Muon g-2 anomaly and Neutrino Magnetic Moments

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Based on: arXiv:2104.03291 [hep-ph] (in collaboration with K.S. Babu, Sudip Jana and Manfred Lindner)

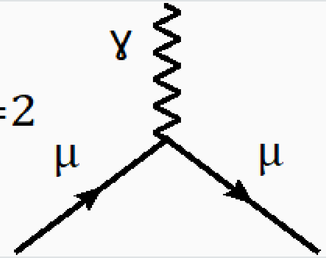
Oklahoma State University

Outline

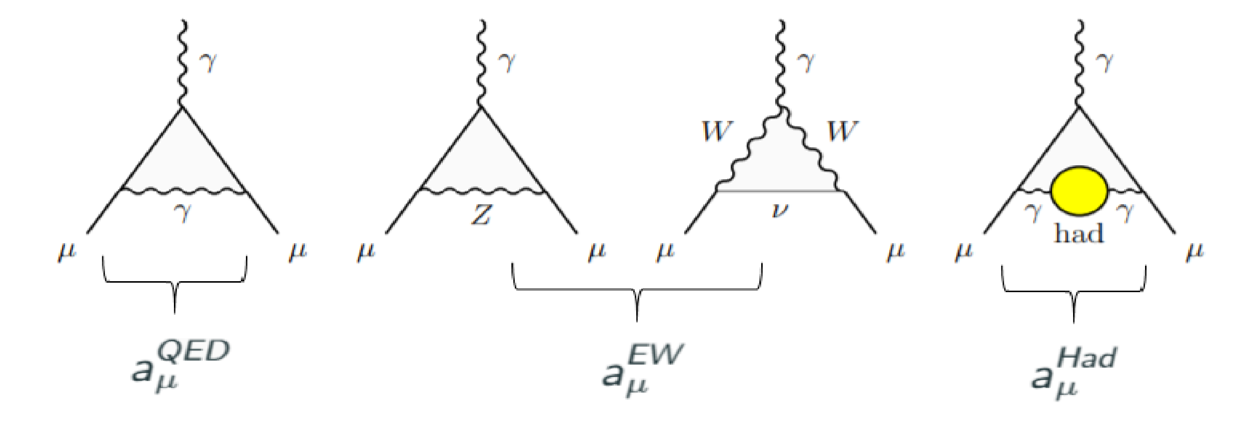
- Muon Magnetic Moment: An Overview
  - Current Status of Muon g-2
  - Observation of Excess Electron Recoil Events in XENON1T
  - XENON1T Electron Recoil Excess: Neutrino Magnetic Moment
  - Horizontal Symmetry for Enhanced Neutrino Magnetic Moment
  - Neutrino Magnentic Moment and Muon g-2 anomaly
  - Conclusions

Muon Magnetic Moment

- Magnetic moment of Leptons: $\vec{\mu}_B = g_\mu \frac{e}{2m_\mu}\vec{S}$
- Lande' g- factor: $g_\mu = 2$



- Due to Quantum corrections, $(g-2)_\mu \neq 0$.
- Anomalous Magnetic Moment: $a_\mu = \frac{(g-2)_\mu}{2}$

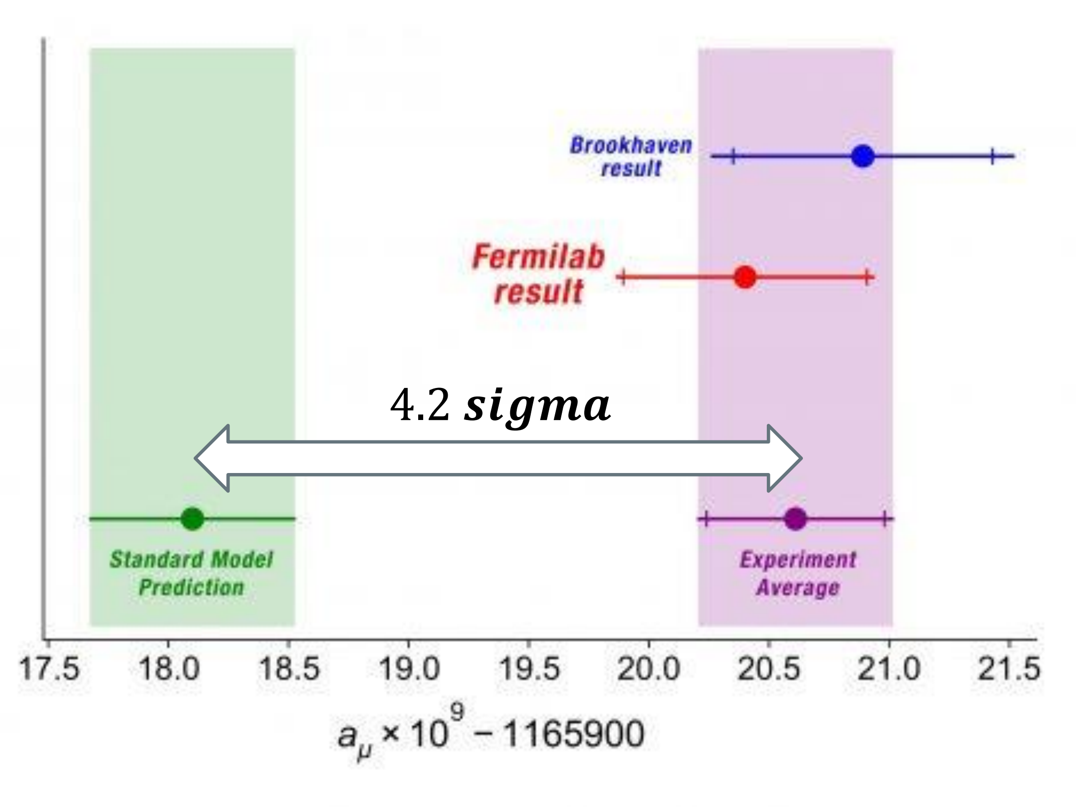


$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{Had}$$

Current Status of muon (g-2)

$$10^{11} a_\mu = \begin{cases} 116591810(43) \ \mathbf{SM} \\ 116592040(54) \ \mathbf{Exp} \end{cases}$$

$$\Delta a_\mu = a_\mu{}^{exp} - a_\mu{}^{SM} = 251(59) \times 10^{-11}$$



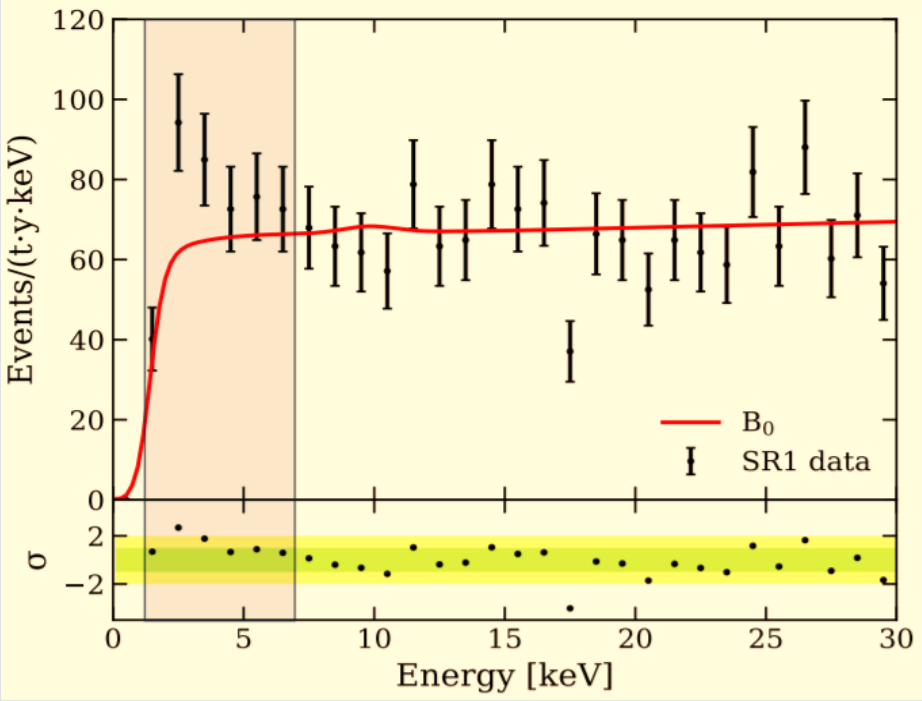
Fermilab Muon g-2 Collaboration, B. Abi *et al.* (2021)

Possible Explanations in different contexts

- *Light Scalars*
- *Dark Matter*
- *Neutrino Masses and mixing*
- *Lepto-quarks : B-anomalies*
- *Axion-like particles*
- *Dark Photons and Gauge extension*
- *Supersymmetry*

***Without any bias, for the full list of references , I will recommend to follow the last paper (2104.15136 until now) appeared on arXiv.

Observation of Excess Electron Recoil Events in XENON1T



XENON Collaboration, E. Aprile *et al.* (2020)

Excess between 1-7 keV

285 *events observed*

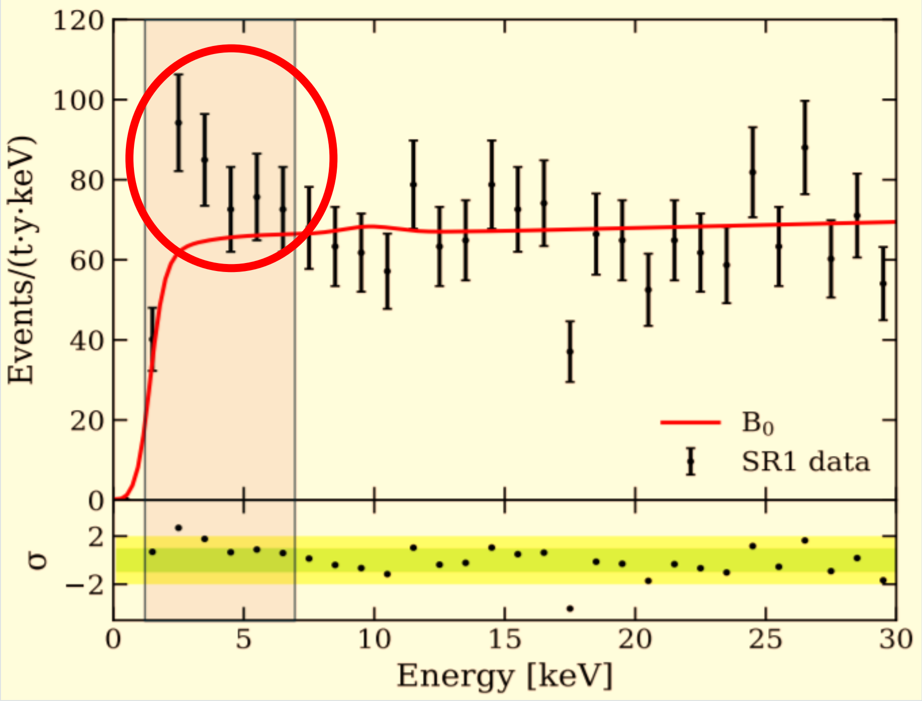
vs.

232 (+/- 15) *events expected (from best-fit)*

Would be a ***3.5σ*** *fluctuation*

(naive estimate – we use likelihood ratio tests for main analysis)

Observation of Excess Electron Recoil Events in XENON1T



The origin of such excess is unclear – it could be due to large background mismodeling.

XENON Collaboration, E. Aprile *et al.* (2020)

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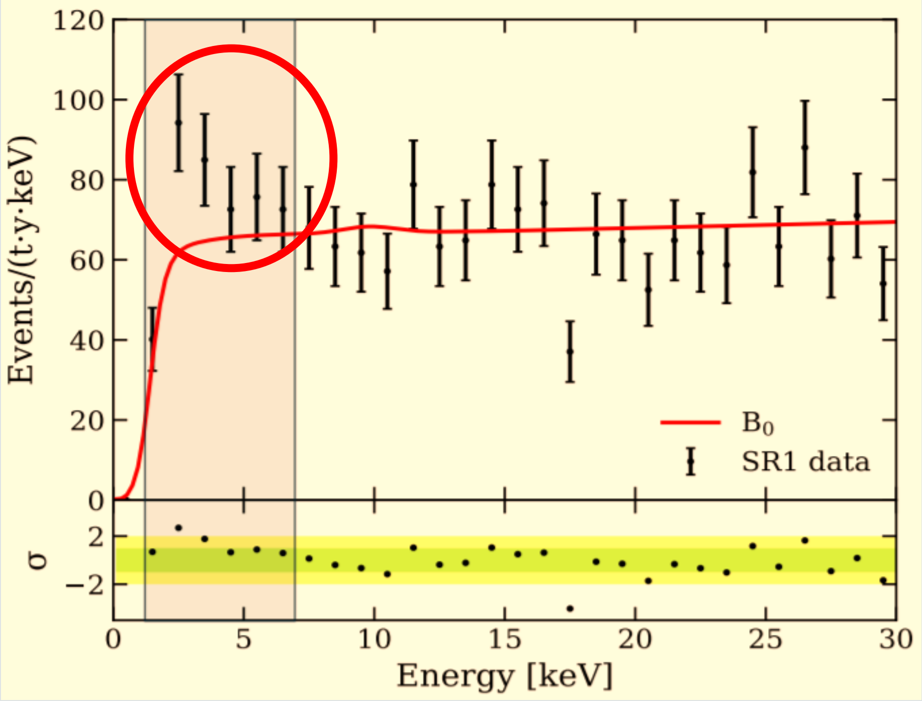


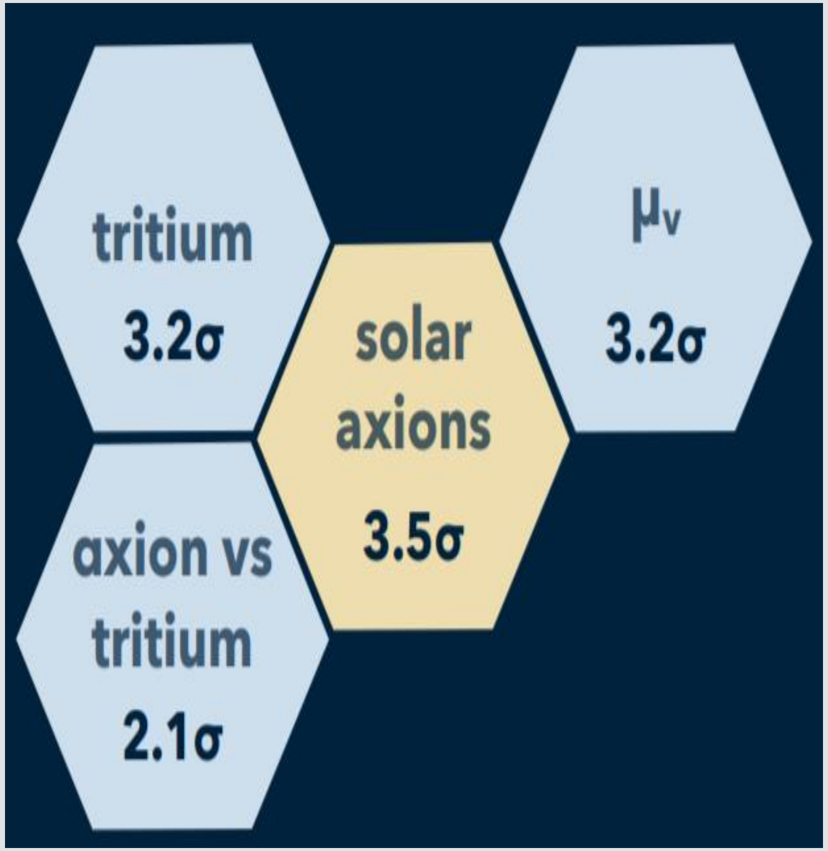
XENON Collaboration, E. Aprile *et al.* (2020)

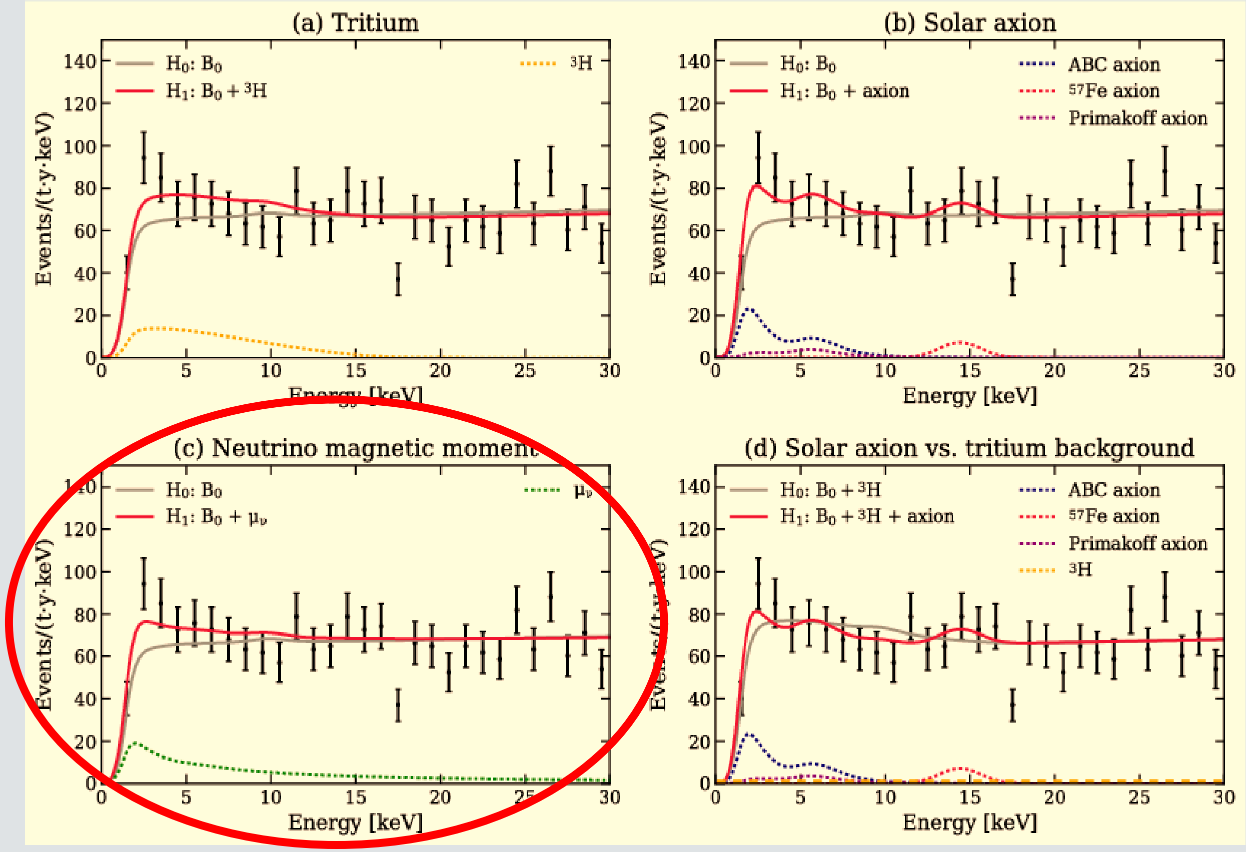
The origin of such excess is unclear – it could be due to large background mismodeling.

However, the Xenon1T result, if due to new physics, would revolutionize the field of particle physics.

Possible Explanations in different contexts..

XENON Collaboration, E. Aprile *et al.* (2020)

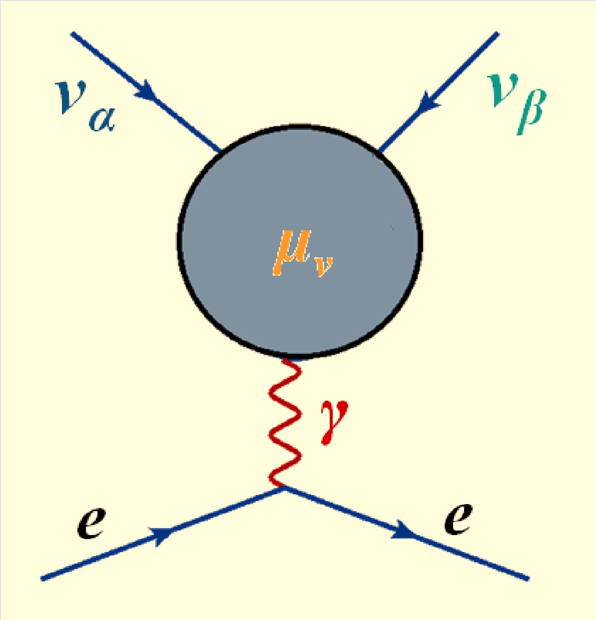




Neutrino Magnetic Moment and XENON1T electron recoil excess

The excess in electron recoil events observed by XENON1T collaboration may be explained by solar neutrinos which have nonzero magnetic moments.

This excess can be explained by neutrino transition magnetic moment with values
$\mu_{\nu_e\nu_\mu} \in (1.65 - 3.42) \times 10^{-11}\, \mu_B$

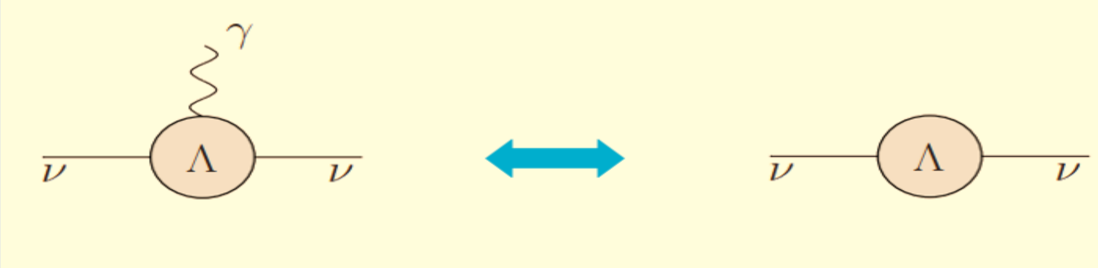


Babu, Jana, Lindner (2020)

Neutrino Magnetic Moment- Mass Conundrum

In the absence of additional symmetries (and without severe fine-tuning), generating a neutrino magnetic moment of order $\mathbf{10^{-11}}\,\boldsymbol{\mu_B}$ will also induce neutrino masses of several orders of magnitude larger than their measured values.

The main reason for this is that the magnetic moment and the mass operators are both chirality flipping, which implies that by removing the photon line from the loop diagram that induces μ_ν one would generate a neutrino mass term.

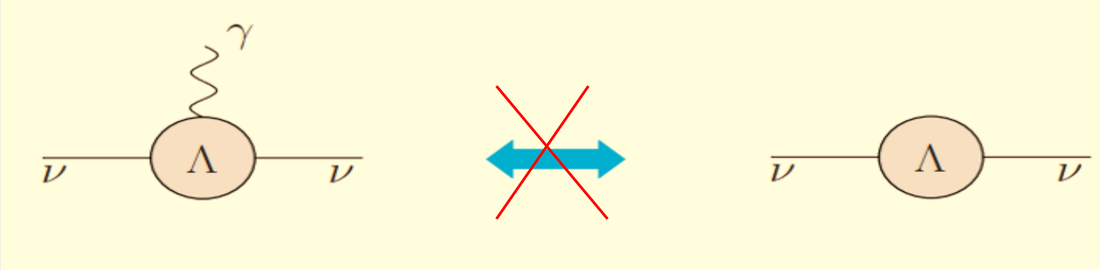


This would lead to the naive estimate of m_ν originating from such diagrams given $\boldsymbol{m_\nu \sim \frac{M^2 \mu_\nu}{2\, m_e \mu_B}}$

$$\boldsymbol{m_\nu \sim \frac{M^2 \mu_\nu}{2\, m_e \mu_B} \sim 0.1\mathrm{MeV}} \quad \text{for } M \sim 100\text{ GeV and } \mu_\nu \sim 10^{-11}\ \mu_B$$

Neutrino Magnetic Moment- Mass Conundrum

To decouple the neutrino magnetic moment from its mass, one need introduce additional symmetries:



A. Spin Symmetry Mechanism:

Barr, Friere and Zee (1990)

Recently, it has been shown that in this context one can achieve neutrino transition magnetic moment as big as $\mathbf{3 \times 10^{-12}\, \mu_B}$, which is not sufficient to explain the observed XENON1T electron recoil excess.

Babu, Jana, Lindner (2020)

B. Horizontal Symmetry:

$SU(2)_H$ Symmetry for Enhanced Neutrino Magnetic Moment

- Even though the neutrino mass operator and the magnetic moment operator both are chirality flipping, there is one important difference in their Lorentz structures.

- The mass operator, being a Lorentz scalar, is symmetric, while the magnetic moment, being a Lorentz tensor operator is antisymmetric in the two fermion fields.

$$\mathcal{L}_{\text{mag.}} = (\nu_e^T \ \ \nu_\mu^T) C^{-1} \sigma_{\mu\nu} \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} F^{\mu\nu}$$

$$\mathcal{L}_{\text{mass}} = (\nu_e^T \ \ \nu_\mu^T) C^{-1} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

Voloshin (1988)
Babu, Mohapatra (1989)
Babu, Jana, Lindner (2020)

- A horizontal symmetry $SU(2)_H$ acting on the electron and the muon families, under which only neutrino magnetic moment interaction is invariant can serve the purpose.

- This allows a nonzero transition magnetic moment, while neutrino mass terms are forbidden.

$SU(2)_H$ Extension of the Zee model

Leptons of the Standard Model transform under *$SU(2)_L \times U(1)_Y \times SU(2)_H$* as follows:

$$
\begin{aligned}
\psi_L &= \begin{pmatrix} \nu_e & \nu_\mu \\ e & \mu \end{pmatrix}_L && (2, -\frac{1}{2}, 2) \\
\psi_R &= (e \quad \mu)_R && (1, -1, 2) \\
\psi_{3L} &= \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix} && (2, -\frac{1}{2}, 1) \\
& \quad \tau_R && (1, -1, 1)
\end{aligned}
$$

The Higgs sector of the model:

$$
\begin{aligned}
\phi_S &= \begin{pmatrix} \phi_S^+ \\ \phi_S^0 \end{pmatrix} && (2, \tfrac{1}{2}, 1) \\
\Phi &= \begin{pmatrix} \phi_1^+ & \phi_2^+ \\ \phi_1^0 & \phi_2^0 \end{pmatrix} && (2, \tfrac{1}{2}, 2) \\
\eta &= (\eta_1^+ \quad \eta_2^+) && (1, 1, 2) \;.
\end{aligned}
$$

Babu, Mohapatra (1989)
Babu, Jana, Lindner (2020)

$SU(2)_H$ Extension of the Zee model

Yukawa Lagrangian of the model:

$$\begin{aligned}\mathcal{L}_{\text{Yuk}} &= h_1 \operatorname{Tr}\left(\bar{\psi}_L \phi_S \psi_R\right) + h_2 \bar{\psi}_{3L} \phi_S \tau_R + h_3 \bar{\psi}_{3L} \Phi i \tau_2 \psi_R^T \\ &\quad + f \eta \tau_2 \psi_L^T \tau_2 C \psi_{3L} + f' \operatorname{Tr}\left(\bar{\psi}_L \Phi\right) \tau_R + H.c.\end{aligned}$$

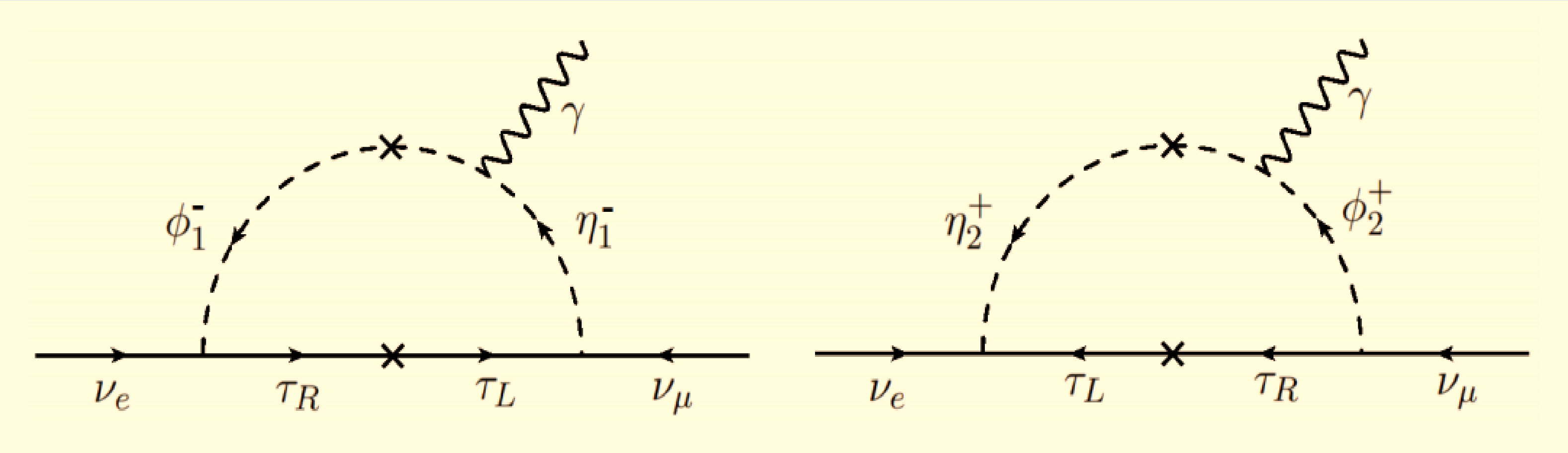
Relevant scalar potential terms:

$$V \supset m_\eta^2(|\eta_1|^2 + |\eta_2|^2) + m_{\phi^+}^2(|\phi_1^+|^2 + |\phi_2^+|^2) + m_{\phi^0}^2(|\phi_1^0|^2 + |\phi_2^0|^2) + \{\mu \eta \Phi^\dagger i \tau_2 \phi_S^* + H.c.\}$$

$$V^{(3)} = \mu \left[\overline{\phi_S^0}\left(\eta_1^+ \phi_1^- + \eta_2^+ \phi_2^-\right) - \phi_S^-\left(\eta_1^+ \bar{\phi}_1^0 + \eta_2^+ \bar{\phi}_2^0\right)\right] + H.c.$$

Neutrino Magnetic Moment

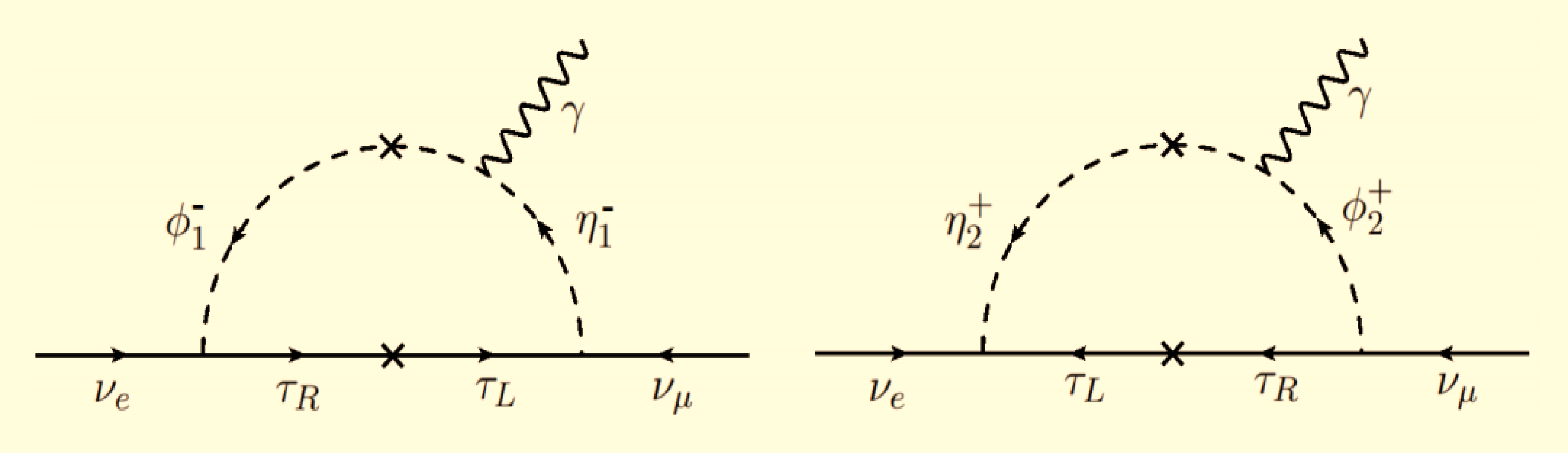
- The Lagrangian of this model does not respect lepton number. This allows a nonzero neutrino transition magnetic moment, while the neutrino mass terms are forbidden.



- In the $SU(2)_H$ symmetric limit, the two diagrams add for neutrino magnetic moment, while they cancel for neutrino mass.

Neutrino Magnetic Moment

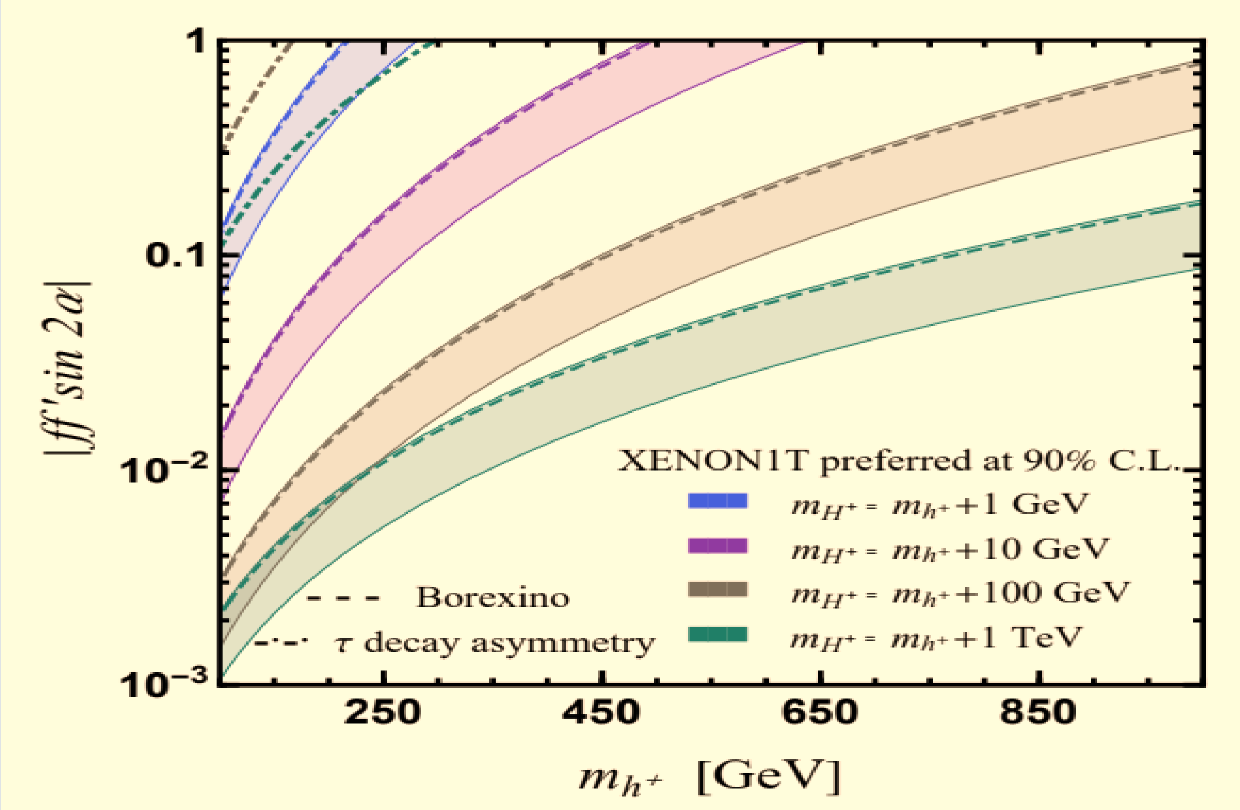
❖ In the $SU(2)_H$ symmetric limit, the two diagrams add for neutrino magnetic moment, while they cancel for neutrino mass.



$$\mu_{\nu_e\nu_\mu} = \frac{ff'}{8\pi^2} m_\tau \sin 2\alpha \left[\frac{1}{m_{h^+}^2} \left\{ \ln \frac{m_{h^+}^2}{m_\tau^2} - 1 \right\} - \frac{1}{m_{H^+}^2} \left\{ \ln \frac{m_{H^+}^2}{m_\tau^2} - 1 \right\} \right]$$

Babu, Mohapatra (1989)

Neutrino Magnetic Moment



Babu, Jana, Lindner (2020)

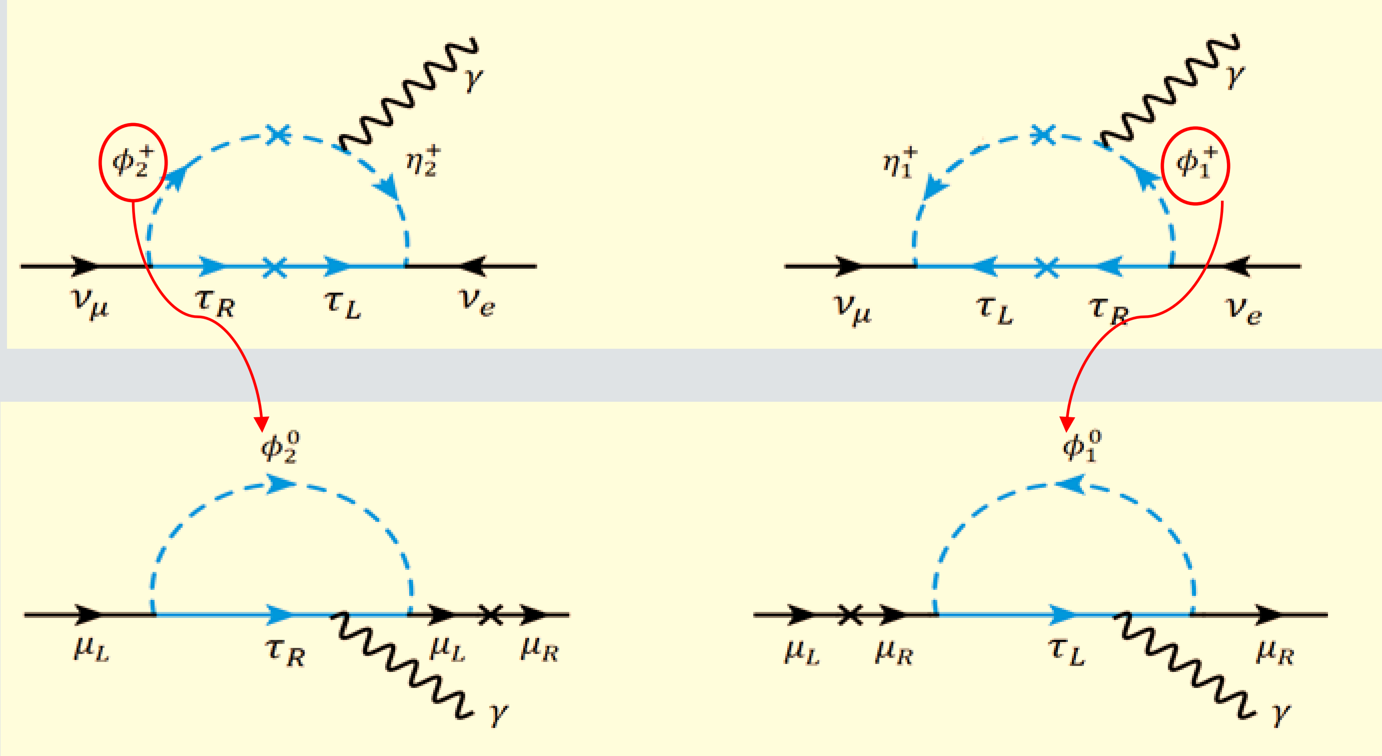
$$\mu_{\nu_e \nu_\mu} = \frac{ff'}{8\pi^2} m_\tau \sin 2\alpha \left[\frac{1}{m_{h^+}^2} \left\{ \ln \frac{m_{h^+}^2}{m_\tau^2} - 1 \right\} - \frac{1}{m_{H^+}^2} \left\{ \ln \frac{m_{H^+}^2}{m_\tau^2} - 1 \right\} \right]$$

Neutrino Magnetic Moment ⟺ Muon Magnetic Moment

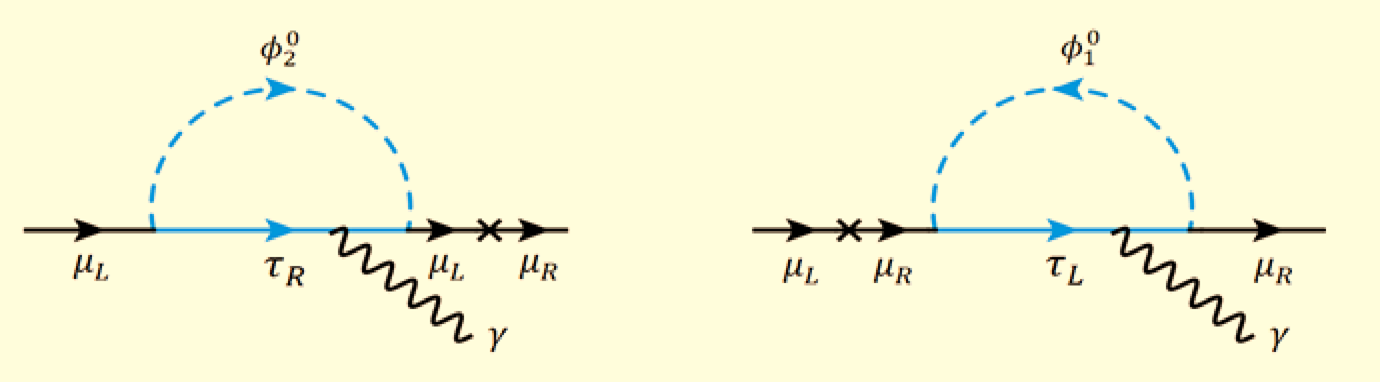
Babu, Jana, Lindner, VPK (2021)

In this setup, there is a direct correlation between the neutrino magnetic moment and muon g-2.

The neutral scalar partners of the charged states that contribute to the neutrino magnetic moment, would leads muon g-2.



Muon Anomalous Magnetic Moment



The corresponding contribution to muon g-2 :

$$\Delta a_\mu^{\varphi^0} = \frac{m_\mu^2}{16\pi^2}\left(|f'|^2 + |h_3|^2\right) F_{\varphi^0}[m_{\phi^0}],$$

$$F_{\varphi^0}[m_{\varphi^0}] = \int_0^1 dx \frac{x^2(1-x)}{m_\mu^2 x^2 + m_{\varphi^0}^2(1-x) + x(m_\tau^2 - m_\mu^2)},$$

The loop corrections mediated by the neutral scalars contribute positively to the muon anomalous magnetic moment.

Muon Anomalous Magnetic Moment

However, the charged scalars also contribute the muon anomalous magnetic moment. Moreover, these loop corrections contribute negatively to the Δa_μ.

$$\Delta a_\mu^{\varphi^+} = \frac{m_\mu^2}{16\pi^2}\left(|f\cos\alpha|^2 + |h_3\sin\alpha|^2\right) F_{\varphi^+}[m_{h^+}] + \frac{m_\mu^2}{16\pi^2}\left(|-f\sin\alpha|^2 + |h_3\cos\alpha|^2\right) F_{\varphi^+}[m_{H^+}],$$

$$F_{\varphi^+}[m_{\varphi^+}] = \int_0^1 dx \frac{x^2(x-1)}{m_\mu^2 x^2 + x(m_{\varphi^+}^2 - m_\mu^2)}.$$

But in this setup, these charged scalar contributions are negligible.

The main reason is that the Yukawa couplings $\boldsymbol{h_3}$ and $\boldsymbol{f}$ are severely constrained .

Muon Anomalous Magnetic Moment

The Yukawa coupling $\boldsymbol{f}$ is constrained from the neutrino mass induced by the explicit breaking of *SU(2)*$_H$ symmetry.

$$m_{\nu_\mu \nu_e} \simeq \frac{f f' m_\tau \sin 2\alpha}{16\pi^2}\left[\frac{\delta m_\eta^2}{m_\eta^2} - \frac{\delta m_\phi^2}{m_\phi^2} + 2(\delta\alpha)\cot 2\alpha \ln\frac{m_\phi^2}{m_\eta^2}\right],$$

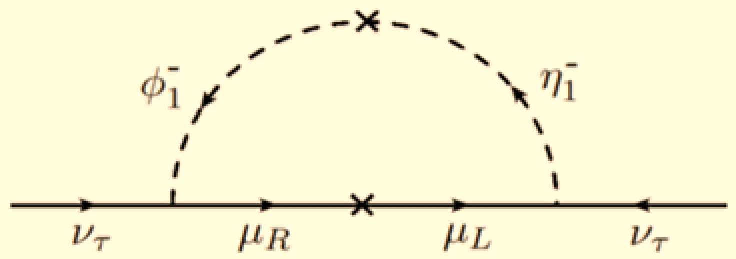
$$\frac{\delta m_\eta^2}{m_\eta^2} = \frac{|f|^2}{16\pi^2}\ln\left(\frac{m_e^2}{m_\mu^2}\right)$$

Explicit *breaking of SU(2)*$_H$ symmetry induce neutrino mass, by demanding that

$$m_\nu \sim 0.1\text{eV} \quad and\ \mu_\nu \sim 10^{-11}\ \mu_B \ \rightarrow |f| \leq 10^{-2}$$

The Yukawa coupling h_3 is constrained from the induced tau neutrino mass within the model

$$m_\nu \sim 0.1\text{eV} \quad and\ \mu_\nu \sim 10^{-11}\ \mu_B \ \rightarrow |h_3| \leq 10^{-2}$$

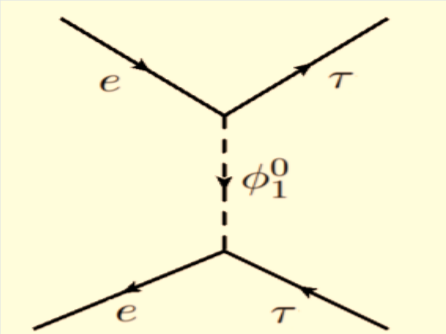


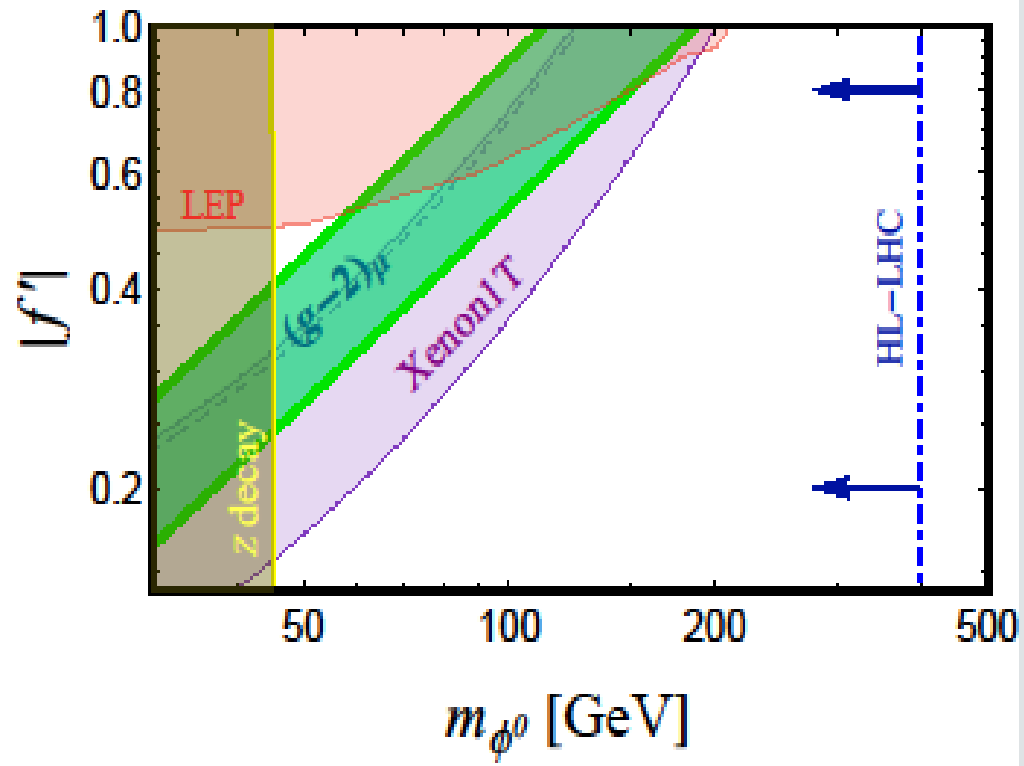
$$m_{\nu_\tau} = \frac{h_3 f \sin 2\alpha}{32\pi^2} m_\mu \ln\left(\frac{m_{h^+}^2}{m_{H^+}^2}\right).$$

Other Constraints

- A lower bound on neutral scalar mass is obtained from the decay width measurements of the $\boldsymbol{Z}$ gauge boson, $m_{\phi^0} > 45$ GeV.

- The Yukawa coupling f' leads to additional contribution to $\boldsymbol{e^-e^+ \to \tau^-\tau^+}$ process at LEP experiment via t-channel neutral scalar exchange.

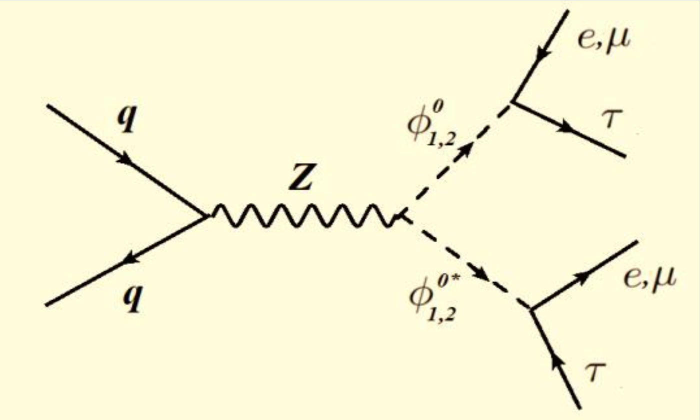




Babu, Jana, Lindner, VPK (2021)

LHC Prospects

- The most promising signal of the model is $\boldsymbol{pp \to e^- e^+ \tau^- \tau^+}$, $\boldsymbol{\mu^- \mu^+ \tau^- \tau^+}$ at the LHC.



- At the HL-LHC with an integrated luminosity of $\mathbf{1\ ab^{-1}}$, the neutral scalars of mass up to 400 GeV can be probed.

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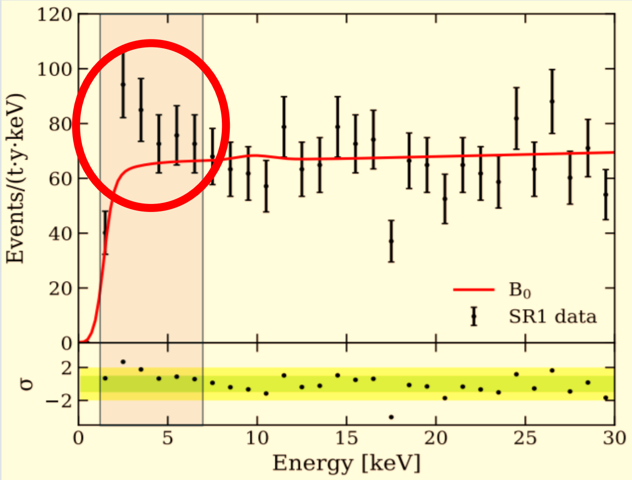
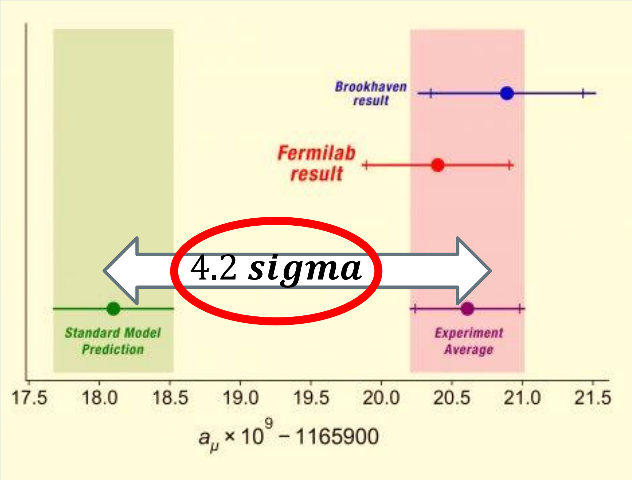
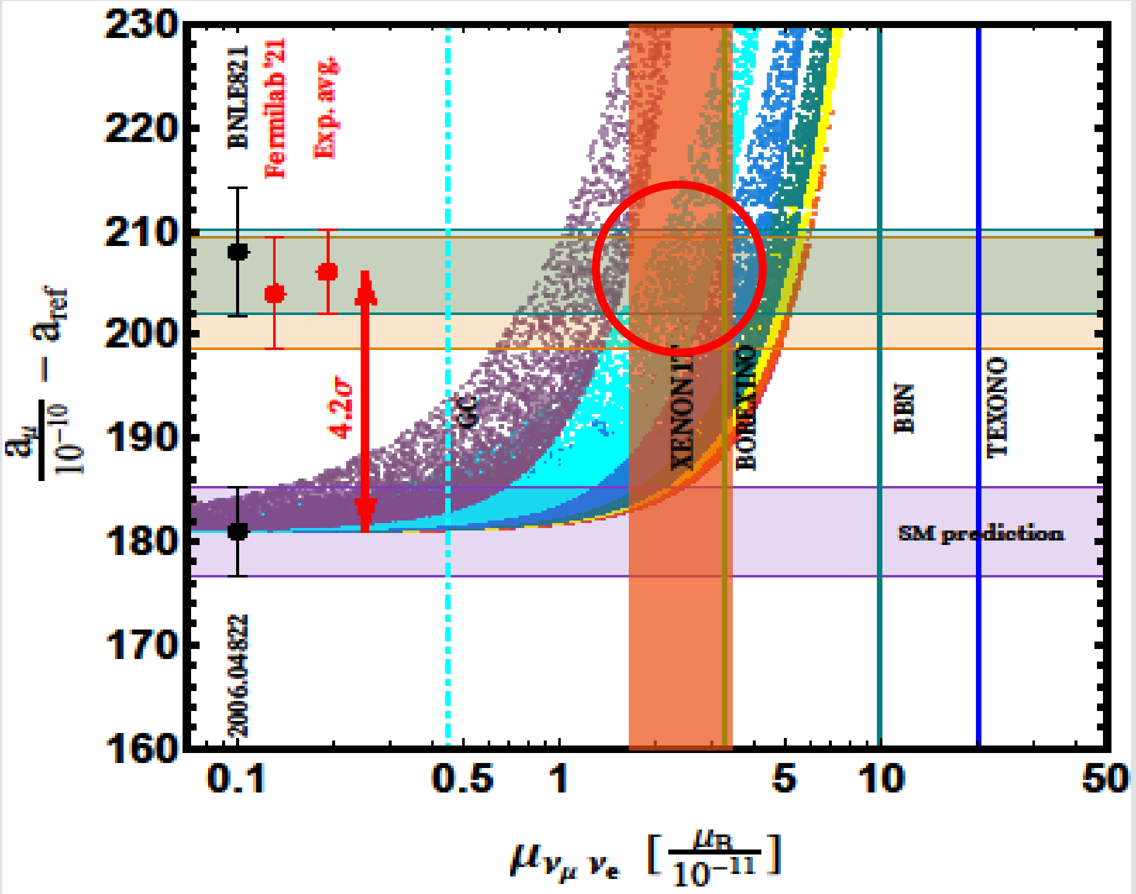
Muon Anomalous Magnetic Moment vs Neutrino Magnetic Moment







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Conclusions

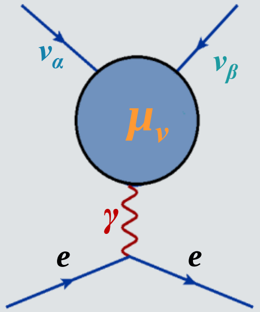
We have analyzed the new contributions to the muon anomalous magnetic moment in a class of models based on a horizontal symmetry that generates naturally large transition magnetic moment for the neutrinos needed to explain the XENON1T electron recoil excess.

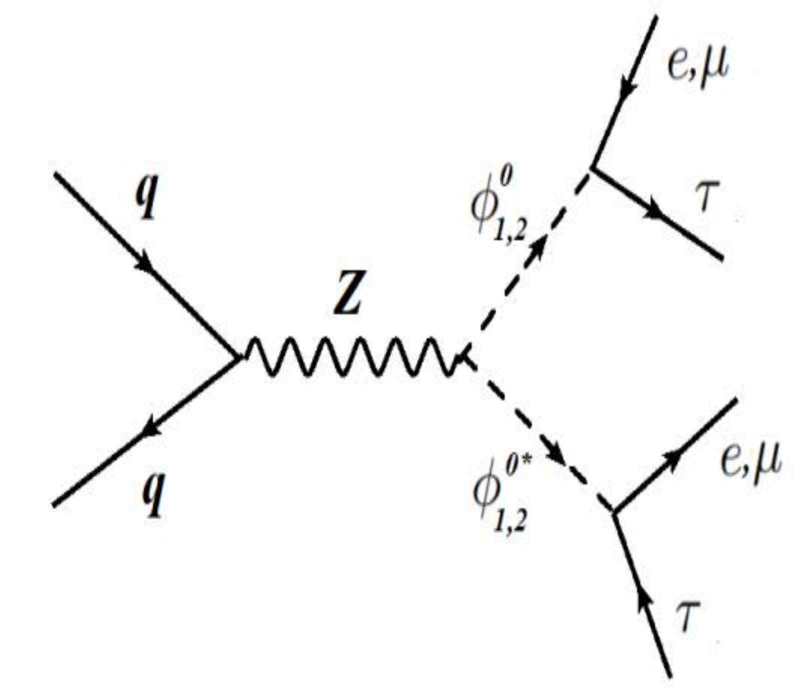
We have shown that in this class models there exist a direct correlation between the muon anomalous magnetic moment and neutrino transition magnetic moment.

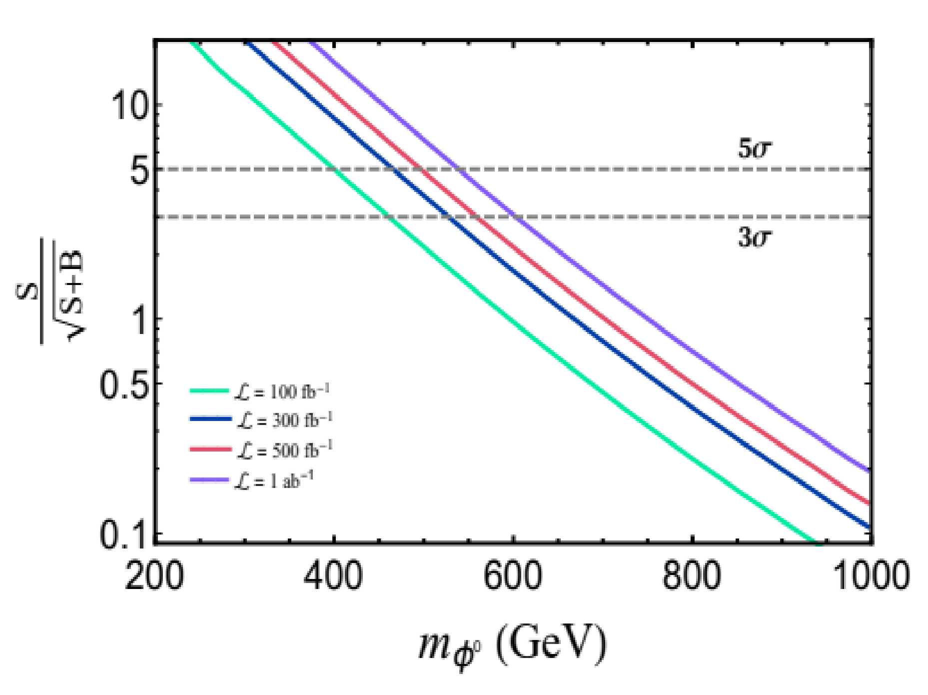
We have also shown that the new scalars present in the theory with masses around 100 GeV can yield the right sign and magnitude for the muon g-2 which has been confirmed recently by the Fermilab collaboration. Such scalars can also yield large neutrino magnetic moment needed to explain the XENON1T electron recoil excess.

Thank You !

B. $SU(2)_H$ Symmetric model for Enhanced Neutrino Magnetic Moment







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Neutrino Magnetic Moment: From Astrophysics and Cosmology

The best limit on μ_ν from this argument arises from red giant branch of globular clusters, resulting in a limit of

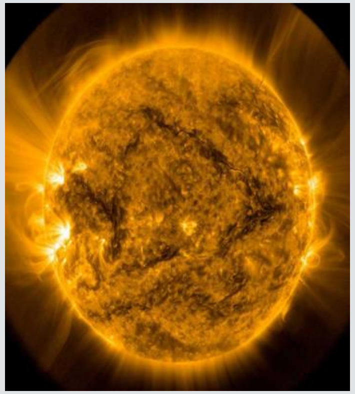
$\mu_\nu < 4.5 \times 10^{-12}\, \mu_B$.

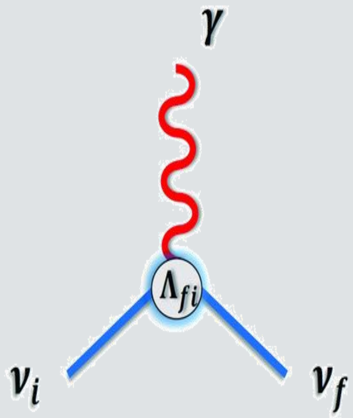
Validity of this limit would make the neutrino magnetic moment interpretation of the XENON1T excess *questionable*.

We note that these indirect constraints from astrophysics may be evaded if the plasmon decay to neutrinos is kinematically forbidden.

There are also cosmological limits arising from big bang nucleosynthesis.

However, these limits are less severe, of order $10^{-10}\, \mu_B$.





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Slide credit: Sudip Jana