Tau 2023

The 17th international workshop on tau lepton physics

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Search for LFV decays with tau leptons in the final state at CMS

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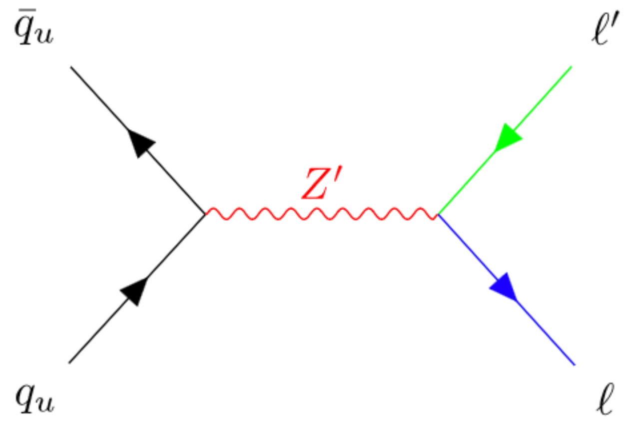
Brief introduction

- The standard model (SM) has proven a solid description of particle interactions up to today energy scales
- One of the goals of LHC is to **search for processes beyond the SM** (BSM) and extend our current understanding of it
- **Lepton Flavour Violating** (LFV) decays represent a diversified ground for BSM searches
- LFV are **strongly suppressed** in the SM, and only allowed at very low branching fraction by neutrino oscillations
  - example: BR ($\tau \longrightarrow 3\mu$) ~ 10^{-55} doi:10.1140/epjc/s10052-020-8059-7

Brief introduction

- New Physics (NP) models may **enhance LFV processes up to detectable rates**
- it may manifest in **BSM decays of known particles**, such as the Higgs or the tau lepton
- …or it may manifest as the direct/indirect **effect of undiscovered particles**, such as new heavy neutral bosons (Z'), supersymmetric particles, QBH, …
- coupling to the third family may be enhanced in some models → **LFUV**
- The CMS experiment can **access a large set of BSM scenarios**

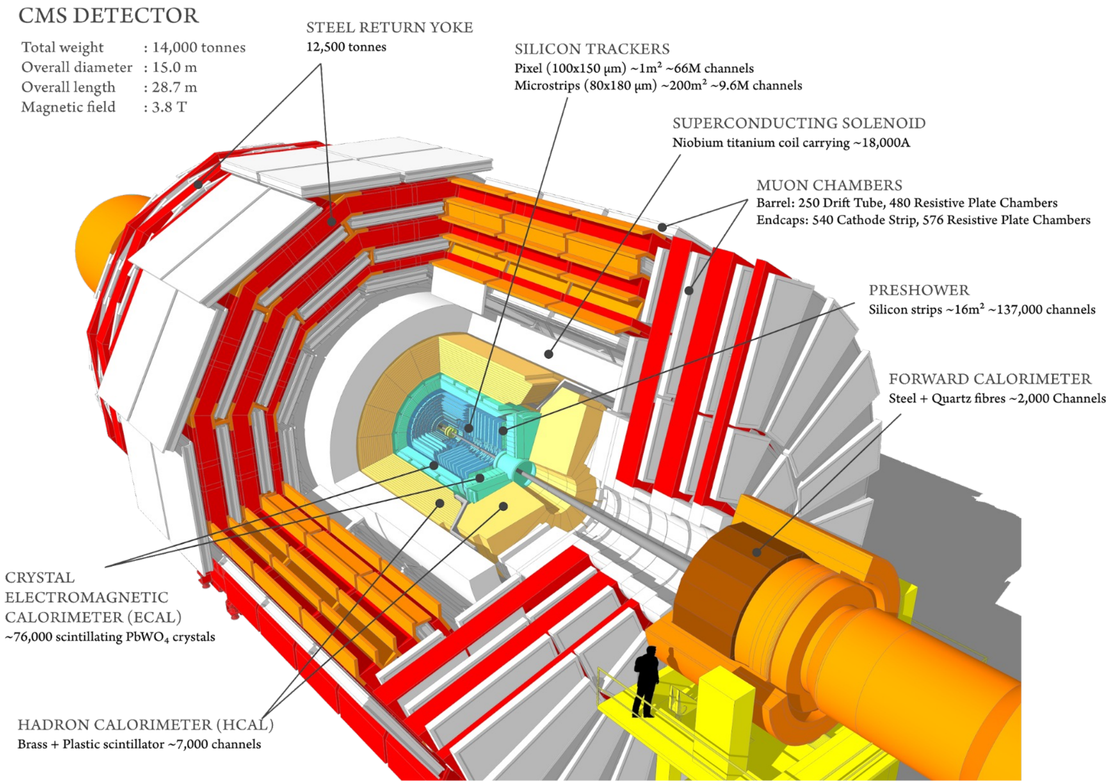


Talk overview

Results from lepton flavour violating decays (LFV) at CMS involving tau leptons

- Search for the LFV **$\tau \rightarrow 3\mu$ decay** in CMS in Run-2 data
- Search for **heavy resonances and quantum black holes in eμ, eτ and μτ** final states in proton-proton collisons at sqrt(s)=13 TeV
- Search for **lepton flavour violating decays of the Higgs boson** in the μτ and eτ final states in proton-proton collision at sqrt(s)=13 TeV
- Test of **lepton flavour universality violation** (LFUV) in semileptonic Bc+ meson decay at CMS

The CMS detector



collected luminosity:

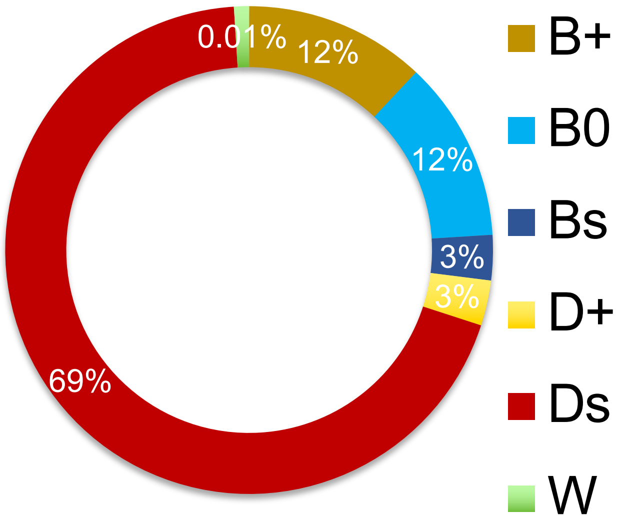
- Run1: 25 /fb pp @ 7 and 8 TeV
- Run2: 140 /fb pp @ 13 TeV
- Run3 ongoing

- cylindric compact (15m x 21m) detector
- high granularity **pixel + strip silicon tracker** for excellent track, PV and SV measurements
- **$PbWO_4$ crystal ECAL and brass+plastic HCAL** to achieve hermeticity and jet+EG shower measurement
- **3.8T solenoid** for pT measurement
- **external muon chambers** outside steel return yoke for a clean muon detection and pT measurement
- **two level trigger system** (hardware + software)

10.48550/arXiv.2312.02371

τ⟶3μ
sources of τ leptons

Two sources of τ leptons by CMS: heavy flavours and W bosons



- **heavy flavour (HF)** mesons are the most abundant source of tau leptons in pp collisions (~10^{11} tau leptons per /fb)
  - low-pT and high |η| → less efficient trigger selection
  - more sensitive to fake signal muons from π's and K's
- production in the **W channel** less abundant (~10^{7} tau leptons per /fb)
  - harder spectra and more central decay → more efficient trigger selection
  - properties of W → τν bring additional handles for background suppression (large missing pT, low hadron activity, larger signal pT)

10.48550/arXiv.2312.02371

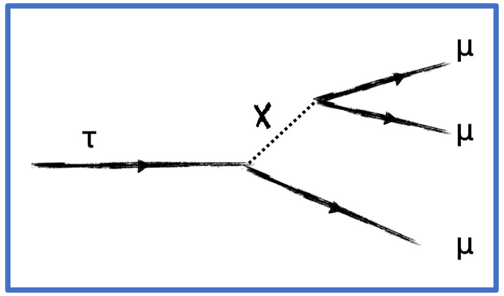
τ⟶3μ overview

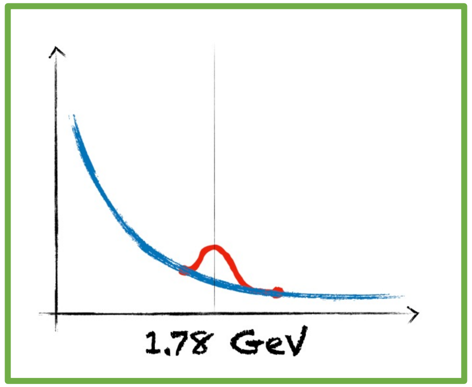
LFV process, strongly suppressed by the SM

- allowed by some BSM models at detectable branching fraction (~10^{-9}) 10.1007/JHEP10(2018)148

pp collision @13 TeV 90 /fb

- 2016 data analysis (30 /fb) already public 10.1007/JHEP01(2021)163
- result extended to full Run2 era





online event selection: dedicated trigger paths selects signal events with three muons or two muons and a track

offline signature: charge-one three muon events from a displaced vertex

figure of merit: three-muon invariant mass distribution

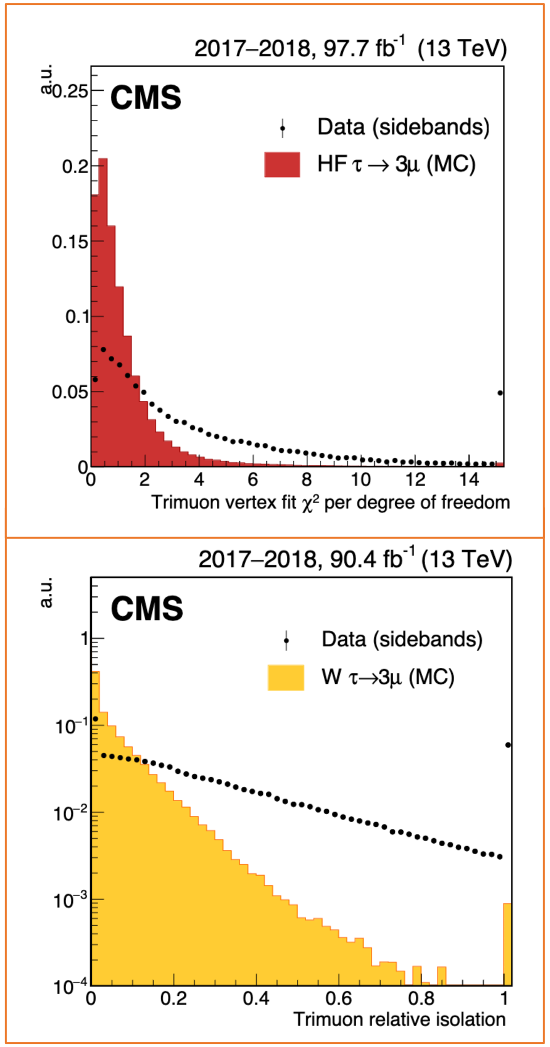
- simultaneous ML fit the signal strength
- categorization based on the invariant mass resolution and production channel

10.48550/arXiv.2312.02371

$\tau \to 3\mu$
background rejection

background sources

- kinematically closed decays of **D mesons**
  - veto $\phi \to \mu\mu$ and $\omega \to \mu\mu$ resonances
  - fake-muon (pions and kaons) by suppression by track quality
- **semileptonic decays** of D mesons
  - involves non-reconstructed particles ⟶ mass below signal region
  - further suppression by a **BDT discriminator**
- **combinatorial:** suppressed by **the BDT discriminator**
- **electroweak W→μν+FSR decays**: 3μ+large MET prompt background survives the MVA selection, removed by cutting on the displacement significance from the interaction point



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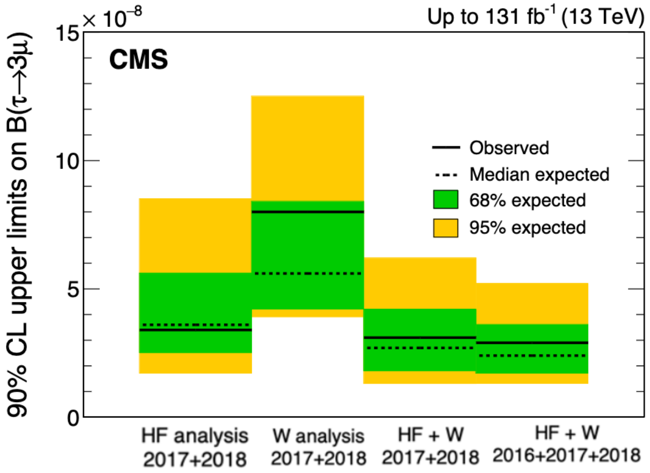
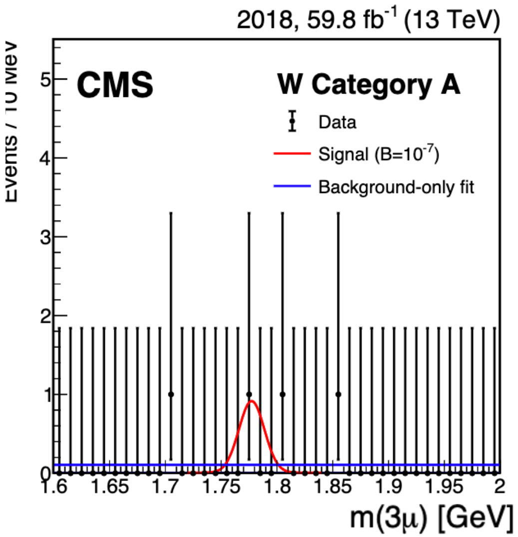
τ⟶3μ results

- Signal strength extracted with **UML fit to the three-muon invariant mass** distribution
  - **categories are combined via simultaneous fit** of the signal strength
  - no signal evidence in data ⟶ upper limit set on the τ→3μ branching fraction
- extend the analysis with the 2016 analysis (doi.org/10.1007/JHEP01(2021)163) to the **full Run2 dataset**
- comparable to the world best UL set by Belle at 2.1 x 10^{-8} @90% CL





observed (expected) upper limit @ 90% of CL

B(τ→3μ) < 2.9 (2.4) x 10^{-8}

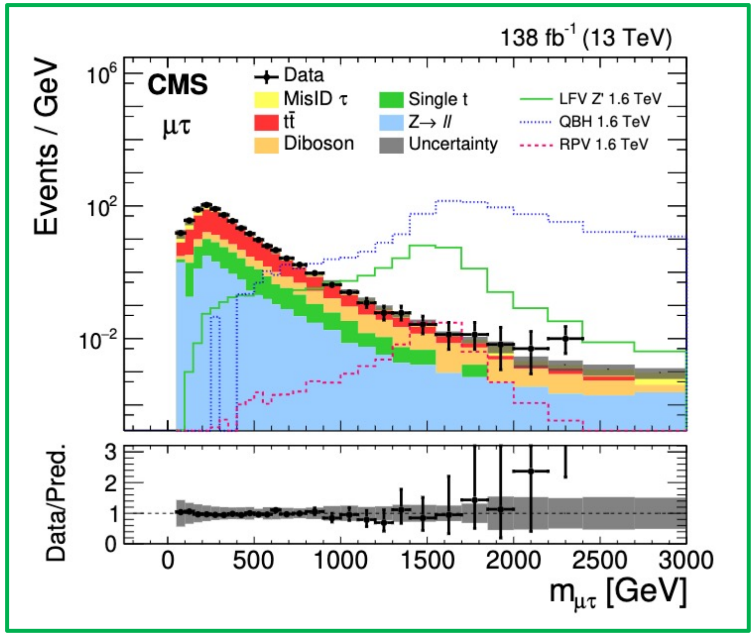
observed (expected) upper limit @ 95% of CL

B(τ→3μ) < 3.6 (3.0) x 10^{-8}

10.1007/JHEP05(2023)227

HIGH-MASS RESONANCES AND QUANTUM BLACK HOLES

- search for **LFV signatures eμ, eτ, μτ** in CMS 13 TeV pp data (138 /fb)
- **signature**: two prompt isolated (tau reconstructed in hadronic decays)
- **signal strength** extracted from **invariant mass distribution** of the di-lepton final state
- results **interpreted in different BSM models**
  - Z' production and LFV coupling
  - sneutrinos production and LFV coupling
  - quantum balck holes (QBH) to LFV final states



example: μτ channel invariant mass (other channels in the backup)

main **background sources**

- **ttbar** (and multi-boson): from MC simulation
- **W+jets and QCD multi-jet**: fake rate estimation from data control regions

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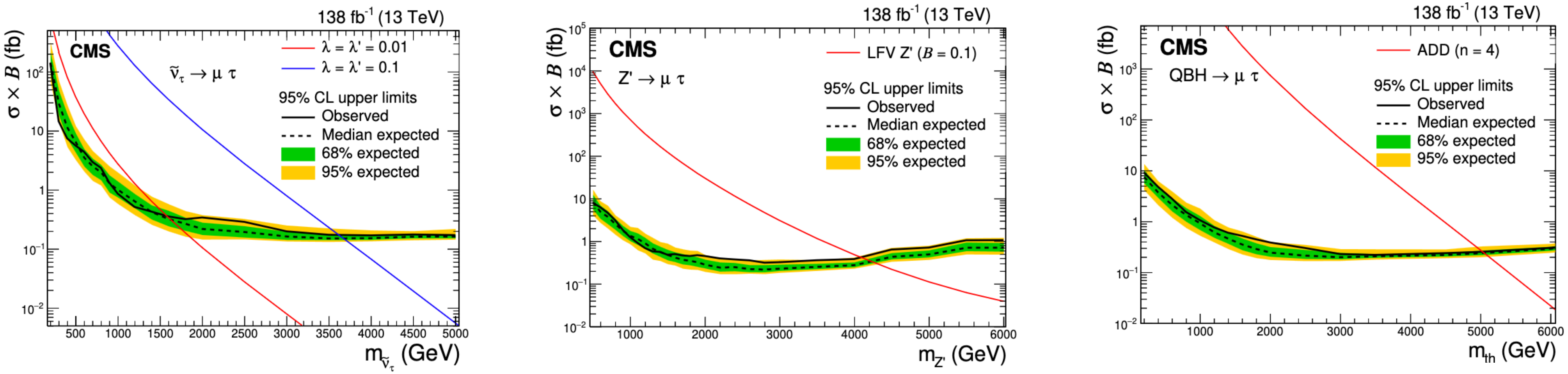
HIGH-MASS RESONANCES AND QUANTUM BLACK HOLES

- no signal evidence found in data → **upper limits** are set for each channel as a funciton of the heavy resonance invariant mass at 95% CL



example: expected and observed upper limits as a function of the heavy resonance mass for the μτ channel (other channels in the backup)

excluded heavy resonances mass values at 95% CL (TeV)

Channel	RPV SUSY $\tilde{\nu}_\tau$ (TeV)		LFV Z′ (TeV)	QBH m_{th} (TeV)
	$\lambda = \lambda' = 0.01$	$\lambda = \lambda' = 0.1$	$\mathcal{B} = 0.1$	$n = 4$
eμ	2.2 (2.2)	4.2 (4.2)	5.0 (4.9)	5.6 (5.6)
eτ	1.6 (1.6)	3.7 (3.7)	4.3 (4.3)	5.2 (5.2)
μτ	1.6 (1.6)	3.6 (3.7)	4.1 (4.2)	5.0 (5.0)

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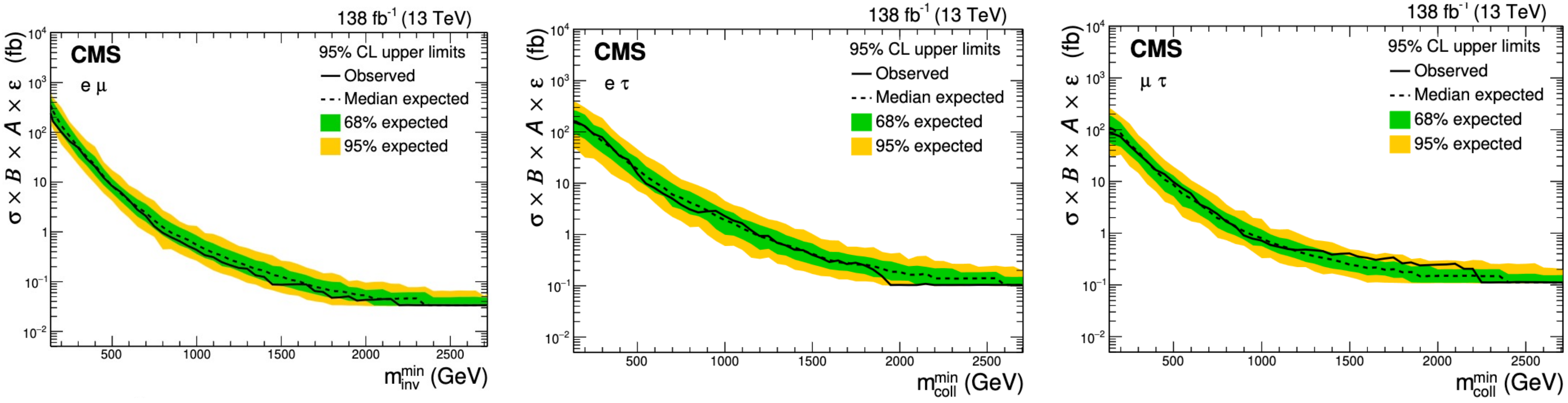
HIGH-MASS RESONANCES AND QBH

- **model-independent interpetation** is obtained reducing the high-mass bins to a single bin starting from a threshoold mass m^{min}

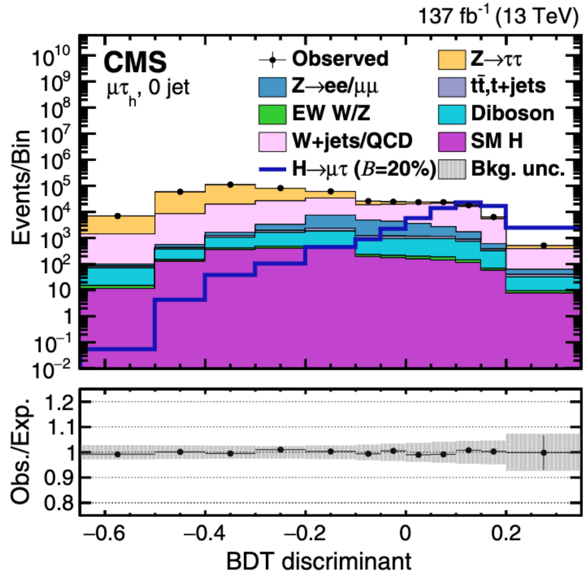


- **model-dependent limits** can be obtained by dividing the above result by the fraction of events above m^{min} for the BSM model under test

10.1103/PhysRevD.104.032013

H→eτ,μτ

- search for **LFV Yukawa couplings** in CMS 13 TeV pp data (137 /fb)
- **signature**: muon/electron and oppositely charged tau lepton
  - $e\tau_h$, $\mu\tau_h$, $e\tau_\mu$, $\mu\tau_e$
  - further categorization based on jet multiplicity (0, 1, 2 jets) and H production mode (ggH, VBF)
- signal strength **extracted from the output distribution of a BDT** with a binned ML fit



example: $\mu\tau_h$ category with 0 jets

main **background sources**

- **Z→ττ**: embedding technique fake rate estimation (Z→μμ collision data replacing the final state with a simulated τ pair)
- **W+jets and QCD multi-jet** → fake rate estimation from control regions

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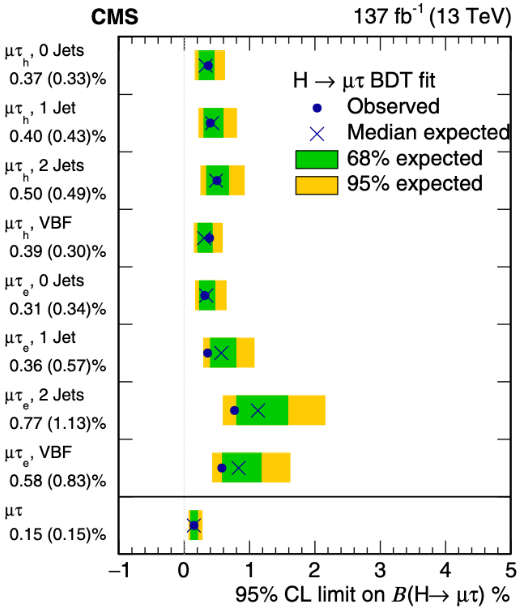
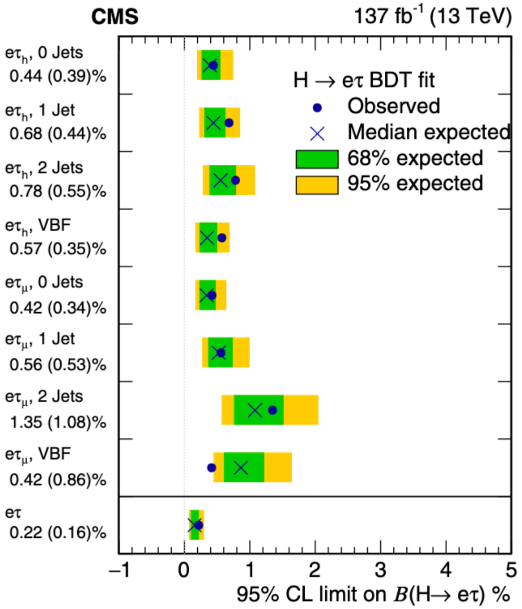
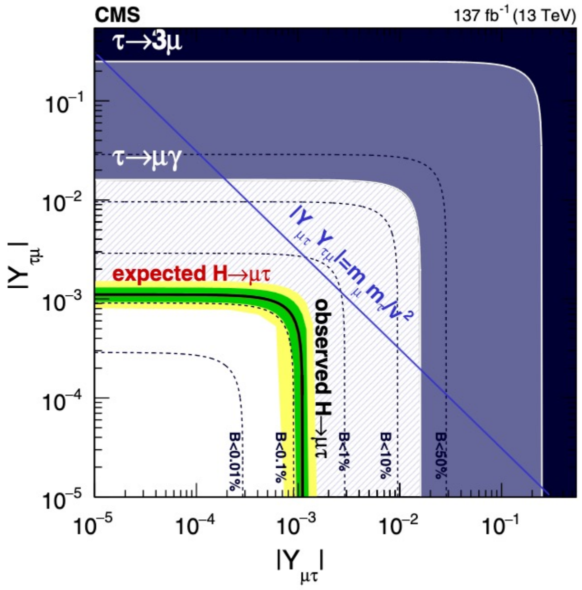
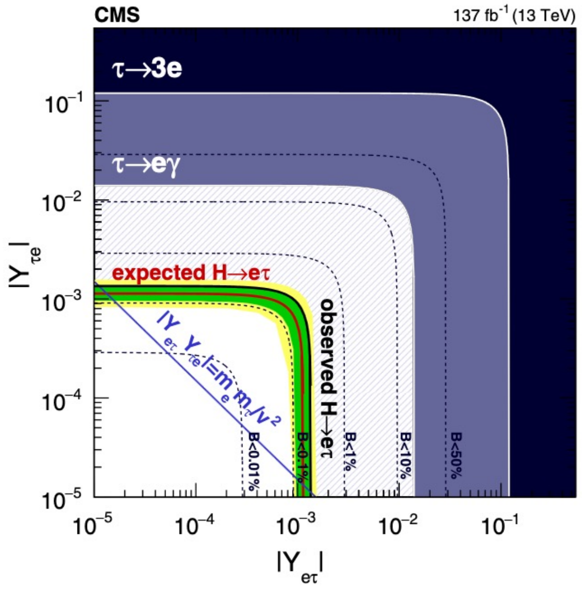
H→eτ,μτ









no significant excess → **upper limits on the branching fractions** at 95% CL

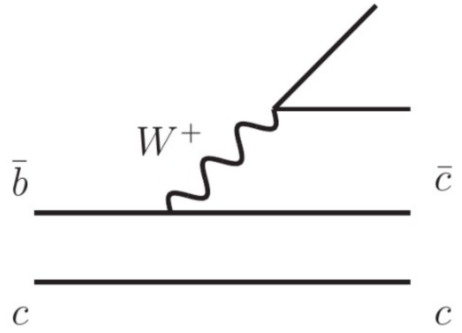
- H→μτ < 0.15 (0.15) %
- H→eτ < 0.22 (0.16) %

results are also interpreted as **exclusion limits on the LFV Yukawa couplings** at 95% CL

- $\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 1.11 \times 10^{-3}$
- $\sqrt{|Y_{e\tau}|^2 + |Y_{\tau e}|^2} < 1.35 \times 10^{-3}$

LFUV: $R_{J/\psi}$ from B^+_c decays

- **LFU**: the coupling of vector bosons to leptons is predicted equal except for lepton mass differences
    - $R_{J/\psi} = \dfrac{\mathcal{B}(B_c^+ \to J/\psi\, \tau^+\, \nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\, \mu^+\, \nu_\mu)} = 0.2582$
    - B_c^+ channel not accessible at B-factories



- a deviation from the SM prediction would be an indication of NP
- CMS $R_{J/\psi}$ measurement on **pp data @ 13TeV (59.9 /fb)** collected during 2018
- **signature**: three muon final state ($J/\psi \to \mu\mu$, $\tau \to \mu\nu\nu$)

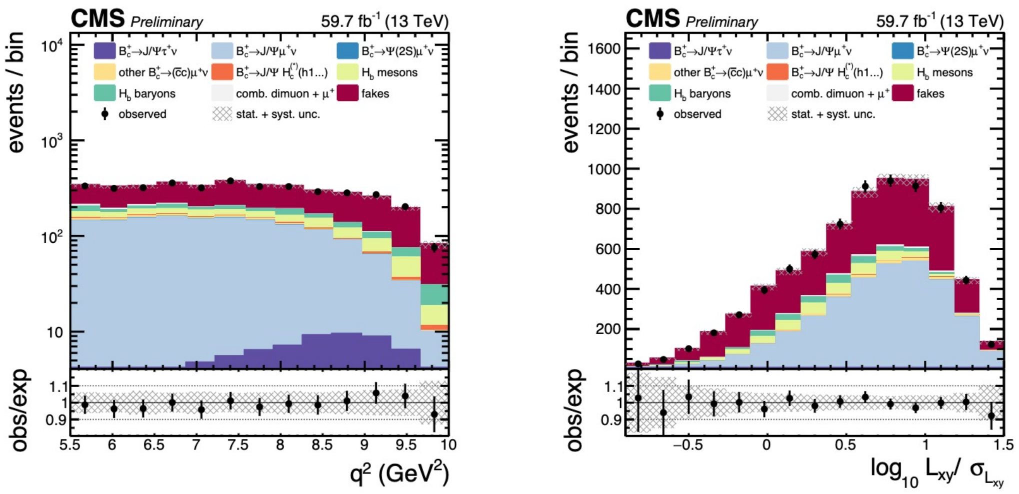
LFUV: $R_{J/\psi}$ from B^+_c decays

contribution of signal channels extracted from two observables with a **binned ML fit**

- $q^2 = (p(B_c^+) - p(J/\Psi))^2$ computed under collinearity hypothesis
- 2D secondary vertex displacement significance

$$R_{J/\psi} = \mathbf{0.17^{+0.18}_{-0.17}\,(stat)^{+0.21}_{-0.22}(syst)^{+0.19}_{-0.18}\,(theo)}$$

compatible with the SM prediction within the experimental uncertainty (0.2582)



main background sources

- **fakes from kaons and pions**: reduced with track-quality cuts and modelled from collision data control regions with inverted selection cuts
- **other B meson and feed down decays**: from simulation
- **combinatorial**: extrapolated from data control regions

Summary

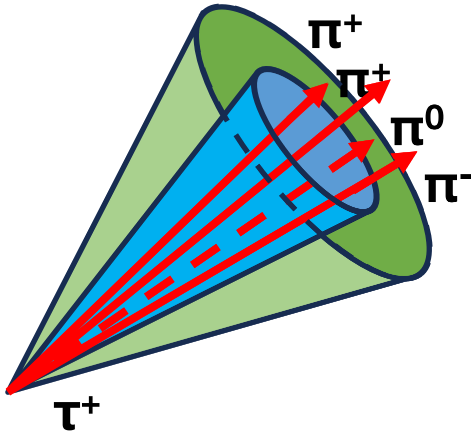
Summary of the talk

- **Lepton flavour symmetries** offer a wide set of possible tests for the standard model, spanning from low-momentum to high-mass observables, involving known and unknown particles
- **At CMS**, LFV and LFUV are under investigation in many fields (B-physics, Higgs, exotica states)
  - **$\tau \to 3\mu$** obs (exp) upper limit set to 2.9 (2.4) x 10^{-8} @ 90% CL comparable to B factories
  - excluded **LFV Higgs decays** to $\mu\tau$ ($e\tau$) to 0.15 (0.22) % @ 95% CL
  - **BSM heavy particles** (Z', QBH and sneutrinos) excluded in their LFV decays to $e\mu$, $e\tau$, $\mu\tau$
  - measurement of the **LFU ratio $R_{J/\psi}$** = 0.17 ± 0.33 compatible with the SM within the experimental uncertainty

Backup

Tau lepton reconstruction in one slide

- tau lepton reconstruction occurs for its **hadronic final state** (~65%), where the tau is reconstructed as a jet of charged and neutral hadrons
  - electron and muon decay modes can only be reconstructed as electron and muon physics objects
- the **hadron-plus-strip algorithm** is used to identify possible candidates among jets
  - looks for charged tracks and EM energy deposits inside some isolated cone, compatible with a tau decay
- tau reconstruction is subject to fakes from jets, muons and electrons
  - a **convolutional DNN** is used to estimate the probability of the candidate being a genuine tau
  - trained on low-level and high-level information from the detector



Decay mode	Meson resonance	$\mathcal{B}$ [%]
$\tau^- \to e^- \bar{\nu}_e \nu_\tau$		17.8
$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$		17.4
$\tau^- \to h^- \nu_\tau$		11.5
$\tau^- \to h^- \pi^0 \nu_\tau$	$\rho(770)$	26.0
$\tau^- \to h^- \pi^0 \pi^0 \nu_\tau$	$a_1(1260)$	10.8
$\tau^- \to h^- h^+ h^- \nu_\tau$	$a_1(1260)$	9.8
$\tau^- \to h^- h^+ h^- \pi^0 \nu_\tau$		4.8
Other modes with hadrons		1.8
All modes containing hadrons		64.8

State of the art and 2016 CMS result $(\tau \longrightarrow 3m)$

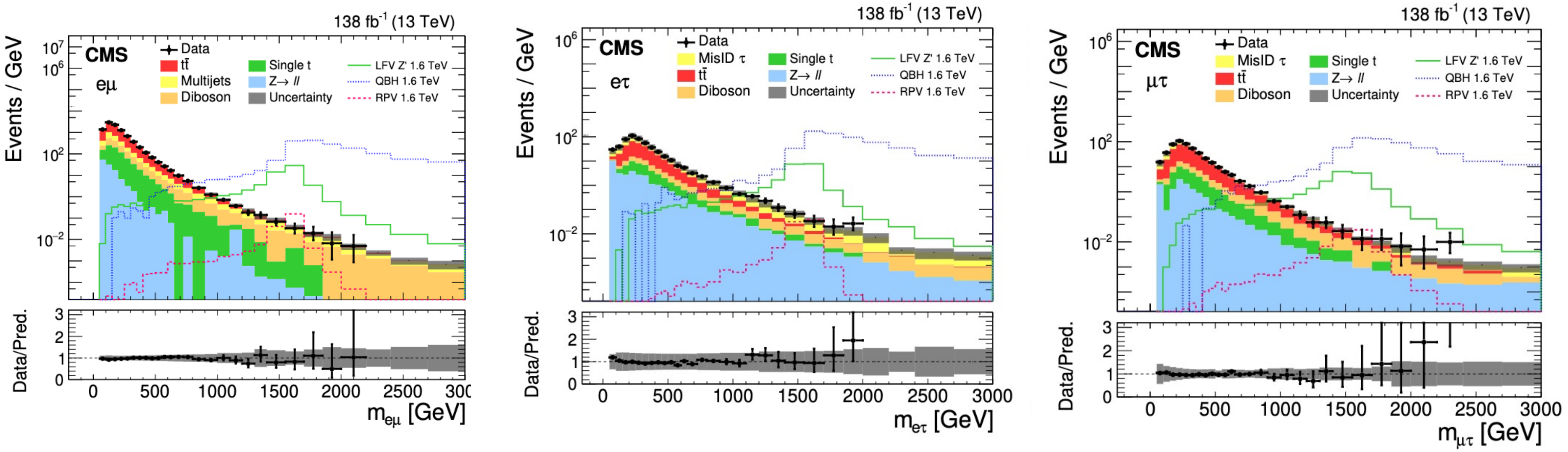
Observed upper limits (x10^{-8} @90% CL)

• **Belle** 782 fb^{-1}	$\mathcal{B}(\tau \longrightarrow 3\mu) < 2.1$	$e^+e^- \to \tau^+\tau^-$	10.1016/j.physletb.2010.03.037
• **BaBar** 468 fb^{-1}	$\mathcal{B}(\tau \longrightarrow 3\mu) < 3.3$	$e^+e^- \to \tau^+\tau^-$	10.1103/PhysRevD.81.111101
• **LHCb** 2 fb^{-1}	$\mathcal{B}(\tau \longrightarrow 3\mu) < 4.6$	HF$\to \tau$	10.1007/JHEP02(2015)121
• **ATLAS** 20.3 fb^{-1}	$\mathcal{B}(\tau \longrightarrow 3\mu) < 38$	W$\to \tau$	10.1140/epjc/s10052-016-4041-9
• **CMS** 33.2 fb^{-1} (partial Run-2)	$\mathcal{B}(\tau \longrightarrow 3\mu) < 8.0$	HF+W$\to \tau$	10.1007/JHEP01(2021)163

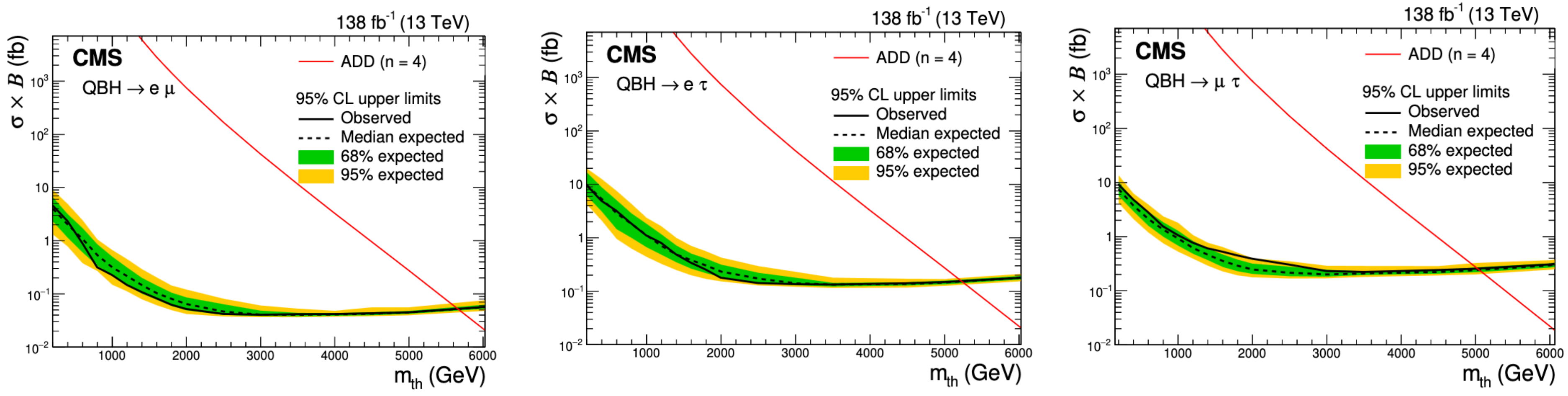
CMS 2016 (partial Run-2) result has proven that the experiment can investigate both the HF and W production channels with a good sensitivity → analysis extended to Run-2 (this presentation)

10.1007/JHEP05(2023)227

HEAVY RESONANCE OBSERVABLES AND QBH LFV CROSS SECTION EXCLUSION LIMITS



invariant and collinear masses for different channels



model-dependent exclusion limits for QBH production and LFV decay in different channels

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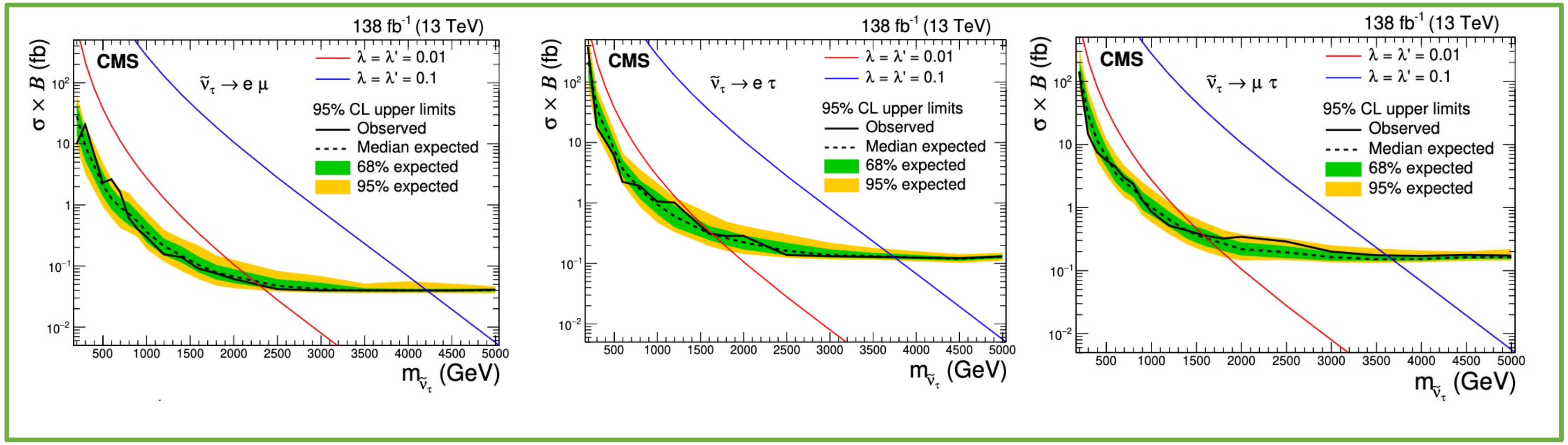
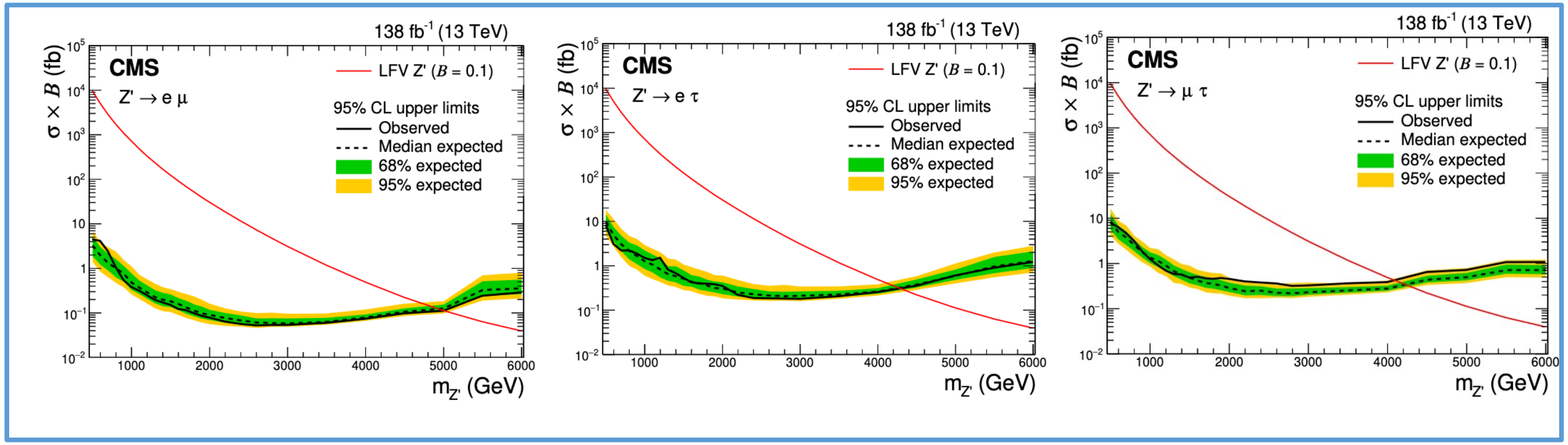
Sneutrinos and Z' LFV cross section boson exclusion limits





- model-dependent exclusion limits for sneutrinos and Z'boson production and LFV decays in different channels

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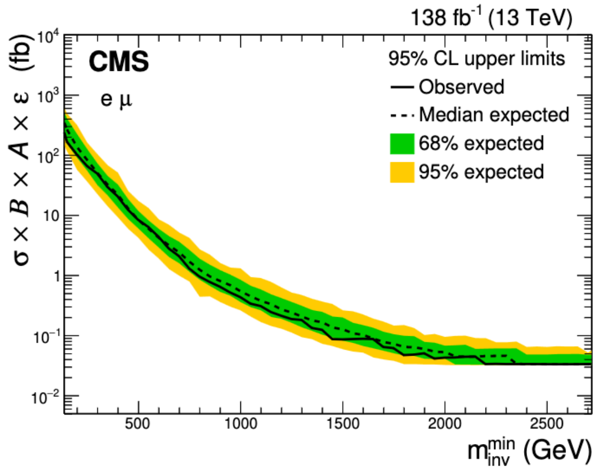
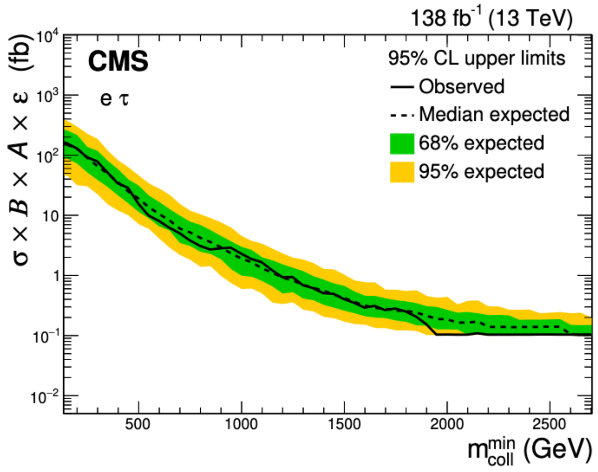
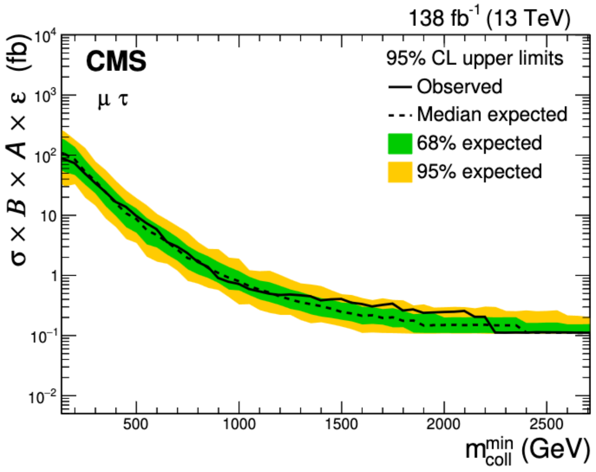
MODEL-INDEPENDENT LFV EXCLUSION LIMITS







- model-independent exclusion limits in different final states (vs. invariant mass cut threshold)
- model dependent limits are recovered counting for the model fraction of events above threshold f_m

$$(\sigma \mathcal{B} A \varepsilon)_{\text{excl}}(\text{total}) = \frac{(\sigma \mathcal{B} A \varepsilon)_{\text{MI}}(m^{\text{min}})}{f_m(m^{\text{min}})}.$$

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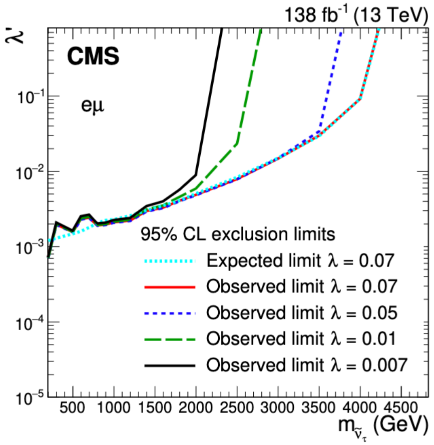
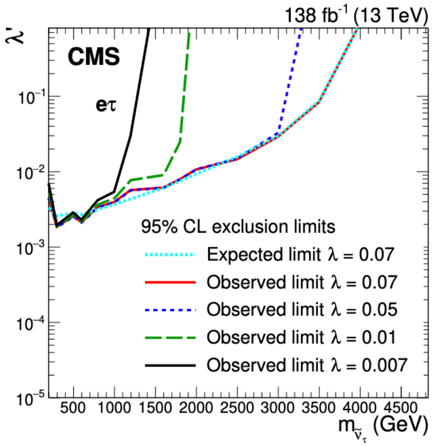
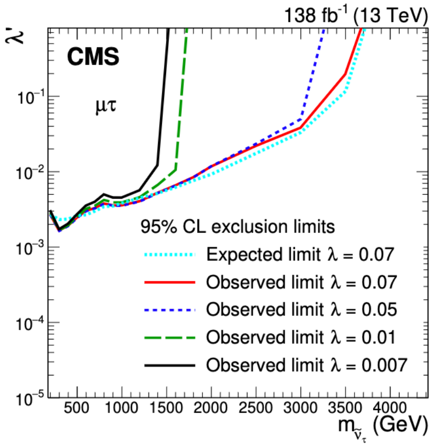
SNEUTRINOS COUPLINGS EXCLUSION LIMITS







- sneutrinos production and decay coupling exclusion regions under small-width approximation

$$\sigma\mathcal{B} \approx (\lambda'_{311})^2[(\lambda_{132})^2 + (\lambda_{231})^2]/\{3(\lambda'_{311})^2 + [(\lambda_{132})^2 + (\lambda_{231})^2]\},$$

10.1007/JHEP03(2013)026

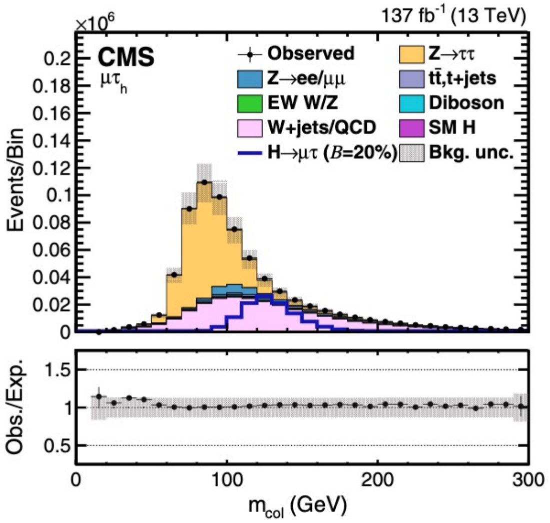
Indirect constraints on LFV Yukawa couplings

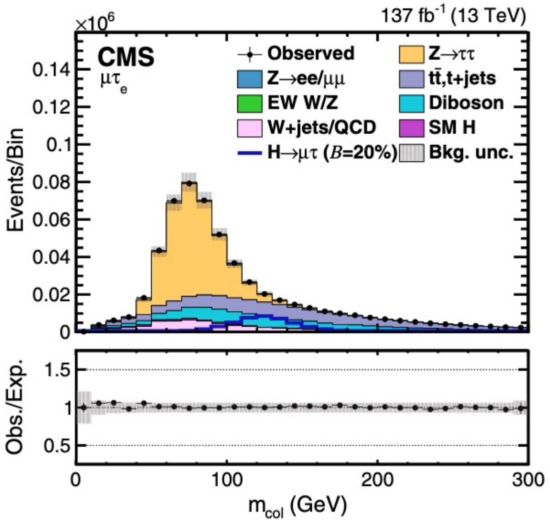
Channel	Coupling	Bound
$\mu \to e\gamma$	$\sqrt{\|Y_{\mu e}\|^2 + \|Y_{e\mu}\|^2}$	$< 3.6 \times 10^{-6}$
$\mu \to 3e$	$\sqrt{\|Y_{\mu e}\|^2 + \|Y_{e\mu}\|^2}$	$\lesssim 3.1 \times 10^{-5}$
electron $g-2$	$\mathrm{Re}(Y_{e\mu} Y_{\mu e})$	$-0.019 \ldots 0.026$
electron EDM	$\|\mathrm{Im}(Y_{e\mu} Y_{\mu e})\|$	$< 9.8 \times 10^{-8}$
$\mu \to e$ conversion	$\sqrt{\|Y_{\mu e}\|^2 + \|Y_{e\mu}\|^2}$	$< 4.6 \times 10^{-5}$
M-$\bar{M}$ oscillations	$\|Y_{\mu e} + Y_{e\mu}^*\|$	< 0.079
$\tau \to e\gamma$	$\sqrt{\|Y_{\tau e}\|^2 + \|Y_{e\tau}\|^2}$	< 0.014
$\tau \to 3e$	$\sqrt{\|Y_{\tau e}\|^2 + \|Y_{e\tau}\|^2}$	$\lesssim 0.12$
electron $g-2$	$\mathrm{Re}(Y_{e\tau} Y_{\tau e})$	$[-2.1 \ldots 2.9] \times 10^{-3}$
electron EDM	$\|\mathrm{Im}(Y_{e\tau} Y_{\tau e})\|$	$< 1.1 \times 10^{-8}$
$\tau \to \mu\gamma$	$\sqrt{\|Y_{\tau\mu}\|^2 + \|Y_{\mu\tau}\|^2}$	0.016
$\tau \to 3\mu$	$\sqrt{\|Y_{\tau\mu}^2 + \|Y_{\mu\tau}\|^2}$	$\lesssim 0.25$
muon $g-2$	$\mathrm{Re}(Y_{\mu\tau} Y_{\tau\mu})$	$(2.7 \pm 0.75) \times 10^{-3}$
muon EDM	$\mathrm{Im}(Y_{\mu\tau} Y_{\tau\mu})$	$-0.8 \ldots 1.0$
$\mu \to e\gamma$	$\left(\|Y_{\tau\mu} Y_{\tau e}\|^2 + \|Y_{\mu\tau} Y_{e\tau}\|^2\right)^{1/4}$	$< 3.4 \times 10^{-4}$

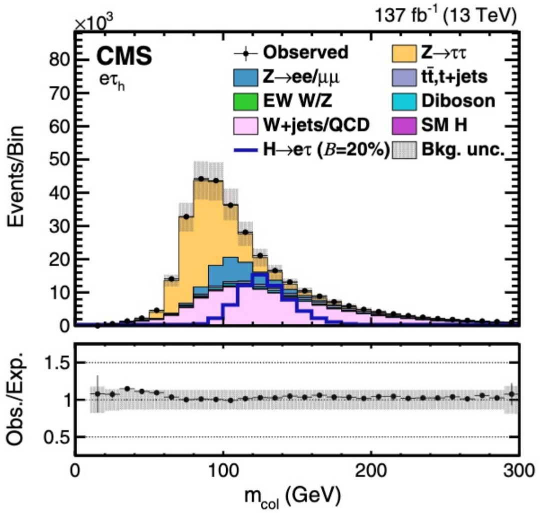
10.1103/PhysRevD.104.032013

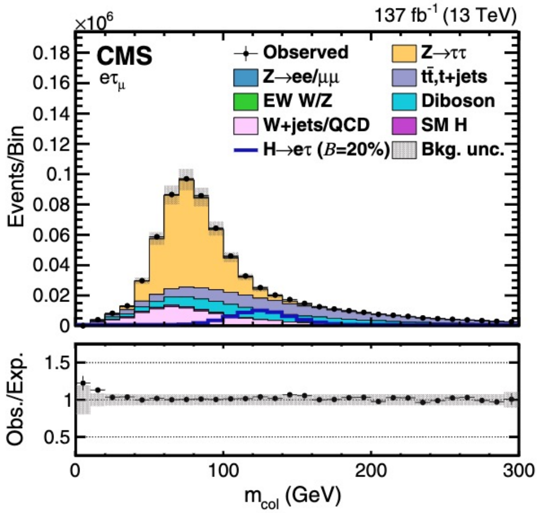
H⟶lτ mass observables

- collinear mass distributions for different channels of the H⟶lτ analysis





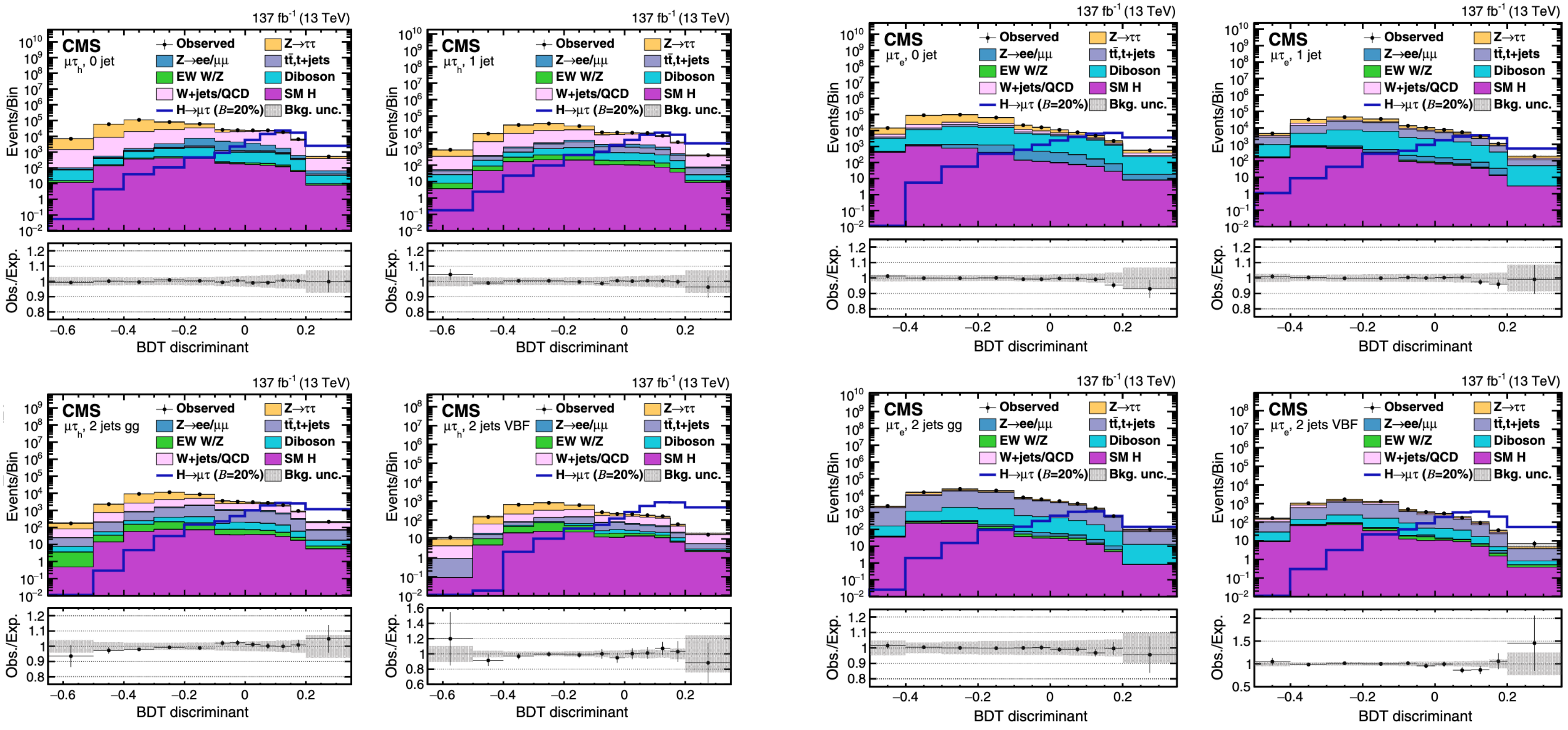




10.1103/PhysRevD.104.032013

H⟶lτ BDT score

- BDT score distribution for different channels and categories of the H⟶lτ analysis



10.1103/PhysRevD.104.032013

H⟶lτ BDT score

- BDT score distribution for different channels and categories of the H⟶lτ analysis