

Search for Lepton Flavor Violating Decays of the Higgs Boson

CMS PAS HIG-14-005

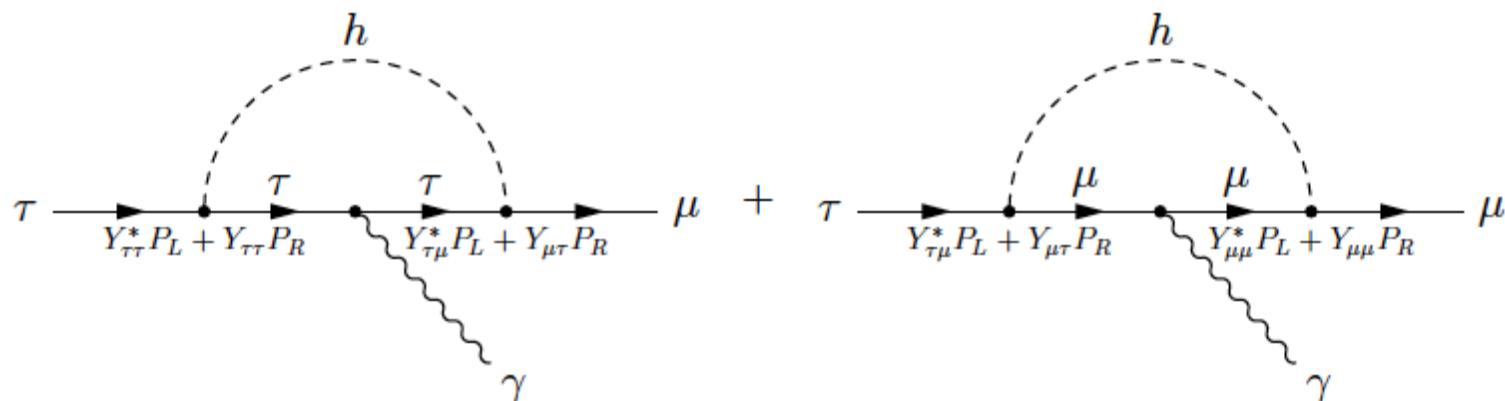
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for the CMS Collaboration

August 28, 2014

Motivation

- Some new physics models may allow for LFV decays of Higgs including composite Higgs models, models with multiple Higgs doublets, non-renormalizable models valid to up to a finite mass scale and many others.
- Existing constraints on LFV coupling constants from $\tau \rightarrow \mu\gamma$, $\tau \rightarrow 3\mu$, etc. allow $\text{BR}(H \rightarrow \tau\mu) = \sim 10\%$

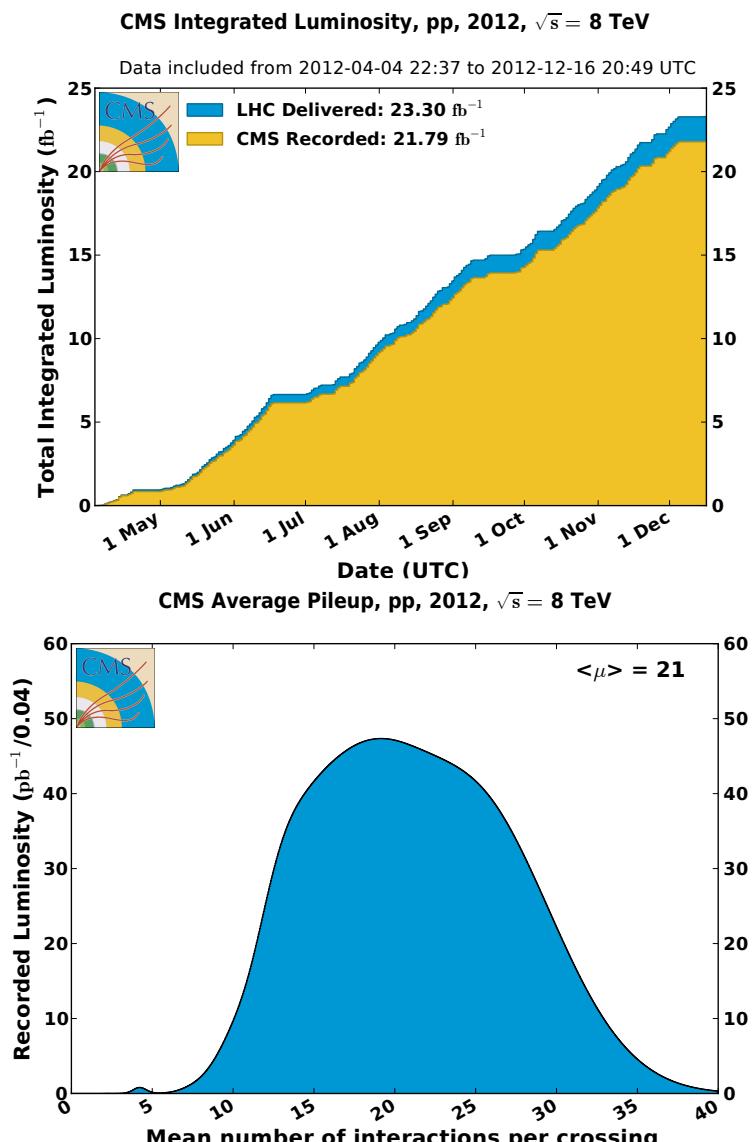


J. D. Bjorken and S. Weinberg, "Mechanism for Nonconservation of Muon Number", Phys. Rev. Lett. 38 (Mar, 1977) 622–625, doi:10.1103/PhysRevLett.38.622., K. Agashe and R. Contino, "Composite Higgs-Mediated FCNC", Phys. Rev. D**80** (2009) 075016, doi:10.1103/PhysRevD.80.075016, arXiv:0906.1542., A. Azatov, M. Toharia, and L. Zhu, "Higgs Mediated FCNC's in Warped Extra Dimensions", Phys. Rev. D**80** (2009) 035016, doi:10.1103/PhysRevD.80.035016, arXiv:0906.1990., H. Ishimori et al., "Non-Abelian Discrete Symmetries in Particle Physics", Prog. Theor. Phys. Suppl. **183** (2010) 1–163, doi:10.1143/PTPS.183.1, arXiv:1003.3552., G. Perez and L. Randall, "Natural Neutrino Masses and Mixings from Warped Geometry", JHEP **0901** (2009) 077, doi:10.1088/1126-6708/2009/01/077, arXiv:0805.4652., G. Blankenburg, J. Ellis, and G. Isidori, "Flavour-Changing Decays of a 125 GeV Higgs-like Particle", Phys. Lett. B**712** (2012) 386–390, doi:10.1016/j.physletb.2012.05.007, arXiv:1202.5704., R. Harnik, J. Kopp, and J. Zupan, "Flavor Violating Higgs Decays", JHEP **1303** (2013) 026, doi:10.1007/JHEP03(2013)026, arXiv:1209.1397.

Large Hadron Collider

3

- Proton-Proton collisions at center of mass energy 8 TeV
- 19.7 fb^{-1} of 2012 data used
- 50 ns bunch spacing
- 21 average interactions per bunch crossing.
Known as “pile up”



Compact Muon Solenoid

CMS DETECTOR

Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

STEEL RETURN YOKE
12,500 tonnes

SILICON TRACKERS
Pixel ($100 \times 150 \mu\text{m}$) $\sim 16\text{m}^2 \sim 66\text{M}$ channels
Microstrips ($80 \times 180 \mu\text{m}$) $\sim 200\text{m}^2 \sim 9.6\text{M}$ channels

SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying $\sim 18,000\text{A}$

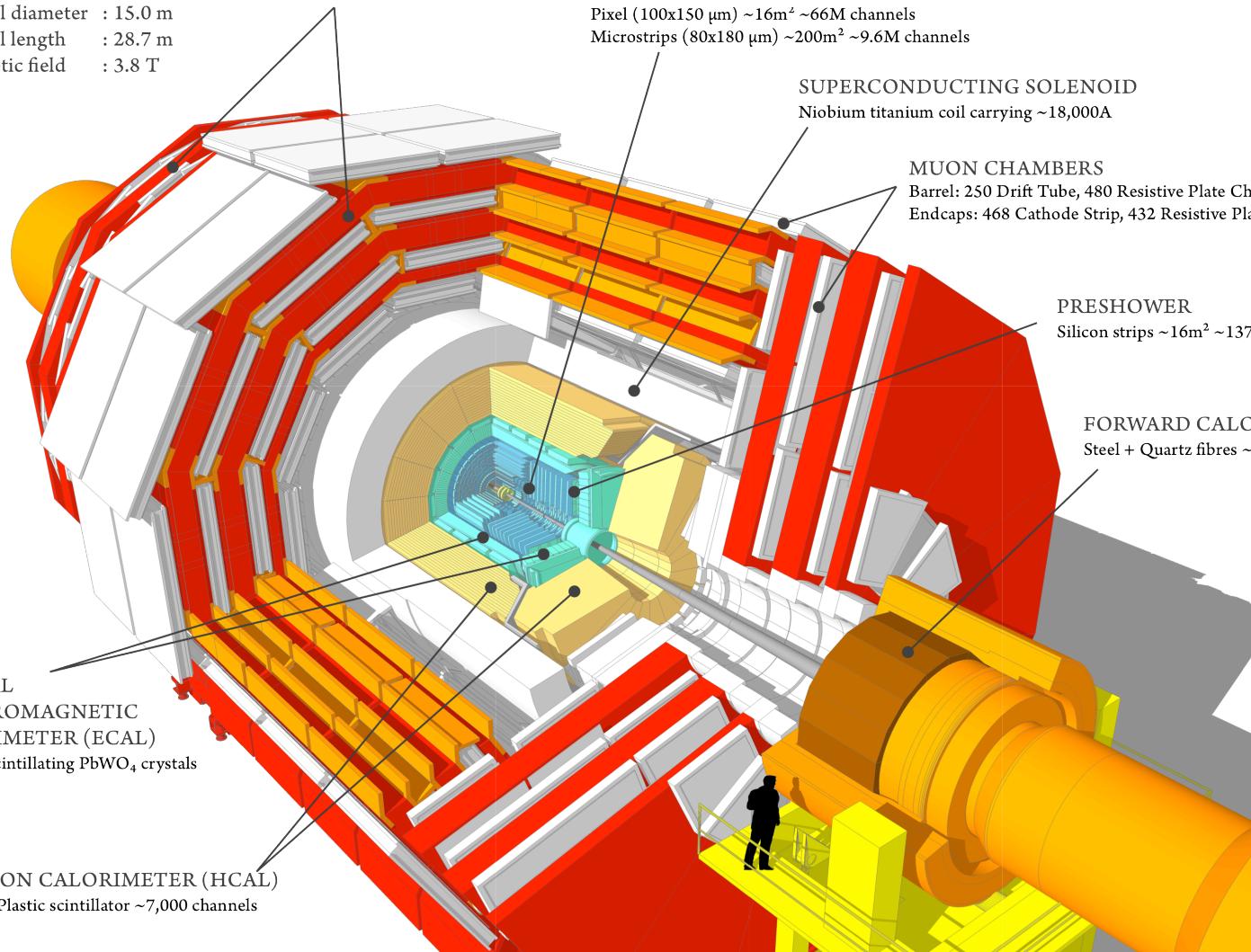
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

PRESHOWER
Silicon strips $\sim 16\text{m}^2 \sim 137,000$ channels

FORWARD CALORIMETER
Steel + Quartz fibres $\sim 2,000$ Channels

CRYSTAL
ELECTROMAGNETIC
CALORIMETER (ECAL)
 $\sim 76,000$ scintillating PbWO_4 crystals

HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator $\sim 7,000$ channels

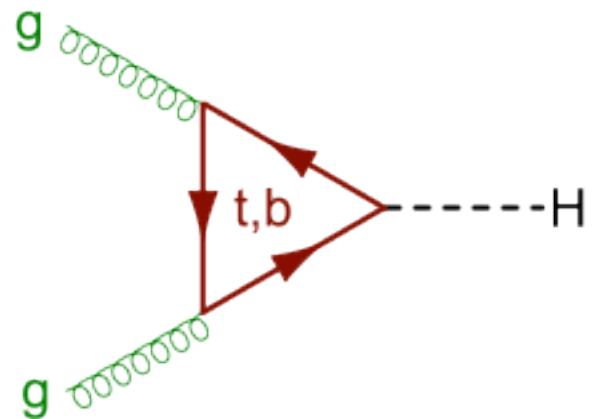


Higgs Production

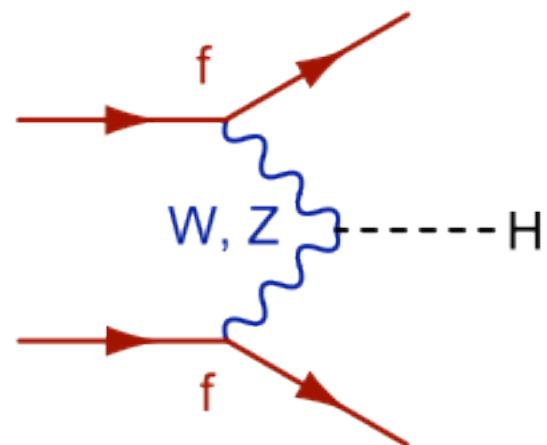
Theoretical Higgs production cross-sections

Process	cross sec.
Gluon Gluon Fusion (GGF)	19.27 pb
Vector Boson Fusion (VBF)	1.578 pb
Assoc. w/ W Boson	0.7046 pb
Assoc. w/ Z Boson	0.4153 pb
Assoc. w/ Top pair	0.1293 pb

Gluon Gluon Fusion

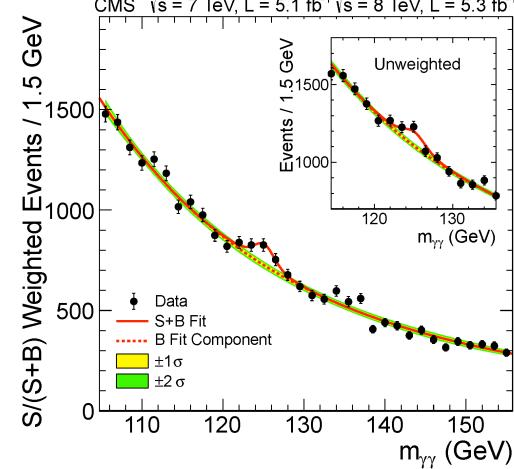
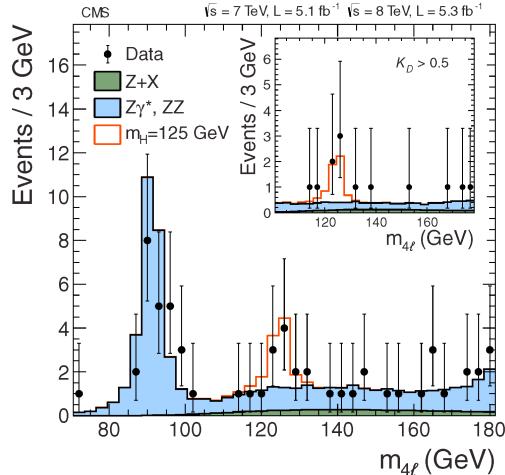


Vector Boson Fusion

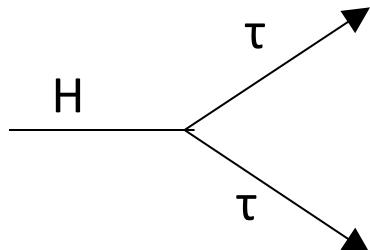


Higgs Discovery

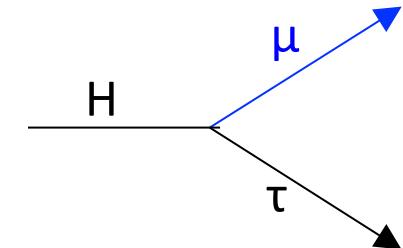
- Higgs discovered with mass ~ 125 GeV (<http://cds.cern.ch/record/1728249>)
- Observed in Standard Model decays
 - $H \rightarrow \tau\tau$
 - $H \rightarrow ZZ$
 - $H \rightarrow WW$
 - $H \rightarrow \gamma\gamma$
- Are there non-Standard Model decay modes?



SM $H \rightarrow \tau\tau$

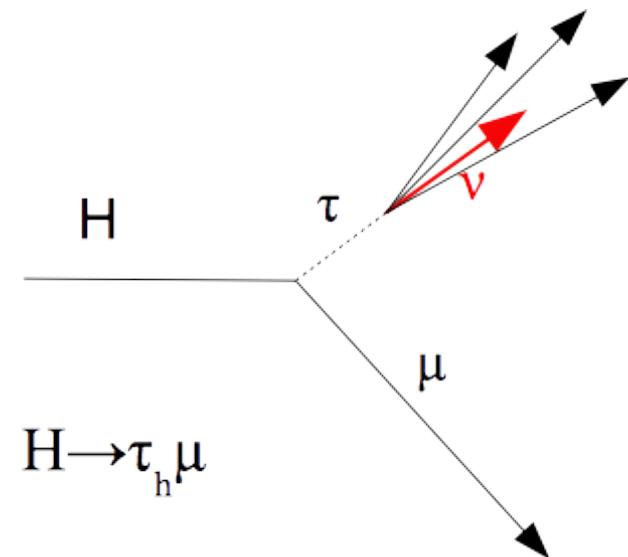
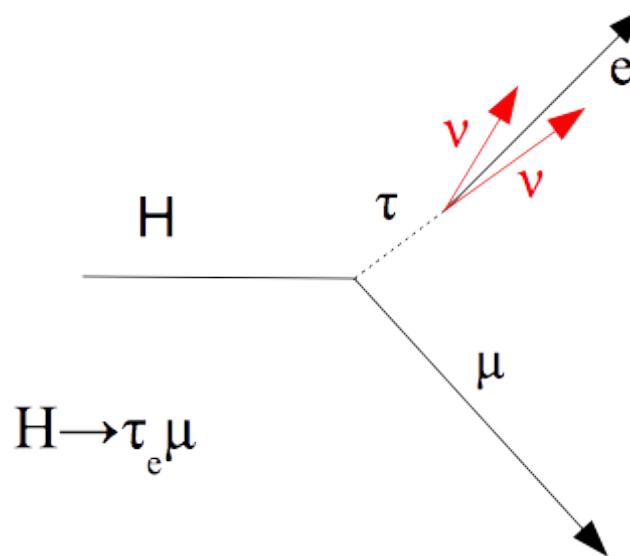


LFV $H \rightarrow \mu\tau$



Channels & Categories

- Two channels are studied: $H \rightarrow \tau_{\text{had}}\mu$ and $H \rightarrow \tau_e\mu$
- Each channel is separated into 0, 1, and 2 jet categories
 - 0 and 1 jet corresponds to GG Higgs production
 - 2 jet corresponds to VBF Higgs production
- Assume $M_{\text{Higgs}} = 125 \text{ GeV}$



Signal Variable and Region

- Collinear Mass
 - approximate neutrino as collinear and define visible fraction of tau momentum

$$\vec{p}_T^\nu = \vec{E}_T^{\text{miss}} \cdot \hat{p}_T^{\tau_{\text{vis}}} \quad x_{\tau_{\text{vis}}} = \frac{|\vec{p}_T^{\tau_{\text{vis}}}|}{|\vec{p}_T^{\tau_{\text{vis}}}| + |\vec{p}_T^\nu|}$$

- approximate Higgs mass is then:

$$M_{\text{collinear}} = \frac{M_{\text{vis}}}{\sqrt{x_{\tau_{\text{vis}}}}}$$

- gives sharp mass peak centered near 125 GeV
- Signal region defined as
 $100 \text{ GeV} < M_{\text{collinear}} < 150 \text{ GeV}$
- Analysis was done with signal region blinded

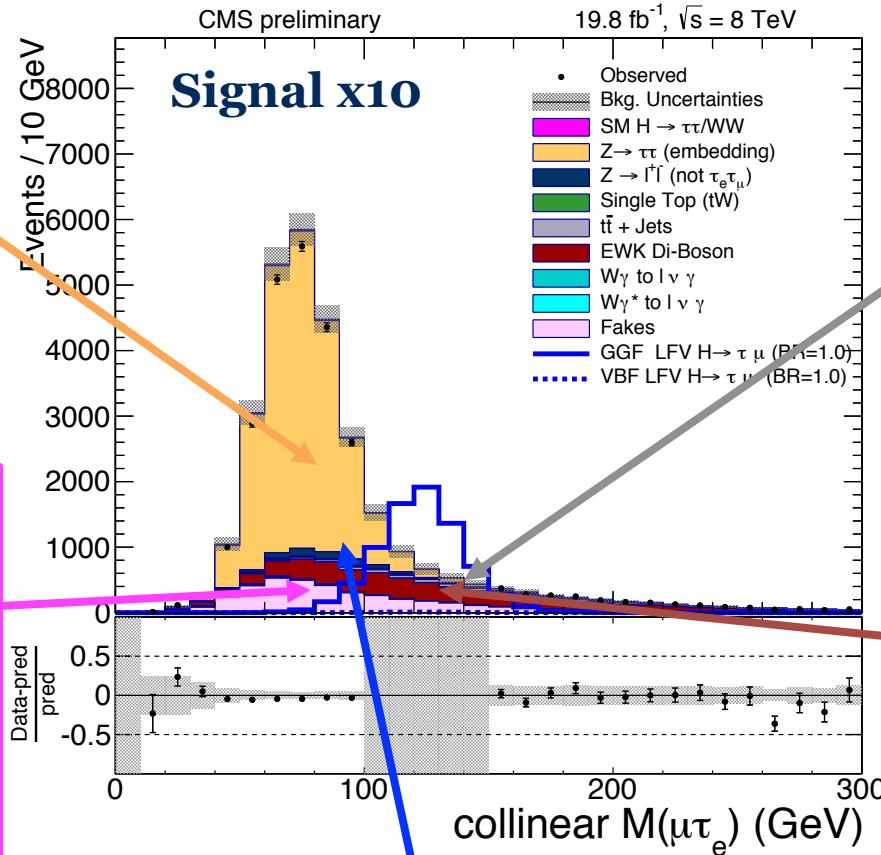
Background Overview

$Z \rightarrow \tau\tau$:

- Normalization from MC simulation
- Shape: Embedded tau sample

$W+Jets/QCD$
 $Multijets$:

- Fakerate Method using Anti-isolated lepton events ($\tau_e \mu$) or Anti-isolated tau events ($\tau_{had} \mu$)



$t\bar{t}$:

- Shape from MC simulations
- Normalization from control region ($\tau_e \mu$) or MC ($\tau_{had} \mu$)

$WW+Jets$:

- Normalization (NLO) and shape from MC simulations

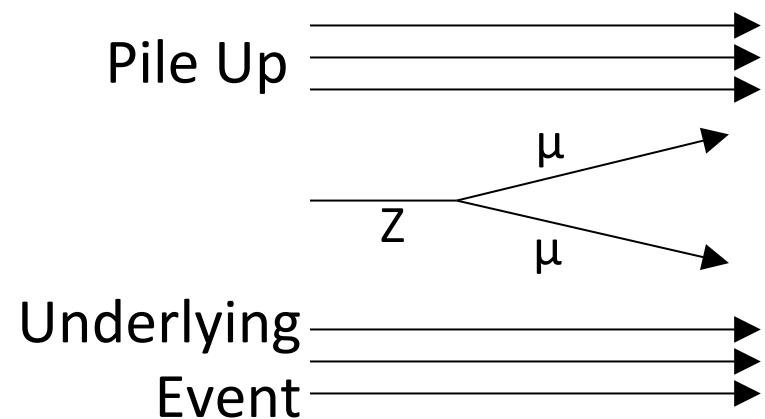
$Z \rightarrow l^+l^-$, $W\text{jets}+\gamma^*$, $\text{SingleTop}, \dots$:

- Normalization and shape from MC simulation

Z \rightarrow $\tau\tau$ Background

10

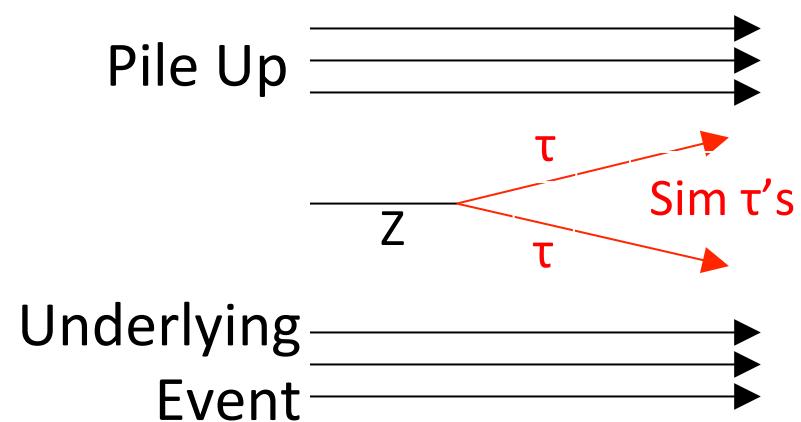
- Dominant background for H \rightarrow $\tau_e\mu$
- Z \rightarrow $\tau\tau$ background via Particle Flow Embedding
 - Z $\rightarrow\mu\mu$ data with μ 's replaced by simulated τ 's
- Validated by comparing to simulated Z $\rightarrow\tau\tau$ ($\tau_e\mu$) or enhanced Z $\rightarrow\tau\tau$ control region $\Delta R_{\mu-\tau} < 0.2$ ($\tau_{had}\mu$)



Z \rightarrow $\tau\tau$ Background

11

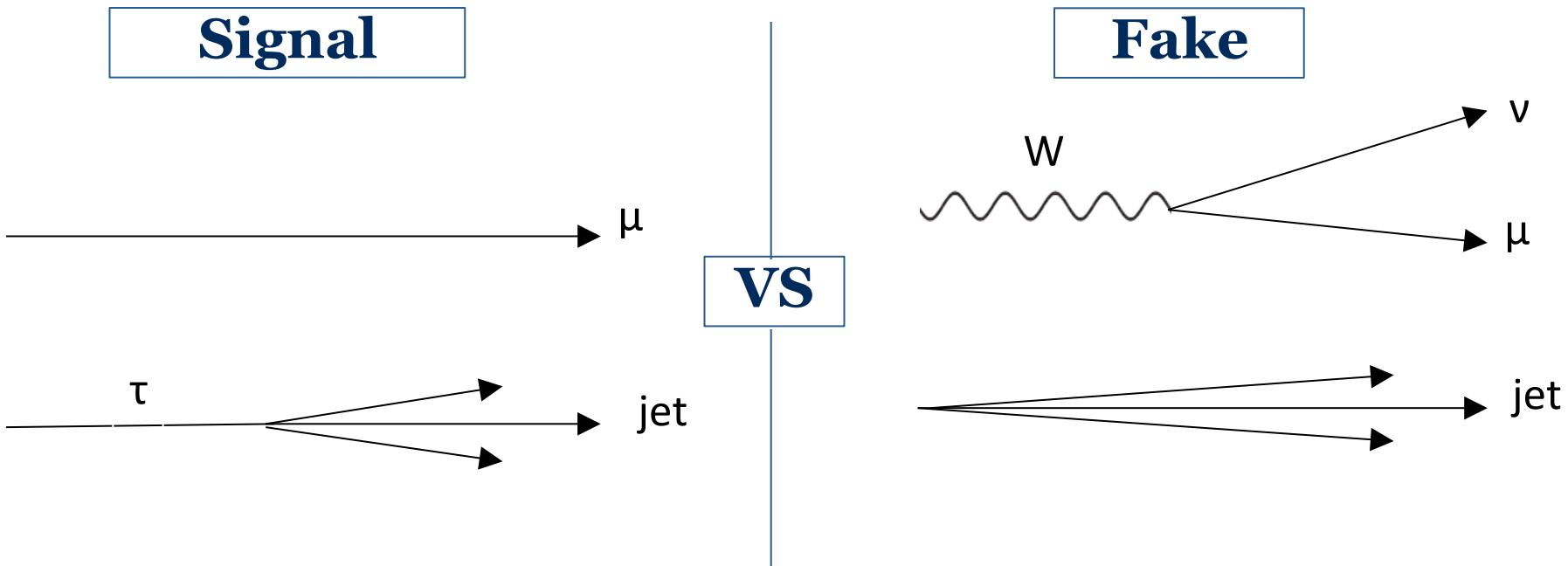
- Dominant background for H \rightarrow $\tau_e\mu$
- Z \rightarrow $\tau\tau$ background via Particle Flow Embedding
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- Validated by comparing to simulated Z $\rightarrow\tau\tau$ ($\tau_e\mu$) or enhanced Z $\rightarrow\tau\tau$ control region $\Delta R_{\mu-\tau} < 0.2$ ($\tau_{had}\mu$)



Fakes Background

12

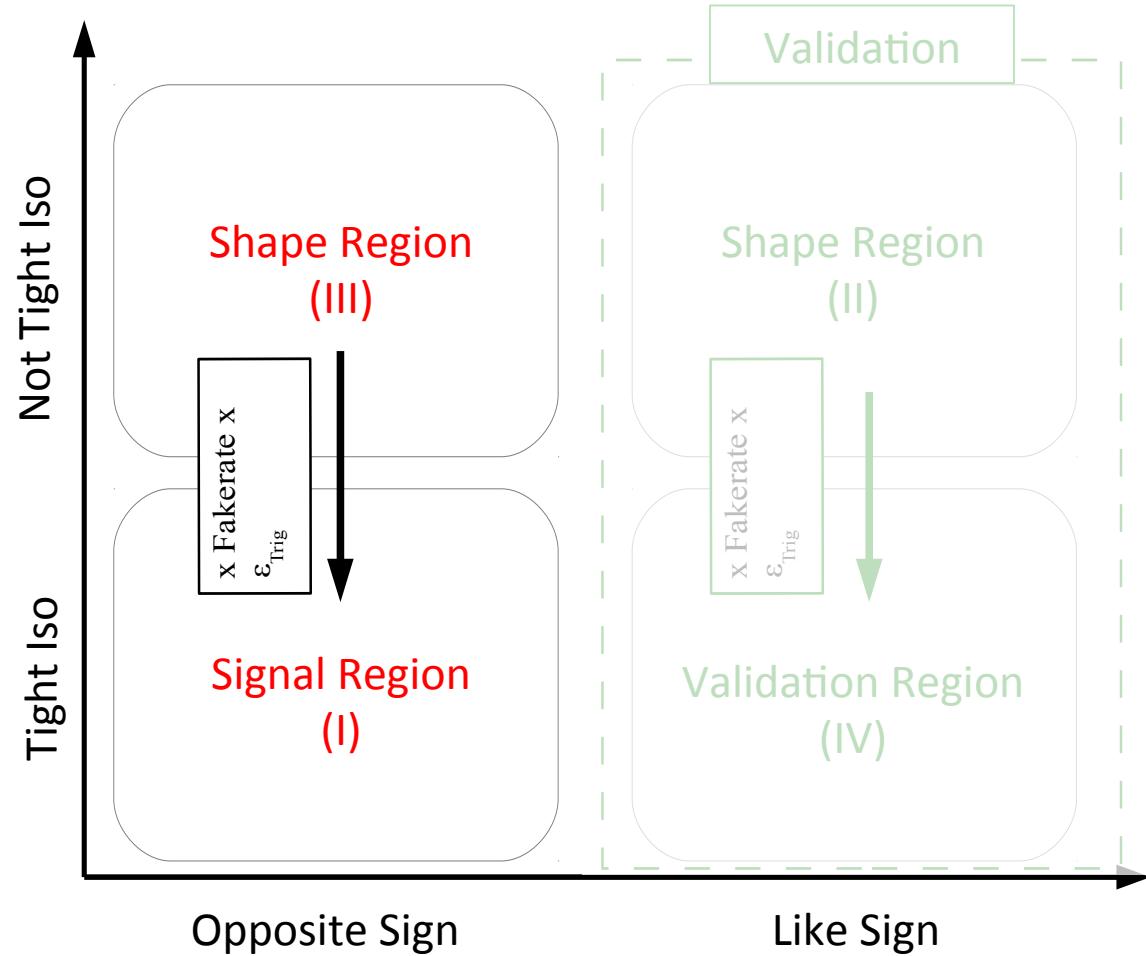
- What is a fake signal?



- Jets can appear to be leptons
- Fake rate measured in $Z \rightarrow \mu\mu + X$ data and compared to MC

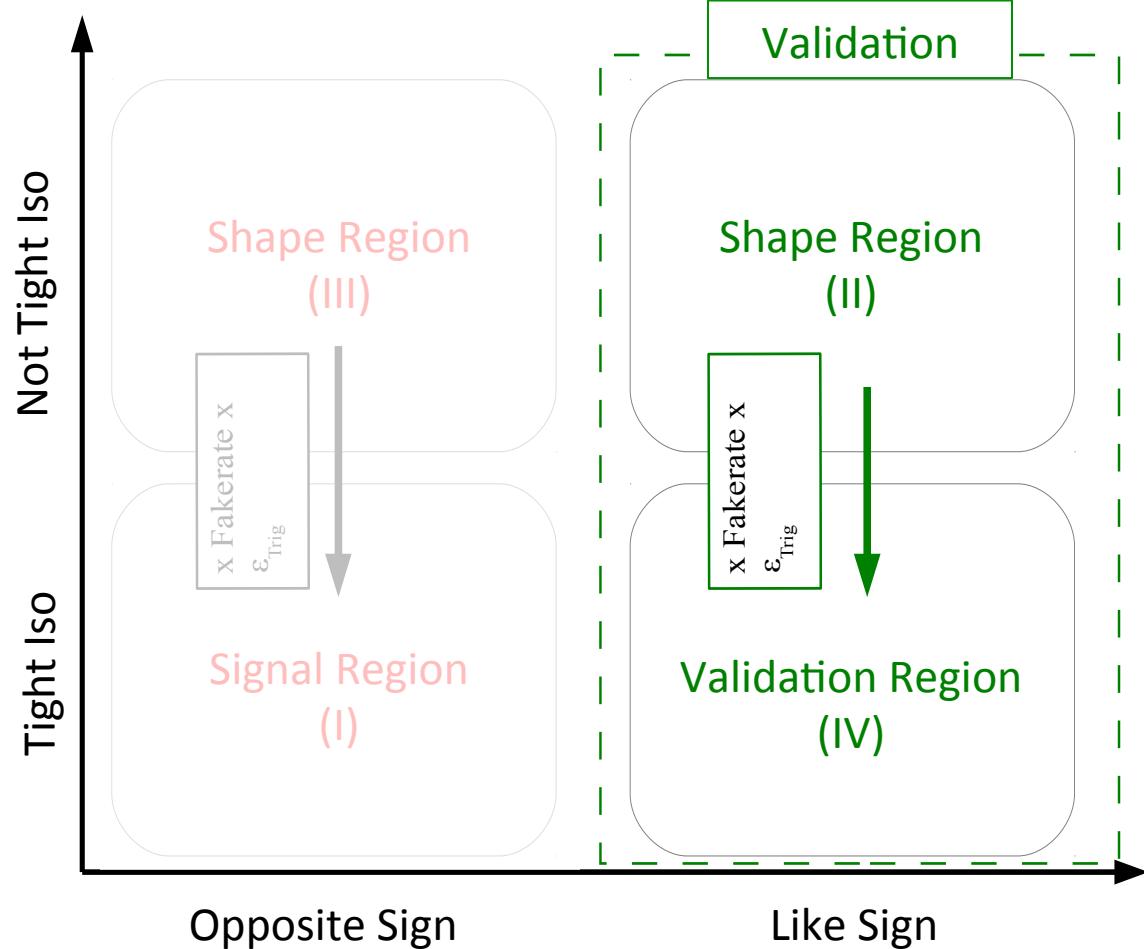
Fakes Background

- Dominant background for $\tau_{\text{had}} \mu$
- Fakes background shape from region III
 - Pass loose lepton iso but not tight
 - Other backgrounds subtracted (negligible)
- Measure fake rate independently and apply to III to get Signal Region I
- SS regions II and IV used to validate fake rate method.
 - Dominated by $W + \text{jets}$



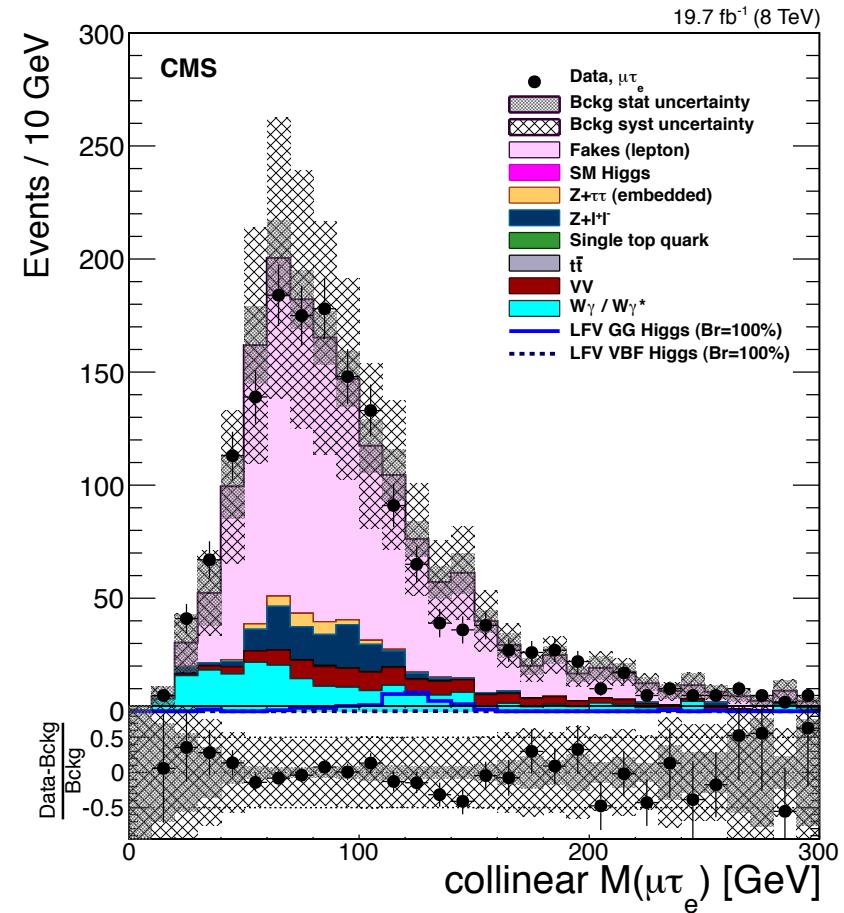
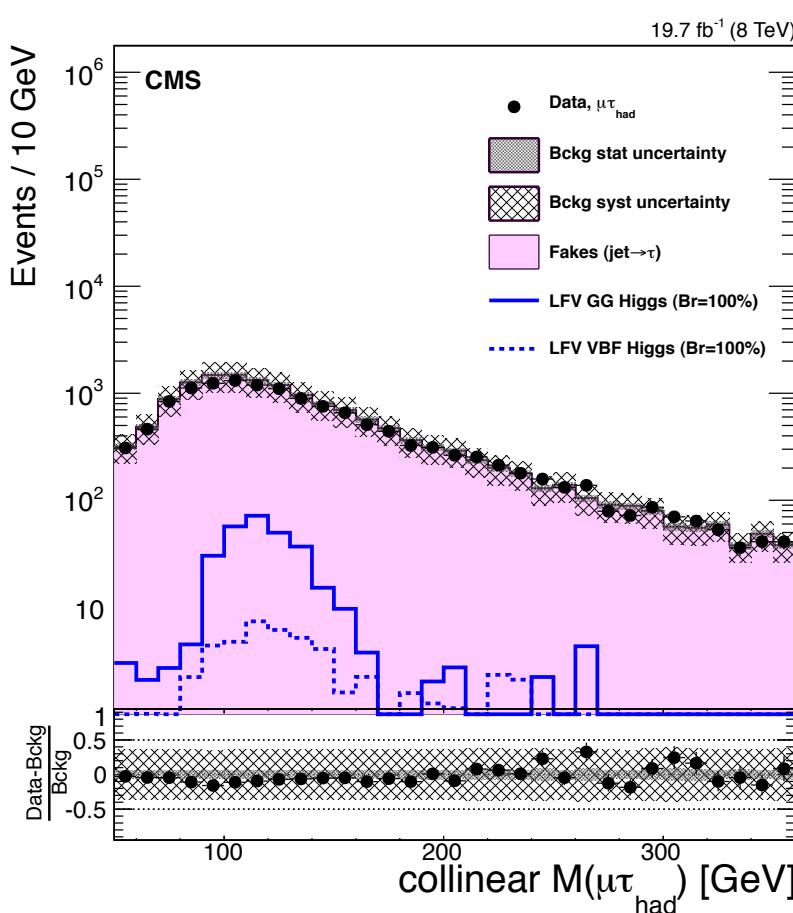
Fakes Background

- Dominant background for $\tau_{\text{had}} \mu$
- Fakes background shape from region III
 - Pass loose lepton iso but not tight
 - Other backgrounds subtracted (negligible)
- Measure fake rate independently and apply to II to get Signal Region IV
- SS regions II and IV used to validate fake rate method.
 - Dominated by W+jets



Fakes Same Sign Validation

15



Validation same sign region (II) shows good agreement in collinear mass for both channels

Full Selection Cut Variables

16

- **μ, e, τ_{had} p_T cuts:** Leptons from signal process are expected to be generally higher than many backgrounds
- **$\Delta\varphi$ cuts:** Signal μ and τ are back-to-back in φ , additionally MET is near τ in φ
- **Transverse Mass cuts:** Invariant mass formed using transverse components of one lepton and missing energy. Used for separation of different processes that have similar lepton+MET but different mother particles.
- **All cuts optimized for $S/\sqrt{S+B}$**

Limit Setting

17

- Two main types of uncertainties considered
 - Independent of $M_{\text{collinear}}$, scale peak height
 - Dependent on $M_{\text{collinear}}$, distort peak shape
- 95% CL upper limits on branching ratio are set using the standard CMS asymptotic CL_s method*
- Each background taken as a template shape. The data is fit with background only, and background plus signal.
- A likelihood method is used to estimate the signal strength which is used to set limits

*ATLAS and CMS Collaborations, LHC Higgs Combination Group, “Procedure for the LHC Higgs boson search combination in Summer 2011”, Technical Report ATL-PHYS-PUB 2011-11, CMS NOTE 2011/005, 2011.

Systematics

18

Systematics

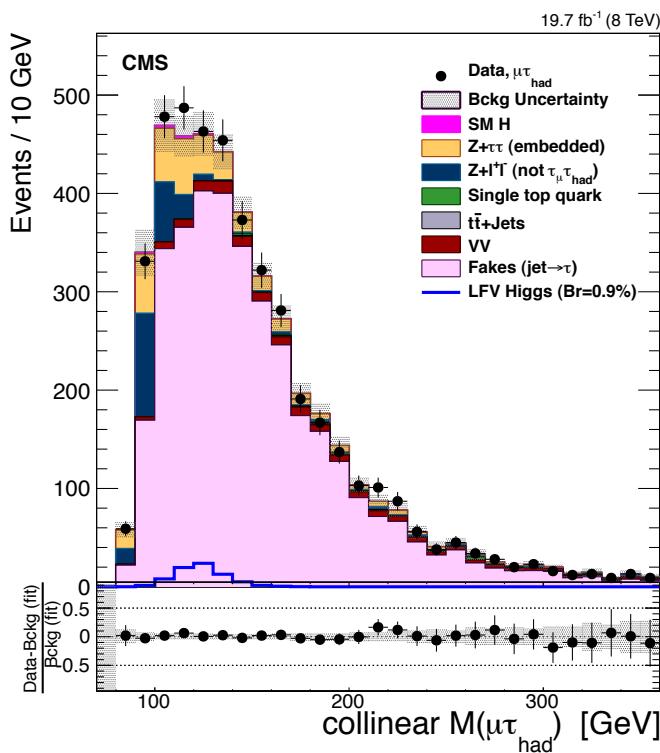
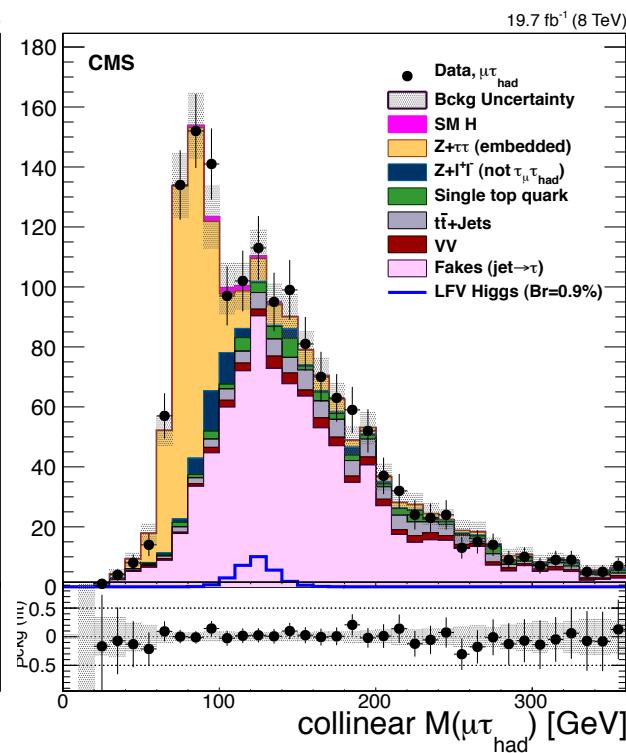
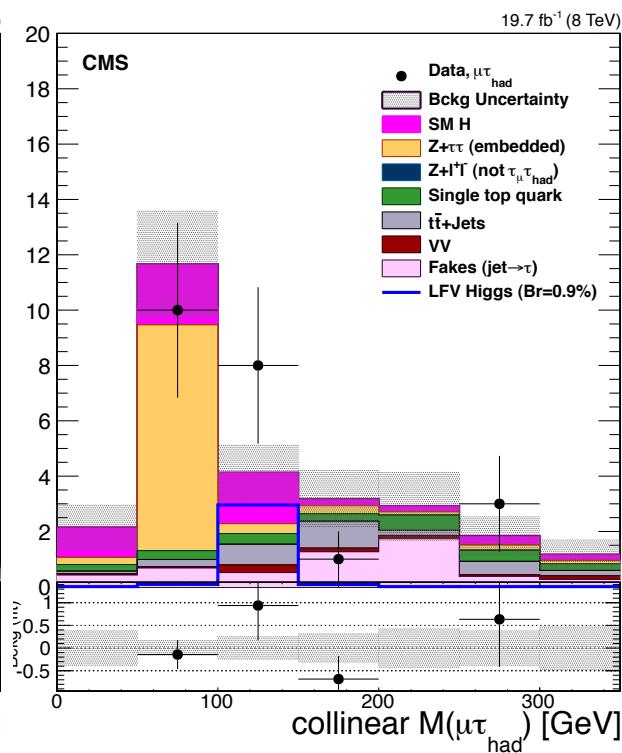
19

Theory Uncertainty	GGF			VBF		
	0 Jet	1 Jet	2 Jet	0 Jet	1 Jet	2 Jet
Parton Density Function	9.7%	9.7%	9.7%	3.6%	3.6%	3.6%
Renormalization Scale	8%	10%	30%	4%	1.5%	2%
Underlying Event / Parton Shower	4%	5%	10%	10%	0%	1%

Dependent on $M_{\text{collinear}}$	$\tau_e \mu$	$\tau_{\text{had}} \mu$
Hadronic Tau Energy Scale	-	3%
Jet Energy Scale	3-7%	3-7%
Unclustered Energy Scale	10%	10%
$Z \rightarrow \tau \tau$ Bias	100%	-
bin-by-bin uncertainty		

M_{coll} Distribution Post-Fit: H → τ_{had}μ

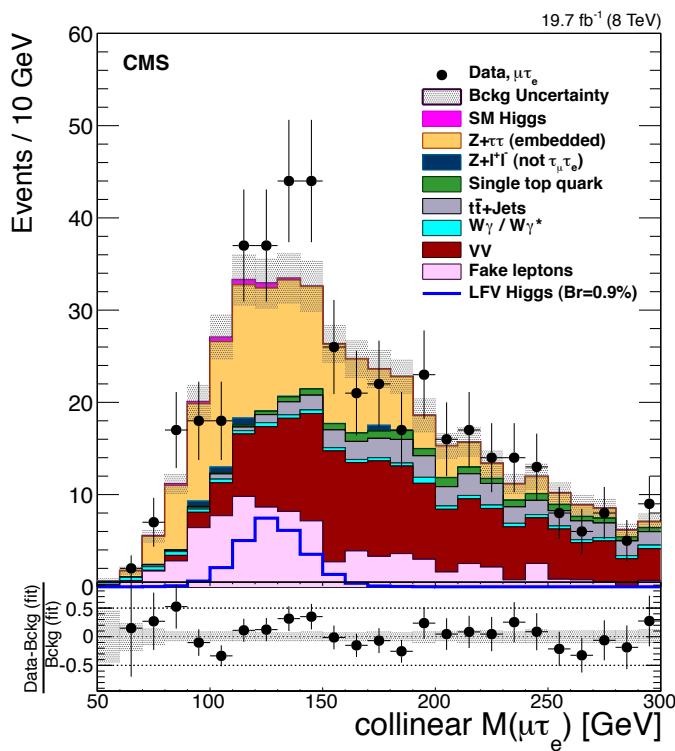
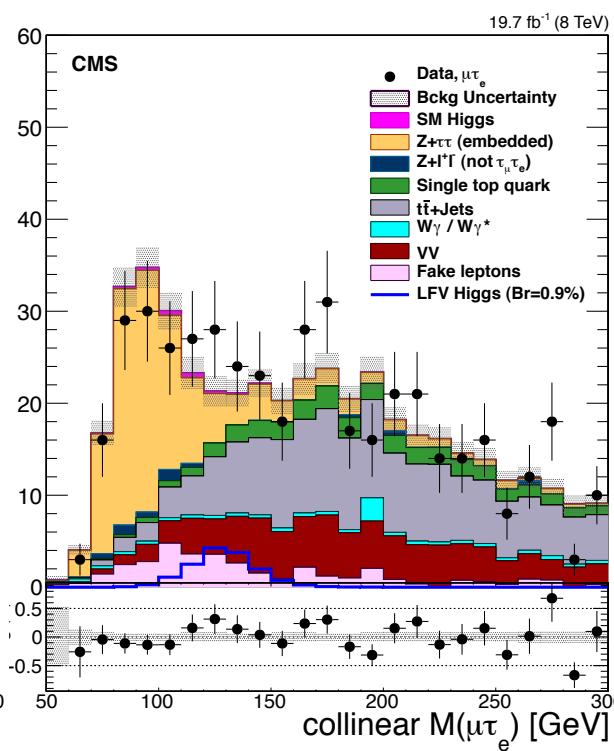
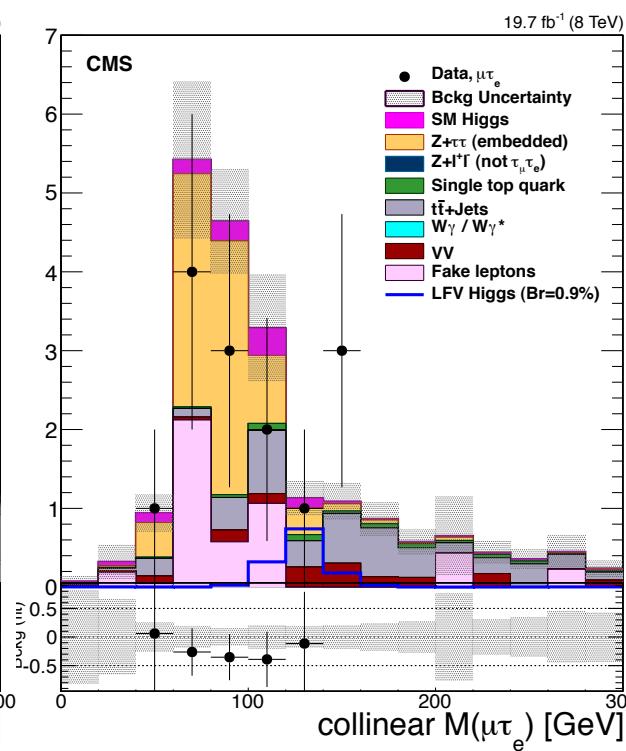
20

0 Jet**1 Jet****2 Jets**

Distributions after fitting for signal + background. Signal shown in blue with best fit branching ratio. Slight excess in each category but still consistent within background uncertainties.

M_{coll} Distribution Post-Fit: $H \rightarrow \tau_e \mu$

21

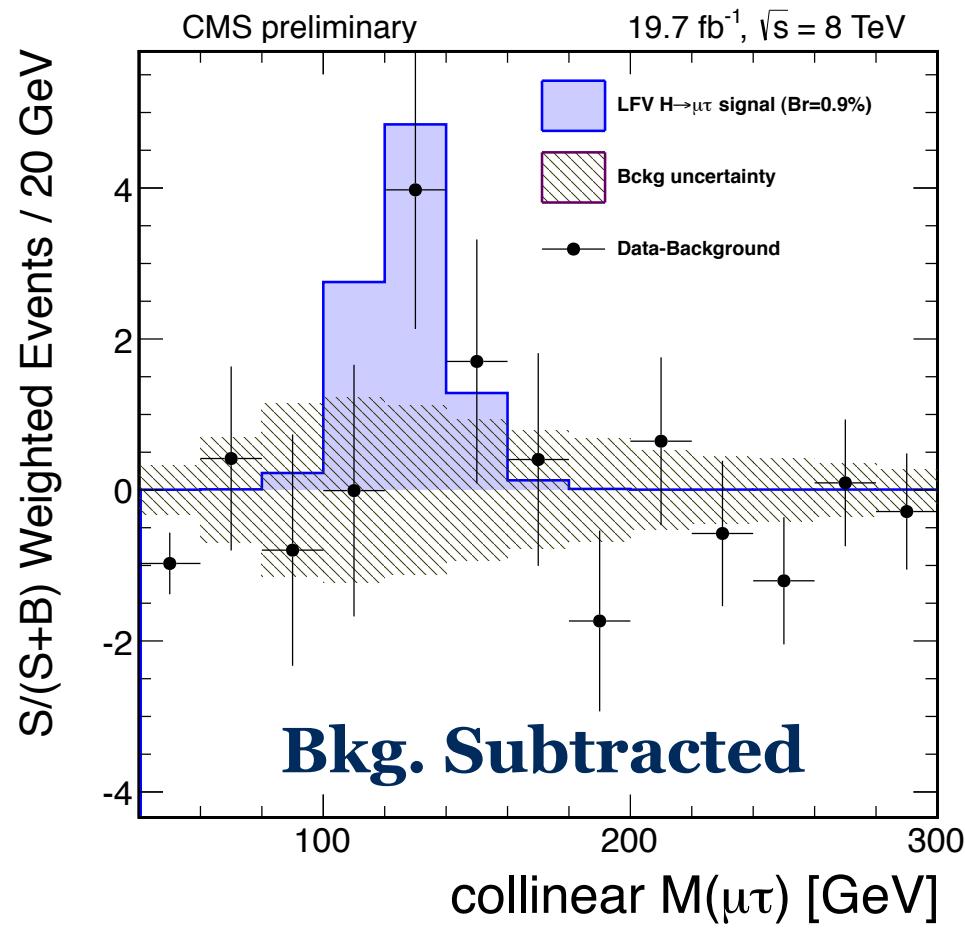
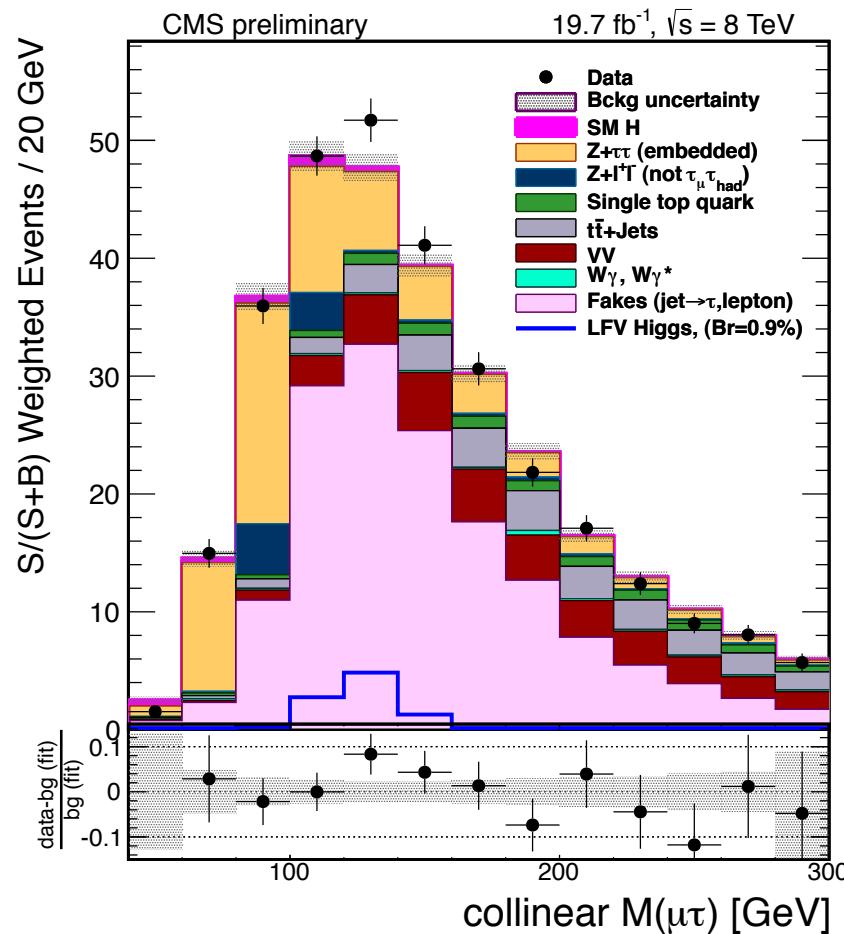
0 Jet**1 Jet****2 Jets**

Distributions after fitting for signal + background. Signal shown in blue with best fit branching ratio. Slight excess in each category but still consistent within background uncertainties.

Weighted M_{coll} Distributions

22

Combined channels and categories bins weighted by significance (S/(S+B))



Branching Ratio Limits

23

	Expected (%)	Observed (%)	Best Fit (%)
$\tau\mu$	$< 0.75 (\pm 0.38)$	< 1.57	$0.89^{+0.40}_{-0.37}$

Combined excess is 2.5 standard deviations
which corresponds to local p-value of 0.007 at
 $M_H=125$ GeV

Limit: Yukawa Coupling

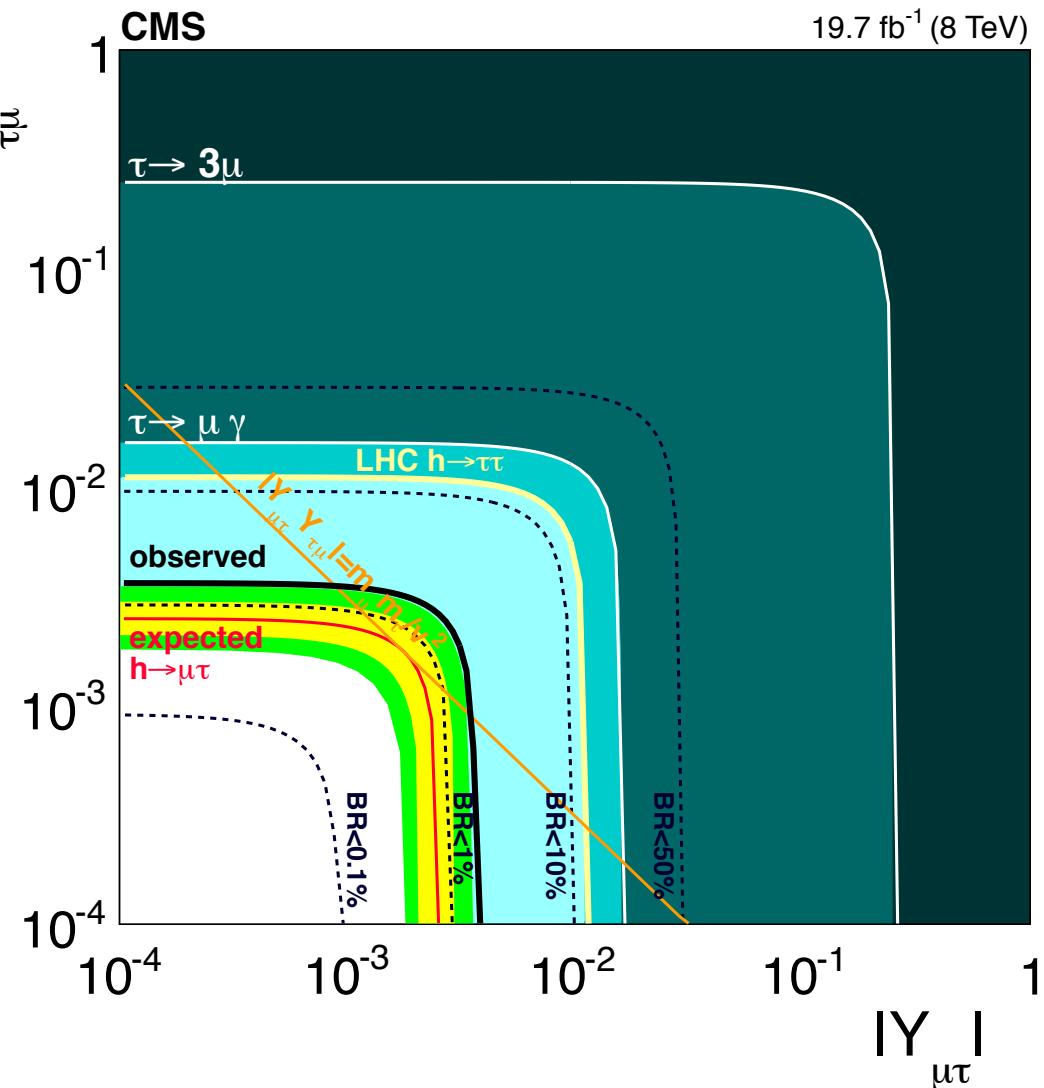
24

- Yukawa couplings governing LFV Higgs:

$$\Gamma(h \rightarrow \ell^\alpha \ell^\beta) = \frac{m_h}{8\pi} \left(|Y_{\ell^\alpha \ell^\beta}|^2 + |Y_{\ell^\beta \ell^\alpha}|^2 \right)$$

- Reinterpreting BR limit into Yukawa coupling limit with BR < 0.89% gives:

$$\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 3.63 \cdot 10^{-3}$$



Conclusions

25

- First direct, dedicated search for LFV Higgs
- limit is approximately an order of magnitude tighter than previous limits
- Slight excess with 2.5σ significance
 - Interpreted as a statistical fluctuation gives a constraint of $B(H \rightarrow \mu \tau) < 1.57\%$ at 95% confidence level
 - Interpreted as a signal, the best fit branching fraction is $B(H \rightarrow \mu \tau) = 0.89\% {}^{+0.40}_{-0.37}$

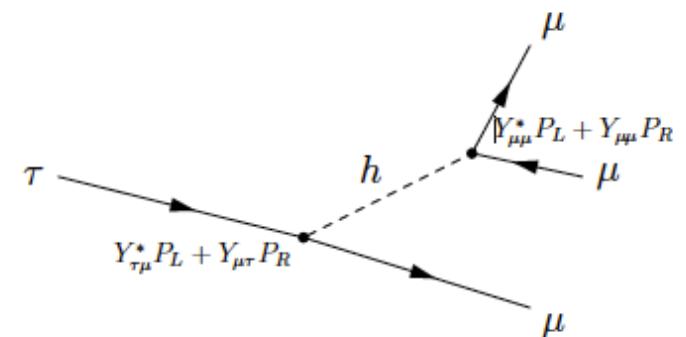
Back Up

Theoretical

27

- Two Higgs doublets, extra dimensions, and composite models can all have LFV Higgs interactions
- $H \rightarrow \tau\mu$ and $H \rightarrow \tau e$ can have order $BR(10\%)$ under currently low energy constraints.
- Off diagonal elements of Y_{ij} that are too large effect a need for fine tuning. Avoided if:

$$|Y_{\tau\mu} Y_{\mu\tau}| \leq \frac{m_\mu m_\tau}{v^2}$$



Existing Limits

28

$\tau \rightarrow \mu\gamma$	$\sqrt{ Y_{\tau\mu} ^2 + Y_{\mu\tau} ^2}$	0.016
$\tau \rightarrow 3\mu$	$\sqrt{ Y_{\tau\mu}^2 + Y_{\mu\tau} ^2}$	$\lesssim 0.25$
muon $g - 2$	$\text{Re}(Y_{\mu\tau} Y_{\tau\mu})$	$(2.7 \pm 0.75) \times 10^{-3}$
muon EDM	$\text{Im}(Y_{\mu\tau} Y_{\tau\mu})$	-0.8...1.0

Reinterpreted ATLAS result of $H \rightarrow \tau\tau$ by Harnik et al.

95% C.L. limit	$\text{BR}(h \rightarrow \tau\mu)$	$\sqrt{Y_{\tau\mu}^2 + Y_{\mu\tau}^2}$
expected	28%	0.018
observed	13%	0.011

Existing Limits

LFV Lagrangian terms:

$$L_V \equiv -Y_{\tau\mu} \bar{\tau}_L \mu_R h - \dots$$

Branching Ratio

$$\text{BR}(h \rightarrow \ell^\alpha \ell^\beta) = \frac{\Gamma(h \rightarrow \ell^\alpha \ell^\beta)}{\Gamma(h \rightarrow \ell^\alpha \ell^\beta) + \Gamma_{\text{SM}}}$$

Assume $\Gamma_{\text{SM}} = 4.1 \text{ MeV}$

then decay width:

$$\Gamma(h \rightarrow \ell^\alpha \ell^\beta) = \frac{m_h}{8\pi} (|Y_{\ell^\beta \ell^\alpha}|^2 + |Y_{\ell^\alpha \ell^\beta}|^2)$$

Channel	Coupling	Bound
$\mu \rightarrow e\gamma$	$\sqrt{ Y_{\mu e} ^2 + Y_{e\mu} ^2}$	$< 3.6 \times 10^{-6}$
$\mu \rightarrow 3e$	$\sqrt{ Y_{\mu e} ^2 + Y_{e\mu} ^2}$	< 0.31
electron $g - 2$	$\text{Re}(Y_{e\mu} Y_{\mu e})$	$-0.019 \dots 0.026$
electron EDM	$ \text{Im}(Y_{e\mu} Y_{\mu e}) $	$< 9.8 \times 10^{-8}$
$\mu \rightarrow e$ conversion	$\sqrt{ Y_{\mu e} ^2 + Y_{e\mu} ^2}$	$< 4.6 \times 10^{-5}$
$M\bar{M}$ oscillations	$ Y_{\mu e} + Y_{e\mu}^* $	< 0.079
$\tau \rightarrow e\gamma$	$\sqrt{ Y_{\tau e} ^2 + Y_{e\tau} ^2}$	< 0.014
$\tau \rightarrow e\mu\mu$	$\sqrt{ Y_{\tau e} ^2 + Y_{e\tau} ^2}$	< 0.66
electron $g - 2$	$\text{Re}(Y_{e\tau} Y_{\tau e})$	$[-2.1 \dots 2.9] \times 10^{-3}$
electron EDM	$ \text{Im}(Y_{e\tau} Y_{\tau e}) $	$< 1.1 \times 10^{-8}$
$\tau \rightarrow \mu\gamma$	$\sqrt{ Y_{\tau\mu} ^2 + Y_{\mu\tau} ^2}$	$< 1.6 \times 10^{-2}$
$\tau \rightarrow 3\mu$	$\sqrt{ Y_{\tau\mu}^2 + Y_{\mu\tau} ^2}$	< 0.52
muon $g - 2$	$\text{Re}(Y_{\mu\tau} Y_{\tau\mu})$	$(2.7 \pm 0.75) \times 10^{-3}$
muon EDM	$ \text{Im}(Y_{\mu\tau} Y_{\tau\mu}) $	$-0.8 \dots 1.0$
$\mu \rightarrow e\gamma$	$(Y_{\tau\mu} Y_{\tau e} ^2 + Y_{\mu\tau} Y_{e\tau} ^2)^{1/4}$	$< 3.4 \times 10^{-4}$

Data Samples & Triggers

30

- Monte Carlo simulation sets (full list in backup)
 - Corrections for Trigger efficiencies and electron and muon ID/ISO
 - Pileup re-weighting is used to remove energy from pile up
 - Pileup jet cleaning to reduce jets from pileup
- $H \rightarrow \tau_{had} \mu$ utilizes a single muon trigger while $H \rightarrow \tau_e \mu$ uses Muon + electron cross trigger

Overview: Data

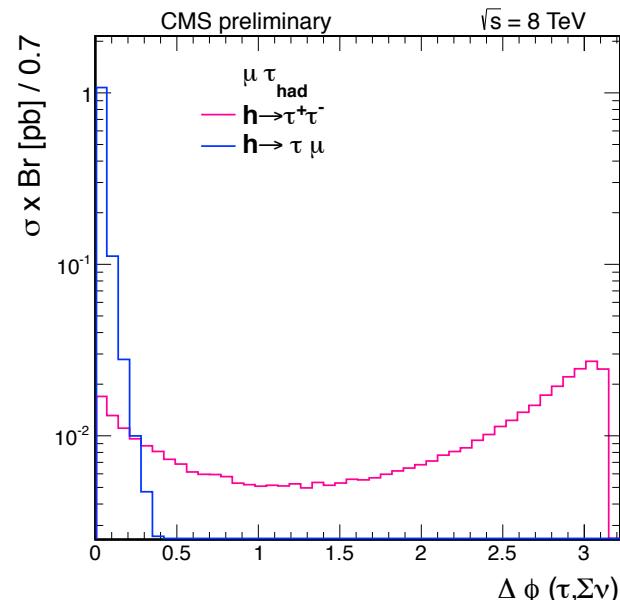
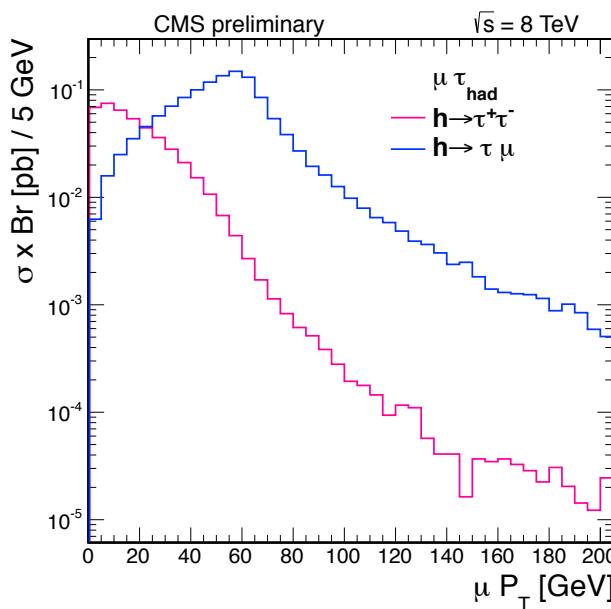
Description	Name	σ (pb)
LFV Higgs Signal	LFV_GluGluHToTauMu_M125_8TeV_Pythia8	19.6
	LFV_VBFHToTauMu_M125_8TeV_Pythia8	1.58
SM Higgs Signal	GluGluHToTauMu_M125_8TeV_Tauola_Pythia6	19.6
	VBFHToTauMu_M125_8TeV_Tauola_Pythia6	1.58
$W \rightarrow l\nu + jets$	WJetsToLNu_TuneZ2Star_8TeV-madgraph +WXJetsToLNu_TuneZ2Star(X=1-4)	37509
$qq \rightarrow l^+l^- + jets$	DYJetsToLL_M50_TuneZ2Star_8TeV madgraph +DYXJetsToLL_M50_TuneZ2Star_8TeV madgraph	3503
$t\bar{t} + jets$	TTJets_FullLeptMGDecays_8TeVmadgraphtauola	24.56
	TTJets_SemiLeptMGDecays_8TeV-madgraphtauola	102.5
t,\bar{t}	/T(bar)_t-channel_TuneZ2star_8TeV-powheg-tauola	11.1
	T(bar)_t-channel-DR_TuneZ2star_8TeV powheg-tauola	56.4 (30.7)
$WW \rightarrow 2l2\nu + jets$	WWTo2L2Nu_TuneZ2star_8TeV_pythia6_tauola	5.76
$ZZ \rightarrow 4l$	ZZJetsTo4L_TuneZ2star_8TeV-madgraph-tauola	0.18
$ZZ \rightarrow 2l2Q$	ZZJetsTo2L2Q_TuneZ2star_8TeV-madgraph-tauola	2.45
$ZZ \rightarrow 2l2\nu$	ZZJetsTo2L2Nu_TuneZ2star_8TeV-madgraph-tauola	0.36
$WZ \rightarrow 2l2Q$	WZJetsTo2L2Q_TuneZ2star_8TeV-madgraph-tauola	2.21
$WZ \rightarrow 3l\nu$	WZJetsTo3LNu_TuneZ2_8TeV-madgraph-tauola	1.06
$W\gamma \rightarrow l\nu\gamma$	WGToLNuG_TuneZ2star_8TeV-madgraph-tauola	461.6
$W\gamma^* \rightarrow l\nu 2e$	WGstarToLNu2E_TuneZ2star_8TeV-madgraph-tauola	5.87 (k-factor: 1.5)
$W\gamma^* \rightarrow l\nu 2\mu$	WGstarToLNu2Mu_TuneZ2star_7TeV-madgraph-tauola	1.91 (k-factor: 1.5)

Difference w.r.t. SM

32

- LFV $H \rightarrow \tau_{\text{had}} \mu$ and $H \rightarrow \tau_e \mu$ are similar to SM $H \rightarrow \tau_{\text{had}} \tau_\mu$ and $H \rightarrow \tau_{\text{had}} \tau_e$ respectively. Thus have similar background sources to the SM processes.
- Muon is prompt thus has higher momentum than in SM
- Fewer neutrinos give different missing energy and topology.

SM vs LFV in simulation



Transverse Mass

33

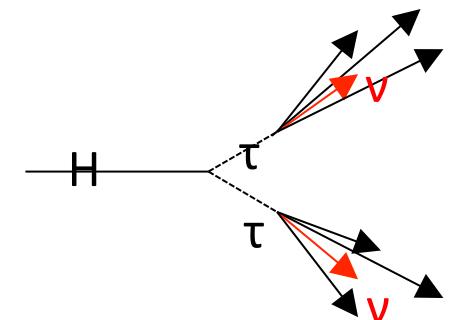
- Defined as

$$M_T^2 = E_{T,\text{total}}^2 - \vec{p}_{T,\text{total}}^2$$

- Where Transverse Energy for each particle is:

$$E_T^2 = m^2 + \vec{p}_T^2$$

- $M_T \leq M$ allowing observation of M even with invisible decay products.



Preselection Requirements

34

Leptons (e, μ)

- Minimum pT cuts
- Detector acceptance cuts
- Isolation criteria
- Identification criteria

Jets (including τ_{had})

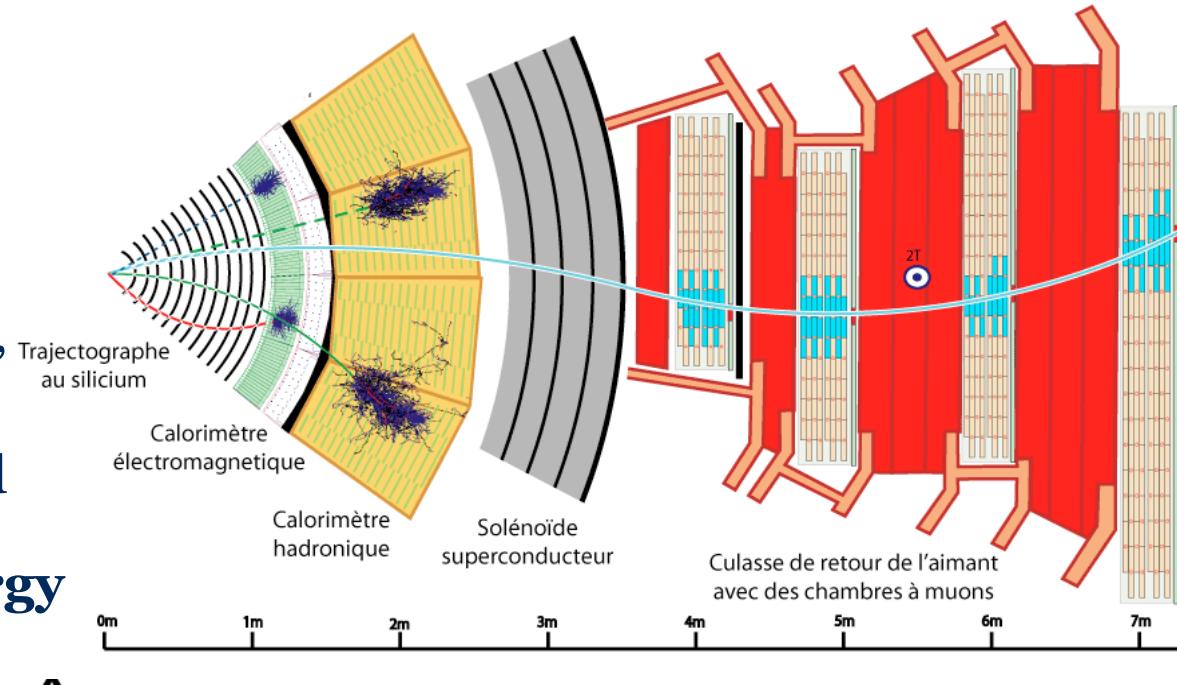
- Minimum pT cuts
- Detector acceptance cuts
- ID requirements
- corrected for pile-up, eta, and pT dependence
- jets from b quarks vetoed

Missing Transverse Energy

- Jet energy corrected

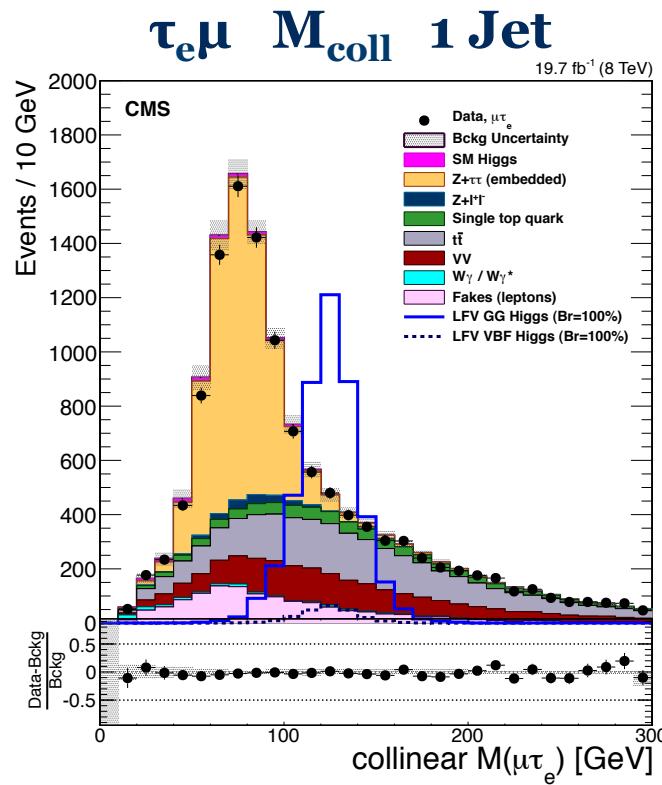
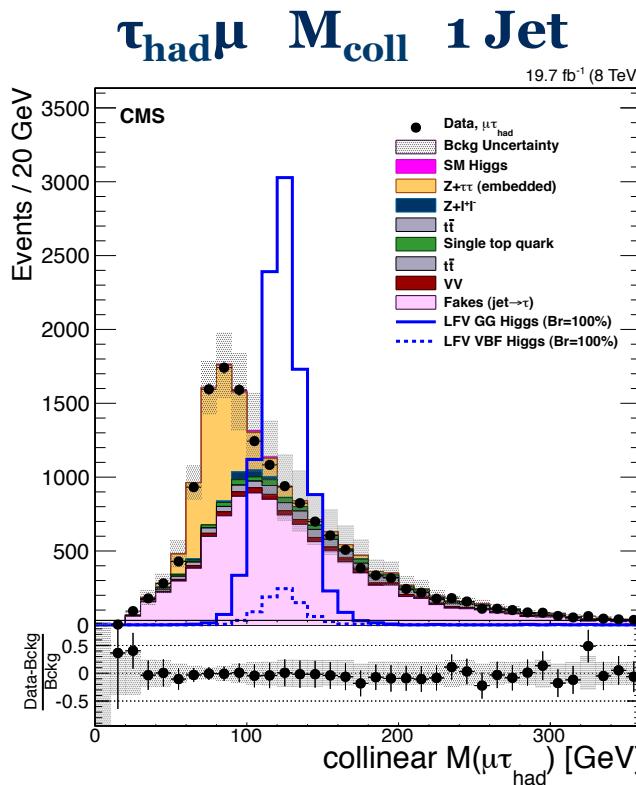
Event

- Leptons oppositely charged
- Veto extra isolated leptons
- Non-overlapping leptons and jets
- Particle Flow Objects
- Trigger on muons or muons+electrons



Preselection Agreement

- Preselection is a set of minimal requirements to give well defined objects and relevant events
- Good agreement in preselection indicates backgrounds are well modeled
- Signal shown x100 for visibility



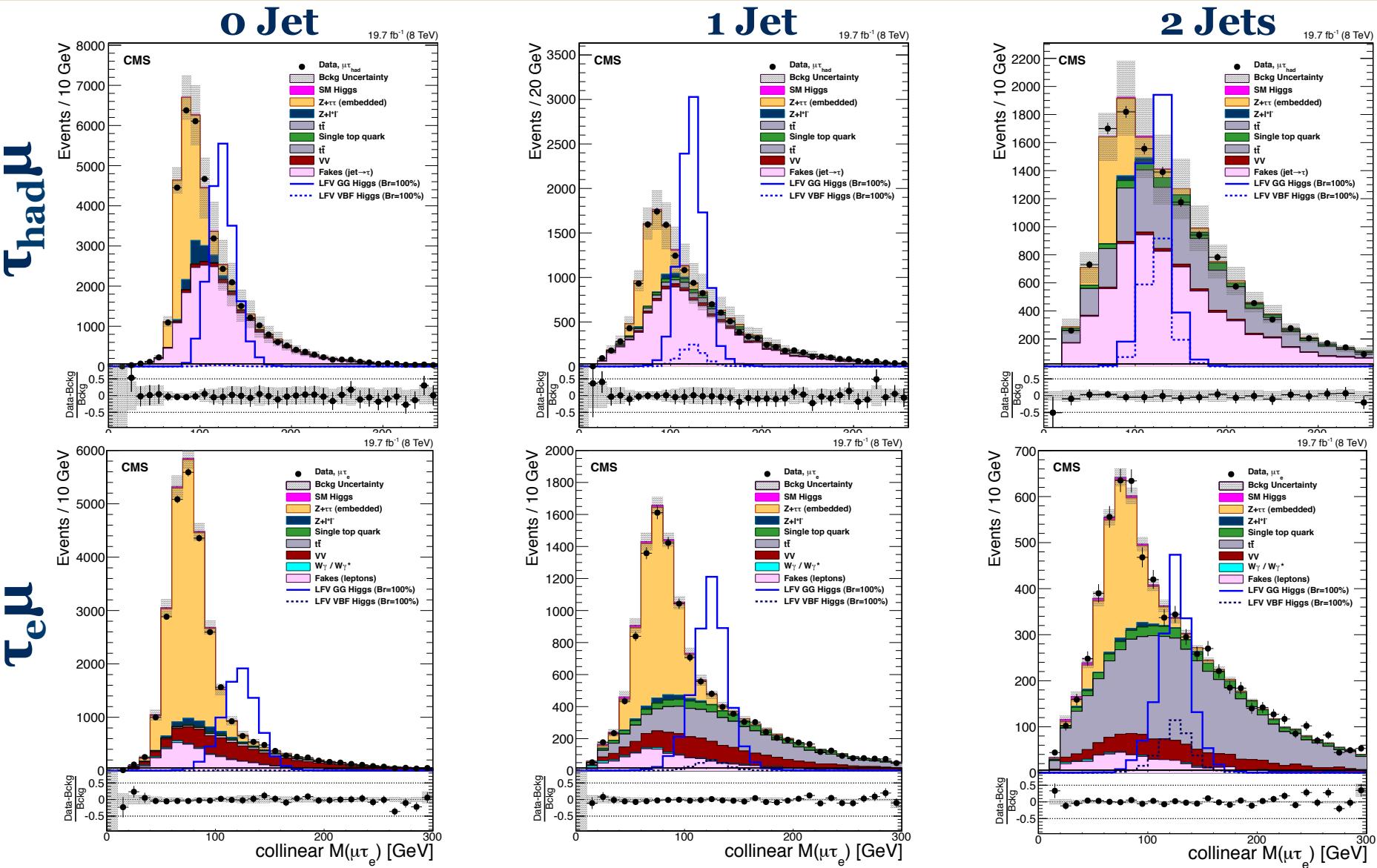
Using fake rate to get background

- Look at data in region that fulfills all signal selection criteria EXCEPT tight isolation
 - specifically passing loose isolation but NOT tight isolation
- Weighting this region by a factor based on fake rate scales the background to match what it would be, were there no fakes.

$$f = \frac{N_{tight}}{N_{loose}} \rightarrow 1 - f = \frac{N_{NOT-tight}}{N_{loose}} \rightarrow N_{loose} = \frac{N_{NOT-tight}}{1 - f}$$
$$N_{tight} = f \cdot N_{loose}$$
$$N_{tight} = N_{NOT-tight} \cdot \frac{f}{1 - f}$$

Preselection Agreement (BR = 100%)

37



Full Selection

38

Variable	$H \rightarrow \tau_e \mu$			$H \rightarrow \tau_{had} \mu$		
	0 Jet	1 Jet	2 Jet	0 Jet	1 Jet	2 Jet
$\mu p_T > [\text{GeV}]$	50	45	25	40	35	30
$e p_T > [\text{GeV}]$	10	10	10	-	-	-
$\tau p_T > [\text{GeV}]$	-	-	-	35	40	40
$\Delta\phi_{\mu-\tau \text{ had}} >$	-	-	-	2.7	-	-
$\Delta\phi_{e-\text{MET}} <$	0.5	0.5	0.3	-	-	-
$\Delta\phi_{e-\mu} >$	2.7	1.0	-	-	-	-
$M_T(e) < [\text{GeV}]$	65	65	25	-	-	-
$M_T(\mu) > [\text{GeV}]$	50	40	15	-	-	-
$M_T(\tau) < [\text{GeV}]$	-	-	-	50	35	35
$\Delta\eta_{\text{jet jet}} >$	-	-	2.5	-	-	3.5
M_{jets}	-	-	550	-	-	550

Optimized for $S/\sqrt{(S+B)}$

Event Yields: Full Selection

39

Sample	$\tau_e \mu$			$\tau_{had} \mu$		
	0 Jet	1 Jet	2 Jet	0 Jet	1 Jet	2 Jet
Fakes	41.5 ± 17.3	16.1 ± 6.8	1.1 ± 0.7	1858.1 ± 558.8	362.9 ± 110	0.5 ± 0.5
$Z \rightarrow \tau \tau$	65.0 ± 3.0	38.6 ± 2.0	1.3 ± 0.2	198.8 ± 11.0	50.5 ± 3.5	0.4 ± 0.2
ZZ, WW	40.8 ± 6.6	21.2 ± 3.5	0.7 ± 0.2	47.0 ± 8.0	14.6 ± 2.6	0.3 ± 0.2
$W\gamma$	2.0 ± 2.1	1.9 ± 1.9	-	-	-	-
$Z \rightarrow ee \text{ or } \mu\mu$	1.6 ± 0.8	1.8 ± 0.8	-	94.5 ± 25.2	17.6 ± 6.7	0.1 ± 0.1
ttbar	4.8 ± 0.7	30.0 ± 3.4	1.8 ± 0.3	2.5 ± 0.6	24.3 ± 3.2	0.7 ± 0.3
t, tbar	1.9 ± 0.2	6.8 ± 0.8	0.2 ± 0.1	2.7 ± 1.2	19.9 ± 3.9	0.4 ± 0.5
SM Higgs	1.9 ± 0.3	1.6 ± 0.2	0.6 ± 0.1	7.0 ± 1.3	4.9 ± 0.7	1.9 ± 0.7
Sum of bkg	159.4 ± 18.9	118.1 ± 8.9	5.6 ± 0.9	2210.4 ± 559.6	494.7 ± 110.4	4.3 ± 1.1
LFV Higgs Sig.	24.2 ± 5.7	13.6 ± 3.1	1.2 ± 0.4	69.7 ± 17.0	29.7 ± 6.7	3.0 ± 1.0
Data	180 ± 13.4	128.0 ± 11.3	6.0 ± 2.4	2255.0 ± 47.5	506.0 ± 22.5	8.0 ± 2.8

Branching Ratio Limits

40

Expected Limits

	0 Jet (%)	1 Jet (%)	2 Jet (%)
$\tau_e \mu$	< 1.32 (± 0.67)	< 1.66 (± 0.85)	< 3.77 (± 1.92)
$\tau_{\text{had}} \mu$	< 2.35 (± 1.20)	< 2.10 (± 1.07)	< 1.94 (± 0.99)
$\tau \mu$		< 0.75 (± 0.38)	

Observed Limits

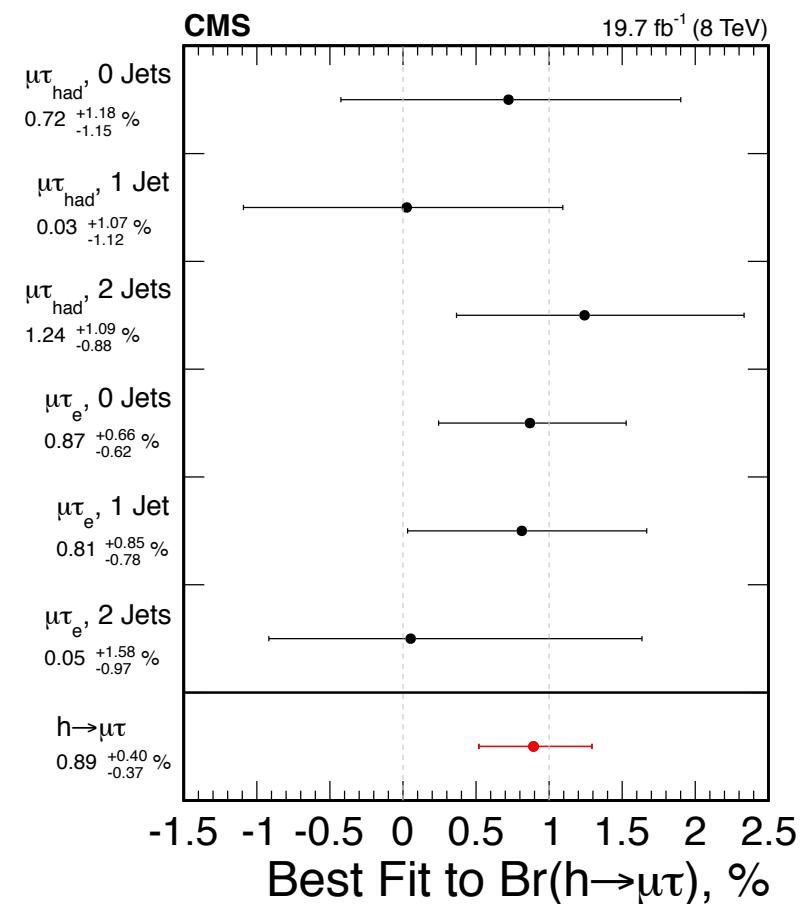
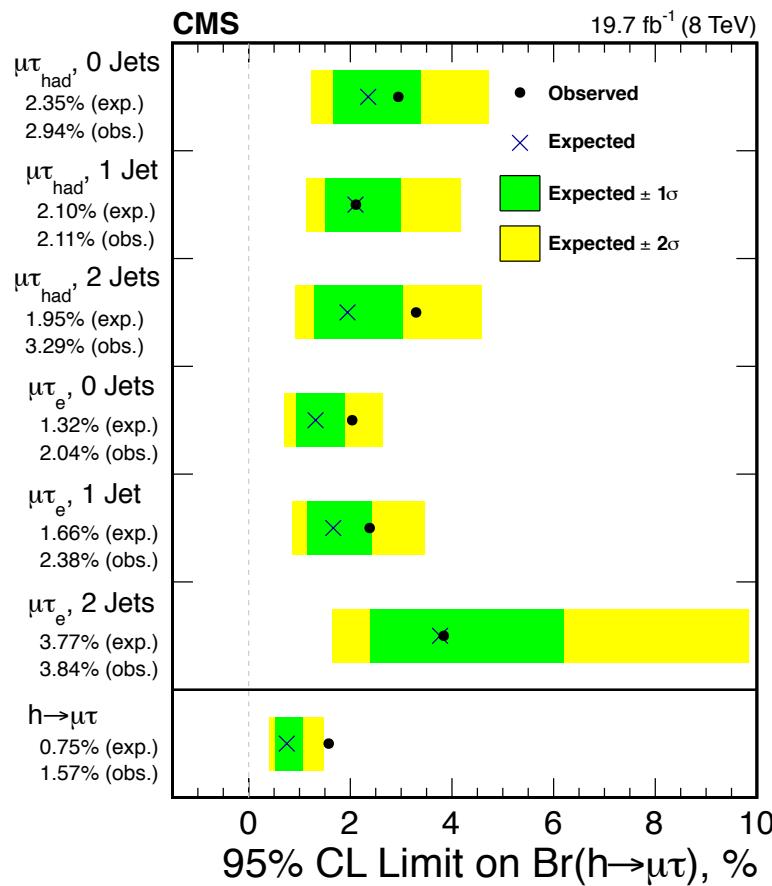
$\tau_e \mu$	< 2.04	< 2.38	< 3.84
$\tau_{\text{had}} \mu$	< 2.94	< 2.11	< 3.29
$\tau \mu$		< 1.57	

Best Fit Branching Ratio

$\tau_e \mu$	$0.87^{+0.66}_{-0.62}$	$0.81^{+0.85}_{-0.78}$	$0.05^{+1.58}_{-0.97}$
$\tau_{\text{had}} \mu$	$0.72^{+1.18}_{-1.15}$	$0.03^{+1.07}_{-1.12}$	$1.24^{+1.09}_{-0.88}$
$\tau \mu$		$0.89^{+0.40}_{-0.37}$	

Branching Ratio Limits

Combined excess is 2.5 standard deviations which corresponds to local p-value of 0.007 at $M_H=125$ GeV



Limit: Yukawa Coupling

42

- Following LFV theory reference: [arXiv:1209.1397](https://arxiv.org/abs/1209.1397)
- LFV Lagrangian terms give width:

$$L_V \equiv -Y_{\tau\mu} \bar{\tau}_L \mu_R h - \dots \implies \Gamma(h \rightarrow \ell^\alpha \ell^\beta) = \frac{m_h}{8\pi} \left(|Y \ell^\alpha \ell^\beta|^2 + |Y \ell^\beta \ell^\alpha|^2 \right)$$

- Define branching ratio and solve for coupling:

$$BR(h \rightarrow \ell^\alpha \ell^\beta) = \frac{\Gamma(h \rightarrow \ell^\alpha \ell^\beta)}{\Gamma(h \rightarrow \ell^\alpha \ell^\beta) + \Gamma_{SM}} \implies \sqrt{|Y \ell^\alpha \ell^\beta|^2 + |Y \ell^\beta \ell^\alpha|^2} = \sqrt{\frac{\Gamma_{SM} \cdot 8\pi \cdot BR}{m_h (1 - BR)}}$$