Leptogenesis and Muon(g-2) from Vector like fermion triplet

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Outlines of the talk….

- Introduction
- Model
- Outcomes and Results
- Conclusions

Baryon Asymmetry of Universe

- Within the baryonic matter, a large asymmetry exists between the particles and antiparticles. This asymmetry is often termed as the Baryon asymmetry of the Universe (BAU). The observed (BAU) is often quantified in terms of the baryon-photon ratio defined as (Planck 2018 results)

$$\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq 6.2 \times 10^{-10}. \qquad (1)$$

- The origin of baryon asymmetry has been a long-standing problem in particle physics and cosmology.
- To generate the required baryon asymmetry dynamically, three requirements were given by Sakharov (A. D Sakharov) called "Sakharov Conditions" as

[1] N.~Aghanim \textit{et al.} [Planck], Planck 2018 results. VI. Cosmological parameters,Astron. Astrophys. \textbf{641}, A6 (2020)
[2] A.~D.~Sakharov,Violation of CP Invariance, C asymmetry, and baryon asymmetry of the universe, Pisma Zh. Eksp. Teor. Fiz. \textbf{5}, 32-35 (1967)

Baryon Asymmetry of Universe (BAU)

(1) Baryon Number Violation,

(2) C and CP violation and

(3) out of equilibrium dynamics.

All these requirements are fulfilled by the Standard Model (SM) with an expanding Universe. However, the required amount of asymmetry can not be generated within the SM. Therefore, it demands new physics beyond the SM.

Leptogenesis

- In a conventional leptogenesis scenario, the decay of heavy right-handed neutrinos into SM lepton doublets and SM Higgs accounts for small lepton asymmetry of the Universe, which later gets converted into baryon asymmetry through sphaleron process. This mechanism is called thermal leptogenesis (R N Mohapatra et. al).
- However, in this conventional method, the scale of right-handed neutrinos is quite high $\gtrsim 10^9$ GeV which is difficult to probe in future collider experiments. This motivates us to search for low-scale leptogenesis scenarios.

[3] R.~N.~Mohapatra and G.~Senjanovic,%``Neutrino Masses and Mixings in Gauge Models with Spontaneous Parity Violation,''Phys. Rev. D \textbf{23}, 165 (1981)

Dark Matter

Apart from the BAU, the existence of non-luminous dark matter (DM), giving a total contribution of around 26% of the present Universe's energy density has been an unsolved puzzle in cosmology and particle physics.

The DM energy density is expressed in the density parameter Ω_{DM}. The Planck 2018 data has reported a value for the DM density parameter at 68% CL as (Planck 2018 Data)

$$\Omega h^2 = 0.12 \pm 0.001 \tag{2}$$

Muon Anomalous Magnetic Moment

- The magnetic moment of muon is written in terms of its spin and charge as

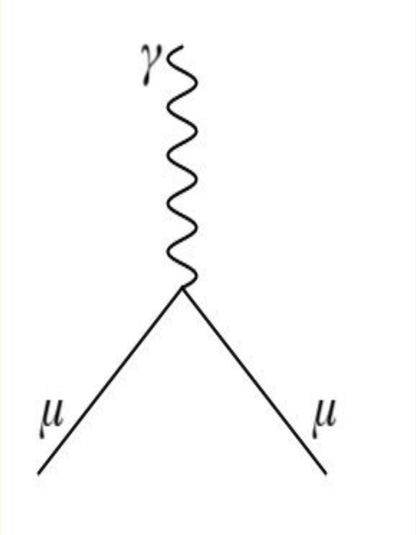
$$\vec{\mu} = g \frac{q}{2m} \vec{S} \qquad (3)$$

Here g is the gyromagnetic ratio and it represents the strength of magnet.

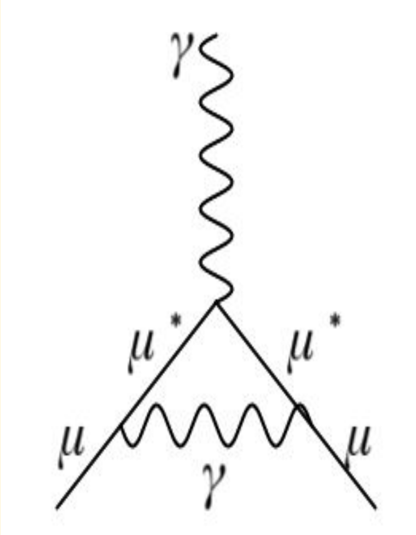
- Dirac predicted g = 2 for electron and subsequently for all spin ½ particles.
- But due to some radiative corrections, this quantity is modified.
- So the anomalous magnetic moment is defined as

$$a_\mu = \frac{g-2}{2}$$

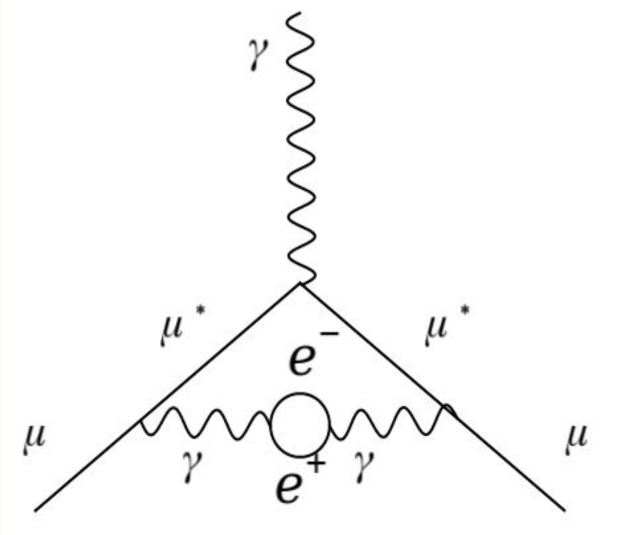
Standard Model Corrections



Dirac
(g = 2)



Schwinger
(g increased
by α/Pi)



Vacuum Polarization
Contribution

- **Combining all these contributions, Standard Model predict the value of anomalous magnetic moment of muon as**

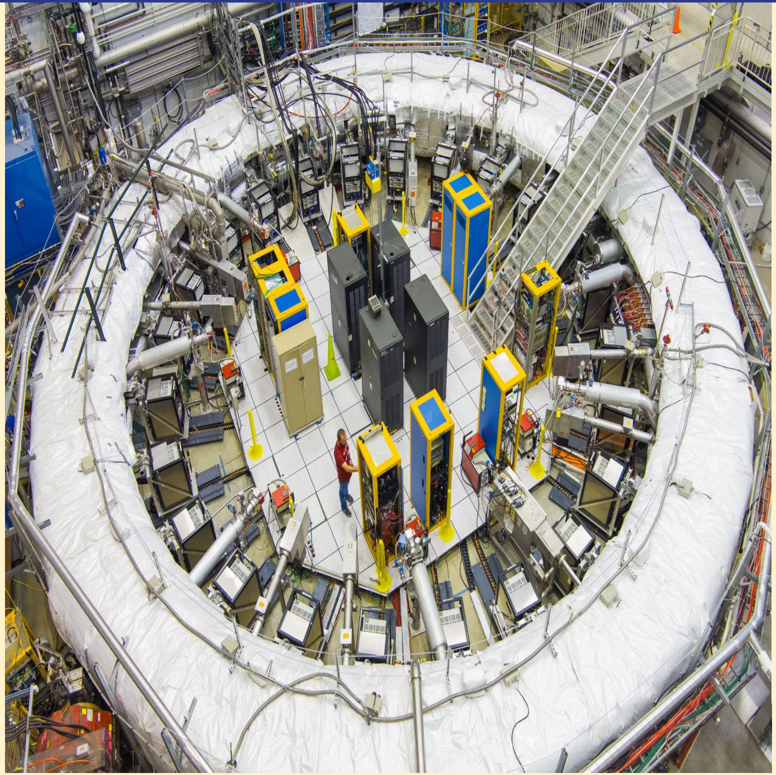
$$a_\mu^{SM} = 116591810\,(43) \times 10^{-11} \tag{4}$$

Refer to https://doi.org/10.1016/j.nuclphysb.2022.115675 for detailed reading.

E989 Experiment at Fermilab

- Previously the muon g-2 measurement was performed at Brookhaven National Laboratory's experiment E821 in 2001.

  The results were different from SM predictions with 3 sigma.



This giant magnet was brought from Brookhaven National Laboratory to Fermilab.

The storage ring is sometimes referred as “700-ton Swiss watch” because of its high precision and huge weight.

Results and Findings..

Combining the previous results from BNL, Fermilab found the value of muon's anomalous magnetic moment as

$$a_\mu^{Exp} = 116592061(41) \times 10^{-11} \quad (5)$$

The difference between the combined experimental result and SM prediction of muons anomalous magnetic moment is

$$\Delta a_\mu^{FNAL} = (2.51 \pm 0.59) \times 10^{-11} \quad (6)$$

These results show a discrepancy of 4.2 σ with SM predictions.

The Model

Symmetry group	L_e, L_μ, L_τ	e_R, μ_R, τ_R	N_1, N_2, N_3	ψ_T	H	S	η
$S(U)_2 \times U(1)_Y$	$(2, -1/2)$	$(1, -1)$	$(1, 0)$	$(3, -1)$	$(2, 1/2)$	$(1, 0)$	$(2, 1/2)$
Z_4	$(1, i, -i)$	$(1, i, -i)$	$(1, i, -i)$	i	1	$-i$	1
Z_2	$+$	$+$	$-$	$-$	$+$	$+$	$-$

The relevant terms in Yukawa Lagrangian are

$$-\mathcal{L} \supseteq \frac{M_{11}}{2} N_1 N_1 + M_{23} N_2 N_3 + y_{\eta 1} \bar{L}_e \tilde{\eta} N_1 + y_{\eta 2} \bar{L}_\mu \tilde{\eta} N_2 + y_{\eta 3} \bar{L}_\tau \tilde{\eta} N_3$$
$$+ y_{12} S N_1 N_2 + y_{13} S^* N_1 N_3 + y_\psi \overline{L_\mu} C \psi^\dagger \tilde{\eta} + m_\psi \overline{\psi} (\psi)^c$$
$$+ y_e \overline{L}_e H e_R + y_\mu \overline{L}_\mu H \mu_R + y_\tau \overline{L}_\tau H \tau_R + H.c. \,, \qquad (7)$$

With $\tilde{\eta} = i\sigma_2 \eta^*$ and the form of scalar potential is

$$V(H,S,\eta) = -\mu_H^2(H^\dagger H) + \lambda_1(H^\dagger H)^2 - \mu_S^2(S^\dagger S) + \lambda_S(S^\dagger S)^2 + \lambda_{HS}(H^\dagger H)(S^\dagger S)$$
$$+ \mu_\eta^2(\eta^\dagger \eta) + \lambda_2(\eta^\dagger \eta)^2 + \lambda_3(\eta^\dagger \eta)(H^\dagger H)$$
$$+\lambda_4(\eta^\dagger H)(H^\dagger \eta) + \frac{\lambda_5}{2}[(H^\dagger \eta)^2 + (\eta^\dagger H)^2] + \lambda_{\eta S}(\eta^\dagger \eta)(S^\dagger S) + H.c..$$

After Higgs acquire vev v and singlet scalar S acquire vev vs, the masses of singlet scalar and Higgs are

$$m_{S,H}^2 = \lambda_1 v^2 + \lambda_S v_S^2 \pm (\lambda_1 v^2 + \lambda_S v_S^2)\sqrt{1+r^2}, \tag{8}$$

Where $r = \frac{\lambda_{HS} v v_S}{\lambda_1 v^2 - \lambda_S v_S^2}$ **. The masses of neutral and charged components of inert doublet are written as**

$$m_{\eta^\pm}^2 = \mu_\eta^2 + \frac{1}{2}\lambda_3 v^2 + \frac{1}{2}\lambda_{\eta S} v_S^2$$
$$m_{\eta_R}^2 = \mu_\eta^2 + \frac{1}{2}\lambda_3 v^2 + \frac{1}{2}(\lambda_4 + \lambda_5)v^2 + \frac{1}{2}\lambda_{\eta S} v_S^2 \tag{9}$$
$$m_{\eta_I}^2 = \mu_\eta^2 + \frac{1}{2}\lambda_3 v^2 + \frac{1}{2}(\lambda_4 - \lambda_5)v^2 + \frac{1}{2}\lambda_{\eta S} v_S^2$$

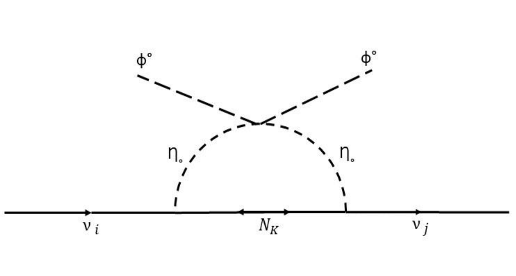
Scotogenic Mechanism for Neutrino Mass

Neutrino mass is generated by scotogenic model. The form of light neutrino mass matrix is

$$M_{ij}^{\nu} = \sum_{k=1}^{3} \frac{d_{ik}d_{jk}M_k}{32\pi^2}\left[L_k(m_{\eta_R}^2) - L_k(m_{\eta_I}^2)\right], \quad (10)$$

$$L_k(m^2) = \frac{m^2}{m^2 - M_k^2} ln \frac{m^2}{M_k^2}. \qquad d_{ik} = y_{\eta i}C_{ik} \quad (11)$$

We have used Cassas-Ibarra (CI) (J. A Casas & A. Ibarra) parameterization for radiative seesaw mechanism (Takashi Toma et al) through which the Yukawa coupling satisfy neutrino data is written as



$$d_{ik} = (\mathrm{U}D_{\nu}^{1/2}R^{\dagger}\Lambda^{1/2})_{ik}. \quad (12)$$

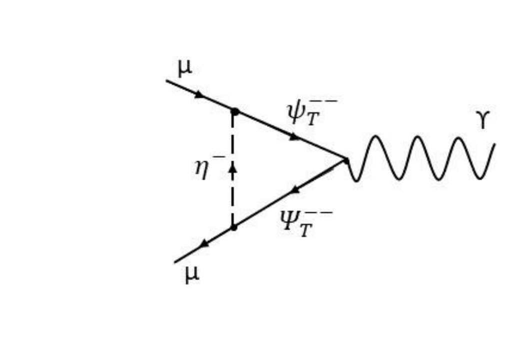
$$\Lambda_k = \frac{2\pi^2}{\lambda_5}\zeta_k\frac{2M_k}{v^2},$$

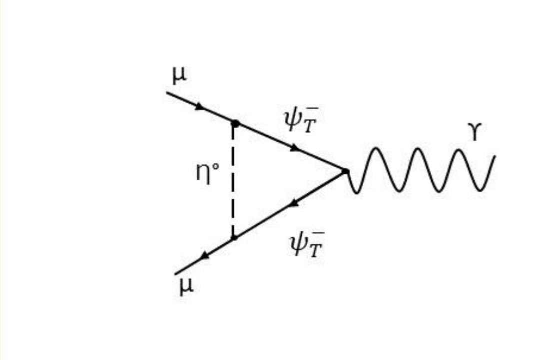
$$\zeta_k = \left(\frac{M_k^2}{8(m_{\eta_R^2} - m_{\eta_I^2})}\left[L_k(m_{\eta_R}^2) - L_k(m_{\eta_I}^2)\right]\right).$$

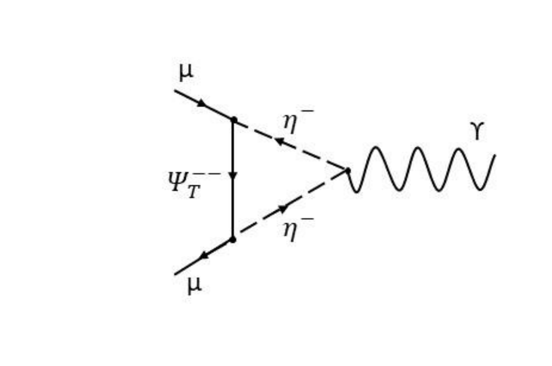
[6] J. A. Casas and A. Ibarra. Oscillating neutrinos and μ → e, γ. Nucl. Phys. B, 618:171–204, 2001
[7] Takashi Toma and Avelino Vicente. Lepton Flavor Violation in the Scotogenic Model.JHEP, 01:160, 2014

Muon (g-2)

The fermion triplet ψ explains muon (g-2) by its coupling with SM muon including inert doublet η .The Feynman diagrams for the same are given as,







Diagrams responsible for positive contribution to muon (g-2) from η and ψ

The additional contribution to muon (g-2) is given as (Ayres Freitas et al)

.

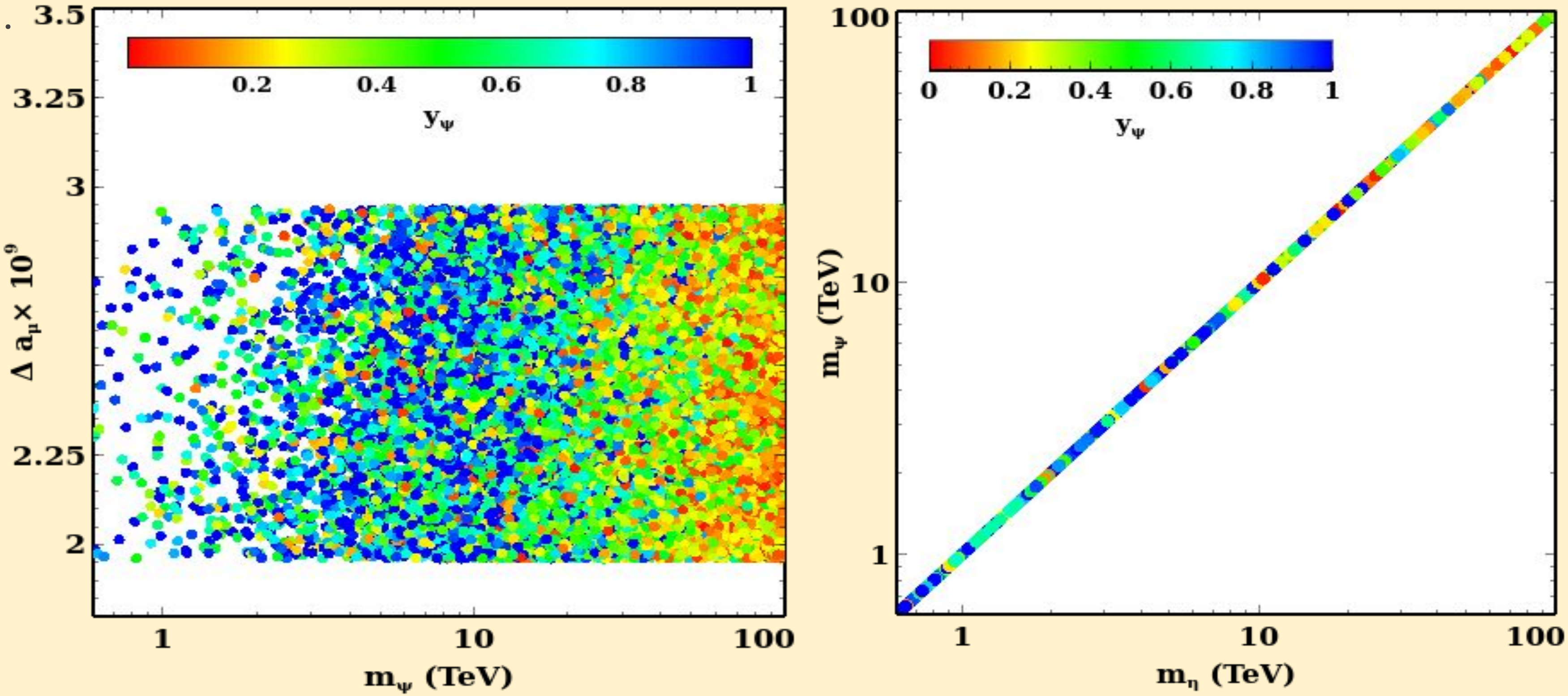
$$\Delta a_\mu = \frac{m_\mu^2 y_\psi^2}{32\pi^2 m_\eta^2}\left[5 f_1(m_\psi^2/m_\eta^2) - 2 f_2(m_\psi^2/m_\eta^2)\right], \tag{13}$$

$$f_1(x) = \frac{1}{6(x-1)^4}\left[x^3 - 6x^2 + 3x + 2 + 6x \ln x\right]$$

$$f_2(x) = \frac{1}{6(x-1)^4}\left[-2x^3 - 3x^2 + 6x - 1 + 6x^2 \ln x\right],$$

where , $x = \frac{m_\psi^2}{m_\eta^2}$

[8] Ayres Freitas, Joseph Lykken, Stefan Kell, and Susanne Westhoff. Testing the Muon g-2 Anomaly at the LHC. JHEP, 05:145, 2014. [Erratum: JHEP 09, 155 (2014)]



Plot showing the parameter space that satisfy the Fermi lab result on muon g-2. Right panel shows the parameter space in $m_\eta - m_\psi$ plane and the left panel shows the allowed data points with m_ψ and Δa_μ

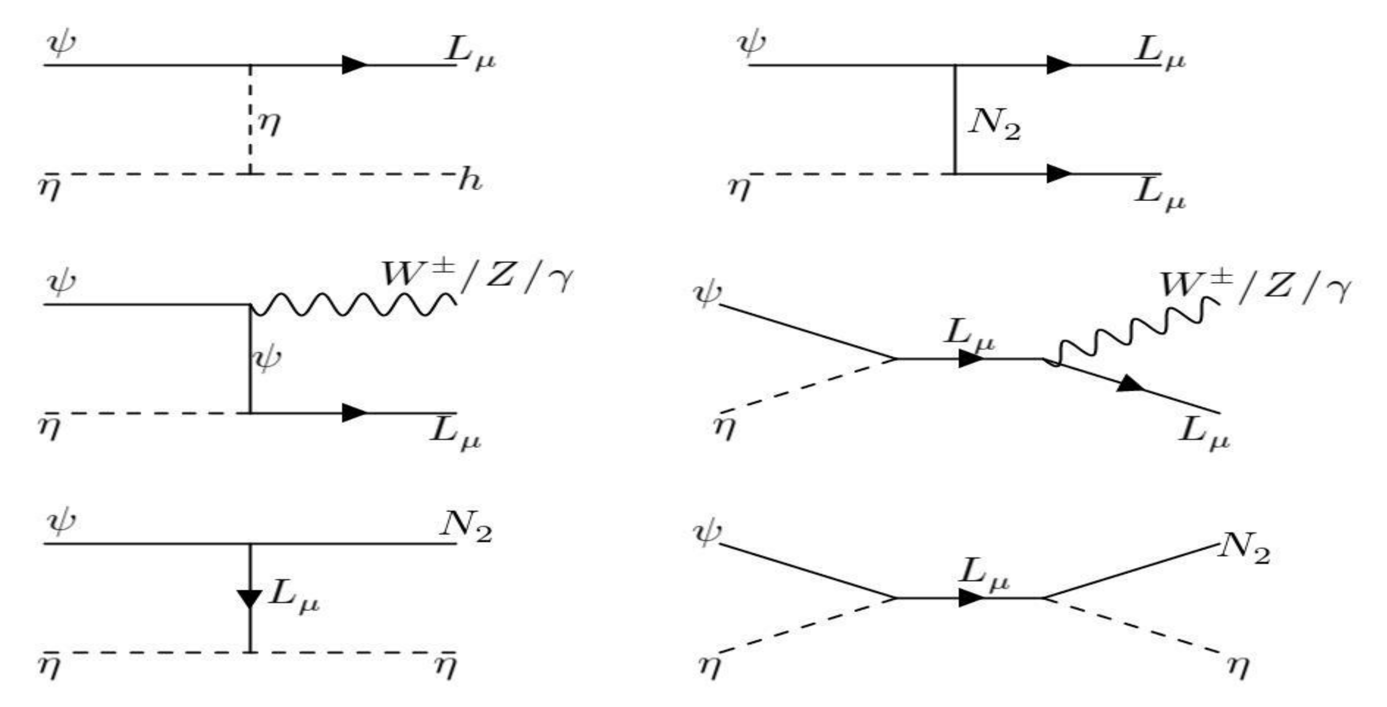
Dark Matter

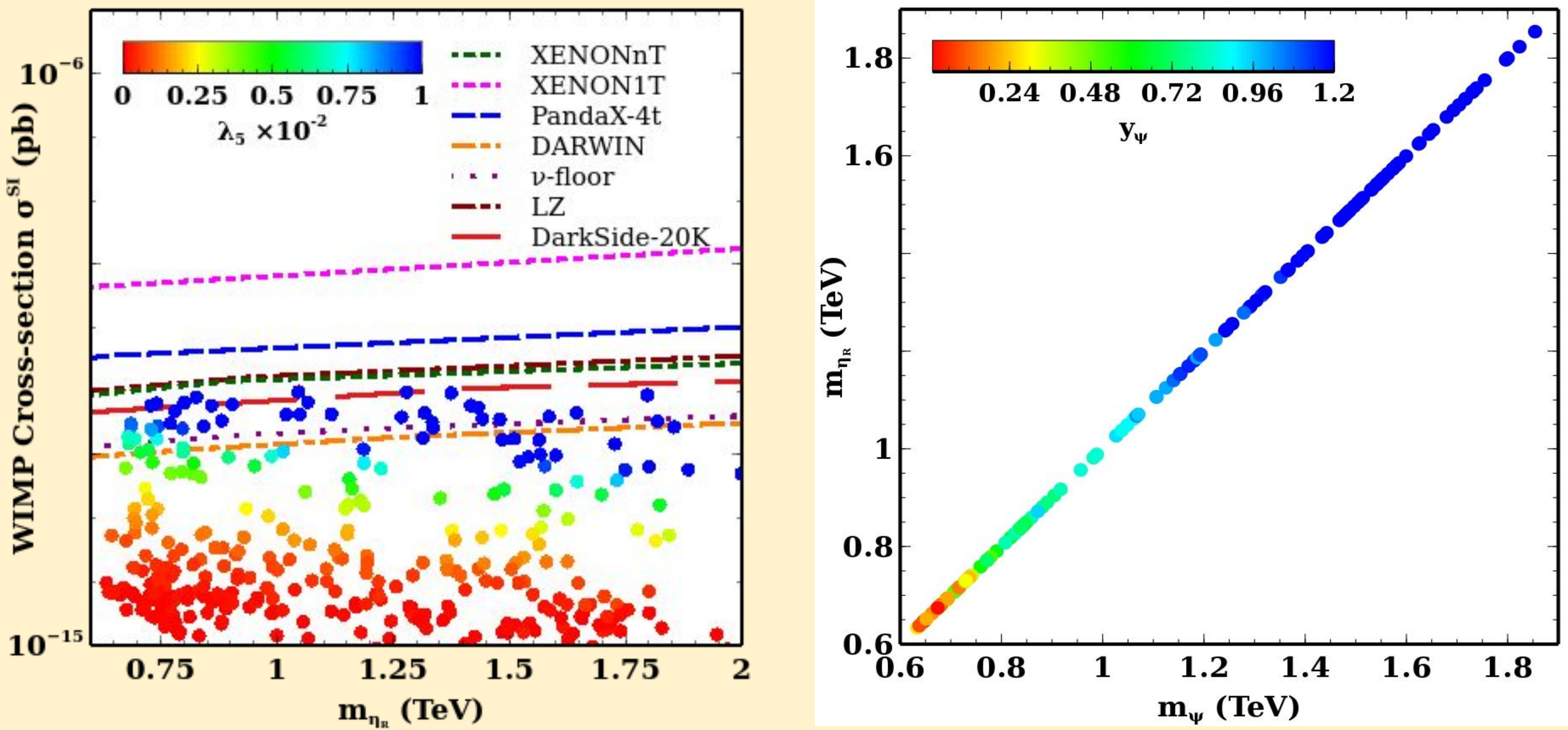
- In the minimal scotogenic model, both scalar and fermionic DM scenarios are possible depending on the lightest Z_2 odd state. The lightest of the neutral components of the inert doublet η serves to be a weakly interacting massive particle (WIMP) DM.

- The model is implemented in Feynrules (Neil et al) to compute all the relevant vertices. To solve the Boltzmann equations and to calculate the relic density of dark matter, micrOMEGAs is used (G. Belanger et al)

[9] Neil D. Christensen and Claude Duhr. FeynRules - Feynman rules made easy. Comput.Phys. Commun., 180:1614–1641, 2009.
[10] G. Belanger, F. Boudjema, A. Pukhov, and A. Semenov. micrOMEGAs: A Tool for dark matter studies. Nuovo Cim. C, 033N2:111–116, 2010.

- Apart from the annihilation and co-annihilation of inert doublet DM, here we also have few additional co-annihilation of the DM with the triplet fermion ψ . The co-annihilation processes are shown as:

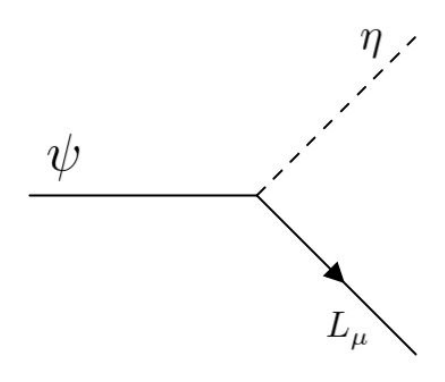


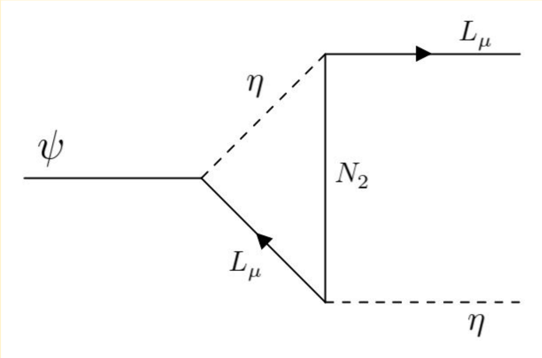


Correlation of Spin Independent Dark matter nucleon scattering cross section σ^{SI} and DM mass m_{η_R} with λ_5 for required dark matter relic density (left) and correlation of mass of DM m_{η_R} and mass of triplet fermion m_ψ with y_ψ (right)

Leptogenesis

- In this model, the right-handed neutrinos can decay to η and a muon/muon neutrino. However, there is no one loop diagram to generate the required CP asymmetry. A net B-L asymmetry can be generated from the decay of the triplet fermion ψ





In this model, the coupling $y_\psi \overline{L_\mu} C \psi^\dagger \tilde{\eta}$ involved in leptogenesis is free from the neutrino mass generation. Therefore we don't have DI bound on the leptogenesis scale.

[11] Thomas Hugle, Moritz Platscher, and Kai Schmitz. Low-Scale Leptogenesis in the Scotogenic Neutrino Mass Model. Phys. Rev. D, 98(2):023020, 2018.

The Boltzmann Equations for the model are

$$\frac{dY_\psi}{dz} = -D_\psi(Y_\psi - Y_\psi^{eq}) - S_A(Y_\psi^2 - (Y_\psi^{eq})^2)$$
$$\frac{dY_{B-L}}{dz} = -\epsilon^\psi D_\psi(Y_\psi - Y_\psi^{eq}) - W_{ID}^\psi Y_{\Delta L} - W_{\Delta L} Y_{B-L} \tag{14}$$

Where the decay term is given as

$$D_\psi = K_\psi(\frac{M_\psi}{M_2} z)\frac{\kappa_1(\frac{M_\psi}{M_2} z)}{\kappa_2(\frac{M_\psi}{M_2} z)} \tag{15}$$

The form of K_ψ is given as

$$K_\psi = \frac{\Gamma_\psi}{H(T{=}M_\psi)} \text{ with } \Gamma_\psi = \frac{M_\psi}{8\pi}(Y_\psi^\dagger Y_\psi)(1 - \frac{m_\eta^2}{M_\psi^2})$$

The inverse decay term and washout due to scattering term are written as

$$W_{ID}^{\psi} = \frac{1}{4}K_{\psi}(\frac{M_{\psi}}{M_2}z)^3\kappa_1(\frac{M_{\psi}}{M_2}z), W_{\Delta L} = \frac{36\sqrt{5}M_{pl}}{\sqrt{\pi}g_l\sqrt{g_*}v^4}\frac{1}{z^2}\frac{1}{\lambda_5^2}M_{\psi}\overline{m_{\zeta}^2}$$

The gauge boson mediated scattering term S_A for fermion triplet ψ is given by

$$S_A = \left(\frac{\pi^2 g^{*1/2} M_{Pl}}{1.66*180 g_{\psi}^2}\right)\frac{1}{M_{\psi}}\left(\frac{I_z}{z\kappa_2(\frac{M_{\psi}}{M_{N_2}}z)^2}\right) \tag{16}$$

where, the form of I_Z is given as,

$$I(z) = \int_4^{\infty}\sqrt{x}\kappa(z\sqrt{x})\hat{\sigma}_A(x)dx$$

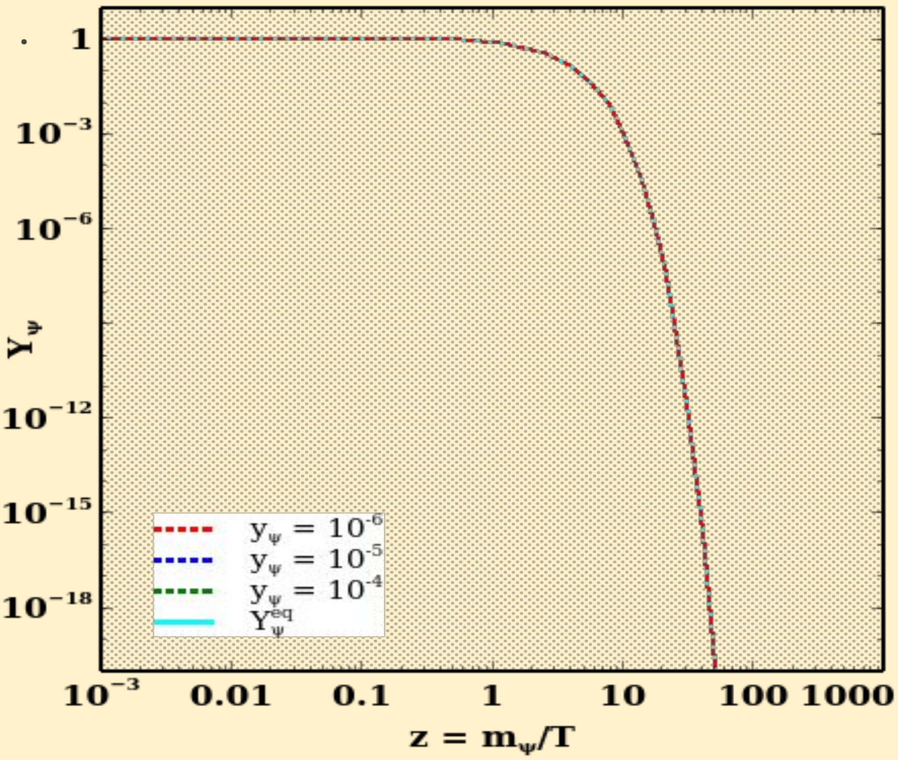
The CP asymmetry from ψ decay is given by

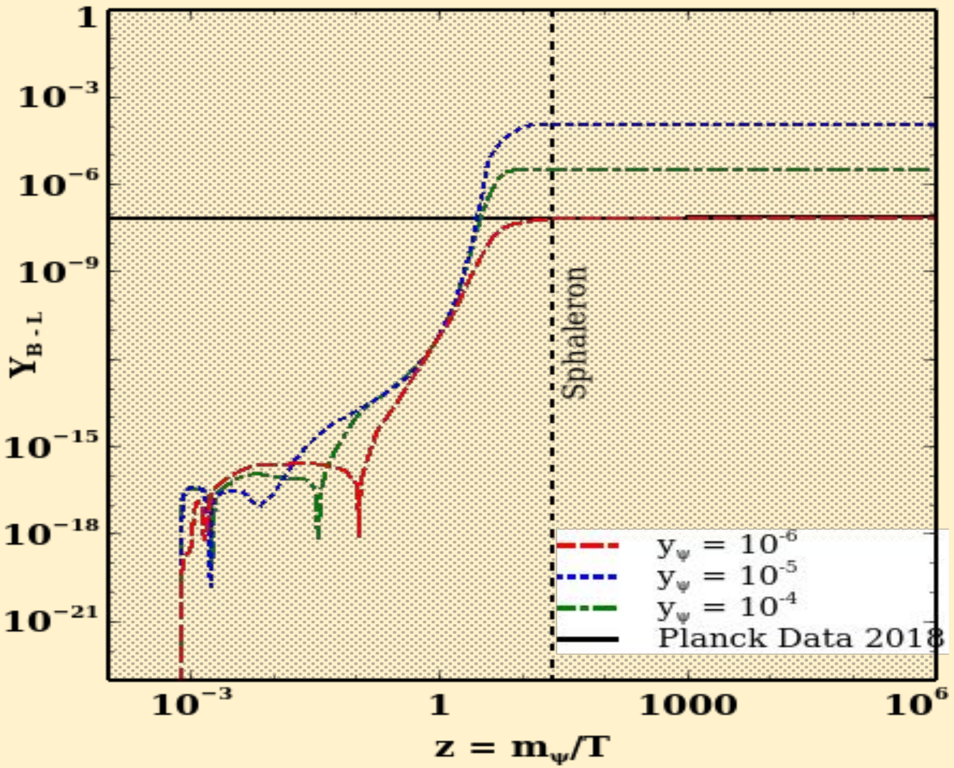
$$\epsilon_\psi = \frac{1}{8\pi(y_\psi^* y_\psi)} \mathrm{Im}\left[(y_\psi^* y_{\eta_2})^2\right] \mathcal{F}\left(\frac{M_2^2}{m_\psi^2}\right), \tag{17}$$

Where,

$$\mathcal{F} = \sqrt{x}\left[1 + \frac{1}{1-x} + (1+x)\ln\left(\frac{x}{1+x}\right)\right]$$

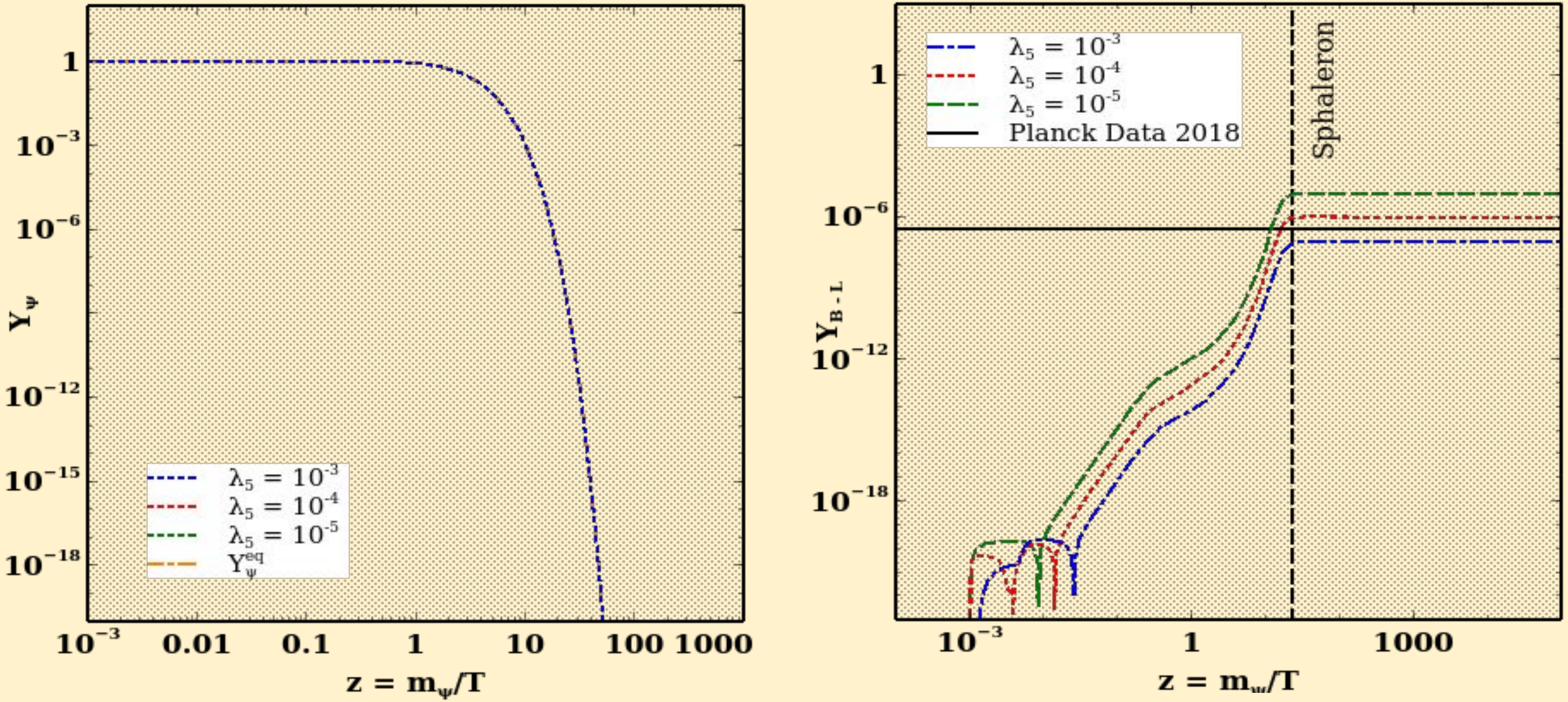
Results for leptogenesis





Variation of comoving number density Y_ψ (left plot) and B-L asymmetry (right plot) with $z = m_\psi/T$ for different benchmark values of the Yukawa couplings y_ψ. The horizontal lines in right panel plot depicts the required B-L asymmetry to generate net baryon asymmetry of the Universe (Planck Data 2018) after sphaleron transition (Vertical dotted line). The other parameters are fixed at

$$M_1 = 7 \times 10^9 GeV, M_2 = 7 \times 10^{10} GeV, M_3 = 7 \times 10^{11} GeV, m_\eta = 500 GeV, m_1 = 10^{-13} eV, m_\psi = 3 TeV and \lambda_5 = 10^{-4}.$$



Variation of comoving number density Y_ψ (left plot) and *B-L* asymmetry (right plot) with $z = m_\psi/T$ for different benchmark values of the Yukawa couplings λ_5. The horizontal lines in right panel plot depicts the required B-L asymmetry to generate net baryon asymmetry of the Universe (Planck Data 2018) after sphaleron transition (Vertical dotted line). The other parameters are fixed at
$M_1 = 10^9 GeV, M_2 = 10^{10} GeV, M_3 = 10^{11} GeV, m_\eta = 600 GeV, m_1 = 10^{-13} eV, m_\psi = 3 TeV and \lambda_5 = 10^{-5}$.

Benchmark Plot

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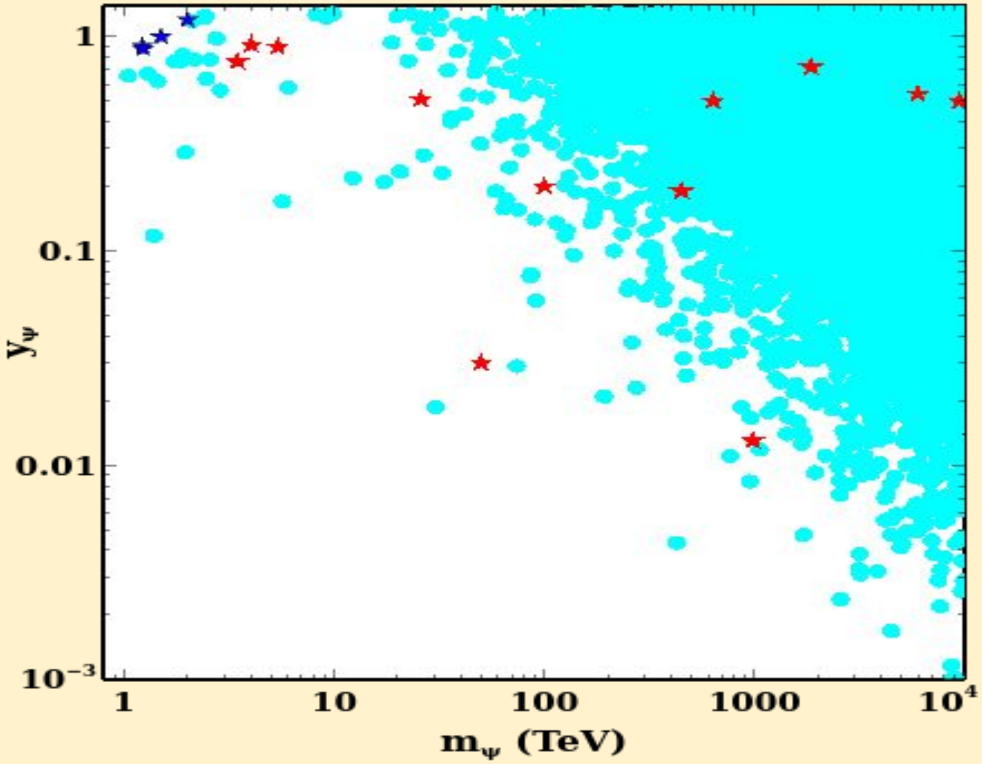

Scan plot in $m_\psi - y_\psi$ plane. Here cyan data points satisfy observed relic density, recent direct detection bounds, muon (g-2) and the red stars represent points that satisfy muon (g-2) and observed asymmetry, while blue stars satisfy dark matter relic also.

Conclusions

- We propose a minimal extension of the scotogenic model that has the potential to explain non-zero neutrino mass, muon (g-2), along with dark matter and baryon asymmetry of the Universe.
- Because of the imposed Z_4 symmetry, the Z_2 odd fermion triplet can provide a one-loop contribution to the muon's anomalous magnetic moment.
- The fermion triplet can also generate net lepton asymmetry (in TeV scale) in the muon sector through its out-of-equilibrium decay.
- Since the Yukawa coupling involved in leptogenesis also contributes to the muon (g-2) it provides a strong correlation between the two.
- Both muon (g-2) and DM relic hints towards a parameter space where $m_\psi \gtrsim m_{DM}$. The requirement of correct asymmetry, DM relic along with muon (g-2) excess tightly constrain the parameter space.
- The model is testable in future LHC experiments.

Thank You for Your Attention!