フレーバー対称性により抑制される暗黒物質の直接検出

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FPWS2022@ 伊豆（ニュー八景園）

9th 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

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Is the Standard Model(SM) Theory of Everything？

➡ Beyond SM phenomena 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).

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<u>We focus on DM
to build Beyond Standard Model (BSM).</u>

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.

秋本さんのDMのイラスト→

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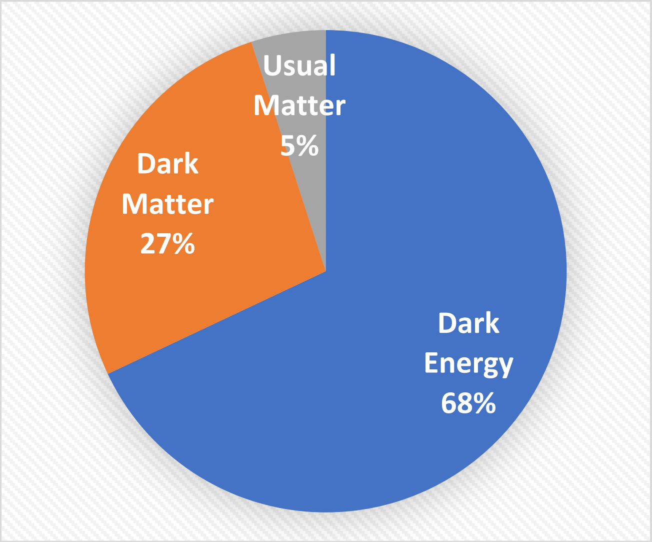
DM in the Universe

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

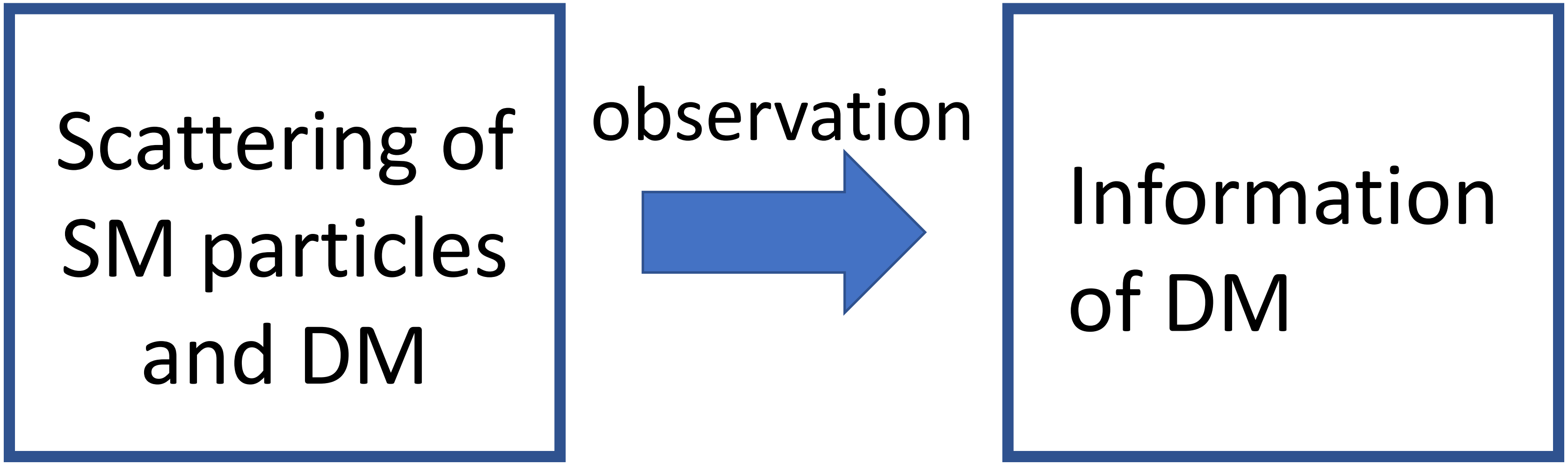


- Boltzmann equation.
  → Theoretical value.

$$\frac{dn_{DM}}{dt} + 3Hn_{DM} = -< \sigma v >_{\mathrm{DM}\to\mathrm{SM}} \left[n_{DM}^2 - \left(n_{DM}^{eq} \right)^2 \right]$$

Direct Detection of DM

To observe scattering between DM and SM particles.



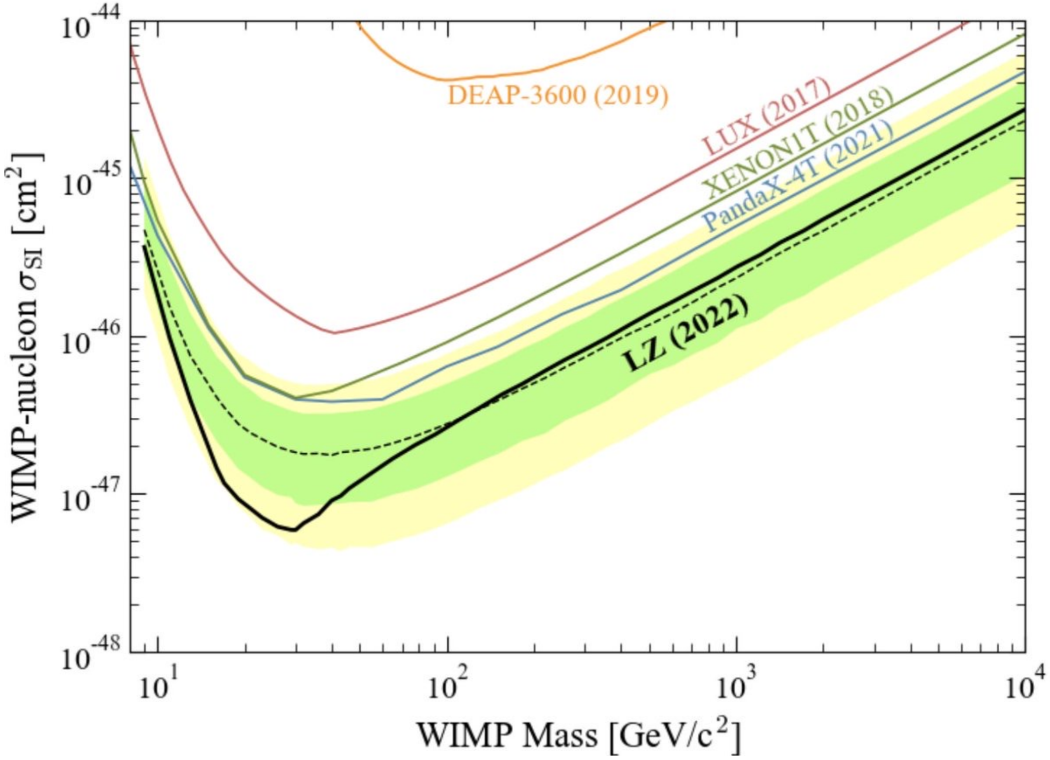
Scattering of SM particles and DM

observation

Information of DM

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 should explain the DM relic abundance and small scattering DM-nucleon cross section at 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.

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

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

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

However,
<u>the origin of flavor off-diagonal interaction is not sure.</u>

→We build a new renormalizable Model.

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Our DM Model

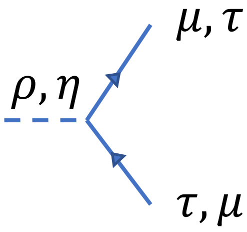
[1]Phys. Rev. D **106**, 035017(2022)

- SM + mediator :$\Phi = \begin{pmatrix} \phi^+ \\ \frac{\rho + i\eta}{\sqrt{2}} \end{pmatrix}$+complex scalar DM: Σ.

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: $(SU(3)_C, SU(2)_L\,)_{U(1)_Y}$

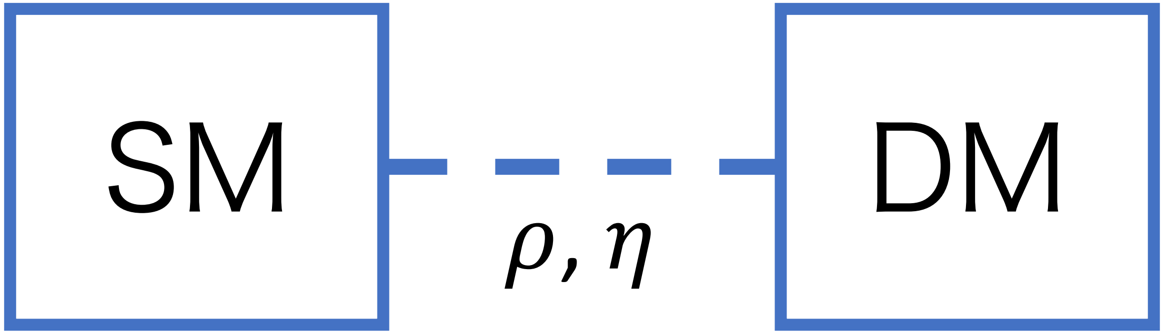
- Z_4 flavor symmetry.
- Φ has flavor off-diagonal coupling between μ and τ.
- Z_2 involved in Z_4 stabilizes DM.
- Renormalizable model.



→ We can evaluate quantum effect.

Coupling Structure of SM-DM

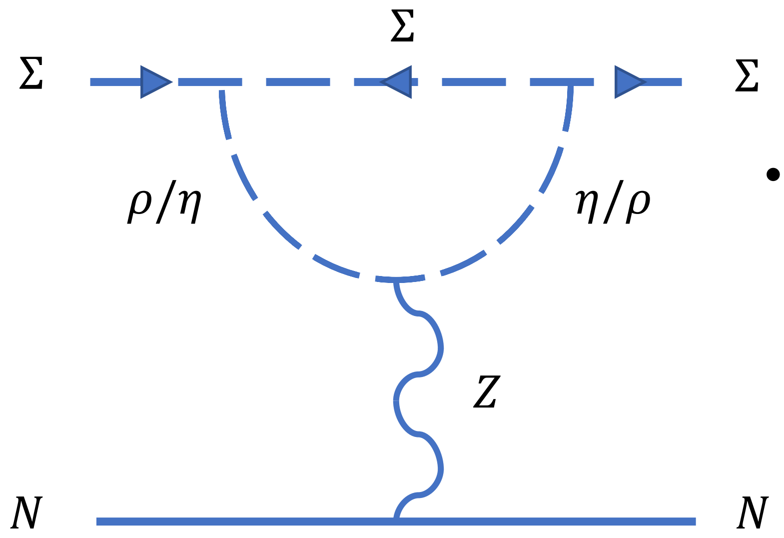
[1]Phys. Rev. D **106**, 035017(2022)



- DM couples to SM mediated only by ρ and η.
- ρ and η have a off-diagonal coupling μ-τ, and do not couple to e and quarks directly.
  → <u>Cross section is suppressed at tree level.</u>
- 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.

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

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

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

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

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DM Relic Abundance

→ can be determined from the CMB observation.

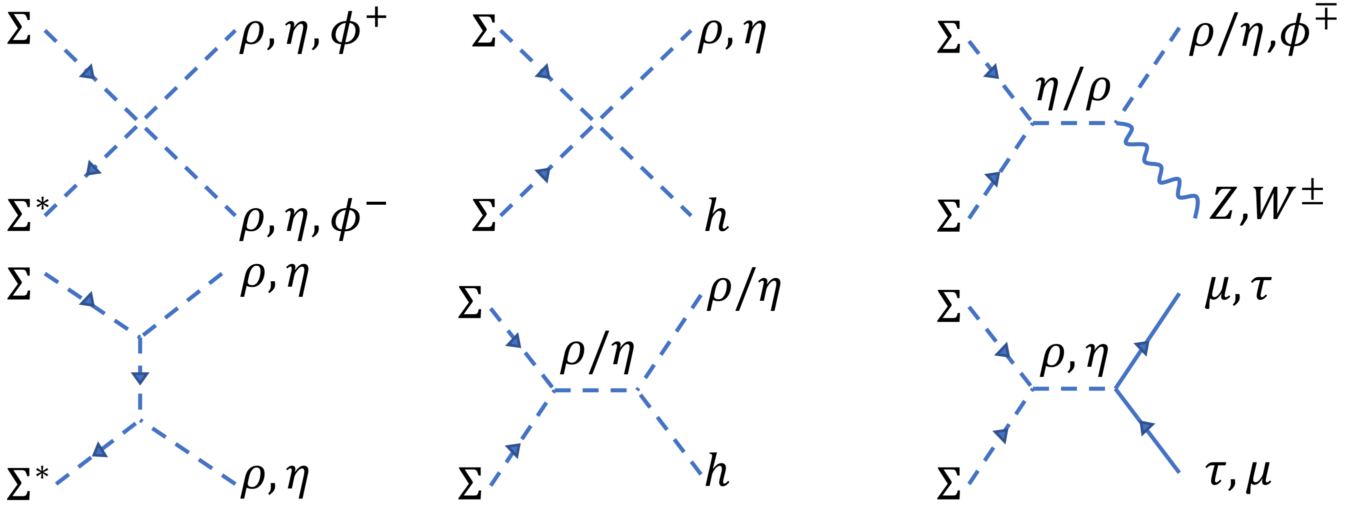
[1]Phys. Rev. D **106**, 035017(2022)

- Boltzmann equation. → Theoretical value.

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

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

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



- Approximate formula can be used.

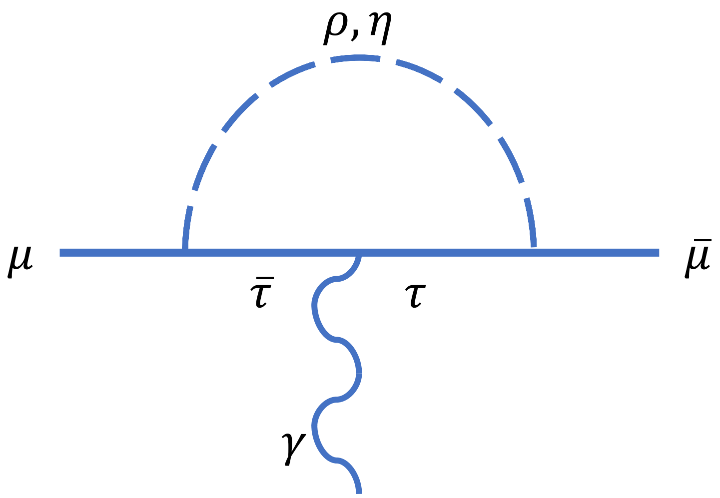
$$\Omega_{DM}h^2 \simeq 0.12 \times \left(\frac{3\times10^{-26}\ cm^3/s}{\frac{1}{2}(\sigma v_{rel})_{eff}}\right)$$

We can examine viable DM parameter space consistent with observation.

- We use micrOMEGAs5_2_4 for our numerical analysis instead of the above formula.

Mediator and Muon g-2

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



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

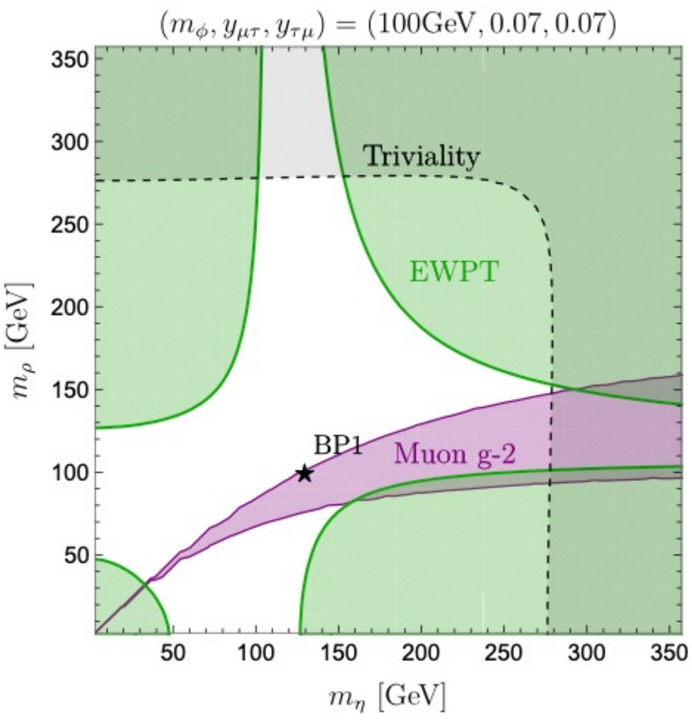
[2] Muon g-2 Collaboration, Phys. Rev. Lett.126, 141802 (2021).

- Correction of this discrepancy is given by ρ and η .

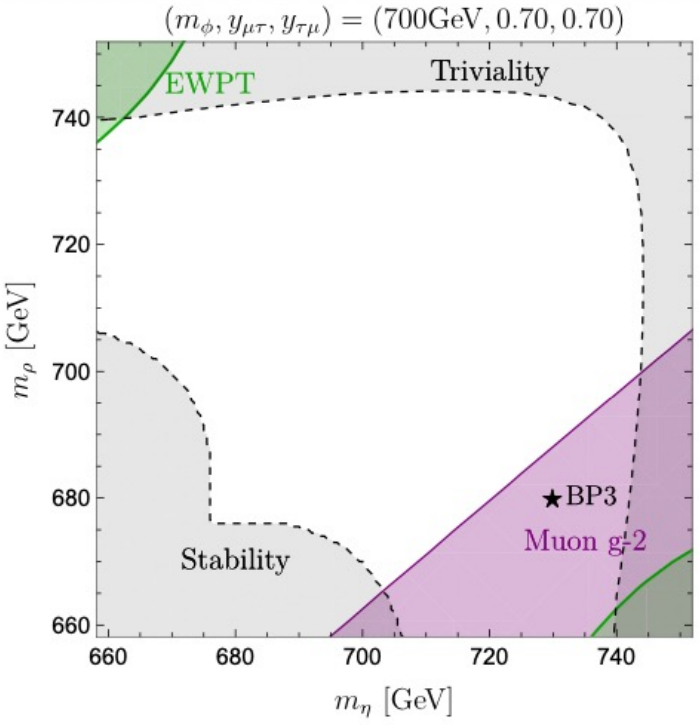
Benchmark Point

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

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



(a) BP1



(c) BP3

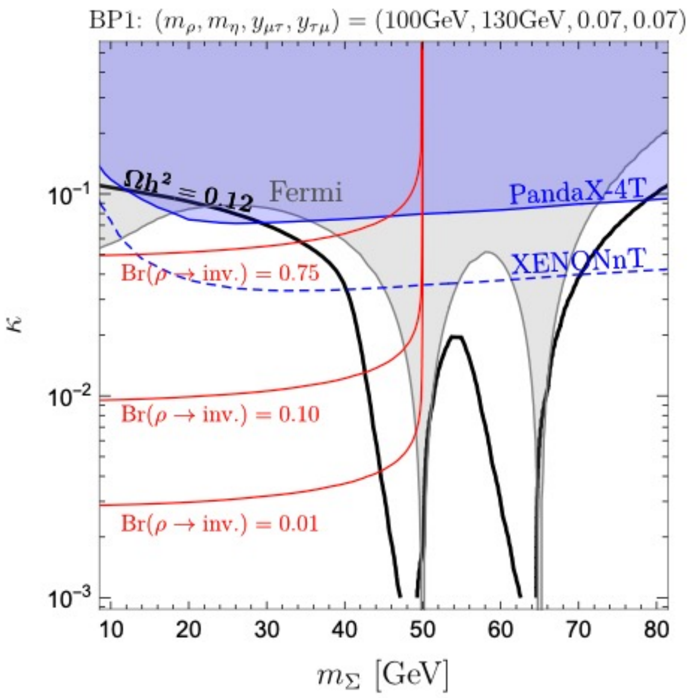
BP1: $(m_\eta, m_\rho) = (130\ GeV, 100GeV)$ BP3: $(m_\eta, m_\rho) = (730\ GeV, 680GeV)$

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

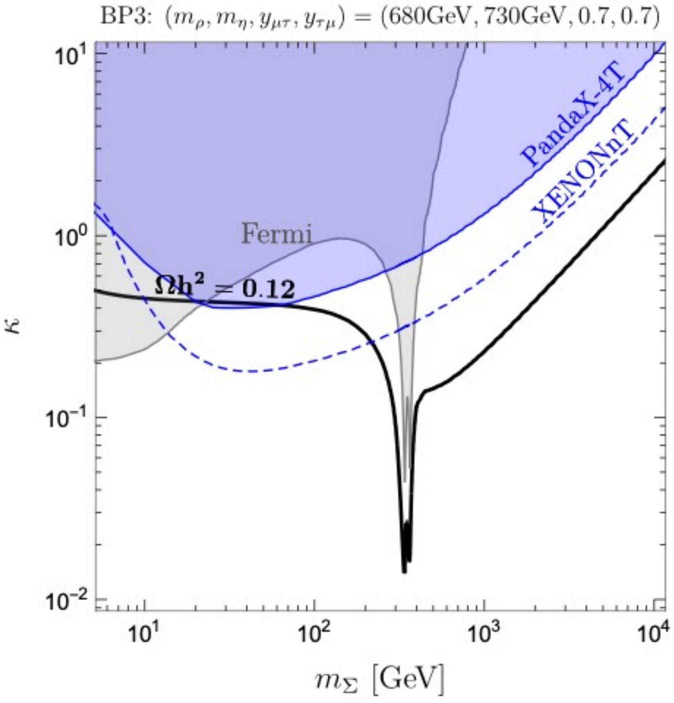
Detection of Possible DM Space

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

- Our model is testable at XENONnT experiment.



(a) BP1



(c) BP3

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

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

Contents

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 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 compere 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)

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

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

$$+\mu_\Sigma^2 |\Sigma|^2 + \lambda_\Sigma |\Sigma|^4 + [\lambda'_\Sigma \Sigma^4 + H.c.] + \lambda_{H\Sigma} |H|^2 |\Sigma|^2 + \lambda_{\Phi\Sigma} |\Phi|^2 |\Sigma|^2$$

$$+\kappa\left[\left(H^\dagger \Phi\right)\Sigma^2 + \mathrm{H.c.}\right]$$

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

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

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

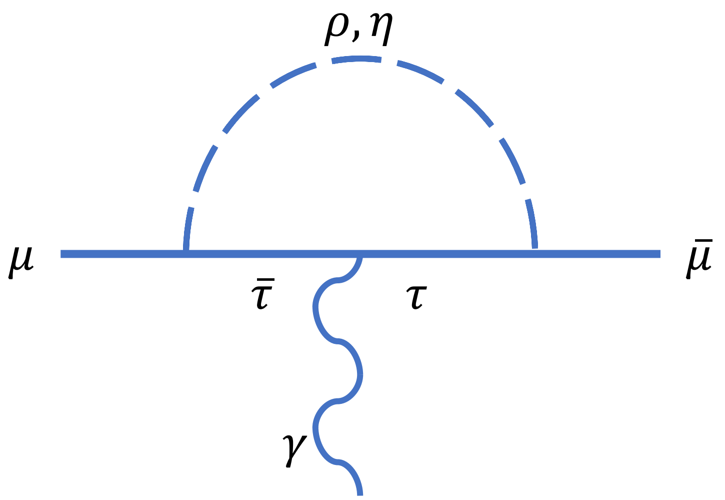
$$m_\Sigma^2 = \mu_\Sigma^2 + \frac{1}{2}\lambda_{H\Sigma} v^2$$

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

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

Correction to Muon g-2

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



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

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

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

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

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

Off-diagonal Flavor Coupling

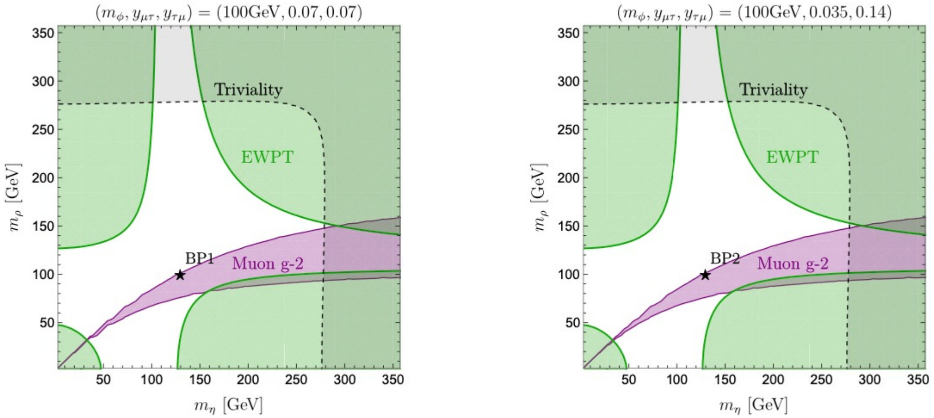
[6] Y, Abe, T. Toma and K. Tsumura, JHEP 06, 142 (2019).

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

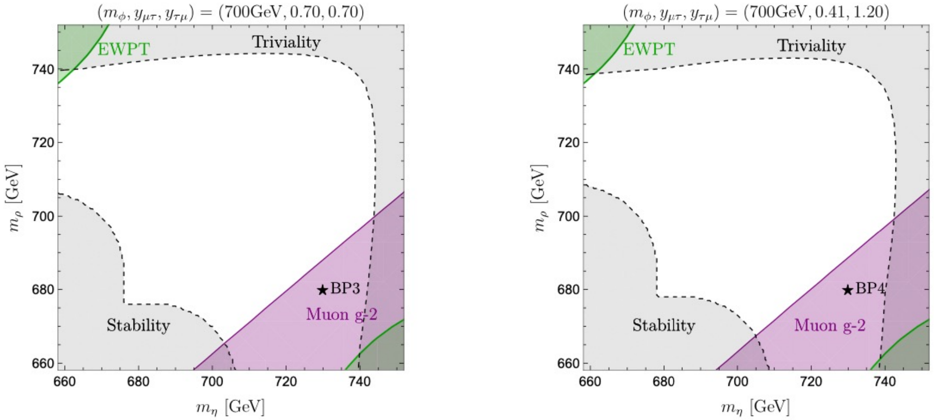
- Φ have the flavor off-diagonal coupling.
- Φ has flavor charge, so the model maintain the flavor symmetry.
- Renormalizable model.

Benchmark Point

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



(a) BP1 (b) BP2



(c) BP3 (d) BP4

BP1: $\left(m_\eta, m_\rho\right) = (130\ GeV, 100GeV)$

BP2: $\left(m_\eta, m_\rho\right) = (130\ GeV, 100GeV)$

BP3: $\left(m_\eta, m_\rho\right) = (730\ GeV, 680GeV)$

BP4: $\left(m_\eta, m_\rho\right) = (730\ GeV, 680GeV)$

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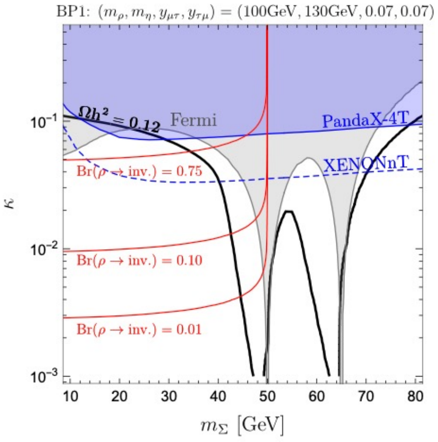
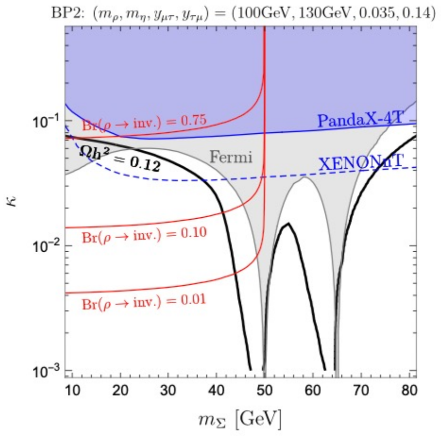
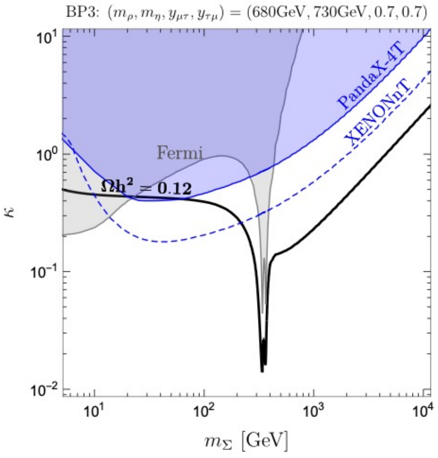


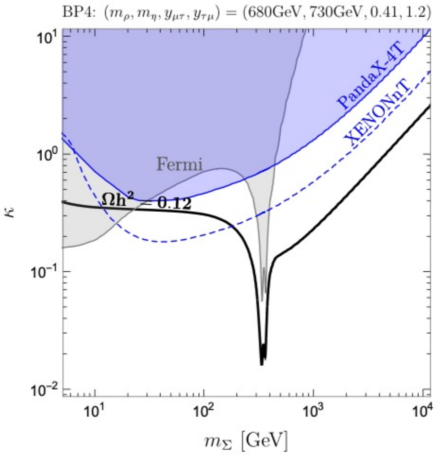
(a) BP1



(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)

$$\mathcal{L}_N = -\frac{1}{2}\left(\overline{N_e^c}\ \overline{N_\mu^c}\ \overline{N_\tau^c}\right)\begin{pmatrix} M_{ee} & \lambda_{e\mu}S^* & \lambda_{e\tau}S \\ \lambda_{e\mu} & & M_{\mu\tau} \\ \lambda_{e\tau}S & M_{\mu\tau} & \end{pmatrix}\begin{pmatrix} N_e \\ N_\mu \\ N_\tau \end{pmatrix}$$

$$-\left(\overline{L_e}\ \overline{L_\mu}\ \overline{L_\tau}\right)\begin{pmatrix} y_{ee}\widetilde{H} & & \\ & y_{\mu\mu}\widetilde{H} & y_{\mu\tau}\widetilde{\Phi} \\ & y_{\tau\mu}\widetilde{\Phi} & y_{\tau\tau}\widetilde{H} \end{pmatrix}\begin{pmatrix} N_e \\ N_\mu \\ N_\tau \end{pmatrix} + \mathrm{H.c.}$$

$\widetilde{H} = i\sigma_2 H^*$

$\widetilde{\Phi} = i\sigma_2 \Phi^*$

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