with m_X of **110-160 GeV** decaying to $e\mu$

* Bonus: **ATLAS search** of $Z \to e\mu$ ($\mathcal{L} = 139\ \text{fb}^{-1}$ at $\sqrt{s} = 13$ TeV): $\mathcal{B}(Z \to e\mu) < 2.62 \cdot 10^{-7}$

Search for LFV decay $H \to e\mu$: analysis strategy

PAS HIG-22-002

$\mathcal{L} = 138\ fb^{-1}$
$\sqrt{s} = 13$ TeV

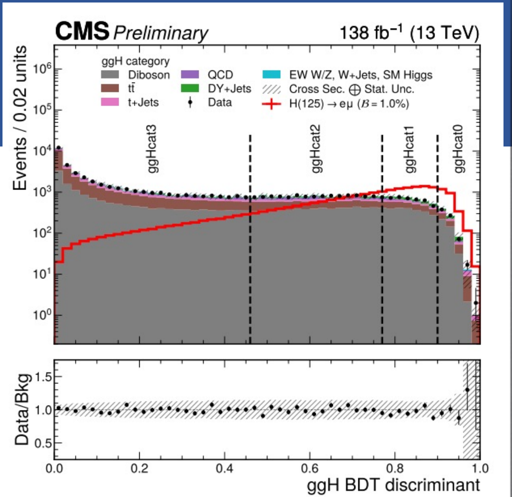
- This analysis targets **dominant production modes** of Higgs at LHC: **ggH** and **VBF**.

- Two levels of **categorization** to maximize analysis' sensitivity:
  1) categorization to target each **production mode**
  2) categorization to separate events into samples of different **sgn-to-bkg ratio**, based on **BDTs score**

- The $\mathbf{m_{e\mu}}$ distributions of H(125) → eμ or X → eμ signal from MC are **fit with** a **parametric model and interpolated btw** generated m_H and m_X **mass points in each category**; $m_{e\mu}$ distributions of **bkg** are **modeled directly from data**.

- **Simultaneous fit of sgn and bkg models to data** performed **to extract an UL** on either B(H(125) → eμ) or on the cross section σ(pp → X → eμ) for a BSM Higgs.
  - constraint on B(H(125) → eμ) translated to UL on $Y_{e\mu}$ (assuming only H(125) → eμ contributes additionally to SM Higgs total decay width)

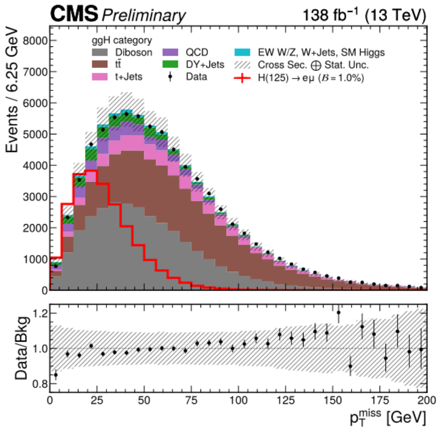
Search for LFV decay H→eμ: multivariate analysis

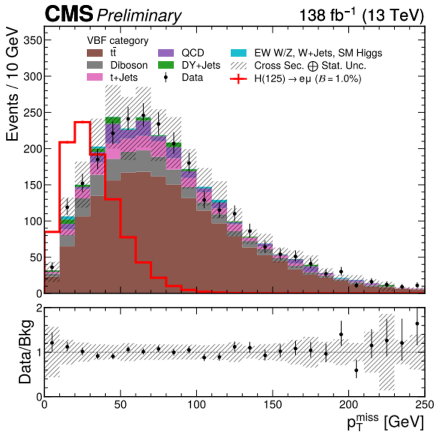


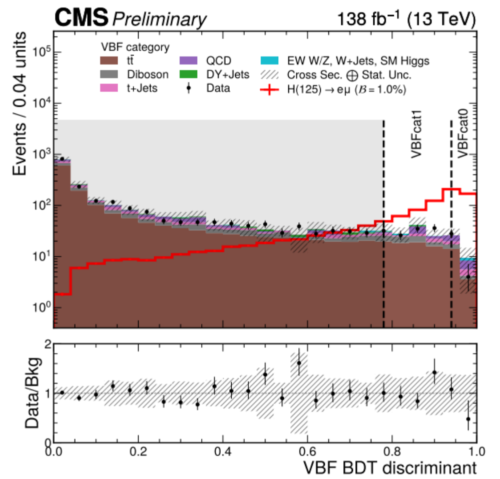
- BDTs trained separately for ggH and VBF categories

- For both BDTs, mixture of simulated sgn evts used in training
  - H(125) → eμ and X → eμ at m_X =110-160 GeV, in step of 10 GeV from both production modes
  - dominant sources of bkg from fully leptonic decays of $t\bar{t}$ and WW diboson evts used in training

Missing transverse momentum is the most discriminating variable in both ggH and VBF cat.



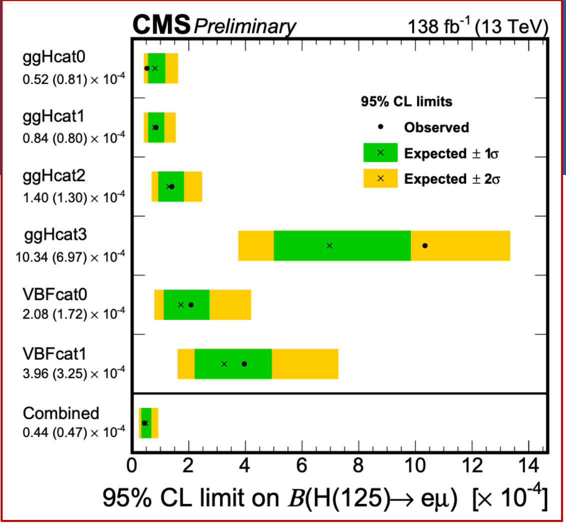




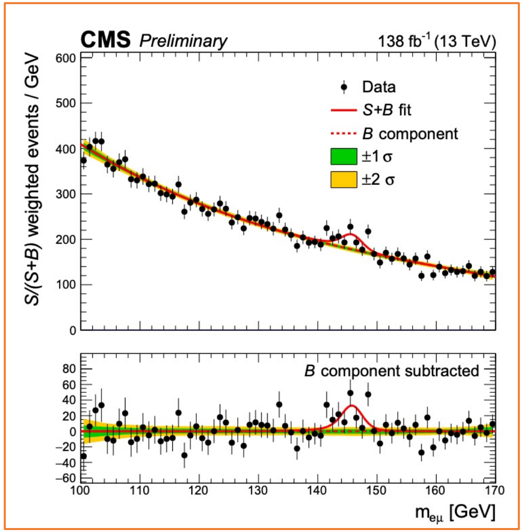
Search for LFV decay $H \to e\mu$: results

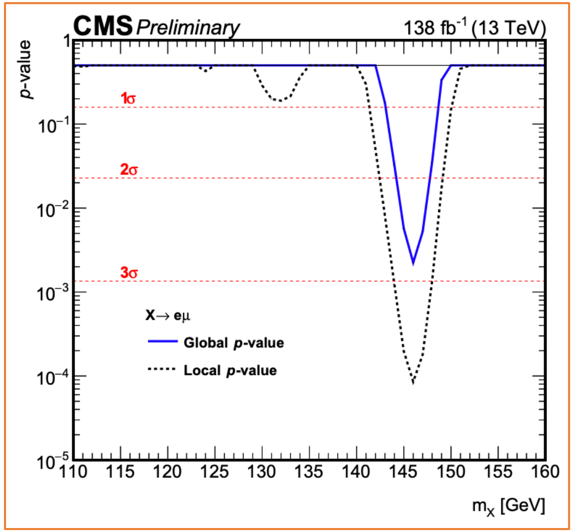
- **No significant excess** observed **for SM Higgs** with mass ~125 GeV
  - observed (expected) UL: $\mathcal{B}(H \to e\mu) < 4.4\ (4.7) \times 10^{-5}$ **@95% C.L.**

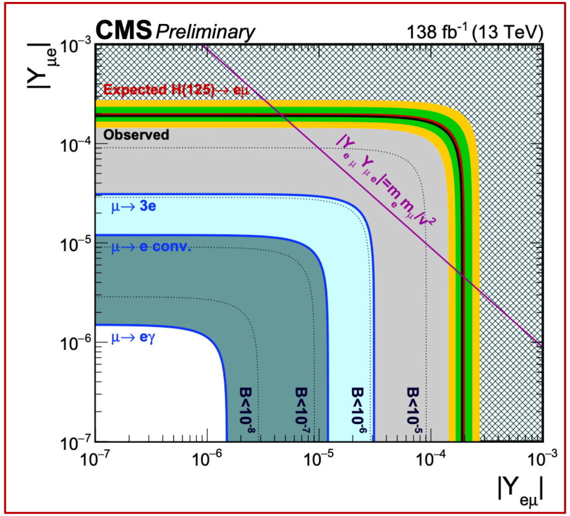
most stringent limit set thus far from direct searches

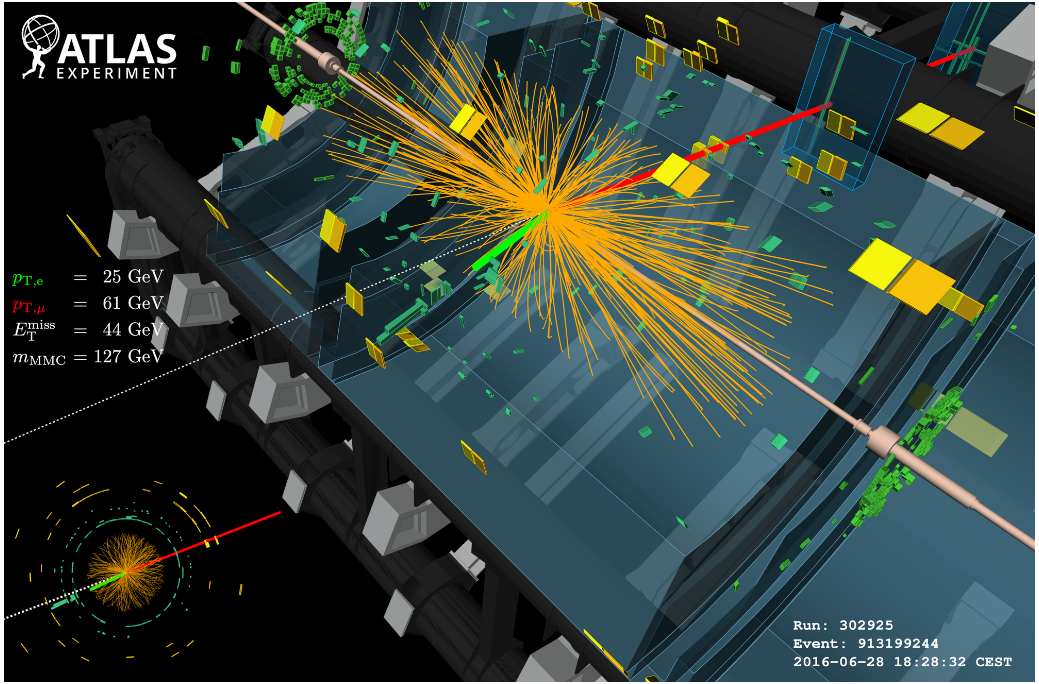


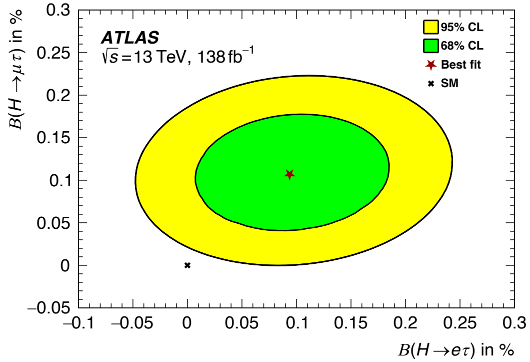
- An **excess of events over the expected bkg** observed at $e\mu$ inv. mass of **~146 GeV** with a **global (local) significance** of **2.8 (3.8)** σ











Search for Higgs LFV decays
H→$e\tau$ and H→$\mu\tau$

ATLAS

Search for LFV decays H→$e\tau$ and H→$\mu\tau$

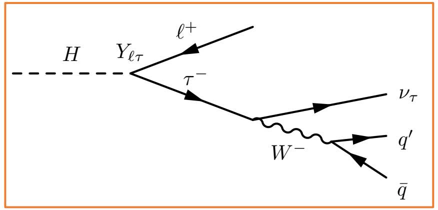
arXiv:2302.05225

$\mathcal{L} = 138\ fb^{-1}$
$\sqrt{s} = 13$ TeV

- ✓ Previous ATLAS search 2016 data ($\mathcal{L} = 36.1\ fb^{-1}$, $\sqrt{s} = 13$ TeV)
  $\mathcal{B}(H \rightarrow e\tau) < 0.47\%$
  $\mathcal{B}(H \rightarrow \mu\tau) < 0.28\%$
  @95% C.L.

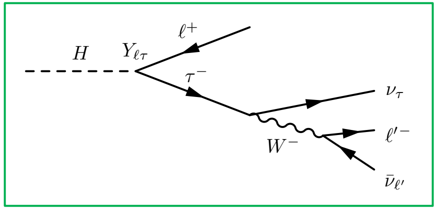
- ✓ CMS search whole Run 2 data ($\mathcal{L} = 137$ fb^{-1}, $\sqrt{s} = 13$ TeV)
  $\mathcal{B}(H \rightarrow e\tau) < 0.22\%$
  $\mathcal{B}(H \rightarrow \mu\tau) < 0.15\%$
  @95% C.L.

- In this analysis: two decay modes: $\ell\tau_{\ell'}$, $\ell\tau_{had}$ considered for each search (ℓ,ℓ' = e or μ)
  - in $\ell\tau_{\ell'}$ only pairs of different-flavor leptons considered (to reject bkg from Drell-Yan)



- Evt selections + multivariate analysis (BDTs, NNs)

- Three statistical analysis:
  1. independent search for $H \rightarrow e\tau$ signal ($H \rightarrow \mu\tau$ assumed to be zero)
  2. independent search for $H \rightarrow \mu\tau$ signal ($H \rightarrow e\tau$ assumed to be zero)
  3. simultaneous determination of $H \rightarrow e\tau$ and $H \rightarrow \mu\tau$ signals



Search for LFV decays $H\to e\tau$ and $H\to\mu\tau$: bkg estimation and mva analysis

arXiv:2302.05225

$\mathcal{L} = 138\ fb^{-1}$
$\sqrt{s} = 13$ TeV

➢ **Two independent methods to estimate bkg**:

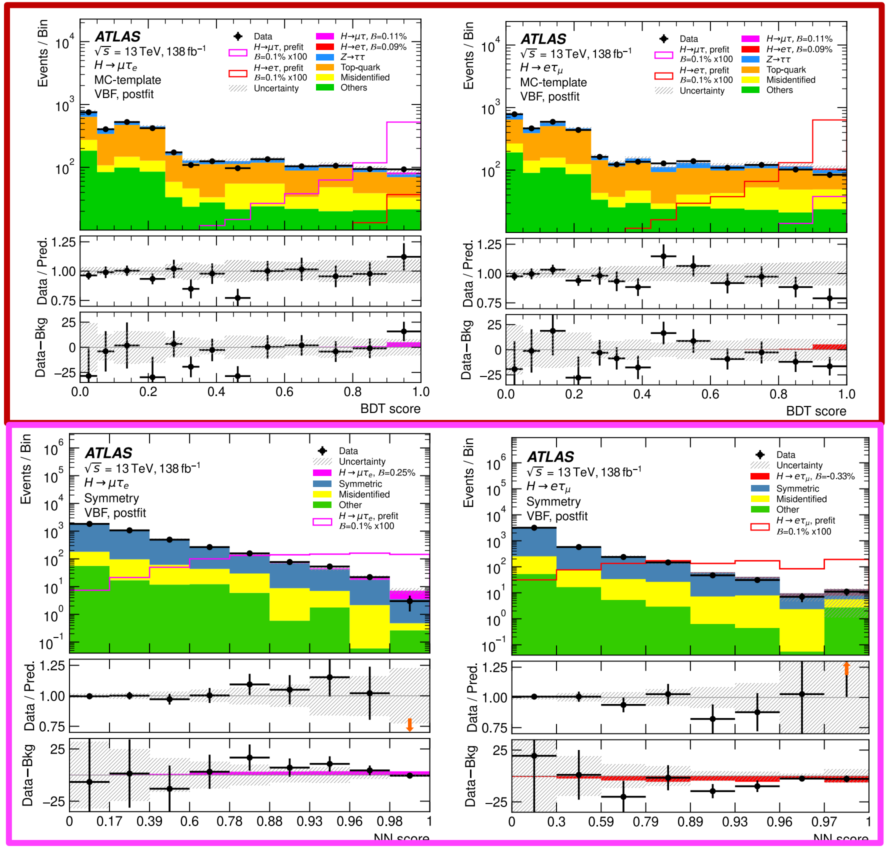
$\ell\tau_{had}$ $\ell\tau_{\ell'}$ ○ **MC template** method: uses templates from MC and a data-driven estimate of the 'misidentified bkg'

$\ell\tau_{\ell'}$ ○ **Symmetry** method: prompt-lepton bkg in SM are assumed to be symmetric under exchange electrons-muons.

Used to derive data-driven bkg estimate for main bkgs

➢ **Two MVA techniques** to separate sgn from bkg:

- **BDTs** for **MC-template** method
- deep **NNs** for **Symmetry** method



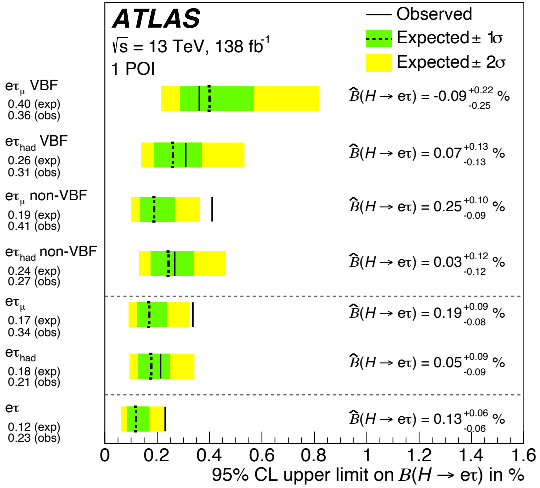
Search for LFV decays $H \to e\tau$ and $H \to \mu\tau$: statistycal analysis & results (I)

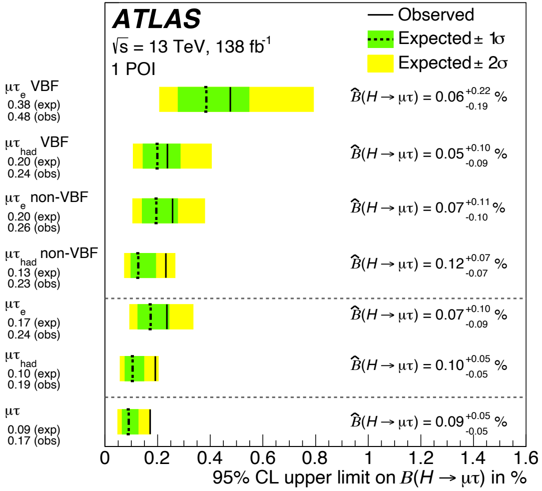
arXiv:2302.05225

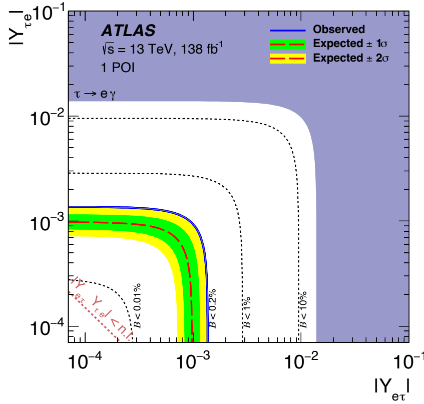
$\mathcal{L} = 138\ fb^{-1}$
$\sqrt{s} = 13$ TeV

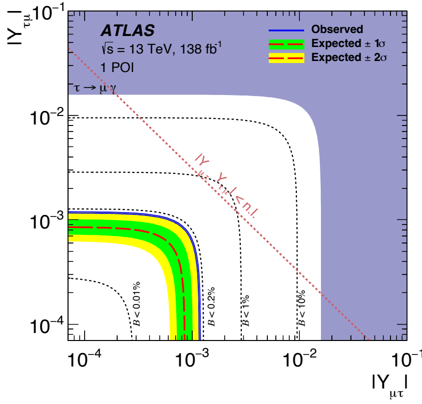
Independent search for $\mathcal{B}(H \to e\tau)$ and $\mathcal{B}(H \to \mu\tau)$

- Statistical analysis uses a likelihood function $\mathcal{L}(\mu, \theta)$, built as product of Poisson probability terms over all bins considered
  - Separate fit with single POI ($H \to e\tau, H \to \mu\tau$) for each search
  - Each search combines $\ell\tau_{had}$ channel and **non-VBF** category of $\ell\tau_{\ell'}$ from **MC-template method** with **VBF** category of the $\ell\tau_{\ell'}$ channel from **Symmetry method**









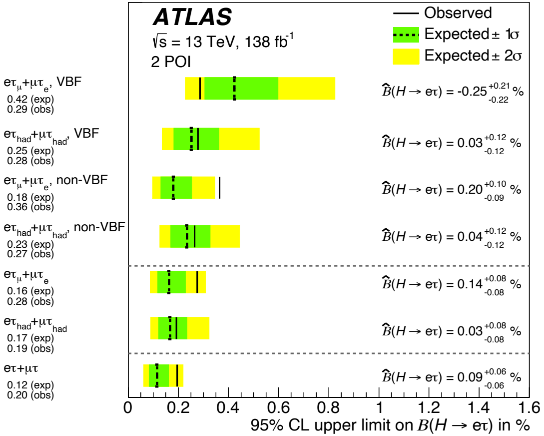
Search for LFV decays $H \to e\tau$ and $H \to \mu\tau$: statistycal analysis & results (II)

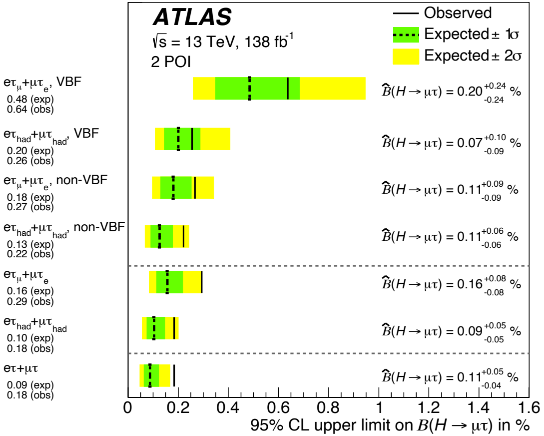
arXiv:2302.05225

$\mathcal{L} = 138\ fb^{-1}$
$\sqrt{s} = 13$ TeV

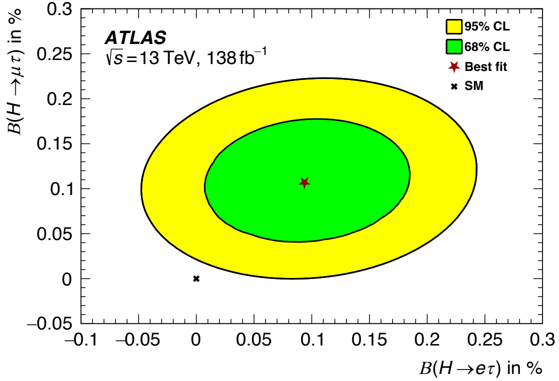
Simultaneous measurement of $H \to e\tau$ and $H \to \mu\tau$

- MC-template method used for simultaneous measurement
  - two POIs estimated in simultaneous fit of $e\tau_\mu$, $e\tau_{had}$, $\mu\tau_e$ and $\mu\tau_{had}$ final states

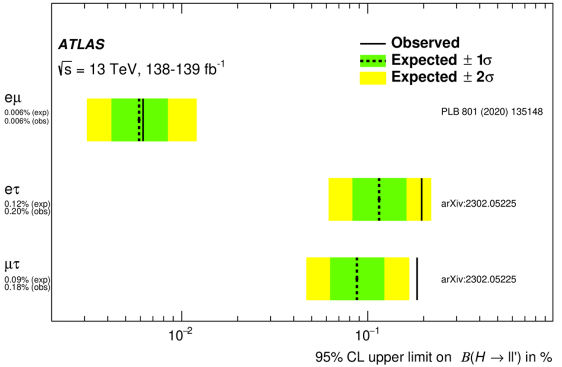




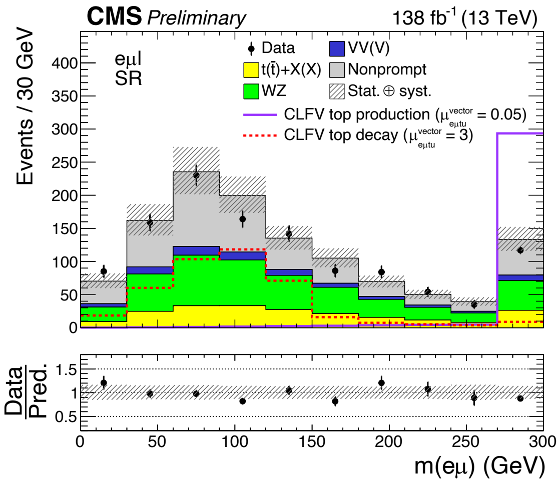
$\mathcal{B}(H \to e\tau) < 0.20\%$ $\mathcal{B}(H \to \mu\tau) < 0.18\%$

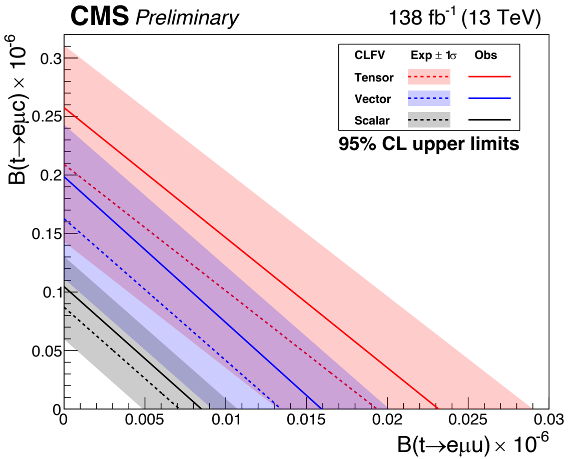


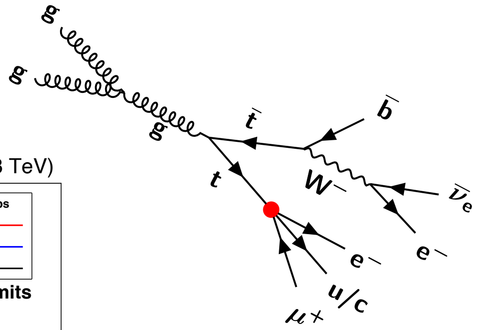
Compatible with SM within 2.1 σ



- For $\mathbf{H \to e\tau}$, **1.6σ excess observed** (from non-VBF cat. of $\ell\tau_{\ell'}$, MC-template method)
- For $\mathbf{H \to \mu\tau}$, **2.4σ excess observed** (from non-VBF cat. of $\ell\tau_{had}$)







Search for CLFV in top quark sector in trilepton final states

Search for CLFV in top quark sector in trilepton final states - introduction

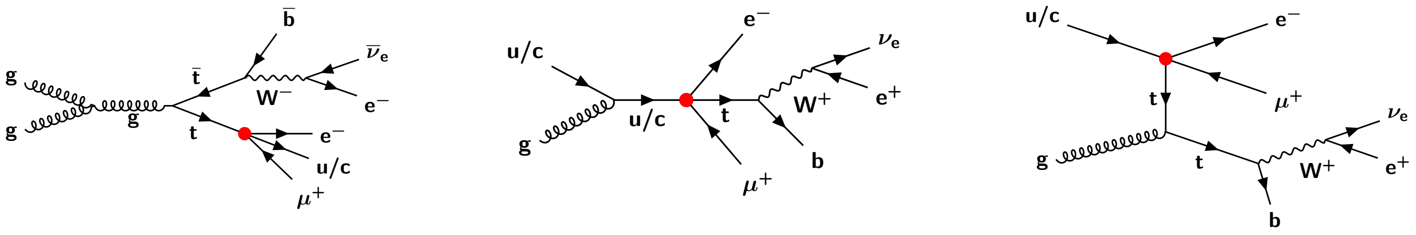
CMS-PAS-TOP-22-005

$\mathcal{L} = 138\ fb^{-1}$
$\sqrt{s} = 13$ TeV

- LHC provides best sensitivity to CLFV searches in 2 or 3 body decays of heavy particles, $\mathbf{X} \rightarrow \ell\ell'(\boldsymbol{Y})$, and in heavy particle production, $\mathbf{pp} \rightarrow \ell\ell'(\boldsymbol{X})$
  - CLFV processes involving top quark predicted to have competitive sensitivity at the LHC

✓ **CMS** previous search for CLFV in top in final states with **2 OS leptons**

- In this search: final states with exactly 3 charged leptons (ℓ), either **electrons** or **muons**
  - **1 lepton** originates **from leptonic decay of the SM top quark**
  - **other 2 leptons** originate **from CLFV interactions**
  - selected events have **at least 1 jet** and **at most 1 jet associated with a b quark**



➡ CLFV signals parametrized with dim-6 EFT operators

Search for CLFV in top quark sector in trilepton final states – analysis strategy

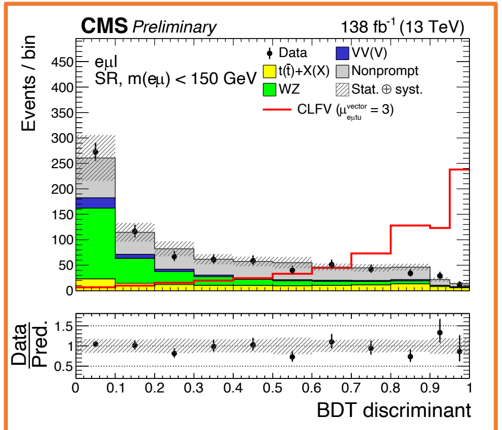
$\mathcal{L} = 138\ fb^{-1}$
$\sqrt{s} = 13$ TeV

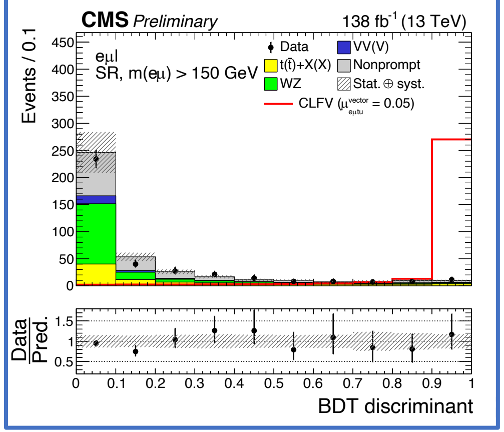
- **SM bkg categorized** into **2 groups**:
  - **prompt bkg**: including SM processes that produce at least 3 leptons via decays of ew bosons
    $\Rightarrow$ modelled with **MC**
  - **nonprompt bkg**: all other processes (such as Drell-Yan production)
    $\Rightarrow$ modelled with a **data-driven technique**

- **Kinematic distributions** of final-state particles **very different** in top **decay - production** CLFV interactions
  - presence of **high-p_T lepton in top production** sgn
  - **flavor of up-type quark** in LFV interaction have **minor impact** on kinematics

- **MVA techniques** (BDTs) used to distinguish btw CLFV signals and the SM bkg

- **BDT output** used to construct **binned likelihood function**, for stat. analysis





Search for CLFV in top quark sector in trilepton final states - Results

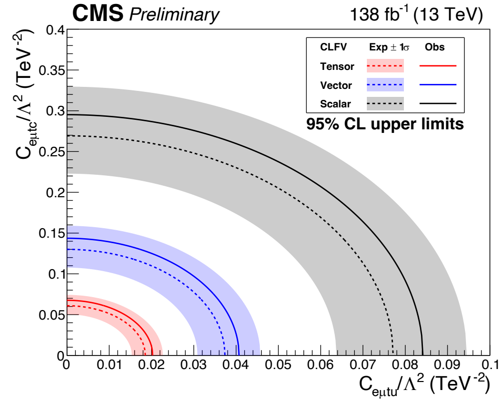
$\mathcal{L} = 138\ fb^{-1}$
$\sqrt{s} = 13$ TeV

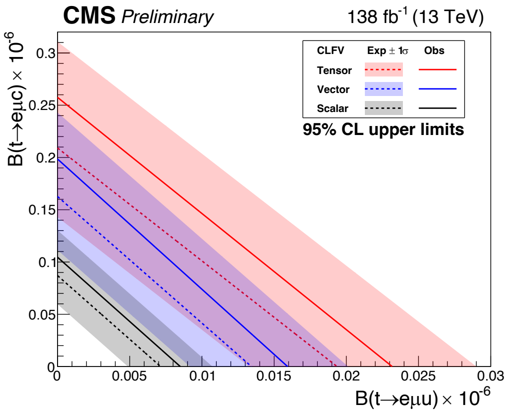
- **Results** are **consistent** with the **SM expectation**
  - **upper limits** set **@95% C.L.**

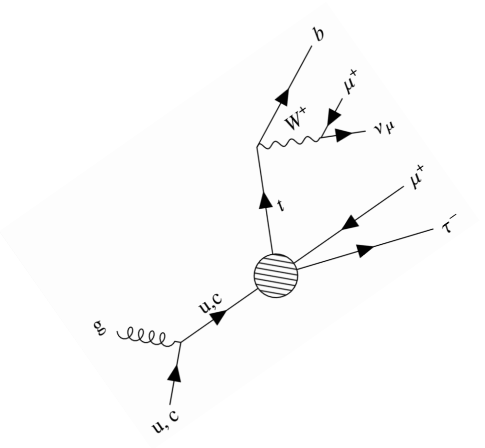
CLFV coupling	Lorentz structure	$C_{e\mu tq}/\Lambda^2$ (TeV^{-2}) exp $(-\sigma, +\sigma)$	obs	$\mathcal{B}(t \to e\mu q) \times 10^{-6}$ exp $(-\sigma, +\sigma)$	obs
$e\mu tu$	tensor	0.019 (0.015, 0.023)	**0.020**	0.019 (0.013, 0.029)	**0.023**
	vector	0.037 (0.031, 0.046)	**0.041**	0.013 (0.009, 0.020)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

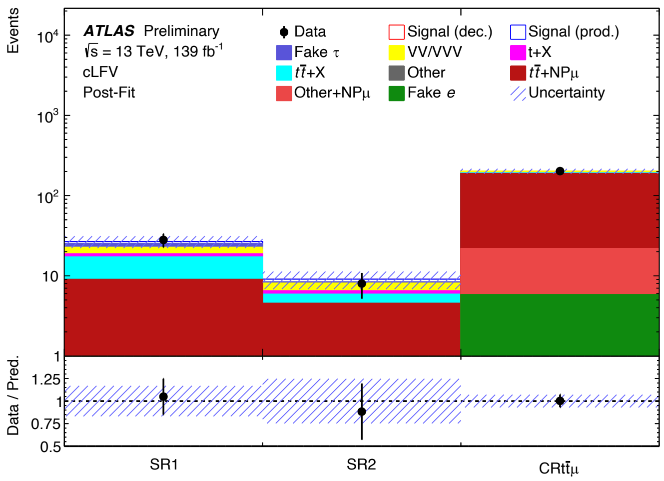
most stringent limits on these processes to date

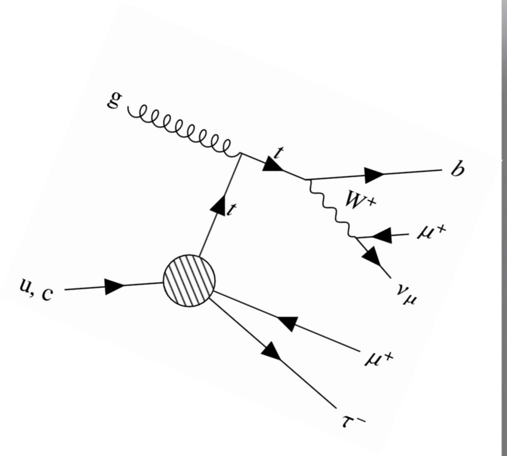
- Assuming a linear relationship btw $\mathcal{B}(t \to e\mu u)$ and $\mathcal{B}(t \to e\mu c)$ in the case of nonvanishing signals, 2D limits can also be obtained through interpolation











CLFV $\mu\tau qt$ interactions in top-quark production and decay

CLFV $\mu\tau qt$ interactions in top-quark production and decay

ATLAS-CONF-2023-001

$\mathcal{L} = 139\ fb^{-1}$

$\sqrt{s} = 13$ TeV

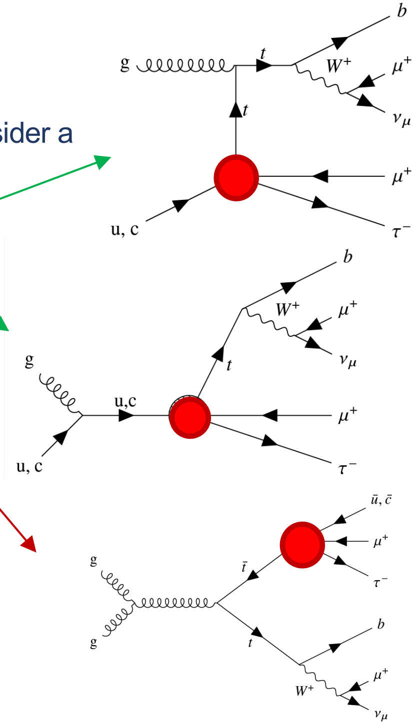
- Several SM extensions, such as those which predict ***leptoquarks***, entail cLFV with a rate as high as BR($t \rightarrow \ell\ell' c$) ≈ **$10^{-6}$**
  - assuming energy scale probed experimentally << scale of new physics, it's convenient to consider a model-independent approach by means of an effective field theory

- This analysis: search for **production of a single top quark** via $gq_k \rightarrow t\ell^{\pm}\ell'^{\mp}$
  - where $\boldsymbol{q_k} = \{\boldsymbol{u}, \boldsymbol{c}\}$ for $\boldsymbol{k} = \{\boldsymbol{1}, \boldsymbol{2}\}$ and $\ell\ell' = \{\mu\tau, \tau\mu\}$

  or **cLFV top decay in $t\bar{t}$** evts is also targeted: $t \rightarrow \ell^{\pm}\ell'^{\mp}q_k$

Final state: **2μ + τ decaying hadronically + at least 1 jet & exactly 1 b-tagged jet (produced by a $\mu\tau qt$ interaction in top production or decay)**

Observed data are interpreted within the EFT framework



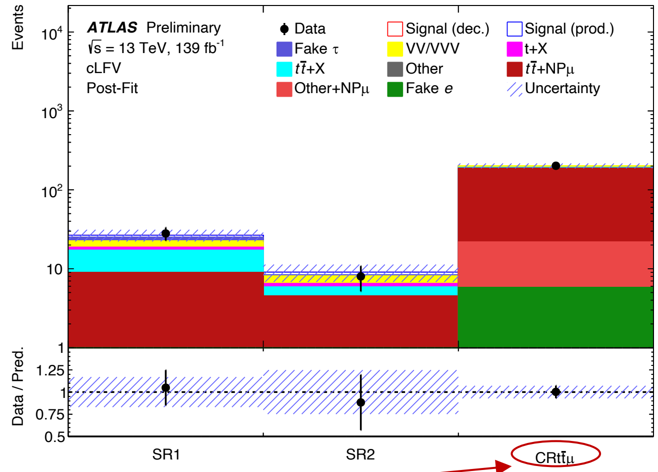
- ✓ **Separate MC samples** generated **for different EFT couplings** contributing to sgn, separately for single-top production and top decay (to determine limits on each coupling)
- ✓ **Two inclusive samples** with **all couplings activated simultaneously** (to determine inclusive BR limit)

CLFV $\mu\tau qt$ interactions in top-quark production and decay: analysis strategy

$\mathcal{L} = 139\ fb^{-1}$
$\sqrt{s} = 13$ TeV

- Two **signal regions** (SRs):
  - **SR1** targeting **cLFV** in **decay** diagrams → > 1 jet (one b-tagged)
  - **SR2** targeting **cLFV** in **production** diagrams → exactly 1 b-tagged jet

- Main **backgrounds:**
  - $t\bar{t}$ events with **non-prompt muons** from HF decays inside jets,
  - associated top production processes ($t\bar{t}Z$, $t\bar{t}W$, $t\bar{t}H$),
  - diboson events (WZ, ZZ),
  - events with jets misidentified as τ leptons («**fake τ**»).



✓ **prompt lepton bkg** modelled by **MC**

✓ yield of **non prompt muon bkg** determined through a **template fit** in dedicated **CR** containing dilepton $t\bar{t}$ events with $1e + 1\mu$, and additional NP muon from hadronic decay

✓ contribution of **fake τ bkg** determined with a **data-driven scale factor method** in a dedicated CR, targeting 2 OS muons + one hadronically decaying τ, designed to be enriched in events with a jet misidentified as a τ lepton.

Signal contribution in SRs estimated with a binned profile-likelihood fit, with syst. uncertainties modelled as nuisance parameters

CLFV $\mu\tau qt$ interactions in top-quark production and decay: results

- **Likelihood function** constructed as **product of Poisson probability terms over all bins** considered
  - depends on **signal strength parameter**, μ_{cLFV}, for sgn cLFV processes, and nuisance parameters, θ, encoding effect of systematics

Profile-likelihood fit to data under sgn+bkg hp, **maximizing** likelihood function over μ_{cLFV} and θ

Expected and observed **95% CL UL on Wilson coefficients** corresponding to **2Q2L EFT operators** which could introduce cLFV top decay in $\mu\tau$ channel

		95% CL upper limits on Wilson coefficients c/Λ^2 [TeV^{-2}]							
		$c_{lq}^{-(ijk3)}$	$c_{eq}^{(ijk3)}$	$c_{lu}^{(ijk3)}$	$c_{eu}^{(ijk3)}$	$c_{lequ}^{1(ijk3)}$	$c_{lequ}^{1(ij3k)}$	$c_{lequ}^{3(ijk3)}$	$c_{lequ}^{3(ij3k)}$
$\mu\tau ut$	Previous (u) [22]	12	12	12	12	26	26	3.4	3.4
	Expected (u)	0.47	0.44	0.43	0.46	0.49	0.49	0.11	0.11
	Observed (u)	0.49	0.47	0.46	0.48	0.51	0.51	0.11	0.11
$\mu\tau ct$	Previous (c) [22]	14	14	14	14	29	29	3.7	3.7
	Expected (c)	1.6	1.6	1.5	1.6	1.8	1.8	0.35	0.35
	Observed (c)	1.7	1.6	1.6	1.6	1.9	1.9	0.37	0.37

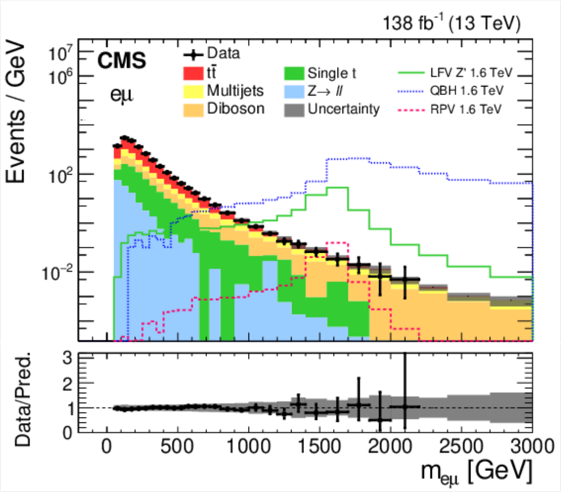
Reinterpretation of previous ATLAS FCNC search

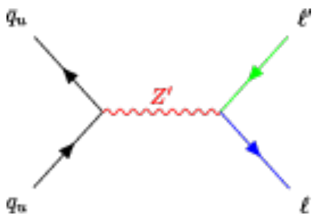
Expected and observed **95% CL UL on BR** using specific Wilson coefficients corresponding to 2Q2L EFT operators

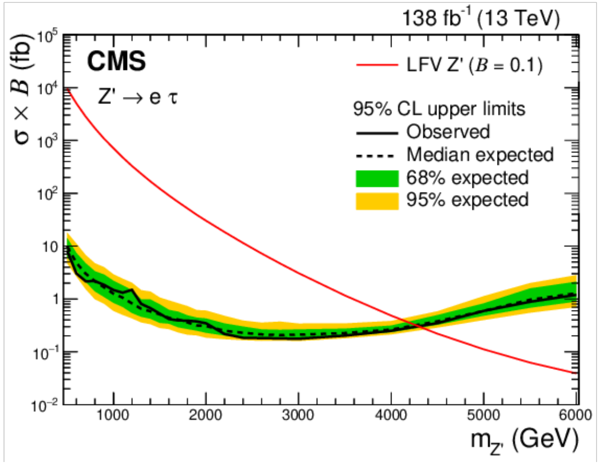
	95% CL upper limits on BR($t \to \mu\tau q$) ($\times 10^{-7}$)							
	$c_{lq}^{-(ijk3)}$	$c_{eq}^{(ijk3)}$	$c_{lu}^{(ijk3)}$	$c_{eu}^{(ijk3)}$	$c_{lequ}^{1(ijk3)}$	$c_{lequ}^{1(ij3k)}$	$c_{lequ}^{3(ijk3)}$	$c_{lequ}^{3(ij3k)}$
Expected (u)	4.6	4.2	4.0	4.5	2.5	2.5	5.8	5.8
Observed (u)	5.1	4.6	4.4	5.0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

A fit using two inclusive MC samples with all EFT operators activated simultaneously used to determine an inclusive BR limit

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







Search for heavy resonances and QBH in $e\mu$, $e\tau$, $\mu\tau$ final states

Search for heavy resonances and QBH in $e\mu$, $e\tau$, $\mu\tau$ final states - intro

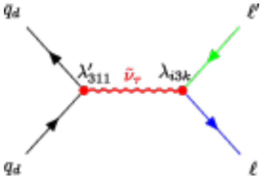
arXiv:2205.06709

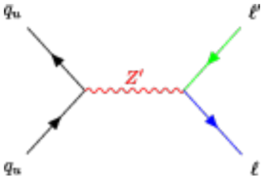
$\mathcal{L} = 138\, fb^{-1}$
$\sqrt{s} = 13$ TeV

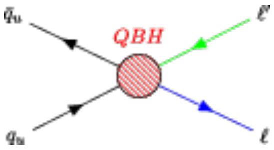
- Extensions of SM can accommodate heavy particles undergoing LFV decays
- Analysis designed to be **as model-independent as possible**

  Results are also interpreted in terms of characteristics of following possible states:

  - a $\boldsymbol{\tau}$ **sneutrino** ($\tilde{\nu}_\tau$), lightest SUSY particle in **RPV SUSY** models
  - a **heavy Z'** gauge boson in **LFV models**
  - **quantum black holes** (QBH) in ADD model (n=4)



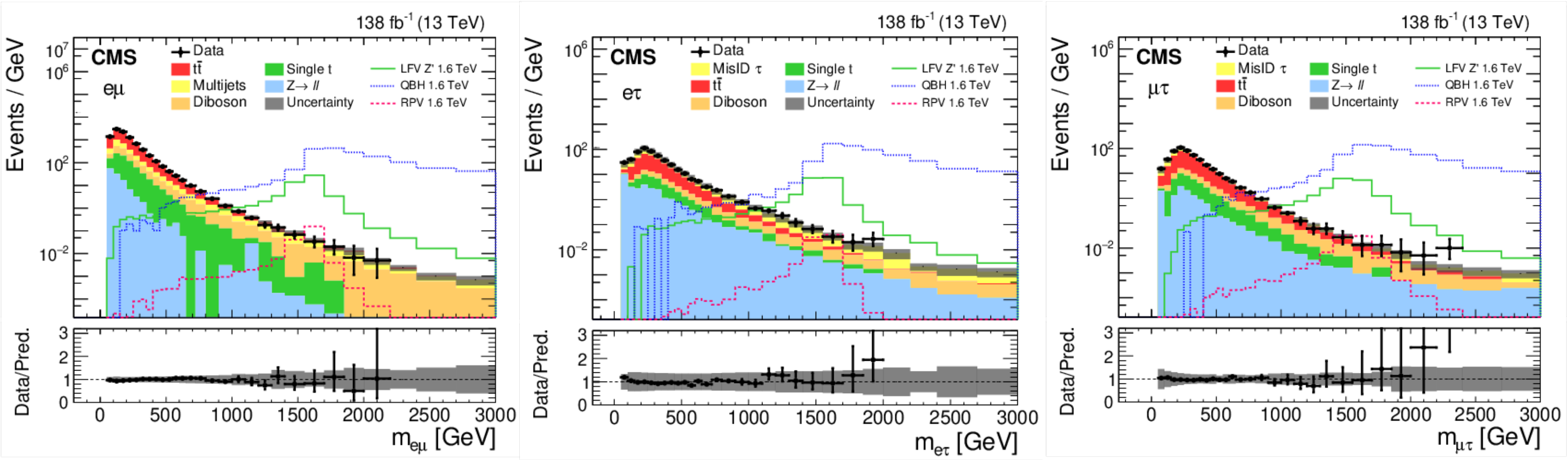




- Only one $\boldsymbol{e\mu}$ and $\boldsymbol{e\tau_h}$ or $\boldsymbol{\mu\tau_h}$ pair considered per evt:
  - if > 1 candidate, pair with highest inv. mass selected

Statistical interpretations performed **by comparing observed inv mass shapes** for different final states **with those expected for sgn and bkg**

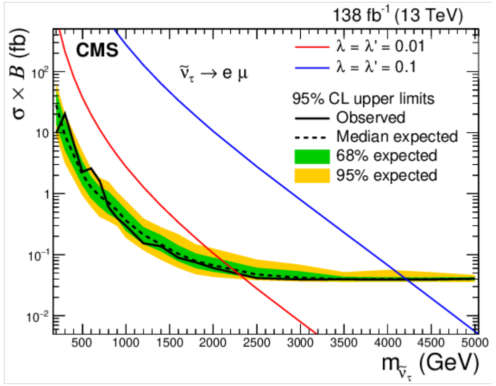
Search for heavy resonances & QBH in $e\mu$, $e\tau$, $\mu\tau$: invariant mass distributions

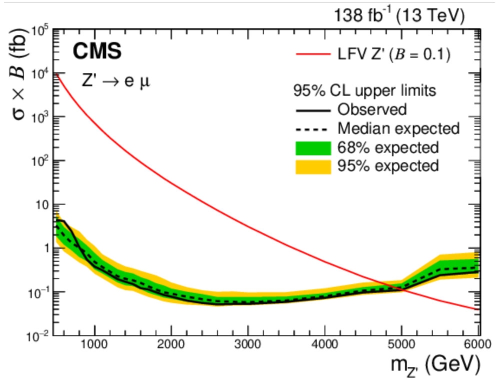


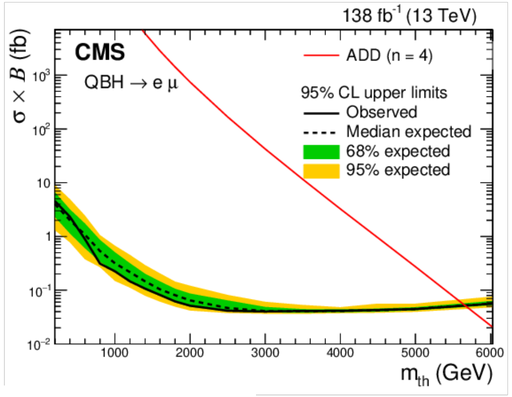
- **RPV SUSY model** ($\lambda = \lambda' = 0.01$) τ sneutrino mass of 1.6 TeV
- **LFV Z'** ($\mathcal{B} = 0.1$) boson with a mass=1.6 TeV,
- **QBH signal** expectation for n=4 and a threshold mass of 1.6 TeV

No significant deviations from expected SM bkg

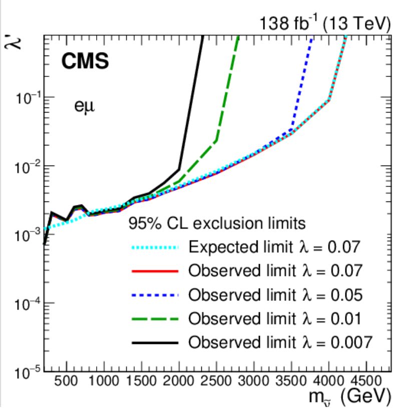
Search for heavy resonances & QBH in $e\mu$, $e\tau$, $\mu\tau$: UL for BSM models





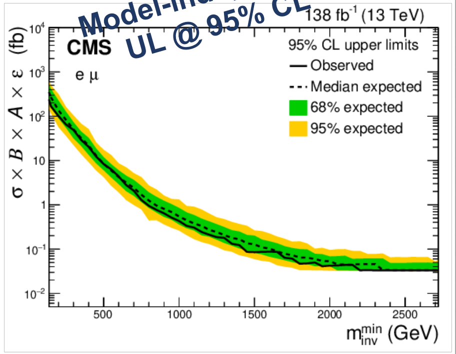


Expected and observed UL on $\sigma \times \mathcal{B}$ @95% CL as a function of τ sneutrino mass in RPV SUSY, Z' with LFV decays, and QBH threshold mass



Exclusion limits @ 95% CL on RPV SUSY model in plane of τ sneutrino mass and λ' coupling

Model-independent UL @ 95% CL



Search for heavy resonances & QBH in $e\mu$, $e\tau$, $\mu\tau$: results

No evidence is found for physics beyond the SM

- **Upper limits** set **@95% C.L.** on the product of the cross section and BR for **LFV signals**:
  - **Resonant τ sneutrinos excluded** for masses up to:
    - **4.2 TeV** in the $e\mu$ channel,
    - **3.7 TeV** in the $e\tau$ channel,
    - **3.6 TeV** in the $\mu\tau$ channel.
  - A **Z′ boson** with **LFV couplings is excluded** up to a mass of for masses up to:
    - **5.0 TeV** in the $e\mu$ channel,
    - **4.3 TeV** in the $e\tau$ channel,
    - **4.1 TeV** in the $\mu\tau$ channel.
  - **Quantum black holes** in the ADD benchmark model **excluded** up to the threshold mass of:
    - **5.6 TeV** in the $e\mu$ channel,
    - **5.2 TeV** in the $e\tau$ channel,
    - **5.0 TeV** in the $\mu\tau$ channel.
- **Model-independent limits also extracted** for comparisons with other models for same final states and similar event selections

Most stringent limits from collider experiments for heavy particles that undergo LFV decays

Backup slides

Search for Higgs LFV decay $H \to e\mu$

CMS

Search for LFV decay $H \to e\mu$: BSM models

- Combined CMS results constrained inclusive BR of potential BSM Higgs decays to be **B(H → BSM) < 0.16** @95% C.L.

  still well-motivated to search for BSM decays of Higgs, including LFV ones!

- Several BSM theories allowing LFV Higgs decay: models with more than one Higgs boson doublet, models with flavor symmetries, the Randall–Sundrum model, composite Higgs models, certain susy models, etc.

- **LFV decays** can occur **through *off-diagonal LFV Yukawa couplings*** $\Upsilon_{e\mu}$, $\Upsilon_{e\tau}$, $\Upsilon_{\mu\tau}$
  - they enhance processes (e.g. $\mu \to 3e$, $\mu \to e$ conversion, $\mu \to e\gamma$) that could proceed via virtual Higgs boson exchange
  - In particular, **most stringent limit** on B(H(125) → eμ) obtained **indirectly** from limit on **$\mu \to e\gamma$** to be **$< 10^{-8}$**
  - However, *indirect limit on H(125) → eμ assumes SM values for not yet tightly constrained Yukawa couplings $\Upsilon_{\mu\mu}$ and unmeasured Υ_{ee}.*

  Direct search for H(125) → eμ remains important!

- Apart from SM Higgs, LFV decays could also arise from extra BSM Higgs bosons in the **Type-III two Higgs doublet model (2HDM)** or other exotic resonances decaying to eμ.

Search for LFV decay H→$e\mu$: analysis strategy

- This analysis targets the two dominant production modes of Higgs at LHC: **ggH** and **VBF**.
  - **final state** of interest in both modes: **prompt, oppositely-charged electron-muon pair**

- Distribution of **$m_{e\mu}$ would exhibit a peak** around **m_H** or **m_X on top of smoothly falling bkg** dominated by fully leptonic decays of $t\bar{t}$ and WW events, and Drell-Yan (DY) events with a misidentified lepton.
  - smaller bkg include leptonic decays of single top, single W, and electroweak W events with jets misidentified as a lepton
  - events of H(125) decaying to a τ or a W pair, diboson processes (WZ, ZZ), and EW Z also provide a small contribution

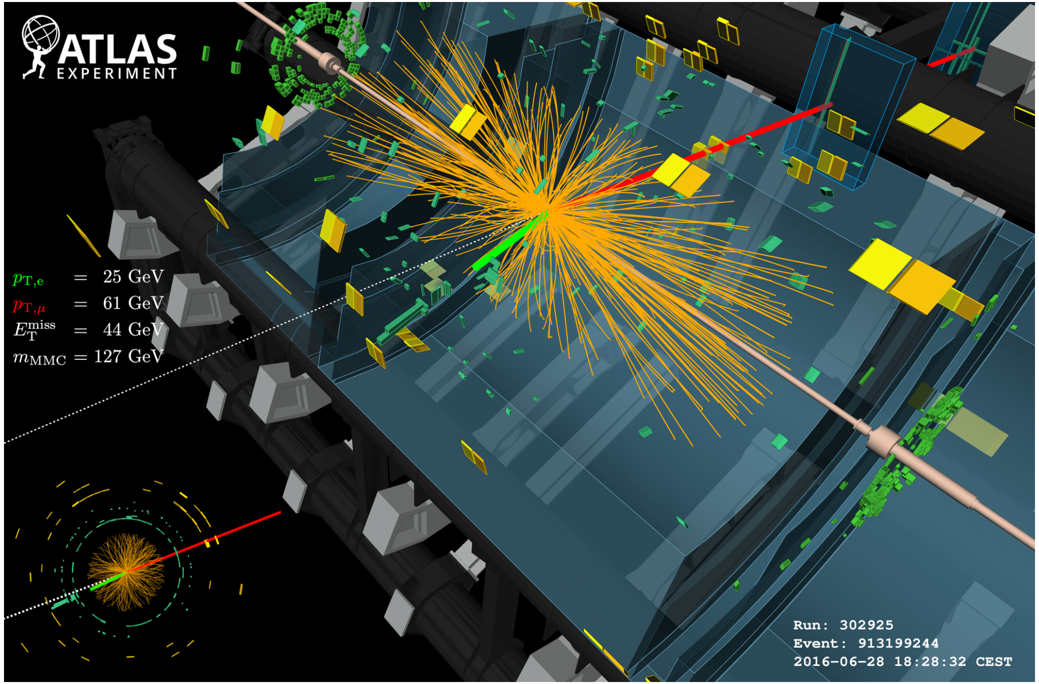
***All bkg** are **simulated** with MC samples, along with signals: **H(125)** → **eμ** and **X** → **eμ** (m_X from 110 − 160 GeV, in steps of 10 GeV)*

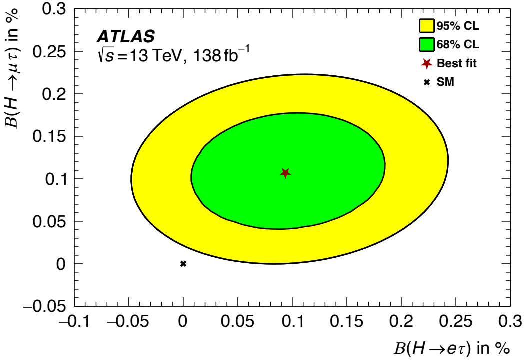
- Sensitivity optimized by first **categorizing events** to **target each production mode**.
- Then, further categorizations to separate events into **samples of different sgn-to-bkg ratio based on BDTs**.
- The **$m_{e\mu}$** distributions of H(125) → eμ or X → eμ signal from MC are **fit with** a **parametric model and interpolated btw** generated m_H and m_X **mass points in each category**; $m_{e\mu}$ distributions of **bkg** are **modeled directly from data**.
- **Simultaneous fit of sgn and bkg models to data** performed **to extract an UL** on either B(H(125) → eμ) or on the cross section σ(pp → X → eμ) for a BSM Higgs boson.
  - constraint on B(H(125) → eμ) translated to UL on $Y_{e\mu}$ (assuming only H(125) → eμ contributes additionally to SM Higgs total decay width)

Search for LFV decay H→$e\mu$: systematic uncertainties

Systematic uncertainties	ggH mode (%)	VBF mode (%)
Muon identification, isolation, and trigger	< 1	< 1
Electron identification, isolation, and trigger	2	2
b tagging efficiency	< 1	< 1
Jet energy scale	1–8	1–3
Unclustered energy scale	2–6	1–6
Trigger timing inefficiency	< 1	< 1
Integrated luminosity	< 2	< 2
Pileup	< 2	< 2
Parton shower	-	3–11
Ren. and fact. scales	4	1
PDF + α_S	3	2
Effect of the ren. and fact. scales on the acceptance	1–10	< 2
Effect of the PDF + α_S on the acceptance	< 1	< 1

Systematic uncertainties in expected signal yields from different sources for ggH and VBF production modes. All uncertainties are treated as ***correlated among categories***.





Search for Higgs LFV decays H→$e\tau$ and H→$\mu\tau$

ATLAS

Search for LFV decays $H \to e\tau$ and $H \to \mu\tau$:
event selections and bkg estimation

- Analysis channels defined accordingly to τ decay mode:
  - Evts in $\ell\tau_{\ell'}$ contain exactly 2 light leptons of OS charge
  - Evts in $\ell\tau_{had}$ contain 1 light lepton + $\tau_{had-vis}$ with OS charge
  - Evts containing $\tau_{had-vis}$ are vetoed in $\ell\tau_{\ell'}$ channel

- 2 independent methods exploited to estimate bkg in $\ell\tau_{\ell'}$
  - **MC template** method: uses templates from MC and a data-driven estimate of the 'misidentified bkg'.
    - in $\ell\tau_{had}$ only the MC-template method is used

Selection	$\ell\tau_{\ell'}$	$\ell\tau_{\text{had}}$
Baseline	exactly 1e and 1μ, OS τ_{had}-veto b-veto $p_T^{\ell_1} > 45$ (35) GeV MC-template (Symmetry method) $p_T^{\ell_2} > 15$ GeV $30\,\text{GeV} < m_{\ell_1\ell_2} < 150\,\text{GeV}$ $0.2 < p_T^{\text{track}}(\ell_2 = e)/p_T^{\text{cluster}}(\ell_2 = e) < 1.25$ (MC-template) track d_0 significance requirement (see text) $\lvert z_0 \sin\theta \rvert < 0.5$ mm	exactly 1ℓ and 1$\tau_{\text{had-vis}}$, OS τ_{had}Tight ID Medium eBDT ($e\tau_{\text{had}}$) b-veto $p_T^{\ell} > 27.3$ GeV $p_T^{\tau_{\text{had-vis}}} > 25$ GeV, $\lvert\eta^{\tau_{\text{had-vis}}}\rvert < 2.4$ $\sum_{i=\ell,\tau_{\text{had-vis}}} \cos\Delta\phi(i, E_T^{\text{miss}}) > -0.35$ $\lvert\Delta\eta(\ell, \tau_{\text{had-vis}})\rvert < 2$
VBF	*Baseline* ≥ 2 jets, $p_T^{j_1} > 40$ GeV, $p_T^{j_2} > 30$ GeV $\lvert\Delta\eta_{jj}\rvert > 3$, $m_{jj} > 400$ GeV	
non-VBF	*Baseline* plus fail *VBF* categorisation – –	veto events if $90 < m_{\text{vis}}(e, \tau_{\text{had-vis}}) < 100$ GeV

  - **Symmetry method**: assumes that prompt-lepton bkg in SM are symmetric under the exchange of electrons and muons to derive data-driven bkg estimate for main bkgs.

  - MC-template method targets measurement of actual values of $\mathcal{B}(H \to e\tau)$ and $\mathcal{B}(H \to \mu\tau)$ individually
  - Symmetry method is sensitive to the difference of BRs

- In stat. analysis, MC-template method in $\ell\tau_{had}$ final state combined with both methods in $\ell\tau_{\ell'}$ final state. Method with higher expected sensitivity is chosen. In simultaneous determination of signals, MC-template method used for both final states.

Search for LFV decays $H \to e\tau$ and $H \to \mu\tau$: multivariate analysis

- **Two MVA techniques** used to separate sgn from bkgs
  - **BDTs** for **MC-template method**
  - deep **NNs** for **Symmetry method**

- **Different MVA techniques** are used **for *non-VBF* and *VBF* categories**, to exploit the VBF topology

❑ **3 BDTs** used in $\ell\tau_{\ell'}$ of **MC-template** method

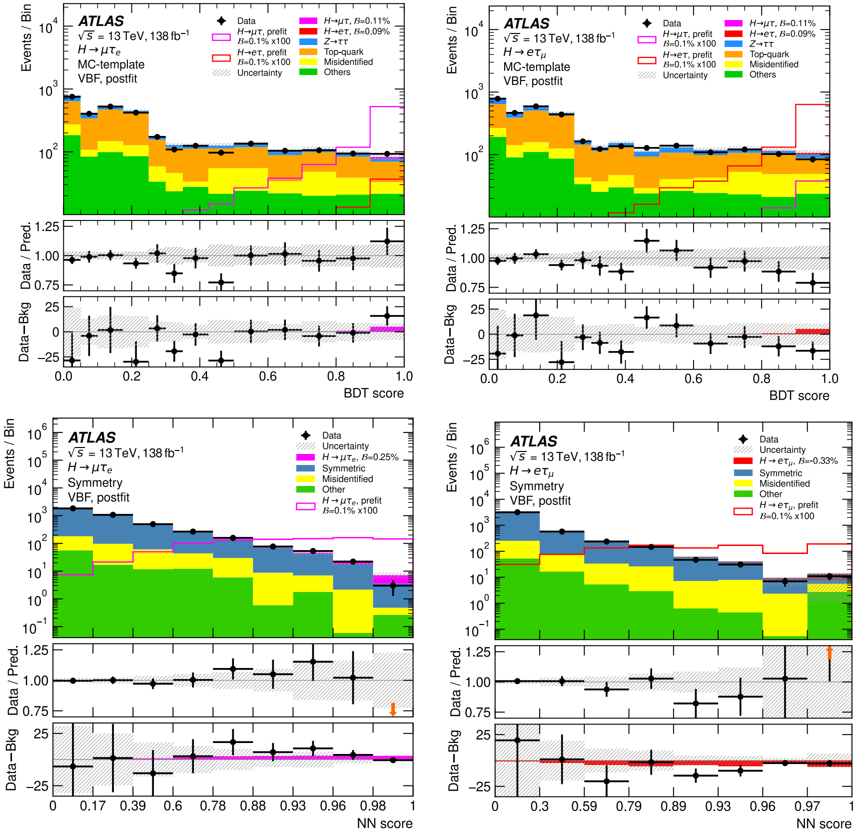
- $e\tau_\mu$ and $\mu\tau_e$ combined in the BDT training
- BDT scores combined using linear weighted sum; weights optimised using expected sgn significance as figure-of-merit

❑ **2 BDTs** used in $\ell\tau_{had}$ of **MC-template** method

- except for non-VBF category in $e\tau_{had}$ (3 BDTs)
- BDT scores combined using linear weighted sum in non-VBF categories, and quadratic weighted sum in VBF ones.

❑ **NNs** used in $\ell\tau_{\ell'}$ of **Symmetry** method

- non-VBF cat.: multiclass classifier with 3 output classes
- VBF cat: 3 single binary classification networks, whose outputs are combined linearly



Search for LFV decays H→$e\tau$ and H→$\mu\tau$: systematic uncertainties

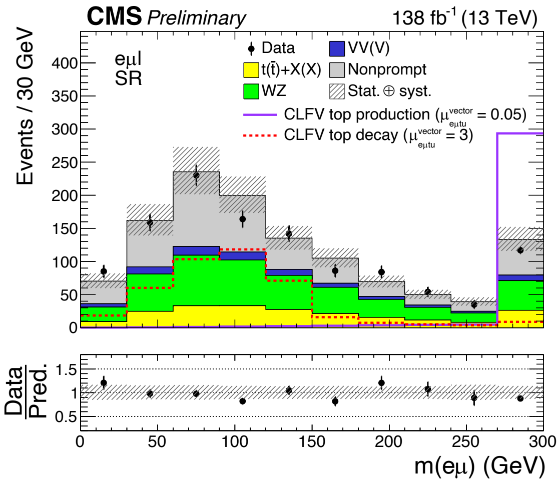
1 POI Source of uncertainty	Impact on observed [10^{-4}] $\hat{\mathcal{B}}(H \to e\tau)$	 $\hat{\mathcal{B}}(H \to \mu\tau)$
Flavour tagging	0.6	0.4
Misidentified background ($\ell\tau_{had}$)	2.1	1.5
Misidentified background ($\ell\tau_{\ell'}$)	2.9	1.6
Jet and E_T^{miss}	1.1	1.1
Electrons and muons	0.2	0.5
Luminosity	0.6	0.5
Hadronic τ decays	0.9	1.0
Theory (signal)	0.9	0.7
Theory (Z + jets processes)	1.0	1.2
Theory (top-quark processes)	0.3	0.3
Theory (diboson processes)	0.4	0.7
$Z \to \ell\ell$ normalisation	0.2	0.7
Symmetric background estimate	0.2	0.1
Background sample size	4.2	2.4
Total systematic uncertainty	5.3	3.9
Data sample size	2.9	2.7
Total	6.1	4.7

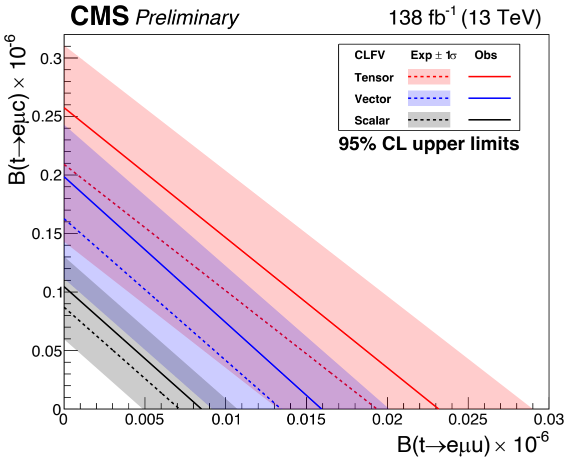
2 POI Source of uncertainty	Impact on observed [10^{-4}] $\hat{\mathcal{B}}(H \to e\tau)$	 $\hat{\mathcal{B}}(H \to \mu\tau)$
Flavour tagging	0.7	0.2
Misidentified background ($e\tau_{had}$)	2.1	0.3
Misidentified background ($e\tau_{\mu}$)	5.8	0.3
Misidentified background ($\mu\tau_{had}$)	0.6	1.4
Misidentified background ($\mu\tau_{e}$)	0.9	1.1
Jet and E_T^{miss}	1.2	0.9
Electrons and muons	1.4	0.5
Luminosity	0.6	0.4
Hadronic τ decays	0.9	0.9
Theory (signal)	0.8	0.8
Theory (Z + jets processes)	0.8	1.0
$Z \to \ell\ell$ normalisation ($e\tau$)	<0.1	<0.1
$Z \to \ell\ell$ normalisation ($\mu\tau$)	0.2	0.9
Background sample size	3.7	2.3
Total systematic uncertainty	5.1	3.6
Data sample size	3.0	2.7
Total	5.9	4.5

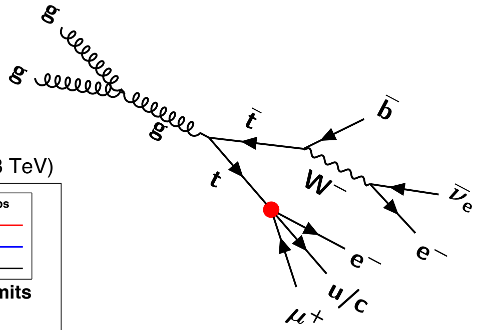
Uncertainties affecting observed B(H → ℓ τ) and their impact as computed by independent fits (1 POI) and simultaneous fit (2 POI)

*Values in the table are multiplied by a factor **100** to improve their readability*

- Exp. uncertainties for reco objects combine eff. and energy/momentum scale and reso uncertainties.
- 'Background sample size' includes bin-by-bin stat. uncertainties in simulated bkg as well as stat. uncertainties in misidentified bkg, which are estimated using data.







Search for CLFV in top quark sector in trilepton final states

Search for CLFV in top quark sector in trilepton final states: Theoretical framework

- CLFV signals parametrized with **dim-6 EFT operators**
  - indices i and j are lepton flavor (i,j= 1, 2 with i != j); k and l are quark flavor indices with condition that one of them is 3 and the other one runs from 1 to 2.

$$\mathcal{L} = \mathcal{L}_{\rm SM}^{(4)} + \frac{1}{\Lambda^2}\sum_a C_a^{(6)} O_a^{(6)} + O(\frac{1}{\Lambda^4}),$$

vector	$O_{lq}^{(1)ijkl}$	$(\bar{l}_i\gamma^\mu l_j)(\bar{q}_k\gamma^\mu q_l)$
	O_{lu}^{ijkl}	$(\bar{l}_i\gamma^\mu l_j)(\bar{u}_k\gamma^\mu u_l)$
	O_{eq}^{ijkl}	$(\bar{e}_i\gamma^\mu e_j)(\bar{q}_k\gamma^\mu q_l)$
	O_{eu}^{ijkl}	$(\bar{e}_i\gamma^\mu e_j)(\bar{u}_k\gamma^\mu u_l)$
scalar	$O_{lequ}^{(1)ijkl}$	$(\bar{l}_i e_j)\ \varepsilon\ (\bar{q}_k u_l)$
tensor	$O_{lequ}^{(3)ijkl}$	$(\bar{l}_i\sigma^{\mu\nu} e_j)\ \varepsilon\ (\bar{q}_k\sigma_{\mu\nu} u_l)$

- **Stat. analysis**: binned likelihood function L(μ, θ) constructed using BDT discriminator distributions. The parameter of interest (POI), denoted by μ, is the signal strength that governs the cross section of the top quark production and decay signals simultaneously

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

Search for CLFV in top quark sector in trilepton final states: event selections & bkg contributions

- Two types of signal-free regions within the eee/μμμ channel
  - non prompt bkg validation region (VR)
  - WZ control region (CR)

- Additional validation region defined in the $e\mu\ell$ channel, inverting mass requirement used to define the SR

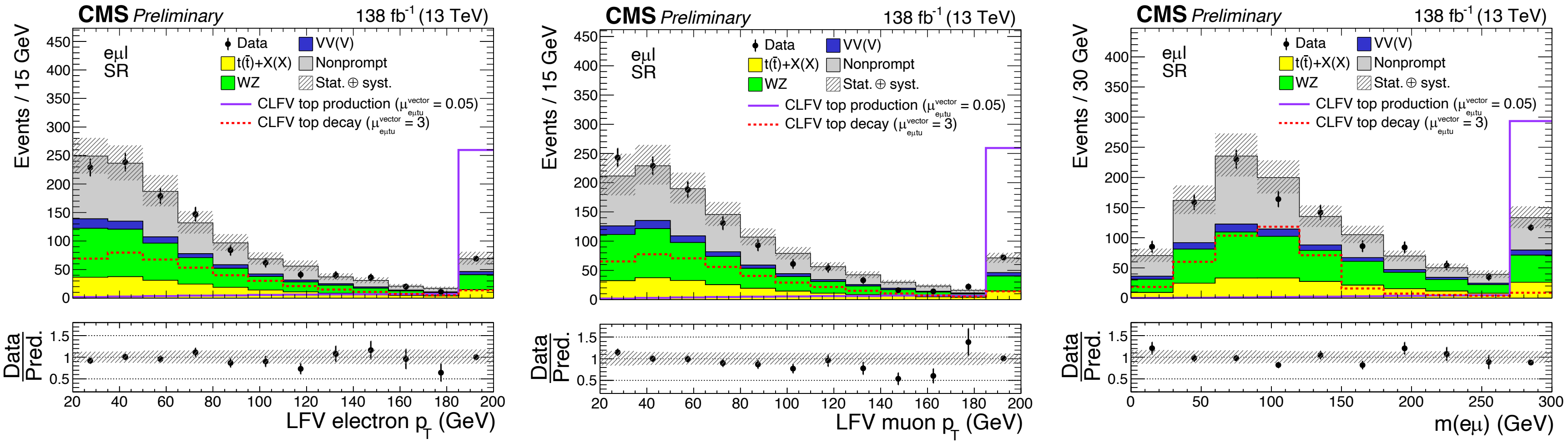
Channel	Region	OnZ	OffZ	$p_T^{miss} > 20\,\text{GeV}$	# jets ≥ 1	# b jets ≤ 1
$eee/\mu\mu\mu$	VR	-	-	-	-	-
	WZ CR	✓	-	✓	✓	✓
$e\mu l$	SR	-	✓	✓	✓	✓
	VR	✓	-	-	-	-
	WZ CR	✓	-	✓	✓	✓

Expected background contributions and number of events observed in data

Process	$m(e\mu) < 150\,\text{GeV}$	$m(e\mu) > 150\,\text{GeV}$
Nonprompt	351 ± 92	146 ± 38
WZ	275 ± 64	145 ± 35
ZZ	33.2 ± 6.5	13.1 ± 2.6
VVV	17.0 ± 8.5	12.0 ± 6.0
$t\bar{t}W$	47.6 ± 10.0	40.0 ± 9.1
$t\bar{t}Z$	39.1 ± 7.9	25.8 ± 5.4
$t\bar{t}H$	28.2 ± 4.5	10.0 ± 1.6
tZq	5.5 ± 1.1	2.5 ± 0.5
Other backgrounds	7.3 ± 3.7	4.5 ± 2.3
Total expected background	805 ± 123	398 ± 57
Data	783	378
CLFV	239 ± 14	6195 ± 305

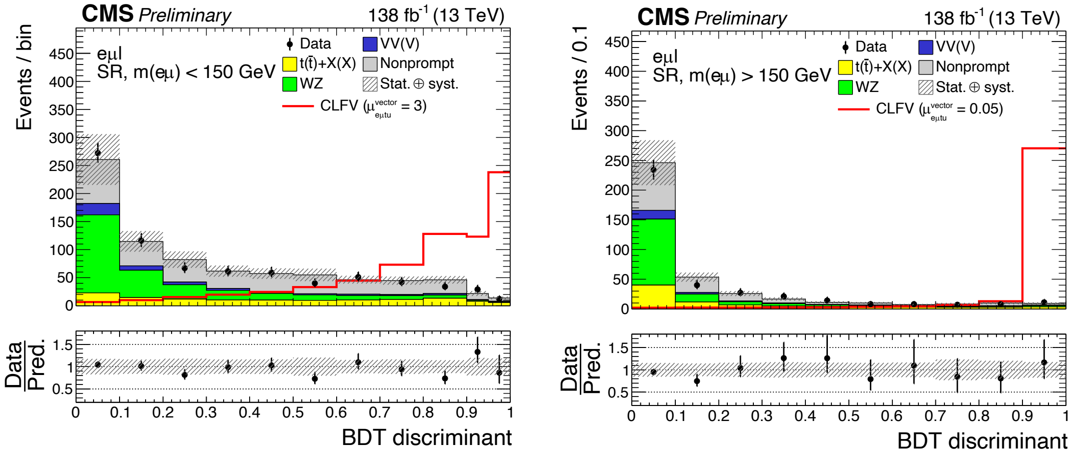
Search for CLFV in top quark sector in trilepton final states: Analysis strategy

- SM background processes entering the final selection are categorized into 2 groups:
  - **prompt bkg**: including SM processes that produce at least 3 leptons via decays of ew bosons ⇒ modelled with **MC**
  - **nonprompt bkg**: all the other processes (such as Drell-Yan production) ⇒ modelled with a **data-driven technique**
- MVA techniques (BDTs) used to separate between CLFV signals and the SM bkg
- Full BDT output used to construct a binned likelihood function, used for the statistical analysis



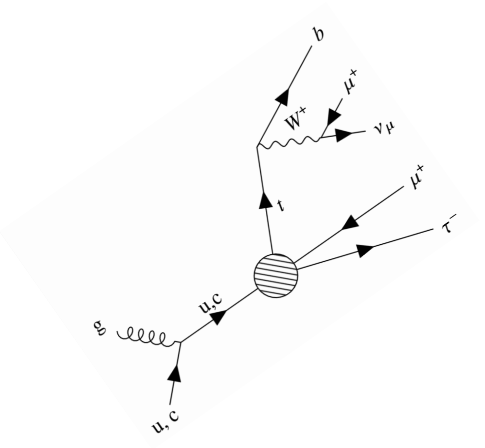
Search for CLFV in top quark sector in trilepton final states : MVA analysis

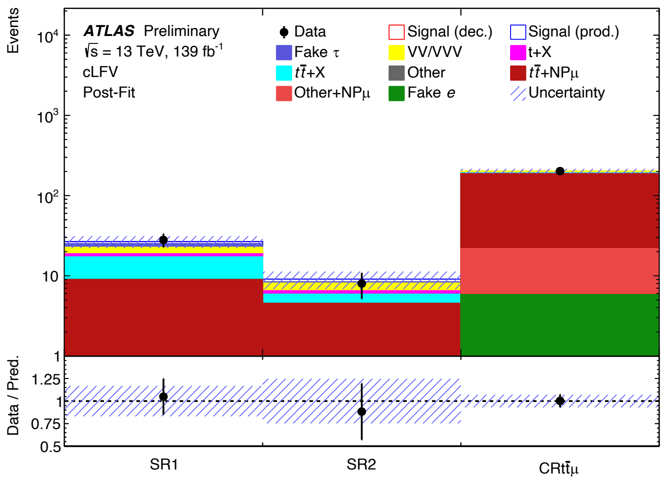
- Kinematic distributions of final-state particles very different in 2 sgn regions: top production and decay CLFV interactions
  - presence of high-p_T lepton in top production sgn
  - flavor of up-type quark in LFV interaction (up vs charm) have minor impact on kinematics

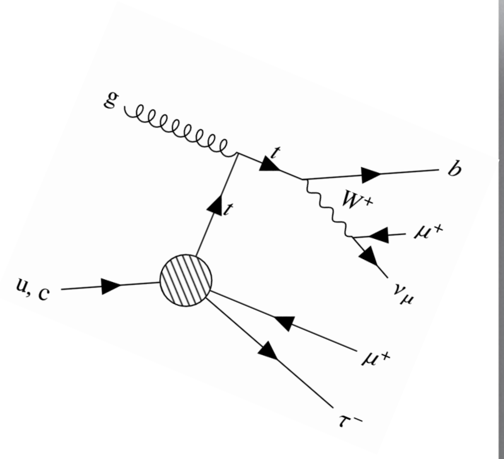


BDT output targeting CLFV top quark decay (left) and production (right) signal

- Most important input variables to the BDT model targeting the top quark
  - **decay**: inv mass of Z boson candidate, number of b-tagged jets, and inv mass of the flavor-violating top quark
  - **production**: invariant mass of the flavor-violating eμ pair, pT of flavor-violating electron, and pT of the flavor-violating muon







CLFV $\mu\tau qt$ interactions in top-quark production and decay

CLFV $\mu\tau qt$ interactions in top-quark production and decay: EFT framework

- Top production and decay processes under study, are described by $SU(3)_C \times SU(2)_L \times U(1)_Y$ **dim-6 EFT operators**
  - list includes all relevant 2Q2L operators that contribute
  - Convention used: l,q: LH lepton and quark doublets, u,e are RH up-type quark and charged-lepton singlets. Indices i, j represent LF generations; k, l are the quark flavor generations.

Operator	Lorentz Structure	
$O_{lq}^{1(ijkl)}$	$(\bar{l}_i\gamma^\mu l_j)(\bar{q}_k\gamma_\mu q_l)$	Vector
$O_{lq}^{3(ijkl)}$	$(\bar{l}_i\gamma^\mu\sigma^I l_j)(\bar{q}_k\gamma_\mu\sigma^I q_l)$	Vector
$O_{eq}^{(ijkl)}$	$(\bar{e}_i\gamma^\mu e_j)(\bar{q}_k\gamma_\mu q_l)$	Vector
$O_{lu}^{(ijkl)}$	$(\bar{l}_i\gamma^\mu l_j)(\bar{u}_k\gamma_\mu u_l)$	Vector
$O_{eu}^{(ijkl)}$	$(\bar{e}_i\gamma^\mu e_j)(\bar{u}_k\gamma_\mu u_l)$	Vector
$^\ddagger O_{lequ}^{1(ijkl)}$	$(\bar{l}_i e_j)\varepsilon(\bar{q}_k u_l)$	Scalar
$^\ddagger O_{lequ}^{3(ijkl)}$	$(\bar{l}_i\sigma^{\mu\nu} e_j)\varepsilon(\bar{q}_k\sigma_{\mu\nu} u_l)$	Tensor

- **Wilson coefficients** may be assigned to each operator in table.
  - Non-zero Wilson coefficients lead to a large cLFV single-top-quark production cross-section and so this process dominates search sensitivity

$$\Gamma(t \to \ell_i^+\ell_j^- q_k) = \frac{m_t}{6144\pi^3}\left(\frac{m_t}{\Lambda}\right)^4 \Big\{4|c_{lq}^{-(ijk3)}|^2 + 4|c_{eq}^{(ijk3)}|^2 + 4|c_{lu}^{(ijk3)}|^2 + 4|c_{eu}^{(ijk3)}|^2 + |c_{lequ}^{1(jik3)}|^2 + |c_{lequ}^{1(ij3k)}|^2 + 48|c_{lequ}^{3(jik3)}|^2 + 48|c_{lequ}^{3(ij3k)}|^2\Big\}$$

The range of Wilson coefficient limits set by re-interpretation of a previous ATLAS FCNC search in the tZq channel corresponds to minimal and maximal BR limits: **BR($t \to \mu\tau u$) < 3.5 × 10^{-5}** and **BR($t \to \mu\tau c$) < 3.0 × 10^{-4}** for respective operators

CLFV $\mu\tau qt$ interactions in top-quark production and decay: theoretical cross sections

- Theoretical cross sections, for single-top production and top decays through cLFV interactions involving vector, scalar and tensor EFT Wilson coefficients

	Cross section $\sigma^{+\text{scale}}_{-\text{scale}} \pm$ PDF (fb)		
	$c^{(ijk3)}_{\text{vector}}$	$c^{1(ijk3)}_{lequ}$	$c^{3(ijk3)}_{lequ}$
Production $\ell\ell' ut$	$118^{+24}_{-19} \pm 1$	$101^{+21}_{-16} \pm 1$	$2150^{+410}_{-320} \pm 20$
Production $\ell\ell' ct$	$7.9^{+1.2}_{-1.0} \pm 1.6$	$6.1^{+1.0}_{-0.8} \pm 1.5$	$153^{+21}_{-18} \pm 29$
Decay $\ell\ell' qt$	$6.9^{+1.8}_{-1.3} \pm 0.1$	$3.46^{+0.90}_{-0.66} \pm 0.03$	$166^{+43}_{-32} \pm 2$

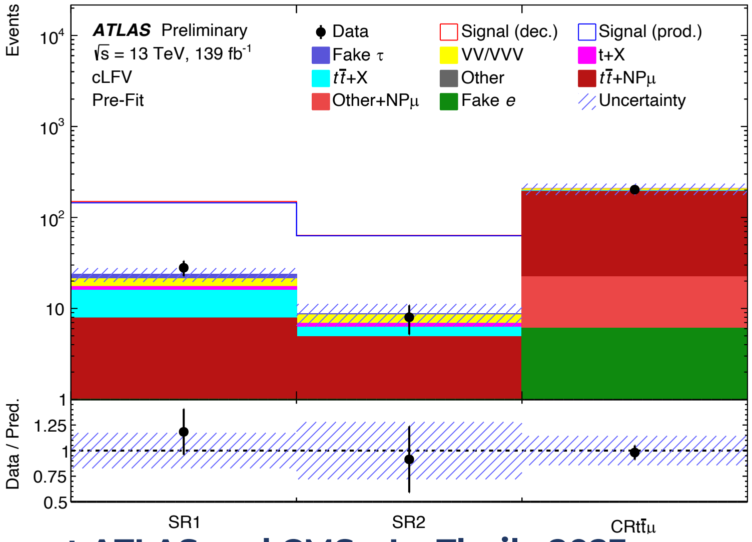
⇒ Signal cross-section **dominated** by the $gu \rightarrow t\ell^{\pm}\ell'^{\mp}$ process which leads to stronger limits on $\mu\tau ut$ interactions than $\mu\tau ct$

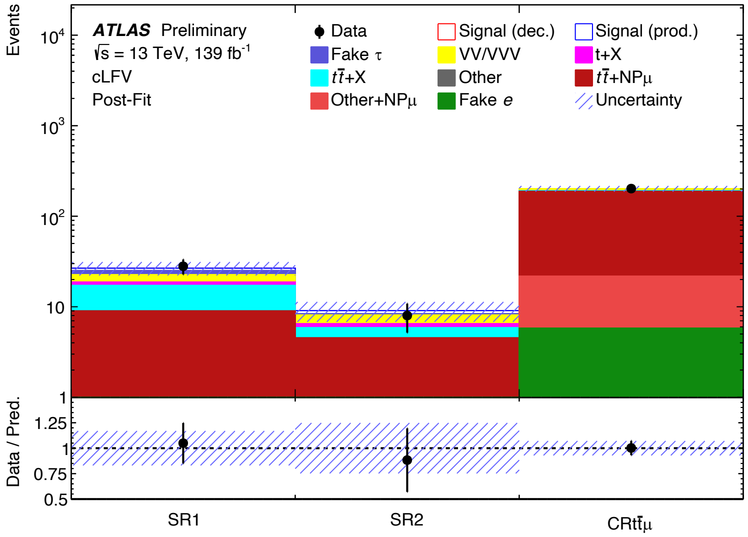
CLFV $\mu\tau qt$ interactions in top-quark production and decay: analysis strategy

Preselection:	
Number of leptons	$N_\ell = 3,\ p_\mathrm{T} > 10\ GeV,\ \lvert\eta\rvert < 2.5$
Leading muon / electron p_T	p_T ¿ 27 GeV
Trigger matching	$\geq$ 1 trigger-matched muon / electron
Sum of lepton charges	$\sum q_i = \pm 1$

	SR1	**SR2**	**CRτ**	**CR$tt\mu$**
Lepton flavour		$2\mu 1\tau_{\text{had-vis}}$		$2\mu 1e$ ($\ell_3 = \mu$)
N_{jets}	≥ 2	1	≥ 2	≥ 2
$N_{b-\text{tags}}$	1	1	1	≤ 2
Muon p_T cut	> 15 GeV	> 15 GeV	> 15 GeV	> 10 GeV
Lowest p_T muon selection	*Tight*	*Tight*	*Tight*	*Loose*
Muon charges	SS	SS	OS	-
$\lvert m_{\mu\mu}^{OS} - M_Z\rvert$	-	-	<10 GeV	>10 GeV

- **Multiple selections** defined for regions which focus on either **cLFV sgn processes**, or to **constrain normalisation of fake-lepton bkg**.
  - All analysis regions are subject to *same preselection cuts*
- **Normalisations** of sgn and non-prompt muon are obtained from **simultaneous profile-likelihood fit to 3 regions** with syst. uncertainties included as nuisance parameters





CLFV $\mu\tau qt$ interactions in top-quark production and decay: systematic uncertainties

- Systematic effects may change expected numbers of evts from sgn and bkg and shape of fitted distributions in SRs and CRs
- These effects are **evaluated by varying each source of syst. uncertainty by ±1σ** and ***considering resulting deviation from the nominal expectation as uncertainty***
- Cross-section uncertainties motivated by SM predictions are applied to each bkg process

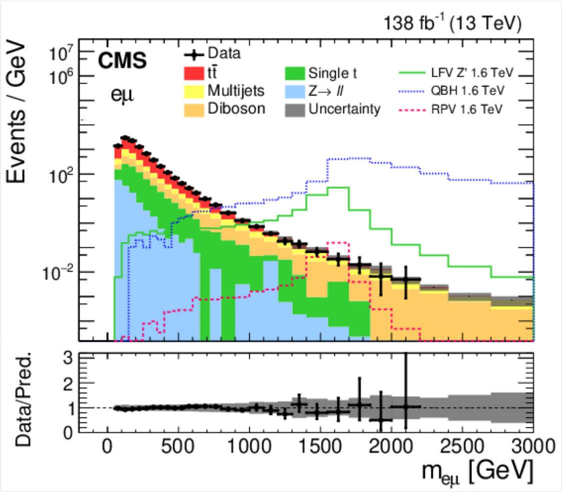
Process	$CR\tau$ (1p)	$CR\tau$ (3p)
Z + fake $\tau_{\text{had-vis}}$	1060 ± 110	341 ± 68
$t\bar{t}$ + fake $\tau_{\text{had-vis}}$	99 ± 22	36 ± 15
Other fake $\tau_{\text{had-vis}}$	24.9 ± 2.4	8.12 ± 0.81
Z + NPμ	0.050 ± 0.068	0.04 ± 0.12
$t\bar{t}$ + NPμ	1.95 ± 0.57	0.38 ± 0.36
$t\bar{t}H$	0.828 ± 0.094	0.257 ± 0.034
$t\bar{t}W$	0.63 ± 0.32	0.22 ± 0.12
$t\bar{t}Z$	15.2 ± 1.9	4.77 ± 0.61
WZ	21.8 ± 6.7	6.4 ± 2.0
ZZ	11.1 ± 3.7	3.0 ± 1.0
t+X	11.7 ± 1.3	3.39 ± 0.41
VVV	0.45 ± 0.23	0.077 ± 0.042
Other	16.8 ± 8.5	5.7 ± 2.9
Total	1270 ± 120	409 ± 71
Data	1314	356

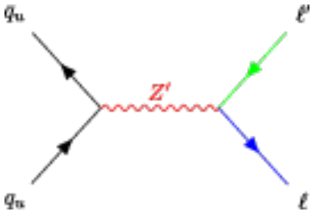
- Largest systematics relate to $t\bar{t}$ modelling and NP muon estimation (highly correlated due to composition of CR$t\bar{t}\mu$).
- Signal modelling uncertainties found to have negligible impact

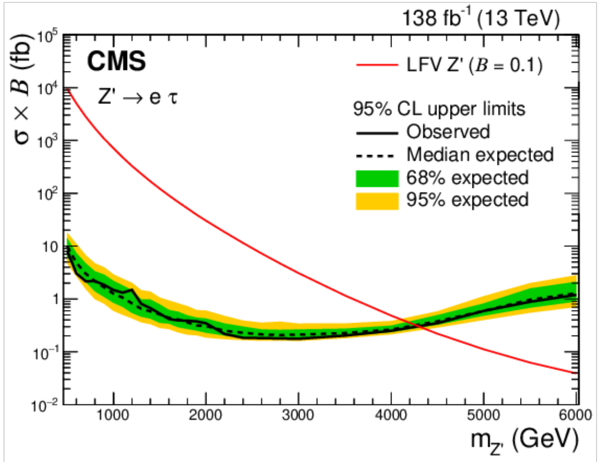
CLFV $\mu\tau qt$ interactions in top-quark production and decay: post-fit event yields

- Post-fit evt yields for each analysis region entering the fit, with correlations on the full syst. uncertainties taken into account as determined in the fit under a sgn+bkg hp.
- The "fake electron" category collects small contributions primarily from $t\bar{t}\,\gamma$ and $Z\gamma$ which enter the event selection due to photon conversions.

Process	**SR1**	**SR2**	**CR$tt\mu$**
$t\bar{t}$ + NPμ	8.2 ± 3.3	4.0 ± 1.5	166 ± 15
Z + NPμ	0.20 ± 0.10	0.025 ± 0.013	1.80 ± 0.87
Fake $\tau_{\text{had-vis}}$	2.54 ± 0.54	0.288 ± 0.066	-
Fake electron	-	-	5.8 ± 3.0
$t\bar{t}H$	2.90 ± 0.75	0.179 ± 0.077	1.25 ± 0.18
$t\bar{t}W$	2.8 ± 2.0	0.92 ± 0.67	1.08 ± 0.54
$t\bar{t}Z$	2.43 ± 0.65	0.254 ± 0.054	0.88 ± 0.24
WZ	2.24 ± 0.81	0.91 ± 0.31	7.3 ± 2.3
ZZ	0.266 ± 0.095	0.222 ± 0.081	1.75 ± 0.55
t+X	1.58 ± 0.13	0.611 ± 0.070	-
W + jets	0.27 ± 0.14	-	-
VVV	1.35 ± 0.67	0.49 ± 0.25	0.47 ± 0.24
Other	0.080 ± 0.040	-	1.11 ± 0.55
Total	26.7 ± 4.5	9.1 ± 2.2	201 ± 14
Signal (production)	1.4 ± 5.4	0.6 ± 2.4	0.008 ± 0.030
Signal (decay)	0.05 ± 0.22	0.007 ± 0.028	0.009 ± 0.034
Data	28	8	202







Search for heavy resonances and QBH in $e\mu$, $e\tau$, $\mu\tau$ final states

Search for heavy resonances & QBH in $e\mu$, $e\tau$, $\mu\tau$: event selections

$e\mu$ final state

- Events with at least:
  - 1 prompt, isolated electron (p_T > 35 GeV, $|\eta|<2.5$)
  - 1 prompt, isolated muon (p_T > 50 GeV, $|\eta|<2.4$)

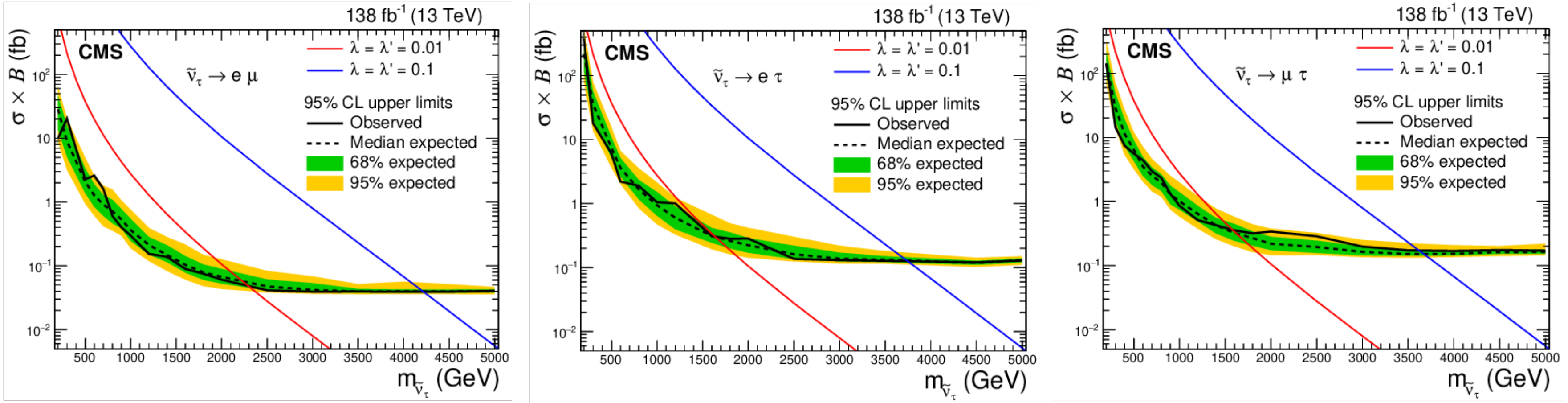
$e\tau$, $\mu\tau$ final state

- Events with at least:
  - 1 prompt, isolated light lepton (electron or muon, with same requirements as for $e\mu$ channel)
  - 1 prompt, isolated τ_h (p_T > 50 GeV, $|\eta|<2.3$)
  - m_T > 120 GeV (to reject misidentified τ_h bkg)
- Muon veto applied in $e\tau$ final state to remove overlap with the $\mu\tau$ and $e\mu$ final states

- Only one $e\mu$ and $e\tau$ or $\mu\tau$ pair is considered per event:
  - if > 1 candidate, pair with highest inv. mass selected)
- Leptons forming the pair are **not required** to have **opposite electric charges**:
  - to prevent loss in sgn efficiency from misidentification of the sign of the lepton charge at large p_T

⇒ **Statistical interpretations** performed **by comparing shapes** of **observed invariant mass** (for $e\mu$) and **collinear mass** distributions (for $e\tau$ or $\mu\tau$) **with those expected for the sgn and bkg**:
  - the collinear mass provides an estimate of the mass of new resonance or QBH based on their observed decay products
  - since sgn mass scale >> m_τ, τ decay products are highly Lorentz boosted in τ direction
  - $m_{coll} = m_{vis} / \sqrt{x_\tau^{vis}}$ with m_{vis}: inv mass of visible τ decay products, x_τ^{vis}: fraction of energy carried by visible τ decay products

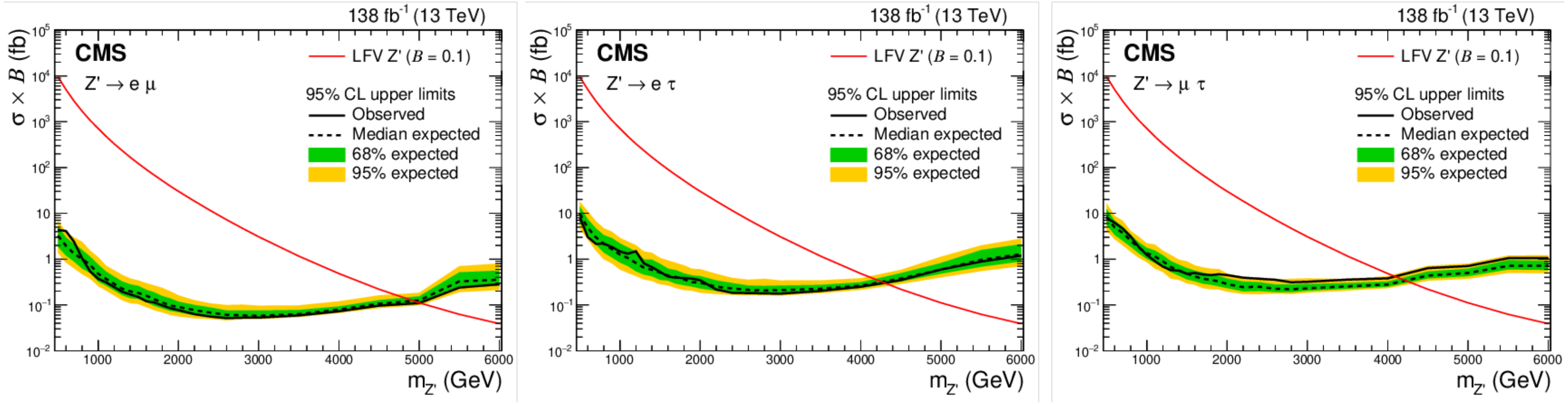
Search for heavy resonances & QBH in $e\mu$, $e\tau$, $\mu\tau$: UL as sneutrion mass in RPV SUSY



Expected and observed 95% CL UL on the product of the cross section and the BR as a function of the τ sneutrino mass in an RPV SUSY model

- Observed (expected) limits shown in black solid (dashed) lines for the $e\mu$, $e\tau$, $\mu\tau$ channels.
- The shaded bands represent **68%** and **95%** uncertainties in expected limits.
- The **red** and **blue** solid lines show predicted product of the cross section and the BR as a function of the tau sneutrion mass for 2 different values of the couplings.

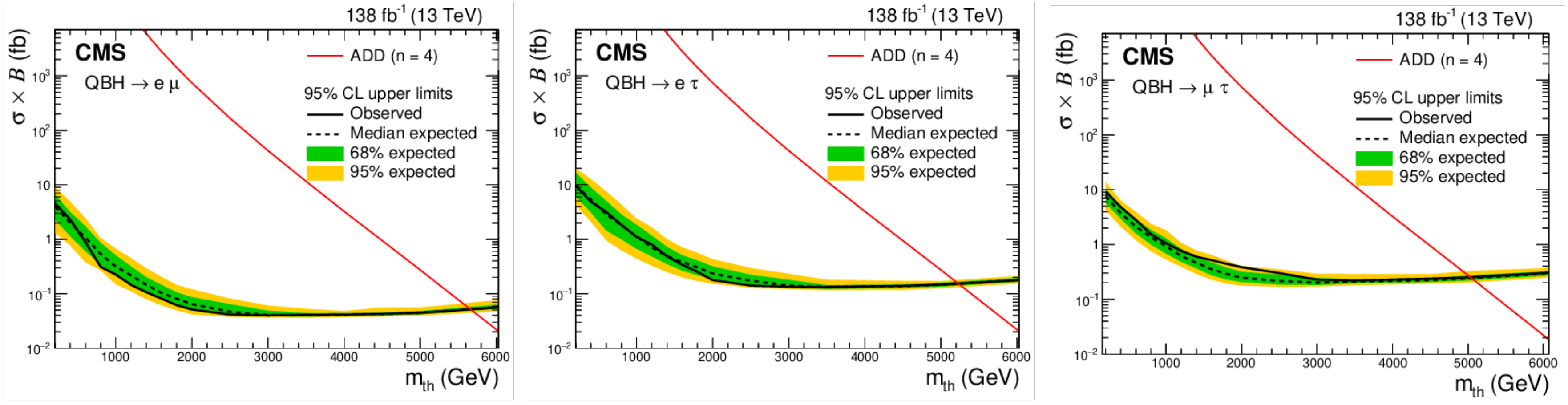
Search for heavy resonances & QBH in $e\mu$, $e\tau$, $\mu\tau$: UL for LFV Z' boson



Expected and observed 95% CL UL on the product of the cross section and the BR for a Z' boson with LFV decays

- Observed (expected) limits shown in black solid (dashed) lines for the $e\mu$, $e\tau$, $\mu\tau$ channels.
- The shaded bands represent **68%** and **95%** uncertainties in expected limits.
- The **red solid lines** show predicted product of the cross section and the BR as a function of Z' mass (with $\mathcal{B} = 0.1$).

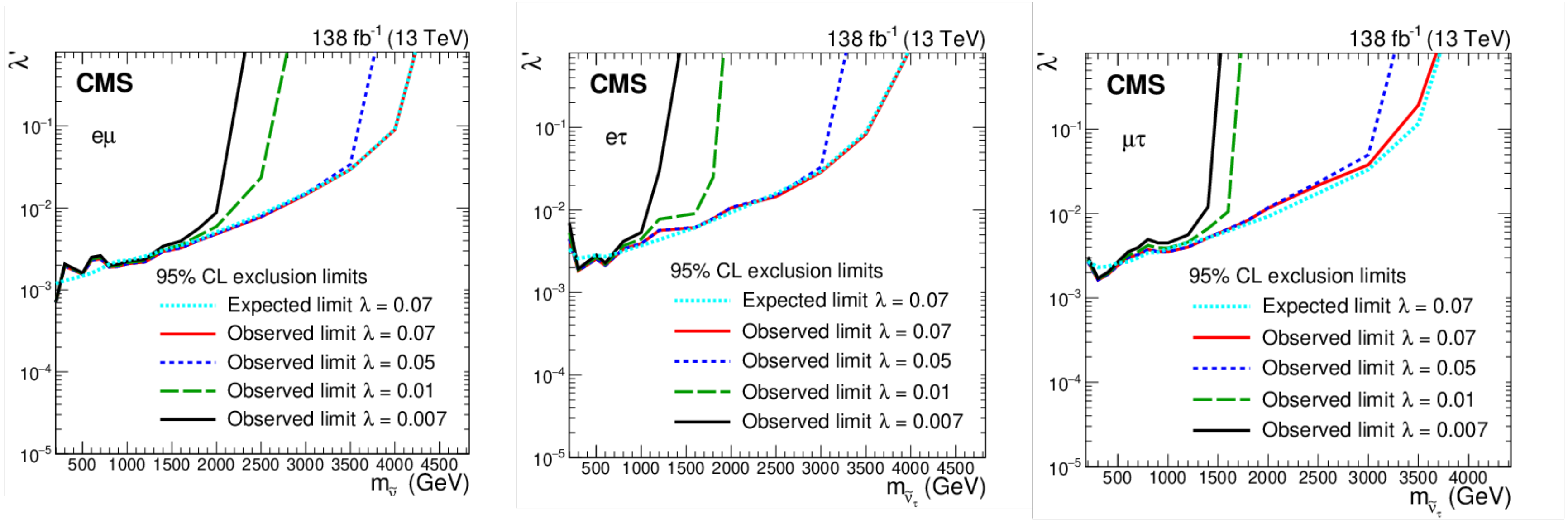
Search for heavy resonances & QBH in $e\mu$, $e\tau$, $\mu\tau$: UL for QBH production



Expected and observed 95% CL UL on the product of the cross section and the BR for QBH production in an ADD model with n = 4 extra dimensions

- Observed (expected) limits shown in black solid (dashed) lines for the $e\mu$, $e\tau$, $\mu\tau$ channels.
- The shaded bands represent **68%** and **95%** uncertainties in expected limits.
- The **red solid lines** show predicted product of the cross section and the BR as a function of QBH threshold mass.

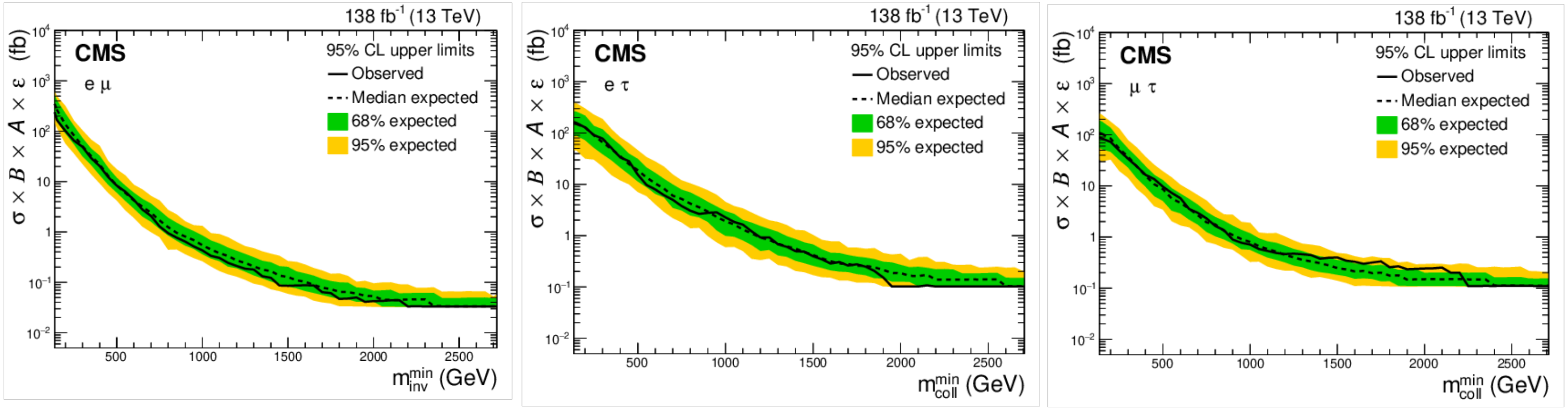
Search for heavy resonances & QBH in $e\mu$, $e\tau$, $\mu\tau$: exclusion limits on RPV SUSY



Exclusion limits @ 95% CL on the RPV SUSY model in the plane of τ sneutrino mass and λ' coupling, for 4 values of λ couplings

- The regions to the left of and above the curves are excluded.

Search for heavy resonances & QBH in $e\mu$, $e\tau$, $\mu\tau$: model-independent UL



Model-independent UL @ 95% CL on the product of the cross section, the BR, acceptance, and efficiency

- Observed (expected) limits shown in black solid (dashed) lines for the $e\mu$, $e\tau$, $\mu\tau$ channels.
- The shaded bands represent **68%** and **95%** uncertainties in expected limits.