Scalar Dark Matter with a $\mu\tau$ Flavored Mediator

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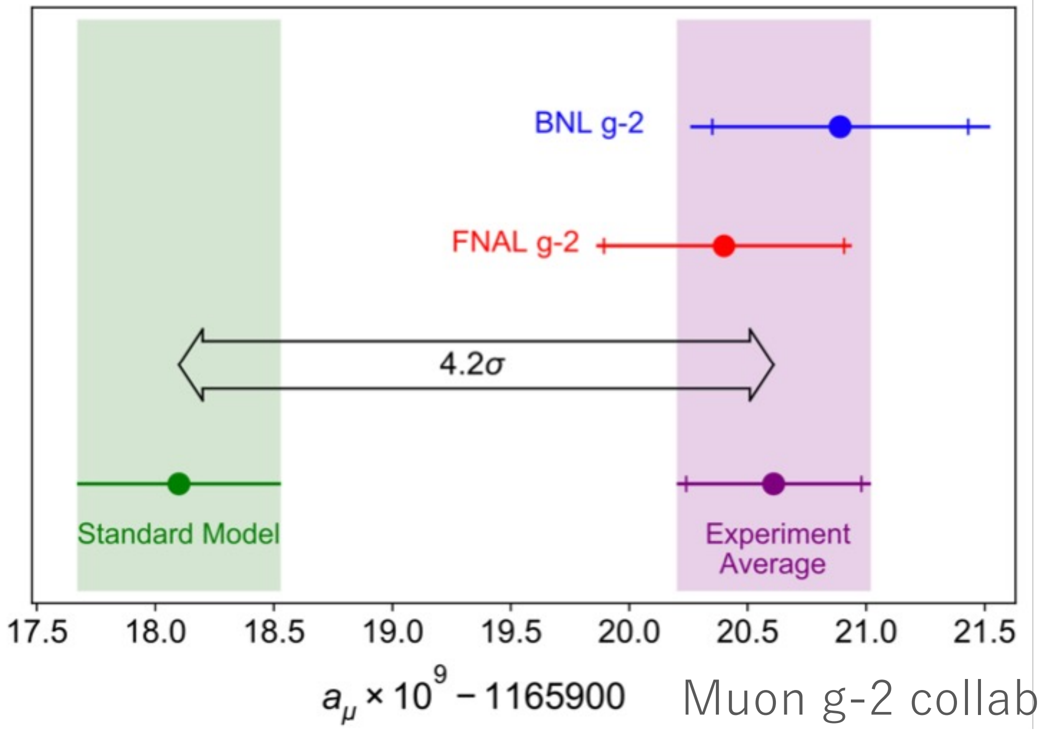
Based on
KA, C. Miyao, S. Okawa, K. Tsumura, PRD **106** (2022) 035017, arXiv : 2205.08998 [hep-ph]

Introduction

Muon anomalous magnetic moment

There is a discrepancy between experimental value and theoretical prediction of the muon g-2



Muon g-2 collaboration,
Phys. Rev. Lett. **126**, 141801 (2021)

$$\Delta a_\mu = a_\mu^{\mathrm{BNL+FNAL}} - a_\mu^{\mathrm{SM}}$$
$$= (25.1 \pm 5.9) \times 10^{-10} \quad (4.2\sigma)$$

$$\frac{m_\mu^2}{16\pi^2}\frac{g_{\mathrm{NP}}^2}{m_{\mathrm{NP}}^2}$$

New Physics ?

Muon anomalous magnetic moment

New Physics for muon g-2

- $\mathrm{U(1)}_{L_\mu - L_\tau}$ gauge boson

  S. Baek, N.G. Deshpande, X.G. He, P. Ko, PRD **64**, 055006 (2001); ⋯

- Supersymmetry

  J. L. Lopez, D. V. Nanopoulos, X. Wang, PRD **49** (1994) 366-372;
  U. Chattopadhyay, P. Nath, PRD **53** (1996) 1648-1657;
  T. Moroi, PRD **53** (1996) 6565-6575; ⋯

- Leptoquark

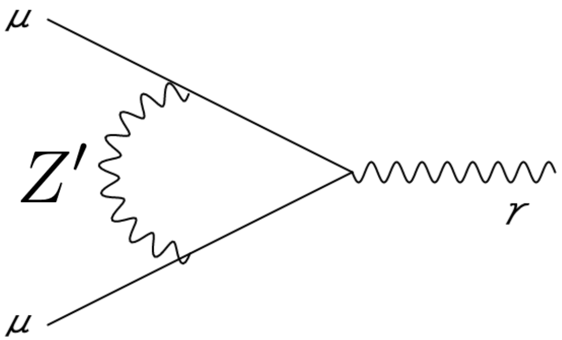
  D. Chakraverty, D. Choudhury, A. Datta, PLB **506** (2001) 103-108;
  K.-M. Cheung, PRD **64** (2001) 033001; ⋯

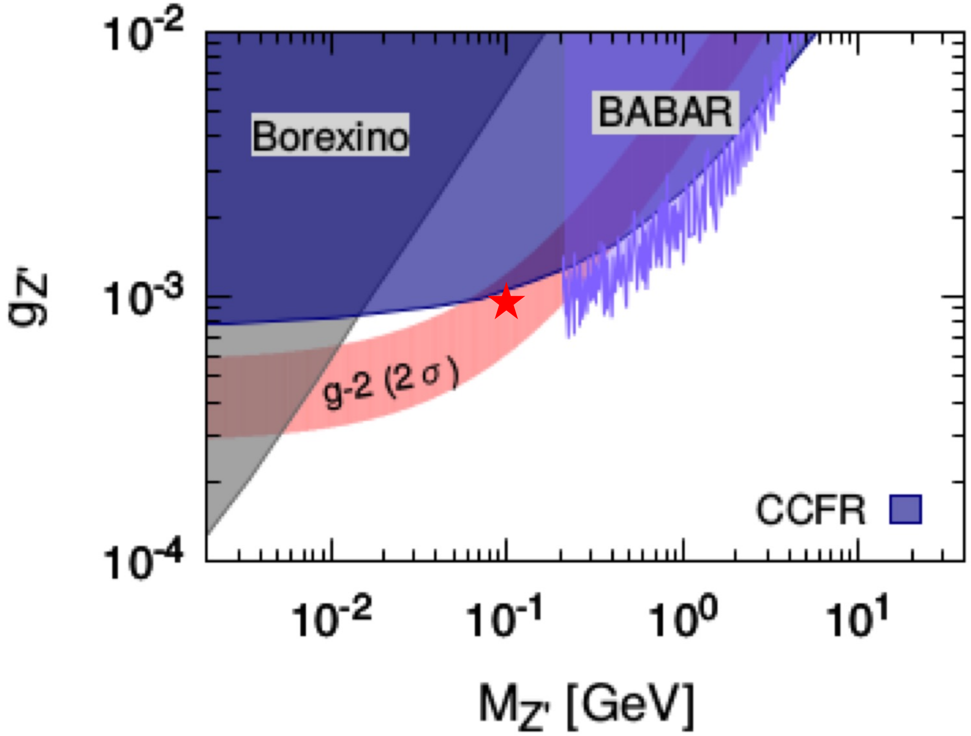
Muon anomalous magnetic moment

New Physics for muon g-2

- $\mathrm{U(1)}_{L_\mu - L_\tau}$ gauge boson

$$\Delta a_\mu = \mathcal{O}(10) \times 10^{-10} \left(\frac{g_{Z'}}{10^{-3}}\right)^2 \left(\frac{100\,\mathrm{MeV}}{m_{Z'}}\right)^2$$





No tree level coupling to electron & quarks

Araki, Hoshino, Ota, Sato, Shimomura, PRD **95**, 5, 055006 (2017)

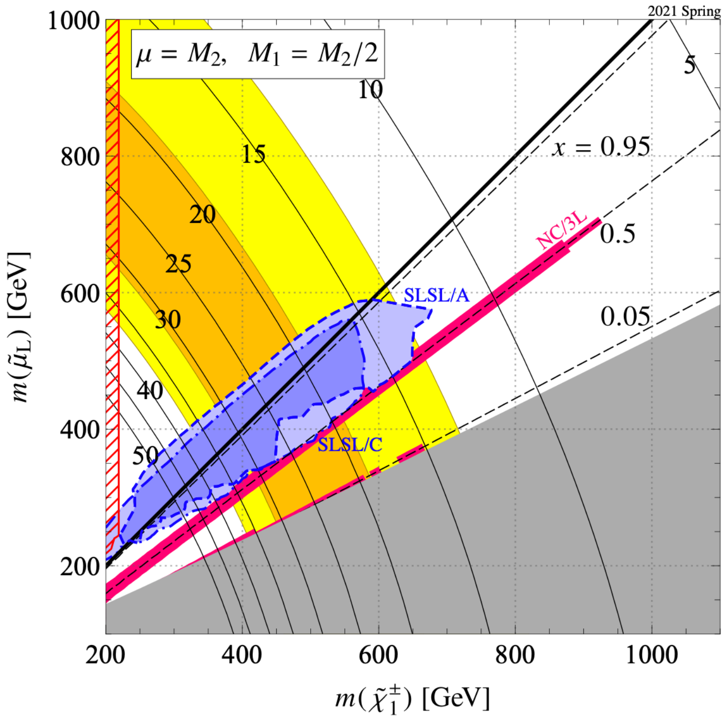
Muon anomalous magnetic moment

New Physics for muon g-2

- Supersymmetry

M. Endo, K. Hamaguchi, S. Iwamoto, T. Kitahara, JHEP **07**, 075 (2021)

$$\mathcal{O}(1) \times 10^{-10} \left(\frac{\alpha_2}{0.03}\right) \left(\frac{400\,\mathrm{GeV}}{m_{\mathrm{SUSY}}}\right)^2$$



$\tan\beta$ enhancement

$$\Delta a_\mu^{\mathrm{SUSY}} = \mathcal{O}(10) \times 10^{-10} \left(\frac{\tan\beta}{10}\right) \left(\frac{\alpha_2}{0.03}\right) \left(\frac{400\,\mathrm{GeV}}{m_{\mathrm{SUSY}}}\right)^2$$

Muon anomalous magnetic moment

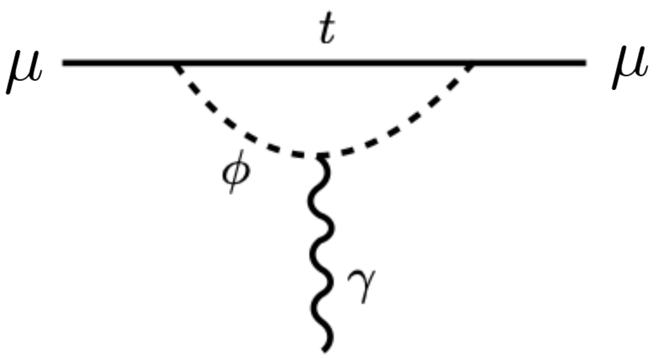
New Physics for muon g-2

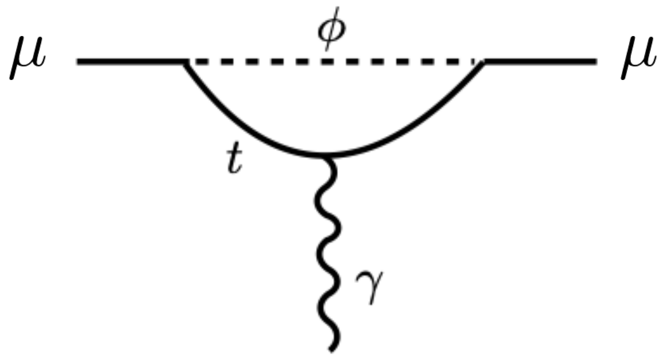
- Leptoquark

$$\mathcal{O}(10^{-2}) \times 10^{-10} \left(\frac{\lambda_{t\mu}}{0.1}\right)^2 \left(\frac{1\,\mathrm{TeV}}{m_{\mathrm{LQ}}}\right)^2$$

Chirality enhancement

$$\Delta a_\mu^{\mathrm{LQ}} = \mathcal{O}(10) \times 10^{-10} \left(\frac{m_t/m_\mu}{10^3}\right) \left(\frac{\lambda_{t\mu}}{0.1}\right)^2 \left(\frac{1\,\mathrm{TeV}}{m_{\mathrm{LQ}}}\right)^2$$





Muon anomalous magnetic moment

Advantage

- $U(1)_{L_\mu - L_\tau}$ gauge boson — No tree level coupling to e^- & q
- Supersymmetry — Enhancement factor
- Leptoquark — Enhancement factor

Another possibility

$\mu\tau$-philic doublet scalar — No tree level coupling to e^- & q; Enhancement factor

Y. Abe, T. Toma, K. Tsumura, JHEP **06**, 142 (2019)

$\mu\tau$-philic doublet scalar

Y. Abe, T. Toma, K. Tsumura, JHEP **06**, 142 (2019)

Symmetry

$$\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$$

&

Z_4 flavor symmetry

Fields

SM fields

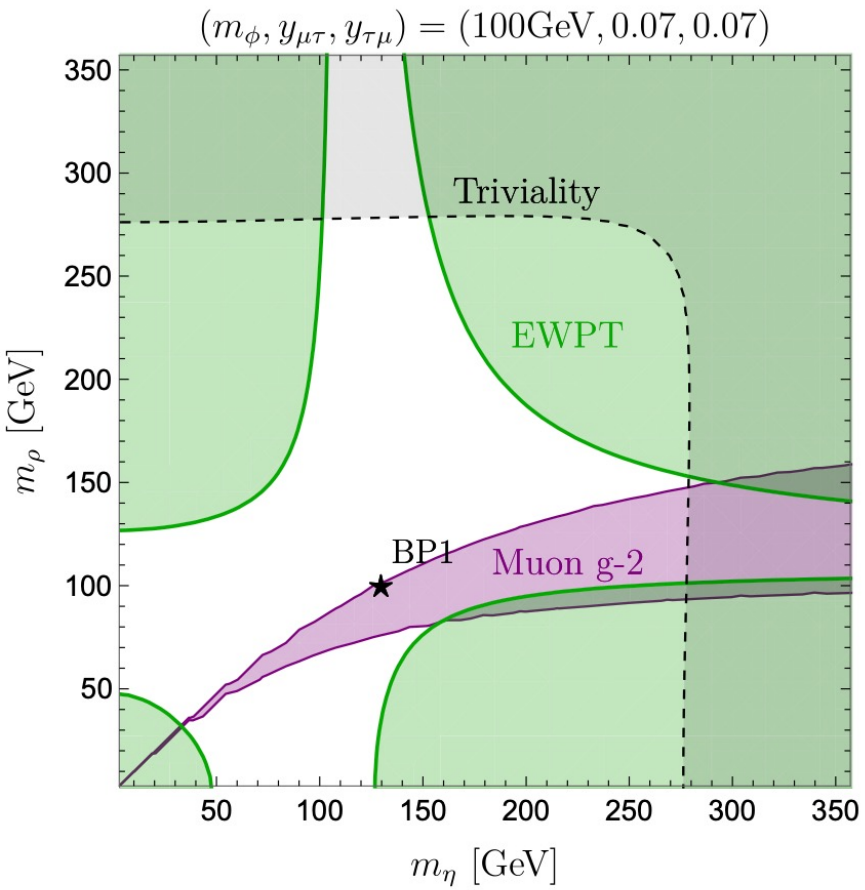
$+\,\Phi$: $\mu\tau$-philic doublet scalar

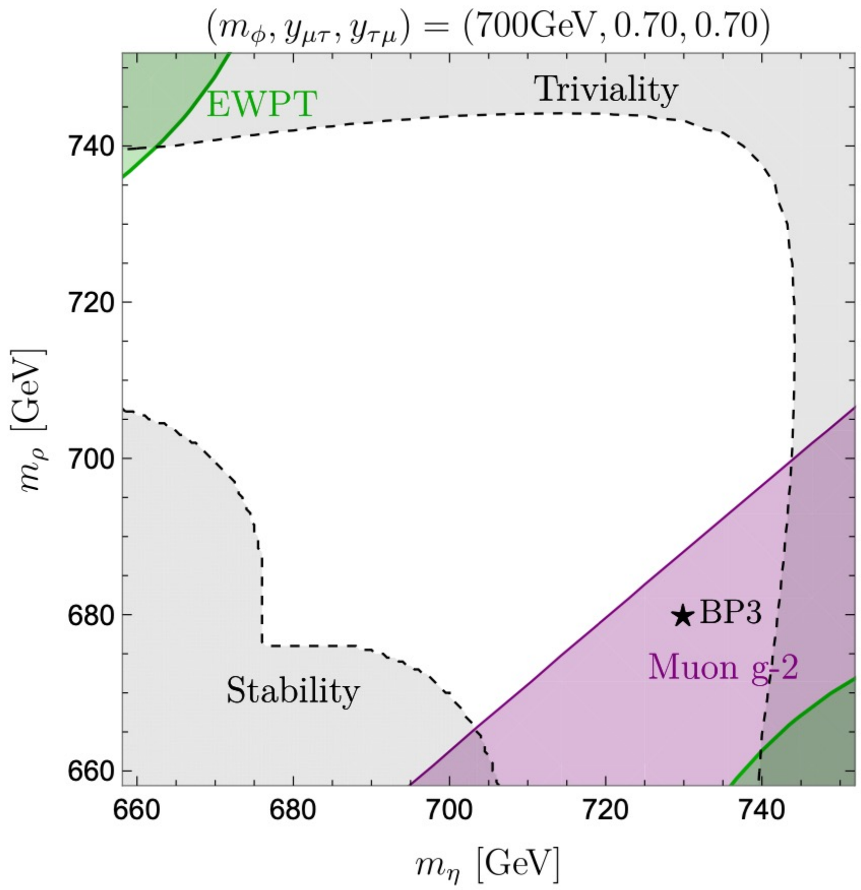
particles	(L_e, L_μ, L_τ)	(e_R, μ_R, τ_R)	H	Φ
SM	$(\mathbf{1},\mathbf{2})_{-1/2}$	$(\mathbf{1},\mathbf{1})_{-1}$	$(\mathbf{1},\mathbf{2})_{1/2}$	$(\mathbf{1},\mathbf{2})_{1/2}$
Z_4	$(1, i, -i)$	$(1, i, -i)$	1	-1

$\mu\tau$-philic doublet scalar

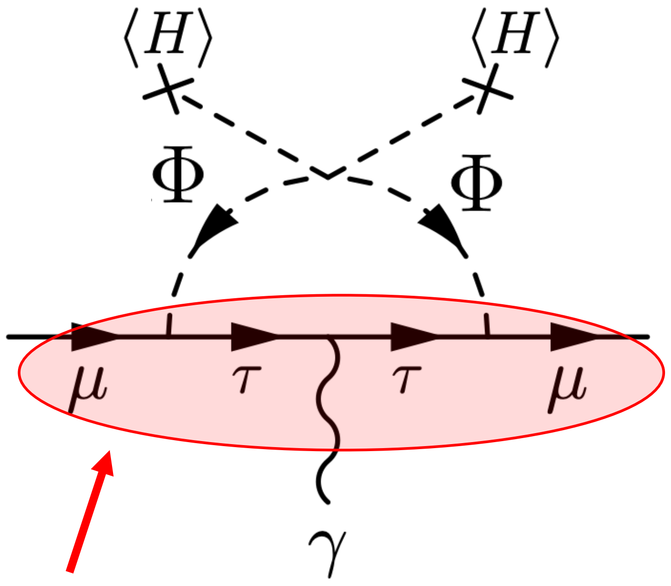
Muon g-2

KA, C. Miyao, S. Okawa, K. Tsumura, PRD **106** (2022) 035017





ρ : CP-even
η : CP-odd heavy scalar
ϕ : charged



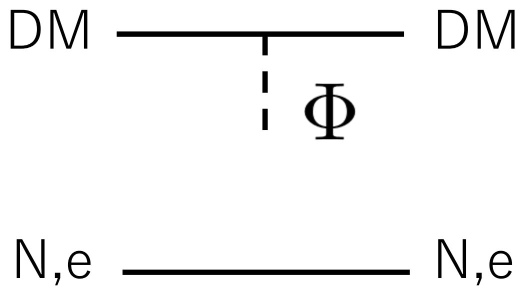
Chirality enhancement

$\times m_\tau / m_\mu$

$\mu\tau$-philic doublet scalar & dark matter

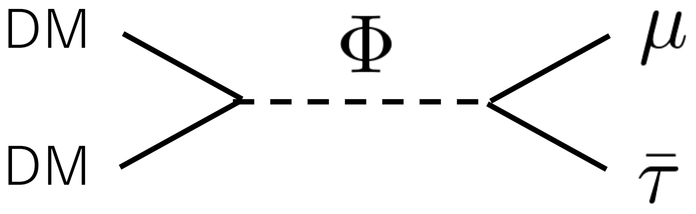
$\mu\tau$-philic doublet scalar is very attractive for DM model

- $\mu\tau$-philic doublet scalar does not couple to electron & nucleon at tree level



➡ Avoid severe constraints from direct detection

- $\mu\tau$-philic doublet scalar couples to μ & τ



➡ DM can annihilate into μ & τ

- Z_4 flavor symmetry guarantees DM stability ?

$\mu\tau$-philic doublet scalar & dark matter

$\mu\tau$-philic doublet scalar is very attractive for DM model

- No coupling to electron and nucleon
  - ➡ Avoiding severe direct detection constraints
- Z_4 flavor symmetry
  - ➡ DM stability

Questions

- Muon $g-2$ can be explained simultaneously ?
- DM can be detected by direct & indirect detection exps.?

Model

DM model with $\mu\tau$-philic mediator

Symmetry

$$\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$$

&

Z_4 flavor symmetry

Fields

SM fields

$+\,\Phi$: $\mu\tau$-philic doublet scalar

$+\,\Sigma$: complex scalar DM

particles	(L_e, L_μ, L_τ)	(e_R, μ_R, τ_R)	H	Φ	Σ
SM	$(\mathbf{1},\mathbf{2})_{-1/2}$	$(\mathbf{1},\mathbf{1})_{-1}$	$(\mathbf{1},\mathbf{2})_{1/2}$	$(\mathbf{1},\mathbf{2})_{1/2}$	$(\mathbf{1},\mathbf{1})_{0}$
Z_4	$(1, i, -i)$	$(1, i, -i)$	1	-1	i

Model

DM model with $\mu\tau$-philic mediator

Lagrangian

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

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

H	Φ	Σ
$(\mathbf{1},\mathbf{2})_{1/2}$	$(\mathbf{1},\mathbf{2})_{1/2}$	$(\mathbf{1},\mathbf{1})_0$
1	-1	i

Φ and Σ have no VEV

Subgroup of Z_4 flavor symmetry

➡ Accidental Z_2 symmetry guarantees DM stability $(\Sigma \to -\Sigma)$

Constraints on $\mu\tau$-philic mediator

Theoretical

- Electroweak precision test

$$S = 0.00 \pm 0.07,\ T = 0.05 \pm 0.06,\ U = 0$$

- Triviality bound

$$|\lambda| \leq 4\pi, \quad |y| \leq \sqrt{4\pi}$$

- Potential stability

$$\lambda_1 > 0,\ \lambda_2 > 0,\ 2\sqrt{\lambda_1\lambda_2} + \lambda_3 > 0,\ 2\sqrt{\lambda_1\lambda_2} + \lambda_3 + \lambda_4 - |\lambda_5| > 0$$

Constraints on $\mu\tau$-philic

Collider experiment

- LEP

$$m_\phi \gtrsim 93.5\,\mathrm{GeV}$$

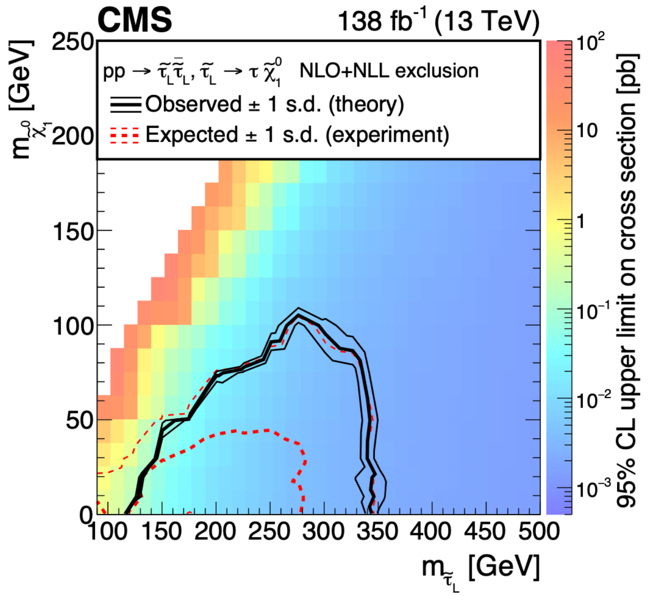
- Slepton search

$$\phi^+ \to \tau^+ \nu_\tau \quad \Rightarrow \quad m_\phi \gtrsim 350\,\mathrm{GeV}$$

$$\phi^+ \to \mu^+ \nu_\mu \quad \Rightarrow \quad m_\phi \gtrsim 550\,\mathrm{GeV}$$

for $m_\phi < m_\rho + m_W$

$100\,\mathrm{GeV} \lesssim m_\phi \lesssim 115\,\mathrm{GeV}$ is allowed



CMS collaboration, 2207.02254

- Neutral scalar search

$$pp \to W^{\pm *} \to \phi^\pm \rho, \phi^\pm \eta$$

$$pp \to Z^* \to \rho\eta$$

L. Wang, Y. Zhang, PRD 100 (2019) 095005;
S. Iguro, Y. Omura, M. Takeuchi, JHEP 11 (2019) 130

$\Rightarrow$ Exclude

$$200\,\mathrm{GeV} \lesssim m_\eta \lesssim 500\,\mathrm{GeV}$$

$$\left(\begin{array}{c} m_\rho < m_\eta \simeq m_\phi \\ \text{or} \\ m_\eta < m_\rho \simeq m_\phi \end{array} \right)$$

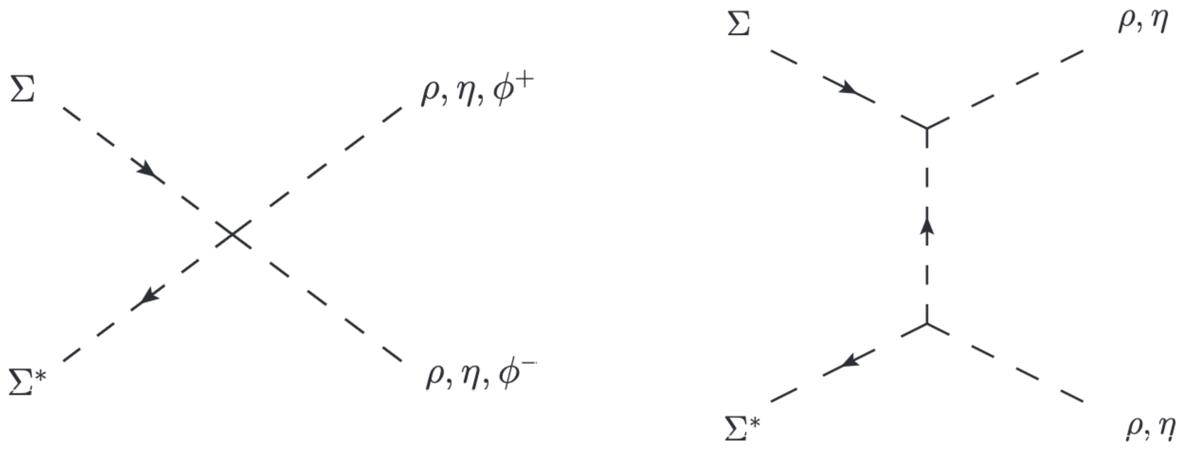
DM Physics

DM Physics

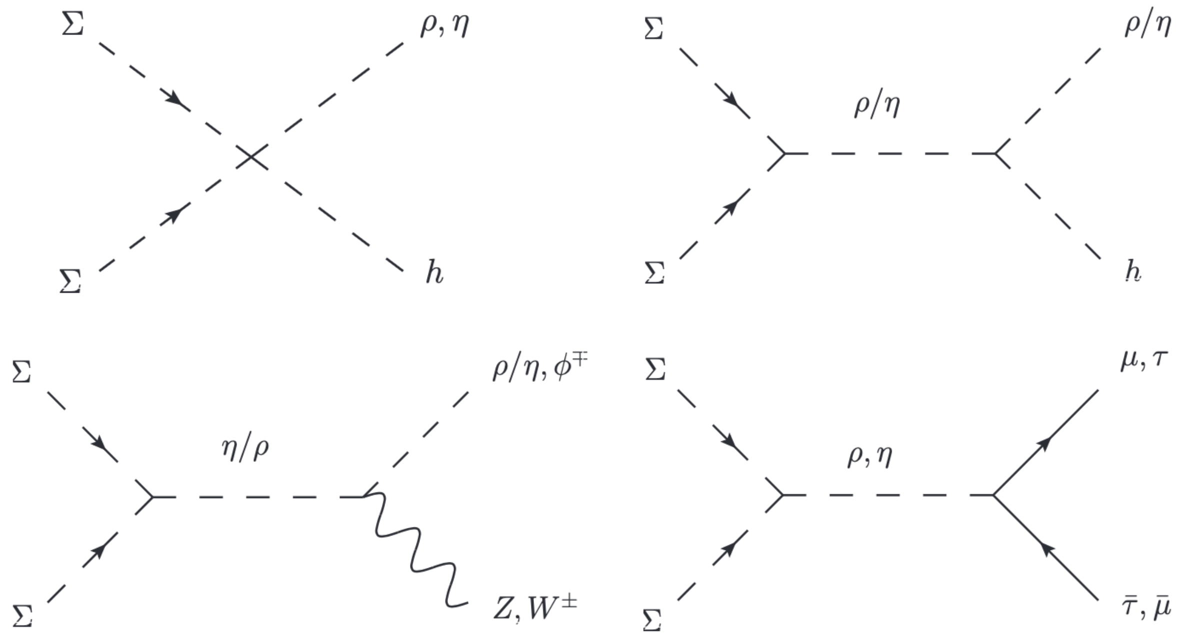
Relic density

Observed DM relic density is realized by thermal freeze-out mechanism

1, $\Sigma\,\Sigma^*$ annihilation

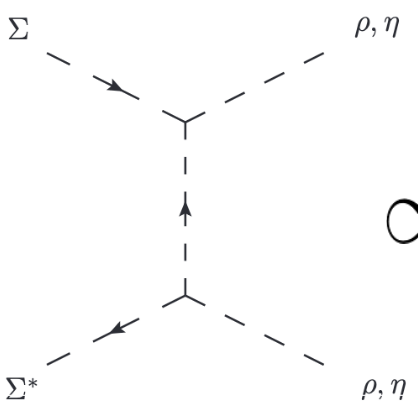


2, $\Sigma\Sigma$ annihilation

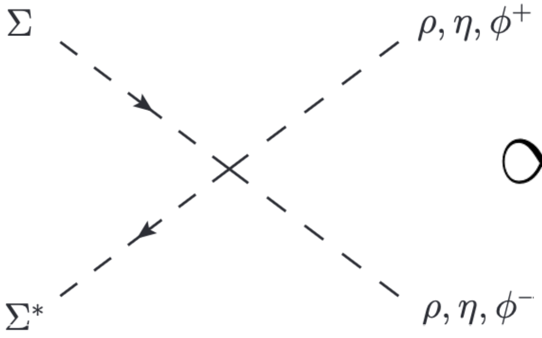


Relic density

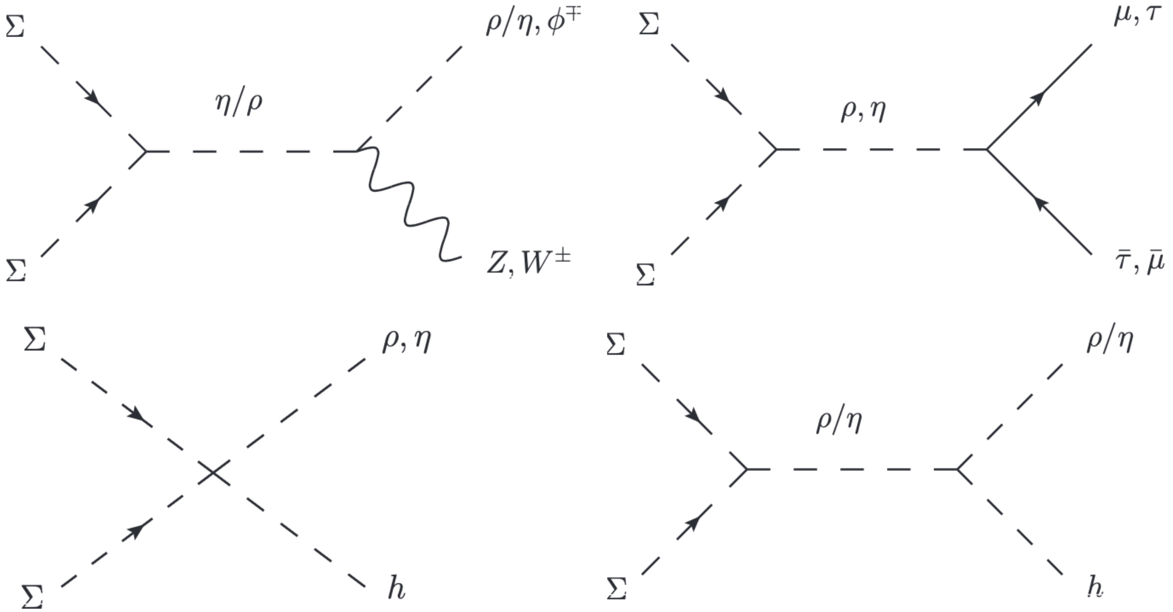
Annihilation process



$\propto \kappa^2$



$\propto \lambda_{\Phi\Sigma}$



$\propto \kappa$

κ is important for DM annihilation

(Assume $\lambda_{\Phi\Sigma} = 0$ for simplicity)

Relic density

Boltzmann equation

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

with

$$n_{\mathrm{DM}}^{(\mathrm{eq})} = n_{\Sigma}^{(\mathrm{eq})} + n_{\Sigma^*}^{(\mathrm{eq})}$$

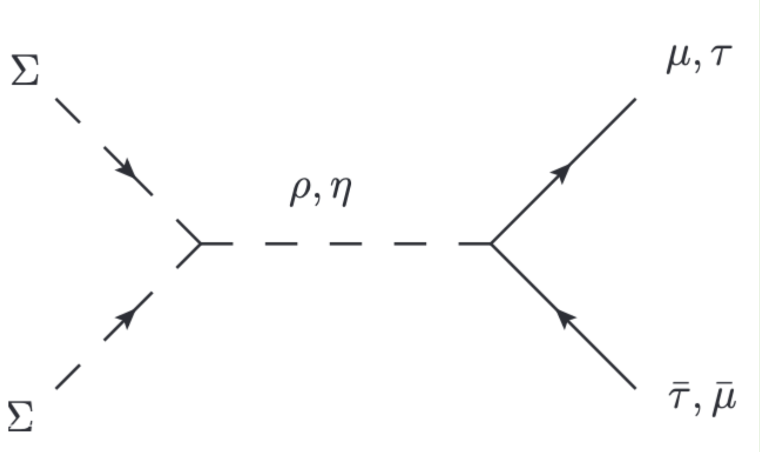
$$(\sigma v_{\mathrm{rel}})_{\mathrm{eff}} = \sum_{ij}\left[(\sigma v_{\mathrm{rel}})_{\Sigma\Sigma^*\to ij} + \frac{1}{2}(\sigma v_{\mathrm{rel}})_{\Sigma\Sigma\to ij} + \frac{1}{2}(\sigma v_{\mathrm{rel}})_{\Sigma^*\Sigma^*\to ij}\right]$$

$$\simeq 6\times 10^{-26}\,\mathrm{cm}^3/\mathrm{s} \quad \Rightarrow \quad \Omega_{\mathrm{DM}}h^2 \simeq 0.12$$

DM Physics

Indirect detection

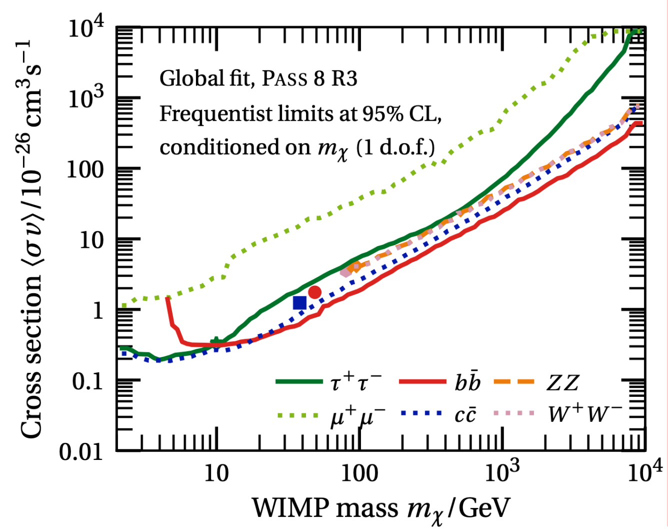
DM annihilates into $\mu^+\tau^-$ and $\tau^+\mu^-$



$\mathrm{DM\ DM} \to \phi^+\phi^-,\ \rho\rho,\ \rho Z,\ \phi^- W^+ \cdots$
$\to$ SM particles

future work

Fermi-LAT gives bound for $\mathrm{DM\ DM} \to \mu^+\mu^-, \tau^+\tau^-$ process



S. Hoof, A. Geringer-Sameth, R. Trotta, JCAP **02**, 012 (2020)

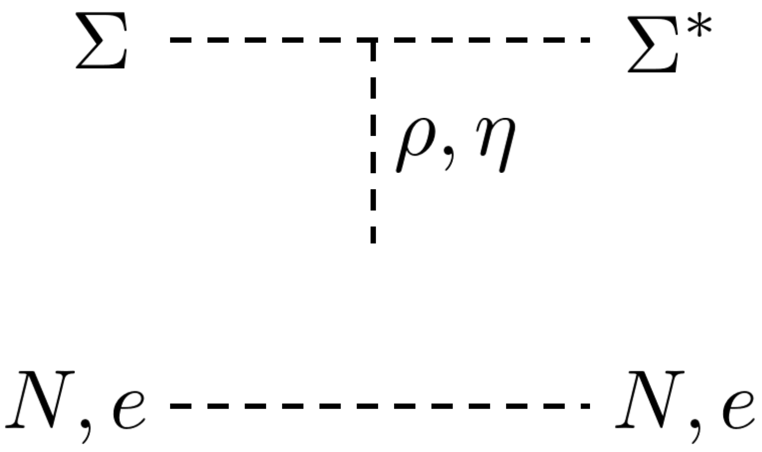
One μ & τ are produced by $\Sigma\Sigma$ and $\Sigma^*\Sigma^*$ annihilation

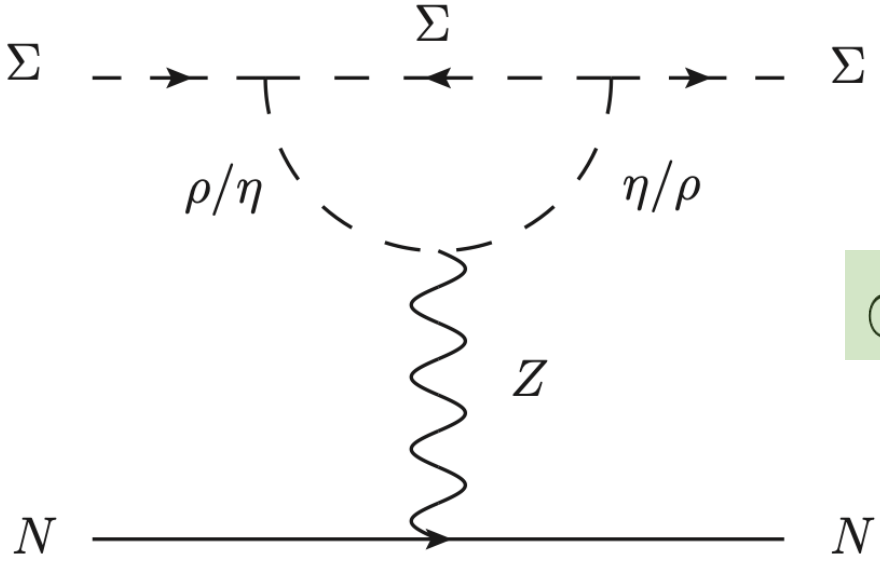
$$(\sigma v_{\mathrm{rel}})_{\Sigma\Sigma\to\mu\bar{\mu},\tau\bar{\tau}} \equiv \frac{(\sigma v_{\mathrm{rel}})_{\Sigma\Sigma\to\mu\bar{\tau}} + (\sigma v_{\mathrm{rel}})_{\Sigma\Sigma\to\tau\bar{\mu}}}{2}$$

DM Physics

Direct detection

Elastic scattering





$\propto \kappa^2$

Tree-level scattering

One-loop penguin diagram

κ is important for not only relic density but also direct detection

Direct detection

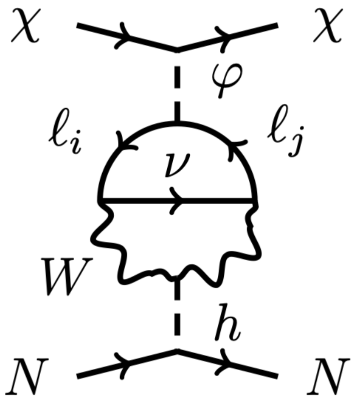
Previous work

I. Galon, A. Kwa, P. Tanedo, JHEP **03**, 064 (2017)

Lepton flavor off-diagonal mediator in EFT framework

$$\mathcal{L}_{\varphi\chi} = \frac{1}{2} y_S \eta \varphi \bar{\chi}\chi + \frac{i}{2} y_P \eta \varphi \bar{\chi}\gamma^5\chi$$

$$\mathcal{L}_{\varphi\,\mathrm{SM}} = g_{ij}\varphi \bar{\ell}_i P_L \ell_j + g^*_{ji}\varphi^* \bar{\ell}_j P_R \ell_i$$

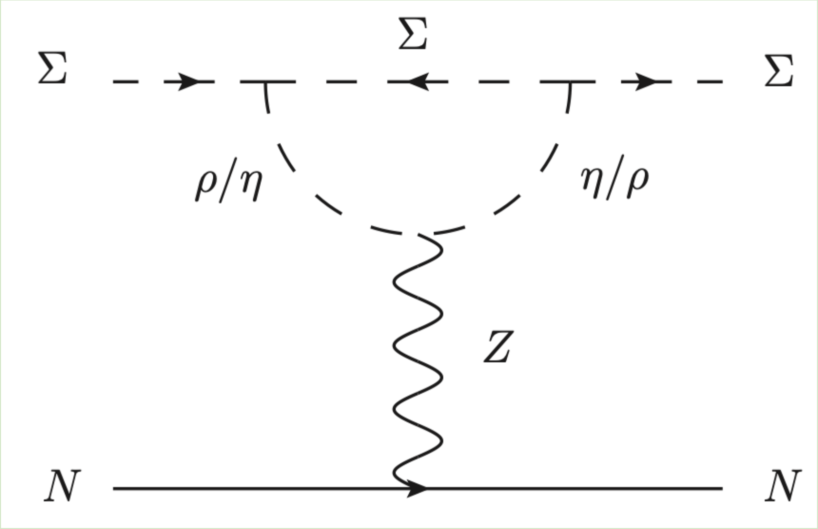


Origin of lepton flavor off-diagonal interaction ?

Impossible direct detection ?

Our work

UV complete model

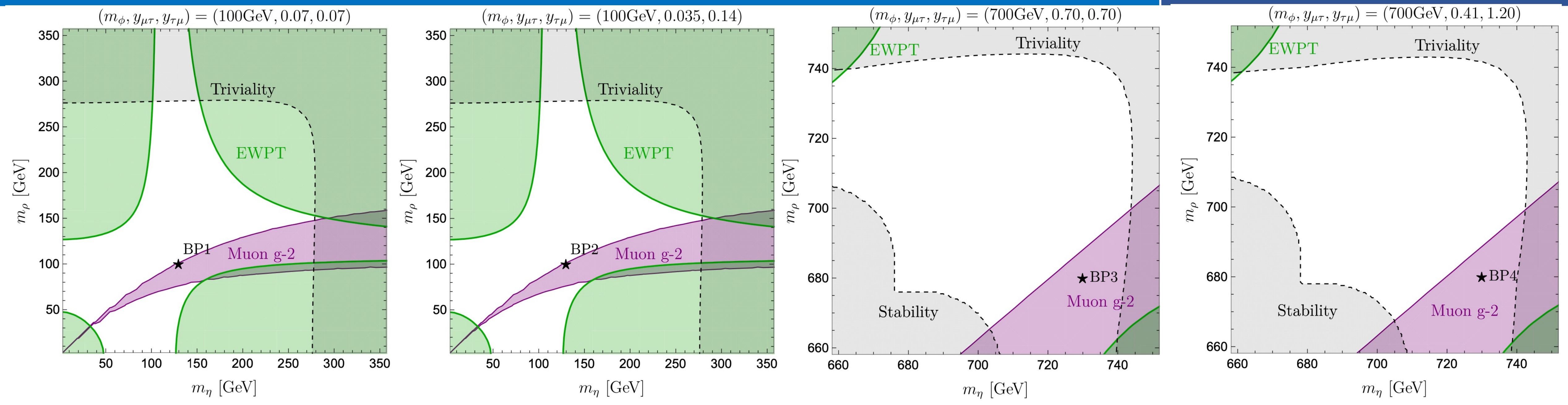


Can be detectable

Result

Result

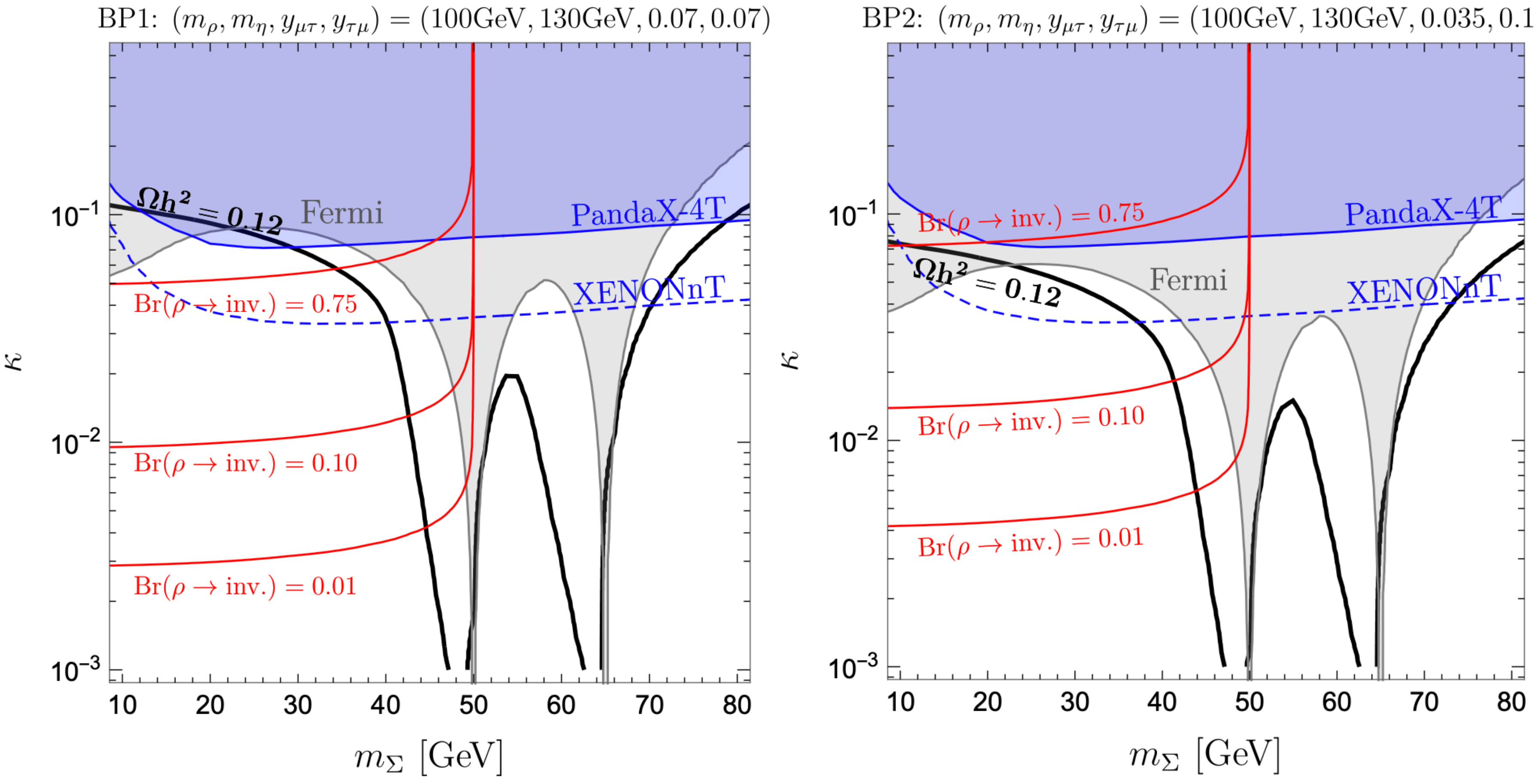
Benchmark point



(a) BP1 (b) BP2 (c) BP3 (d) BP4

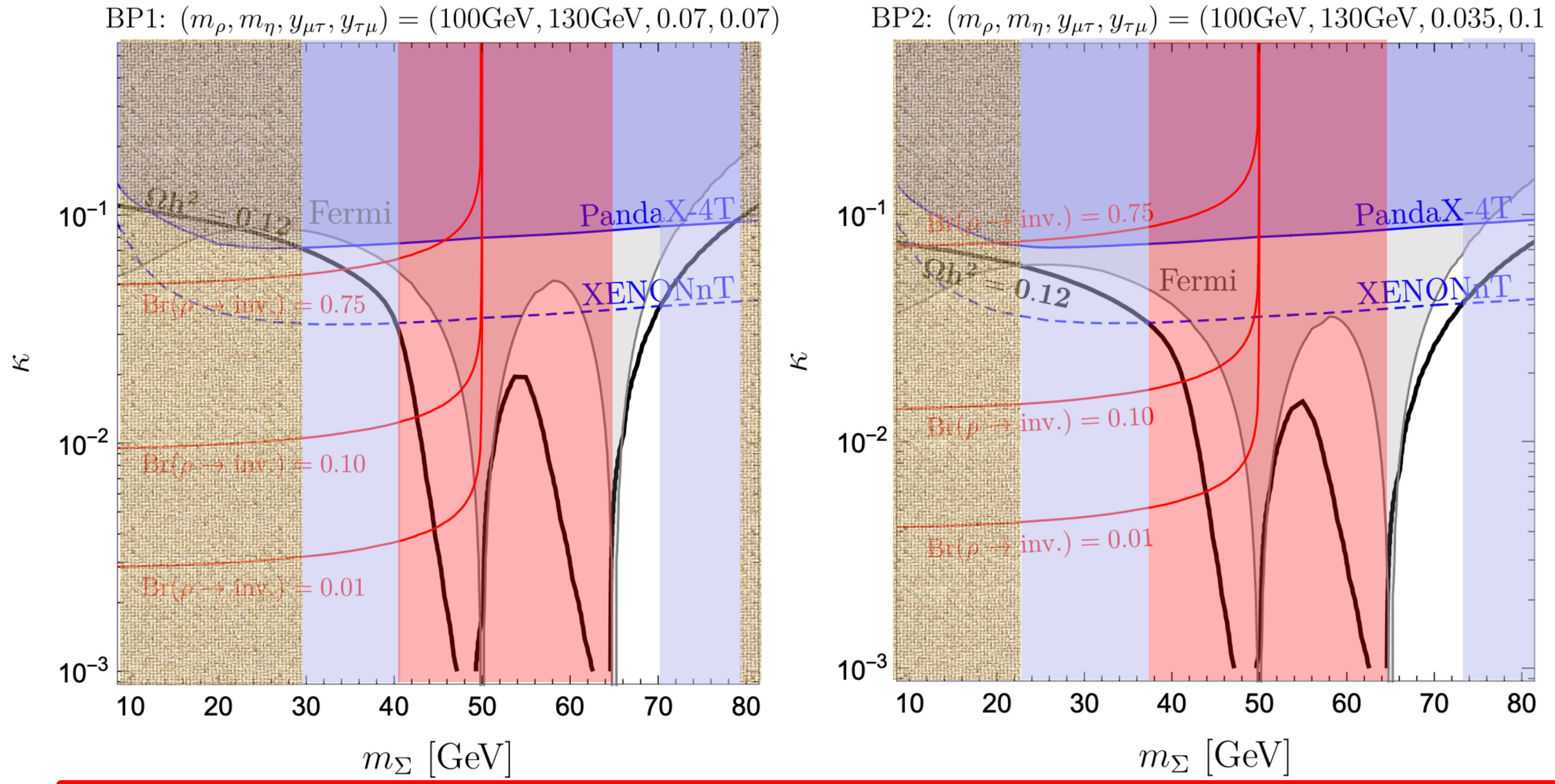
$$\text{BP1} : (m_{\phi^\pm}, m_\rho, m_\eta) = (100\,\text{GeV}, 100\,\text{GeV}, 130\,\text{GeV}), \quad (y_{\mu\tau}, y_{\tau\mu}) = (0.07, 0.07)\ ,$$
$$\text{BP2} : (m_{\phi^\pm}, m_\rho, m_\eta) = (100\,\text{GeV}, 100\,\text{GeV}, 130\,\text{GeV}), \quad (y_{\mu\tau}, y_{\tau\mu}) = (0.035, 0.14)\ ,$$
$$\text{BP3} : (m_{\phi^\pm}, m_\rho, m_\eta) = (700\,\text{GeV}, 680\,\text{GeV}, 730\,\text{GeV}), \quad (y_{\mu\tau}, y_{\tau\mu}) = (0.7, 0.7)\ ,$$
$$\text{BP4} : (m_{\phi^\pm}, m_\rho, m_\eta) = (700\,\text{GeV}, 680\,\text{GeV}, 730\,\text{GeV}), \quad (y_{\mu\tau}, y_{\tau\mu}) = (0.41, 1.2)\ .$$

Limit on κ (Light DM case)



(a) BP1 (b) BP2

Limit on κ （Light DM case)



already excluded

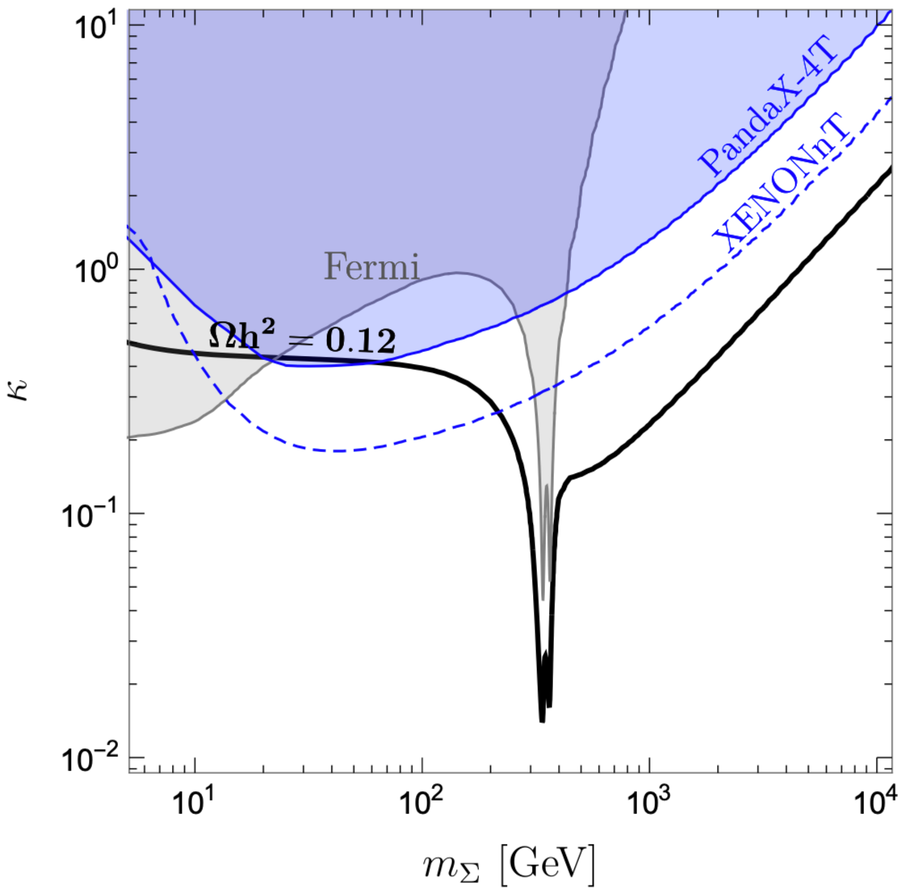
can explore by XENONnT

can explore ρ and η by collider ?

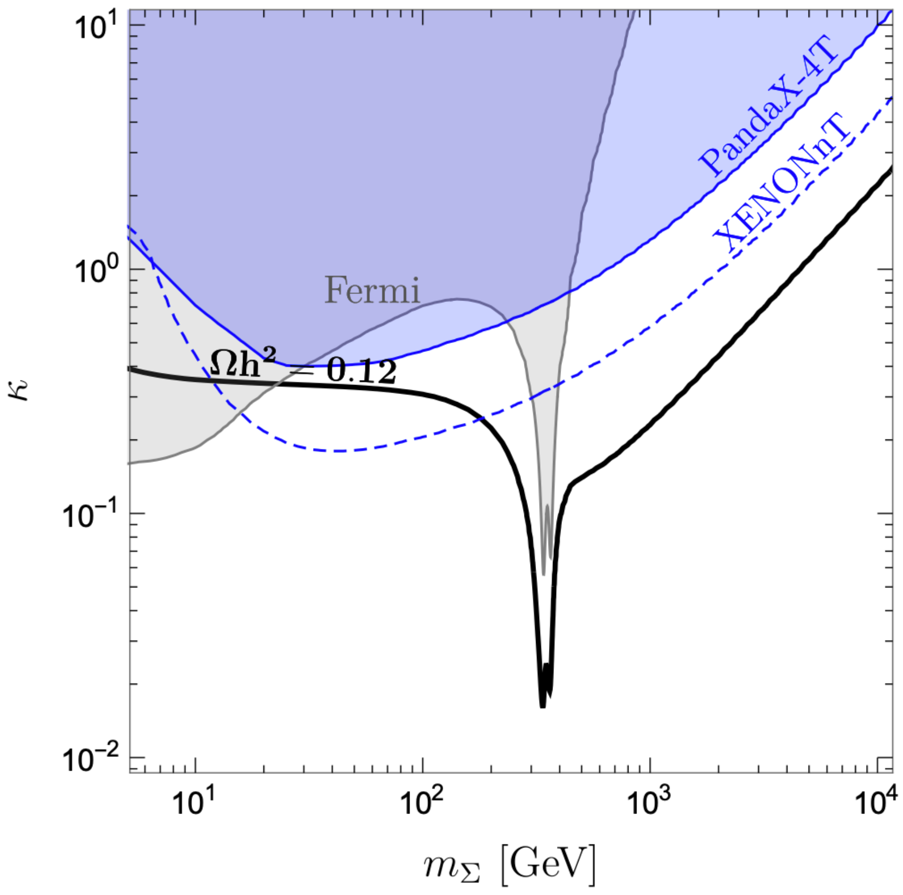
Future direct detection exp. can explore DM except for resonant region

Limit on κ (Heavy DM case)

BP3: $(m_\rho, m_\eta, y_{\mu\tau}, y_{\tau\mu}) = (680\text{GeV}, 730\text{GeV}, 0.7, 0.7)$

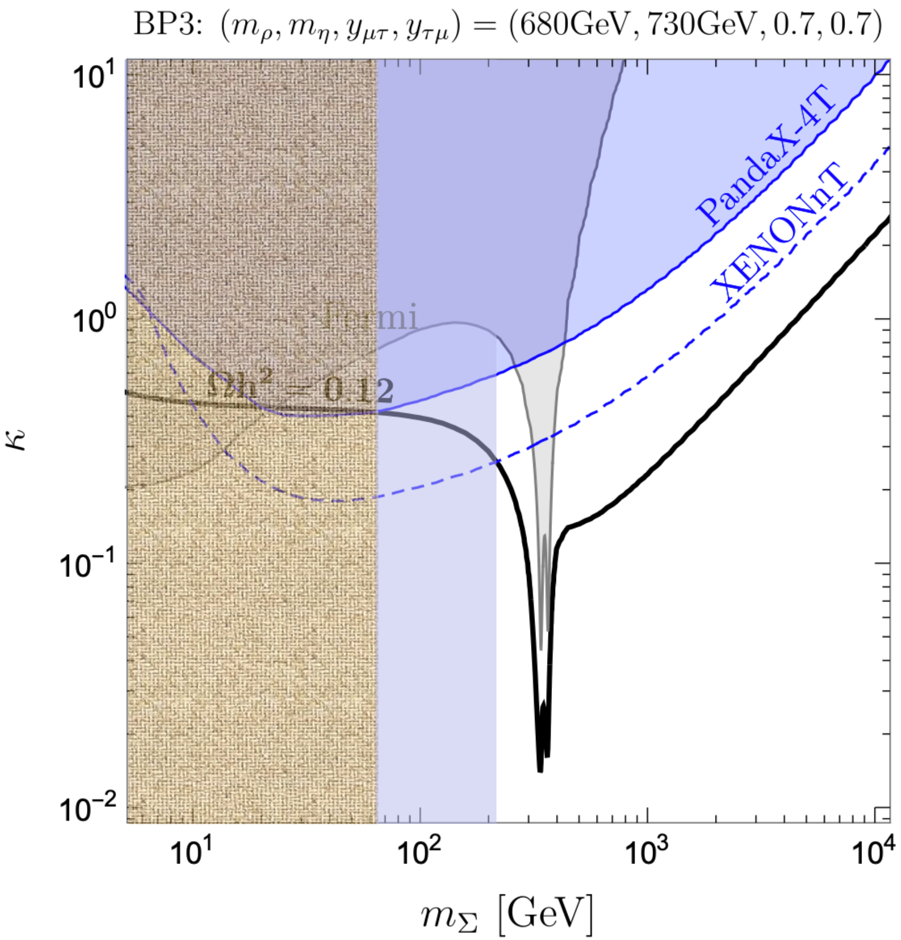


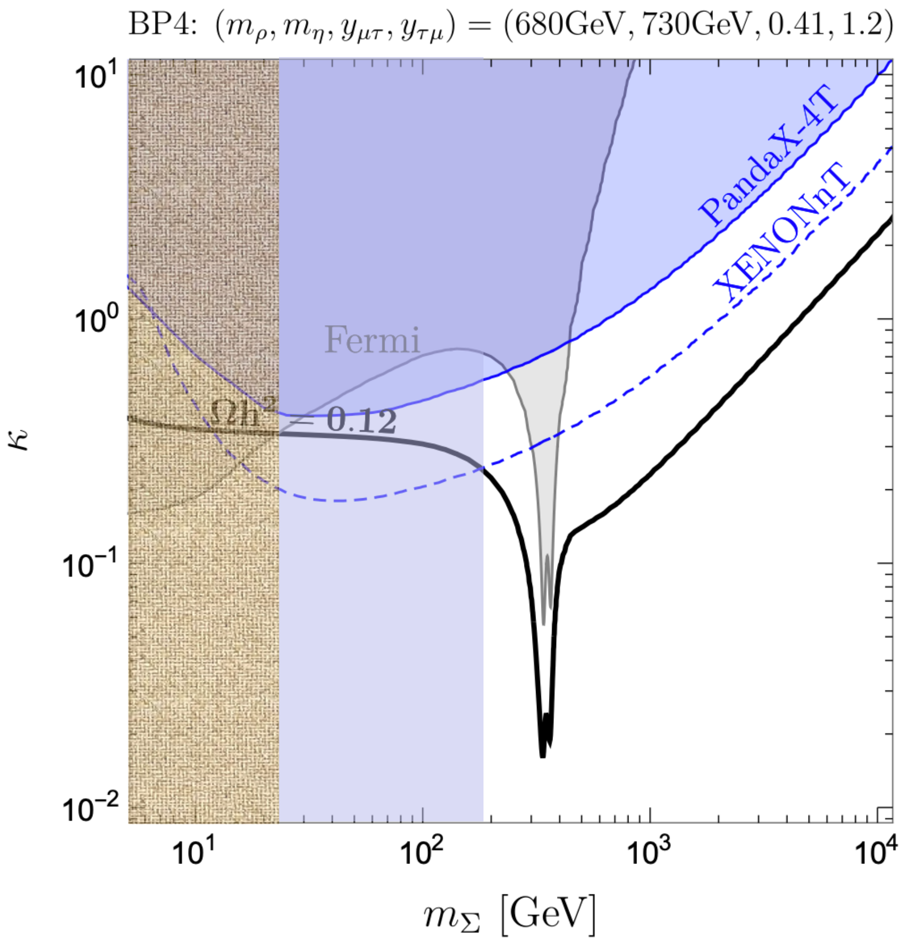
BP4: $(m_\rho, m_\eta, y_{\mu\tau}, y_{\tau\mu}) = (680\text{GeV}, 730\text{GeV}, 0.41, 1.2)$



Result

Limit on κ (Heavy DM case)





already excluded

can explore by XENONnT

DM with $m_\Sigma \lesssim 200\,\text{GeV}$ can be searched by XENONnT

Summary

○ We've considered **dark matter model** with ***μτ*-philic scalar mediator**.

○ $\mu\tau$-philic mediator has no coupling to electron and quarks at one-loop level

➡ $\mu\tau$-philic mediator can explains **DM relic abundance and muon g-2 simultaneously**.

○ We've explored the **possibility of the DM direct detection** through the one-loop process.

Appendix

Muon g-2

Contribution from $\mu\tau$-philic scalar

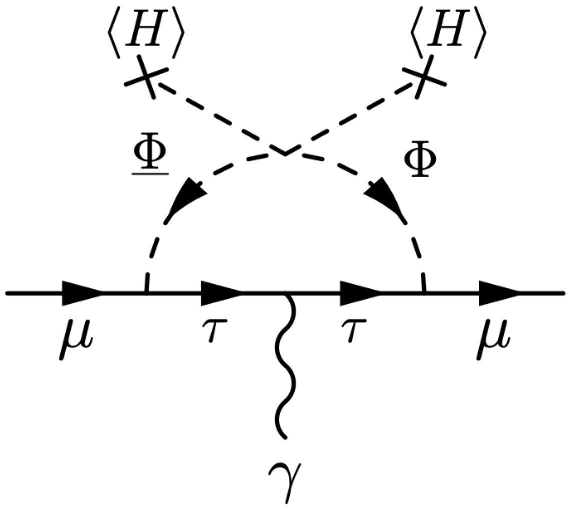
Y. Abe, T. Toma, K. Tsumura, JHEP **06**, 142 (2019)

$$\Delta a_\mu^{\rm new} = \frac{{\rm Re}(y_{\mu\tau}y_{\tau\mu})}{(4\pi)^2}\left[\frac{m_\mu m_\tau}{m_\rho^2} I_1(m_\mu^2/m_\rho^2, m_\tau^2/m_\rho^2) - \frac{m_\mu m_\tau}{m_\eta^2} I_1(m_\mu^2/m_\eta^2, m_\tau^2/m_\eta^2)\right] + \frac{|y_{\mu\tau}|^2 + |y_{\tau\mu}|^2}{2(4\pi)^2}\left[\frac{m_\mu^2}{m_\rho^2} I_2(m_\mu^2/m_\rho^2, m_\tau^2/m_\rho^2) + \frac{m_\mu^2}{m_\eta^2} I_2(m_\mu^2/m_\eta^2, m_\tau^2/m_\eta^2)\right]$$

with

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

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



Appendix

Scalar masses

Scalar potential

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

Φ and Σ have no VEV

Scalar mass

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

$$m_\rho^2 = \mu_\Phi^2 + \frac{1}{2}(\lambda_3 + \lambda_4 + \lambda_5)v^2 , \quad m_\Sigma^2 = \mu_\Sigma^2 + \frac{1}{2}\lambda_{H\Sigma}v^2 .$$

Annihilation cross section

1, $\Sigma\,\Sigma^*$ annihilation

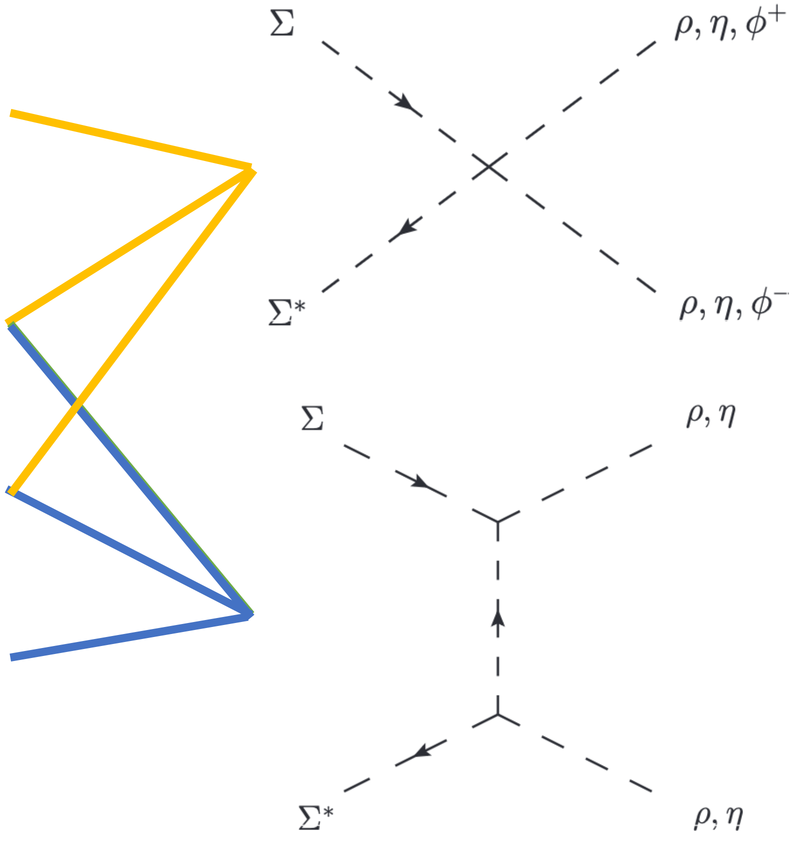
$$(\sigma v_{\rm rel})_{\Sigma\Sigma^*\to\phi^+\phi^-} = \frac{\lambda_{\Phi\Sigma}^2}{32\pi m_\Sigma^2}\sqrt{1-\frac{m_\phi^2}{m_\Sigma^2}}\,,$$

$$(\sigma v_{\rm rel})_{\Sigma\Sigma^*\to\rho\rho} = \frac{1}{64\pi m_\Sigma^2}\left(\frac{2\kappa^2 v^2}{2m_\Sigma^2-m_\rho^2}-\lambda_{\Phi\Sigma}\right)^2\sqrt{1-\frac{m_\rho^2}{m_\Sigma^2}}\,,$$

$$(\sigma v_{\rm rel})_{\Sigma\Sigma^*\to\eta\eta} = (\sigma v_{\rm rel})_{\Sigma\Sigma^*\to\rho\rho}\Big|_{m_\rho\to m_\eta}\,,$$

$$(\sigma v_{\rm rel})_{\Sigma\Sigma^*\to\rho\eta} = \frac{2v_{\rm rel}^2}{3\pi}\frac{(\kappa v)^4 m_\Sigma^2}{(4m_\Sigma^2-m_\rho^2-m_\eta^2)^4}\beta_{\rho\eta}^3$$

with $\beta_{ij} = \sqrt{1-\frac{m_i^2+m_j^2}{2m_\Sigma^2}+\frac{(m_i^2-m_j^2)^2}{(4m_\Sigma^2)^2}}$



Appendix

Annihilation cross section

$$a = (4m_\Sigma^2 - m_\mu^2 - m_\tau^2)\left(\frac{1}{4m_\Sigma^2 - m_\rho^2} - \frac{1}{4m_\Sigma^2 - m_\eta^2}\right)^2 ,$$

$$b = (4m_\Sigma^2 - m_\mu^2 - m_\tau^2)\left(\frac{1}{4m_\Sigma^2 - m_\rho^2} + \frac{1}{4m_\Sigma^2 - m_\eta^2}\right)^2 ,$$

$$c = -4m_\mu m_\tau \left[\left(\frac{1}{4m_\Sigma^2 - m_\rho^2}\right)^2 - \left(\frac{1}{4m_\Sigma^2 - m_\eta^2}\right)^2\right] .$$

2, Σ Σ annihilation

$$(\sigma v_{\rm rel})_{\Sigma\Sigma\to\rho h} = \frac{\kappa^2}{32\pi m_\Sigma^2}\left(1 + \frac{v^2(\lambda_3+\lambda_4+\lambda_5)}{4m_\Sigma^2 - m_\rho^2}\right)^2 \beta_{\rho h} ,$$

$$(\sigma v_{\rm rel})_{\Sigma\Sigma\to\rho Z} = \frac{\kappa^2}{32\pi m_\Sigma^2}\left(\frac{4m_\Sigma^2}{4m_\Sigma^2 - m_\eta^2}\right)^2 \beta_{\rho Z}^3 ,$$

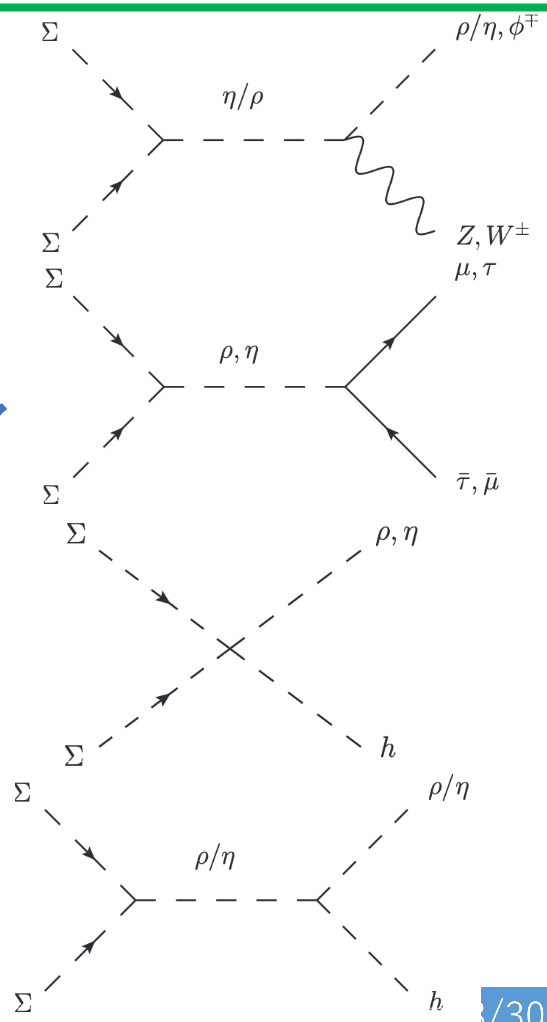
$$(\sigma v_{\rm rel})_{\Sigma\Sigma\to\eta h,\eta Z} = (\sigma v_{\rm rel})_{\Sigma\Sigma\to\rho h,\rho Z}\Big|_{\substack{m_\rho\leftrightarrow m_\eta \\ \lambda_5\to-\lambda_5}} ,$$

$$(\sigma v_{\rm rel})_{\Sigma\Sigma\to\phi^- W^+} = \frac{\kappa^2}{32\pi m_\Sigma^2}\left(\frac{4m_\Sigma^2}{4m_\Sigma^2 - m_\rho^2} + \frac{4m_\Sigma^2}{4m_\Sigma^2 - m_\eta^2}\right)^2 \beta_{\phi W}^3 ,$$

$$(\sigma v_{\rm rel})_{\Sigma\Sigma\to\phi^+ W^-} = \frac{\kappa^2}{32\pi m_\Sigma^2}\left(\frac{4m_\Sigma^2}{4m_\Sigma^2 - m_\rho^2} - \frac{4m_\Sigma^2}{4m_\Sigma^2 - m_\eta^2}\right)^2 \beta_{\phi W}^3 ,$$

$$(\sigma v_{\rm rel})_{\Sigma\Sigma\to\mu\bar\tau} = \frac{\kappa^2 v^2}{64\pi m_\Sigma^2}\left[a\,|y_{\mu\tau}|^2 + b\,|y_{\tau\mu}|^2 + c\,{\rm Re}(y_{\mu\tau}y_{\tau\mu})\right]\beta_{\mu\tau} ,$$

$$(\sigma v_{\rm rel})_{\Sigma\Sigma\to\tau\bar\mu} = \frac{\kappa^2 v^2}{64\pi m_\Sigma^2}\left[b\,|y_{\mu\tau}|^2 + a\,|y_{\tau\mu}|^2 + c\,{\rm Re}(y_{\mu\tau}y_{\tau\mu})\right]\beta_{\mu\tau}$$



Appendix

Direct detection

Relevant interaction Lagrangian

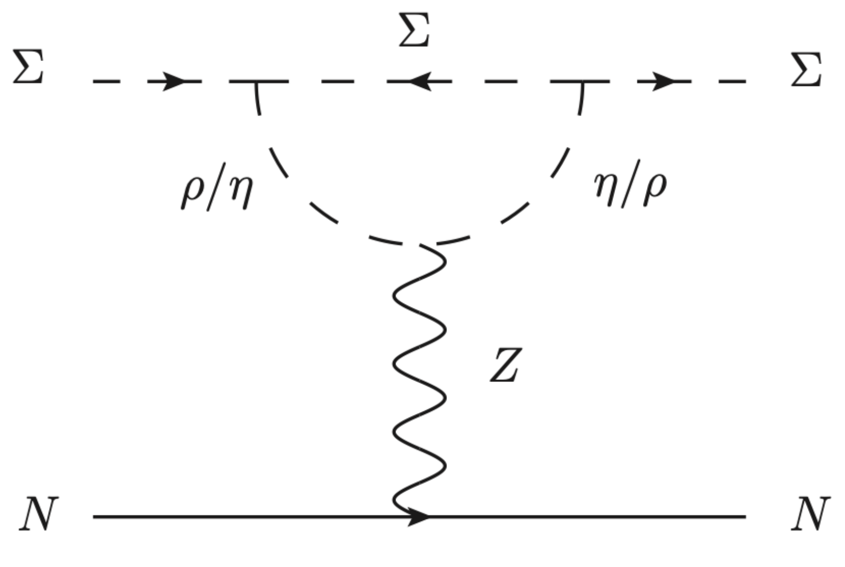
$$\mathcal{L}^{\mathrm{eff}}_{\Sigma q} = \sum_{q=u,d,s} C_{V,q} \left\{\Sigma^* i\partial_\mu \Sigma - (i\partial_\mu \Sigma^*)\Sigma\right\} (\bar{q}\gamma^\mu q)$$

with

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

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

$$f(x) = x^2 + x^2(2 - x^2)\log x + x^3\sqrt{x^2 - 4}\log\left(\frac{x + \sqrt{x^2 - 4}}{2}\right)$$



Direct detection

Spin-independent elastic scattering

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

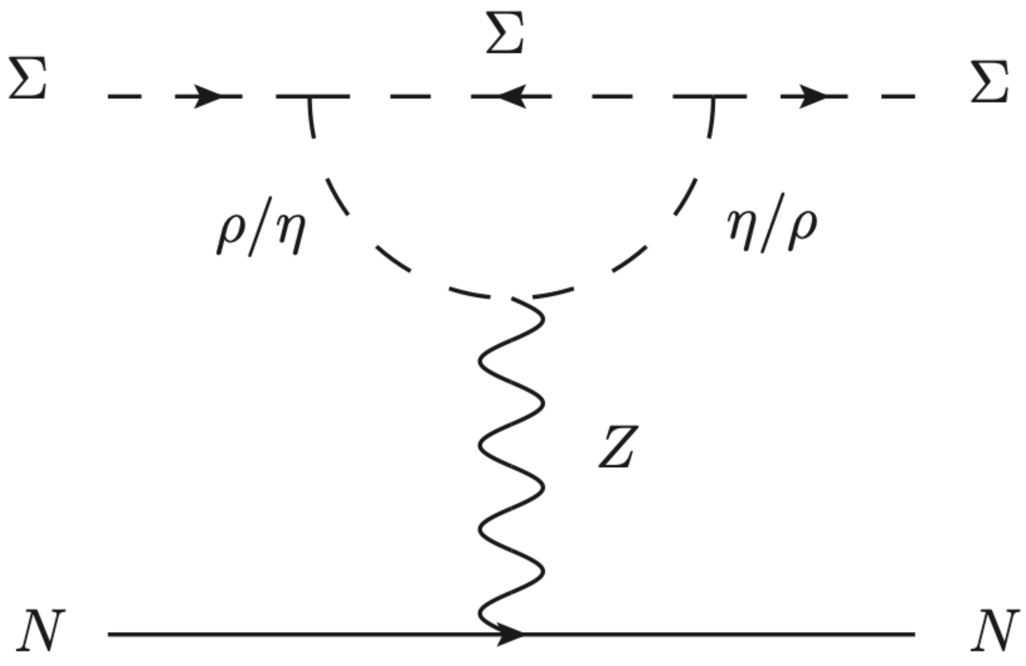
with

$$\mu_N = m_\Sigma m_N / (m_\Sigma + m_N)$$

$$C_{V,p} = 2C_{V,u} + C_{V,d} \ , \quad C_{V,n} = C_{V,u} + 2C_{V,d}$$

$Z(A)$: atomic (mass) number

m_N : target nucleus mass



Neutrino mass & mixing

3 right-handed neutrinos

➡ Neutrino mass & its lightness through seesaw mechanism

But …

Exact Z_4 flavor symmetry

➡ Observed neutrino mixing cannot be obtained

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

$Z_4 \times Z_2$ symmetric model

Fields

SM fields $+\,\Phi$: $\mu\tau$-philic doublet scalar
$+\,\Sigma$: complex scalar DM
$+\,N_\alpha$: right-handed neutrino
$+\,S$: Z_4-breaking singlet scalar

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

Appendix

$Z_4 \times Z_2$ symmetric model

Neutrino mass matrix has
two-zero minor structure

$$\mathcal{M}_\nu^{-1} = \begin{pmatrix} * & * & * \\ * & 0 & * \\ * & * & 0 \end{pmatrix}$$

Detail in KA, K. Hamaguchi, N. Nagata, S.-Y. Tseng, K. Tsumura, PRD 99, 5, 055029 (2019)

Lagrangian

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

→ ○ Neutrino mass & mixing

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