Searches for Charged Lepton Flavor Violation at ATLAS and CMS

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on behalf of the ATLAS and CMS collaborations

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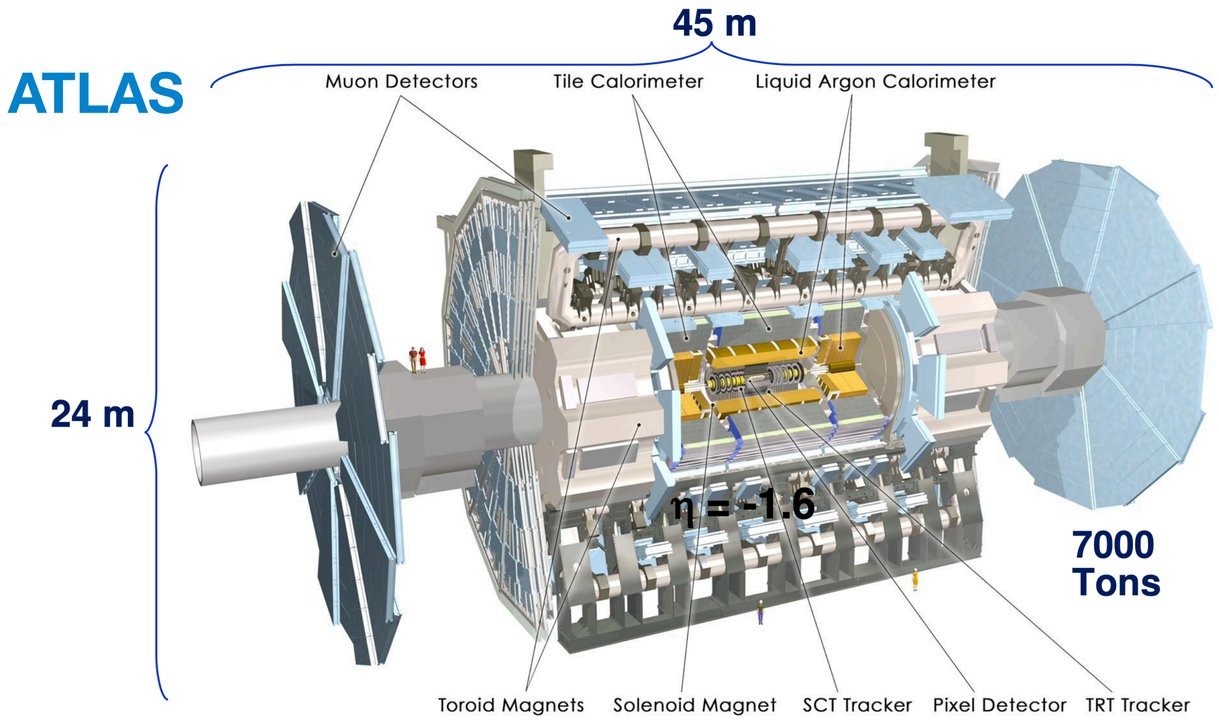
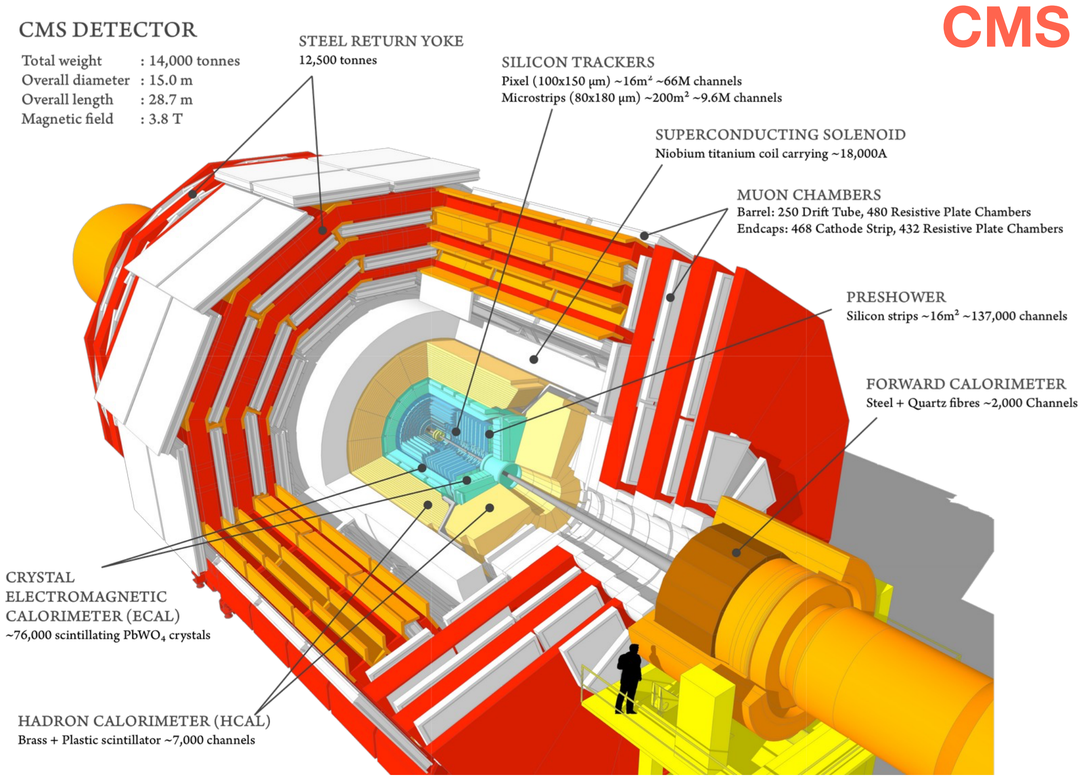
Outline

- Intro
- Z LFV decays
- Higgs LFV decays
- Near Higgs eμ search
- Tau CLFV decay $\tau \rightarrow \mu\mu\mu$
- LFV in Top quark processes
- High-mass LFV searches

ATLAS and CMS experiments

- 2 magnet systems (central 2T solenoid and large toroids in muon spectrometer)
- electron scale uncertainty ~0.7% in central region
- muon momentum scale uncertainty 0.05%
- τ energy scale uncertainty 2% (3%) for 1- (3-) prong τ-lepton





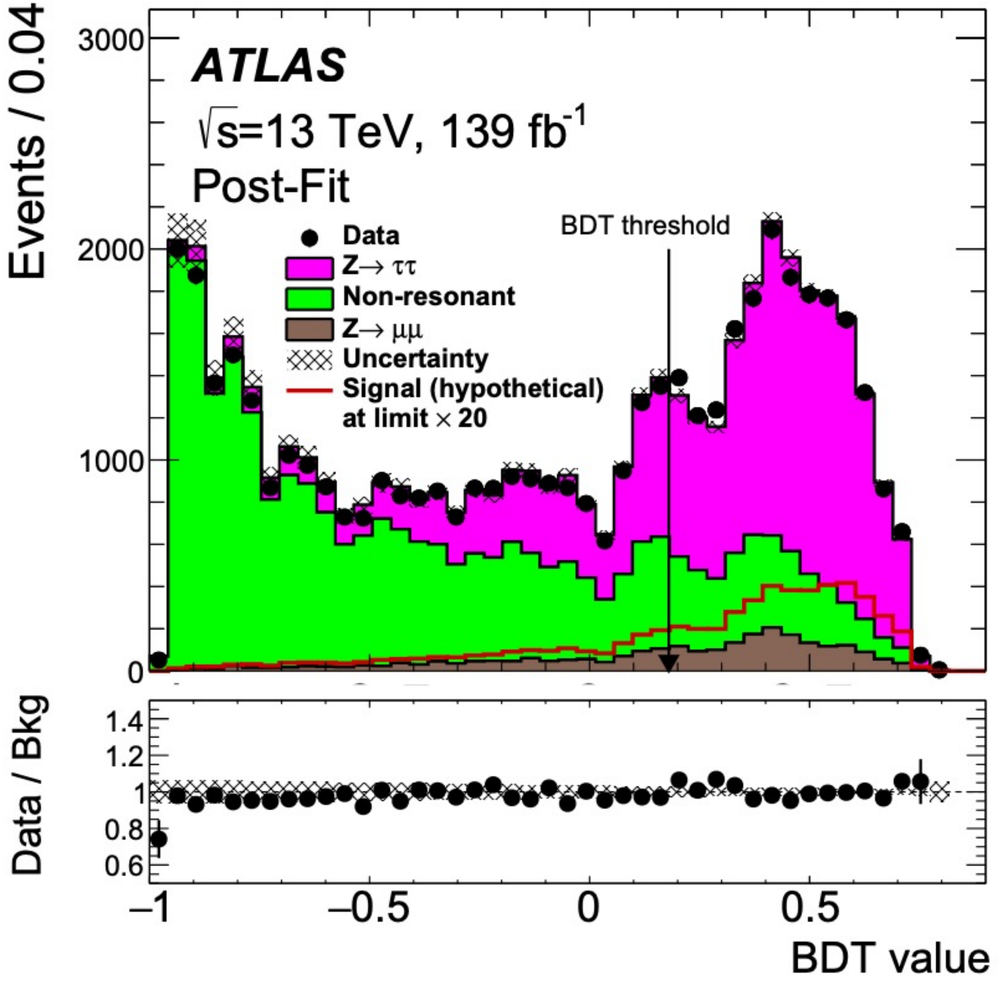
- one large 4T solenoid
- electron scale uncertainty ~0.3% (central region)
- muon momentum scale uncertainty 0.2%
- τ energy scale uncertainty < 1.2%

Intro

- It has been about 11 years since the discovery of the Higgs boson at the LHC
  - ATLAS and CMS have discovered (>5σ) all main production processes and decay channels
    - Searches for decays to 2nd generation fermions and other rare decays already show impressive results
- It's not all about the Higgs LFV searches! ATLAS and CMS have an extensive program of searches for BSM physics probing LFV using:
  - Rare Z decays
  - Top quark processes
  - High-mass searches

Z LFV search

- Final state: $Z \to e^{\pm}\mu^{\mp}$
- Main background: $Z \to \tau\tau \to e\mu\nu\bar{\nu}\nu\bar{\nu}$
- Sub-leading bkg: $Z \to \mu\mu$ with one μ faking an e
- Both bkgs are modeled using MC simulations
- Background suppression using a Boosted-decision-tree (BDT), which takes as input kinematic and lepton-ID variables

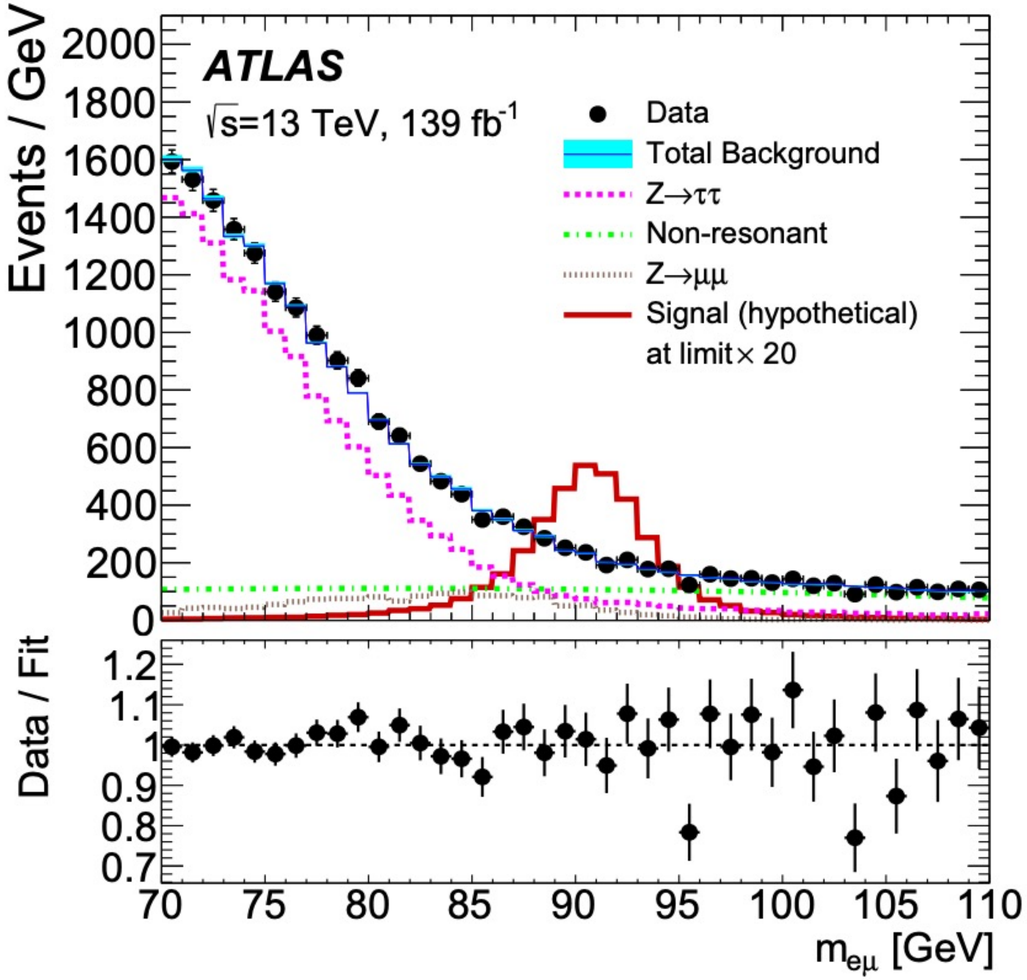


arxiv:2204.10783 [HEP]

Z LFV search

- Parametrized fit to the eμ inv mass to extract the signal yield
- The signal component should peak at $m_{e\mu} = 91$ GeV
- The observed (expected) upper limit on the B($Z \rightarrow e\mu$) is 2.62 (2.37)x10^{-7} at 95% CL

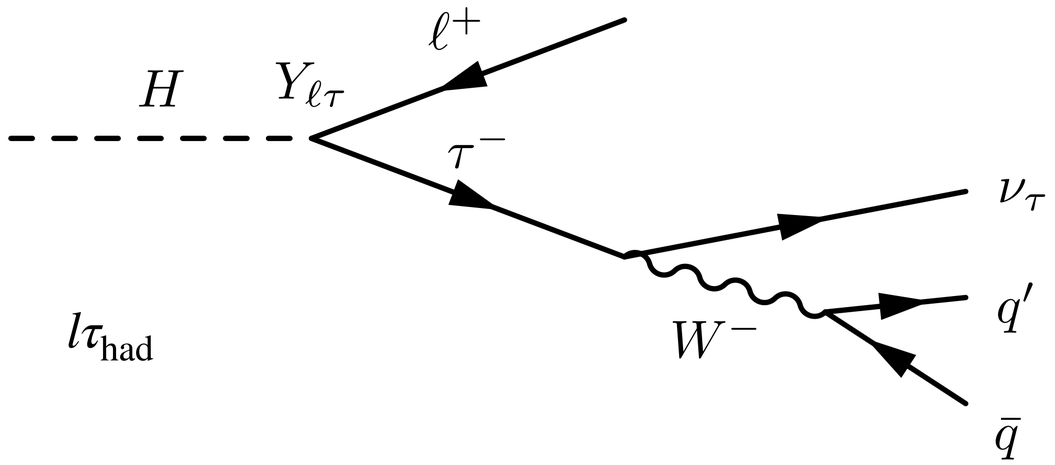
Background	Best-fit contribution in mass window [70, 110] GeV	[85, 95] GeV
$Z \rightarrow \tau\tau$	13716 ± 185	951 ± 13
$Z \rightarrow \mu\mu$	1557 ± 209	533 ± 72
Non-resonant	4105 ± 259	1075 ± 68

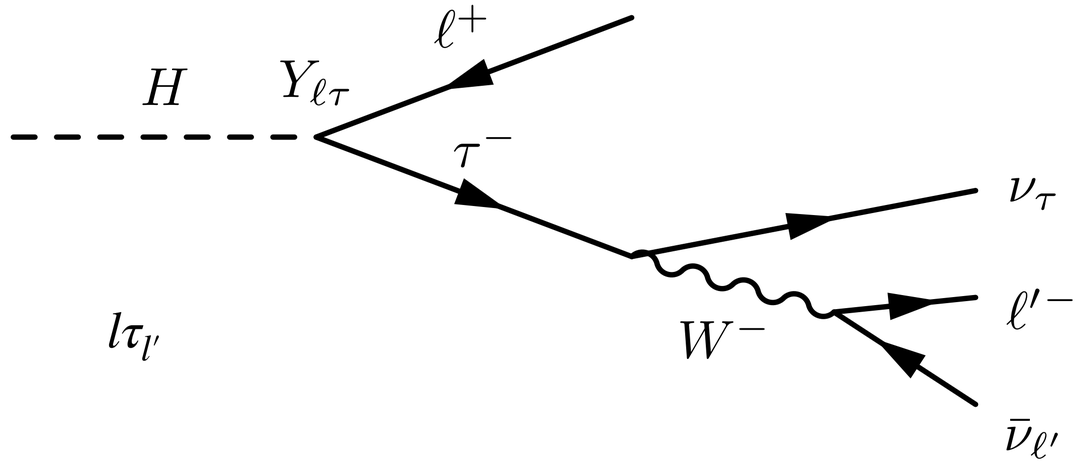


arxiv:2204.10783 [HEP]

Search for $H \to l\tau$ (l=e or μ)

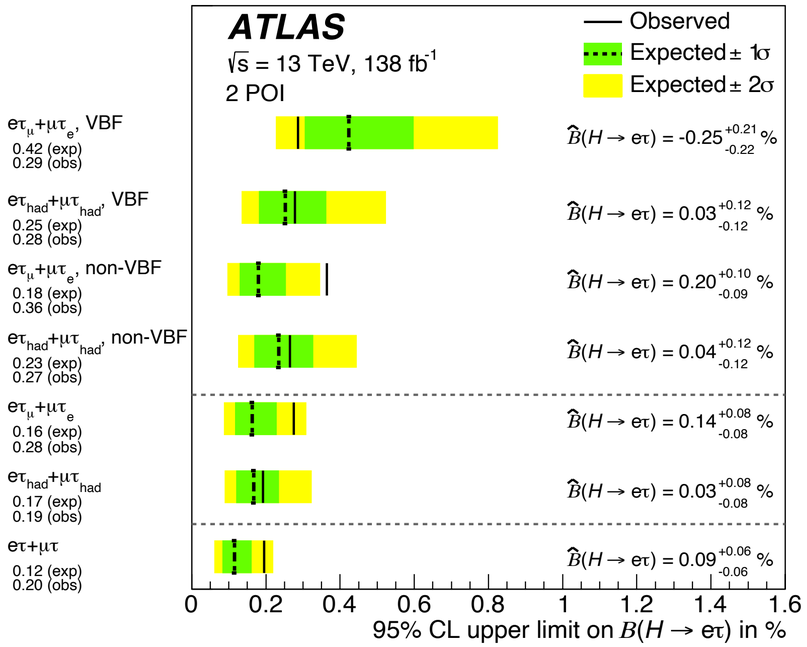
- $H \to e\tau$ and $H \to \mu\tau$ are independent signals (two searches); two background estimation methods targeting leptonic tau decays ($l\tau_l'$) and one for hadronic tau decays ($l\tau_{\text{had}}$)
  - Background estimation methods:
    - **MC-template**: fake taus from data-driven and the other backgrounds from MC templates for $l\tau_{\text{had}}$ and $l\tau_l'$:
    - **Symmetry-based**: fake taus from data-driven and the other backgrounds mainly via data-driven symmetry method for $l\tau_l'$
- The $l\tau_l'$ requires light leptons with different flavor to suppress background from $Z \to ll$
- Events categorization based on VBF and non-VBF Higgs production

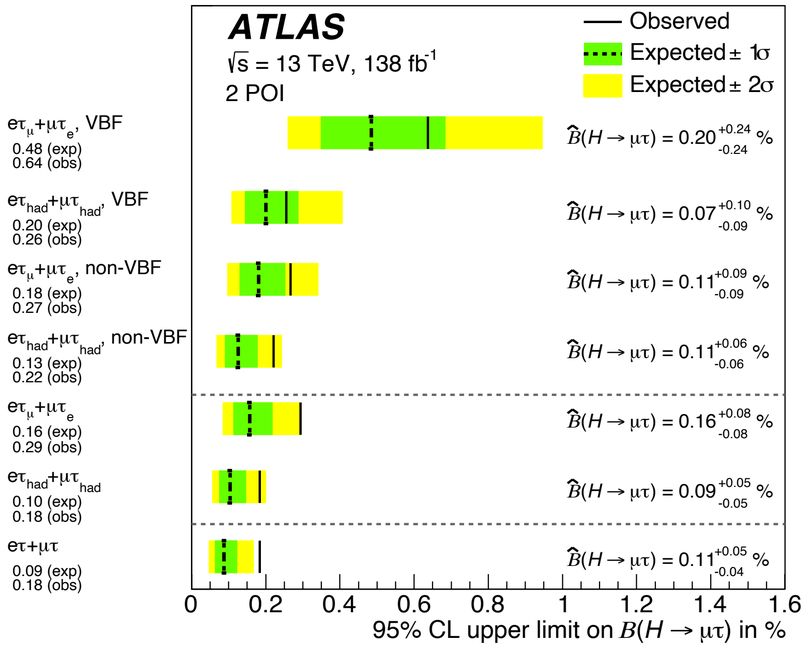


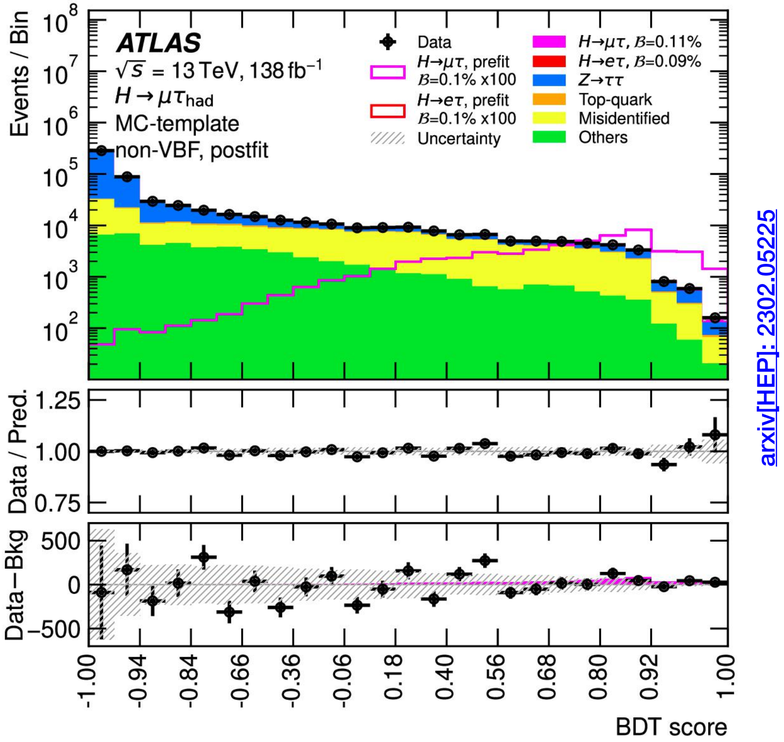


Search for $H \to l\tau$ (l=e or μ) in ATLAS

- The main backgrounds are: $Z \to \tau\tau$, Top processes, W+jets and QCD
- Misidentified tau well modeled using a data-driven method
- MVA to discriminate signal from background





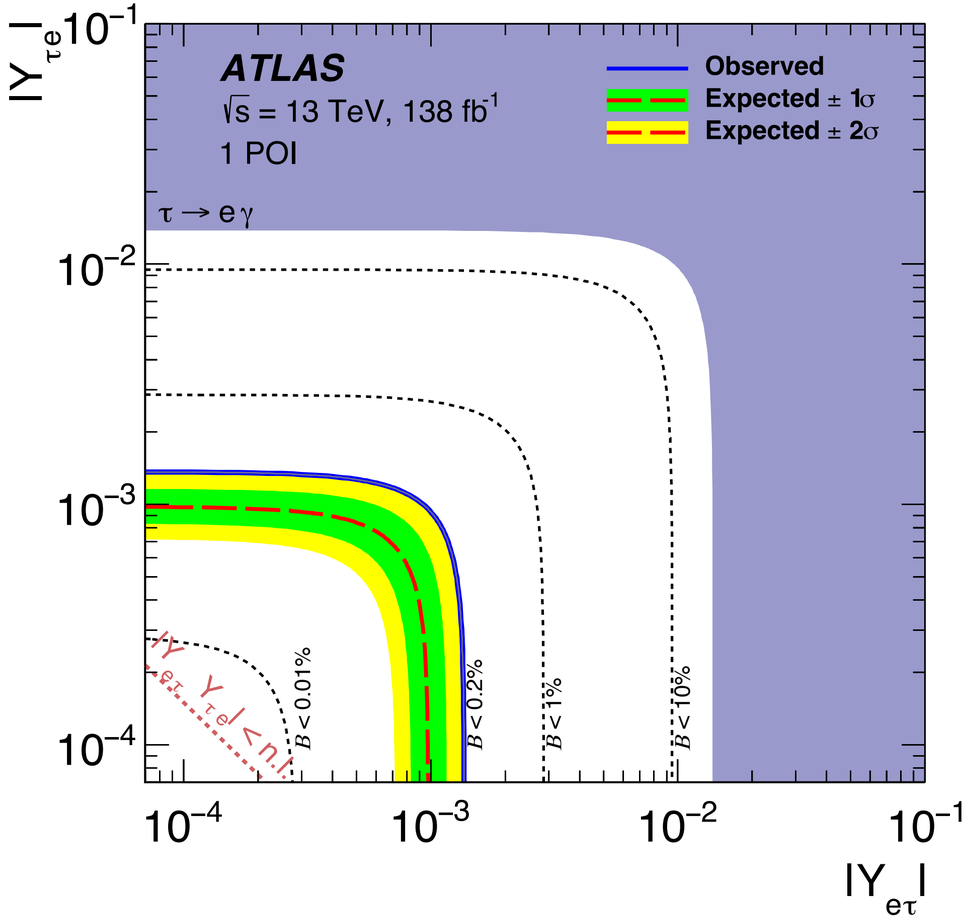


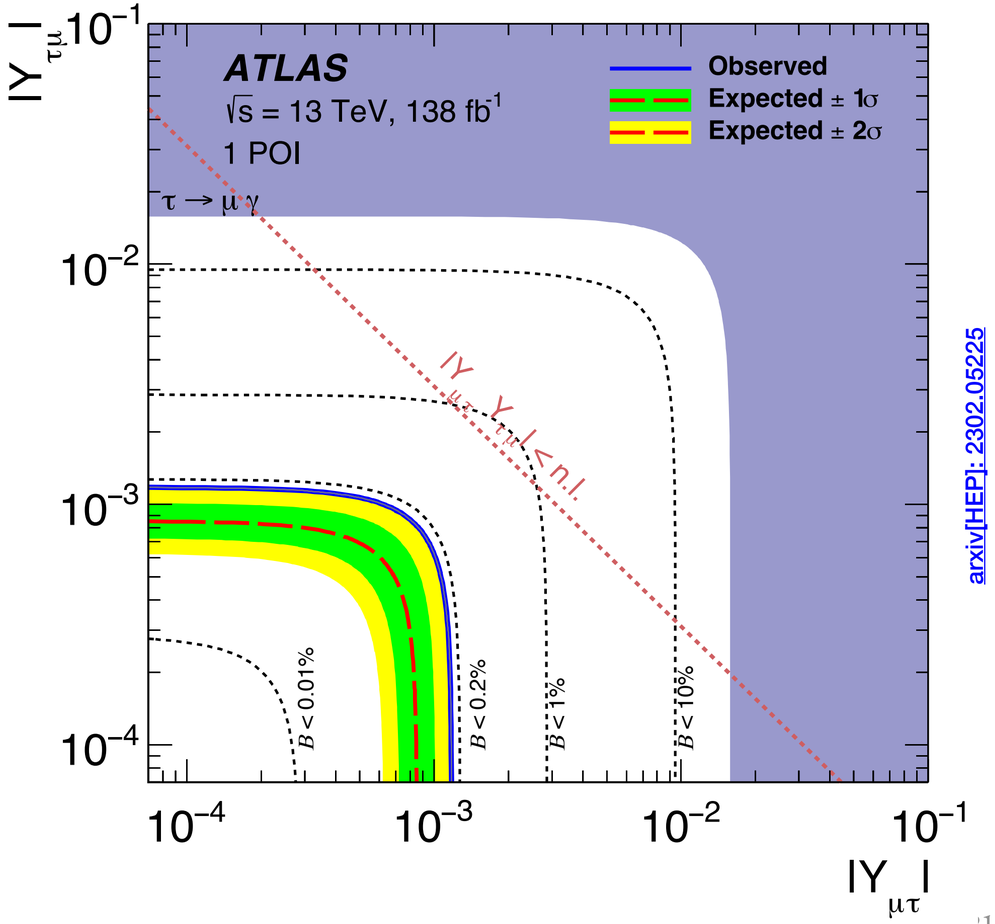
arxiv[HEP]: 2302.05225

Search for $H \to l\tau$ (l=e or μ) in ATLAS

- The $B(H \to l\tau)$ is related to the non-diagonal Yukawa coupling matrix elements

$$|Y_{\ell\tau}|^2 + |Y_{\tau\ell}|^2 = \frac{8\pi}{m_H} \frac{\mathcal{B}(H \to \ell\tau)}{1 - \mathcal{B}(H \to \ell\tau)} \Gamma_H(\mathrm{SM})$$

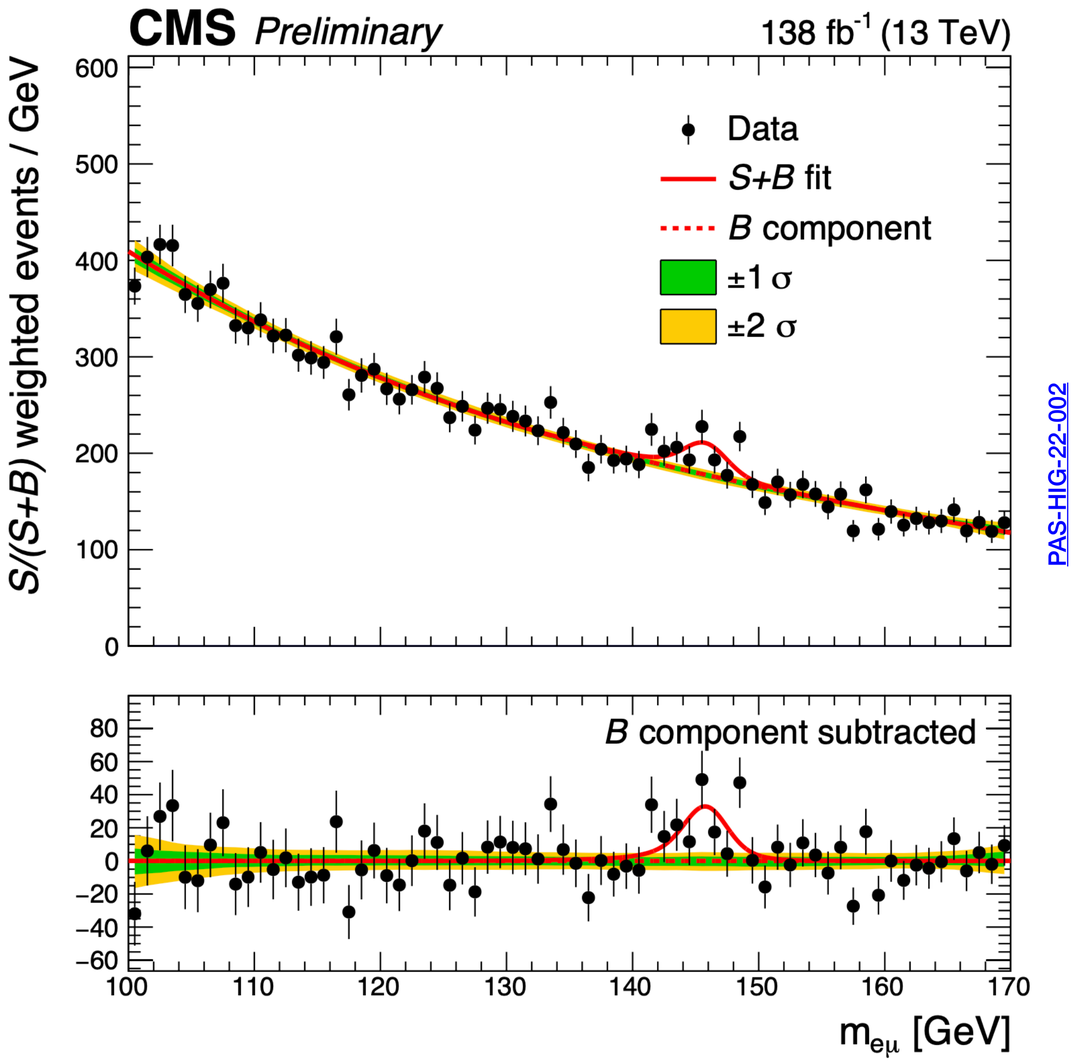




arxiv[HEP]: 2302.05225

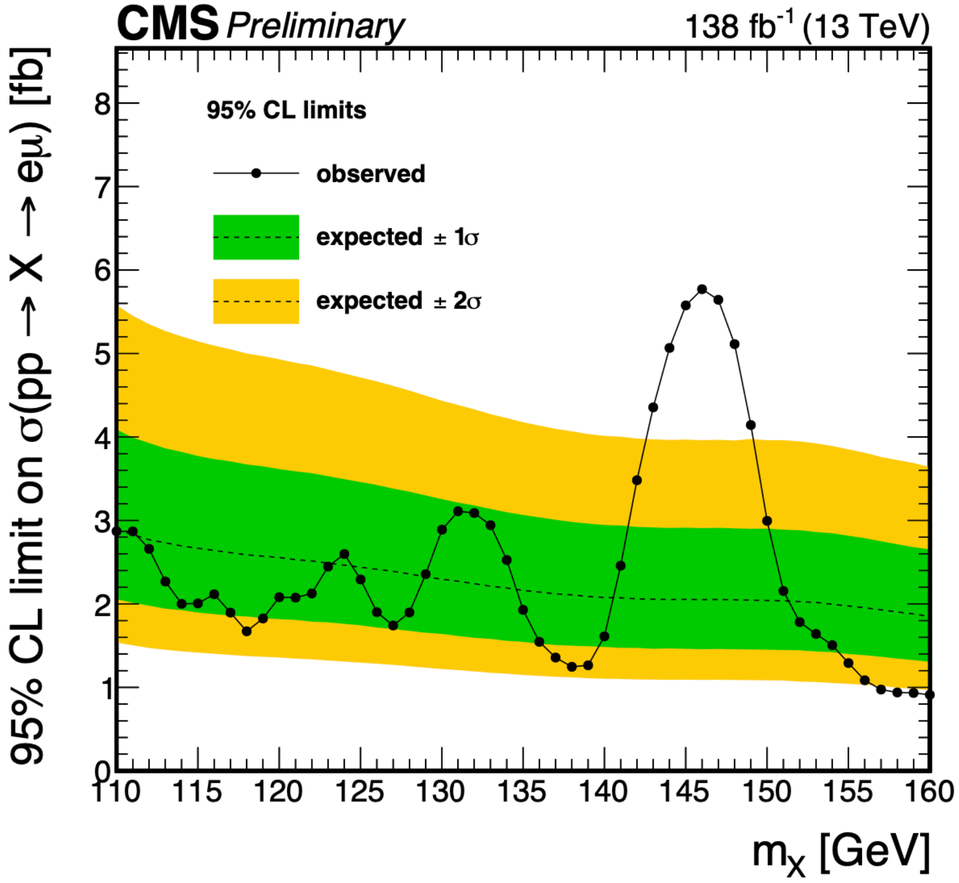
Near Higgs eμ search in CMS

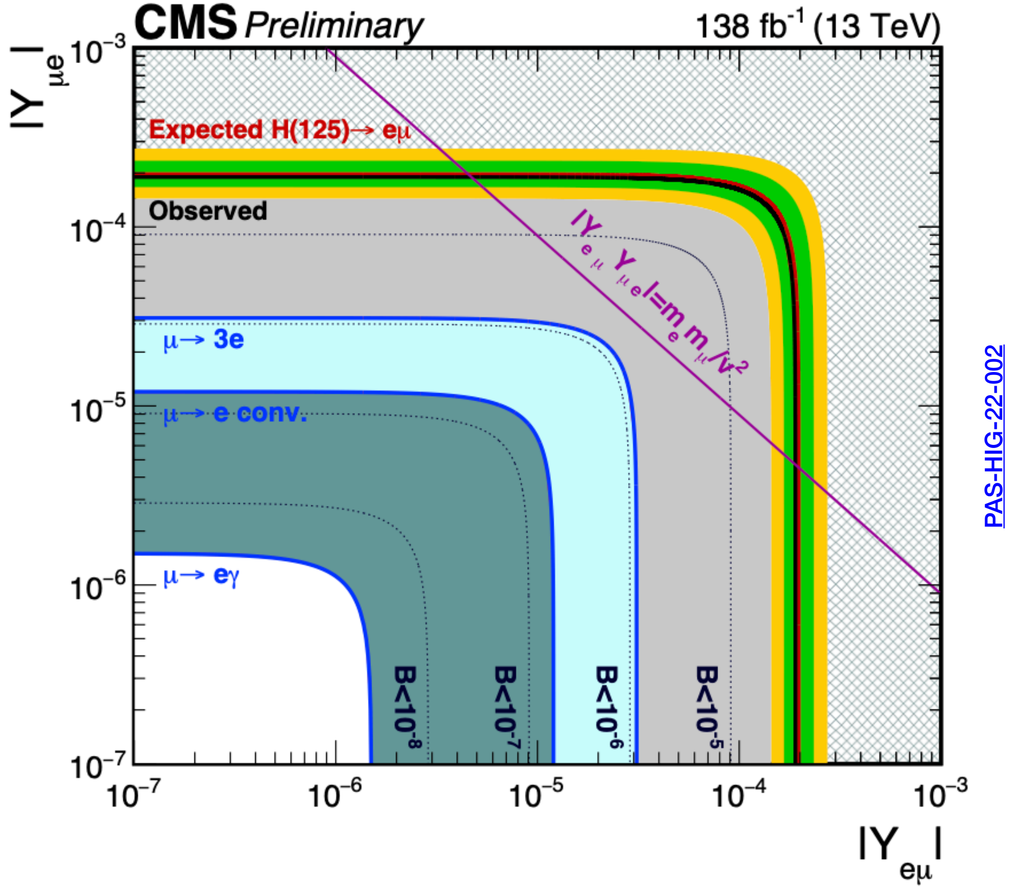
- CMS searched also for $X \to e^{\pm}\mu^{\mp}$ near the Higgs mass
- Two categories to split VBF from non-VBF production modes
- Background modeled using a Bernstein polynomial function



Near Higgs eμ search in CMS

- Possible sign of structure ~146 GeV
  - 2.8 (3.8) σ global (local) significance





PAS-HIG-22-002

Near Higgs eμ search in ATLAS

- ATLAS search for $H(125) \rightarrow e\mu$ not directly comparable with CMS analysis, but back-of-the-envelope calculation from sideband data disfavors a narrow-width excess, as observed by CMS

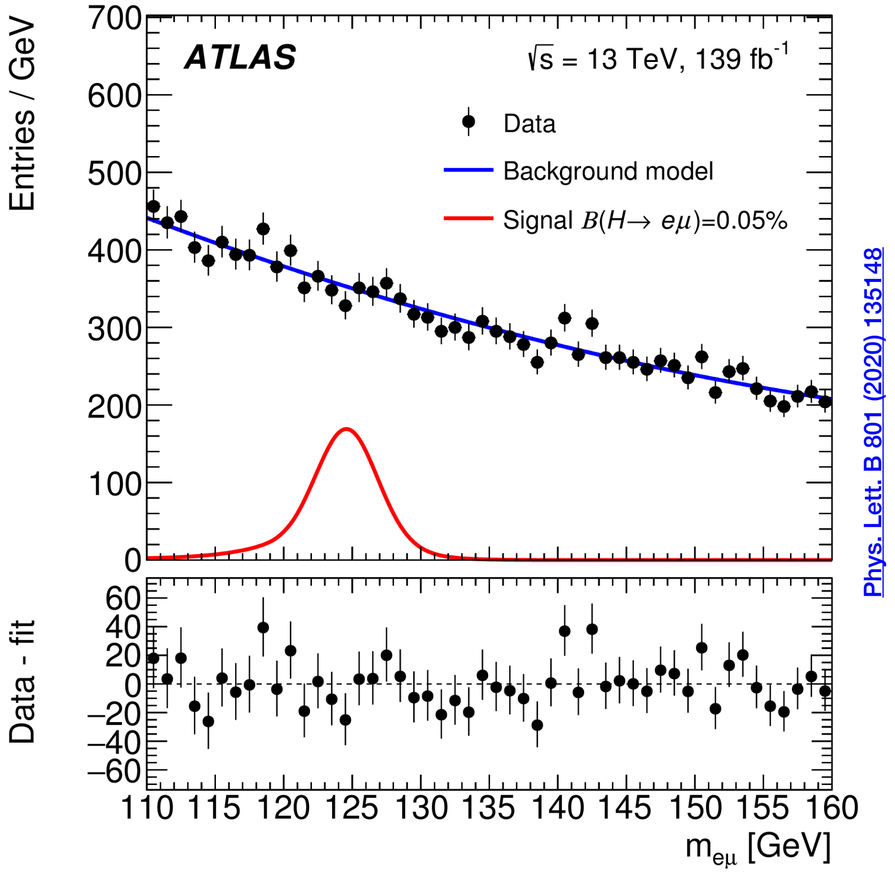
Back-of-the-envelope calculation courtesy of N. Berger and T. Masubuchi

Limit for 125 GeV Higgs:
BR(H→eμ) < 6.2x10^{-5} (observed)
< 5.9x10^{-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)

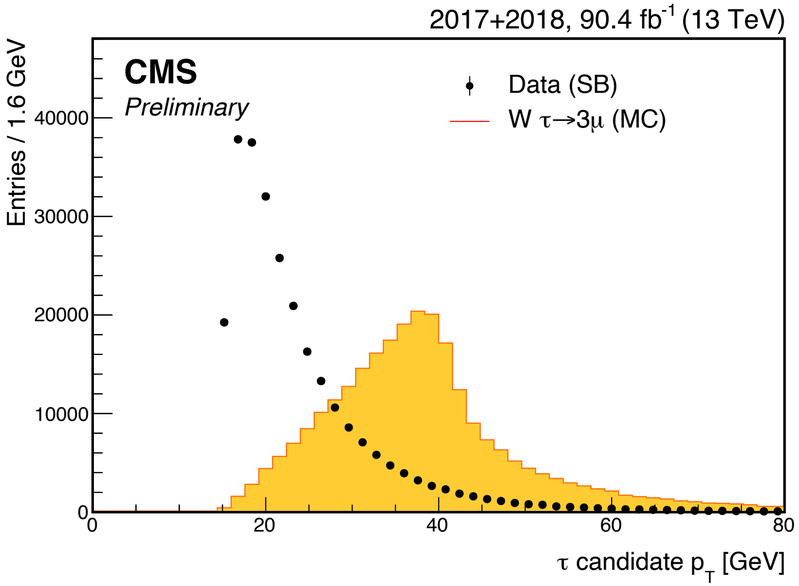
Rough scaling of backgrounds (slightly lower at 146 GeV than 125 GeV:
σ x BR < ~3 fb (expected and observed, since no excess seen)

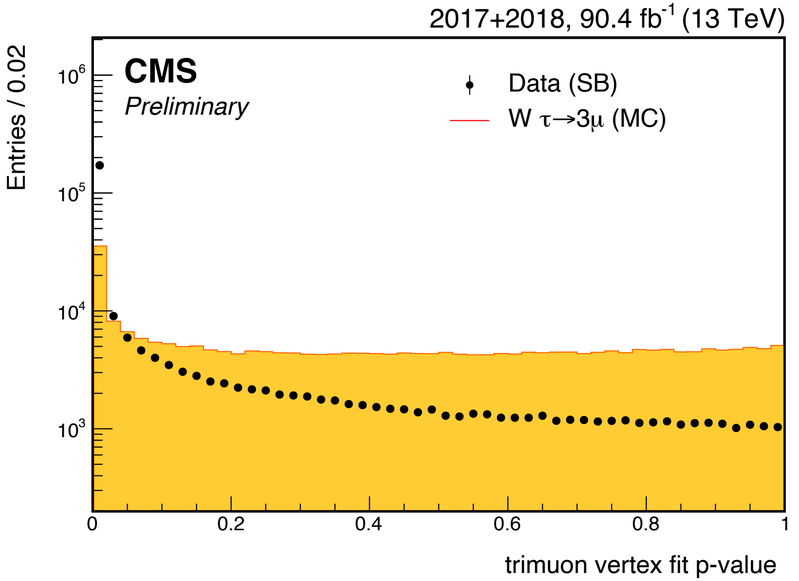
Not entirely conclusive (ballpark estimates + no directly comparable analysis), but CMS excess is disfavoured by ATLAS.



$\tau \to \mu\mu\mu$ decay

- Search for LFV $\tau \to \mu\mu\mu$ decay with 90.4 fb^{-1}
- It includes tau production from heavy flavor (B, D) and W decays
  - $W \to \tau\nu$ populates more the high pT
- Muon pT>7, 1, 1 GeV fit to common vertex
- pT(3μ) > 15 GeV
- BDT to separate signal from background
  - Muon identification
  - $\tau \to \mu\mu\mu$ vertex: chi2, pointing angle
- Split into three categories based on 3μ mass resolution

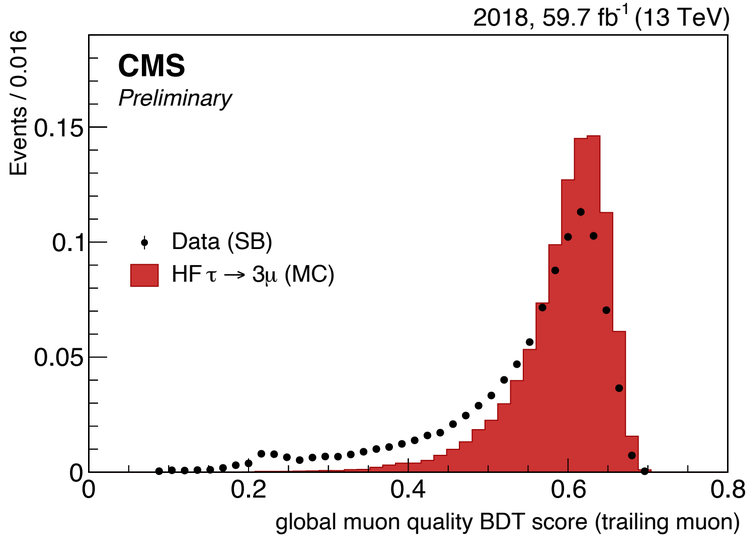


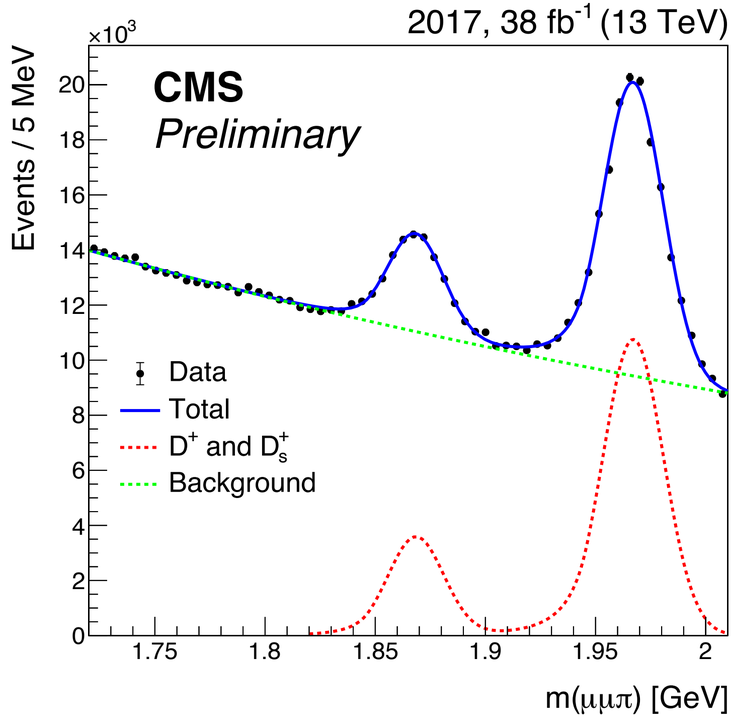


PAS-BPH-21-005

$\tau \to \mu\mu\mu$ Heavy flavor production

- Background dominated by π or K decay-in-flight and hadron tracks faking muons
  - BDT used to provide discrimination
- Three categories of mass resolution used
- BDT used to discriminate signal from background
- Signal normalized to $D_s^+ \to \phi(\mu^+\mu^-)\pi^+$ to minimize the dependence on B or D x-sec and muon selection efficiencies

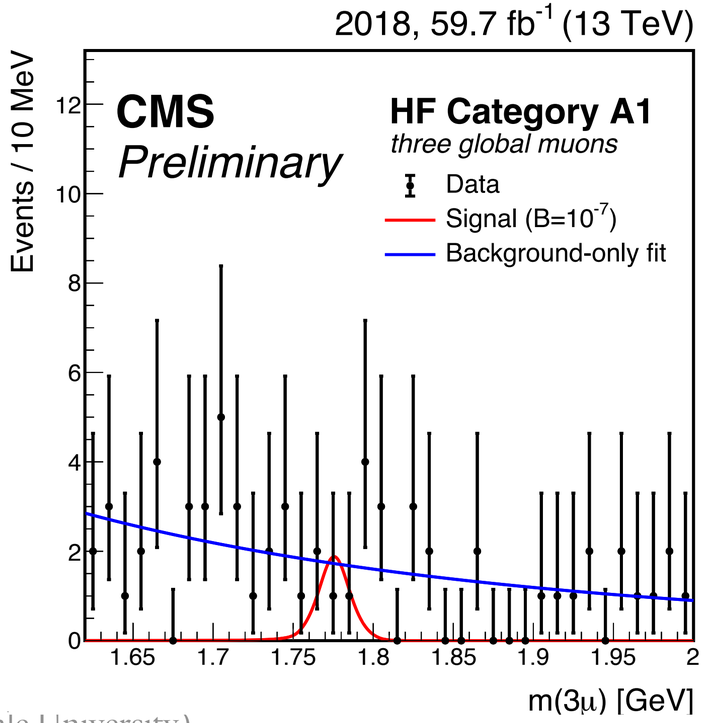


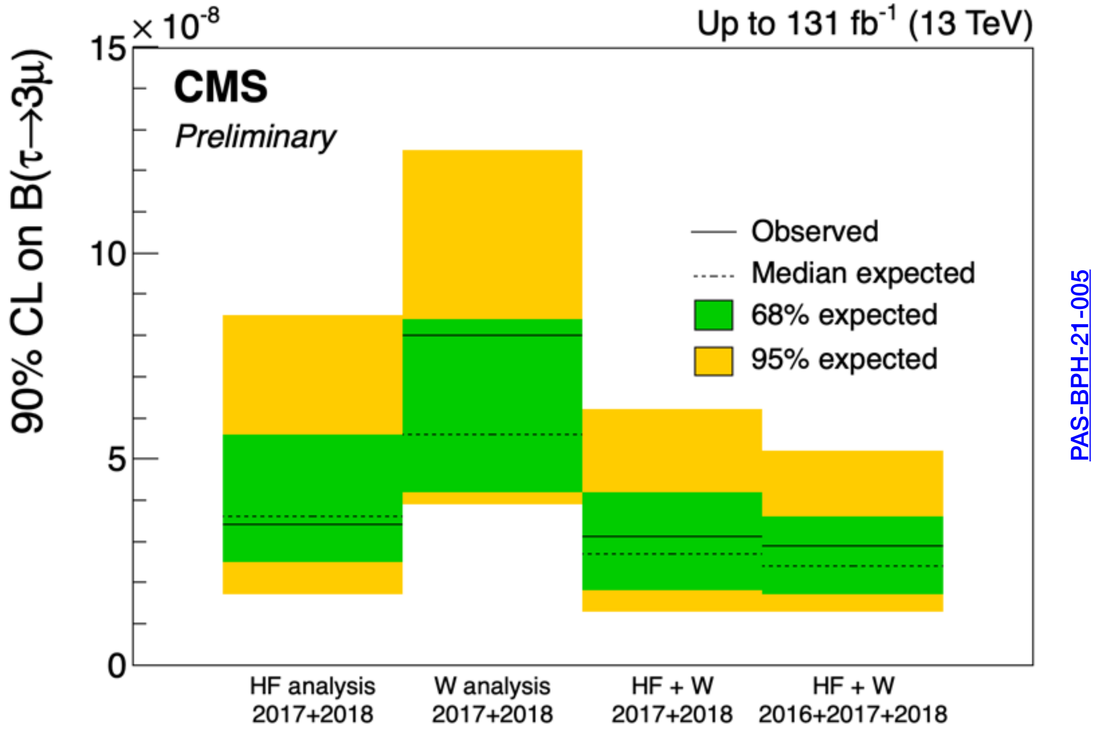


PAS-BPH-21-005

$\tau \to \mu\mu\mu$ decay

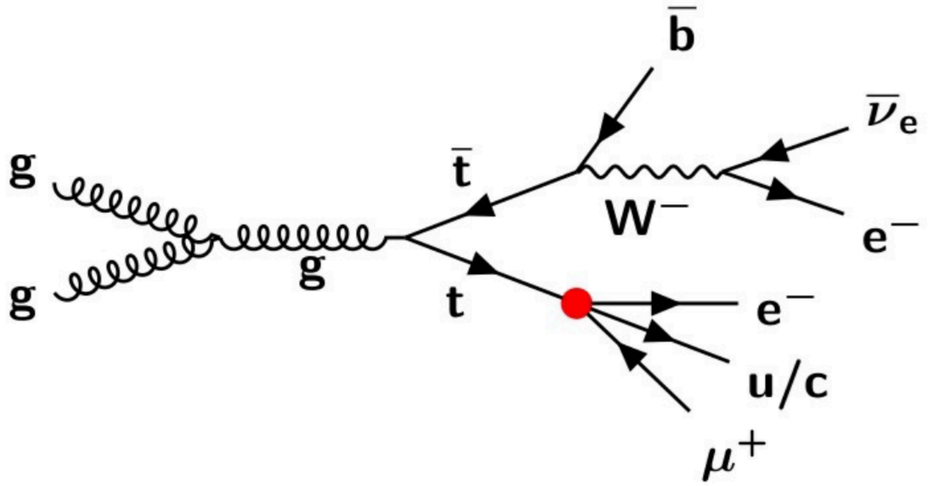
- Final result extracted from simultaneous parametrized fit to all the signal regions including the results from 2016 data
- Br($\tau \to \mu\mu\mu$) < 2.9 x10^{-8} at 90% CL
  - Getting very close to the world limit from Belle (2.1x10^{-8} at 90% CL)

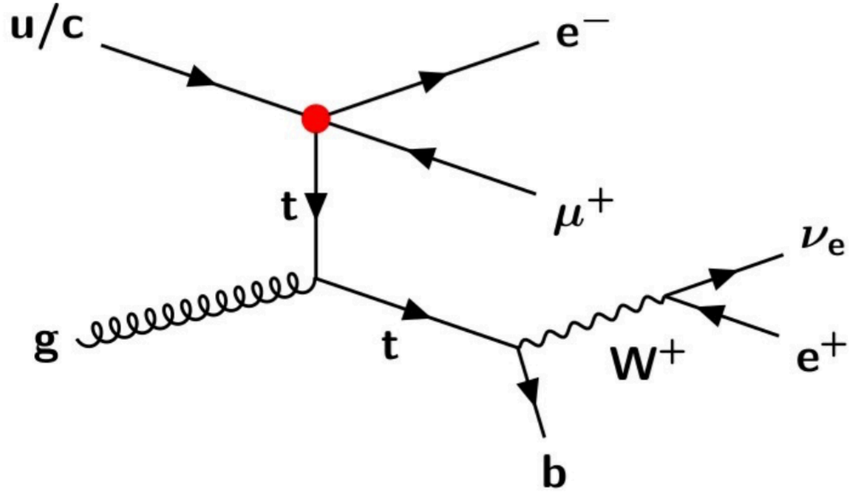




LFV from Top->3l+jets final state @ CMS

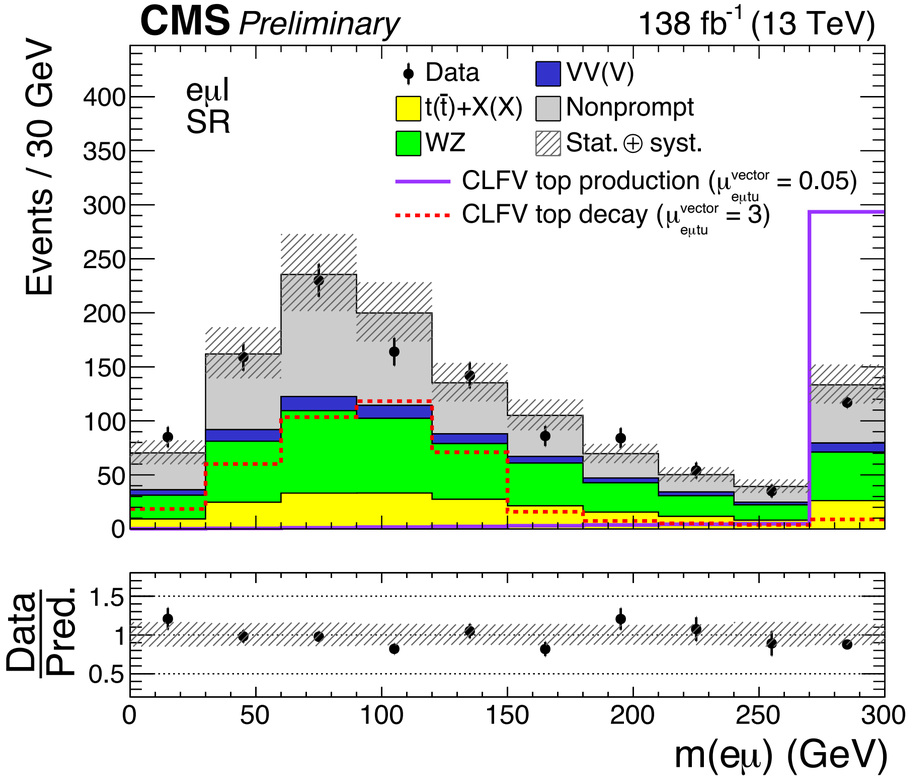
- Final state: eμ*l* + b-jet + ≥ 1 jet
  - eμ from LFV interaction
  - *l* from SM Top quark decay
- SM Top candidates assigned using: b-jet, extra light-lepton and the MET
- Possible in production and decay of Top quarks
- Inv-mass(eμ) used to define production (> 150 GeV) and decay (< 150 GeV) regions

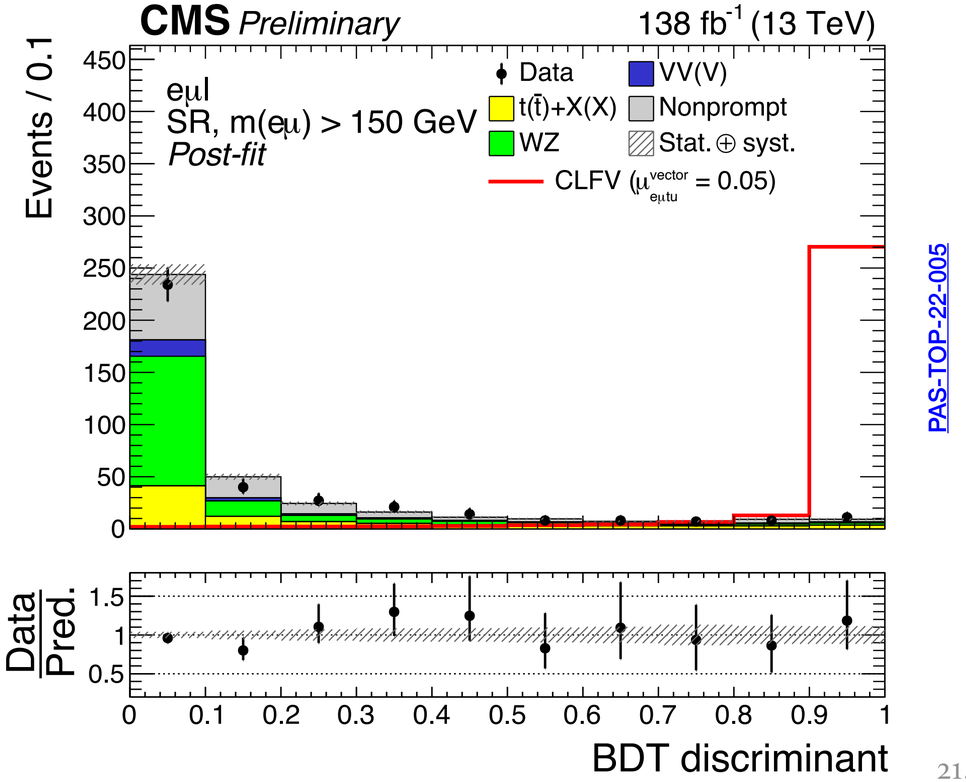




LFV from Top->3l+jets: background @ CMS

- Prompt bkg from SM processes with three real leptons (VV and VVV)
- Non-prompt bkg from one or more non-prompt leptons (b, c, or π decays)
- BDT trained to discriminate signal from background in the final fit

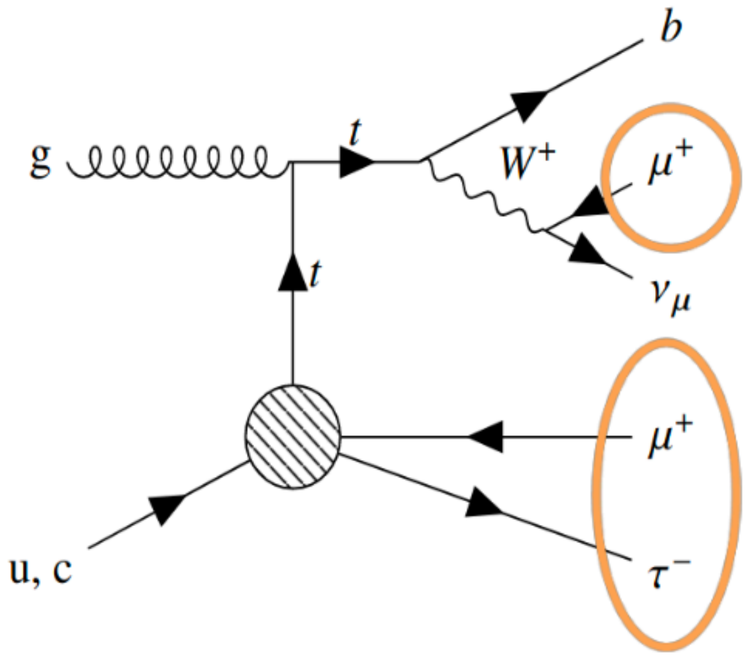


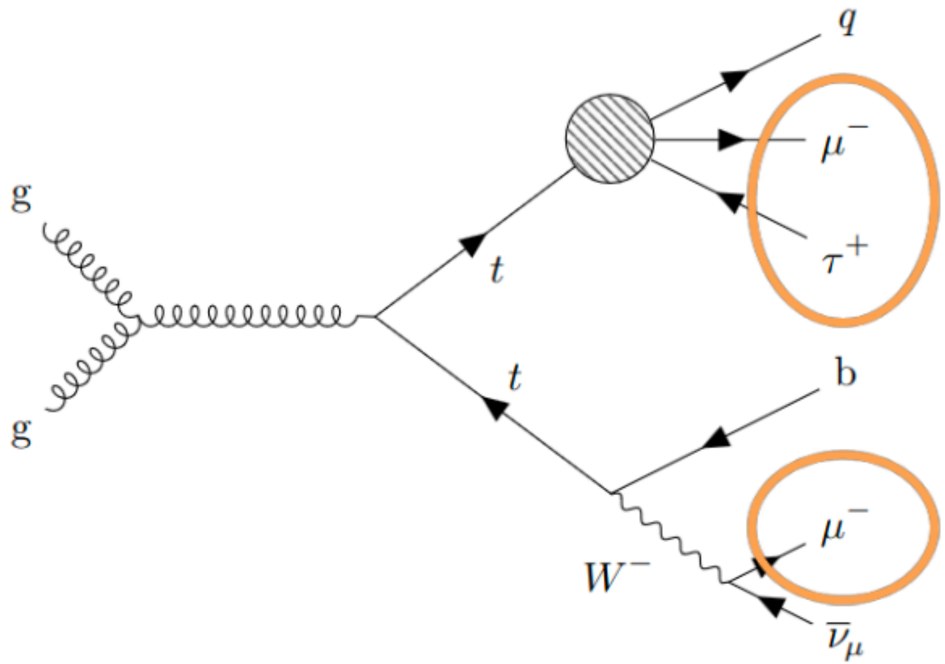


PAS-TOP-22-005

LFV from Top->3l+jets final state @ ATLAS

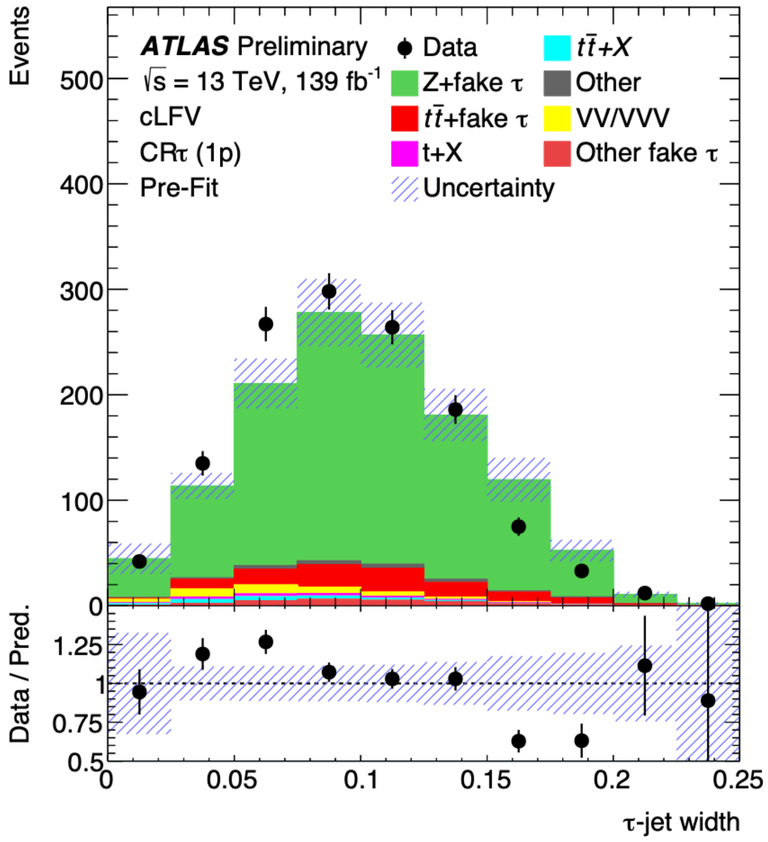
- Final state: τ + same-sign μμ + b-jet (+ ≥ 1 jet)
  - τμ from the LFV interaction
  - μ from SM Top quark decay
- Top quark decay and production diagrams differ by 1 jet

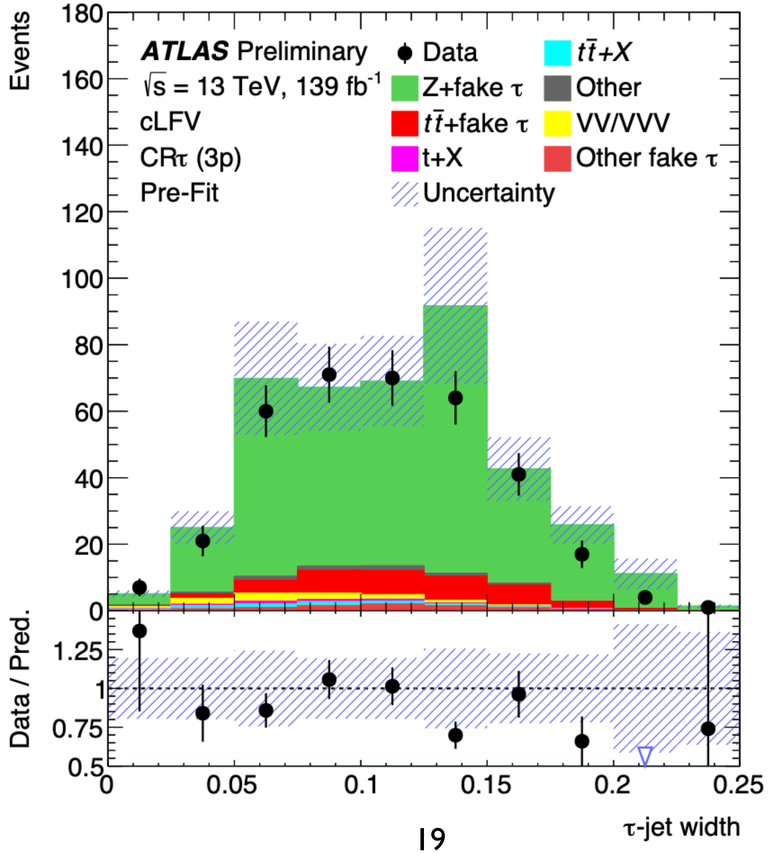


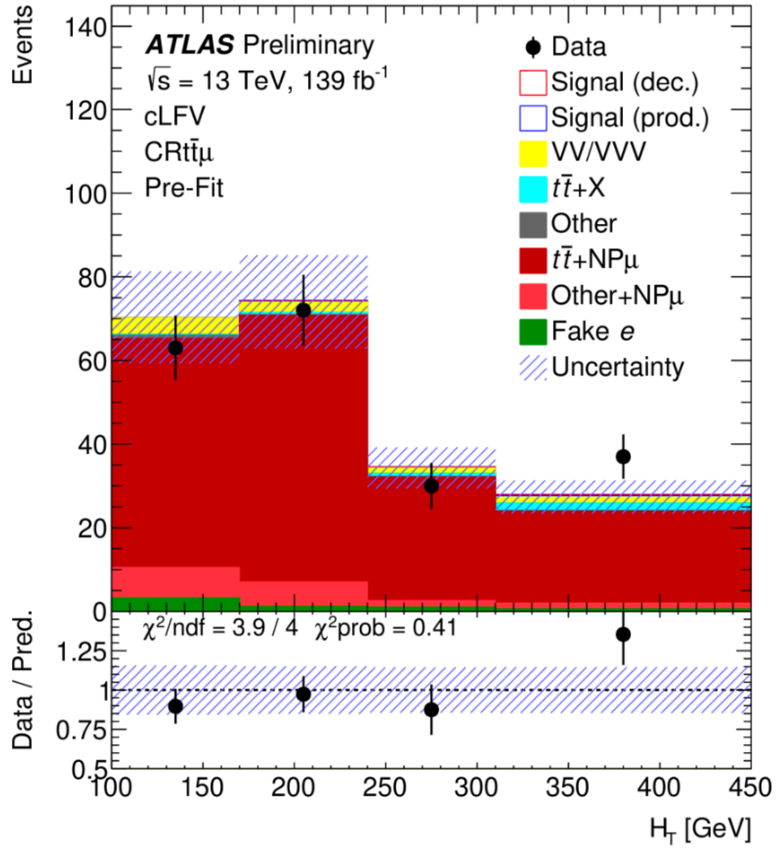


LFV from Top->3l+jets: background @ ATLAS

- The dominant background is due to $t\bar{t}$ events reconstructed with 3 leptons due to a non-prompt muon from a heavy-flavor decay inside a jet, typically a b-jet
- Fake taus from QCD jets are estimated using the Fake method
- Same-sign muons provide significant background reduction
- Control regions for fake-tau and fake/non-prompt-muon backgrounds







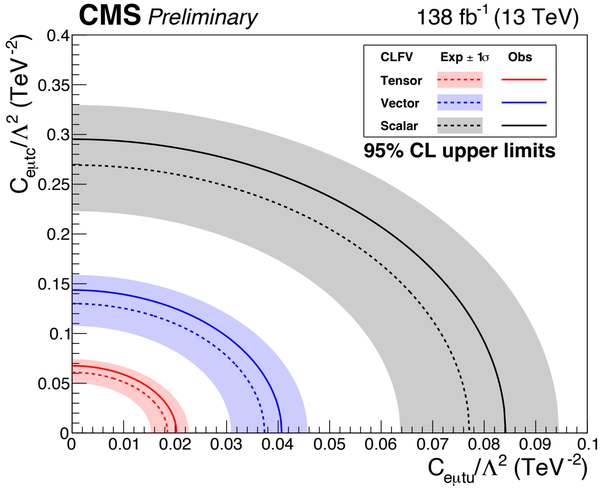
ATLAS-CONF-2023-001

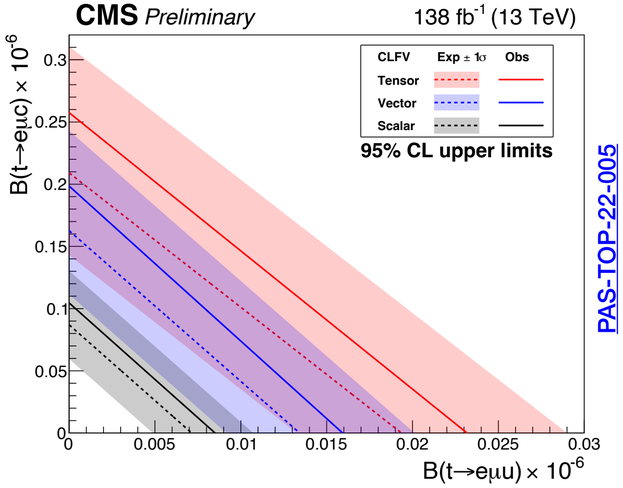
LFV from Top->3l+jets: interpretations

- Limit on Wilson coefficients and limits on branching fractions
- EFT limits w.r.t. the previous results improved by a factor ~[8, 50]

	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}

ATLAS-CONF-2023-001





PAS-TOP-22-005

	95% CL upper limits on Wilson coefficients c/Λ^2 [TeV^{-2}]							
	$c_{lq}^{-(ijk3)}$	$c_{eq}^{(ijk3)}$	$c_{lu}^{(ijk3)}$	$c_{eu}^{(ijk3)}$	$c_{lequ}^{1(ijk3)}$	$c_{lequ}^{1(ij3k)}$	$c_{lequ}^{3(ijk3)}$	$c_{lequ}^{3(ij3k)}$
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
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

ATLAS-CONF-2023-001

High Mass searches

- Variety of New Physics models can produce heavy resonances decaying to lepton pairs
  - if LFV couplings are included, can expect final states with two different-flavor (charged) light leptons and no neutrinos
- Target dilepton mass > 600 GeV with back-to-back topology
- When a tau is involved, the neutrino direction is taken as the same as the visible tau components
  - This results in a mass resolution of ~4% for eτ and 12% for $\mu\tau$ for a 2 TeV benchmark Z'

High Mass searches: backgrounds

Final states: $X \to e^{\pm}\mu^{\mp}$, $e^{\pm}\tau^{\mp}$, $\mu^{\pm}\tau^{\mp}$

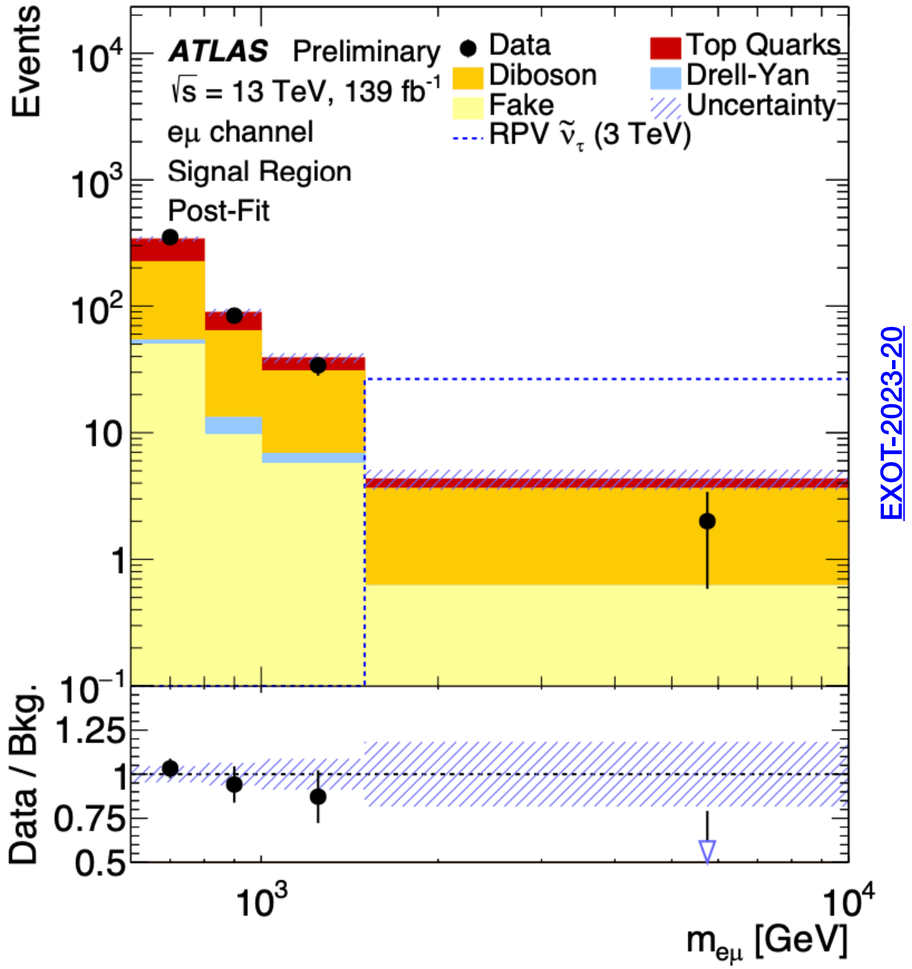
Two main background components:

Irreducible

- SM processes with true opposite charge different flavor leptons (VV, $t\bar{t}$, $Z \to \tau\tau$)
- Estimated from MC simulations corrected with data using dedicated background-enriched regions

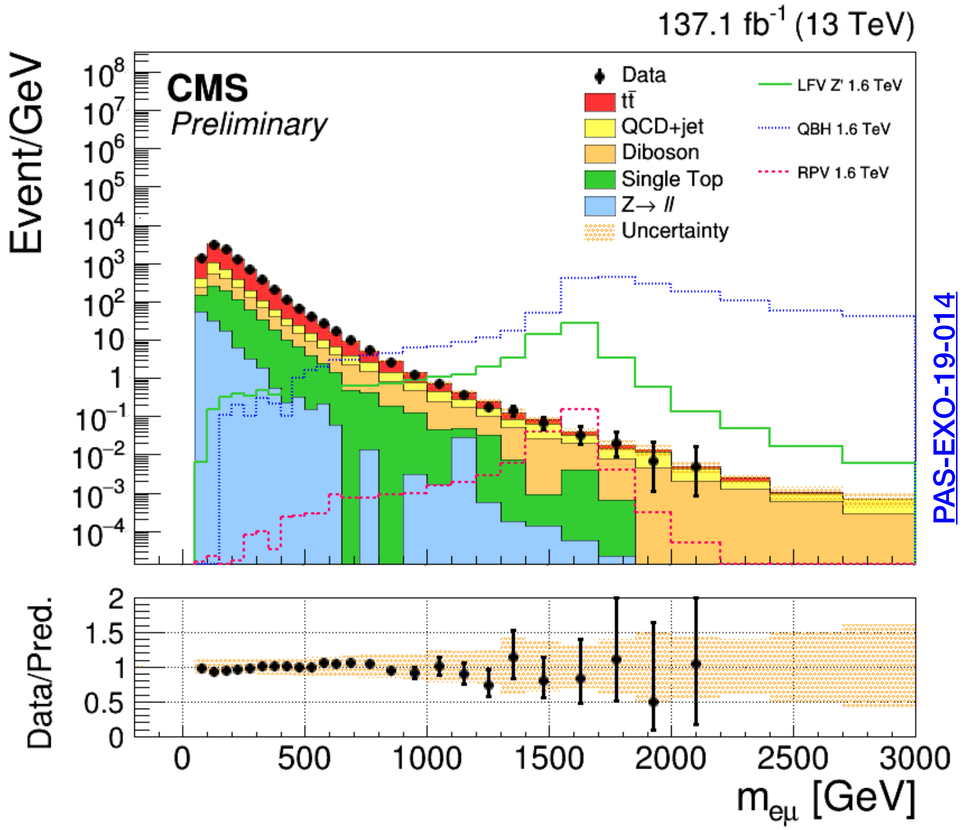
Reducible

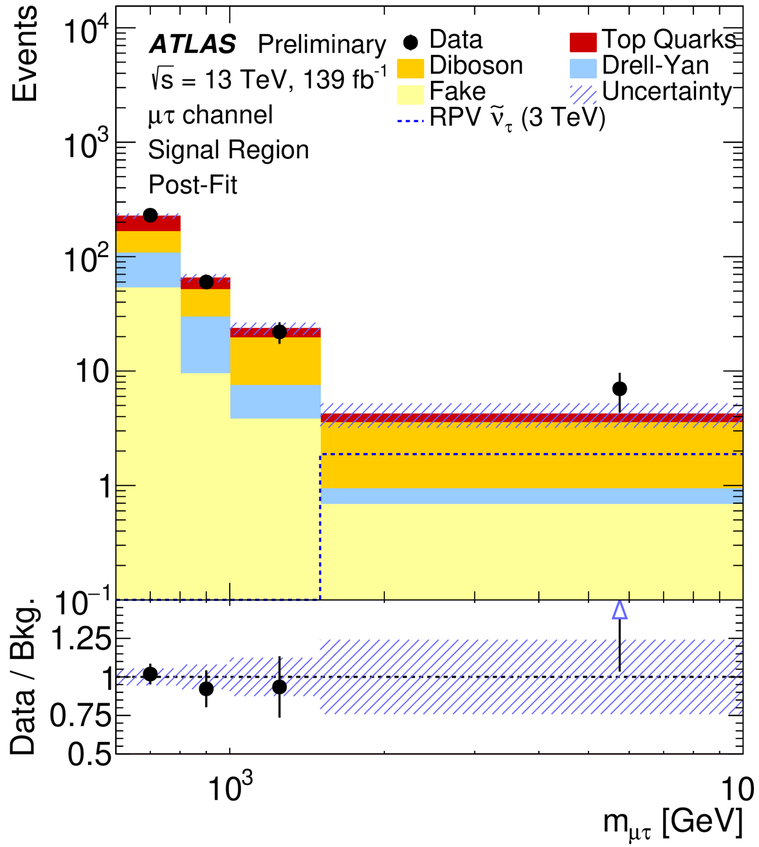
- Jets mis-reconstructed as leptons (W+jets, multijet)
- Non-prompt e or μ
- QCD jets faking τ_{had} derived scaling the background enriched control region (CR) yield by SR/CR ratio from MC simulation

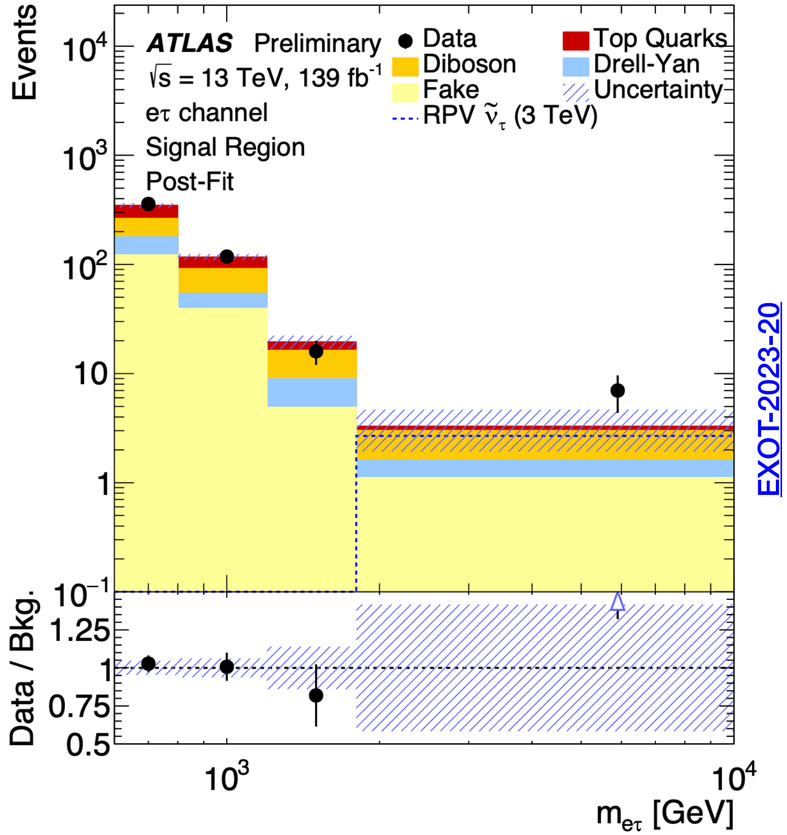


High Mass searches: results

- ATLAS shows an interesting excess ~2 sigma in the highest mass bin in eτ and $\mu\tau$ channels
- Similar search performed by CMS doesn't confirm the excess in the sneutrino search

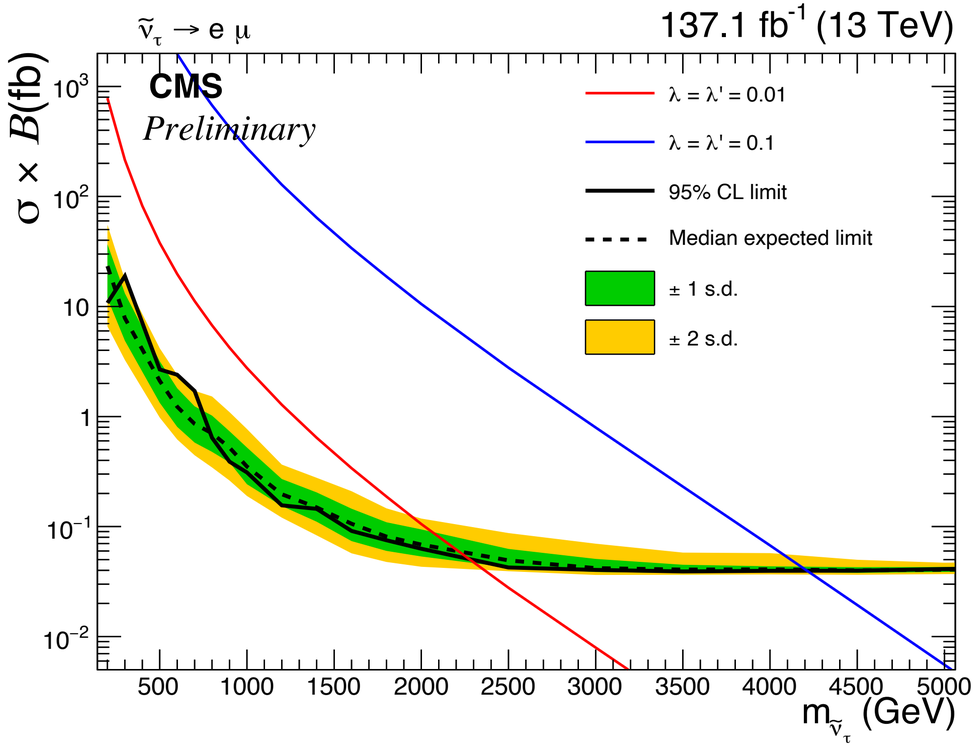






High Mass searches: results

- Results interpreted as limit on a variety of BSM models: Z', RPV, quantum black holes, sneutrinos



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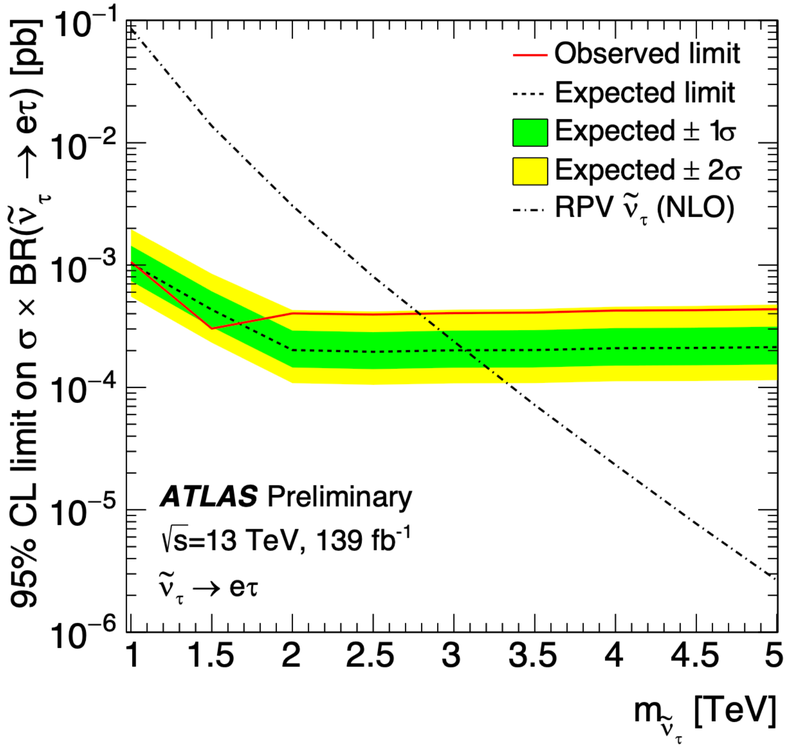

EXOT-2019-20

Summary

- LHC experiments delivered many searches of LFV processes
- The LHC has world's best sensitivity to many LFV channels including Z, Higgs, and Top decays and high mass searches
- CMS limit on Br($\tau \rightarrow \mu\mu\mu$) it is getting very close to the results from Belle
- No clear signs of LFV yet, but several interesting hints to be followed up with more data