Correlating Muon (*g* – *2*) Anomaly with Neutrino Magnetic Moments

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LPNHE in Paris, France

Based on:
arXiv: 2007.04291 [hep-ph], ***JHEP 10 (2020) 040***

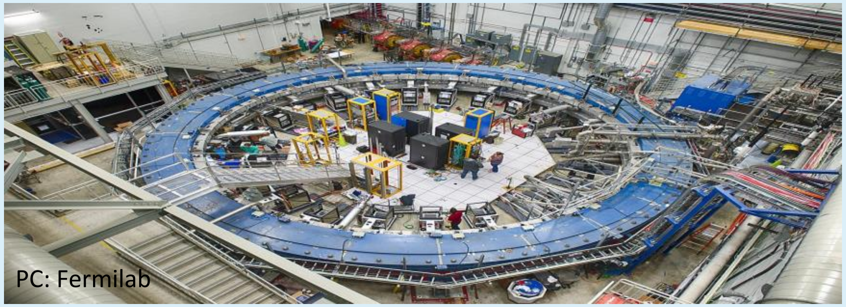
K.S. Babu **SJ** **Manfred Lindner**

Muon magnetic moment

- Here, thousands of muons zip around an giant ~ 50 ft circular magnet at close to the speed of light.
- After making a few hundred laps in less than a millisecond, the muons decay and are soon replaced by another bunch.

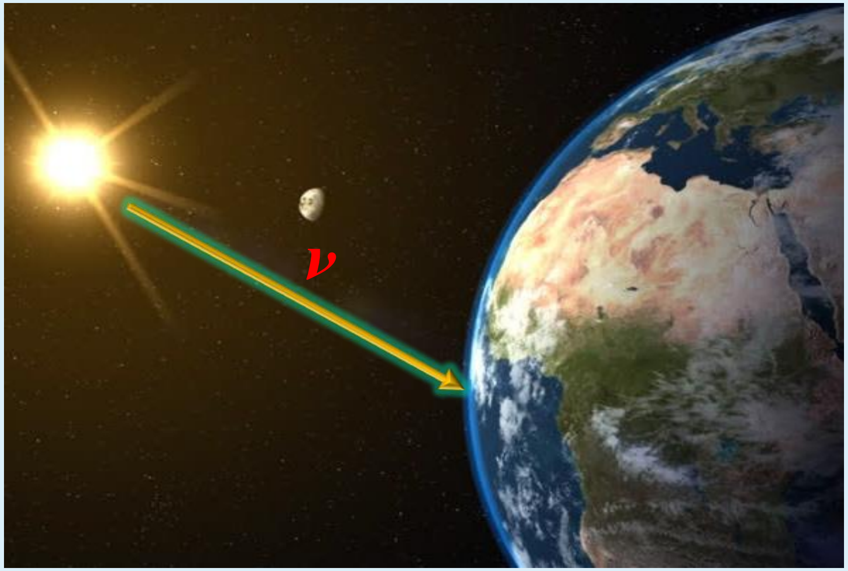
- To understand the properties of muon: Specifically, to know about the muons' "**magnetic moment**"—

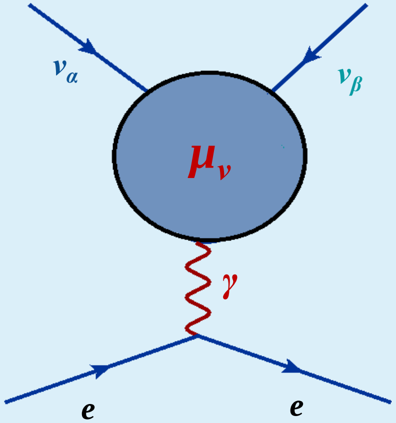
How much do they rotate on their axes in a powerful magnetic field— as they race around the magnet?

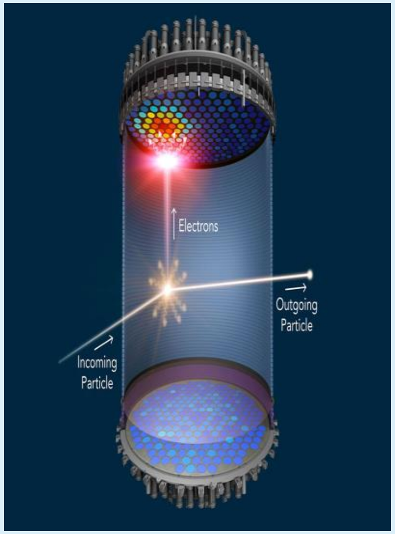


PC: Fermilab

Neutrino magnetic moment







PC: XENON collaboration

Neutrino magnetic moments: experimental status

- *The quest for measuring a possible magnetic moment of the neutrino was begun <u>even before the discovery of the neutrino</u>. Cowan, Reines and Harrison set an upper limit on in the process of measuring background for a free neutrino search experiment with reactor antineutrinos.*

- *Reines was awarded the 1995 Nobel Prize in Physics for his co-detection of the neutrino with Clyde Cowan in the neutrino experiment.*

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PHYSICAL REVIEW VOLUME 96, NUMBER 5 DECEMBER 1, 1954

Upper Limit on the Neutrino Magnetic Moment*

C. L. COWAN, JR., F. REINES, AND F. B. HARRISON
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(Received August 18, 1954)

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Reactor based experiments

- **KRASNOYARSK (1992):** $\mu_\nu < 2.7 \times 10^{-10}\,\mu_B$
- **ROVNO (1993):** $\mu_\nu < 1.9 \times 10^{-10}\,\mu_B$
- **MUNU (2005):** $\mu_\nu < 1.2 \times 10^{-10}\,\mu_B$
- **TEXONO (2010):** $\mu_\nu < 2.0 \times 10^{-10}\,\mu_B$
- **GEMMA (2012):** $\mu_\nu < 2.9 \times 10^{-11}\,\mu_B$

Accelerator based experiment

- **LAPMF (1993):** $\mu_\nu < 7.4 \times 10^{-10}\,\mu_B$
- **LSND (2002):** $\mu_\nu < 6.4 \times 10^{-10}\,\mu_B$

Solar neutrino experiment

- **Borexino (2017):** $\mu_\nu < 2.8 \times 10^{-11}\,\mu_B$
- **XENON1T (2020):** $\mu_\nu \sim \{1.4, 2.9\} \times 10^{-11}\,\mu_B$

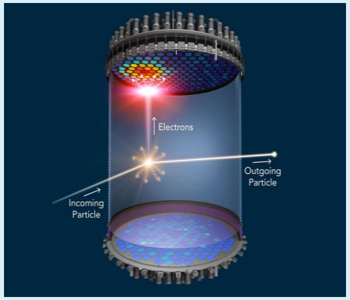
Excess between 1-7 keV

285 events observed

vs.

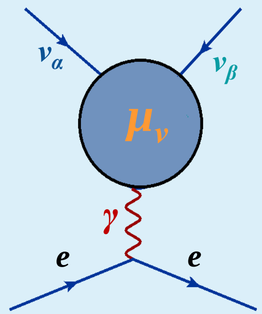
232 (+/- 15) events expected (from best-fit)

Would be a 3.5σ fluctuation
(naive estimate – we use likelihood ratio tests for main analysis)



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

Neutrino magnetic moments: experimental status



In order to compute XENON1T signal prediction and analyze the recoiled electron spectrum for a single component transition magnetic moment, one can define the differential event rate in terms of the reconstructed recoiled energy (T) as

$$\frac{dN}{dT_r} = n_e \times \int_{E_\nu^{min}}^{E_\nu^{max}} dE_\nu \int_{T^{th}}^{T^{max}} dT \left(\frac{d\sigma_{\nu_e e}}{dT} P_{ee} + \frac{d\sigma_{\nu_\mu e}}{dT} P_{e\mu} \right) \times \frac{d\phi}{dE_\nu} \times \epsilon(T) \times \mathcal{G}(T, T_r)$$

number of target electrons in fiducial volume of one ton Xenon

solar neutrino flux spectrum

$$\phi_{pp} = 5.94 \times 10^{10} \mathrm{cm}^{-2}\mathrm{s}^{-1},$$

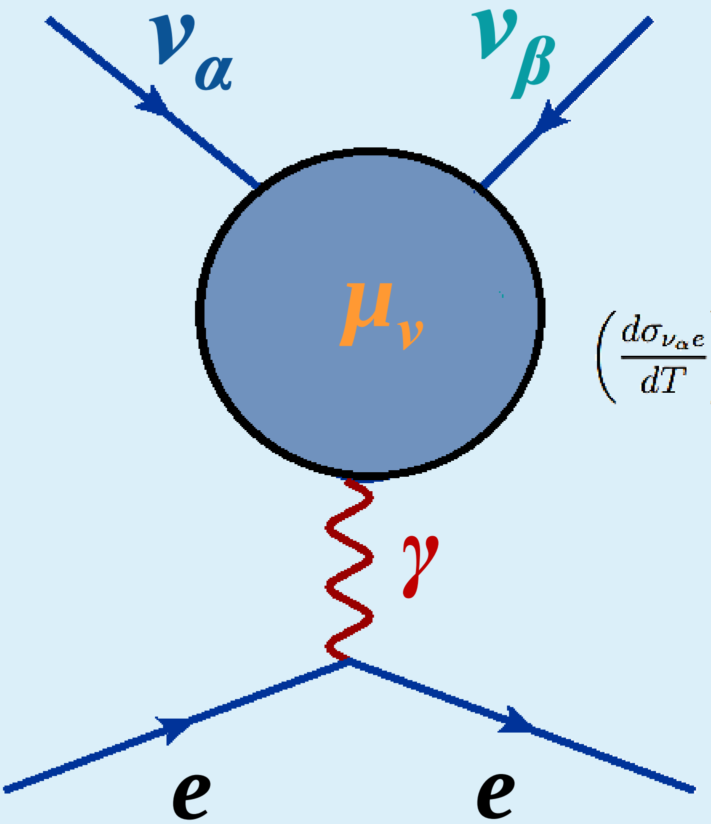
$$\phi_{^7Be} = 4.86 \times 10^{9} \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

detector efficiency

a normalized Gaussian smearing function in order to account for the detector finite energy resolution

It is clear that the pp flux is dominant with the ^{7}Be flux an order of magnitude smaller. Flux from ^{8}B and other sources are even smaller at low energies. It is sufficient then to keep only the pp flux in the calculation of electron recoil excess.

Neutrino magnetic moments: experimental status



The differential cross section for the neutrino-electron scattering in the presence of a magnetic moment

$$\left(\frac{d\sigma_{\nu_\alpha e}}{dT}\right)_{tot} = \left(\frac{d\sigma_{\nu_\alpha e}}{dT}\right)_{SM} + \frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T} - \frac{1}{E_\nu}\right)\left(\frac{\mu_{eff}}{\mu_B}\right)^2$$

$$\left(\frac{d\sigma_{\nu_\alpha e}}{dT}\right)_{SM} = \frac{G_F^2 m_e}{2\pi}\left[(g_V^\alpha + g_A^\alpha)^2 + (g_V^\alpha - g_A^\alpha)^2\left(1 - \frac{T}{E_\nu}\right)^2 + \left(g_A^{\alpha^2} - g_V^{\alpha^2}\right)\frac{m_e T}{E_\nu^2}\right],$$

The flavor dependent vector and axial vector coupling is given by:

$$\begin{aligned} g_V^e &= 2\sin^2\theta_W + \frac{1}{2}; \quad g_A^e = +\frac{1}{2} \\ g_V^{\mu,\tau} &= 2\sin^2\theta_W - \frac{1}{2}; \quad g_A^{\mu,\tau} = -\frac{1}{2} \end{aligned}$$

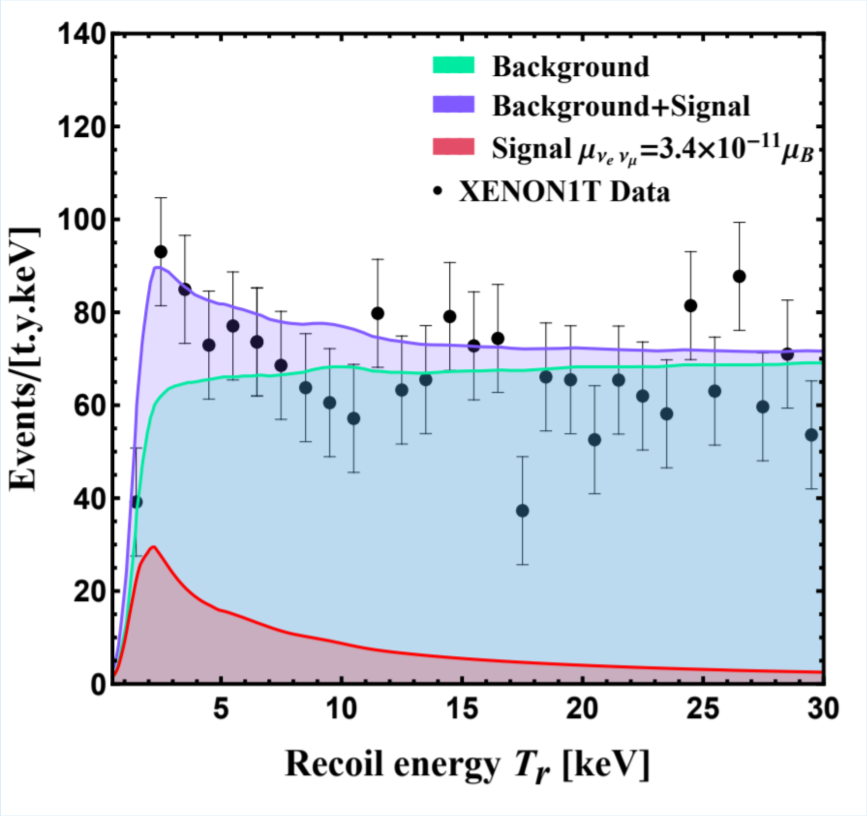
Neutrino magnetic moments: experimental status

One sees that owing to the presence of sizable neutrino magnetic moment, and the resulting 1/T enhancement in the cross section, the signal spectrum gives a good fit to the observed data in the electron recoil energy range between

(1 − 7) keV peaking around 2.5 keV.

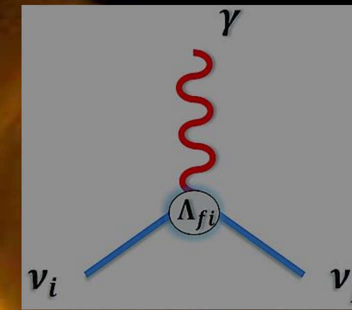
We show the consistency of this scenario when a single component transition magnetic moment takes values

$\mu_{\nu_e \nu_\mu} \in (1.65 - 3.42) \times 10^{-11}\, \mu_B$



Babu, SJ, Lindner (2020)

Neutrino Magnetic Moments: from astrophysics and cosmology



Evolution of stars can provide indirect constraints on the magnetic moments.

Photons in the plasma *of stellar environments* ***can decay*** *either into $\nu\bar{\nu}$ for the case of Dirac neutrinos or into $\nu_\alpha\nu_\beta$ for the case of Majorana neutrinos.*

If such decays occur too rapidly, that would ***drain energy of the star****, in conflict with standard stellar evolution models which appear to be on strong footing.*

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

$\boldsymbol{\mu_\nu < 4.5 \times 10^{-12}\ \mu_B}$. *Raffelt et al.(2013, 2021)*

There are also cosmological limits arising from big bang nucleosynthesis. However, these limits are ***less severe****, of order* $\boldsymbol{10^{-10}\ \mu_B}$. *Fuller, Balantekin et al. (2015)*

Background courtesy: NASA

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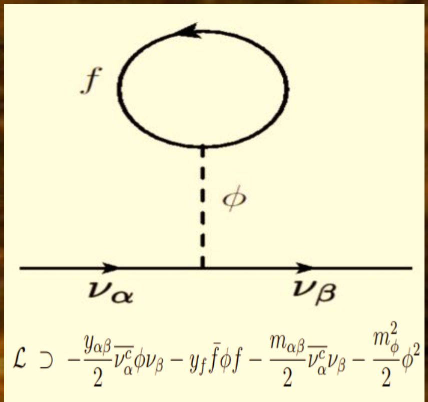
Neutrino Trapping Mechanism

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



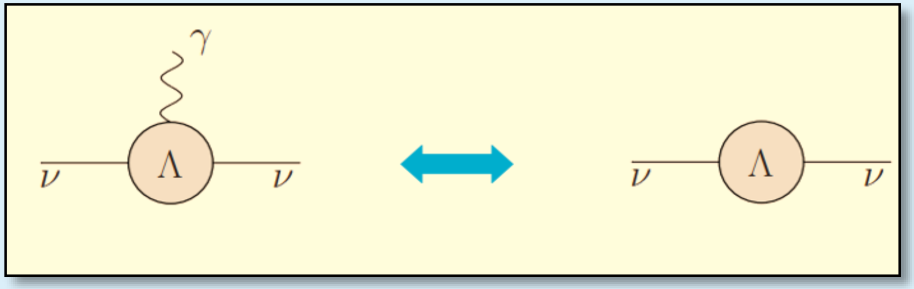
- *We closely follow the recent field theoretic evaluation of the* ***medium-dependent mass of the neutrino*** *in the presence of a light scalar that also couples to ordinary matter in illustrating our mechanism. Such interactions would provide the neutrino with a matter-dependent mass.*

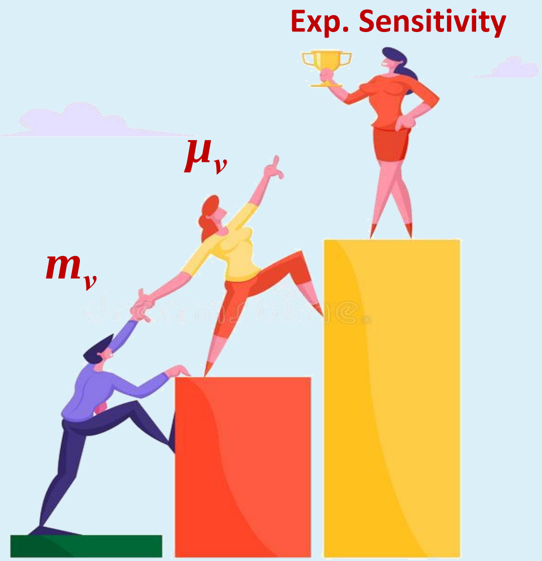
- *Phenomenological implications of this scenario, including* ***long-range force effects****, were studied and phenomenological constraints from laboratory experiments,* ***fifth force experiments****,* ***astrophysics and cosmology*** *are analyzed. [Parke et al. (2018), Smirnov et al.(2019), Babu et al. (2019)]*

Background courtesy: NASA

Babu, **SJ**, Lindner (2020)

Neutrino magnetic moment – mass conundrum





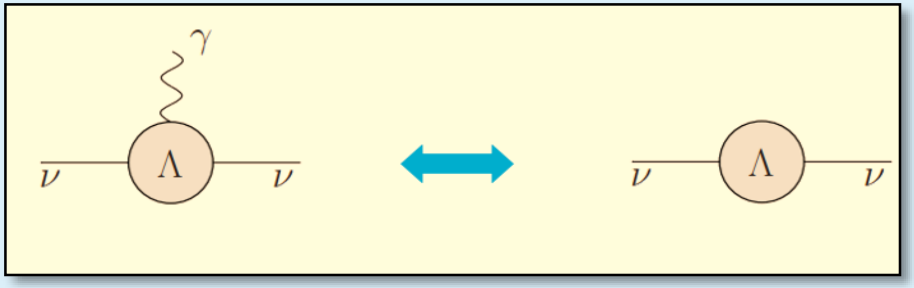
*In **the absence of additional symmetries (and without severe fine-tuning)** one would expect **neutrino masses several orders of magnitude larger than their measured values**., if $\mu_\nu \sim 10^{-11}\,\mu_B$*

*The main reason for this expectation 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:

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

Neutrino magnetic moment – mass conundrum



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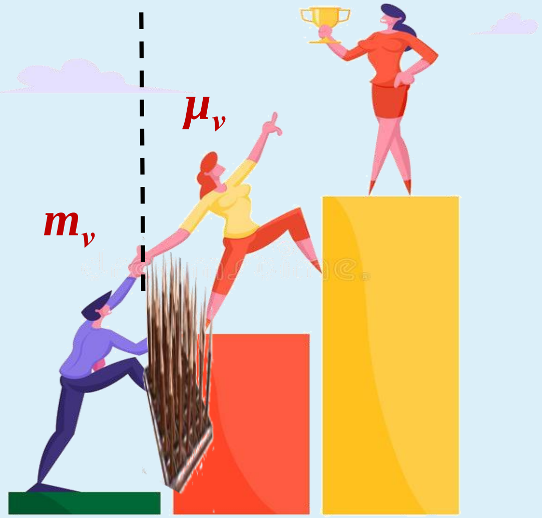


*This **magnetic moment–mass conundrum** was well recognized **three decades ago** when there was great interest in explaining **the apparent time variation of solar neutrino flux detected by the Chlorine experiment in anti-correlation with the Sun-spot activity**.*

Such a time variation could be explained if the neutrino has a $\mu_\nu \sim 10^{-10}\,\mu_B$ which would lead to spin-flip transition inside the solar magnetic field. Such transitions could even undergo a matter enhanced resonance.

Lim, Marciano (1988), Akhmedov (1988)

*In the **late 1980's and early 1990's** there were **significant theoretical activities** that addressed the compatibility of a large neutrino magnetic moment with a small mass.*

After that, in the theory side, no interesting developments have been made. These discussions become very relevant today.

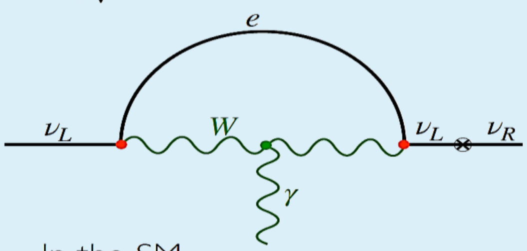
Neutrino magnetic moment – mass conundrum

SM + ν_R

The magnetic moment and mass operators for the neutrino have the same chiral structure, which for a Dirac neutrino has the form:

$$\mathcal{L} \supset \mu_\nu \overline{\nu}_L \sigma_{\mu\nu} \nu_R F^{\mu\nu} + m_\nu \overline{\nu}_L \nu_R + \text{H.c.}$$

$$\mu_\nu = \frac{e G_F m_\nu}{8\sqrt{2}\pi^2} = 3 \times 10^{-20} \mu_B \left(\frac{m_\nu}{0.1 \text{ eV}}\right)$$



In the SM

$$\mu_\nu^{SM} \sim 10^{-20}\ \mu_B$$

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Bell, Cirigliano, Ramsey-Musolf, Vogel, and Wise (2005)

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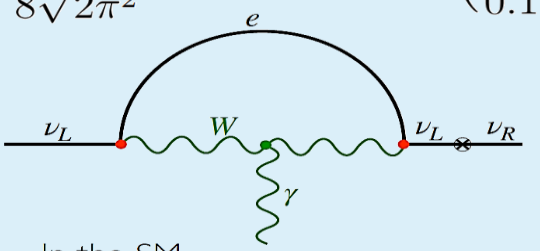

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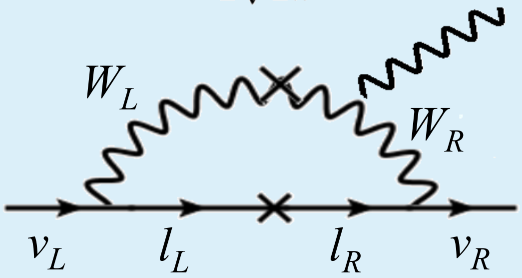
In left-right symmetric models, the right-handed neutrino couples to a W_R gauge boson, which also has mixing with the W boson:

$$\mu_\nu \simeq \frac{G_F m_\ell}{2\sqrt{2}\pi^2} \sin 2\xi$$



This mixing angle is constrained by muon decay asymmetry parameters, as well as by $b \to s\gamma$ decay rate, indirect LHC limits leading to a limit

$$\mu_\nu < 10^{-15} \mu_B$$

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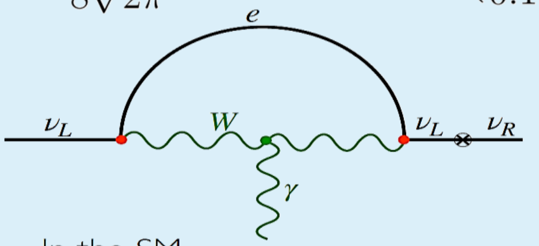

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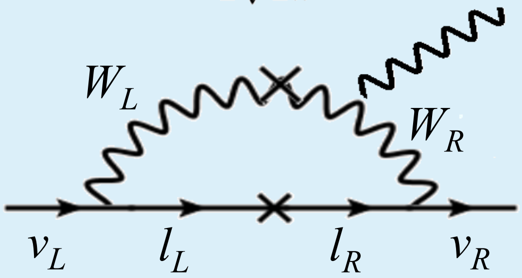

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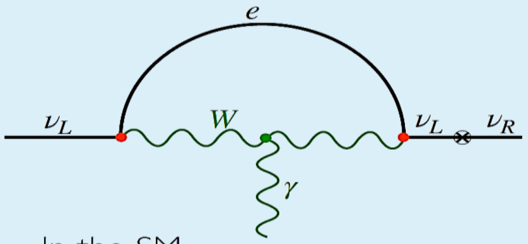

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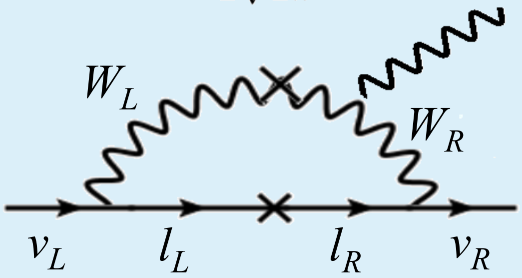

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Majorana scenario

If neutrinos are Majorana particles, their transition magnetic moments resulting from Standard Model interactions is given by

$$\mu_{ij} = -\frac{3eG_F}{32\sqrt{2}\pi^2}(m_i \pm m_j) \sum_{\ell=e,\mu,\tau} U^*_{\ell i} U_{\ell j} \frac{m_\ell^2}{m_W^2}$$

The resulting transition magnetic moment is even smaller than the previous estimate: at most of order $\mu_\nu \sim 10^{-23}\ \mu_B$

P. B. Pal and L. Wolfenstein (1982)

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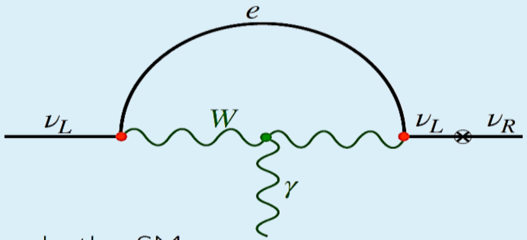

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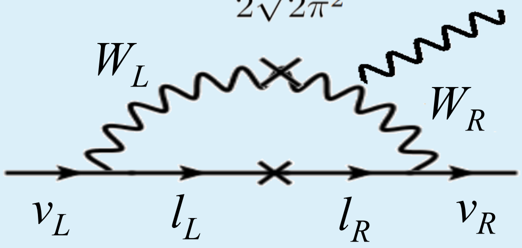

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Clearly, these values are well below the sensitivity of current experiments!

Neutrino magnetic moment – mass conundrum

A. Spin Symmetry Mechanism

In renormalizable gauge theories there are ***no direct couplings*** *of the type* $\gamma W^{+} S^{-}$ *where* S^{-} *is a charged scalar field.*

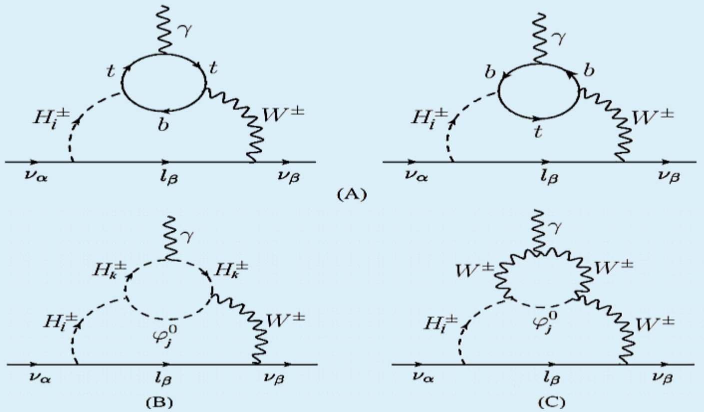
As for its contribution to m_ν*, it is well known that for* ***transversely polarized vector bosons, the transition from spin 1 to spin 0 cannot occur.*** *Only the* ***longitudianl mode, the Goldstone mode, would contribute to such transitions.***

This implies that in the two loop diagram utilizing the $\gamma W^{+} S^{-}$ *for generating* μ_ν*, if the photon line is removed, only the longitudinal* $W^{\pm}$ *bosons will contribute, leading to a suppression factor of* m_l^2/m_W^2 *in the neutrino mass.*

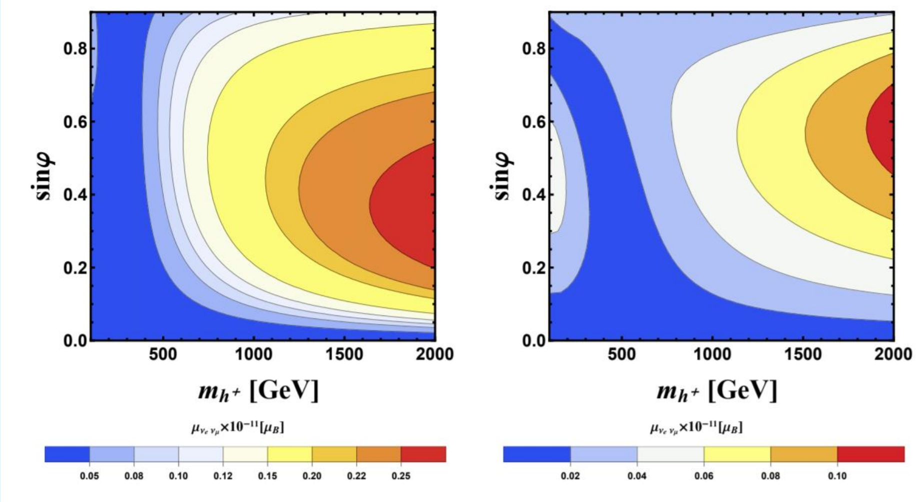
However, the contribution of two-loop graphs for the neutrino transition magnetic moments have not been quantitatively analyzed thus far.

We perform a thorough analysis and derive admissible values of the neutrino transition magnetic moment in the Zee model as well as in its BFZ extension.

Barr, Freire, and Zee (1990), Babu et al. (1992), Babu, **SJ,** Lindner (2020)

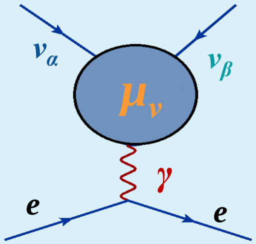


Babu, **SJ,** Lindner (2020)



In this optimized setup, one can achieve neutrino transition magnetic moment as big as $\sim 10^{-12}\,\mu_B$

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



While 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.*

In 1988, Voloshin proposed a new ***$SU(2)_\nu$ symmetry*** *that transforms ν into ν^c.*

A neutrino mass term, being symmetric under this exchange, would then be forbidden by the $SU(2)_\nu$ symmetry, while the magnetic moment operator, $\nu^T C\sigma_{\mu\nu}\nu^c F^{\mu\nu}$ is antisymmetric under the exchange.

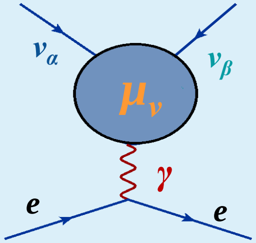
1989: ***Barbieri and R. N. Mohapatra*** *pointed out that its hard to implement the* ***Voloshin symmetry*** *since it does not commute with SM.*

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

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

Voloshin (1988)
Babu, Mohapatra (1989)
Babu, **SJ,** Lindner (2020)

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



A ***horizontal symmetry acting on the electron and the muon families*** *can serve the same purpose, which is easier to implement as such a symmetry commutes with the weak interactions.*

Our simplification is that the symmetry is only ***approximate, broken explicitly by electron and muon masses****.*

The explicit breaking of $SU(2)_H$ *by the lepton masses is* ***analogous to chiral symmetry breaking in the strong interaction sector by masses of the light quarks****.*

$SU(2)_H$ ***cannot be exact****, as it would imply* $m_e = m_\mu$*. We propose to include explicit but small breaking of* $SU(2)_H$*, so that realistic electron and muon masses can be generated.*

We have computed the one-loop corrections to the neutrino mass from these explicit breaking terms and found them to small enough so as to not upset the large magnetic moment solution.

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

$$\psi_L = \begin{pmatrix} \nu_e & \nu_\mu \\ e & \mu \end{pmatrix}_L \qquad (2, -\frac{1}{2}, 2)$$

$$\psi_R = (e \quad \mu)_R \qquad (1, -1, 2)$$

$$\psi_{3L} = \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix} \qquad (2, -\frac{1}{2}, 1)$$

$$\tau_R \qquad (1, -1, 1)$$

Higgs sector:

$$\phi_S = \begin{pmatrix} \phi_S^+ \\ \phi_S^0 \end{pmatrix} \qquad (2, \frac{1}{2}, 1)$$

$$\Phi = \begin{pmatrix} \phi_1^+ & \phi_2^+ \\ \phi_1^0 & \phi_2^0 \end{pmatrix} \qquad (2, \frac{1}{2}, 2)$$

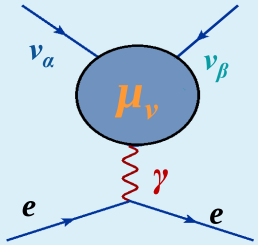
$$\eta = (\eta_1^+ \quad \eta_2^+) \qquad (1, 1, 2) \ .$$

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

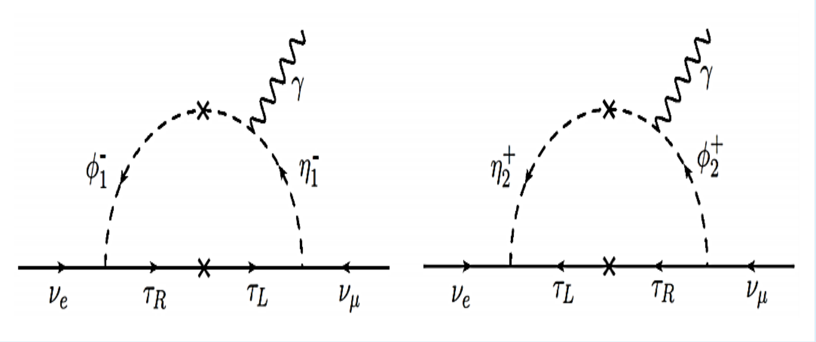
Here $SU(2)_H$ acts horizontally, while $SU(2)_L$ acts vertically.

Babu, **SJ,** Lindner (2020)

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



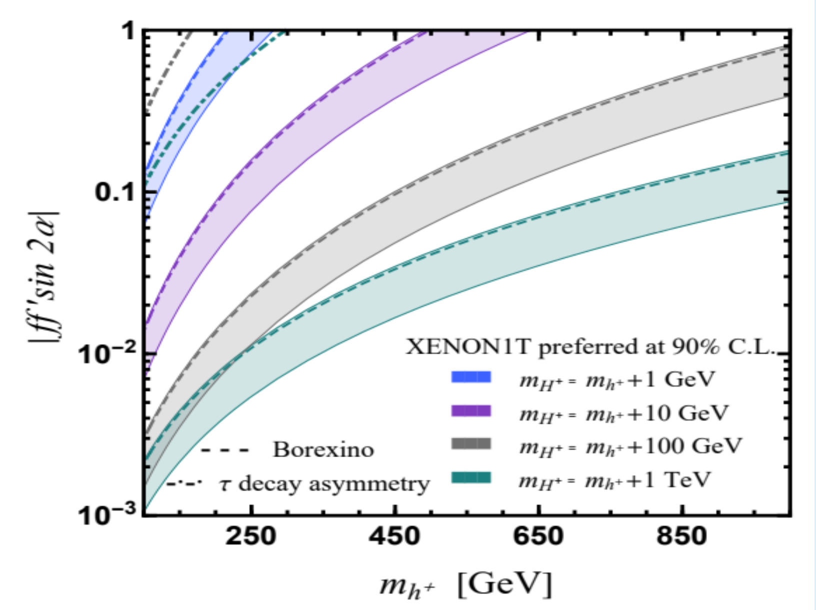
- *The Lagrangian of the model* ***does not respect lepton number****. The $SU(2)_H$ limit of the model however respects $L_e - L_\mu$ symmetry. This allows a nonzero transition magnetic moment, while neutrino mass terms are forbidden.*



- *Feynman diagrams generating neutrino transition magnetic moment in the $SU(2)_H$ model. There are additional diagrams where the photon is emitted from the τ lepton line. The same diagrams with the photon line removed would contribute to Majorana mass of the neutrino.*

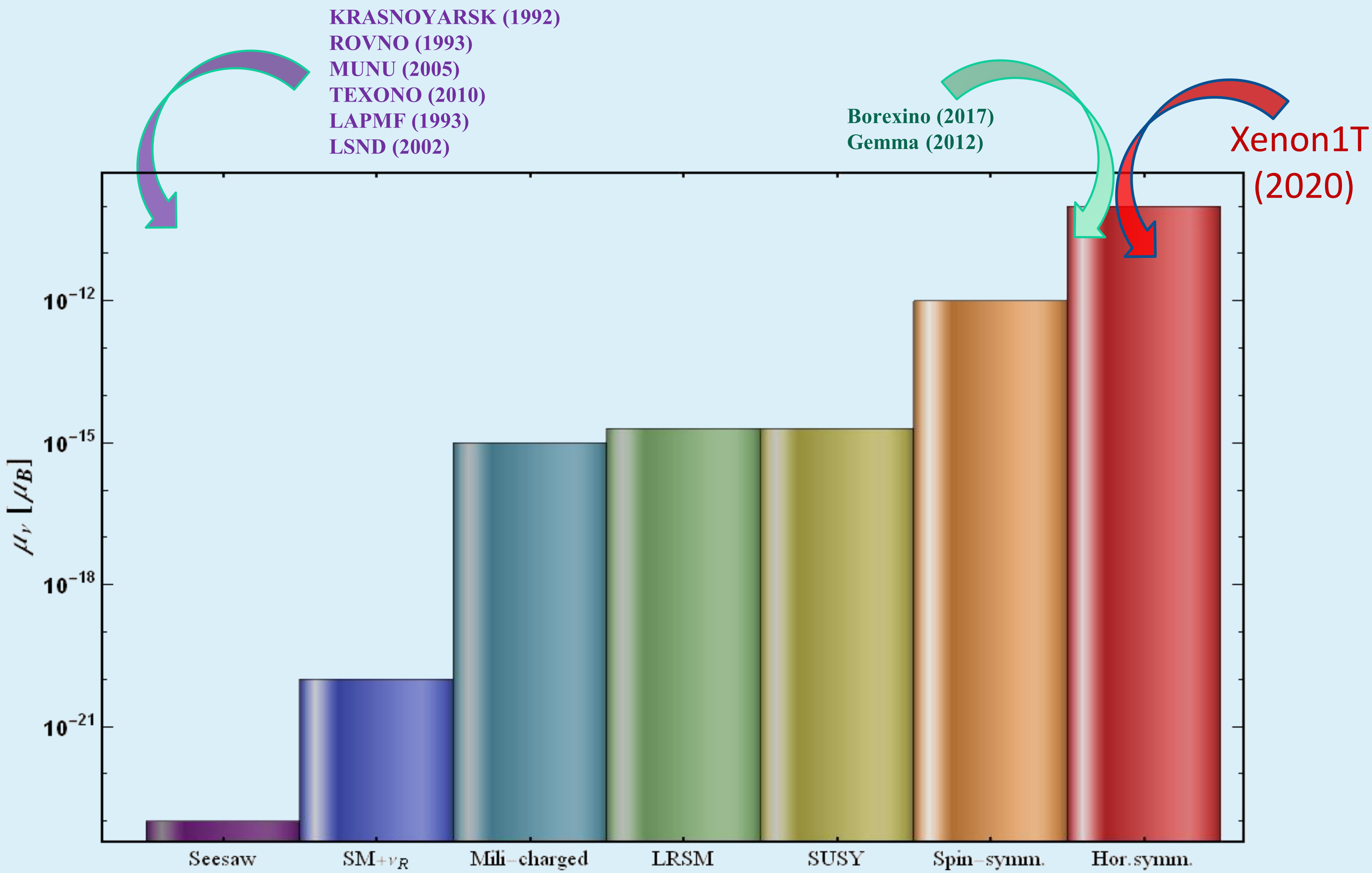
- *In the* ***$SU(2)_H$ symmetric limit, the two diagrams add for $\mu_{\nu e \nu \mu}$****, while they* ***cancel for m_ν****.*

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



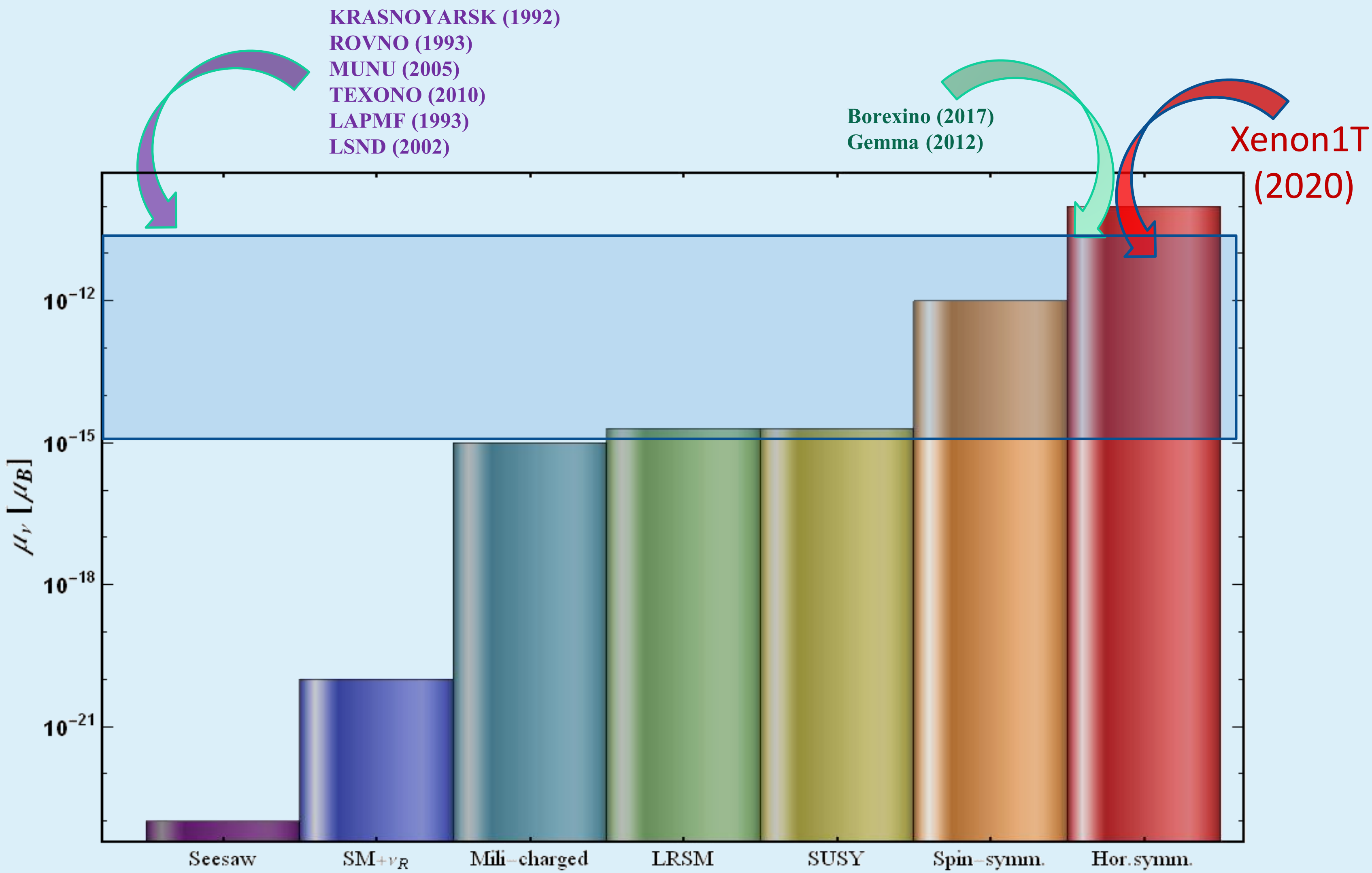
Babu, **SJ**, Lindner (2020)

Neutrino Magnetic Moment



Babu, **SJ**, Lindner (2020)

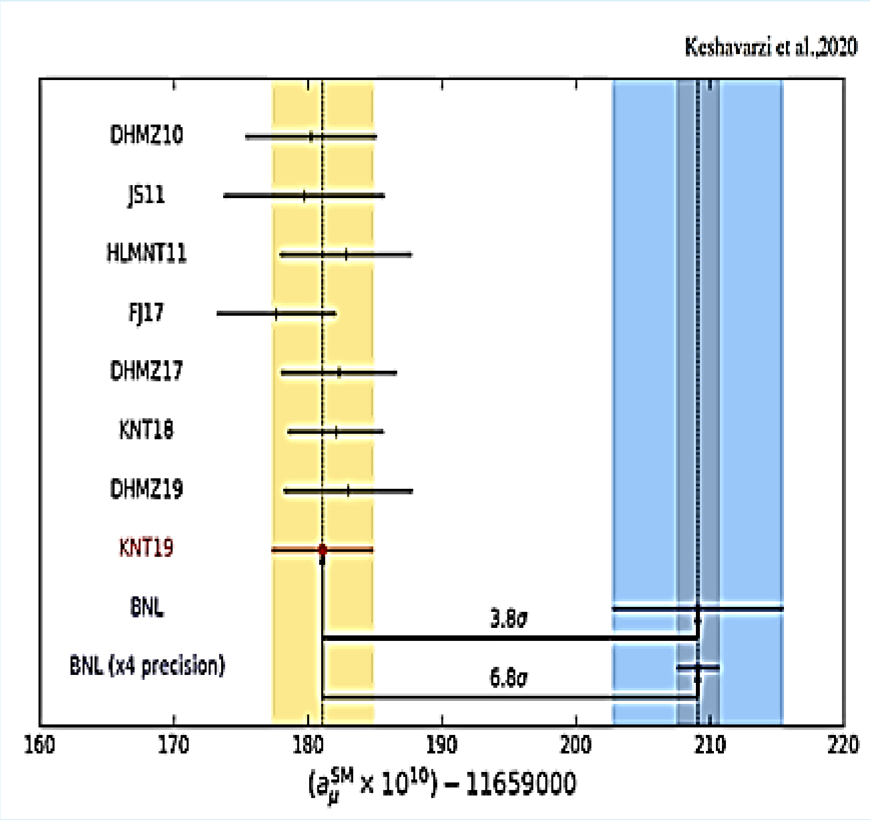
Neutrino Magnetic Moment



Babu, SJ, Lindner (2020)

Muon g-2: experimental status

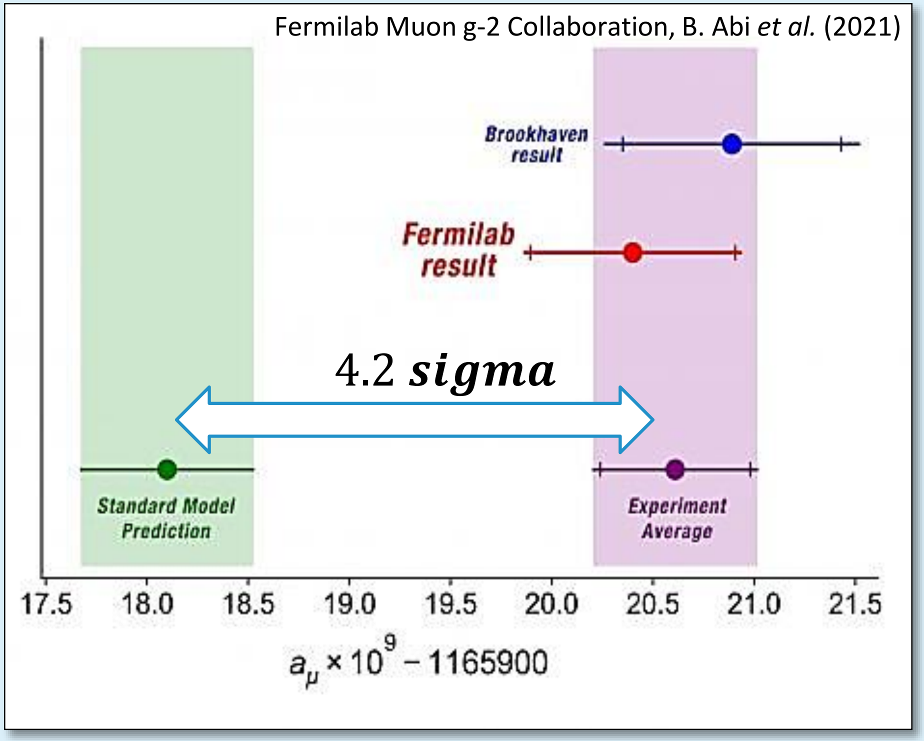
Before Fermilab muon g-2 announcement:



$$10^{11} a_\mu = \begin{cases} 116591810(43) & \text{SM} \\ 116592089(63) & \text{exp} \end{cases} \Rightarrow \Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 279(76) \times 10^{-11} \quad 3.7\sigma$$

T. Aoyama *et al*. (2000), G. Bennett *et al*. (2006)

After Fermilab muon g-2 announcement:

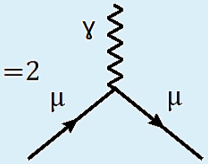


$$10^{11} a_\mu = \begin{cases} 116591810(43) & \textbf{SM} \\ 116592040(54) & \textbf{Exp} \end{cases}$$

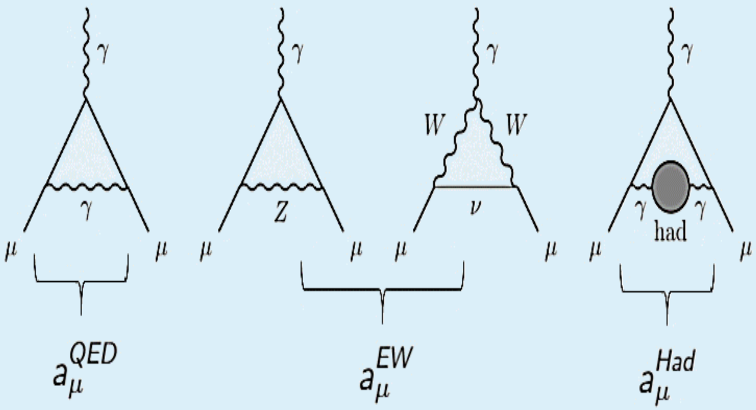
$$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 251(59) \times 10^{-11}$$

Muon and Neutrino Magnetic Moments in the SM

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



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

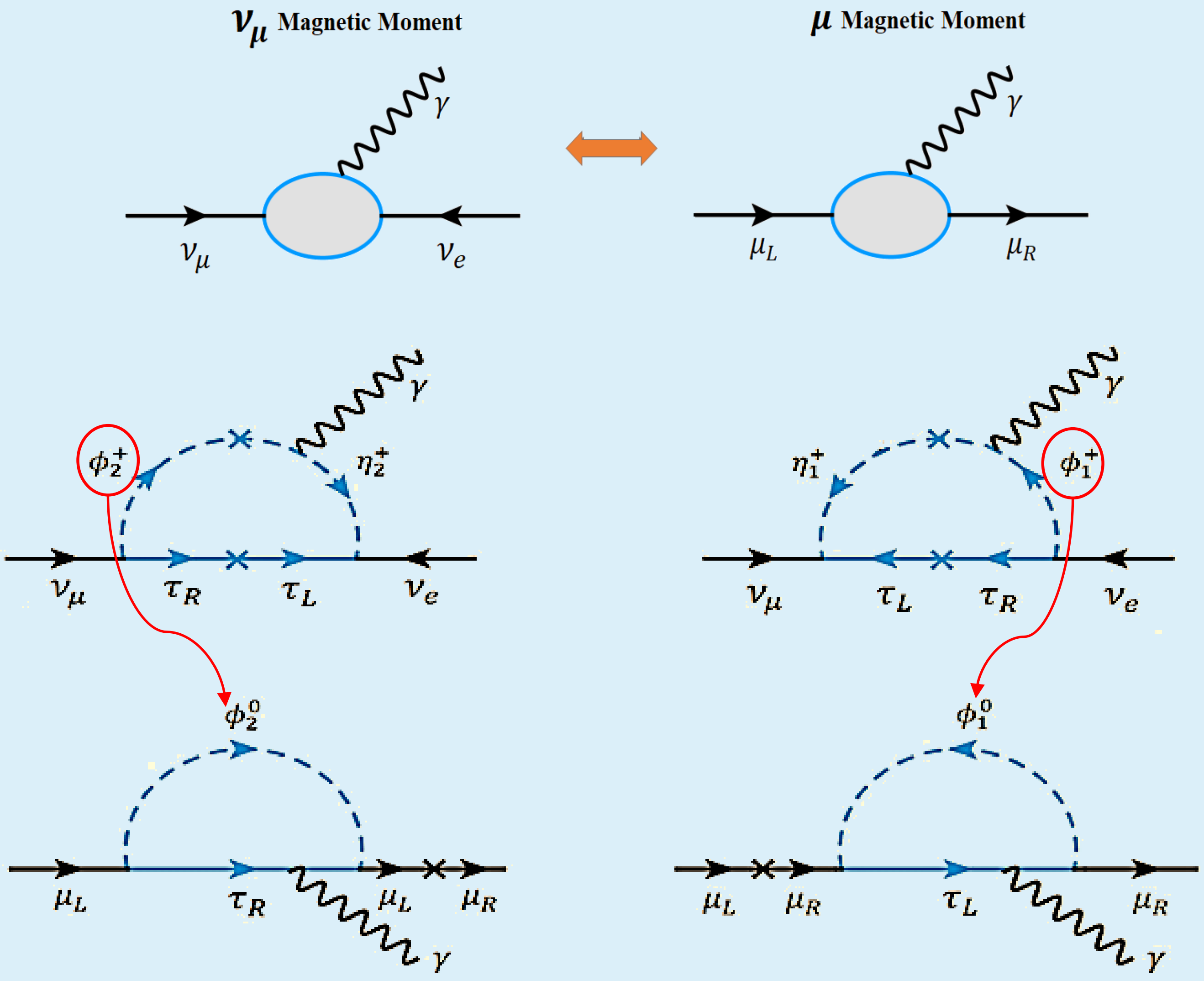


$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{Had}$$

Contribution	**Value (x10^{-11})**
QED	116,584,718.931±.104
Weak force	153.6±1.0
Hadronic vacuum polarization (dispersive)	6,845±40
NOT USED (Lattice hadronic vacuum polarization)	7116±184
Hadronic light-by-light (dispersive+lattice)	92±18
Total Standard Model Value	**116,591,810±43**
Difference from 2001 experiment	**279±76**

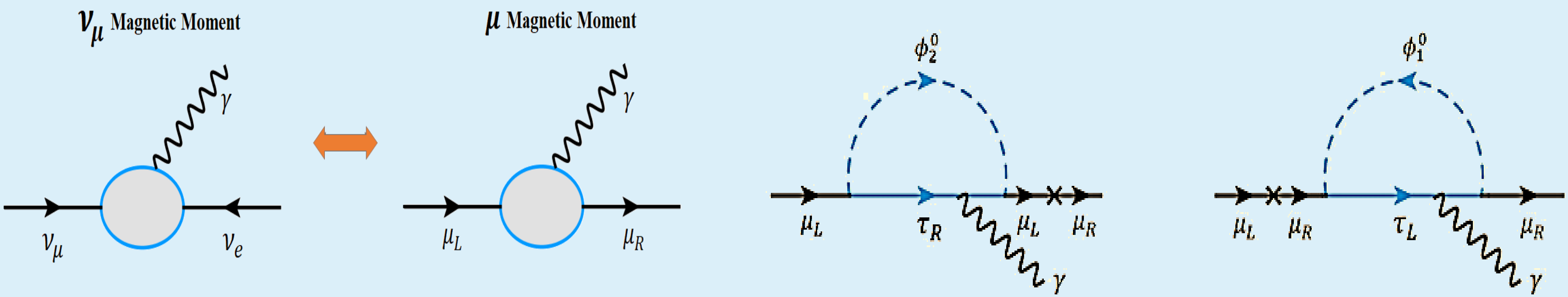
No neutrino magnetic moments in the SM!

Neutrino magnetic moment – Muon g-2 Anomaly



Babu, **SJ,** Lindner, Kovilakam (2021)

Neutrino magnetic moment – Muon g-2 Anomaly



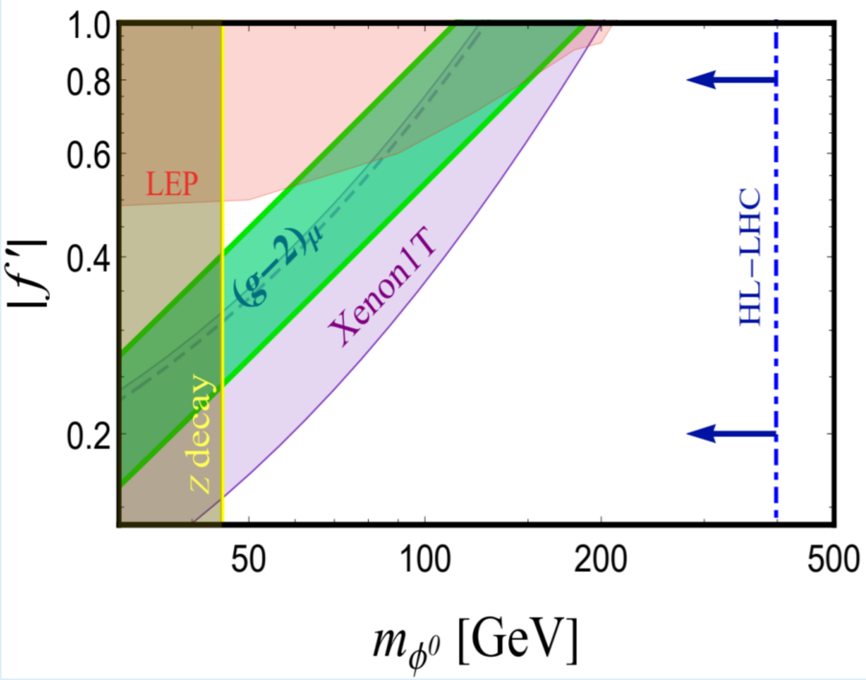
A direct correlation between the neutrino magnetic moment and muon g-2

LFV coupling without Lepton flavor violation

Outside chirality flipping

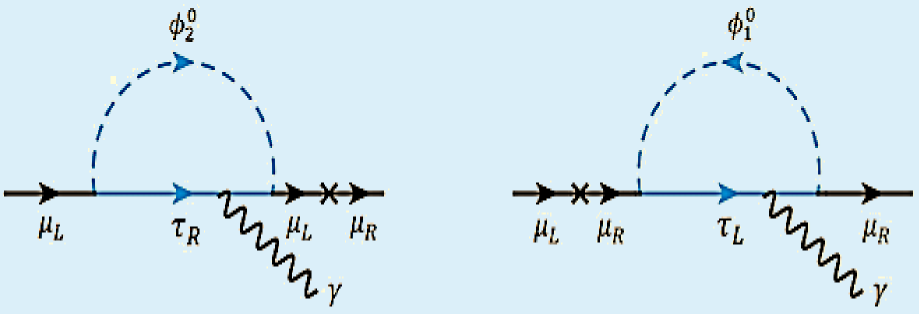
Sign and strength are automatic here, no control over it.

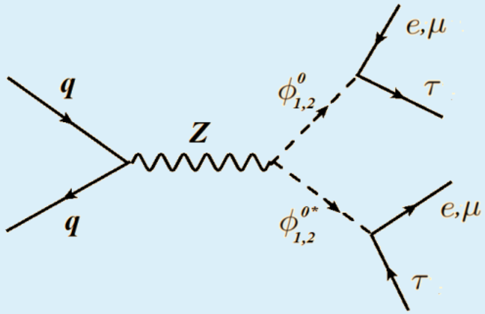
A minimal unified framework for three different components:
μ_ν , m_ν , *muon g-2*



Babu, **SJ,** Lindner, Kovilakam (2021)

Neutrino magnetic moment – Muon g-2 Anomaly





Testable at the upcoming run of LHC

A direct correlation between the neutrino magnetic moment and muon g-2

LFV coupling without Lepton flavor violation

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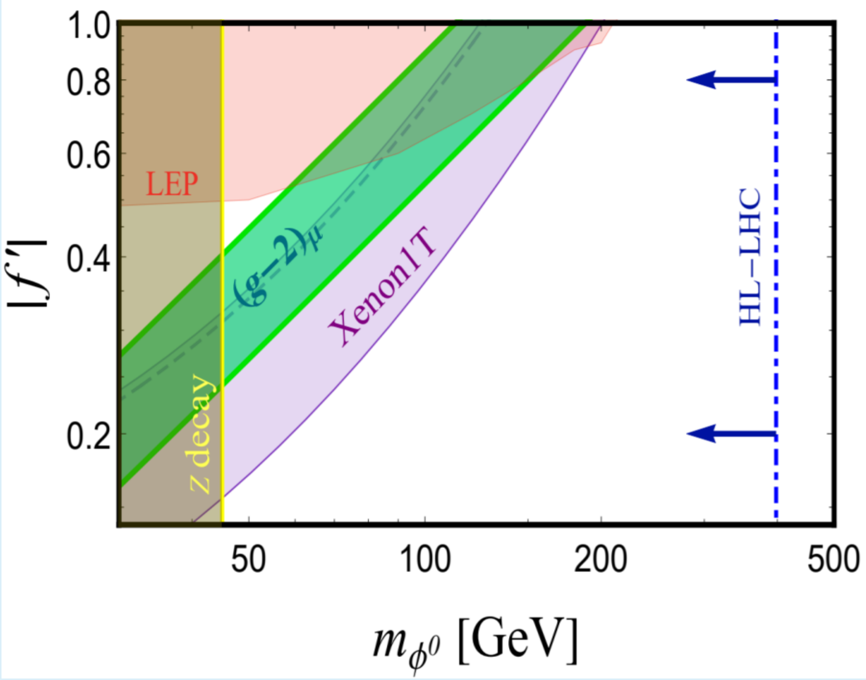
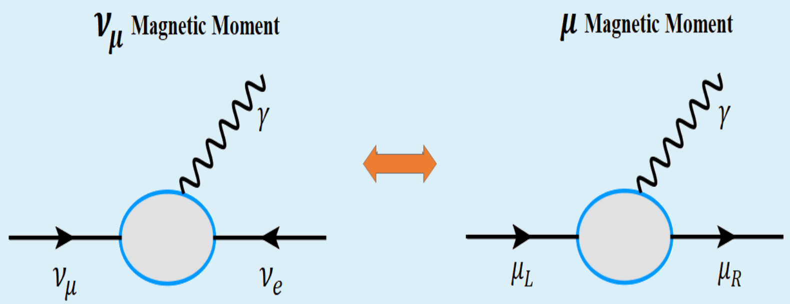
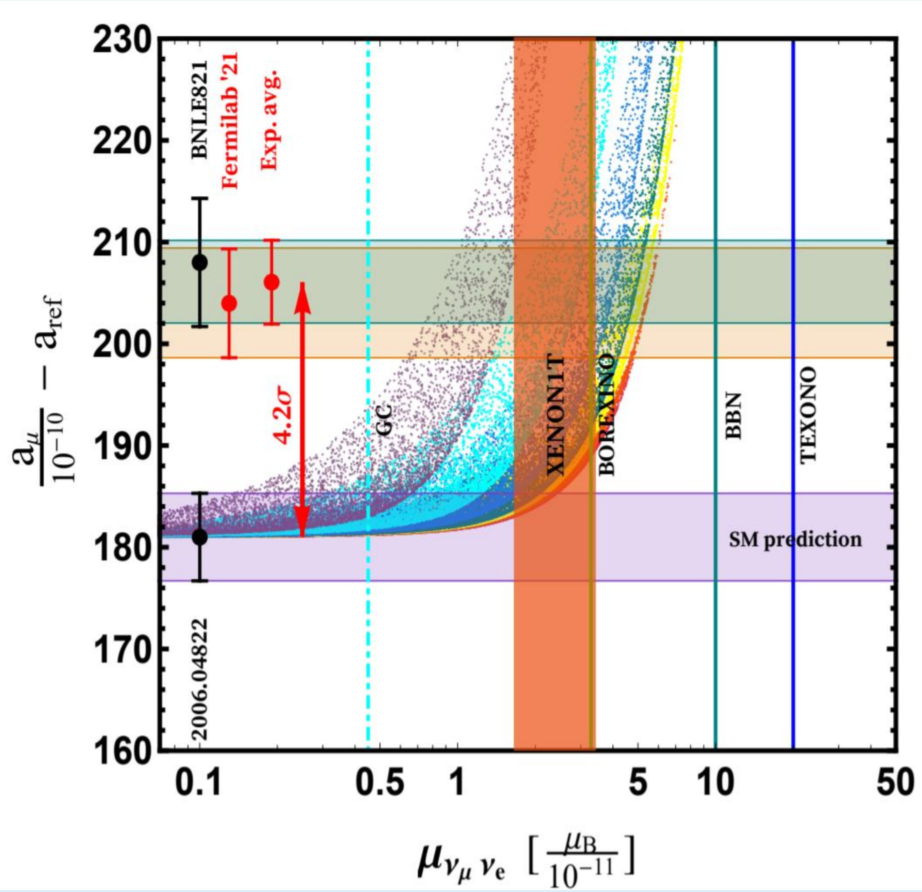


Babu, **SJ,** Lindner, Kovilakam (2021)

Neutrino magnetic moment – Muon g-2 Anomaly





A direct correlation between the neutrino magnetic moment and muon g-2

LFV coupling without Lepton flavor violation

Outside chirality flipping

Sign and strength are automatic here, no control over it.

A minimal unified framework for three different components:
Large μ_ν, m_ν , *muon g-2*

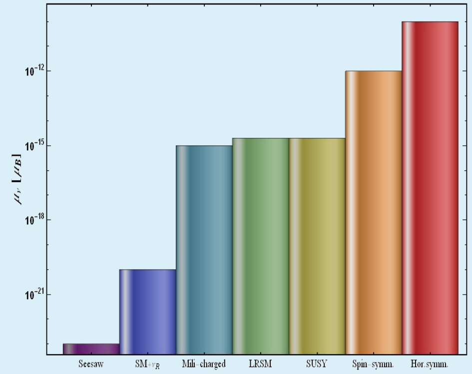
Babu, **SJ,** Lindner, Kovilakam (2021)

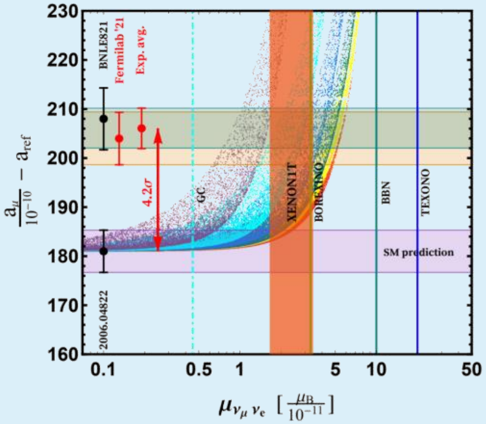
Summary

A minimal unified framework for
Large μ_ν, m_ν, ***muon g-2***

Neutrino trapping mechanism to evade astrophysical limit

Direct correlation between μ_ν **and** ***muon g-2***





Thus, the theoretical and experimental investigation of neutrino electromagnetic interactions can serve as a powerful tool in the search for the fundamental theory behind the neutrino mass generation mechanism.


thank you!