LFV Higgs decays and FCNC at CMS experiment

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Exotic Higgs decays at Fermilab
21st-22nd May 2015

Outline

- LFV Higgs decay:
  - search for H→μτ at CMS (8 TeV)
- Flavour-changing-neutral-current (FCNC)
  - search for associate production t-H at CMS (8 TeV)

Lepton-flavour-violating Higgs decays

- The Standard Model (SM) forbids LFV decays of the Higgs boson
  - No off-diagonal element in the Yukawa matrix

$$Y = \begin{bmatrix} Y_{ee} & 0 & 0 \\ 0 & Y_{\mu\mu} & 0 \\ 0 & 0 & Y_{\tau\tau} \end{bmatrix}$$

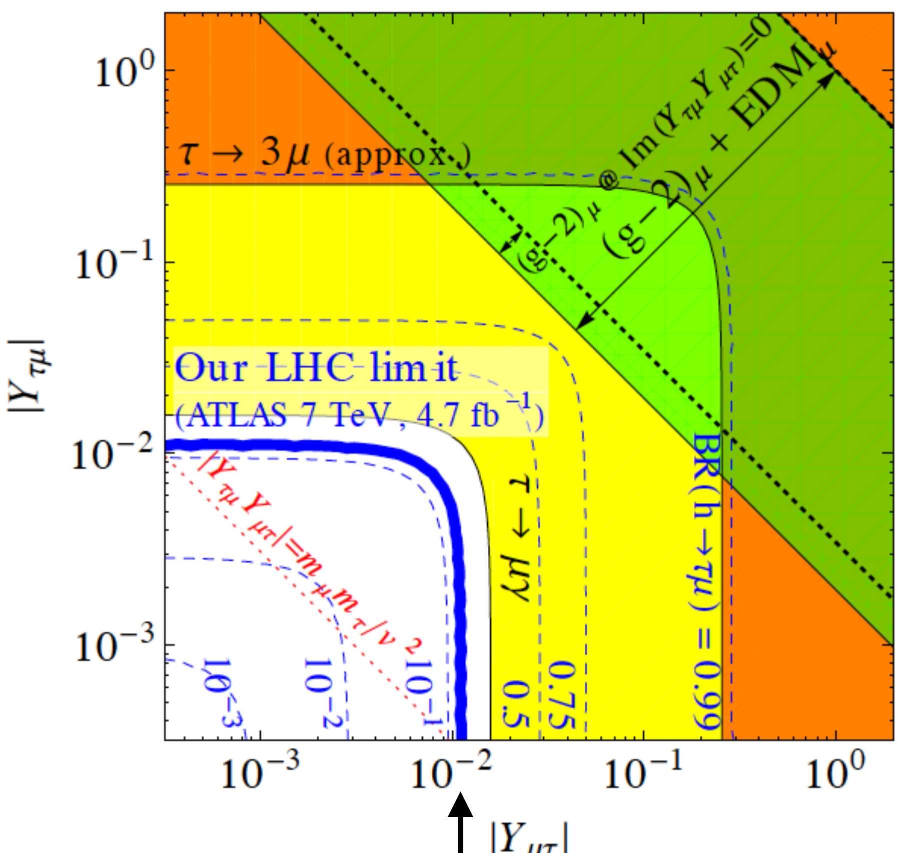
- Alternative models foresee LFV decays
  - General MHDM: flavor violating decays allowed (tree level)
  - 2HDM Type-I: impose a discrete symmetry to couple only one doublet to fermions
  - 2HDM Type-II: impose a discrete symmetry to couple Q=2/3 quarks to one doublet and Q=-1/3 quarks to the other

$$Y = \begin{bmatrix} Y_{ee} & Y_{e\mu} & Y_{e\tau} \\ Y_{\mu e} & Y_{\mu\mu} & Y_{\mu\tau} \\ Y_{\tau e} & Y_{\tau\mu} & Y_{\tau\tau} \end{bmatrix}$$

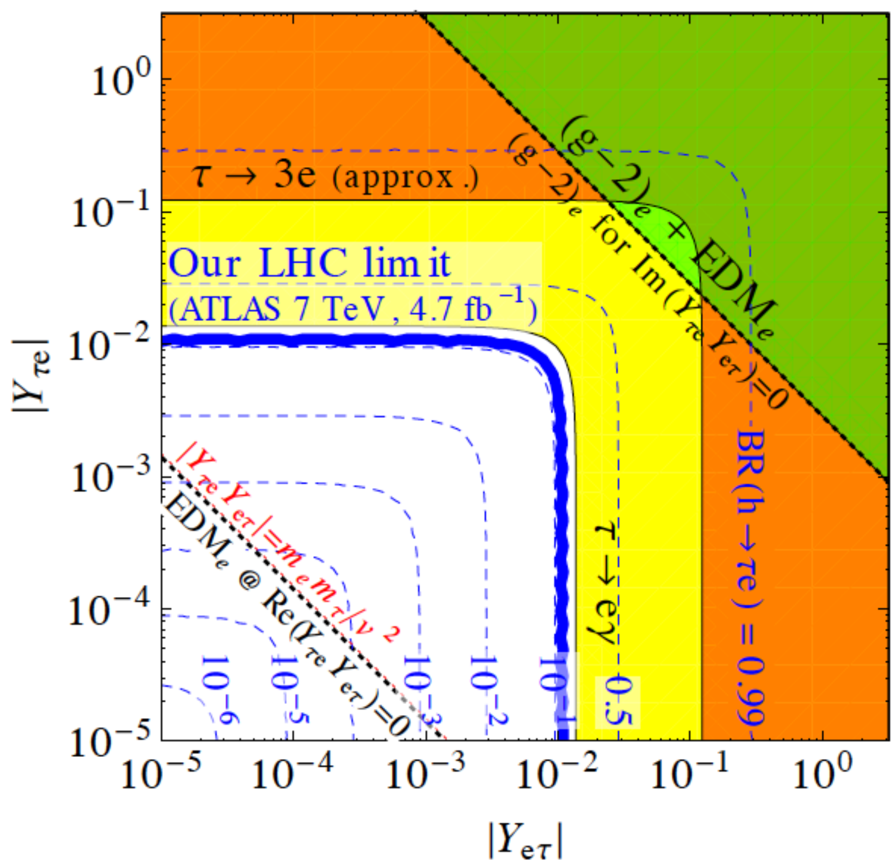
  - 2HDM Type-III: no discrete symmetries are introduced, but phenomenological constraints on the flavour changing couplings

Coupling constraints from indirect searches

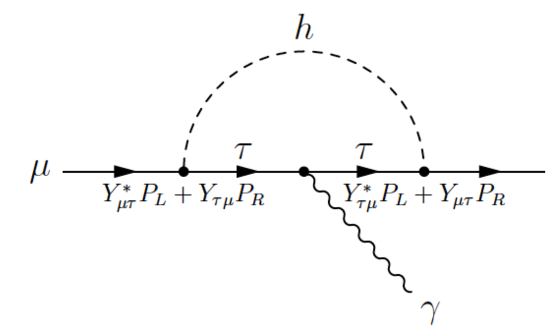
$Y_{\mu\tau}$ constrained by indirect searches
$Y_{\mu\tau} < O(10^{-2})$



it does not contain CMS measurement

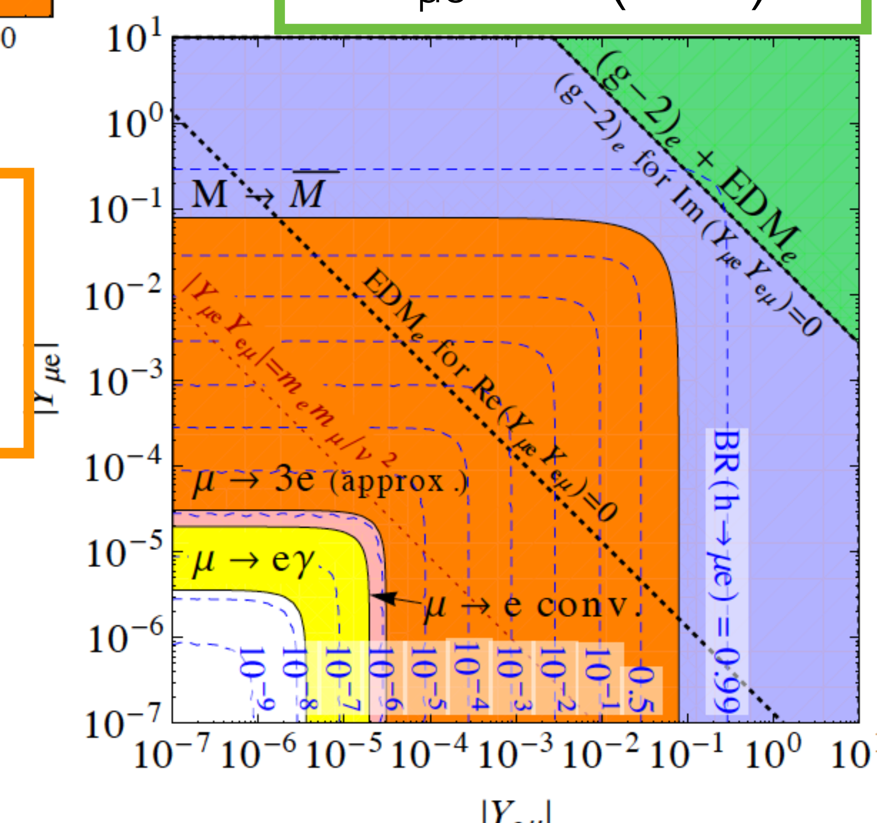


$Y_{e\tau}$ constrained by indirect searches
$Y_{e\tau} < O(10^{-2})$



from arXiv:1209.1397v2

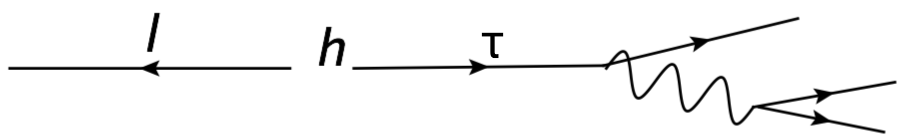
$Y_{\mu e}$ constrained by $\mu \to e\gamma$ search
$Y_{\mu e} < O(10^{-6})$

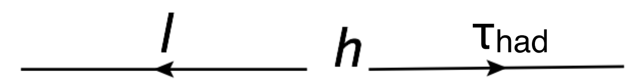


CMS H→μτ search

- Assumption: m_H = 125 GeV

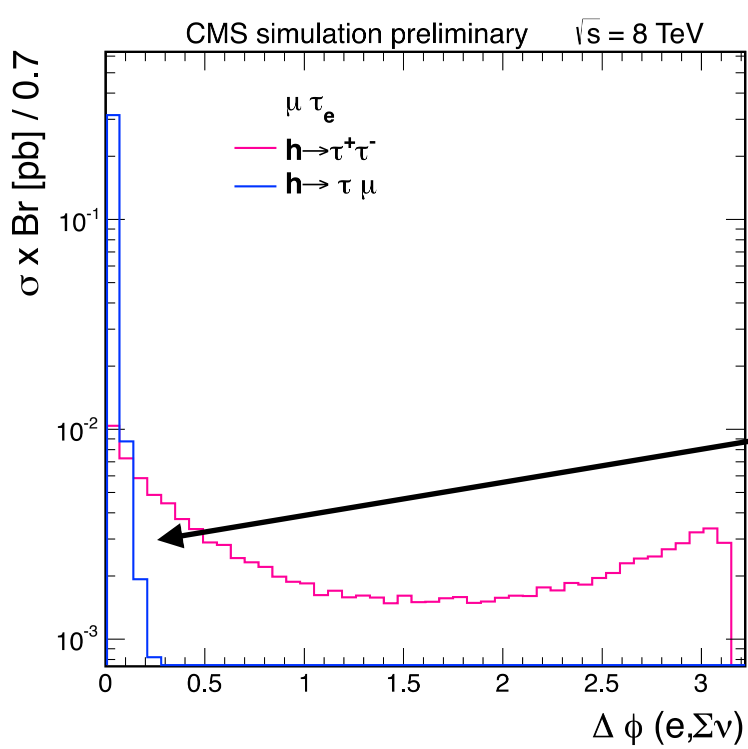
- 2 channels: τ→e and τ→hadrons

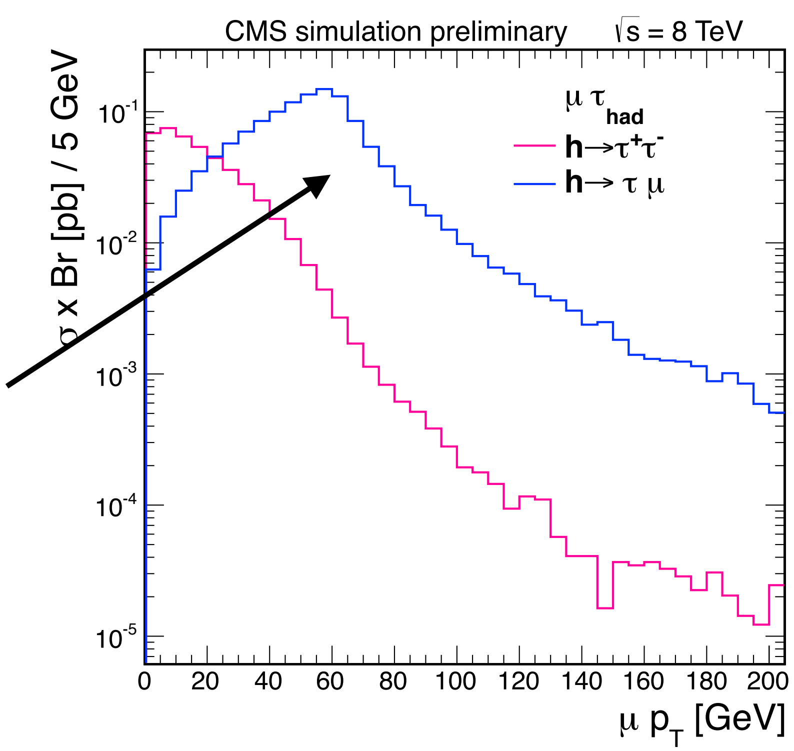




1 or 3 prong

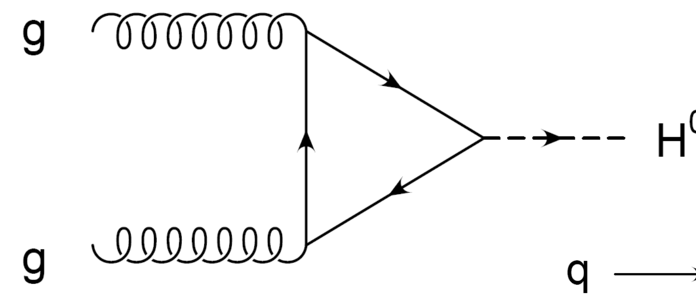
- Similar signature to SM H→ττ, but
  - prompt decay of leptons from H, therefore harder p_T spectrum: able to use Single lepton trigger
  - Collinear decays of the tau, less neutrinos and missing transverse energy

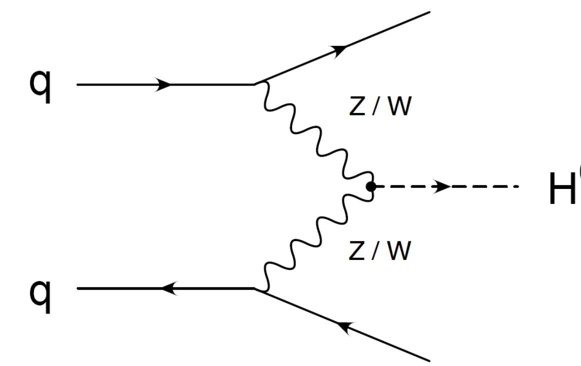


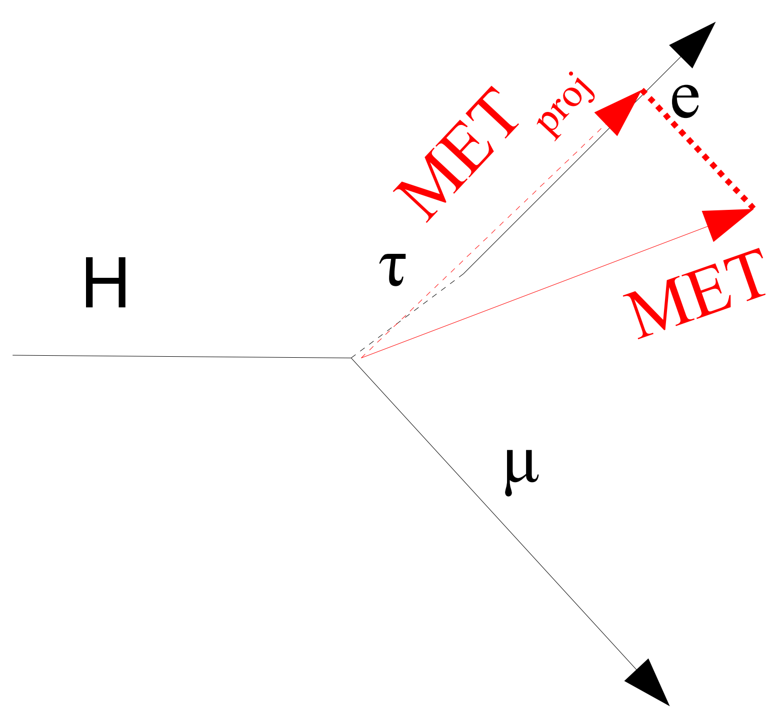


CMS analysis strategy

- 2 production mode: gluon-gluon fusion and vector boson fusion
  - each channel is split into 3 categories:
    - 0, 1 jet: more sensitive to the GGF
    - 2 jets more sensitive to the VBF







- Mass reconstruction:
  - Assume neutrinos are collinear with tau direction and thus with the lepton
  - Collinear mass approximation (projection method)

$$M_{colMass} = \frac{M_{vis}}{\sqrt{x_\tau}}, \qquad x_\tau = \frac{p_T^\tau}{p_T^\tau + MET_{proj}}$$

$$MET_{proj} = \frac{E_x^{miss} \cdot p_x^\tau + E_y^{miss} \cdot p_y^\tau}{p_T^\tau}$$

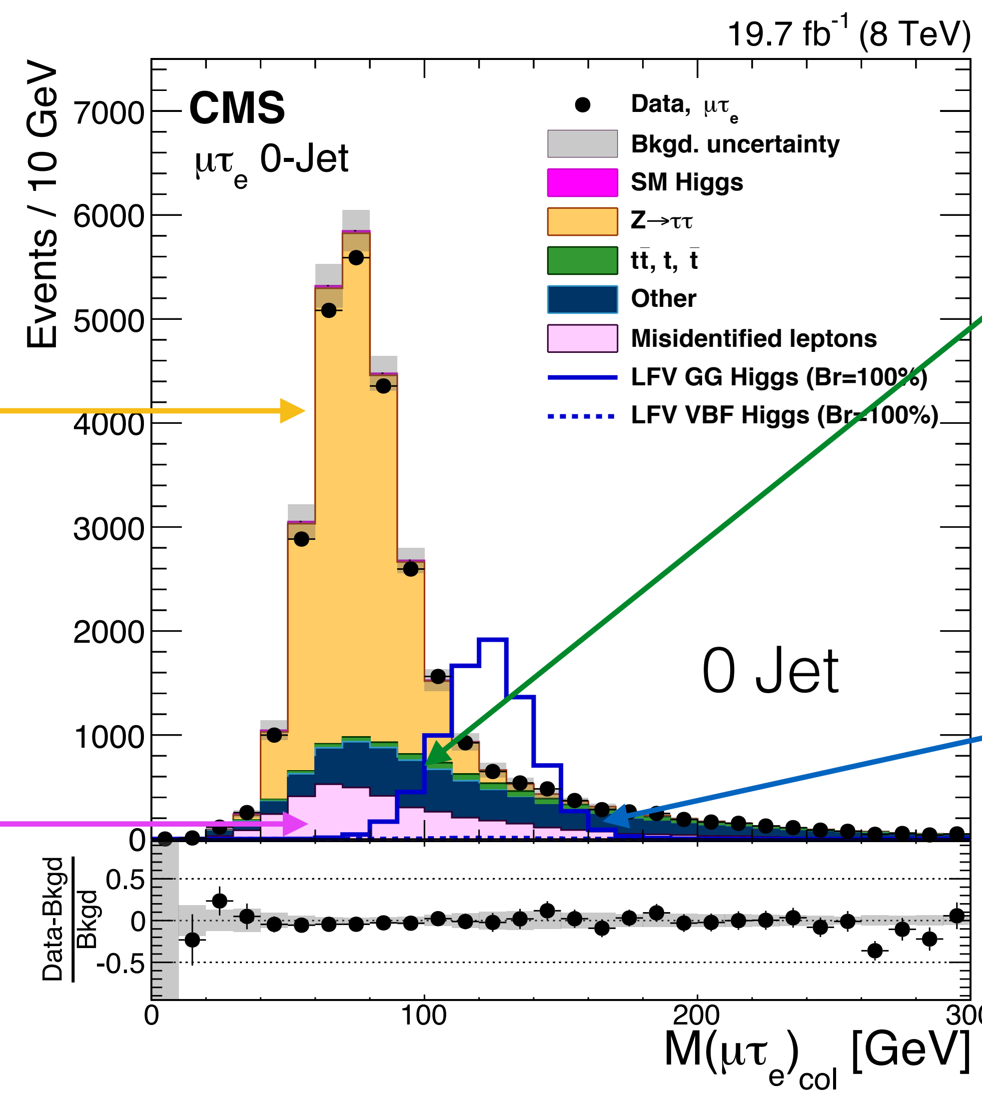
Backgrounds: $H \to \mu\tau_e$

Data Driven Bkg

$Z \to \tau\tau$:
- Normalization from MC
- Shape from PFEmbedding method

Dominant in 0,1 jet cat.

W+Jets/QCD Multijets:
- extracted from data (control region)
- Shape from anti-isolated lepton events



single t, $t\bar{t}$:
- Shape from MC simulation, normalisation cross checked with a control region

Important in 2jet cat.

EWK Dibosons (WW) + jets:
- Normalisation (NLO) and shape from MC simulation

W+ jets + $\gamma^{(*)}$, $Z \to ee$:
- Normalisation and shape from MC simulation

plot not from final selections

for clarity: $BR(H \to \mu\tau) = 100\%$

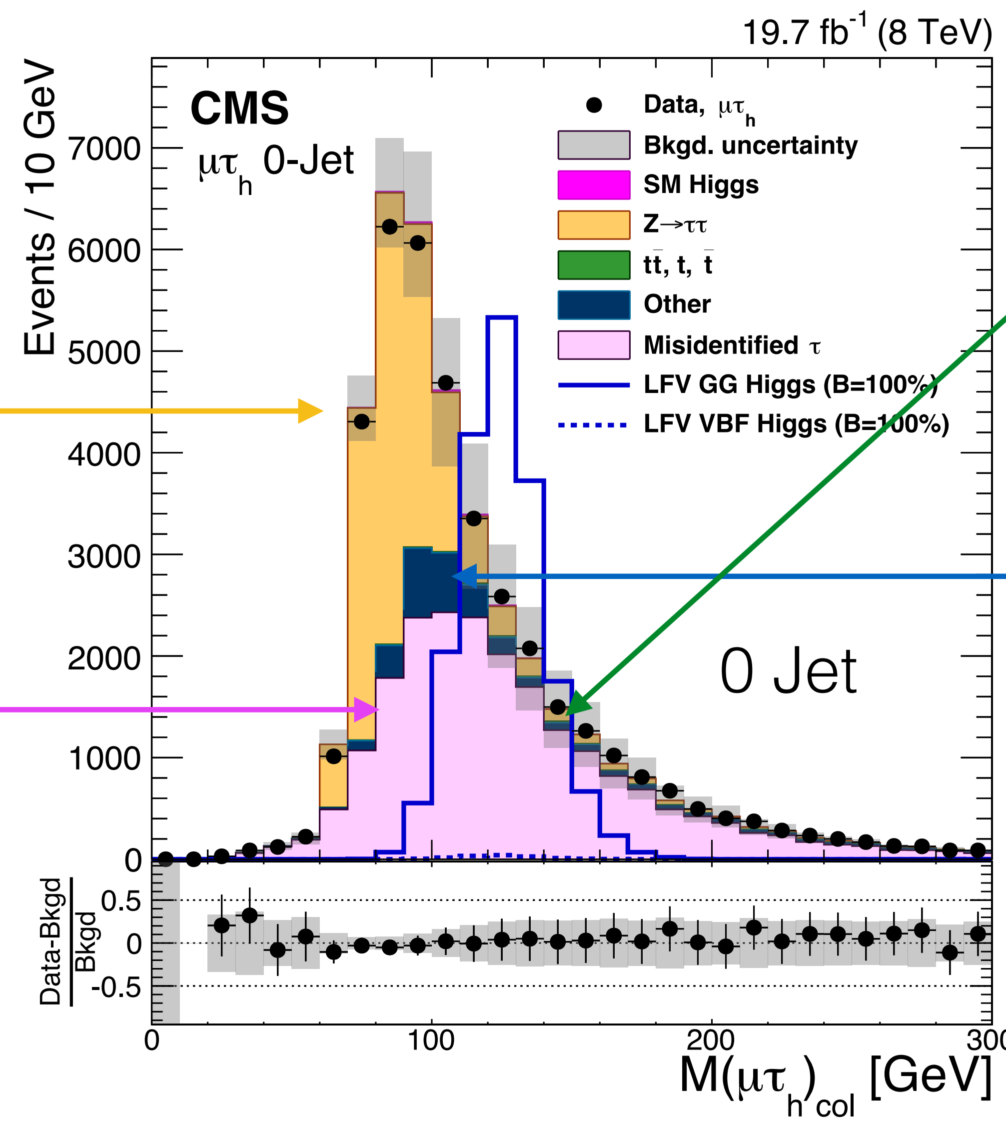
Backgrounds: $H \to \mu\tau_{had}$

Data Driven Bkg

$Z \to \tau\tau$:
- Normalization from MC
- Shape from PFEmbedding method

W+Jets/QCD Multijets:
- extracted from data (control region)
- Shape from anti-isolated lepton events

Dominant background in all the categories



$t\bar{t}$, single t:
- Normalisation and shape from MC simulation

EWK Dibosons (WW) + jets:
- Normalisation (NLO) and shape from MC simulation

$Z \to ee$:
- Normalisation and shape from MC simulation

plot not from final selections

for clarity: $BR(H \to \mu\tau) = 100\%$

Signal region

signal region cuts

Variable	$H \to \mu\tau_e$			$H \to \mu\tau_{had}$		
	0-jet	1-jet	2-jet	0-jet	1-jet	2-jet
$p_T^{\mu} >$ [GeV]	50	45	25	40	35	30
$p_T^{e} >$ [GeV]	10	10	10	-	-	-
$p_T^{\tau} >$ [GeV]	-	-	-	35	40	40
$\Delta\phi_{\vec{\mu}-\vec{\tau_{had}}} >$	-	-	-	2.7	-	-
$\Delta\phi_{\vec{e}-\vec{E}_T\!\!\!/} <$	0.5	0.5	0.3	-	-	-
$\Delta\phi_{\vec{e}-\vec{\mu}} >$	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

selected events

Sample	$H \to \mu\tau_{had}$			$H \to \mu\tau_e$		
	0-jet	1-jet	2-jet	0-jet	1-jet	2-jet
Fakes	1858.1 ± 558.8	362.9 ± 110.0	0.5 ± 0.5	41.5 ± 17.3	16.1 ± 6.8	1.1 ± 0.7
$Z \to \tau\tau$	198.8 ± 11.0	50.5 ± 3.5	0.4 ± 0.2	65.0 ± 3.0	38.6 ± 2.0	1.3 ± 0.2
ZZ, WW	47.0 ± 8.0	14.6 ± 2.6	0.3 ± 0.2	40.8 ± 6.6	21.2 ± 3.5	0.7 ± 0.2
$W\gamma$	–	–	–	2.0 ± 2.1	1.9 ± 1.9	–
$Z \to ee$ or $\mu\mu$	94.5 ± 25.2	17.6 ± 6.7	0.1 ± 0.1	1.6 ± 0.8	1.8 ± 0.8	–
$t\bar{t}$	2.5 ± 0.6	24.3 ± 3.2	0.7 ± 0.3	4.8 ± 0.7	30.0 ± 3.4	1.8 ± 0.3
$t, \bar{t}$	2.7 ± 1.2	19.9 ± 3.9	0.4 ± 0.5	1.9 ± 0.2	6.8 ± 0.8	0.2 ± 0.1
SM Higgs background	7.0 ± 1.3	4.9 ± 0.7	1.9 ± 0.7	1.9 ± 0.3	1.6 ± 0.2	0.6 ± 0.1
Sum of backgrounds	2210.4 ± 559.6	494.7 ± 110.4	4.3 ± 1.1	159.4 ± 18.9	118.1 ± 8.9	5.6 ± 0.9
LFV Higgs signal	69.7 ± 17.0	29.7 ± 6.7	3.0 ± 1.0	24.2 ± 5.7	13.6 ± 3.1	1.2 ± 0.4
data	2255.0 ± 47.5	506.0 ± 22.5	8.0 ± 2.8	180.0 ± 13.4	128.0 ± 11.3	6.0 ± 2.4

BR=0.84% → (LFV Higgs signal)

Systematics

Systematic Uncertainty	$H \to \mu\tau_e$			$H \to \mu\tau_{had}$		
	0-jet	1-jet	2-jet	0-jet	1-jet	2-jet
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 muon and electron background	40%	40%	40%	-	-	-
misidentified hadronic tau background	-	-	-	30+10*%	30%	30%
WW, ZZ+jets background	15%	15%	15%	15%	15%	65%
$t\bar{t}$+jets 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%

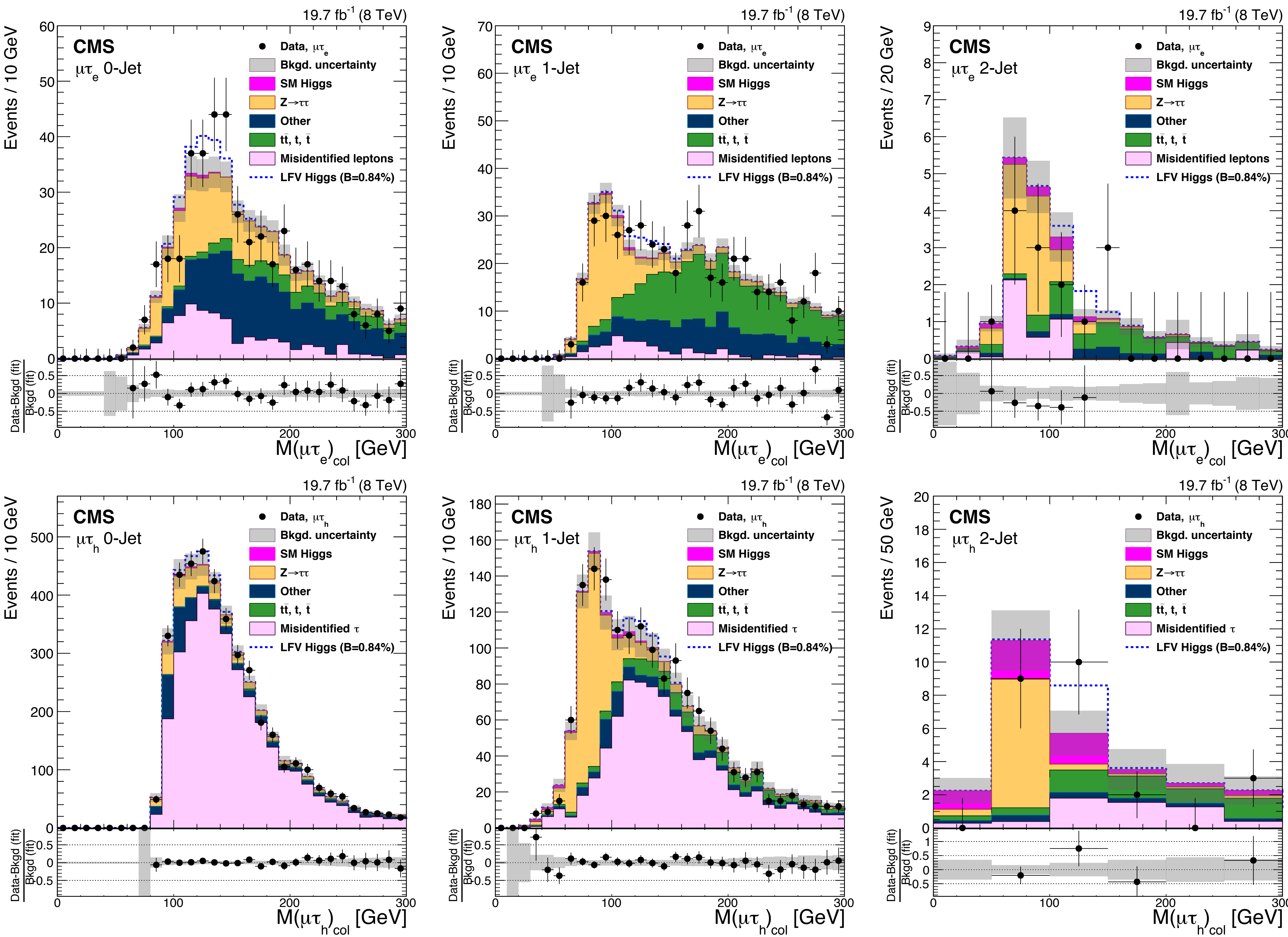
Uncertainty	Gluon-Gluon Fusion			Vector Boson Fusion		
	0-jet	1-jet	2-jet	0-jet	1-jet	2-jet
parton density function	+9.7%	+9.7%	+9.7%	+ 3.6%	+3.6%	+3.6%
renormalization scale	+8 %	+10 %	-30%	+4 %	+1.5%	+2%
underlying event/parton shower	+4%	-5%	-10%	+10%	0%	-1%

Systematic	$H \to \mu\tau_e$	$H \to \mu\tau_{had}$
Hadronic Tau energy scale	-	3%
Jet Energy scale	3-7%	3-7%
Unclustered energy scale	10%	10 %
$Z(\tau\tau)$ Bias	100%	-

signal region: M_{coll}

$H \to \mu\tau_e$

$H \to \mu\tau_h$

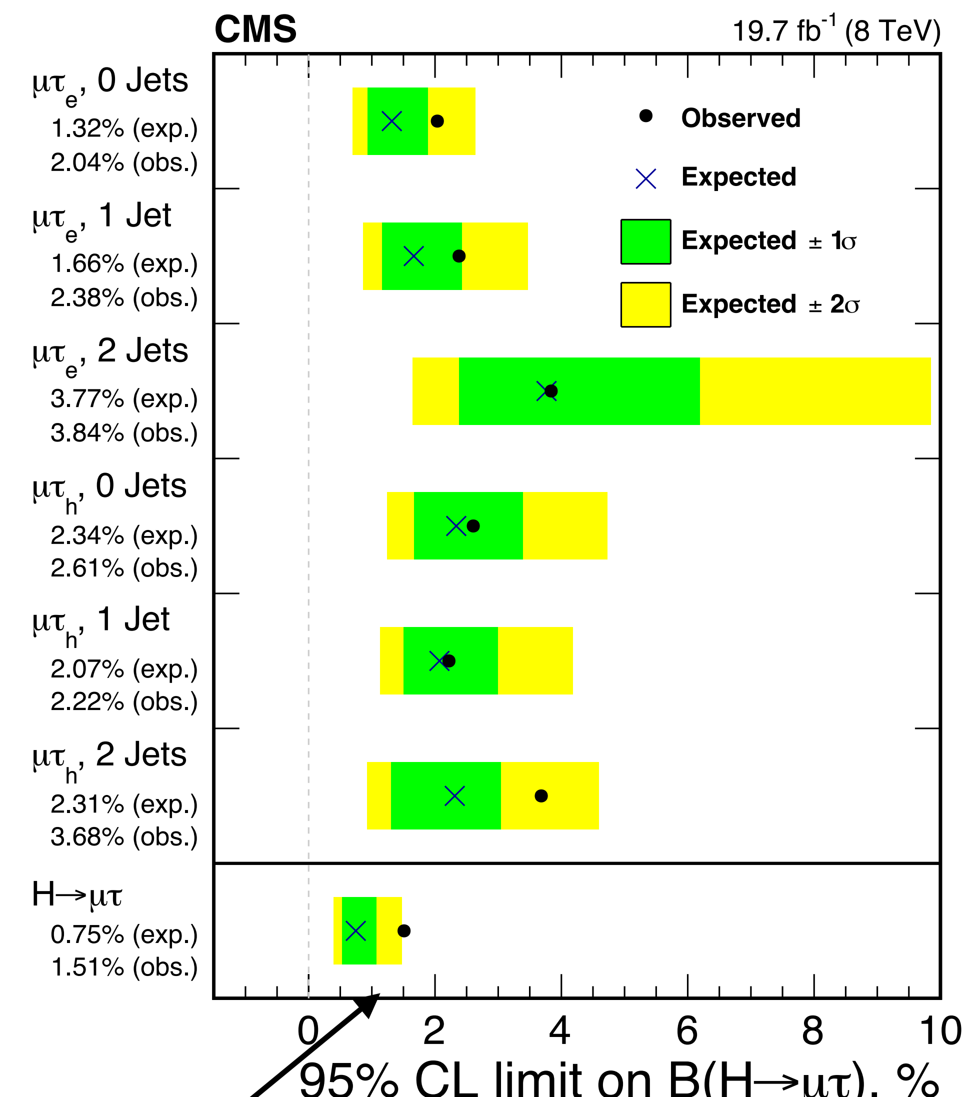


Limits on BR

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

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

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



Mild excess ~ 2.4 σ when combining all channels and production modes:
limit on BR(H→μτ) =1.57% (Expected 0.75%)

Limits on Yukawa coupling $Y_{\mu\tau}$

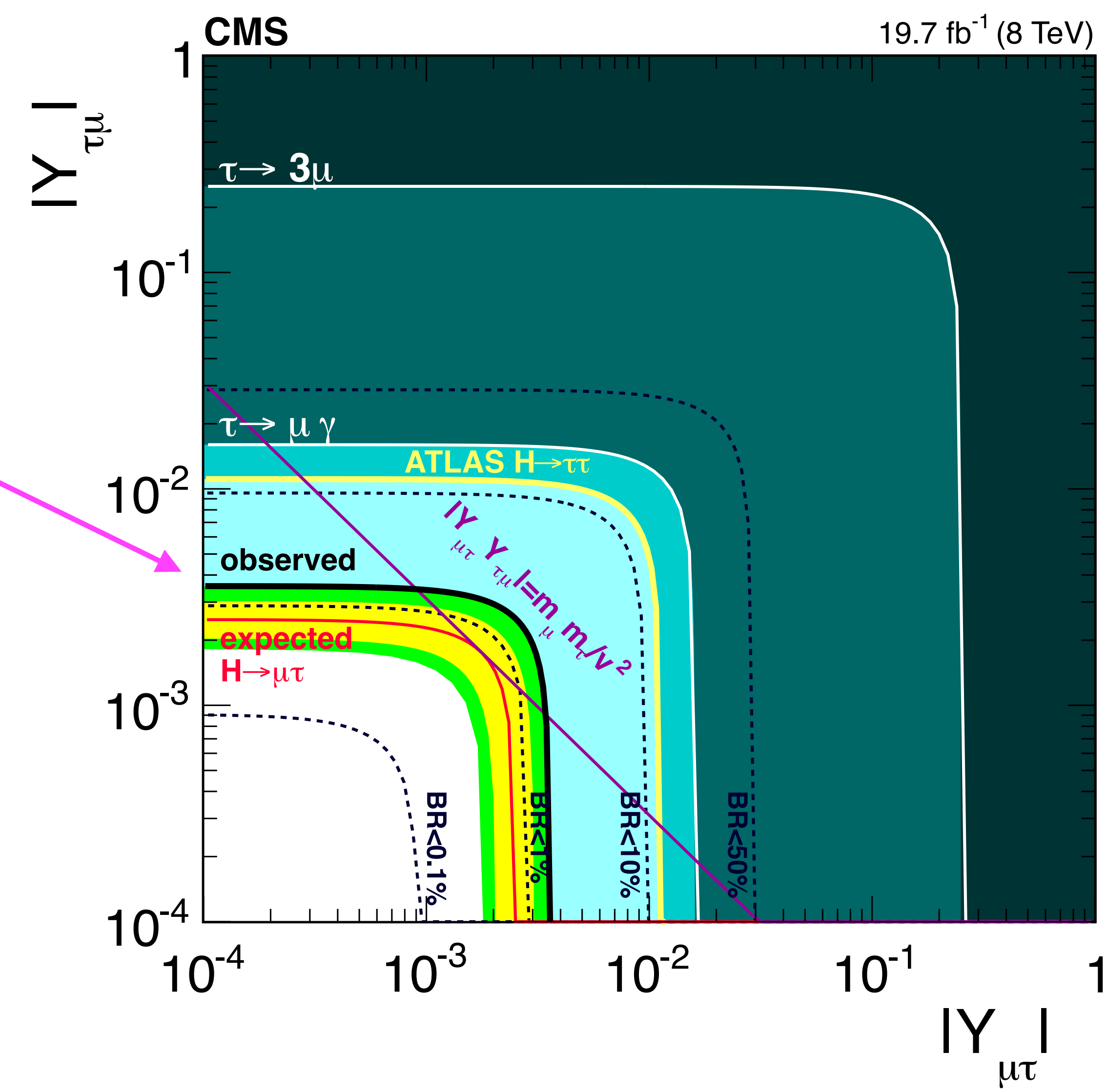
Interpretation of the constraint on $B(H \to \mu\tau)$ to LFV Yukawa coupling:

$$\Gamma(H \to l^\alpha l^\beta) = \frac{m_H}{8\pi}\left(|Y_{l^\beta l^\alpha}|^2 + |Y_{l^\alpha l^\beta}|^2\right)$$

$$BR(H \to \mu\tau) = \frac{\Gamma(H \to l^\alpha l^\beta)}{\Gamma(H \to l^\alpha l^\beta) + \Gamma_{SM}}$$

where Γ_{SM} = 4.1 MeV

$$\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 3.6 \times 10^{-3}$$



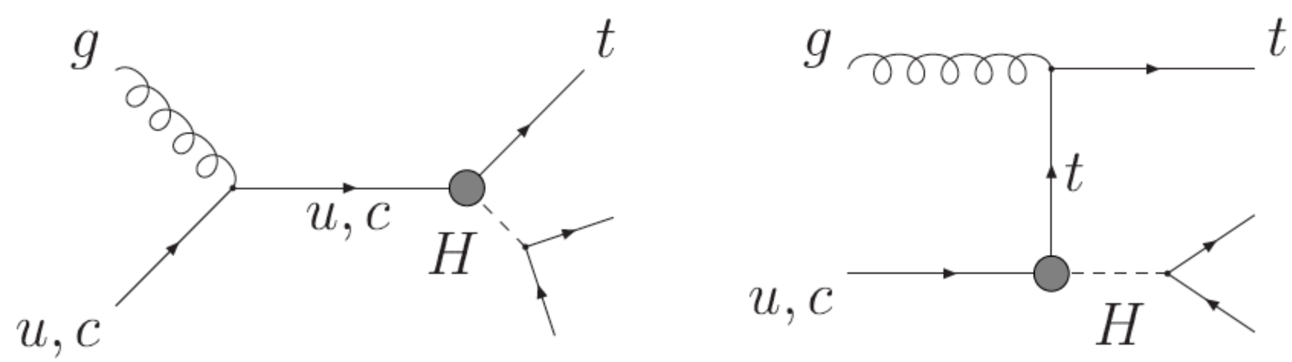
Other channels and prospect for Run2

- Other channels under approval for summer conferences
  - $H \rightarrow e\tau$ in muonic and hadronic tau decays. Same strategy. m_H=125 GeV
  - $H \rightarrow \mu e$. 110 GeV< m_H < 160 GeV
- Prospect for Run2
  - Larger background: top-related background cross sections grow faster than Higgs cross section.
  - Harsher pile up conditions
  - Ongoing studies…

	scale factor 13TeV/8TeV
H (ggf)	2.28
H (vbf)	2.38
$t\bar{t}$	3.25
t (t-channel)	2.56
t (tW-channel)	3.21

FCNC in t-H production

- Top flavour changing neutral current are suppressed in the SM
    - GIM suppression relaxed in models beyond the SM



$$\Gamma(t \to qH) = \frac{\alpha}{32 s_W^2} |g_{qt}|^2 m_t \left(1 - \frac{M_H^2}{m_t^2}\right)^2$$

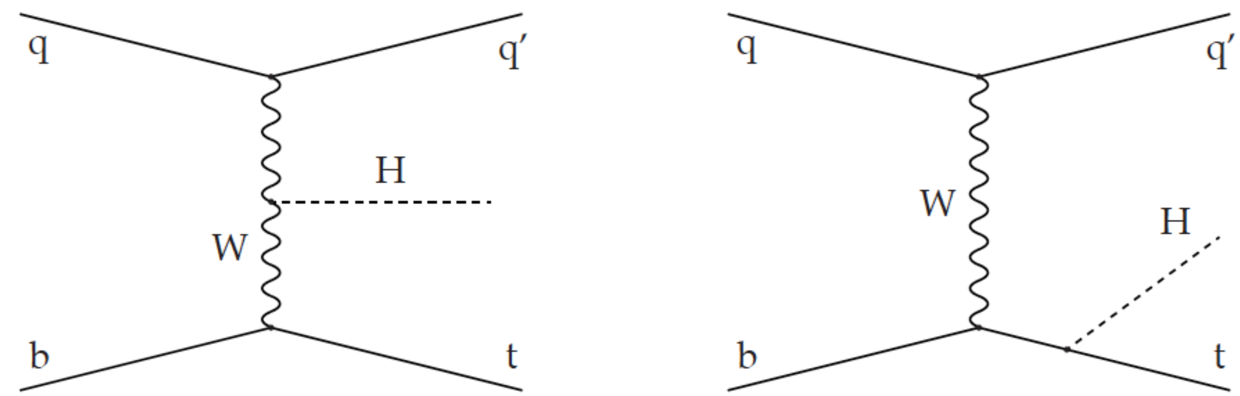
$$BR(t \to qH) = 3.88 \times 10^{-2} g_{qt}^2$$

from arxiv 0409342v4

FCNC in t-H production at CMS

- CMS searches for associate production of a single top quark and a Higgs Boson

- In the SM, as the couplings of the Higgs boson to the W boson and the top quark have opposite-sign:



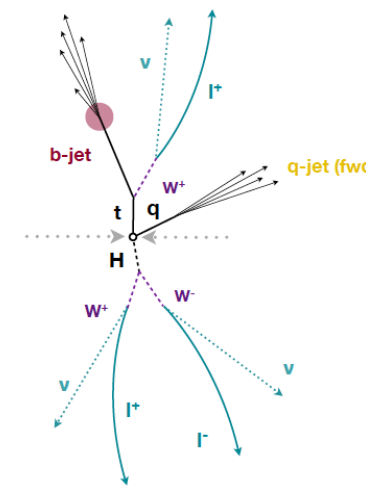
  - destructive interference: production cross section at NLO ~18fb

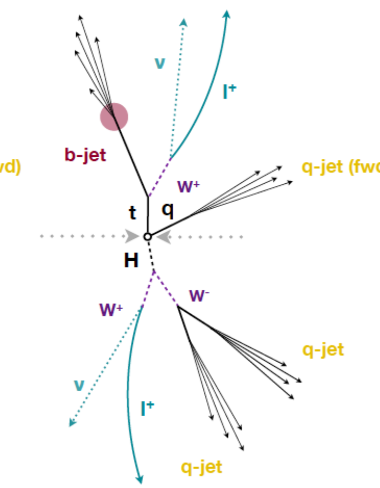
- A negative Higgs boson coupling to fermions is still allowed (but disfavoured) by global fits

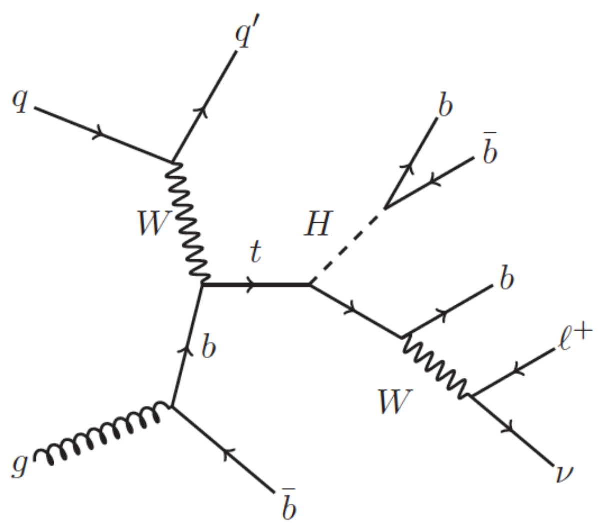
  - constructive interference: up to 15-fold increase of t-H production cross section

CMS t-H analyses

tHq in leptonic states: H→WW, H→ττ
- two categories: 3 leptons and 2 leptons same sign + 2 light quark jets from Ws
- HIG-14-026

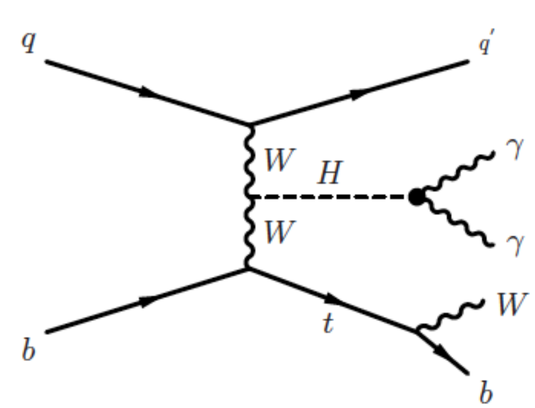


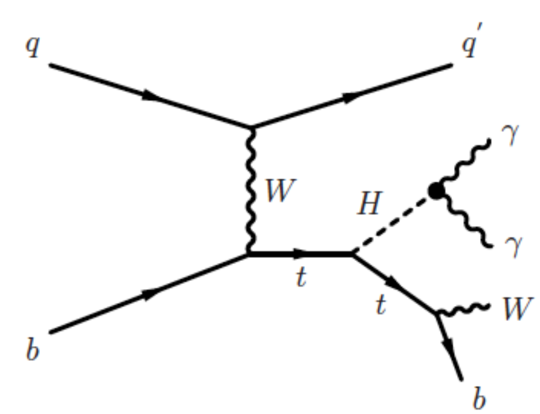




tHq with H→bb
- two categories: 3 or 4 b-jets
- HIG-14-001

tHq with H →γγ
HIG-14-015

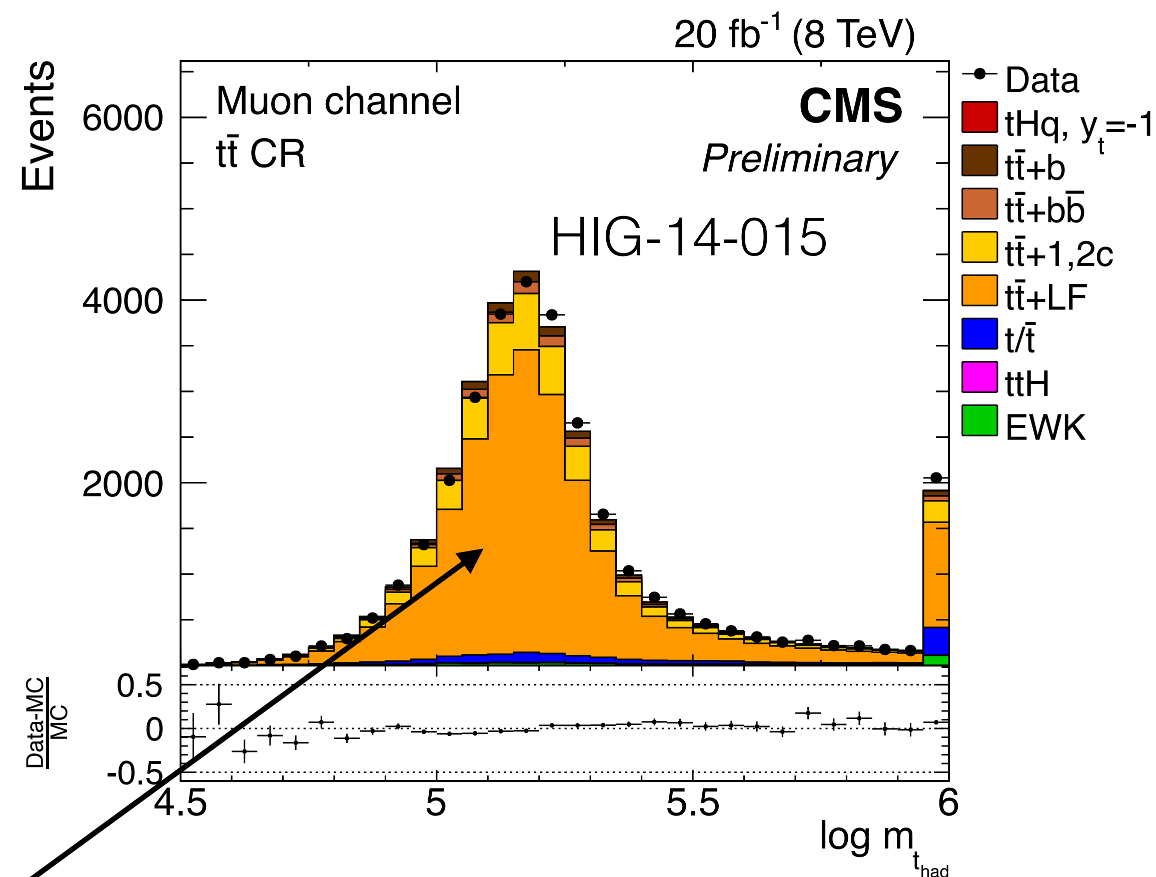




Backgrounds

tH(ll):
- $t\bar{t}$ and charge-mis-id evt from data
- $t\bar{t}H$ (PYTHIA)
- $t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}\gamma$, $t\bar{t}\gamma^*$, $t\bar{t}WW$, tbZ from MADGRAPH5
- WW, WZ, ZZ, $W^\pm W^\pm qq$, $W^\pm W^\pm$(DPI) from MADGRAPH5
- WWW,WWZ,WZZ from MADGRAPH5

Signal simulation:
- *5-flavour scheme,*
  MADGRAPH5 + PHYTIA6 with CTEQ6L1



tH(γγ):
- $t\bar{t}H$ from MC simulation (MADGRAPH5)
- WH, ZH from MC simulation (PHYTIA)
- γγ+jets, γ+jets from $m_{\gamma\gamma}$ sidebands
- tγγ, $t\bar{t}\gamma\gamma$ from $m_{\gamma\gamma}$ sidebands

Signal simuation:
- MADGRAPH5

tH(bb):
- $t\bar{t}$ from MC simulation, cross-checked with data
- $t\bar{t}H$ (PYTHIA)
- W+jets, Z/γ^* +jets from MC(MADGRAPH+PYTHIA)
- single-t (t, tW, s channels) from MC (POWHEG+PYTHIA)
- WW, WZ, ZZ from MC (PHYTHIA)
- QCD Multijet from data

Signal simulation:
- *4-flavour scheme,*
  MADGRAPH5 + PHYTIA6 (TAUOLA)

tH(ll): Yields and Systematics

Process	$\mu\mu$	$e\mu$	$\ell\ell\ell$
$W^{\pm}W^{\pm}qq$	4.60 ± 0.68	6.03 ± 0.85	–
WZ, WW, ZZ	5.47 ± 2.10	8.83 ± 3.25	1.19 ± 0.14
Rare SM bkg.	1.40 ± 0.68	2.57 ± 1.23	0.11 ± 0.03
$t\bar{t}\gamma^*$	0.50 ± 0.20	1.04 ± 0.42	–
$t\bar{t}\gamma$	0.09 ± 0.03	2.02 ± 0.60	–
$t\bar{t}Z$	2.23 ± 0.41	2.87 ± 0.50	2.21 ± 0.36
$t\bar{t}W^{\pm}$	10.18 ± 2.24	14.85 ± 3.32	3.03 ± 0.51
$t\bar{t}H$	2.26 ± 0.34	3.24 ± 0.47	1.52 ± 0.18
Charge Mis-ID	–	6.96 ± 1.76	–
Non-Prompt	33.34 ± 8.34	63.74 ± 12.46	31.44 ± 6.52
Total Background	$\mathbf{60.07 \pm 8.95}$	$\mathbf{112.13 \pm 13.53}$	$\mathbf{39.50 \pm 6.55}$
$tH(\tau\tau)W$	0.10 ± 0.12	0.13 ± 0.14	0.12 ± 0.12
tH(WW)W	0.28 ± 0.29	0.47 ± 0.48	0.35 ± 0.35
$tH(\tau\tau)q$	0.59 ± 0.61	0.90 ± 0.91	0.56 ± 0.58
tH(WW)q	2.55 ± 2.62	3.73 ± 3.84	1.73 ± 1.80
Total Signal	$\mathbf{3.53 \pm 2.71}$	$\mathbf{5.22 \pm 3.98}$	$\mathbf{2.76 \pm 1.93}$
Data	**66**	**117**	**42**

- Multivariate analyses
  - tH(ll):
    - 3 variable categories: forward activity, jet and bjet multeplicity, lepton kinematic and charge

Source of uncertainty	Type	Exclusive source (%)	Removal (%)
Luminosity	rate	< 1	< 1
Pileup	rate	< 1	< 1
Lepton trigger efficiency	rate	< 1	< 1
Lepton selection efficiencies	rate	< 1	< 1
Electron energy scale	shape	< 1	< 1
Jet energy corrections	shape	< 1	< 1
b-tagging efficiencies	shape	< 1	< 1
Flavour Scheme	rate	2	1
Higgs branching fractions	rate	< 1	< 1
Renormalization/factorization scale	rate	< 1	< 1
Parton density functions (pdf)	rate	< 1	< 1
Irreducible background normalization	rate	< 1	< 1
μ fake-rate normalization (SS)	rate	26	19
e fake-rate normalization (SS)	rate	12	5
μ fake-rate leptons shape (SS)	shape	< 1	1
e fake-rate leptons shape (SS)	shape	< 1	2
Non-prompt closure test (3ℓ)	rate	3	3
QCD control region variation for fake-rate (3ℓ)	shape	1	< 1
Fake-rate variation within stat. uncert. (3ℓ)	shape	1	< 1
Charge misidentification (SS)	rate	< 1	< 1
Stat. uncert. for non-prompt leptons (3ℓ)	shape	2	3
Stat. uncert. for non-prompt leptons (SS)	shape	4	3

- most important systematics: fake rate normalisation unc.

tH(bb): Yields and Systematics

3 b-jets

Process	Muon channel	Electron channel
$t\bar{t}$	1058±5	718±4
Single top	39±3	27±3
Electroweak	17^{+7}_{-5}	11±7
$t\bar{t}H$	12.87±0.17	9.35±0.15
Total background	1128±9	767±10
tHq, $y_t = -1$	7.54±0.03	5.15±0.02
S/B ratio	0.7%	0.7%

4 b-jets

Process	Muon channel	Electron channel
$t\bar{t}$	29.1±0.8	19.8±0.7
Single top	$1.1^{+0.8}_{-0.6}$	1.2±1.0
Electroweak	4^{+6}_{-4}	5^{+6}_{-4}
$t\bar{t}H$	1.72±0.06	1.43±0.05
Total background	37^{+6}_{-4}	29^{+7}_{-4}
tHq, $y_t = -1$	0.835±0.010	0.580±0.009
S/B ratio	2.3%	2.0%

cross section uncertainties

Process	pdf			QCD Scale			
	gg	$q\bar{q}$	qg	$t\bar{t}$	V	VV	$t\bar{t}H$
tHq			2%				
$t\bar{t}H$	9%						12.5%
$t\bar{t}$	2.6%			3%			
Single top			4.6%	2%			
W+jets		4.8%			1.3%		
Z+jets		4.2%			1.2%		
Dibosons						3.5%	

- Multivariate analyses
  - discriminating variables depends on the hypothesis (signal or ttbar) are based on f b-jets and lepton c charge, light or b jets and top kinematics, charge of t decay product
  - most important systematics: btag and luminosity, theoretical uncertainties

Source	Type	impact as exclusive source on final limit [%]	improvement of final limit after removal [%]
JES	shape	17	3
JER	shape	< 1	< 1
BTag light flavor	shape	13	< 1
BTag heavy flavor	shape	17	< 1
Pile up	normalization	< 1	< 1
Unclustered energy	shape	3	1
Lepton efficiency	normalization	5	< 1
Luminosity	normalization	10	< 1
Cross section (PDF)	normalization	8	< 1
Cross section (Scale)	normalization	9	< 1
MC Bin-by-Bin unc.	shape	< 1	< 1
Q^2 scale ($tHq + t\bar{t}$)	shape	20	4
Matching	shape	2	2
Top p_T reweighting	shape	19	2
$t\bar{t}$ HF rates (b)	normalization	13	< 1
$t\bar{t}$ HF rates ($b\bar{b}$)	normalization	15	< 1
$t\bar{t}$ HF rates (c / $c\bar{c}$)	normalization	13	1

tH(γγ): Yields and Systematics

- cut and cout analysis:
  non resonant background shapes extracted from control regions,
  resonant background from MC

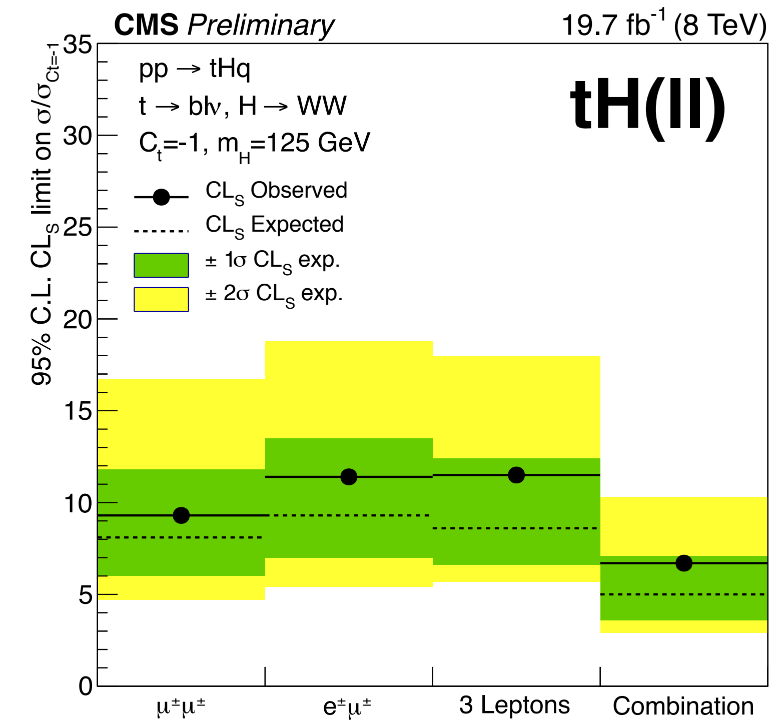
Process	Yield
tHq ($C_t = -1$)	0.67
$t\bar{t}$H	0.03 + 0.05†
VH	0.01 + 0.01†
other H	0

	tHq	$t\bar{t}$H	VH	Continuous BG
Luminosity	±2.6%	±2.6%	±2.6%	-
PDF	+3.1/-2.5 %	±8%	±11%	-
QCD Scale	+4.8/-4.3 %	+11/-14 %	±2.3%	-
Signal Model	±5.5%	-	-	-
Photon Energy Resolution	+4/-2 %	+4/-2 %	+4/-2 %	-
Photon Energy Scale	+1/-4 %	+1/-4 %	+1/-4 %	-
Photon ID Efficiency	±2%	±2%	±2%	-
Vertex Efficiency	±0.1%	±0.1%	±0.1%	-
HLT	$<$ 0.1%	$<$ 0.1%	$<$ 0.1%	-
JEC	±1.5%	+3/-5 %	±8%	-
JER	±0.5%	±3%	+8/-0 %	-
b-tagging	±2%	±1.5%	±0.1%	-
PU ID	±2%	±0.5%	±2%	-
Lepton Reconstruction	±1%	±1%	±1%	-
BG shape	-	-	-	33%

Limits

- **tH(ll):**

Channel	Observed	Expected	68% prob. band	95% prob. band
SS $\mu\mu$	9.3	8.1	[6.0, 11.8]	[4.7, 16.7]
SS $e\mu$	11.4	9.3	[7.0, 13.5]	[5.4, 18.8]
3ℓ	11.5	8.6	[6.6, 12.4]	[5.7, 18.0]
combined	6.7	5.0	[3.6, 7.1]	[2.9, 10.3]



- **tH(bb):**
  - 1.1 σ upward deviation

	Expected	Observed
MC-driven	$\mathbf{5.14^{+2.14}_{-1.44}}$	**7.57**
Data-driven cross-check	$6.24^{+2.26}_{-1.71}$	6.95

- **tH(γγ):**
  - no events observed
  - both expected and observed limits $\sigma(tH) < 4.1\ \sigma_{Ct=-1}(tH)$

Working on the combination of the three channels

Summary

- CMS performed searches for LFV Higgs decays and indirectly FCNC
  - interesting results
    - LFV: $H \rightarrow e\tau$, $H \rightarrow e\mu$ results coming soon
    - FCNC: combination coming soon
  - Run 2:
    - LFV Higgs decay in 3 channels
    - tH(bb), tH(ll)

Non-prompt analyses