Search for Lepton-Flavor-Violating (LFV) Decays of the Higgs Boson

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for the CMS Collaboration

June 12, 2015

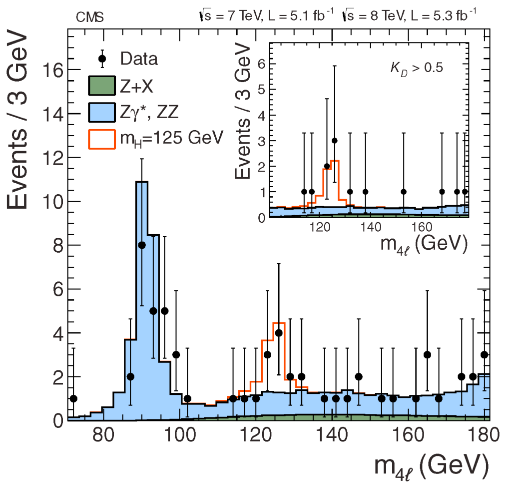
CMS: http://arxiv.org/abs/1502.07400

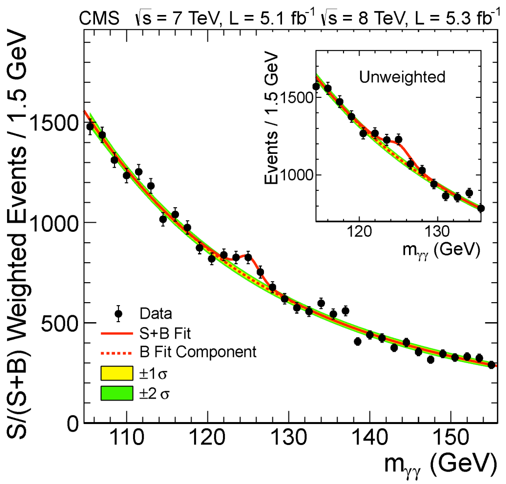
Physics Analysis Summary: http://cds.cern.ch/record/1740976

ATLAS: An independent re-interpretation of SM H->ττ is in the literature (Harnik,Zupan and Kopp JHEP **1303** (2013) 026)

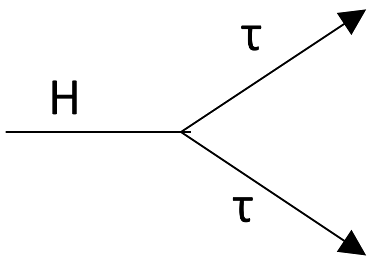
Investigating the Higgs Properties

- Higgs discovered with mass ~125 GeV
  (http://cds.cern.ch/record/1728249)
- Observed in Standard Model decays
  - H → τ τ
  - H → ZZ
  - H → WW
  - H → γ γ
- Are there non-Standard Model decay modes of the 125 GeV Higgs Boson?

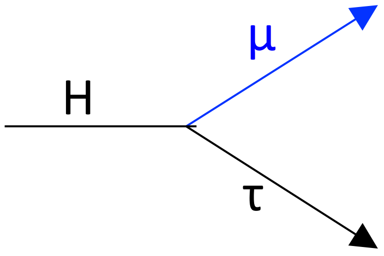




SM H → τ τ

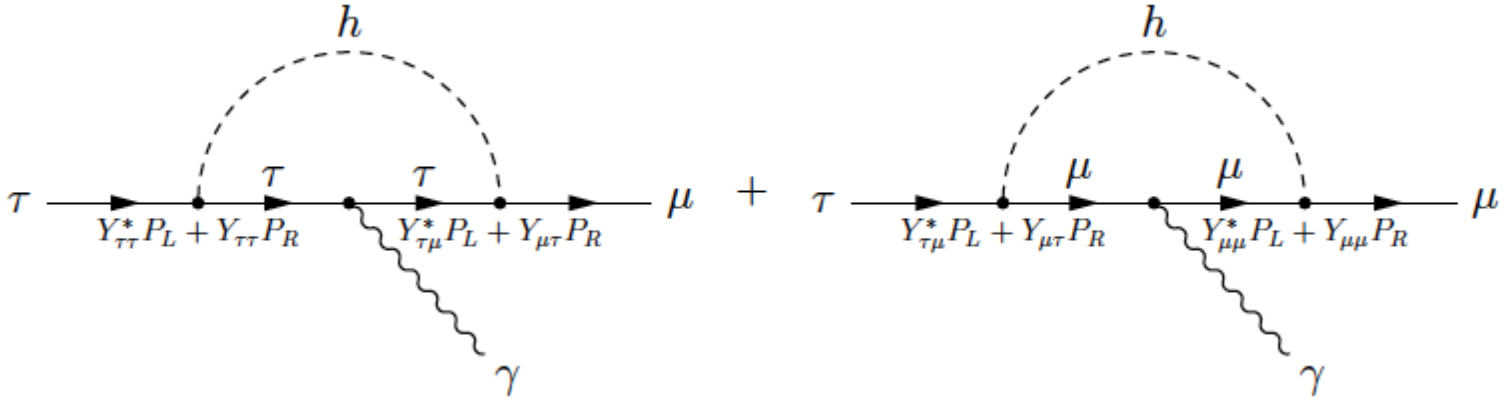


LFV H → μ τ



An Extensive Literature on possible LFV Higgs Decays

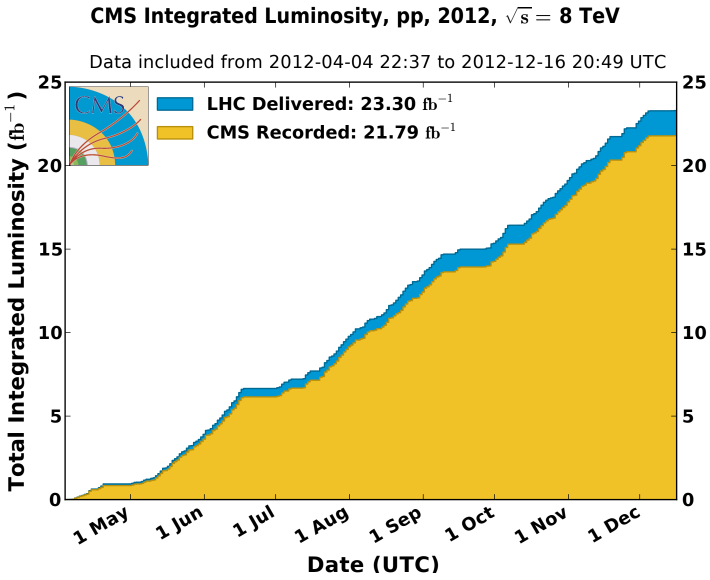
- Some new physics models may allow for LFV decays of Higgs including composite Higgs models, models with multiple Higgs doublets, non-renormalizable models valid to up to a finite mass scale and many others.
- Existing constraints on LFV coupling constants from indirect processes τ→μγ, τ→3μ, muon g-2, allow BR(H→τμ) = ~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. **D80** (2009) 075016, doi:10.1103/PhysRevD.80.075016, arXiv:0906.1542., A. Azatov, M. Toharia, and L. Zhu, "Higgs Mediated FCNC's inWarped Extra Dimensions", Phys.Rev. D80 (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 fromWarped 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. **B712** (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.

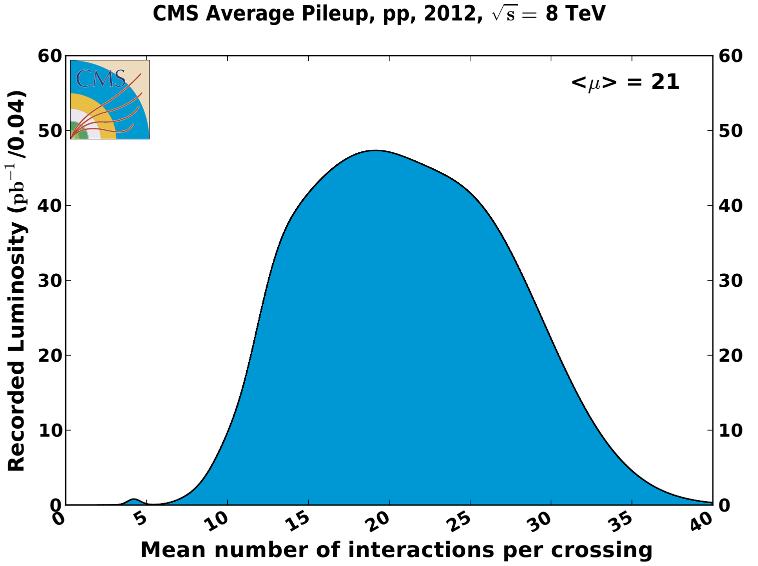
Data Set

- 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”



CMS Integrated Luminosity, pp, 2012, $\sqrt{s} = 8$ TeV

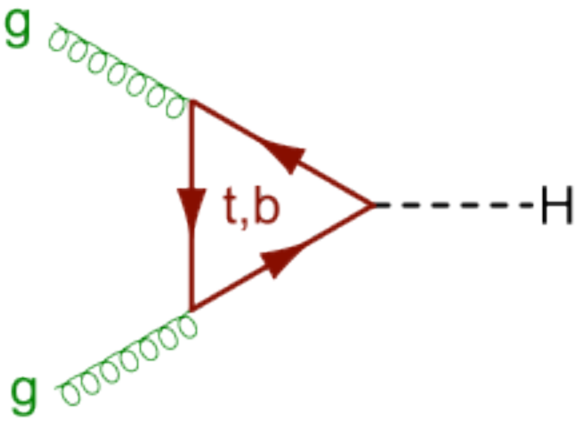
Data included from 2012-04-04 22:37 to 2012-12-16 20:49 UTC



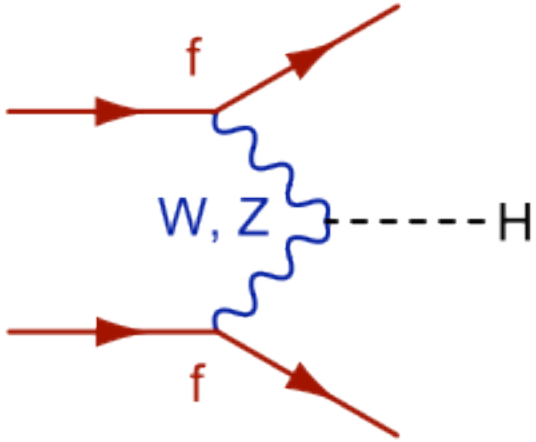
CMS Average Pileup, pp, 2012, $\sqrt{s} = 8$ TeV

Higgs Production in 8 TeV pp collisions

Gluon Gluon Fusion



Vector Boson Fusion

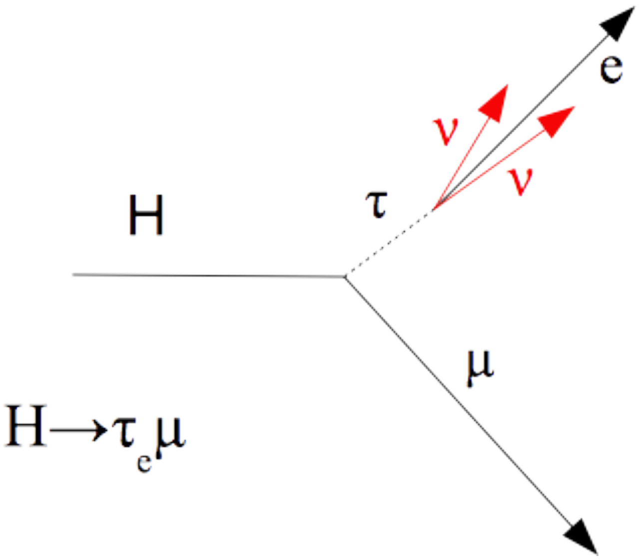


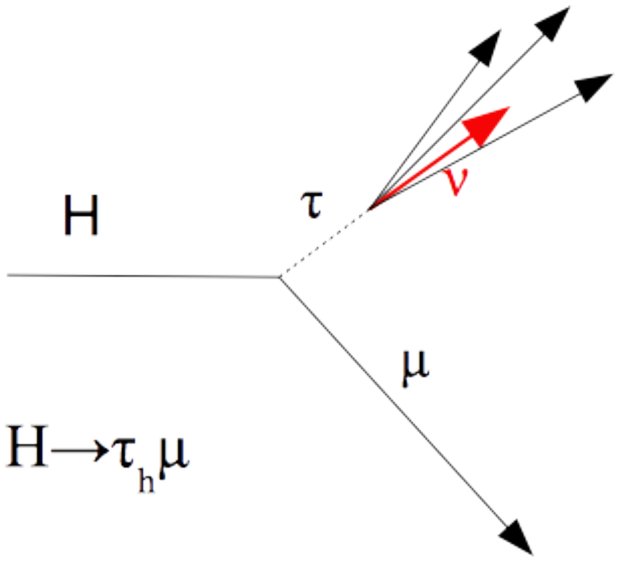
$\sigma_{\text{production}}$ 19.3 fb (90%) 1.6 fb (7%)

Different production mechanisms distinguished by number of jets in event.

Two Channels each with three Categories

- Two channels are studied: $H \rightarrow \tau_{had}\mu$ 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

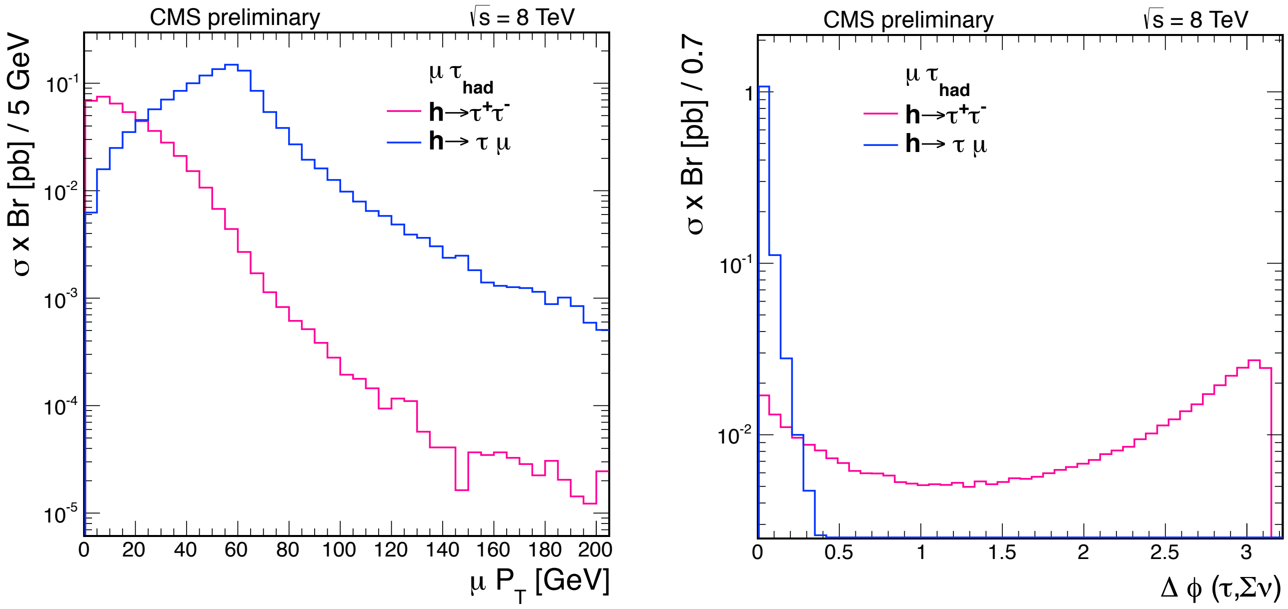




Similarities and differences to SM H->ττ searches

- LFV $H \rightarrow \tau_{had}\mu$ and $H \rightarrow \tau_{e}\mu$ are similar to SM $H \rightarrow \tau_{had}\tau_{\mu}$ and $H \rightarrow \tau_{had}\tau_{e}$ 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

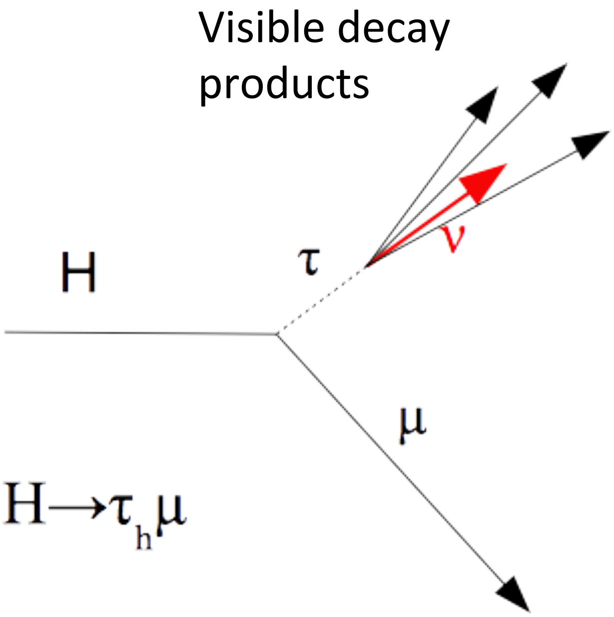


Standard Model searches not very sensitive because of different kinematics

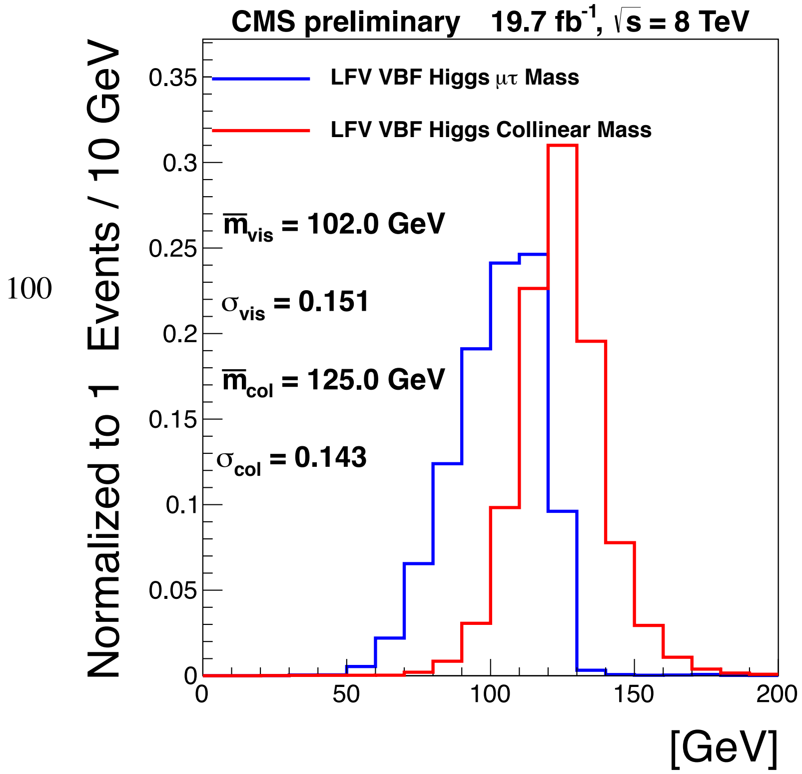
Selection Variables

- **μ, e, τ_{had} p_T cuts**: Leptons from signal process are expected to be generally higher than many backgrounds
- **Δφ 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.
- **linear cuts (no MVA's) optimized for $S/\sqrt{(S+B)}$ with signal region blinded**

Signal Variable – Collinear Mass (M_{col})



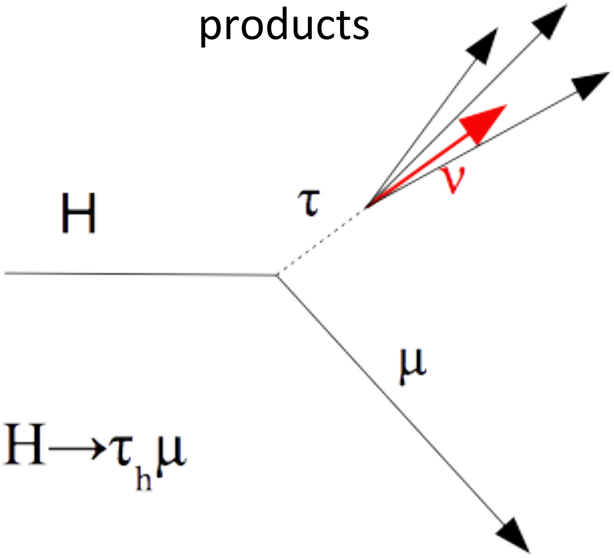
Approximate neutrino as collinear with the tau



Collinear Mass reduces bias and improves resolution versus visible Mass

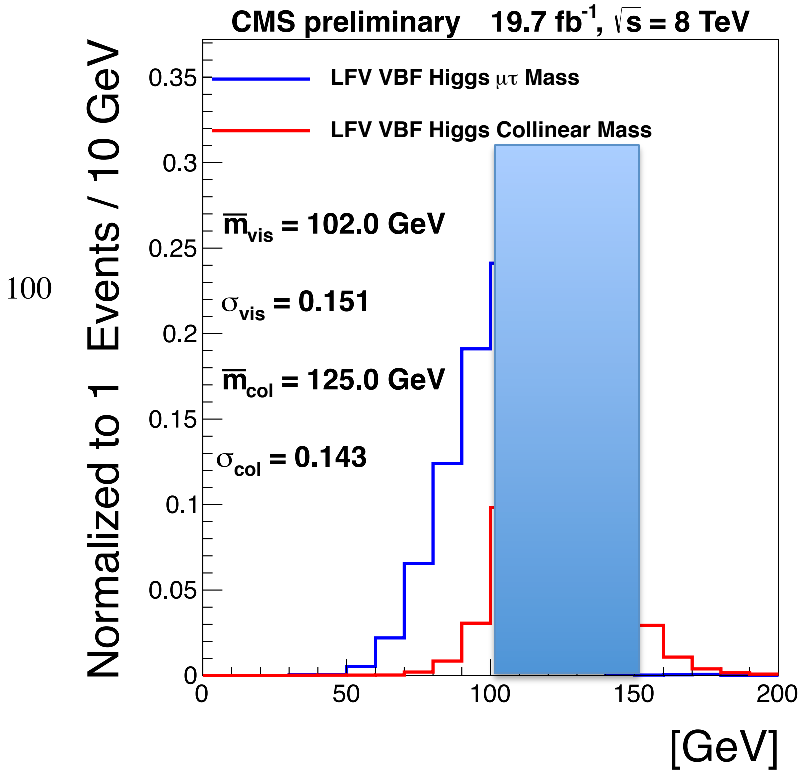
Signal region 100 < M_{col} < 150 GeV

Signal Variable – Collinear Mass (M_{col})



Visible decay products

Approximate neutrino as collinear with the tau



Collinear Mass reduces bias and improves resolution versus visible Mass

Signal region 100 < M_{col} < 150 GeV blinded

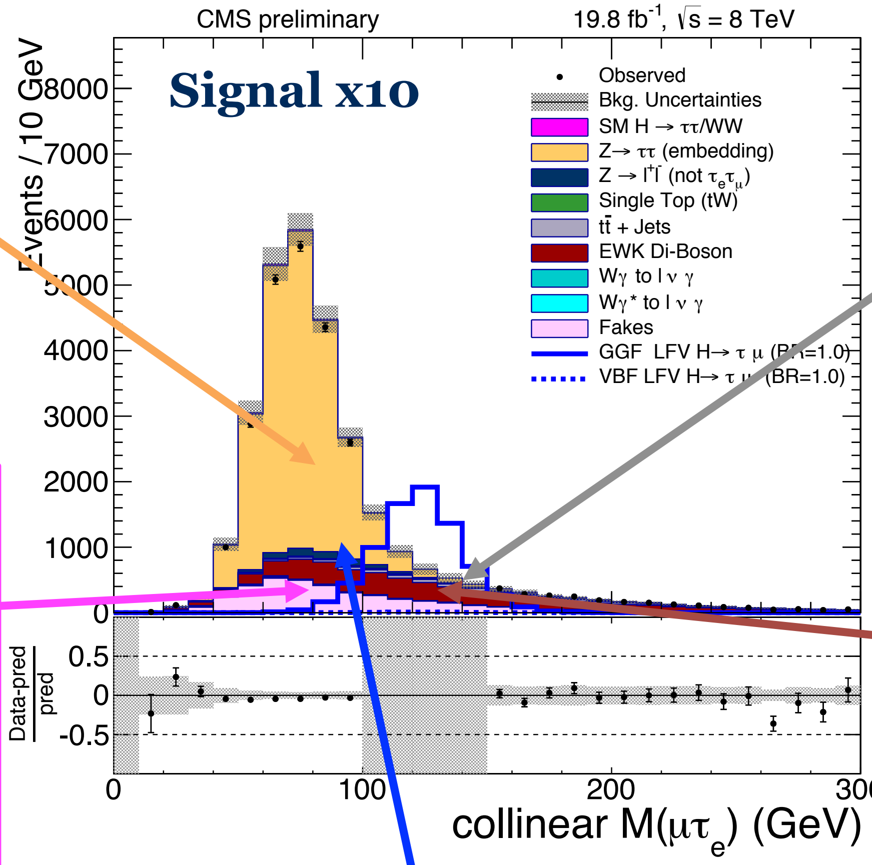
Background Overview

$Z \rightarrow \tau\tau$:

- 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:

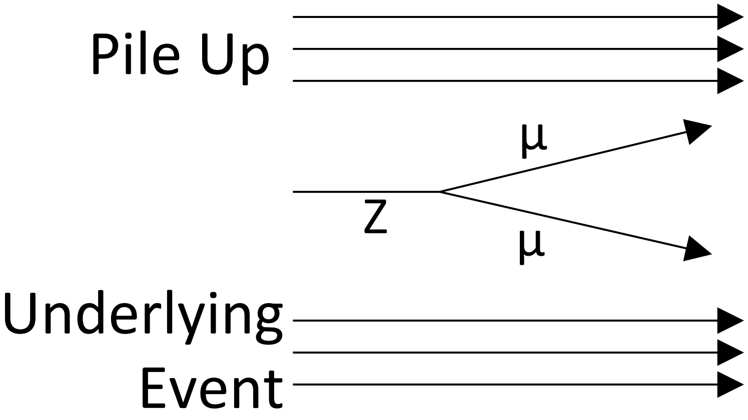
- Normalization(NLO) and shape from MC simulations

$Z \rightarrow l^+l^-$, Wjets+γ(*), SingleTop,…:

- Normalization and shape from MC simulation

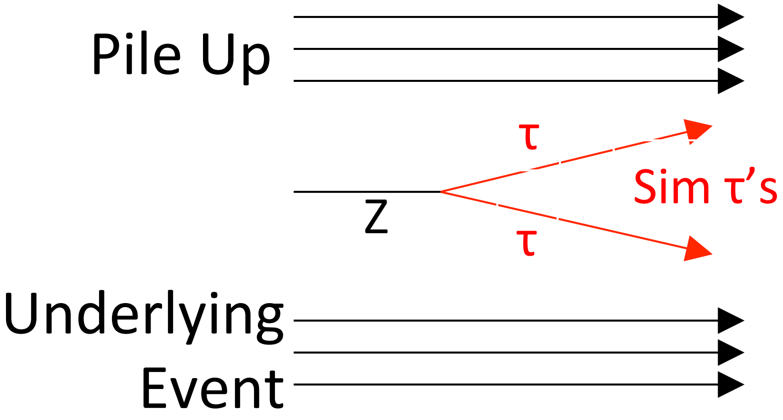
$Z \rightarrow \tau\tau$ Background

- 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 $\Delta R_{\mu\text{-}\tau} < 0.2$ ($\tau_{had}\mu$)



Z→ττ Background

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



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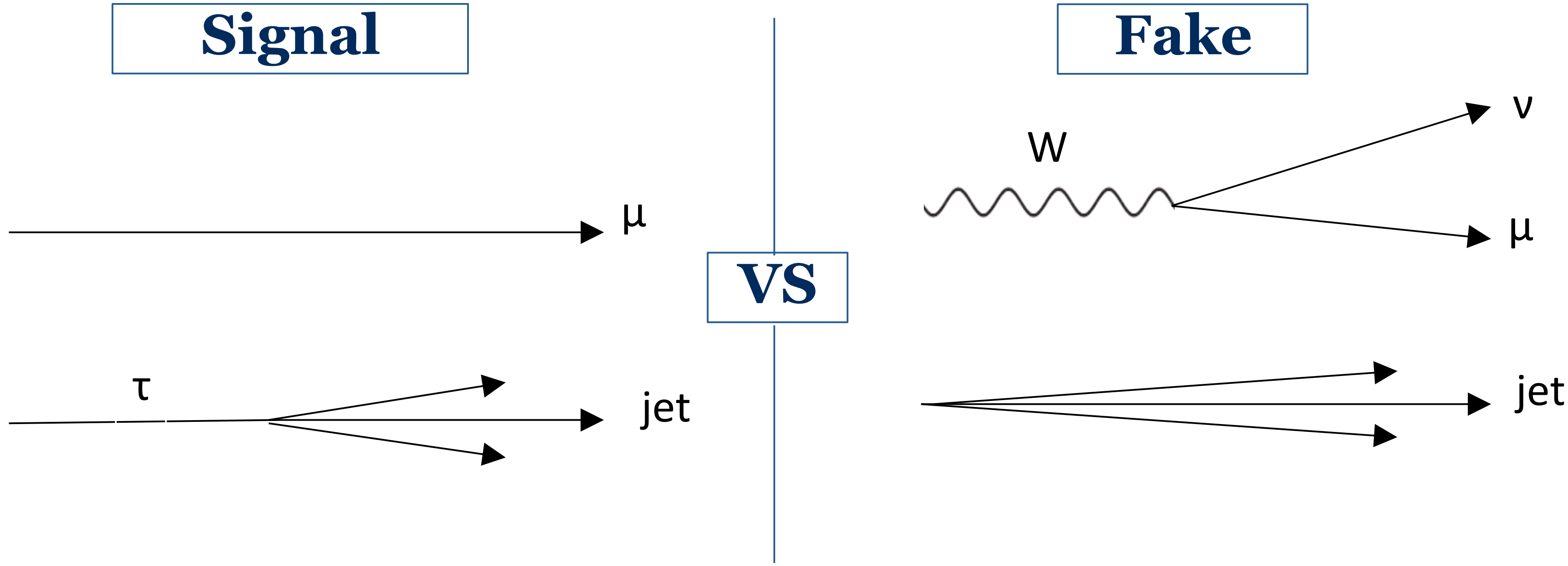
Fakes Background

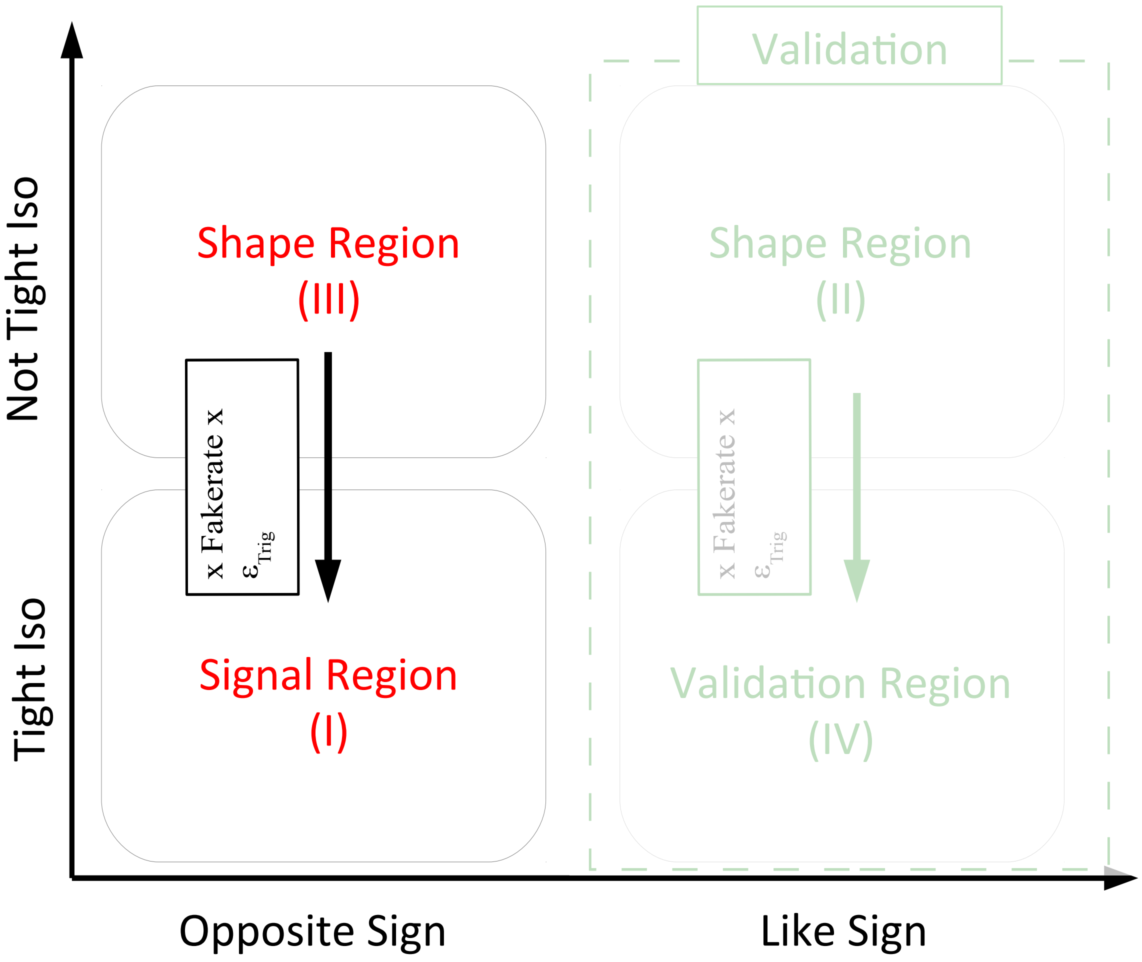
- What is a fake signal?



- Jets can appear to be leptons
- Fake rate measured in Z→μμ+X data and compared to MC

Fakes Background

- Dominant background for $\tau_{had}\mu$
- 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+jets



Validation

Not Tight Iso

Tight Iso

Shape Region (III)

x Fakerate x ε_{Trig}

Signal Region (I)

Shape Region (II)

x Fakerate x ε_{Trig}

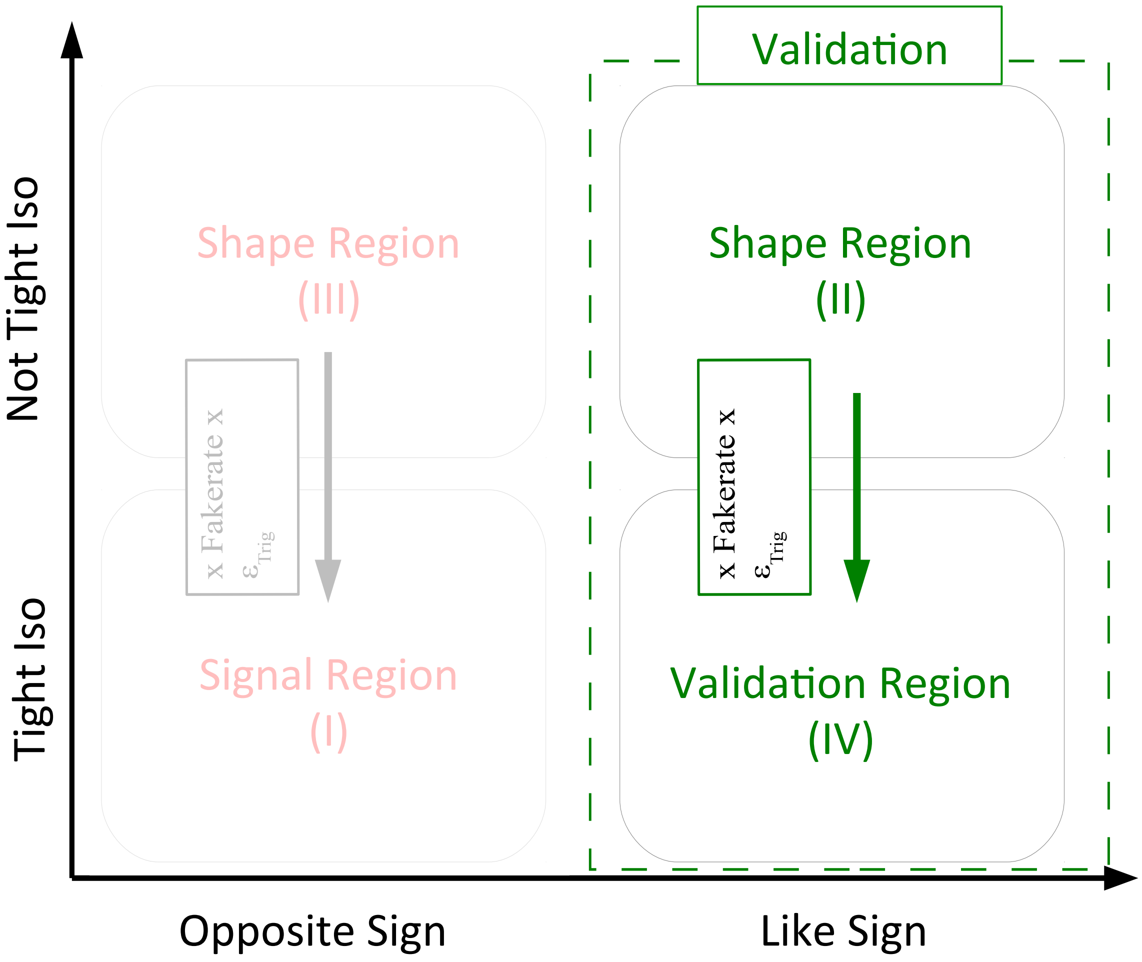
Validation Region (IV)

Opposite Sign

Like Sign

Fakes Background

- Dominant background for $\tau_{had}\mu$
- 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



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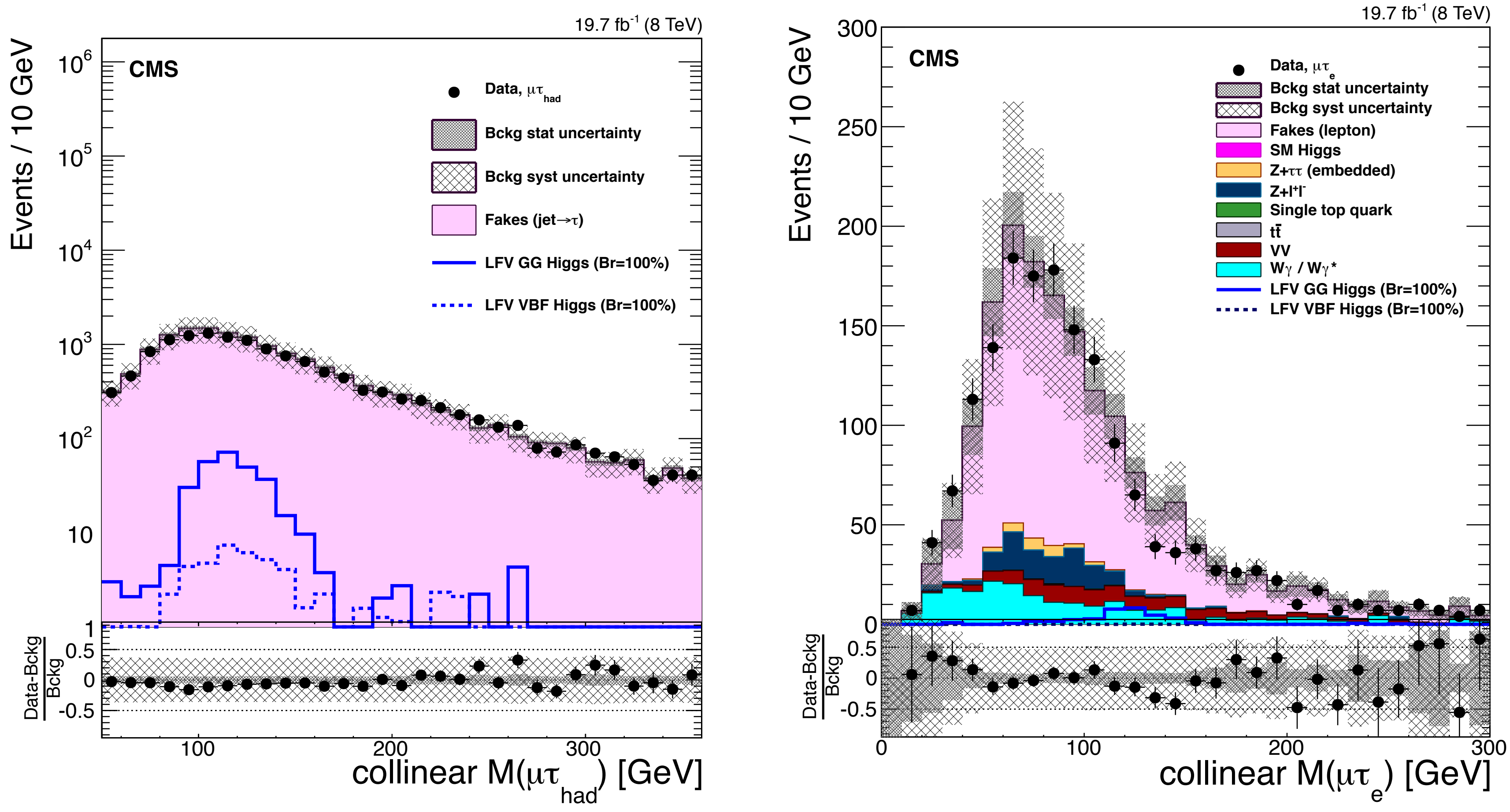
Fakes Same Sign Validation

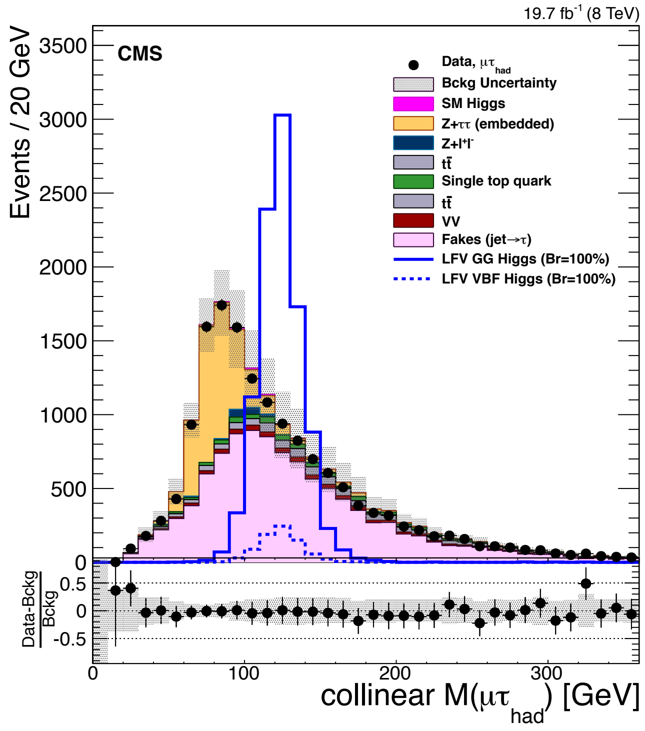


Validation same sign region (II) shows good agreement in collinear mass for both channels

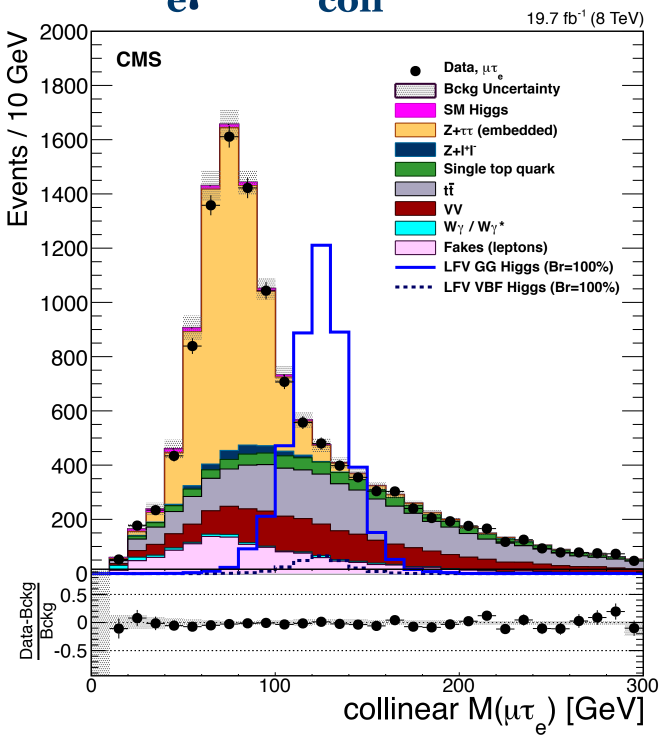
Preselection Agreement

- 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

$\tau_{had}\mu$ M_{coll} 1 Jet



$\tau_e\mu$ M_{coll} 1 Jet



Establishing Signal /Setting Limits

- Two main types of uncertainties considered
  - Normalization (independent of M_{col}), scale peak height
  - Shape (vary with $M_{collinear}$) 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

Independent of $M_{collinear}$	**$\tau_e\mu$**			**$\tau_{had}\mu$**			**Method**
	0 Jet	1 Jet	2 Jet	0 Jet	1 Jet	2 Jet	
Elec. Trig/ID/Iso	3%	3%	3%	-	-	-	TnP, POG rec
Muon Trig/ID/Iso	2%	2%	2%	2%	2%	2%	TnP, POG rec
Hadronic Tau Eff.	-	-	-	9%	9%	9%	TnP, POG rec
Luminosity	2.6%	2.6%	2.6%	2.6%	2.6%	2.6%	pix. cluster counting
$Z \rightarrow \tau\tau$	3+3*%	3+5*%	3+10*%	3+5*%	3+5*%	3+10*%	measured xsec
$Z \rightarrow \mu\mu, ee$	30%	30%	30%	30%	30%	30%	measured xsec
Muon & Elec. Fake	40%	40%	40%	-	-	-	SS sideband
Tau had Fakes	-	-	-	30+10*%	30%	30%	fake rate vs MC/ QCD, POG rec
WW, ZZ +jets bkg.	15%	15%	15%	15%	15%	65%	measured xsec
ttbar+jets	10%	10%	10+10*%	10%	10%	10%	measured xsec
$W+\gamma$ bkg	100%	100%	100%	-	-	-	measured xsec
B-tagging veto	3%	3%	3%	-	-	-	TnP
Single Top bkg.	10%	10%	10%	10%	10%	10%	measured xsec

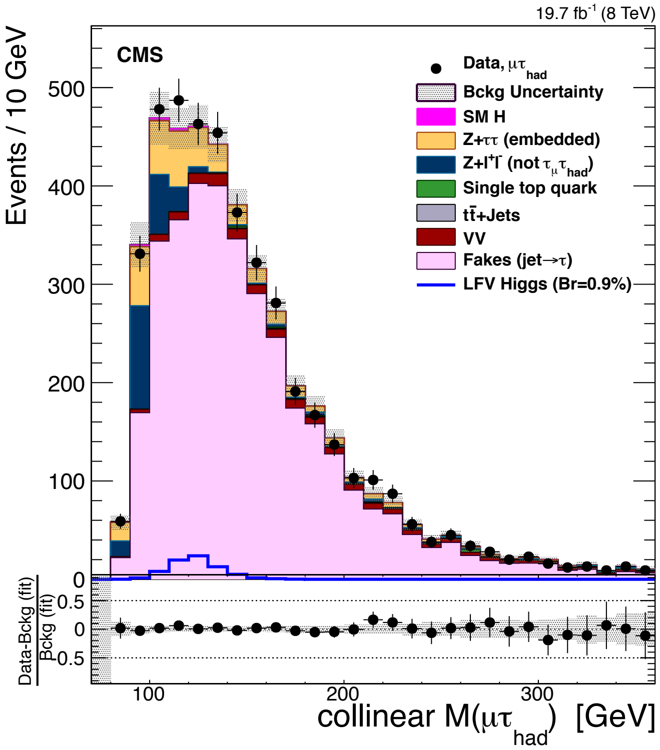
Systematics

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%

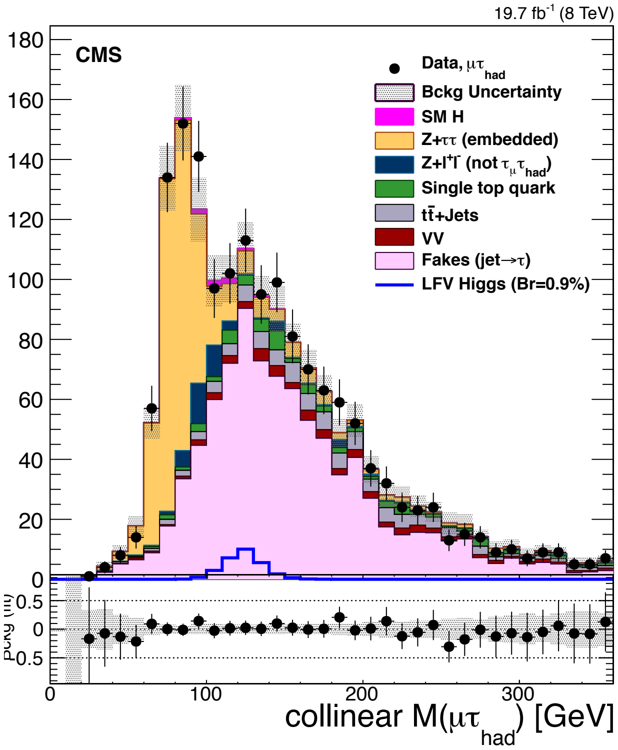
Dependent on $M_{collinear}$	$\tau_e\mu$	$\tau_{had}\mu$
Hadronic Tau Energy Scale	-	3%
Jet Energy Scale	3-7%	3-7%
Unclustered Energy Scale	10%	10%
Z → τ τ Bias	100%	-
bin-by-bin uncertainty		

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

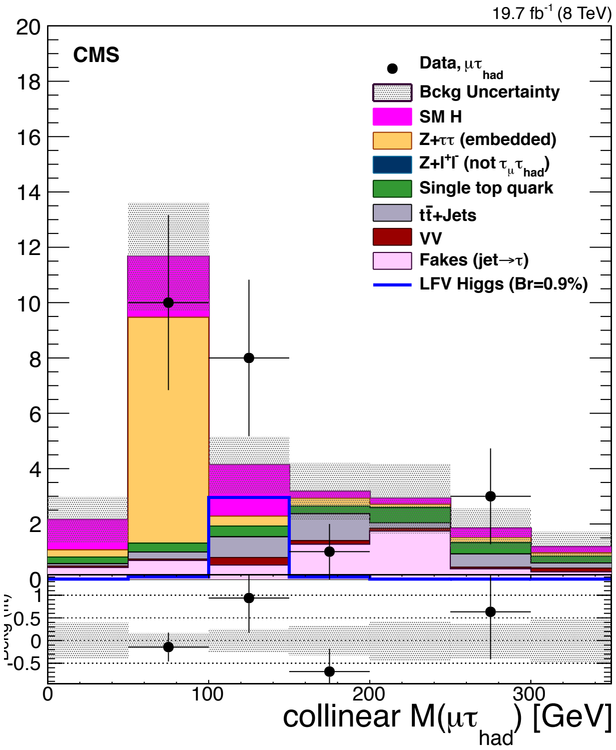
0 Jet



1 Jet

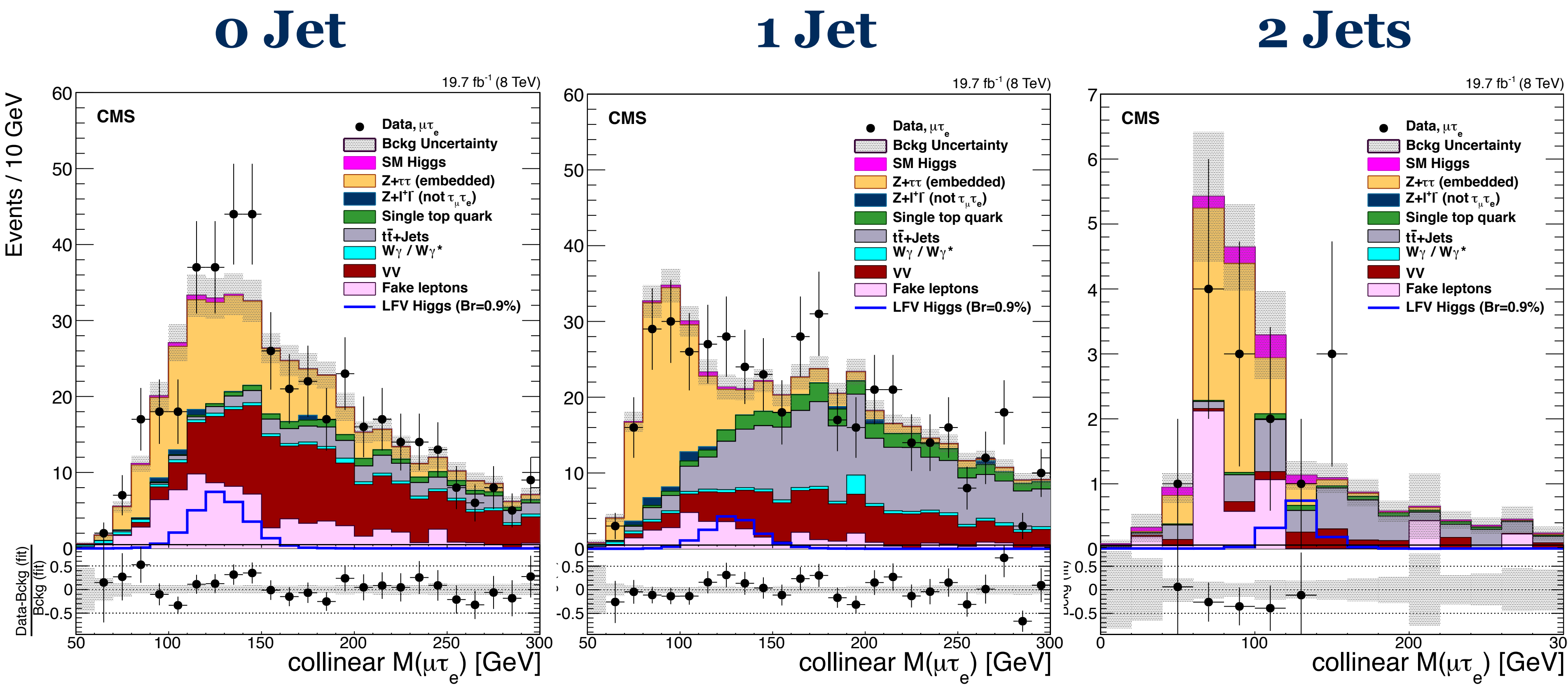


2 Jets



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: $H \rightarrow \tau_e \mu$

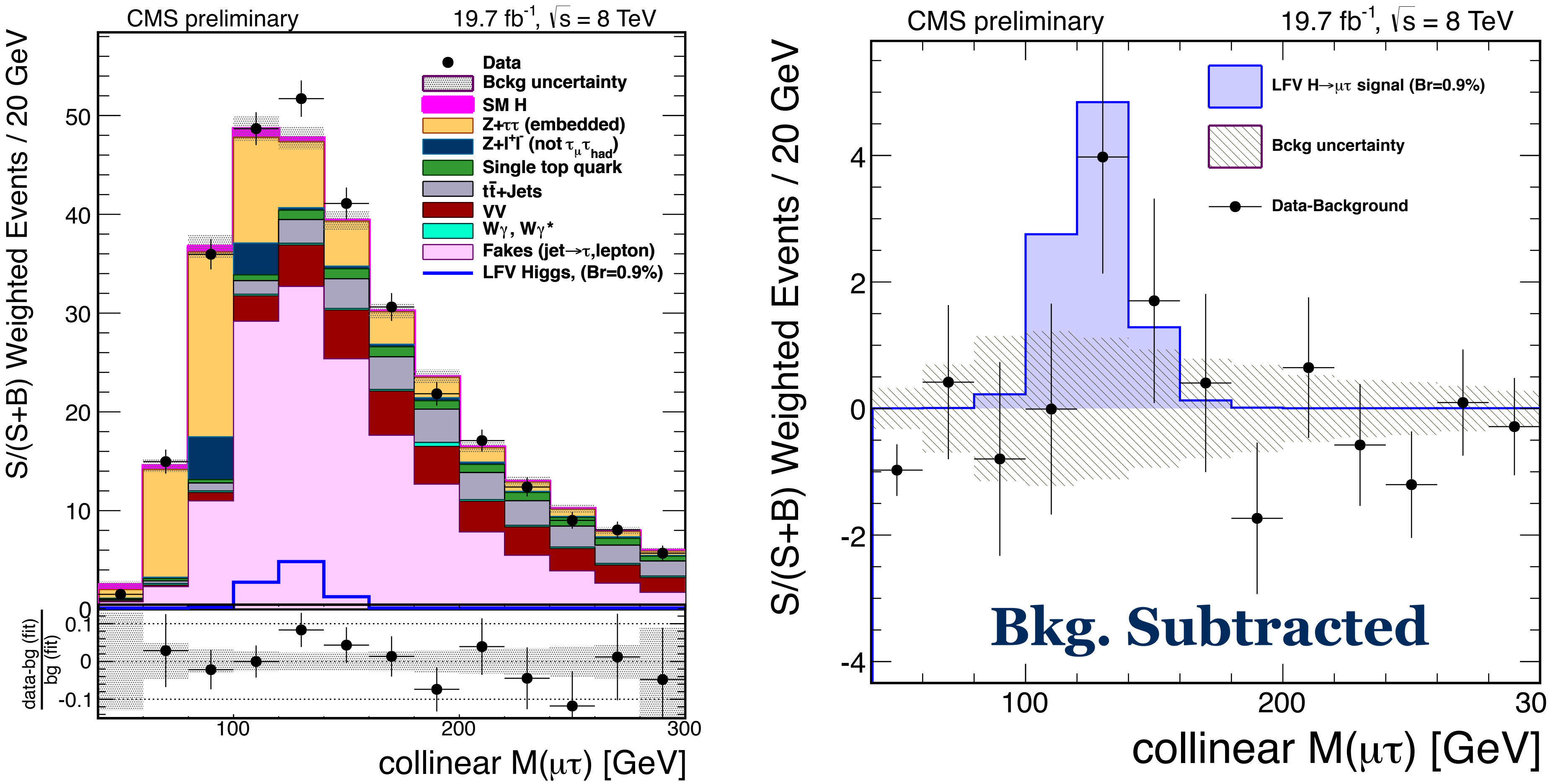


0 Jet **1 Jet** **2 Jets**

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

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



Bkg. Subtracted

Branching Ratio Limits

	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

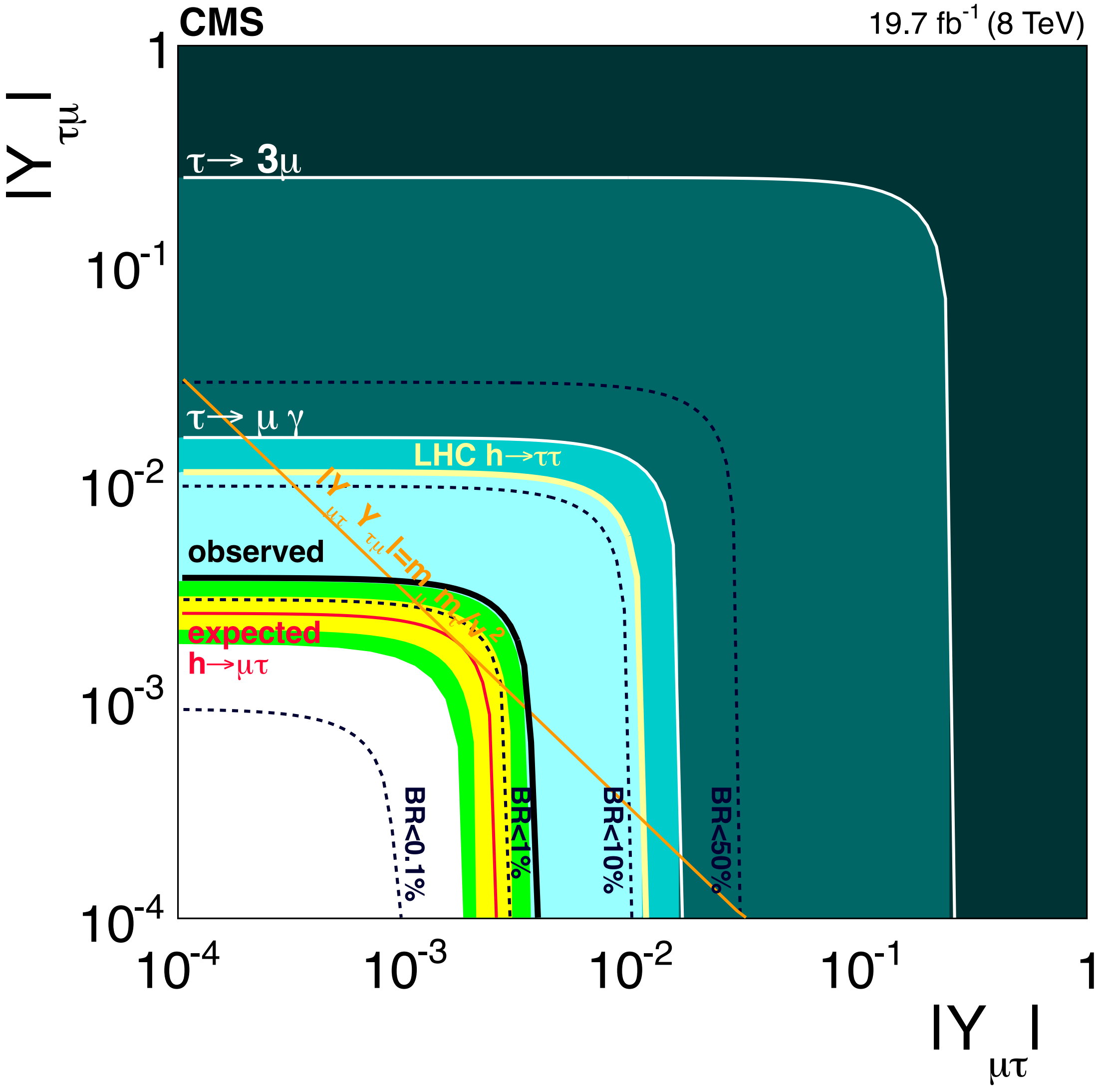
Limit: Yukawa Coupling

- Yukawa couplings governing LFV Higgs:

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

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

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



Outlook

CMS Run 1 paper on H->eτ and H -> eμ will be submitted in a few weeks. (The paper is under internal review but unfortunately not ready for this conference)

ATLAS will have results on LFV Higgs search for the summer conferences

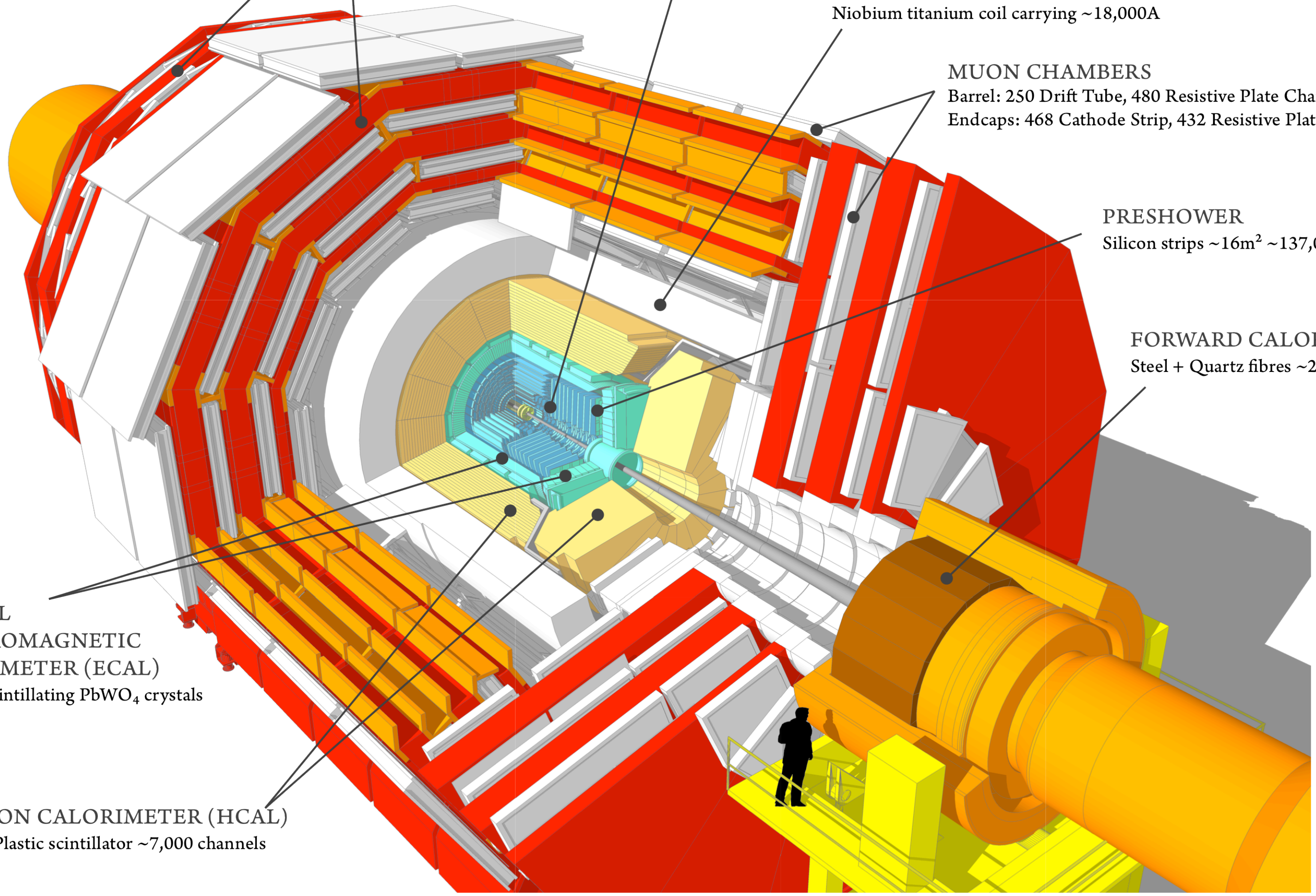
CMS: A new tau lepton identification algorithm with improved background rejection has been deployed for Run 2 (which started last week). We intend to apply this to existing 7 TeV data and combine with ~10 fb-1 of run 2 data for our first update

Conclusions

- First direct, dedicated search for LFV Higgs @ 125 GeV
- 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 $B(H \rightarrow \mu\,\tau) = 0.89\%\,^{+0.40}_{-0.37}$
- e-tau results coming soon. Investigating possible analysis improvements for μ-tau before next run

Back 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 (100x150 μm) ~16m^2 ~66M channels
Microstrips (80x180 μm) ~200m^2 ~9.6M channels

SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A

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

PRESHOWER
Silicon strips ~16m^2 ~137,000 channels

FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels

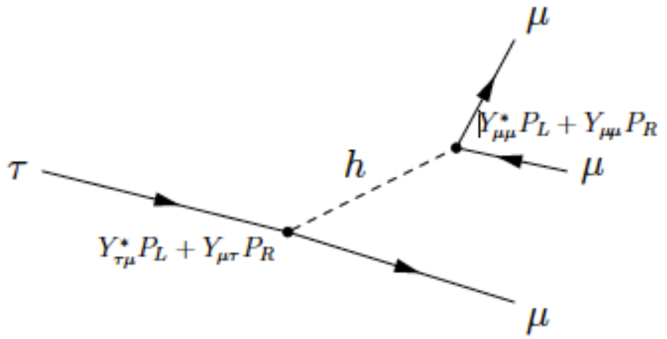
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating $PbWO_4$ crystals

HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

Theoretical

- Two Higgs doublets, extra dimensions, and composite models can all have LFV Higgs interactions
- H→τμ and H→τe 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:

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



Existing Limits

$\tau \to \mu\gamma$	$\sqrt{\lvert Y_{\tau\mu}\rvert^2 + \lvert Y_{\mu\tau}\rvert^2}$	0.016
$\tau \to 3\mu$	$\sqrt{\lvert Y_{\tau\mu}^2 + \lvert Y_{\mu\tau}\rvert^2}$	$\lesssim 0.25$
muon $g-2$	$\mathrm{Re}(Y_{\mu\tau}Y_{\tau\mu})$	$(2.7 \pm 0.75) \times 10^{-3}$
muon EDM	$\mathrm{Im}(Y_{\mu\tau}Y_{\tau\mu})$	$-0.8 \ldots 1.0$

Reinterpreted ATLAS result of H→ττ by Harnik et al.

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

Existing Limits

LFV Lagrangian terms:

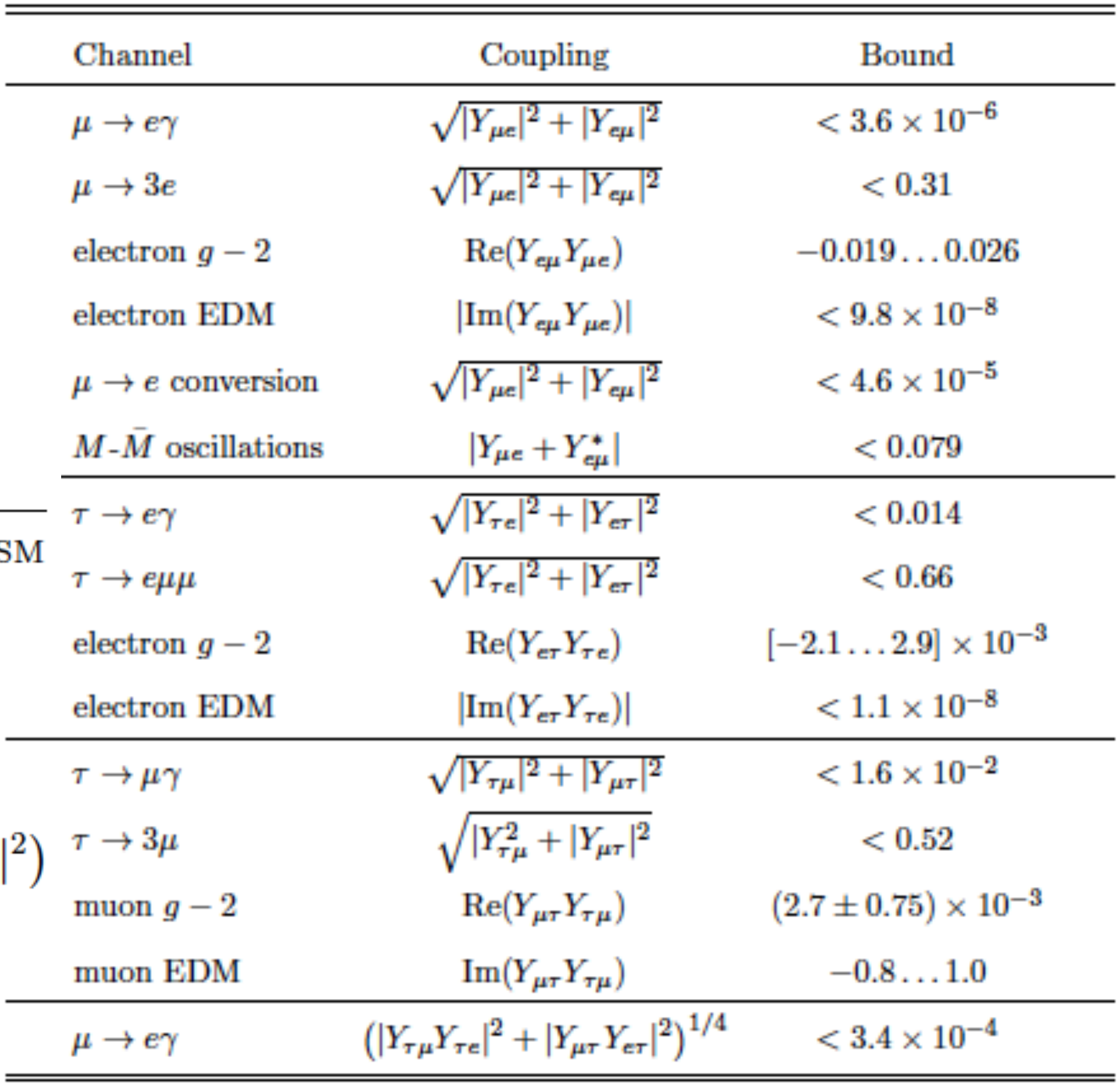
$$L_V \equiv -Y_{\tau\mu}\bar{\tau}_L\mu_R h - \ldots$$

Branching Ratio

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

Assume Γ_{SM} = 4.1 MeV then decay width:

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



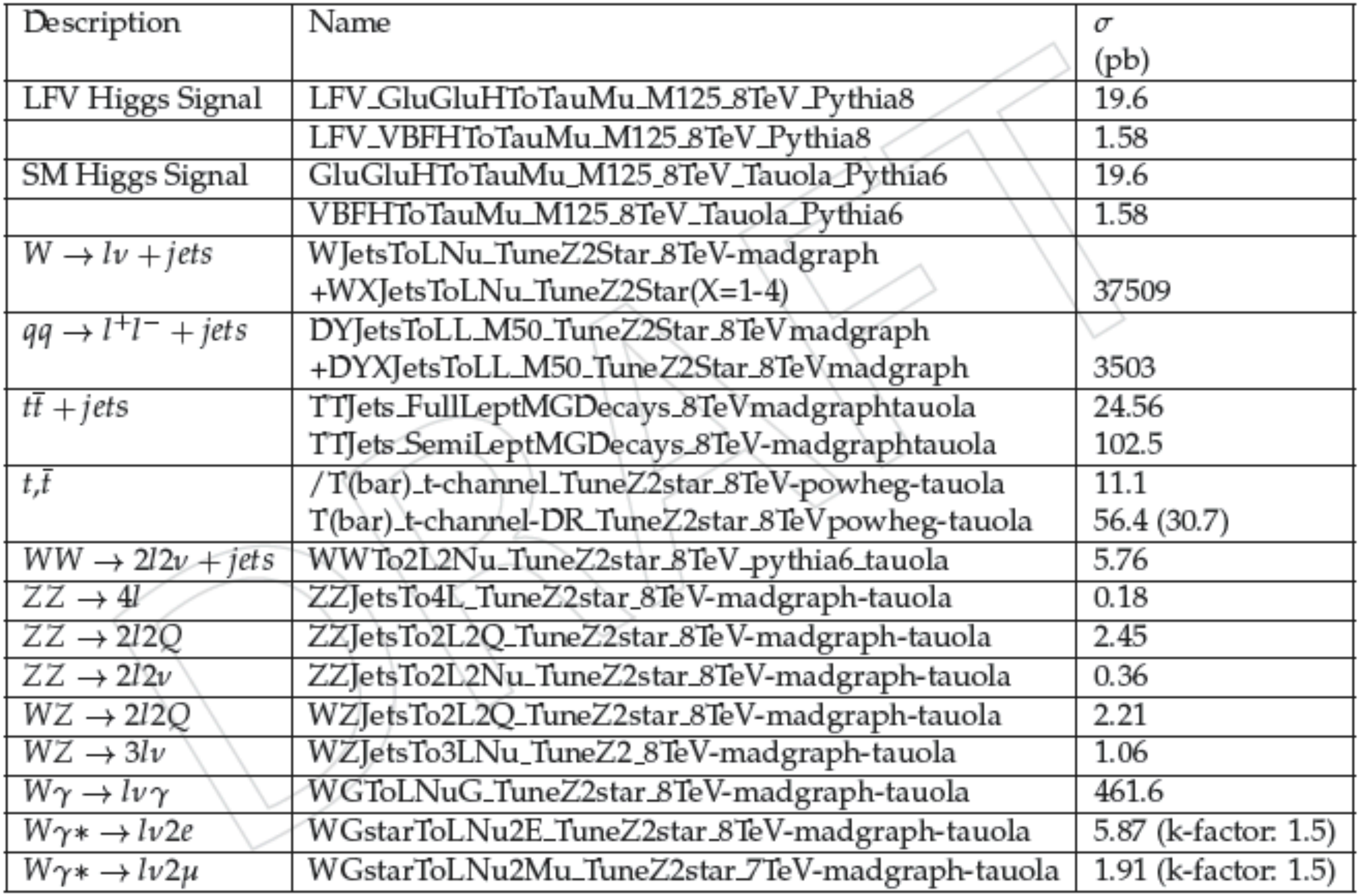
Channel	Coupling	Bound
$\mu \to e\gamma$	$\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$	$< 3.6 \times 10^{-6}$
$\mu \to 3e$	$\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$	< 0.31
electron $g-2$	$\mathrm{Re}(Y_{e\mu}Y_{\mu e})$	$-0.019 \ldots 0.026$
electron EDM	$\lvert\mathrm{Im}(Y_{e\mu}Y_{\mu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

Data Samples & Triggers

- 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→$\tau_{had}\mu$ utilizes a single muon trigger while H→$\tau_{e}\mu$ 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_8TeVmadgraph +DYXJetsToLL_M50_TuneZ2Star_8TeVmadgraph	3503
$t\bar{t} + jets$	TTJets_FullLeptMGDecays_8TeVmadgraphtauola TTJets_SemiLeptMGDecays_8TeV-madgraphtauola	24.56 102.5
$t,\bar{t}$	/T(bar)_t-channel_TuneZ2star_8TeV-powheg-tauola T(bar)_t-channel-DR_TuneZ2star_8TeVpowheg-tauola	11.1 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)

Transverse Mass

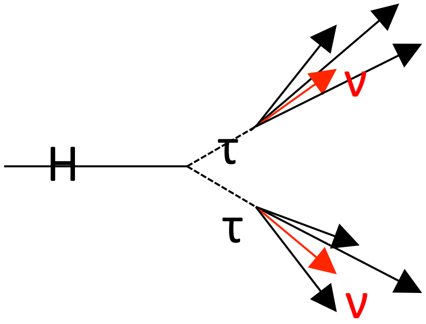
- Defined as

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

- 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

Leptons (e, μ)

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

Jets (including τ_{had})

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

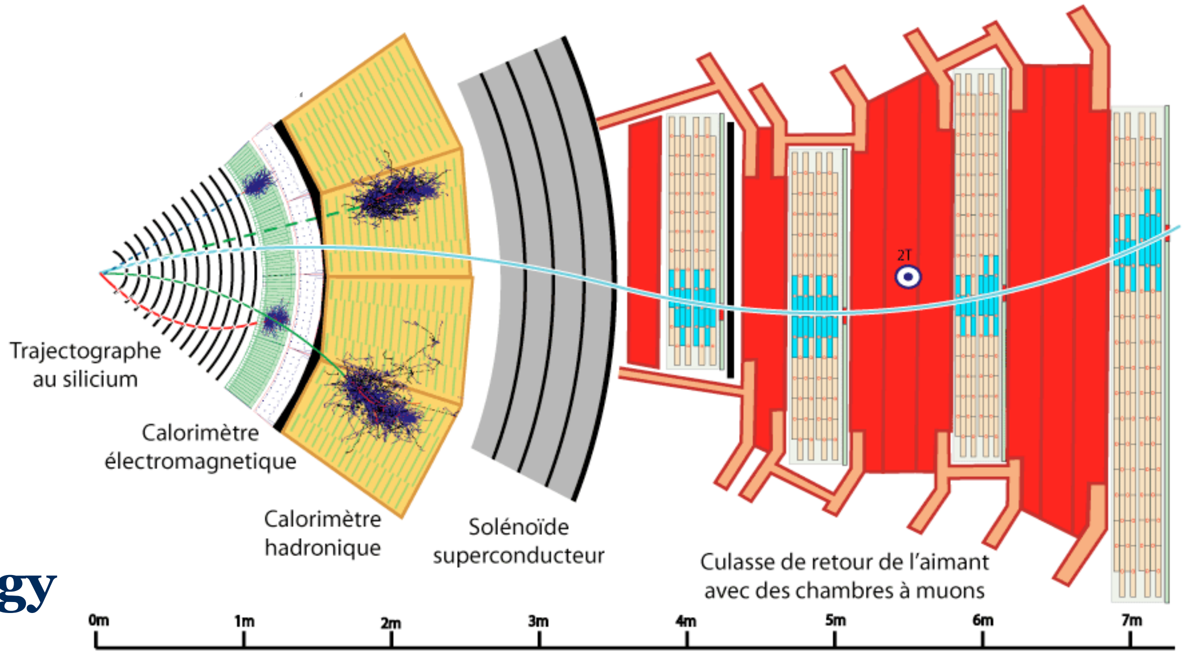
Missing Transverse Energy

- Jet energy corrected

^

Event

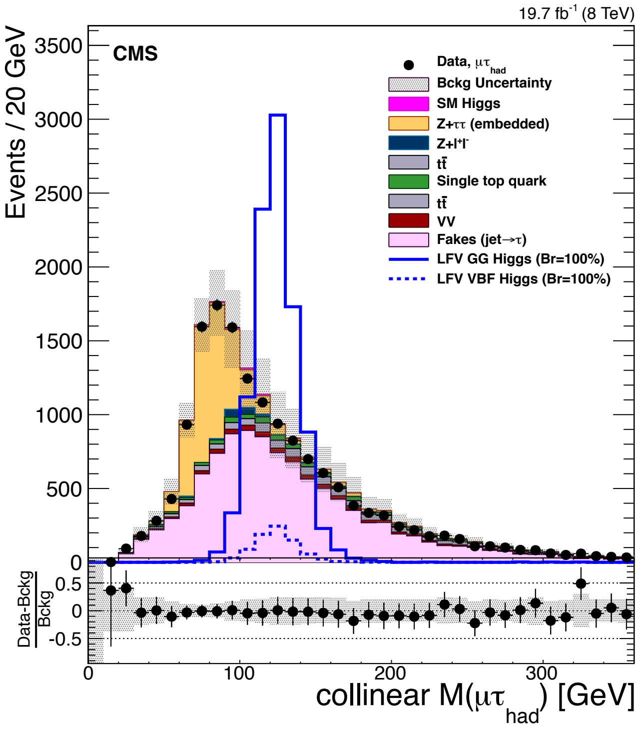
- Leptons oppositely charged
- Veto extra isolated leptons
- Non-overlapping leptons and jets
- Particle Flow Objects
- Trigger on muons or muons+electrons



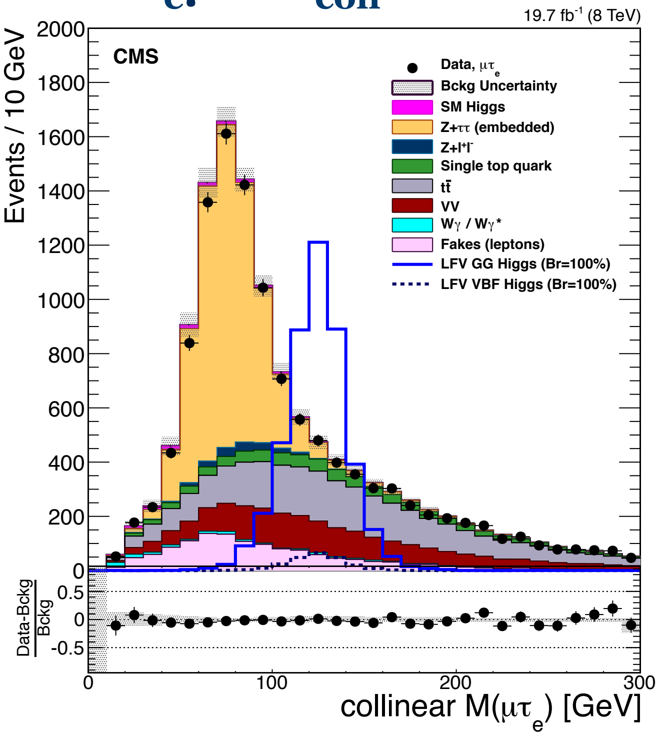
Preselection Agreement

- 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

$\tau_{had}\mu$ M_{coll} 1 Jet



$\tau_{e}\mu$ M_{coll} 1 Jet



Signal Variable and Region

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

$$\vec{p}_T^{\,\nu} = \vec{E}_T^{miss} \cdot \hat{p}_T^{\tau_{vis}} \qquad x_{\tau_{vis}} = \frac{\left|\vec{p}_T^{\,\tau_{vis}}\right|}{\left|\vec{p}_T^{\,\tau_{vis}}\right| + \left|\vec{p}_T^{\,\nu}\right|}$$

  - approximate Higgs mass is then:

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

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

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.

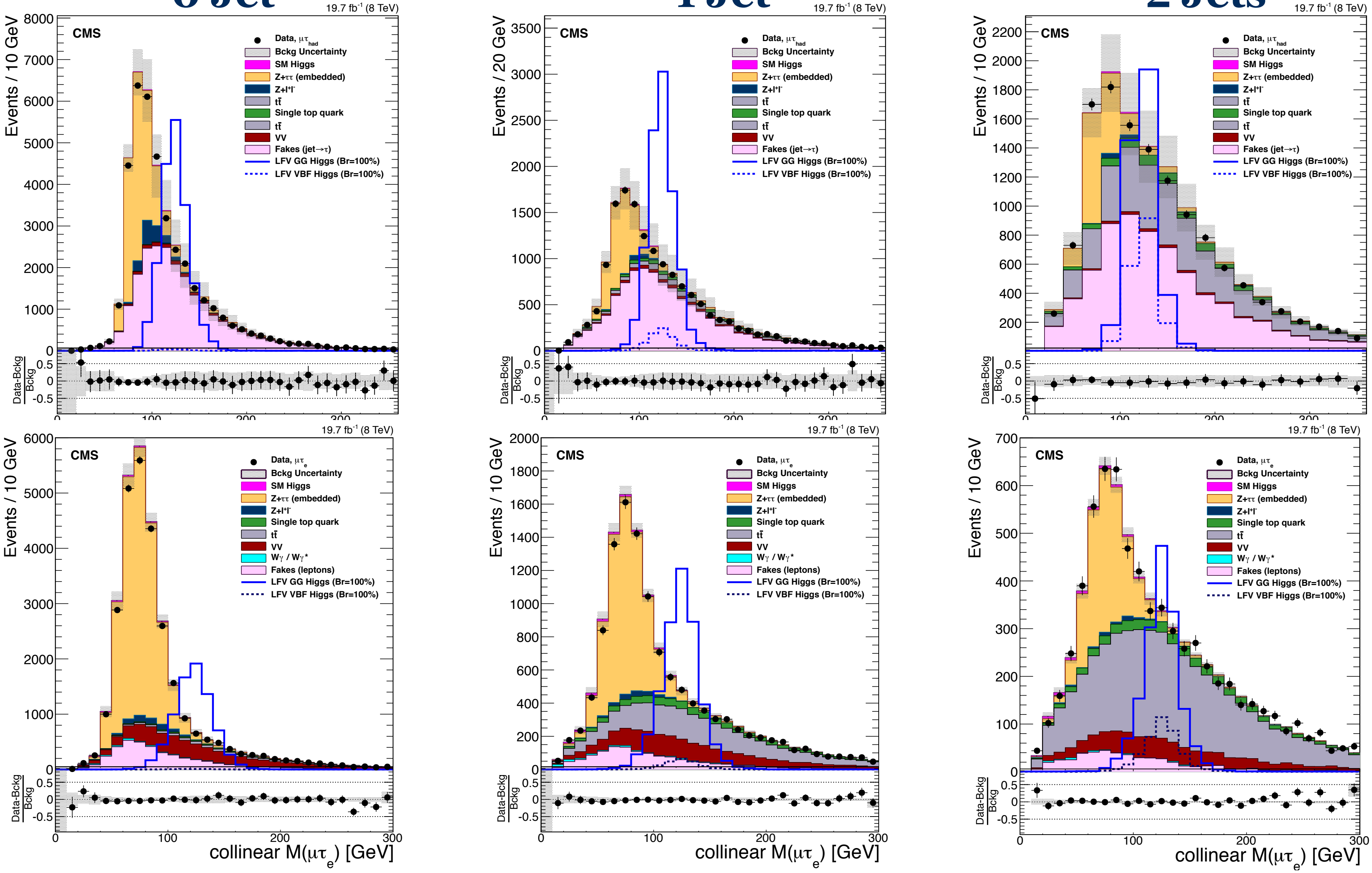
$$\begin{tikzcd}
f = \dfrac{N_{tight}}{N_{loose}} \arrow[r] \arrow[d] & 1 - f = \dfrac{N_{NOT-tight}}{N_{loose}} \arrow[r] & N_{loose} = \dfrac{N_{NOT-tight}}{1 - f} \arrow[dll, bend left] \\
N_{tight} = f \cdot N_{loose} \arrow[rr] & & \boxed{N_{tight} = N_{NOT-tight} \cdot \dfrac{f}{1 - f}}
\end{tikzcd}$$

Preselection Agreement (BR = 100%)

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

$\tau_{had}\mu$

$\tau_{e}\mu$



Full Selection

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

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

Event Yields: Full Selection

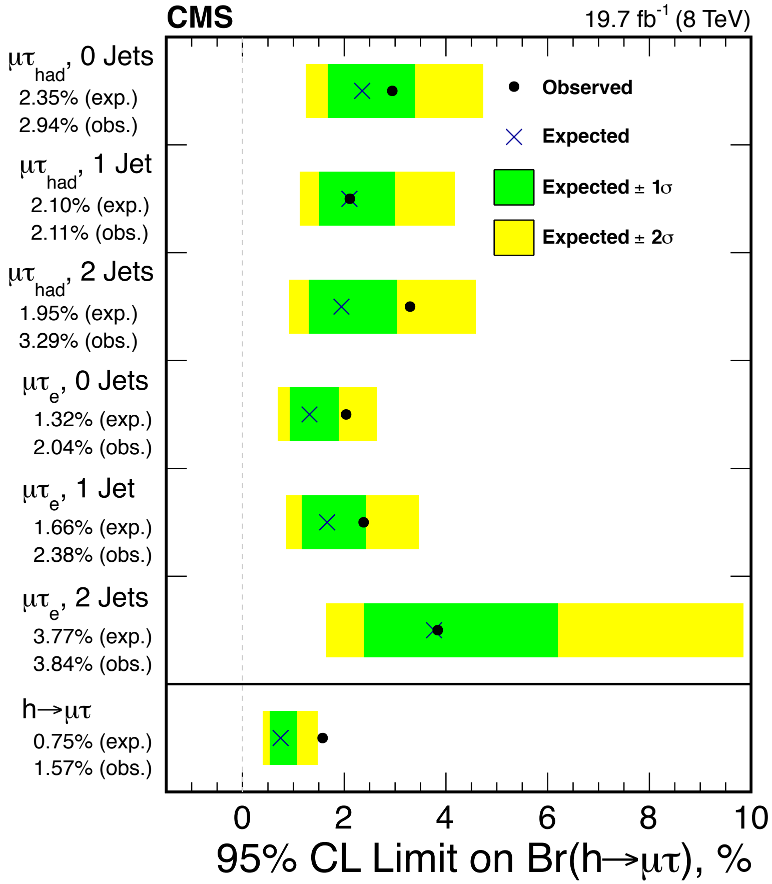
Sample	$\tau_e\mu$			$\tau_{had}\mu$		
	0 Jet	1 Jet	2 Jet	0 Jet	1 Jet	2 Jet
Fakes	41.5 ± 17.3	16.1 ± 6.8	1.1 ± 0.7	1858.1±558.8	362.9±110	0.5 ± 0.5
Z → τ τ	65.0 ± 3.0	38.6 ± 2.0	1.3 ± 0.2	198.8±11.0	50.5 ± 3.5	0.4 ± 0.2
ZZ, WW	40.8 ± 6.6	21.2 ± 3.5	0.7 ± 0.2	47.0 ± 8.0	14.6 ± 2.6	0.3 ± 0.2
Wγ	2.0 ± 2.1	1.9 ± 1.9	-	-	-	-
Z → ee or μμ	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

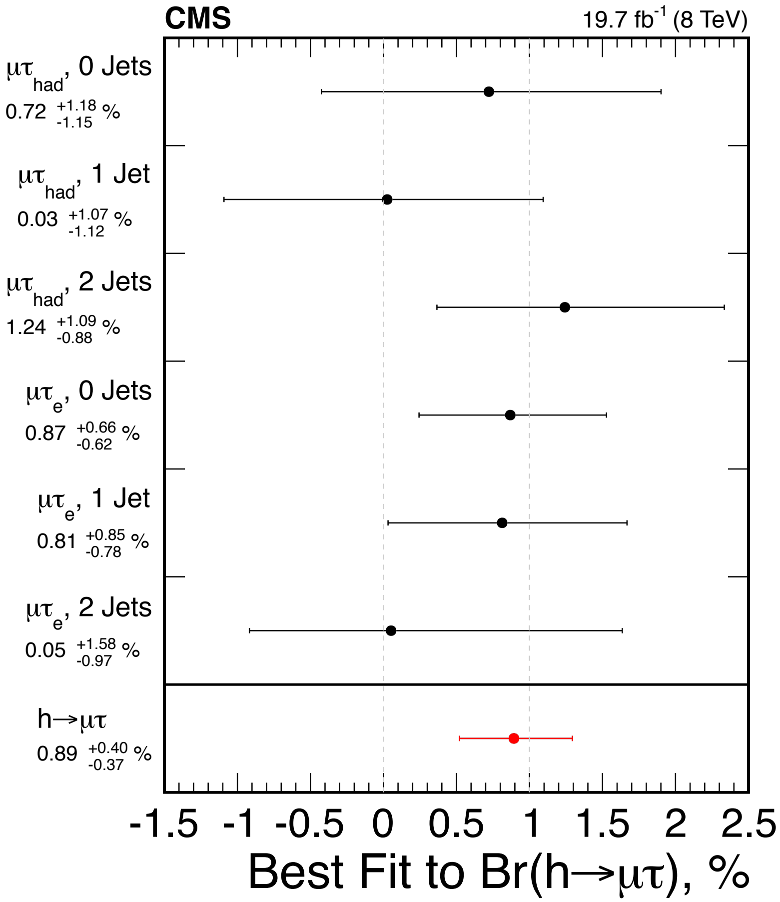
Branching Ratio Limits

Expected Limits			
	0 Jet (%)	1 Jet (%)	2 Jet (%)
$\tau_e\mu$	< 1.32 (±0.67)	< 1.66 (±0.85)	< 3.77 (±1.92)
$\tau_{had}\mu$	< 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
$\tau_{had}\mu$	< 2.94	< 2.11	< 3.29
$\tau\mu$	< 1.57		
Best Fit Branching Ratio			
$\tau_e\mu$	$0.87^{+0.66}_{-0.62}$	$0.81^{+0.85}_{-0.78}$	$0.05^{+1.58}_{-0.97}$
$\tau_{had}\mu$	$0.72^{+1.18}_{-1.15}$	$0.03^{+1.07}_{-1.12}$	$1.24^{+1.09}_{-0.88}$
$\tau\mu$	$0.89^{+0.40}_{-0.37}$		

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

- Following LFV theory reference: arXiv:1209.1397
- LFV Lagrangian terms give width:

$$L_V \equiv -Y_{\tau\mu}\overline{\tau}_L\mu_R h - \ldots \quad \Rightarrow \quad \Gamma\left(h \to \ell^\alpha \ell^\beta\right) = \frac{m_h}{8\pi}\left(\left|Y\ell^\alpha \ell^\beta\right|^2 + \left|Y\ell^\beta \ell^\alpha\right|^2\right)$$

- Define branching ratio and solve for coupling:

$$BR\left(h \to \ell^\alpha \ell^\beta\right) = \frac{\Gamma\left(h \to \ell^\alpha \ell^\beta\right)}{\Gamma\left(h \to \ell^\alpha \ell^\beta\right) + \Gamma_{SM}} \quad \Rightarrow \quad \boxed{\sqrt{\left|Y\ell^\alpha \ell^\beta\right|^2 + \left|Y\ell^\beta \ell^\alpha\right|^2} = \sqrt{\frac{\Gamma_{SM}\cdot 8\pi \cdot BR}{m_h\left(1 - BR\right)}}}$$