Experimental results on Lepton Flavor Universality

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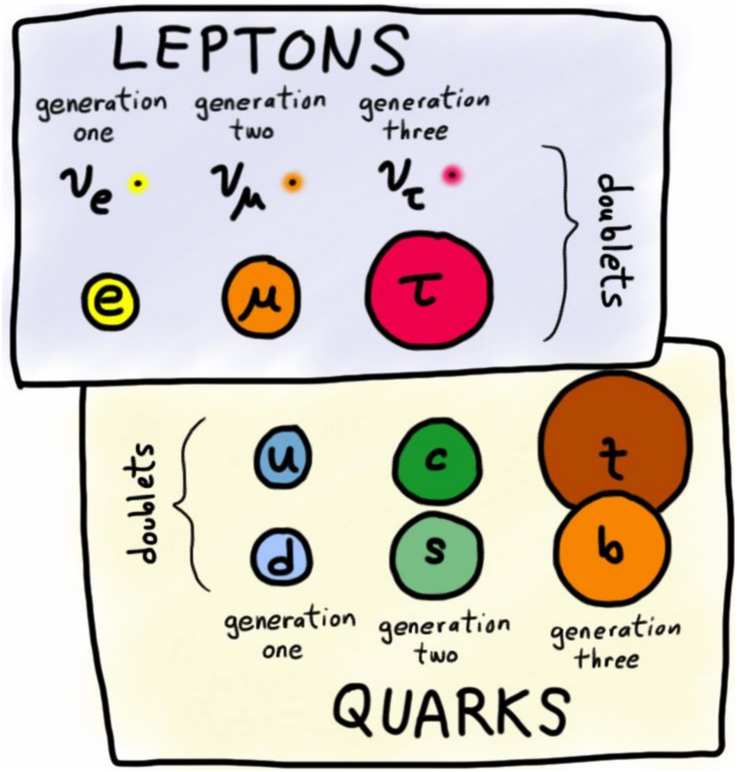
Lepton Flavor Universality

- No observed transitions coupling charged leptons from different generations (ex. H → eμ)

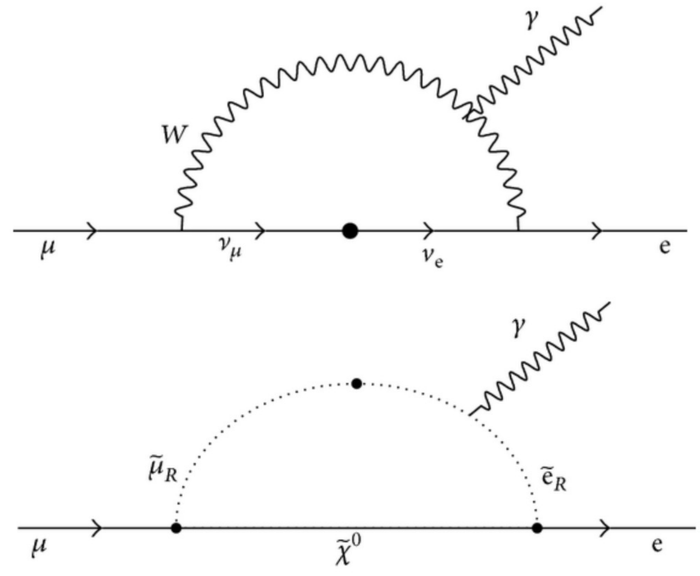
- But why not?
  - Weak force mixes quarks of different generations
  - Neutrino mixing shows lepton flavor violation in neutral leptons

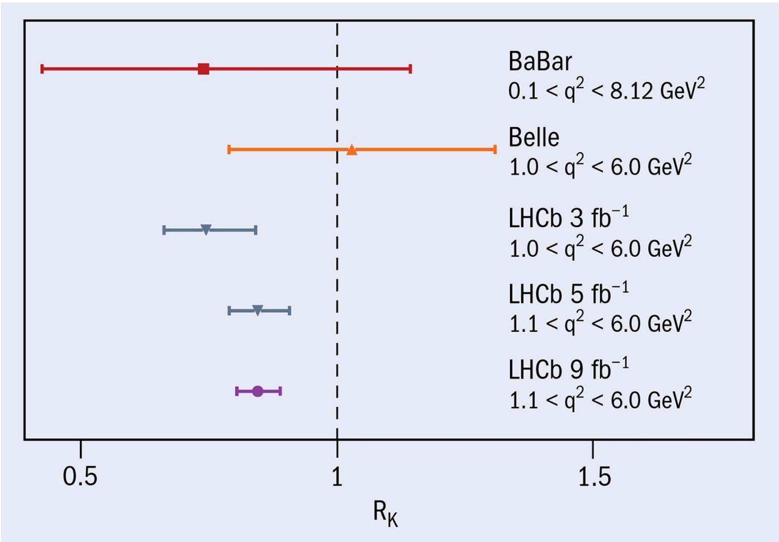


Lepton Flavor Violation

- Neutrino mixing does allow LFV in SM
  - But at rates far below current experimental sensitivity
- New physics contributions can significantly enhance LFV rates
- Recent "flavor anomalies" have driven renewed interest in searches for LFV
  - Many related high-mass searches (Z', leptoquarks, etc.) not covered here

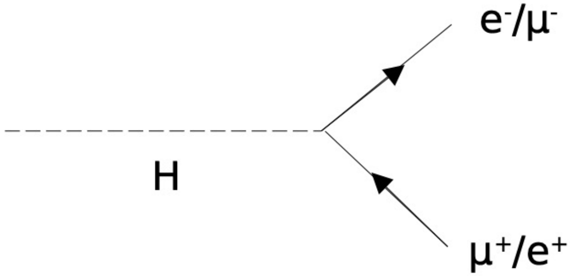
(see G. Padovano, H. Saka, E. Vourliotis)

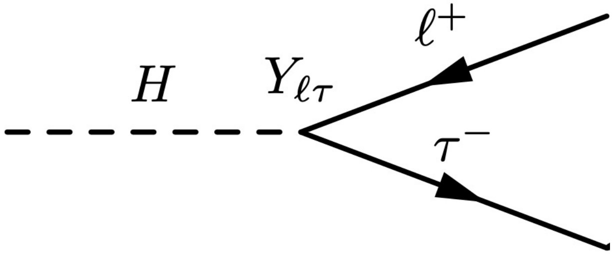




LFV in Higgs and Z Decays

- Classic charged LFV search at the LHC
  - Z and Higgs decays in eμ, eτ, and $\mu\tau$ final states
  - Clean signature with triggerable high p_T leptons
  - Similar searches from CMS and ATLAS

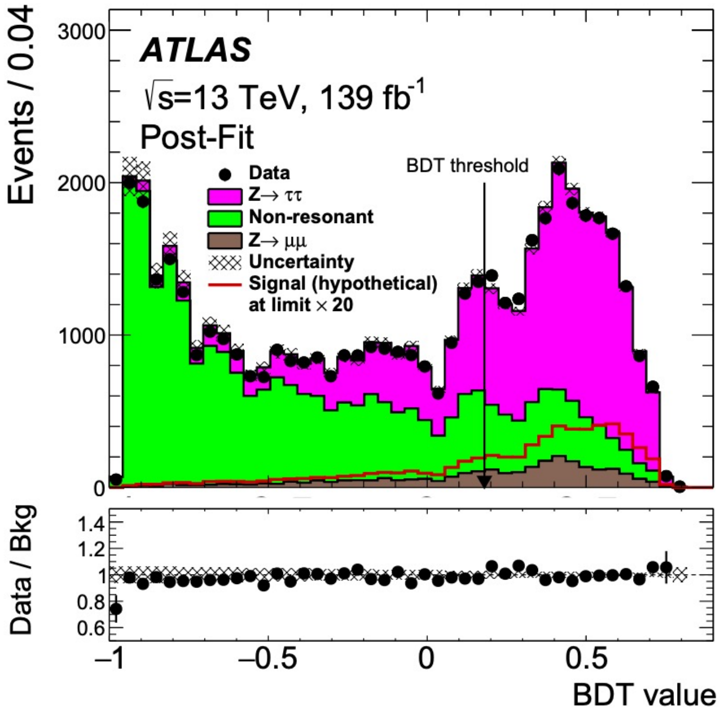


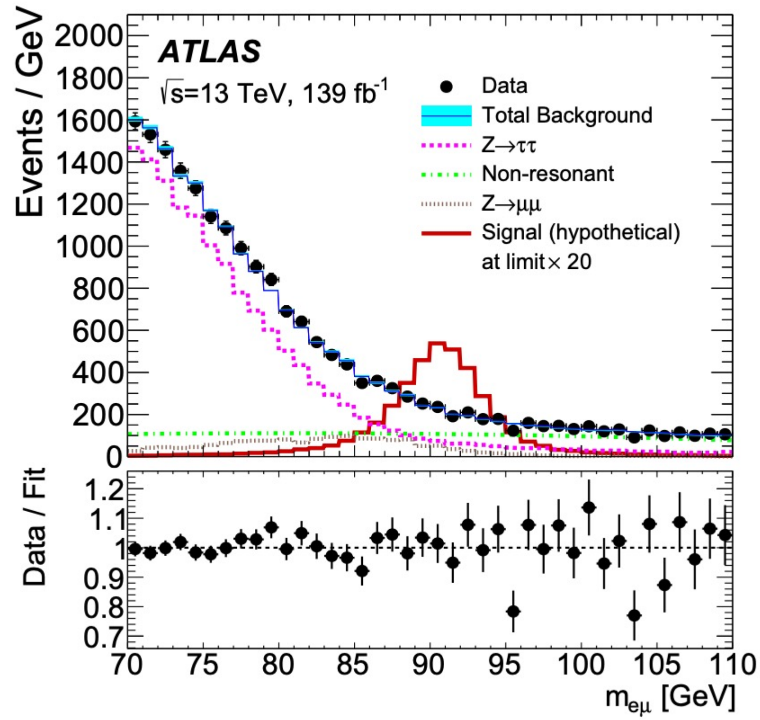


- Select events with two opposite charge leptons with different flavor
  - Include hadronic and leptonic tau decays
- Separate templates for different production channels for Higgs

Z → eμ Search

arXiv:2204.10783

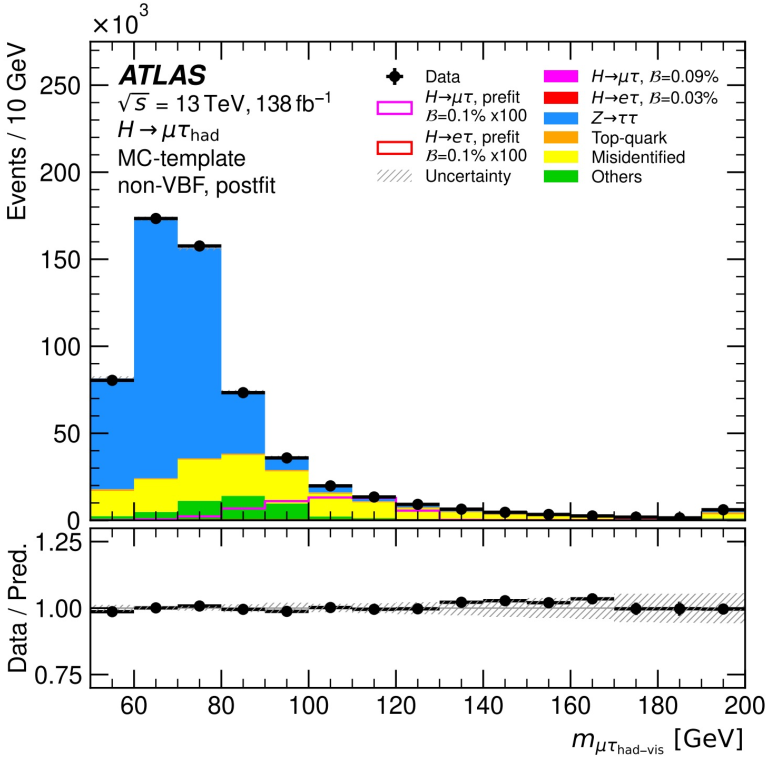




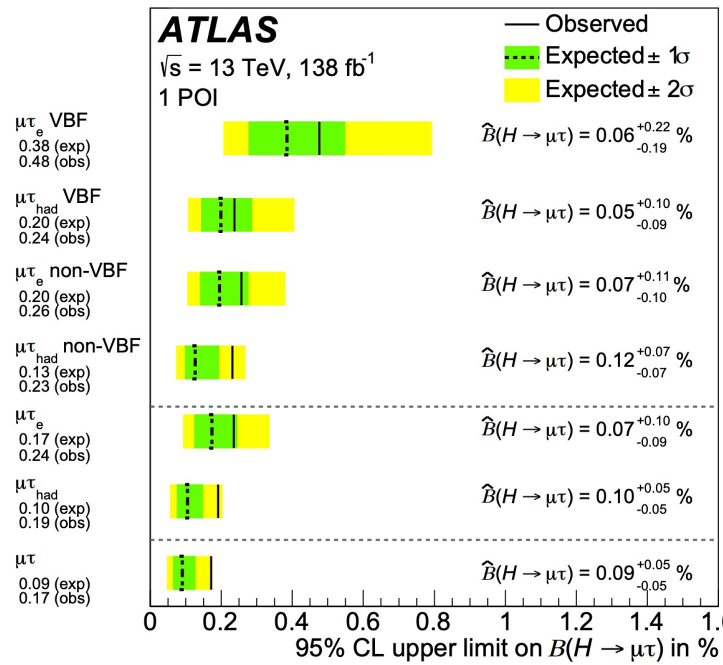
- Boosted Decision Tree from kinematic and lepton ID variables
- Fit to eμ mass to extract signal
- Normalize eμ search to Drell Yan events

arXiv:2302.05225

Higgs → $\tau\ell$ Search



- Mass peak less sharp due to neutrinos in tau decays
- MVA-based tau ID with fake rate measured in data control regions
- Multiple background methods used to cross check



- Separate search channels for VBF and non-VBF Higgs production
- Combine limits from all channels

Summary of H/Z limits

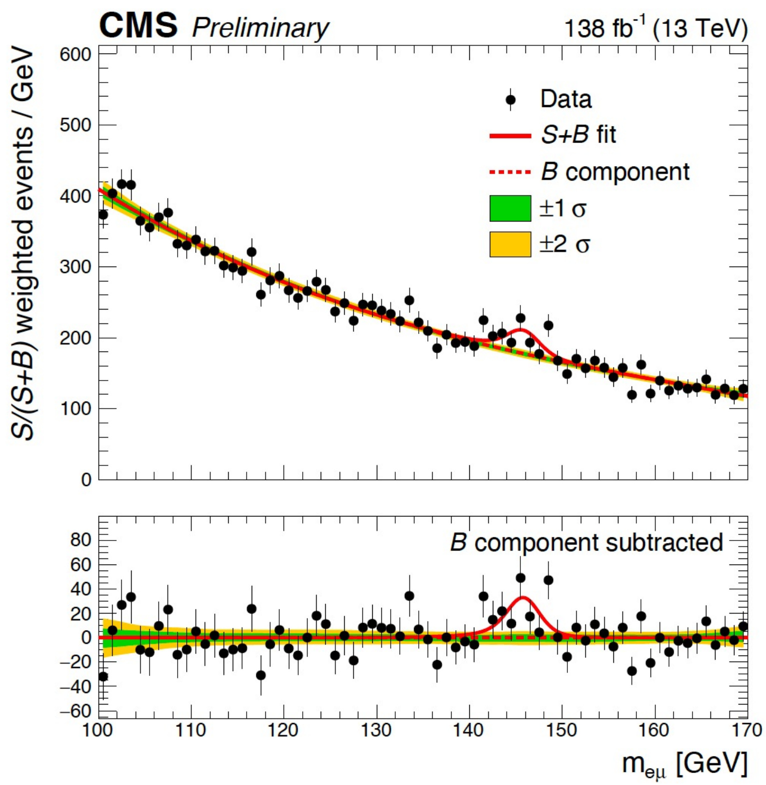
- No signal observed in any channel
- Interpret results as 95% CL upper limits

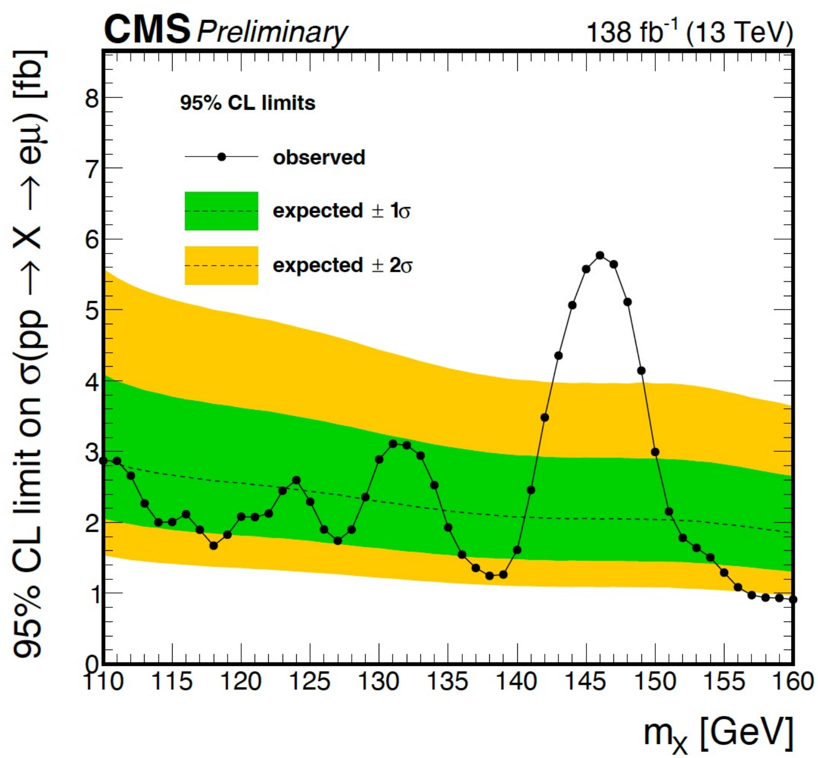
95% CL UL	ATLAS	CMS
$H \rightarrow e\mu$	$6.2 * 10^{-5}$ PLB 801 (2020) 135148	$4.4 * 10^{-5}$ PAS-HIG-22-002
$H \rightarrow e\tau$	$2.0 * 10^{-3}$ 2302.05225	$2.2 * 10^{-3}$ PRD 104, 032013 (2021)
$H \rightarrow \mu\tau$	$1.8 * 10^{-3}$ 2302.05225	$1.5 * 10^{-3}$ PRD 104, 032013 (2021)
$Z \rightarrow e\mu$	$2.6 * 10^{-7}$ 2204.10783	
$Z \rightarrow e\tau$	$8.1 * 10^{-6}$ Nature Phys 17, 819 (2021)	
$Z \rightarrow \mu\tau$	$9.5 * 10^{-6}$ Nature Phys 17, 819 (2021)	

Near Higgs $e\mu$ Search

- CMS H → $e\mu$ search also scanned around the Higgs mass
- Possible sign of structure ~146 GeV
  - 2.8 (3.8) σ global (local) significance

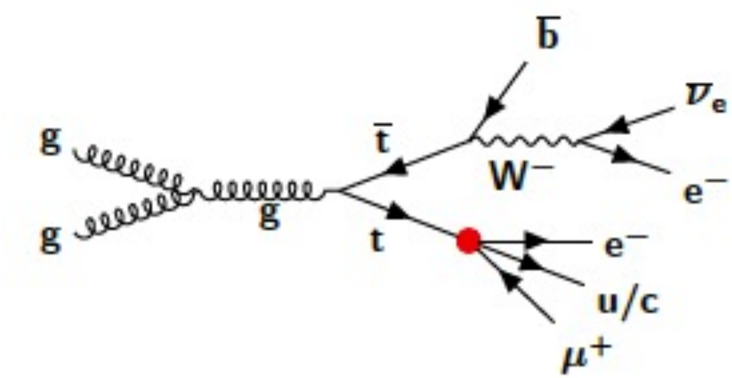
PAS-HIG-22-002

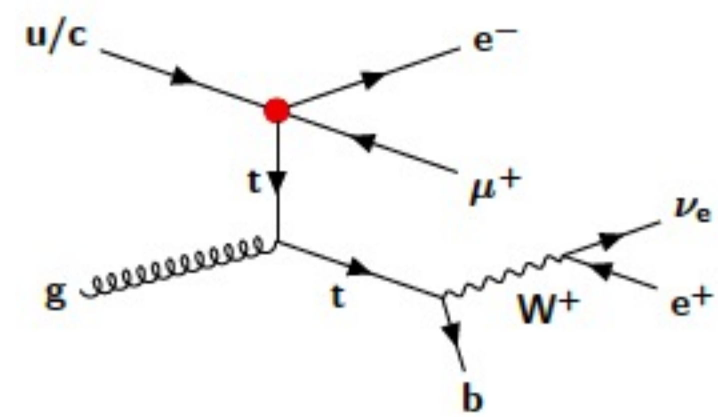




LFV in Top Decays

- Search for LFV in vertex coupling 2 flavors of leptons and quarks (ex: e, μ, t, c)
  - Possible in both production and decay of top quarks



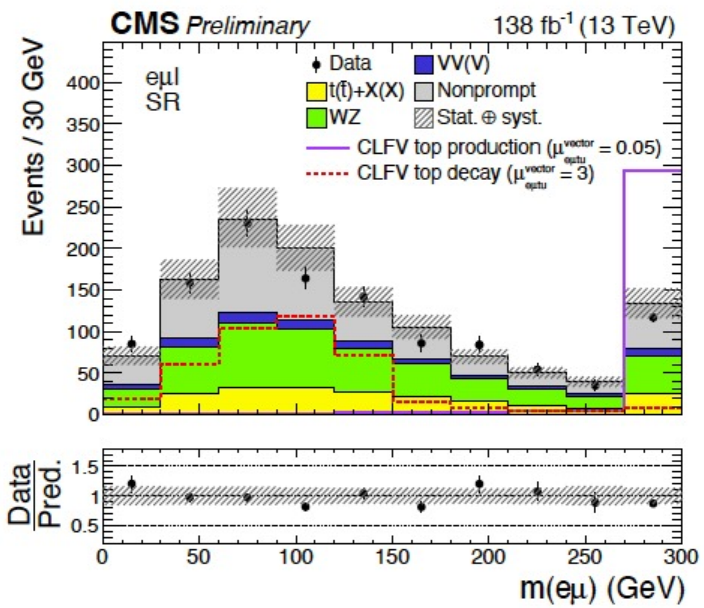


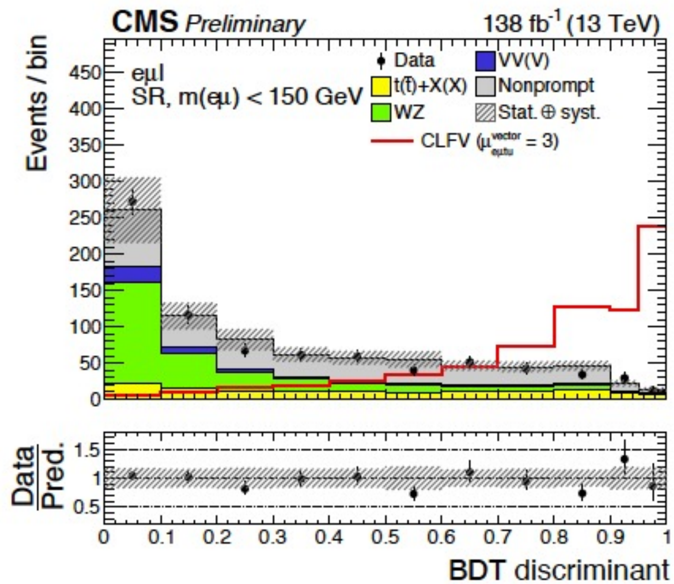
- Select events with
  - Opposite charge e/μ pair plus additional charged lepton
  - ≥ 1 jet with no more than 1 tagged as b
- Build SM top candidate from most b-like jet, extra lepton, and MET
- Build BSM top candidate from opposite charge e/μ pair and jet that gives mass closest to the top
- Divide signal region into m(eμ) > and < 150 GeV to target production/decay regions

Top Background Predictions

- Prompt backgrounds from SM processes with three real leptons (di- and tri-boson production)
  - Estimated from MC simulation
- Non-prompt backgrounds from one or more non-prompt leptons (b, c or π decays)
  - Estimated from tight-to-loose ratio measured and validated in data
- Boosted Decision Trees trained to discriminate signal from background

PAS-TOP-22-005



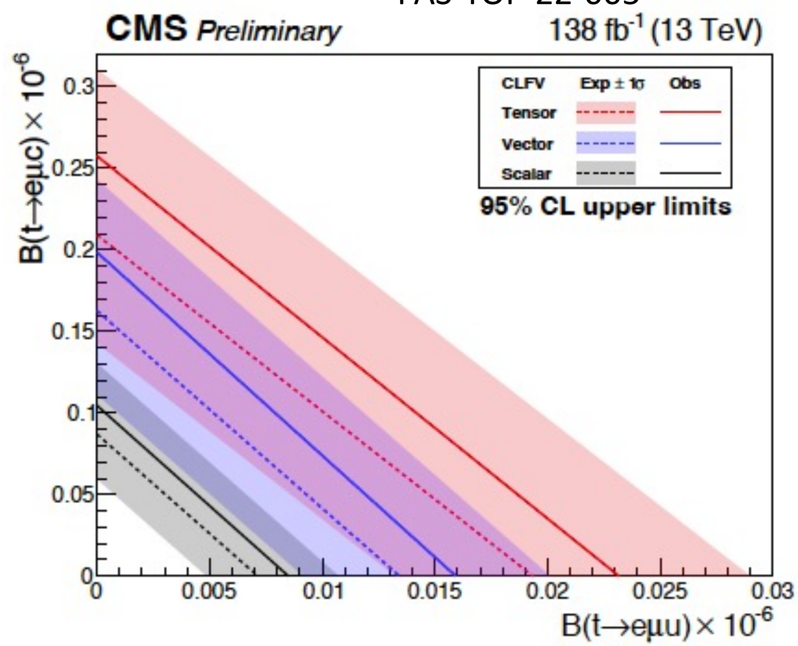


Top LFV Interpretations

- Interpret as constraints on BSM Wilson coefficients and limits on top branching fractions
- Search in similar channel with τ leptons from ATLAS

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

PAS-TOP-22-005



ATLAS- CONF-2023-001

	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}

New for LHCP 2023

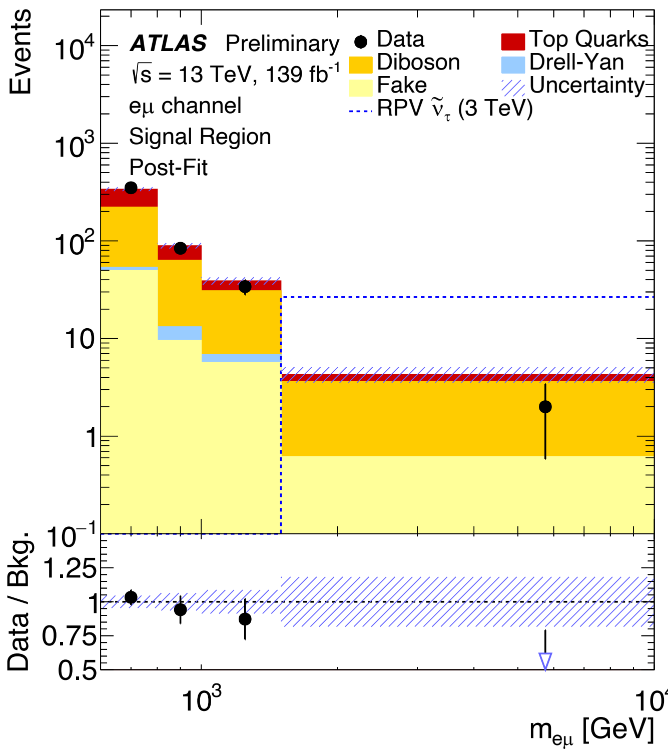
High Mass LFV Decays

- Variety of New Physics models can produce heavy resonances decaying to lepton pairs (ex: Z')
  - If LFV couplings are included, can expect Z' → eμ, eτ, and/or $\mu\tau$
- Select different flavor lepton pairs with p_T > 65 GeV
  - Include taus in 1 or 3 prong hadronic channels
- Target dilepton mass > 600 GeV and exactly 2 leptons back-to-back
- For tau channels, neutrino direction assumed same as visible tau components
  - Achieves mass resolution of 4% for eτ and 12% for $\mu\tau$ for 2 TeV benchmark Z'

High Mass LFV Backgrounds

- Irreducible
  - SM processes with true opposite charge different flavor leptons (diboson, tt, Z→$\tau\tau$)
  - Estimated from MC simulation corrected by data in background-enriched control regions
- Reducible
  - Jets misreconstructed as leptons (W+jets, multijet)
  - Non-prompt e or μ estimated from data with tight-to-loose ratio method
  - Jet faking hadronic τ derived scaling background-enriched control region yield by SR/CR ratio from simulation

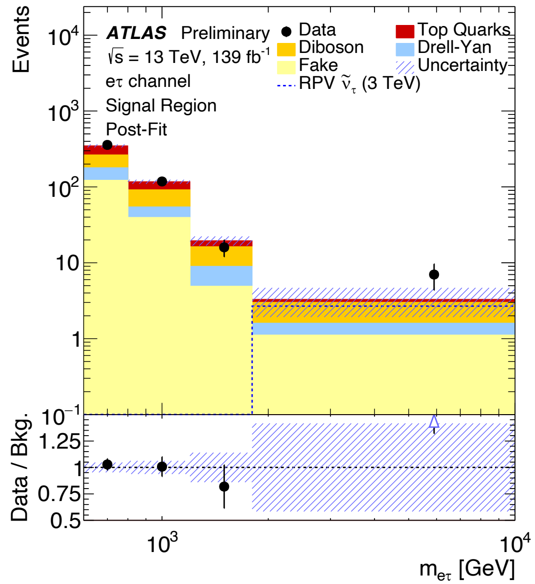
EXOT-2019-20

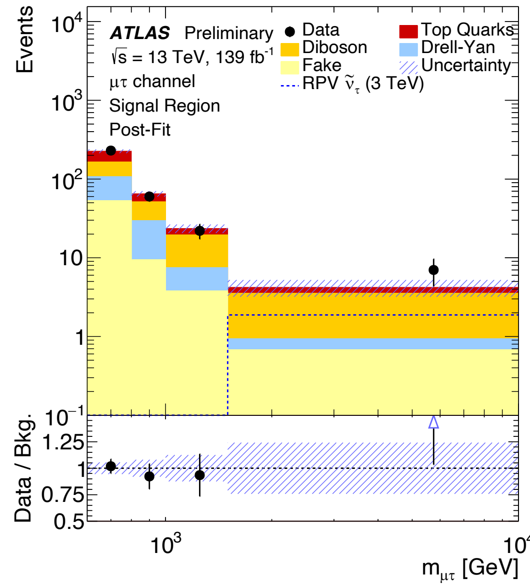


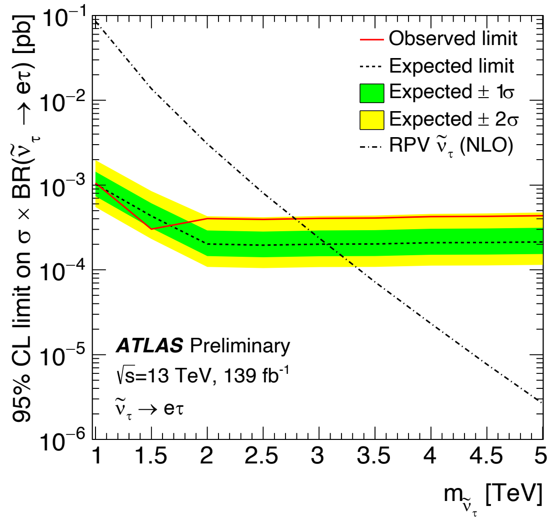
High Mass Results

EXOT-2019-20

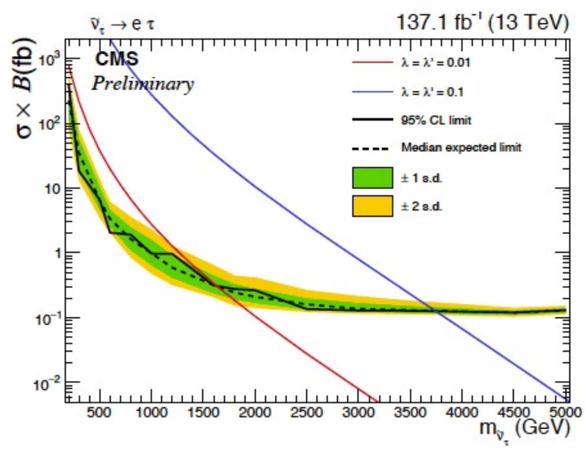
- Interpret results as limits on variety of BSM models: Z', RPV sneutrinos, quantum black holes
- Interesting excess ~2σ in highest mass bin in eτ and $\mu\tau$ channels
- Similar search performed by CMS → no sign of excess visible in sneutrino limits







PAS-EXO-19-014

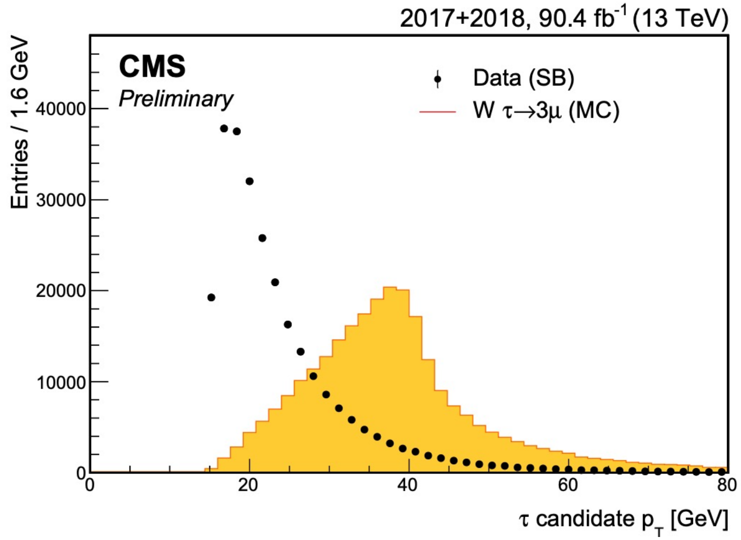


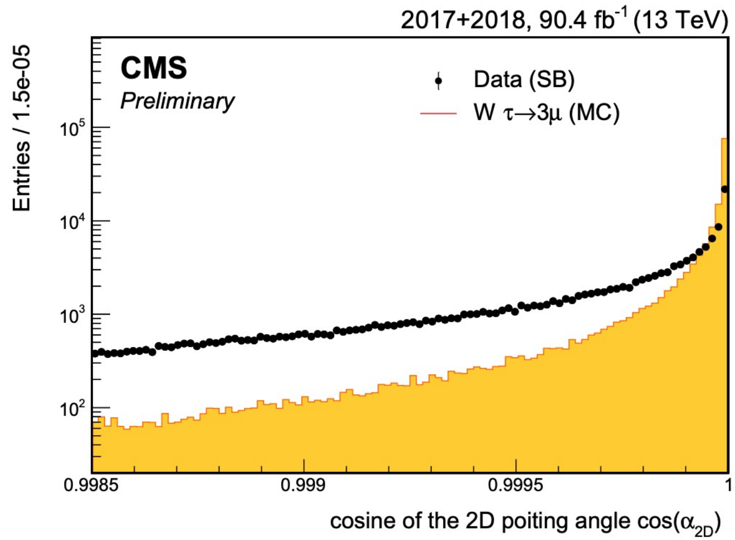
New for LHCP 2023

LFV in tau Decays

PAS-BPH-21-005

- Search for LFV $\tau \rightarrow 3\mu$ decays
  - New: add 2017–2018 data
- Include τ production from heavy flavor (B, D) decays and W decays
- W $\rightarrow \tau,\nu$ results in high p_T τ
- Muon p_T > 7, 1, 1 GeV fit to common vertex
- $p_T(3\mu)$ > 15 GeV
- BDT to separate signal (MC) vs background (data sidebands)
  - W decay: MET, tau p_T, etc.
  - τ -> 3μ vertex: χ^2, pointing angle
  - Muon identification
- Split into three categories based on 3μ mass resolution

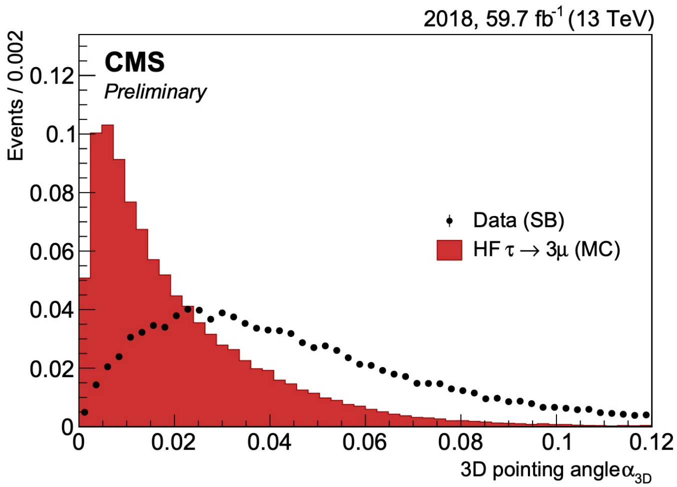


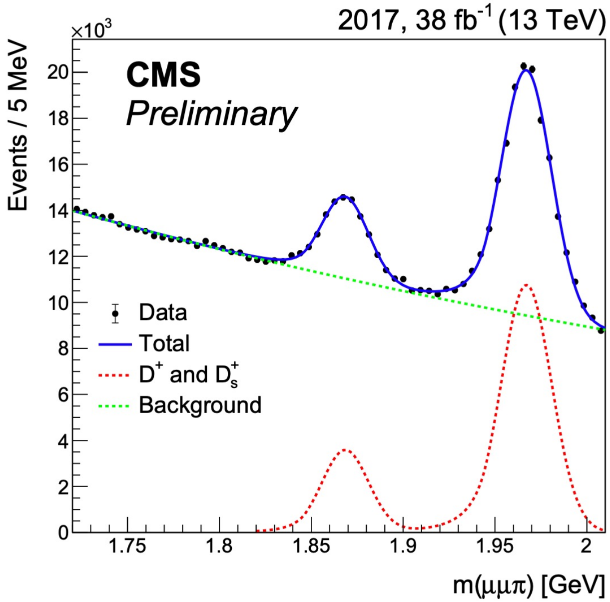


$\tau \rightarrow 3\mu$ Heavy Flavor Production

PAS-BPH-21-005

- Fit 3 low p_T muons to common displaced vertex
- Background dominated by pion or kaon decay-in-flight and hadron tracks matching muon stubs ➔ use muon quality BDT
- Divide into three categories of 3μ mass resolution (~12, 19, 25 MeV)
- Second event-level BDT trained to select signal vs background
    - Divide into 4 bins and fit the 3μ mass to extract signal in 3 most signal-like bins
- Signal normalized to $D_S^+ \rightarrow \phi(\mu^+\mu^-)\pi^+$ to minimize dependence on B or D cross sections and muon selection efficiencies

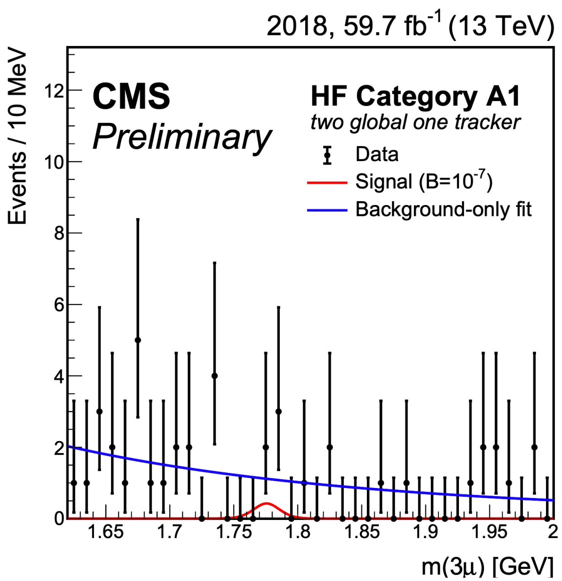


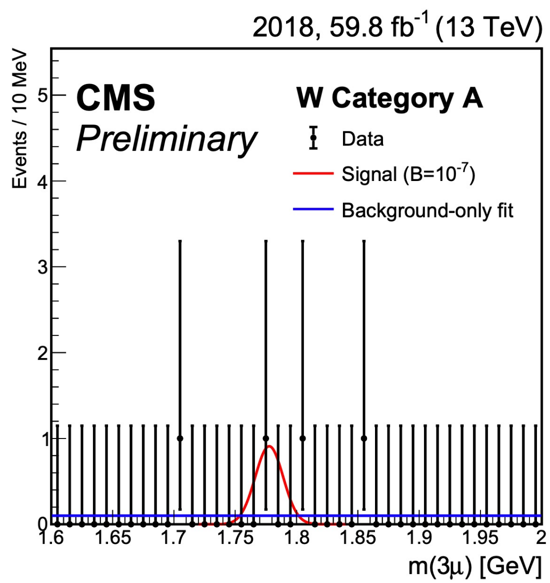


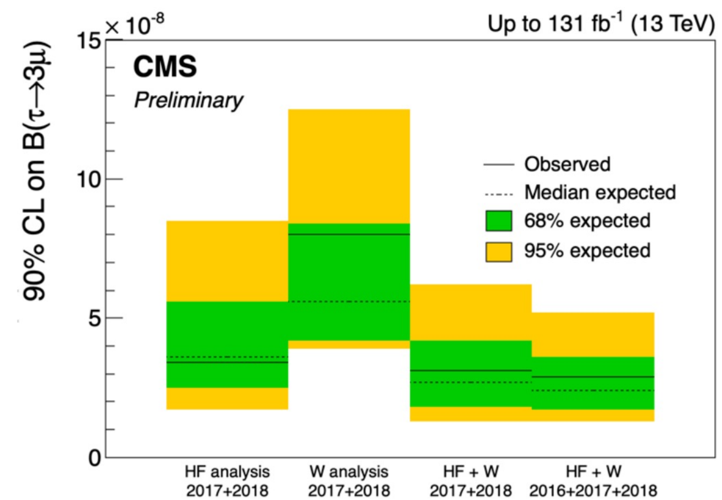
LFV in tau Decays

- No signal observed
- Final results extracted from simultaneous fit to all new signal regions, plus previous 2016 results
- $\mathcal{B}(\tau \rightarrow 3\mu) < 2.9 \times 10^{-8}$ at 90% CL
  - World's best still from B-factories: Belle $< 2.1 \times 10^{-8}$

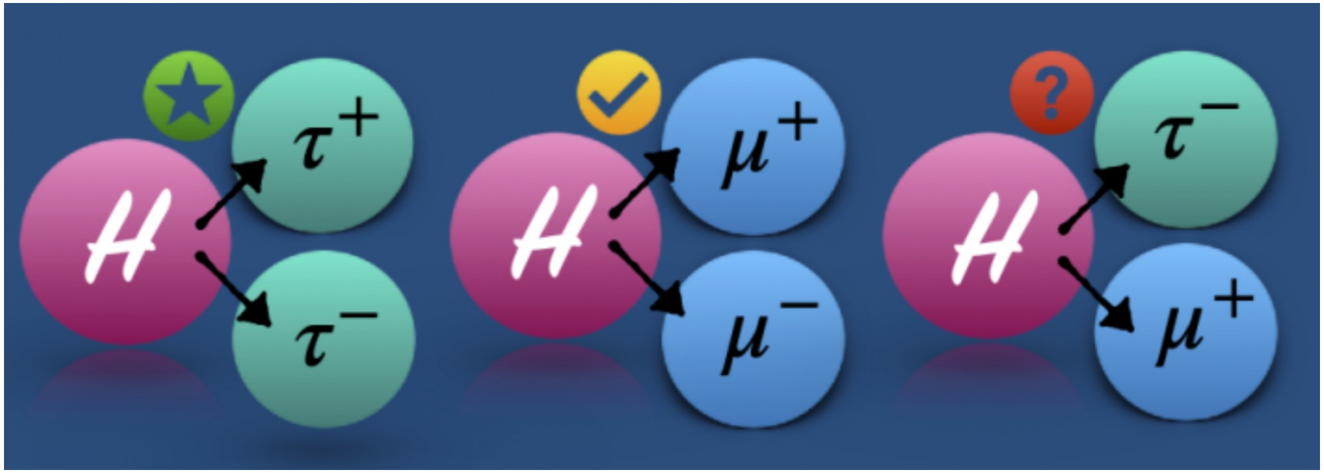
PAS-BPH-21-005







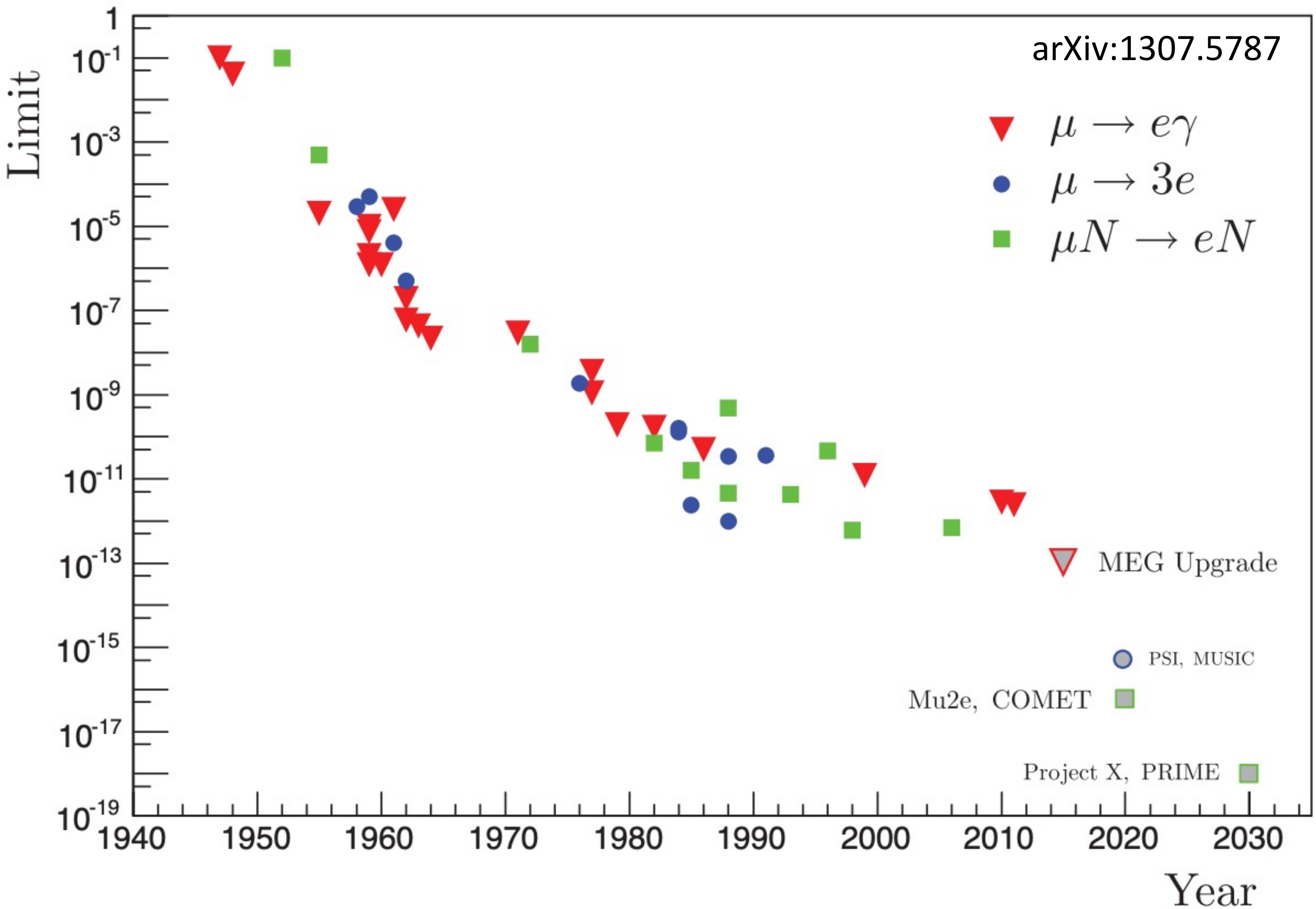
Conclusions



- Lepton Flavor Violation in charged lepton sector is an intriguing arena to search for new physics
- The LHC has world's best sensitivity to many LFV channels including Z, Higgs, and Top decays and high mass searches
- No clear signs of LFV yet, but several interesting hints to be followed up with more data
- Especially important as the picture for heavy flavor anomalies continues to become more clear

Additional Slides

History of $\mu \to e\gamma$, $\mu N \to eN$, and $\mu \to 3e$



CMS High Mass

- Mass plots of CMS High Mass search