Muonphilic Dark Matter explanation of gamma-ray galactic center excess

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1. Motivation
2. The muonphilic DM explanation to the GCE
3. The simplified muonphilic DM models
4. The global fitting with GCE, DM relic density, DM direct detection and muon g-2 excess
5. Conclusion

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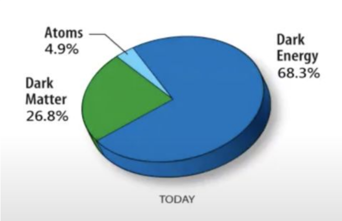
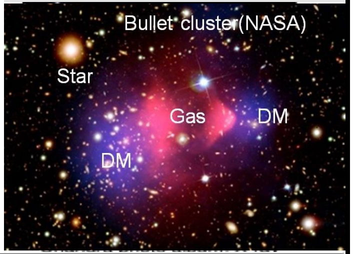
Motivation – Dark Matter

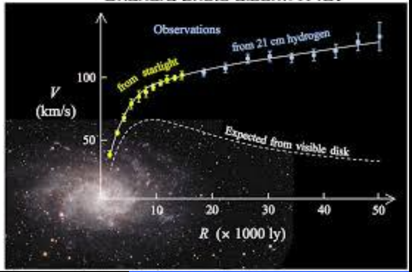
Evidences for Dark Matter (DM)
- WMAP measurement (Ω_m=0.25)
- rotation curves of galaxies
- the "bullet" cluster

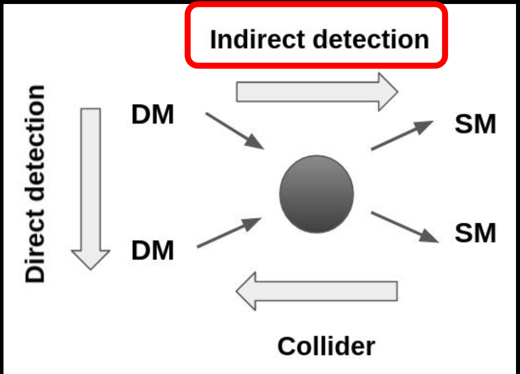
Open Problems
- DM nature
- DM interactions
- DM formation mechanism

Detection techniques
- signals from colliders
- direct detection
- indirect detection of annihilation products such as neutrinos, antiprotons or gamma-rays



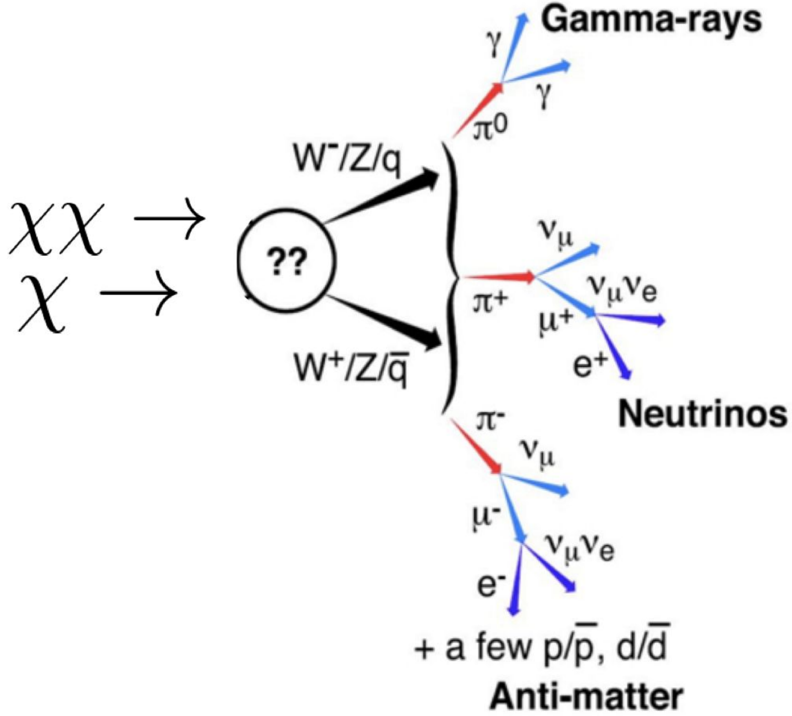


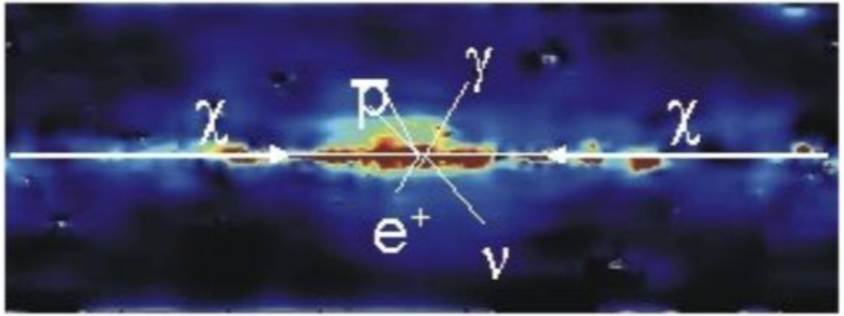




Mattia Fornasa and Marco Taoso

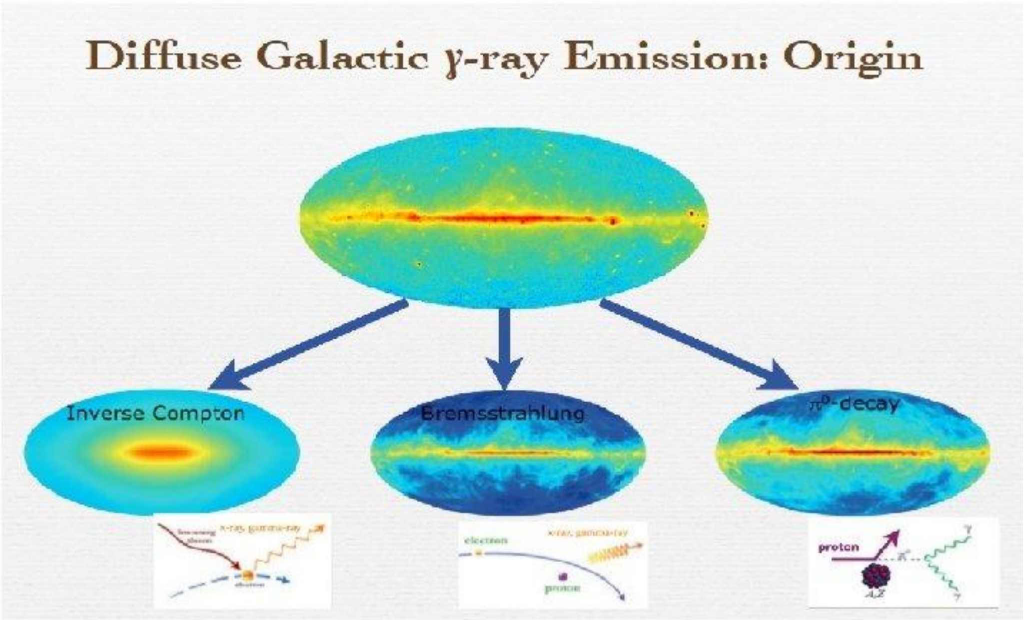
DM indirect detection





Pamela ,ATIC, Fermi,
HESS, AMS02, DAMPE
and so on

Fermi LAT Gamma-rays can provide good test of the DM models



Other explanations :

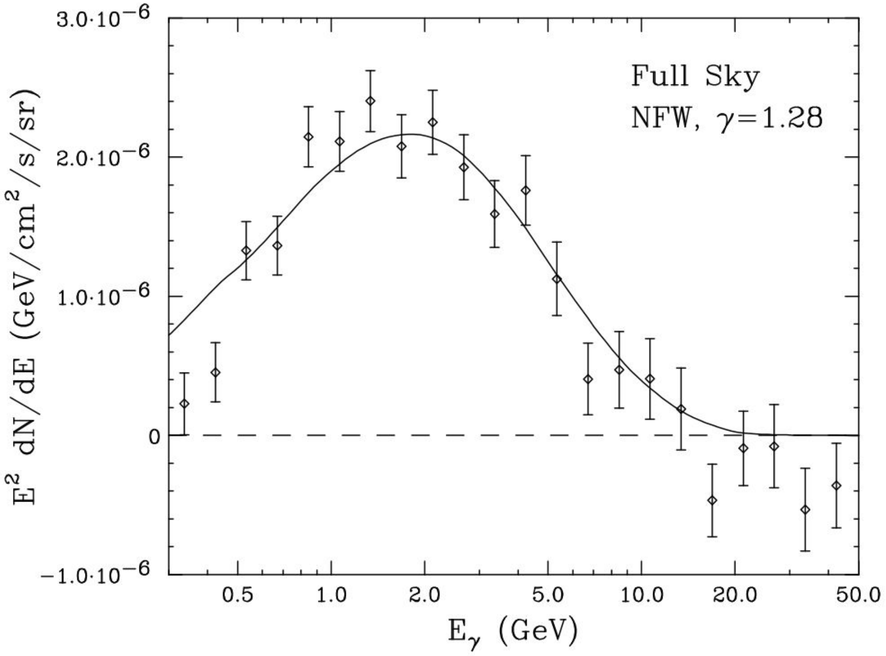
(1) From some undetected point sources (pulsars) in the inner Galaxy

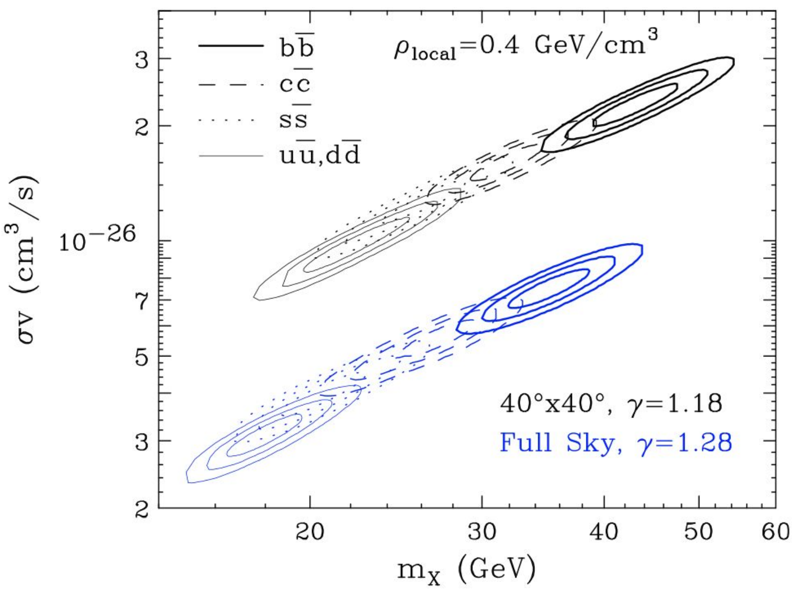
(2) The stellar origin in the Galactic bulge

Leane 2019/2020,
Macias 2018/2019,
Bartels 2018

The GeV excess

Phys.Dark Univ. 12 (2016) 1-23 e-Print: 1402.6703 [astro-ph.HE]





a 36.6 GeV dark matter particle annihilating to $b\bar{b}$

with a cross section of $\sigma v = 0.75 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}\ \times [(0.4\,\mathrm{GeV}/\mathrm{cm}^3)/\rho_{\mathrm{local}}]^2$.

Gamma-ray galactic center excess

The systematic uncertainties of these GCE analyses are still unclear. It can be a challenge to discover or exclude the DM origin by only using GCE Fermi data.

However,

with the help from other astrophysical data, such as Fermi-LAT observations of dwarf spheroidal galaxies (dSphs) and AMS-02 cosmic-ray data, we can abandon the DM explanation of GCE if all the above data do not support DM annihilation.

→ The strategy in Di Mauro and Winkle (2021)

"Multimessenger constraints on the dark matter interpretation of the Fermi-LAT Galactic center excess"

Gamma-ray galactic center excess

“However, we find that the GCE DM signal is excluded by the AMS-02 anti-proton flux data for all hadronic and semi-hadronic annihilation channels unless the vertical size of the diffusion halo is smaller than 2 kpc -- which is in tension with radioactive cosmic ray fluxes and radio data. Furthermore, AMS-02 e+ data rule out pure or mixed channels with a component of e+ e-. The only DM candidate that fits the GCE spectrum and is compatible with constraints obtained with the combined dSphs analysis and the AMS-02 anti-proton and e+ data annihilates purely into $\mu^+ \mu^-$, has a mass of 60 GeV and roughly a thermal cross section.”

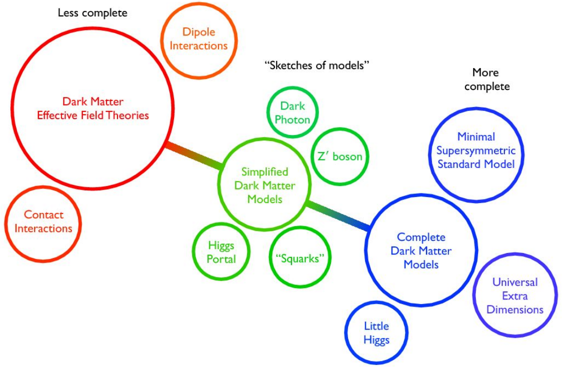
→ Di Mauro and Winkle (2021)

Motivation of this work

Based on their claim, the muonphilic DM is the natural choice to explain the GCE.

The next question is what kind of interactions can explain GCE and also satisfy the relic density, DM direct detection, collider constraints and (maybe) muon g-2 excess.

We start from the simplified muonphilic DM models and do a comprehensive study.



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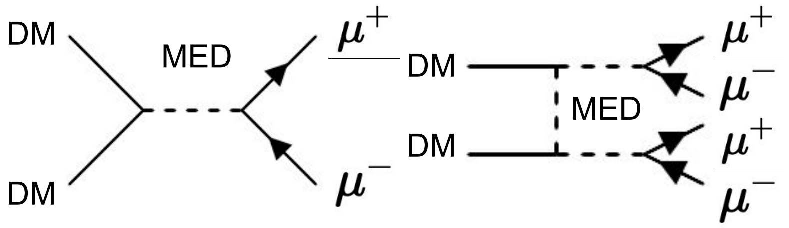
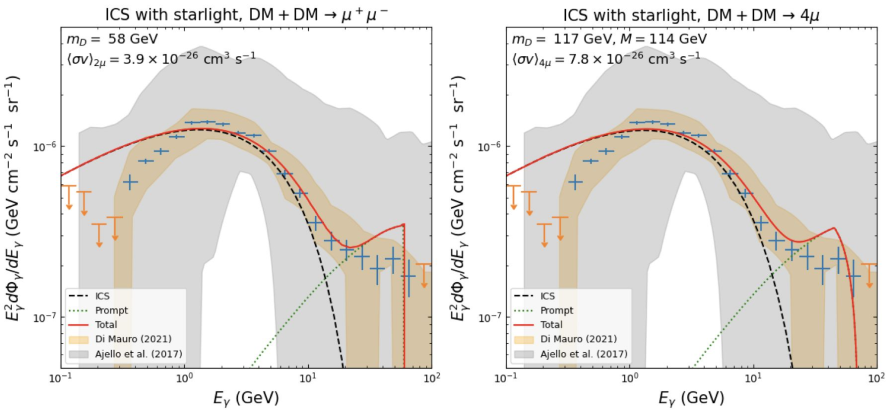
The muonphilic DM explanation to the GCE

1. The favoured annihilation cross sections (μ+μ− final state) and DM masses are

$$\langle \sigma v \rangle_{2\mu} = 3.9^{+0.5}_{-0.6} \times 10^{-26}\ \mathrm{cm}^3 s^{-1}, \quad \text{and } m_D = 58^{+11}_{-9}\,\mathrm{GeV}.$$

2. If requiring the same ICS gamma ray fluxes to explain GCE, a twice higher annihilation cross section is needed for 4μ final state. Therefore, it will be difficult to explain the GCE and relic density measurement simultaneously in the sceanrio of DM + DM → MED + MED.





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The simplified muonphilic DM models

We restrict ourselves to only concern SM singlet DM and MED with

spin-0 (real/complex), ½ (Majorana/Dirac), 1(real/complex) DM candidates

(1) Z2 even meidator : spin-0(real), 1(real)
(2) Z2 odd mediator : spin-0 (complex), ½ (Dirac), 1(complex)

	Scalar	Fermion	Vector
Dark Matter	S	χ	X^μ
Mediator	ϕ	ψ	V^μ

The simplified muonphilic DM models

	Z_2 even mediator		
types	Lagrangian	$\langle\sigma v\rangle_{2\mu}$ $\simeq a+bv^2$	$\langle\sigma v\rangle_{4\mu}$ $\simeq a+bv^2$
χ and ϕ	$\mathcal{L}_1=(g_D\bar{\chi}\chi+g_f\bar{f}f)\phi$	$a=0$	$a=0$
	$\mathcal{L}_2=(g_D\bar{\chi}\chi+g_f\bar{f}i\gamma^5f)\phi$	$a=0$	$a=0$
	$\mathcal{L}_3=(g_D\bar{\chi}i\gamma^5\chi+g_f\bar{f}f)\phi$	**Case (i)**	$a=0$
	$\mathcal{L}_4=(g_D\bar{\chi}i\gamma^5\chi+g_f\bar{f}i\gamma^5f)\phi$	**Case (i)**	$a=0$
χ and V_μ	$\mathcal{L}_5=(g_D\bar{\chi}\gamma^\mu\gamma^5\chi+g_f\bar{f}\gamma^\mu f)V_\mu$	$a=0$	**Case (A)**
	$\mathcal{L}_6=(g_D\bar{\chi}\gamma^\mu\gamma^5\chi+g_f\bar{f}\gamma^\mu\gamma^5f)V_\mu$	**Case (ii)**	**Case (A)**
	$\mathcal{L}_7=(g_D\bar{\chi}\gamma^\mu\chi+g_f\bar{f}\gamma^\mu f)V_\mu$	**Case (i)**	**Case (C)**
	$\mathcal{L}_8=(g_D\bar{\chi}\gamma^\mu\chi+g_f\bar{f}\gamma^\mu\gamma^5f)V_\mu$	**Case (i)**	**Case (C)**
S and ϕ	$\mathcal{L}_9=(M_{D\phi}S^\dagger S+g_f\bar{f}f)\phi$	**Case (i)**	**Case (B)**
	$\mathcal{L}_{10}=(M_{D\phi}S^\dagger S+g_f\bar{f}i\gamma^5f)\phi$	**Case (i)**	**Case (B)**
	$\mathcal{L}_{9'}=(g_DS^\dagger S\phi+g_f\bar{f}f)\phi$	—	$b=0$
	$\mathcal{L}_{10'}=(g_DS^\dagger S\phi+g_f\bar{f}i\gamma^5f)\phi$	—	$b=0$

s-channel

S and V_μ	$\mathcal{L}_{11}=(ig_DS^\dagger\overleftrightarrow{\partial}_\mu S+g_D^2S^\dagger SV_\mu+g_f\bar{f}\gamma_\mu f)V^\mu$	$a=0$	**Case (C)**
	$\mathcal{L}_{12}=(ig_DS^\dagger\overleftrightarrow{\partial}_\mu S+g_D^2S^\dagger SV_\mu+g_f\bar{f}\gamma_\mu\gamma^5f)V^\mu$	$a=0$	**Case (C)**
X_μ and ϕ	$\mathcal{L}_{13}=(M_{D\phi}X^\mu X_\mu^\dagger+g_f\bar{f}f)\phi$	**Case (i)**	**Case (D)**
	$\mathcal{L}_{14}=(M_{D\phi}X^\mu X_\mu^\dagger+g_f\bar{f}i\gamma^5f)\phi$	**Case (i)**	**Case (D)**
	$\mathcal{L}_{13'}=(g_DX^\mu X_\mu^\dagger\phi+g_f\bar{f}f)\phi$	—	$b=0$
	$\mathcal{L}_{14'}=(g_DX^\mu X_\mu^\dagger\phi+g_f\bar{f}i\gamma^5f)\phi$	—	$b=0$
X_μ and V_μ	$\mathcal{L}_{15}=ig_D\{X^{\mu\nu}X_\mu^\dagger V_\nu-X^{\mu\nu\dagger}X_\mu V_\nu+X_\mu X_\nu^\dagger V^{\mu\nu}\}$ $+g_D^2\{X_\mu^\dagger X^\mu V_\nu V^\nu-X_\mu^\dagger V^\mu X_\nu V^\nu\}+g_f\bar{f}\gamma^\mu fV_\mu$	$a=0$	**Case (C)**
	$\mathcal{L}_{16}=ig_D\{X^{\mu\nu}X_\mu^\dagger V_\nu-X^{\mu\nu\dagger}X_\mu V_\nu+X_\mu X_\nu^\dagger V^{\mu\nu}\}$ $+g_D^2\{X_\mu^\dagger X^\mu V_\nu V^\nu-X_\mu^\dagger V^\mu X_\nu V^\nu\}+g_f\bar{f}\gamma^\mu\gamma^5fV_\mu$	$a=0$	**Case (C)**

The simplified muonphilic DM models

First, for 2μ final state, we can simplify the analytical expressions of σv [39] near resonance as

$$\sigma v \propto \frac{C_0}{(4R - R^2)^2} \left(\mathcal{C}_1 - \frac{\mathcal{C}_2}{4R - R^2} v^2 \right), \tag{12}$$

where C_0 (in GeV^{-2}) and $\mathcal{C}_{1,2}$ are positive coefficients. The resonance parameter R is defined as $R \equiv (2m_D - M)/m_D$. The conditions $\mathcal{C}_2 v^2 \leq \mathcal{C}_1(4R - R^2)$ is to be kinematics allowed and $R \leq 2$ is for a physical mass M.

The simplified muonphilic DM models

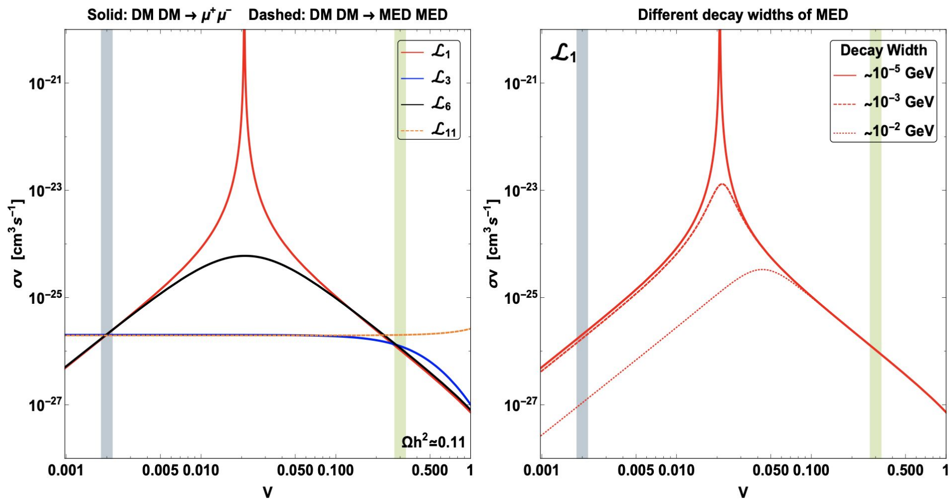


FIG. 2. The schematic demonstration of σv as function of v. The parameters of benchmark $\mathcal{L}_{1,3,6}$ are $m_D/\,\text{GeV} = (72.99, 73.11, 73.02)$, $M/\,\text{GeV} = (146.0, 143.5, 146.0)$, and $g_D g_f \times 10^3 = (3.319, 2.494, 3.030)$, respectively. For $\mathcal{L}_{11}$, the corresponding parameters are $(m_D, M, g_D) = (68.64\ \text{GeV}, 5.85\ \text{GeV}, 8.53 \times 10^{-3})$. The right panel is the result of $\mathcal{L}_1$ for different decay widths of mediator.

The simplified muonphilic DM models

t-channel

	Z_2 odd mediator		
types	Lagrangian	$\langle\sigma v\rangle_{2\mu}$	DM field
χ and ϕ	$\mathcal{L}_{17} = g_D \bar{\chi} P_R f \phi$+h.c.	s	Dirac
χ and V_μ	$\mathcal{L}_{18} = g_D \bar{\chi} \gamma^\mu P_R f V_\mu$+h.c.	s	Dirac
✗ χ and ϕ	$\mathcal{L}_{19} = g_D \bar{\chi} P_R f \phi$+h.c.	p	Majorana
✗ χ and V_μ	$\mathcal{L}_{20} = g_D \bar{\chi} \gamma^\mu P_R f V_\mu$+h.c.	p	Majorana
S and ψ	$\mathcal{L}_{21} = g_D \bar{\psi} P_R f S$+h.c.	**Case (i)**	Real
✗ S and ψ	$\mathcal{L}_{22} = g_D \bar{\psi} P_R f S$+h.c.	p	Complex
X_μ and ψ	$\mathcal{L}_{23} = g_D \bar{\psi} \gamma^\mu P_R f X_\mu^\dagger$+h.c.	s	Real/Complex

The simplified muonphilic DM models

Compared with the Z2-even mediator case, there is no resonance enhancement in t-channel models.

Thus, we are safe to exclude the p-wave interactions L_19, L_20, L_22 because they are not able to simultaneously generate the correct relic density and the DM annihilation cross section required by GCE.

The charged mediator such as slepton suffers from the stringent lower mass limit 103.5 GeV from LEP.

Therefore, we foucs on L_21 only with the following scaned parameters :

$$30 \text{ GeV} < m_D < 100 \text{ GeV}, \, m_D < M < 1000 \text{ GeV}, \, 10^{-6} < g_D < 2.$$

Content

THE LIKELIHOODS

$$\chi^2_{\rm tot} = \chi^2_{\rm GCE} + \chi^2_{\Omega h^2} + \chi^2_{\rm DD}.$$

1. Fermi GCE:

$$\chi^2_{\rm GCE} = \sum_{i=1}^{19} \left(\frac{dN}{dE_i} - \frac{dN_0}{dE_i} \right)^2 / 19\sigma_i^2,$$

2. PLANCK Relic density:

$$\Omega h^2 = 0.1186 \pm 0.002.$$

$$\chi^2_{\Omega h^2} = \left(\frac{\mu_t - \mu_0}{\sqrt{\sigma^2_{\rm theo} + \sigma^2_{\rm exp}}} \right)^2,$$

$$\sigma_{\rm theo} = \tau \mu_t.$$

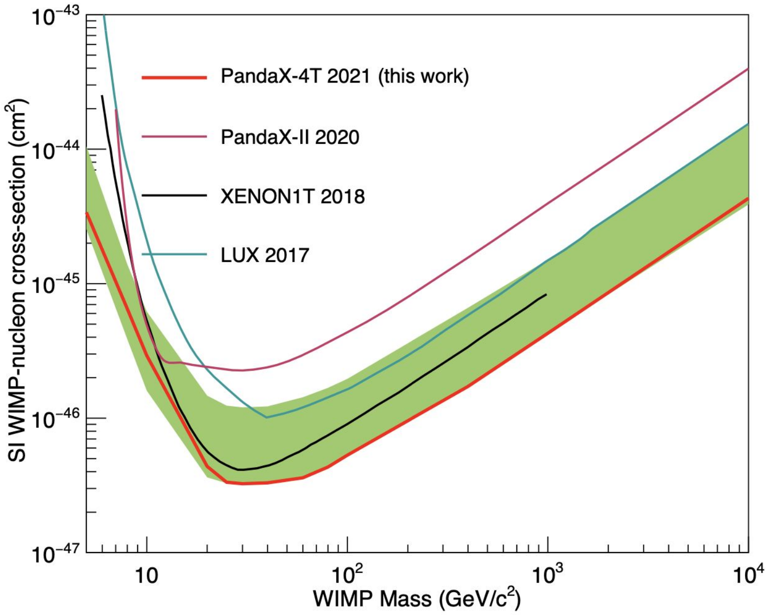
$$\tau = 10\%$$

3. PandaX-4T:

$$\chi^2_{\rm DD} = \left(\frac{\sigma^{\rm SI}_{\chi p}}{\sigma^{\rm SI, 90\%}_{\chi p} / 1.64} \right)^2,$$ 1.64 is the unit of 90% confidence level.

PandaX-4T

a stringent limit to the dark matter-nucleon spin-independent interactions, with a lowest excluded cross section (90% C.L.) of $3.3 \times 10^{-47}\text{cm}^2$ at a dark matter mass of 30 GeV/c^2.



2107.13438

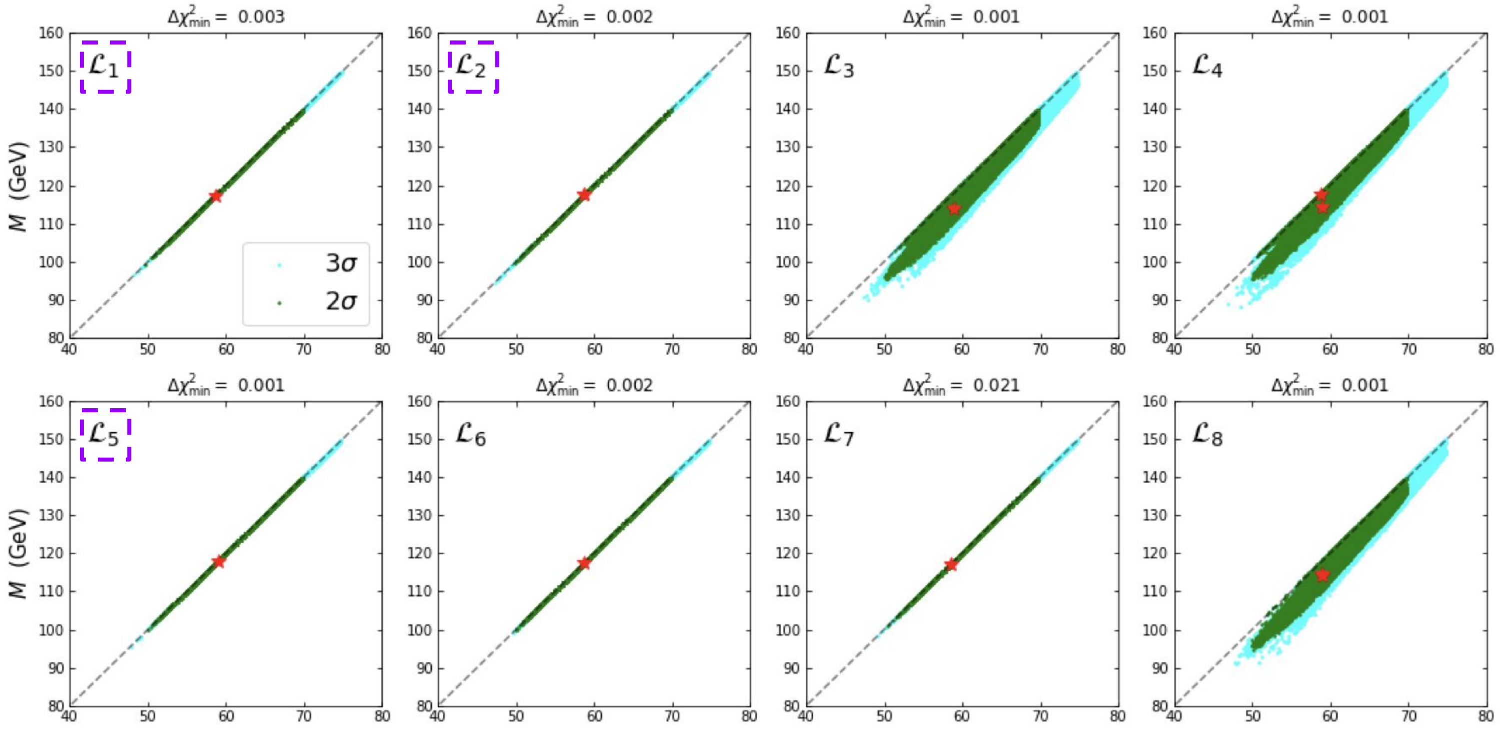
The range for the scaned parameters in s-channel models

For each model, we perform several MCMC scans individually to optimize the coverage and the parameters are scanned in the following range

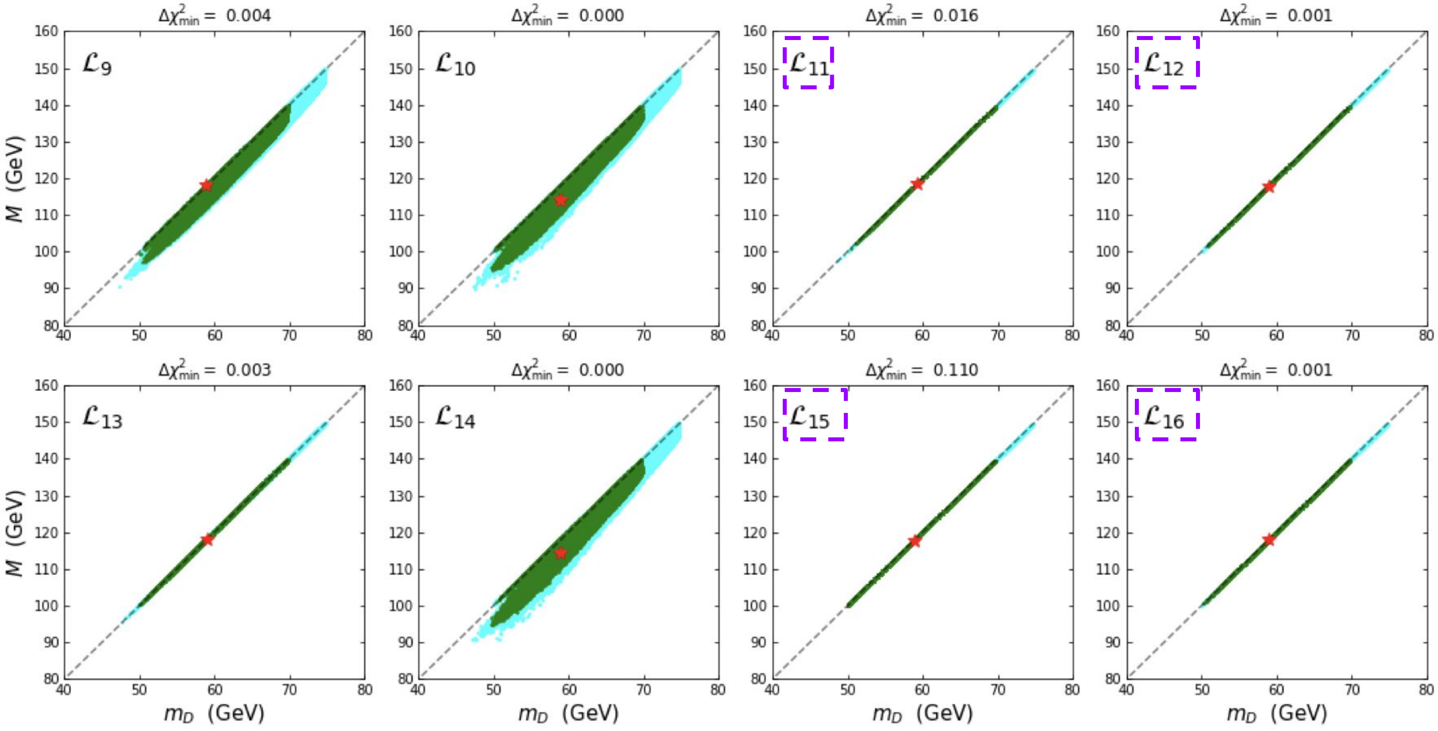
$$30~\text{GeV} < m_D < 200~\text{GeV},\ 10^{-4}~\text{GeV} < M < 1000~\text{GeV},$$
$$10^{-6} < g_f < 2,\ 10^{-6} < g_D < 2,\ 10^{-6}~\text{GeV} < M_{D\phi} < 1000~\text{GeV}. \tag{13}$$

$$\Delta\chi^2_{\text{min}} = \chi^2_{\text{min}} - \chi^2_0.$$
$$\chi^2_0 = 5.15,$$

The parameter space in s-channel models



The parameter space in s-channel models



The parameter space in L_21 (t-channel model)

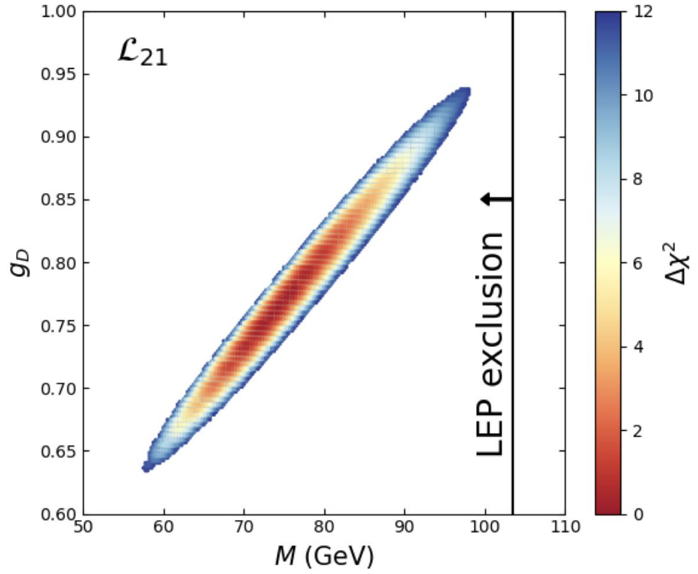


FIG. 5. Samples with $\Delta\chi^2 = \chi^2 - \chi^2_{\rm min} < 12$ for $\mathcal{L}_{21}$. The color bar is $\Delta\chi^2$. The vertical black solid line is the LEP upper limit 103.5 GeV [25].

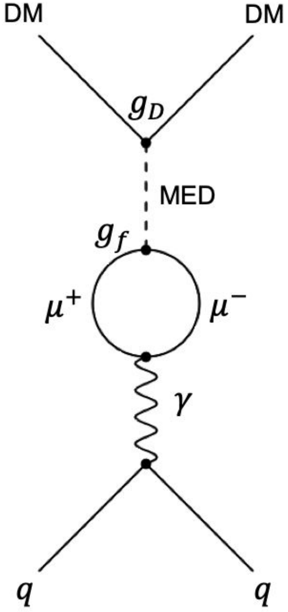
DISCUSSION OF DM DIRECT DETECTION

1. For the simplified muonphilic DM models, there is no tree level DM-nuclei elastic scattering.
2. First, we consider the Z2-even mediator case and define the general lepton current as $\bar{l}\Gamma_l l$. The one loop contributions are nonzero only for vector and tensor lepton currents, namely $\Gamma_l = \gamma_\mu, \sigma_{\mu\nu}$ Therefore, only L_5, L_7, L_11, L_15 can generate one loop contributions to the DM-nuclei elastic scattering.
3. For the scalar lepton current, $\Gamma_l = 1$, the one loop contribution vanishes since a scalar current cannot couple to a vector current. The DM-quark interaction can only be induced at two loop level for L_1, L_3, L_9, L_13.
4. For pseudo-scalar and axial vector lepton currents $\Gamma_l = \gamma_5, \gamma_\mu\gamma_5$, the diagrams vanish to all loop orders. The interaction with γ_5 gives either zero or a fully anti-symmetric tensor $\epsilon^{\alpha\beta\mu\nu}$. Since there are only three independent momenta in the 2 → 2 scattering process, two indices can be contracted with the same momentum and return a zero amplitude square. Therefore, we can ignore the DM-nuclei elastic scattering for L_2, L_4, L_6, L_8, L_10, L_12, L_14, L_16.

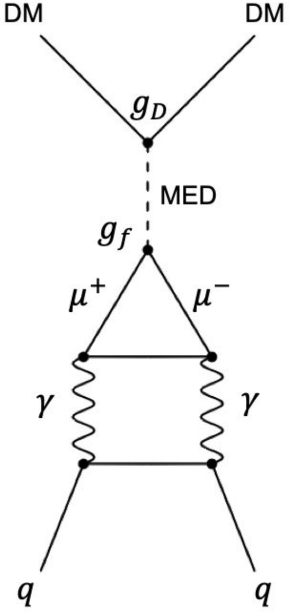
DISCUSSION OF DM DIRECT DETECTION

1. For the Z2-odd mediator case, the DM-nuclei scattering cross sections are suppressed for the self-conjugate DM, namely real scalar, Majorana fermion, and real vector, since the self-conjugate DM couples to a single photon in t-channel simplified models only through the anapole moment. This leads to that DM-quark scattering amplitude is suppressed in the non-relativistic limit as for L_19, L_20, L_21, L_23.
2. On the other hand, if the muonphilic DM are complex scalar, Dirac fermion and complex vector, the one-loop induced DM-quark interactions cannot be ignored.

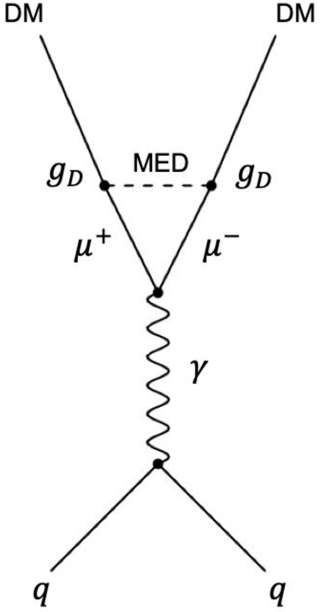
DISCUSSION OF DM DIRECT DETECTION



Z_2 even 1 loop diagram

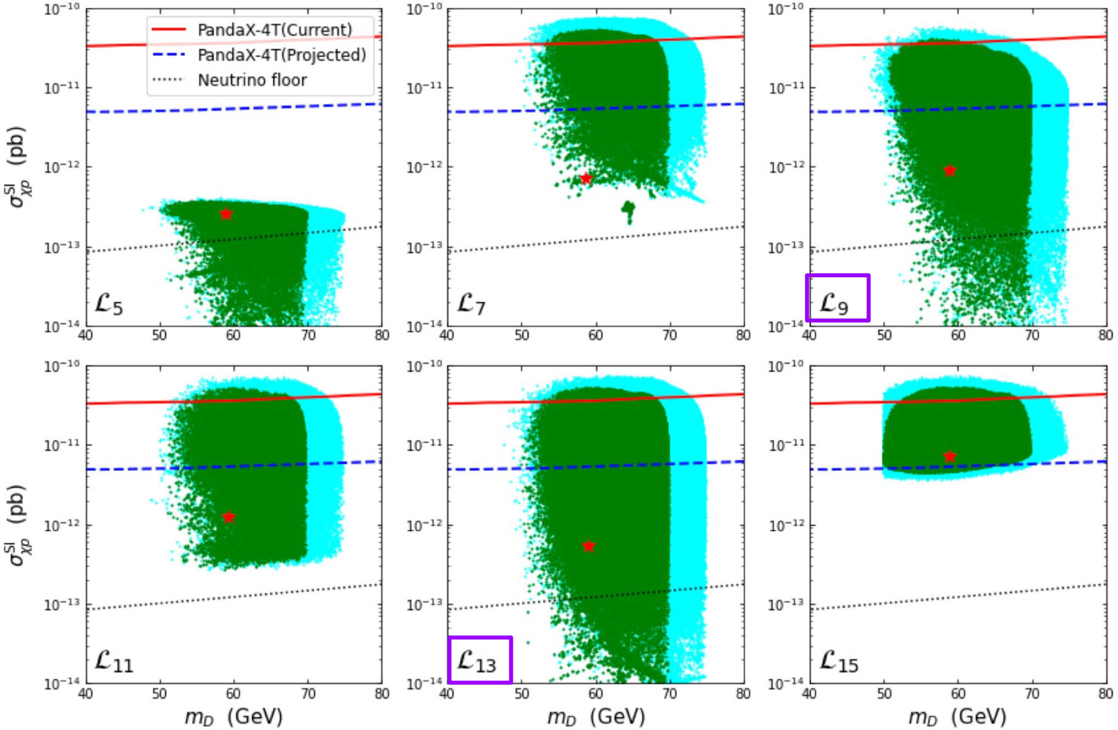


Z_2 even 2 loop diagram



Z_2 odd 1 loop diagram

DISCUSSION OF DM DIRECT DETECTION



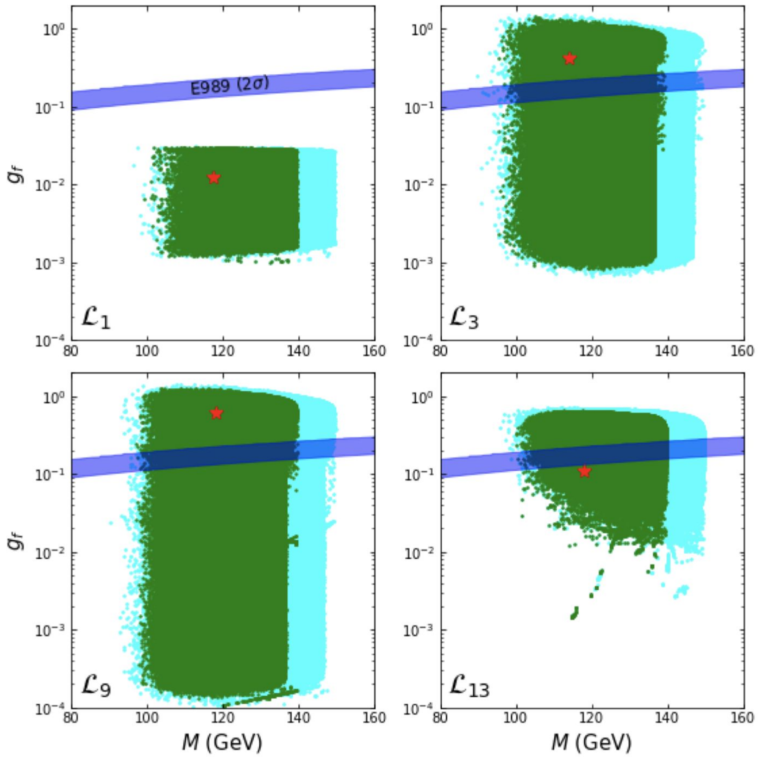
THE MUON g − 2 EXCESS

A deviation $\delta a_\mu = (2.51 \pm 0.59) \times 10^{-9}$ with 4.2σ significance deviating from the value of the SM prediction.

(1) The contribution from pseudo-scalar and axial-vector mediator are negative at one loop level.
(2) For the contributions from vector mediator, δa_μ is too small to reach 2σ region.
(3) Thus, only the contributions form scalar mediators are considered.

Therefore, as long as the E989 result can be confirmed in the near future, only L_3 (fermionic DM), L_9 (scalar DM) and L_{13} (vector DM) are allowed to explain the correct <u>DM relic density</u>, <u>GCE</u> and <u>muon g − 2 excess</u> simultaneously.

THE MUON g − 2 EXCESS



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5. **Conclusion**

Conclusion

1. According to Di Mauro and Winkle (2021), only $\chi\chi \to \mu\mu$ annihilation can explain all the astrophysical observations consistently.
2. Motivated by such a claim, we perform a comprehensive analysis for the muonphilic DM from the particle physics point of view.
3. For muonphilic DM models with Z2-even mediators, the favoured regions show an interesting feature that only the narrow phase spaces of resonances are remained to accommodate both GCE and DM relic density.
4. For the muonphilic DM models with Z2-odd mediators, all of interaction types with Z2-odd mediators are excluded.

Conclusion

5. Although the muonphlic DM can only scatter with proton via loop contributions, the current PandaX-4T σ^{SI} upper limit is still sensitive to this kind of models.

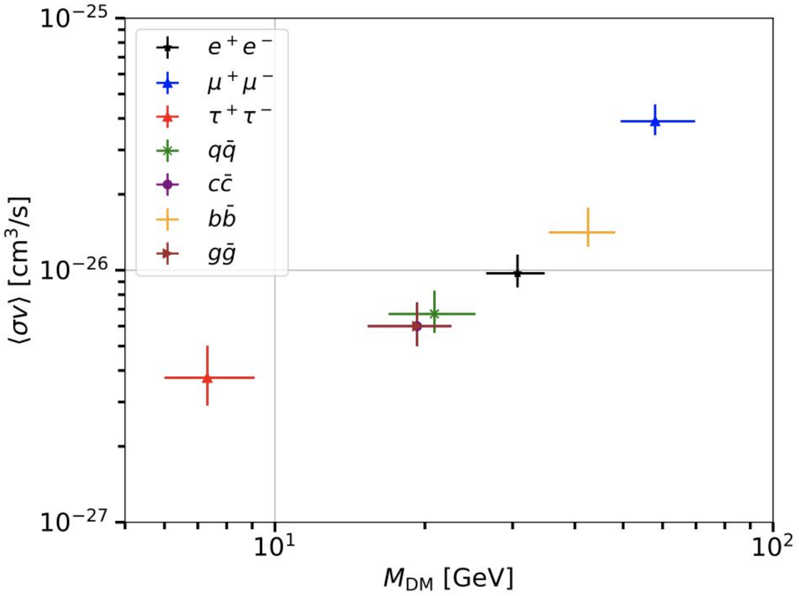
6. If muon g − 2 result from E989 can be confirmed, only the scalar mediator is allowed and the possible interaction types are L_3 (fermionic DM), L_9 (scalar DM) and L_13 (vector DM). Among these three models, only L_3 cannot be tested by future DD experiments.

Thank you

for your attention

Back-up

The GCE fitting results from Di Mauro and Winkle (2021)



Channel	$M_{\rm DM}$ [GeV]	$\langle \sigma v \rangle$ [$\times 10^{-26}$ cm^3/s]	$\chi^2(\tilde{\chi}^2)$
e^+e^-	30^{+4}_{-4}	$1.13^{+0.21}_{-0.12}$	161.61 (5.39)
$\mu^+\mu^-$	58^{+11}_{-9}	$3.9^{+0.5}_{-0.6}$	164.12 (5.47)
$\tau^+\tau^-$	$7.2^{+1.9}_{-1.2}$	$0.43^{+0.15}_{-0.10}$	1178.40 (39.3)
$q\bar{q}$	21^{+4}_{-4}	$0.77^{+0.19}_{-0.12}$	208.89 (6.96)
$c\bar{c}$	20^{+3}_{-5}	$0.70^{+0.16}_{-0.11}$	214.11 (7.14)
$b\bar{b}$	42^{+6}_{-7}	$1.41^{+0.35}_{-0.18}$	176.47 (5.88)
gg	19^{+3}_{-4}	$0.70^{+0.16}_{-0.11}$	214.14 (7.14)