NATURALLY LARGE RADIATIVE HIGGS LEPTON-VIOLATING DECAY MEDIATED BY LEPTON-FLAVORED DARK MATTER

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ZHAOFENG KANG, KIAS

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Outline

* Lepton-flavor conservation in SM
* Higgs lepton-flavor-violation (HLFV)
* HLFV from lepton-flavored DM
* Conclusions

Lepton-flavor conservation in SM

- The leptonic structure of SM

  3 generations in $SU(2)_L$ doubelt ℓ_L and singlet e_R but NO singlet N_R. Charged leptons gain masses via Higgs mechanism:

$$y^e_{ab}\bar{\ell}_{L,a}He_{R,b}+c.c.\to y^e_{ab}\frac{v+h}{\sqrt{2}}\bar{e}_{L,a}e_{R,b}+c.c.\to m_{e_a}\bar{e}_ae_a+\frac{m_{e_a}}{v}h\bar{e}_ae_a$$

too simple
too boring

- Neutrino should be massless, as a result of no N_R !!!

This is funny because neutrino are found to be massive, although extremely light $m_\nu \lesssim 0.1$eV!!! It is a clear evidence for new physics beyond SM. How to understand neutrino mass origin?

- Accidental lepton-flavor conservation

  It is true both at tree and loop levels, due to the absence of FCNC and GIM mechanism

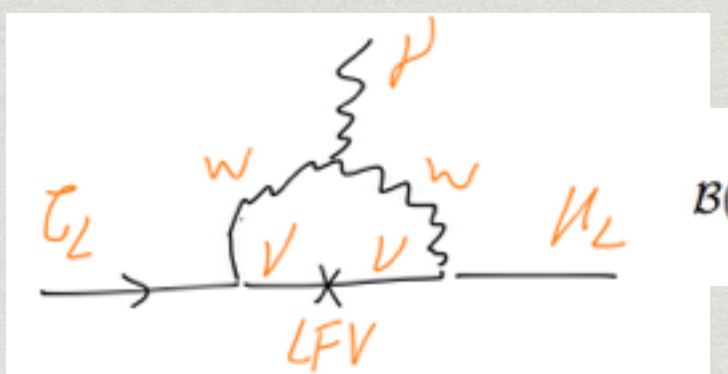
Lepton-flavor conservation in SM

- Lepton-flavor violation (LFV)

  Observed in neutrino oscillation like $\nu_\mu \rightleftarrows \nu_e$.

- Can LFV leave hints in other processes?

  for instance, in charged lepton-flavor-violating (CLFV) decay



$$\mathcal{B}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{i1}}{M_W^2}\right|^2 \sim 10^{-54}$$

1. CLFV with LFV insertion, only via neutrino oscillation, is absolutely undetectable.
2. On the other hand, any observation of CLFV must be signal of new physics
3. Currently, the most stringent bounds: $Br(\mu \to e\gamma) < 10^{-13}$, $Br(\tau \to \mu\gamma) < 4.3\times10^{-8}$

As for $Br(\mu \to eee) < 10^{-14}$ etc gives much weaker constraints.

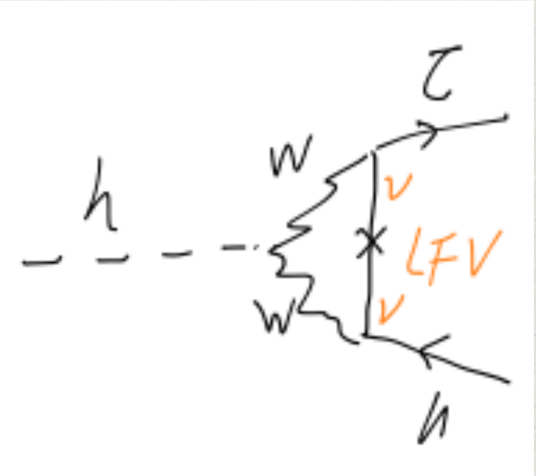
Higgs lepton-flavor-violation (HLFV)

- Again, almost zero in SM

  No FCNC & LFV only via neutrino oscillation mean both vanishing tree- & loop-level HLFV decays

  So HLFV is sensitive to NP, being goal @ LHC

  J. Bjorken and S. Weinberg, Phys.Rev.Lett. 38, 622 (1977).



- LHC status of HLFV

  CMS Collaboration [CMS Collaboration], CMS-PAS-HIG-14-005.

  In 2012 with 4.7/fb of 7TeV ATLAS data gave Br($h \to \tau\mu$/e)≲10%

  In 2014 with 19.7/fb of 8 TeV CMS data gave upper bound & best fit (2.4σ excess) at 95% C.L.:

  $\mathrm{Br}(h \to \tau\mu) < 1.57\%$ **or ?** $\mathrm{Br}(h \to \tau\mu) = (0.84^{+0.39}_{-0.37})\%$.

  Br($h \to \tau\tau$)~10%,
  Br($h \to \mu\mu$)~0.01%

- Prospects 300/fb of 13 TeV LHC

  J. Kopp and M. Nardecchia, JHEP 1410, 156 (2014)

  Y. n. Mao and S. h. Zhu, arXiv:1505.07668

  $\mathrm{Br}(h \to \mu\tau) < 7.7 \times 10^{-4}$

Higgs lepton-flavor-violation (HLFV)

- Radiative HLFV and neutrino mass origins

  LFV must be present in seesaw models, but HLFV decays are too small to be observed. In type-I seesaw RHNs decouple

  In the radiative seesaw models such as Ma's model, large HLFV is not provided despite of detectable CLFV

- Tree level HLFV via 2HDM+ with FCNC

  SM Higgs doublet is a component of larger multiplets for A_4/S_4

  Local $L\mu$-$L\tau$ requires additional Higgs doublet which just modifies the flavor structure of the 2'th and 3'th generation of leptons

A. Crivellin, G. D'Ambrosio and J. Heeck, Phys. Rev. Lett. 114, no. 15, 151801 (2015).

Higgs lepton-flavor-violation (HLFV)

- HLFV confronting CLFV

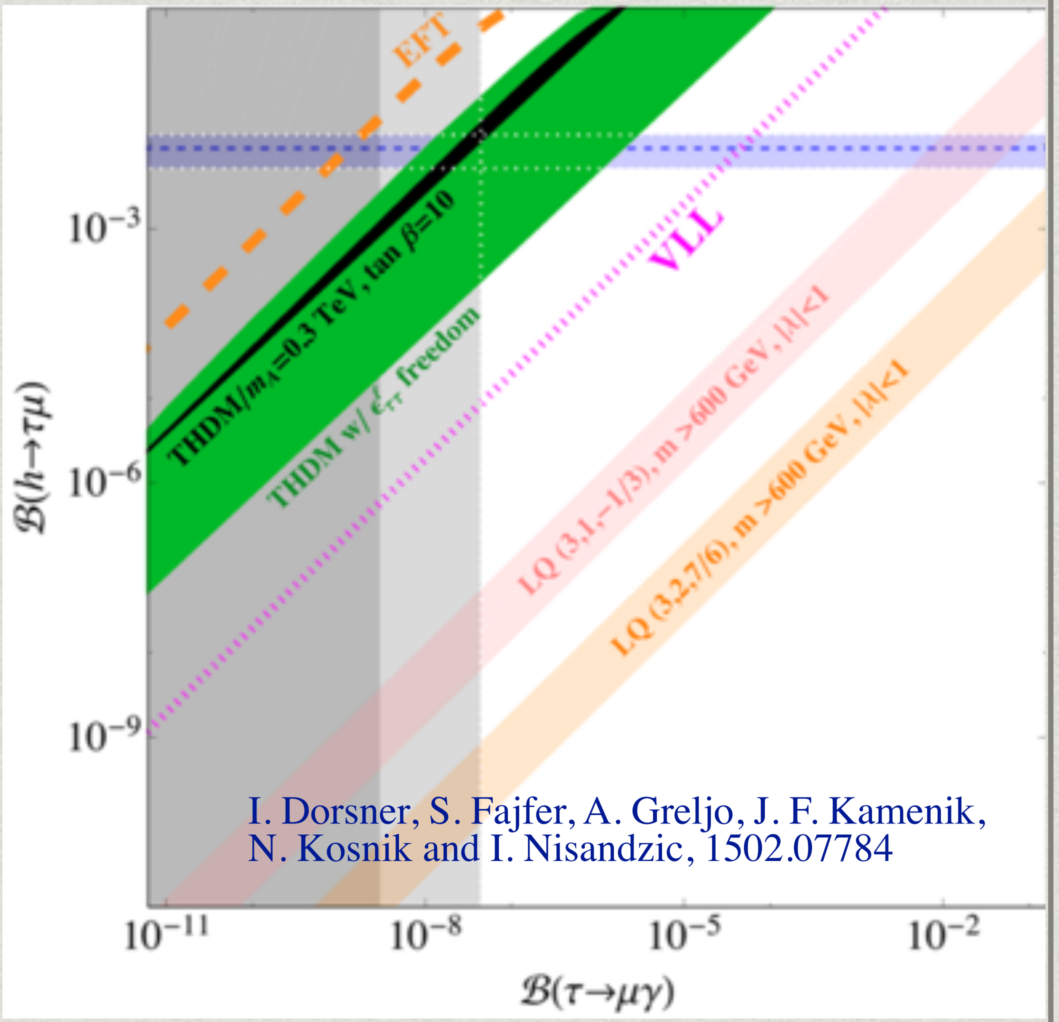
HLFV usually induces CLFV (but not vice verse). Then, is it possible to get Br($h\to\tau\mu$)/Br($\tau\to\mu\gamma$)≳10^5?

Serious for radiative HLFV, which may share the loop with CLFV

EFT analysis is safe but not in UV:

$$\mathcal{L}_{Y_\ell} = -\lambda^{\alpha}_{ij}\bar{L}_i H_\alpha E_j - \lambda'^{\alpha\beta\gamma}_{ij}\frac{1}{\Lambda^2}\bar{L}_i H_\alpha E_j (H^\dagger_\beta H_\gamma) + \text{h.c.}\,,$$

R. Harnik, J. Kopp and J. Zupan, JHEP 1303, 026 (2013).



- Radiative HLFV and Higgs diphoton rate

Both have new charged particles significantly coupling to Higgs

HLFV from lepton-flavored DM

- Lepton-flavored dark matter

A hypothesis that DM interacts dominantly with the lepton sector, violating lepton flavor. Majorana DM case:

$$-\mathcal{L} = \mathcal{L}_{\rm SM} + \left(-y_{La}\bar{l}_a P_R \chi \widetilde{\phi_\ell} + y_{Ra}\bar{e}_a P_L \chi \phi_e + h.c.\right) + \left(-\mu\, H^\dagger \widetilde{\phi}_\ell \phi_e^* + c.c.\right) + \lambda_{-1}|\phi_e|^2|\phi_\ell|^2 + \lambda_0|H|^2|\phi_e|^2 + V_{\rm 2HDM},$$

Traced back to the cosmic ray anomalies era; essentially a non-MFV version of slepton neutralino in SUSY

Natural way to leptonic DM: mediator quantum numbers specify interactions of the Majorana DM dominantly with leptons

Ma's radiative neutrino model is a "derivation" of lepton-flavored DM except for ϕ_e, which is absent there but crucial here

Previous studies only consider one chirality and thus HLFV is absent; here the large chirality flip by the μ-term in the slepton sector is the key for large HLFV tolerated by CLFV.

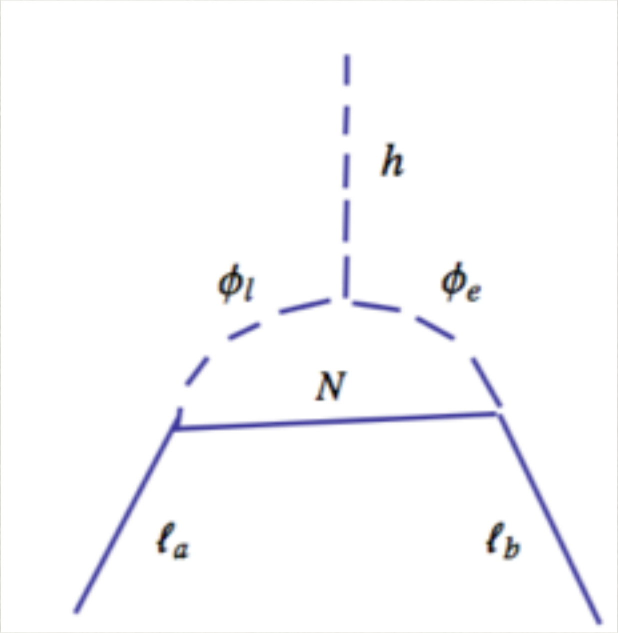
HLFV from lepton-flavored DM

- HLFV versus CLFV: Feyman diagrams

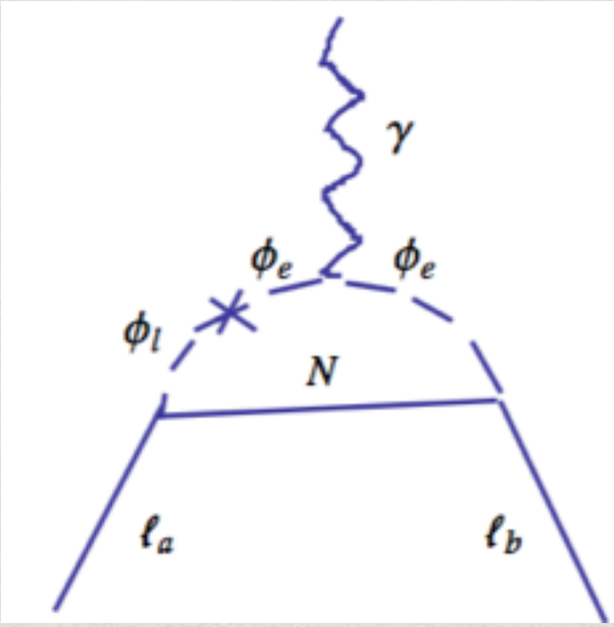
(In flavor basis) same particles run in the loop, but different in:

A) HLFV is enhanced by μ and survives in the decoupling limit;

B) CLFV is not proportional to μ and goes to zero if the sleptons mixing angle vanishes



leptons legs in both diagrams carry opposite charities.



HLFV from lepton-flavored DM

- HLFV versus CLFV: formulas

Lagrangian in components

$$-\mathcal{L} = m^2_{\tilde{e}_i}|\tilde{e}_i|^2 + \frac{M_\alpha}{2}\bar{N}^C_\alpha P_R N_\alpha + \frac{1}{2}m_h^2 h^2 + A_{ij} h \tilde{e}_i^* \tilde{e}_j + \left[\tilde{e}_i \bar{e}_a \left(\lambda^L_{ia\alpha} P_L + \lambda^R_{ia\alpha} P_R\right) N_\alpha + h.c.\right]$$

HLFV decay amplitude:

$$i\mathcal{M} = -i\bar{u}_b(-p_2 + p_1)\left(F_L P_L + F_R P_R\right) v_a(p_2),$$

$$x_i \equiv M^2/m^2_{\tilde{e}_i}.$$

$$F_L = \frac{1}{16\pi^2} M_\alpha C_0(-p_2, p_1 - p_2, M_\alpha, m_i, m_j) A_{ij} \left(\lambda^R_{ia\alpha}\right)^* \lambda^L_{jb\alpha}$$
$$= \frac{1}{16\pi^2}\frac{\mu}{\sqrt{2}M_\alpha} y_{Rb\alpha} y^*_{La\alpha}\left[\frac{1}{2}\sin^2 2\theta \left(G(x_1) + G(x_2)\right) + \cos^2 2\theta\, G(x_1, x_2)\right],$$

Independent on if DM is Dirac or Majorana

terms suppressed by lepton masses are neglected; they ∝ $(y_R)^2$ or $(y_L)^2$

Branching ratio in decoupling and maximal mixing limit

$$\mathrm{Br}(h \to \bar{\tau}\mu) = 1.2 \times 10^{-2}\left(\frac{\mu}{5\mathrm{TeV}}\right)^2\left(\frac{1\mathrm{TeV}}{M}\right)^2\left(\frac{G(x_1,x_2)}{0.2}\right)^2\left(\frac{|y_{R\tau} y^*_{L\mu}|}{1}\right)^2$$

$$\mathrm{Br}(h \to \bar{\tau}\mu) = 1.3 \times 10^{-2}\left(\frac{\mu}{10\mathrm{TeV}}\right)^2\left(\frac{1\mathrm{TeV}}{M}\right)^2\left(\frac{G(x_1) + G(x_2)}{0.4}\right)^2\left(\frac{|y_{R\tau} y^*_{L\mu}|}{0.5}\right)^2$$

HLFV from lepton-flavored DM

- HLFV versus CLFV: formulas

CLFV decay can be described by the effective Hamiltonian

$$\mathcal{H}_{\text{eff}} = C_L \overline{\mu_L} \sigma^{\mu\nu} \tau_R F_{\mu\nu} + C_R \overline{\mu_R} \sigma^{\mu\nu} \tau_L F_{\mu\nu}.$$

$$\Gamma(\tau \to \mu\gamma) = \frac{(m_\tau^2 - m_\mu^2)^3}{4\pi m_\tau^3}\left[|C_L|^2 + |C_R|^2\right]$$

with the Wilsonian coefficient given by

$$C_L = \frac{e}{32\pi^2}\left[\left\{\frac{m_\mu}{M^2} y_{Ra} y^*_{Rb}\left(s_\theta^2 F_1(x_1) + c_\theta^2 F_1(x_2)\right) + \frac{m_\tau}{M^2} y_{La} y^*_{Lb}\left(c_\theta^2 F_1(x_1) + s_\theta^2 F_1(x_2)\right)\right.\right.$$
$$\left. - \frac{1}{M} y_{La} y^*_{Rb} s_\theta c_\theta \left(F_2(x_1) - F_2(x_2)\right)\right],$$

This relative negative sign is very important, and it provides a way to suppress CLFV decay through cancelation in two ways: degenerate $x_1 \simeq x_2$ or with a special relationship. E.g., for $x_1 \gg x_2$, one has

The third term is dominant, but it is suppressed by the mixing angle, GOOD NEWS!

$$M \simeq \frac{m_{\tilde{e}_1} m_{\tilde{e}_2}}{\sqrt{3m_{\tilde{e}_1}^2 + m_{\tilde{e}_2}^2}}.$$

HLFV from lepton-flavored DM

- Natural large HLFV

Estimation of ratio R_τ=Br($h\to\tau\mu$)/Br($\tau\to\mu\gamma$) in the decoupling limit:

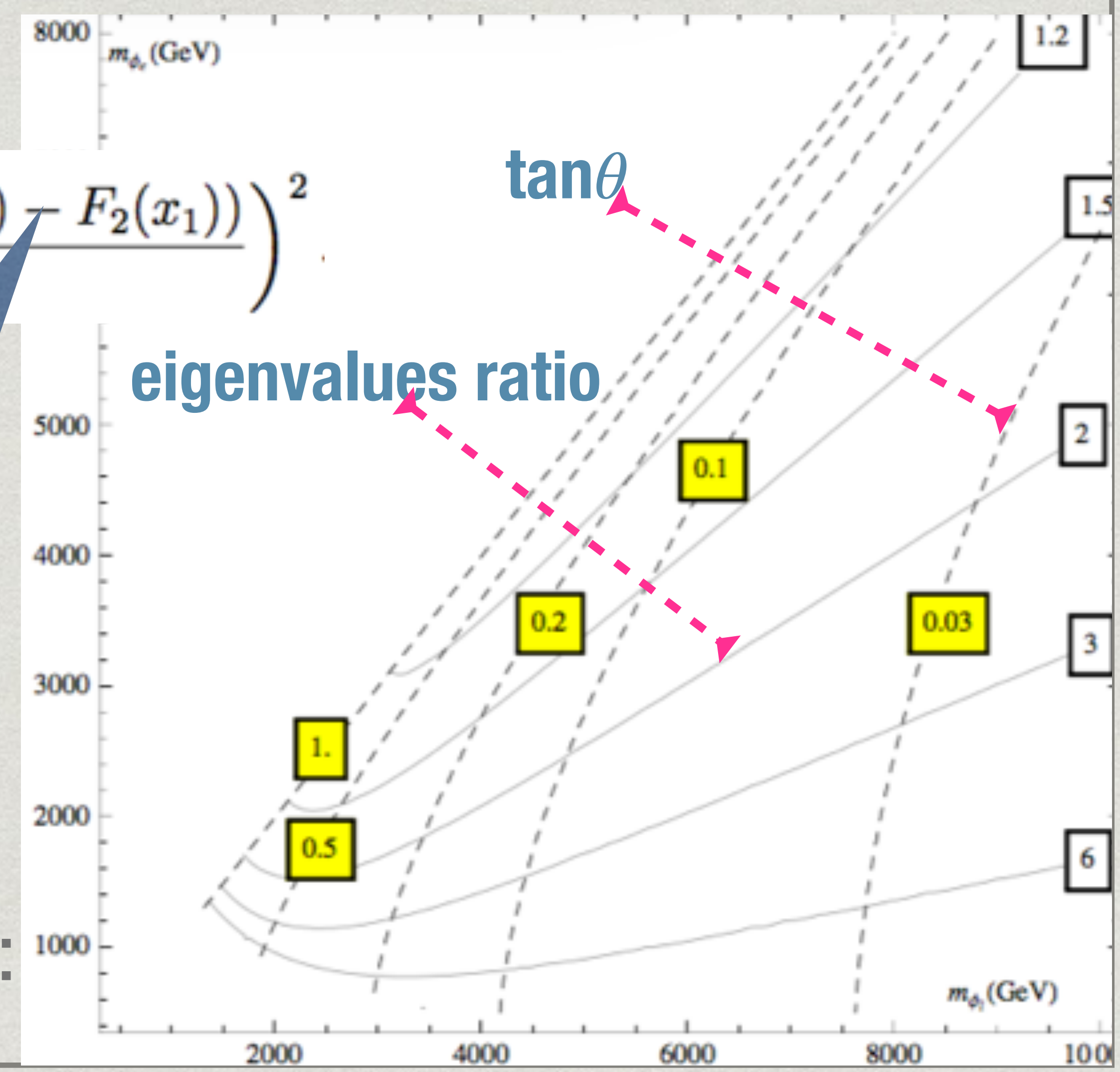
$$R_\tau \approx 2.5\times 10^5 \left(\frac{\mu}{10\,\mathrm{TeV}}\right)^2 \left(\frac{0.1}{\sin\theta}\right)^2 \left(\frac{G(x_1,x_2)/(F_2(x_2)-F_2(x_1))}{20}\right)^2.$$

In the maximal mixing limit:

$$R_\tau \approx 2.7\times 10^5 \left(\frac{\mu}{10\,\mathrm{TeV}}\right)^2 \left(\frac{(G(x_1)+G(x_2))/(F_2(x_2)-F_2(x_1))}{200}\right)^2.$$

without 1/sinθ enhancement, the ratio of loop functions should be very large~O(100), which can be achieved only via substantial cancelation between $F_2(x_1)$ and $F_2(x_2)$, thus incurring fine-tuning

Mixing and eigenvalues of sleptons:



HLFV from lepton-flavored DM

- **Natural large HLFV?!**

Cancelation and fine-tuning (slepton & DM masses as variables)

$$\Delta = \max\{|\Delta_i|\}|_{i=1,2,3} \quad \text{with} \quad \Delta_i \equiv \frac{\partial \log(F_2(x_2) - F_2(x_1))}{\partial \log \mu_i} \qquad x_i \equiv M^2/m^2_{\tilde{e}_i}.$$

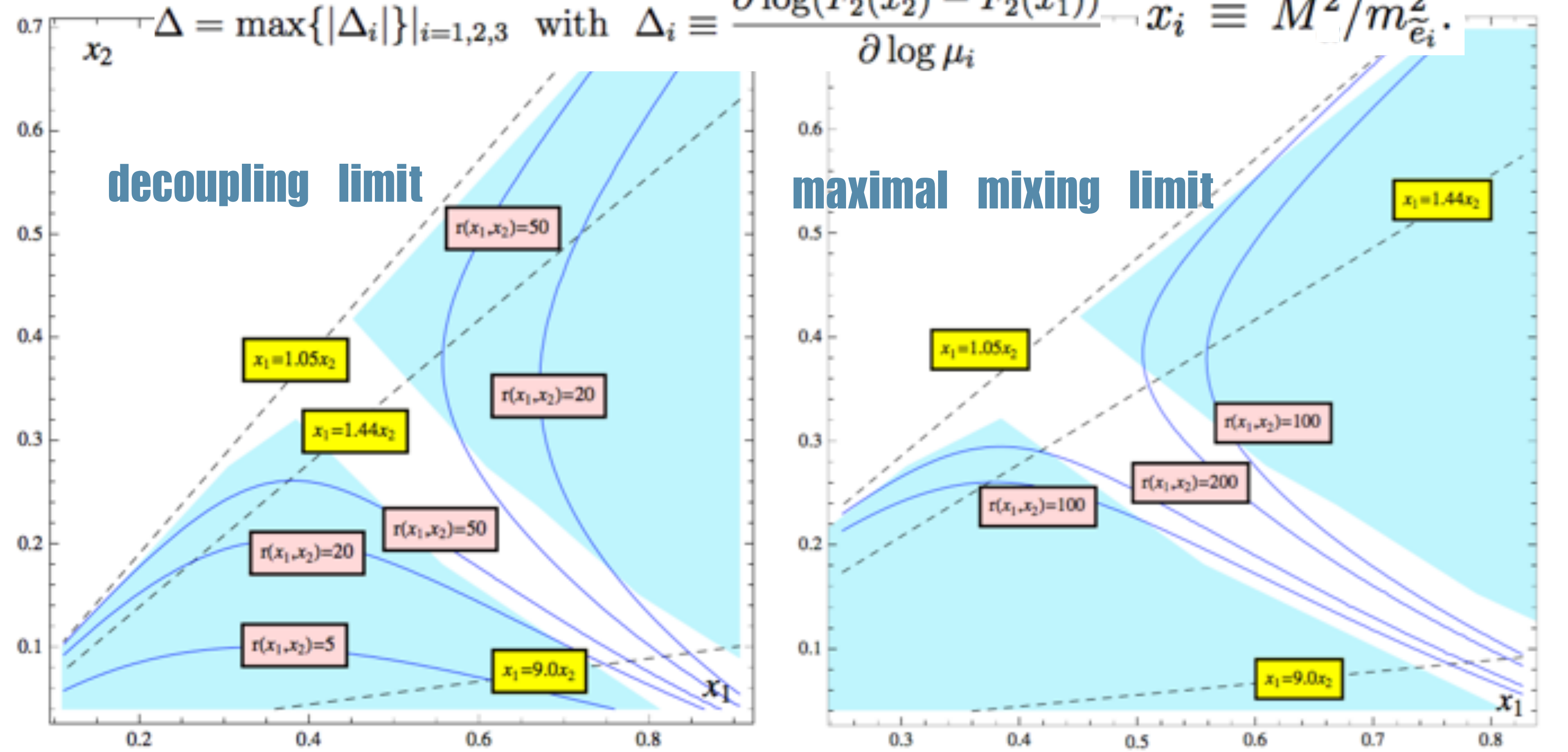


FIG. 4: Contour plots of loop functions ratio $r(x_1, x_2)$ (blue lines), which is $G(x_1, x_2)/(F_2(x_2) - F_2(x_1)$ in the decoupling limit (left) and $(G(x_1)+G(x_2))/(F_2(x_2) - F_2(x_1)$ in the maximal mixing limit (right panel). Regions with fine-tuning better than 5% are shaded. Besides, we label three selected ratios of the masses of two charged scalars (dashed lines).

HLFV from lepton-flavored DM

- Large HLFV leave hints in Higgs diphoton rate?

Large μ & lighter slepton means sizable modification to $h \to \gamma\gamma$

$$r_\gamma = r_{\mathrm{SM},\gamma} + \delta r_\gamma \approx -0.81 + \frac{1}{24}\frac{v\mu\sin 2\theta}{2m^2_{\tilde{e}_1}}$$

if the other one does not decouple…

$$\delta r_\gamma \approx \frac{v\mu\sin 2\theta}{24}\left(\frac{1}{2m^2_{\tilde{e}_1}} - \frac{1}{2m^2_{\tilde{e}_2}}\right)$$

Constraining slepton system in two ways

$$-0.05 \lesssim \delta r_\gamma / r_{\mathrm{SM},\gamma} \lesssim 0.20$$

A small modification

not serious in the decoupling limit

$$-3.4 \times \left(\frac{m_{\tilde{e}_1}}{300\mathrm{GeV}}\right)^2 \mathrm{TeV} \lesssim \mu\sin 2\theta < 0 \quad \text{or} \quad 0 < \mu\sin 2\theta \lesssim 7.2 \times \left(\frac{m_{\tilde{e}_1}}{300\mathrm{GeV}}\right)^2 \mathrm{TeV}.$$

$$-2.20 \lesssim \delta r_\gamma / r_{\mathrm{SM},\gamma} \lesssim -1.95$$

sign reverse! Almost establish an equation

$$\mu\sin 2\theta \approx -28.4 \times \left(\frac{m_{\tilde{e}_1}}{300\mathrm{GeV}}\right)^2 \left(\frac{\delta r_\gamma}{-2.0 r_{\mathrm{SM},\gamma}}\right) \mathrm{TeV}.$$

HLFV from lepton-flavored DM

- Majorana dark matter relic density

S-wave annihilation may work, due to the presence of both chirality slepton $\sigma v_r \approx a + b v_r^2$

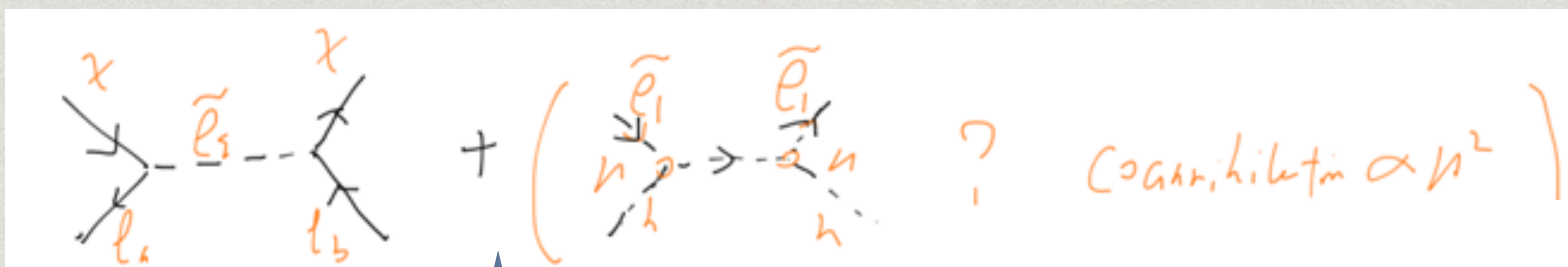
$$a = \frac{1}{16\pi M^2}\frac{1}{(1+x_i^{-1})^2}\left(|\lambda^L_{ia}\lambda^R_{ib}|^2 + |\lambda^R_{ia}\lambda^L_{ib}|^2\right),$$

$$b = \frac{1}{96\pi M^2}\frac{1}{(1+x_i^{-1})^4}\left[2|\lambda^L_{ia}|^2|\lambda^L_{ib}|^2(1+x_i^{-2}) - |\lambda^L_{ia}|^2|\lambda^R_{ib}|^2\left(1+4x_i^{-1}-3x_i^{-2}\right) + (L \leftrightarrow R)\right].$$

vanish in the limit of single chiral coupling

p-wave annihilation can also work

Coannhilation: enjoy large μ



$$\sigma_{hh} v \approx \frac{1}{64\pi}\frac{1}{m^2_{\tilde{e}_1}}\left(\frac{\mu^2/2}{m^2_{\tilde{e}_1}}\right)^2$$

a good agreement with suppressing Br($\tau \to \mu\gamma$)

$$M \simeq \frac{m_{\tilde{e}_1} m_{\tilde{e}_2}}{\sqrt{3m^2_{\tilde{e}_1} + m^2_{\tilde{e}_2}}}.$$

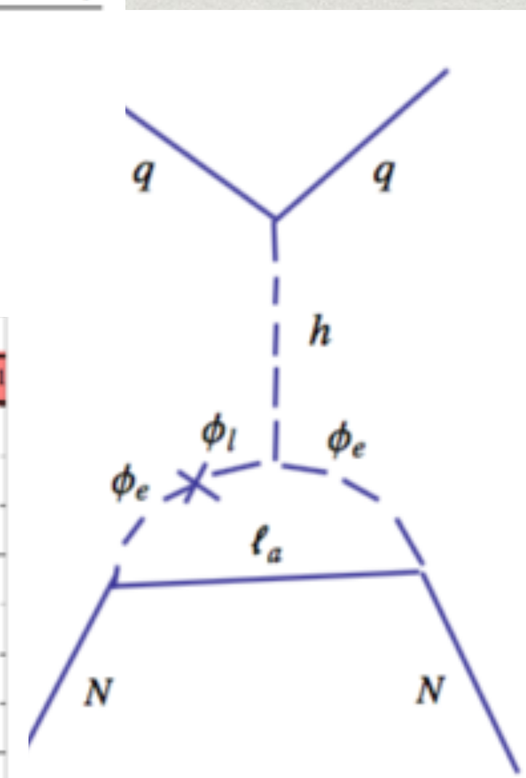
$x_1 \gg x_2$ → $m_{\tilde{e}_1}$

HLFV from lepton-flavored DM

- Radiative dark matter direct detection

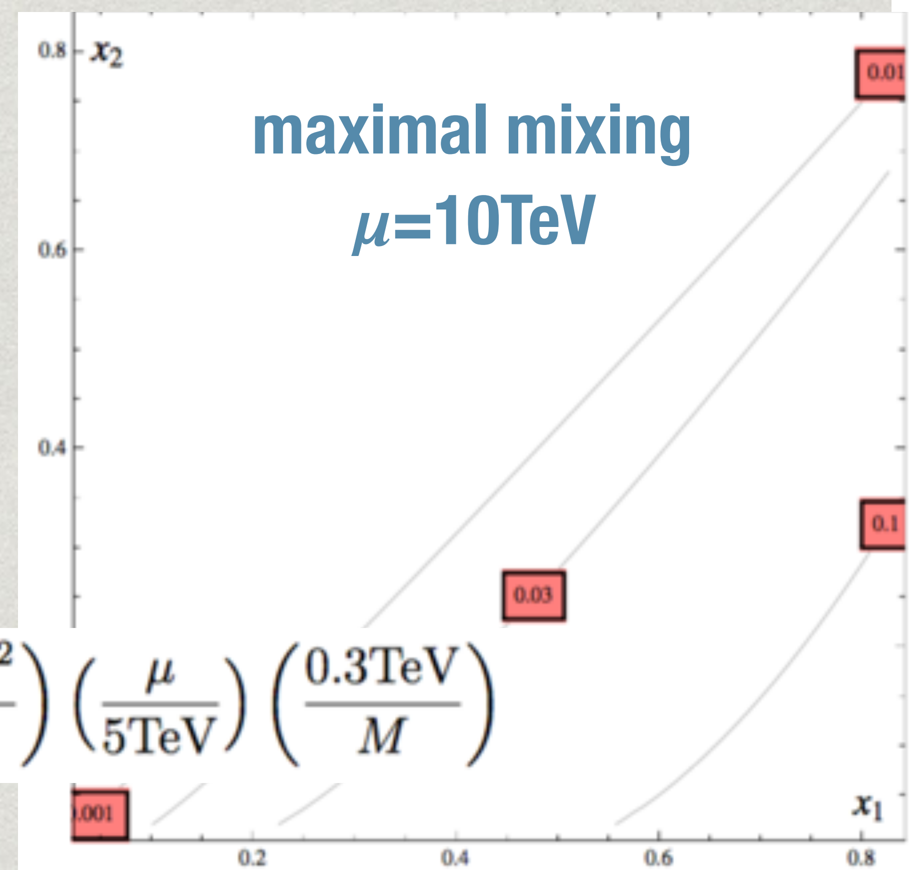
Higgs-mediated DM-nucleon scattering $\mathcal{O}_h = \lambda_{hN}(0) h \bar{N} N,$

$$\lambda_{hN}(0) \approx \sin\theta \frac{|y_{La}|^2 + |y_{Ra}|^2}{32\pi^2} \frac{\mu}{\sqrt{2}M} \left[2 + \frac{(1-x_1)\log(1-x_1)}{x_1} - \frac{(1-x_2)\log(1-x_2)}{x_2} + \frac{1-x_1}{1-x_2} \log\frac{x_2}{x_1} - \mathcal{G}(x_1, x_2)\left(\frac{1}{x_2} + \frac{1}{x_1} - 2\right) + 2\mathcal{G}(x_1, x_1)\left(\frac{1}{x_1} - 1\right)\right],$$



Bound on ~100 GeV DM by LUX:

$$\sigma^p_{\rm SI} \approx 4.0 \times 10^{-8} \left(\lambda_{hN}(0)/0.1\right)^2 \text{pb}$$



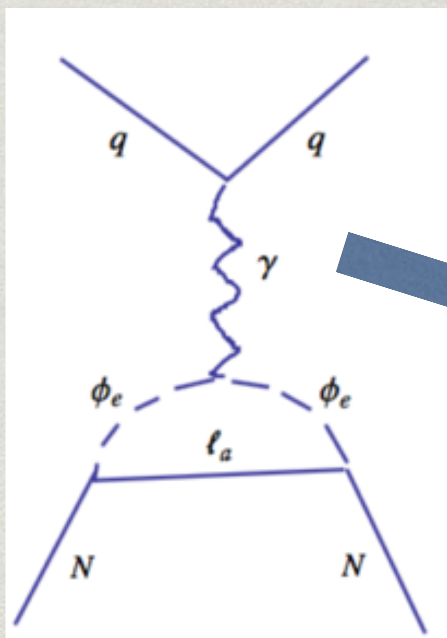
an estimation on effective coupling:

$$\lambda_{hN}(0) \approx 0.01 \times \left(\frac{\sin\theta}{0.2}\right)\left(\frac{|y_{La}|^2 + |y_{Ra}|^2}{1}\right)\left(\frac{\mu}{5\text{TeV}}\right)\left(\frac{0.3\text{TeV}}{M}\right)$$

HLFV from lepton-flavored DM

- Radiative dark matter direct detection

Photon-mediated, anapole: $\mathcal{O}_A = \mathcal{A}\bar{N}\gamma^\mu\gamma^5 N\partial^\nu F_{\mu\nu}$,

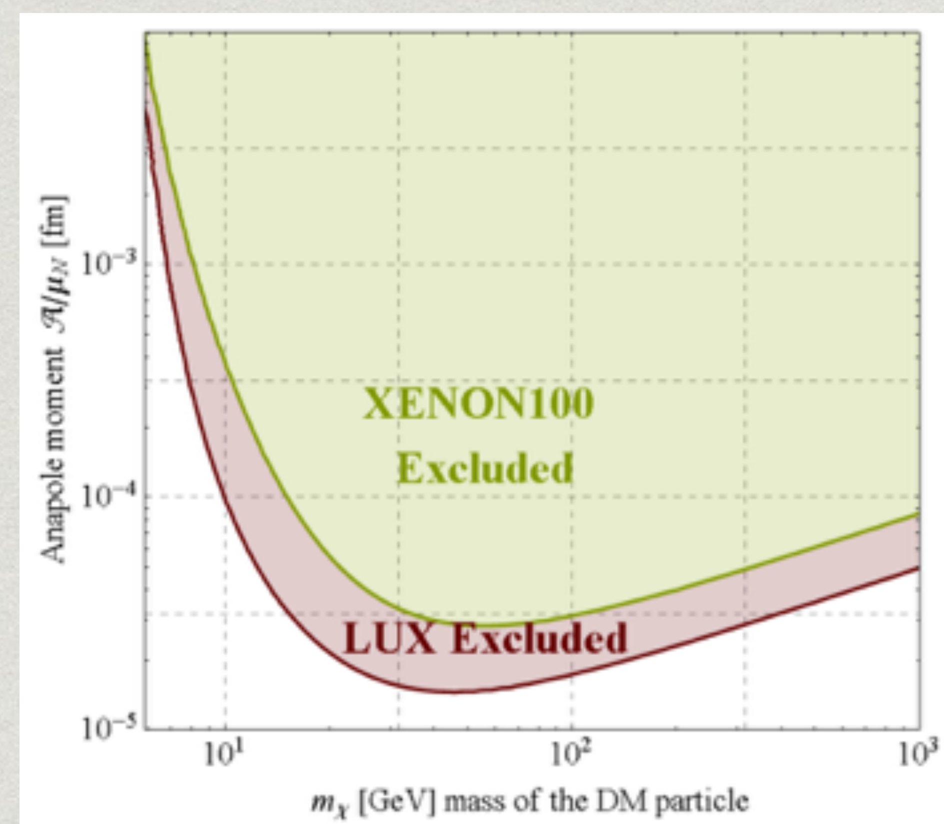


As a CP-self-conjugate particle, this is the leading order operator. The dimension-five operators such as $\bar{N}\sigma^{\mu\nu}NF_{\mu\nu} = 0$ automatically

$$\mathcal{A} \approx -\frac{e\left(|\lambda^L_{ia}|^2 + |\lambda^R_{ia}|^2\right)}{192\pi^2 M^2}\left(-3\log(x_i\epsilon_a) - \frac{x_i+3}{1-x_i}\log\frac{x_i^{-1}-1}{\sqrt{\epsilon_a}}\right)$$

Typically, the resulting scattering rate is a few orders weaker than the current sensitivity. For M=100 GeV,

$$\mathcal{A}/\left(|\lambda^L_{ia}|^2 + |\lambda^R_{ia}|^2\right) \sim \mathcal{O}(10^{-7})\text{GeV}^{-2}.$$

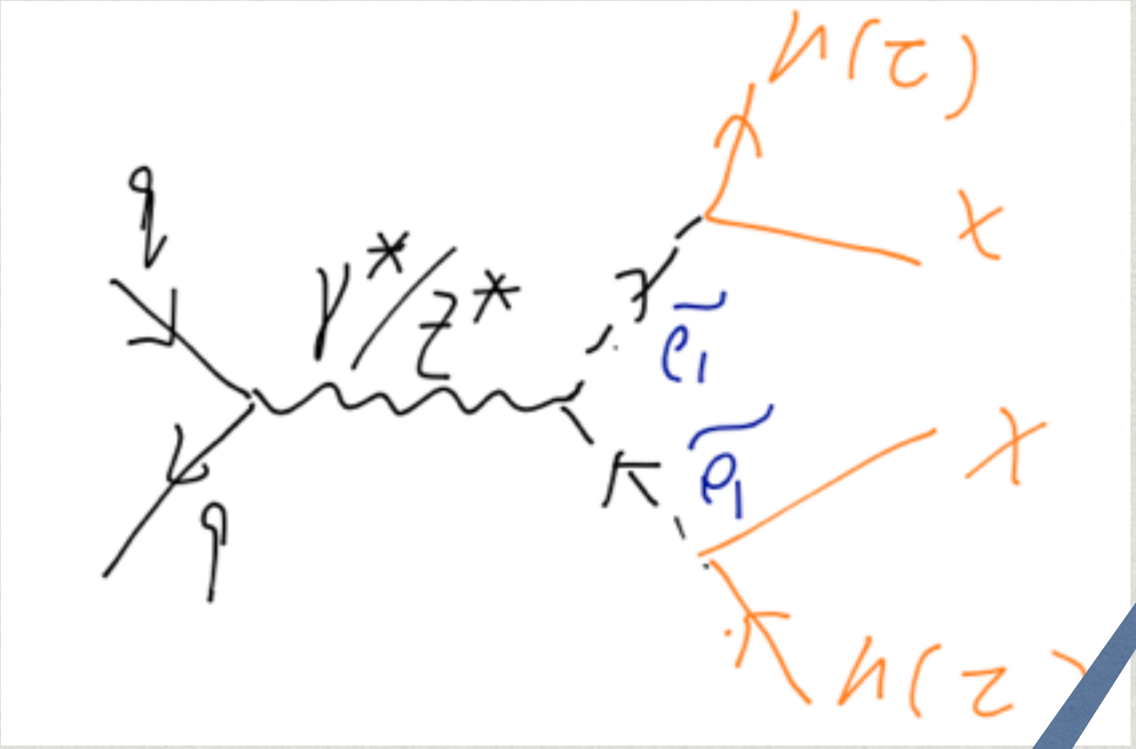


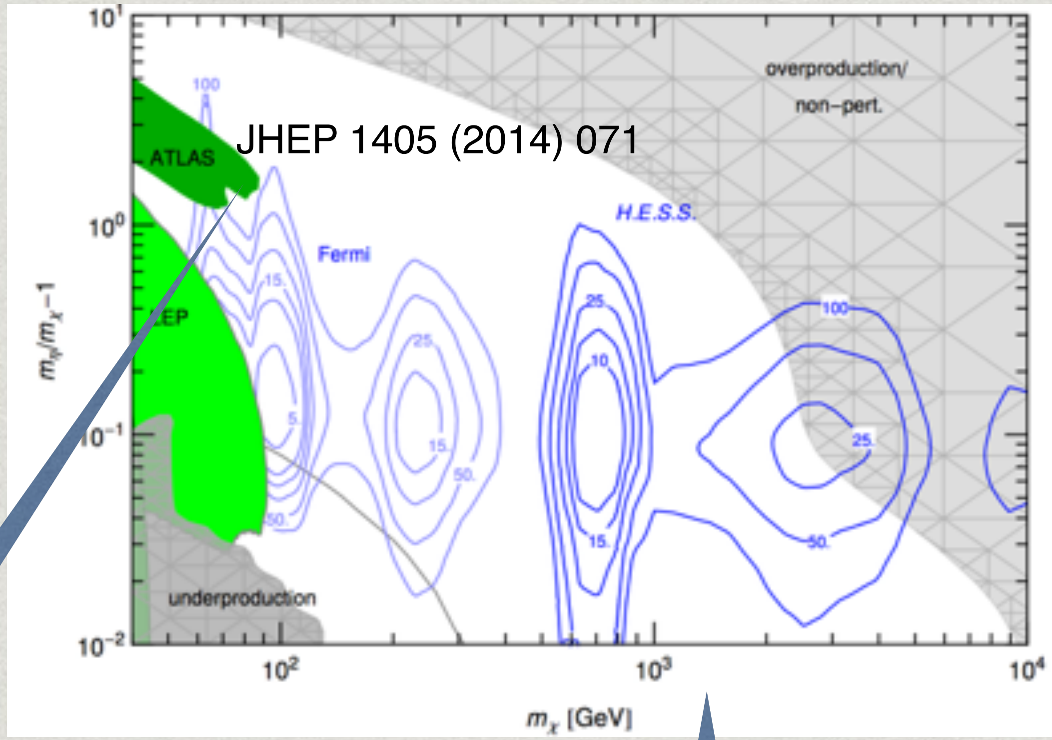
J. Kopp, L. Michaels and J. Smirnov, JCAP 1404, 022 (2014).

HLFV from lepton-flavored DM

- Dilepton+MET at LHC

  Similar to slepton search at LHC, but here the final states can be a pair of μ or τ or $\mu+\tau$, depending on the choice of parameters





Demonstration for the opposite sign di-muon case from the right-handed sumon, reaching 250 GeV only

Only sensitive to mildly large mass splitting>100 GeV, otherwise the resulting lepton is too soft

Conclusions

- LFV is an established fact from neutrino oscillation, but its effect in the SM is undetectable. Therefore any observation of LFV definitely means new physics.
- At the LHC era it is of interest to investigate LFV in Higgs decays. And the current data might give interesting hints.
- It is hard to obtain large HLFV confronting CLFV. In this talk we relate radiative HLFV with lepton-flavored dark matter and find it could naturally provide HLFV $Br(h \to \tau\mu) \sim 1\%$
- Thank you!