Flavour Specific Decays of Higgs Bosons at the LHC

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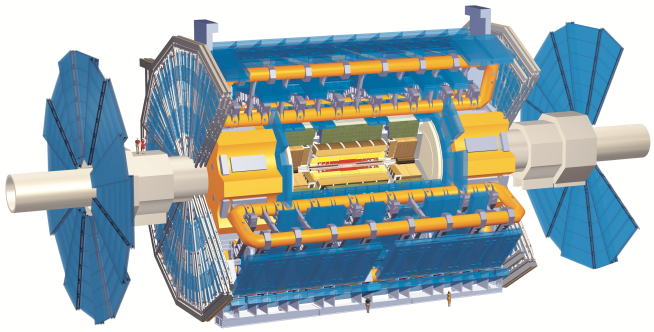
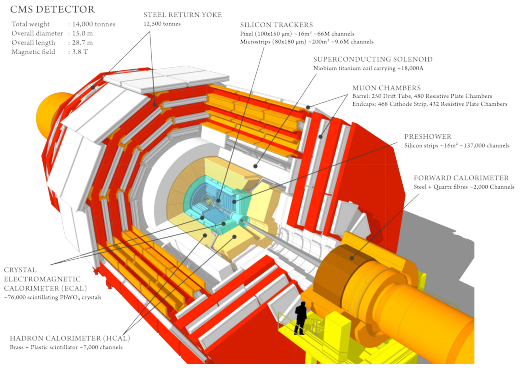
for the ATLAS and CMS Collaborations
June 8, 2017





Contents

Focus is on new (2017) run 2 results*:

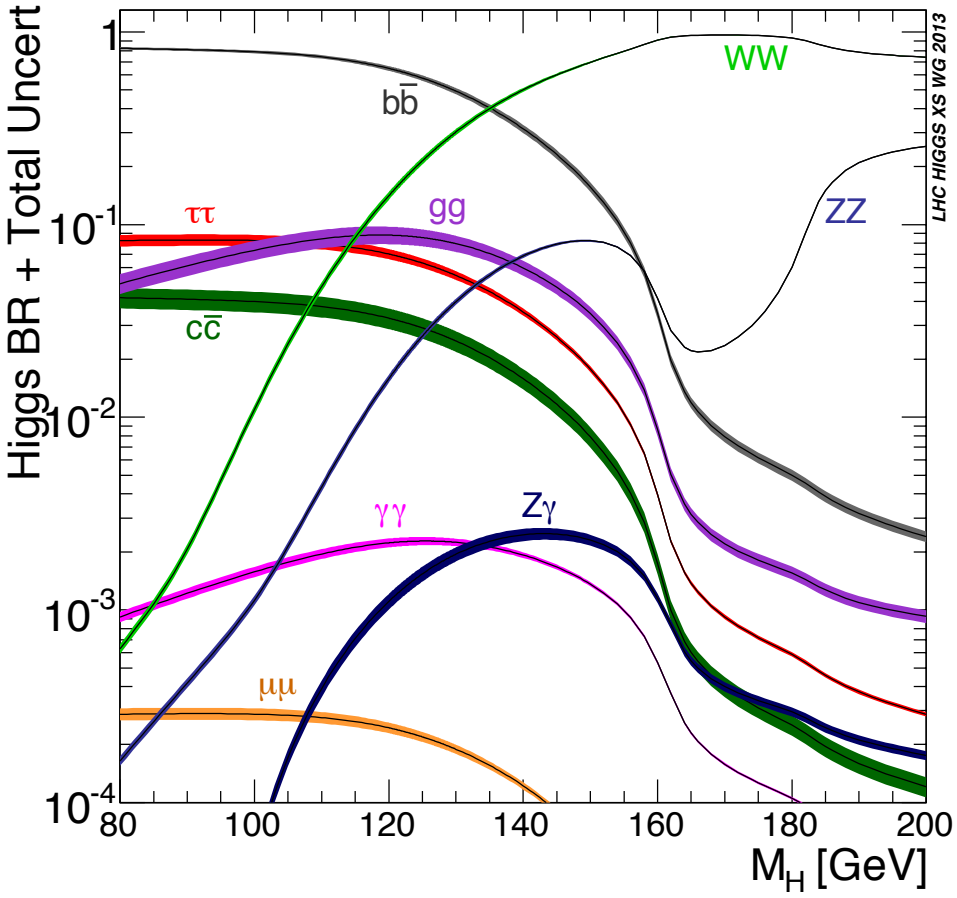
- Standard Model(SM) Searches
  - H →bb (CMS)(CMS-PAS-HIG-17-010)
  - H →ττ (CMS) (CMS-PAS-HIG-16-043)
  - H →μμ (ATLAS) (ATLAS-CONF-2017-014)

- Beyond SM Search for LFV
  - H →eτ , H →μτ (CMS)(CMS-PAS-HIG-17-001)

*Summary of Run 1 results can be found in JHEP 08 (2016) 045

Expected SM Higgs Branching Fractions

Higgs Yukawa couplings responsible for the mass generation of fermions



M_H=125 GeV

B(H →bb) ~ 58 %

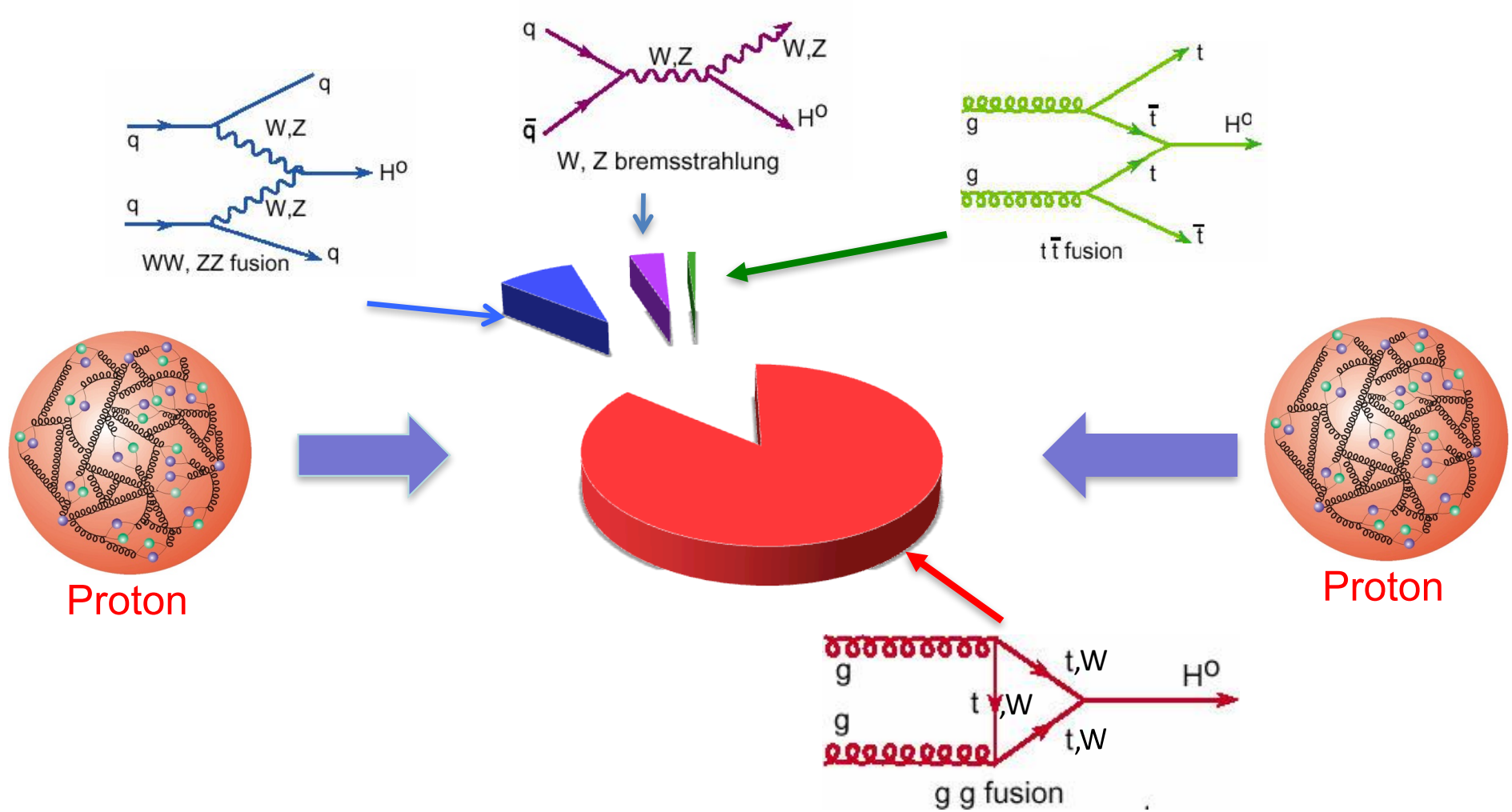
B(H →ττ) ~ 6 %

B(H →μμ) ~ .002 %

(coupling proportional to fermion mass)

To date the Higgs decays to fermions have not been definitively observed (~5σ) in a single measurement (ATLAS+CMS H →ττ Run 1 combined is 5.5σ) although there is evidence (>~3σ) for H →ττ from both collaborations

Higgs Production Mechanisms



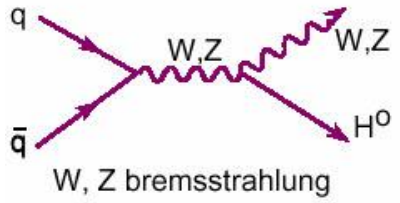
Gluon fusion dominates but vector boson fusion (VBF), ZH and WH, and ttH have distinct signatures that provide higher sensitivity

Inclusive search for H →bb (CMS)

CMS 35.9 fb^{-1} @13 TeV

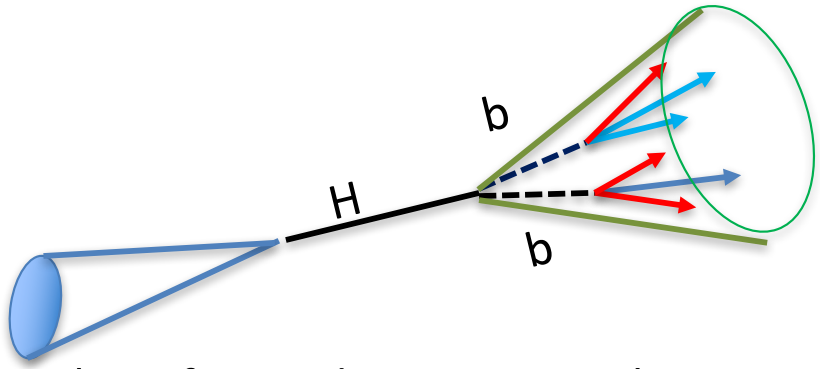
- Main challenge is the QCD production of bb which swamps the Higgs signal

- Searches to date have used ZH and WH production (the H is Lorentz boosted which allows better discrimination)



- New technique proposed to use high P_T Higgs (>450 GeV) recoiling against ISR jet

- b quarks are boosted so form one jet cluster



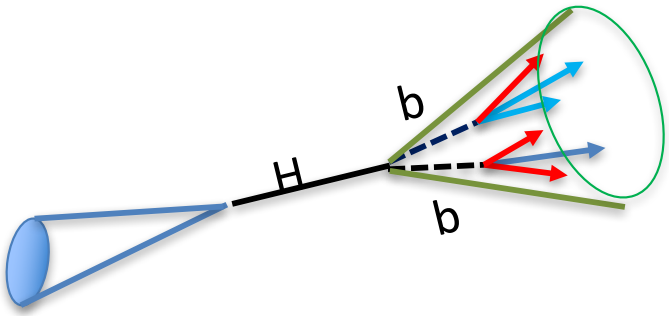
- Technique also allows to resolve t quark loop in gluon fusion diagram to probe ttH Yukawa coupling

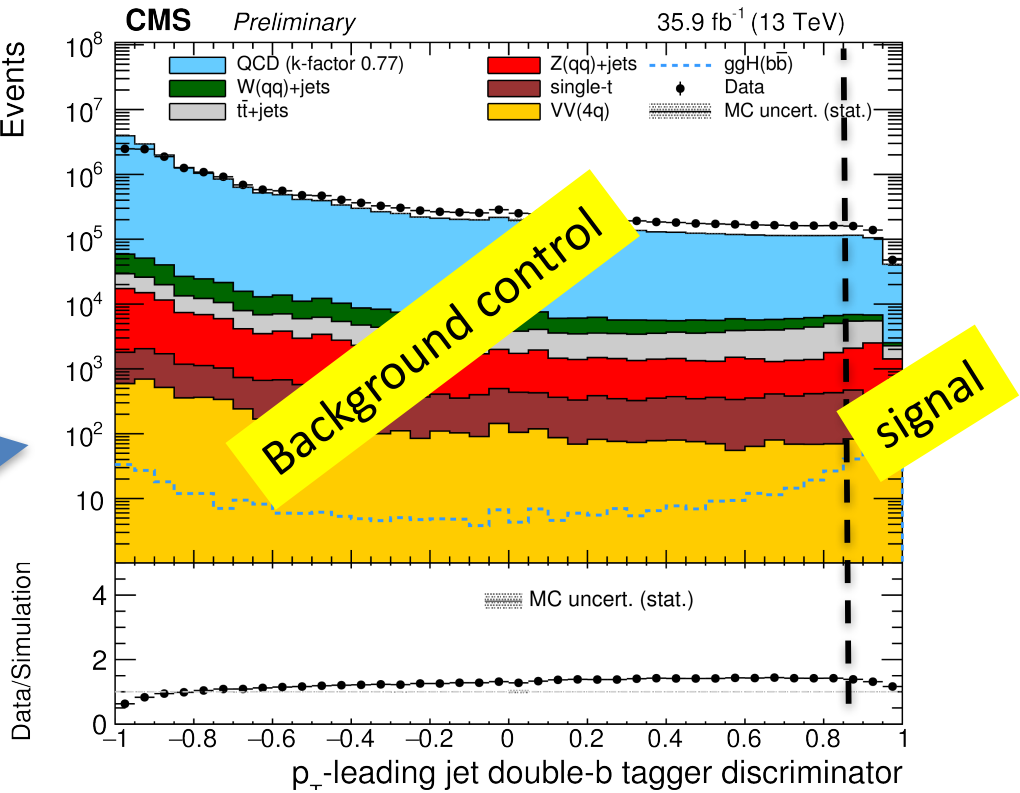
H →bb Jet substructure

- Granularity of CMS detector allows individual particles to be reconstructed in jet
- Veto events with isolated leptons and large missing energy
- Soft Drop algorithm recursively removes soft gluon radiation, pileup and underlying event. (JHEP 05 (2014) 146)
- Energy correlation functions: $\Sigma_{i<j} E_i E_j \Delta R_{ij}$ used to enhance two prong contribution
- Multivariate discriminator used to select double b tags in jet

Use discriminator to divide into signal and background control region

CMS 35.9 fb^{-1} @13 TeV



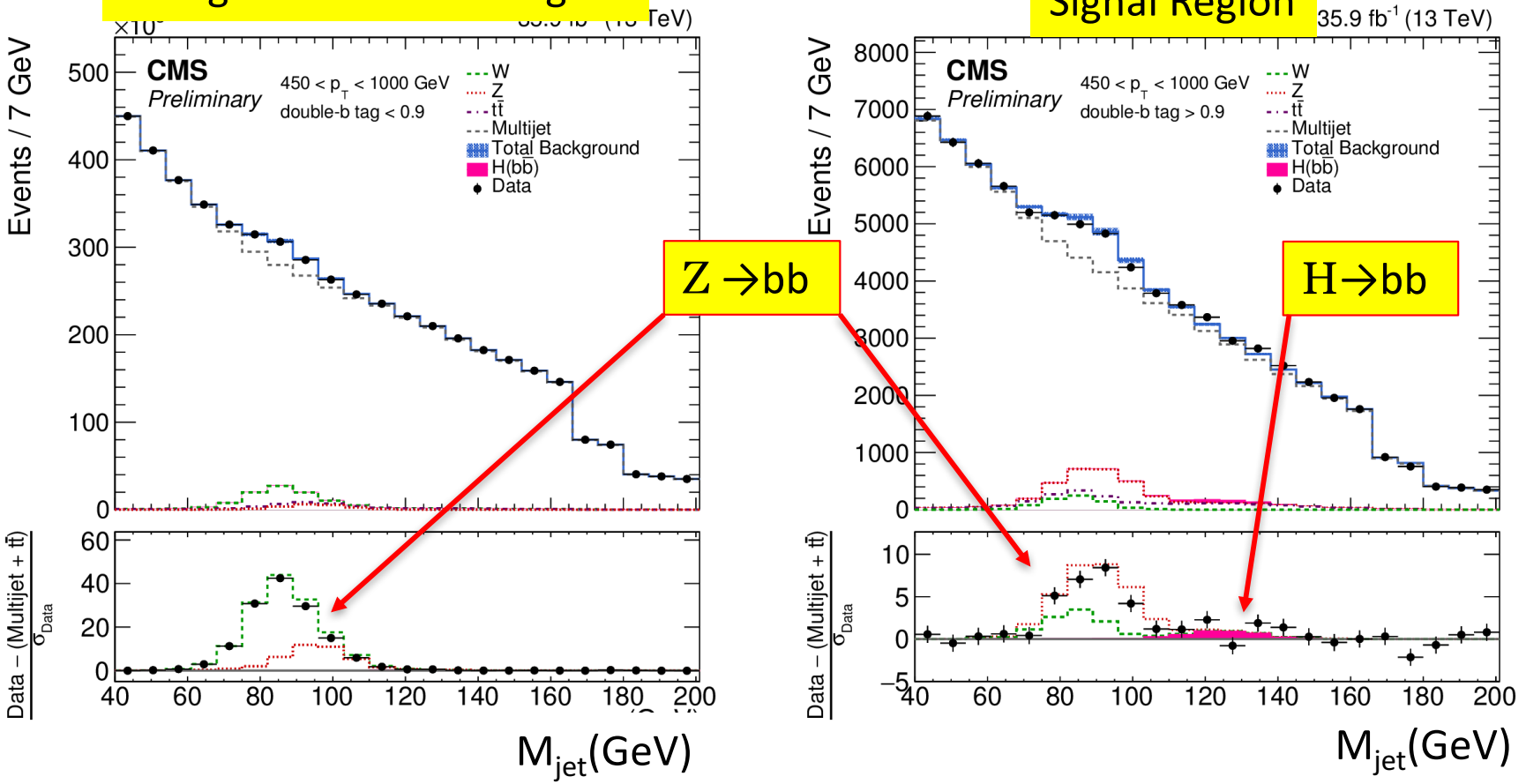


H →bb Results

CMS 35.9 fb^{-1} @13 TeV

Background Control Region

Signal Region

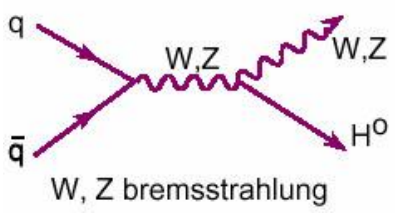


Z →bb observed at 5.1σ with a hint of H→bb at 1.5σ ($\mu(bb)=\sigma/\sigma_{SM} = 2.3\pm1.7$) .

(Compare to PDG 2017 average for previous ATLAS/CMS/Tevatron searches $\mu(bb)=\sigma/\sigma_{SM} = 0.82\pm0.30$)

Recent (2016) ATLAS H →bb results

ATLAS-CONF-2016-091 :



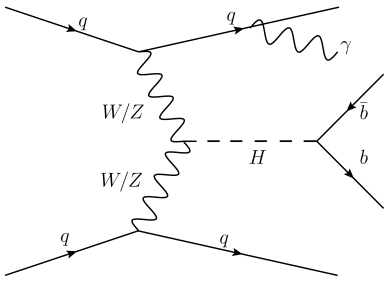
W, Z bremsstrahlung

- 13.2 fb^{-1} @ 13 TeV
- W,Z identified with lepton final states
- New multivariate b-tagger
- Validated with 3σ observation of (W/Z)Z →bb

$\mu=\sigma/\sigma_{SM} = 0.21\pm0.51 \quad (0.4\sigma)$

(*cf. CMS HIG-16-003 2.3 fb-1@ 13 TeV* $\mu=\sigma/\sigma_{SM} < 3$)

ATLAS-CONF-2016-063:



- 12.6 fb^{-1} @ 13 TeV
- Photon plus two jets to identify VBF production
- Limit on (W/Z)Zγ production $\mu=\sigma/\sigma_{SM} < 2.0$

$\mu=\sigma/\sigma_{SM} < 4$

Run 1 ATLAS+CMS $\mu=\sigma/\sigma_{SM} = 0.70\pm0.30 \quad (2.6\sigma)$

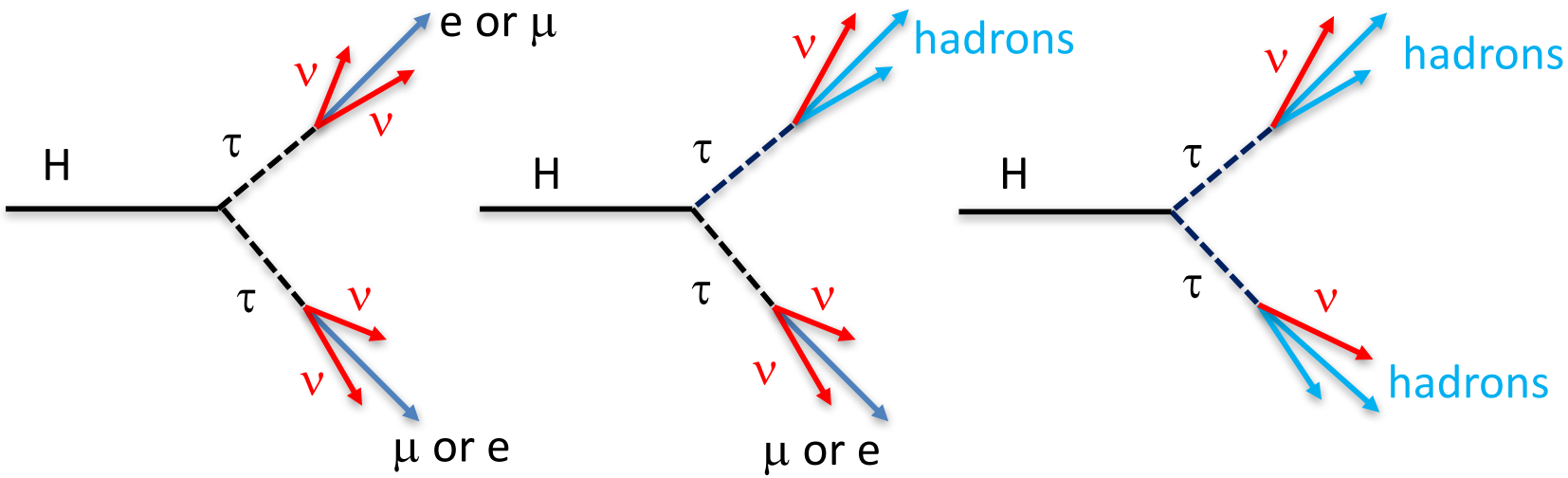
(Also ttH(bb) in talk by Andrea Massironi)

(New results from CMS in associated production expected soon)

Search for H(125) $\rightarrow\tau\tau$

CMS 35.9 fb^{-1} @13 TeV

Search in four channels



$H \rightarrow e\mu$

$H \rightarrow e\tau_h$

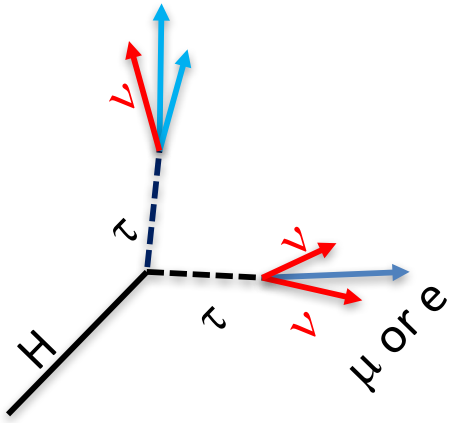
$H \rightarrow \mu\tau_h$

$H \rightarrow \tau_h\tau_h$

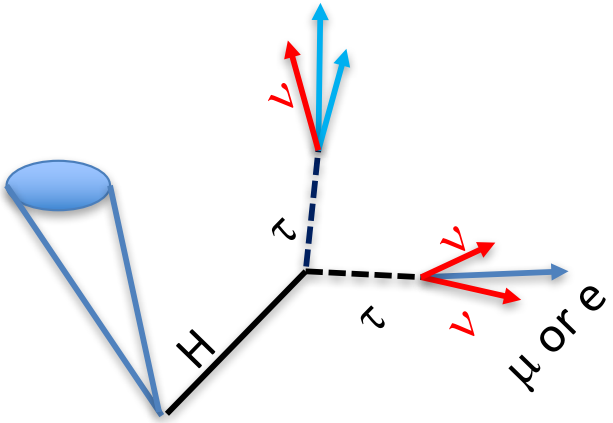
Search for H $\rightarrow\tau\tau$

CMS 35.9 fb^{-1} @13 TeV

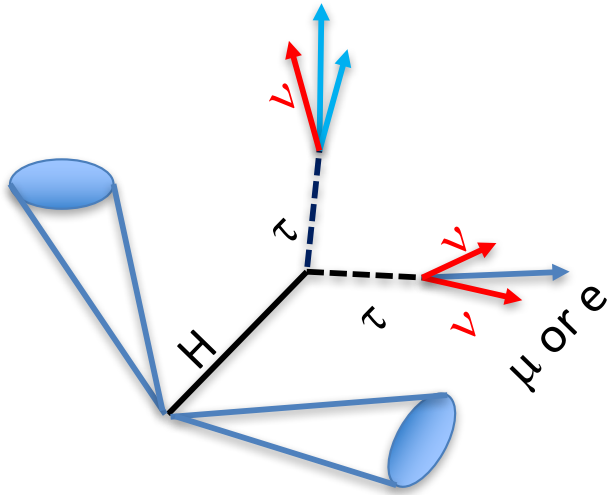
0-Jet

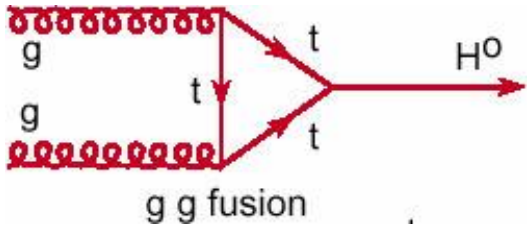


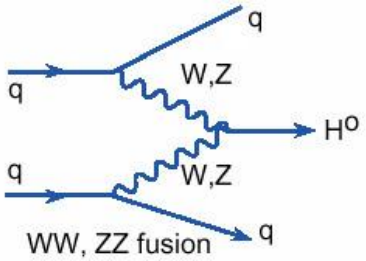
1-Jet (or > 2 jets)



2-Jet



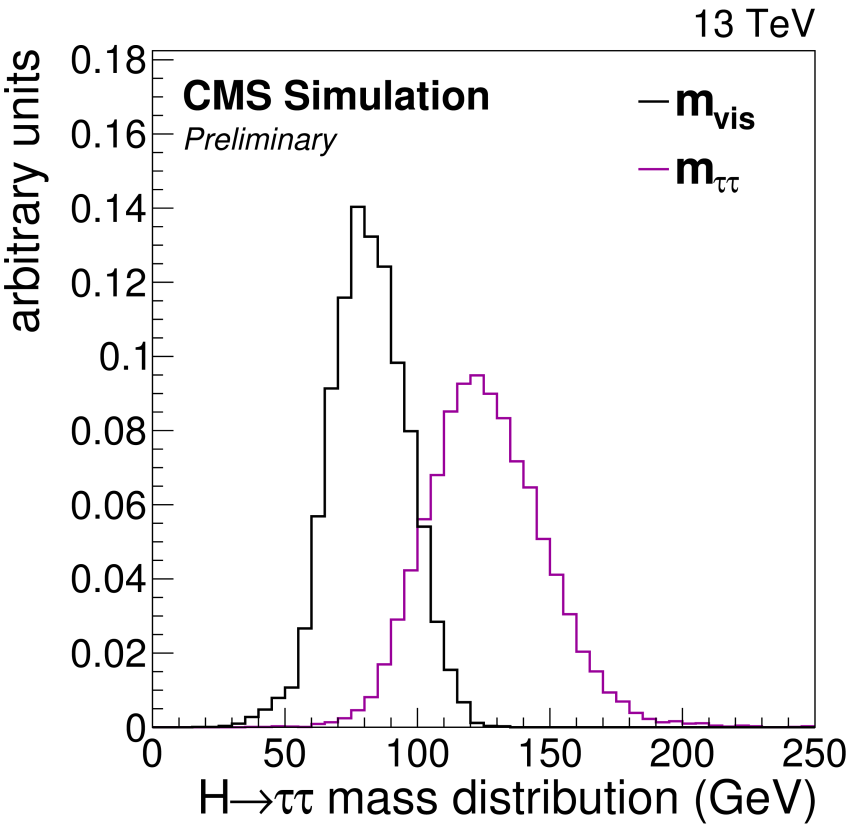




- For each channel define three categories according to the numbers of jets (P_T>30 GeV)
- Categories enhance contribution from production process for greater sensitivity

Selection Variables

CMS 35.9 fb^{-1} @13 TeV



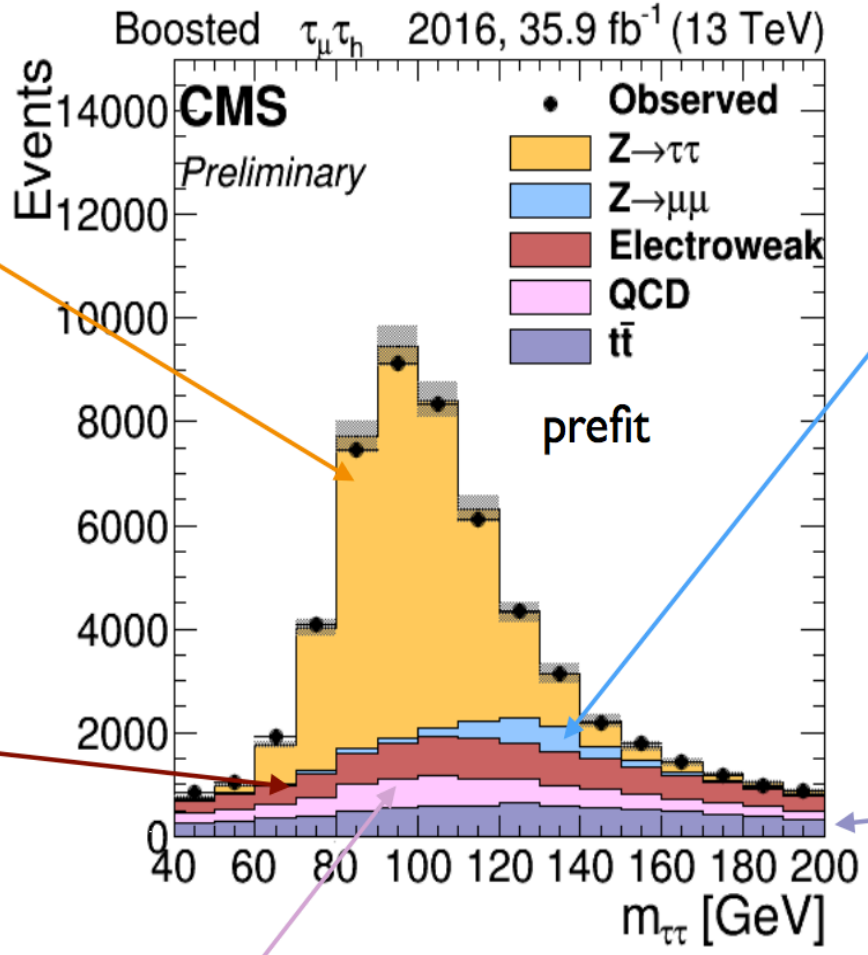
m_{vis} Invariant mass of visible components (i.e excludes neutrino's)

$m_{\tau\tau}$ mass from dynamical likelihood fit (estimates most likely neutrino vector from kinematics)

Signal extracted with 2 dimensional fits. One dimension m_{vis} or m_{tt} and other depends on mode and category; either τ_h decay mode, p_T^{μ} , $p_T^{\tau\tau}$ or m_{jj}

Overview of H $\rightarrow\tau\tau$ Background Estimation

Z->ττ simulation: Madgraph N-Jet binned Drell-Yan Samples, corrections derived from Z(μμ) CR and applied



DY ℓ->τ fakes simulation: Madgraph N-Jet binned Drell-Yan Samples, corrections derived from Z(μμ) CR and applied. Additional ℓ->τ fake corrections.

W+Jets/VV: datadriven in control region for ℓτ

QCD: datadriven in control region, for ℓτ, ττ, eμ

TTbar: powheg MC eμ, ℓτ, ττ: datadriven all channels

H →ττ: Signal and Backgrounds in 2d fits

CMS 35.9 fb^{-1} @13 TeV

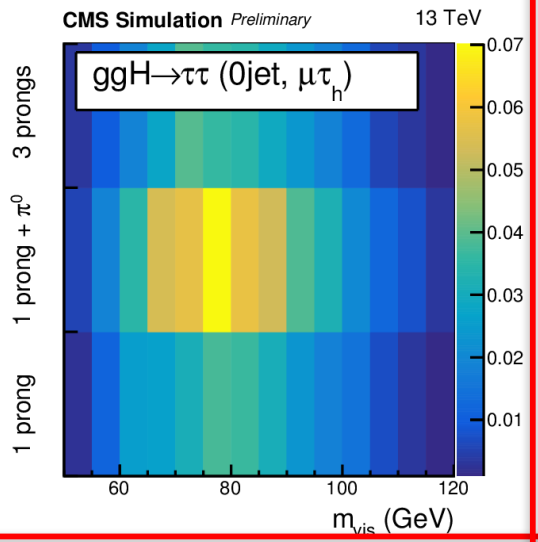
0-Jet

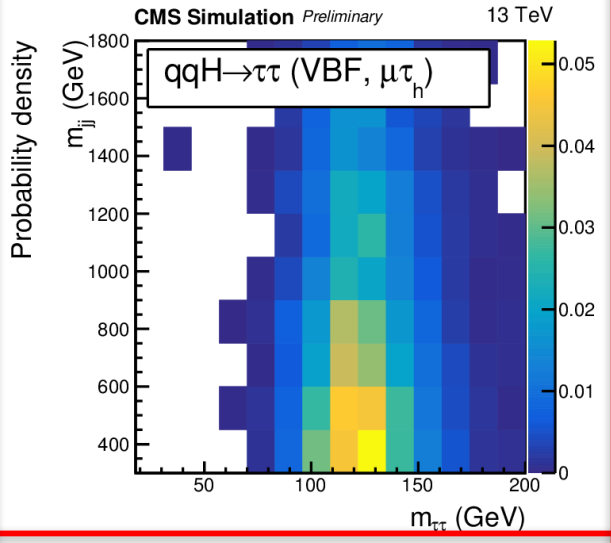
2-jet

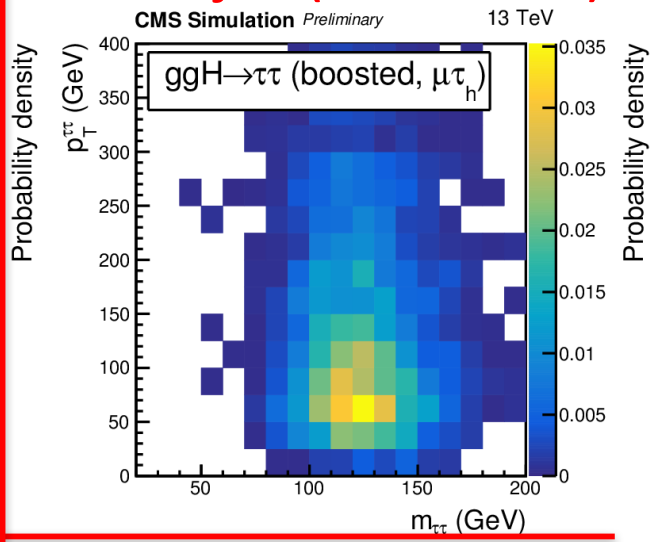
1-jet (or > 2-Jet)

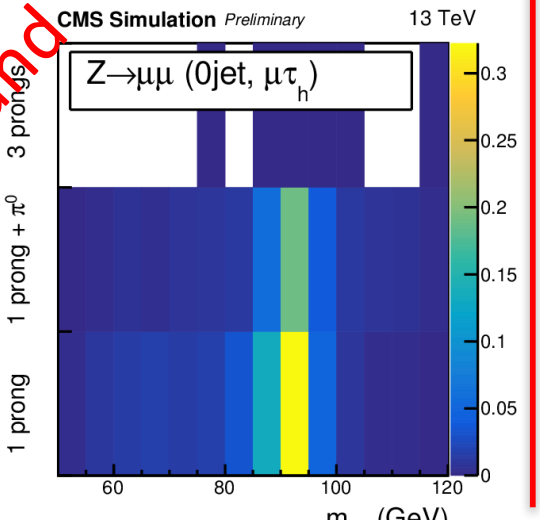
Signal

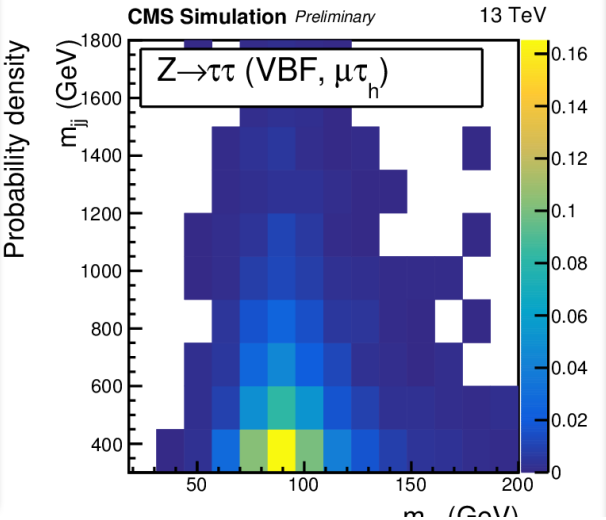
Background

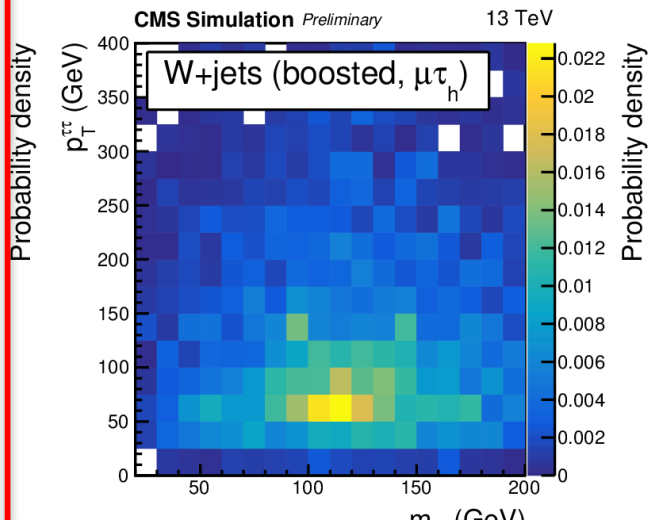










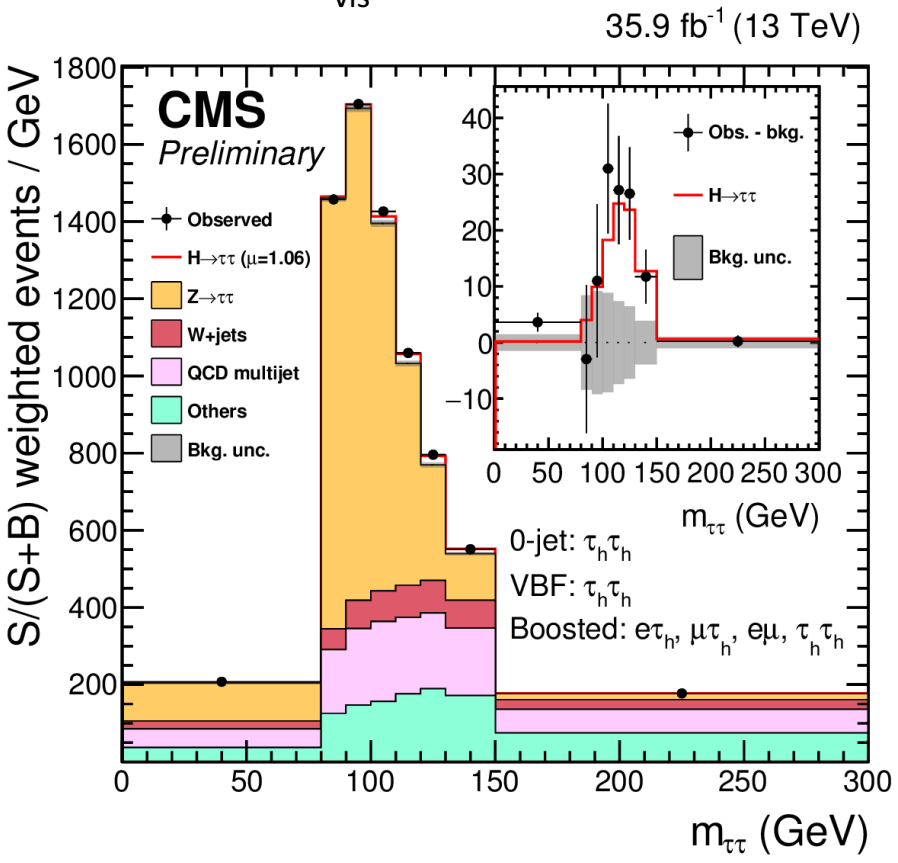


H $\rightarrow\tau\tau$: Observed $m_{\tau\tau}$ projections

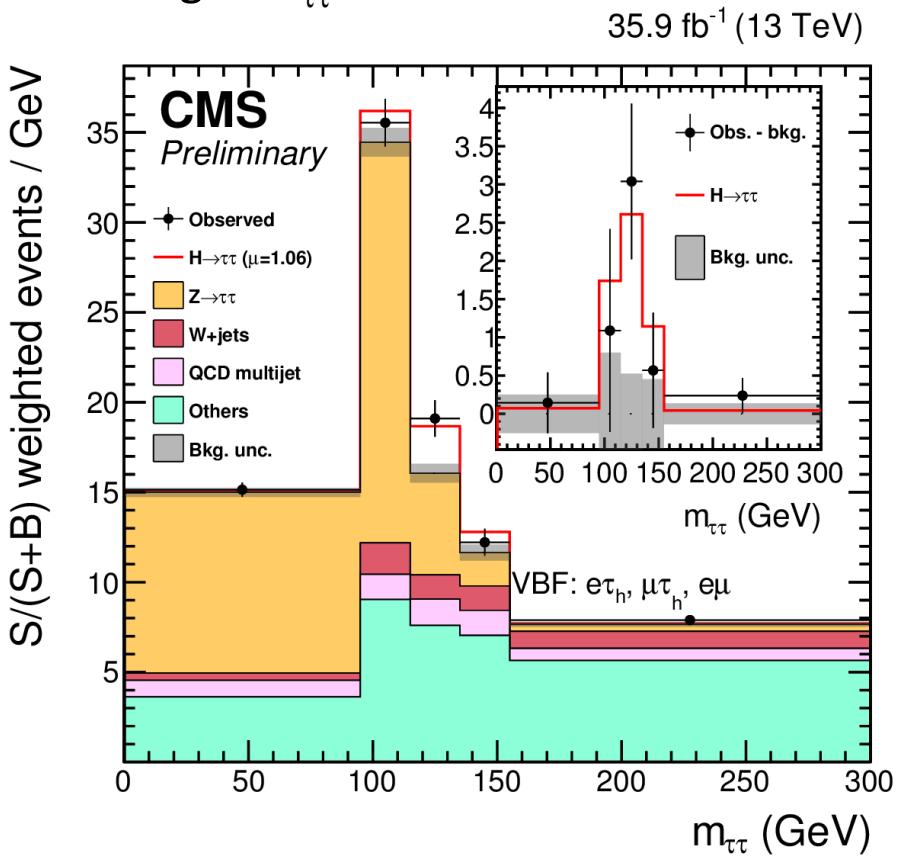
CMS 35.9 fb^{-1} @13 TeV

- For visualization into categories that use m_{vis} or $m_{\tau\tau}$ in the 2d fits and significance weight

Left: m_{vis}



Right $m_{\tau\tau}$

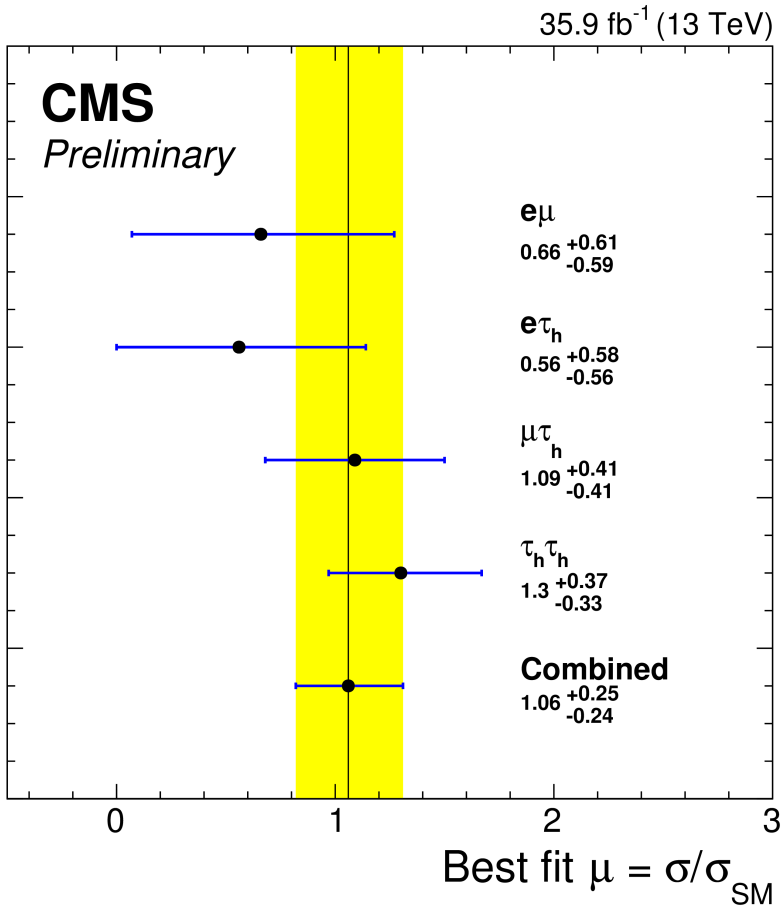


H(125) $\rightarrow\tau\tau$ signal observed at 4.9σ significance

(expected significance 4.7σ)

H $\rightarrow\tau\tau$ result compared to SM prediction

CMS 35.9 fb^{-1} @13 TeV



- Signal strength of $\mu=\sigma/\sigma_{SM}$ = 1.06$\pm$0.25 consistent with SM

$H \rightarrow \tau\tau$ in context

No new public result from ATLAS in Run 2

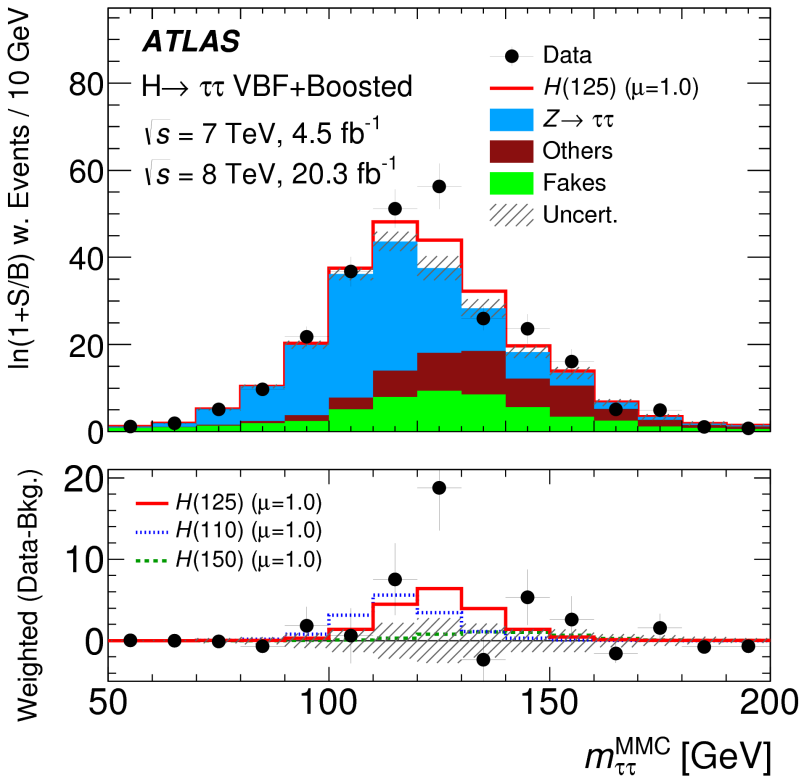
Run 1 (8 TeV) Summary:

ATLAS: *JHEP 04 (2015) 117*
$\mu = \sigma/\sigma_{SM} = 1.47 \pm 0.40$ at 4.5σ

CMS: *JHEP 05 (2014) 104*
$\mu = \sigma/\sigma_{SM} = 0.79 \pm 0.40$ at 3.2σ

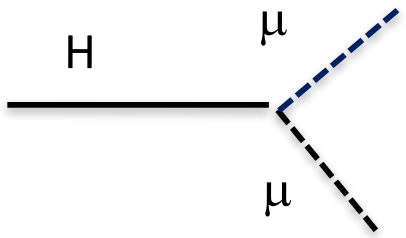
Run 1 Combined: $\mu = \sigma/\sigma_{SM} = 1.11 \pm 0.23$ at 5.5σ
CMS Run 2: $\mu = \sigma/\sigma_{SM} = 1.06 \pm 0.25$ at 4.9σ

ATLAS Run 1 Result

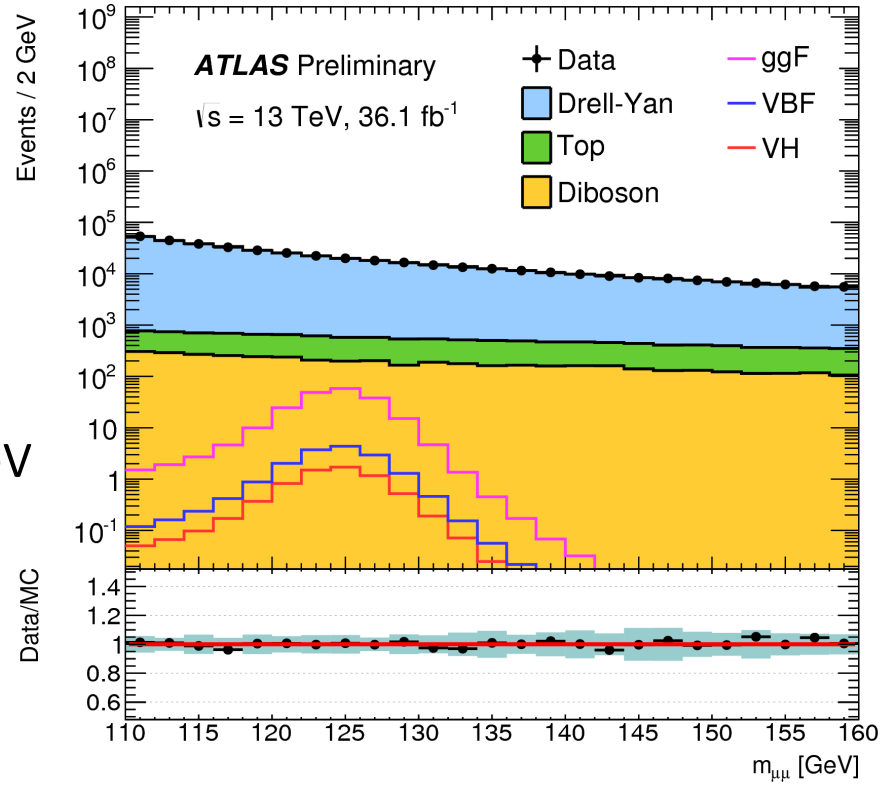


Search for H(125) →μμ

ATLAS 36.1 fb^{-1} @13 TeV

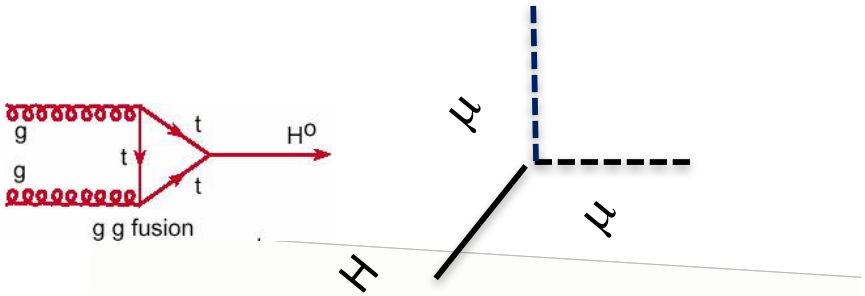


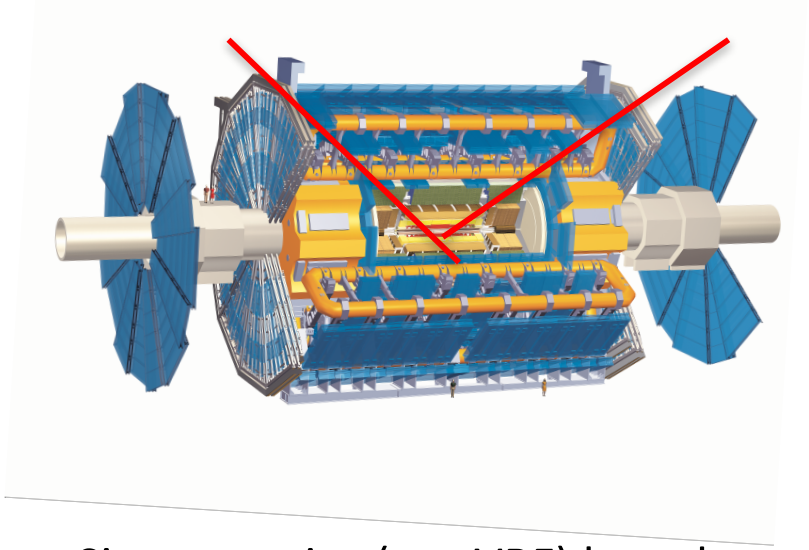
- Fully reconstruct H from prompt muons
- Simulated Signal Peak FWHM 5.6 to 7.5 GeV
- Principal background is Z →μμ
- H(125) tends to have higher $p_T^{\mu\mu}$ than background

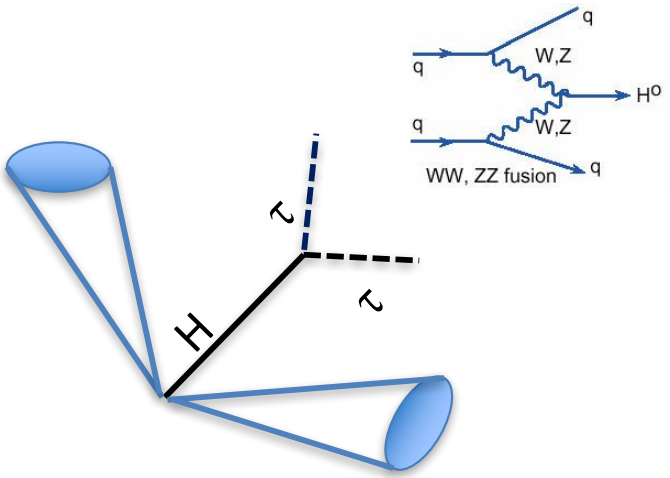


H(125) →μμ Selection Categories

ATLAS 36.1 fb^{-1} @13 TeV







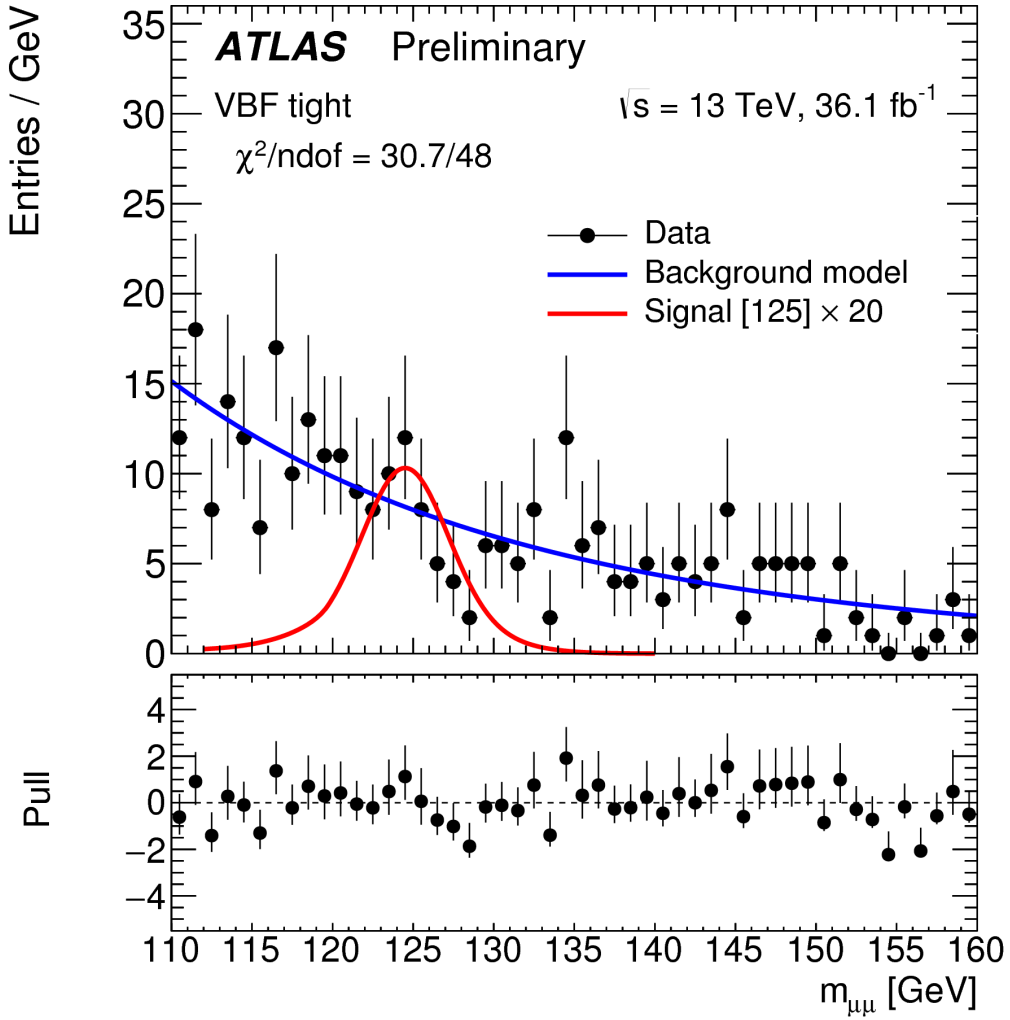
Six categories (not VBF) based on

- 2: Muon in barrel or endcap
- x 3 ranges in $p_T^{\mu\mu}$

Two Vector Boson Fusion categories based on BDT (jet-jet kinematic variables plus $p_T^{\mu\mu}$)

H(125) →μμ Results

ATLAS 36.1 fb^{-1} @13 TeV

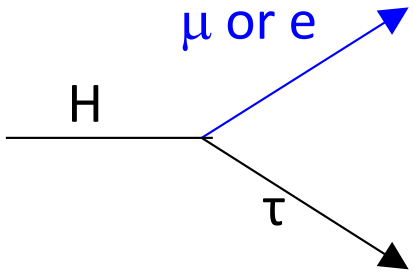


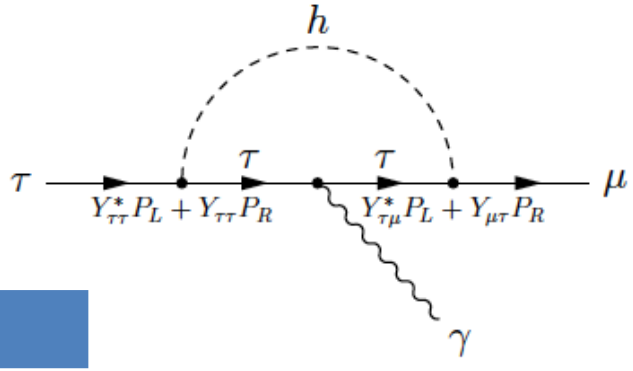
- Fit data to parametric functions for signal and background (no simulation needed !)
- No evidence for a signal
- $\mu=\sigma/\sigma_{SM} < 3.0$ @95% C.L.
- Combined with ATLAS run 1 (7 TeV)
  $\mu=\sigma/\sigma_{SM} < 2.8$ @95% C.L.
- CMS Run 1 (7 TeV)
  $\mu=\sigma/\sigma_{SM} < 7.4$ @95% C.L
  (No Run2 result public yet)

Search for Lepton Flavor Violating H(125) Decays (CMS)

- Forbidden in the Standard Model
- Allowed in many models of new physics: SUSY, composite Higgs, Randall-Sundrum ….
- Indirect constraints from $\tau \rightarrow \mu\gamma$, $\tau \rightarrow e\gamma$, $\mu \rightarrow e\gamma$
  $B(H \rightarrow e\tau) < 10\%$, $B(H \rightarrow \mu\tau) < 10\%$, $B(H \rightarrow e\mu) < 10^{-8}$

  Run 1 Searches set limits @95 % C.L.



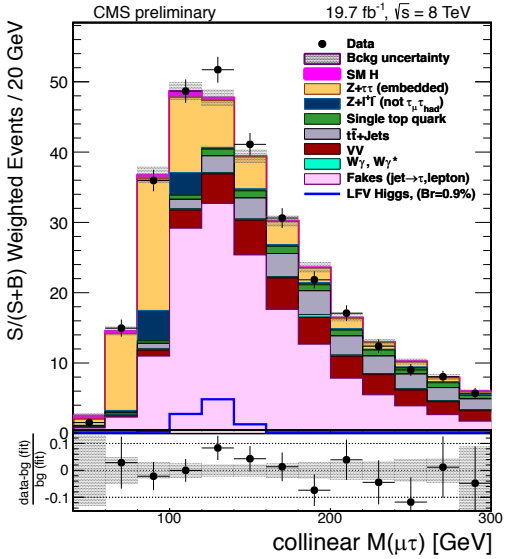


	B(H →eτ)	B(H →μτ)	B(H →eμ)
ATLAS	< 1.04 %	< 1.43 %	-
CMS	< 0.69 %	< 1.51 %	< 0.035 %

Phys. Lett. B 749 (2015) 337, Physics Letters B 763 (2016) 472
Eur. Phys. J. C77 (2017) 2 70, JHEP 11 (2015) 211

H(125) →μτ Run 1 observed excess

CMS **H(125) →μτ** significance weighted



- CMS Run 1 analysis:

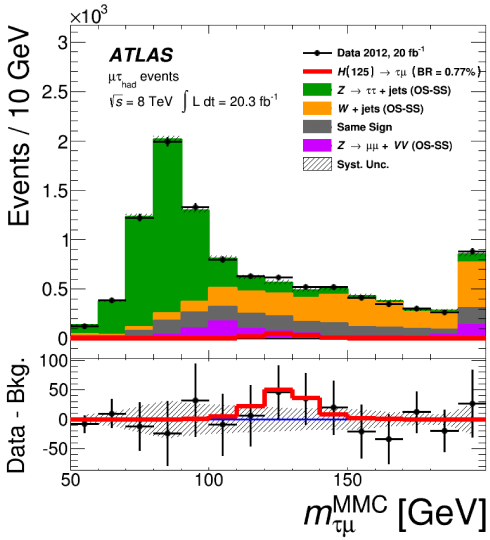
  Cut based analysis using collinear mass as signal variable with template fits of data driven background distributions

  2.4σ excess with best fit $B(H \rightarrow \mu\tau) = 0.8 \pm 0.4\ \%$

- ATLAS Run 1 analysis

  Cut based analysis with data driven background Estimates (different technique to CMS)

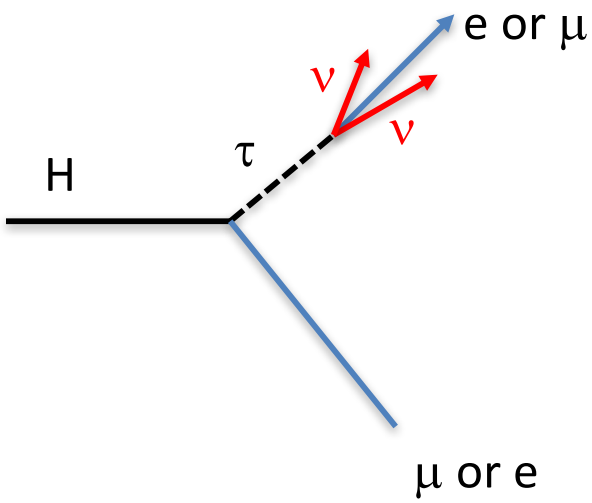
  1.3σ excess with best fit $B(H \rightarrow \mu\tau) = 0.8$

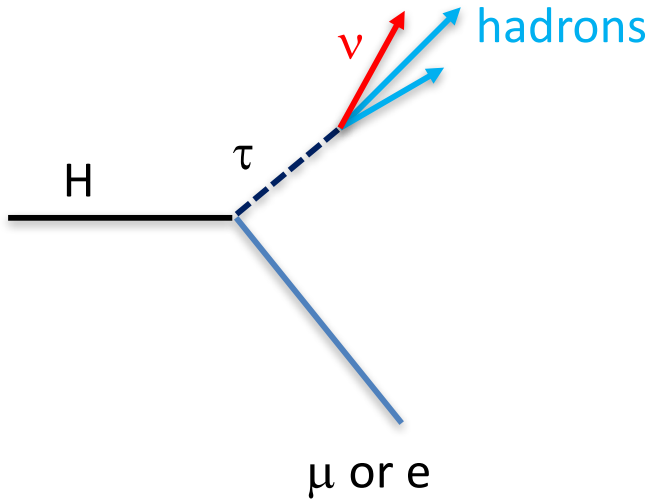


Decay Channels in the Search for LFV H(125) Decays

CMS 35.9 fb^{-1} @13 TeV

Search in four channels





$H \rightarrow e\tau_{\mu}$

$H \rightarrow \mu\tau_{e}$

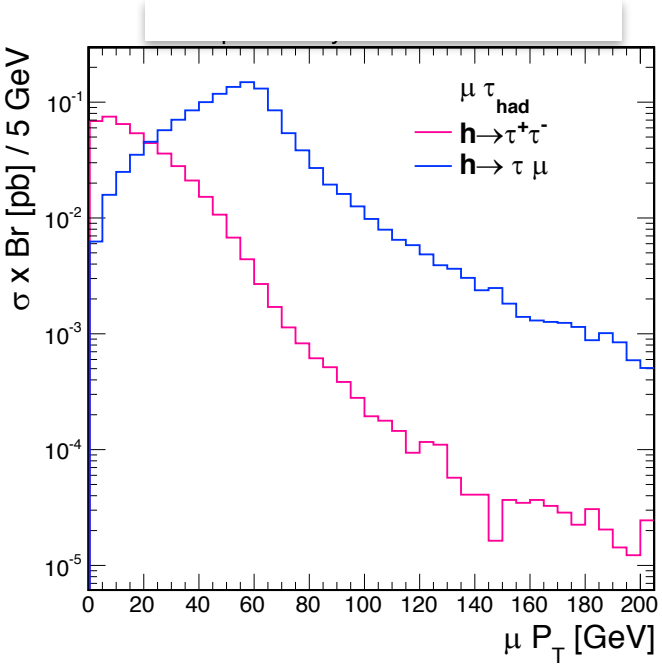
$H \rightarrow e\tau_{h}$

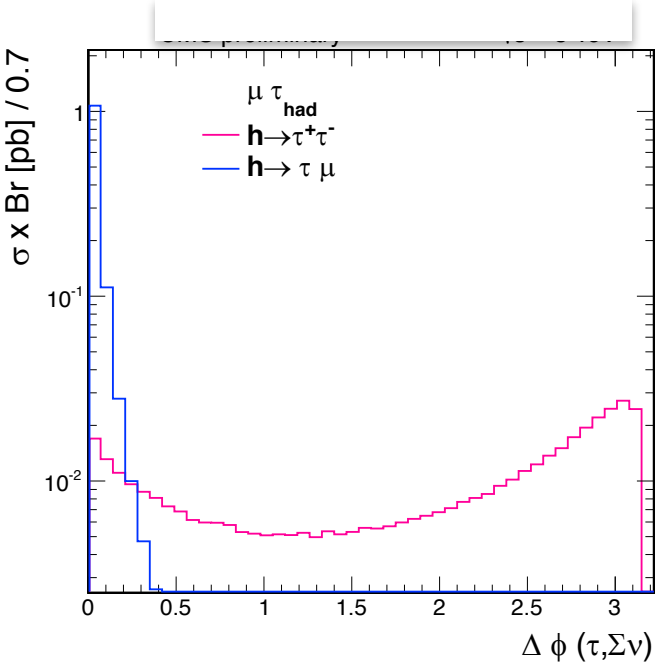
$H \rightarrow \mu\tau_{h}$

Similarities and differences to SM H->ττ searches

- LFV $H\rightarrow\tau_{had}\mu/e$ and $H\rightarrow\tau_{e/m}\mu/e$ 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

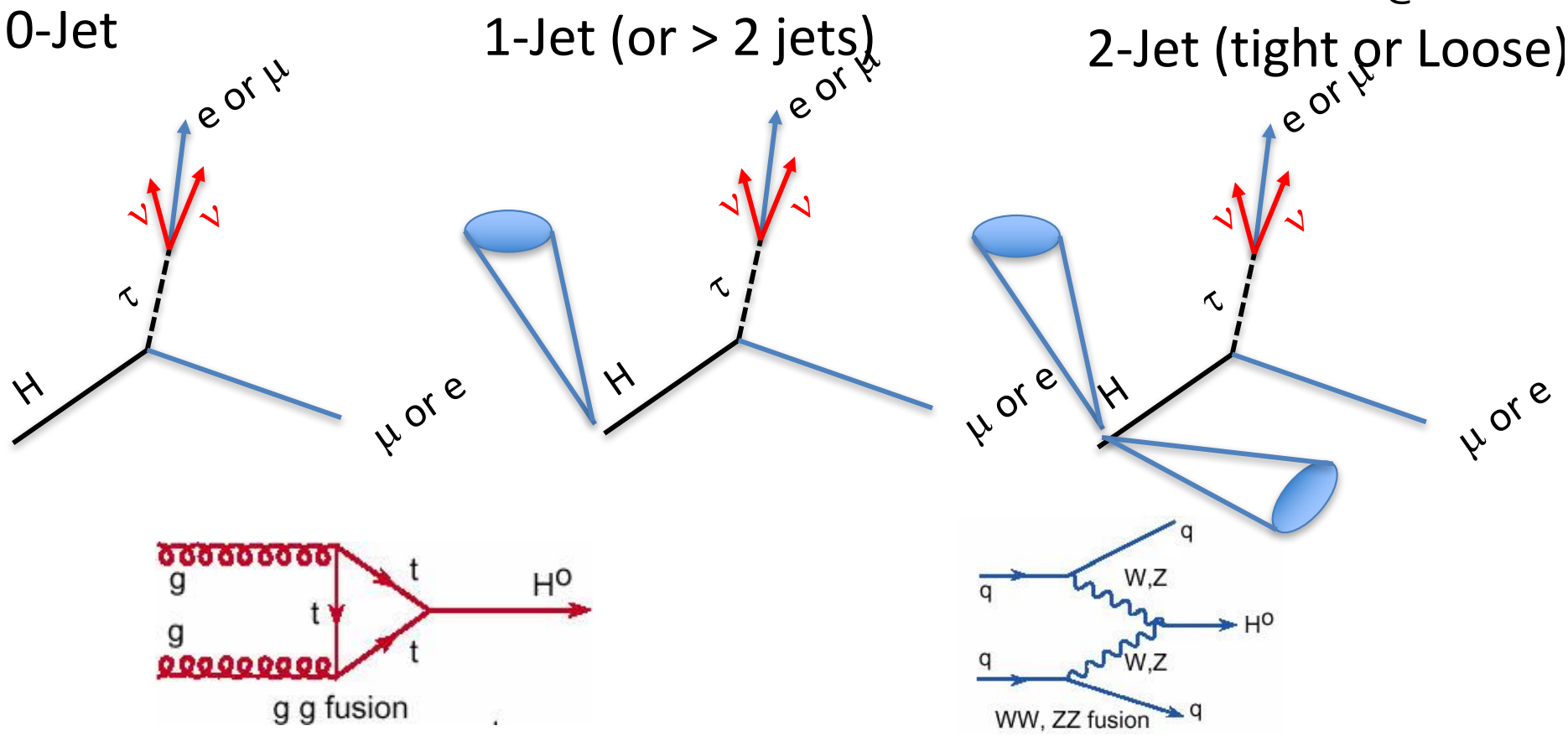




Standard Model H→ττ searches not very sensitive because of different kinematics

Categories in the Search for LFV H(125) Decays

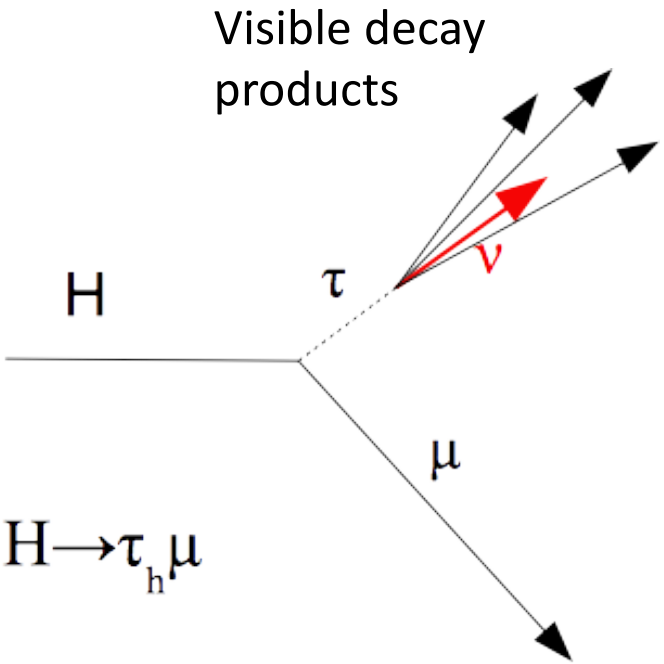
CMS 35.9 fb^{-1} @13 TeV



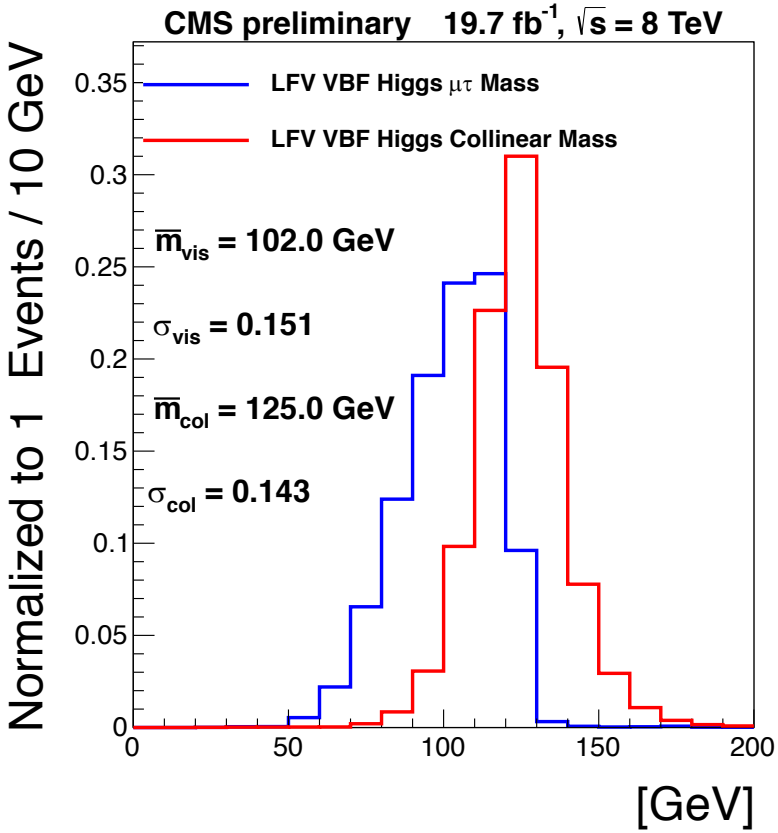
- For each channel define four categories according to the numbers of jets (P_T>30 GeV) (VBF has two catagories for tight and loose)

LFV H(125) Important Signal Variable – Collinear Mass (M_{col})

CMS 35.9 fb^{-1} @13 TeV



Approximate neutrino as collinear with the visible products of the tau decay



100

Collinear Mass reduces bias and improves resolution versus visible Mass

LFV H(125) Selection Variables

- **μ, e, τ_{had} p_T cuts**: Leptons from signal process are expected to be generally higher **p_T** 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.
- Two variants of analysis
  1. Boosted Decision Tree including above variables and M_{col}
  2. Cut based analysis using M_{col} as signal variable (to cross-check BDT in case of an observation)

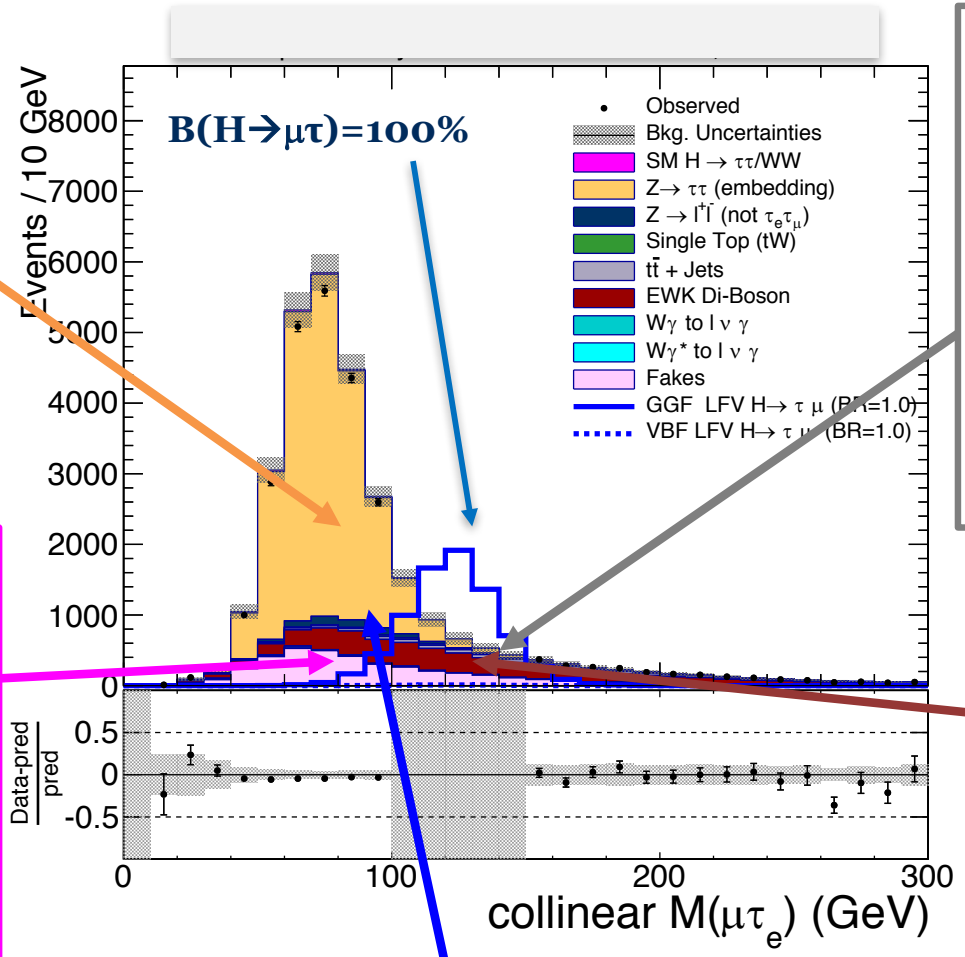
LFV H(125) Background Overview

Z → ττ:

- simulation validated with $Z \rightarrow ee, \mu\mu, \tau\tau$ data

W+Jets/QCD Multijets:

Data driven using Fake rate and same Sign/opposite sign methods



tt̄:

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

WW+Jets:

- Normalization(NLO) and shape from MC simulations

Z→l⁺l⁻, Wjets+γ(*), SingleTop,…:

- Normalization and shape from MC simulation

H→μτ Results

BDT fit

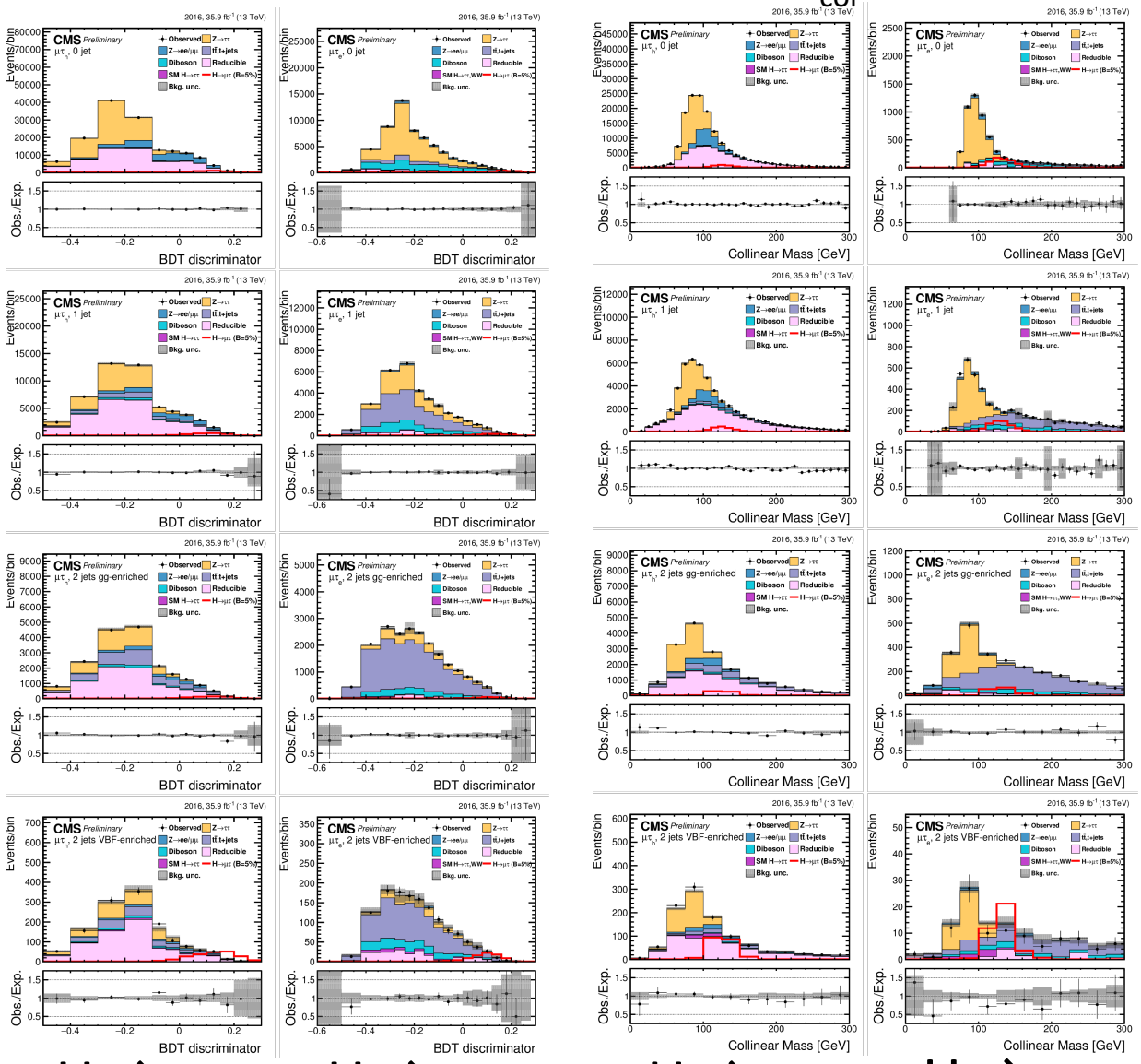
M_{col} fit

0-jet

1-jet

2-jet (loose)

2-jet (tight)



$H \rightarrow \mu\tau_e$ $H \rightarrow \mu\tau_h$ $H \rightarrow \mu\tau_e$ $H \rightarrow \mu\tau_h$

CMS 35.9 fb^{-1} @13 TeV

No Excess observed

$B(H \rightarrow \mu\tau) < 0.25\%$

@95% C.L.

(No Run 2 public result from ATLAS yet)

H→eτ Results

BDT fit

M_col fit

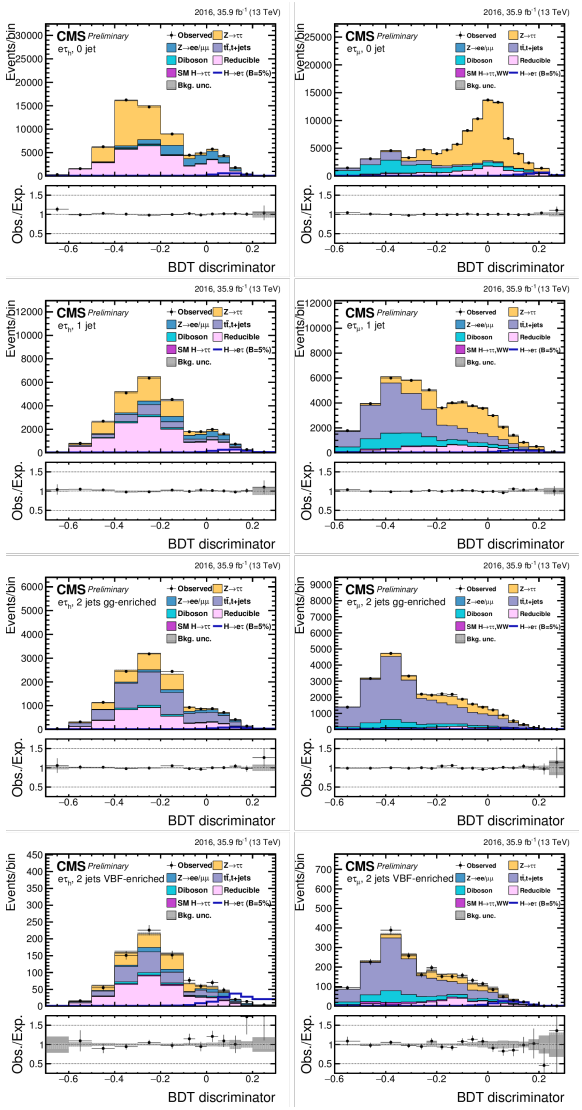
CMS 35.9 fb^{-1} @13 TeV

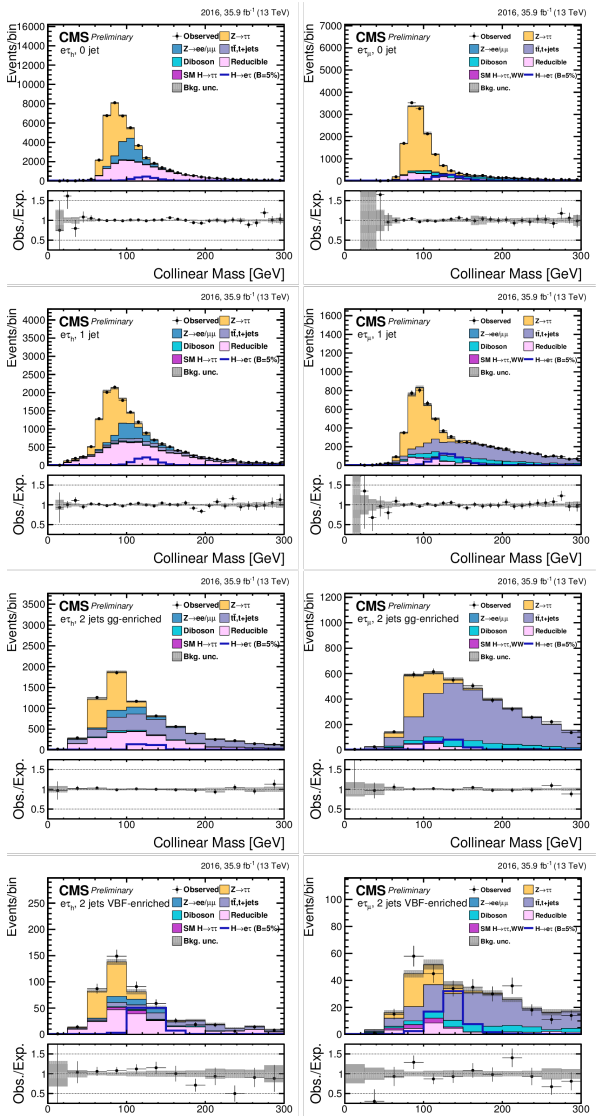
0-jet

1-jet

2-jet (loose)

2-jet (tight)





$H \rightarrow e\tau_{\mu}$ $H \rightarrow e\tau_{h}$ $H \rightarrow e\tau_{\mu}$ $H \rightarrow e\tau_{h}$

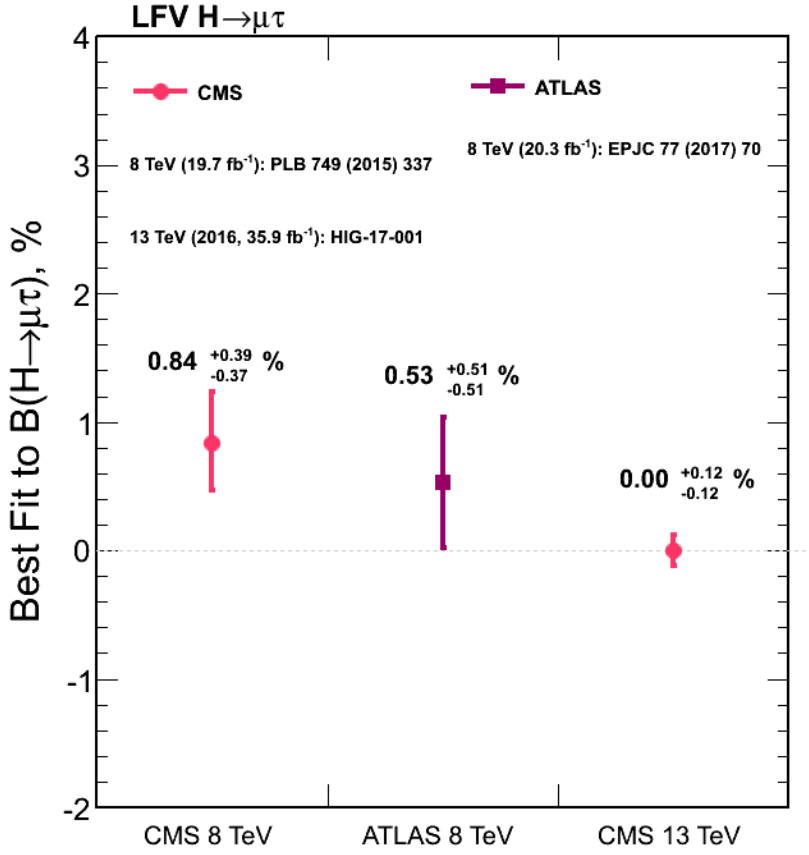
No Excess observed

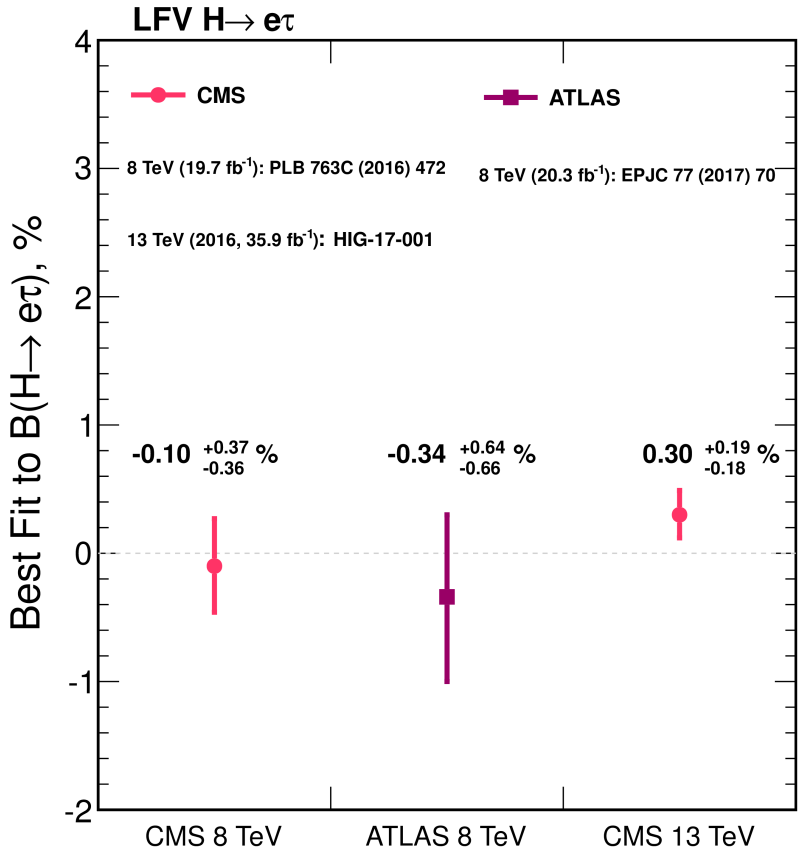
$B(H \rightarrow e\tau) < 0.61\%$

@95% C.L.

(No Run 2 public result from ATLAS yet)

LFV H results comparison





Summary

Recent results in flavor specific Higgs decays

Standard Model(SM) Searches

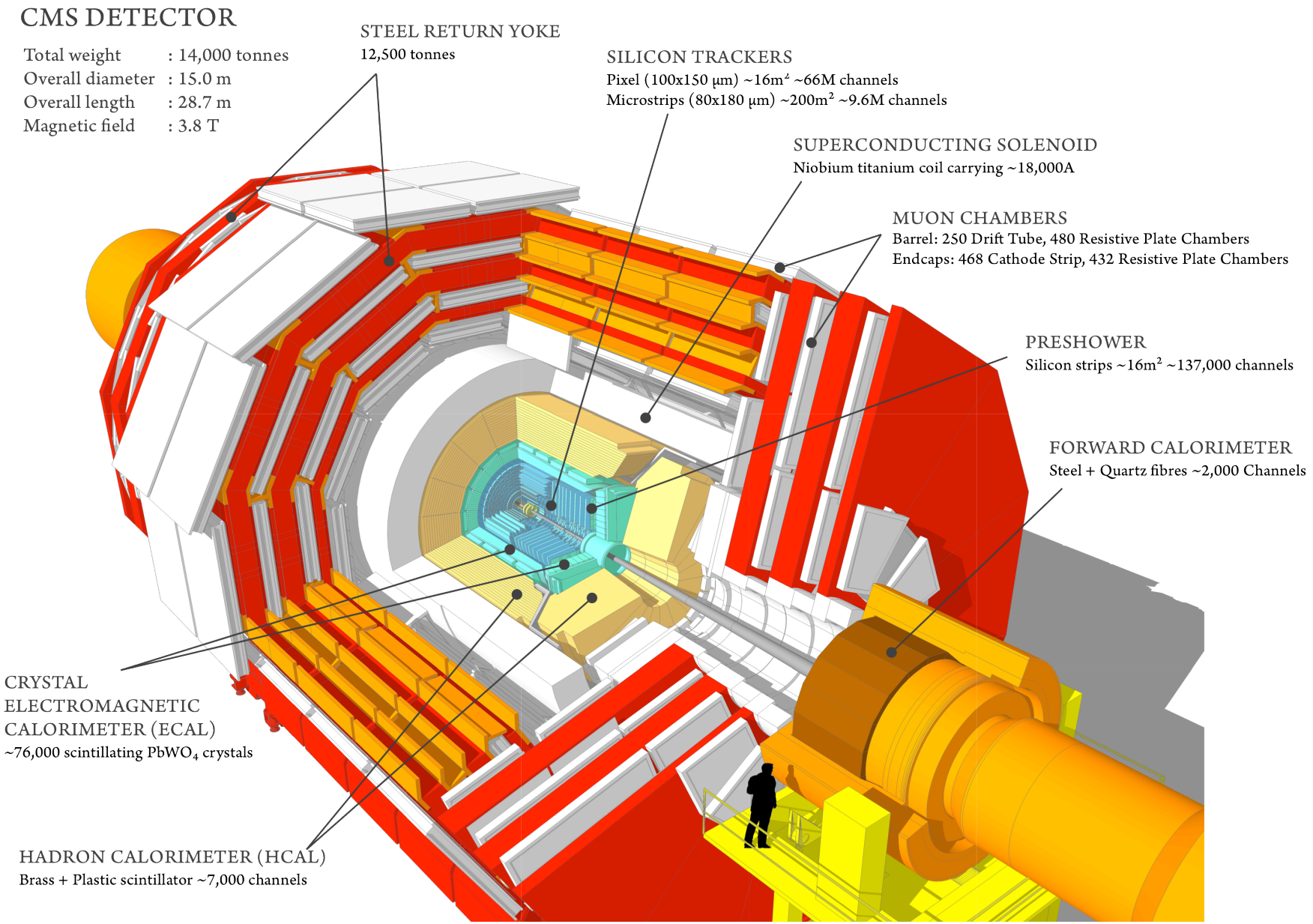
- $H \rightarrow \mu\mu$ (ATLAS) No evidence yet
- $H \rightarrow \tau\tau$ (CMS) 5σ observation in a single measurement
- $H \rightarrow bb$ (CMS) New technique with hint of excess but no evidence yet

Beyond SM Search for LFV

- $H \rightarrow e\tau$, $H \rightarrow \mu\tau$ (CMS) No evidence. Run 1 excess no longer there

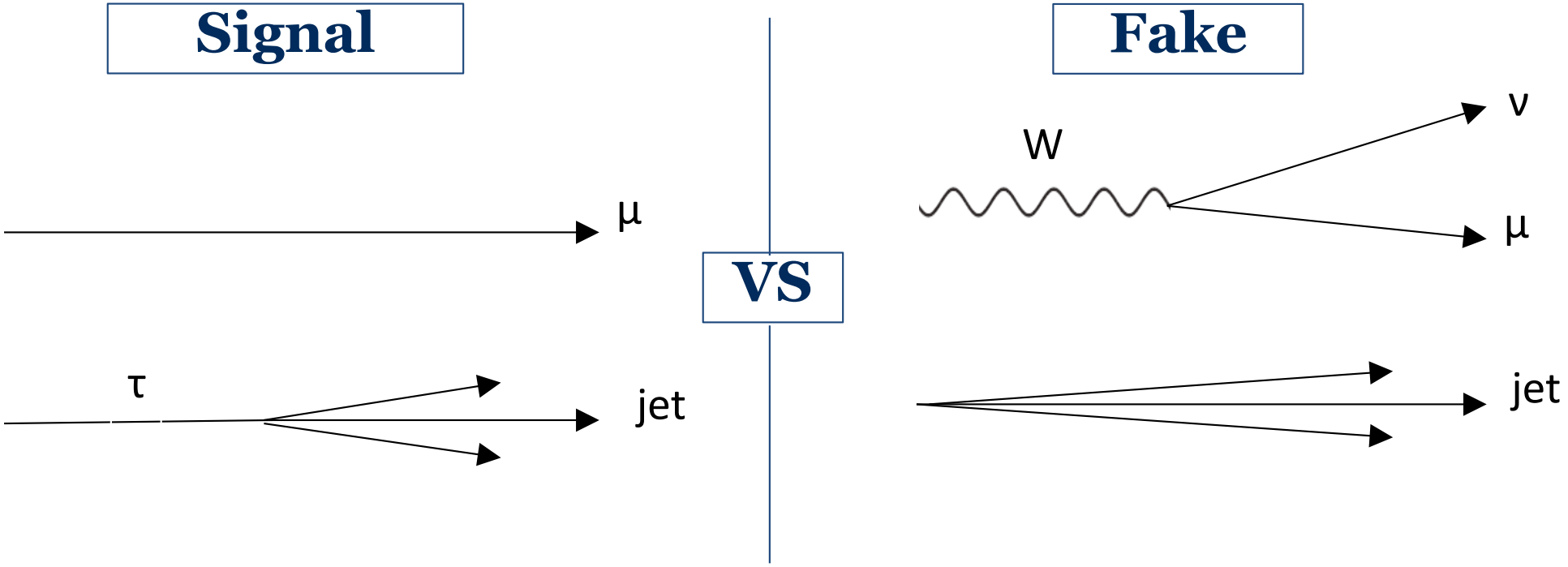
Backup Slides

Compact Muon Solenoid



Fakes Background

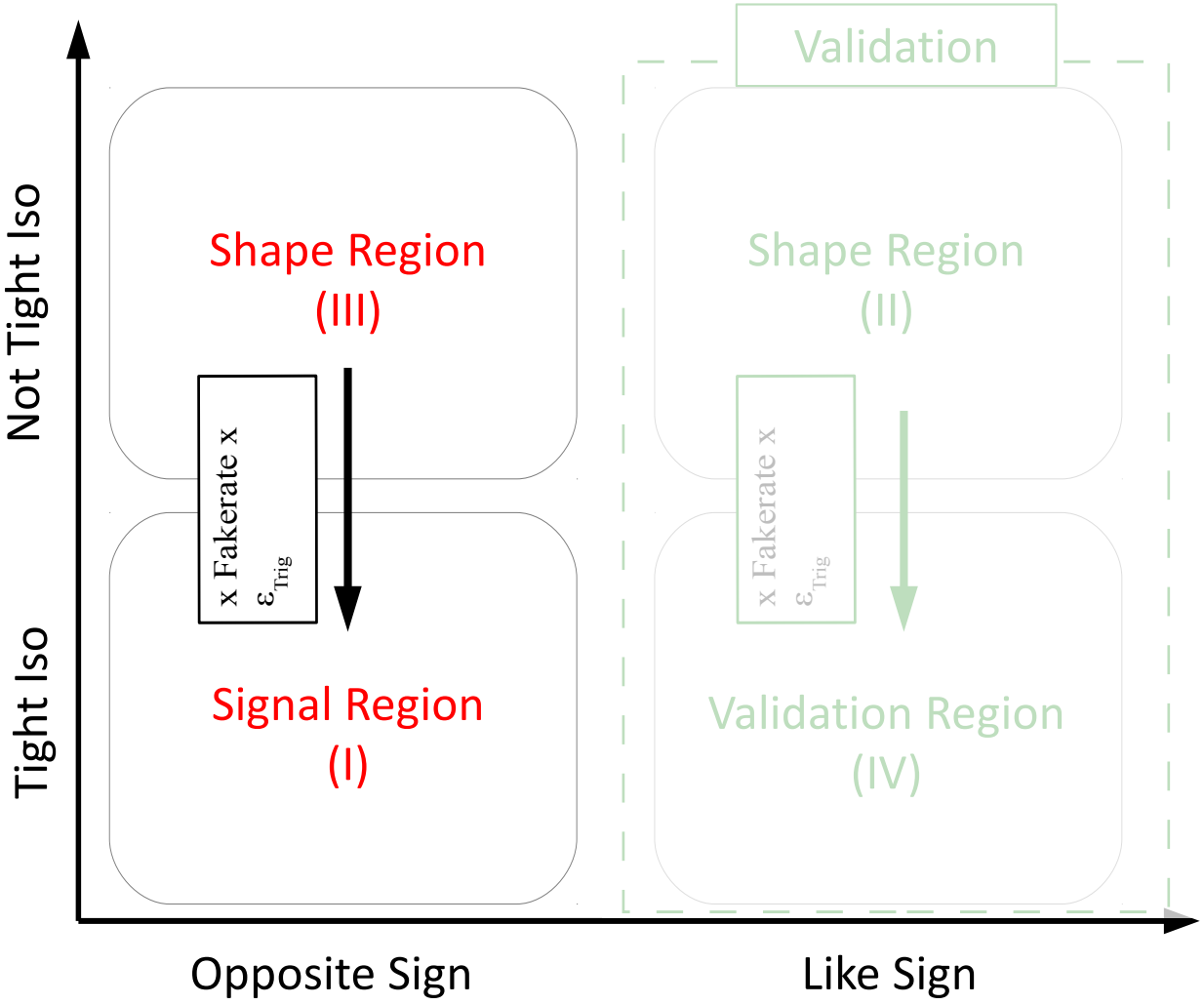
- What is a fake signal?



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

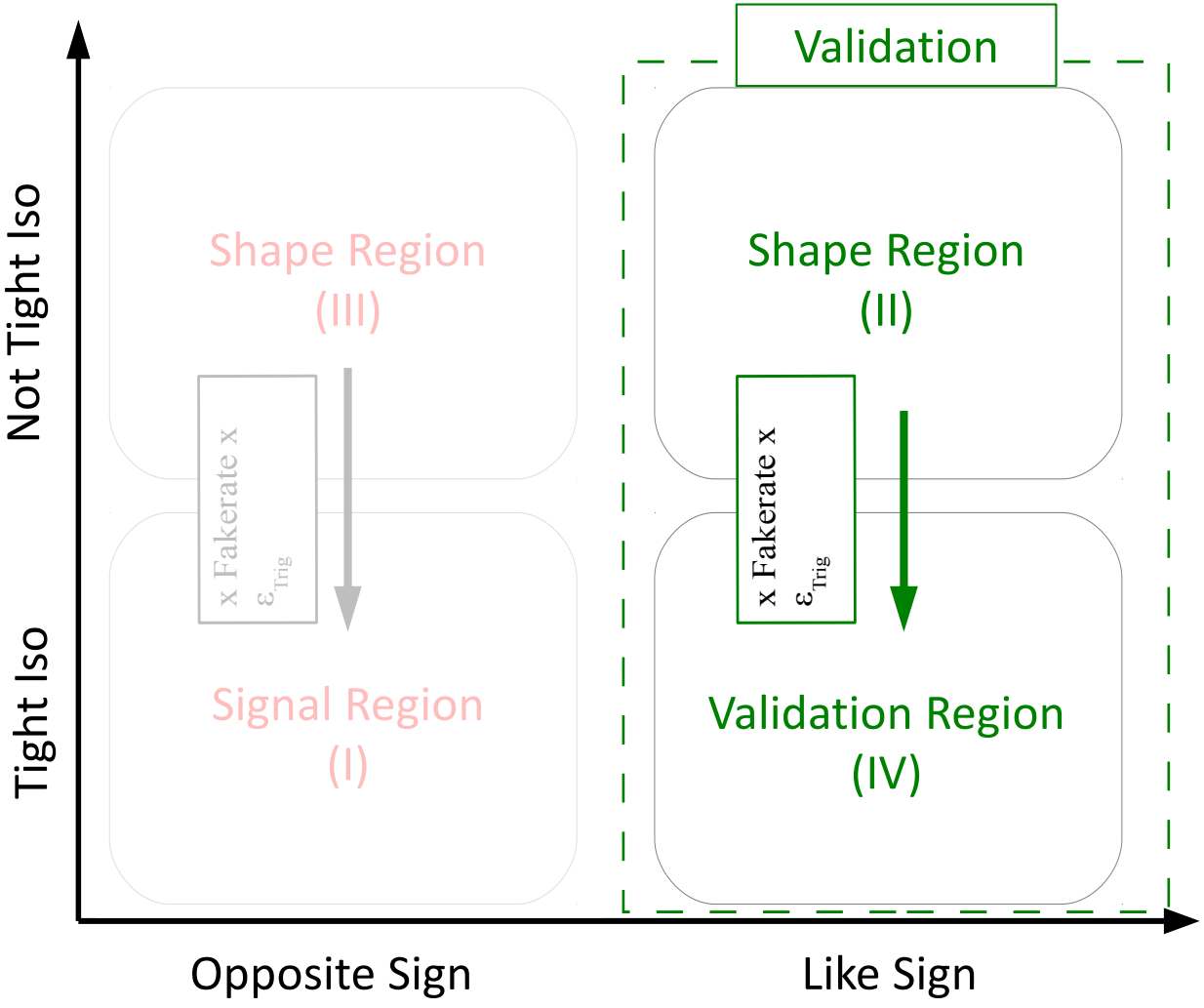
Fakes Background

- 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



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



Existing Limits

$\tau \to \mu\gamma$	$\sqrt{\lvert Y_{\tau\mu}\rvert^2 + \lvert Y_{\mu\tau}\rvert^2}$	0.016
$\tau \to 3\mu$	$\sqrt{\lvert Y^2_{\tau\mu} + \lvert Y_{\mu\tau}\rvert^2}$	$\lesssim 0.25$
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	BR($h \to \tau\mu$)	$\sqrt{Y^2_{\tau\mu} + Y^2_{\mu\tau}}$
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 $\Gamma_{\mathrm{SM}} = 4.1$ 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	$\mathrm{Im}(Y_{\mu\tau}Y_{\tau\mu})$	$-0.8 \ldots 1.0$
$\mu \to e\gamma$	$\left(\lvert Y_{\tau\mu}Y_{\tau e}\rvert^2 + \lvert Y_{\mu\tau}Y_{e\tau}\rvert^2\right)^{1/4}$	$< 3.4 \times 10^{-4}$

Transverse Mass

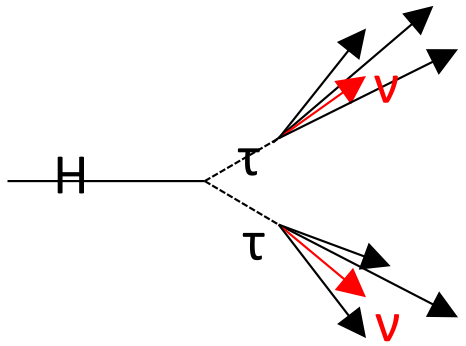
- Defined as

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

- 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.



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
  $100\ \text{GeV} < M_{collinear} < 150\ \text{GeV}$
- 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.

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

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

Limit: Yukawa Coupling

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

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

- Define branching ratio and solve for coupling:

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