

Scalar Dark Matter with a $\mu\tau$ flavored mediator

Coh Miyao(Kyushu U.)

KEK-ph @ KEK

29th November 2022

Based on: K. Asai, C. Miyao, S. Okawa, K. Tsumura,
Phys. Rev. D **106**, 035017(2022)

Contents

- Beyond Standard Model and Dark Matter
- Current Status and Previous Works
- Our Model and Evaluation at 1-loop level
- Testability of DM Model
- Conclusion and Outlook

Contents

- **Beyond Standard Model and Dark Matter**
- Current Status and Previous Works
- Our Model and Evaluation at 1-loop level
- Testability of DM Model
- Conclusion and Outlook

Is the Standard Model(SM) Theory of Everything ?

 Beyond SM phenomena are revealed...

For examples,

- Neutrino oscillation.
- Dark Matter(DM).
- Muon $g-2$ discrepancy between SM and experiments.
[2] Muon $g-2$ Collaboration, Phys. Rev. Lett.126, 141802 (2021).
-



We focus on DM
to build Beyond Standard Model (BSM).

What is Dark Matter?

- A lot of evidence.
 - Rotation speed of galaxies, gravitational lens effect, and so on.
- Unknown identity.
 - If DM is elementary particle, it should be described by BSM.

Image of DM by Akimoto-san →



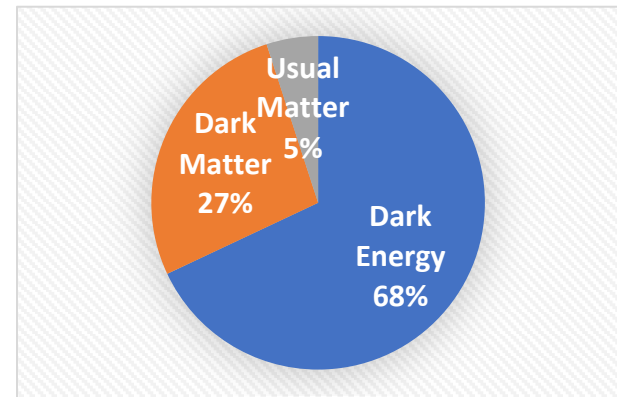
Contents

- Beyond Standard Model and Dark Matter
- **Current Status and Previous Works**
- Our Model and Evaluation at 1-loop level
- Testability of DM Model
- Conclusion and Outlook

DM in the Universe

- Occupation about 27% of the universe.
→ Determined by observations.

- Boltzmann equation.
→ Theoretical value.



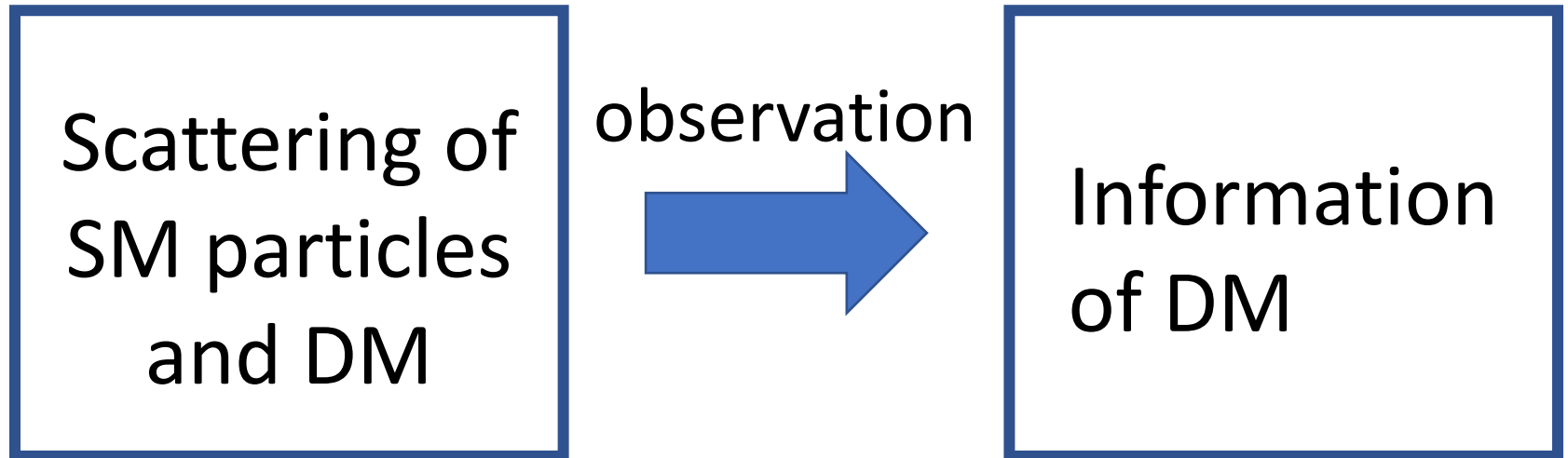
$$\frac{dn_{DM}}{dt} + 3Hn_{DM} = -\langle \sigma v \rangle_{DM \rightarrow SM} [n_{DM}^2 - (n_{DM}^{eq})^2]$$

Magnitude of $\langle \sigma v \rangle_{DM \rightarrow SM}$ should be reasonably large value to explain the observed value.

Direct Detection of DM

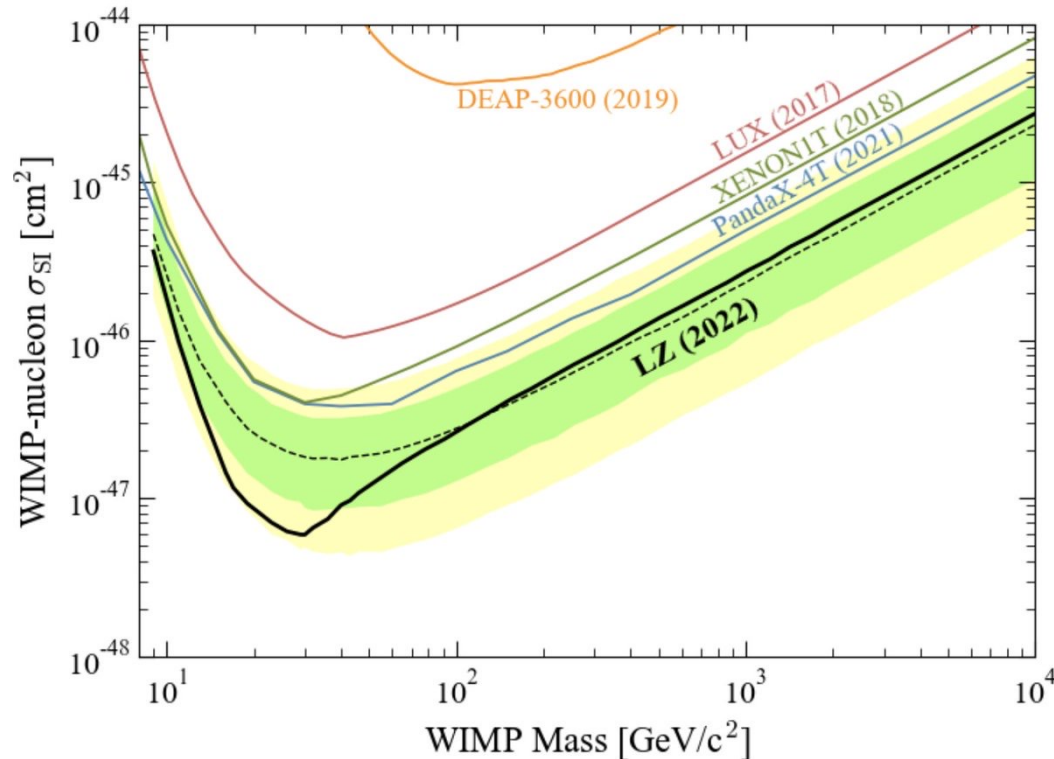


To observe scattering between DM and SM particles.



The Latest Result of Experiment

[4] LZ Collaboration, J. Aalbers et al., arXiv: 2207.03764 (hep-ex) (2022)



Cited from [4]

- DM-nucleon cross section is suppressed strongly.

- We need some idea to explain the DM relic abundance and small DM-nucleon scattering cross section at the same time.



- We focus on the previous work which can explain small cross section by flavor structure.

Idea in Previous Work

[5] I. Golon, A. Kawa and P. Tenedo, JHEP03, 064 (2017).

- Effective theory including flavor violating interaction.

$$\mathcal{L}_{\varphi\chi} \propto \frac{1}{2} y_s \varphi \bar{\chi} \chi + \frac{i}{2} y_P \varphi \bar{\chi} \gamma^5 \chi$$

$$\mathcal{L}_{\varphi SM} = g_{ij} \varphi \bar{l}_i P_L l_j + g_{ji}^* \varphi^* \bar{l}_j P_R l_i$$

χ : dark matter l_i : charged lepton φ : mediator

- DM-nucleon cross section is suppressed by flavor structure.

However,
the origin of flavor off-diagonal interaction is not sure.

→ We build a new renormalizable Model.

Contents

- Beyond Standard Model and Dark Matter
- Current Status and Previous Works
- **Our Model and Evaluation at 1-loop level**
- Testability of DM Model
- Conclusion and Outlook

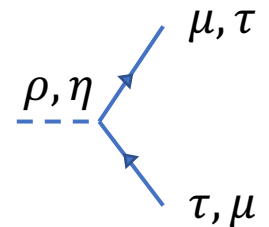
Our DM Model

- SM + mediator : $\Phi = \begin{pmatrix} \phi^+ \\ \frac{\rho+i\eta}{\sqrt{2}} \end{pmatrix}$ + complex scalar DM: Σ . [1]Phys. Rev. D **106**, 035017(2022)

particle	(L_e, L_μ, L_τ)	(e_R, μ_R, τ_R)	H	Φ	Σ
SM	$(1, 2)_{-1/2}$	$(1, 1)_{-1}$	$(1, 2)_{1/2}$	$(1, 2)_{1/2}$	$(1, 1)_0$
Z_4	$(1, i, -i)$	$(1, i, -i)$	1	-1	i

Notation of SM quantum number: $(SU(3)_C, SU(2)_L)_{U(1)_Y}$

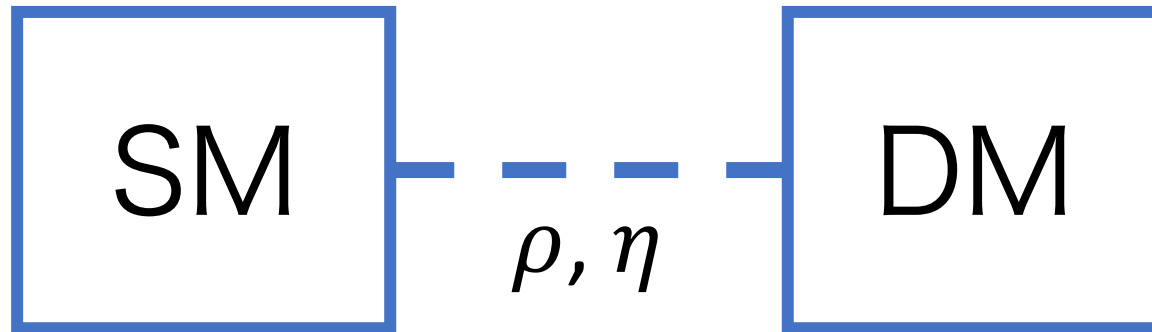
- Z_4 lepton flavor symmetry.
- Φ has flavor off-diagonal interaction between μ and τ .
- Z_2 involved in Z_4 stabilizes DM.
- Renormalizable model.



→ We can evaluate quantum effect.

Coupling Structure of SM-DM

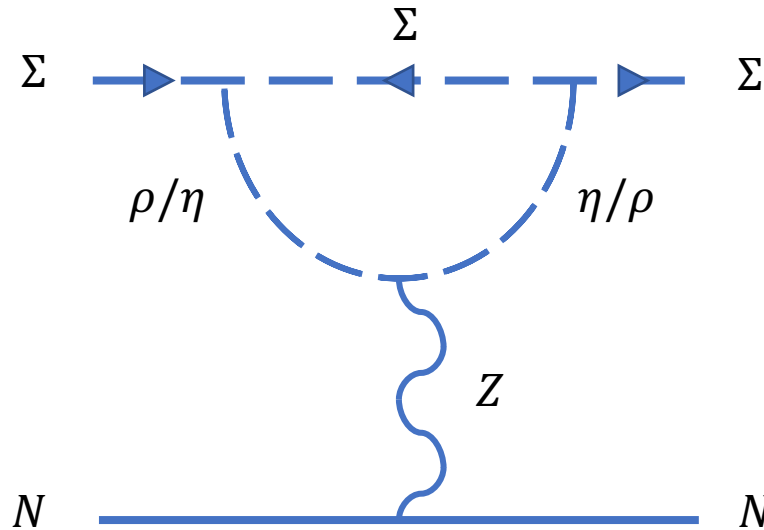
[1] Phys. Rev. D **106**, 035017(2022)



- DM couples to SM mediated only by ρ and η .
- ρ and η have a off-diagonal interaction μ - τ , and do not couple to e and quarks directly.
 - Cross section is suppressed at tree level.
- DM can couple to nucleons at 1-loop level.

Direct Detection at 1-loop level

[1] Phys. Rev. D **106**, 035017(2022)



- Cross-section at 1-loop level in our model.

→ Prediction.

$$\sigma_{SI} = \frac{\mu_N [Z C_{V,p} + (A - Z) C_{V,d}]^2}{\pi}$$

$$C_{V,q} = a_Z \frac{1}{m_Z^2} \frac{g}{2 \cos \theta_W} (T_3 - 2Q_q \sin \theta_W),$$

$$a_Z = \frac{(k\kappa)^2}{(4\pi)^2} \frac{g}{2 \cos \theta_W} \times \frac{1}{m_\rho^2 - m_\eta^2} \left[f\left(\frac{m_\rho}{m_\Sigma}\right) - f\left(\frac{m_\eta}{m_\Sigma}\right) \right]$$

$$C_{V,p} = 2C_{V,u} + C_{V,d}, \quad C_{V,n} = C_{V,u} + 2C_{V,d}, \quad \mu_N = \frac{m_\Sigma m_N}{m_\Sigma + m_N}$$

Contents

- Beyond Standard Model and Dark Matter
- Current Status and Previous Works
- Our Model and Evaluation at 1-loop level
- **Testability of DM Model**
- Conclusion and Outlook

DM Relic Abundance

→ can be determined from the CMB observation.

[1]Phys. Rev. D **106**, 035017(2022)

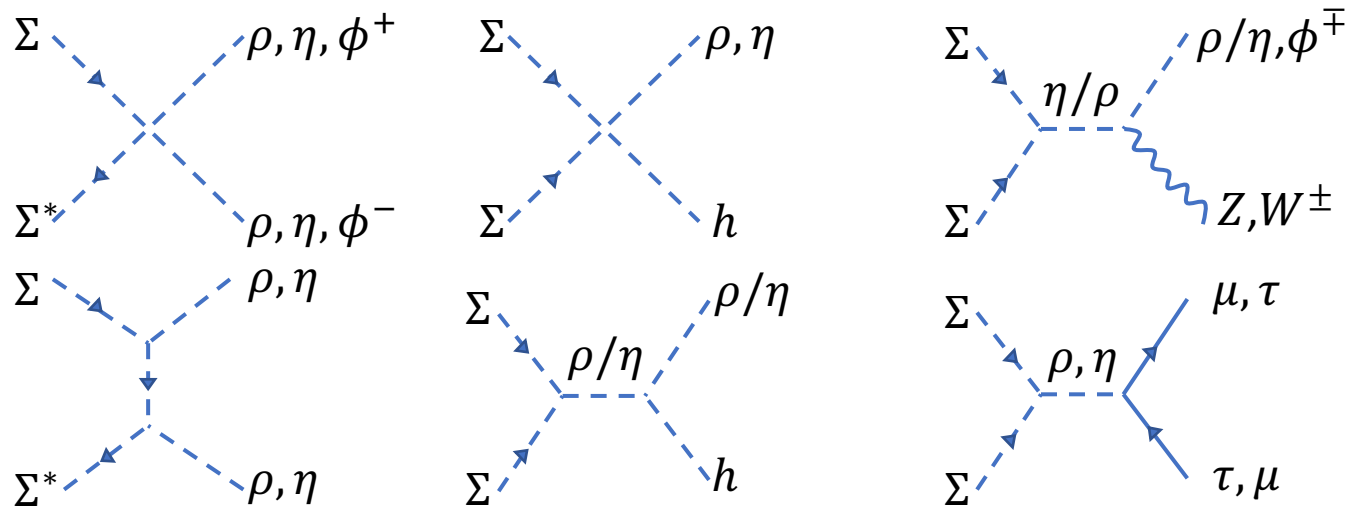
- Boltzmann equation. → Theoretical value.

$$\frac{dn_{DM}}{dt} + 3Hn_{DM} = -\frac{1}{2}(\sigma v_{rel})_{eff} [n_{DM}^2 - (n_{DM}^{eq})^2]$$

$$\underline{(\sigma v_{rel})_{eff}} = \sum_{ij} \left[\sigma v_{\Sigma\Sigma^* \rightarrow ij} + \frac{1}{2} \sigma v_{\Sigma\Sigma \rightarrow ij} + \frac{1}{2} \sigma v_{\Sigma^*\Sigma^* \rightarrow ij} \right]$$

Depends on models.

- Diagrams contributing to $(\sigma v_{rel})_{eff}$.



- Approximate formula can be used.



$$\Omega_{DM} h^2 \simeq 0.12 \times \left(\frac{3 \times 10^{-26} \text{ cm}^3 / \text{s}}{\frac{1}{2} (\sigma v_{rel})_{eff}} \right)$$

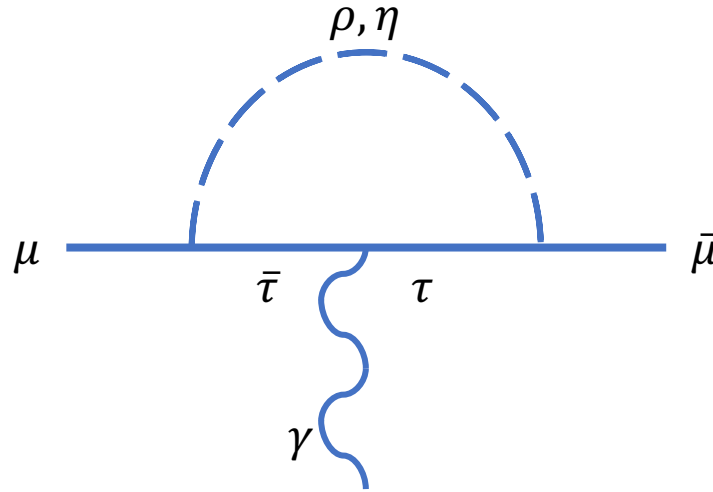


We can examine viable DM parameter space consistent with observation.

- Too many variables to discuss the testability.
 → We focus on the previous work.

Previous Work of explanation to Muon $g-2$ Discrepancy

[6] Y, Abe, T. Toma and K. Tsumura, JHEP 06, 142 (2019).



- Muon $g-2$ discrepancy between SM and experiments should be corrected.

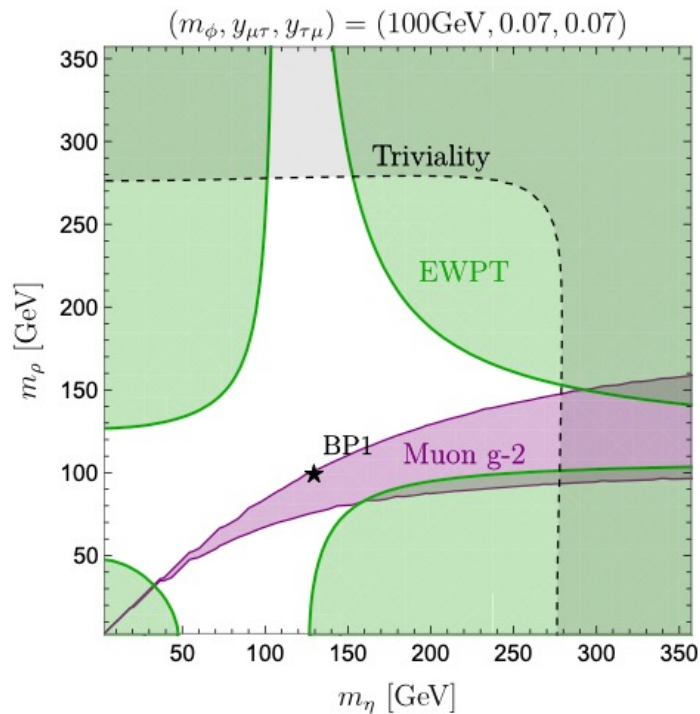
[2] Muon $g-2$ Collaboration, Phys. Rev. Lett.126, 141802 (2021).

- Correction of this discrepancy is given by ρ and η which is same particles in our model.

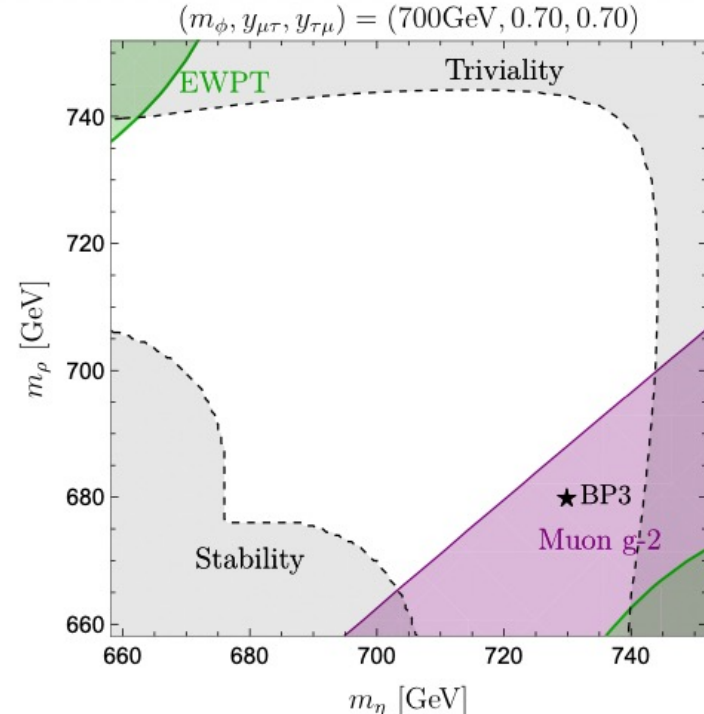
Benchmark Point

[1] Phys. Rev. D **106**, 035017(2022)

- We can select BP of the mediator which gives muon g-2 correction.



(a) BP1



(c) BP3

BP1: $(m_\eta, m_\rho) = (130 \text{ GeV}, 100 \text{ GeV})$

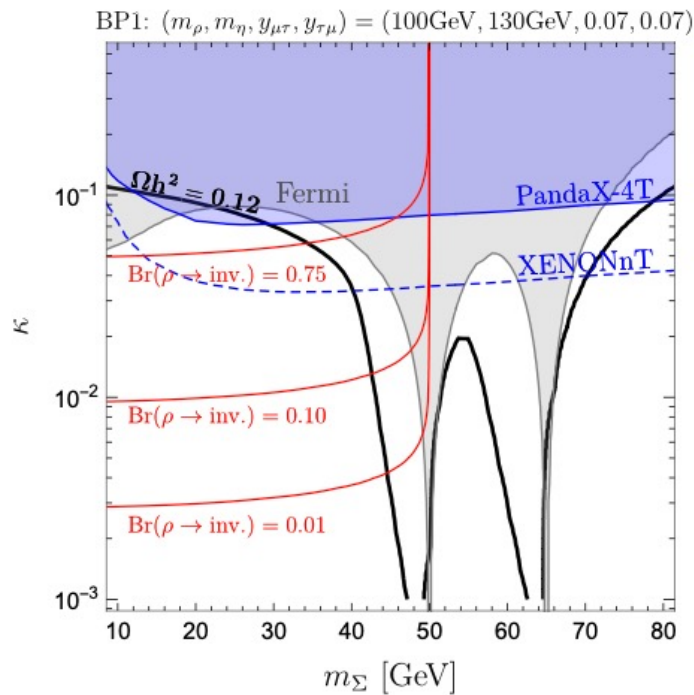
BP3: $(m_\eta, m_\rho) = (730 \text{ GeV}, 680 \text{ GeV})$

Cited from [Phys. Rev. D **106**, 035017(2022)]

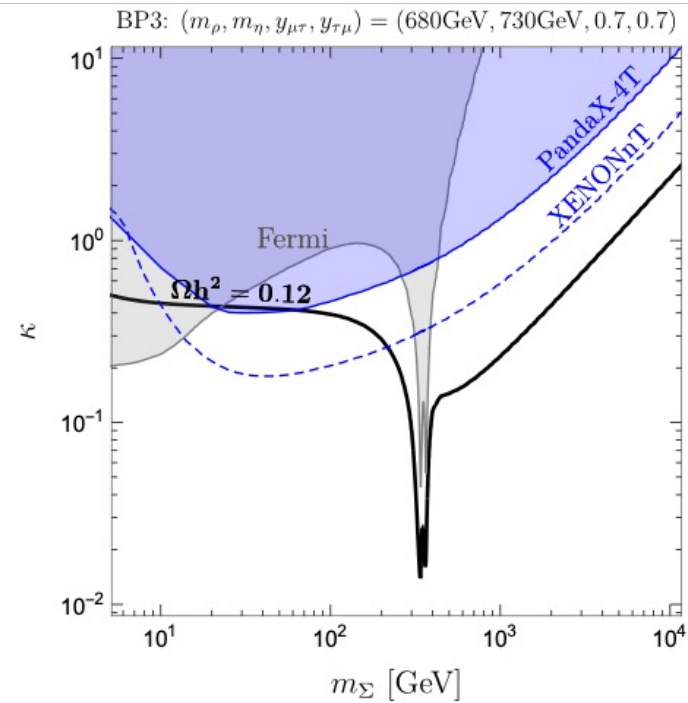
Detection of Possible DM Space

[1] Phys. Rev. D **106**, 035017(2022)

- Our model is testable at XENONnT experiment.



(a) BP1



(c) BP3

κ : quartic $(\kappa[(H^\dagger\Phi)\Sigma^2 + \text{H. c.}] \subset \mathcal{L}$

Cited from [Phys. Rev. D **106**, 035017(2022)]

Contents

- Beyond Standard Model and Dark Matter
- Current Status and Previous Works
- Our Model and Evaluation at 1-loop level
- Testability of DM Model
- **Conclusion and Outlook**

Conclusion

- DM-nucleon cross section suppression is explained by flavor structure.
- We evaluated the cross section at 1-loop level.
- Our model can explain DM and muon $g-2$ at the same time.
- Our model is testable in the future experiments.

Outlook

- To consider extended models which have mediator couples to not only μ - τ pair but also other lepton pairs and compare them.

Reference

- [1] K. Asai, C. Miyao, S. Okawa, K. Tsumura, Phys. Rev. D **106**, 035017(2022).
- [2] Muon g-2 Collaboration, Phys. Rev. Lett.126, 141802 (2021).
- [3] Summer School for YONUPA Lecture, S. Matsumoto (2012).
- [4] LZ Collaboration, J. Aalbers et al., arXiv: 2207.03764 [hep-ex] (2022).
- [5] I. Golon, A. Kawa and P. Tenedo, JHEP03, 064 (2017).
- [6] Y, Abe, T. Toma and K. Tsumura, JHEP 06, 142 (2019).

Back up

Properties of DM

[3] Summer School for YONUPA Lecture, S. Matsumoto (2012).

- No electromagnetic interaction.
- Weakly interaction with other particles.
- Stable or a longer lifetime than the universe at least.

Idea of Portal



- DM interact with SM only by mediator as a portal.
- This structure is useful to explain DM properties.
- Candidate of mediator: Higgs, Z boson, non-SM particles...

Lagrangian of Our Model

[1]Phys. Rev. D **106**, 035017(2022)

$$\mathcal{L} = \mathcal{L}_{SM} + |D_\mu \Phi|^2 + |D_\mu \Sigma|^2 - (y_{\mu\tau} L_\mu^\dagger \Phi \tau_R + y_{\tau\mu} L_\tau^\dagger \Phi \mu_R + H.c.) - V(H, \Phi, \Sigma)$$

$$V(H, \Phi, \Sigma) = \mu_\Phi^2 |\Phi|^2 + \lambda_2 |\Phi|^4 + \lambda_3 |H|^2 |\Phi|^2 + \lambda_4 |H^\dagger \Phi|^2 + \frac{\lambda_5}{2} [(H^\dagger \Phi)^2 + H.c.] \\ + \mu_\Sigma^2 |\Sigma|^2 + \lambda_\Sigma |\Sigma|^4 + [\lambda'_\Sigma \Sigma^4 + H.c.] + \lambda_{H\Sigma} |H|^2 |\Sigma|^2 + \lambda_{\Phi\Sigma} |\Phi|^2 |\Sigma|^2 \\ + \kappa [(H^\dagger \Phi) \Sigma^2 + H.c.]$$

$$m_{\phi^\pm}^2 = \mu_\Phi^2 + \frac{1}{2} \lambda_3 v^2$$

$$m_\rho^2 = \mu_\Phi^2 + \frac{1}{2} (\lambda_3 + \lambda_4 + \lambda_5) v^2$$

$$m_\eta^2 = \mu_\Phi^2 + \frac{1}{2} (\lambda_3 + \lambda_4 - \lambda_5) v^2$$

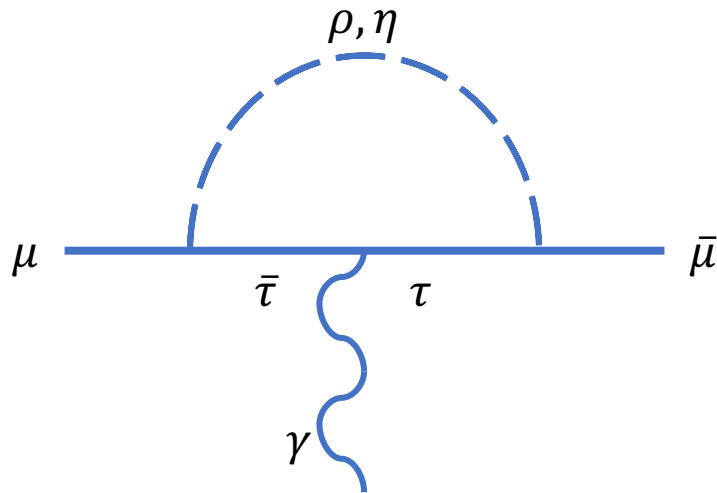
$$m_\Sigma^2 = \mu_\Sigma^2 + \frac{1}{2} \lambda_{H\Sigma} v^2$$

$$H = (0, (v + h)/\sqrt{2})^T$$

$$\Phi = (\phi^+, (\rho + i\eta)/\sqrt{2})^T$$

Correction to Muon g-2

[6] Y. Abe, T. Toma and K. Tsumura, JHEP 06, 142 (2019).



$$I_1(\alpha, \beta) \equiv \int_0^1 dx \frac{(1-x)^2}{x - x(1-x)\alpha + (1-x)\beta}$$

$$I_2(\alpha, \beta) \equiv \frac{1}{2} \int_0^1 dx \frac{x(1-x)^2}{x - x(1-x)\alpha + (1-x)\beta}$$

$$\Delta a_\mu^{\text{new}} = \frac{\text{Re}(y_{\mu\tau} y_{\tau\mu})}{(4\pi)^2} \left[\frac{m_\mu m_\tau}{m_\rho^2} I_1 \left(\frac{m_\mu^2}{m_\rho^2}, \frac{m_\tau^2}{m_\rho^2} \right) - \frac{m_\mu m_\tau}{m_\eta^2} I_1 \left(\frac{m_\mu^2}{m_\eta^2}, \frac{m_\tau^2}{m_\eta^2} \right) \right]$$

$$+ \frac{|y_{\mu\tau}|^2 + |y_{\tau\mu}|^2}{2(4\pi)^2} \left[\frac{m_\mu^2}{m_\rho^2} I_2 \left(\frac{m_\mu^2}{m_\rho^2}, \frac{m_\tau^2}{m_\rho^2} \right) + \frac{m_\mu^2}{m_\eta^2} I_2 \left(\frac{m_\mu^2}{m_\eta^2}, \frac{m_\tau^2}{m_\eta^2} \right) \right]$$

→ We can detect particles to correct the discrepancy to be within 2σ .

Off-diagonal Flavor Coupling

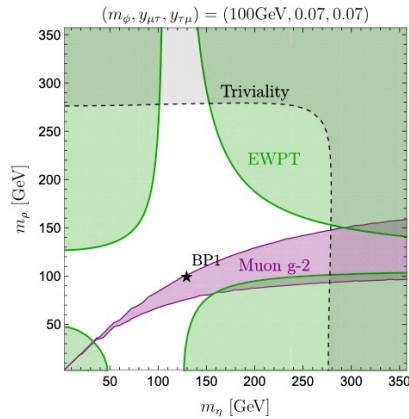
[6] Y, Abe, T. Toma and K. Tsumura, JHEP 06, 142 (2019).

$$-\mathcal{L}_{Yukawa} = \bar{l}_R \begin{pmatrix} y_e H^\dagger & & \\ & y_\mu H^\dagger & y_{\mu\tau} \Phi^\dagger \\ & y_{\tau\mu} \Phi^\dagger & y_\tau H^\dagger \end{pmatrix} L + \text{H. c.}, \Phi = \begin{pmatrix} \phi^+ \\ (\rho + i\eta)/\sqrt{2} \end{pmatrix}$$

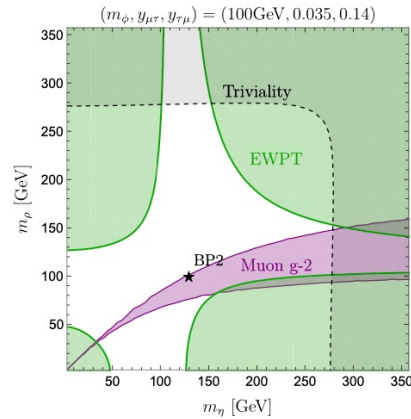
- Φ have the flavor off-diagonal coupling.
- Φ has flavor charge, so the model maintain the flavor symmetry.
- Renormalizable model.

Benchmark Point

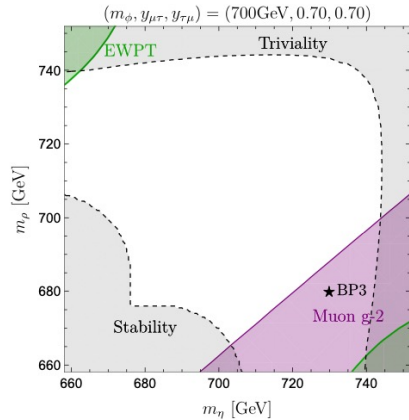
[1] Phys. Rev. D **106**, 035017(2022)



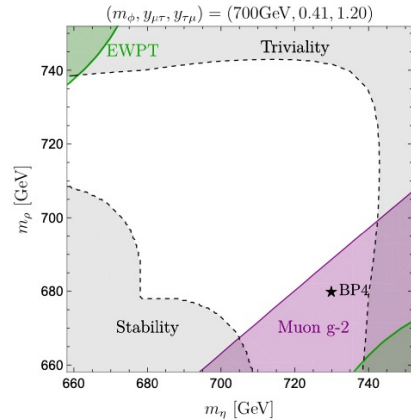
(a) BP1



(b) BP2



(c) BP3



(d) BP4

$$\text{BP1: } (m_\eta, m_\rho) = (130 \text{ GeV}, 100 \text{ GeV})$$

$$\text{BP2: } (m_\eta, m_\rho) = (130 \text{ GeV}, 100 \text{ GeV})$$

$$\text{BP3: } (m_\eta, m_\rho) = (730 \text{ GeV}, 680 \text{ GeV})$$

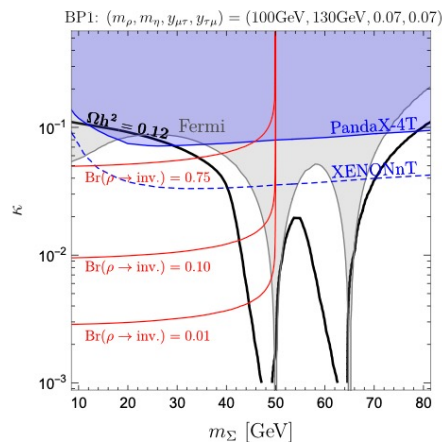
$$\text{BP4: } (m_\eta, m_\rho) = (730 \text{ GeV}, 680 \text{ GeV})$$

Cited from [Phys. Rev. D **106**, 035017(2022)]

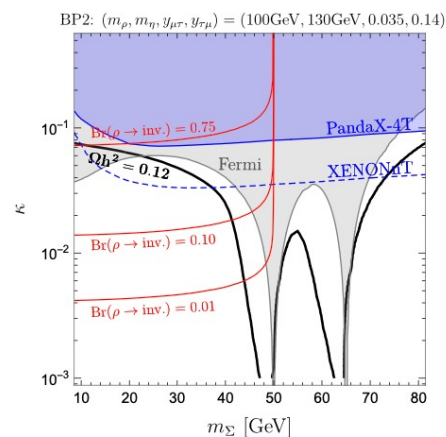
Detection of Possible DM Space

Cited from [Phys. Rev. D **106**, 035017(2022)]

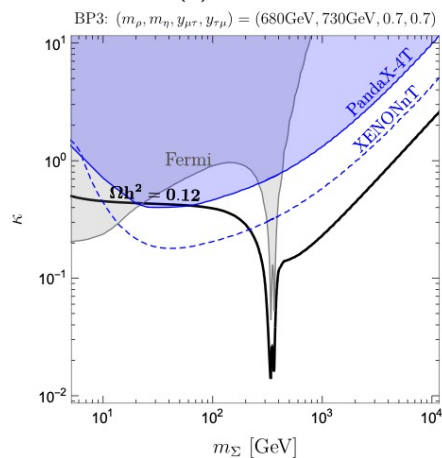
[1]Phys. Rev. D **106**, 035017(2022)



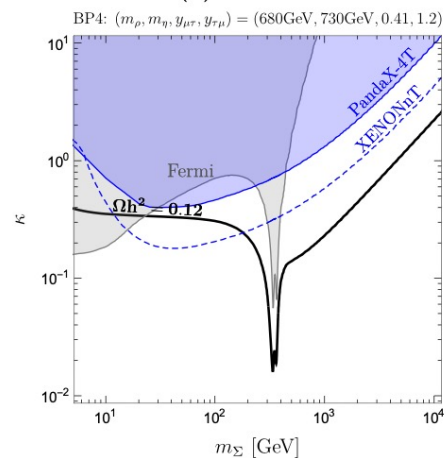
(a) BP1



(b) BP2



(c) BP3



(d) BP4

Neutrino Mass 1

[1]Phys. Rev. D **106**, 035017(2022)

particle	(L_e, L_μ, L_τ)	(e_R, μ_R, τ_R)	H	Φ	Σ	(N_e, N_μ, N_τ)	S
SM	$(1, 2)_{-1/2}$	$(1, 1)_{-1}$	$(1, 2)_{1/2}$	$(1, 2)_{1/2}$	$(1, 1)_0$	$(1, 1)_0$	$(1, 1)_0$
Z_4	$(1, i, -i)$	$(1, i, -i)$	1	-1	i	$(1, i, -i)$	i
Z_2	+	+	+	+	-	+	+

Notation of SM quantum number: $(SU(3)_C, SU(2)_L)_{U(1)_Y}$

- RH neutrinos (N_e, N_μ, N_τ) and a Z_4 -breaking singlet scalar S are introduced.
- Z_4 charged S has a nonzero VEV and breaks Z_4 .
- Z_2 is introduced for DM stability.

Neutrino Mass 2

[1]Phys. Rev. D **106**, 035017(2022)

$$\mathcal{L}_N = -\frac{1}{2} (\overline{N_e^c} \overline{N_\mu^c} \overline{N_\tau^c}) \begin{pmatrix} M_{ee} & \lambda_{e\mu} S^* & \lambda_{e\tau} S \\ \lambda_{e\mu} & & M_{\mu\tau} \\ \lambda_{e\tau} S & M_{\mu\tau} & \end{pmatrix} \begin{pmatrix} N_e \\ N_\mu \\ N_\tau \end{pmatrix} \\ - (\overline{L_e} \overline{L_\mu} \overline{L_\tau}) \begin{pmatrix} y_{ee} \tilde{H} & & \\ & y_{\mu\mu} \tilde{H} & y_{\mu\tau} \tilde{\Phi} \\ & y_{\tau\mu} \tilde{\Phi} & y_{\tau\tau} \tilde{H} \end{pmatrix} \begin{pmatrix} N_e \\ N_\mu \\ N_\tau \end{pmatrix} + \text{H. c.}$$

$$\tilde{H} = i\sigma_2 H^* \\ \tilde{\Phi} = i\sigma_2 \Phi^*$$

After H and S got VEV, the neutrinos obtain Dirac and Majorana mass.