Status and perspectives of LFV at ATLAS and CMS

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Outline: ATLAS and CMS LFV searches

- Search for LFV $\tau \to 3\mu$ decay — CMS
- Search for LFV in high mass dilepton final states $e\mu, e\tau, \mu\tau$ — ATLAS
- Search for Higgs LFV decays — CMS, ATLAS
  - $\mathrm{H} \to e\mu$
  - $\mathrm{H} \to e\tau, \mathrm{H} \to \mu\tau$
- Search for CLFV in top quark sector in
  - trilepton +jet(s) final states — CMS
  - $\mu\tau qt$ interactions in top-quark production and decay — ATLAS
- Bonus: Search for a high mass dimuon resonance + b quark jets — CMS

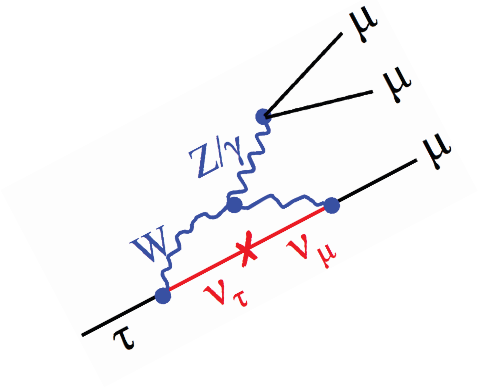
Introduction – Lepton Flavor Violation

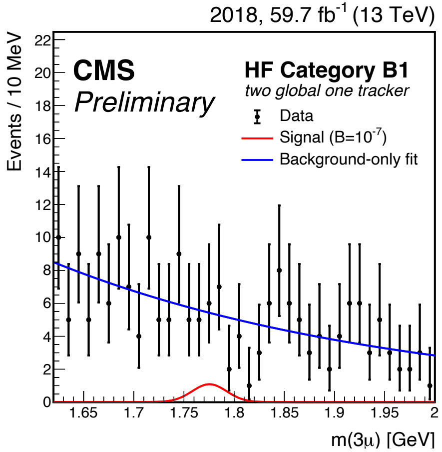
- Three lepton families (flavors) exist in the standard model (SM) of particle physics, and the number of leptons of each family is conserved in their interactions.

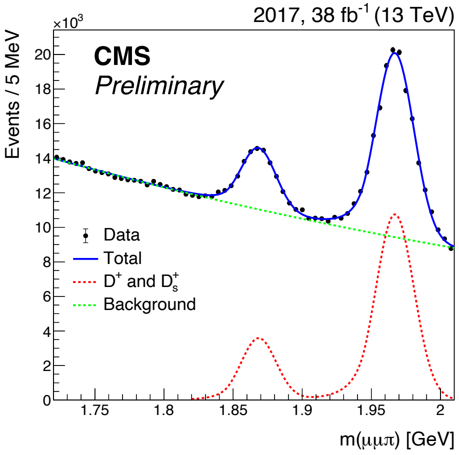
- Nevertheless, this conservation is not postulated by any fundamental principle of the theory (*accidental symmetry*), and neutrino oscillations indicate that processes violating this conservation do occur in nature.

- According to current knowledge, lepton-flavor-violating processes in charged-lepton interactions (CLFV) 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 LFV $\tau \to 3\mu$ decay

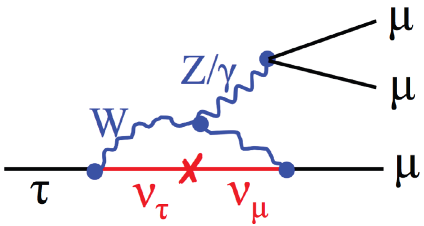
Search for LFV $\tau \to 3\mu$ decay
Introduction and state of the art

CMS-PAS-BPH-21-005

$\mathcal{L} = 131\ fb^{-1}$
$\sqrt{s} = 13$ TeV

- In the SM there is **NO symmetry** that enforces the **conservation of the lepton flavor**
  - CLFV decays are possible in the SM through neutrino oscillations:

    $\mathcal{B}(\tau \to 3\mu) \sim \mathbf{10^{-54}}$ *too rare to be observed*
  - BSM theories predict: $\mathcal{B}(\tau \to 3\mu) \sim \mathbf{10^{-8}}$-- $\mathbf{10^{-9}}$ ***at reach with next-to-come data***



- Two main channels for **τ** production at LHC:
  - **Heavy Flavor (HF) channel**: **τ** from D, B mesons decays
  - **W channel**: **τ** from W bosons decays

Process	number of τ leptons (L=33 fb^{-1})
$pp \to c\,\bar{c} + ...$	
$D \to \tau\nu$	4.0×10^{12} (95% D_s, 5% $D^\pm$)
$pp \to b\,\bar{b} + ...$	
$B \to \tau\nu + ...$	1.5×10^{12} (44% $B^\pm$, 45% B^0, 11% B_s^0, 0% $B_c^\pm$)
$B \to D(\tau\nu) + ...$	6.3×10^{11} (98% D_s, 2% $D^\pm$)
$pp \to W + ... \to \tau\nu + ...$	6.7×10^8
$pp \to Z + ... \to \tau\tau + ...$	$1.3 \times 10^8 (60 < m(\tau\tau) < 120\ GeV)$

- Best upper limit set by **Belle** $\mathcal{B}(\tau \to 3\mu) < \mathbf{2.1 \cdot 10^{-8}}$ at 90% C.L.
- At LHC:
  - **LHCb (Run 1):** $\mathcal{B}(\tau \to 3\mu) < \mathbf{4.6 \cdot 10^{-8}}$ at 90% C.L. — HF channel
  - **ATLAS (Run 1):** $\mathcal{B}(\tau \to 3\mu) < \mathbf{3.8 \cdot 10^{-7}}$ at 90% C.L. — W channel
  - **CMS (2016 data):** $\mathcal{B}(\tau \to 3\mu) < \mathbf{8.0 \cdot 10^{-8}}$ at 90% C.L. — HF channel & W channel

Search for LFV $\tau \rightarrow 3\mu$ decay
Analysis strategy

CMS-PAS-BPH-21-005

$\mathcal{L} = 131\, fb^{-1}$
$\sqrt{s} = 13$ TeV

- **Selection of events with D,B mesons and W bosons decaying into τ**

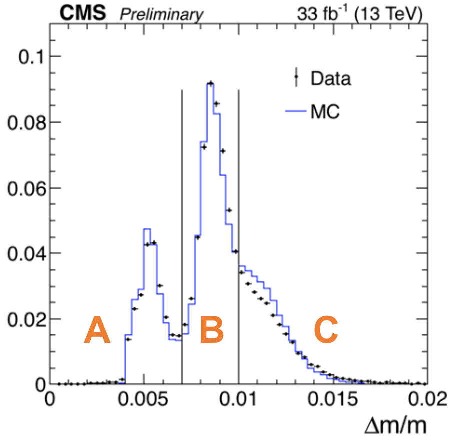
  HF channel: low p_T muons, large bkg (~10^7 signal) from
  - semi-leptonic B mesons decays with pions and/or kaons reconstructed as muons
  - decays in flight

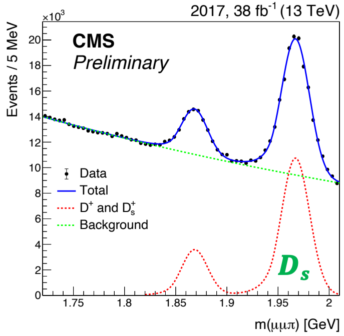
  VETO to suppress events from decays of hadronic resonances in 2 muons:
  η, ω(783), ρ(770), φ(1020), J/ψ, ψ(2S), Υ(1S), Υ(2S), Υ(3S), Z

- **Events classification into exclusive categories** (total: 36 cat.)
  - to increase analysis sensitivity
  - based on resolution of 3 mu mass and muon ID

- **Multivariate analysis with Boosted Decision Tree**
  - each category split into 4 sub-categories based on BDT output
  - most bkg-like sub-category is discarded

- **Control channel : $D_s \rightarrow \phi\pi \rightarrow \mu\mu\pi$**
  - signal normalization directly from data
  - monitor trigger performance
  - control region for the main analysis



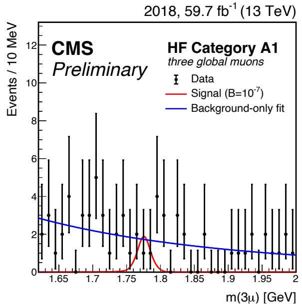


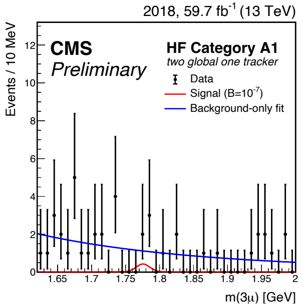
Search for LFV $\tau \rightarrow 3\mu$ decay

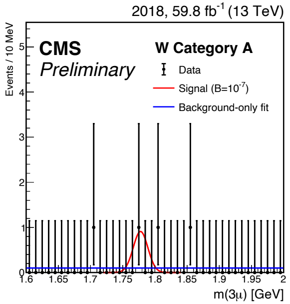
Signal extraction and results

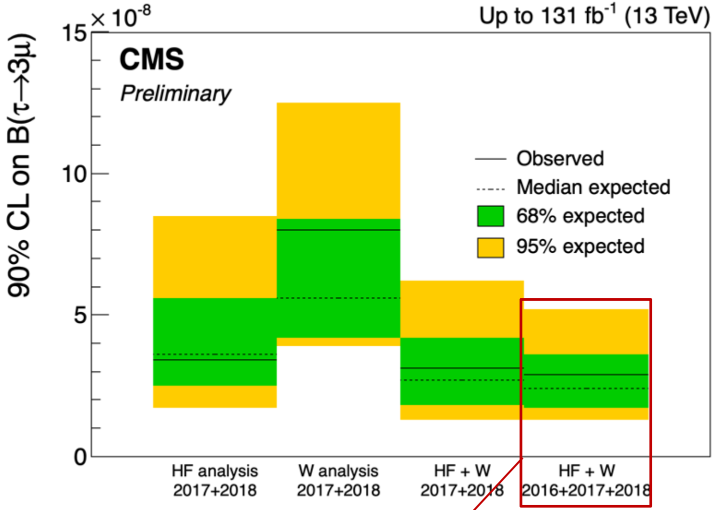
➢ Simultaneous unbinned maximum likelihood fit of 3 muons inv. mass in all the analysis categories (2017+2018 data)

- signal MC fit with Gaussian + Crystal Ball functions (with same mean)
- bkg fit with an exponential function









HF: Upper limit observed (expected) at 90% C.L.

$$\mathcal{B}(\tau \rightarrow 3\mu) < 3.4\ (3.6) \cdot 10^{-8}$$

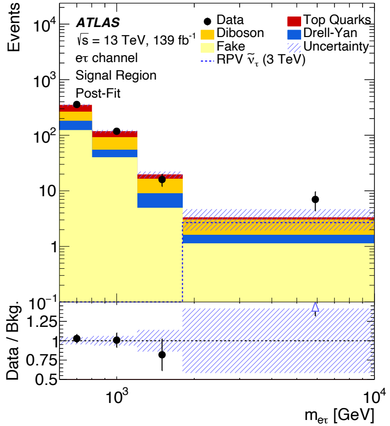
W: Upper limit observed (expected) at 90% C.L.

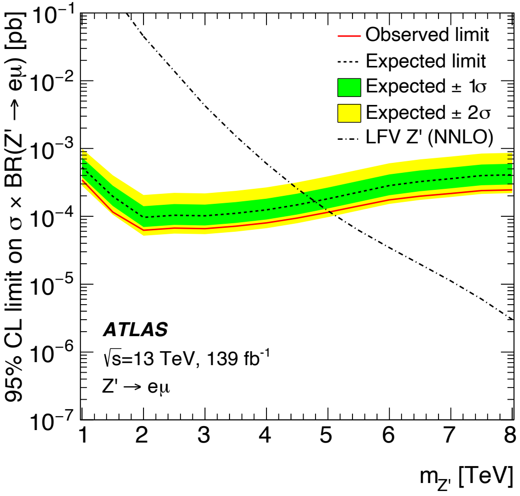
$$\mathcal{B}(\tau \rightarrow 3\mu) < 8.0\ (5.6) \cdot 10^{-8}$$

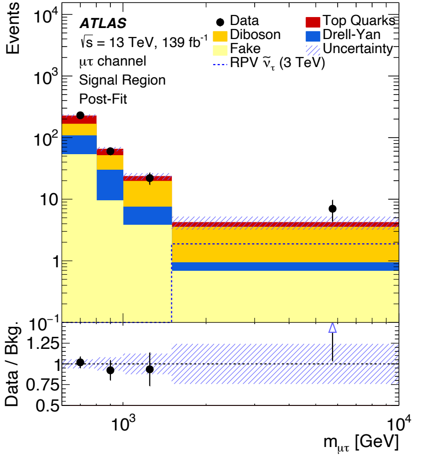
Combination with 2016 results

$$\mathcal{B}(\tau \rightarrow 3\mu) < 2.9\ (2.4) \cdot 10^{-8}$$

- In the combination, events in common btw channels are removed from the HF one







Search for LFV in high mass in dilepton final states $e\mu$, $e\tau$, $\mu\tau$

ATLAS

Search for LFV in high mass in dilepton final states $e\mu$, $e\tau$, $\mu\tau$ - Intro and state of the art

JHEP 10 (2023) 082

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

- Many SM extensions predict LFV couplings, such as models with Z ′ bosons, scalar neutrinos in R-parity-violating (RPV) SUSY and quantum black holes (QBH) in low-scale gravity.
  - Dilepton LFV processes usually **occur at TeV scale**, with a **clear detector signature of a prompt, different-flavor lepton pair**

- Limits (in TeV) from **previous ATLAS search** with 2015-2016 data ($\mathcal{L} = 36.1\ fb^{-1}$, $\sqrt{s} = 13$ TeV) @95% C.L.
- **CMS search** whole Run 2 data ($\mathcal{L} = 138\ \mathrm{fb}^{-1}$, $\sqrt{s} = 13$ TeV) in backup

	Z′	Neutrinos in RPV SUSY	QBH (ADD/RS)
eμ channel	**4.5**	**3.4**	**5.5 / 3.4**
eτ channel	**3.7**	**2.9**	**4.9 / 2.9**
μτ channel	**3.5**	**2.6**	**4.5 / 2.6**

This analysis is **looking for a localized excess in dilepton inv. mass distribution (TeV range)**

- **3 signal regions** (SR) defined by decay mode ($e\mu, e\tau, \mu\tau$ – only hadronically decaying τ considered)
  - control regions (CR) to extract normalization of prominent SM bkg: top and dibosons production
  - final simultaneous fit (SR & CR), performed separately in each decay mode
- **4 benchmark models** (Z′, RPV SUSY $\tilde{\nu}_\tau$ and QBH: ADD n=6; RS n=1) used **to interpret the results**

Search for LFV in high mass in dilepton final states $e\mu$, $e\tau$, $\mu\tau$ – Statistical analysis and results

JHEP 10 (2023) 082

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

- Binned profile-likelihood fits to dilepton inv. mass in SR and CRs
  - Agreement with SM in $e\mu$ channel SR.
  - Mild tension btw 2.0-2.3 TeV in τ-lepton channel SRs

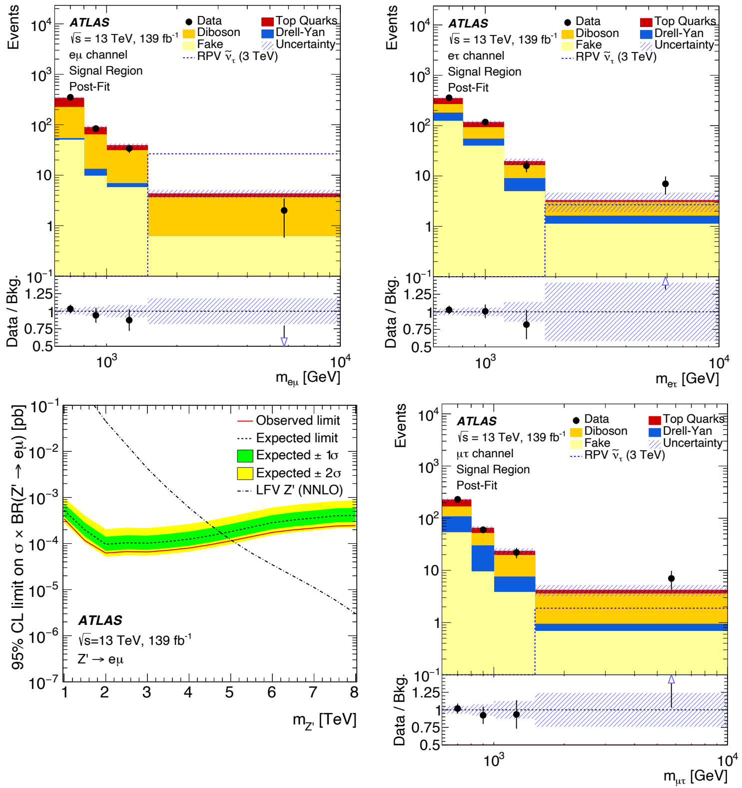
    → SM still statistically consistent with data within 2σ.

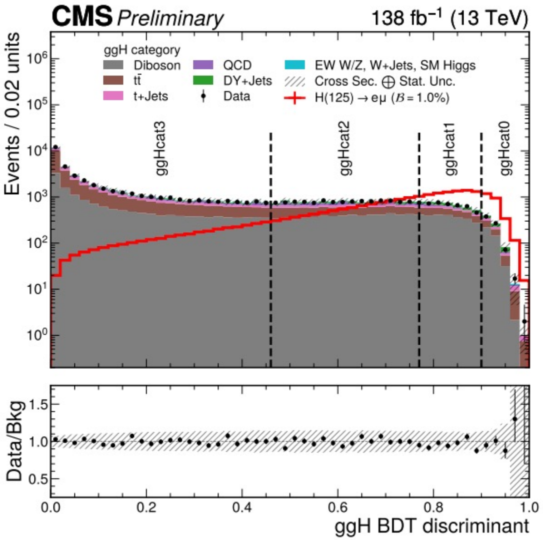
- Set upper limits on signal production cross-section for each scenario*

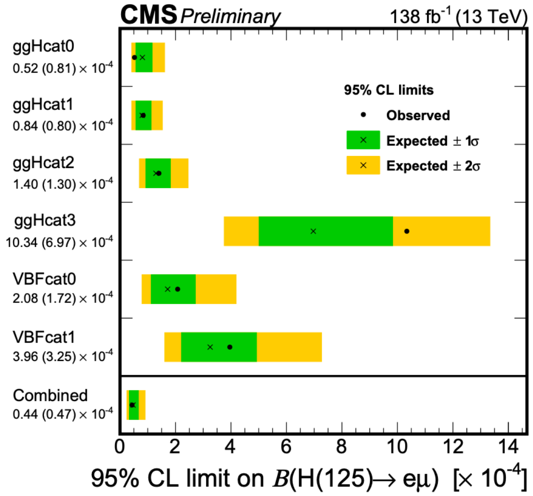
Model	Observed (expected) 95% CL lower limit [TeV]		
	$e\mu$ channel	$e\tau$ channel	$\mu\tau$ channel
LFV Z'	5.0 (4.8)	4.0 (4.3)	3.9 (4.2)
RPV SUSY $\tilde{\nu}_\tau$	3.9 (3.7)	2.8 (3.0)	2.7 (2.9)
QBH ADD $n = 6$	5.9 (5.7)	5.2 (5.5)	5.1 (5.2)
QBH RS $n = 1$	3.8 (3.6)	3.0 (3.3)	3.0 (3.1)

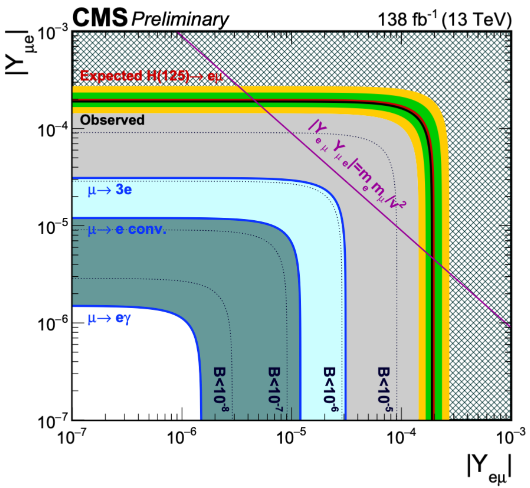
* Major improvement with respect to previous ATLAS search:

- four times larger data sample
- application of b-jet veto
- more accurate data-driven bkg estimates
- better particle reconstruction and identification









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

Search for LFV decay H→$e\mu$

Introduction and state of the art

Phys. Rev. D108 (2023) 072004

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

- LFV Higgs decays forbidden in SM, but arise in BSM theories (like ones with > 1 Higgs boson doublet, models, the Randall–Sundrum model, composite Higgs models, some SUSY models, ...)
- In BSM theories, **LFV decays** can occur **through *off-diagonal LFV Yukawa couplings*** $\Upsilon_{e\mu}$, $\Upsilon_{e\tau}$, $\Upsilon_{\mu\tau}$

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

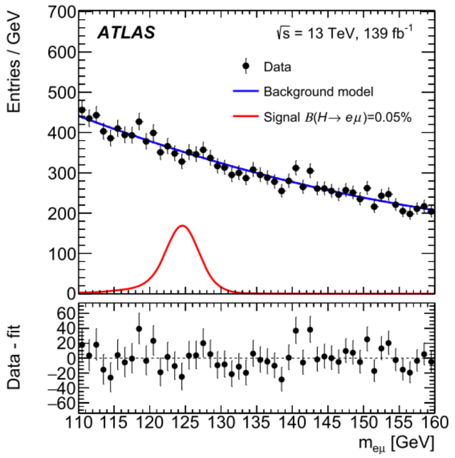
$$\mathcal{B}(H \to e\mu) < 6.2\ (5.9) \cdot 10^{-5} \quad @95\%\ \text{C.L.}$$

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

$$\mathcal{B}(Z \to e\mu) < 2.62 \cdot 10^{-7}$$

CMS: search for **LFV decay** of **SM** or **BSM Higgs** X (m_X = 110-160 GeV) to $e\mu$

- Two levels of **categorization** to maximize analysis' sensitivity:
  1) Based on **production mode** (ggH, VBF)
  2) Based on **signal-to-bkg ratio** → **BDTs score**
- **Simultaneous fit of signal and bkg models to data to extract an UL** on either BR(H(125) → eμ) or on $\sigma(pp \to X \to e\mu)$
  - constraint on BR(H(125) → eμ) translated to UL on $\Upsilon_{e\mu}$

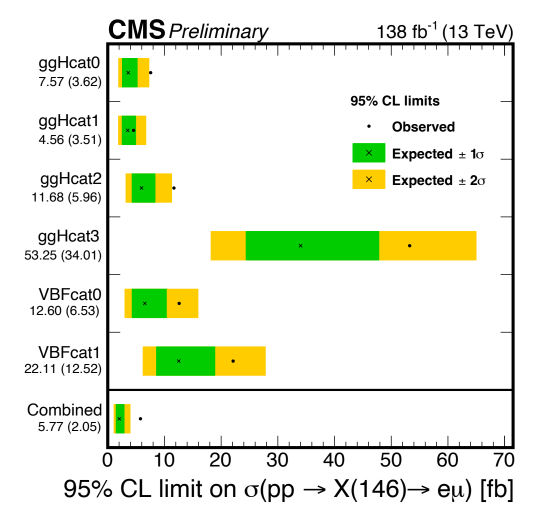


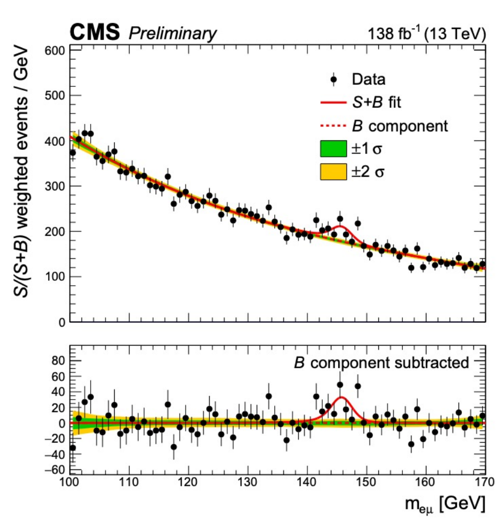
Search for LFV decay H→$e\mu$: Results

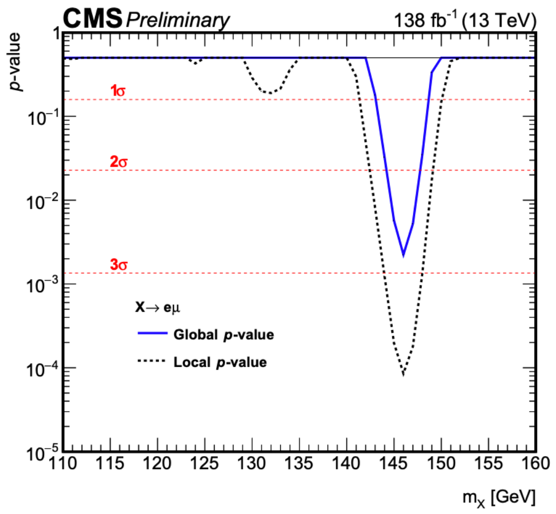
- **No significant excess** observed **for SM Higgs** (mass ~125 GeV)
  - observed (expected) UL: $\mathcal{B}(H \to e\mu) < 4.4\ (4.7) \times 10^{-5}$ **@95% C.L.**

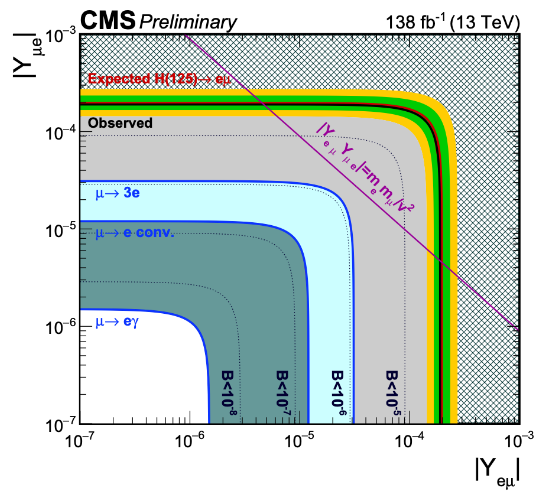
most stringent limit set thus far from direct searches!

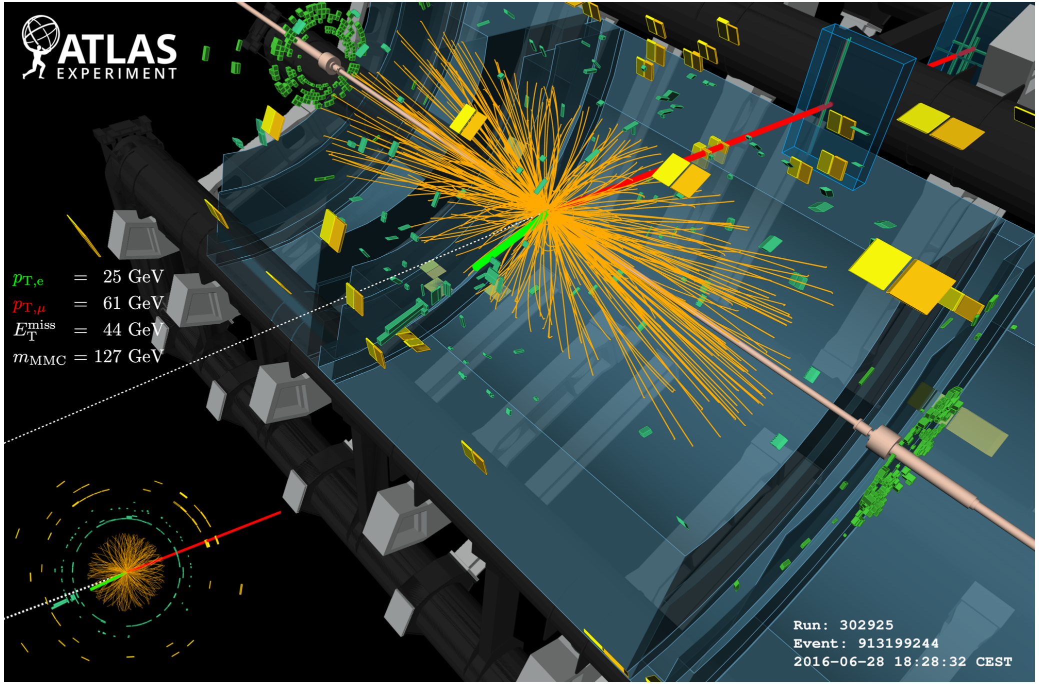
- An **excess of events** observed at **~146 GeV** with a **global (local) significance** of **2.8 (3.8) σ**

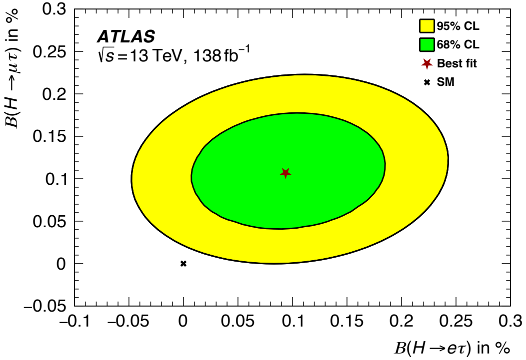












Search for Higgs LFV decays
H→$e\tau$ and H→$\mu\tau$

ATLAS

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

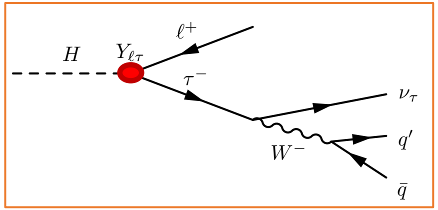
arXiv:2302.05225

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

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

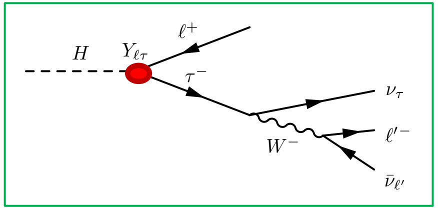
- ✓ **CMS search** whole Run 2 data ($\mathcal{L} = 137$ fb^{-1}, $\sqrt{s} = 13$ TeV)
  $\mathcal{B}(H \to e\tau) < 0.22\%$
  $\mathcal{B}(H \to \mu\tau) < 0.15\%$
  @95% C.L.

➢ 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 Drell-Yan bkg)



➢ Event selections + multivariate analysis (BDTs, NNs)

➢ Three statistical analysis:
  1. independent search for $H \to e\tau$ signal ($H \to \mu\tau$ null)
  2. independent search for $H \to \mu\tau$ signal ($H \to e\tau$ null)
  3. simultaneous determination of $H \to e\tau$ and $H \to \mu\tau$ signals



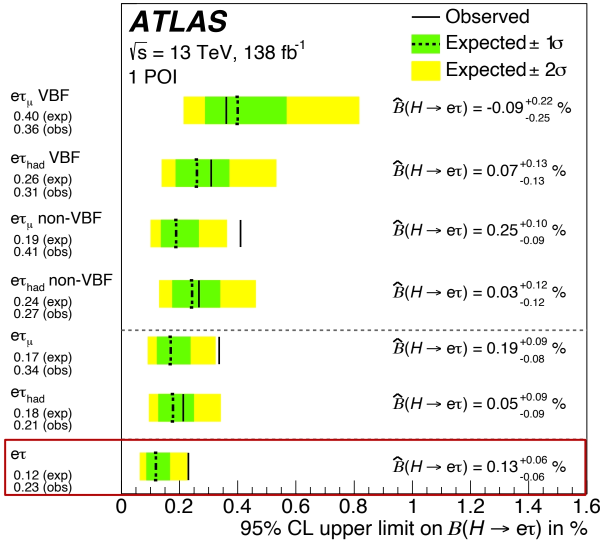
Search for LFV decays $H \to e\tau$ and $H \to \mu\tau$: statistical analysis & results (I)

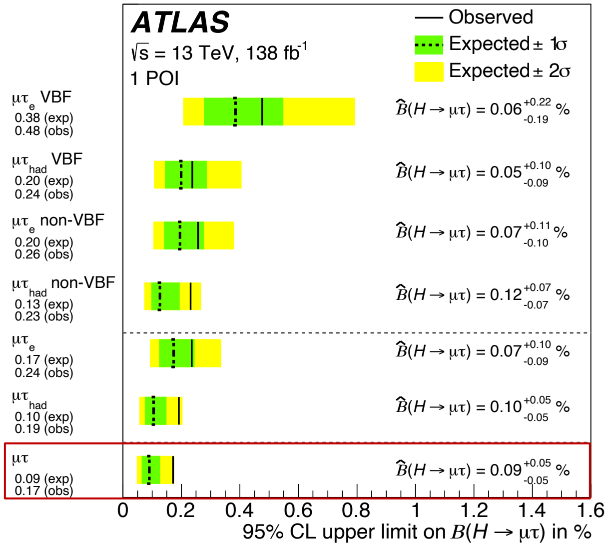
arXiv:2302.05225

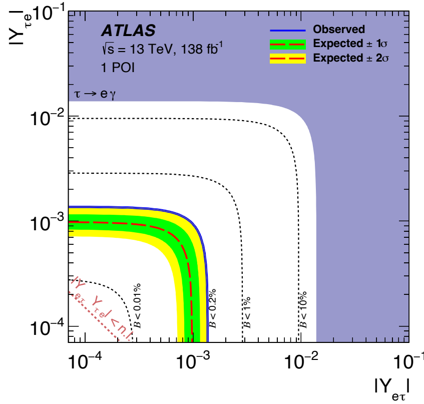
$\mathcal{L} = 138\, fb^{-1}$
$\sqrt{s} = 13$ TeV

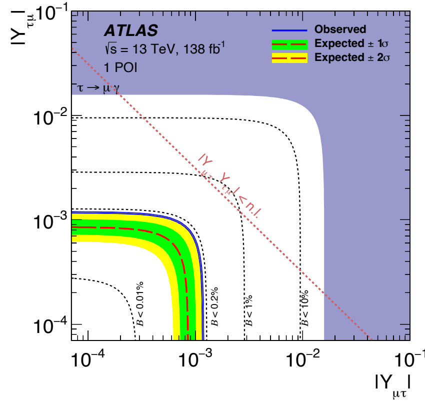
Independent search for $\mathcal{B}(H \to e\tau)$ and $\mathcal{B}(H \to \mu\tau)$

- Likelihood function $\mathcal{L}(\mu, \theta)$: product of Poisson probability terms over all bins considered
  - Separate fit with single POI ($\boldsymbol{H \to e\tau, H \to \mu\tau}$) for each search







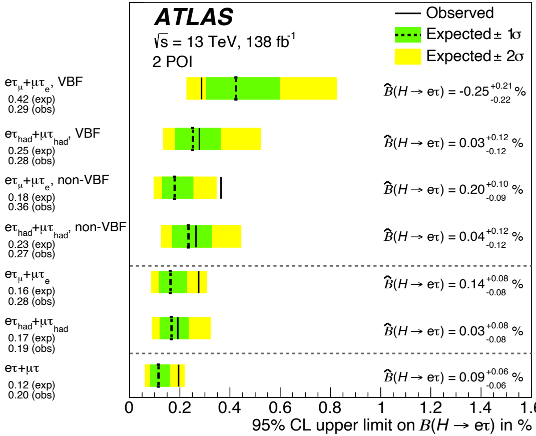


Search for LFV decays H→$e\tau$ and H→$\mu\tau$: statistical analysis & results (II)

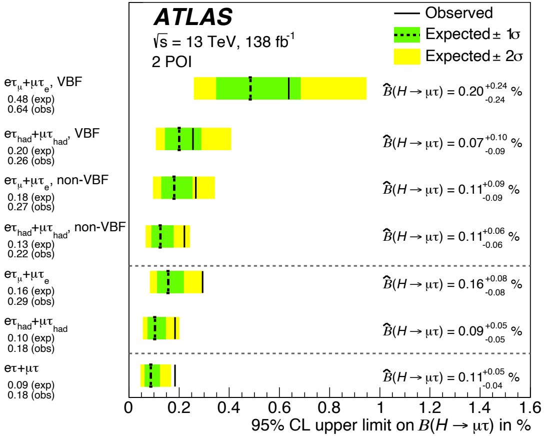
arXiv:2302.05225

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

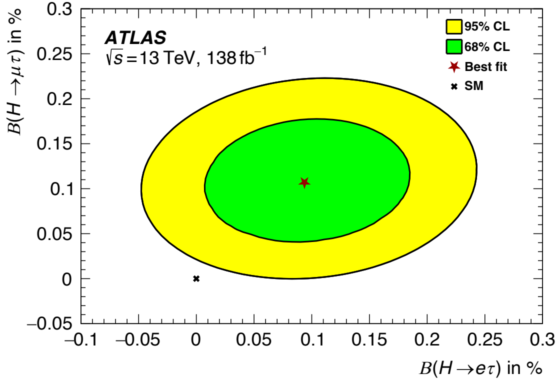
Simultaneous measurement of $H \to e\tau$ and $H \to \mu\tau$



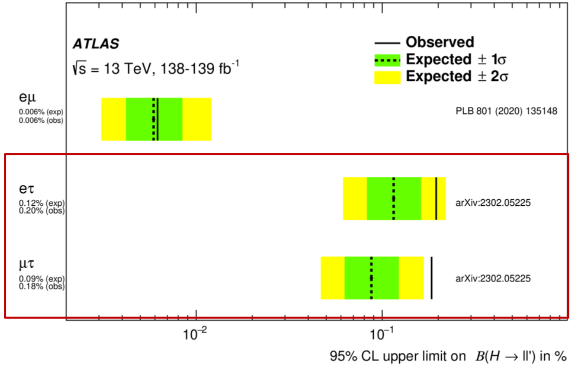
$\mathcal{B}(H \to e\tau) < 0.20\%$



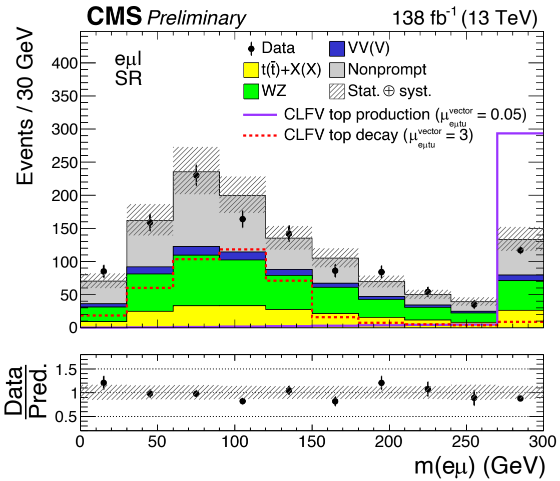
$\mathcal{B}(H \to \mu\tau) < 0.18\%$

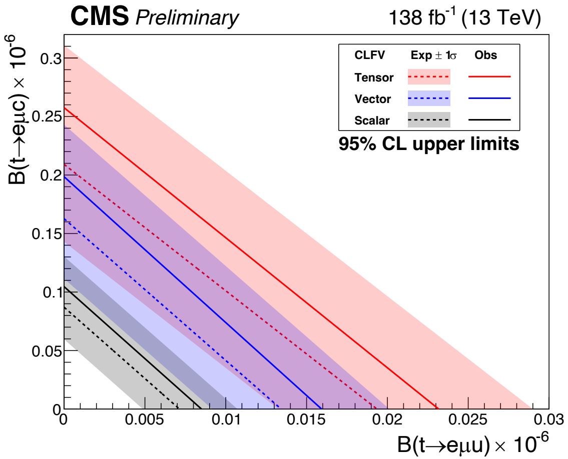


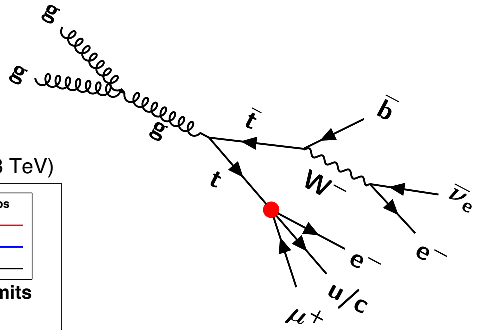
Compatible with SM within ***2.1 σ***



- For H→$e\tau$, **1.6σ** excess observed
- For H→ $\mu\tau$, **2.4σ** excess observed







Search for CLFV in top quark sector in trilepton final states

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

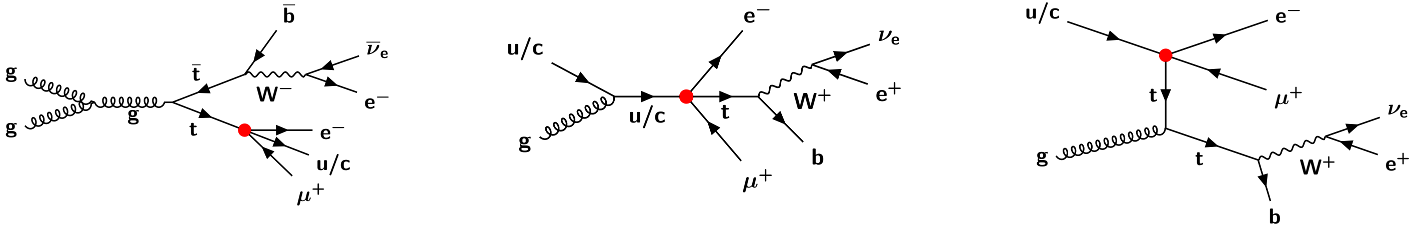
CMS-PAS-TOP-22-005

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

- LHC provides best sensitivity to CLFV searches in 2-3 body decays of heavy particles, $\mathbf{X} \rightarrow \ell\ell'(\Upsilon)$, and in heavy particle production, $\mathbf{pp} \rightarrow \ell\ell'(X)$
  - 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

CMS-PAS-TOP-22-005

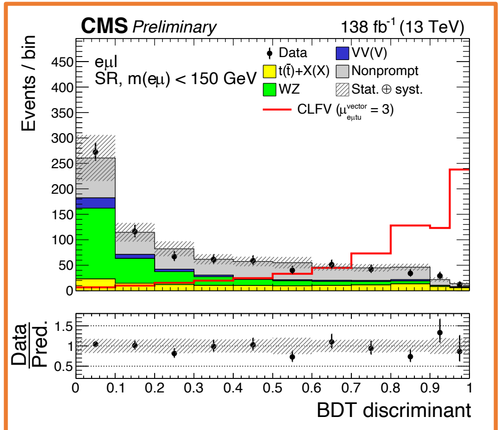
$\mathcal{L} = 138\ fb^{-1}$
$\sqrt{s} = 13$ TeV

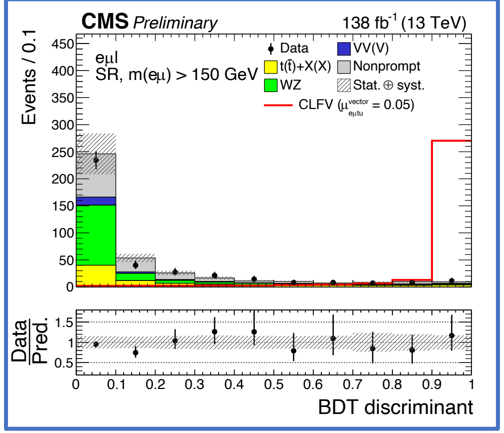
- **SM bkg categorized** into **2 groups**:
  - **prompt bkg**: processes with at least 3 leptons (from ew boson decays) ⇒ modelled with **MC**
  - **non prompt bkg**: other processes (like Drell-Yan) ⇒ modelled with **data-driven technique**

- Final-state particles **kinematic distributions 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 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

CMS-PAS-TOP-22-005

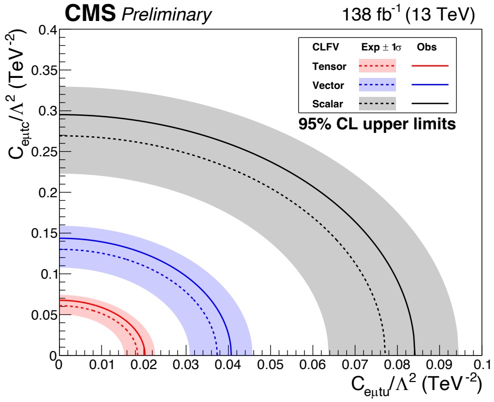
$\mathcal{L} = 138\ fb^{-1}$
$\sqrt{s} = 13$ TeV

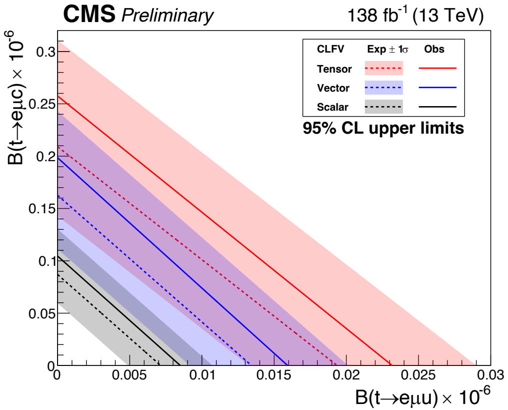
- **Results consistent with SM expectation**
  - **Upper limits** set **@95% C.L.**

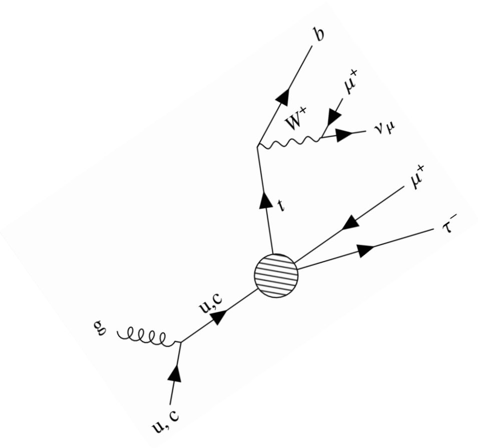
CLFV coupling	Lorentz structure	$C_{e\mu tq}/\Lambda^2$ (TeV^{-2}) exp $(-\sigma, +\sigma)$	obs	$\mathcal{B}(t \to e\mu q) \times 10^{-6}$ exp $(-\sigma, +\sigma)$	obs
$e\mu tu$	tensor	0.019 (0.015, 0.023)	**0.020**	0.019 (0.013, 0.029)	**0.023**
	vector	0.037 (0.031, 0.046)	**0.041**	0.013 (0.009, 0.020)	**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**

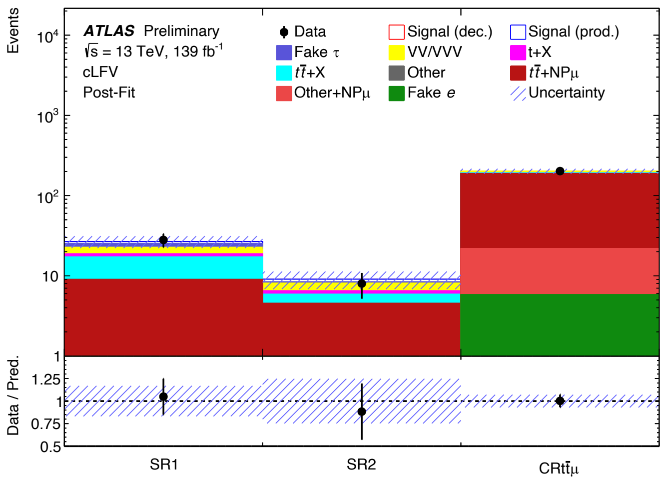
most stringent limits on these processes to date

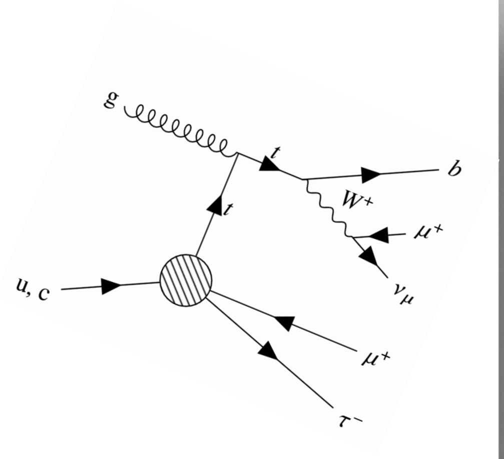
- Assuming a linear relationship btw $\mathcal{B}(t\to e\mu u)$ and $\mathcal{B}(t \to e\mu c)$ in case of nonvanishing signals, **2D limits** can also be obtained through interpolation











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

ATLAS

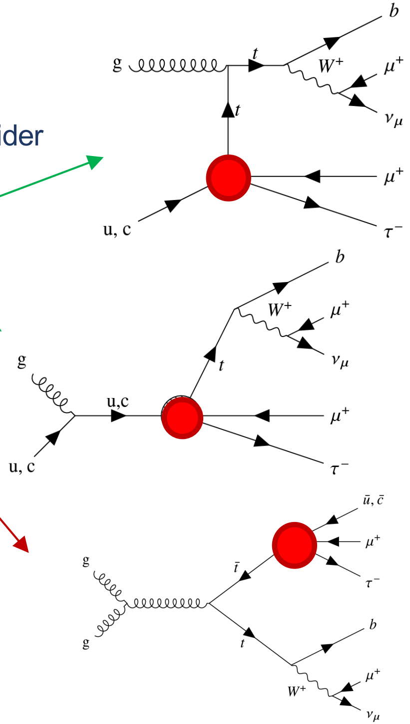
CLFV $\mu\tau qt$ interactions in top-quark production and decay

[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 $\mathbf{BR}(t \rightarrow \ell\ell' c) \approx 10^{-6}$
  - assuming energy scale probed experimentally << scale of new physics, it's convenient to consider a **model-independent approach by means of EFT**
- This analysis: search for **production of a single top quark** via $gq_k \rightarrow t\ell^{\pm}\ell'^{\mp}$
  - where $q_k = \{u, c\}$ for $k = \{1, 2\}$ and $\ell\ell' = \{\mu\tau, \tau\mu\}$

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



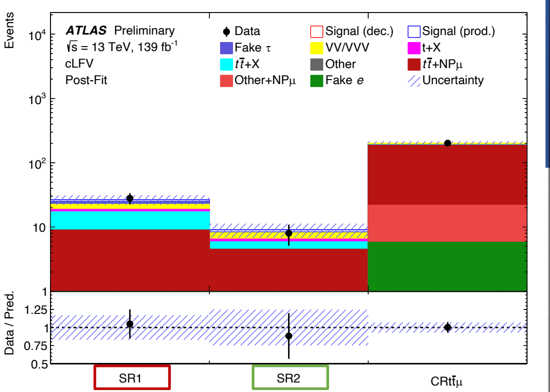
Final state: 2μ + τ decaying hadronically + at least 1 jet & exactly 1 b-tagged jet (produced by a $\mu\tau qt$ interaction in top production or decay)

Observed data are interpreted within the EFT framework

✓ **Separate MC samples** generated **for different EFT couplings** contributing to signal, separately for single-top production/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 - Results



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

Profile-likelihood fit to data under signal+bkg hypothesis, maximizing likelihood function

Expected/observed **95% CL UL on Wilson coefficients corresponding to 2Q2L EFT operators**

	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

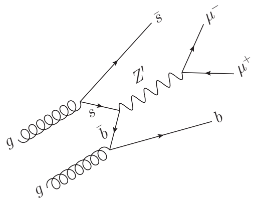
Expected/observed **95% CL UL on BR**

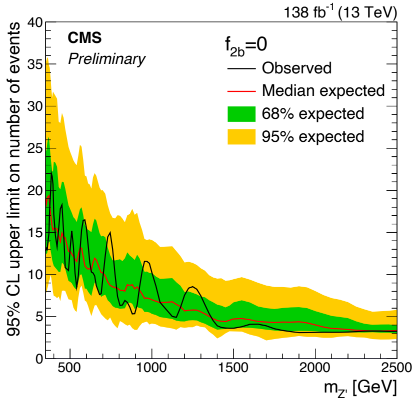
	95% CL upper limits on BR($t \to \mu\tau q$) ($\times 10^{-7}$)							
	$c_{lq}^{-(ijk3)}$	$c_{eq}^{(ijk3)}$	$c_{lu}^{(ijk3)}$	$c_{eu}^{(ijk3)}$	$c_{lequ}^{1(ijk3)}$	$c_{lequ}^{1(ij3k)}$	$c_{lequ}^{3(ijk3)}$	$c_{lequ}^{3(ij3k)}$
Expected (u)	4.6	4.2	4.0	4.5	2.5	2.5	5.8	5.8
Observed (u)	5.1	4.6	4.4	5.0	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

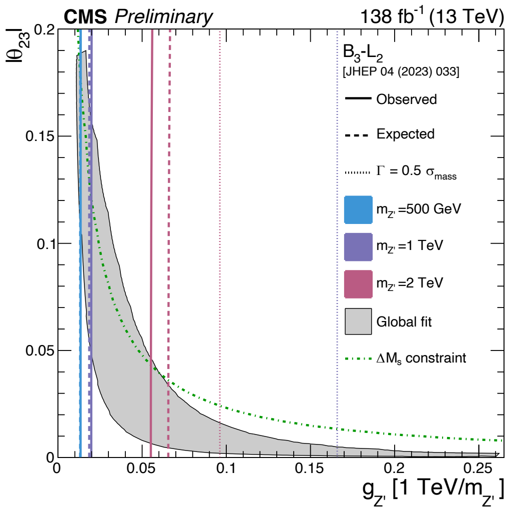
Reinterpretation of previous ATLAS FCNC search

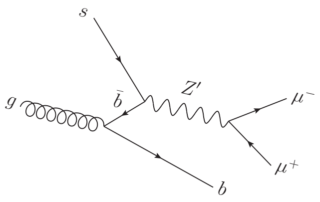
Fit with inclusive MC samples (with all EFT operators activated simultaneously) **to determine inclusive BR limit**

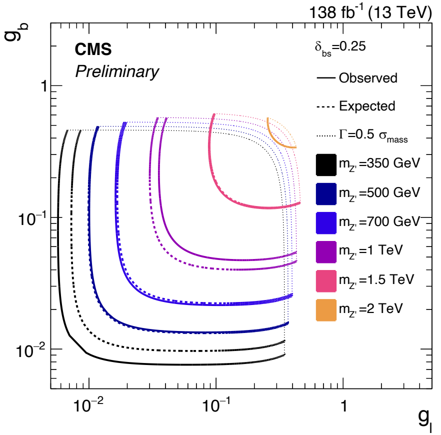
	95% CL upper limits on BR($t \to \mu\tau q$)	
	Stat. only	All systematics
Expected	8×10^{-7}	10×10^{-7}
Observed	9×10^{-7}	11×10^{-7}











Search for a high mass dimuon resonance associated with b quark jets

Search for high mass dimuon resonance associated with *b* quark jets – Intro and state of the art

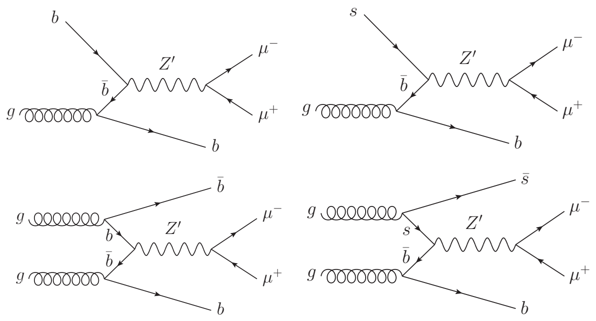
CMS-PAS-EXO-22-016

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

- Several BSM theories predict existence of **new neutral vector boson Z'** (**mass ~ TeV scale**) **decaying to lepton pairs**.
  - In scenarios with Z' **coupling to b and s quarks**, the Z' existence has implications for low-energy $b \to s\ell\ell$ observables

- Inclusive searches for BSM Z' performed at LHC by ATLAS and CMS
  - Limited by Drell–Yan, *might not be sensitive to scenarios where Z' couples to 2nd or 3rd quark generation*.

- This analysis: **search for $Z' \to \mu\mu$ with at least one b quark jets**
  - Already performed at LHC by ATLAS and CMS but *suffered from large $t\bar{t}$ bkg* (t decaying to b+W, with $W \to \ell\nu$) → *substantially reduced in this analysis!*



Theoretical model

Relevant interactions described by lepton flavor-universal model with a simplified Lagrangian, with 4 coupling parameters:

- g_ℓ coupling for all charged leptons,
- g_ν coupling for all neutrinos,
- g_b coupling that scales both Z'bb and Z'sb interactions,
- separate δ_{bs} parameter that scales only Z'sb interaction

$$\mathcal{L}_{BSM} = Z'_\eta \left\{ g_\ell \sum_{f=e,\mu,\tau} \bar{f}\gamma^\eta P_L f + g_\nu \sum_{f=\nu_e,\nu_\mu,\nu_\tau} \bar{f}\gamma^\eta P_L f + g_b \left[\bar{b}\gamma^\eta P_L b + \delta_{bs} (\bar{s}\gamma^\eta P_L b + \text{h.c.}) \right] \right\}.$$

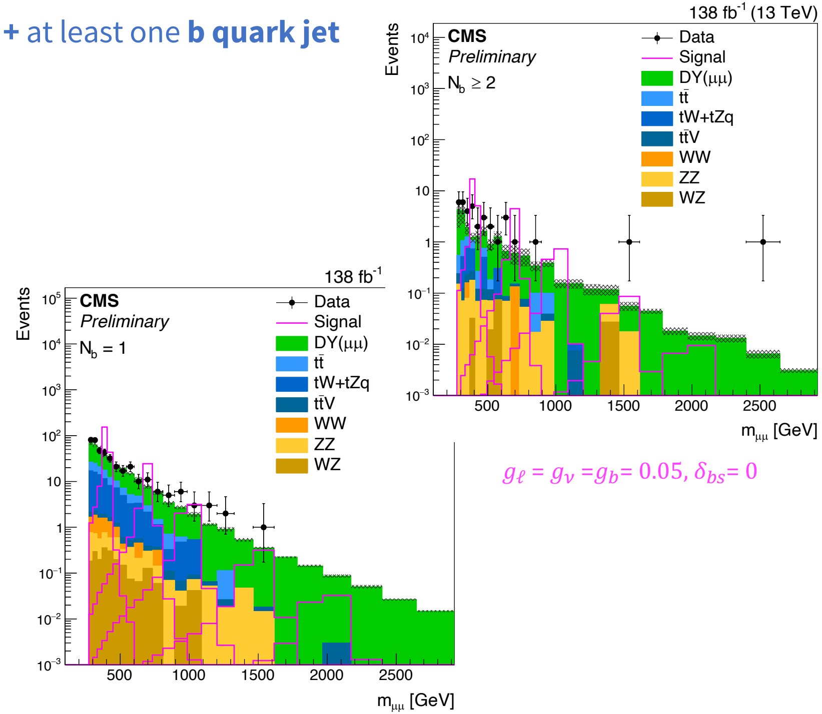
Search for high mass dimuon resonance associated with *b* quark jets – Analysis strategy

CMS-PAS-EXO-22-016

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

Search for **narrow $Z' \rightarrow \mu\mu$** ($\Gamma(Z') < m_{\mu\mu}$ resolution, **$m_{Z'}$ > 350 GeV**) **+** at least one **b quark jet**

- **Event categorization** based on **b quark jet multiplicity**: N_b=1, $N_b \geq 2$
- **Dominant bkg** from **Drell–Yan** process and **$t\bar{t}$ production**.
  - Drell–Yan reduced by b quark jet requirement.
  - $t\bar{t}$ suppressed by requiring $\min(m_{\mu b}) - m_t >$ 175 GeV.
  - Veto on additional lepton or isolated high p_T charged hadron to suppress other (subdominant) bkgs
- **SM bkg estimated from data**
  - SM MC used to visually compare obs $m_{\mu\mu}$ to exp SM bkg
- **Constraints on event yield extracted by fitting $m_{\mu\mu}$ to analytic functions** within **mass ranges sliding** with $m_{Z'}$ to be probed.
  - Signal: Gaussian + doublesided CB with common reso width σ_{mass}.
  - Fits to data within a mass window of ±10 σ_{mass} around probed $m_{Z'}$.



Constraints on event yield reinterpreted in terms of parameters of specific models with Z' couplings to b quarks

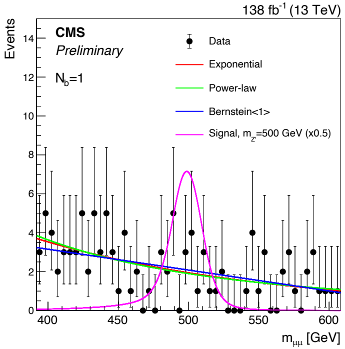
Search for high mass dimuon resonance associated with *b* quark jets – Results

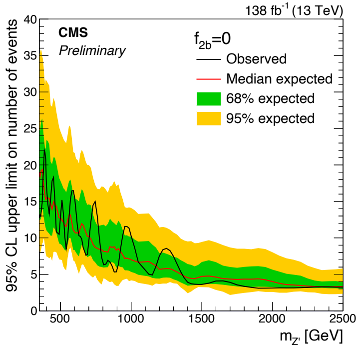
CMS-PAS-EXO-22-016

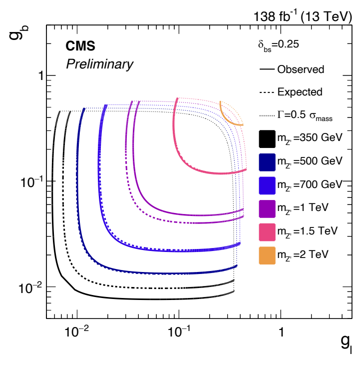
$\mathcal{L} = 138\ fb^{-1}$
$\sqrt{s} = 13$ TeV

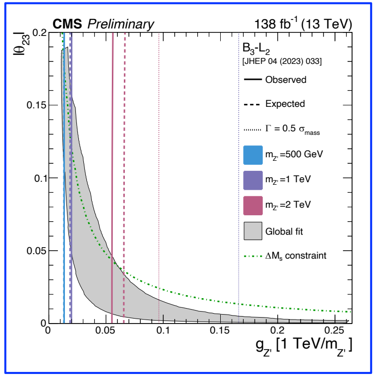
No significant excess observed across explored mass range

- **Model-independent limits set at 95% C.L.** on signal events with $N_b \geq 1$, varying relative fraction of events in $N_b \geq 2$ category (f_{2b}).
- **Results interpreted for LFU model** (with $g_\nu = g_\ell$, and either $\delta_{bs} = 0$ or 0.25). Exclusion ranges restricted to $\Gamma(Z') < \sigma_{\text{mass}}/2$.
  - For $m_{Z'} = 350$ GeV (2 TeV), $\delta_{bs} \leq 0.25$, **most of parameter space** with $0.0057 < g_\ell < 0.35$ ($0.25 < g_\ell < 0.43$) and $0.0079 < g_b < 0.46$ ($0.34 < g_b < 0.57$) **excluded at 95% C.L.**
- **Constraints set also on $B_3 - L_2$ model** ($g_{Z'}$ coupling to SM fermions, θ_{23} mixing angle btw 2nd – 3rd quark generations). Exclusion ranges restricted to $\Gamma(Z') < \sigma_{\text{mass}}/2$.
  - **Most of allowed parameter space excluded for $m_{Z'} \leq 500$ GeV,**
  - Less stringent constraints for higher $m_{Z'}$.





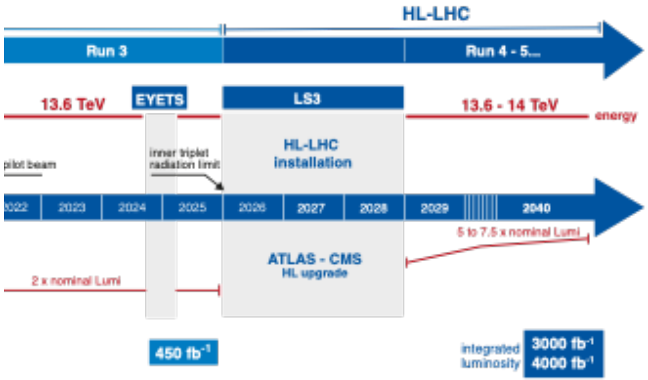




Summary and perspectives

- An overview of the LFV searches carried out by ATLAS and CMS was provided
  - all these analysis are **statistically limited**
  - (almost) all of them have set the **most stringer UL up to date**
    - $\tau \rightarrow 3\mu$ still better constrained by Belle

- With the next data taking periods (Run3 ongoing, HL-LHC to come), ATLAS and CMS will highly benefit from an **increased statistics**, but also
  - **new trigger strategies** and data taking techniques, as shown by F. Simone, are already being used during Run3 to maximize the experiment acceptance to rare decays;
  - **new detectors** will be added, and the existing detectors will be modified, in view of the HL-LHC, **improving the performance** under many aspects (trigger, vertex reconstruction, pseudorapidity coverage, ...)



Backup slides

Search for LFV $\tau \to 3\mu$ decay

CMS

Search for LFV $\tau \to 3\mu$ decay

Control channel

- Expected number of signal events from $\mathbf{D_s^+}$ meson / **W** boson decays that pass the dimuon triggers

$$N_{3\mu(D)} = N_{\mu\mu\pi} \frac{\mathcal{B}(D_s^+ \to \tau^+ \nu)}{\mathcal{B}(D_s^+ \to \phi\pi^+ \to \mu^+\mu^-\pi^+)} \frac{\mathcal{A}_{3\mu(D)}}{\mathcal{A}_{\mu\mu\pi}} \frac{\epsilon^{reco}_{3\mu(D)}}{\epsilon^{reco}_{\mu\mu\pi}} \frac{\epsilon^{2\mu trig}_{3\mu(D)}}{\epsilon^{2\mu trig}_{\mu\mu\pi}} \mathcal{B}(\tau \to 3\mu),$$

$$N_{3\mu(W)} = \mathcal{L}\,\sigma(pp \to W + X)\,\mathcal{B}(W \to \tau\nu_\tau)\,\mathcal{A}_{3\mu(W)}\,\epsilon_{3\mu(W)}\,\mathcal{B}(\tau \to 3\mu),$$

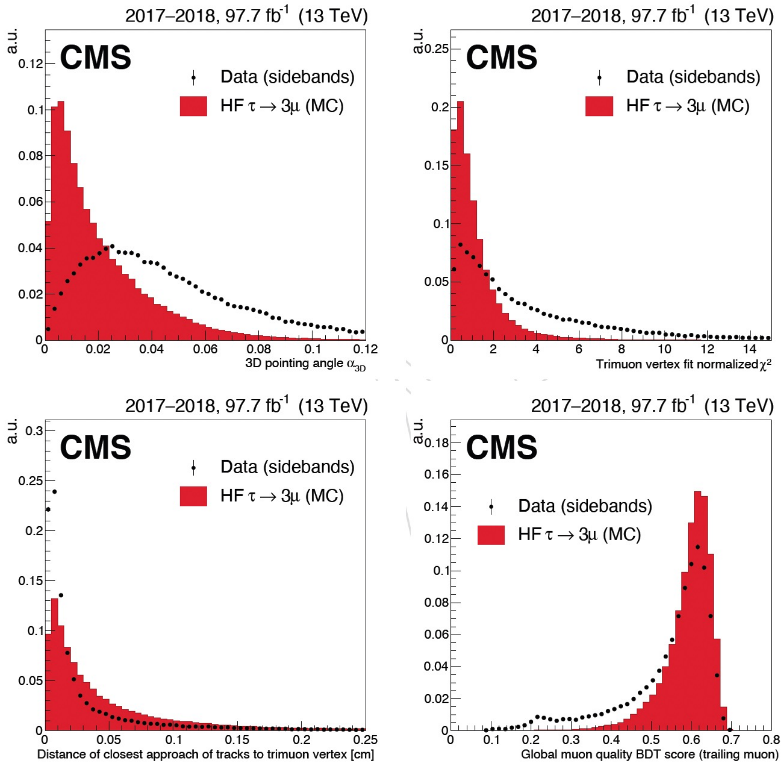
- Expected number of signal events from $\mathbf{B} \to \boldsymbol{\tau} + \mathbf{X}$ decays that pass the dimuon triggers

$$N_{3\mu(B)} = N_{\mu\mu\pi} f \frac{\mathcal{B}(B \to \tau + X)}{\mathcal{B}(B \to D_s^+ + X)\mathcal{B}(D_s^+ \to \phi\pi^+ \to \mu^+\mu^-\pi^+)} \frac{\mathcal{A}_{3\mu(B)}}{\mathcal{A}_{\mu\mu\pi}} \frac{\epsilon^{reco}_{3\mu(B)}}{\epsilon^{reco}_{\mu\mu\pi}} \frac{\epsilon^{2\mu trig}_{3\mu(B)}}{\epsilon^{2\mu trig}_{\mu\mu\pi}} \mathcal{B}(\tau \to 3\mu).$$

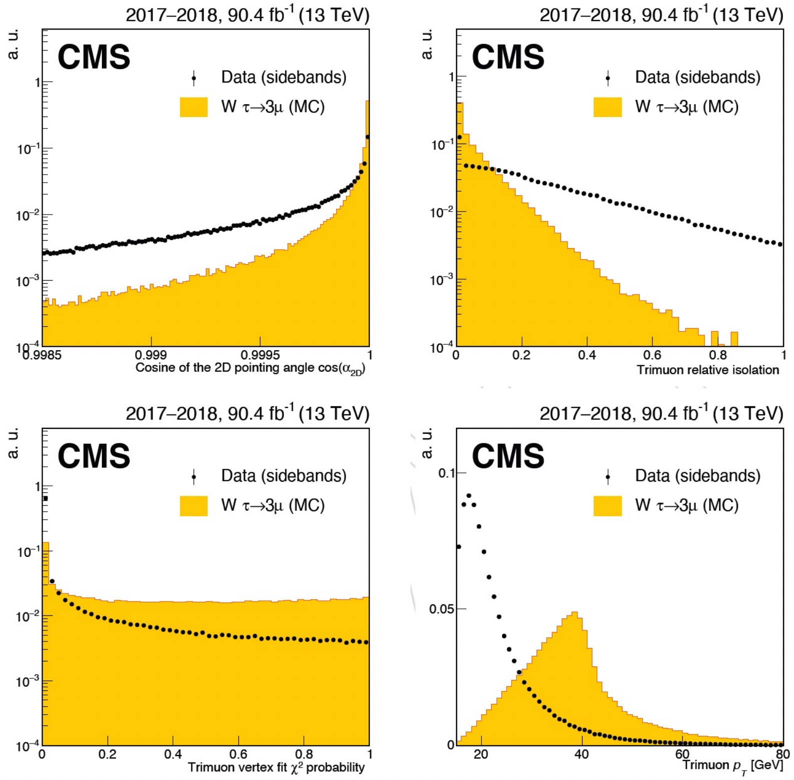
can be calculated as the ratio of cross sections $f = \sigma(pp \to B)\,BR(B \to D_s^+ + X)/\sigma(pp \to D_s^+)$.

- Since $\mathbf{D_s^+}$ produced from b hadron decays tend to decay farther from the PV than directly produced ones, the simulation predicted value of *f* is validated by fitting its *proper decay length* distribution in data

Search for LFV $\tau \to 3\mu$ decay
Most discriminating BDT variables (HF channel)



Search for LFV $\tau \to 3\mu$ decay
Most discriminating BDT variables (W channel)



Search for a high mass dimuon resonance associated with b quark jets

CMS

Search for high mass dimuon resonance associated with *b* quark jets – Systematic uncertainties

Source	Normalization $N_b = 1$	Normalization $N_b \geq 2$	Shape
Luminosity	1.6%		—
Trigger	1–5%		—
Jet energy scale	1–1.5%	2–5%	—
b-tagging	1%	5%	—
μ reconstruction	2.5%		—
μ identification	5%		—
Fit window size	$\lesssim 5\%$		—
MC sample size	$< 1\%$	$< 5\%$	—
μ momentum scale in $\overline{m}_{\mu\mu}$	—		$\lesssim 0.1\%\ m^2_{Z'}/(1\ \text{TeV})$
μ momentum resolution in $\overline{\sigma}_{\text{mass}}$	—		$\lesssim 10\%\ \sigma_{\text{mass}}$

- The fit parameter $m_{\mu\mu}$ corresponds to position of the max of $m_{\mu\mu}$ distribution after detector effects,
- σ_{mass} is the resolution parameter used in the fit, distinguished from values of σ_{mass} extracted from simulation.

Search for LFV in high mass in dilepton final states $e\mu$, $e\tau$, $\mu\tau$

ATLAS

Search for LFV in high mass in dilepton final states $e\mu$, $e\tau$, $\mu\tau$ – Theoretical framework (I)

Z′ boson

- A common SM extension is the **addition of an extra U(1) gauge symmetry** resulting in a **massive neutral vector boson (Z′)**.
- The [Sequential Standard Model]() (SSM) is used as benchmark in this search,
  - Z′ boson is assumed to have the same quark couplings and chiral structure as the SM Z boson but allowing for LFV couplings.
  - Additional LFV coupling parameters Q_{ij} are assigned for $Z' \to \ell_i \ell_j$ processes. Q_{ij} parameters equal to SM Z boson coupling for *i*=*j*.

Scalar neutrinos in RPV SUSY

- In the RPV SUSY model, the Lagrangian terms allowing LFV can be expressed as $$\frac{1}{2}\lambda_{ijk}L_iL_j\bar{e}_k + \lambda'_{ijk}L_iQ_j\bar{d}_k,$$
  - *L* and *Q* are the SU(2) doublet superfields of leptons and quarks,
  - *e* and *d* are the SU(2) singlet superfields of charged leptons and down-type quarks,
  - λ and λ' are Yukawa couplings,
  - indices *i*, *j*, and *k* denote generations.
- A τ-sneutrino ($\tilde{\nu}_\tau$) may be produced by $d\bar{d}$ annihilation and later decay into $e\mu$, $e\tau$, $\mu\tau$ (results apply to any sneutrino flavor).
  - For theoretical prediction of $\sigma \times \mathrm{BR}$, the $\tilde{\nu}_\tau$ coupling to first-generation quarks (λ'_{311}) assumed to be 0.11 for all channels. In addition,
    - $\lambda_{312} = \lambda_{321} = 0.07$ for the $e\mu$ final state,
    - $\lambda_{313} = 0.07$ for the $e\tau$ final state,
    - $\lambda_{323} = 0.07$ for the $\mu\tau$ final state,
    - $\lambda_{331} = \lambda_{332} = 0$, due to the gauge invariance for these channels → $\sigma \times \mathrm{BR}$ in eμ channel ~2 $\sigma \times \mathrm{BR}$ in $e\tau$ or $\mu\tau$ channel.

Search for LFV in high mass in dilepton final states $e\mu$, $e\tau$, $\mu\tau$ – Theoretical framework (II)

QBH

- Various models introduce extra spatial dimensions to reduce the value of the Planck mass and resolve the hierarchy problem. In this search, interpretations are based on 2 models:
  - the Arkani-Hamed-Dimopoulos-Dvali (ADD) model, assuming 6 extra dimensions,
  - the Randall-Sundrum (RS) model, with 1 extra dimension.
- Due to the increased strength of gravity at short distances, in these models, at the LHC states exceeding the threshold mass (m_{th}) to form black holes could be produced
  - m_{th} assumed to be equivalent to the extra-dimensional Planck scale. Quantum gravity regime applied only when considering mass < 3 – 5 m_{th} (for masses beyond this region, thermal black holes are expected to be produced).
  - QBHs could decay into two-particle final states, and they would have a continuum mass distribution from m_{th} up to the beginning of the thermal regime, assumed to start at 3 m_{th}. The decay of the QBH would be governed by a yet unknown theory of quantum gravity.
- The two main assumptions of the extra-dimension models considered in this paper are:
  - gravity couples with equal strength to all SM particle degrees of freedom
  - gravity conserves local symmetries (color, electric charge), but can violate global symmetries (lepton-flavor and baryon-number conservation)
- QBHs decaying into different-flavor, opposite-charge lepton pairs are created via $q\bar{q}$ (gg) with a BR to $\ell\ell'$ of 0.87% (0.34%)

Search for LFV in high mass in dilepton final states $e\mu$, $e\tau$, $\mu\tau$ – Event selection, bkg estimation

- Candidate signal events have a reconstructed primary vertex with at least two associated different-flavor, opposite-sign leptons.
  - Leptons back-to-back in transverse plane with $\Delta\phi_{\ell\ell'} > 2.7$
  - Dilepton pair invariant mass > 600 GeV
  - Veto on b-tagged jets to reject events with top quarks

Region	Channels	Requirements
	Nominal $\Delta\phi_{\ell\ell'}$	
SR	$e\mu$, $e\tau$ and $\mu\tau$	$\Delta\phi_{\ell\ell'} > 2.7$, no b-jet, $m_{\ell\ell'} > 600$ GeV
$t\bar{t}$ CR	$e\mu$, $e\tau$ and $\mu\tau$	$\Delta\phi_{\ell\ell'} > 2.7$, at least one b-jet, $m_{\ell\ell'} > 600$ GeV
	Reversed $\Delta\phi_{\ell\ell'}$	
Low $\Delta\phi_{\ell\ell'}$ $t\bar{t}$ CR	$e\mu$	$\Delta\phi_{\ell\ell'} < 2.7$, at least one b-jet, $m_{\ell\ell'} > 600$ GeV
WW CR	$e\mu$	$\Delta\phi_{\ell\ell'} < 2.7$, no b-jet, $m_{\ell\ell'} > 600$ GeV

- Bkg processes can be divided into 2 categories:
  - **Irreducible bkg**: from processes producing 2 different-flavor OS prompt leptons (diboson, $t\bar{t}$, single-top tW, and $Z/\gamma^* \to \tau\tau$ production)
    - **Modelled with MC samples,** corrected by factors derived in CR.
    - ***$t\bar{t}$*** ("top quarks" bkg) and ***WW*** ("diboson" bkg) are **dominant processes in all channels**
      - **dedicated $t\bar{t}$ CR** in $\Delta\phi_{\ell\ell'} < 2.7$ to control the tt contamination (~ 40% in the *WW* CR)
      - *WW* CRs not defined for $e\tau$, $\mu\tau$ channels, due to non-negligible contributions from fake bkg
    - Other irreducible bkg processes (e.g., $Z \to \ell\ell'$) evaluated directly with MC simulation
  - **Reducible bkg:** from jets mis-reconstructed as leptons (W+jets, multijet production)
    - **Estimated from data**
    - Small contribution in $e\mu$ channel (~10% in SR), leading components in $e\tau$ and $\mu\tau$ channels (20-30% of total bkg in SR)

Search for LFV in high mass in dilepton final states $e\mu$, $e\tau$, $\mu\tau$ – Systematic uncertainties

Source of uncertainty (in percent)	Impact on observed $\mu_{\text{RPV}}^{e\mu}$	Impact on observed $\mu_{\text{RPV}}^{e\tau}$	Impact on observed $\mu_{\text{RPV}}^{\mu\tau}$
Electrons	2.2	0.85	NA
Muons	2.8	NA	4.4
τ-leptons	NA	9.7	11
Jets and $E_{\text{T}}^{\text{miss}}$	2.1	0.8	0.8
Flavour tagging	2.1	<0.1	0.1
Other (luminosity, JVT, pile-up)	0.6	0.4	0.7
Fake backgrounds	0.6	3.2	9.7
Background modelling	9.6	2.1	7.3
Top and Diboson normalisations	8.7	1.6	1.8
Simulation statistical uncertainty	28	9.6	15
Total systematic uncertainty	32	14	23
Data statistical uncertainty	53	48	71
Total uncertainty	62	50	74

Post-ft impact of uncertainties in the RPV SUSY $\tilde{\nu}_\tau$ model for each measurement (similar results for Z′ and QBH models)

- Largest systematic due to statistical uncertainties associated with bkg estimate and bkg modelling in $e\mu$ channel
- In $\boldsymbol{\tau}$-lepton channels, uncertainties dominated by statistical precision of bkg estimate, experimental uncertainties related to $\boldsymbol{\tau}$, and estimate of fake bkg.

Total uncertainties dominated by statistical precision in all three channels

Search for LFV in high mass in dilepton final states $e\mu$, $e\tau$, $\mu\tau$ – Statistical analysis (details)

- Binned likelihood function ($\mathcal{L}(\mu, \theta)$): product of Poisson probability terms over all bins considered. It depends on:
  - parameter of interest (POI),
  - signal strength parameter μ, factor multiplying the theoretical signal production cross-section and
  - set of nuisance parameters θ that encode effect of systematic uncertainties in signal and bkg expectations (implemented in the likelihood function as Gaussian constraints). The nuisance parameters adjust the expected event yields for signal and bkg according to the best fit to data. The likelihood function is fitted to data to test for presence of a signal.

- Test statistic q_μ defined as profile likelihood ratio $q_\mu = -2\, ln\, \mathcal{L}(\mu, \hat{\hat{\theta}})/\mathcal{L}(\hat{\mu}, \hat{\theta})$
  - $\hat{\mu}$, $\hat{\theta}$: values of the parameters that simultaneously maximize the likelihood function,
  - $\hat{\hat{\theta}}$ values of the nuisance parameters that maximize likelihood function for a fixed value of μ.
  - Compatibility of observed data with bkg-only hypothesis is tested by setting $\mu = 0$ in the test statistic q_0 .

- Fits to dilepton inv mass distribution performed simultaneously in SR and CRs, following a modified frequentist method
  - $e\mu$ channel: *WW* and low $\Delta\phi_{\ell\ell'}$ $t\bar{t}$ CRs included in the fit to extract overall norm. of diboson bkg while keeping norm. of top quark bkg uncorrelated in the high- and low-$\Delta\phi_{\ell\ell'}$ regions. Separate norm. factors of top quark bkg used for high- and low-$\Delta\phi\ell\ell'$ regions in simultaneous fit, by which their correlation is determined.
  - $e\tau$, $\mu\tau$ channels: only $t\bar{t}$ CRs included in the fit; diboson corr. factors from CR-only fit results and included as fixed norm factors.

- Upper limits on signal production cross-section for computed using q_μ in the CLs method with the asymptotic approximation.
  - A given signal scenario is excluded at 95% C.L. if value of signal production cross-section yields a CLs value < 0.05.

Search for LFV in high mass in dilepton final states $e\mu$, $e\tau$, $\mu\tau$ – Post-fit yields

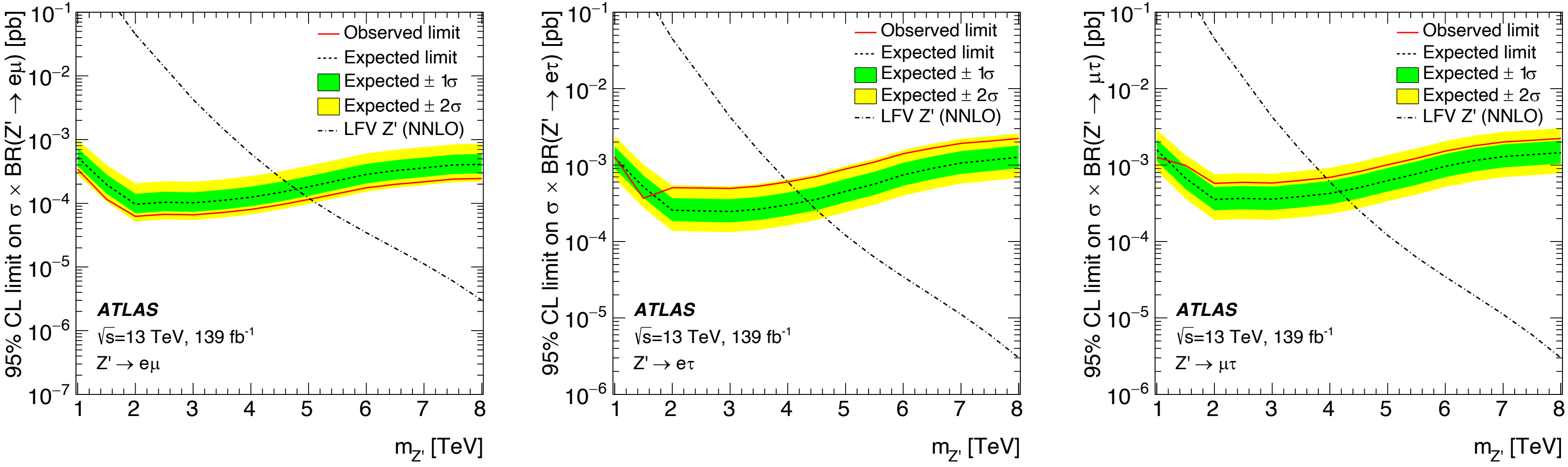
- **Observed data and expected bkg event yields in CRs and SRs for each channel reported in tables**
  - $e\mu$ bkg dominated by $t\bar{t}$ and diboson events,
  - W+jets events are dominant for the $e\tau$ and $\mu\tau$ fnal states.

Process	$e\mu$ channel	$e\tau$ channel	$\mu\tau$ channel
Top Quarks	151±15	114±10	79.4±6.4
Diboson	246±28	125±27	94±20
Fake	66±11	172±34	67±25
Drell–Yan	8.6±0.5	76.1±8.9	78.0±7.9
Total background	471±21	488±21	319±16
Data	470	499	319

Process	$t\bar{t}$ CR	WW CR	Low $\Delta\phi_{\ell\ell'}$ $t\bar{t}$ CR
Top Quarks	660±27	55.4±5.9	279±18
Diboson	11.3±2.4	54.3±8.4	7.5±2.3
Fake	29.3±5.9	18.3±3.8	16.6±4.9
Drell–Yan	0.25±0.03	0.26±0.03	0
Total background	701±26	128.2±8.3	304±17
Data	700	133	301

Process	$e\tau$ channel $t\bar{t}$ CR	$\mu\tau$ channel $t\bar{t}$ CR
Top Quarks	406±21	305±17
Diboson	9.6±2.8	6.1±1.6
Fake	6.8±1.2	8.6±2.6
Drell–Yan	2.1±0.1	3.6±0.7
Total background	424±20	324±17
Data	422	324

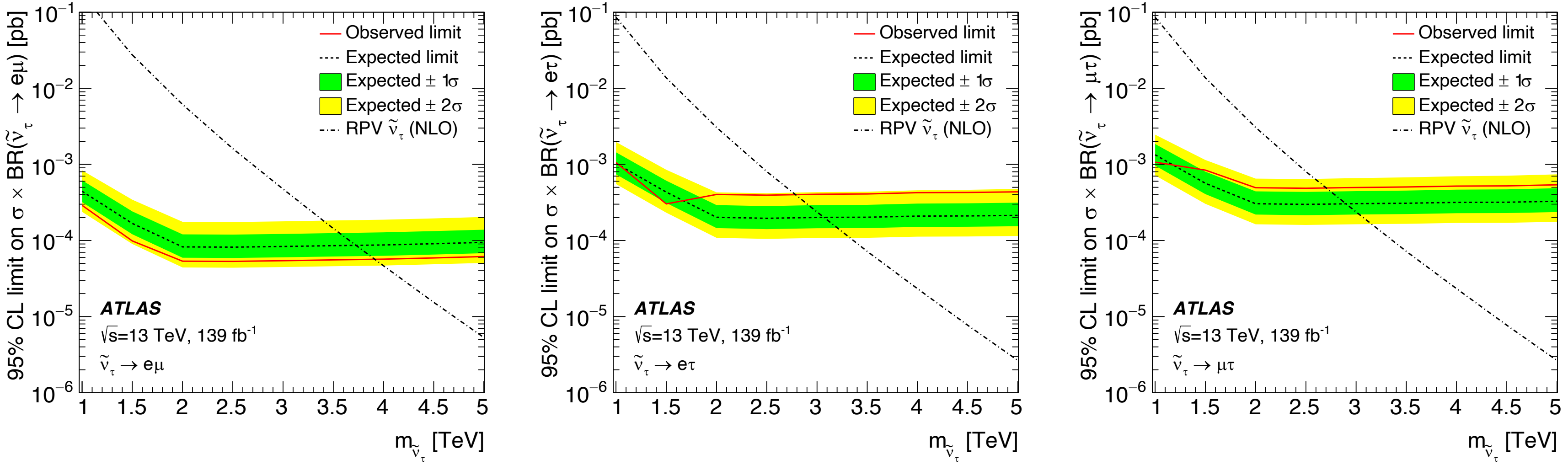
Search for LFV in high mass in dilepton final states $e\mu$, $e\tau$, $\mu\tau$ – Upper limits Z'



Observed and expected 95% CL upper limits on Z′ boson $\sigma \times \mathrm{BR}$ for decays into each different final state.

- Signal theoretical $\sigma \times \mathrm{BR}$ lines for the Z′ model obtained from simulation of each process, while Z′ is corrected to NNLO.
- Theoretical uncertainties not considered in mass limit calculation.
- Expected limits shown with ±1 and ±2 standard deviation uncertainty band.

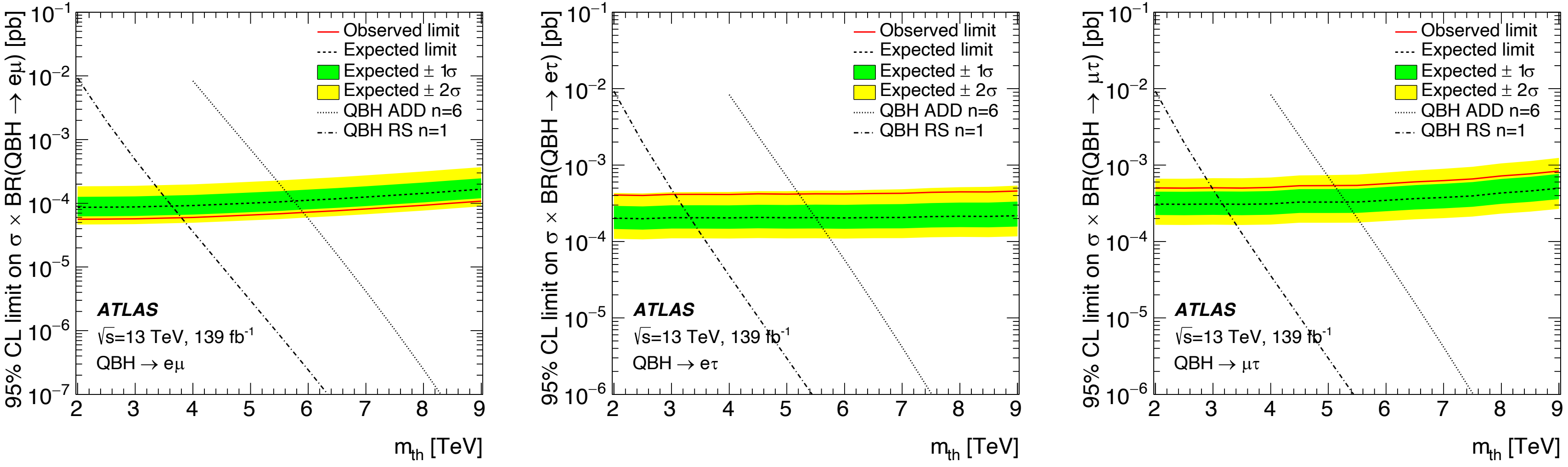
Search for LFV in high mass in dilepton final states $e\mu$, $e\tau$, $\mu\tau$ – Upper limits RPV SUSY



Observed and expected 95% CL upper limits on RPV $\tilde{\upsilon}_\tau$ $\sigma \times \mathrm{BR}$ for decays into each different final state.

- Simulated RPV $\tilde{\upsilon}_\tau$ is corrected to NLO.
- Theoretical uncertainties not considered in mass limit calculation.
- Expected limits shown with ±1 and ±2 standard deviation uncertainty band.

Search for LFV in high mass in dilepton final states $e\mu$, $e\tau$, $\mu\tau$ – Upper limits QBH



Observed and expected 95% CL upper limits on QBH ADD and RS $\sigma \times \mathrm{BR}$ for decays into each different final state.

- Signal theoretical $\sigma \times \mathrm{BR}$ lines for QBH ADD model assuming six extra dimensions, and RS model with one extra dimension obtained from simulation of each process.
- Theoretical uncertainties not considered in mass limit calculation.
- Acceptance times efficiency of ADD and RS QBH models agree to within 1% and same curve is used for limit extraction.
- Expected limits shown with ±1 and ±2 standard deviation uncertainty band.

Search for Higgs LFV decay $\mathbf{H} \rightarrow e\mu$

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. μ → 3e, μ → e conversion, μ → eγ) that could proceed via virtual Higgs boson exchange
  - In particular, **most stringent limit** on B(H(125) → eμ) obtained **indirectly** from limit on **μ → eγ** 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 $H \to e\mu$: analysis strategy

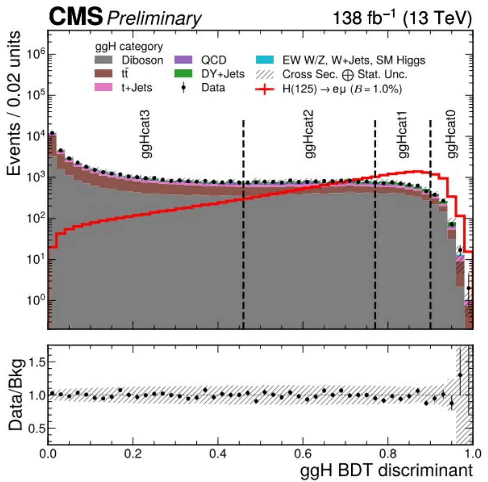
- This analysis targets the two dominant production modes of Higgs at LHC: **ggH** and **VBF**.
  - **final state** of interest in both modes: **prompt, oppositely-charged electron-muon pair**

- 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)

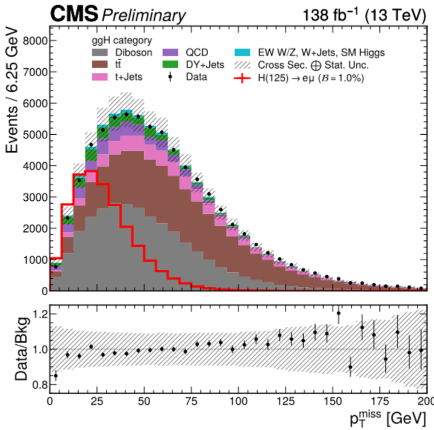
Search for LFV decay $H \to e\mu$: multivariate analysis

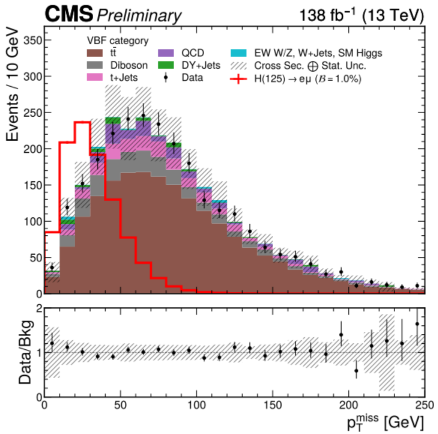


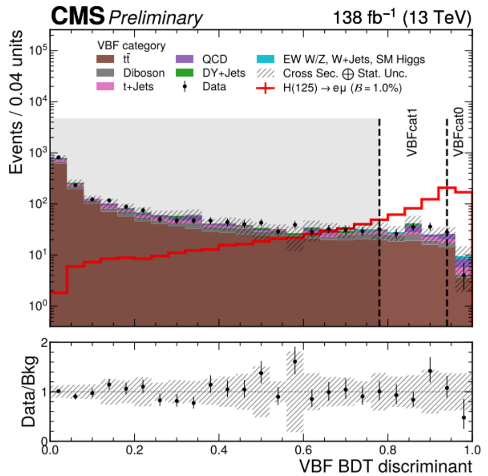
- BDTs trained separately for ggH and VBF categories

- 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

p_T^{miss} : Most discriminating variable in both ggH and VBF categories





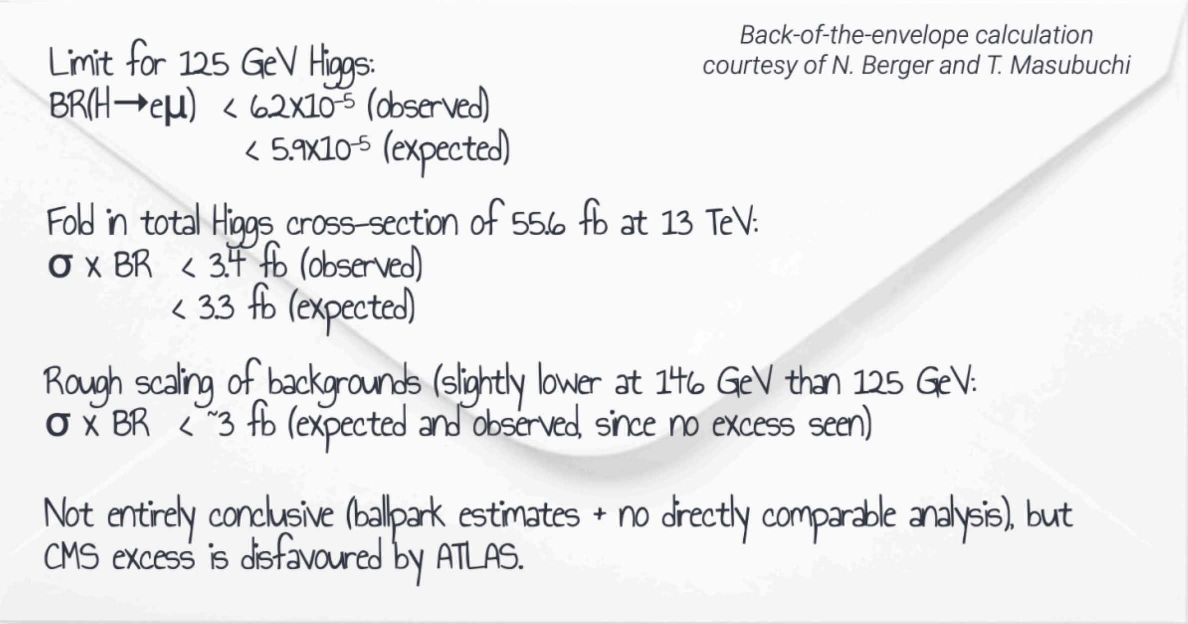


Search for LFV decay $H \to e\mu$: systematic uncertainties

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 LFV decay H→$e\mu$: feedback from ATLAS



Back-of-the-envelope calculation courtesy of N. Berger and T. Masubuchi

Limit for 125 GeV Higgs:
BR(H→$e\mu$) < 6.2×10^{-5} (observed)
< 5.9×10^{-5} (expected)

Fold in total Higgs cross-section of 55.6 fb at 13 TeV:
σ x BR < 3.4 fb (observed)
< 3.3 fb (expected)

Rough scaling of backgrounds (slightly lower at 146 GeV than 125 GeV:
σ x BR < ~3 fb (expected and observed, since no excess seen)

Not entirely conclusive (ballpark estimates + no directly comparable analysis), but CMS excess is disfavoured by ATLAS.

ATLAS search for not directly comparable with CMS analysis, but back-of-the envelope calculation from sideband data disfavors a narrow-width excess (observed by CMS)

Search for Higgs LFV decays

H→$e\tau$ and H→$\mu\tau$

ATLAS

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

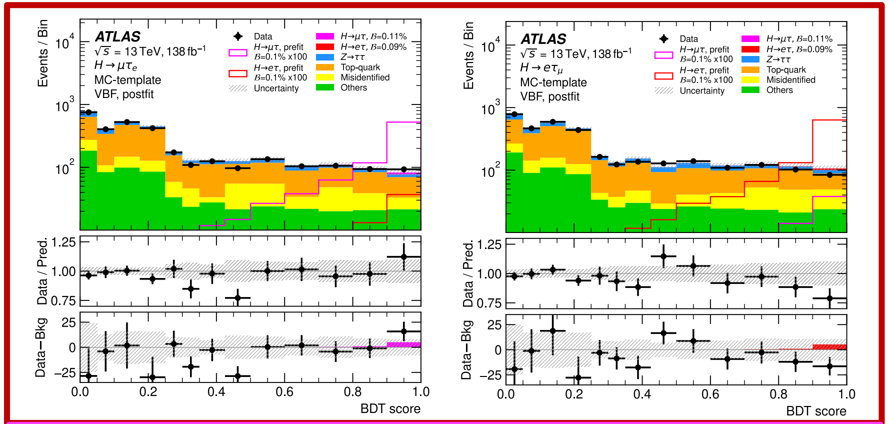
arXiv:2302.05225

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

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

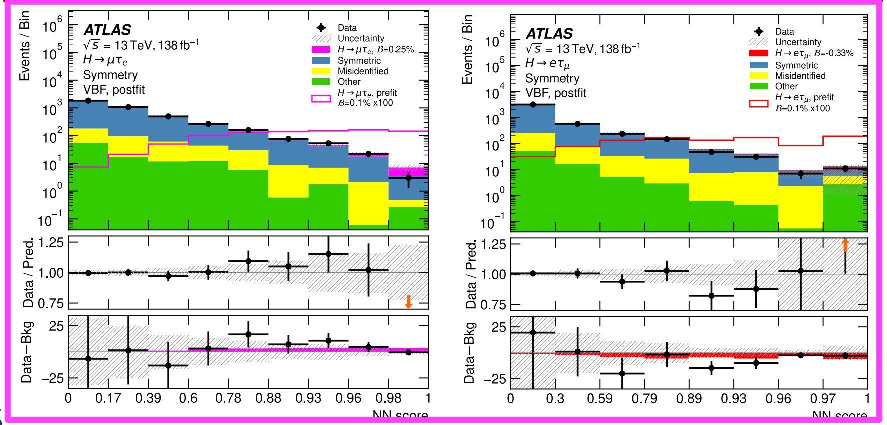
$\ell\tau_{had}$ $\ell\tau_{\ell'}$ ○ **MC template** method: templates from MC + data-driven estimate of 'misidentified bkg'

$\ell\tau_{\ell'}$ ○ **Symmetry** method: prompt-lepton bkg in SM assumed to be symmetric under exchange electrons-muons. Used to derive data-driven estimate for main bkgs



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

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



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

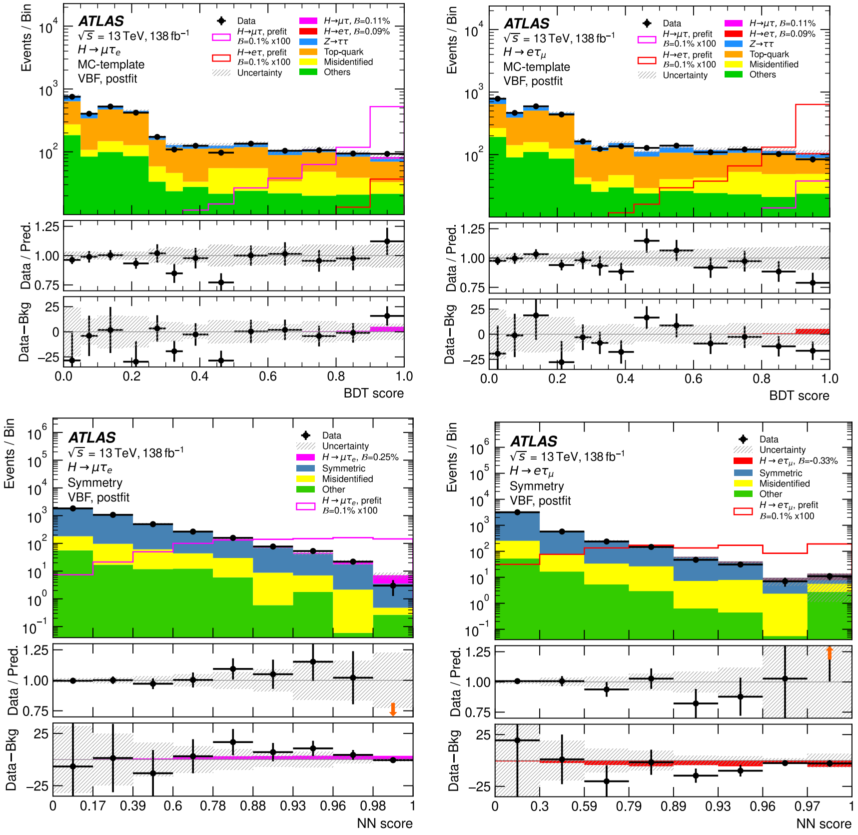
- **Two MVA techniques** used to separate sgn from bkgs
  - **BDTs** for **MC-template method**
  - deep **NNs** for **Symmetry method**

- **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

CMS

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.

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

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

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

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)

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

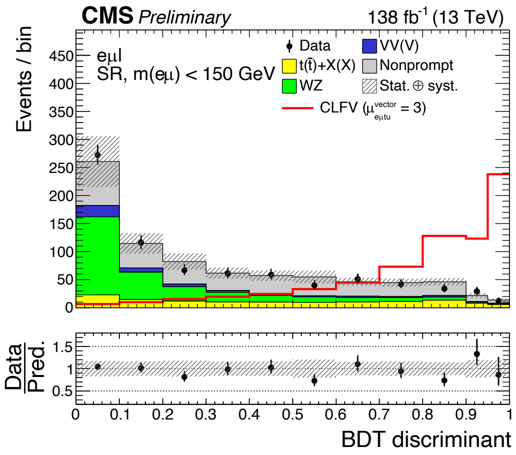
- Additional validation region defined in the $e\mu\ell$ channel, inverting mass requirement used to define the SR

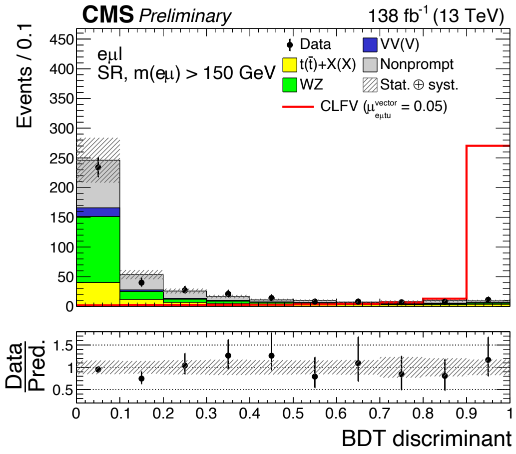
Expected background contributions and number of events observed in data

Process	$m(e\mu) < 150\,GeV$	$m(e\mu) > 150\,GeV$
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 : 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

ATLAS

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 $gu \to t\ell^{\pm}\ell'^{\mp}$ process which leads to stronger limits on $\mu\tau ut$ interactions than $\mu\tau ct$

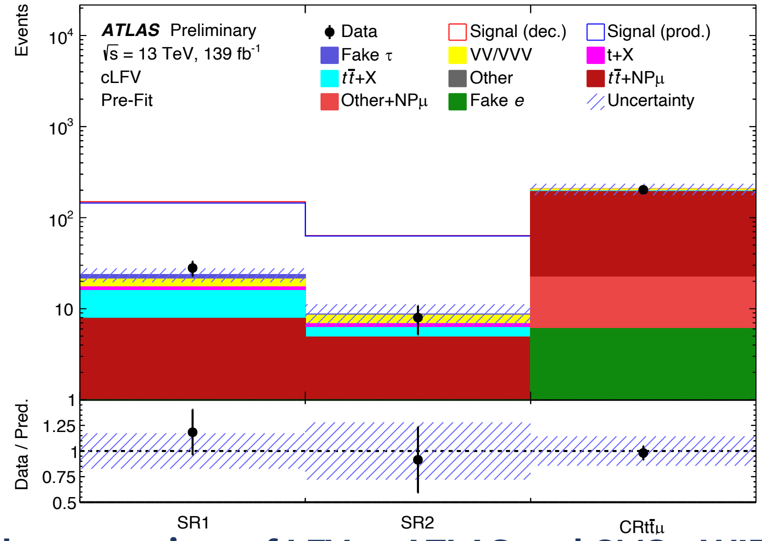
CLFV $\mu\tau qt$ interactions in top-quark production and decay: analysis strategy

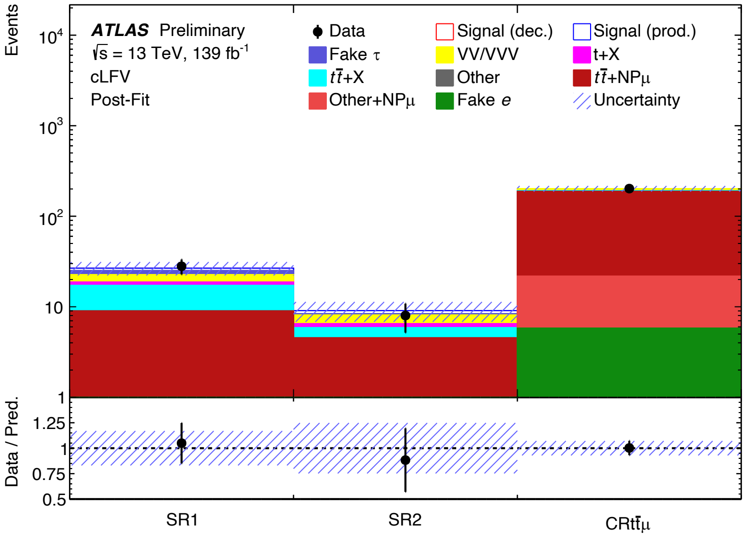
Preselection:	
Number of leptons	$N_\ell = 3,\ p_T > 10$ GeV, $\|\eta\| < 2.5$
Leading muon / electron p_T	p_T ¿ 27 GeV
Trigger matching	$\geq$ 1 trigger-matched muon / electron
Sum of lepton charges	$\sum q_i = \pm 1$

- **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*

	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	-
$\|m_{\mu\mu}^{OS} - M_Z\|$	-	-	<10 GeV	>10 GeV

- **Normalisations** of sgn and non-prompt muon are obtained from **simultaneous profile-likelihood fit to 3 regions** with syst. uncertainties included as nuisance parameters

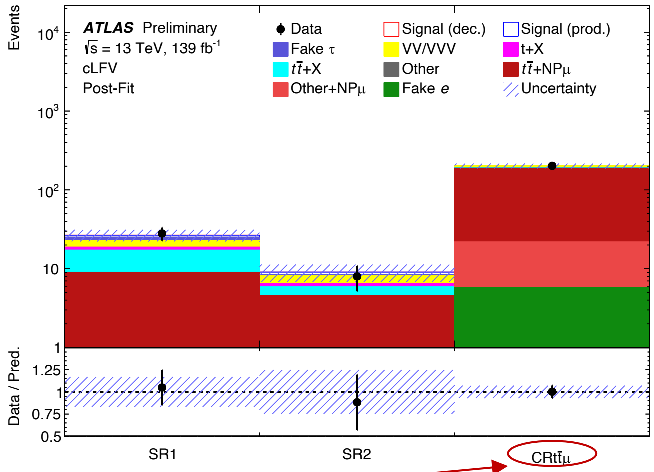




CLFV $\mu\tau qt$ interactions in top-quark production and decay: analysis strategy (II)

- 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 $1e$ + 1μ, 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: 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 considered as determined in the fit under a signal+bkg hypothesis.
- 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

CMS

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

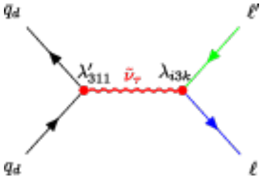
arXiv:2205.06709

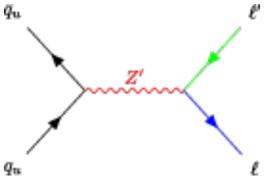
$\mathcal{L} = 138\ fb^{-1}$
$\sqrt{s} = 13$ TeV

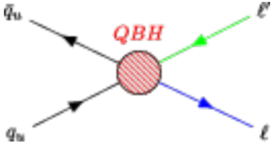
- Extensions of SM can accommodate heavy particles undergoing LFV decays
- Analysis designed to be **as model-independent as possible**

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

  - a τ **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 $e\mu$ and $e\tau_h$ or $\mu\tau_h$ pair considered per event:
  - 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 signal and bkg**

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

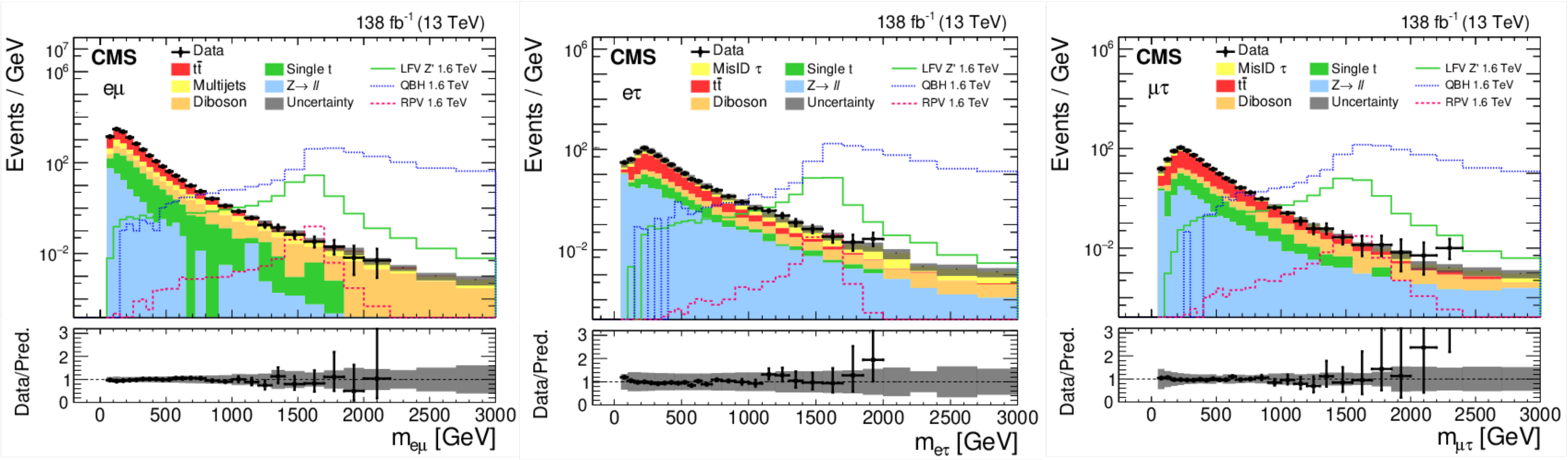
- Events with at least:
  - 1 prompt, isolated light lepton (electron or muon, with same requirements as for $e\mu$ channel)
  - 1 prompt, isolated τ_h (p_T > 50 GeV, $|\eta|<2.3$)
  - m_T > 120 GeV (to reject misidentified τ_h bkg)
- Muon veto applied in $e\tau$ final state to remove overlap with the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

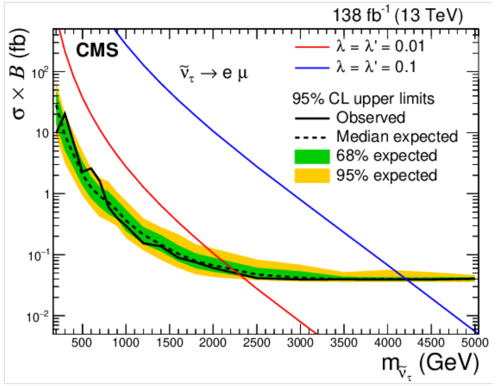
Search for heavy resonances & QBH in $e\mu$, $e\tau$, $\mu\tau$: invariant mass distributions

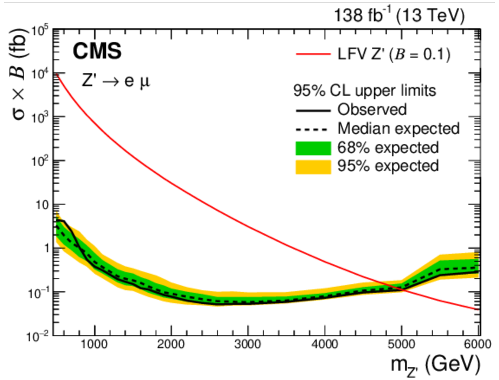


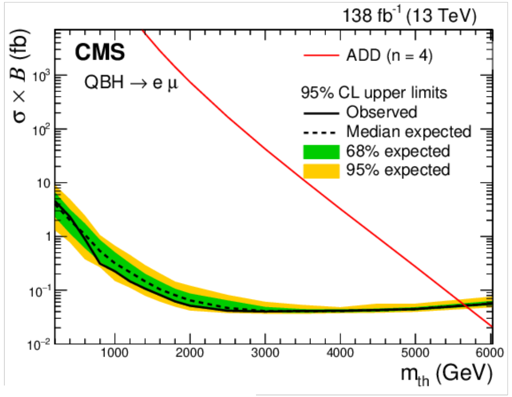
- **RPV SUSY model** ($\lambda = \lambda' = 0.01$) τ sneutrino mass of 1.6 TeV
- **LFV Z'** ($\mathcal{B} = 0.1$) boson with a mass=1.6 TeV,
- **QBH signal** expectation for n=4 and a threshold mass of 1.6 TeV

No significant deviations from expected SM bkg

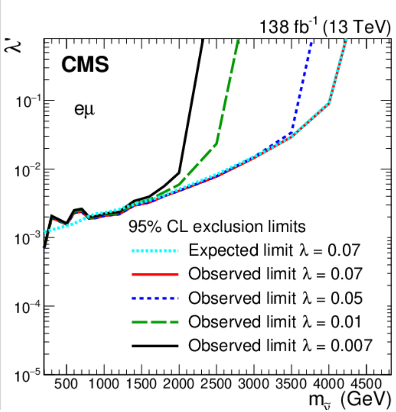
Search for heavy resonances & QBH in $e\mu$, $e\tau$, $\mu\tau$: UL for BSM models





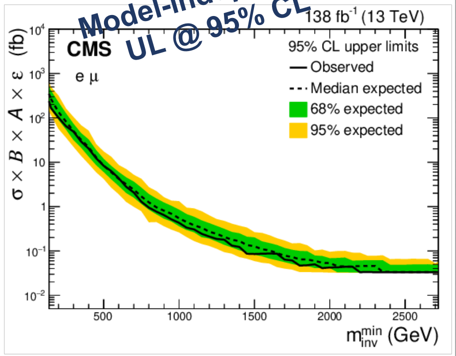


Expected and observed UL on $\sigma \times \mathcal{B}$ @95% CL as a function of τ sneutrino mass in RPV SUSY, Z' with LFV decays, and QBH threshold mass

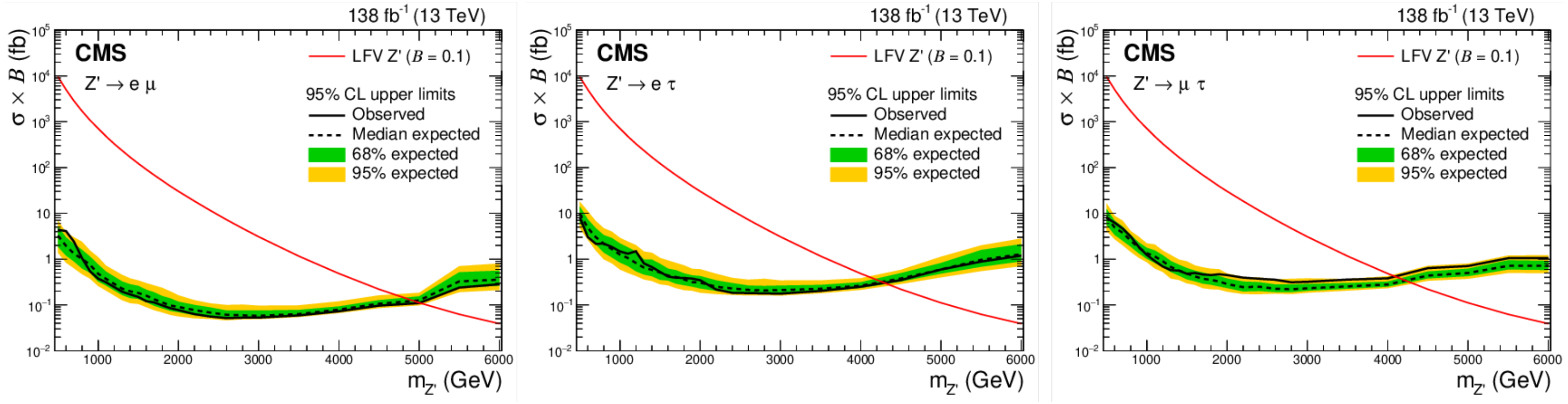


Exclusion limits @ 95% CL on RPV SUSY model in plane of τ sneutrino mass and λ' coupling

Model-independent UL @ 95% CL



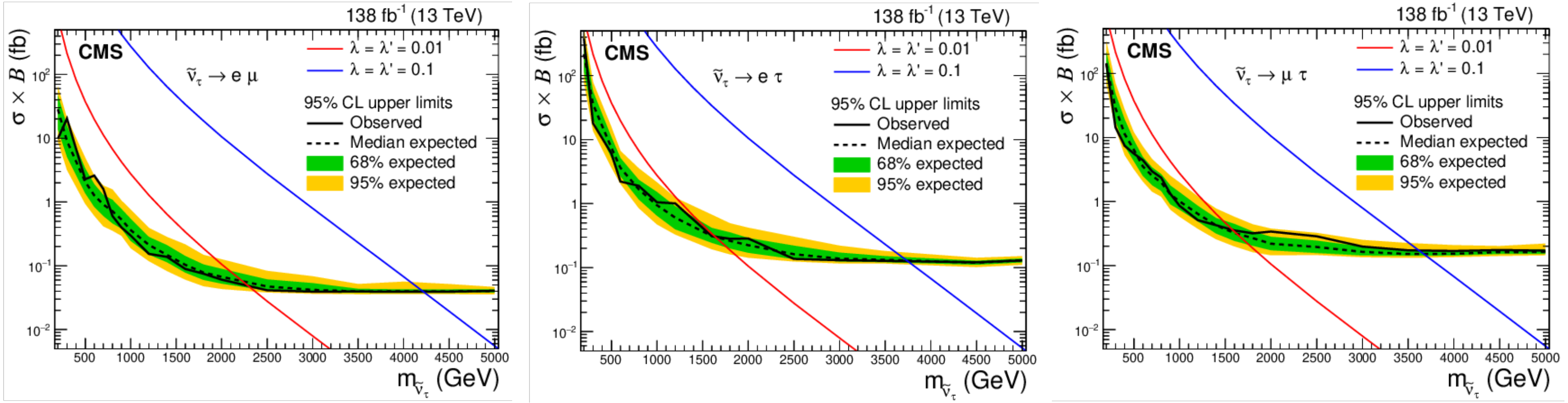
Search for heavy resonances & QBH in $e\mu$, $e\tau$, $\mu\tau$: UL for LFV Z' boson



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 $\mathcal{B} = 0.1$).

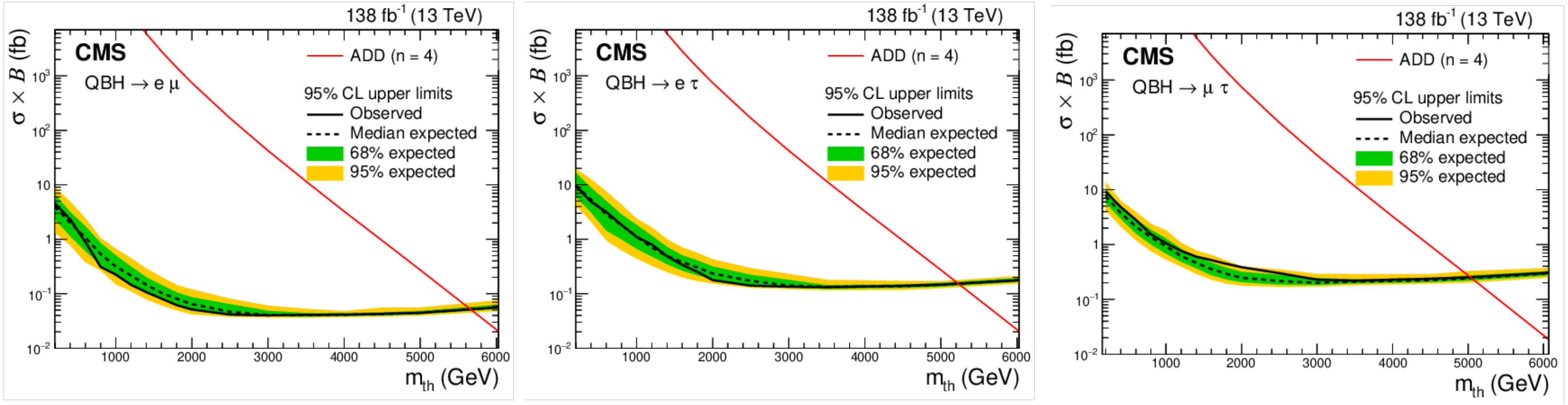
Search for heavy resonances & QBH in $e\mu$, $e\tau$, $\mu\tau$: UL as sneutrion mass in RPV SUSY



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.

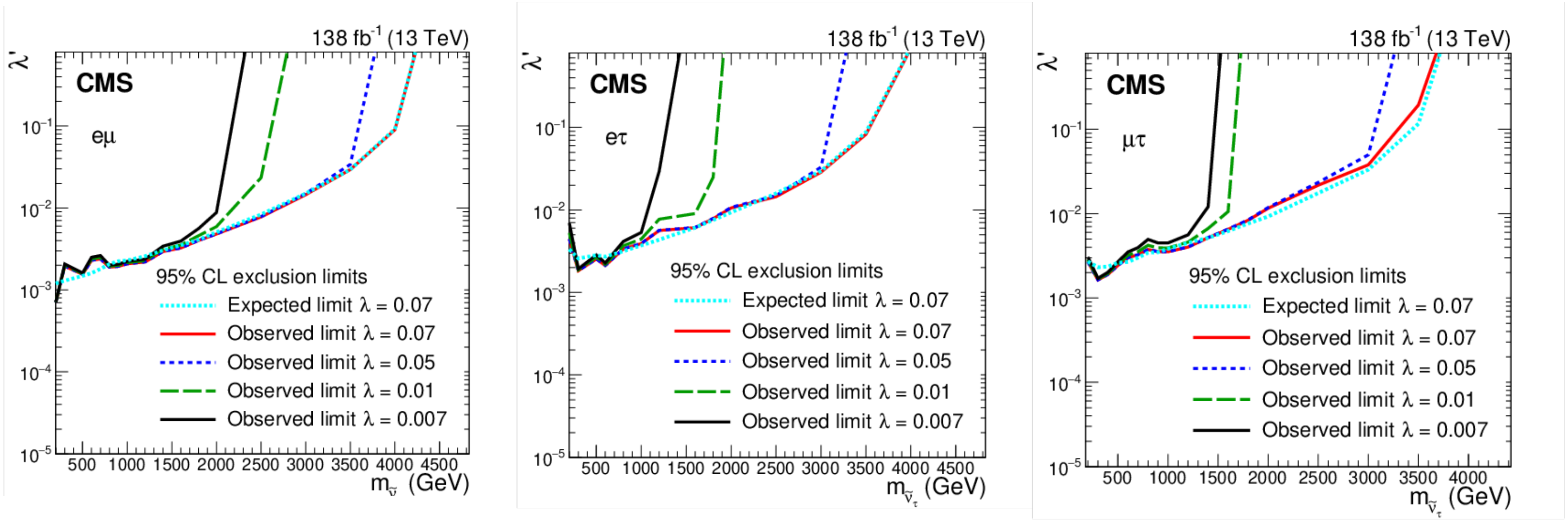
Search for heavy resonances & QBH in $e\mu$, $e\tau$, $\mu\tau$: UL for QBH production



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.

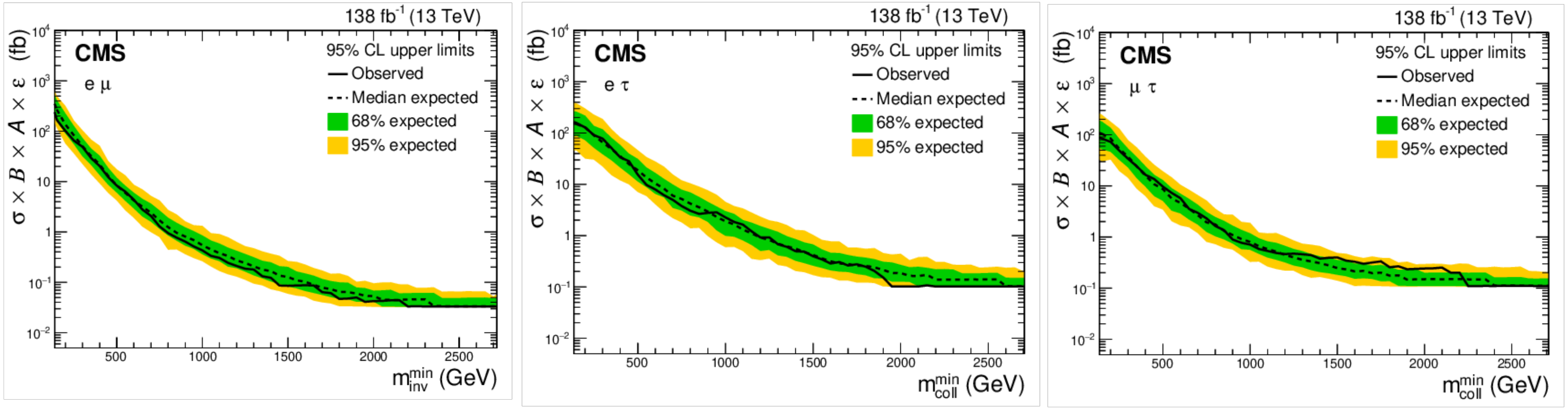
Search for heavy resonances & QBH in $e\mu$, $e\tau$, $\mu\tau$: exclusion limits on RPV SUSY



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.

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

No evidence is found for physics beyond the SM

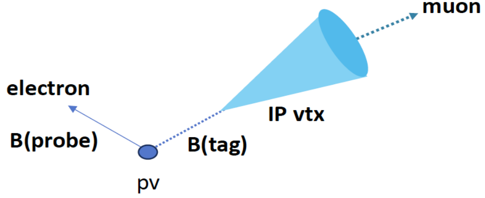
- **Upper limits** set **@95% C.L.** on the product of the cross section and BR for **LFV signals**:
  - **Resonant τ sneutrinos excluded** for masses up to:
    - **4.2 TeV** in the $e\mu$ channel,
    - **3.7 TeV** in the $e\tau$ channel,
    - **3.6 TeV** in the $\mu\tau$ channel.
  - A **Z′ boson** 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

Lepton flavor universality violation

R(K): test of LFU in $B^{\pm} \to K^{\pm}\ell^{+}\ell^{-}$ decays

- **First R(K) measurement by CMS**, with 2018 **B-parking** data

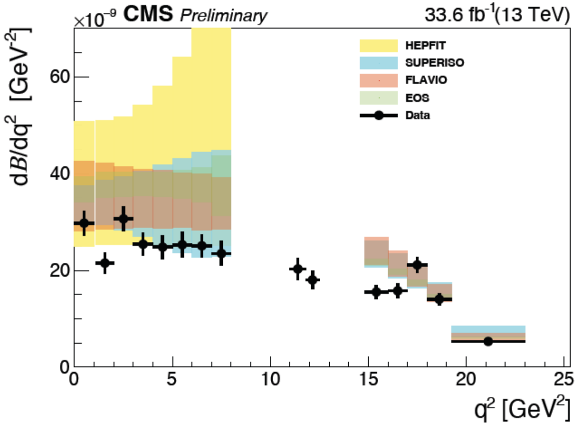


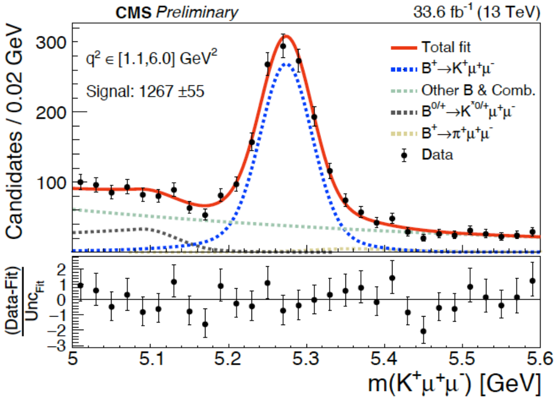
Results:

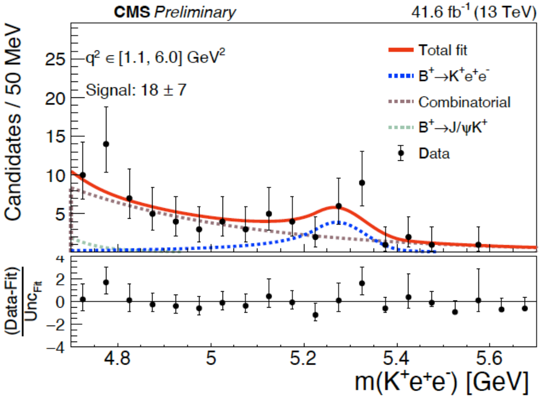
- **Differential measurement of $\mathbf{BR}(\boldsymbol{B^{\pm} \to K^{\pm}\mu^{+}\mu^{-}})$** in a wide q² range
- Measurement in the low-q² bin in agreement with the world-average, with **unc. reduced by 40%**
- **R(K)** in $q^2 \in [1.1; 6.0]$ GeV²

$$= 0.78^{+0.46}_{-0.23}\,(stat)^{+0.09}_{-0.05}(syst)$$

$$R(\mathrm{K})(q^2) = \frac{\mathcal{B}(\mathrm{B}^+ \to \mathrm{K}^+\mu^+\mu^-)(q^2)}{\mathcal{B}(\mathrm{B}^+ \to \mathrm{J}/\psi(\mu^+\mu^-)\mathrm{K}^+)} \Bigg/ \frac{\mathcal{B}(\mathrm{B}^+ \to \mathrm{K}^+\mathrm{e}^+\mathrm{e}^-)(q^2)}{\mathcal{B}(\mathrm{B}^+ \to \mathrm{J}/\psi(\mathrm{e}^+\mathrm{e}^-)\mathrm{K}^+)}$$





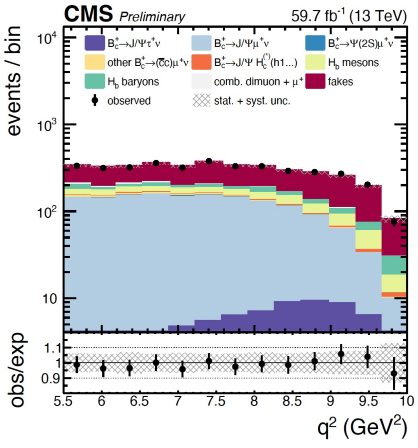


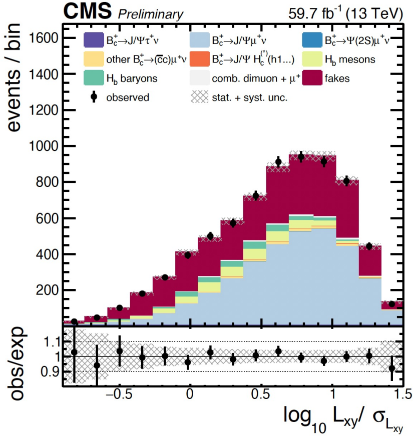
[BPH-22-005]

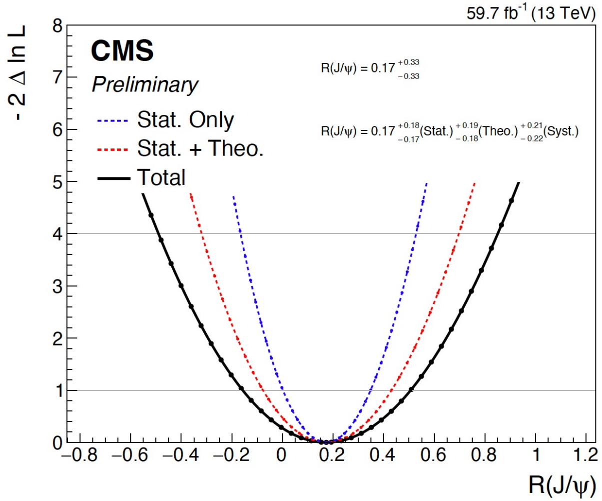
R(J/Psi): LFU test in semileptonic decays $B_c^{\pm} \to J/\psi \ell^+ \nu$

- **First measurement of R(J/Psi) by CMS** with 2018 data
- Tau leptonic decay $\tau^+ \to \mu^+ \nu_\mu \bar{\nu}_\tau$, 3μ trigger optimized for the $J/\psi + \mu$ final state
- R(J/Psi) extracted from sim. maximum likelihood fit on q² and $L_{xy}/\sigma_{L_{xy}}$
- Result in agreement with SM (0.3 σ) and LHCb (1.3 σ), limited by stats and theoretical uncertainties on the Bc form factors

$$R(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\, \tau^+ \nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\, \mu^+ \nu_\mu)} = 0.17^{+0.18}_{-0.17}\,(\text{stat.})^{+0.21}_{-0.22}\,(\text{syst.})^{+0.19}_{-0.18}\,(\text{theo.}) = 0.17 \pm 0.33,$$



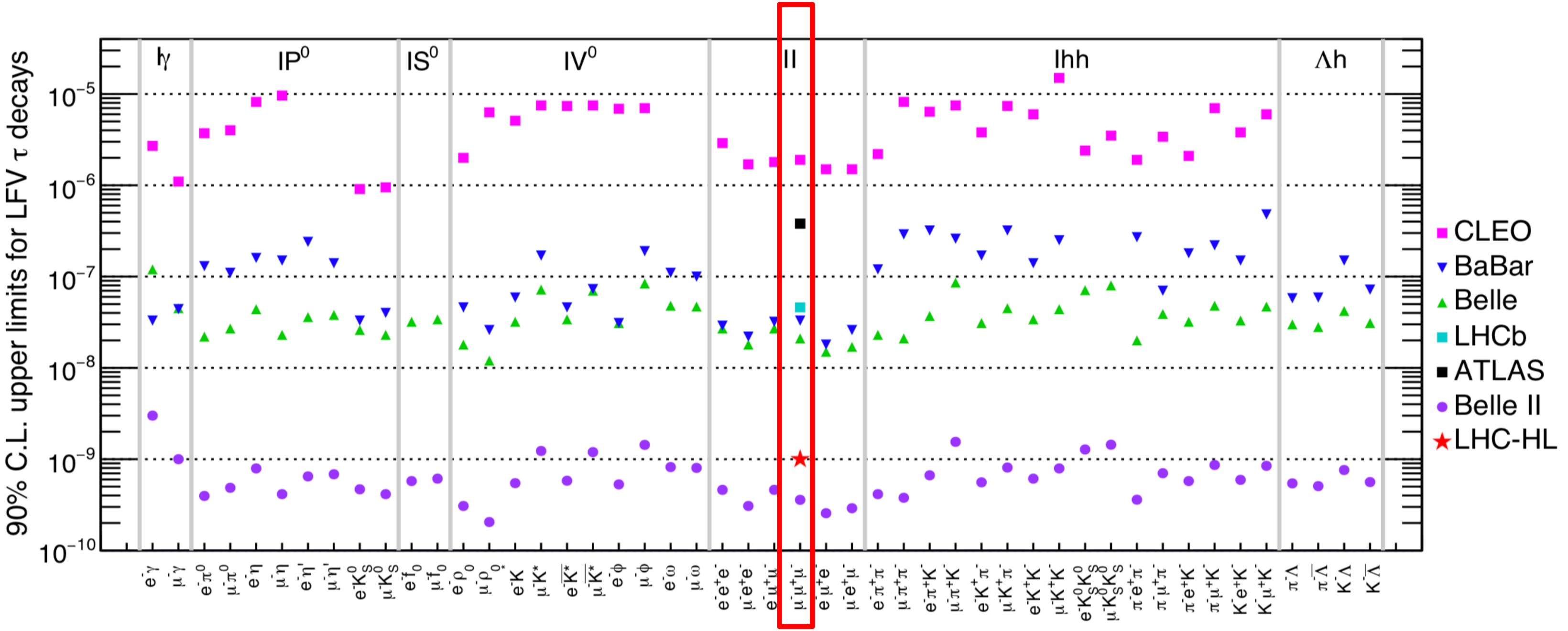




BPH-22-012

Upgrades, projections,
a glance to the future

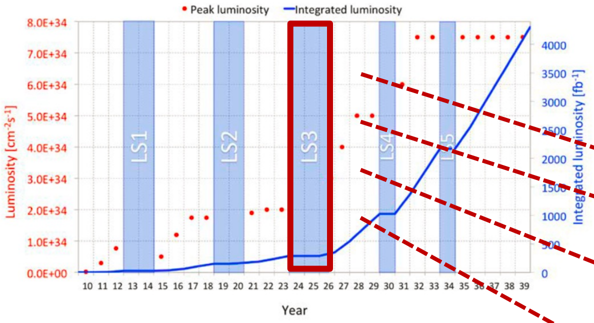
Future perspectives for LFV search in τ decays

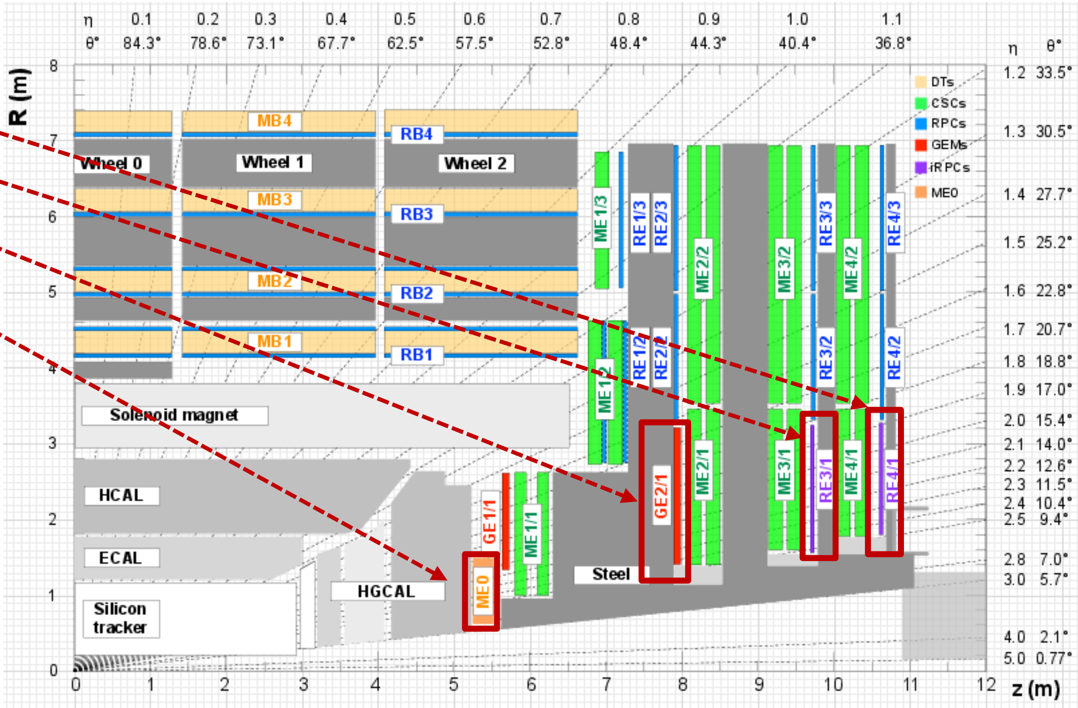


Bounds on Tau Lepton Flavor Data from the existing experiments are compiled by HFLAV; projections of the Belle-II bounds were performed by the Belle-II collaboration assuming 50 ab^{-1} of integrated luminosity.

arXiv:1812.07638

CMS muon system upgrade during LS3





CMS muon system upgrade

- GE2/1, RE3/1, RE4/1 stations will provide additional measurements of the muon tracks, reinforcing the redundancy of the system
- the ME0 station will extend the muon system coverage from $|\eta| = 2.4$ to 2.8