Study of GeV Dark Matter and Neutrino Floor with $(g-2)_\mu$ Anomaly in $U(1)_{L_\mu - L_\tau}$

Kuldeep Deka

Department of Physics and Astrophysics, University of Delhi, India-110007

in a collaboration with **Soumya Sadhukhan** and **Manvinder Pal Singh** (Based on **arXiv:2203.17122**)

kuldeepdeka.physics@gmail.com

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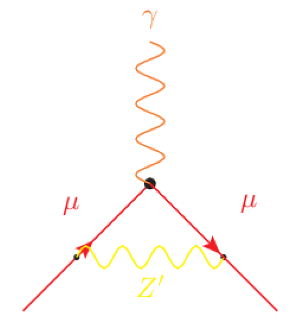
Abstract

In this work, we investigate the impact of recent anomalous $(g-2)_\mu$ measurement with $\sim 4\sigma$ deviation from the SM, probing its effect on a light GeV scale fermionic dark matter (DM). The $(g-2)_\mu$ anomaly can be readily explained in the a beyond the SM (BSM) $U(1)_{L_\mu - L_\tau}$ scenario, where only a portion of hitherto allowed parameter space can explain the anomaly. We also study the neutrino floor enhancement, which is the neutrino background in the DM direct detection experiments and investigate how $(g-2)_\mu$ constraint impacts the enhancement of the neutrino floor. The GeV scale DM is severely constrained by the $(g-2)_\mu$ result in the parameter regions of neutrino floor enhancement where absence of s-channel resonant annihilation of the DM results in over abundance of the DM relic. Even if a t-channel annihilation aided by large couplings can bring the relic density in the observed range, direct detection cross section shoots up. Consequently, super-GeV (with mass $1-10$ GeV) DM gets almost ruled out where as sub-GeV (with mass $0.1-1$ GeV) DM gets severely constrained.

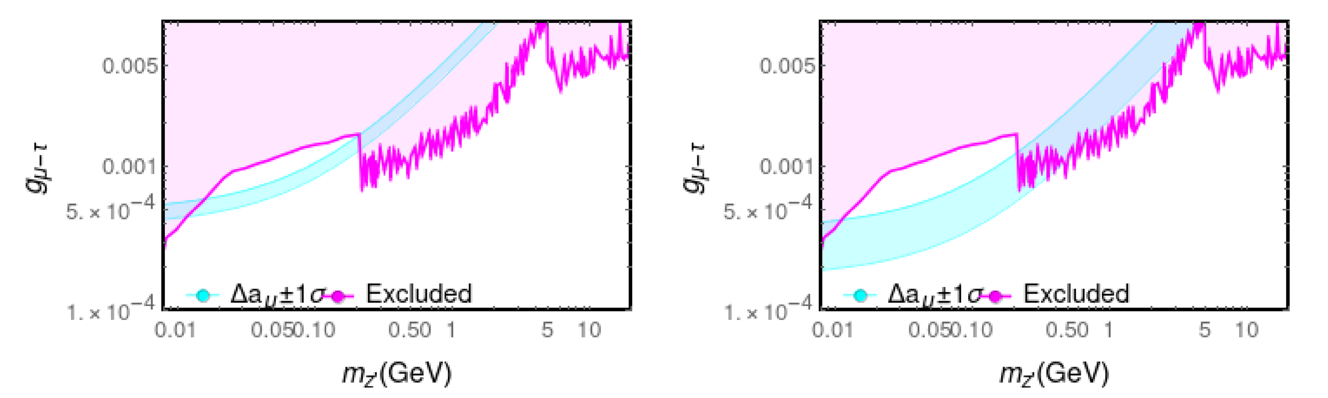
(g-2) of muon in $U(1)_{L_\mu - L_\tau}$

- $\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = (251 \pm 59) \times 10^{-11}$ a combined discrepancy of 4.2σ deviation from the SM when using dispersive techniques for the hadronic vacuum polarisation.

$$\Delta a_\mu = \frac{g_{\mu-\tau}^2}{8\pi^2}\int_0^1 dx \frac{2m_\mu^2 x^2(1-x)}{x^2 m_\mu^2 + (1-x)m_{Z'}^2}.$$



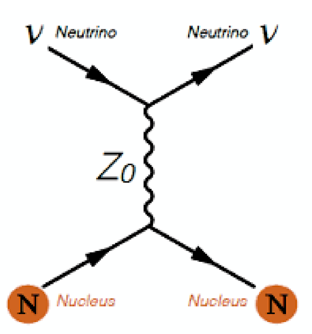
- The allowed parameter space are:



CEνNS and Neutrino Floor

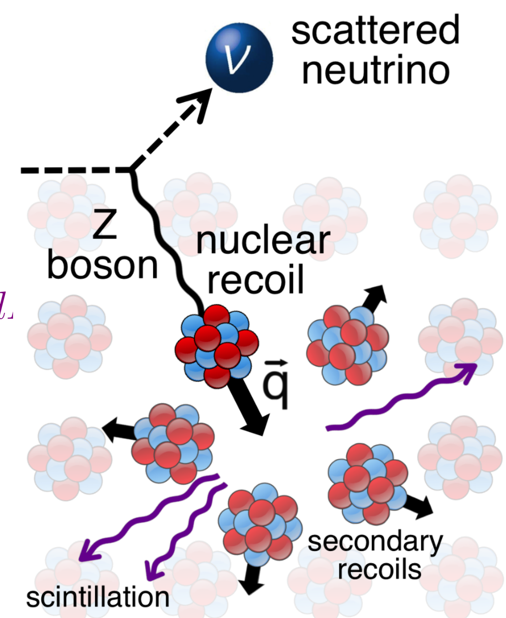
- The differential neutrino nucleus scattering cross section in SM and $U(1)_{\mu-\tau}$ model are:

$$\frac{d\sigma_{SM}}{dE_r} = G_f^2 \frac{m_N}{4\pi} Q_{\nu N}^2 \left(1 - \frac{E_r m_N}{2E_\nu^2}\right) F^2(E_r).$$
$$Q_{\nu N} = N - (1 - 4\sin^2\theta_w)Z$$



$$\frac{d\sigma_{\mu-\tau}}{dE_r} = \frac{d\sigma_{SM}}{dE_r} - \frac{m_N G_f Q_{\nu N\mu-\tau} Q_{\nu N}\left(1-\frac{E_r m_N}{2E_\nu^2}\right)F^2(E_r)}{\sqrt{2}\pi\left(2E_r m_N + m_{Z'}^2\right)} + \frac{m_N Q_{\nu N\mu-\tau}^2\left(1-\frac{E_r m_N}{2E_\nu^2}\right)F^2(E_r)}{2\pi\left(2E_r m_N + m_{Z'}^2\right)^2},$$

$$Q_{\nu N\mu-\tau} = g_{\mu-\tau}^2 \frac{2\alpha_{EM}}{\pi}\delta_{\mu\tau} Z$$



- The Neutrino rate equation is:

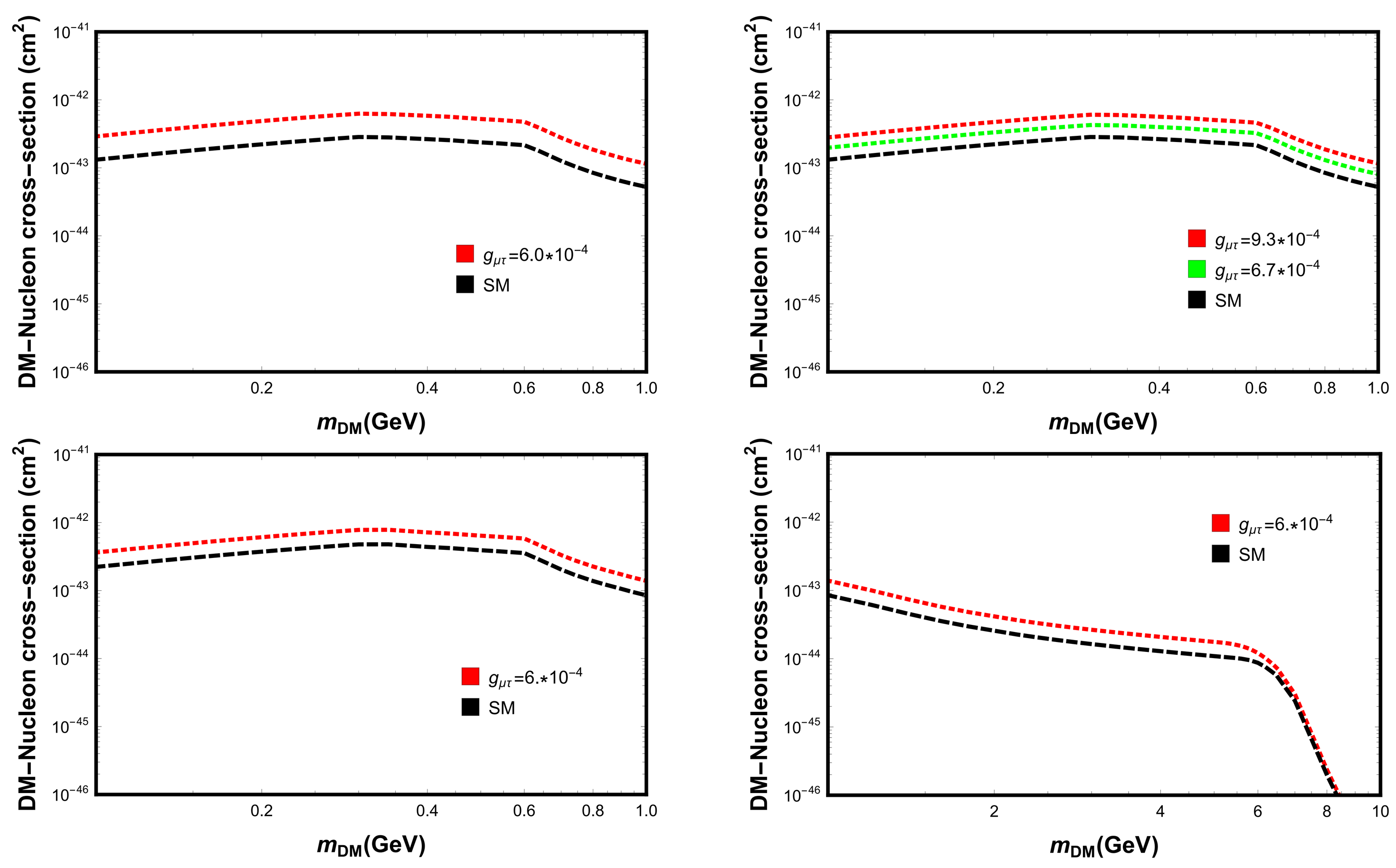
$$\frac{dR_{\nu-N}}{dE_r} = \frac{\epsilon}{m_N}\int_{E_\nu^{min}} \mathcal{A}(E_r)\left.\frac{d\phi_\nu}{dE_\nu}\right|_{\nu_\alpha} P(\nu_\alpha \to \nu_\beta, E_\nu)\frac{d\sigma(E_\nu, E_r, \nu_\beta)}{dE_r} d.$$

- The spin-independent (SI) DM-nucleon scattering rate equation is:

$$\frac{dR_{DM-N}}{dE_r} = \epsilon\frac{\rho_{DM}\sigma_n^0 A^2}{2m_{DM}\mu_n^2}F^2(E_r)\int_{v_{min}}\frac{f(v)}{v}d^3v$$

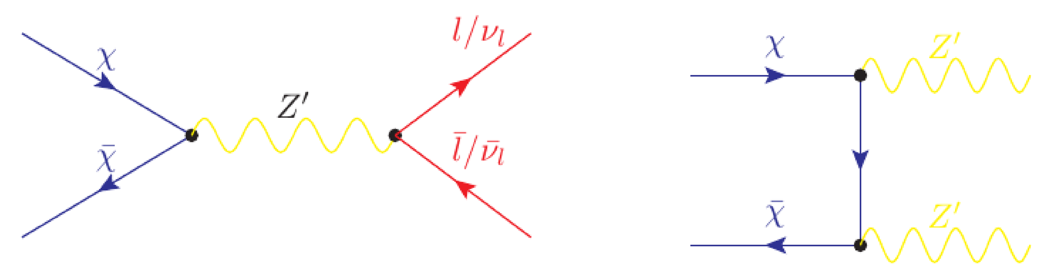
- The neutrino-floor is then given by:

$$\sigma_n^0 = \frac{2.3}{1}\left(\int_{E_{th}}^{E_{max}}\frac{1}{m_N}\int_{E_\nu^{min}}\left.\frac{d\phi_\nu}{dE_\nu}\right|_{\nu_\alpha} P(\nu_\alpha\to\nu_\beta, E_\nu)\frac{d\sigma(E_\nu,E_r,\nu_\beta)}{dE_r}dE_\nu\right) \times \left(\frac{\rho_{DM}A^2}{2m_{DM}\mu_n^2}\int_{E_{th}}^{E_{DM}^{max}}F^2(E_r)\int_{v_{min}}\frac{f(v)}{v}d^3v\right)^{-1}$$



- The left top two plots are for Ge-based detectors with Z' mass of 16 and 25 MeV respectively. The bottom plots are for Xe based detectors with Z' mass fixed at 16 MeV.

Dark Matter



- The s-channel diagram contributions to the DM annihilation:

$$\langle\sigma v\rangle(\chi\bar\chi \to \ell\bar\ell) \approx \frac{q_\chi^2 Y_\ell'^2 g_{\mu-\tau}^4}{2\pi}\sqrt{1-\frac{m_\ell^2}{m_\chi^2}}\frac{2m_\chi^2 + m_\ell^2}{(4m_\chi^2 - m_{Z'}^2)},$$
$$\langle\sigma v\rangle(\chi\bar\chi \to \nu\bar\nu) \approx \frac{q_\chi^2 Y_\ell'^2 g_{\mu-\tau}^4}{2\pi}\frac{m_\chi^2}{(4m_\chi^2 - m_{Z'}^2)},$$

where $Y_\ell' = 1 - 1$ for the muons and tau leptons respectively.

- The t-channel contribution is computed as

$$\langle\sigma v\rangle(\chi\bar\chi \to Z'Z') \approx \frac{q_\chi^4 g_{\mu-\tau}^4}{16\pi m_{\chi^2}}\left(1-\frac{m_{Z'}^2}{m_\chi^2}\right)^{3/2}\left(1-\frac{m_{Z'}^2}{2m_\chi^2}\right)^{-2},$$

providing total thermally averaged annihilation cross section as $\langle\sigma v\rangle = \langle\sigma v\rangle(\chi\bar\chi\to\ell\bar\ell) + \langle\sigma v\rangle(\chi\bar\chi\to\nu\bar\nu) + \langle\sigma v\rangle(\chi\bar\chi\to Z'Z')$.

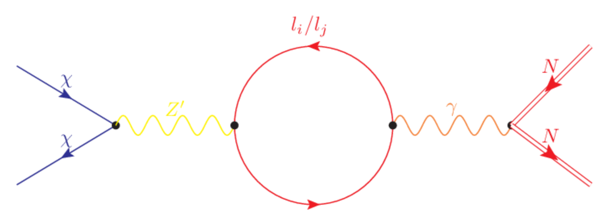
- the DM relic density is given as,

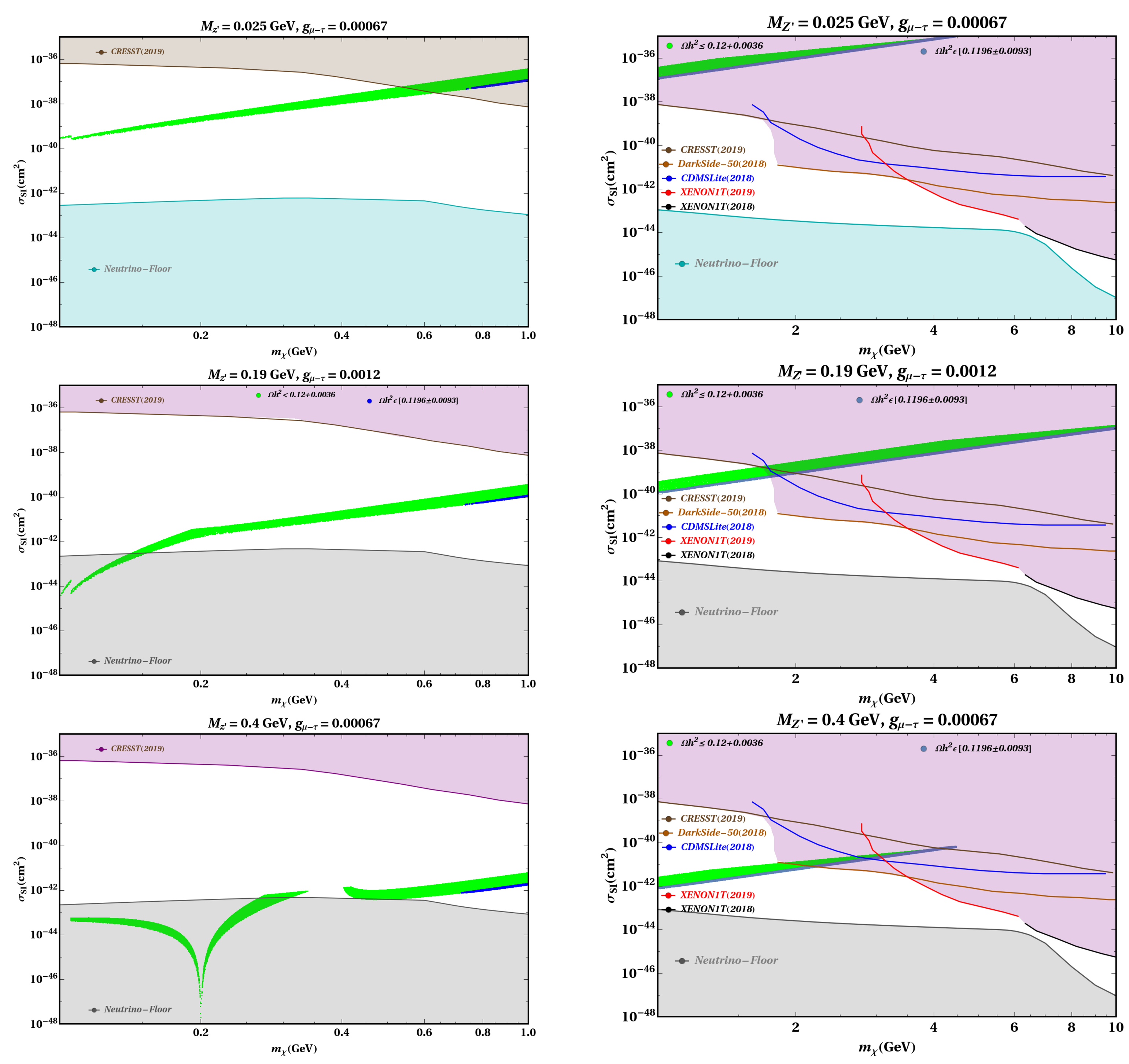
$$\Omega h^2 \approx \frac{1.04\times 10^9 x_F \mathrm{GeV}^{-1}}{\sqrt{g}M_{pl}\langle\sigma v\rangle},$$

where x_F dictates the time or temperature of the thermal freeze out given as $x_F = \frac{m_\chi}{T_F}$, with T_F as the freeze out temperature.

- The expression for spin-independent cross section for the D-Nucleon scattering can be written as, which has the contribution from the loop induced diagram on the right:

$$\sigma_{SI} = \frac{\mu_N^2}{9\pi A^2}\left(\frac{\alpha_{EM} Z g_{\mu-\tau}^2 q_\chi}{\pi m_{Z'}^2}\log\frac{m_\mu^2}{m_\tau^2}\right)^2$$





Summary and Outlook

- In this work, we have investigated viability of $U(1)_{L_\mu - L_\tau}$ model to simultaneously explain $(g-2)_\mu$ and DM relic density along with possible modification in the neutrino floor.
- We found that the parameter range $m_{Z'}$ in $10-200$ MeV and gauge coupling $g_{\mu-\tau} \sim (0.5-1.0)\times 10^{-3}$ remains viable to explain anomalous $(g-2)_\mu$ which is prescribed by latest FNAL experimental measurements.
- We then studied this allowed region to explore possible modification of the neutrino floor. We found that with increasing $m_{Z'}$, neutrino floor reaches maximum enhancement of 2.25 times and 1.65 times for Germanium and Xenon based experiments respectively, for a benchmark point $\left(m_{Z'} = 25\,MeV, g_{\mu-\tau} = 9.3\times 10^{-4}\right)$. Above this mass, floor enhancement gradually decreases with increasing $m_{Z'}$.
- With the inclusion of $(g-2)_\mu$, the benchmark point $\left(m_{Z'} = 25\,MeV, g_{\mu-\tau} = 6.7\times 10^{-4}\right)$ shows the maximum enhancement of 2.15 times and 1.62 times for Germanium and Xenon based DM direct detection experiments respectively.
- Although there are significant enhancement of the neutrino floor in these parts of the parameter space, we cannot explain the entire DM relic density there because of direct detection constraints.
- If we move towards a parameter space with higher Z' mass where the floor enhancement is not prominent, we can satify both muon $(g-2)$ and exact relic density constraints.
- If we give up muon $(g-2)$, this model still has a large part of parameter space in the sub-GeV DM mass range and also reasonable parameter space in the 1-10 GeV mass range.