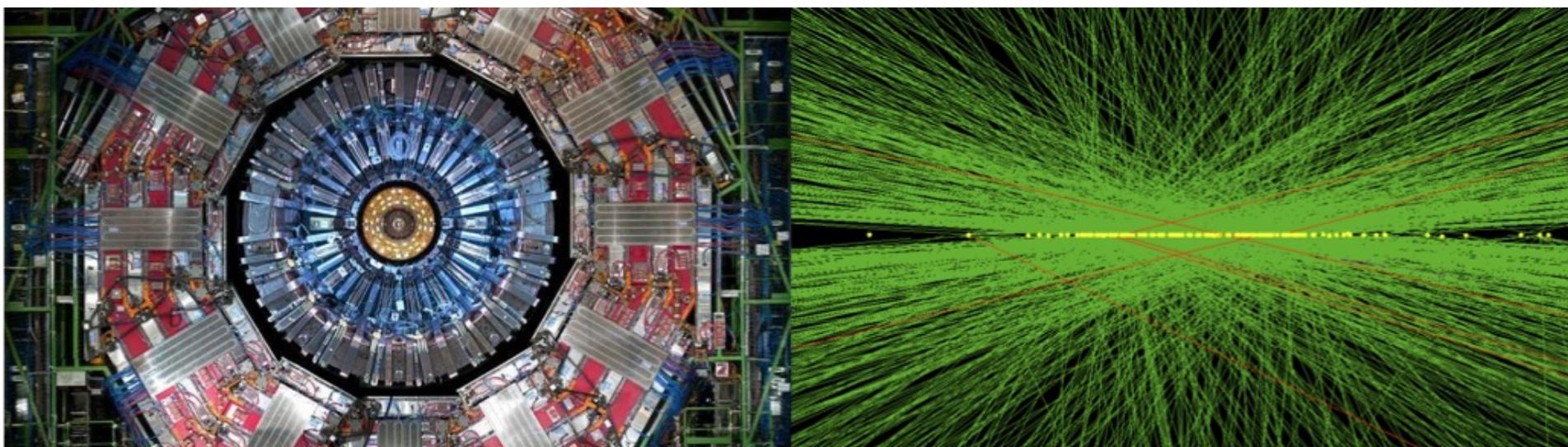


# Lepton Flavor Violating Decays of Bosons with the CMS Experiment at the LHC

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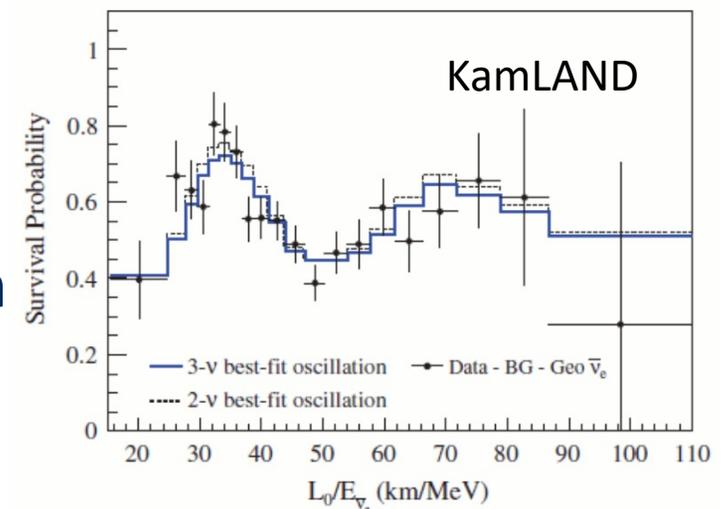
for the CMS Collaboration  
August 25, 2025



# Introduction

- Lepton Flavor Violation (LFV) is not present in the Standard Model of particle physics ( $m_\nu=0$ ).

- But since  $m_\nu \neq 0$  neutrinos oscillate and lepton flavor violation occurs in the neutral leptons.



[A. Gando et al., Phys. Rev. D83 \(2011\) 052002.](#)

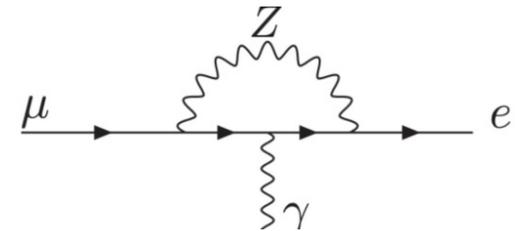
- A natural question is whether LFV occurs in the charged leptons as a signal of physics beyond the standard model.

# Searches for charged lepton flavor violation

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- CFLV occurs in many extensions to the SM

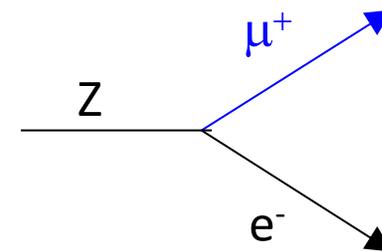
- Supersymmetry
- Leptoquark models
- Randal-Sundrum models



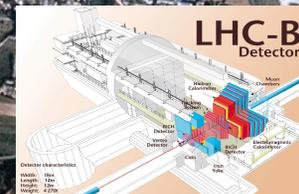
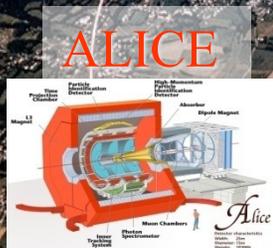
- Many experiments to search for CLFV

- Dedicated experiments in muon beams as MEG ( $\mu^- \rightarrow e^- \gamma$ ), SINDRUM ( $\mu^- \rightarrow e^- e^+ e^-$ ), Mu2e ( $\mu^- \rightarrow e^-$ ) ....
- General purpose collider experiments BaBar/BELLE, BES, LEP, ATLAS/CMS in quark, lepton and boson decays.

- Focus today on using the large samples of Z and H (125) bosons at CMS to search for  $Z/H \rightarrow l_1 l_2$  ( $l=e, \mu, \tau$ ) and also searches for  $Z'$  and high mass H CLFV decays



# The LHC and its Experiments



$138 \text{ fb}^{-1}$  @  
 $\sqrt{s} = 13 \text{ TeV}$

# produced in  
collisions at CMS

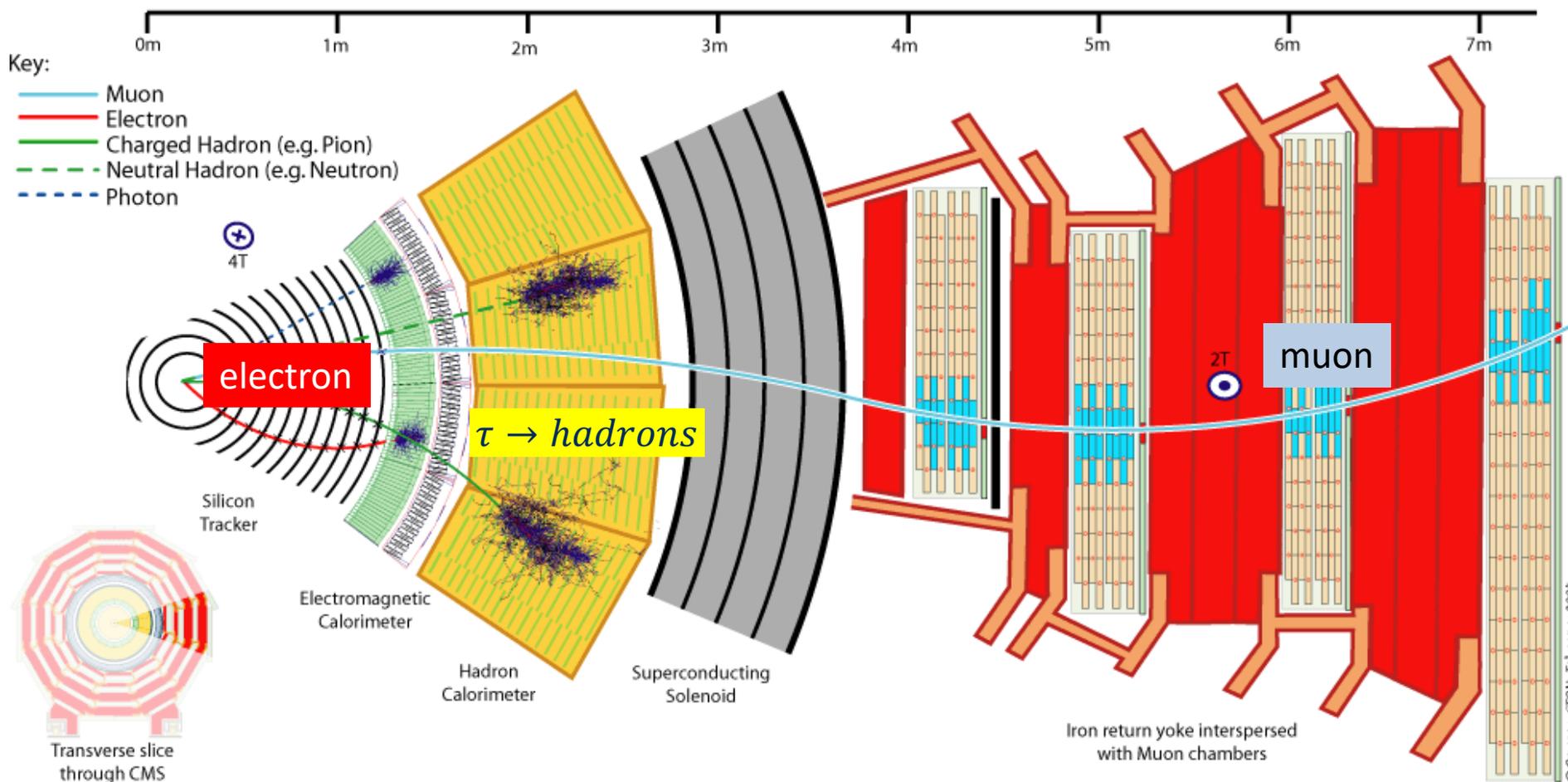
Z Bosons

8 Billion

H(125) Bosons

8 Million

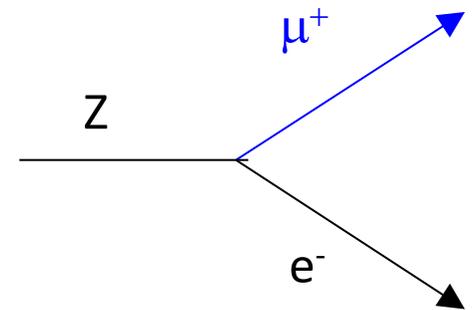
# The CMS detector for LFV searches



Electrons, muons and hadronic tau decays reconstructed and identified using modern machine learning techniques to optimally use the detector hit information

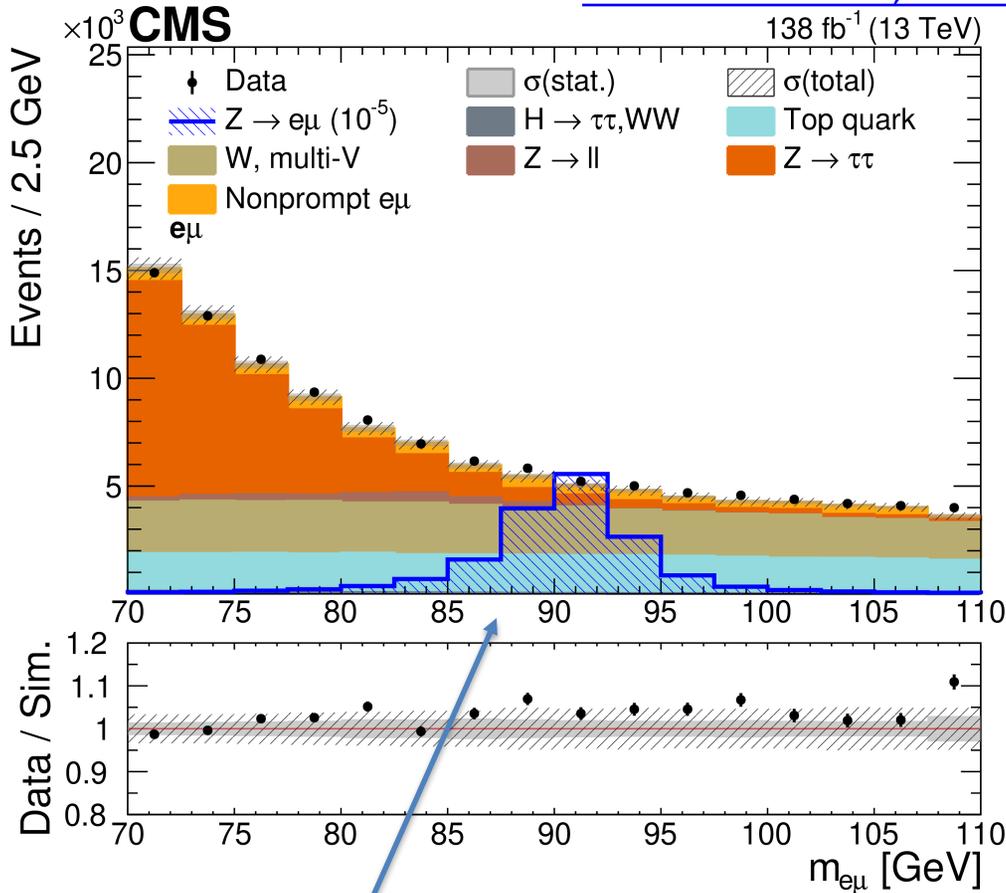
# Search for $Z \rightarrow e^- \mu^+$

- SM extended to include  $m_\nu \neq 0$  predicts:  $B(Z \rightarrow e^- \mu^+) \sim \mathcal{O}(10^{-60})$   
[J. Illana and T. Riemann Phys. Rev. 3 63 \(2001\) 053004](#)
- Low energy experiments constrain:  $B(Z \rightarrow e^- \mu^+) < 10^{-12}$   
[W. Marciano, T. Mori, J. Roney Ann. Rev. Nucl. Part. Sci 58\(2008\) 315](#)
- Previous best limit from LHC:  $B(Z \rightarrow e^- \mu^+) < 2.6 \times 10^{-7}$   
[ATLAS Phys. Rev. D 108 \(2023\) 032015](#)
- **Clean signature with low backgrounds**
  - Isolated high  $P_T$   $\mu^+$  and  $e^-$
  - Fully reconstruct  $M_Z$
  - Boosted Decision Tree constructed from kinematic variables to suppress backgrounds from  $t\bar{t}$ ,  $WW$

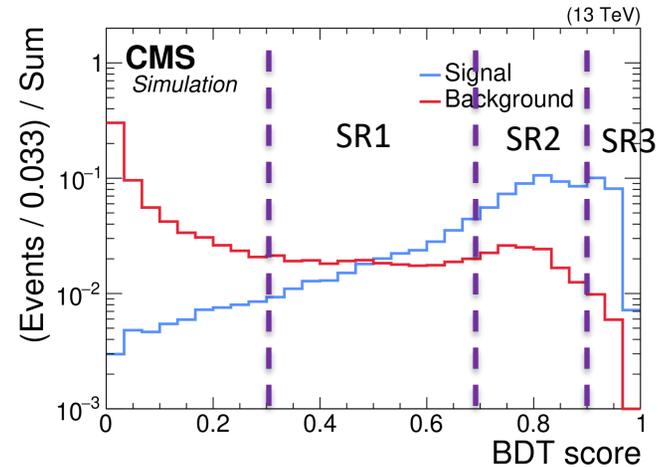


# Search for $Z \rightarrow e^- \mu^+$

CMS-SMP-23-003 ; CERN-EP-2025-130



Simulated signal for  $B(Z \rightarrow e^- \mu^+) = 10^{-5}$



Simultaneous fit of signal and background functions in  $m_{e\mu}$  for three signal regions (SR) defined in BDT distribution above

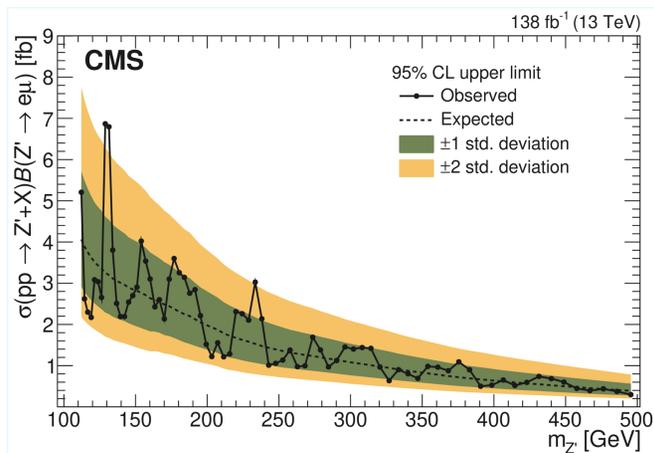
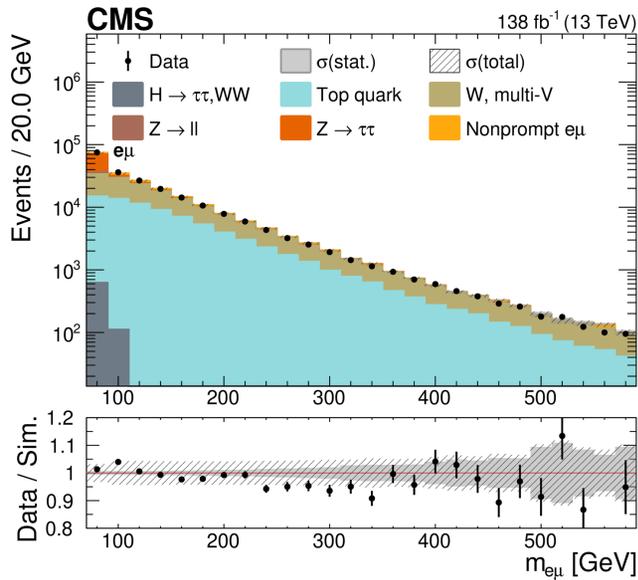
No excess observed:

$B(Z \rightarrow e^- \mu^+) < 1.9 \times 10^{-7}$  @ 95% C.L.

Most stringent limits to date

(cf. ATLAS  $B(Z \rightarrow e^- \mu^+) < 2.7 \times 10^{-7}$  @ 95% C.L.)

# Search for $Z' \rightarrow e^- \mu^+$



[CMS-SMP-23-003 ; CERN-EP-2025-130](#)

Many of the same BSM models that allow  $Z \rightarrow e^- \mu^+$  also allow higher mass  $Z'$  with the Possibility also of CFLV decays

Same analysis technique as for  $Z \rightarrow e^- \mu^+$  but with sliding  $m_{e\mu}$  window

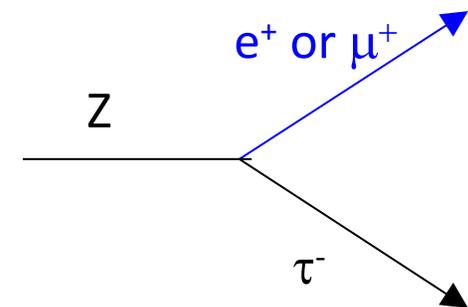
Scan  $110 \text{ GeV} < m_{e\mu} < 500 \text{ GeV}$

No excess observed and set  $m_{e\mu}$  dependent limits on  $\sigma(\text{pp} \rightarrow Z'+X) \cdot B(Z' \rightarrow e^- \mu^+)$

Most stringent limits to date

# Search for $Z \rightarrow e^- \tau^+$ and $Z \rightarrow \mu^- \tau^+$

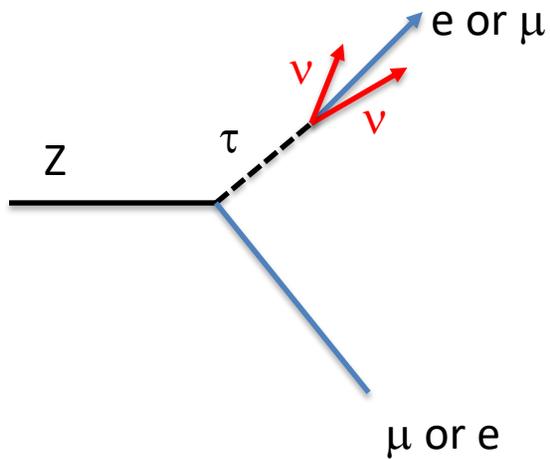
- SM extended to include  $m_\nu \neq 0$  predicts:  $B(Z \rightarrow e^- \tau^+, \mu^- \tau^+) < \mathcal{O}(10^{-54})$   
[\(J. Illana and T. Riemann Phys. Rev. 3 63 \(2001\) 053004\)](#)
- Low energy experiments constrain:  $B(Z \rightarrow e^- \tau^+) < 10^{-7}$ ,  $B(Z \rightarrow \mu^- \tau^+) < 2 \times 10^{-7}$   
 (from  $\tau \rightarrow \mu \gamma, e \gamma$ ,  $e^+ e^- \rightarrow \mu^- (e^-) \tau^+$ )  
[W. Marciano, T. Mori, J. Roney Ann. Rev. Nucl. Part. Sci 58\(2008\) 315](#)
- Previous best limit from LHC:  $B(Z \rightarrow e^- \tau^+) < 5 \times 10^{-6}$ ,  $B(Z \rightarrow \mu^- \tau^+) < 6.5 \times 10^{-6}$   
[\(ATLAS Phys. Rev. Lett. 127 \(2022\) 271801\)](#)
- **Signature less distinct than  $Z \rightarrow e^- \mu^+$** 
  - Prompt  $e^+$  or  $\mu^+$
  - No full reconstruction of  $m_Z$  due to neutrinos in the  $\tau$  decay
  - Missing  $P_T$
  - More significant backgrounds from  $Z \rightarrow \tau^- \tau^+$  and jets faking leptons



# Search for $Z \rightarrow e^- \tau^+$ and $Z \rightarrow \mu^- \tau^+$

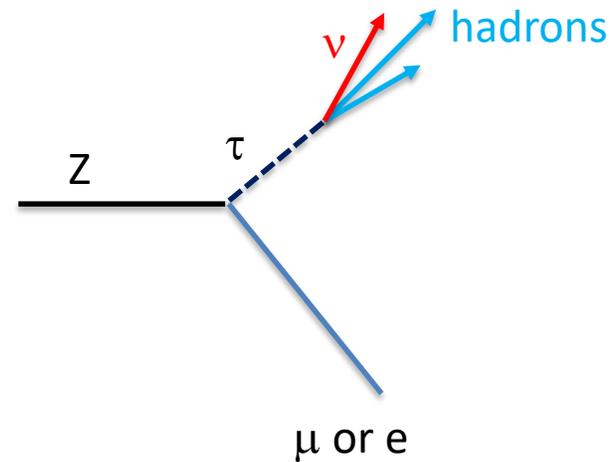
10

Search in four channels



$$Z \rightarrow e \tau_{\mu}$$

$$Z \rightarrow \mu \tau_e$$



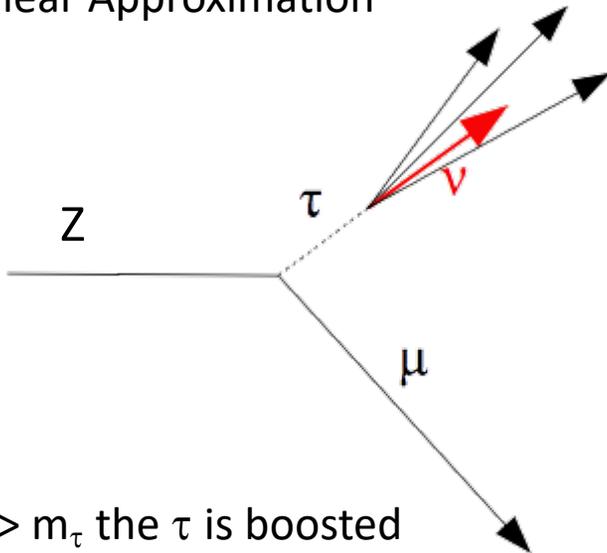
$$Z \rightarrow e \tau_h$$

$$Z \rightarrow \mu \tau_h$$

# Search for $Z \rightarrow e^- \tau^+$ and $Z \rightarrow \mu^- \tau^+$

CMS-SMP-23-003 ; CERN-EP-2025-130

## Collinear Approximation



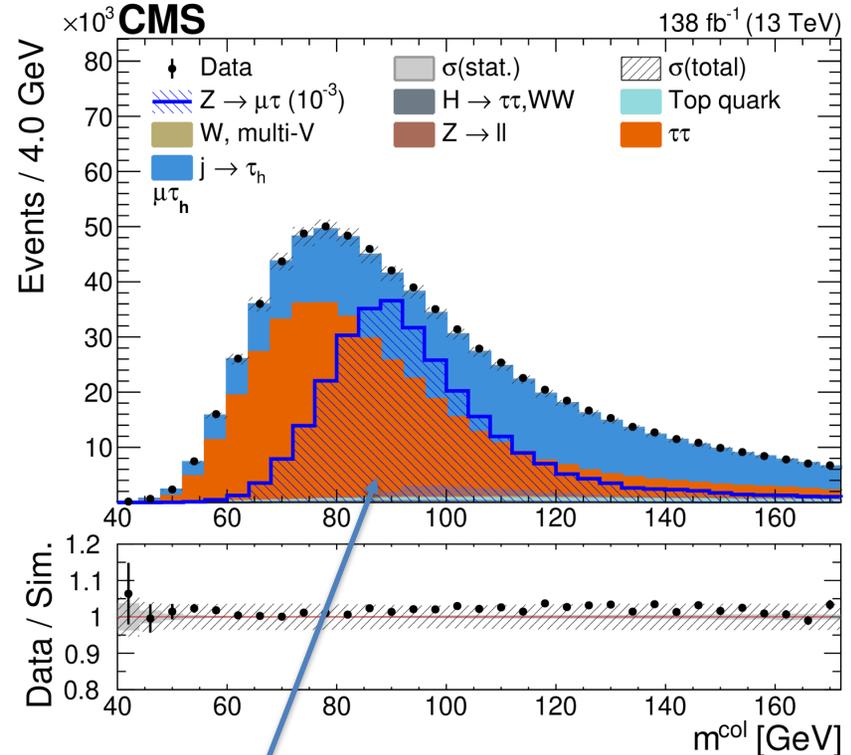
As  $m_Z \gg m_\tau$  the  $\tau$  is boosted

Assume  $\nu$  collinear with vector sum of visible  $\tau$  products

Component of missing  $P_T$  in the direction of visible tau products estimates  $P_\nu$

Construct  $m^{\text{col}}$

8/25/25

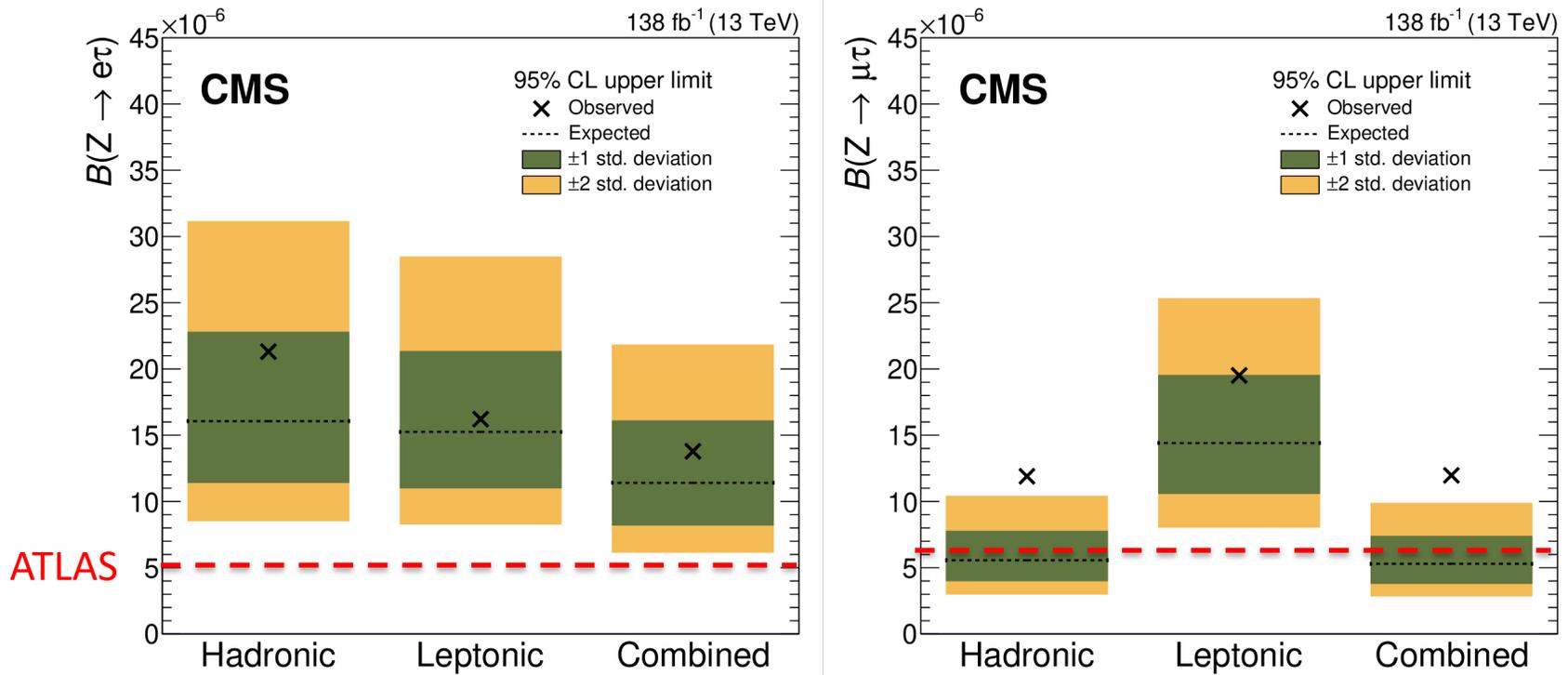


Simulated signal for  $B(Z \rightarrow \mu^- \tau^+) = 10^{-3}$

$Z \rightarrow \tau^+ \tau^-$  and jet backgrounds from data driven techniques

# Search for $Z \rightarrow e^- \tau^+$ and $Z \rightarrow \mu^- \tau^+$

[CMS-SMP-23-003 ; CERN-EP-2025-130](#)

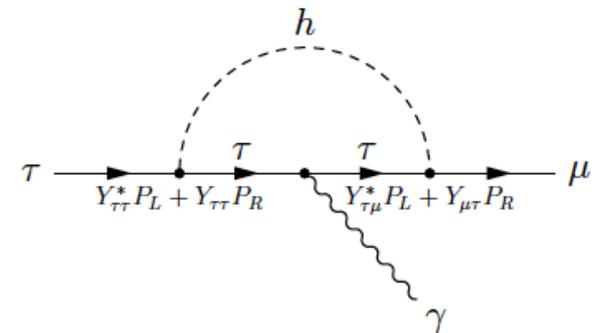
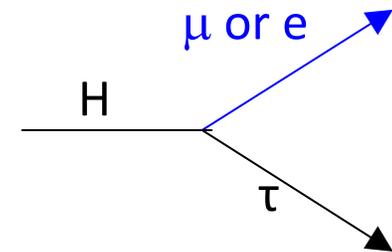


No excess over background observed. Limits set are comparable to the ATLAS run 2 results and an order of magnitude above low energy constraints

# Search for Lepton Flavor Violating H(125) Decays

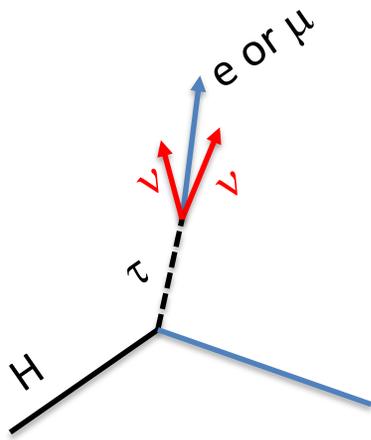
13

- Not present in the Standard Model
- Allowed in many models of new physics: SUSY, composite Higgs, Randall-Sundrum ....
- Indirect constraints from  $\tau \rightarrow \mu\gamma$ ,  $\tau \rightarrow e\gamma$ ,  $\mu \rightarrow e\gamma$   
 $B(H \rightarrow e\tau) < 10\%$ ,  $B(H \rightarrow \mu\tau) < 10\%$ ,  $B(H \rightarrow e\mu) < 10^{-8}$
- Low energy constraints much less stringent than for equivalent Z decays but H sample three orders of magnitude less statistics
- Similar signatures to the equivalent Z decays but selections optimized for H production and decay kinematics (so the searches are independent)

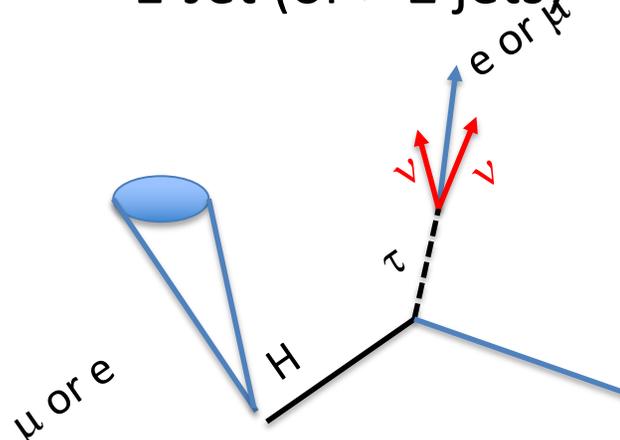


# LFV H Searches

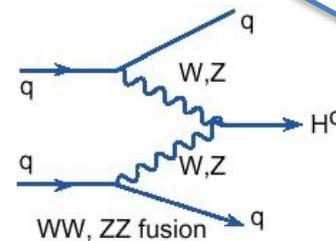
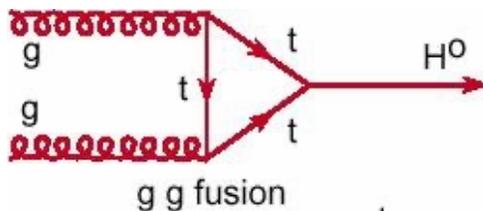
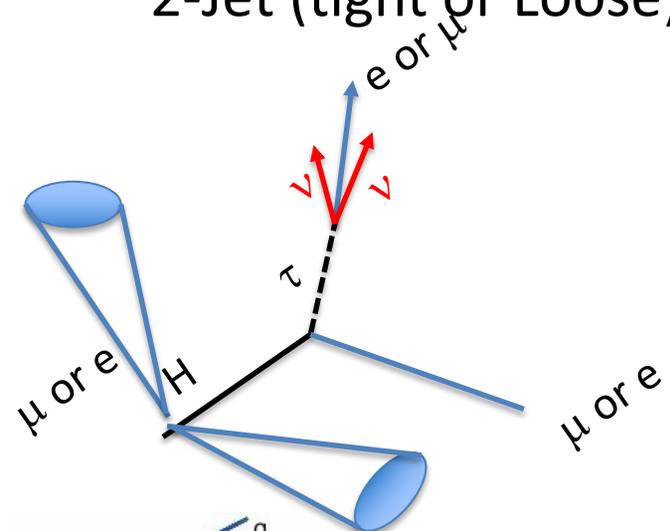
0-Jet



1-Jet (or > 2 jets)



2-Jet (tight or Loose)



Example: The production kinematics for H are significantly different to Z so different event topologies are exploited in the selection

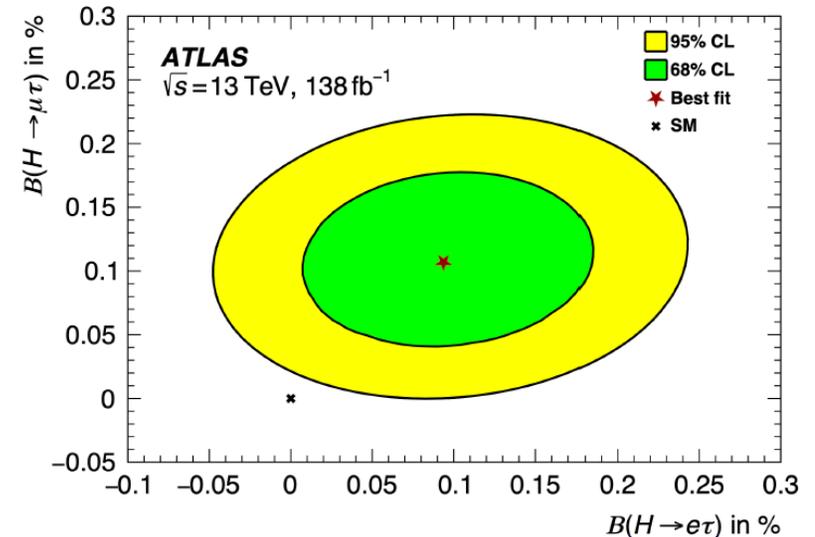
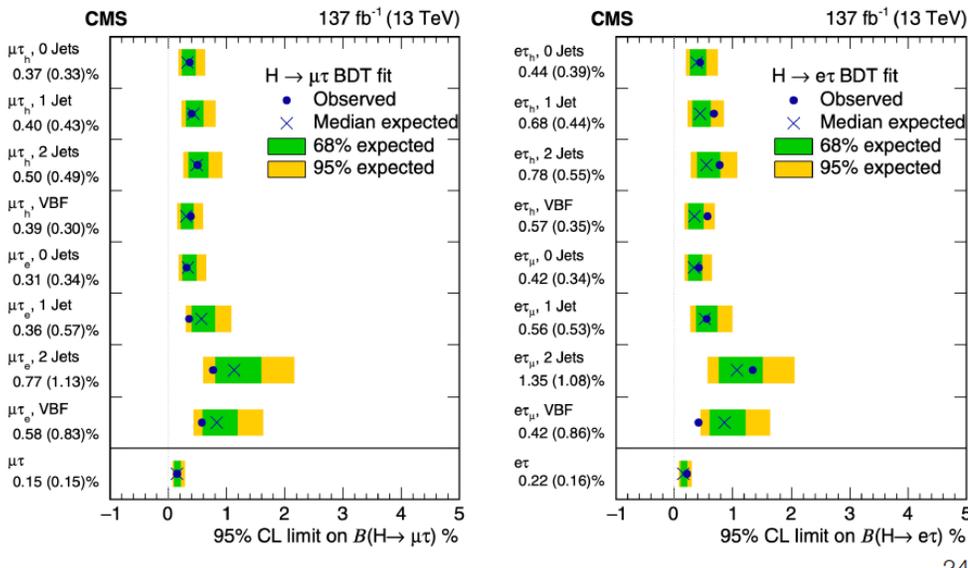
# Search for $H(125) \rightarrow e^- \tau^+$ and $H(125) \rightarrow \mu^- \tau^+$

## CMS (Phys. Rev. D 104, 032013 (2021))

- A 95% CL observed (expected) upper limits of
  - $B(H \rightarrow e\tau) < 0.22$  (0.16) %
  - $B(H \rightarrow \mu\tau) < 0.15$  (0.15) % are reported

## ATLAS (CERN-EP-2022-279)

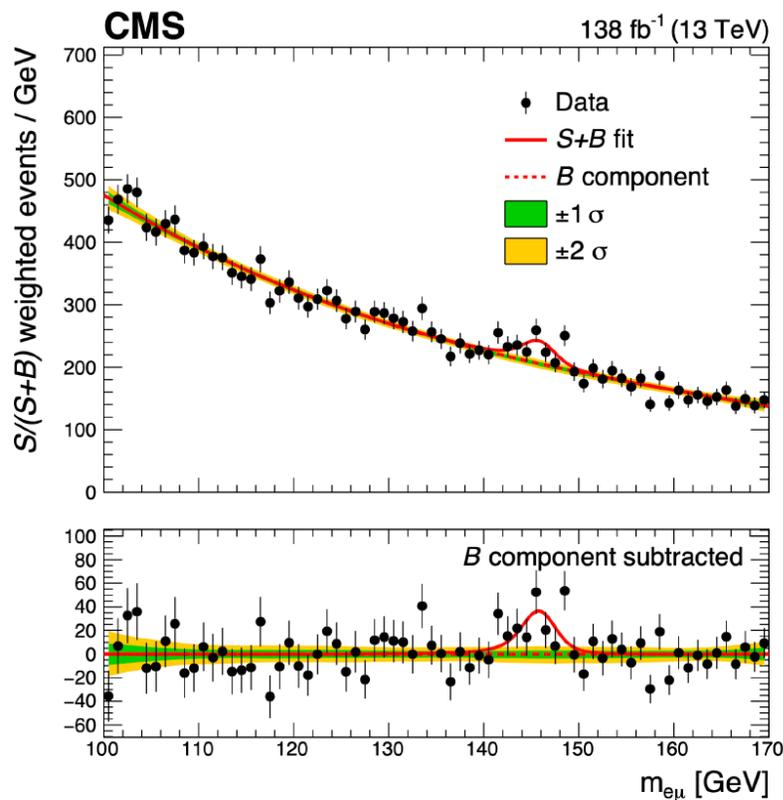
- A 95% CL observed (expected) upper limits of
  - $B(H \rightarrow e\tau) < 0.20$  (0.12) %
  - $B(H \rightarrow \mu\tau) < 0.18$  (0.09) % are reported



Constraints from direct searches are an order of magnitude stronger than low energy experiments

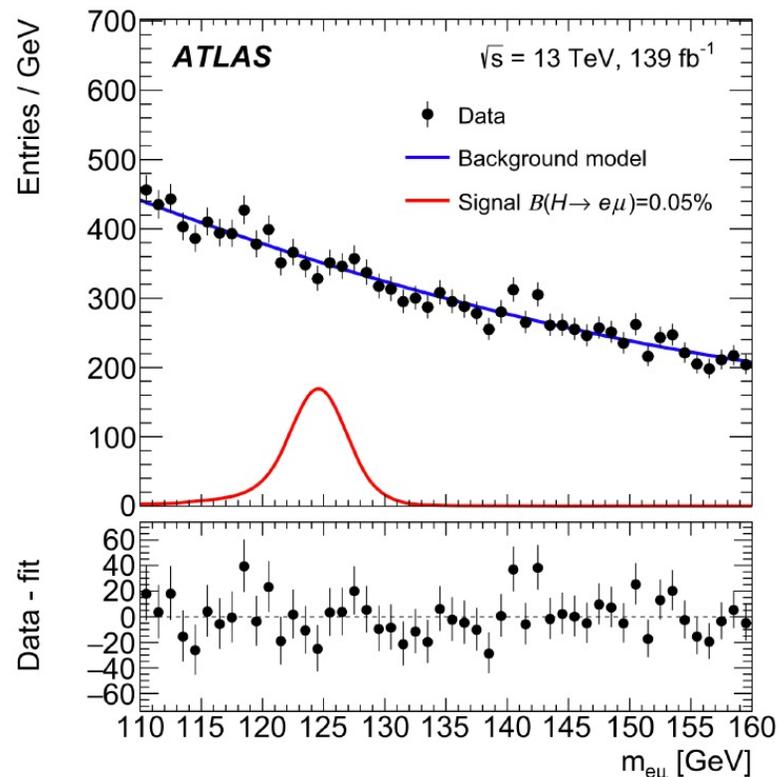
# Search for $H \rightarrow e^- \mu^+$

[Phys. Rev. D 108 \(2023\) 072004](#)



$B(H \rightarrow e^- \mu^+) < 4.4 \times 10^{-5}$  @ 95% C.L.

[Phys. Lett. B 801 \(2020\) 135148](#)

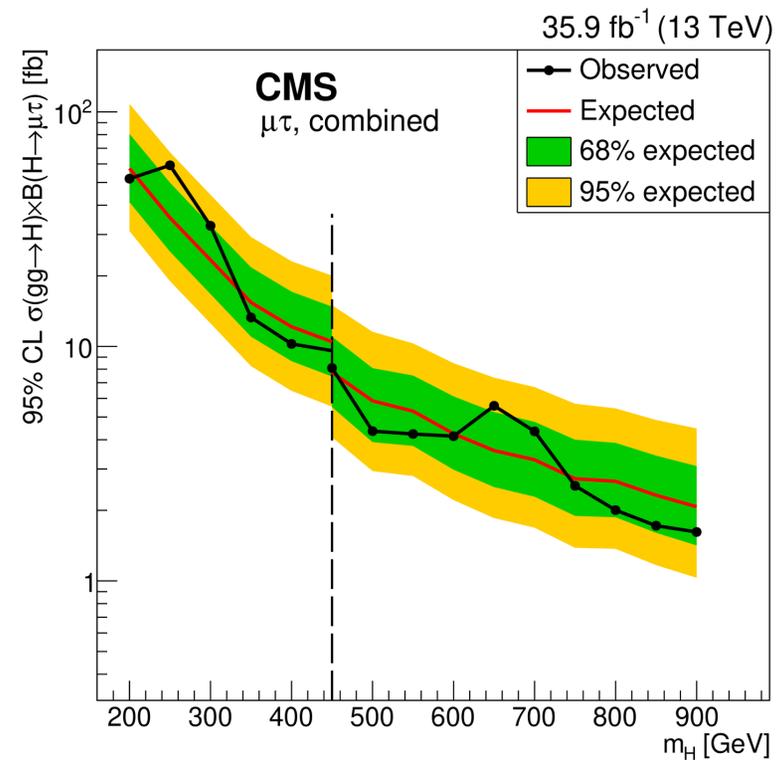
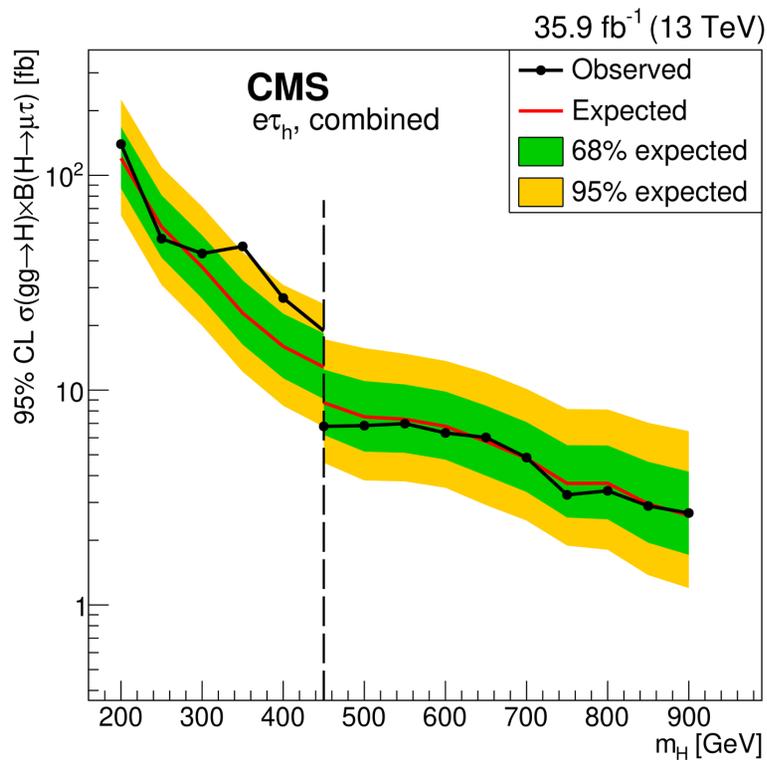


$B(Z \rightarrow e^- \mu^+) < 6.2 \times 10^{-5}$  @ 95% C.L.

CMS sees a  $3\sigma$  excess at 146 GeV but it is not present in ATLAS data

# Mass Scans for $H \rightarrow e^- \tau^+$ and $H \rightarrow \mu^- \tau^+$

[JHEP 03 \(2020\) 103](#)



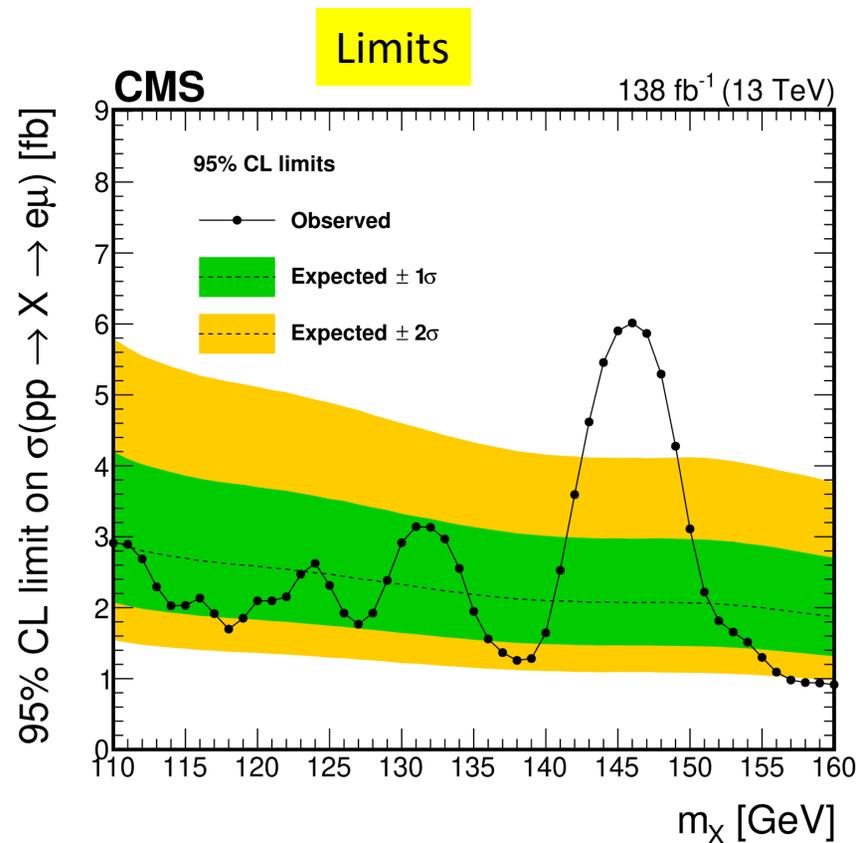
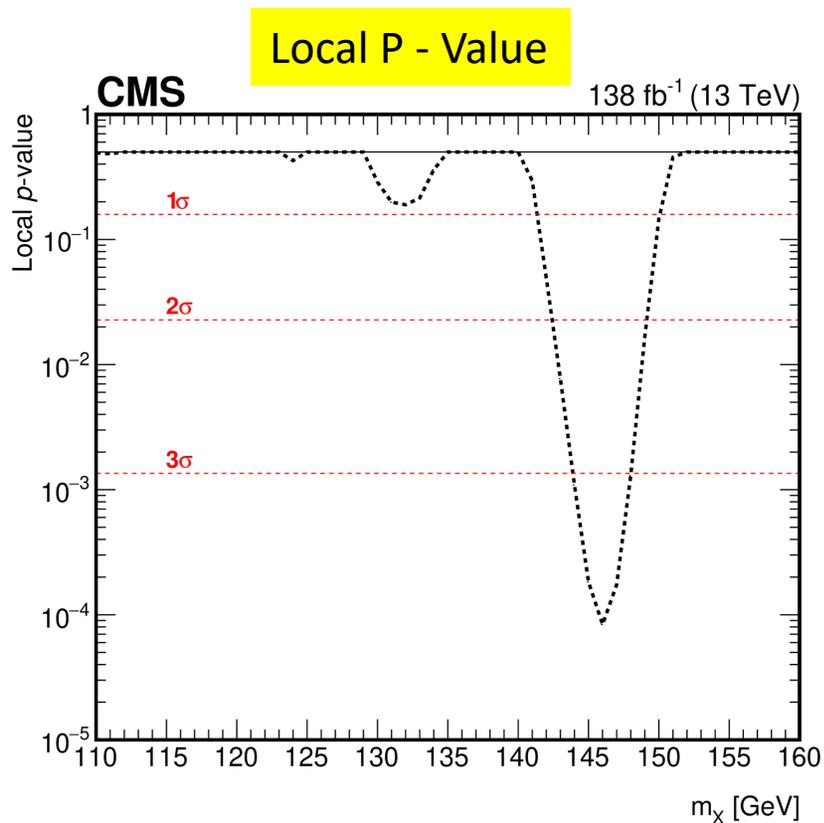
Mass scans with an earlier subset of CMS run 2 data show no excess (update in progress)

# Summary

- Lepton flavor violation in Z and H decays would be a clear signature if new physics
- Direct searches are complementary to low energy measurements
- New results in Z and Z' LFV searches but unfortunately no LFV yet in either Z or H decays @ the LHC.

# Additional Slides

# CMS Search for $H \rightarrow e^- \mu^+$



Local(global) significance of 3.8(2.8) $\sigma$  at  $m_{e\mu}=146$  GeV. Limits set @ 95% C.L.