

Correlating muon $g-2$ with neutrino magnetic moments

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In collaboration with **K.S. Babu, Manfred Lindner and Vishnu P.K.**

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

arXiv: 2104.03291 [hep-ph], JHEP 10 (2021) 240



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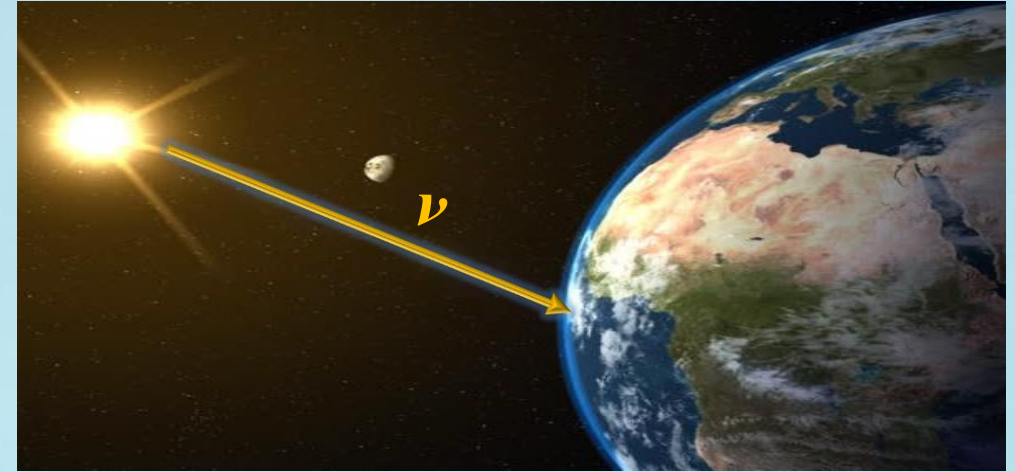
FLASY 2022
Lisbon, Portugal
June, 2022



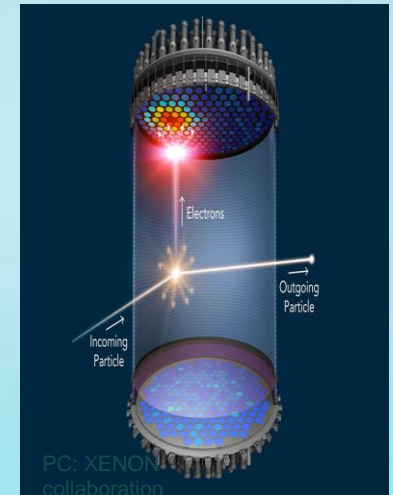
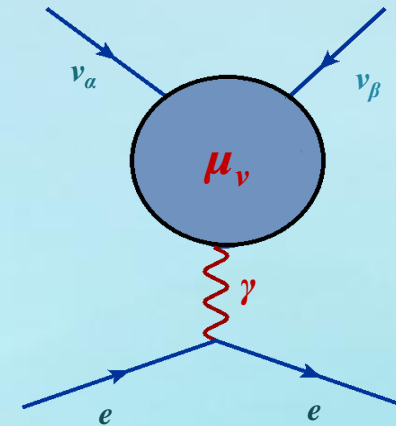
MAX-PLANCK-GESELLSCHAFT

Charged lepton magnetic moments

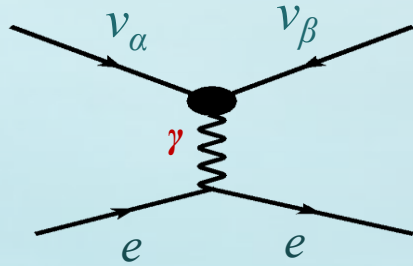
Neutrino magnetic moments



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

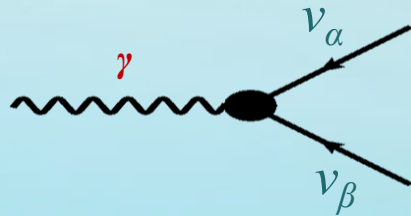


Consequences of neutrino magnetic moments



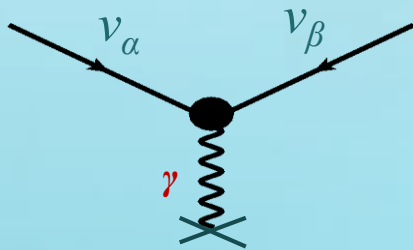
Scattering

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



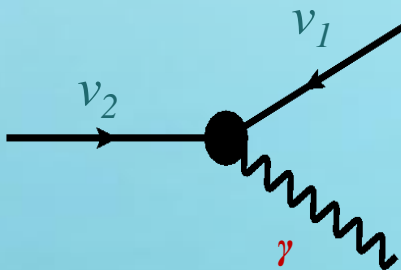
Plasmon decays
in stars

$$\Gamma = \frac{\mu_\nu^2}{24\pi} \omega_{\text{pl}}^3$$



Spin precession in
external B field

$$i\frac{d}{dr} \begin{pmatrix} \nu \\ \bar{\nu} \end{pmatrix} = \begin{pmatrix} 0 & B_\perp M \\ -B_\perp M & 0 \end{pmatrix} \begin{pmatrix} \nu \\ \bar{\nu} \end{pmatrix}$$



Decay or Cherenkov
effect

$$\Gamma = \frac{\mu_\nu^2}{8\pi} \left(\frac{m_2^2 - m_1^2}{m_2}\right)^3$$

Neutrino magnetic moments: experimental status

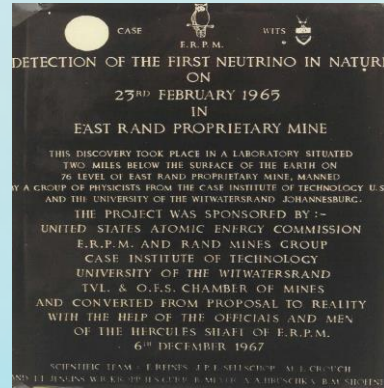
- The quest for measuring neutrino magnetic moments was begun even before the discovery of the neutrino.



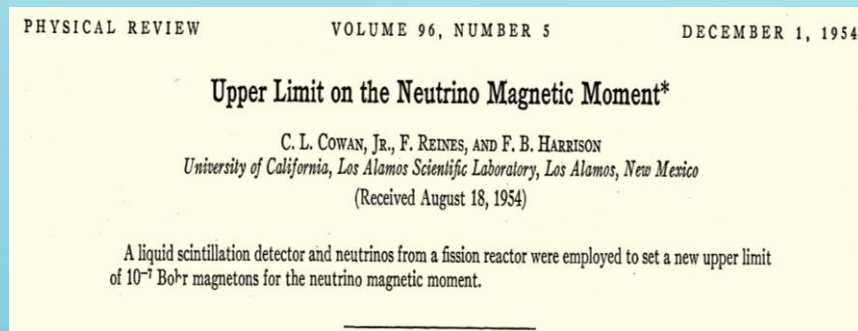
Frederick Reines

1995 Nobel Prize in Physics

for his co-detection of the neutrino with Clyde Cowan in the neutrino experiment.



- **Cowan, Reines and Harrison** set an upper limit in the process of measuring background for a free neutrino search experiment with reactor antineutrinos.



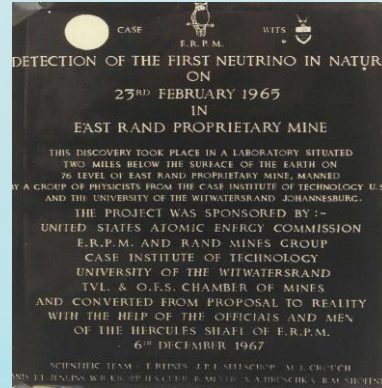
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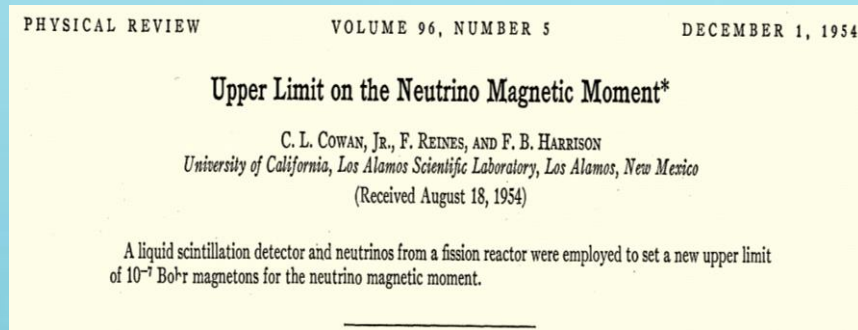


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Reactor

- 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): $\mu_\nu < 2.9 \times 10^{-11} \mu_B$
- CONUS (2022): $\mu_\nu < 7.0 \times 10^{-11} \mu_B$

Accelerator

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

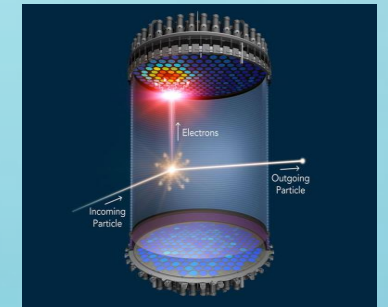
Solar

- 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

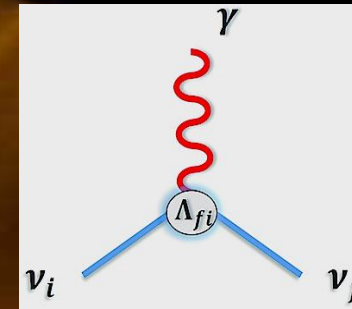
285 events observed
vs.
232 (+/- 15) events expected (from best-fit)

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: from astrophysics and cosmology



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.*

The best limit on μ_ν arises from red giant branch of globular clusters: $\mu_\nu < 1.5 \times 10^{-12} \mu_B$ Raffelt et al.(2013, 2021)

Cosmological limits arising from big bang nucleosynthesis are less severe, of order $10^{-10} \mu_B$. Fuller et al. (2015)

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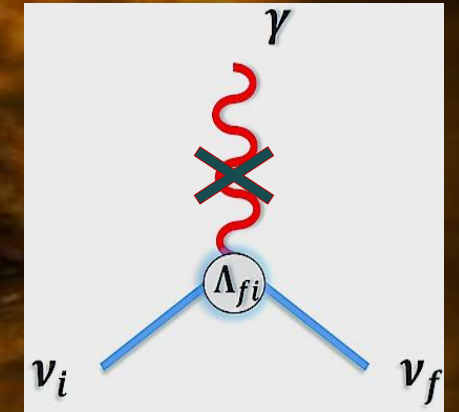
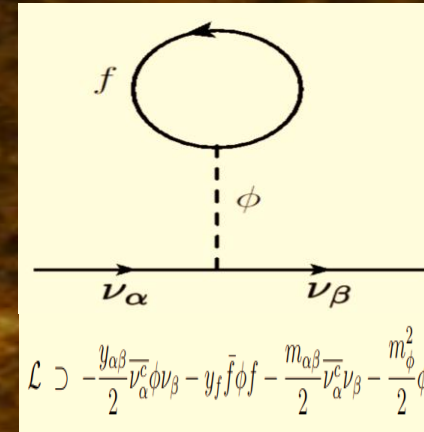
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Neutrino Trapping Mechanism

- Constraints from astrophysics may be evaded if the plasmon decay to neutrinos is kinematically forbidden.



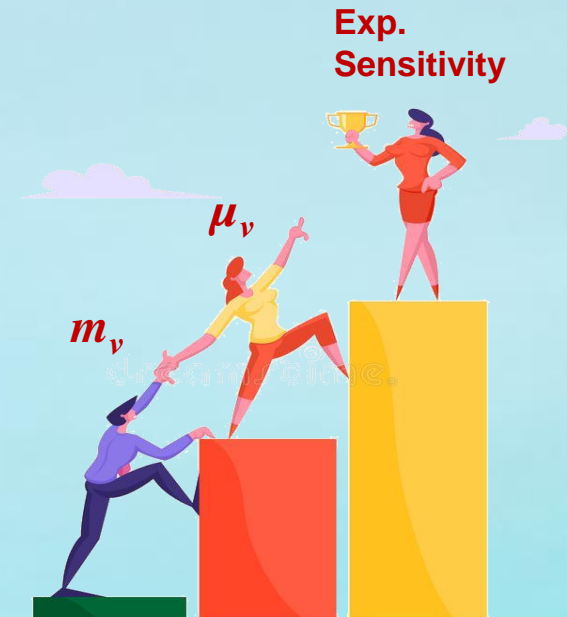
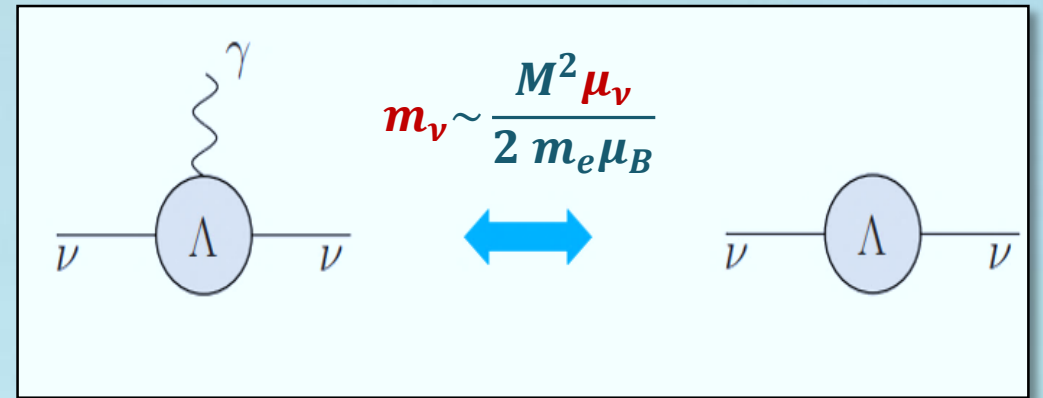
Babu, SJ, Lindner (2020)

- Medium-dependent mass of the neutrino in the presence of a light scalar that also couples to ordinary matter in illustrating the mechanism.
- For phenomenological implications, see Parke et al. (2018), Smirnov et al. (2019), Babu et al. (2019)

Neutrino magnetic moment – mass conundrum

- The magnetic moment and the mass operators are both *chirality flipping*.
- By *removing the photon line* from the loop diagram that induces μ_ν , one would generate a *neutrino mass* term.
- In *absence of additional symmetries* (and *without severe fine-tuning*), neutrino masses are several orders of magnitude larger than their measured values, if $\mu_\nu \sim 10^{-11} \mu_B$.

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



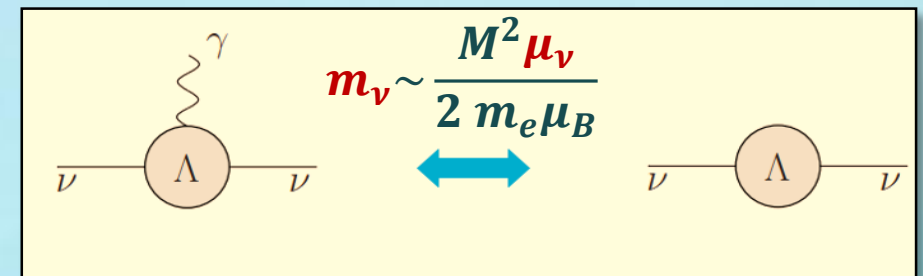
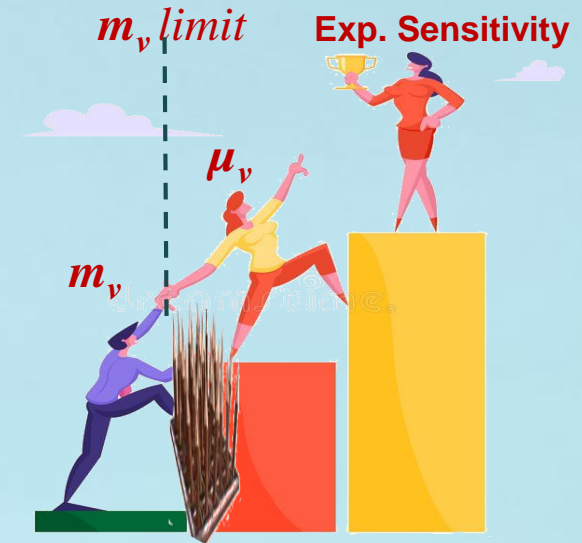
Neutrino magnetic moment – mass conundrum

*This 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.***

*NMM 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.

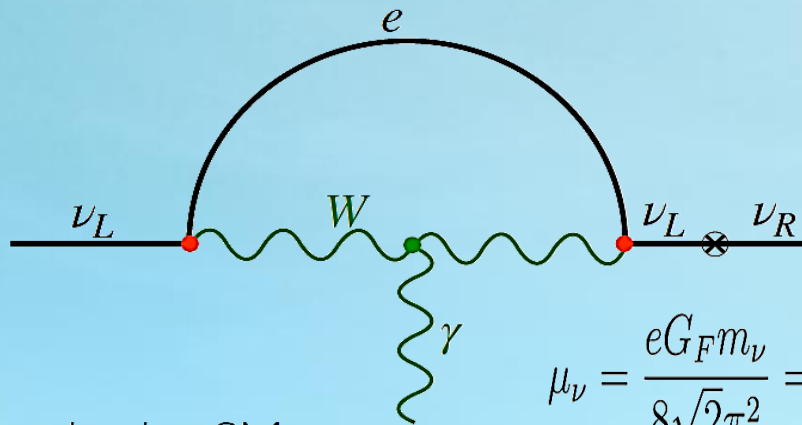


Neutrino magnetic moments in beyond the Standard Model

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:

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



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

In the SM

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

K. Fujikawa and R. Shrock (1980)

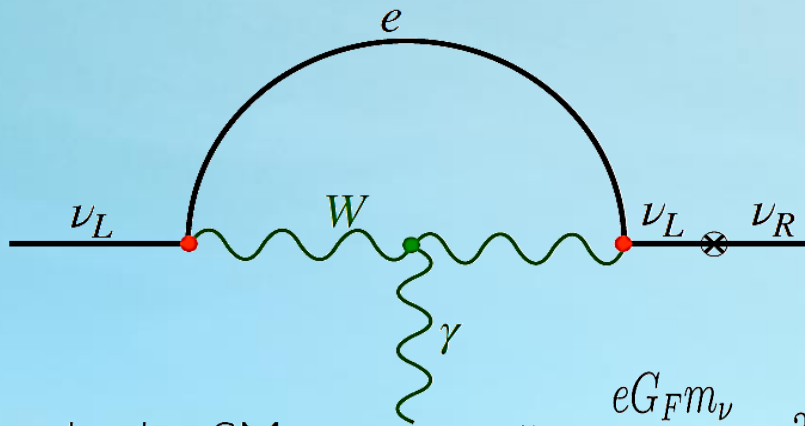
Bell et al. (2005)

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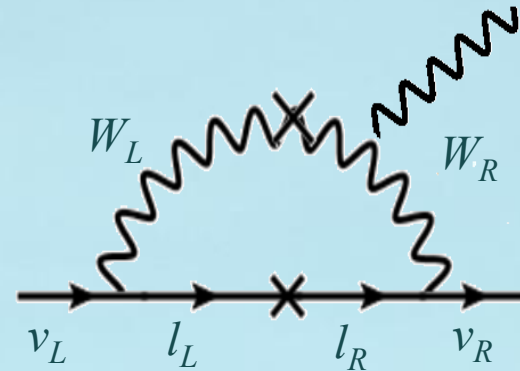
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Bell et al. (2005)

Left-Right Symmetric Model

Right-handed neutrino couples to a W_R gauge boson, which also has mixing with the W boson.



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

Czakon, Gluza, Zralek (1999)
Giunti and A. Studenikin (2014)

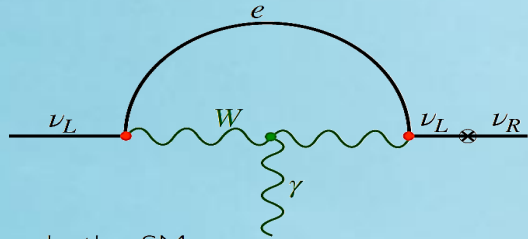
This mixing angle is constrained by **muon decay asymmetry parameters**, $b \rightarrow s\gamma$ decay rate, indirect LHC limits leading to a limit $\mu_\nu < 10^{-15} \mu_B$

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:

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



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In the SM

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

Supersymmetric theory

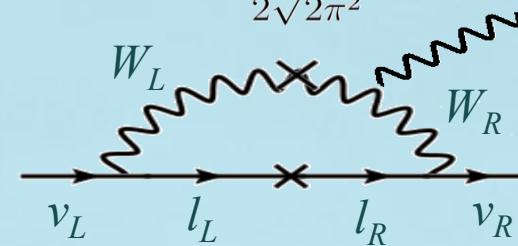
In **supersymmetric extensions** of the SM, lepton number may be violated by R-parity breaking interactions. In such contexts, without relying on additional symmetries, NMM will be (imposing experimental constraints on the SUSY parameters) of the order at most about $10^{-15} \mu_B$.

$$\mu_\nu \sim \lambda'^2 / (16\pi^2) m_\ell^2 A_\ell / M_\ell^4$$

Left-Right Symmetric Model

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

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



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

Czakon, Gluza, Zralek (1999)
Giunti and A. Studenikin (2014)

Majorana scenario

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

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

At most of order $\mu_\nu \sim 10^{-23} \mu_B$

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

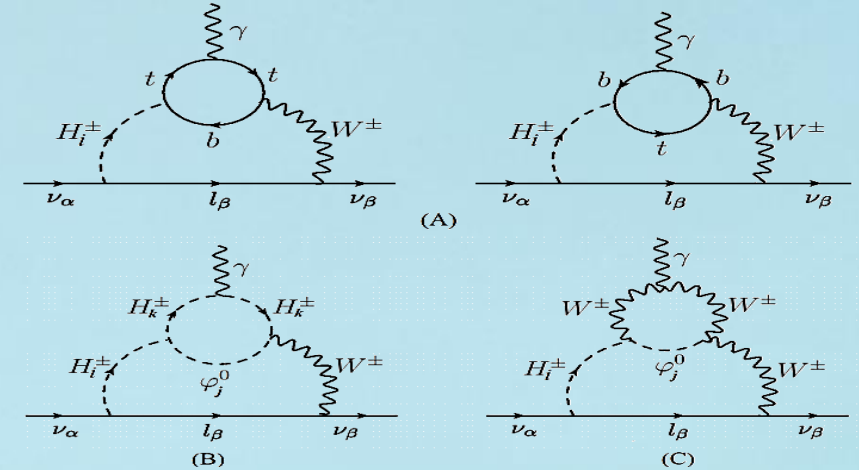
For a review, see Giunti and A. Studenikin (2014)

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

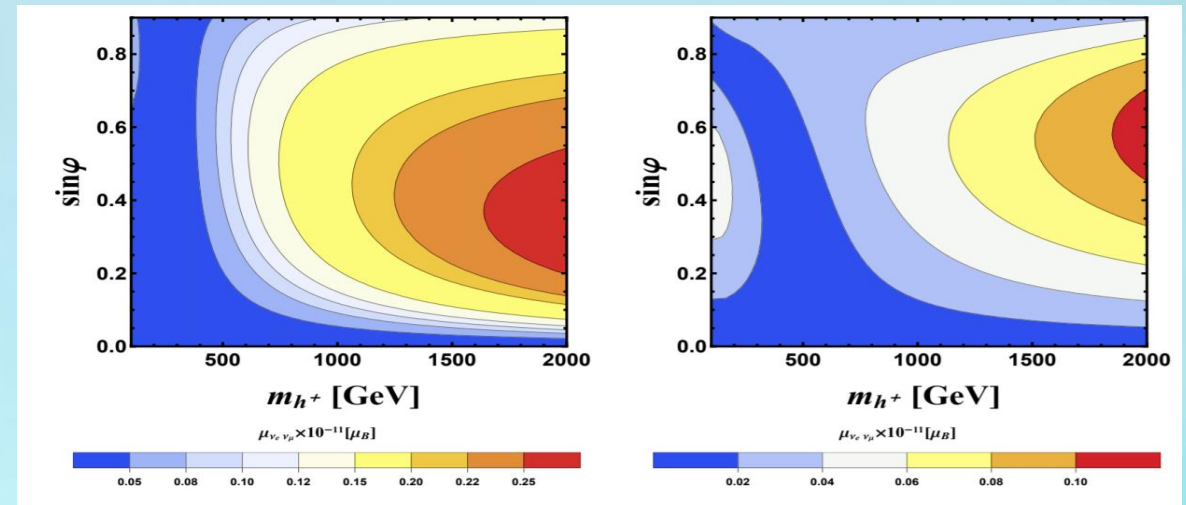
Neutrino magnetic moment – mass conundrum

A. Spin Symmetry Mechanism

- In renormalizable gauge theories there are **no direct couplings** of the type $\gamma W^+ S^-$.
- As for its contribution to m_ν , for transversely polarized vector bosons, the transition from **spin 1 to spin 0 cannot occur**. Only the longitudinal 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.



Babu, SJ, Lindner (2020)



Barr, Freire, and Zee (1990), Babu et al. (1992), 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.

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

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

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, 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 $m_e = m_\mu$. Explicit but small breaking of $SU(2)_H$, so that realistic electron and muon masses can be generated.

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

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

Higgs sector:

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

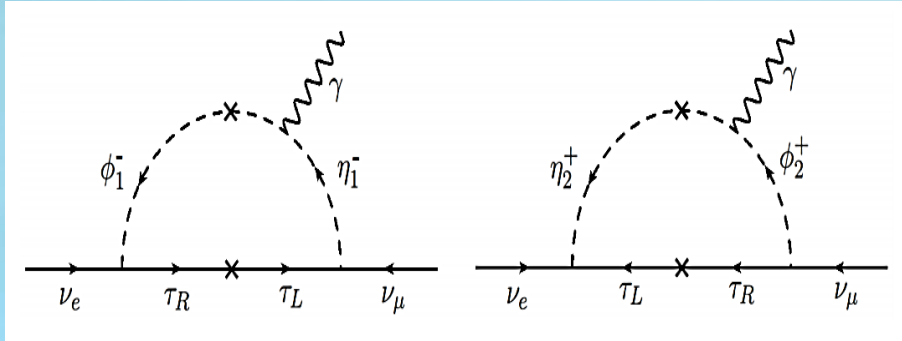
Babu, **SJ**, Lindner (2020)

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

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

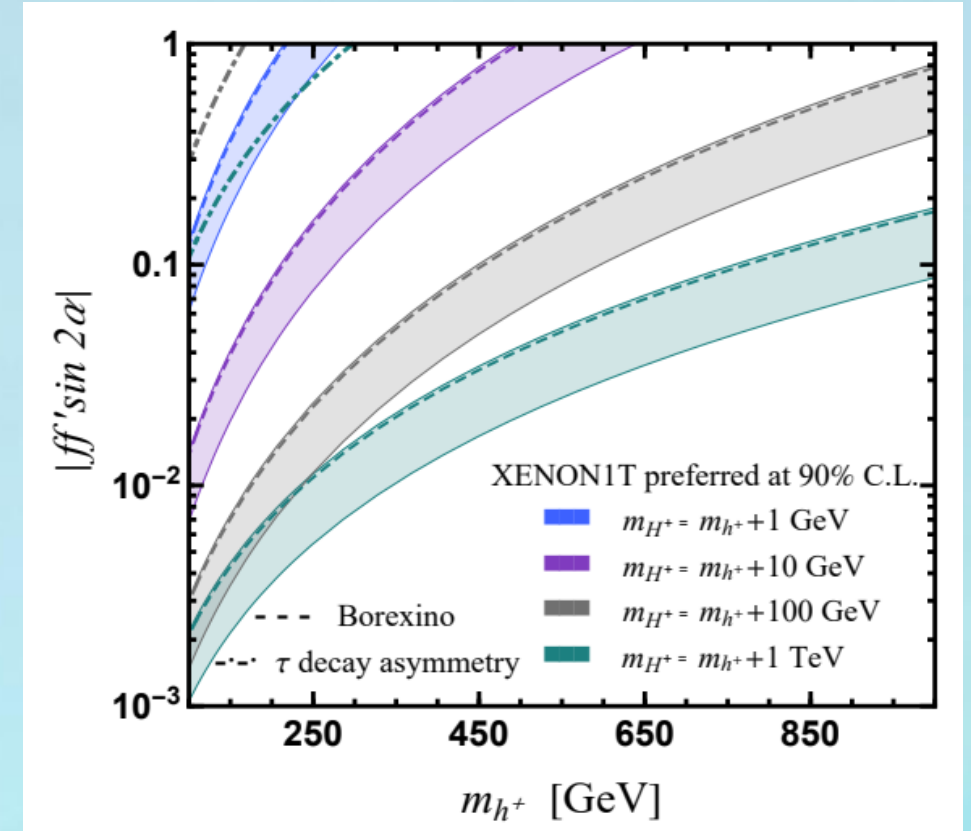
B. $SU(2)_H$ Symmetry for Enhanced Neutrino Magnetic Moment

- ❖ 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.



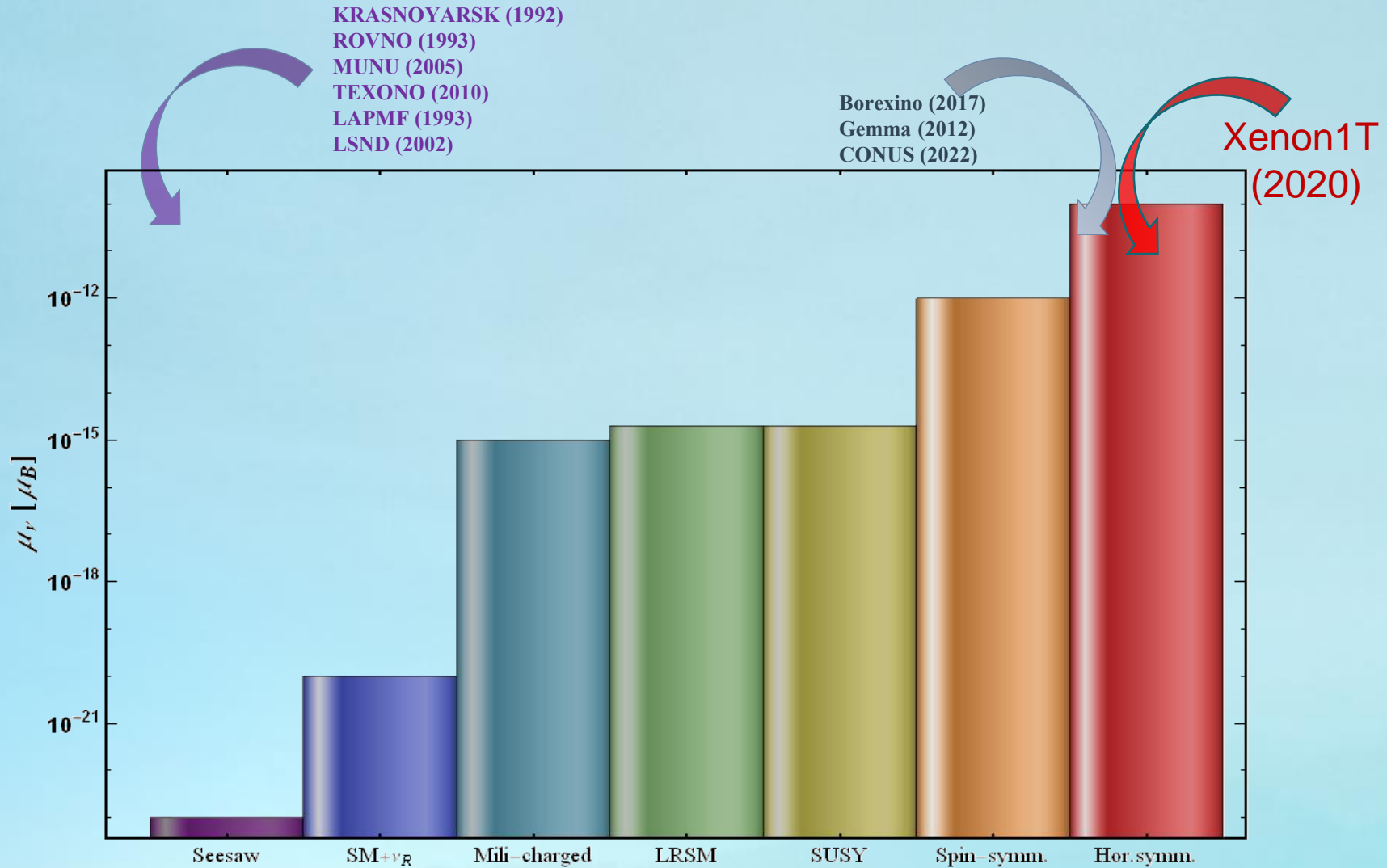
- ❖ In the $SU(2)_H$ symmetric limit, the two diagrams add for $\mu_{\nu_e\nu_\mu}$ while they **cancel** for m_ν .

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



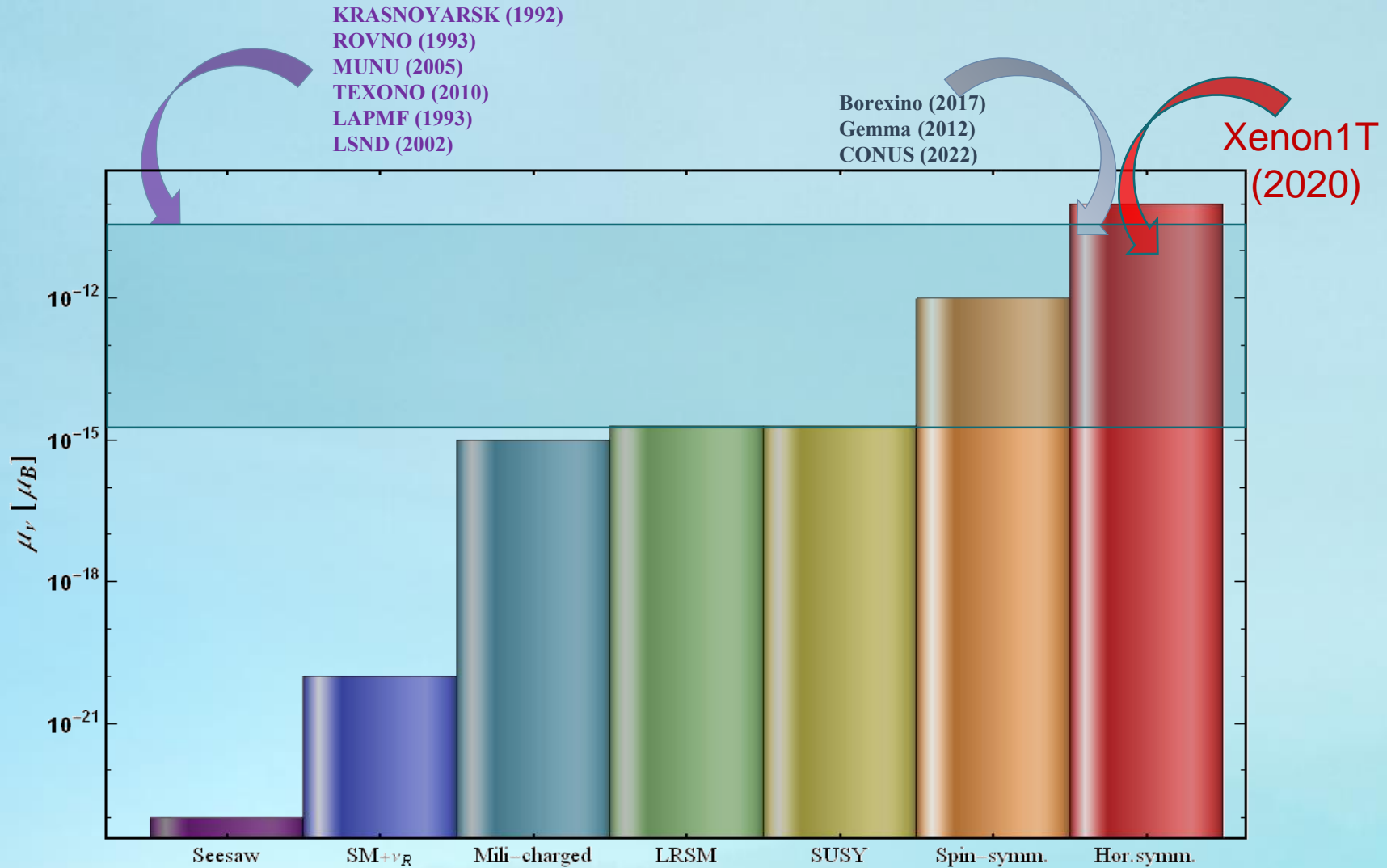
Babu, SJ, Lindner (2020)

Neutrino magnetic moments: a global picture



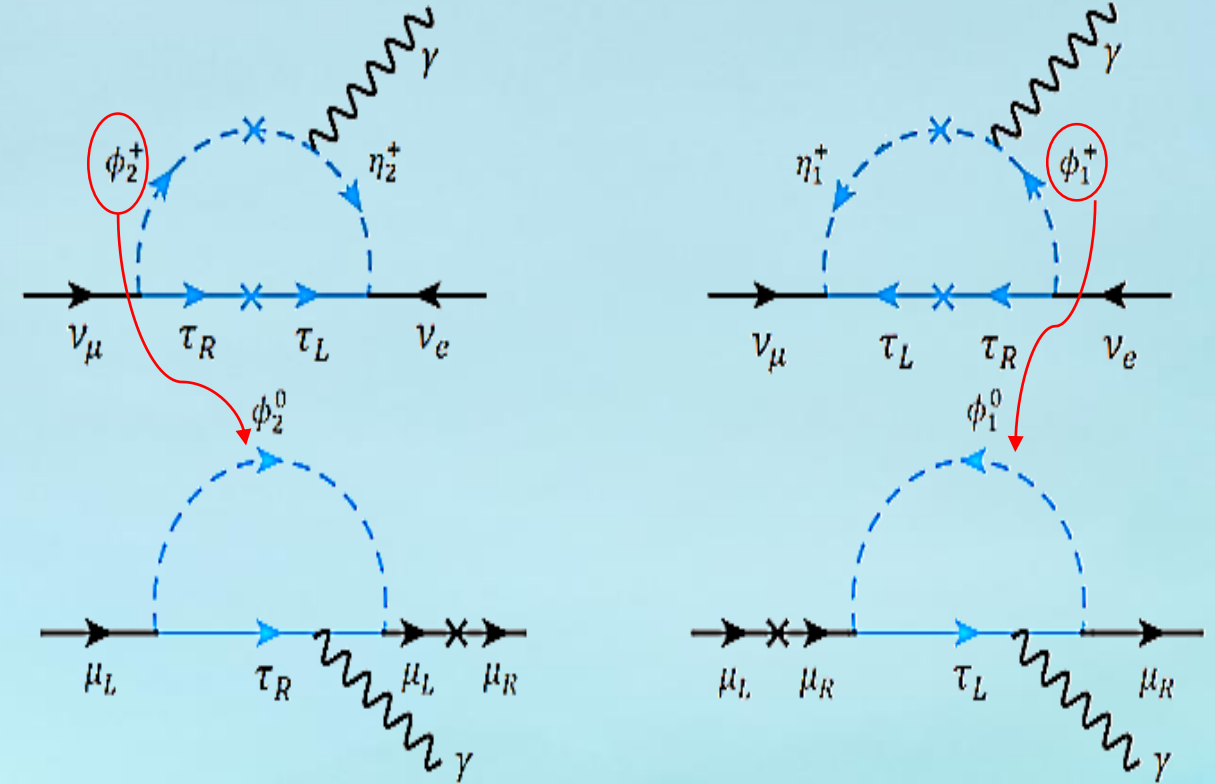
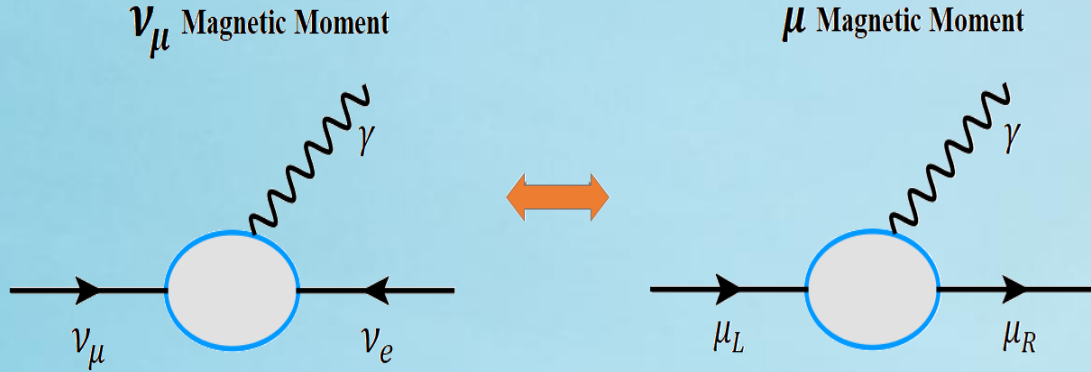
SJ, PoS(DISCRETE2020-2021)037

Neutrino magnetic moments: a global picture



SJ, PoS(DISCRETE2020-2021)037

Neutrino magnetic moments – charged lepton $g-2$ correlation

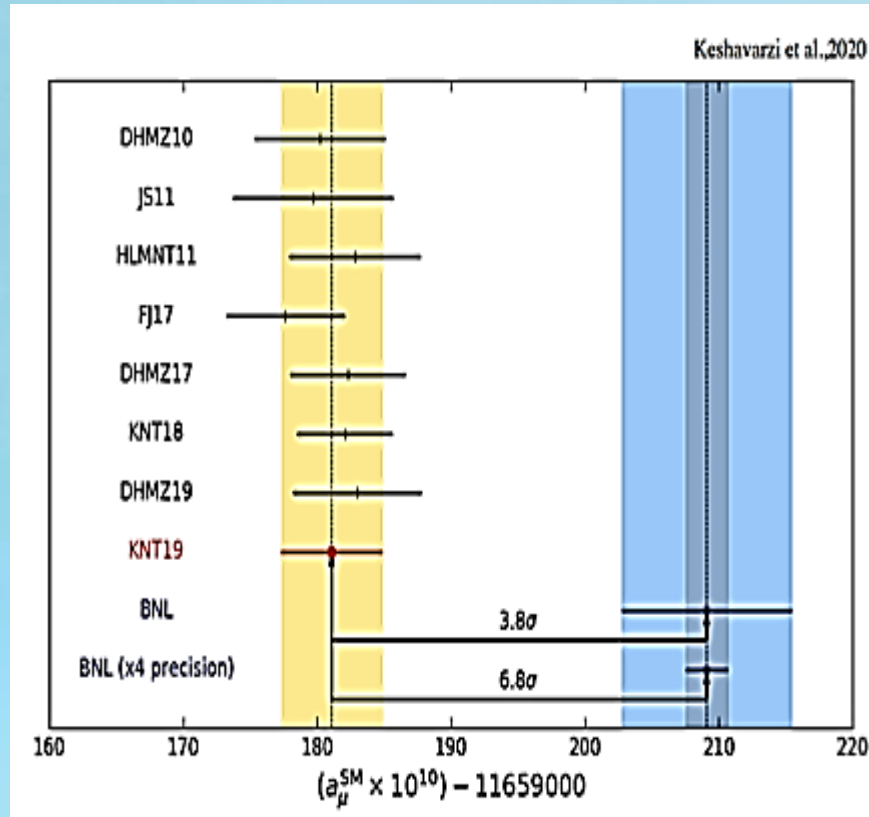


The models that induce neutrino magnetic moments while maintaining their small masses naturally also predict observable shifts in the charged lepton anomalous magnetic moment.

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

Muon $g-2$ anomaly: experimental status

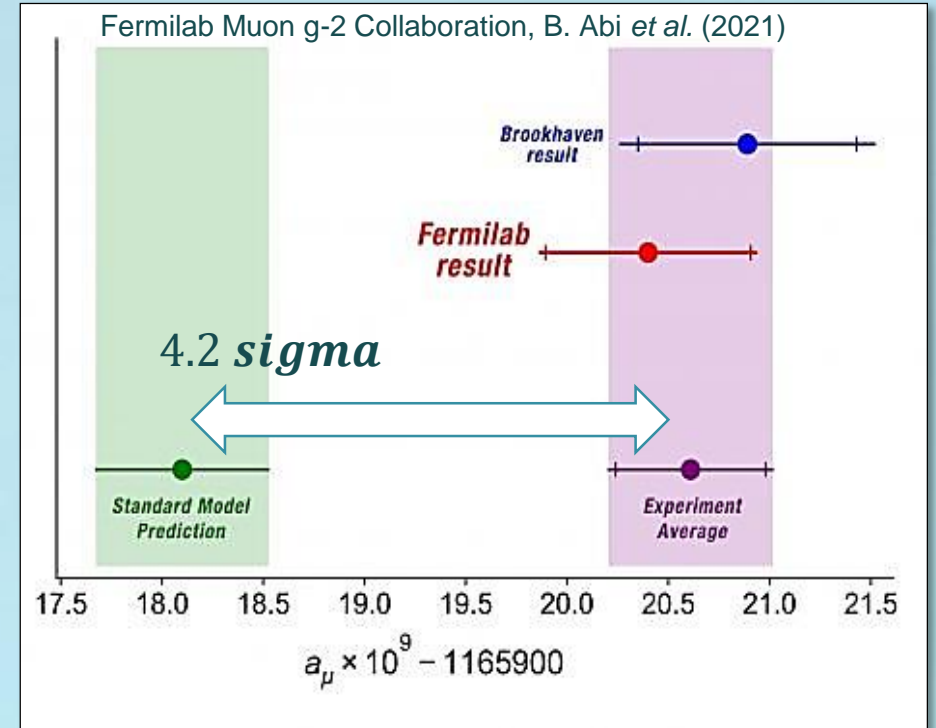
Before Fermilab muon $g-2$ announcement:



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

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

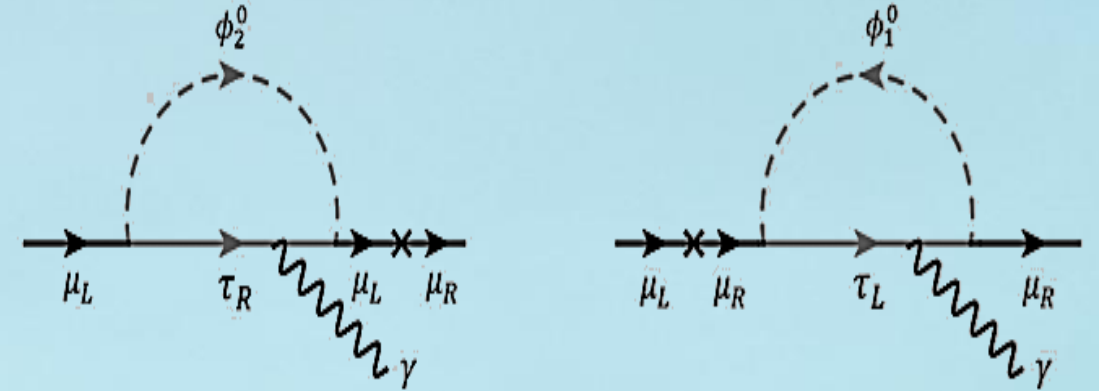
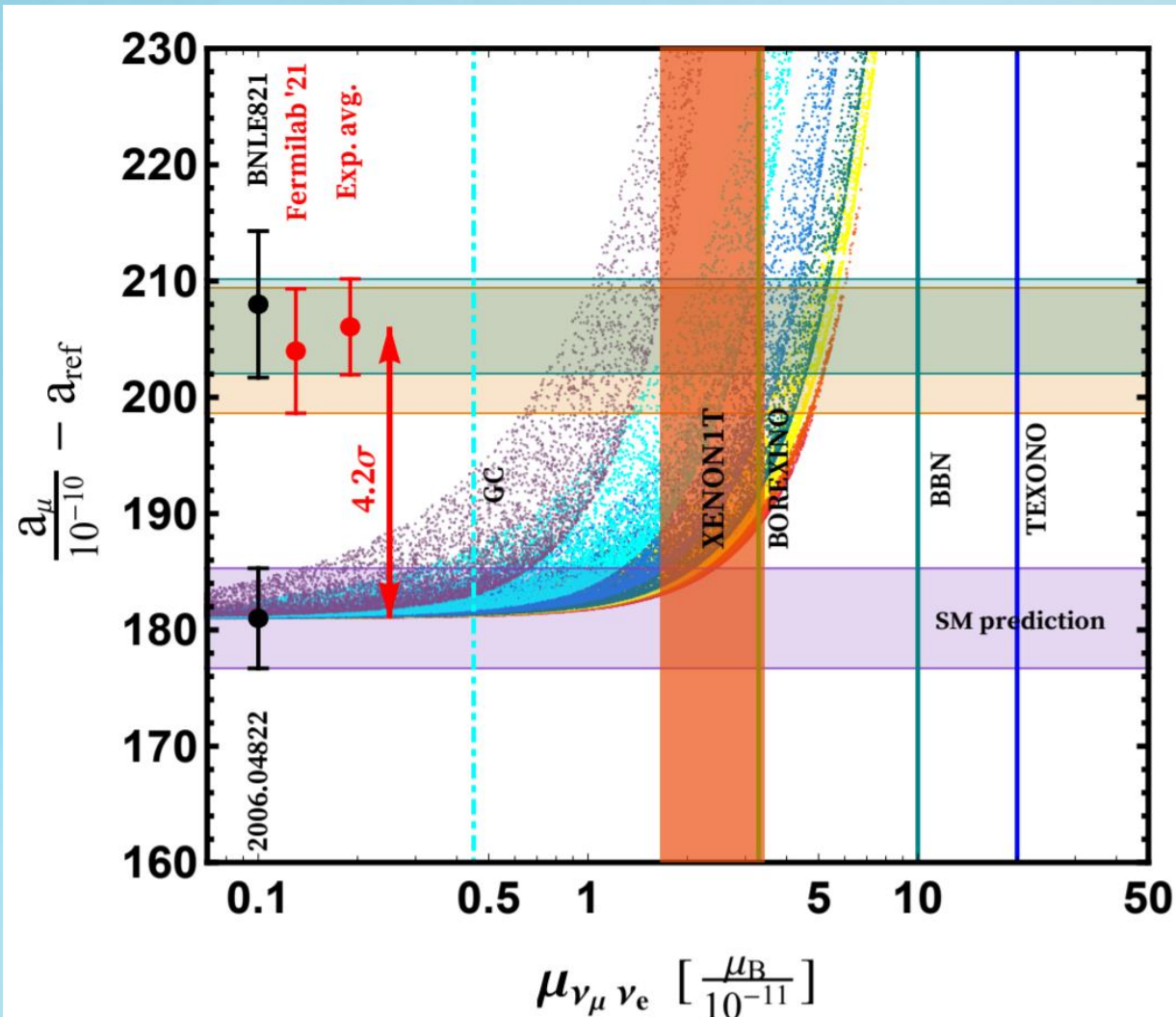
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$$10^{11} a_\mu = \begin{cases} 116591810(43) & \text{SM} \\ 116592040(54) & \text{Exp} \end{cases}$$

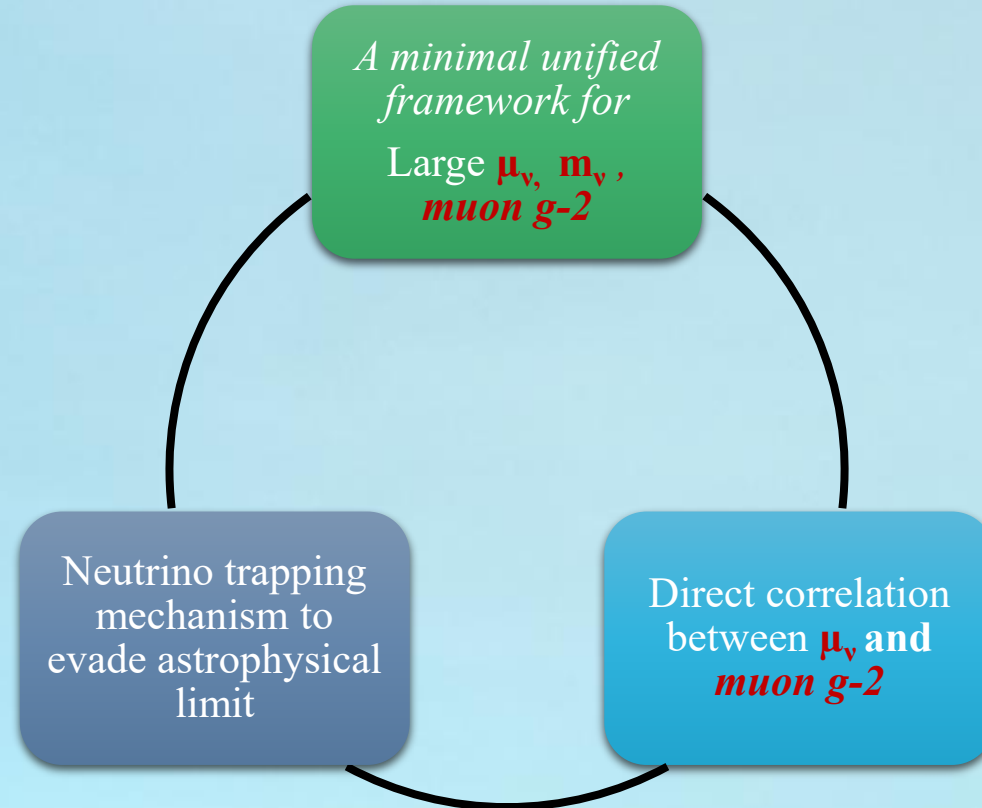
$$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 251(59) \times 10^{-11}$$

Neutrino magnetic moments – Muon $g-2$ anomaly

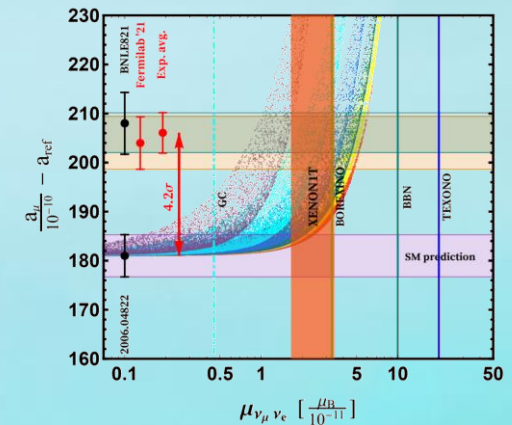
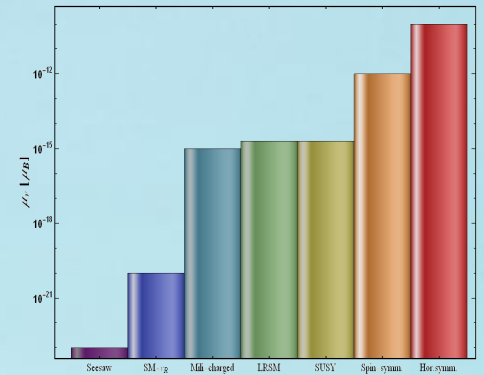


- A direct correlation between the neutrino magnetic moment and muon $g-2$
- Sign and strength are automatic here, no control over it.
- A minimal unified framework: $\mu_\nu, m_\nu, (g-2)_\mu$.

Summary



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!