One loop contributions to neutral Higgs decay $h \to \mu\tau$

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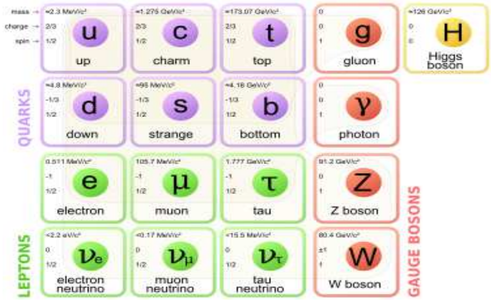
Outline

1. **Introduction**
2. **Lepton-flavored Dark Matter Model**
3. **LFV Higgs decay $h \to \mu\tau$**
4. **Physical results**
5. **Conclusion and outlook**

Introduction

- The discovery of the Standard Model (SM) Higgs was a milestone of Particle Physics [1]



- Is the SM to be the fundamental theory for describing the Universe?

[1] Phys.Lett. B 716, 1 (2012) [ATLAS]; Phys. Lett. B 716, 30 (2012) [CMS].

1. **Several questions can not be explained by the SM:**
   - the gauge hierarchy problem,
   - the unification of fundamental forces in the nature,
   - the origin of matter-antimatter asymmetry,
   - the observed dark matter and dark energy in the Universe,
   - $\cdots$
2. **The nature of Higgs field and its potential is still unknown?**

$$\mathcal{L}_{\rm Y} = ?; \quad \mathcal{V}(\Phi) = ?.$$

$\Longrightarrow$ Higgs's couplings must be measure precisely to search (in-)directly for Beyond the SM.

- The CMS and ATLAS reported for rare Higgs decay $h \to \mu\tau$ searches [2]
  - **CMS: Br($h \to \mu\tau$)** $= (0.84^{+0.39}_{-0.37})\%$.
  - **ATLAS: Br($h \to \mu\tau$)** $= (0.77 \pm 0.62)\%$.
- At the 300 fb^{-1} of 13 TeV LHC, the sensitivity can reach down to $\mathcal{O}(10^{-4})$ [JHEP **1410**, 156 (2014)]. $\Longrightarrow$ The LHC excess will be confirmed or excluded.

[2] CMS Collaboration, Phys. Lett. B 749, 337 (2015); ATLAS Collaboration, JHEP 1511 (2015) 211.

Introduction

- **In the canonical seesaw mechanism:** A. Pilaftsis, Phys. Lett. B 285 (1992) 68; E. Arganda, et al. Phys. Rev. D **71**, 035011 (2005). $\Leftarrow$ LFV Higgs decay is too small to be observed.
- **Radiative seesaw models:** A. Zee, Phys. Lett. B 93, 389 (1980); Nucl. Phys. B 264, 99 (1986); K. S. Babu, Phys. Lett. B 203, 132 (1988); E. Ma, Phys. Rev. D 73, 077301 (2006) $\Leftarrow$ could not generate large LFV Higgs decay.
- **In the inverse seesaw mechanism:** E. Arganda, et al. Phys. Rev. D **91**, no. 1, 015001 (2015); arXiv:1508.04623 [hep-ph]. $\Leftarrow$ LFV Higgs decay can be accommodated.

- **Two (or even more)-Higgs doublet model (2HDM):** A. Vicente, Phys. Rev. D 90, no. 11, 115004 (2014); J. Heeck, et al. Nucl. Phys. B **896**, 281 (2015); Y. Omura, et al. JHEP **1505**, 028 (2015); A. Crivellin, et al. Phys. Rev. Lett. **114**, no. 15, 151801 (2015).
- **Class of 331 models:** L. T. Hue, et al. Nucl.Phys. B907 (2016) 37-76; Phys. Rev. D 93, 115026 (2016); Nucl.Phys.B 873 (2013) 207-247; Nuclear Physics B, 864 (2012) 85-112.
- **Supersymmetric Standard Models:** Brignole, et al. Phys.Lett. B566 (2003) 217-225; Nucl.Phys. B701 (2004) 3-53; Arganda, E. et al. Phys.Rev. D93 (2016) no.5; JHEP 1603 (2016) 055; etc. $\Leftarrow$ can explain the LHC excess.

In this talk

- Investigating LFV Higgs decay in Lepton-flavored Dark Matter Model;
- Present one-loop contributions to LFV Higgs decay in terms of Passarino-Veltman functions (C-functions);
- Using LoopTools package to investigate the numerical results;
- Discuss on new intereting results in comparison with previous work: S. Baek, et al. **JHEP 1603** (2016) 106.

- A Majorana DM candidate, N;
- A scalar partner for each SM left-handed lepton doublet l_L and right-handed lepton signlet e_R: (ϕ_ℓ and ϕ_e)

$$\phi_\ell = (\phi_\ell^+, \phi_l^0)^T \quad \text{with} \quad Y = \frac{1}{2};$$
$$\phi_e \quad \text{with} \quad Y = -1.$$

- New particles are odd with Z_2 dark matter parity.

See detail: E. Ma, Phys. Rev. **D 73**, 077301 (2006); S. Baek, et al. **JHEP 1603** (2016) 106.

Lepton-flavored Dark Matter Model

The Lagrangian containing all LFVHD couplings is

$$
\begin{aligned}
-\mathcal{L} &= -\mathcal{L}_{\rm SM} + m^2_{\phi_\ell}|\phi_\ell|^2 + m^2_{\phi_e}|\phi_e|^2 + \frac{1}{2}M\,\bar{N}\,N \\
&+ \left(-y_{L_a}\bar{l}_a P_R N\tilde{\phi}_\ell + y_{R_a}\bar{e}_a P_L N\phi_e + \text{h.c.}\right) \qquad (1) \\
&+ \left(-\mu H^\dagger\tilde{\phi}_\ell\phi_e^* + \text{h.c.}\right) + \lambda_{-1}|\phi_l|^2|\phi_e|^2 \\
&+ \lambda_0|H|^2|\phi_e|^2 + \mathrm{V}_{\rm 2HDM}.
\end{aligned}
$$

The Higgs doublets is given

$$
\begin{aligned}
V_{\rm 2HDM} &= \frac{\lambda_1}{2}|\phi_\ell|^4 + \frac{\lambda_2}{2}|H|^4 + \lambda_3|\phi_\ell|^2|H|^2 \qquad (2) \\
&+ \lambda_4\left(\phi_e^\dagger H\right)\left(H^\dagger\phi_e\right) + \left(\frac{\lambda_5}{2}\left(\phi_\ell^\dagger H\right)^2 + h.c\right).
\end{aligned}
$$

- Couplings λ_{-1} and λ_0 are not important in our ensuing discussions and are set to be zero.
- Most parameters in $V_{2\mathrm{HDM}}$ are irrelevant to our phenomenological studies.
- Radiative corrections lead to neutrino masses:

$$m_\nu \sim \lambda_5 \frac{y_{La}^2}{16\pi^2}\left(\frac{v}{m_{\phi_\ell}}\right)^2 M, \tag{3}$$

$\Longrightarrow m_\nu \sim$ eV, then $\lambda_5 << 1$.

see E. Ma, **Phys. Rev. D 73**, 077301 (2006).

The mass spectrum of the mediators

$$\begin{aligned} \tilde{e}_1 &= \cos\theta(\phi_\ell^+)^* - \sin\theta\ \phi_e, \\ \tilde{e}_2 &= \sin\theta(\phi_\ell^+)^* + \cos\theta\,\phi_e, \end{aligned} \tag{4}$$

where the mixing angle

$$\tan\theta = \frac{1}{\sqrt{2}v\mu}\left[\Delta m_\phi^2 + \sqrt{(\Delta m_\phi^2)^2 + 2v^2\mu^2}\,\right]; \tag{5}$$

and

$$m_{\tilde{e}_{1,2}}^2 = \frac{1}{2}\left[m_{\phi_\ell}^2 + m_{\phi_e}^2 \mp \sqrt{(\Delta m_\phi^2)^2 + 2v^2\mu^2}\,\right]. \tag{6}$$

We also have the following relation

$$m_{\tilde{e}_2}^2 = m_{\tilde{e}_1}^2 + \frac{\sqrt{2}v\mu}{\sin 2\theta}. \tag{7}$$

Note: $\Delta m_\phi^2 \equiv m_{\phi_\ell}^2 - m_{\phi_e}^2$.

The interaction Lagrangian in the mass basis are given by

$$-\mathcal{L}_{\text{int}} = m_{\tilde{e}_i}^2 |\tilde{e}_i|^2 + \frac{M}{2}\bar{N}N + \frac{1}{2}m_h^2 h^2 + A_{ij} h \tilde{e}_i^* \tilde{e}_j + \left[\tilde{e}_i \bar{e}_a \left(\lambda_{ia}^L P_L + \lambda_{ia}^R P_R\right) N + h.c\right], \quad (8)$$

where $a = 1, 2, 3$ the generation index and couplings can be written as

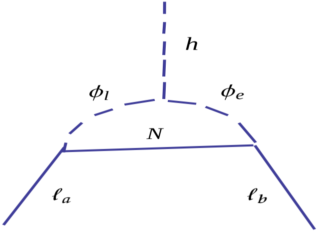
$$A_{11} = -A_{22} = -\frac{\mu}{\sqrt{2}} \sin 2\theta, \quad (9)$$

$$A_{12} = A_{21} = \frac{\mu}{\sqrt{2}} \cos 2\theta, \quad (10)$$

$$\lambda_{1a}^L = -\sin\theta y_{Ra}, \quad \lambda_{2a}^L = \cos\theta y_{Ra}; \quad (11)$$

$$\lambda_{1a}^R = \cos\theta y_{La}, \quad \lambda_{2a}^R = \sin\theta y_{La}, \quad (12)$$

LFV Higgs decay $h \to \mu\tau$



The decay width of $h \to \mu\tau$ is calculated:

$$\Gamma(h \to \bar{l}_a l_b) = \frac{m_h}{16\pi}\left(|F_L|^2 + |F_R|^2\right).$$

The form factors F_L and $F_R(L \leftrightarrow R)$ are presented in terms of C-functions.

$$\begin{aligned} F_L &= \frac{1}{16\pi^2} M\, C(-p_2, p_1 - p_2, M, m_{\tilde{e}_i}, m_{\tilde{e}_j}) A_{ji} y_{\lambda^R_{ia}} y^*_{\lambda^L_{jb}} \\ &\simeq \frac{1}{16\pi^2}\frac{\mu}{\sqrt{2}M} y_{Rb} y^*_{La} \times \\ &\quad \times \left[\frac{1}{2}\sin^2 2\theta\,(G(x_1) + G(x_2)) + \cos^2 2\theta\, G(x_1, x_2)\right], \end{aligned}$$

with $G(x_1, x_2) = -\frac{1}{M^2} C(M, m_{\tilde{e}_1}, m_{\tilde{e}_2})$; $G(x_i) = -\frac{1}{M^2} C(M, m_{\tilde{e}_i}, m_{\tilde{e}_i})$ and $x_i = \frac{m_{\tilde{e}_i}}{M}$ for $i = 1, 2$.

LFV Higgs decay $h \to \mu\tau$

The BR of LFVHD can be written as

$$\mathrm{Br}(h \to \mu\tau) = 1.2 \times 10^{-2} \times \left(\frac{\mu}{5\mathrm{TeV}}\right)^2 \left(\frac{1\mathrm{TeV}}{M}\right)^2 \times \left(\frac{|y_{R_\tau} y^*_{L_\mu}|}{1}\right)^2 \times \left| \frac{[(G(x_1) + G(x_2)] \sin^2 2\theta}{0.4} + \frac{G(x_1, x_2) \cos^2 2\theta}{0.2} \right|^2 .$$

The relation between $\mathrm{Br}(\tau \to \mu\gamma)$ and $\mathrm{Br}(h \to \mu\tau)$ can be presented

$$\mathrm{Br}(\tau \to \mu\gamma) = \frac{10^{-5}}{2.8} \left(\frac{5\mathrm{TeV} \sin 2\theta}{2\mu}\right)^2 \times \left| \frac{400(F_2(x_2) - F_2(x_1))}{[G(x_1) + G(x_2)] \sin^2 2\theta + 2G(x_1, x_2) \cos^2 2\theta} \right|^2 \times \mathrm{Br}(h \to \mu\tau)$$

with $F_2(x) \equiv \frac{-1+x^2-2x\ln x}{2x(1-x)^2}$. **(see S. Baek, et al. JHEP 1603 (2016) 106.)**

The ratio $R_\tau \equiv \mathrm{Br}(h \to \tau\mu)/\mathrm{Br}(\tau \to \mu\gamma) \gtrsim 2 \times 10^5$.

- Decoupling limit ($\sin\theta = 0.1$):

$$R_\tau \approx 2.8 \times 10^5 \left(\frac{\mu}{10\mathrm{TeV}}\right)^2 \left(\frac{0.1}{\sin\theta}\right)^2 \left(\frac{G(x_1,x_2)/(F_2(x_2)-F_2(x_1))}{20}\right)^2.$$

- Maximal mixing ($\theta = \frac{\pi}{4}$):

$$R_\tau \approx 2.8 \times 10^5 \left(\frac{\mu}{10\mathrm{TeV}}\right)^2 \left(\frac{(G(x_1)+G(x_2))/(F_2(x_2)-F_2(x_1))}{200}\right)^2.$$

Define:

$$r(x_1,x_2) \equiv G(x_1,x_2)/(F_2(x_2)-F_2(x_1)) \quad \textbf{for decoupling limit};$$

$$\equiv (G(x_1)+G(x_2))/(F_2(x_2)-F_2(x_1)) \quad \textbf{for maximal mixing}.$$

Remind: $x_i = \frac{m_{\tilde{e}_i}}{M}$ for $i = 1, 2$.

(I) constraint from $\mathrm{Br}(\tau \to \mu\gamma)$

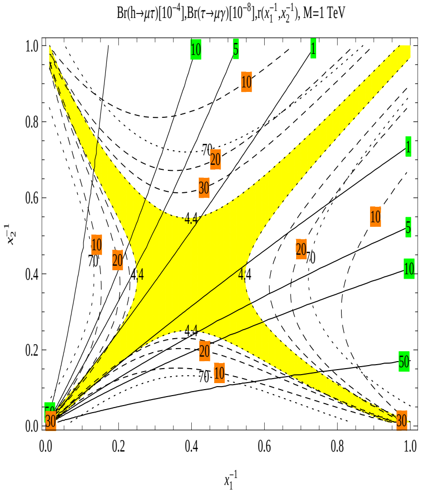
- $\mathrm{Br}(\tau \to \mu\gamma) < 4.4 \cdot 10^{-8}$ (at 90% CL: B. Aubert et al. (BaBar Collaboration), **PRL., 104, 021802 (2010).)**
- **Plot** $\mathrm{Br}(\tau \to \mu\gamma)[10^{-8}]$, $\mathrm{Br}(h \to \mu\tau)[10^{-4}]$**, and** $r(x_1^{-1}, x_2^{-1})$ **in the same figure.**

Numerical sampling

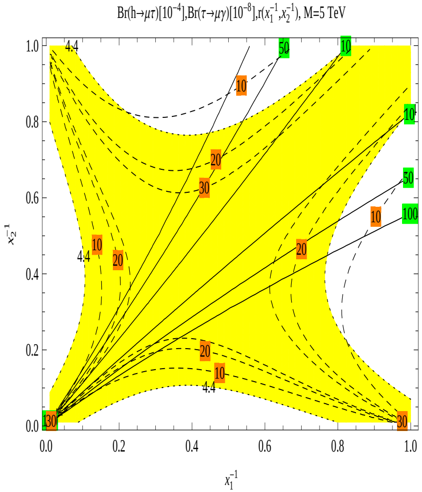
- $x_1^{-1}, x_2^{-1} = [0, 1]$, $M = 1$ TeV, and $M = 5$ TeV;
- Decoupling limit: $\sin\theta = 0.1$;
- Maximal limit: $\sin\theta = 1/\sqrt{2}$.

Physical results (I)

$\mathrm{Br}(\tau \to \mu\gamma)[10^{-8}]$, $\mathrm{Br}(h \to \mu\tau)[10^{-4}]$, and $r(x_1^{-1}, x_2^{-1})$; $\sin\theta = 0.1$

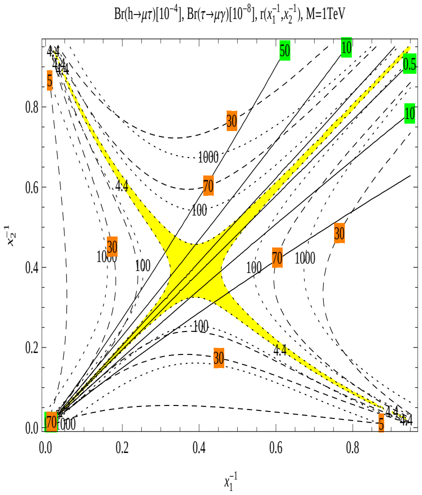


$M = 1$ TeV

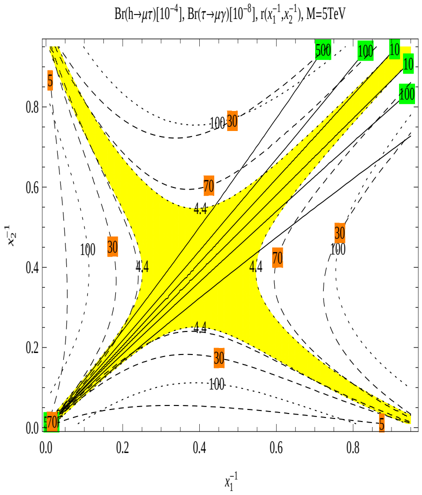


$M = 5$ TeV

$\mathrm{Br}(\tau \to \mu\gamma)[10^{-8}]$, $\mathrm{Br}(h \to \mu\tau)[10^{-4}]$, and $r(x_1^{-1}, x_2^{-1})$; $\sin\theta = 1/\sqrt{2}$



$M = 1$ TeV



$M = 5$ TeV

- Two allowed regions giving large $\mathrm{Br}(h \to \mu\tau)$:
  i) $x_1 \sim x_2 \gg 1$ or $m_{\tilde{e}_1} \sim m_{\tilde{e}_2} \gg M$;
  ii) $x_1 \to 1$ while $x_2 \to \infty$ assuming that $x_2 > x_1$: $M \sim m_{\tilde{e}_1} \ll m_{\tilde{e}_2}$. (same conclusions with S. Baek, et al. JHEP 1603 (2016) 106.)
- The large $r(x_1^{-1}, x_2^{-1})$ does not always correspond to large $\mathrm{Br}(h \to \mu\tau)$ when the experimental constraint of $\mathrm{Br}(\tau \to \mu\gamma)$ is considered. (New)
- The allowed region as well as large $\mathrm{Br}(h \to \mu\tau)$ are sensitive with the variation of M but seem not sensitive with the change of $r(x_1^{-1}, x_2^{-1})$. (New)

Hints in $h \to \gamma\gamma$ from $\tilde{e}_i$-loop [D. Carmi, et al., **JHEP 1210**, 196 (2012)]. At 68.3% C.L. there are two allowed regions:

$$-0.05 \lesssim \delta c_\gamma / c_{\mathrm{SM},\gamma} \lesssim 0.20, \quad -2.20 \lesssim \delta c_\gamma / c_{\mathrm{SM},\gamma} \lesssim -1.95.$$

In our case, we have

$$0 \leq \delta_\gamma \equiv \frac{\delta_{c_\gamma}}{c_{\mathrm{SM},\gamma}} = \frac{1}{48 \times 0.81} \times \times \frac{(\mu v)^2}{m_{\tilde{e}_1}^2 (m_{\tilde{e}_1}^2 + \sqrt{2}\mu v \sin 2\theta)} < 0.20, \quad (13)$$

where we have use $\left(m_{\tilde{e}_2}^2 - m_{\tilde{e}_1}^2\right) \sin 2\theta = \sqrt{2}\mu v$.

(new results in comparison with S. Baek, et al. **JHEP 1603** (2016) 106.)

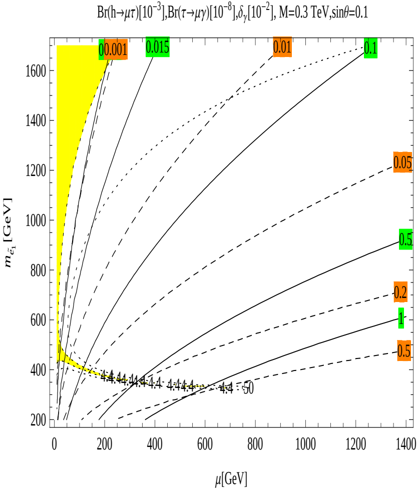
(II) Including the hints in $h \to \gamma\gamma$

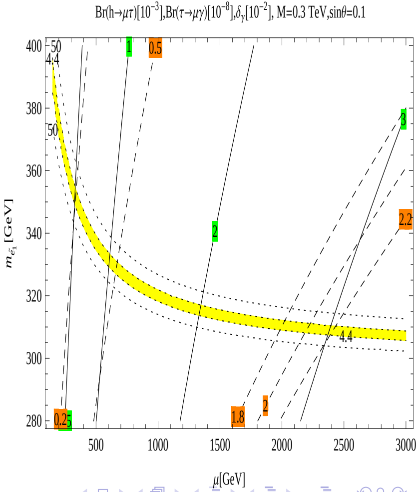
- $M = 300$ GeV and $M = 1$ TeV;
- Decoupling limit: $\sin\theta = 0.1$;
- Maximal limit: $\sin\theta = 1/\sqrt{2}$.
- $m_{\tilde{e}_1} \in [200, 2000]$ GeV.
- $\mu \in [0, 30]$ TeV.

$\mathrm{Br}(\tau \to \mu\gamma)[10^{-8}]$, $\mathrm{Br}(h \to \mu\tau)[10^{-3}]$, **and** $\delta_\gamma[10^{-2}]$ **will be shown in same plot.**

$\mathrm{Br}(\tau \to \mu\gamma)[10^{-8}]$, $\mathrm{Br}(h \to \mu\tau)[10^{-3}]$, and $\delta_\gamma[10^{-2}]$

$M = 300$ GeV, $\sin\theta = 0.1$

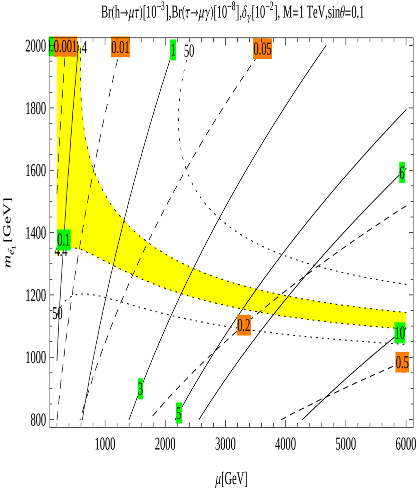


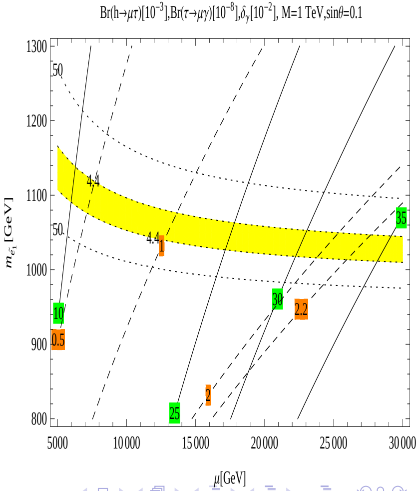


Physical results (II)

$\mathrm{Br}(\tau \to \mu\gamma)[10^{-8}]$, $\mathrm{Br}(h \to \mu\tau)[10^{-3}]$, and $\delta_\gamma[10^{-2}]$

$M = 1000$ GeV and $\sin\theta = 0.1$

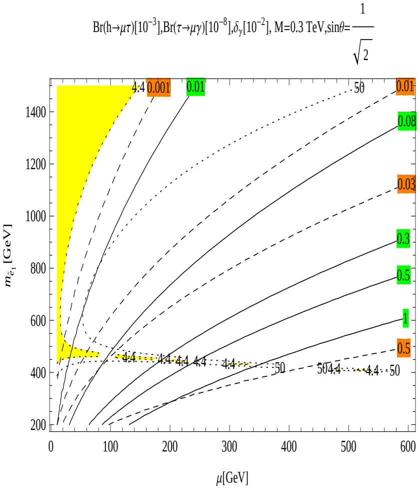


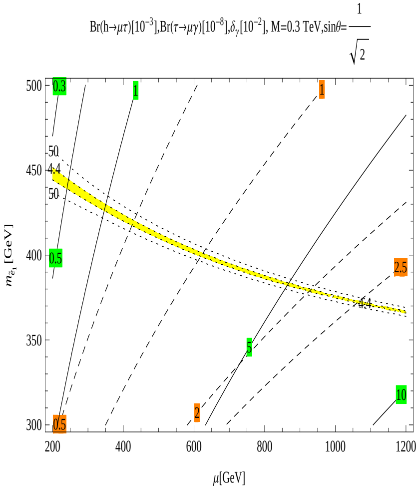


Physical results (II)

$\text{Br}(\tau \to \mu\gamma)[10^{-8}]$, $\text{Br}(h \to \mu\tau)[10^{-3}]$, **and** $\delta_\gamma[10^{-2}]$

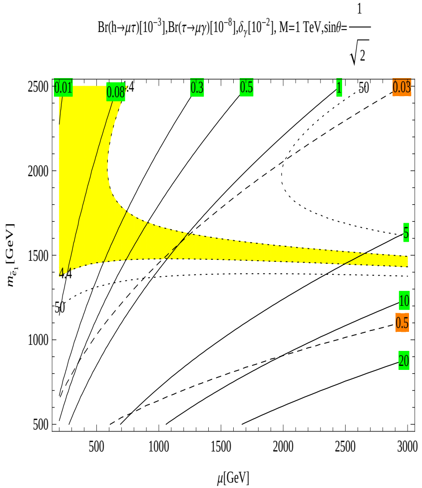
$M = 300$ GeV and $\sin\theta = 1/\sqrt{2}$.

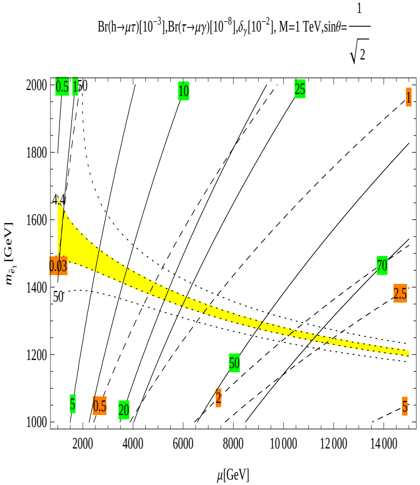




$\mathrm{Br}(\tau \to \mu\gamma)[10^{-8}]$, $\mathrm{Br}(h \to \mu\tau)[10^{-3}]$, and $\delta_\gamma[10^{-2}]$

$M = 1000$ GeV and $\sin\theta = 1/\sqrt{2}$





Physical results (II)

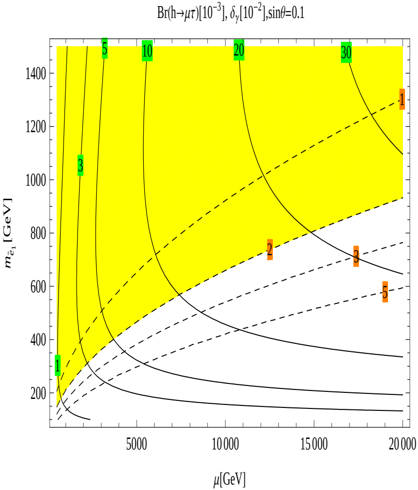
- The allowed region from constraint of $\mathrm{Br}(\tau \to \mu\gamma)$ consists of two distinguish parts:
  i) large $m_{\tilde{e}_1}$ and small μ;
  ii) $m_{\tilde{e}_1}$ is round the value of M while μ is arbitrary large.
- Region i) gives $\mathrm{Br}(h \to \mu\tau)$ smaller than 10^{-5} with small $M = 300$ GeV and 10^{-3} with large $M = 1$ TeV.
- Region ii) gives very close to the recent experimental value of $\mathrm{Br}(h \to \mu\tau)$

The most interesting region giving large BR$(h \to \mu\tau)$ corresponds to $M \leq 1$ TeV and $M \sim m_{\tilde{e}_1} \ll m_{\tilde{e}_2}$.

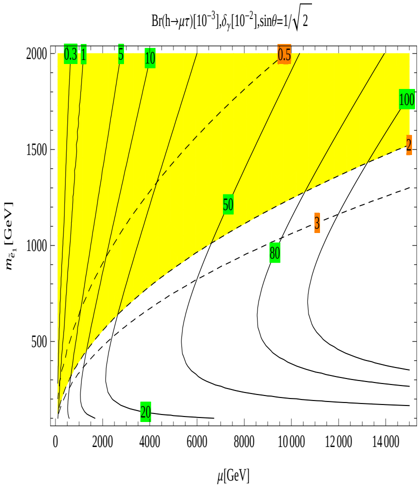
- Focus on the region $M \leq 1$ TeV and $M = m_{\tilde{e}_1} \ll m_{\tilde{e}_2}$.
- One has $x_1 = 1 \ll x_2$. Confirming that $\lim_{x_1 \to 1} F_2(x_1) = 0$ and $\lim_{x_2 \to \infty} F_2(x_2) = 0$, resulting very suppressed $\mathrm{Br}(\tau \to \mu\gamma)$.
  - $m_{\tilde{e}_1} \in [200, 2000]$ GeV.
  - $\mu \in [0, 14]$ TeV.

$\mathrm{Br}(h \to \mu\tau)$, and δ_γ will be shown in same plot.

$\mathrm{Br}(h \to \mu\tau)[10^{-3}]$, **and** $\delta_\gamma < 0.2$



$\sin\theta = 0.1$



$\sin\theta = 1/\sqrt{2}$.

Physical results (III)

- For $\sin\theta = 1/\sqrt{2}$: $m_{\tilde{e}_1} \sim M < 1$ TeV, the $\mu \lesssim 3$ TeV.
- For $\sin\theta = 0.1$: $m_{\tilde{e}_1} \sim M < 1$ TeV, the $\mu \lesssim 12$ TeV.

For study relic Dark matter density; investigating (in-)direct searches for DM:
$\Longrightarrow$ see our paper in PTEP *10.1093/ptep/ptw158*].

Conclusions

- We have just investigated LFV Higgs decay in Lepton-flavored Dark Matter Model;
- The one-loop contributions to LFV Higgs decay was presented in terms of Passarino-Veltman functions (C-functions);
- Using LoopTools package to investigate the numerical results;
- Two allowed regions giving large $\mathrm{Br}(h \to \mu\tau)$:
  i) $x_1 \sim x_2 \gg 1$ or $m_{\tilde{e}_1} \sim m_{\tilde{e}_2} \gg M$;
  ii) $x_1 \to 1$ while $x_2 \to \infty$ assuming that $x_2 > x_1$: $M \sim m_{\tilde{e}_1} \ll m_{\tilde{e}_2}$.

Conclusions

We found many interesting results that did not metioned in S. Baek, et al. **JHEP 1603** (2016) 106.

- $\text{Br}(h \to \mu\tau)$ depends strongly on M.
- LFVHD can be arbitrary large with very large M if the following condition is satisfied: $M \sim m_{\tilde{e}_1} \ll m_{\tilde{e}_2}$.
- $M < 1$ TeV, the Br of LFVHD near the recent experimental report only occurs in the region having $M \sim m_{\tilde{e}_1}$.
- $M < 1$ TeV, the LFVHD constraint from experiment leads to $\mu < 3(13)$ TeV in the case of maximal (decoupling) limit.

Outlook

We will discuss on collider signals in this model based on this paper in future works

1. Large Hadron Collider (LHC):
   - $pp \to \tilde{e}_i^+ \tilde{e}_j^- \to (\ell^+ \overline{N})(\ell^- N)$;
   - $pp \to \gamma^*, Z^* \to \widetilde{\ell}^0 \widetilde{\ell}^{0*}, \widetilde{\ell}^+ \widetilde{\ell}^-$;
   - $pp \to W^{\pm *} \to \widetilde{\ell}^{\pm} \widetilde{\ell}^0$.
2. International Linear Collider (ILC):
   - $e^+ e^- \to Z^*, \gamma^* \to \tilde{e}_i^+ \tilde{\ell}_j^-, \phi_\ell^0 \phi_\ell^{0*}$.
   - DM search $e^+ e^- \to \overline{N} N \gamma$.
   - Lepton pair production: $e^+ e^- \to l_i^+ l_i^-$,
   - multi-flavor lepton final state $e^+ e^- \to l_i^+ l_j^-$ $(i \neq j)$.

Thank you very much for your attention!