

Emanations of Dark Matter

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Physics beyond the Standard Model

- Muon anomalous magnetic moment
- Dark matter
- Neutrino mass
- Leptogenesis

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Based on the work of Thomas Hambye, Kristjan Kannike, Ernest Ma, and Martti Raidal, [hep-ph/0609228](https://arxiv.org/abs/hep-ph/0609228)

Magnetic momentum

- $\mu_\mu = g_\mu \frac{e}{2m} S$
- The gyromagnetic ratio $g_\mu = 2$
- Anomalous magnetic moment $a = \frac{1}{2}(g_\mu - 2)$
- Experimental $\Delta a_\mu \sim 10^{-9}$
- Corrections from QED, EW loops, hadronic loop corrections

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- Corrections from QED, EW loops, hadronic loop corrections
- Corrections from **new physics**

Dark matter

Most of the matter is dark:

- Density of matter $\Omega_{\text{matter}} = 0.26$
- Density of baryon matter $\Omega_{\text{B}} = 0.04$
- Density of **dark matter** $\Omega_{\text{M}} = 0.22$

Neutrino mass

- $m_e = 0.511 \text{ MeV}$
- $m_\nu \sim 0.1 \text{ eV}$
- Effective dimension five operator in SM $\frac{1}{\Lambda} LL\Phi\Phi$

Leptogenesis

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} = \frac{n_B}{n_\gamma} = (6.15 \pm 0.25) \times 10^{-10}$$

- Baryon number B is violated
- C and CP are violated (otherwise baryons and antibaryons behave in the same way)
- The universe was not in thermal equilibrium

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In leptogenesis, the asymmetry is generated in leptons and converted to baryon asymmetry

Leptogenesis

The asymmetry is proportional to

$$\epsilon_1 = \frac{\Gamma(N_1 \rightarrow l\Phi) - \Gamma(N_1 \rightarrow \bar{l}\bar{\Phi})}{\Gamma(N_1 \rightarrow l\Phi) + \Gamma(N_1 \rightarrow \bar{l}\bar{\Phi})}$$

where N_i are neutral singlet leptons

New particles in the model

- All new particles are *odd* under a Z_2 symmetry
- All Standard Model particles are *even* under the symmetry

New particles in the model

particles	$SU(2) \times U(1)$	$U(1)_L$	$(-1)^L$	Z_2
$L_\alpha = (\nu_\alpha, l_\alpha)$	$(2, -1/2)$	1	—	+
l_α^c	$(1, 1)$	-1	—	+
$\Phi = (\phi^+, \phi^0)$	$(2, 1/2)$	0	+	+
N_i	$(1, 0)$	1	—	—
N_i^c	$(1, 0)$	-1	—	—
$\eta = (\eta^+, \eta^0)$	$(2, 1/2)$	0	+	—
χ^-	$(1, -1)$	0	+	—

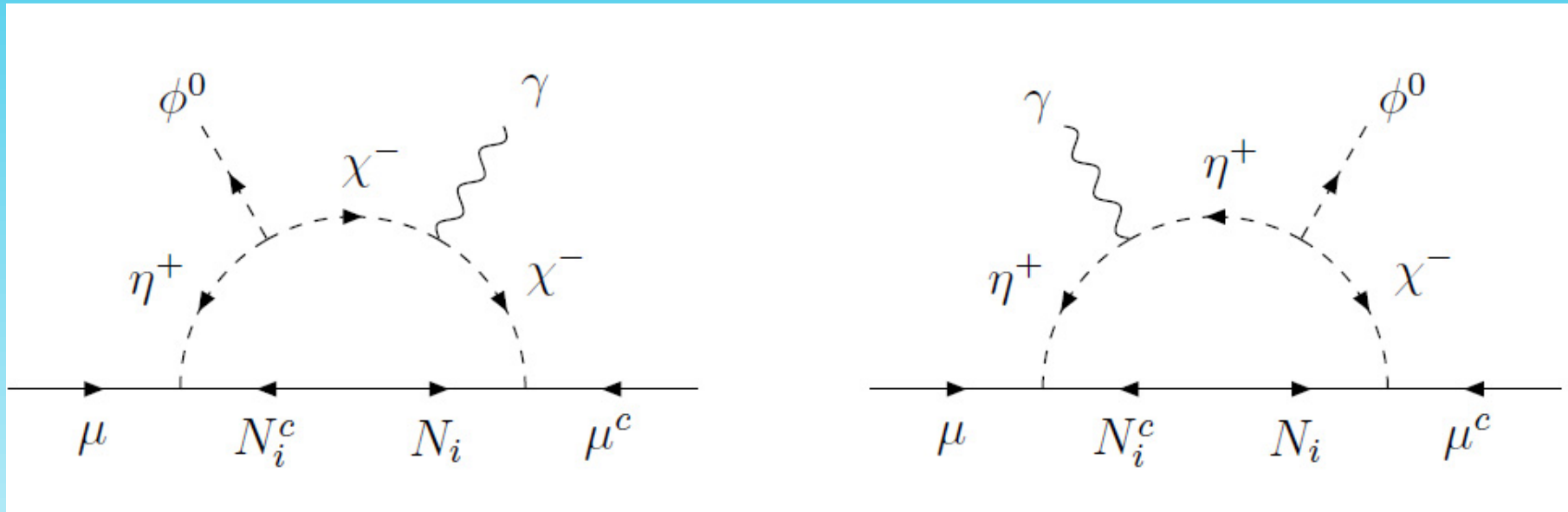
The Lagrangian

$$\begin{aligned} \mathcal{L} = & f_\alpha(\nu_\alpha\phi^- + l_\alpha\bar{\phi}^0)l_\alpha^c + h_{\alpha i}(\nu_\alpha\eta^0 - l_\alpha\eta^+)N_i^c + h'_{\alpha i}l_\alpha^c\chi^-N_i \\ & + M_iN_iN_i^c + \mu(\phi^+\eta^0 - \phi^0\eta^+)\chi^- + \frac{1}{2}\lambda_5(\eta^\dagger\Phi)^2 + H.c. \end{aligned}$$

Dark matter

- $\frac{1}{2}\lambda_5(\eta^\dagger\Phi)^2$
- $\eta^0 = (S + iA)/\sqrt{2}$, where $m_S^2 - m_A^2 = 2\lambda_5 v^2$
- The lightest particle odd under Z_2 can be $Re(\eta^0)$ or $Im(\eta^0)$ with mass $m_0 \sim 60$ to 80 GeV

Muon anomalous magnetic moment



Muon anomalous magnetic moment

$$X^+ = \chi^+ \cos \theta - \eta^+ \sin \theta$$

$$Y^+ = \chi^+ \sin \theta + \eta^+ \cos \theta$$

- $\sin \theta \cos \theta (m_X^2 - m_Y^2) = \mu v$
- $\Delta a_\mu = \frac{-\sin \theta \cos \theta}{16\pi^2} \sum_i h_{\mu i} h'_{\mu i} \frac{m_\mu}{M_i} [F(x_i) - F(y_i)]$
- $x_i = m_X^2/M_i^2, y_i = m_Y^2/M_i^2$
- $F(x) = \frac{1}{(1-x)^3} [1 - x^2 + 2x \ln x]$

Muon anomalous magnetic moment

- $x_i = m_X^2/M_i^2$, $y_i = m_Y^2/M_i^2$
- $y_i \ll x_i \simeq 1$, $M_i \sim 1$ TeV, and
 $(-h_{\mu i}h'_{\mu i} \sin \theta \cos \theta/16\pi^2) \sim 10^{-5}$

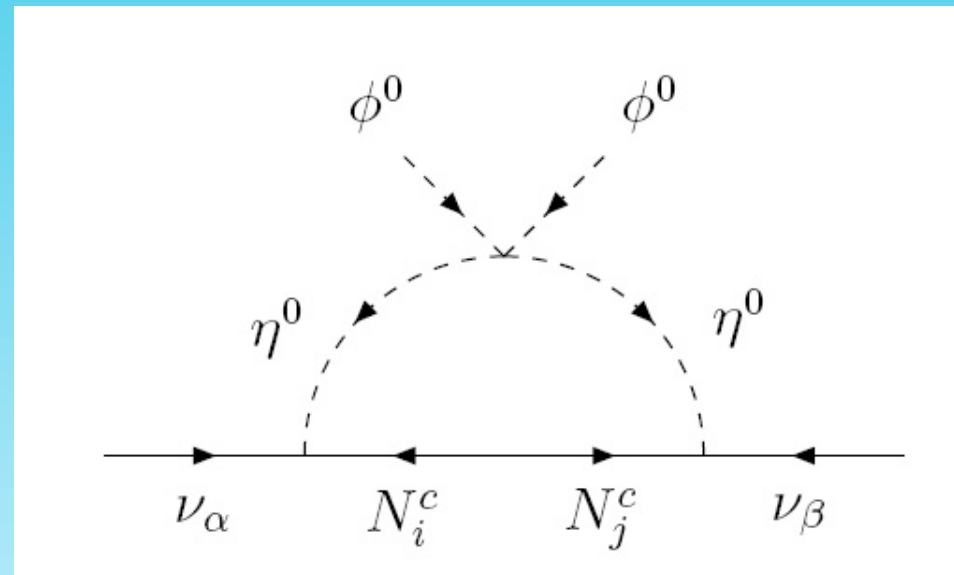
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- Predicted $\Delta a_\mu \sim 10^{-9}$

Neutrino mass

- Small Majorana mass terms $\frac{1}{2}m_{ij}N_i^c N_j^c + \frac{1}{2}m'_{ij}N_i N_j + H.c.$
- $U(1)_L \rightarrow (-1)^L$

Neutrino mass



Neutrino mass

$$(\mathcal{M}_\nu)_{\alpha\beta} = \sum_{i,j} h_{\alpha i} h_{\beta j} \tilde{m}_{ij},$$

where $\tilde{m}_{ij} = |2\lambda_5 v^2 m_{ij} I_{ij}|$

- $\mu(\phi^+\eta^0 - \phi^0\eta^+)\chi^- + \frac{1}{2}\lambda_5(\eta^\dagger\Phi)^2 + H.C.$

Neutrino mass

- Suppressed by: $1/M_i$, $\lambda_5/16\pi^2$, m_{ij}
- $M_{i,j} \sim 1$ TeV, $m_{ij} \sim 0.1$ GeV, $h_{\alpha i} \sim \mathcal{O}(10^{-2})$, $\lambda_5 \sim \mathcal{O}(10^{-2})$,
and $m_0 \sim v \sim 10^2$ GeV,
- then $\mathcal{M}_{\nu ij} \sim 0.1$ eV

Leptogenesis

- N_1 and N_1^c are mixed into mass eigenstates ψ_1 and ψ_1'
- The decay of ψ_1 as ψ_1' as the intermediate state gives only a negligible contribution to leptogenesis, unfortunately
- Contributions from ψ_1 and ψ_1' decaying via ψ_2 and ψ_2' are needed for successful leptogenesis

Leptogenesis

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- The decay of ψ_1 as ψ'_1 as the intermediate state gives only a negligible contribution to leptogenesis, unfortunately
- Contributions from ψ_1 and ψ'_1 decaying via ψ_2 and ψ'_2 are needed for successful leptogenesis
- Then $\epsilon_1^{h'} \propto \frac{\Delta M_1 \Delta M_2}{16\pi(M_2^2 - M_1^2)^3}$

Leptogenesis

- $\epsilon_1^{h'} \propto \frac{\Delta M_1 \Delta M_2}{16\pi(M_2^2 - M_1^2)^3}$
- resonant leptogenesis $M_1 \simeq M_2$
- non-resonant leptogenesis with $M_2 \gg M_1$

Leptogenesis

- $M_1 = 2 \text{ TeV}$ and $M_2 = 5 \text{ TeV}$
- $\Delta M_1/M_1 \sim \mathcal{O}(1)$ and $\Delta M_2/M_2 \sim \mathcal{O}(10^{-4})$
- $h_2 \sim \mathcal{O}(10^{-2})$
- $h'_2 \sim \mathcal{O}(10^{-1})$
- $h_1 \sim h'_1 < 10^{-7}$
- $\lambda_5 \sim \mathcal{O}(10^{-2})$

Conclusions

- Our model can be directly verified at LHC experiments by discovering N_i , N_i^c , (η^+, η^0) and χ^+ which all have $\mathcal{O}(10^{-1})$ couplings except N_1 and N_1^c
- Strongly enhanced Δa_μ
- Novel leptogenesis from interference of different generations of N_i and N_i^c

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- Strongly enhanced Δa_μ
- Novel leptogenesis from interference of different generations of N_i and N_i^c
- Thank you!