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

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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:

$$y^{\ell}_{ij}\bar{L}_i\tilde{H}E_j + \frac{c^{\nu}_{ij}}{\Lambda^2}L_iHL_jH \xrightarrow{\cancel{EWSB}} m^{\ell}_i\delta_{ij}\left(1+\frac{h}{v}\right)\bar{\ell}_i\ell_j + m^{\nu}_{ij}\nu_i\nu_j$$

$$\boxed{\text{Higgs Physics drives flavor structure}}$$

- 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 - sensitive to underlying flavor theory $\Longrightarrow$ $\boxed{\text{New Physics}}$

Leptonic Flavor Anomalies

Several Hints of (Flavor) New Physics:

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

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

CMS	0.89 ± 0.39
ATLAS	$\begin{cases} \tau_h & 0.53 \pm 0.51 \\ \tau_e & 0.77 \pm 0.62 \end{cases}$

$$\boxed{\text{CMS result} \sim 2.4\sigma}$$

LFV Higgs Couplings

Simplest SM-extensions will give rise to

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

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

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

τ Physics

The dominant τ decay modes

Leptonic:

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

Hadronic:

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

$$\boxed{\text{inherent Missing-Energy signature}}$$

τ's @ The LHC

Trigger:

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

$$\boxed{\text{fully reconstructs } \tau_{vis}}$$

but

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

τ-LHC searches are $\cancel{E}_T$-inclusive

τ Reconstruction:

- **The collinear approximation**

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

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

- **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

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

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

Variable	$\text{H} \to \mu\tau_\text{e}$			$\text{H} \to \mu\tau_\text{h}$		
[GeV]	0-jet	1-jet	2-jet	0-jet	1-jet	2-jet
$p_\text{T}^\mu >$	50	45	25	45	35	30
$p_\text{T}^\text{e} >$	10	10	10	—	—	—
$p_\text{T}^{\tau_\text{h}} >$	—	—	—	35	40	40
$M_\text{T}^\text{e} <$	65	65	25	—	—	—
$M_\text{T}^\mu >$	50	40	15	—	—	—
$M_\text{T}^{\tau_\text{h}} <$	—	—	—	50	35	35
[radians]						
$\Delta\phi_{\vec{p}_\text{T}^\mu - \vec{p}_\text{T}^{\tau_\text{h}}} >$	—	—	—	2.7	—	—
$\Delta\phi_{\vec{p}_\text{T}^\text{e} - \vec{E}_\text{T}^\text{miss}} <$	0.5	0.5	0.3	—	—	—
$\Delta\phi_{\vec{p}_\text{T}^\text{e} - \vec{p}_\text{T}^\mu} >$	2.7	1.0	—	—	—	—

from CMS-HIG-14-005

CMS $h \to \tau\mu$

event yields (minor differences between CDS and arXiv versions)

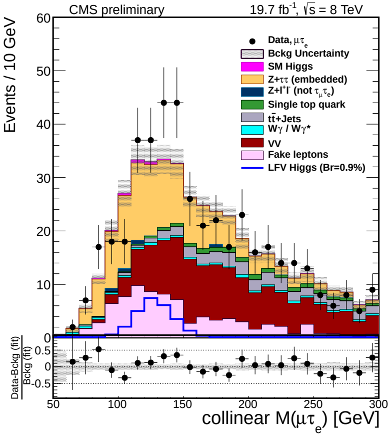
Sample	$H \to \mu\tau_{had}$			$H \to \mu\tau_e$		
	0-jet	1-jet	2-jet	0-jet	1-jet	2-jet
Fakes	1858.1 ± 558.8	362.9 ± 110.0	0.5 ± 0.5	41.5 ± 17.3	16.1 ± 6.8	1.1 ± 0.7
$Z \to \tau\tau$	198.8 ± 11.0	50.5 ± 3.5	0.4 ± 0.2	65.0 ± 3.0	38.6 ± 2.0	1.3 ± 0.2
ZZ, WW	47.0 ± 8.0	14.6 ± 2.6	0.3 ± 0.2	40.8 ± 6.6	21.2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

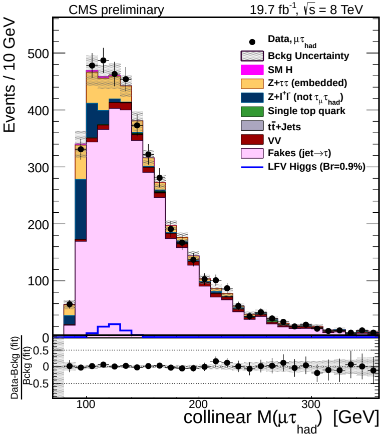
where $BR(h \to \tau\mu) = 0.89\%$

CMS $h \to \tau\mu$

$\tau_e + 0j$



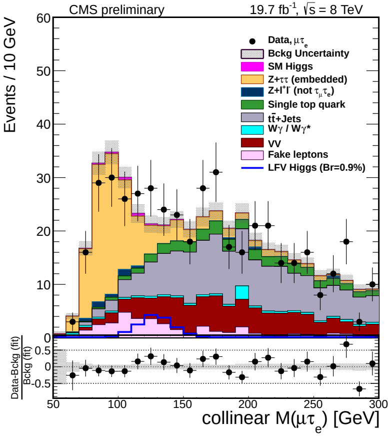
$\tau_h + 0j$



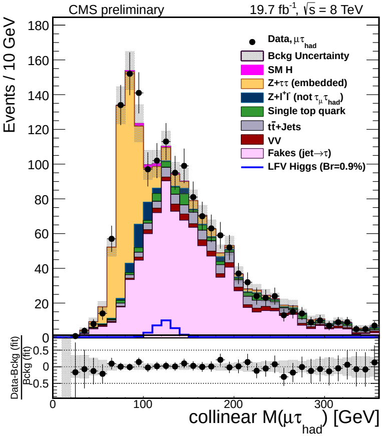
from CMS-HIG-14-005

CMS $h \to \tau\mu$

$\tau_e + 1j$



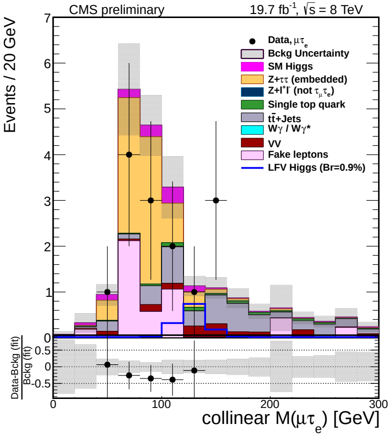
$\tau_h + 1j$



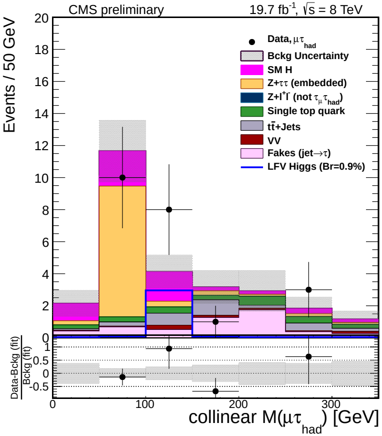
from CMS-HIG-14-005

CMS $h \to \tau\mu$

$\tau_e + 2j$



$\tau_h + 2j$

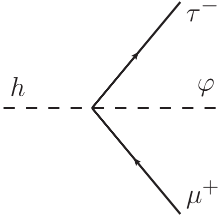


from CMS-HIG-14-005

Conspiracy and Dark Matter

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

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



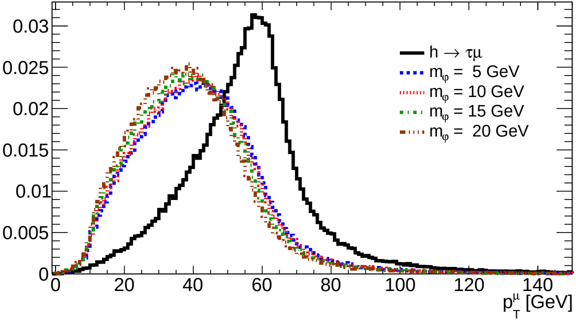
BR's of 2-body and to 3-body are comparable

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

Conspiracy and Dark Matter

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

- softer decay products

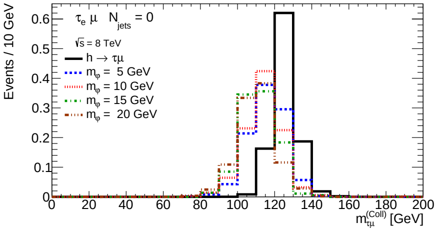


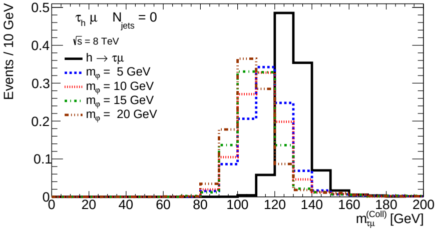
- angularly denser

$$\boxed{\text{search acceptance reduced}}$$

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

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





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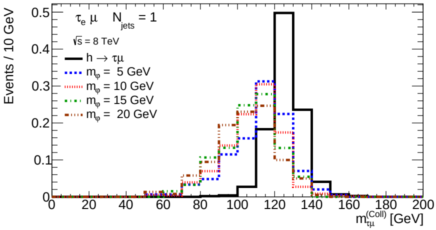

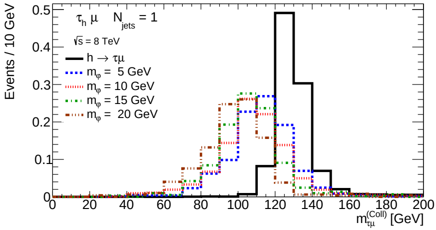

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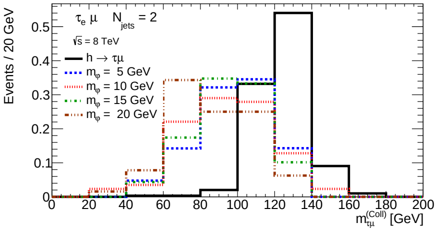
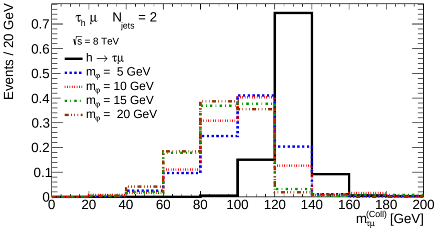




Recast Results

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

Model Building

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

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

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

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

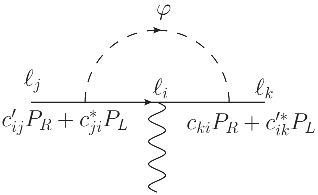
A flavor theory at $\Lambda = 1~{\rm TeV}$ determines all couplings

Model Building - Feasibility

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

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

induces 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:

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

Flavor Conserving constraints:

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

Other constraints:

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

Symmetry Arguments

SM lepton flavor symmetry

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

Naively broken by $c, \ c'$ couplings
Unless,

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

Then break to residual subgroup

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

Symmetry Arguments

Now φ has charge 2:

- Suppressed CLFV transitions
- Still contribute to flavor diagonal observables.

Can we build a Froggatt-Nielsen realization ?

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

Froggatt-Nielsen 101

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

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

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

Then

$$\boxed{Y^\ell_{ij} = \alpha_{ij} \lambda^{|n^Y_{ij}|}}$$

Froggatt-Nielsen 101 + New Scalar

If φ is light we can also expect

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

leading to

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

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

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

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

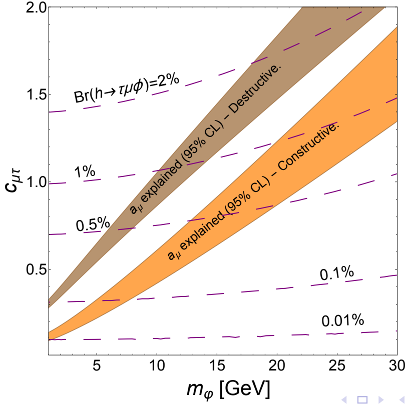
Flavor Checklist

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}[?]	$\begin{cases} D\ 1.8 \times 10^{-13} \\ T\ 1.9 \times 10^{-13} \end{cases}$
$\mathrm{Br}(\tau^- \to e^+\mu^-\mu^-)$	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

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



Conclusions

- If indeed NP accounts for the excess in $h \to \tau\mu$ it may teach us about the origins of the SM flavor structure.
- Alternatively, the excess could be explained by systematics associated with missing-energy (or statistical as the 13 TeV may show)
- Interestingly, an $\mathcal{O}(10\ \mathrm{GeV})$ scalar with $\tau\mu$ couplings can account for the $(g-2)_\mu$ anomaly.
- Future Directions: τ and searches for missing energy

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

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