Search for Lepton Flavor Violation in Z and Higgs decays with the CMS Experiment

Alexander Nehrkorn for the CMS Collaboration

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DFG

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Bundesministerium für Bildung und Forschung

CMS Germany

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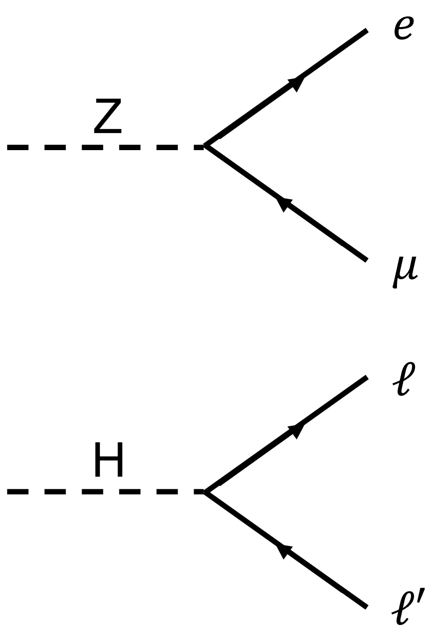
Outline

- Introduction
- Searches for lepton flavor violation (LFV) in . . .
  - . . . decays of the Z boson
  - . . . decays of the Higgs boson
- Summary



Lepton flavor violation

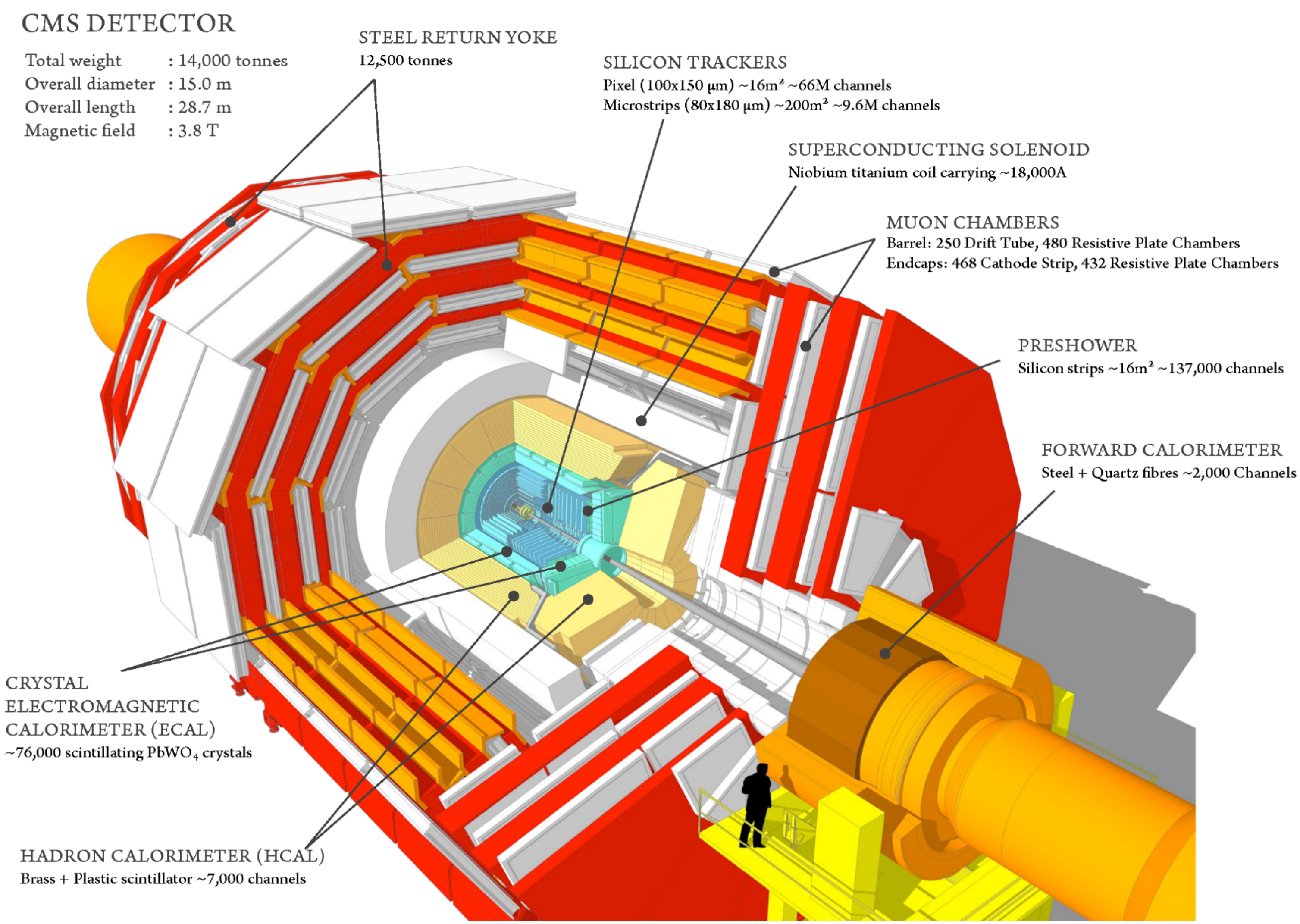
- Lepton flavor is conserved in particle interactions in the standard model (SM)
  - Reason for this is not an underlying symmetry but the lack of observed LFV

- An analysis of the atmospheric neutrino flux in 1998 resulted in the first evidence of neutrino oscillations (doi:10.1103/PhysRevLett.81.1562)
  → proves neutral LFV

- What about charged LFV?
  - Many searches carried out by low and high energy experiments without success
    - e.g. $\mu \rightarrow e\gamma$, $\mu \rightarrow 3e$, $\tau \rightarrow e\gamma$, $Z \rightarrow \mu\tau$, . . .
  - Charged LFV enhanced in a lot of BSM theories → good probe for new physics

→ Let's look for it in LHC data

Introduction



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Search for LFV in Z decays

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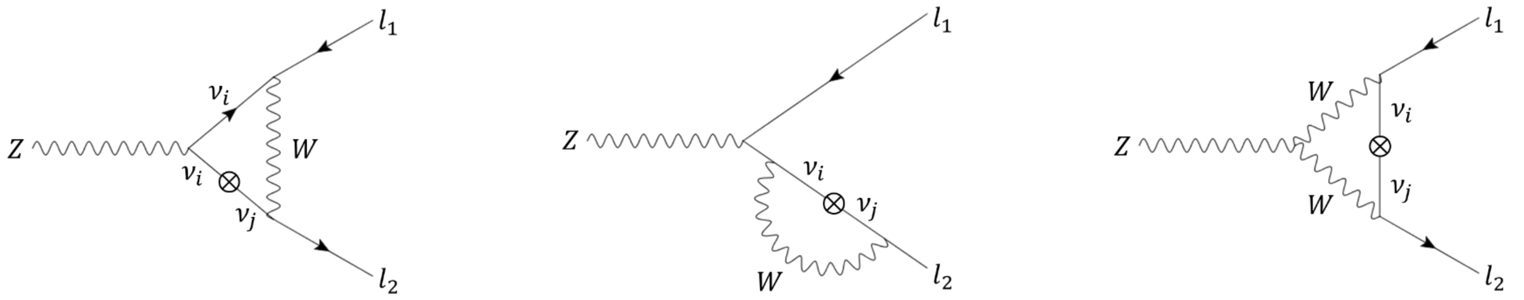
Search for LFV in Z decays

arXiv:hep-ph/0010193

Introduction

- Neutrino oscillation predicts LFV in Z decays, but $\mathcal{B}(Z \to e\mu) < 10^{-60}$



- Good probe for new physics

- Current constraints:
  - Indirect from $\mu \to 3e$: $\mathcal{B}(Z \to e\mu) < 5 \cdot 10^{-13}$
  - Direct from ATLAS: $\mathcal{B}(Z \to e\mu) < 7.5 \cdot 10^{-7}$

Phys. Rev. D. 90, 072010 (2014)

Search strategy

Lepton selection

↓

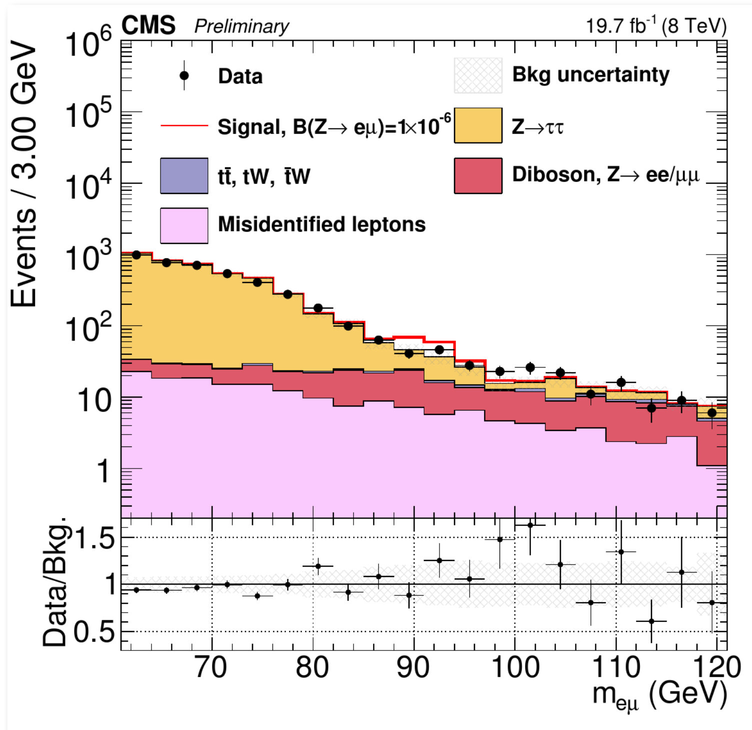
Calculate $m_{e\mu}$

↓

Background suppression

$p_T(jet)$ $p_T(Z)$

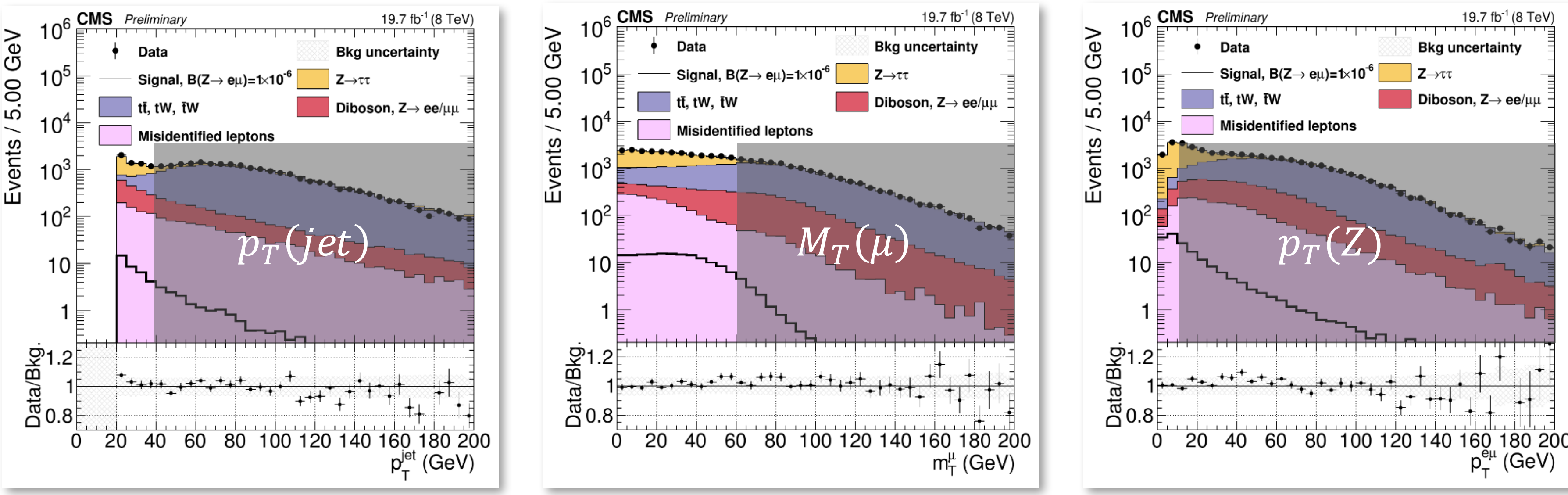
$M_T(\mu)$



→ Determine $\mathcal{B}(Z \to e\mu)$

→ Determine limit on $\mathcal{B}(Z \to e\mu)$

Background supression



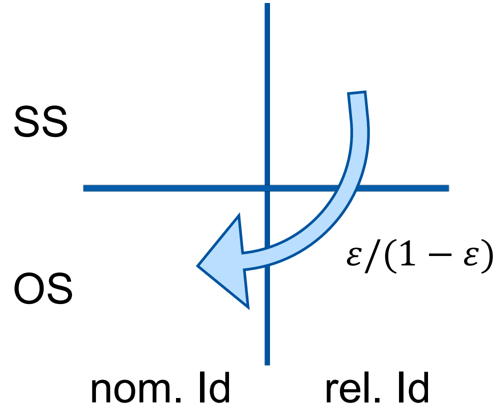
Reduce top-pair contribution

Reduce top-pair & W^+W^- contribution

Reduce top-pair, W^+W^- & fake lepton contribution

Background estimation

- $Z \to \tau\tau$, top-antitop, diboson and single-top events from simulation
  - Normalization from (N)NLO cross section calculations
- W+jets & multijet background: fake rate method
  - Measure rate of leptons passing relaxed identification criteria and subsequently nominal ones in background enriched data sample → fake rate ε
  - Apply weights $\varepsilon/(1-\varepsilon)$ to events in data where
    - 1 lepton does not pass: W+jets
    - Neither lepton passes: multijet background



Systematic uncertainties

Source	Uncertainty Background	Uncertainty Signal
Luminosity	2.6%	2.6%
Pileup	3.3%	0.8%
Trigger	0.3%	0.5%
Muon Id	0.5%	0.8%
Muon p_T scale	2.9%	0.2%
Muon p_T resolution	0.4%	0.1%
Electron Id	0.5%	0.8%
Electron energy scale	3.1%	1.1%
Electron energy resolution	0.3%	0.4%
Jet energy scale	0.2%	$< 0.1\%$
Jet energy resolution	$< 0.1\%$	$< 0.1\%$
E_T^{miss}	0.6%	2.2%
Dilepton p_T	0.4%	1.1%
PDF	1.0%	1.0%
Limited number of simulated events	10.6%	1.2%
Normalization	6.8%	3.3%

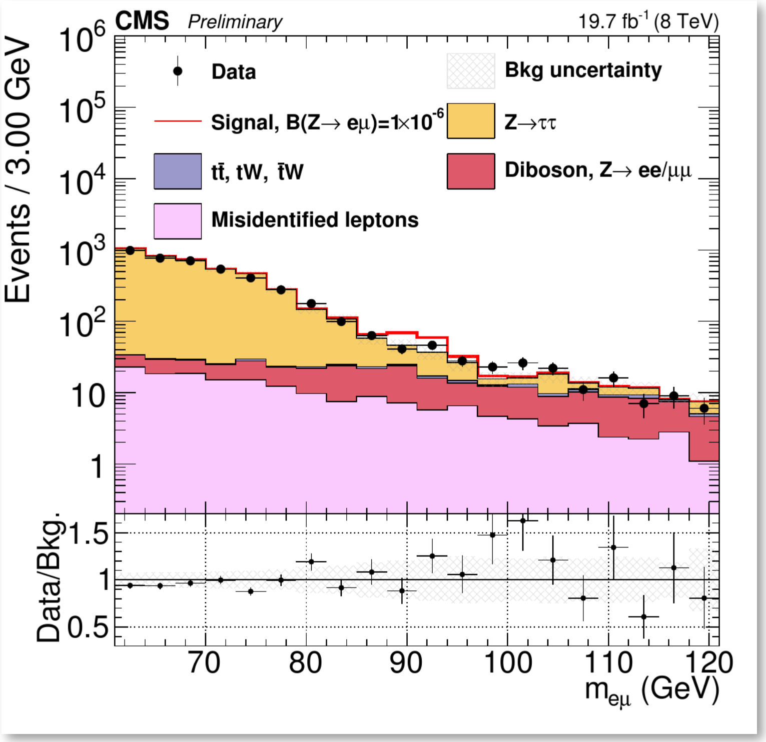
Search for LFV in Z decays

Results

- Count events in window around Z mass: (91 ± 3) GeV
- Background prediction of 83 ± 9
- Events found in data: 87
- Use CLs method to determine limit:

$$\mathcal{B}(Z \to e\mu)_{expected} < (6.7^{+2.8}_{-2.0}) \cdot 10^{-7}$$

$$\mathcal{B}(Z \to e\mu)_{observed} < 7.3 \cdot 10^{-7}$$



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Search for LFV in Higgs decays

Search for LFV in Higgs decays

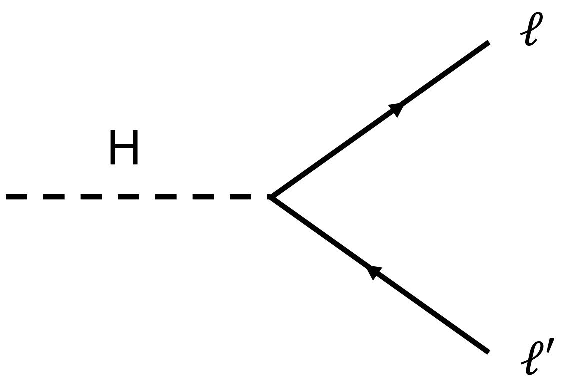
arXiv:1209.1397

Introduction

- LFV couplings to the Higgs possible, e.g. if SM only valid to finite scale Λ

$$Y_{ij} = \frac{m_i}{v}\delta_{ij} + \frac{v^2}{\sqrt{2}\Lambda^2}\hat{\lambda}_{ij}$$

- LFV Higgs couplings would allow processes like $\mu \to e$, $\tau \to \mu$ and $\tau \to e$ via a virtual Higgs boson



- $\mathcal{B}(H \to e\mu) < \mathcal{O}(10^{-8})$ @ 95% CL from $\mu \to e\gamma$
- $\mathcal{B}(H \to e\tau/\mu\tau) < \mathcal{O}(10\%)$ @ 95% CL from $\tau \to e\gamma/\mu\gamma$ and e/μ g-2 measurements
- $\mathcal{B}(H \to e\tau/\mu\tau) < 13\%$ @ 95% CL from theoretical reinterpretation of $H \to \tau\tau$ search results from ATLAS

→ direct search very promising

Search for LFV in Higgs decays

Search strategy

Lepton selection

Categorisation: n_{jet} = 0, 1 or 2

Calculate $m_{\ell\ell'}$

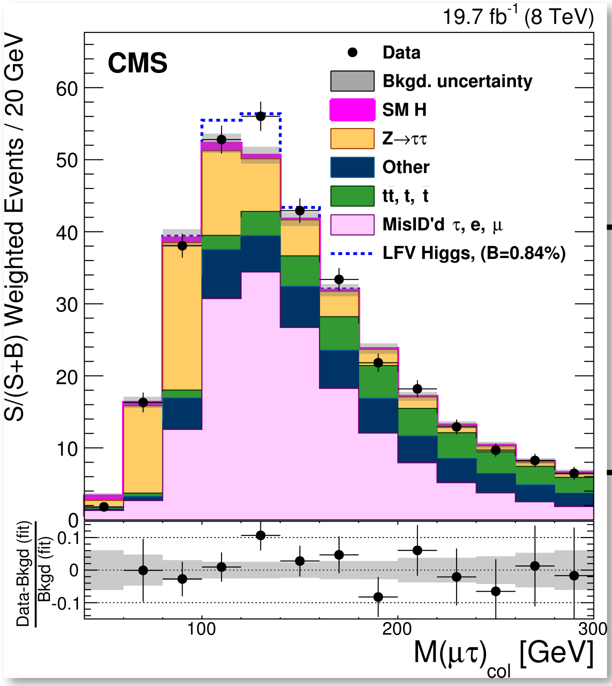
Background suppression

$p_T(\ell)$

$\Delta\phi(\ell, \ell')$

$M_T(\ell)$

$\Delta\phi(E_T^{miss}, \ell)$



Determine $\mathcal{B}(H \to \ell\ell')$

Determine limit on $\mathcal{B}(H \to \ell\ell')$

Background estimation

$H \to e\tau$ and $H \to \mu\tau$

- Embedding for $Z \to \tau\tau$
  - Measure $Z \to \mu\mu$ in data and replace μ by simulated τ
- Misidentified leptons
  - Use ABCD method
  - Regions split by charge of pair and isolation of τ
- Top-pair background
  - Shape from simulation but normalization from data
- Others from simulation

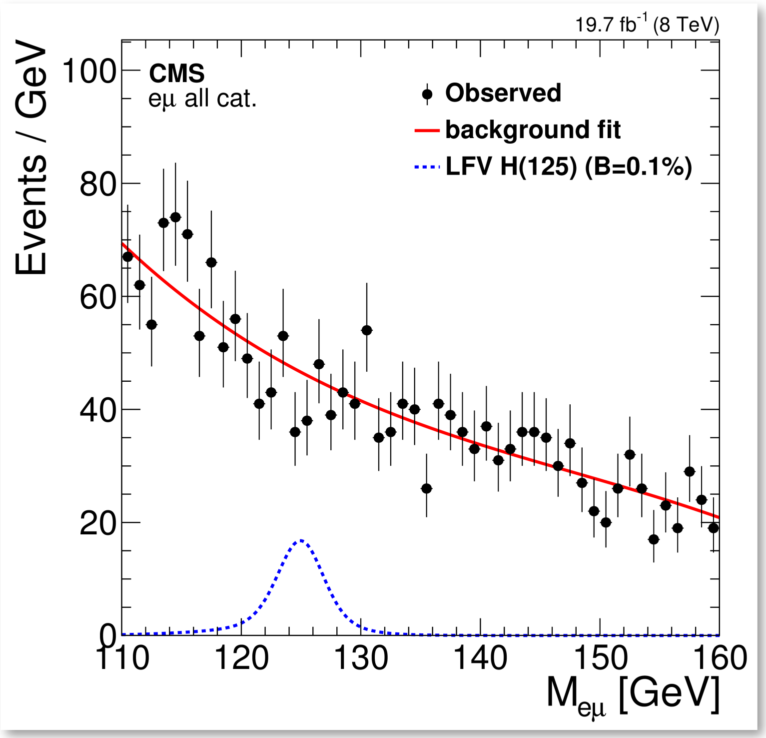
$H \to e\mu$

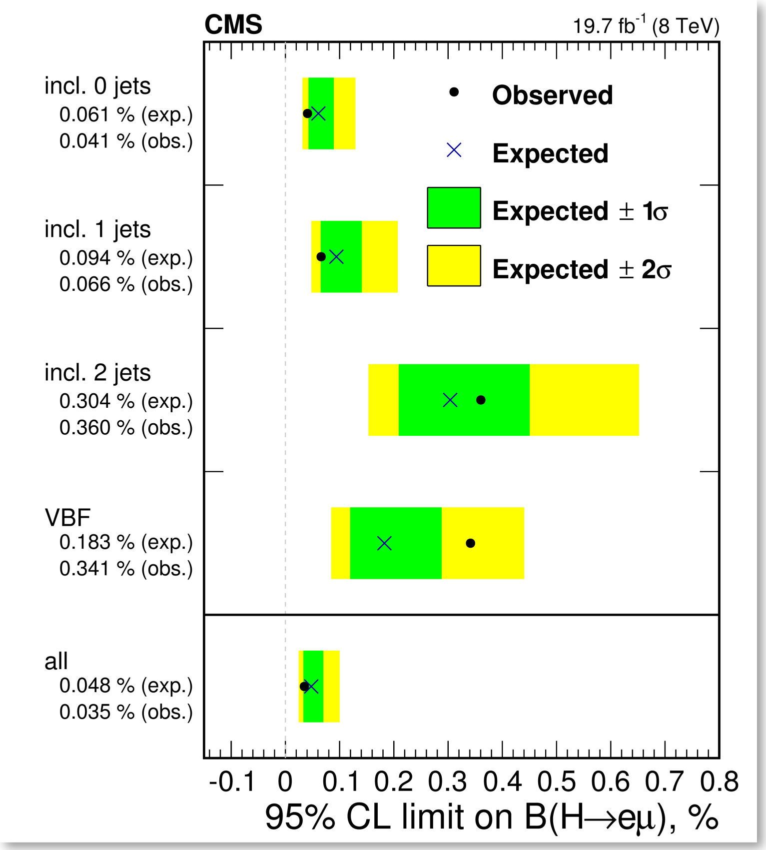
- Backgrounds
  - Polynomial of order 4
  - Sum of power law functions
  - Sum of exponential functions
- Signal
  - Sum of two Gaussians
  - Resolutions depend on location of leptons (barrel or endcap)

Search for LFV in Higgs decays

arXiv:1607.03561

Results: $H \rightarrow e\mu$



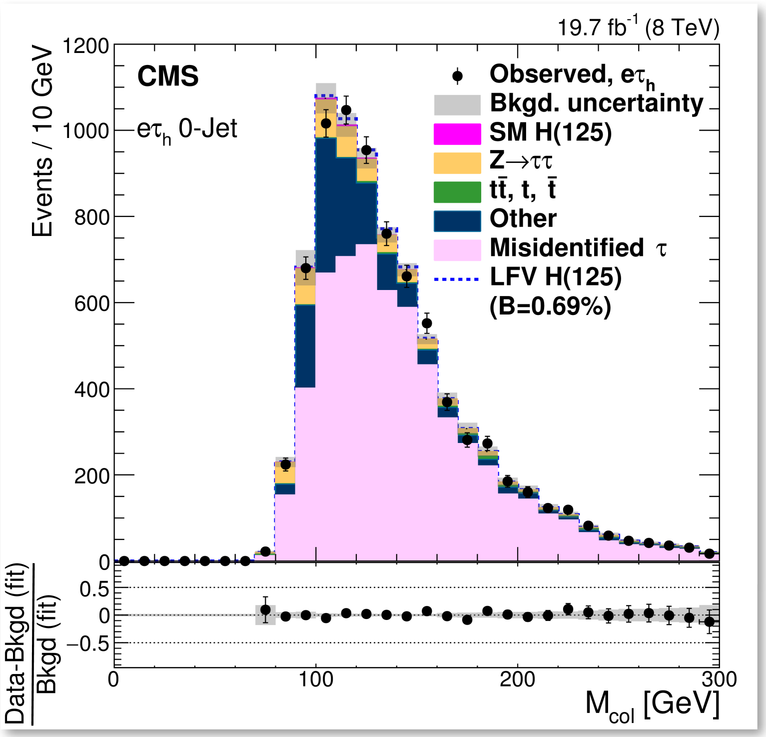


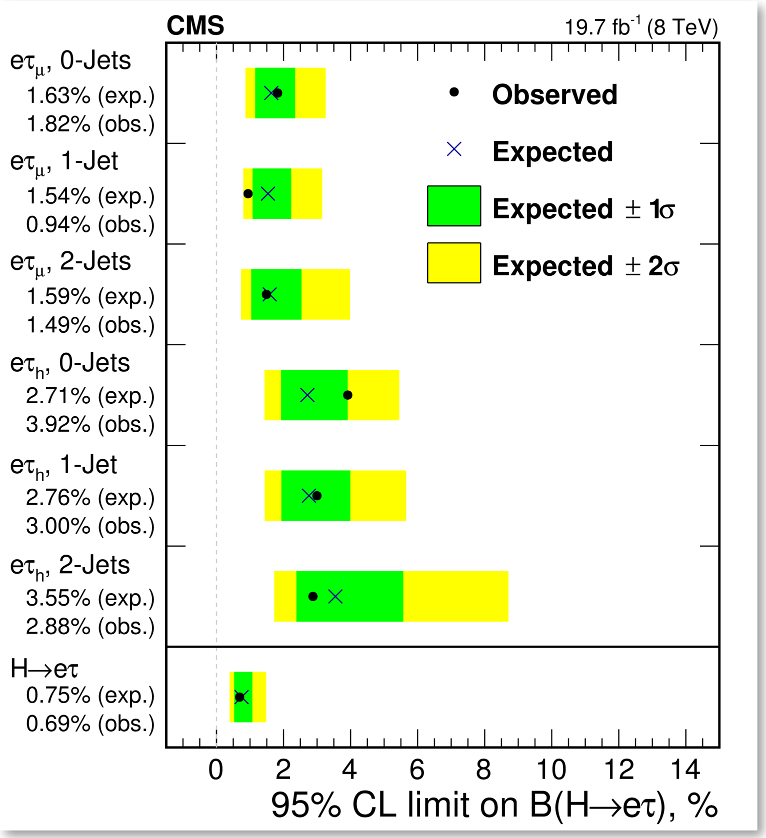
$$\mathcal{B}(H \rightarrow e\mu) < 0.035\% \text{ @ } 95\% \text{ CL}$$

Search for LFV in Higgs decays

arXiv:1607.03561

Results: $H \to e\tau$



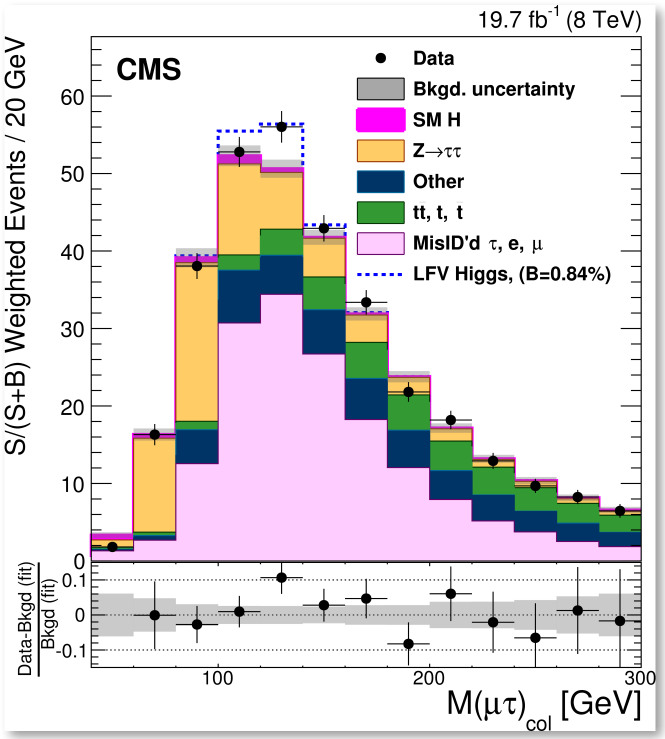


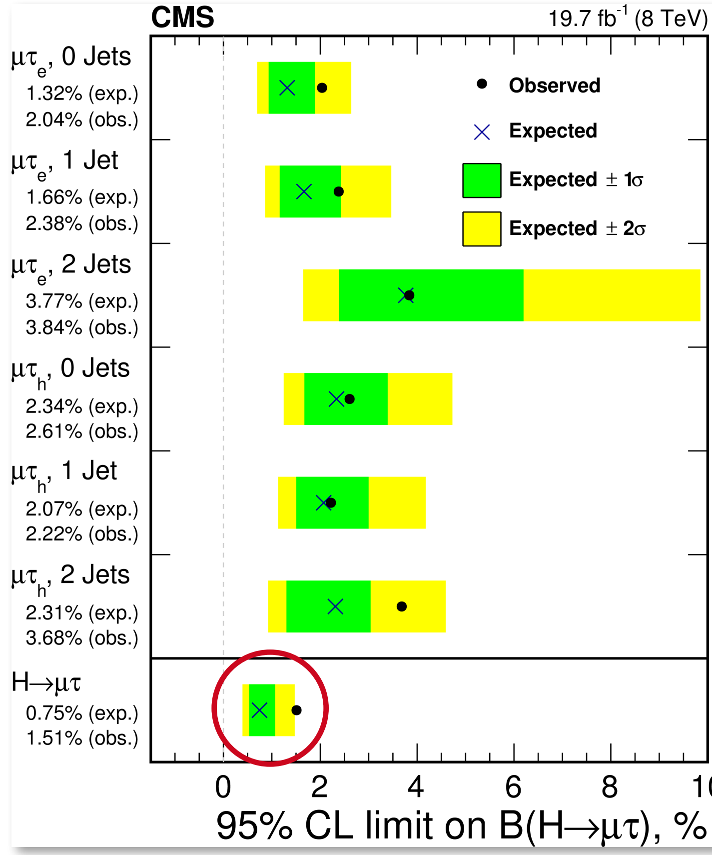
$\mathcal{B}(H \to e\tau) < 0.69\%$ @ 95% CL

Search for LFV in Higgs decays

Phys. Lett. B 749 (2015) 337

Results: $H \rightarrow \mu\tau$





$$\mathcal{B}(H \rightarrow \mu\tau) = (0.84^{+0.39}_{-0.37})\%$$

$$\mathcal{B}(H \rightarrow \mu\tau) < 1.51\% \text{ @ 95\% CL}$$

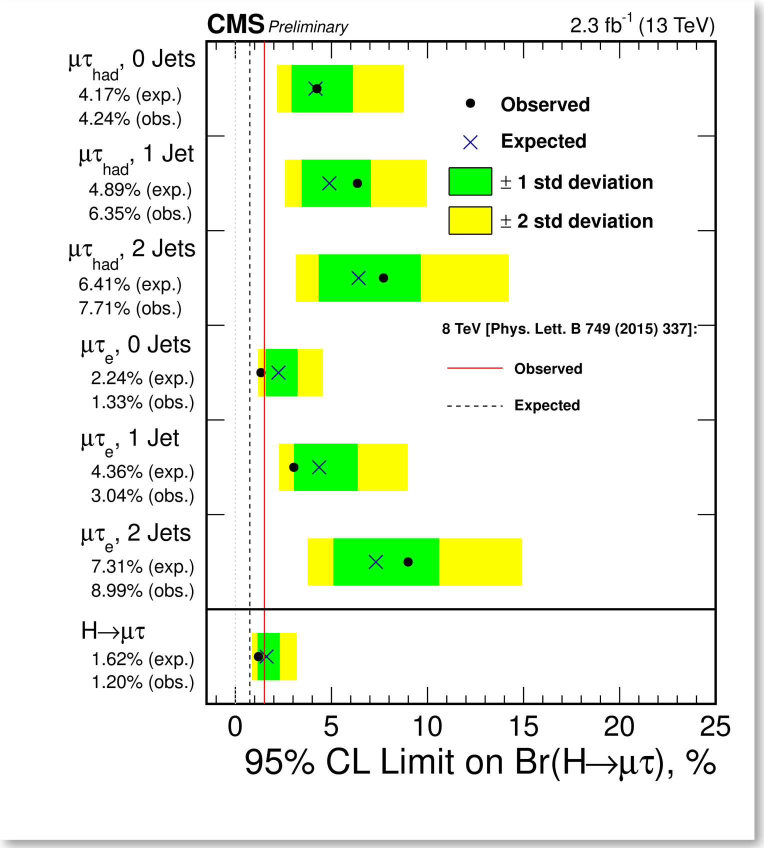
Search for LFV in Higgs decays

CMS-PAS-HIG-16-005

$H \rightarrow \mu\tau$ @ 13 TeV

- Very similar analysis
- Uses 2.3 fb^{-1} of data from 2015
- Excess from 8 TeV data not confirmed but also not excluded!

$\mathcal{B}(H \rightarrow \mu\tau) < 1.20\%$ @ 95% CL



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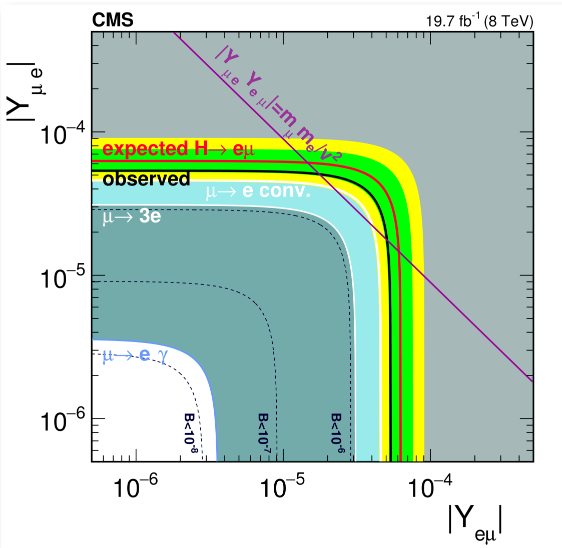
arXiv:1607.03561

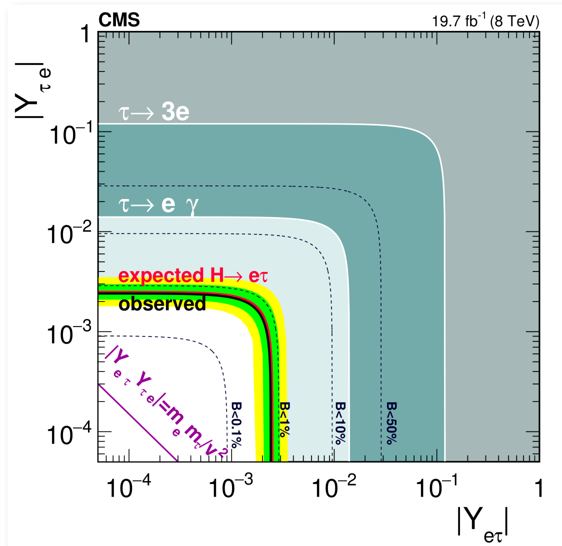
CMS-PAS-HIG-16-005

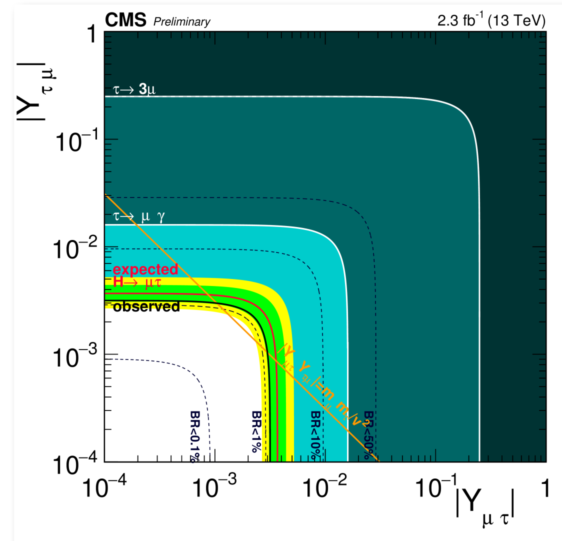
Search for LFV in Higgs decays

Limits on flavor violating Yukawa couplings

$$\sqrt{|Y_{\ell\ell'}|^2 + |Y_{\ell\ell'}|^2} \propto \frac{\mathcal{B}(H \to \ell\ell')}{1 - \mathcal{B}(H \to \ell\ell')}$$







$$\sqrt{|Y_{e\mu}|^2 + |Y_{\mu e}|^2} < 5.4 \cdot 10^{-4}$$

$$\sqrt{|Y_{e\tau}|^2 + |Y_{\tau e}|^2} < 2.4 \cdot 10^{-3}$$

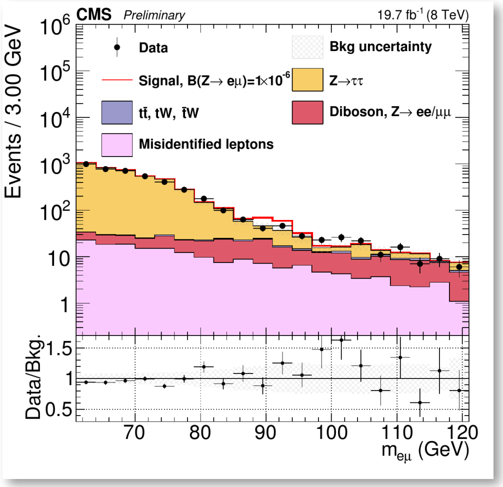
$$\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 3.16 \cdot 10^{-3}$$

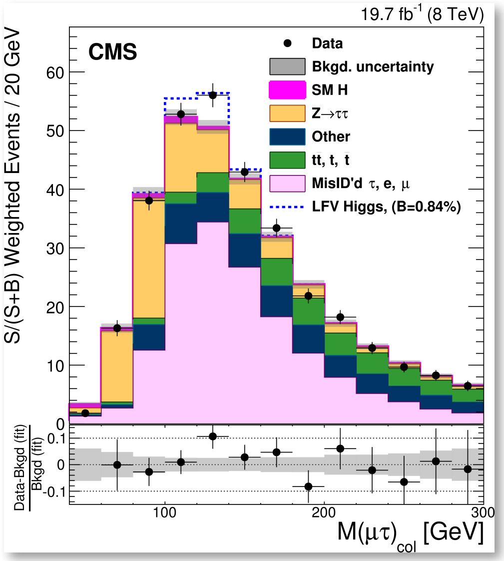
- Able to set unprecedented limits in $H \to e\tau$ & $H \to \mu\tau$

Summary

- $Z \to e\mu$: CMS-PAS-EXO-13-005
  - Obtained most stringent limit on branching fraction
  - Currently limited by statistical precision and normalization uncertainties
- $H \to e\mu$, $H \to e\tau$, $H \to \mu\tau$: Phys. Lett. B 749 (2015) 337

  arXiv:1607.03561 CMS-PAS-HIG-16-005
  - 2.4σ excess in $H \to \mu\tau$ found in 8 TeV data
    - Neither confirmed nor excluded by 13 TeV data so far
  - Limits on branching fraction & LFV Yukawa couplings set
    - Improvement by $\mathcal{O}(10)$ to previous indirect limits





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Backup

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Event yields & normalization uncertainties

Event yields in signal region after selection

Process	Events
$Z \to \tau\tau$	41 ± 9
WW	17 ± 1
Misidentified leptons	12.8 ± 0.5
$Z \to ee/\mu\mu$	10 ± 2
$t\bar{t}$	1.3 ± 0.5
$tW/\bar{t}W$	0.6 ± 0.6
WZ	0.3 ± 0.1
ZZ	< 0.1
Total background	83 ± 9
Data	87

Normalization uncertainty relative to total background yield in signal region

Background process	Uncertainty
$Z \to \ell\ell\ (\ell = e, \mu, \tau)$	2.0%
WW, WZ, ZZ	3.1%
$t\bar{t}$	$< 0.1\%$
$tW/\bar{t}W$	$< 0.1\%$
Misidentified leptons	5.7%
Total background	6.8%

arXiv:1607.03561

$H \rightarrow e\mu$: background models for all categories

Category	Description	N-jets	p_{T}^{ℓ} [GeV]	E_{T}^{miss} [GeV]	Background model	
					Function	Order
0	$e_B\mu_B$	0	>25	<30	polynomial	4
1	$e_B\mu_B$	1	>22	<30	polynomial	4
2	$e_B\mu_B$	2	>25	<25	power law	1
3	$e_B\mu_{EC}$	0	>20	<30	polynomial	4
4	$e_B\mu_{EC}$	1	>22	<20	exponential	1
5	$e_B\mu_{EC}$	2	>20	<30	exponential	1
6	$e_{EC}\mu_{B\text{ or }EC}$	0	>20	<30	polynomial	4
7	$e_{EC}\mu_{B\text{ or }EC}$	1	>22	<20	power law	1
8	$e_{EC}\mu_{B\text{ or }EC}$	2	>20	<30	polynomial	4
9	VBF Tight	2	>22	<30	exponential	1
10	VBF Loose	2	>22	<25	exponential	1

Systematic uncertainties: $H \rightarrow e\mu$

Experimental uncertainties	
background model	<1
trigger efficiency	1.0
lepton identification	2.0
lepton energy scale	1.0
dilepton mass resolution	5.0
pileup	0.7–2.3
b quark jet veto efficiency	0.05–0.70
luminosity	2.6
jet energy scale (inclusive categories)	0.6–22
jet energy scale (VBF categories)	0.1–78
jet energy resolution (inclusive categories)	2.8–12
jet energy resolution (VBF categories)	0.0–49
acceptance (PDF variations)	0.8–5.1
Theoretical uncertainties	
GF normalization/factorization scale	$^{+7.2}_{-7.8}$
GF parton distribution function	$^{+7.5}_{-6.9}$
VBF normalization/factorization scale	± 0.2
VBF parton distribution function	$^{+2.6}_{-2.8}$

Systematic uncertainty	Gluon fusion			Vector boson fusion		
	0-jet	1-jet	2-jet	0-jet	1-jet	2-jet
parton distribution function	9.7	9.7	9.7	3.6	3.6	3.6
renormalization/factorization scale	8	10	30^{-}	4	1.5	2
underlying event/parton shower	4	5^{-}	10^{-}	10	<1	1^{-}

arXiv:1607.03561

Systematic uncertainties: $H \rightarrow e\tau$

Systematic uncertainty	$H \rightarrow e\tau_\mu$			$H \rightarrow e\tau_h$		
	0-jet	1-jet	2-jet	0-jet	1-jet	2-jet
muon trigger/ID/isolation	2	2	2	—	—	—
electron trigger/ID/isolation	3	3	3	1	1	2
efficiency of τ_h	—	—	—	6.7	6.7	6.7
$Z \rightarrow \tau\tau$ background	$3 \oplus 5^*$	$3 \oplus 5^*$	$3 \oplus 10^*$	$3 \oplus 5^*$	$3 \oplus 5^*$	$3 \oplus 10^*$
$Z \rightarrow \mu\mu$, ee background	30	30	30	30	30	30
misidentified leptons background	40	40	40	30	30	30
pileup	2	2	10	4	4	2
WW, WZ, ZZ+jets background	15	15	15	15	15	15
$t\bar{t}$ background	10	10	$10 \oplus 10^*$	10	10	$10 \oplus 33^*$
single top quark background	25	25	25	25	25	25
b-tagging veto	3	3	3	—	—	—
luminosity	2.6	2.6	2.6	2.6	2.6	2.6

Normalization uncertainties

Shape uncertainties

Systematic Uncertainty	$H \rightarrow e\tau_\mu$	$H \rightarrow e\tau_h$
$Z \rightarrow \tau\tau$ bias	2	—
$Z \rightarrow$ ee bias	—	5
jet energy scale	3–7	3–7
jet energy resolution	1–10	1–10
unclustered energy scale	10	10
τ_h energy scale	—	3

Systematic uncertainties: $H \to \mu\tau$

8 TeV

Systematic uncertainty	$H \to \mu\tau_e$			$H \to \mu\tau_h$		
	0-Jet	1-Jet	2-Jets	0-Jet	1-Jet	2-Jets
electron trigger/ID/isolation	3	3	3	—	—	—
muon trigger/ID/isolation	2	2	2	2	2	2
hadronic tau efficiency	—	—	—	9	9	9
luminosity	2.6	2.6	2.6	2.6	2.6	2.6
$Z \to \tau\tau$ background	3+3*	3+5*	3+10*	3+5*	3+5*	3+10*
$Z \to \mu\mu$, ee background	30	30	30	30	30	30
misidentified μ, e background	40	40	40	—	—	—
misidentified τ_h background	—	—	—	30+10*	30	30
WW, ZZ+jets background	15	15	15	15	15	65
$t\bar{t}$ background	10	10	10+10*	10	10	10+33*
$W + \gamma$ background	100	100	100	—	—	—
b-tagging veto	3	3	3	—	—	—
single top production background	10	10	10	10	10	10

13 TeV

Systematic uncertainty	$H \to \mu\tau_e$	$H \to \mu\tau_h$
Muon trigger/ID/isolation	3%	3%
Electron trigger/ID/isolation	3%	—
Hadronic τ efficiency	—	10%
b-tagging veto	3%	—
$Z \to \tau\tau$ background	10%$\oplus$5%	10%$\oplus$5%
$Z \to \mu\mu$, ee background	10%$\oplus$5%	10%$\oplus$5%
Misidentified μ, e background	40%$\oplus$10%	—
Misidentified τ_h background	—	30%$\oplus$10%
WW, ZZ background	10%$\oplus$5%	10%$\oplus$5%
$t\bar{t}$ background	20%$\oplus$5%	20%$\oplus$5%
$W + \gamma$ background	10%$\oplus$5%	—
Single top production background	10%	10%
Jet energy scale	3-20%	3-20%
Hadronic τ energy scale	—	3%
Misidentified lepton shape	$\pm\sigma$	$\pm\sigma$
Theory uncertainty	10%	10%
Luminosity	2.7%	2.7%