Searching for charged lepton flavor violation with the CMS detector

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Why search for charged LFV?

Neutral lepton flavor violation (LFV) has already been detected. Neutrino oscillations were observed for the first time in 1998 at the Super-Kamiokande.

$\rightarrow$ Minimal Standard Model (SM) with no neutrino masses cannot be right.

Many new physics models explaining the neutrino masses predict a large rate for CLFV processes.

CLFV processes also exist in a minimal extension of the SM with neutrino masses (due to loop corrections), but the rates are unobservably small.

Searches for charged LFV are thus very sensitive to new physics.

Searches performed at CMS

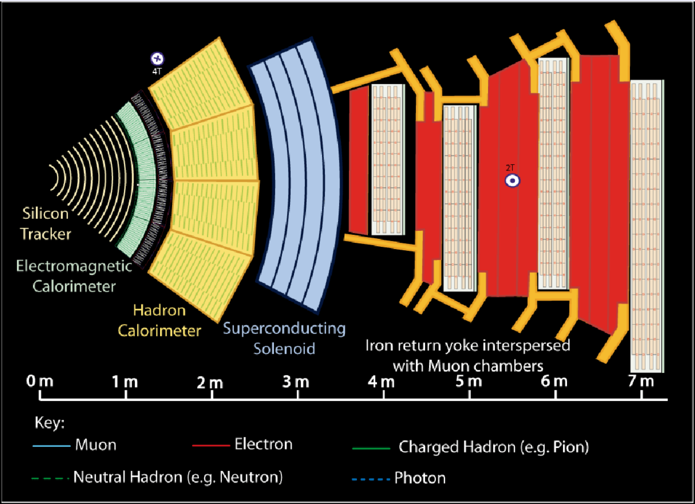
Various CLFV searches were performed at CMS:

- CLFV decays of SM neutral bosons (Z, H).
  $\rightarrow$ Sensitive e.g. to models with extra dimensions, models with heavy neutral leptons
- $\mathrm{X} \rightarrow \mathrm{e}\mu$ searches, where X is a new massive resonance or quantum black hole (QBH).
  $\rightarrow$ R-parity violating supersymmetric (RPV SUSY) models, models with extra dimensions.

The LHC: 27 km hadron collider at CERN.
Data used in the analyses shown in this presentation comes from proton-proton collisions.

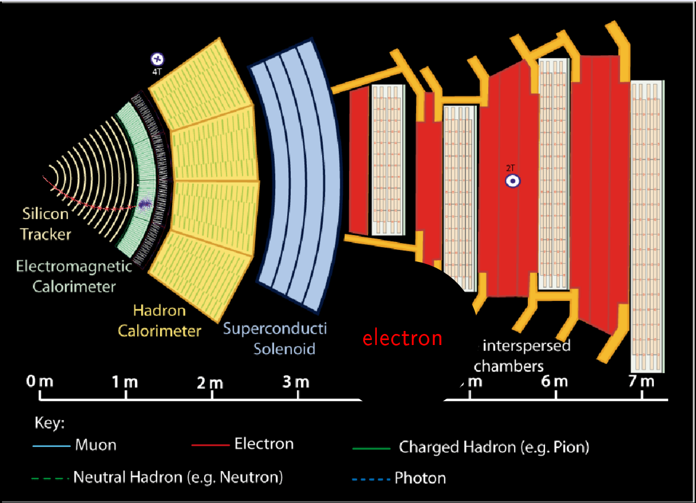
- 2012: 8 TeV center-of-mass energy, 23 fb^{-1} of luminosity delivered.
- 2015-6: 13 TeV, 4 + 40 fb^{-1}
  (increase in both the energy and the volume of data collected)

The CMS detector



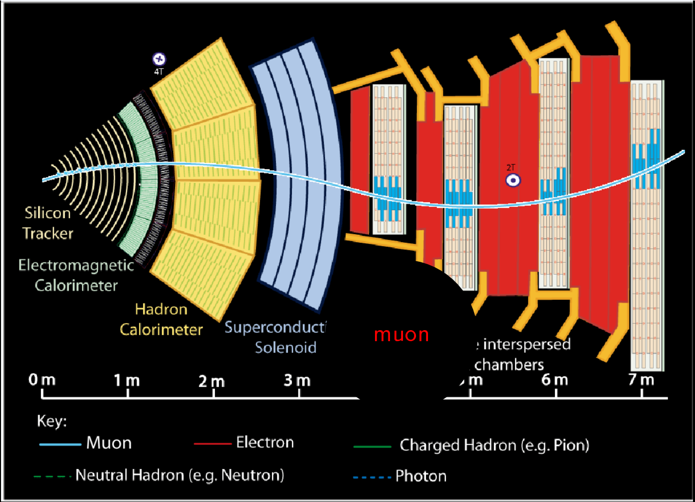
CMS is composed of many subdetectors. They allow the detection of photons, charged and neutral hadrons,

The CMS detector



CMS is composed of many subdetectors. They allow the detection of photons, charged and neutral hadrons, electrons,

The CMS detector



CMS is composed of many subdetectors. They allow the detection of photons, charged and neutral hadrons, electrons, muons.

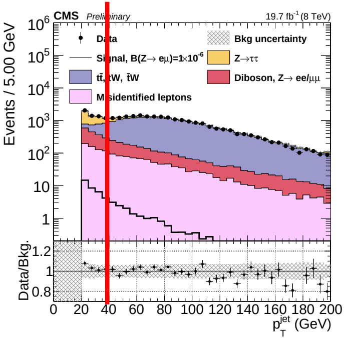
Searches for CLFV decays of the SM Z and H bosons

CMS-PAS-EXO-13-005

Analysis based 19.7 fb^{-1}, 8 TeV data collected in 2012.

Main backgrounds:

- $Z \to \tau\tau$
- Diboson (two W or Z)
- tW
- BG with misindentified leptons (W or Z + jets)



Large background compared to signal, strong selections needed:

Isolated e and μ, 3rd lepton veto, veto on jets with $p_T > 40$ GeV (see figure), μ transverse mass veto, Z $p_T < 10$ GeV

Search for $Z \to e\mu$ decays: results

CMS-PAS-EXO-13-005

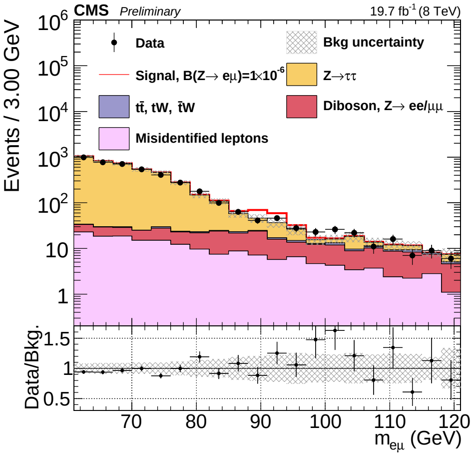
95% confidence-level (CL) limits on $B(Z \to e\mu)$:

- Expected: $6.7 \cdot 10^{-7}$
- Observed: $7.3 \cdot 10^{-7}$

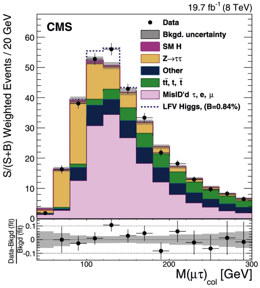
Previous high-energy limits:

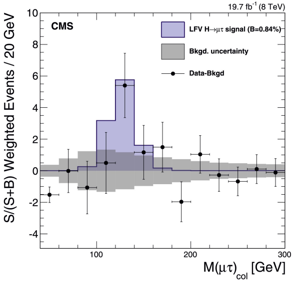
- LEP: $1.7 \cdot 10^{-6}$
- ATLAS: $7.5 \cdot 10^{-7}$

Indirect low-energy limit:
$5 \cdot 10^{-13}$
(very strict, but still worth checking at high energy)



- Indirect low-energy constraints from $\mu \to e\,\gamma$, $\tau \to e(\mu)\,\gamma$
  - $B(H \to e\,\mu) < O(10^{-9})$
  - $B(H \to e(\mu)\,\tau) < O(0.1)$
- CMS direct search on 2012 data (19.7 fb^{-1}, 8 TeV), 95% CL limits: $B(H \to e\,\mu) < 0.035\%$, $B(H \to e\,\tau) < 0.69\%$, $B(H \to \mu\,\tau) < 1.51\%$ (2.4σ excess ↓)





ATLAS found no excess on any channel.

Follow-up needed, especially for less-constrained $e\tau$ and $\mu\tau$ channels.

PLB 749 (2015) 337, CMS-HIG-14-005

Search for $H \to e\tau$, $H \to \mu\tau$

CMS-PAS-HIG-17-001, published JHEP 06 (2018) 001

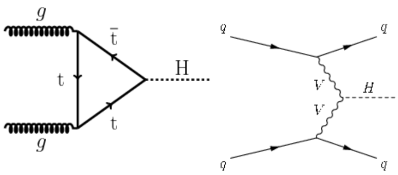
2016 data - 13 TeV, 35.9 fb^{-1}

Final states analysed: $e\tau_h$, $e\tau_\mu$, $\mu\tau_h$, $\mu\tau_e$

($e\tau_e$ and $\mu\tau_\mu$ not considered because of large $Z \to ll$ background)

Two main production modes for H boson: ggH and VBF.

$\to$ Analysis subdivided according to number of jets: 0, 1 (both ggH-enriched) and 2 (split into ggH- and VBF-enriched categories).



ggH VBF

Main backgrounds:

- $Z \to \tau\tau$
- MisID'd leptons (W+jets and QCD multijets - data-driven estimate)
- $t\bar{t}$, WW, WZ, ZZ
- $H \to \tau\tau$, $Z \to \mu\mu$, $Z \to ee$

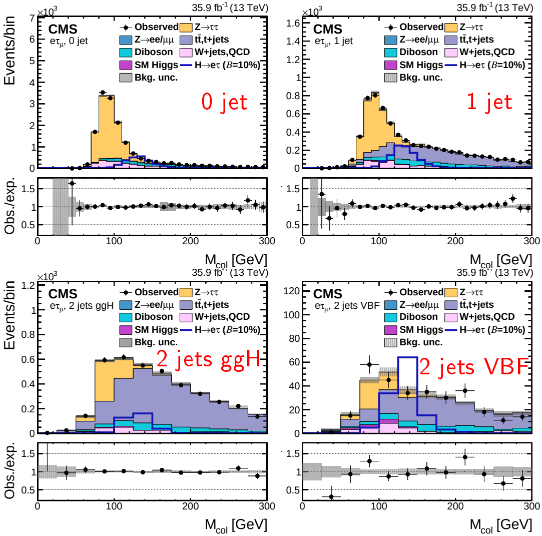
Search for $\mathrm{H} \rightarrow e\tau$, $\mathrm{H} \rightarrow \mu\tau$

Collinear mass ($\mathrm{M_{col}}$) fit analysis

Max-likelihood fit of $\mathrm{M_{col}}$, make data and simulations match as much as possible.

Cross-check of the main analysis (next slide).

$e\tau_\mu$ final state $\rightarrow$

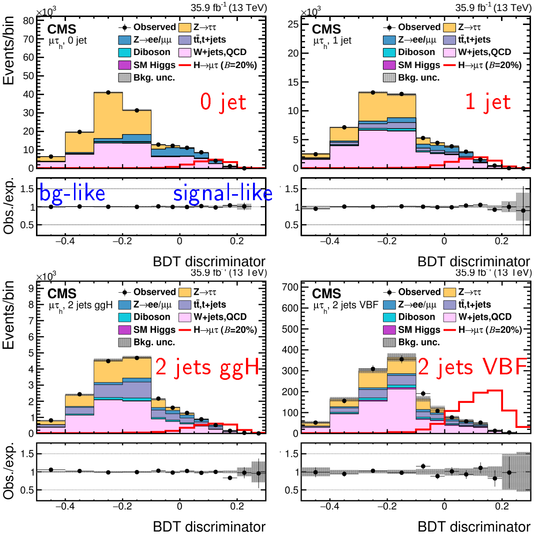


Search for H $\to e\tau$, H $\to \mu\tau$

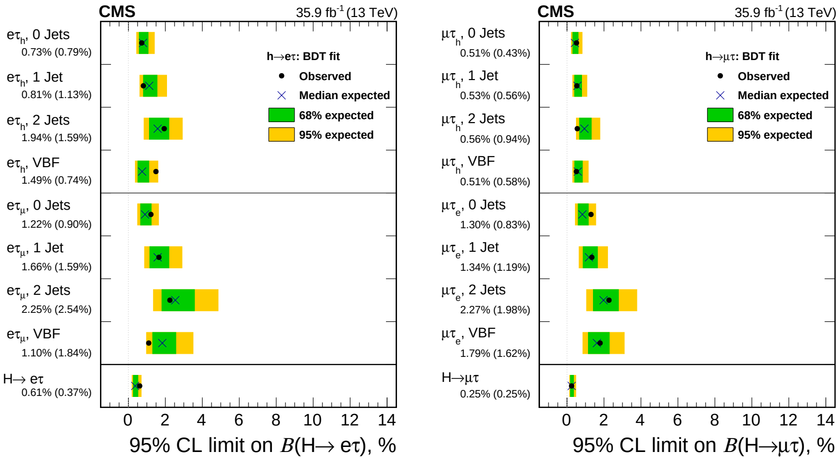
Loose selections + Boosted Decision Tree (BDT)

8 kinematic variables are fed into a BDT algorithm optimized to discriminate signal from background (bg).

$\mu\tau_h$ final state $\to$



Search for $\mathrm{H} \to e\tau$, $\mathrm{H} \to \mu\tau$: results

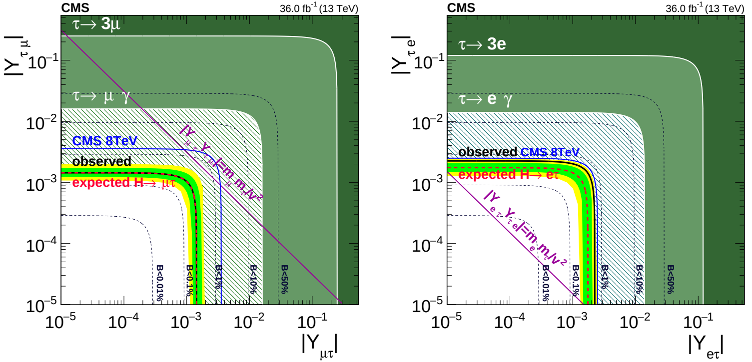


$B(\mathrm{H} \to e\,\tau) < 0.61\%$ (0.37% exp.) $B(\mathrm{H} \to \mu\,\tau) < 0.25\%$ (0.25% exp.)

$\mu\tau$ excess observed in 2012 data no longer present

Search for H $\to e\tau$, H $\to \mu\tau$: results

95% CL limits on Higgs CLFV Yukawa couplings



$$\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 1.43 \cdot 10^{-3} \qquad \sqrt{|Y_{e\tau}|^2 + |Y_{\tau e}|^2} < 2.26 \cdot 10^{-3}$$

Searches for heavy X $\to$ LFV

Search for X $\to e\mu$

New: CMS-PAS-EXO-16-058, published JHEP 04 (2018) 073
Analysis of 2016 data: 13 TeV, 35.9 fb^{-1}

Previously:

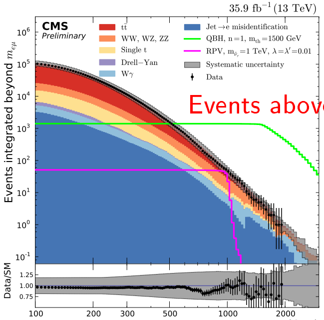
- 2012 (8 TeV, 19.7 fb^{-1}) : EPJC 76 (2016) 317
- 2015 (13 TeV, 2.7 fb^{-1}) : CMS-PAS-EXO-16-001

In preparation: 2016-17 analysis with all 3 CLFV final states ($e\mu$, $e\tau$, $\mu\tau$)

Minimal selections in order to remain model independent:

- p_T requirement (trigger)
- η requirement (acceptance)
- ID selections on e and μ

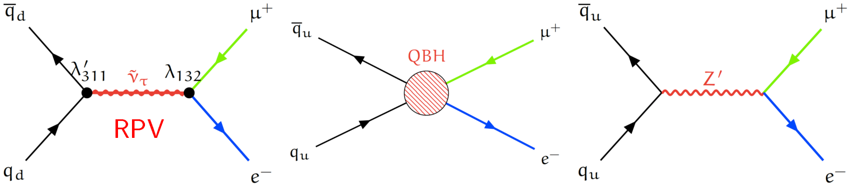
Backgrounds: $t\bar{t}$, WW, WZ, ZZ, $Z \to \tau\tau$ (Drell-Yan), MisID jet→e



Search for X $\rightarrow e\mu$

Many possible interpretations. Three will be considered:

- R-parity violating supersymmetry (RPV SUSY)
- Quantum black holes (QBH) in models with extra dimensions
- Z' coming from extra U(1) symmetry, with CLFV decays



Search for X $\rightarrow e\mu$: results under RPV SUSY interpretation

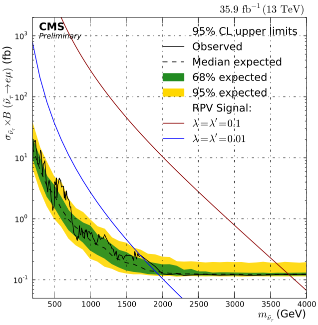
In RPV SUSY, fermion number and flavor are violated at tree-level by interactions between fermions and their superpartners.

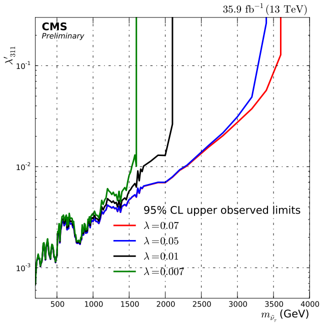
$$W_{\mathrm{RPV}} = \frac{1}{2}\lambda_{ijk}L_iL_j\overline{E}_k + \lambda'_{ijk}L_iQ_j\overline{D}_k$$

L = lepton doublet, E = lepton singlet, Q = quark doublet, D = quark singlet

Assumptions:

- lightest supersymmetric particle = $\tilde{\nu_\tau}$
- $\lambda_{ijk} = 0$ and $\lambda'_{ijk} = 0$ except $\lambda_{132} = \lambda_{231}$ and λ'_{311} (relevant to $\tilde{\nu_\tau}$)





← Exclusion contours in the $(m_{\tilde{\nu_\tau}}, \sigma B)$ and $(m_{\tilde{\nu_\tau}}, \lambda')$ planes

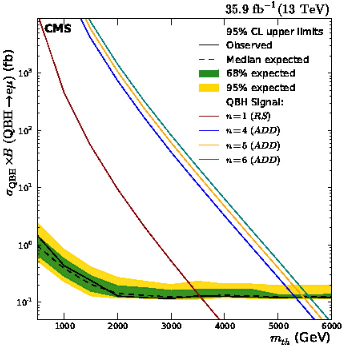
95% CL limits:
$m_{\tilde{\nu_\tau}} > 1.7\ (3.8)$ TeV
assuming
$\lambda = \lambda' = 0.01\ (0.1)$

Search for X $\rightarrow e\mu$: results under QBH interpretation

Extra spatial dimensions $\rightarrow$ low effective Planck masses (e.g. TeV scale)
$\rightarrow$ possible production of microscopic black holes

QBH properties

- spin 0, colorless, neutral, LFV
- not a resonance
- Cross-section function of the threshold mass and number of extra dimensions n



$\leftarrow$ Exclusion contour in the $(m_{th}, \sigma B)$ plane

95% CL limits:
$m_{th} > 5.3$-5.6 TeV with n=4-6 in an ADD model.
$m_{th} > 3.6$ TeV in the n=1 warped RS model.

Search for X $\to e\mu$: results under Z' interpretation

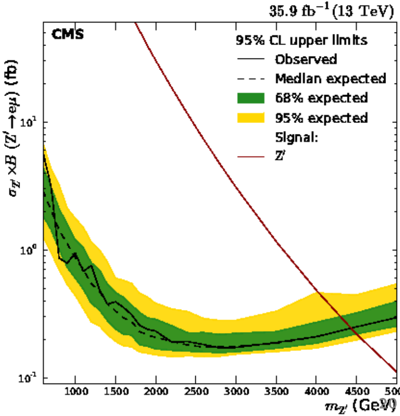
Any SM extension with an extra U(1) symmetry will provide a Z' boson.
Assumptions:

- Similar couplings to the SM Z boson
- 10 % of the decays are to the LFV $e\mu$ final state

Exclusion contour in the $(m_{Z'}, \sigma B)$ plane $\to$

95% CL limit:
$m_{Z'} > 4.4$ TeV.

Limits improved by more than 1 TeV (here and also in the other interpretations).



Summary

Neutrinos oscillate $\rightarrow$ can charged leptons change flavor as well?

CLFV processes are exceedingly rare in the SM:
any observation would be evidence for new physics.

CLFV searches performed at CMS:

- $\mathrm{Z} \rightarrow \mathrm{e}\mu$: $B(\mathrm{Z} \rightarrow \mathrm{e}\mu) < 7.3 \cdot 10^{-7}$ (2012 data)
- $\mathrm{H} \rightarrow \mathrm{LFV}$
  - $B(\mathrm{H} \rightarrow \mathrm{e}\mu) < 0.035\%$ (2012 data)
  - $B(\mathrm{H} \rightarrow \mathrm{e}\tau) < 0.37\%$ (2016 data)
  - $B(\mathrm{H} \rightarrow \mu\tau) < 0.25\%$ (2016 data - does not confirm 2012 excess)
- $\mathrm{X} \rightarrow \mathrm{e}\mu$: $m_{Z'} > 4.4$ TeV (2016 data, **published this year**)

Prospects:

- More CLFV analyses are in preparation with the 2016-17 dataset.
- Updates expected with full Run 2 dataset (Run 2 ends this year).
- Longer term: LHC Run 3 and the HL-LHC are expected to deliver a further 300 and 3000 fb^{-1} of data to analyse. Intensity frontier (small couplings & branching ratios) will be pushed.