Leptophilic dark matter and h→μτ

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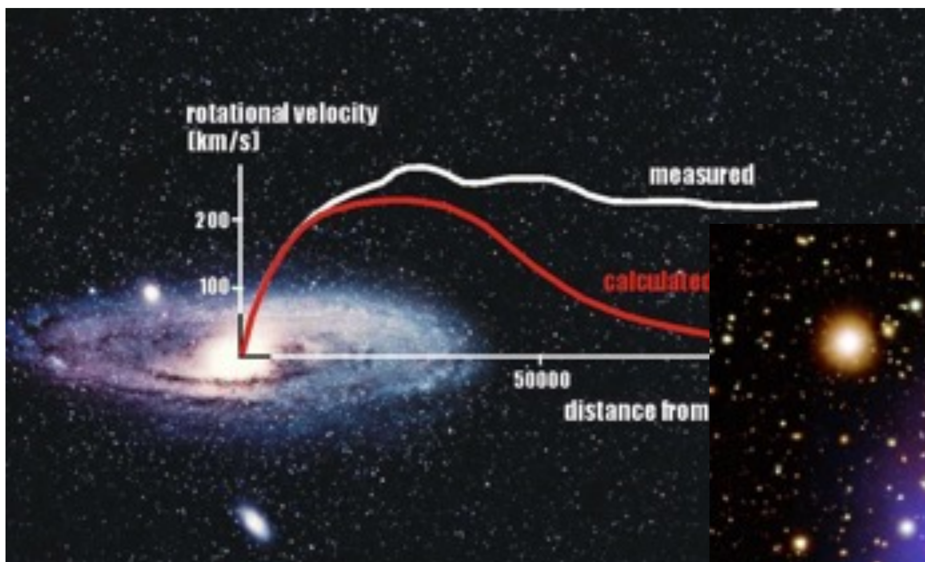
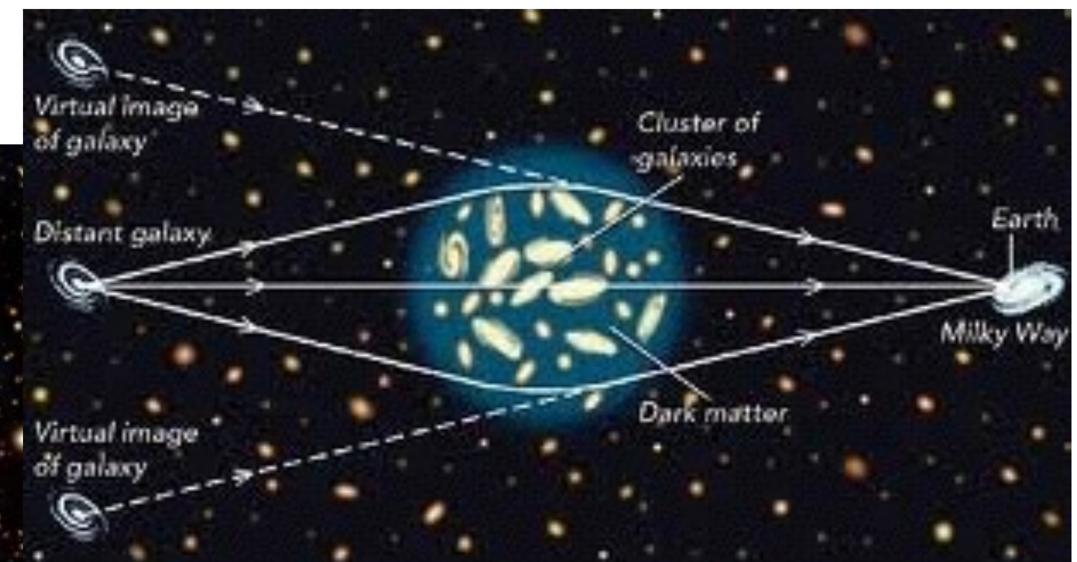
University of Bergen

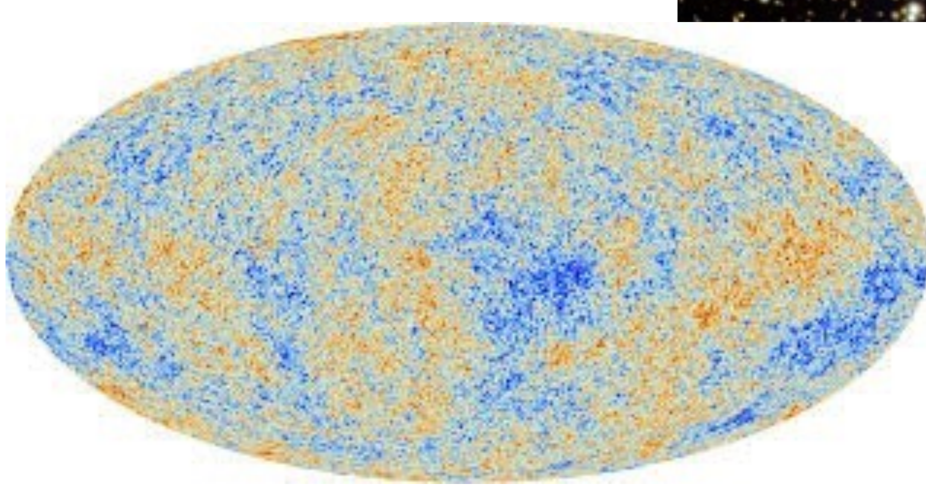
Based on
SB, Zhao-Feng Kang, JHEP1603(2016) 106 [arXiv:1510.00100]
SB, Takaaki Nomura, Hiroshi Okada, PLB759(2016) 91 [arXiv:1604.03738]

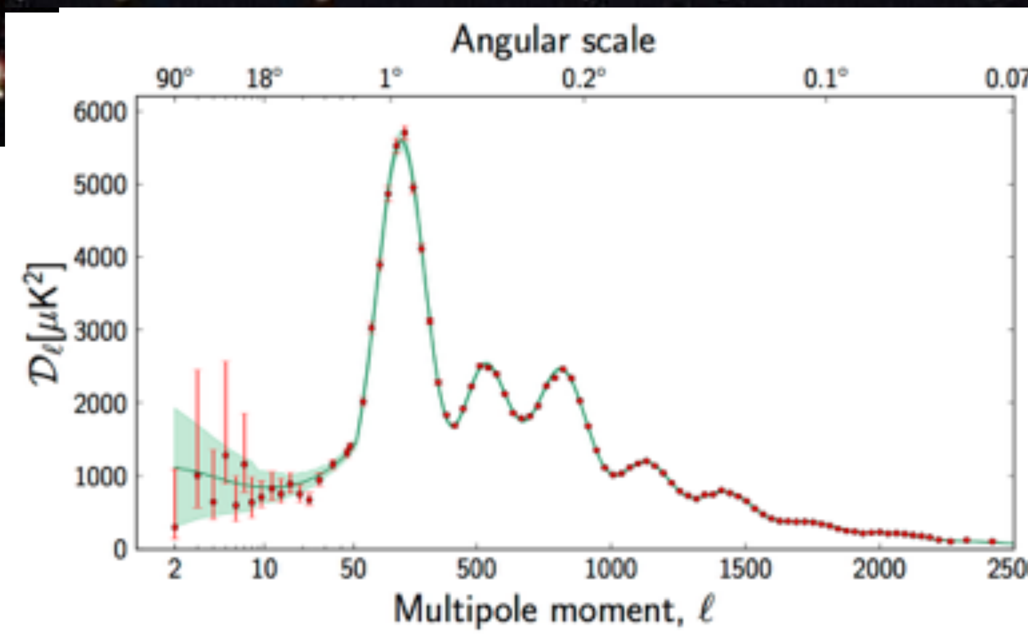
Dark Matter

- What is nature of dark matter?
- How does it interact with each other or with the SM particles?



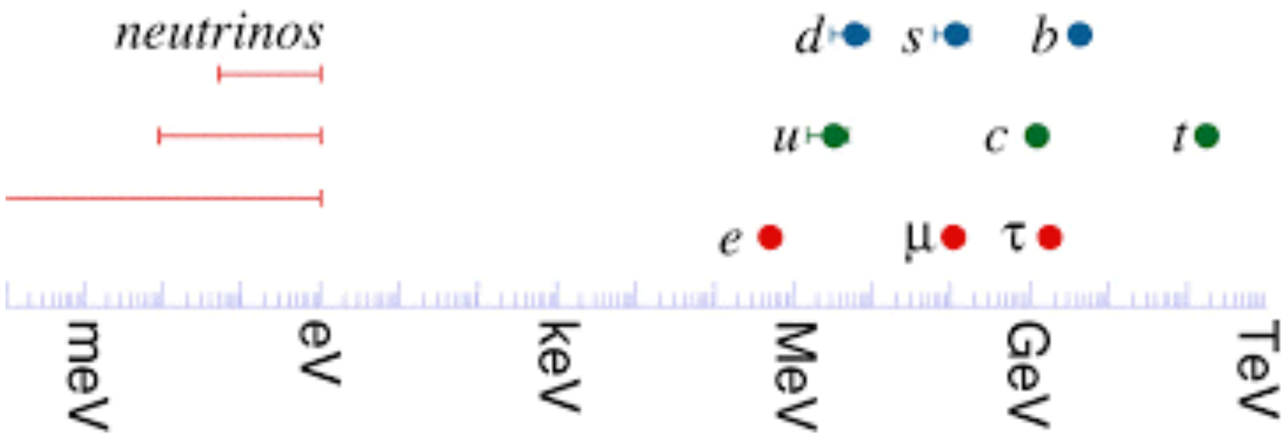






Neutrinos

- Why are neutrinos so light?



LFV Higgs decay

- CMS reported 2.4σ excess, using 19.7fb^{-1} at $\sqrt{s} = 8$ TeV,

$$\mathcal{B}(h \to \mu\tau) = (0.84^{+0.39}_{-0.37})\%$$

$$\mathcal{B}(h \to \mu\tau) < 1.51\% \ @95\% CL$$

CMS cn, arXiv:1502.07400

- ATLAS result with similar dataset is consistent with CMS

ATLAS cn, arXiv:1508.03372

$$\mathcal{B}(h \to \mu\tau) = (0.77 \pm 0.62)\%$$

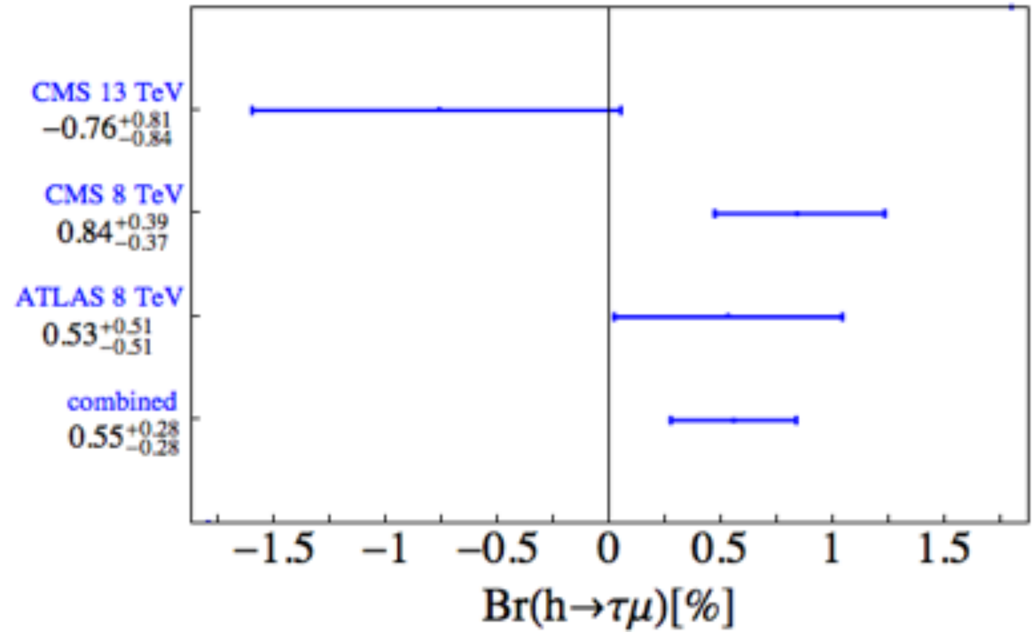
$$\mathcal{B}(h \to \mu\tau) < 1.85\% \ @95\% CL$$

- CMS with 13 TeV data of 2.3fb^{-1}

$$\mathcal{B}(h \to \mu\tau) = (-0.76 \pm 0.81)\%$$

$$\mathcal{B}(h \to \mu\tau) < 1.20\% \ @95\% CL$$

CMS PAS HIG-16-005



- LHC Run II can probe down to ~10^{-3}

LFV Higgs decay

- Although LFV Higgs decay is allowed in the SM at loop-level, this process is highly suppressed by small neutrino masses and GIM mechanism.

- Measurement of LFV Higgs decay → New Physics

muon (g-2)

- ~3 σ deviation from the SM

F. Jegerlehner, A. Nyffeler (2009);
M. Benayoun, et.al.(2012)

$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = (295 \pm 88) \times 10^{-11}$$

- To address these issues simultaneously, we considered leptophilic DM models.

Model 1

	N	φ_l	φ_e
$SU(2)_L$	1	2	1
$U(1)_Y$	0	1/2	-1
Z_2	-	-	-

- N: SM-singlet Majorana fermion, which we assume DM candidate
- φ_l, φ_e: scalar doublet, and singlet

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

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

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$$

leptophilic DM portal

H→μτ

$$
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$$

Neutrino masses

- The model has all the ingredients for radiative neutrino mass generation a la Ma model

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

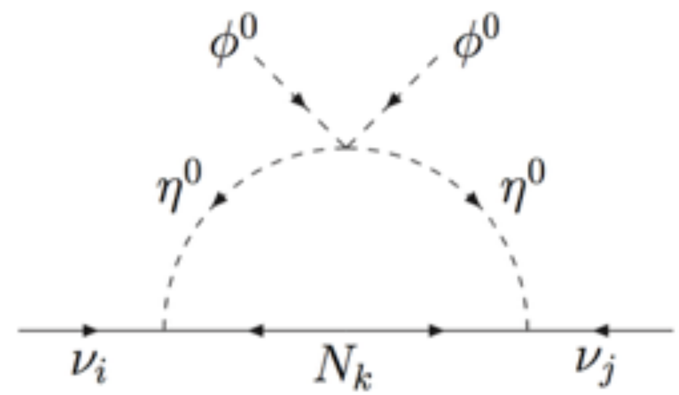


FIG. 5: One-loop scotogenic neutrino mass.

Ma, 0905.0221

LFV Higgs decay, H→μτ

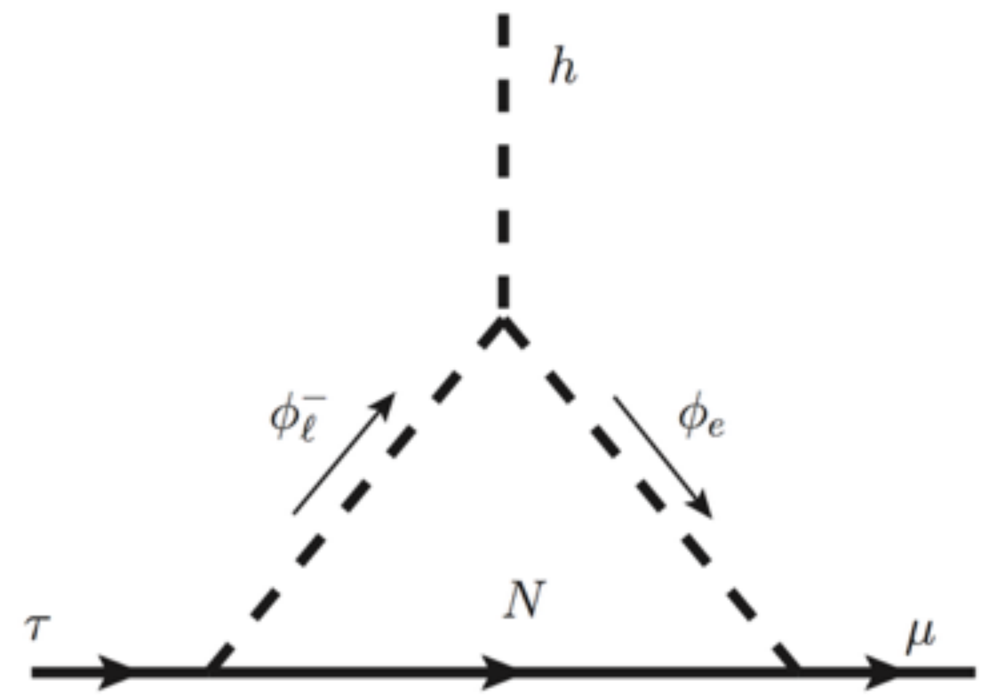
$$i\mathcal{M} = +i\bar{u}_b\left(F_L P_L + F_R P_R\right) v_a$$

$$\boxed{F_L \simeq \frac{1}{16\pi^2}\frac{\mu}{\sqrt{2}M_\alpha} y_{Rb\alpha} y^*_{La\alpha}\left[\frac{1}{2}\sin^2 2\theta\left(G(x_1)+G(x_2)\right)+\cos^2 2\theta\, G(x_1,x_2)\right]}$$

- θ: mixing angle of charged scalars φ_l^-, φ_e

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

- Large μ can enhance the LFV H decay either
in the decoupling regime (θ ≪1)
or
in the maximal mixing regime (θ≈π/4)



LFV Higgs decay, H→μτ

- Decoupling limit

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

- Maximal mixing

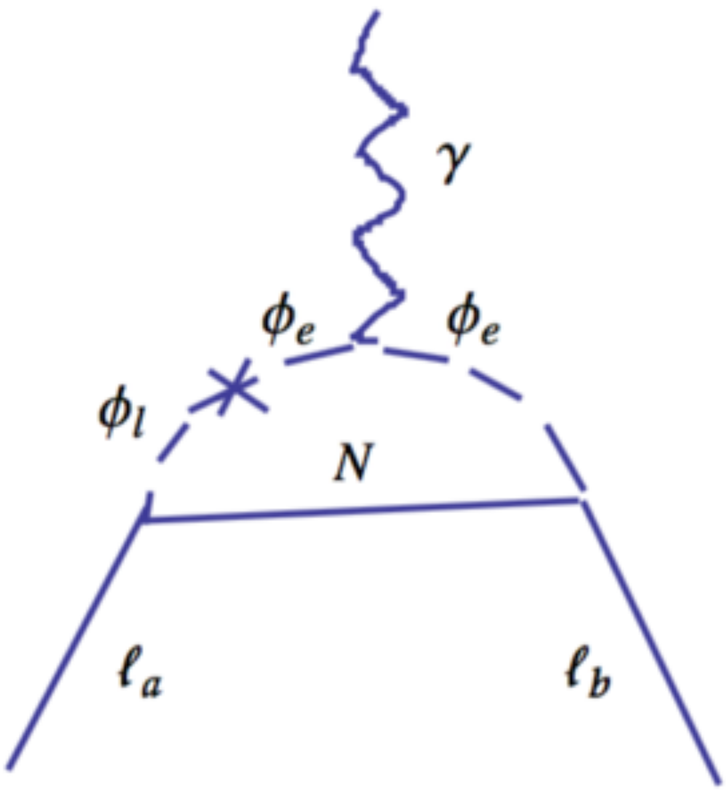
$$\mathrm{Br}(h \to \bar{\tau}\mu) = 1.2 \times 10^{-2} \left(\frac{\mu}{10\mathrm{TeV}}\right)^2 \left(\frac{1\mathrm{TeV}}{M}\right)^2 \left(\frac{G(x_1) + G(x_2)}{0.4}\right)^2 \left(\frac{|y_{R\tau} y^*_{L\mu}|}{0.5}\right)^2$$

$\tau \to \mu\gamma$ constraint

- $B(\tau \to \mu\gamma) < 4.4 \times 10^{-8}$

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

$$\boxed{C_L = \frac{e}{32\pi^2 M} y_{L\mu} y^*_{R\tau} s_\theta c_\theta \left(F_2(x_1) - F_2(x_2)\right)}$$



- $\tau \to \mu\gamma$ is easily suppressed in the decoupling regime, $C_L \to 0$ if $\theta \to 0$.

- Fine-tuning is required in the maximal mixing case

h→γγ constraint

- Effective operator: $\mathcal{L}_{\rm eff} = r_\gamma \frac{\alpha}{\pi v} h F_{\mu\nu} F^{\mu\nu}$

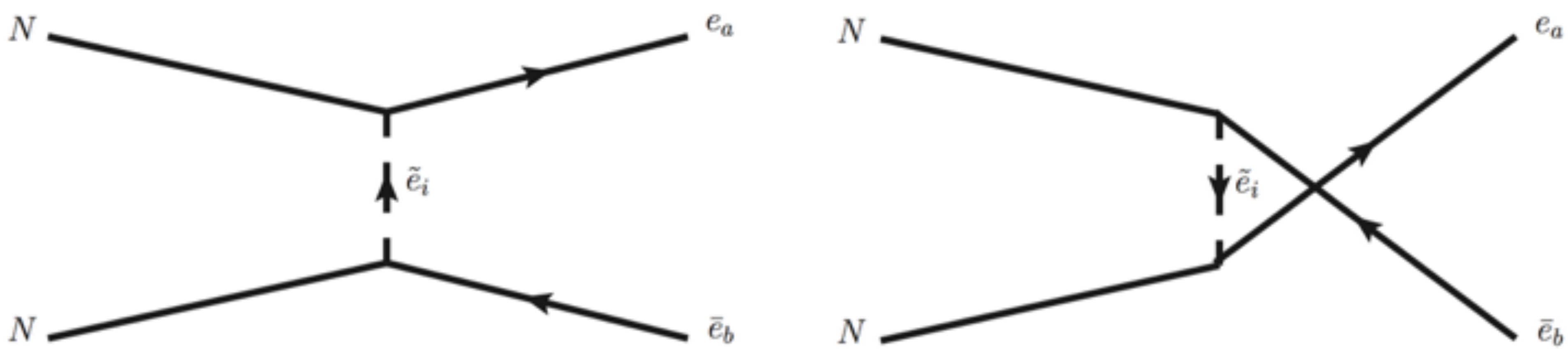
$$r_\gamma = r_{\rm SM,\gamma} + \delta r_\gamma \approx -0.81 + \frac{1}{24}\frac{v\mu\sin 2\theta}{2m_{\tilde{e}_1}^2}$$

$$-0.05 \lesssim \delta r_\gamma / r_{\rm SM,\gamma} \lesssim 0.20, \quad -2.20 \lesssim \delta r_\gamma / r_{\rm SM,\gamma} \lesssim -1.95 \qquad \text{at } 68.3\% \text{ C.L.}$$

$$-2.8 \times \left(\frac{m_{\tilde{e}_1}}{300\text{GeV}}\right)^2 \text{TeV} \lesssim \mu \sin 2\theta \lesssim 0.7 \times \left(\frac{m_{\tilde{e}_1}}{300\text{GeV}}\right)^2 \text{TeV},$$

$$28 \times \left(\frac{m_{\tilde{e}_1}}{300\text{GeV}}\right)^2 \text{TeV} \lesssim \mu \sin 2\theta \lesssim 31 \times \left(\frac{m_{\tilde{e}_1}}{300\text{GeV}}\right)^2 \text{TeV},$$

Relic density of DM



$$\sigma v_r \approx a + b v_r^2$$

$$\Omega h^2 \approx \frac{0.88 \times 10^{-10} x_f \mathrm{GeV}^{-2}}{g_*^{1/2}(a + 3b/x_f)}$$

- In our case, s-wave annihilation is allowed

$$a \approx \frac{1}{64\pi M^2} \sin^2 2\theta \left(|y_{La}y_{Rb}|^2 + |y_{Ra}y_{Lb}|^2\right) \sum_i \frac{1}{(1+x_i)^2}.$$

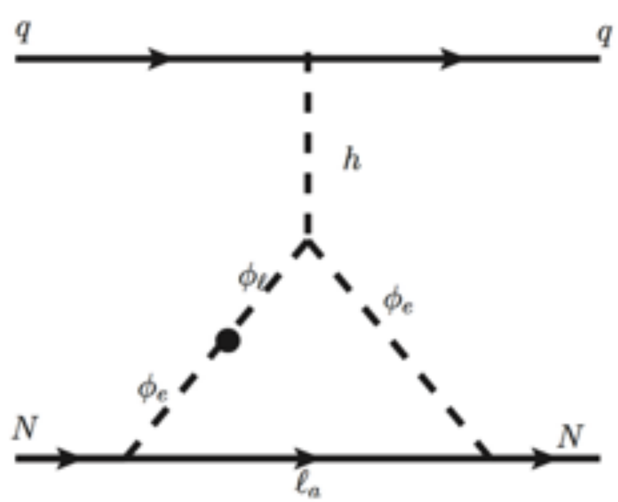
$$\boxed{a \simeq 0.8 \times \left(\frac{400\,\mathrm{GeV}}{M}\right)^2 \left(\frac{\sin^2\theta}{0.1}\right) \frac{\left(|y_{La}y_{Rb}|^2 + |y_{Ra}y_{Lb}|^2\right)}{1.0} \mathrm{pb}}$$

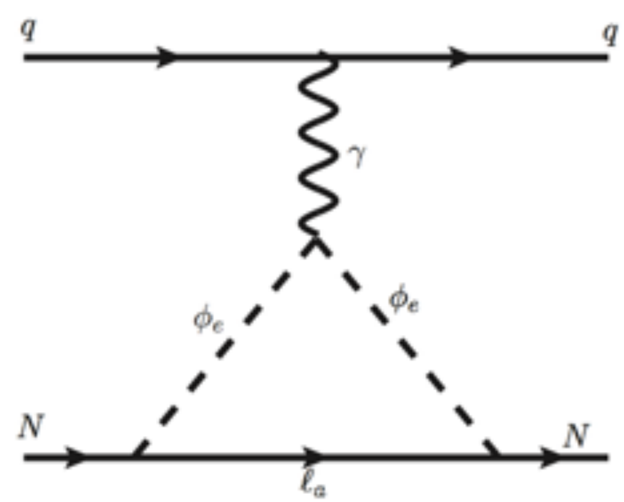
and the correct relic density is obtained in the decoupling regime

Direct DM detection

- DM-nucleon scattering is absent at tree-level.
- At one-loop, DM can interact with nucleon via Higgs or photon exchange.

$\mathcal{O}_h = \lambda_{hN}(0) h \bar{N} N$ $\qquad$ $\mathcal{O}_A = \mathcal{A} \bar{N} \gamma^\mu \gamma^5 N \partial^\nu F_{\mu\nu}$





$O(10^{-2})$ $\qquad$ $O(10^{-4})$

of current LUX bound $\sigma^p_{\mathrm{SI}} \approx 4.0 \times 10^{-8}\mathrm{pb}$

Model 2

	Lepton Fields			Scalar Fields	
	L_L	e_R	$L'_{L(R)}$	Φ	$S_{1,2}$
$SU(2)_L$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$
$U(1)_Y$	$-\frac{1}{2}$	-1	$-\frac{1}{2}$	$\frac{1}{2}$	0
Z_2	$+$	$+$	$-$	$+$	$-$

- S_1 :DM candidate

$$-\mathcal{L}_Y \supset \sum_{\alpha=1,2}\left((y_L^{\alpha})_{ij}\bar{L}_{L_i}L'_{R_j}S_\alpha - \sum_{\beta=1,2}\lambda_{\Phi S_\alpha S_\beta}|\Phi|^2 S_\alpha S_\beta + \text{h.c.}\right)$$

- LFV Higgs decay and CLFV
- Muon g-2
- Neutrino masses
- DM relic density, direct detection
- LHC signature

Model 2

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	L_L	e_R	$L'_{L(R)}$	Φ	$S_{1,2}$
$SU(2)_L$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$
$U(1)_Y$	$-\frac{1}{2}$	-1	$-\frac{1}{2}$	$\frac{1}{2}$	0
Z_2	$+$	$+$	$-$	$+$	$-$

- S_1 :DM candidate

Lepton portal, source of LFV

$$-\mathcal{L}_Y \supset \sum_{\alpha=1,2}\left(\boxed{(y_L^\alpha)_{ij}\bar{L}_{L_i}L'_{R_j}S_\alpha} - \boxed{\sum_{\beta=1,2}\lambda_{\Phi S_\alpha S_\beta}|\Phi|^2 S_\alpha S_\beta} + \text{h.c.}\right)$$

Higgs portal

- LFV Higgs decay and CLFV
- Muon g-2
- Neutrino masses
- DM relic density, direct detection
- LHC signature

DM relic density

X $\equiv S_R$ or S_I Both Higgs and lepton portal diag.

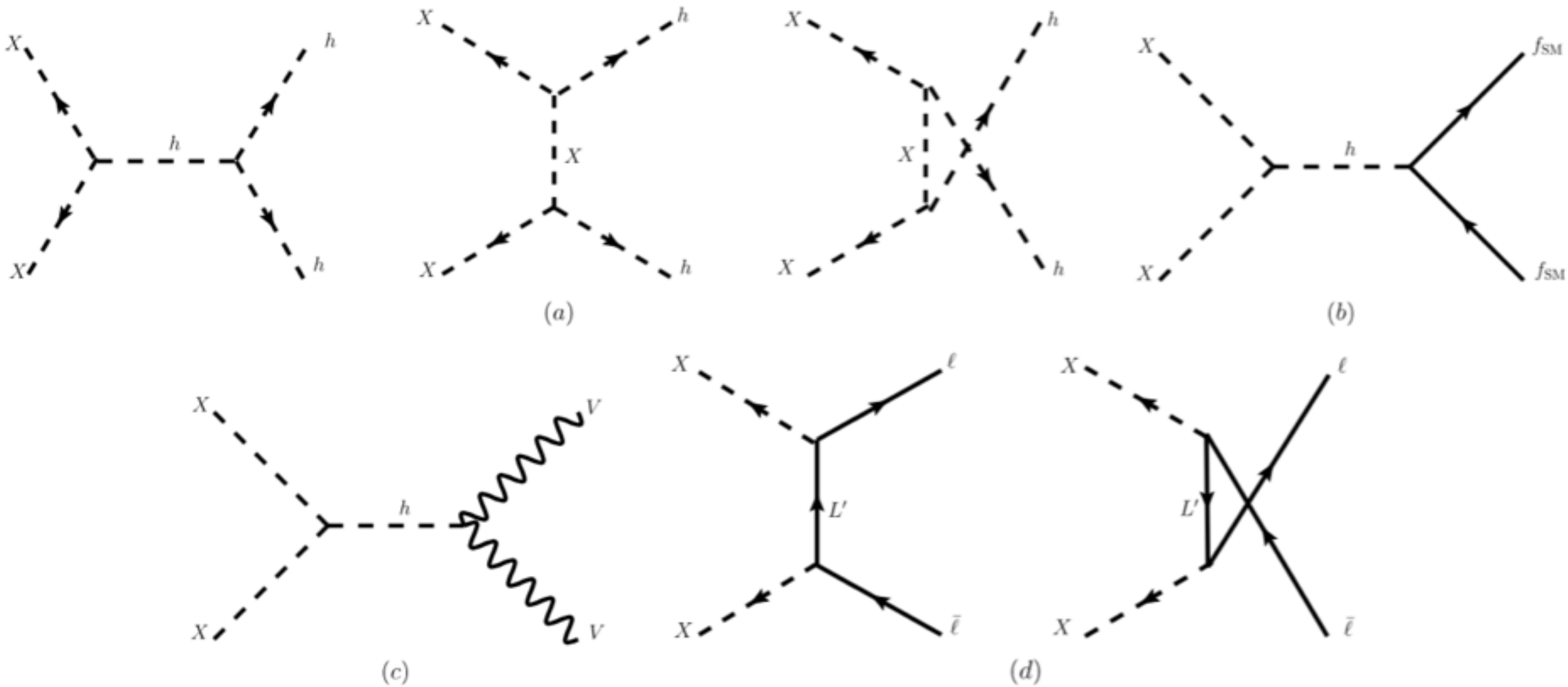
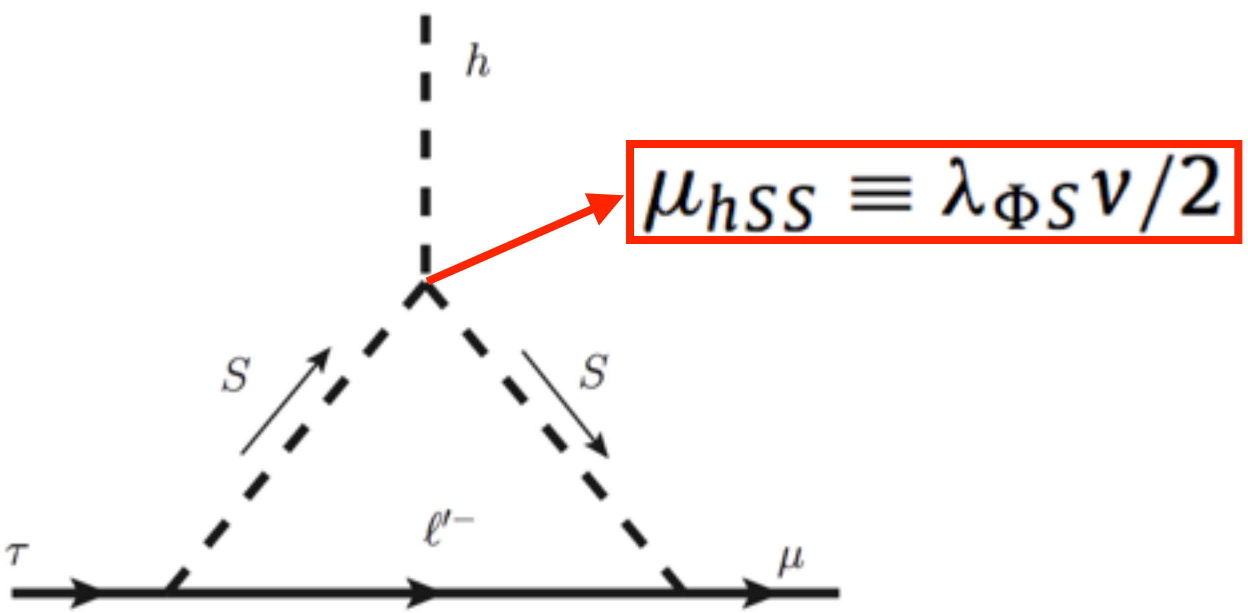
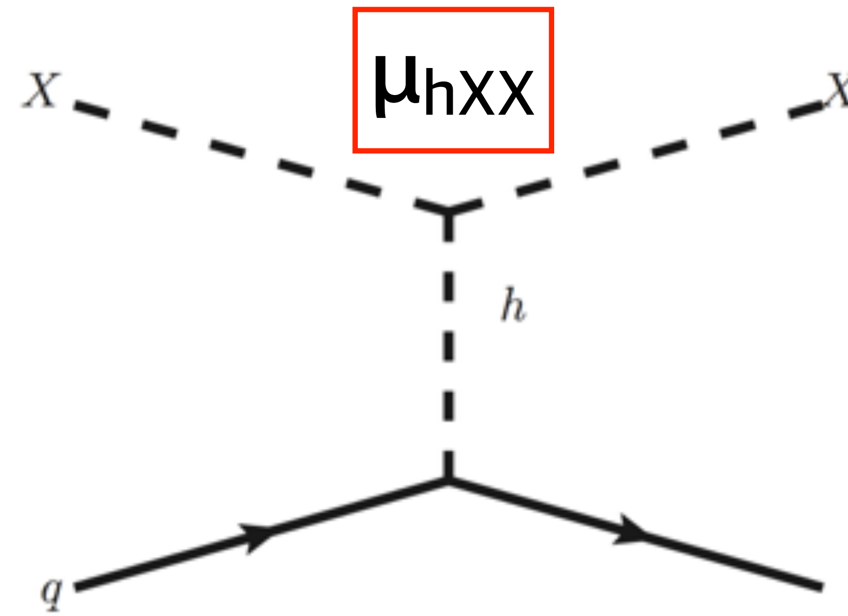


Fig. 2. Feynman diagrams for the DM annihilations.

$h \to \mu\tau$ and direct detection

- Use only Higgs portal interaction

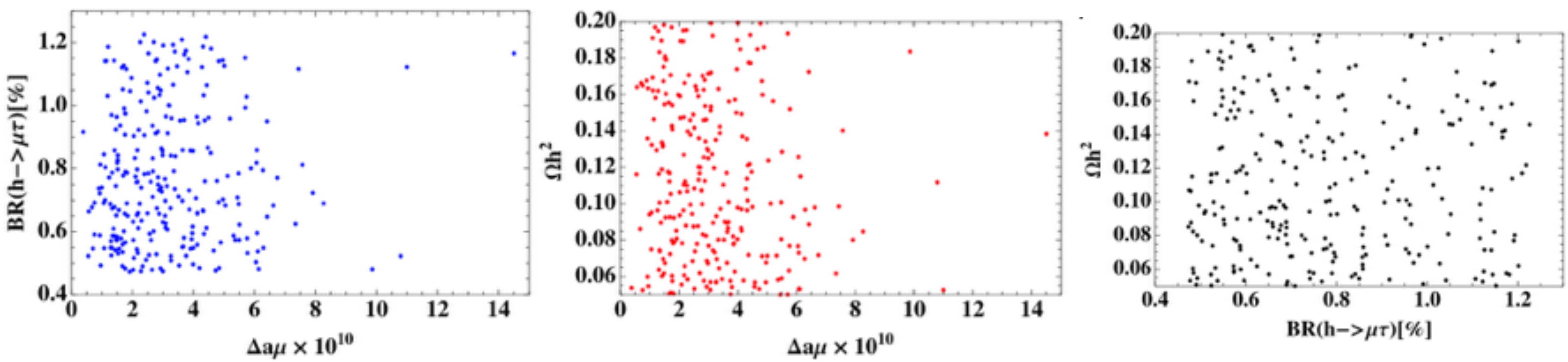




- Constraints from direct detection experiments are too stringent.
- Introduced two scalars $S_{1,2}$

Results

- h→μτ, muon (g-2), relic density satisfying constraints from direct detection and CLFV, and perturbativity.

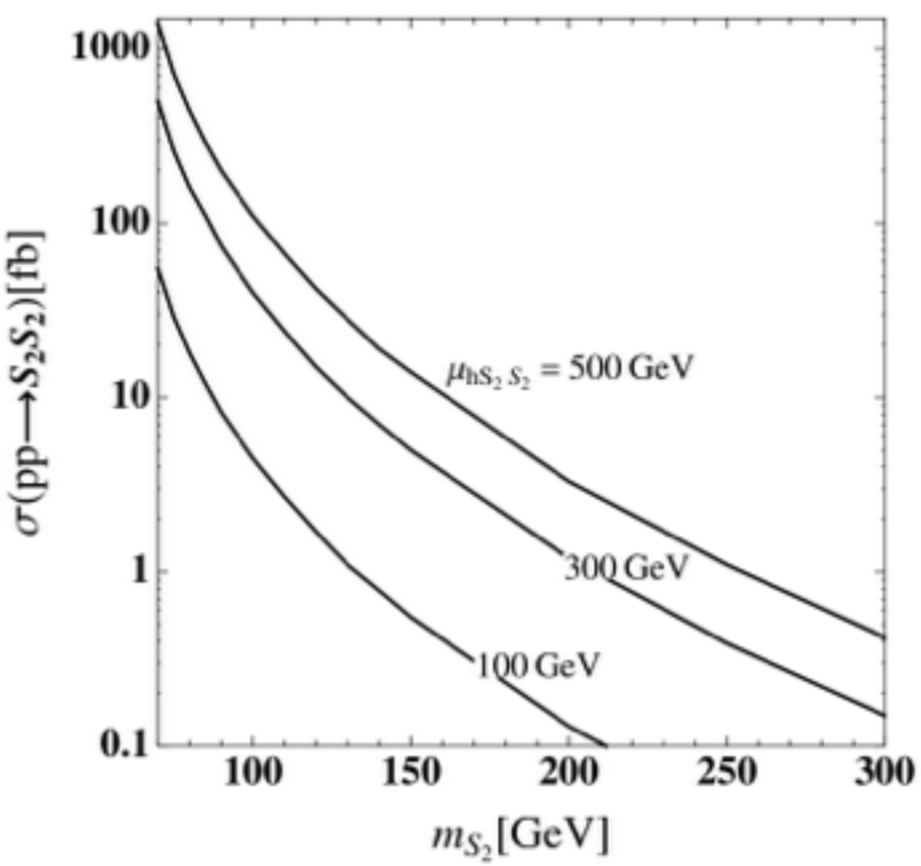


$$M_X \in [100\text{ GeV}, 500\text{ GeV}], \quad \mu_{hSS} \in [50\text{ GeV}, 500\text{ GeV}],$$
$$M_L (= M_{E_i} = M_{N_i}) \in [M_X, \ 1\text{ TeV}],$$
$$(y_L)_{\ell,m} \in [-0.01, 0.01], \ (\ell, m) = ((1,1), (2,1), (3,1)),$$
$$(y_L)_{i,j} \in [-\sqrt{4\pi}, 4\pi], \ (i,j) \neq (\ell, m),$$

- h→μτ, relic abundance, muon (g-2) (@2σ) can be explained.

Collider signature

- S_2 may be searched for at the LHC.
- $gg \to h \to S_2 S_2$ followed by $S_2 \to S_1 h$. The signature is two Higgs boson + missing transverse energy.



Number of expected $hh\cancel{E}_T$ events at the LHC 14 TeV for several values of m_{S_2} and $\mu_{hS_2S_2}$ with luminosity of 100 fb^{-1}.

	$m_{S_2} = 100$ GeV	$m_{S_2} = 200$ GeV	$m_{S_2} = 300$ GeV
$\mu_{hS_2S_2} = 100$ GeV	4.5×10^2	13.	1.7
$\mu_{hS_2S_2} = 200$ GeV	4.0×10^3	1.2×10^2	15.
$\mu_{hS_2S_2} = 300$ GeV	1.1×10^4	3.3×10^2	42.

Conclusions

- Leptophilic dark matter model can explain O(1)% $h \to \tau\mu$ signal.
- $\tau \to \mu\gamma$, $h \to \gamma\gamma$ constraints can be evaded.
- The correct relic density can be obtained.
- Direct detection cross section is typically two-orders of magnitude smaller than the current LUX bound (Model 1); can be evaded by introducing additional scalar (Model 2).
- The new particles can be searched for at the LHC.