NEUTRON STAR HEATING AND THE $(g-2)_\mu$ DISCREPANCY

Maura E. Ramirez-Quezada

In collaboration with: K. Hamaguchi & N. Nagata
arXiv:2204.02413

東京大学 THE UNIVERSITY OF TOKYO

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OUTLINE

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2. DM + $(g-2)_\mu$ and DM capture in NS
3. DM Models for $(g-2)_\mu$: I & II
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$(g-2)_\mu$

Muon g-2 Collab.
arXiv: 2104.03281

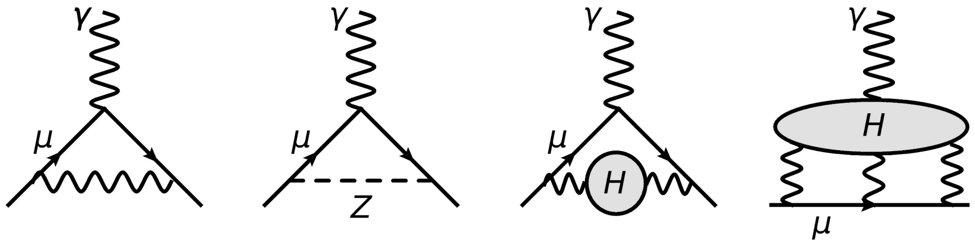
Magnetic moment $\vec{\mu} = g\left(\frac{e}{2m}\vec{s}\right)$

$g = 2$ At tree level

$g \neq 2$ Radiative corrections

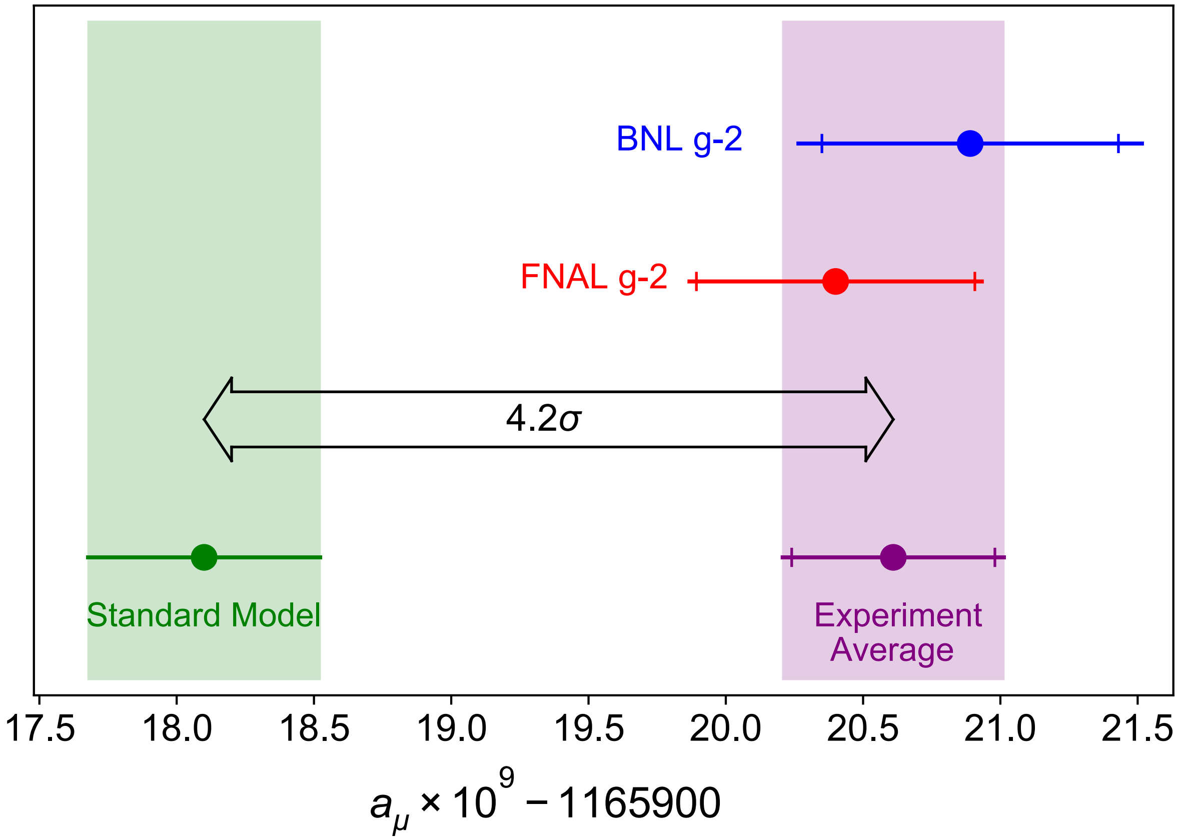
$a_\mu = \frac{g-2}{2}$ anomalous magnetic moment

SM:



Electromagnetic,
Strong,
Weak iterations

$$a_\mu(\mathrm{SM}) = 116591810(43) \times 10^{-11}\ (0.37\mathrm{ppm})$$



$$a_\mu(\mathrm{Exp}) = 116592061(41) \times 10^{-11}\ (0.35\mathrm{ppm})$$

Discrepancy

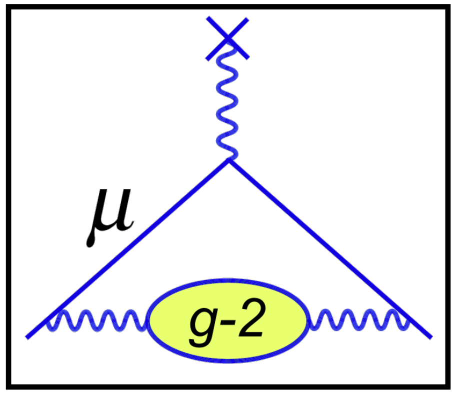
$$\Delta a_\mu = 251(59) \times 10^{-11}$$

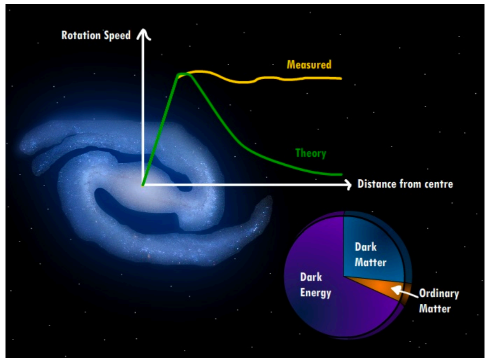
New physics!?

Several BSM scenarios have been proposed in order to explain this discrepancy

- weakly-interacting massive particles (WIMPs) coupling to muons

These scenarios could explain



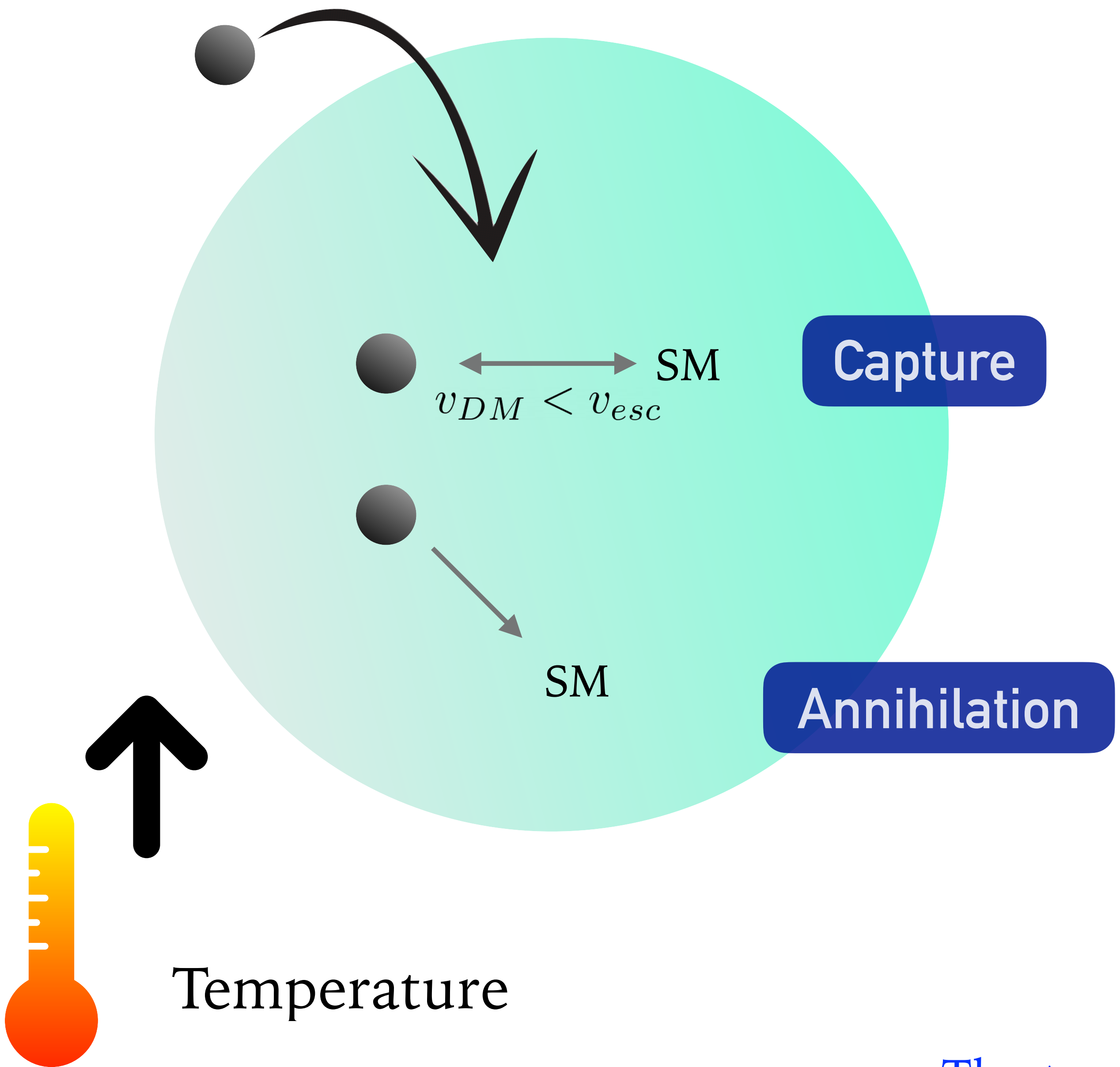


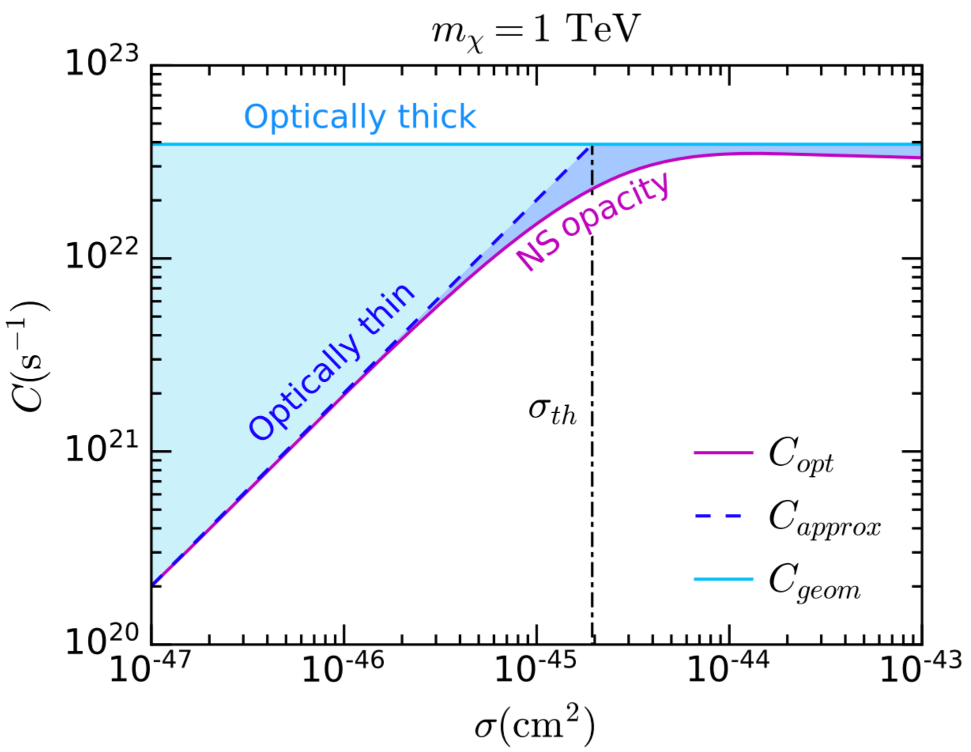
- Large number of possibilities for this class of extension models:

1. Model I: Majorana fermion DM couples to the Higgs field at tree level.
2. Model II: Majorana fermion DM doesn't couples to the Higgs field at tree level.

$$M_\chi \sim 1\,\text{TeV}$$

Considerable regions of parameter space required to explain DM+$(g-2)_\mu$ are beyond the reach of the next-generation DM direct detection experiments





arXiv: 2004.14888

DM heating?

The temperature observation of neutron stars (NSs) offers a promising way to probe these scenarios by means of the DM accretion and annihilation in NS core.

MODEL I

DM-Higgs couples at tree level

$$\mathcal{L}_{\rm int} = \mathcal{L}_{\rm mass} + \mathcal{L}_{\rm Yukawa} + \mathcal{L}_{\rm quart}$$

$$\mathcal{L}_{\rm mass} = -\frac{1}{2}\left(\chi_S, \xi_{D^0}, \eta_{D^0}\right)\mathcal{M}_\chi \begin{pmatrix}\chi_S\\ \xi_{D^0}\\ \eta_{D^0}\end{pmatrix} - M_{F_D}\xi_{D^-}\eta_{D^+} + \text{h.c.}$$

$$-M_{\tilde{e}}^2|\tilde{e}|^2 - M_{\tilde{\nu}}^2|\tilde{\nu}|^2 \quad ,$$

$$\mathcal{M}_\chi = \begin{pmatrix} M_{F_S} & \frac{y_{1H}v}{\sqrt{2}} & \frac{y_{2H}v}{\sqrt{2}} \\ \frac{y_{1H}v}{\sqrt{2}} & 0 & M_{F_D} \\ \frac{y_{2H}v}{\sqrt{2}} & M_{F_D} & 0 \end{pmatrix}$$

$$0 < M_{\chi_1} \leq M_{\chi_2} \leq M_{\chi_3}$$

DM candidate

$$\begin{pmatrix}\chi_S\\ \xi_{D^0}\\ \eta_{D^0}\end{pmatrix} = V_\chi \begin{pmatrix}\chi_1\\ \chi_2\\ \chi_3\end{pmatrix} .$$

Unitary matrix

Two cases

- Singlet-like
  $M_{F_S} < M_{F_D}$
- Doublet-like
  $M_{F_S} > M_{F_D}$

$$\mathcal{L}_{\rm Yukawa} = -\frac{h}{\sqrt{2}}\overline{\psi_i^0}\left[\left(C_{\chi hL}\right)_{ij}P_L + \left(C_{\chi hR}\right)_{ij}P_R\right]\psi_j^0$$

DM -muon interaction

$$-\left\{\overline{\psi_i^0}\left[y_1\left(V_\chi\right)_{1i}P_L + y_2^*\left(V_\chi\right)_{2i}^*P_R\right]\mu\,\tilde{e}^* + \text{h.c.}\right\}$$

$$-\left[y_1\left(V_\chi\right)_{1i}\overline{\psi_i^0}P_L\nu\tilde{\nu}^* - y_2\bar{\mu}P_L\psi^-\tilde{\nu} + \text{h.c.}\right]$$

Field	Spin	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
χ_S	1/2	**1**	**1**	0
ξ_D	1/2	**1**	**2**	−1/2
η_D	1/2	**1**	**2**	1/2
$\widetilde{L}$	0	**1**	**2**	−1/2

MODEL II

DM-Higgs doesn't couple at tree level

DM candidate

$$\mathcal{L}_{\text{mass}} = -\left(\tfrac{1}{2}M_{F_S}\chi_S\chi_S + \text{h.c.}\right) - \left(\widetilde{e}^*,\ \widetilde{\bar{e}}\right)\mathcal{M}_e^2\begin{pmatrix}\widetilde{e}\\ \widetilde{\bar{e}}^*\end{pmatrix} - M_{\widetilde{\nu}}^2\left|\widetilde{\nu}\right|^2$$

Unitary matrix

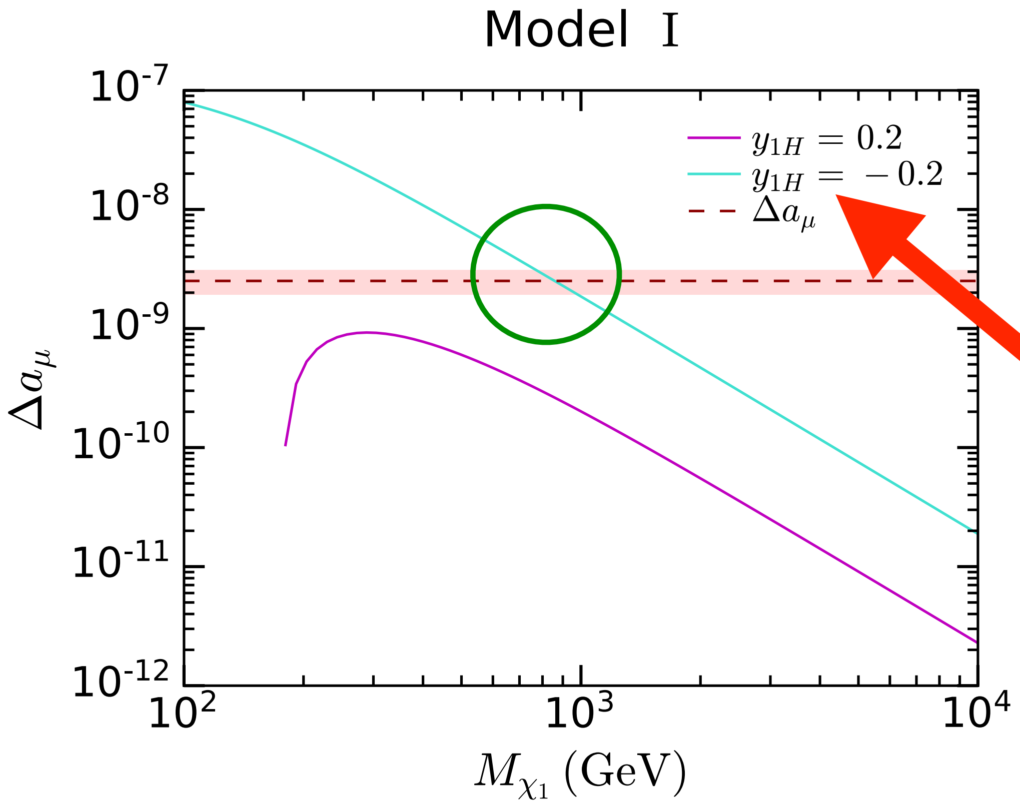
$$\mathcal{M}_e^2 = \begin{pmatrix} M_{\tilde{L}}^2 + \frac{\lambda_L+\lambda_L'}{2}v^2 & \frac{v}{\sqrt{2}}a_H \\ \frac{v}{\sqrt{2}}a_H & M_{\tilde{\bar{e}}}^2 + \frac{\lambda_{\bar{e}}}{2}v^2 \end{pmatrix} \rightarrow \begin{pmatrix}\widetilde{e}\\ \widetilde{\bar{e}}^*\end{pmatrix} = U_e\begin{pmatrix}\widetilde{e}_1\\ \widetilde{e}_2\end{pmatrix}$$

$$\mathcal{L}_{\text{Yukawa}} = -\left\{\overline{\psi^0}\left[y_1\left(U_e\right)_{1i}^* P_L + y_2^*\left(U_e\right)_{2i}^* P_R\right]\mu\,\widetilde{e}_i^* + \text{h.c.}\right\} - \left[y_1\overline{\psi^0}P_L\nu\widetilde{\nu}^* + \text{h.c.}\right]$$

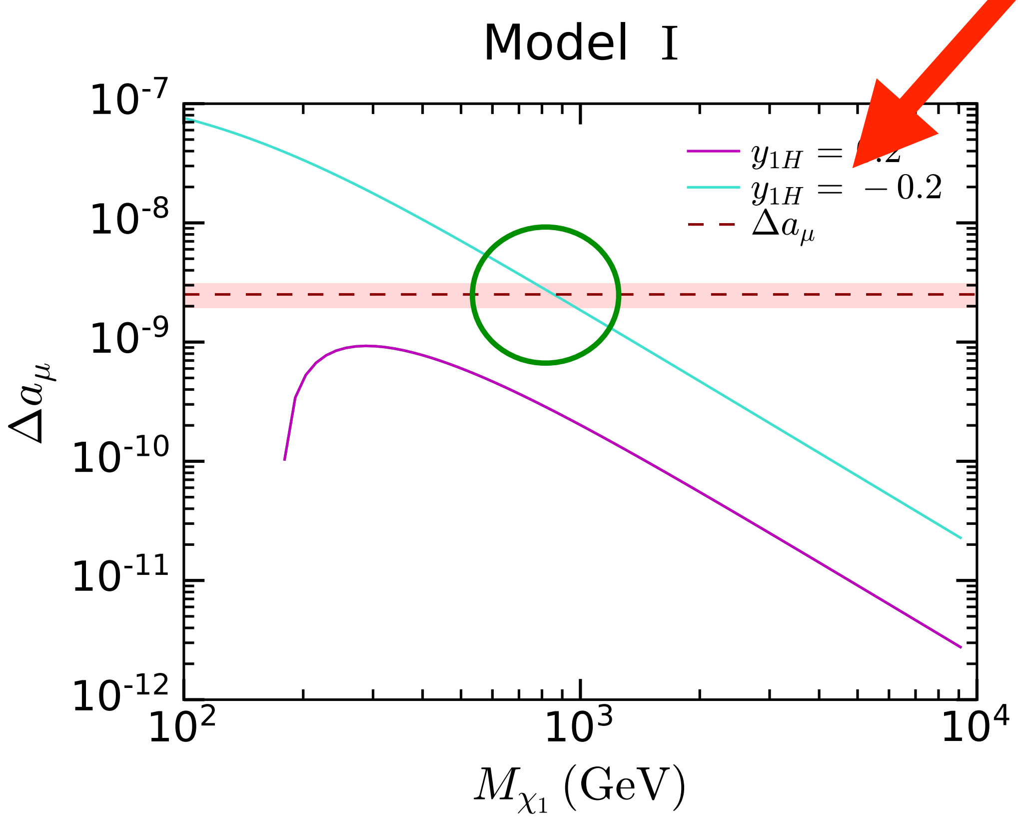
DM -muon interaction

Field	Spin	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
χ_S	1/2	**1**	**1**	0
$\widetilde{L}$	0	**1**	**2**	−1/2
$\widetilde{\bar{e}}$	0	**1**	**1**	1

$(g-2)_\mu$



Singlet-like



Doublet-like

$y_{1H} = -0.2$

$$M_{F_D}/M_{F_S} = 1.1$$

$$M_{F_S}/M_{F_D} = 1.1$$

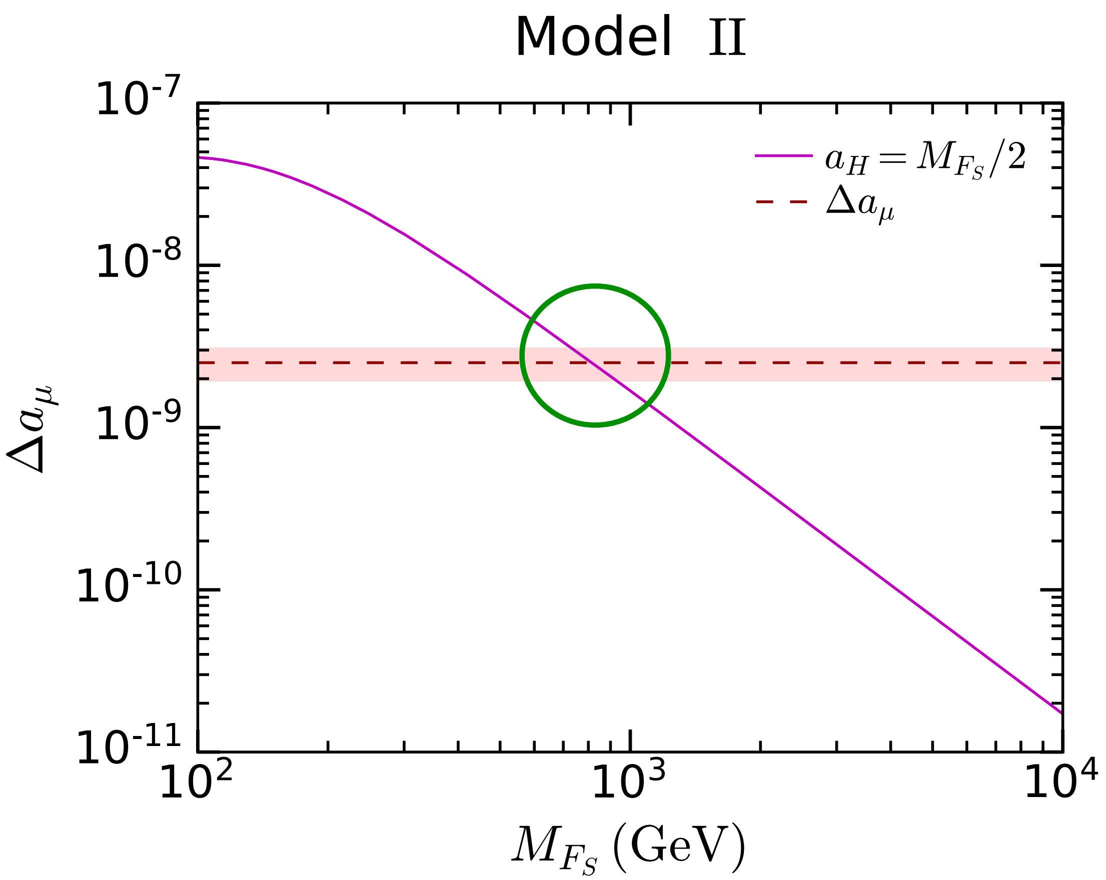
This model could explain the observed discrepancy in the $(g-2)_\mu$ if the DM mass is

$M_{\chi_1} \simeq 800$ GeV Singlet-like

Doublet-like $M_{\chi_1} \simeq 1$ TeV

The relic abundance of χ_1 can coincide with the observed DM density

arXiv: 1804.00009



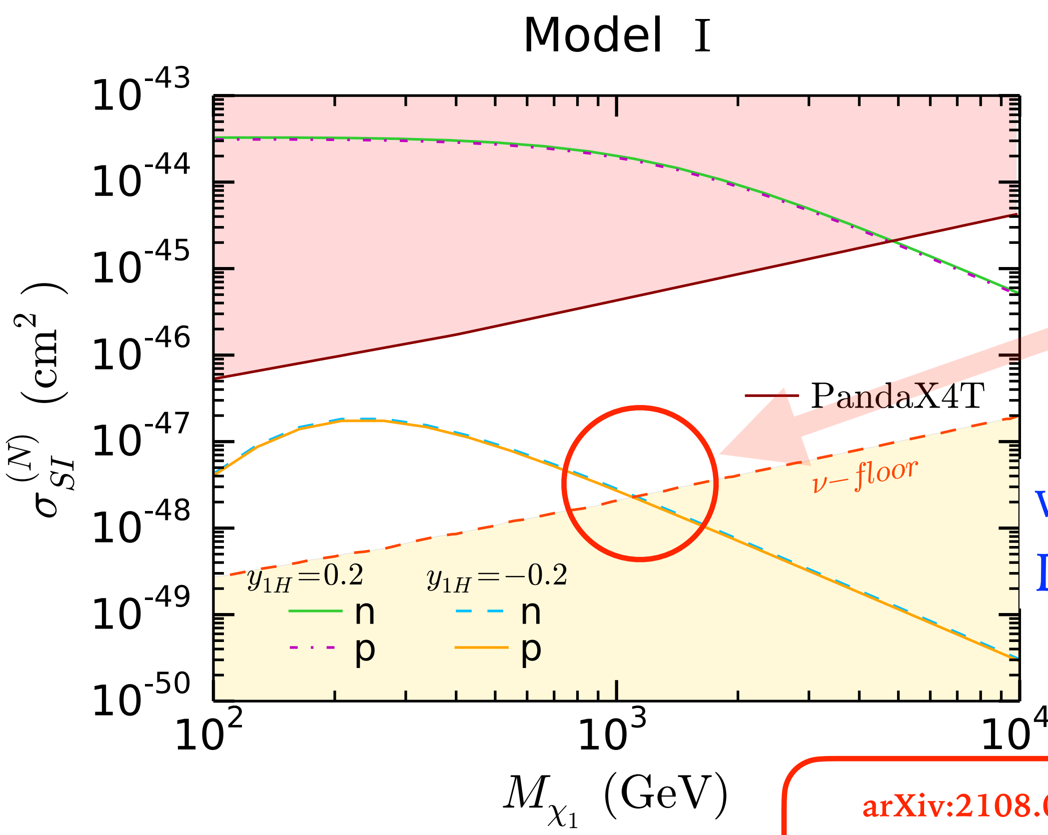
$$M_{\tilde{\tilde{e}}}/M_{F_S} = 1.1$$

The observed deviation in the $(g-2)_\mu$ can be explained if the

$$M_{F_S} =\simeq 800 \text{ GeV}$$

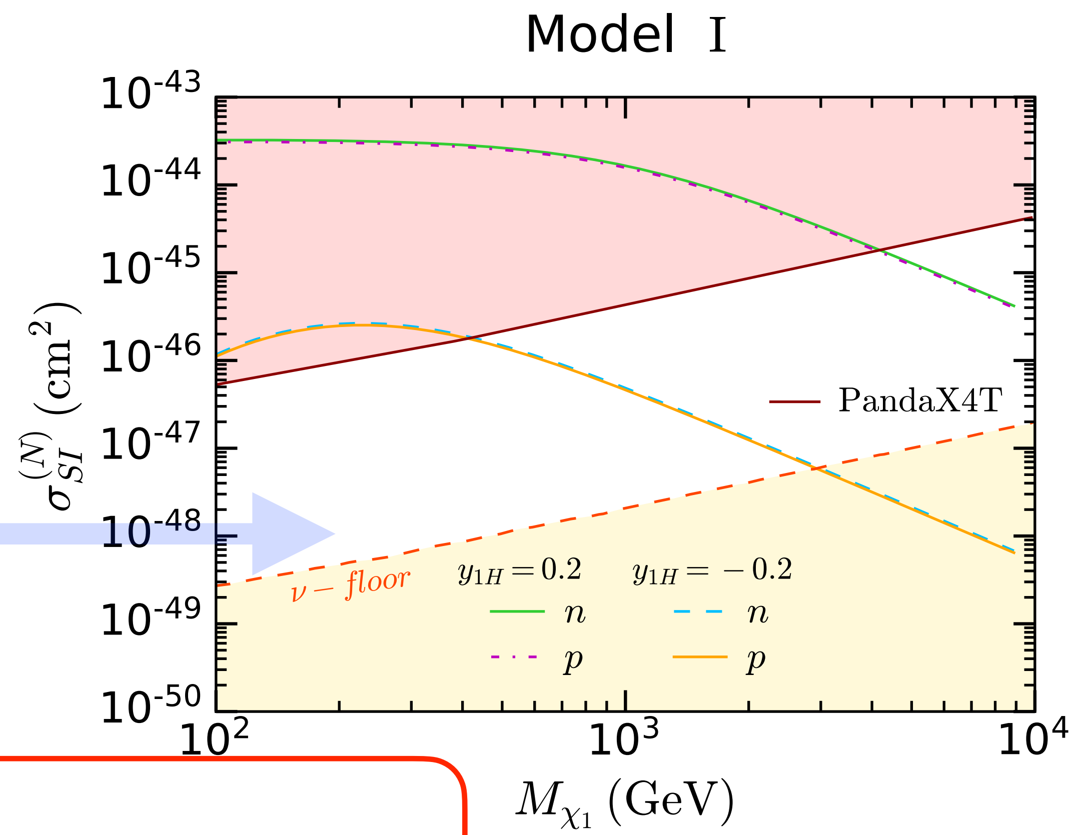
the observed DM density can be explained with this size of the DM mass

arXiv:2002.12534



Complicated for DD experiments

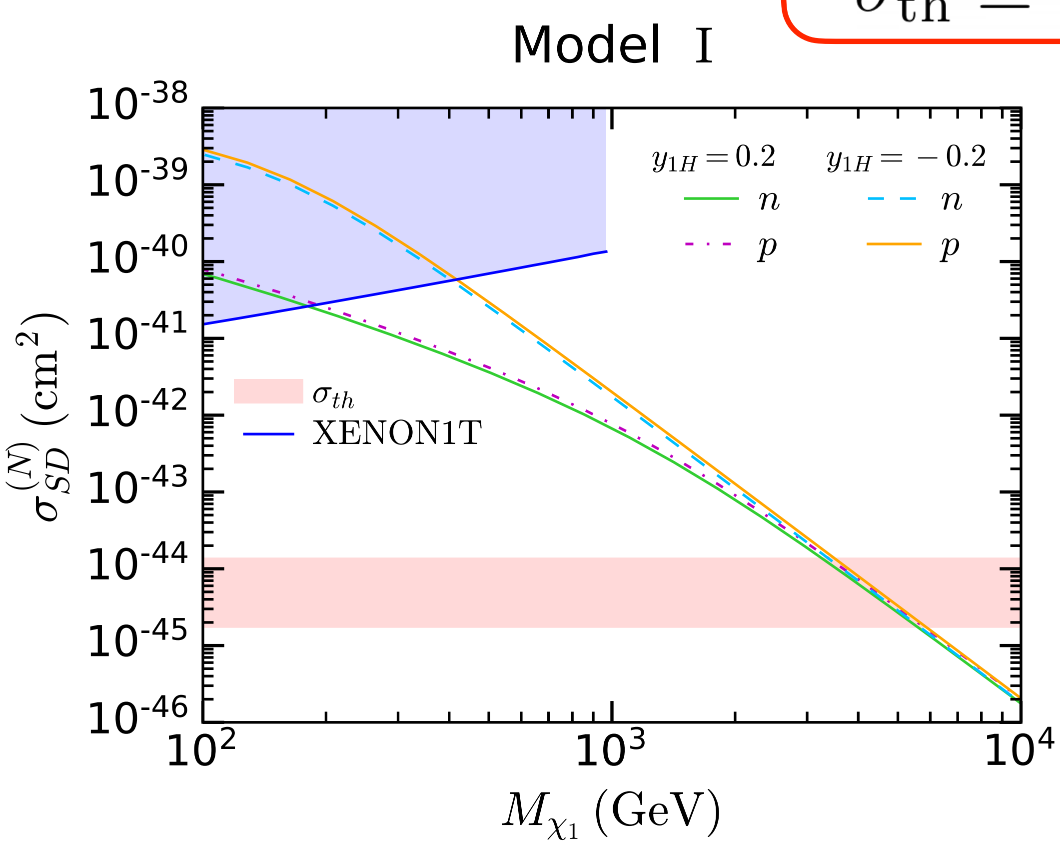
within reach of future DM DD experiments



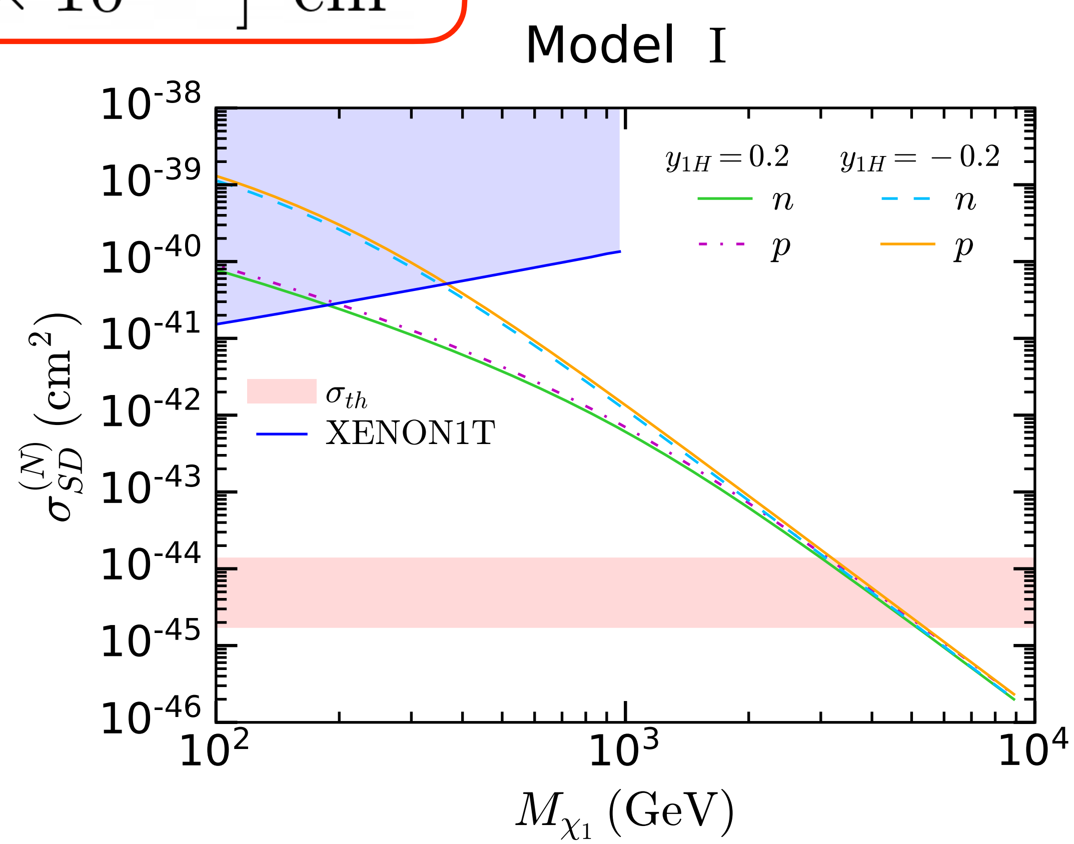
arXiv:2108.02525

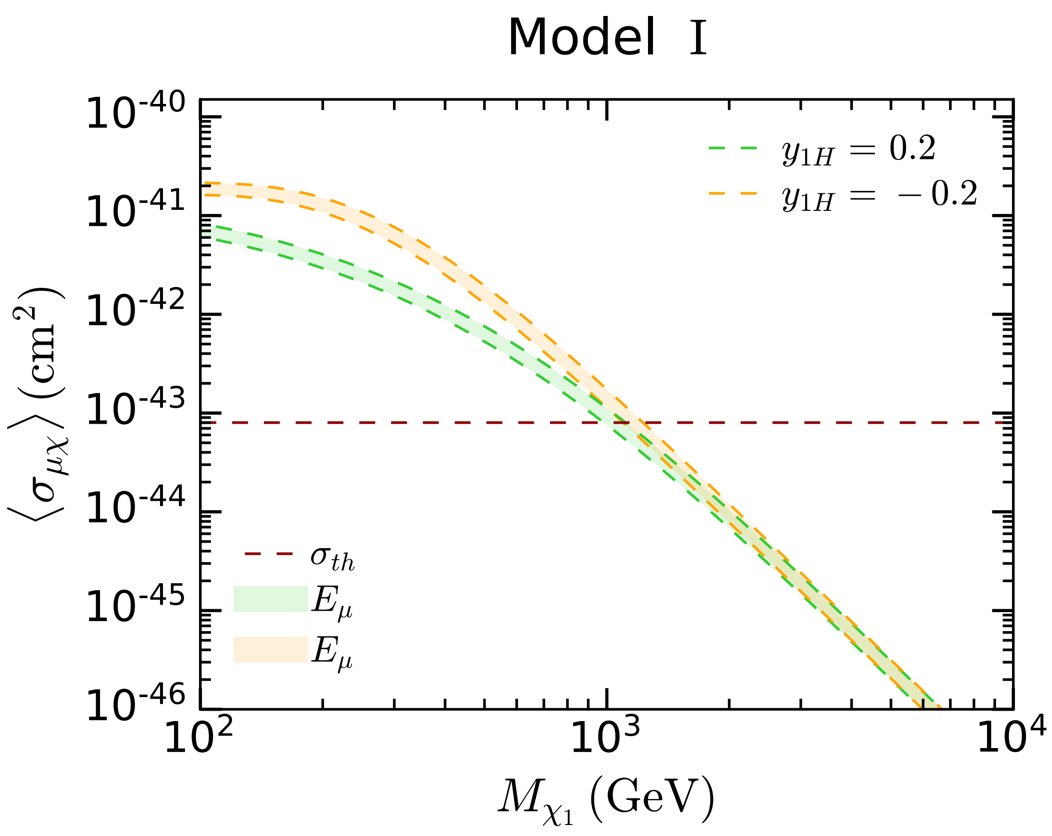
arXiv: 2004.14888

$$\sigma_{\rm th} \simeq [1.7\times 10^{-45}, 1.4\times 10^{-44}]\ \ \mathrm{cm}^2$$

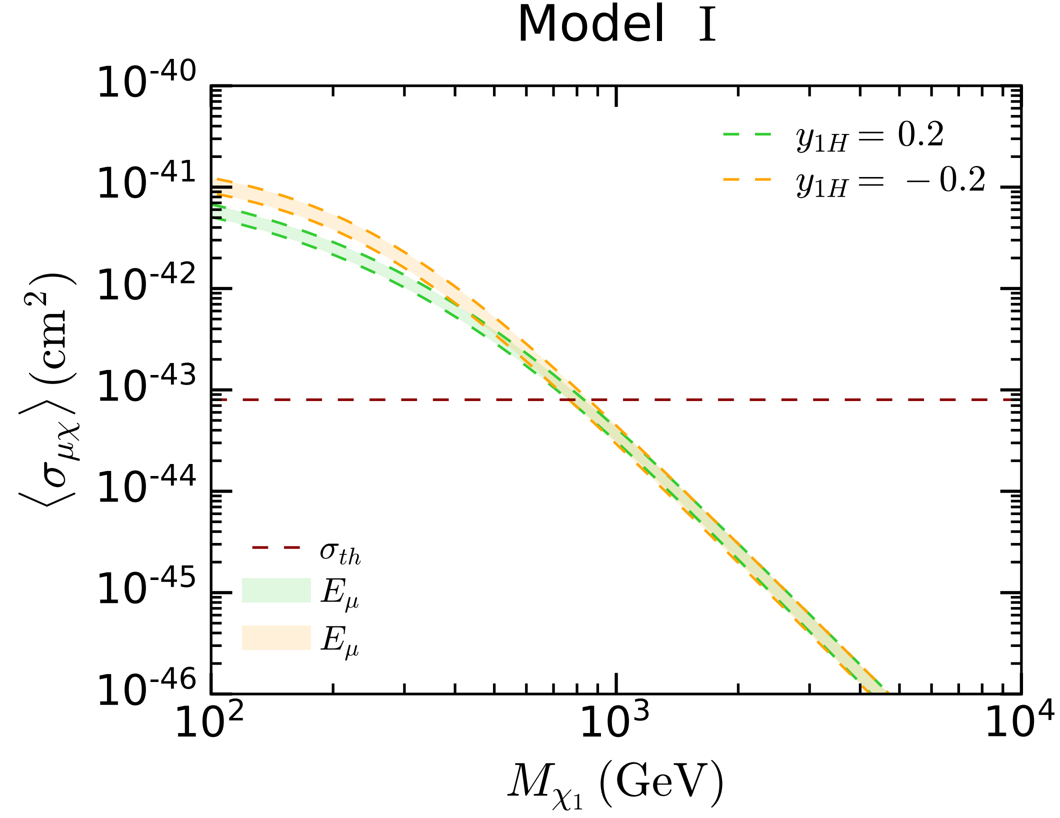


DD limits evaded in the $(g-2)_\mu$ favored parameter regions





Singlet-like



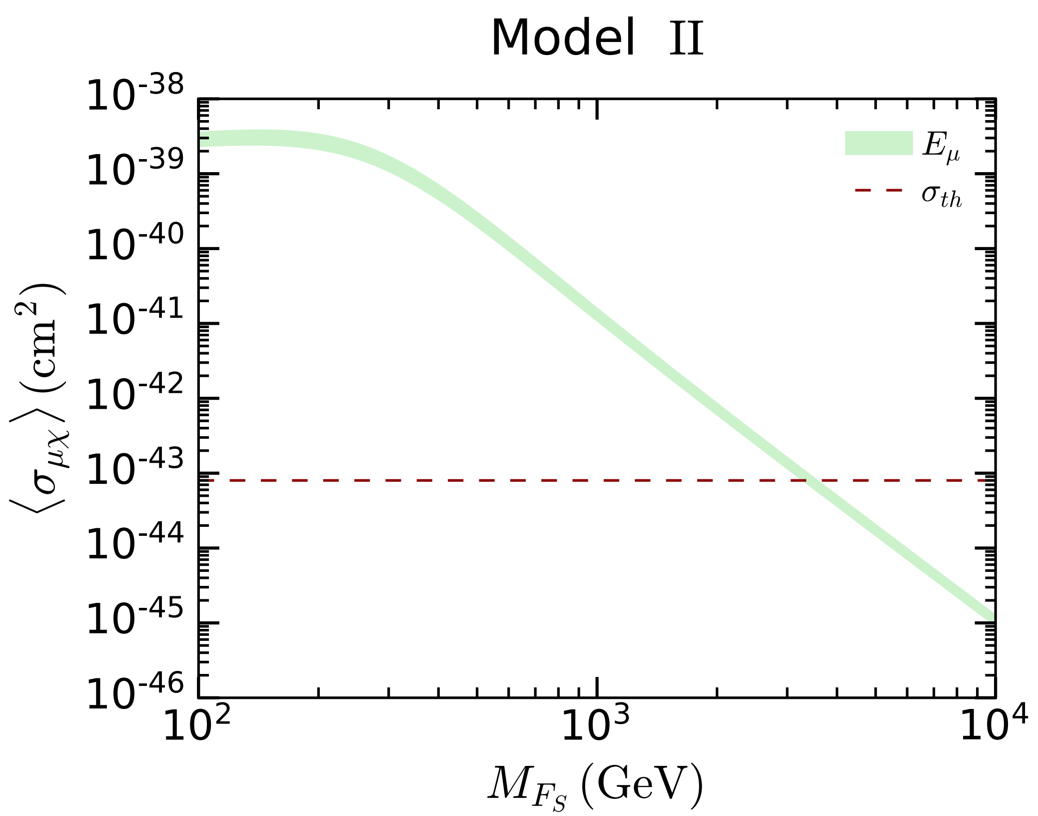
Doublet-like

arXiv: 2010.13257

$\sigma_{\rm th} \simeq 8 \times 10^{-44}$ cm^2

$M_{\rm NS} = 1.5\ M_\odot$

$R_{\rm NS} = 12.593$ km



The DM search using the NS temperature observation might play an important role in testing these scenarios in the future

Effects that are missing

- Nucleon structure
- Nucleon interactions

arXiv:2012.08918

SUMMARY

- We have studied two representative DM models, Model I and II, where WIMP DM particles have renormalizable couplings to muons

  The experimental value of the $(g-2)_\mu$ discrepancy can be explained with a DM mass of ~ 1 TeV

- DM particles from these models efficiently accumulate in NSs - DM-muon scattering cross

  DM capture in NSs is effective and the DM heating operates maximally

Temperature observation of old NSs ***could*** provide a promising way of testing the WIMP DM models for the muon $(g-2)_\mu$ discrepancy

However, despite of using an excellent treatment on the capture rate in NS, it is still very simplified and important effects might impact the capture probability.

THANK YOU

BACKUP

Model I

$$\mathcal{L}_{\text{mass}} = -\left(\frac{1}{2}M_{F_S}\chi_S\chi_S + M_{F_D}\xi_D\eta_D + \text{h.c.}\right) - M_{\tilde{L}}^2|\widetilde{L}|^2 \ ,$$

$$\mathcal{L}_{\text{Yukawa}} = -y_{1H}\chi_S(\xi_D\cdot H) - y_{2H}\chi_S\eta_D H^\dagger - y_1\chi_S L_\mu\widetilde{L}^\dagger - y_2\mu_R^c(\xi_D\cdot\widetilde{L}) + \text{h.c.} \ ,$$

$$\mathcal{L}_{\text{quart}} = -\lambda_L|\widetilde{L}|^2|H|^2 - \lambda_L'\widetilde{L}^\dagger\tau_a\widetilde{L}H^\dagger\tau_a H + \dots \ ,$$

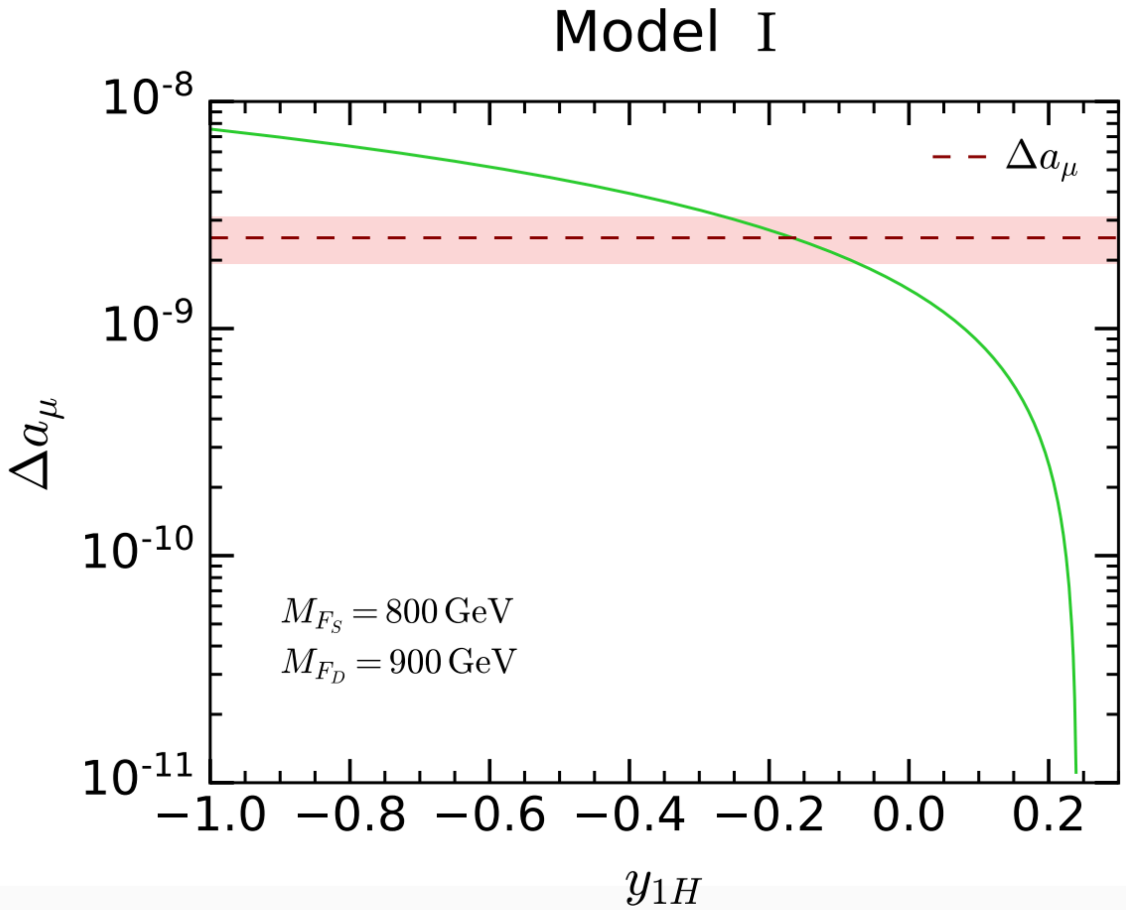
Model II

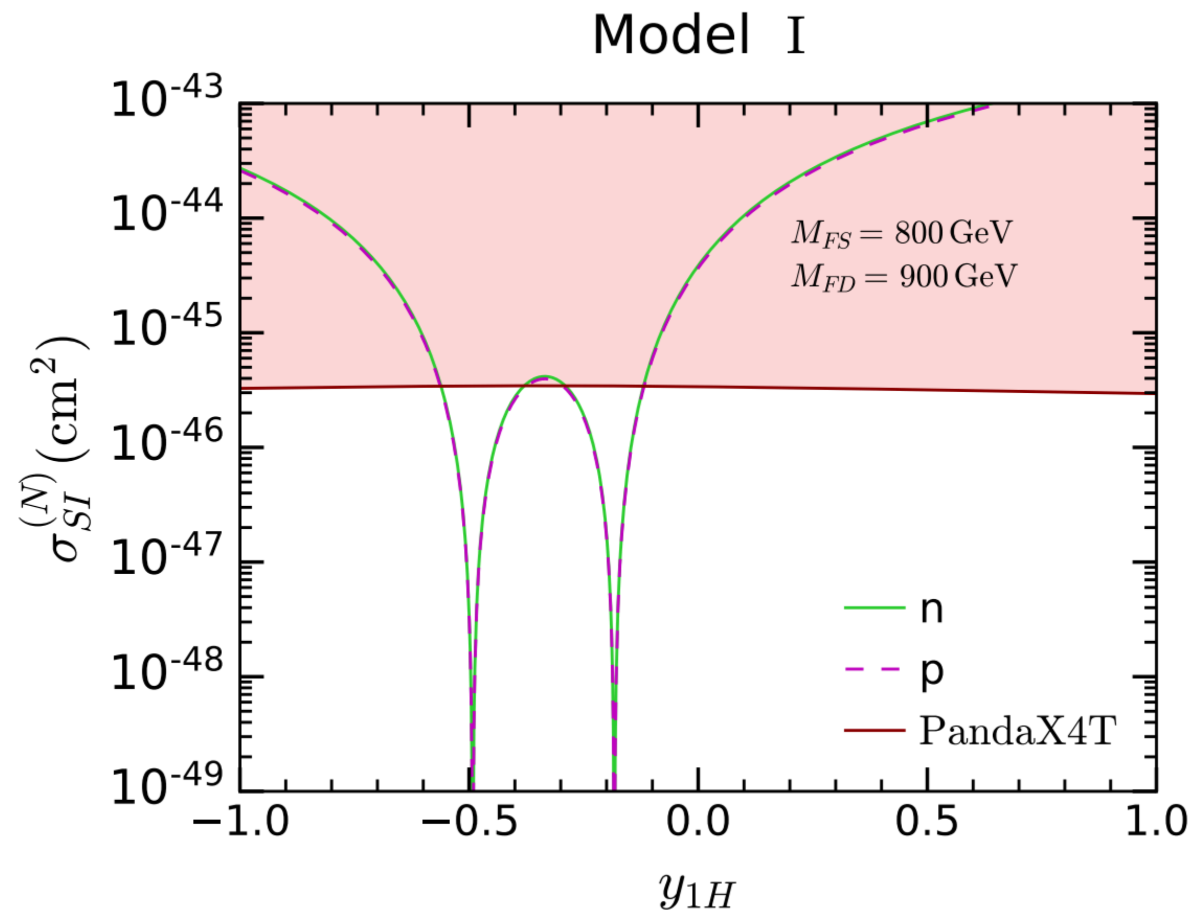
$$\mathcal{L}_{\text{mass}} = -\left(\frac{1}{2}M_{F_S}\chi_S\chi_S + \text{h.c.}\right) - M_{\tilde{L}}^2|\widetilde{L}|^2 - M_{\tilde{\bar{e}}}^2|\widetilde{\bar{e}}|^2 \ ,$$

$$\mathcal{L}_{\text{Yukawa}} = -y_1\,\chi_S L_\mu\widetilde{L}^\dagger - y_2\,\chi_S\mu_R^c\widetilde{\bar{e}}^\dagger + \text{h.c.} \ ,$$

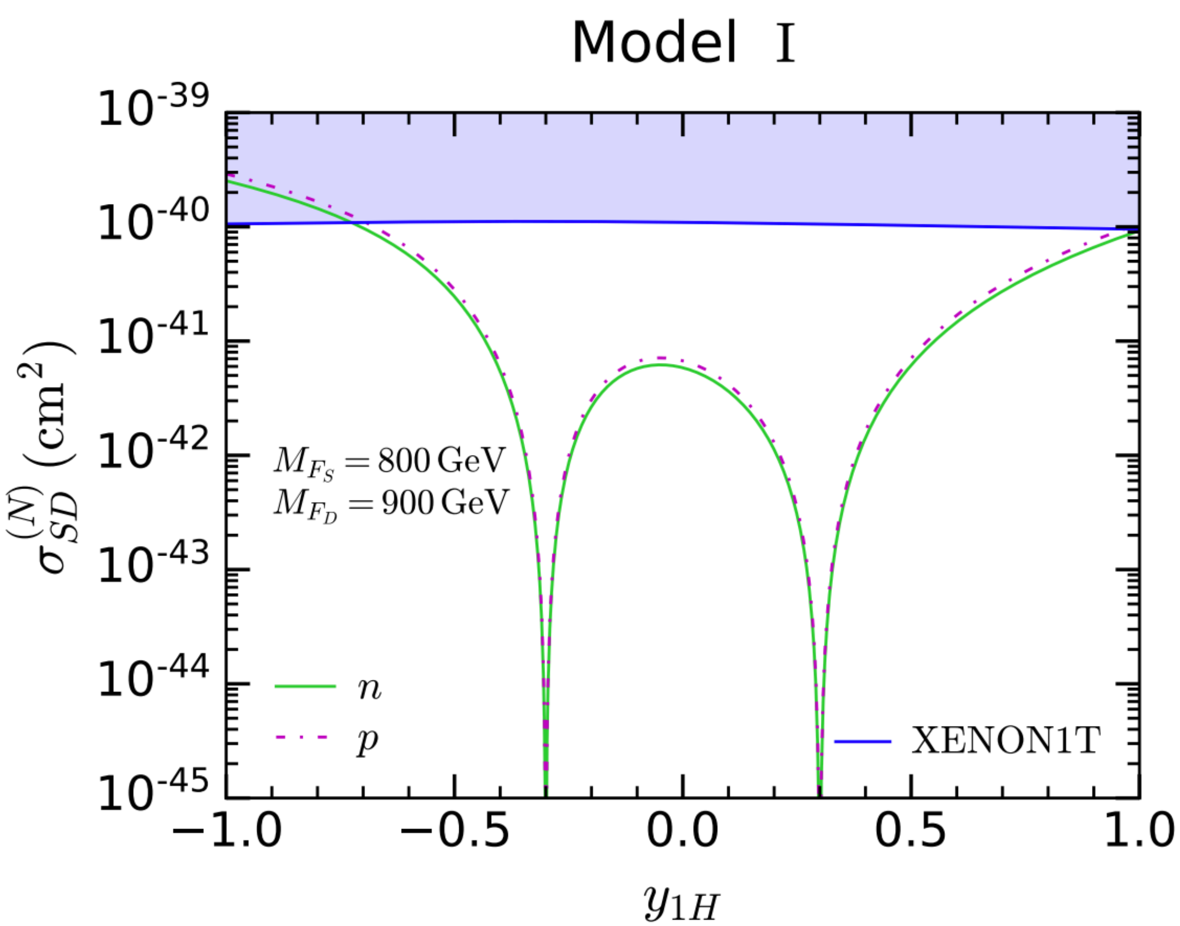
$$\mathcal{L}_{\text{tri}} = -a_H\,\widetilde{\bar{e}}\widetilde{L}H^\dagger + \text{h.c.} \ ,$$

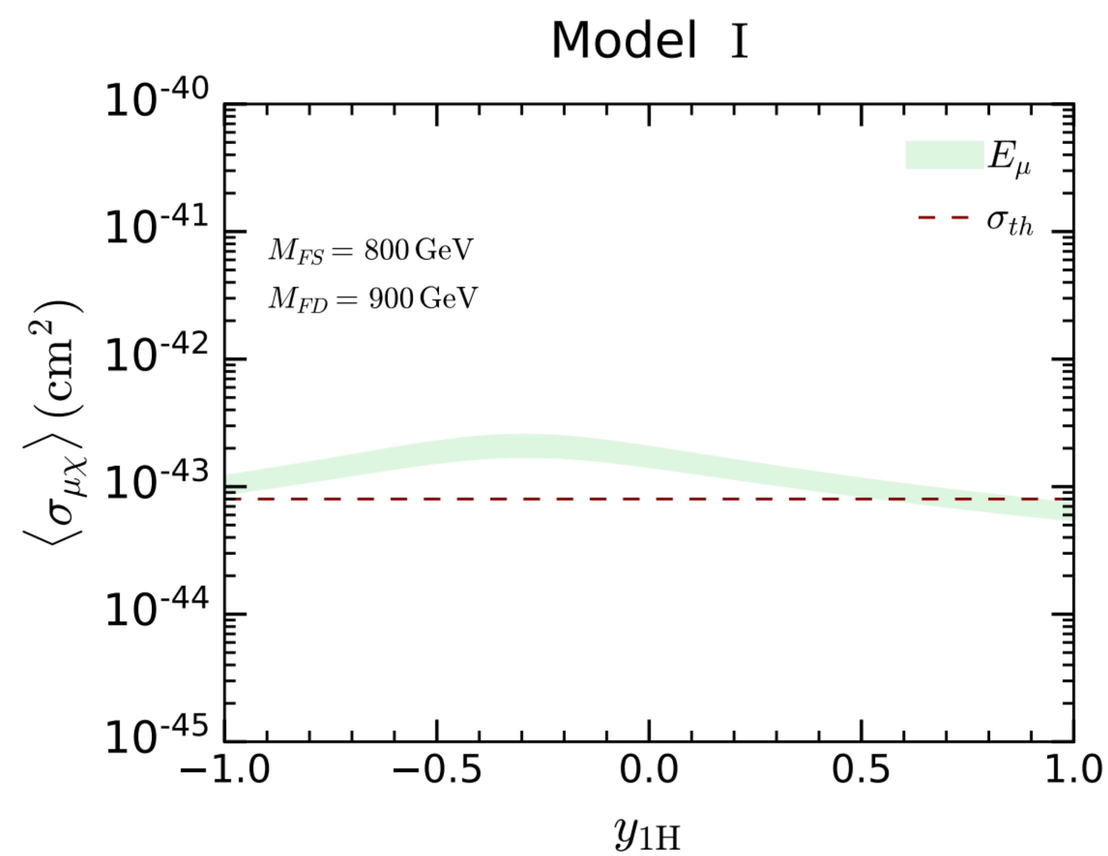
$$\mathcal{L}_{\text{quart}} = -\sum_{f=L,\bar{e}}\lambda_f|\widetilde{f}|^2|H|^2 - \lambda_L'\widetilde{L}^\dagger\tau_a\widetilde{L}H^\dagger\tau_a H + \dots \ .$$

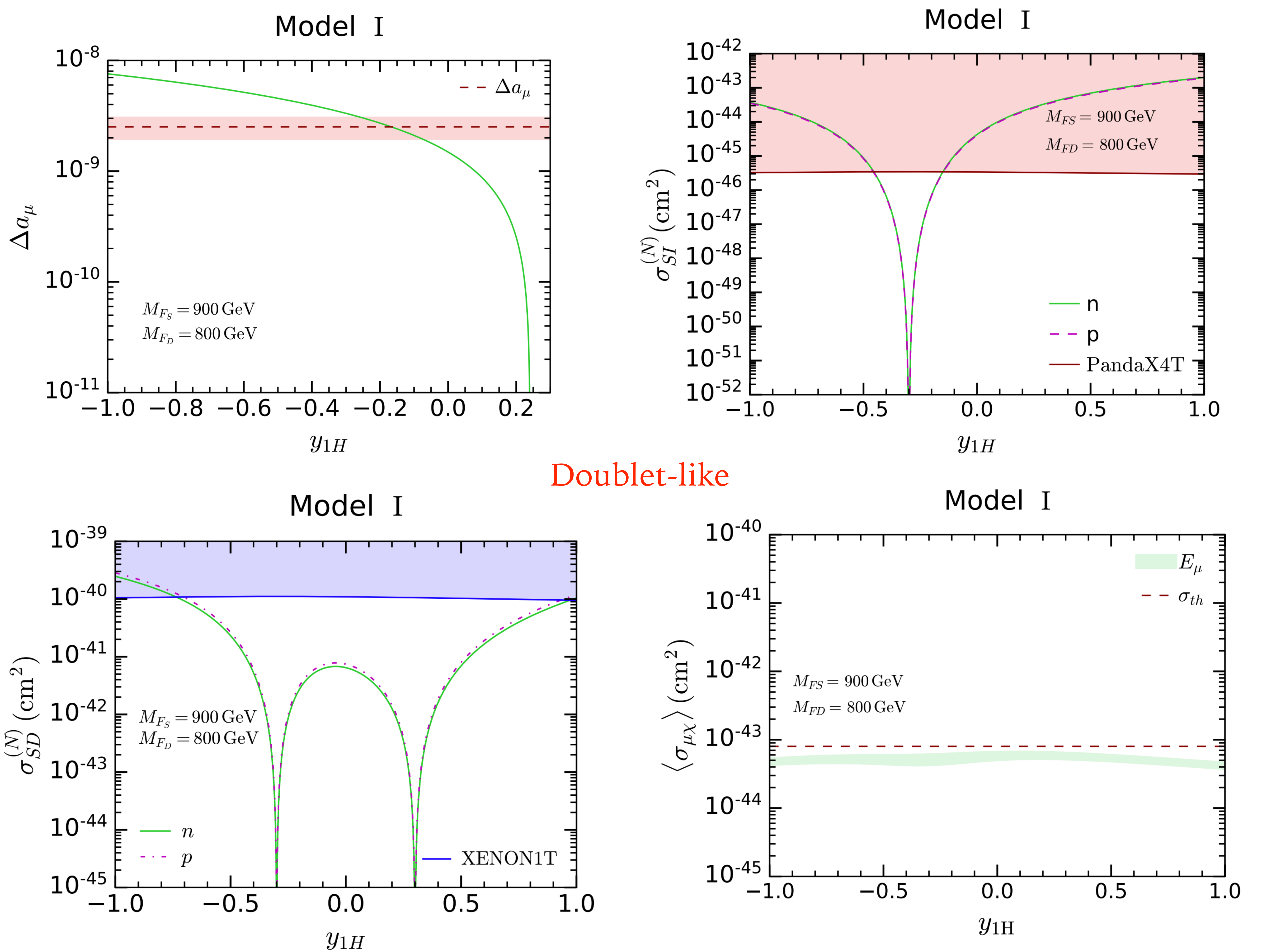




Singlet-like







Model I
10^{-8}
10^{-9}
10^{-10}
10^{-11}
Δa_μ
$M_{F_S} = 900\,\mathrm{GeV}$
$M_{F_D} = 800\,\mathrm{GeV}$
−1.0 −0.8 −0.6 −0.4 −0.2 0.0 0.2
y_{1H}
Model I
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
10^{-50}
10^{-51}
10^{-52}
$\sigma_{SI}^{(N)}\,(\mathrm{cm}^2)$
$M_{FS} = 900\,\mathrm{GeV}$
$M_{FD} = 800\,\mathrm{GeV}$
n
p
PandaX4T
−1.0 −0.5 0.0 0.5 1.0
y_{1H}
Doublet-like
Model I
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
$\sigma_{SD}^{(N)}\,(\mathrm{cm}^2)$
$M_{F_S} = 900\,\mathrm{GeV}$
$M_{F_D} = 800\,\mathrm{GeV}$
n
p
XENON1T
−1.0 −0.5 0.0 0.5 1.0
y_{1H}
Model I
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
E_μ
σ_{th}
$\langle \sigma_{\mu\chi} \rangle\,(\mathrm{cm}^2)$
$M_{FS} = 900\,\mathrm{GeV}$
$M_{FD} = 800\,\mathrm{GeV}$
−1.0 −0.5 0.0 0.5 1.0
$y_{1\mathrm{H}}$

Model I

$$\Delta a_\mu = -\frac{m_\mu}{8\pi^2 M_{\tilde{e}}^2} \sum_{i=1,2,3} M_{\chi_i} \mathrm{Re}\left[y_1 y_2 \left(V_\chi\right)_{1i} \left(V_\chi\right)_{2i}\right] f_{LR}^S\left(\frac{M_{\chi_i}^2}{M_{\tilde{e}}^2}\right)$$
$$-\frac{m_\mu^2}{8\pi^2 M_{\tilde{e}}^2} \sum_{i=1,2,3} \left[\left|y_1 \left(V_\chi\right)_{1i}\right|^2 + \left|y_2 \left(V_\chi\right)_{2i}\right|^2\right] f_{LL}^S\left(\frac{M_{\chi_i}^2}{M_{\tilde{e}}^2}\right)$$
$$+\frac{m_\mu^2 |y_2|^2}{8\pi^2 M_{\tilde{\nu}}^2} f_{LL}^F\left(\frac{M_{F_D}^2}{M_{\tilde{\nu}}^2}\right),$$

Model II

$$\Delta a_\mu = -\frac{m_\mu M_{F_S}}{8\pi^2} \sum_{i=1,2} \frac{1}{M_{e_i}^2} \mathrm{Re}\left[y_1 y_2 \left(U_e\right)_{1i}^* \left(U_e\right)_{2i}\right] f_{LR}^S\left(\frac{M_{F_S}^2}{M_{e_i}^2}\right)$$
$$-\frac{m_\mu^2}{8\pi^2} \sum_{i=1,2} \frac{1}{M_{e_i}^2} \left[\left|y_1 \left(U_e\right)_{1i}^*\right|^2 + \left|y_2 \left(U_e\right)_{2i}\right|^2\right] f_{LL}^S\left(\frac{M_{F_S}^2}{M_{e_i}^2}\right)$$

DM-muon amplitude

$$\frac{d\sigma_{\chi\mu}}{dt} = \frac{1}{16\pi\lambda(s, M_{\mathrm{DM}}^2, m_\mu^2)} \cdot \frac{1}{4} \sum_{\mathrm{spins}} |\mathcal{A}|^2$$

$$\longrightarrow \quad \bar{s} \simeq M_{\mathrm{DM}}^2 \gg \bar{s} - M_{\mathrm{DM}}^2 \simeq 2E_\chi E_\mu \gg |t|, E_\mu^2$$