Dark sectors and enhanced $h \to \tau\mu$ transitions

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May 12, 2017

based on arXiv:1701:08767 [hep-ph] w. J. Zupan
seeded by arXiv:1610.08060 [hep-ph] w. P. Tanedo and A. Kwa

Motivation - Flavor in the Leptonic Sector

In the SM:

$$y_{ij}^{\ell}\bar{L}_i\tilde{H}E_j + \frac{c_{ij}^{\nu}}{\Lambda^2}L_iHL_jH \quad \overset{EWSB}{\Longrightarrow} \quad m_i^{\ell}\delta_{ij}\left(1+\frac{h}{v}\right)\bar{\ell}_i\ell_j + m_{ij}^{\nu}\nu_i\nu_j$$

Higgs Physics drives flavor structure

- Flavor puzzle:

$$(y_e,\ y_\mu,\ y_\tau) \approx 10^{(-6,-4,-2)}, \quad m_v - \text{tiny}, \quad U_{PMNS} - \mathcal{O}(1)\ \text{mix}$$

- @LHC - can probe underlying flavor theory $\Longrightarrow$ **New Physics**

Leptonic Flavor Anomalies

Several Hints of (Flavor) New Physics:

- Higgs LFV decays: $h \to \tau\mu$
- $(g-2)_\mu$
- Proton radius
- B leptonic decay ratios

$\Longrightarrow$

$$BR(h \to \tau^\pm \mu^\mp)\Big|_{\sqrt{s}=8\ \mathrm{TeV}} \quad \text{in } \%$$

CMS	0.89 ± 0.39
ATLAS	τ_h 0.53 ± 0.51 τ_e 0.77 ± 0.62

CMS result $\sim 2.4\sigma$

τ Physics

The dominant τ decay modes

Leptonic:

$$\tau \to \ell \nu_\tau \bar{\nu}_\ell \qquad \sim 35\%$$

Hadronic:

$$\tau \to \nu_\tau \pi$$
$$\tau \to \nu_\tau \pi\pi \qquad \sim 65\%$$
$$\tau \to \nu_\tau \pi\pi\pi$$

inherent Missing-Energy signature

τ's @ The LHC

Trigger on the visible-τ decay products

- leptonic, $\tau_e \implies$ lepton triggers: $\sim p_T > 20$ GeV
- hadronic, $\tau_h \implies$ 1-prong, 3-prong: "hadron + strips"

fully reconstructs τ_{vis}

but

partially reconstructs τ_{inv} $(1\nu,\ \text{or}\ 2\nu)$

τ-LHC searches are $\not{E}_T$-inclusive

τ's @ The LHC

τ Reconstruction:

- **The collinear approximation**

Ellis, Hinchliffe, Soldate, & van der Bij (1988)

$$\text{boosted } \tau : \quad \tau_{vis} \parallel \tau_{inv} \implies \begin{cases} \vec{p}_{\tau_{inv}} = \hat{p}_{\tau_{vis}} \left(\vec{p}_{\tau_{vis}} \cdot \vec{\not{E}}_T \right) \\ p^2_{\tau_{inv}} = 0 \end{cases}$$

- **The Missing Mass Calculator** (MMC) / **SVFIT**

Elagin, Murat, Pranko, & Safonov

Bianchini, Conway, Friis, & Veelken

CMS $h \to \tau\mu$

In $h \to \tau\mu$ CMS uses

$$m^{\mathrm{Coll}} = \sqrt{(p_\mu + p_{\tau_{vis}} + p_{\nu' s})^2}$$

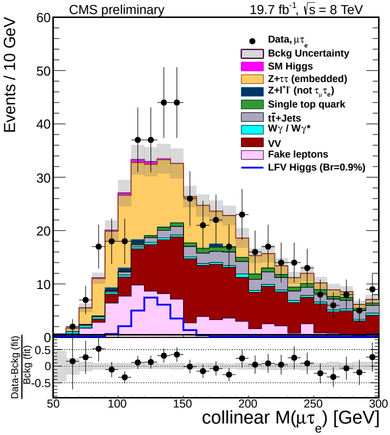
SR: $100\ \mathrm{GeV} < \mathrm{m}^{\mathrm{Coll}} < 150\ \mathrm{GeV}$, with cuts

Variable	$\mathrm{H} \to \mu\tau_e$			$\mathrm{H} \to \mu\tau_h$		
[GeV]	0-jet	1-jet	2-jet	0-jet	1-jet	2-jet
$p_T^\mu >$	50	45	25	45	35	30
$p_T^e >$	10	10	10	—	—	—
$p_T^{\tau_h} >$	—	—	—	35	40	40
$M_T^e <$	65	65	25	—	—	—
$M_T^\mu >$	50	40	15	—	—	—
$M_T^{\tau_h} <$	—	—	—	50	35	35
[radians]						
$\Delta\phi_{\vec{p}_T^\mu - \vec{p}_T^{\tau_h}} >$	—	—	—	2.7	—	—
$\Delta\phi_{\vec{p}_T^e - \vec{E}_T^{miss}} <$	0.5	0.5	0.3	—	—	—
$\Delta\phi_{\vec{p}_T^e - \vec{p}_T^\mu} >$	2.7	1.0	—	—	—	—

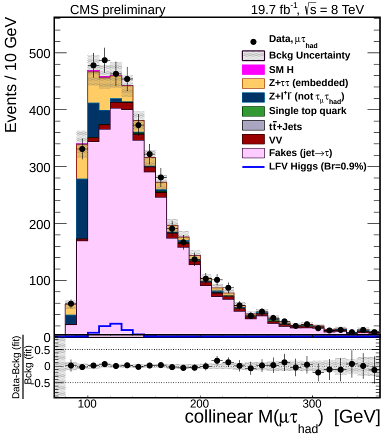
from CMS-HIG-14-005

CMS $h \to \tau\mu$

$\underline{\tau_e + 0j}$



$\underline{\tau_h + 0j}$



from CMS-HIG-14-005

fit 0, 1, & 2 jet channels $\Rightarrow BR(h \to \tau\mu) = 0.89\%$

LFV Higgs Couplings

Simplest SM-extensions (w. only $h \to EWSB$):

$$\mathcal{L} \supset Y^{\ell}_{ij} \bar{L}_i H E_j + \frac{\lambda_{ij}}{\Lambda^2} \bar{L}_i H E_j \left(H^\dagger H\right)$$

Kopp, Harnik & Zupan

implies

$$m = \frac{v}{\sqrt{2}} V_L \left(Y + \frac{v^2}{2\Lambda^2} \lambda \right) V_R^\dagger, \qquad y = \frac{1}{\sqrt{2}} V_L \left(Y + 3 \frac{v^2}{2\Lambda^2} \lambda \right) V_R^\dagger$$

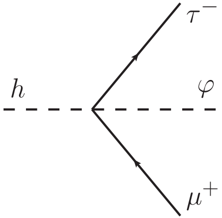
Then in the mass basis

$$\boxed{y_{ij} = \frac{m_i}{v} \delta_{ij} + \frac{v^2}{\sqrt{2}\Lambda^2} V_L \lambda V_R^\dagger}$$

Conspiracy and Dark Matter

Additional $\not{E}_T$ source: new light complex scalar φ

$$\frac{1}{\Lambda}\frac{h}{\sqrt{2}}\bar{\tau}_L\mu_R\varphi, \quad \text{or} \quad \frac{1}{\Lambda}\frac{h}{\sqrt{2}}\bar{\mu}_L\tau_R\varphi^*$$



2- & 3-body BR's are comparable

$$\frac{Br(h \to \tau^\pm\mu^\mp\varphi\ /\varphi^*)}{Br(h \to \tau^+\tau^-)} \simeq \frac{1}{6}\left(\frac{m_h}{4\pi\Lambda y_\tau}\right)^2 = 0.66 \times \left(\frac{500\mathrm{GeV}}{\Lambda}\right)^2\left(\frac{0.01}{y_\tau}\right)^2$$

Conspiracy and Dark Matter

In $h \to \tau\mu$: $\not{E}_T \supset 1 \text{ or } 2\ \nu'\text{s}$

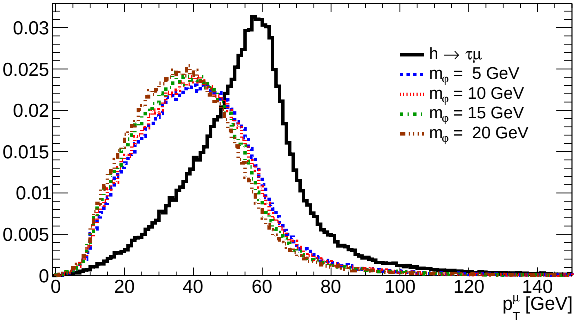
In $h \to \tau\mu\varphi$: $\not{E}_T \supset 1 \text{ or } 2\ \nu'\text{s} + \varphi$

φ is captured by reconstructing m^{Coll}

Conspiracy and Dark Matter

Can $h \to \mu\tau\phi$ mimic $h \to \mu\tau$:

- softer decay products



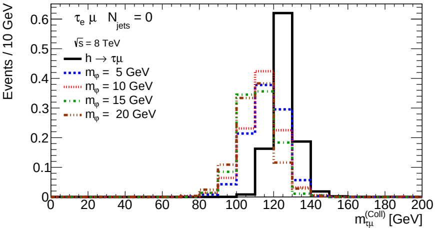
- angularly denser

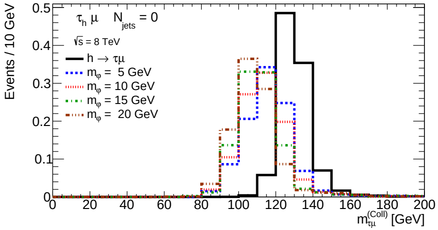
search acceptance reduced

Conspiracy and Dark Matter

Can $h \to \mu\tau\phi$ mimic $h \to \mu\tau$:

- Broadening and shifting of $m_{\tau\mu}^{\mathrm{Coll}}$, (worry about $Z \to \tau_h\mu\Big|_{MMC}$)





(with similar plots for 1 & 2 jets)

Recast Results

For $\Lambda = 1$ TeV:

Decay	m_φ [GeV]	Br	Coupling
$h \to \tau\mu$	–	3.6×10^{-3}	$Y_{23} = 2.4 \times 10^{-3}$
$h \to \tau\mu\varphi$	5	1.9×10^{-2}	$c_{23} = 1.4$
$h \to \tau\mu\varphi$	10	2.6×10^{-2}	$c_{23} = 1.7$
$h \to \tau\mu\varphi$	15	3.4×10^{-2}	$c_{23} = 2.1$
$h \to \tau\mu\varphi$	20	4.8×10^{-2}	$c_{23} = 2.7$

Reasonable agreement with CMS: $Y_{\tau\mu} = (3.7 \pm 0.8) \cdot 10^{-3}$

Recast Results - Upshot

To account for $h \to \tau\mu$:

- $m_\varphi \sim \mathcal{O}(10\ \mathrm{GeV})$ - light(ish) New Physics
- $c_{23} \sim \mathcal{O}(1)$ - very different than the SM Yukawa structure
- φ invisibly decays $\Longrightarrow$ Dark Matter

Model Building

The model: $\varphi =$ mediator to flavorful Dark-Sector

$$\mathcal{L}_{\rm vis.} \supset -y^{\ell}_{ij}\bar{L}_i H E_j + {\rm h.c.}$$

$$\mathcal{L}_{\rm vis-med.} \supset \frac{c_{ij}}{\Lambda}\bar{L}_i H E_j \varphi + \frac{c'_{ij}}{\Lambda}\bar{L}_i H E_j \varphi^* + {\rm h.c.}$$

$$\mathcal{L}_{\rm dark} \supset g^{L}_{ab}\varphi\,\bar{\chi}_a P_L \chi_b + g^{R}_{ab}\varphi\,\bar{\chi}_a P_R \chi_b + {\rm h.c.}, \qquad a,b = 1,2.$$

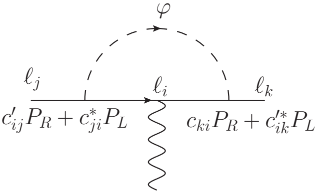
A flavor theory at $\Lambda = 1~{\rm TeV}$ **determines all couplings**

Model Building - Feasibility

Account for both Y, c, c', and g^L, g^R ?

$$\mathcal{L}^{EWSB}_{\text{vis-med.}} \supset \frac{v}{\sqrt{2}\Lambda}\left[\bar{\ell}_i\left(c_{ij}P_R + c'^*_{ji}P_L\right)\ell_j\varphi + \bar{\ell}_i\left(c'_{ij}P_R + c^*_{ji}P_L\right)\ell_j\varphi^*\right]$$

- mediate tree-level LFV processes
- induces LFV dipoles



$$\mathcal{L}_{\text{dipole}} \supset \frac{e}{8\pi^2} m_j\, \bar{\ell}_k \sigma^{\mu\nu}\left(c^L_{kj}P_L + c^R_{kj}P_R\right)\ell_j F_{\mu\nu}$$

Constraints

Flavor Violating constraints:

- $\ell_j \to \ell_k \gamma$
- $\ell_j \text{ Nuc} \to \ell_{\rm k} \text{ Nuc}$
- $\ell_j \to \ell_i \ell_m \bar{\ell}_k$
- $\ell_j \to \ell_i \ell_m \bar{\ell}_k \nu \bar{\nu}$

Flavor Conserving constraints:

- Δa_{ℓ_j}
- $Z \to \ell_i \bar{\ell}_i$ Universality
- FB-asymmetry

Other constraints:

- $Z \to \ell_j \bar{\ell}_m \varphi$
- $Z \to \text{inv}(2\varphi)$
- $\ell_j \to \ell_i \chi \bar{\chi}$
- $\ell \to 3\ell\varphi/\varphi^*$

Symmetry Arguments

SM lepton flavor symmetry

$$U(1)_e \otimes U(1)_\mu \otimes U(1)_\mu$$

Naively broken by c, c' couplings
Unless,

Turn on a single Off-Diagonal coupling, $c_{\mu\tau}$

Then break to residual subgroup

$$U(1)_e \otimes U(1)_{\mu-\tau}$$

Symmetry Arguments

Now φ has charge 2:

- Suppressed CLFV transitions (arise at higher-loop)
- Still contribute to flavor diagonal observables

Can we build such a Flavor Theory realization at $\Lambda = 1\ \mathrm{TeV}$?

Non-trivial, need $y,\ c_{\mu\tau}$ + Symmetry Structure

Froggatt-Nielsen 101

$U(1)$ flavor symmetry $\Longrightarrow$ higher-dim op's $\Longrightarrow$ Flavorful couplings

$$\mathcal{L}_{\text{vis.}} \supset -\alpha_{ij}\bar{L}_i H E_j \left(\frac{S \text{ or } S^*}{M}\right)^{|n_{ij}^Y|} .$$

- $\alpha_{ij} \sim \mathcal{O}(1)$
- S - complex is a scalar SM-signlet, $[S]_Q = -1$
- $n_{ij}^Y = [\bar{L}_i]_Q + [E_j]_Q + [H]_Q$, $\quad \begin{cases} n_{ij}^Y > 0 \Rightarrow S \\ n_{ij}^Y < 0 \Rightarrow S^* \end{cases}$
- $\lambda = \frac{\langle S \rangle}{M} \simeq 0.2$ (Cabibo angle)

Then

$$\boxed{Y_{ij}^{\ell} = \alpha_{ij}\lambda^{|n_{ij}^Y|}}$$

Froggatt-Nielsen 101 + New Scalar

If φ is light we can also expect

$$\mathcal{L}_{\text{med.}} \supset \beta_{ij} \bar{L}_i H E_j \left(\frac{S \text{ or } S^*}{M} \right)^{|n^c_{ij}|} \frac{\varphi}{\Lambda} + \beta'_{ij} \bar{L}_i H E_j \left(\frac{S \text{ or } S^*}{M} \right)^{|n^{c'}_{ij}|} \frac{\varphi^*}{\Lambda}$$

leading to

$$\mathcal{L}_{\text{vis-med.}} \supset \frac{c_{ij}}{\Lambda} \bar{L}_i H E_j \varphi + \frac{c'_{ij}}{\Lambda} \bar{L}_i H E_j \varphi^*$$

with

$$c_{ij} \sim \lambda^{|n^c_{ij}|}, \qquad c'_{ij} \sim \lambda^{|n^{c'}_{ij}|}$$

Similarly, $\chi - \varphi$ interactions can be generated and chosen to be dominant.

The Model

$$
\begin{aligned}
[\bar{L}_1]_Q &= (7,1), & [E_1]_Q &= (-7,7),\\
[\bar{L}_2]_Q &= (-6,-2), & [E_2]_Q &= (6,-3),\\
[\bar{L}_3]_Q &= (-2,-4), & [E_3]_Q &= (1,6),\\
[H]_Q &= (0,0), & [\varphi]_Q &= (5,-4).
\end{aligned}
$$

These are consistent with the lepton mass eigenvalues

$$\{m_e,\ m_\mu,\ m_\tau\} \sim \frac{v}{\sqrt{2}}\{\lambda^8, \lambda^5, \lambda^3\},$$

$$c \sim \begin{pmatrix} \lambda^9 & \lambda^{18} & \lambda^{10} \\ \lambda^9 & \lambda^8 & 1 \\ \lambda^5 & \lambda^{14} & \lambda^6 \end{pmatrix}, \quad c' \sim \begin{pmatrix} \lambda^{17} & \lambda^{10} & \lambda^{14} \\ \lambda^{19} & \lambda^6 & \lambda^{14} \\ \lambda^{17} & \lambda^4 & \lambda^{12} \end{pmatrix}.$$

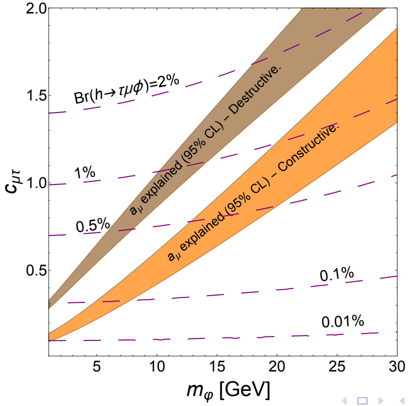
Flavor Checklist

LFV Process	Present Bound	Our Model
Radiative Decays		
$\mathrm{Br}(\mu^+ \to e^+\gamma)$	5.7×10^{-13} [?]	3.1×10^{-17}
$\mathrm{Br}(\tau^\pm \to e^\pm\gamma)$	3.3×10^{-8} [?]	1.1×10^{-16}
$\mathrm{Br}(\tau^\pm \to \mu^\pm\gamma)$	4.4×10^{-8} [?]	1.8×10^{-11}
$\mu \to e$ Conversion in Nuclei		
$\Gamma(\mu \to e)_{\mathrm{Au}}/\Gamma_{\mathrm{capture\,Au}}$	7×10^{-13} at 90% CL [?]	1.2×10^{-19}
3-Body Decays		
$\mathrm{Br}(\mu^+ \to e^+e^+e^-)$	1.0×10^{-12}[?]	D 1.9×10^{-19}
$\mathrm{Br}(\tau^- \to \mu^-\mu^+\mu^-)$	2.1×10^{-8}[?]	T 1.4×10^{-9}
$\mathrm{Br}(\tau^- \to e^-e^+e^-)$	2.7×10^{-8}[?]	D 1.1×10^{-18}
$\mathrm{Br}(\tau^- \to e^-\mu^+\mu^-)$	2.7×10^{-8}[?]	T 1.9×10^{-13}
$\mathrm{Br}(\tau^- \to \mu^-e^+e^-)$	1.8×10^{-8}[?]	D 1.8×10^{-13}; T 1.9×10^{-13}
$\mathrm{Br}(\tau^- \to e^+\mu^-\mu^-)$	1.7×10^{-8}[?]	T 4.9×10^{-26}
$\mathrm{Br}(\tau^- \to \mu^+e^-e^-)$	1.5×10^{-8}[?]	T 2.1×10^{-27}
Muon $g-2$		
Δa_μ	$288(80) \times 10^{-11}$ [?]	4.3×10^{-9}

$(g-2)_\mu$

The anomalous magnetic moment we express as

$$a_\mu = \frac{m_\mu}{16\pi^2}\int_0^1 dx(1-x)^2 \frac{x m_\mu |c_{23}|^2 + m_\tau 2Re\{c_{23}c_{32}^*\}}{x m_\varphi^2 + (1-x)m_\tau^2 - x(1-x)m_\mu^2},$$



Conclusions

- Searches with τ signatures at the LHC are $\not{E}_T$-inclusive, and are therefore sensitive to additional invisible particles in the event
- Interestingly, an invisibly decaying $\mathcal{O}(10\ \mathrm{GeV})$ scalar with $\mathcal{O}(1)$ $\tau\mu$ couplings can account for the observed CMS-8TeV $h \to \tau\mu$ excess
- Surprisingly, the $(g-2)_\mu$ anomaly can also be accounted for this mass and coupling range
- A TeV-scale theory of flavor can generate the SM Leptonic Yukawas, as well as the couplings which account for the excess
- Low-energy constraints may be avoid, if the couplings exhibit a residual global symmetry structure $U(1)_e \otimes U(1)_\mu \otimes U(1)_\tau \to U(1)_e \otimes U(1)_{\tau-\mu}$

Thank you for your attention

Backup Slides

$(g-2)_\mu$

The anomalous magnetic moment we express as

$$a_{\ell_j} = \frac{m_j}{16\pi^2} \sum_i \int_0^1 dx (1-x)^2 \frac{x m_j S_i^{(j)} + m_i P_i^{(j)}}{x m_\varphi^2 + (1-x) m_i^2 - x(1-x) m_j^2},$$

where

$$\begin{aligned} S_i^{(j)} &= \frac{v^2}{2\Lambda^2} \left(c_{ij}^* c_{ij} + c_{ij}'^* c_{ij}' + c_{ji}^* c_{ji} + c_{ji}'^* c_{ji}' \right), \\ P_i^{(j)} &= \frac{v^2}{2\Lambda^2} \left(c_{ji}'^* c_{ij} + c_{ij}^* c_{ji}' + c_{ij}'^* c_{ji} + c_{ji}^* c_{ij}' \right). \end{aligned}$$

The Model - Flavor Basis

The flavor dependent couplings in the flavor-basis are

$$Y^\ell \sim \begin{pmatrix} \lambda^8 & \lambda^{15} & \lambda^{15} \\ \lambda^{18} & \lambda^5 & \lambda^9 \\ \lambda^{12} & \lambda^{11} & \lambda^3 \end{pmatrix},$$

$$c \sim \begin{pmatrix} \lambda^9 & \lambda^{24} & \lambda^{16} \\ \lambda^9 & \lambda^{14} & 1 \\ \lambda^5 & \lambda^{20} & \lambda^6 \end{pmatrix}, \quad c' \sim \begin{pmatrix} \lambda^{17} & \lambda^{10} & \lambda^{14} \\ \lambda^{27} & \lambda^6 & \lambda^{18} \\ \lambda^{21} & \lambda^4 & \lambda^{12} \end{pmatrix}.$$

generate the rotation matrices

$$V_{L_L} \sim \begin{pmatrix} 1 & \lambda^{10} & \lambda^{12} \\ \lambda^{10} & 1 & \lambda^6 \\ \lambda^{12} & \lambda^6 & 1 \end{pmatrix}, \qquad V_{E_R} \sim \begin{pmatrix} 1 & \lambda^{13} & \lambda^9 \\ \lambda^{13} & 1 & \lambda^8 \\ \lambda^9 & \lambda^8 & 1 \end{pmatrix}$$

CMS $h \to \tau\mu$

event yields (minor differences between CDS and arXiv versions)

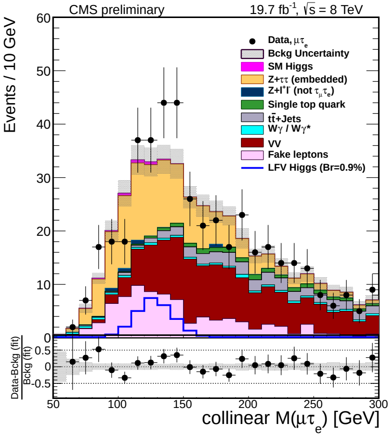
Sample	$H \to \mu\tau_{had}$			$H \to \mu\tau_e$		
	0-jet	1-jet	2-jet	0-jet	1-jet	2-jet
Fakes	1858.1 ± 558.8	362.9 ± 110.0	0.5 ± 0.5	41.5 ± 17.3	16.1 ± 6.8	1.1 ± 0.7
$Z \to \tau\tau$	198.8 ± 11.0	50.5 ± 3.5	0.4 ± 0.2	65.0 ± 3.0	38.6 ± 2.0	1.3 ± 0.2
ZZ, WW	47.0 ± 8.0	14.6 ± 2.6	0.3 ± 0.2	40.8 ± 6.6	21.2 ± 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

from CMS-HIG-14-005

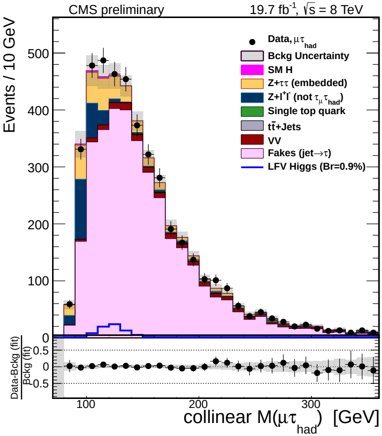
where $BR(h \to \tau\mu) = 0.89\%$

CMS $h \to \tau\mu$

$\tau_e + 0j$



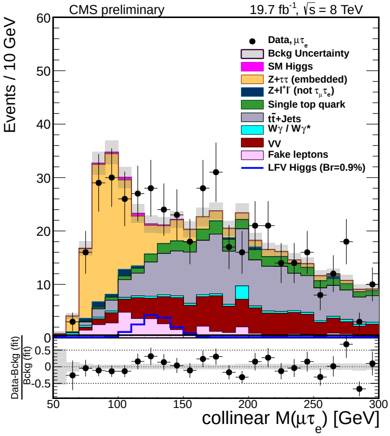
$\tau_h + 0j$



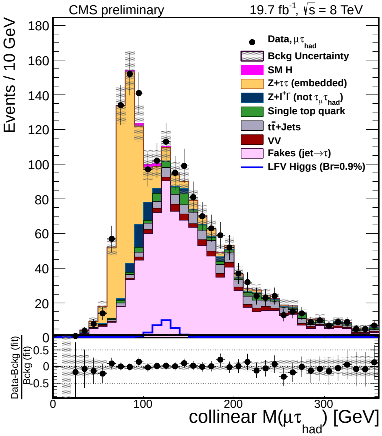
from CMS-HIG-14-005

CMS $h \to \tau\mu$

$\tau_e + 1j$



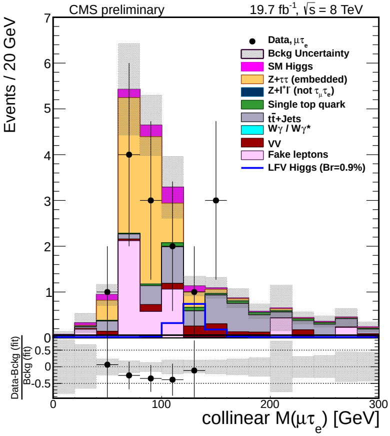
$\tau_h + 1j$



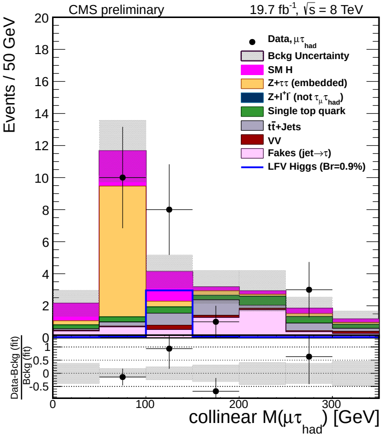
from CMS-HIG-14-005

CMS $h \to \tau\mu$

$\tau_e + 2j$



$\tau_h + 2j$

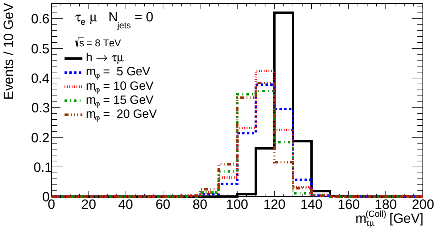


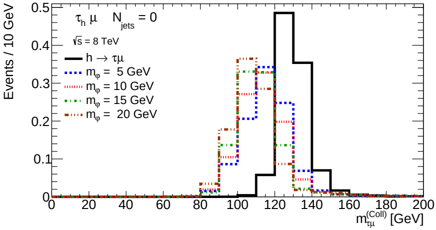
from CMS-HIG-14-005

Conspiracy and Dark Matter

Can $h \to \mu\tau\phi$ mimic $h \to \mu\tau$:

- Broadening and shifting of $m_{\tau\mu}^{\rm Coll}$, worry about $Z \to \tau\mu$





Conspiracy and Dark Matter

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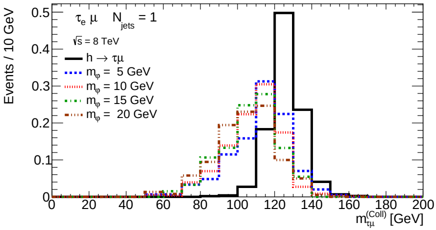

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