Light from the Neutrinos and Pathways to New Physics

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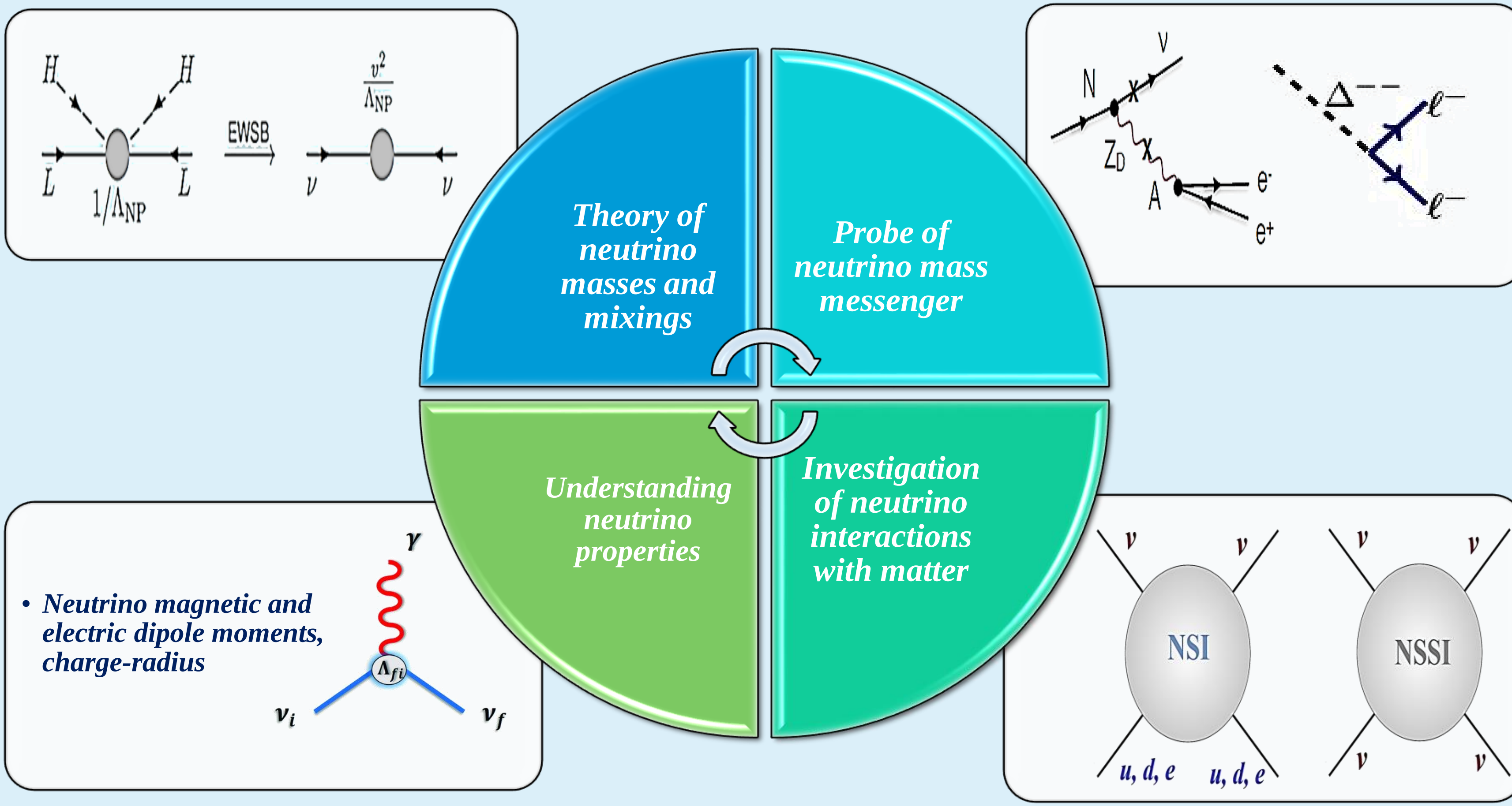
8th Feb, 2022

Outline



Theory of neutrino masses and mixings
Probe of neutrino mass messenger
Understanding neutrino properties
Investigation of neutrino interactions with matter
H
H
L
L
$1/\Lambda_{NP}$
EWSB
$\frac{v^2}{\Lambda_{NP}}$
ν
ν
N
ν
Z_D
χ
χ
A
e^-
e^+
Δ^{--}
ℓ^-
ℓ^-
• Neutrino magnetic and electric dipole moments, charge-radius
γ
Λ_{fi}
ν_i
ν_f
NSI
NSSI
ν
ν
u, d, e
u, d, e
ν
ν
ν
ν

Neutrino Oscillations: Harbinger of New Physics

Neutrino flavor oscillations have been firmly established from:

- **Solar neutrinos** (Homestake, SAGE, GALLEX, Kamiokande, Super-Kamiokande, SNO, Borexino,…)
- **Atmospheric neutrinos** (Super-Kamiokande, IceCube,…)
- **Reactor neutrinos** (KamLand, DayaBay, RENO, DoubleChooz …)
- **Accelerator neutrinos** (T2K, MINOS, NOVA…)

Oscillations can happen only if neutrinos have non-zero masses

- $\nu_\alpha = \sum_{i=1}^{3} U_{\alpha i}\,\nu_i$, $\alpha = (e, \mu, \tau)$
- **U is assumed to be unitary (Needs experimental check!)**

*"**Majorana phases**" (α, β) do not affect the oscillation probabilities, while the single "**Dirac phase**" δ does*

CP phase δ is unknown

- Recent **T2K** result (Nature, 2020): $\boldsymbol{\delta = -1.89^{+0.70}_{-0.58}}$

*All **three mixing angles** and **two mass splittings** have been measured with few percent precision*

There is a mass ordering ambiguity, normal ordering vs. inverted ordering (Sign of Δm^2_{31} is currently unknown)

Unitarity of U_{PMNS} remains to be tested

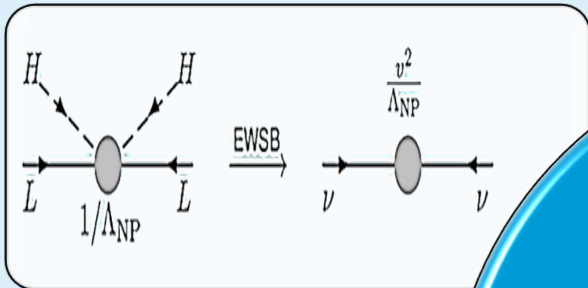
Flavor eigenstate **PMNS matrix** *Mass eigenstate*

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\boxed{\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}}}_{\text{Atmospheric term}} \underbrace{\boxed{\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13}\end{pmatrix}}}_{\text{Reactor term}} \underbrace{\boxed{\begin{pmatrix}\cos\theta_{12} & \cos\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}}_{\text{Solar term}} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

- Oscillation parameters:
  - Mixing angles: $\theta_{12}, \theta_{13}, \theta_{23}$
  - Mass squared differences: $\Delta m^2_{21}, \Delta m^2_{32}$ and the sign of Δm^2_{32}
  - Complex phase: $\delta \equiv \delta_{CP}$

$$U_{\text{PMNS}} = \begin{pmatrix} c_{12}c_{13} & c_{13}s_{12} & e^{-i\delta}s_{13}\\ -c_{23}s_{12} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23}\\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - c_{23}s_{12}s_{13}e^{i\delta} & c_{13}c_{23}\end{pmatrix} \cdot P$$

$$s_{ij} \equiv \sin(\theta_{ij}),\ c_{ij} \equiv \cos(\theta_{ij}),\ P = diag.\{e^{i\alpha}, e^{i\beta}, 1\}$$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EWSB
$\frac{v^2}{\Lambda_{NP}}$
L
$1/\Lambda_{NP}$
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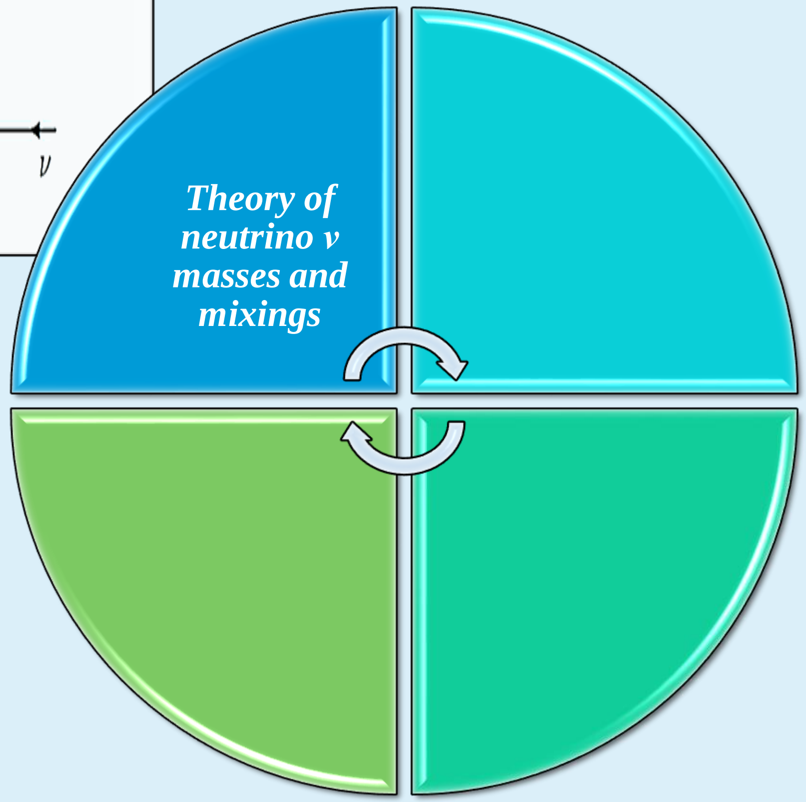

Theory of neutrino ν masses and mixings

Neutrino mass generation

❖ "Technically natural" in t'Hooft sense. Small values are protected by symmetry. At a cut-off scale Λ:

"natural" - $\delta m_f \sim g^2/(16\pi^2)\, m_f \ln(\Lambda^2/m_f^2)$

"unnatural" - $\delta m_H^2 \sim -\, y_t^2/(8\pi^2)\, \Lambda^2$

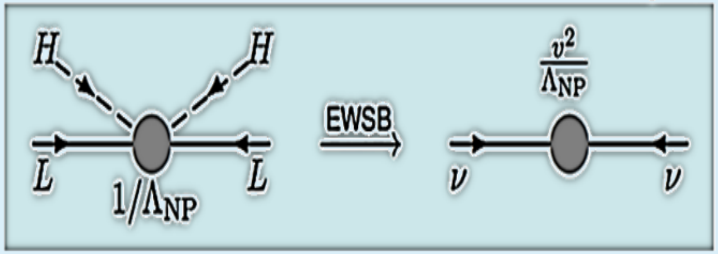
Two ways to generate small values naturally:

❖ Suppression by integrating out heavy states : the higher dimension $1/\Lambda^n$, the lower Λ can be.

❖ Suppression by loop radiative generation: the higher loops $1/(16\pi^2)^n$, the lower cut off scale can be.

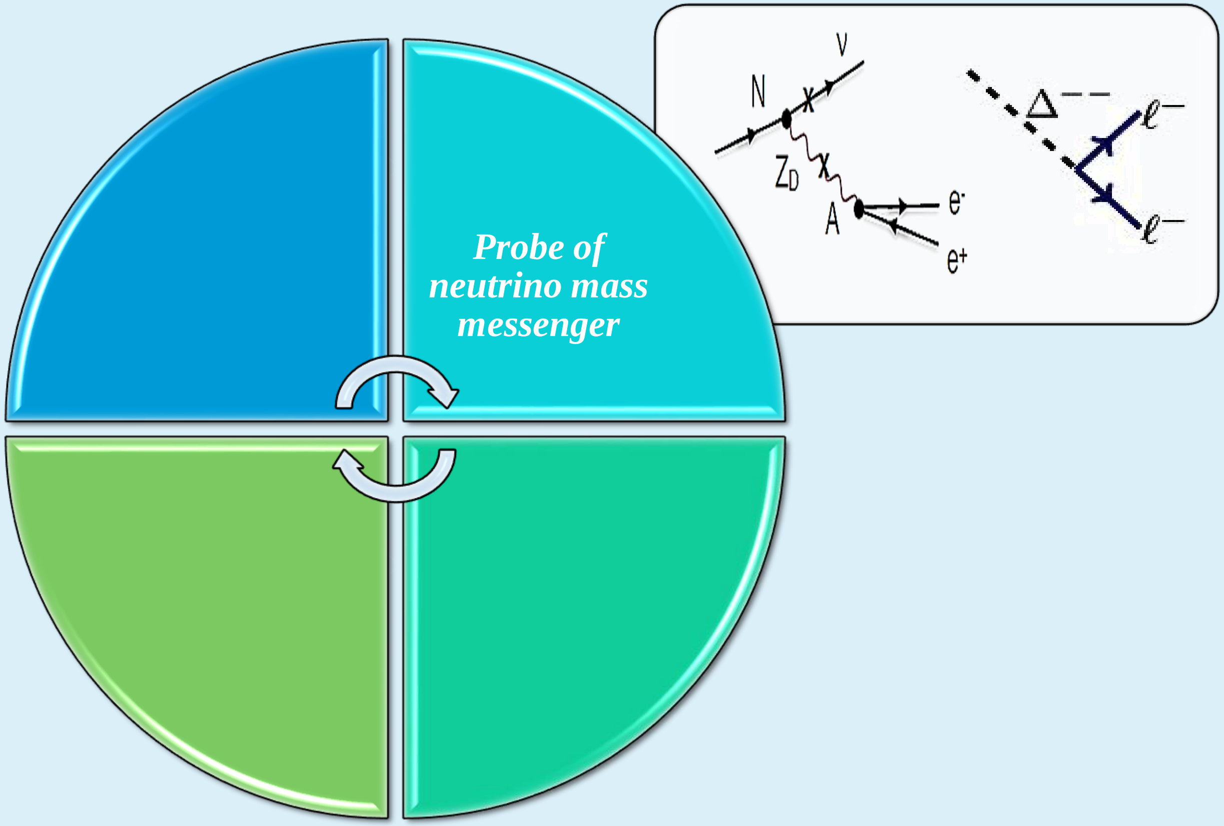
- Lowest higher dim. operator $\mathcal{O}^{d=5}$: $\mathcal{L}_{d=5} = \frac{1}{\Lambda_{NP}} LLHH$

Weinberg, PRL43 (79) 1566



- Realization of Weinberg op. –
  - See-saw: there are many seesaw realizations –
    - ⋆ Type-I Minkowski (77), Ramond,Slansky (79), Yanagida (79), Glashow (79), Mohapatra, Senjanovic (80)
    - ⋆ Type-II Schechter,Valle (80), Lazarides, Shafi, Wetterich (81), Mohapatra, Senjanovic (81)
    - ⋆ Type-III Foot, Lew, He, Joshi (89), Ma (98)
    - ⋆ Linear, Inverse, etc ...
  - Loop-induced:
    - ⋆ 1-loop Zee (80), Ma (99)
    - ⋆ 2-loop Babu (88)

See Babu's talk



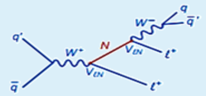
Probe of neutrino mass messenger
N
ν
Z_D
A
e^-
e^+
Δ^{--}
ℓ^-
ℓ^-

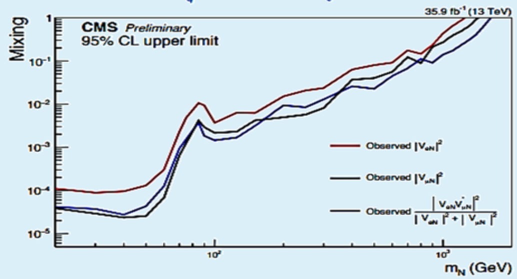
Testing Seesaw: prompt signature at the LHC

Testing type-I Seesaw

[Keung, Senjanović (PRL '83); Datta, Guchait, Pilaftsis (PRD '94); Panella, Cannoni, Carimalo, Srivastava (PRD '02); Han, Zhang (PRL '06); del Aguila, Aguilar-Saavedra, Pittau (JHEP '07); Atre, Han, Pascoli, Zhang (JHEP '09)]

Same-sign dilepton plus jets (without $\not{E}_T$)



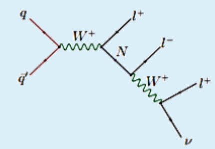


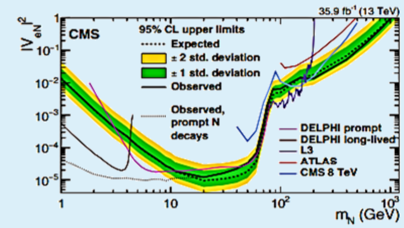
[CMS PAS EXO-17-028]

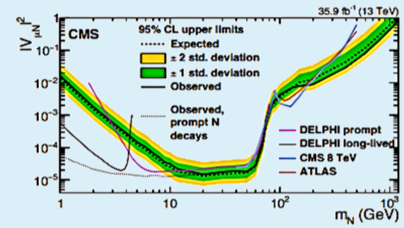
Testing Inverse Seesaw

[del Aguila, Aguilar-Saavedra (PLB '09; NPB '09); Chen, BD (PRD '12); Das, Okada (PRD '13); Das, BD, Okada (PLB '14); Izaguirre, Shuve (PRD '15); Dib, Kim (PRD '15); Dib, Kim, Wang (PRD '17; CPC '17); Dube, Gadkari, Thalapillil (PRD '17)]

Trilepton plus $\not{E}_T$

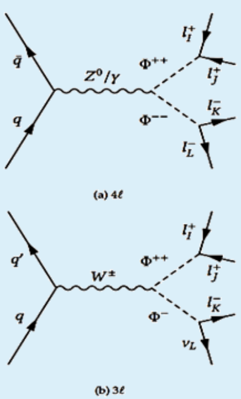


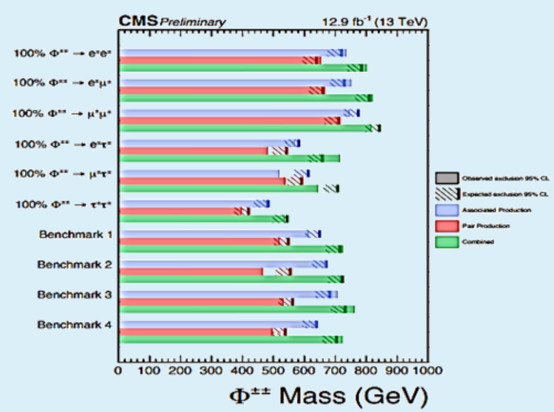




[CMS Collaboration, Phys. Rev. Lett. **120**, 221801 (2018)]

Testing type-II Seesaw



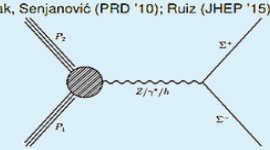


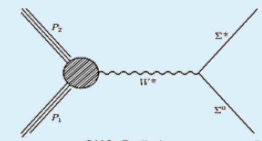
[CMS-PAS-HIG-16-036]

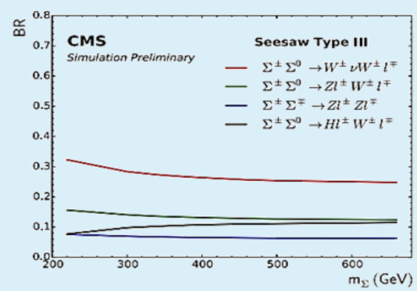
Rizzo (1982); Huitu, Maalampi, Pietila, Raidal (1997); Gunion, Loomis, Pitts (1996); Akeryod, Aoki (2005); Han, Mukhopadhyaya, Ci, Wang (2005), N. Sahu, Uma Sankar (2005); Sarma, Devi, Singh (2007); Chao, Luo, Xing, Zhao (2007); Perez, Han, Huang, Li, Wang (2008); McDonald, Sahu, Sarkar (2008); Chiang, Nomura, Tsumura (2012); Dev, D. Ghosh, Okada, Saha (2013); Nayak, Parida (2015); Cai, Han, Ruiz (2017), Babu , SJ (2017)……

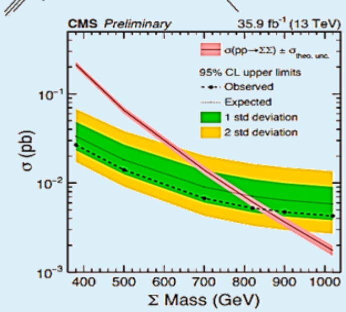
Testing type-III Seesaw

- Multi-lepton signatures. Franceschini, Hambye, Strumia (PRD '08); Li, He (PRD '09); Arhrib, Bajc, Ghosh, Han, Huang, Puljak, Senjanović (PRD '10); Ruiz (JHEP '15)









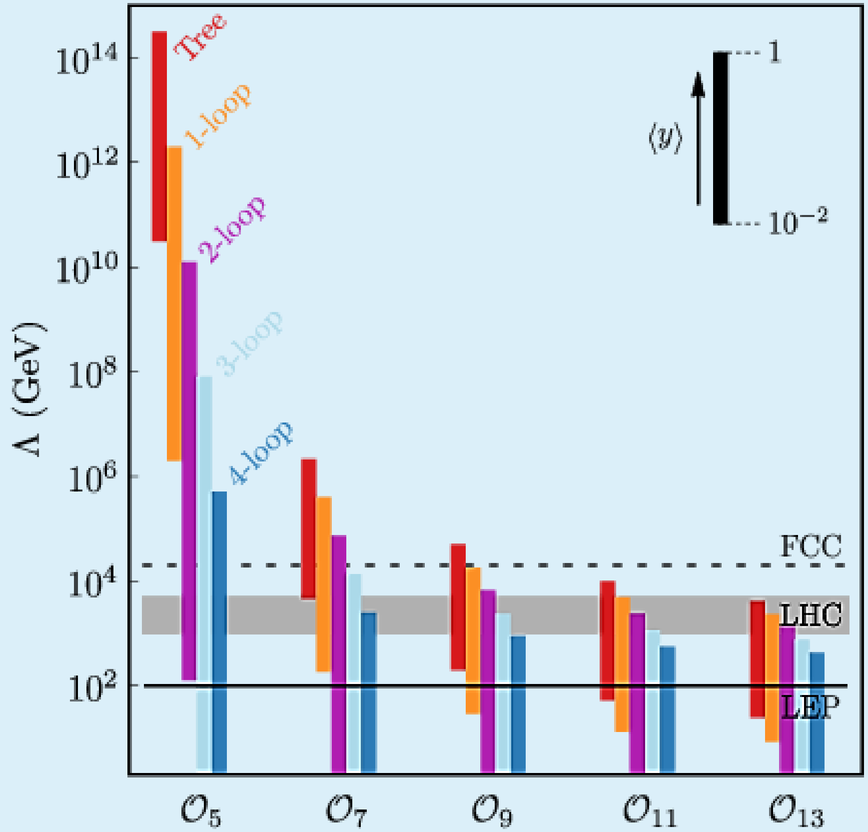
Neutrino masses from light physics

In an effective theory, the Lagrangian should be described as

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \frac{1}{\Lambda_{\rm NP}}\mathcal{O}^{d=5} + \frac{1}{\Lambda_{\rm NP}^2}\mathcal{O}^{d=6} + \frac{1}{\Lambda_{\rm NP}^3}\mathcal{O}^{d=7} + \cdots$$

Neutrino masses from a n-loop-induced dim-d operator

$$m_\nu = v \times \left(\frac{1}{16\pi^2}\right)^n \times \left(\frac{v}{\Lambda_{\rm NP}}\right)^{d-4}$$



Neutrino masses from light physics

Gauge $U(1)_D$: SM has no charge, RH neutrinos N have charge +1

Anomaly cancellation: N' with opposite charge should be included

anomaly cancellation is a requirement to have a consistent QFT

Walks and quacks like inverse seesaw

$$\mathcal{M}_\nu = \begin{array}{cc} \begin{pmatrix} 0 & m & 0 \\ m & 0 & M \\ 0 & M & \mu \end{pmatrix} & \begin{array}{cc} \nu & 0 \\ N & + \\ N' & - \end{array} \end{array} \Longrightarrow \quad m_\nu = \mu \frac{m^2}{M^2}$$

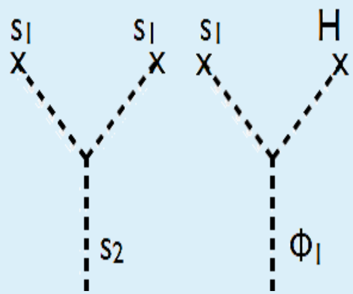
m and μ are forbidden by dark symmetry, they need to be generated dynamically

Minimum scalar content

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & y\phi_1 & 0 \\ y\phi_1 & 0 & M \\ 0 & M & y' s_2 \end{pmatrix}$$

Φ_1 = doublet with dark charge +1
s_2 = singlet with dark charge +2

Add s_1 with charge +1 and something special happens:
Φ_1 and s_2 start with no vevs, s_1 develops a vev like the Higgs



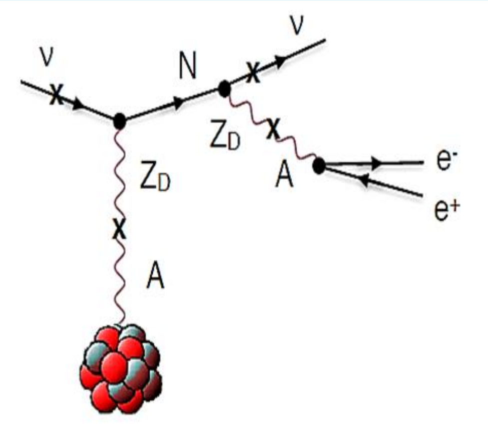
Φ_1 and s_2 vevs are **induced**, like in type II seesaw, and thus can be naturally very small!

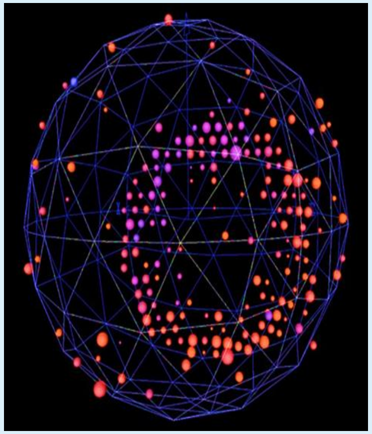
Bertuzzo, SJ, Machado, Z. Funchal (PLB' 2018)

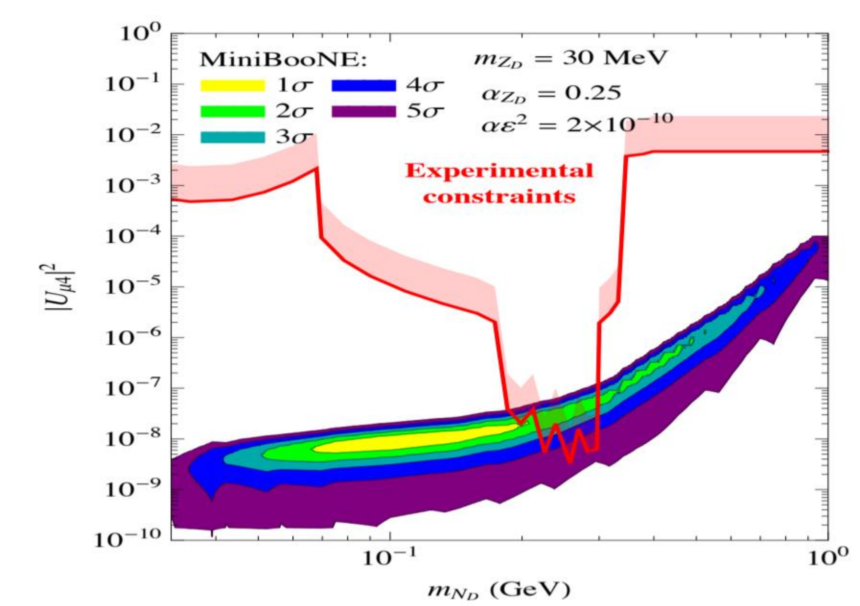
Explanation of MiniBooNE's low energy excess

- There is a dark sector with a novel interaction
- Right-handed neutrinos are part of the dark sector and are subject to new interaction
- Mixing between RH and LH neutrinos leads to interaction in active neutrino sector
- Mixing between Z_D and photon leads to interaction with protons
- Relevant part of the Lagrangian :

$$\mathcal{L}_{\mathcal{D}} \supset \frac{m_{Z_{\mathcal{D}}}^2}{2} Z_{\mathcal{D}\mu} Z_{\mathcal{D}}^{\mu} + g_{\mathcal{D}} Z_{\mathcal{D}}^{\mu} J_{\mathcal{D}\mu} + e\epsilon\, Z_{\mathcal{D}}^{\mu} J_{\mu}^{\mathrm{em}} + \frac{g}{c_W}\epsilon'\, Z_{\mathcal{D}}^{\mu} J_{\mu}^{Z}$$



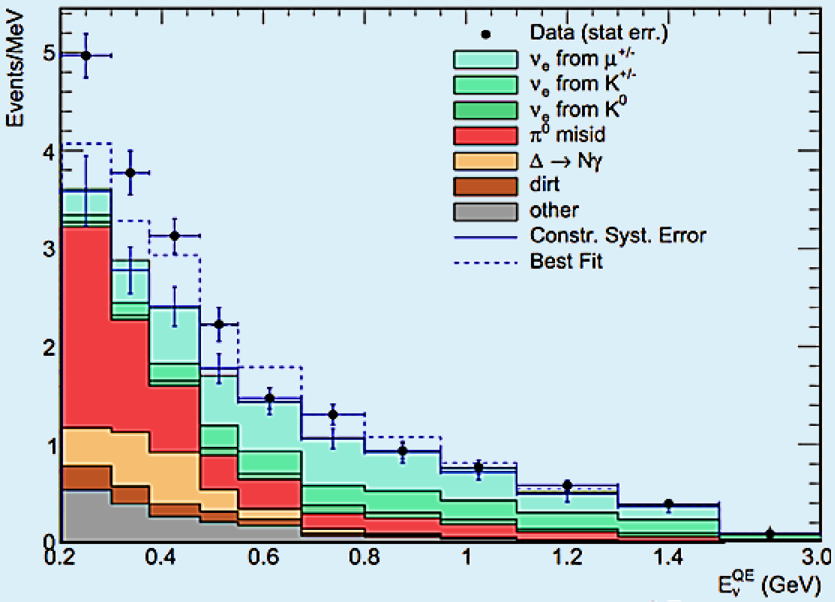


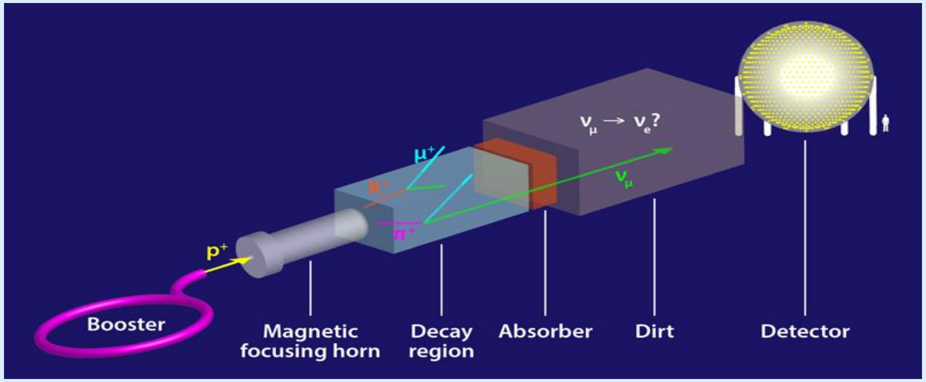


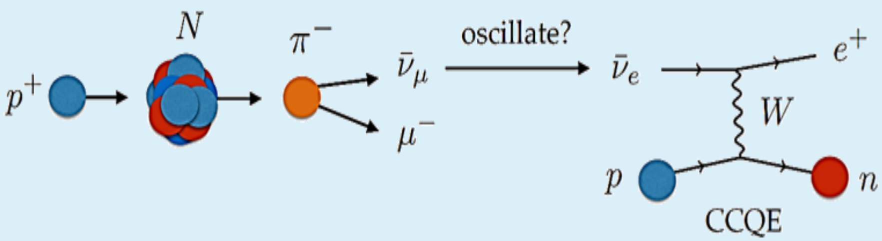
Bertuzzo, SJ, Machado, Z. Funchal (PRL' 2018)

Connection with MiniBooNE anomaly

MiniBooNE Collaboration [hep-ex/1805.12028](hep-ex/1805.12028)







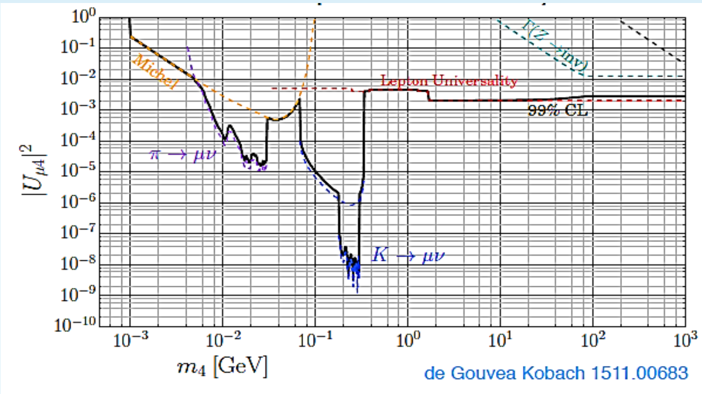
❖Observation of a Significant Excess of Electron-Like Events in the MiniBooNE Short Baseline Neutrino Experiment

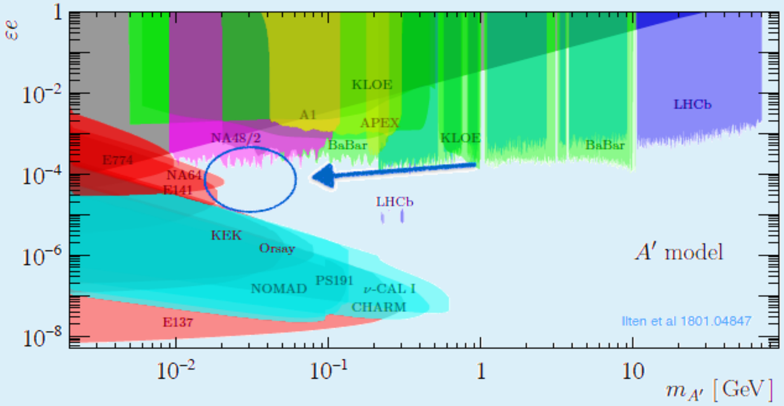
❖Double neutrino-mode data in 2016-2017 (6.46×10^{20} + 6.38×10^{20} POT)

❖Event excess: 381.2 ± 85.2 (4.5σ)

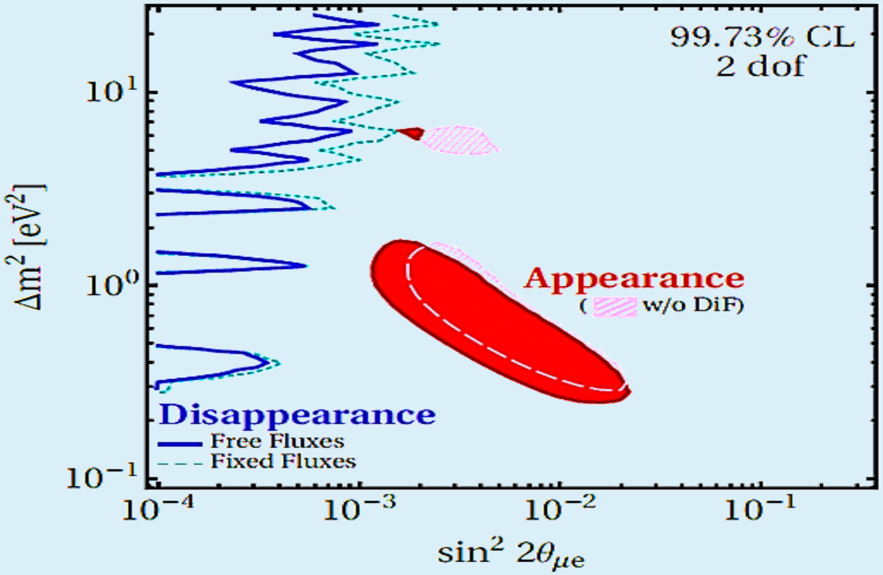
Constraints

Model Independent Constraint on Heavy Sterile Neutrino





- Z_D phenomenology is similar to dark photon case
- LHC constraints are not expected to be stringent below 1 GeV



$\sin^2 2\theta_{\mu e} = 4\,|U_{e4}\, U_{\mu 4}|^2$

4.7 σ tension between Appearance and Disappearance data sets under eV sterile interpretation

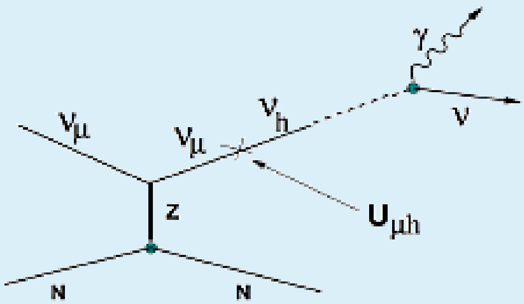
Cosmological bounds further threat the eV sterile ν hypothesis

Mona Dentler et al. (2018)
Collin et al. (2016)
Gariazzo et al (2017)

Bertuzzo, SJ, Machado, Z. Funchal (PRL' 2018)

Beyond standard physics in neutrino experiments

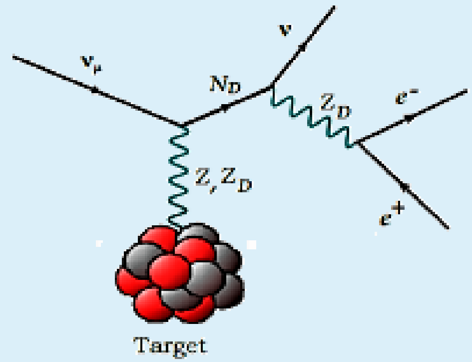
ν magnetic moment



Explains MiniBooNE

Gninenko 0902.3802
Fischer et al. (2019)
so many people...

Dark neutrinos

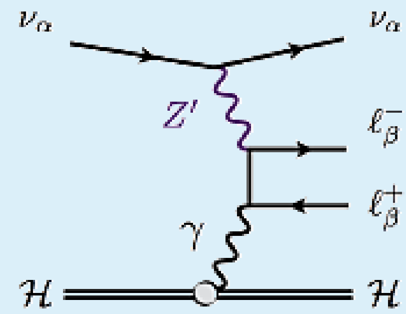


Explains MiniBooNE

Explains m_ν

Bertuzzo et al 1807.09877, 1807.02500
Ballett et al 1808.02915, *Arguelles et al 1812.08768*

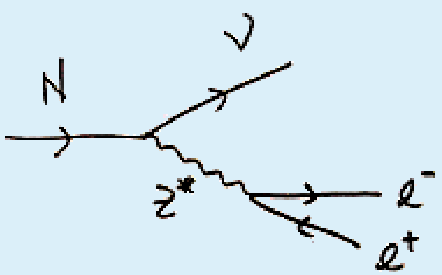
New gauge bosons (e.g. L_μ-L_τ)



Explains $(g-2)_\mu$

Altmannshofer et al 1406.2332
Ballet et al 1902.08579

Heavy neutrinos

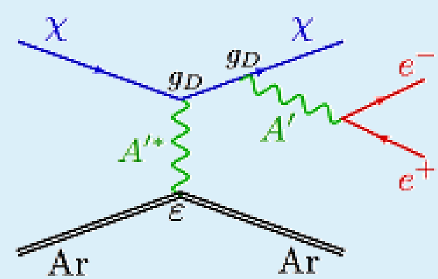


Explains m_ν

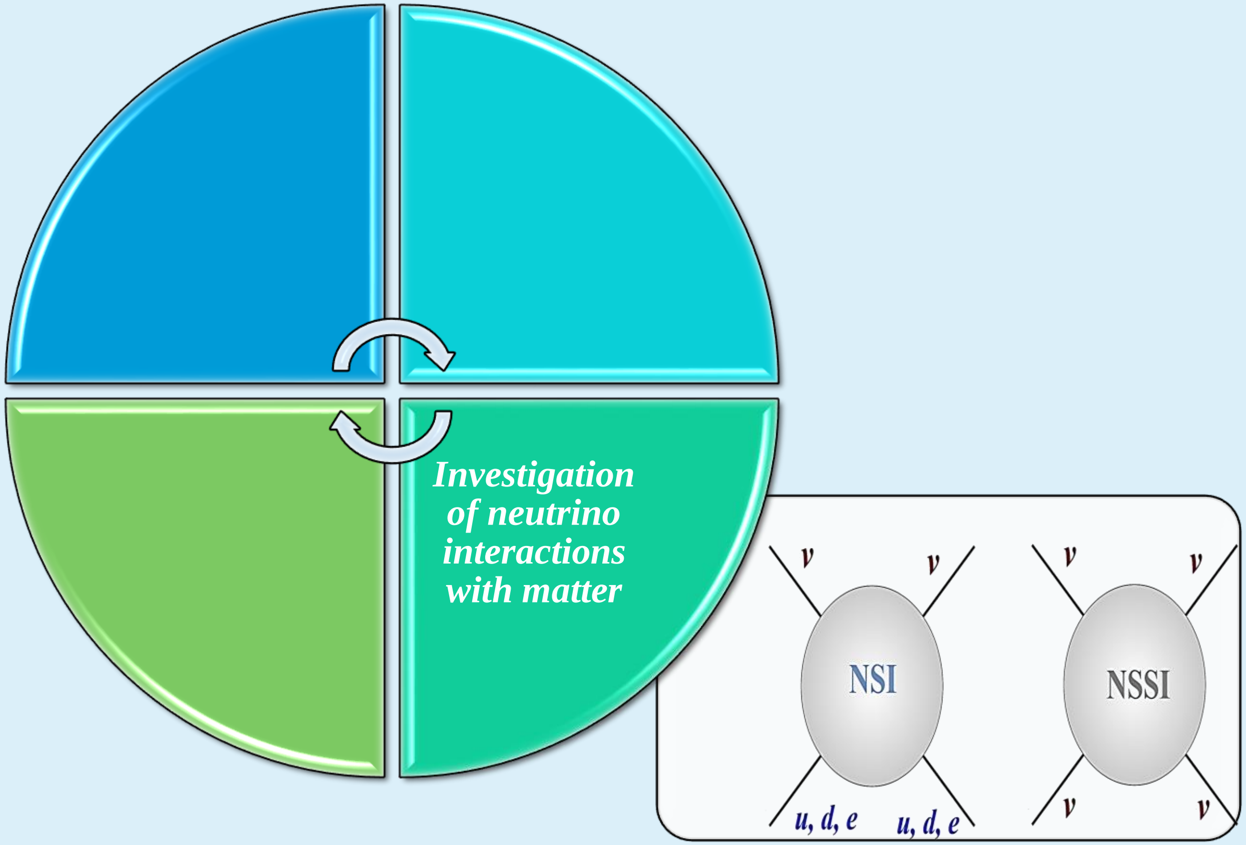
Neutrino decay
Decoherence
Non-unitarity
Non-standard interactions
Ultra-light scalars
Dark matter
Extra dimensions
New forces/mediators
Millicharged particles
Neutrino self interactions
...

de Gouvêa et al 1809.06388

Dark tridents



Explains DM


Investigation of neutrino interactions with matter
ν
ν
NSI
u, d, e
u, d, e
ν
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NSSI
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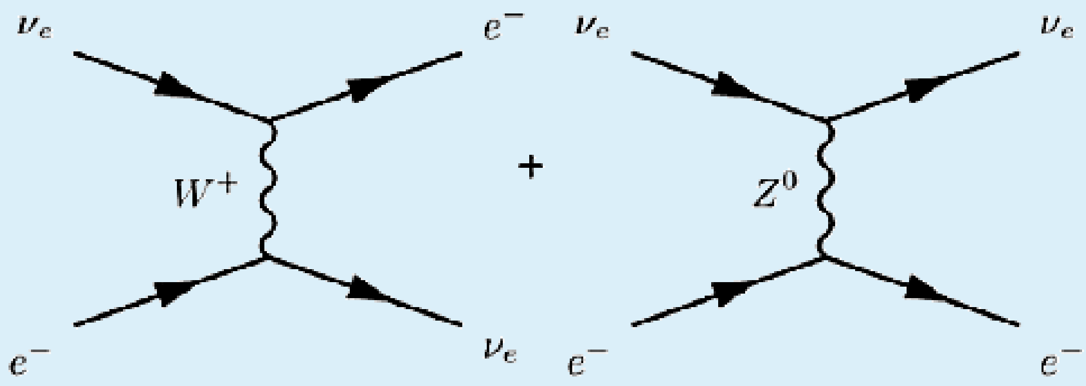
Neutrino Standard Interaction



Charged current and Neutral current

- Coherent forward scattering of ν_e off electron in matter generates a matter potential:

  $V = \sqrt{2} G_F N_e \approx 8.2 \times 10^{-12}$ eV in solar core (Wolfenstein)

- Modifies refractive index of ν_e (Mikheyev-Smirnov)
- Neutral current interaction is universal

Neutrino NSI

Unknown couplings involving neutrinos.

Potentially observable effects in neutrino oscillation experiments. It can affect mass ordering and CP violation.

NSI effects happen in the neutrino production, propagation through matter, and the detection processes.

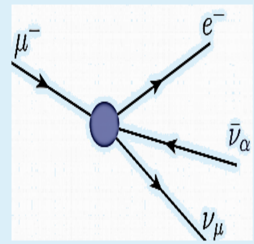
Most important effect of NSI is in neutrino propagation in matter *Wolfenstein (1978)*

There have been ***a variety of phenomenological studies*** *of NSI in the context of oscillations, but* ***relatively lesser effort*** *has gone into the* ***UV completion of models*** *that yield such NSI.*

A ***major challenge*** *in generating sizable NSI:* ***charged lepton flavor violation***

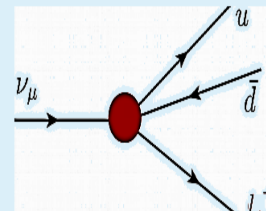
$$\mathcal{L}^{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\delta\mathcal{L}^{d=5} + \boxed{\frac{1}{\Lambda^2}\delta\mathcal{L}^{d=6}} + \ldots$$

NSI affecting production



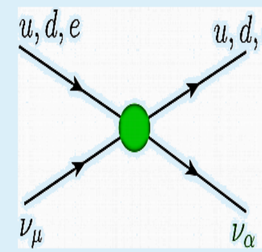
$\varepsilon^{e\mu,P}_{\mu\alpha}\left(\bar{e}\gamma^\rho P\mu\right)\left(\bar{\nu}_\mu\gamma_\rho P_L\nu_\alpha\right)$

NSI affecting detection



$\varepsilon^{ud,P}_{\mu\alpha}\left(\bar{d}\gamma^\rho Pu\right)\left(\bar{\nu}_\mu\gamma_\rho P_L l_\alpha\right)$

NSI affecting propagation



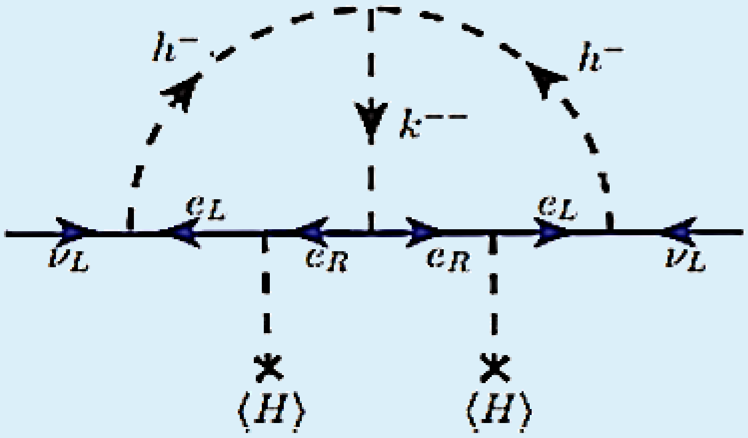
$\varepsilon^{f,P}_{\mu\alpha}\left(\bar{f}\gamma^\rho Pf\right)\left(\bar{\nu}_\mu\gamma_\rho P_L\nu_\alpha\right)$

$$\mathcal{L}_{\rm NC} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \varepsilon^{f,P}_{\alpha\beta}(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta)(\bar{f}\gamma_\mu Pf)$$

$$\mathcal{L}_{\rm CC} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \varepsilon^{f,P}_{\alpha\beta}(\bar{\nu}_\alpha\gamma^\mu P_L\ell_\beta)(\bar{f}\gamma_\mu Pf')$$

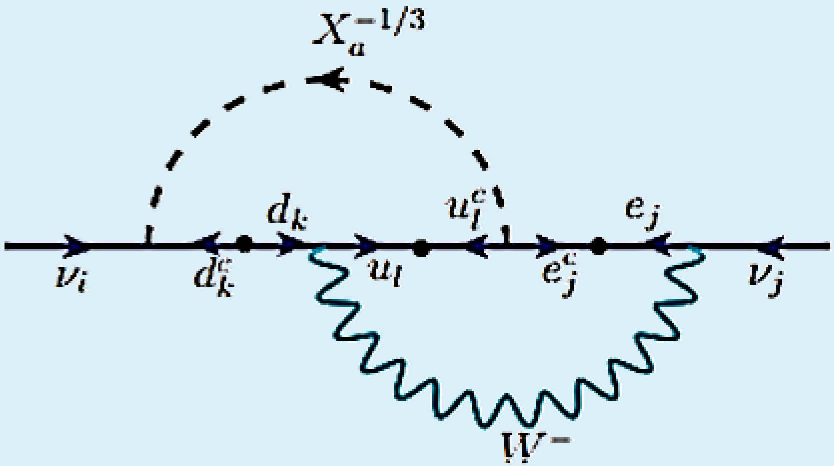
Type-I Radiative Mechanism

- Obtained from effective d = 7, 9, 11... operators with $\Delta L = 2$ selection rule
- If the loop diagram has at least one Standard Model particle, this can be cut to generate such effective operators



$$\mathcal{O}_9 = L_i L_j L_k e^c L_l e^c \epsilon^{ij} \epsilon^{kl}$$

Zee, Babu



$$\mathcal{O}_8 = L_i \bar{e^c} \bar{u^c} d^c H_j \epsilon^{ij}$$

Babu, Julio (2010)

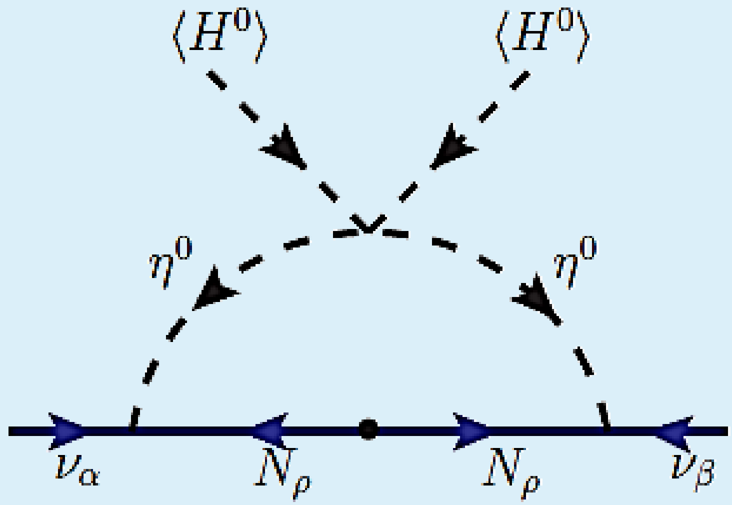
Classification: Babu, Leung (2001),
de Gouvea, Jenkins (2008)

See Babu's talk

Dev, Babu, **SJ**, Thapa (2019)

Type-II Radiative Mechanism

- No Standard Model particles inside loop
- Cannot be cut to generate $d = 7, 9, ...$ operators
- Scotogenic model is an example



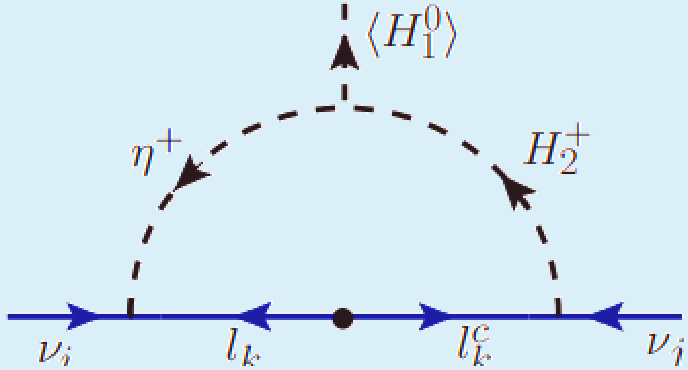
- Neutrino mass has no chiral suppression; new scale can be large
- Other considerations (dark matter) require TeV scale new physics Ma (2006)
- These models predict negligible NSI

NSI in Zee model

- Yukawa coupling matrices:

$$f = \begin{pmatrix} 0 & f_{e\mu} & f_{e\tau} \\ -f_{e\mu} & 0 & f_{\mu\tau} \\ -f_{e\tau} & -f_{\mu\tau} & 0 \end{pmatrix}, \qquad Y = \begin{pmatrix} Y_{ee} & Y_{e\mu} & Y_{e\tau} \\ Y_{\mu e} & Y_{\mu\mu} & Y_{\mu\tau} \\ Y_{\tau e} & Y_{\tau\mu} & Y_{\tau\tau} \end{pmatrix}$$

- Neutrino mass

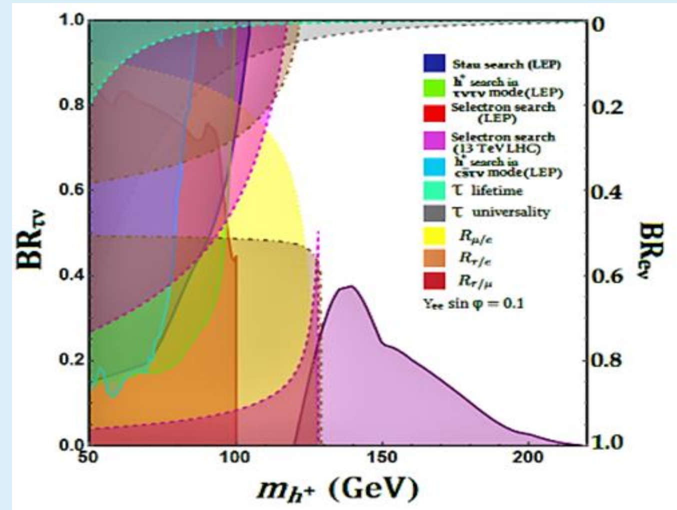


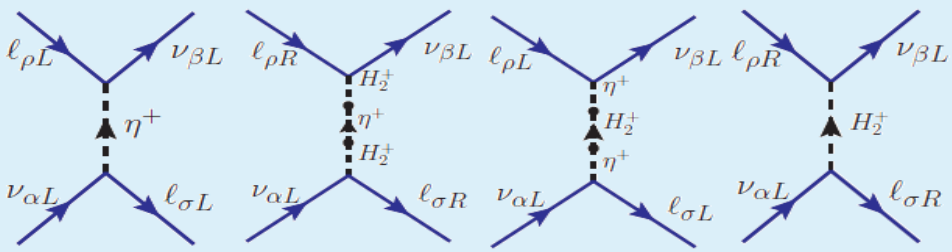
$$M_\nu = \kappa\,(f M_l Y^T + Y M_l f^T)$$
$$\kappa = \frac{1}{16\pi^2} \sin 2\varphi \log \frac{m_{h^+}^2}{m_{H^+}^2}$$

- If $Y \propto M_l$, which happens with a Z_2, then model is ruled out
  Wolfenstein (1980)
- In general, Y is not proportional to M_l, and the model gives reasonable fit to oscillation data
- NSI arises via the exchange of $h^\pm$ and $H^\pm$

NSI in Zee model

- Electroweak T parameter sets limits on mixing $\sin\varphi$
- $\mu \to e + \gamma$ type processes limit products of couplings
- $\mu \to 3e$ type processes lead to further constraints
- τ lifetime and universality constraints
- Lepton universality in $W^\pm$ decays
- Theoretical constraint from avoiding charge breaking minima
- LEP direct search limits on charged scalars
- Constraints from LHC searches
- Higgs precision physics limits





- The singly-charged scalars η^+ and H^+ induce NSI at tree level:

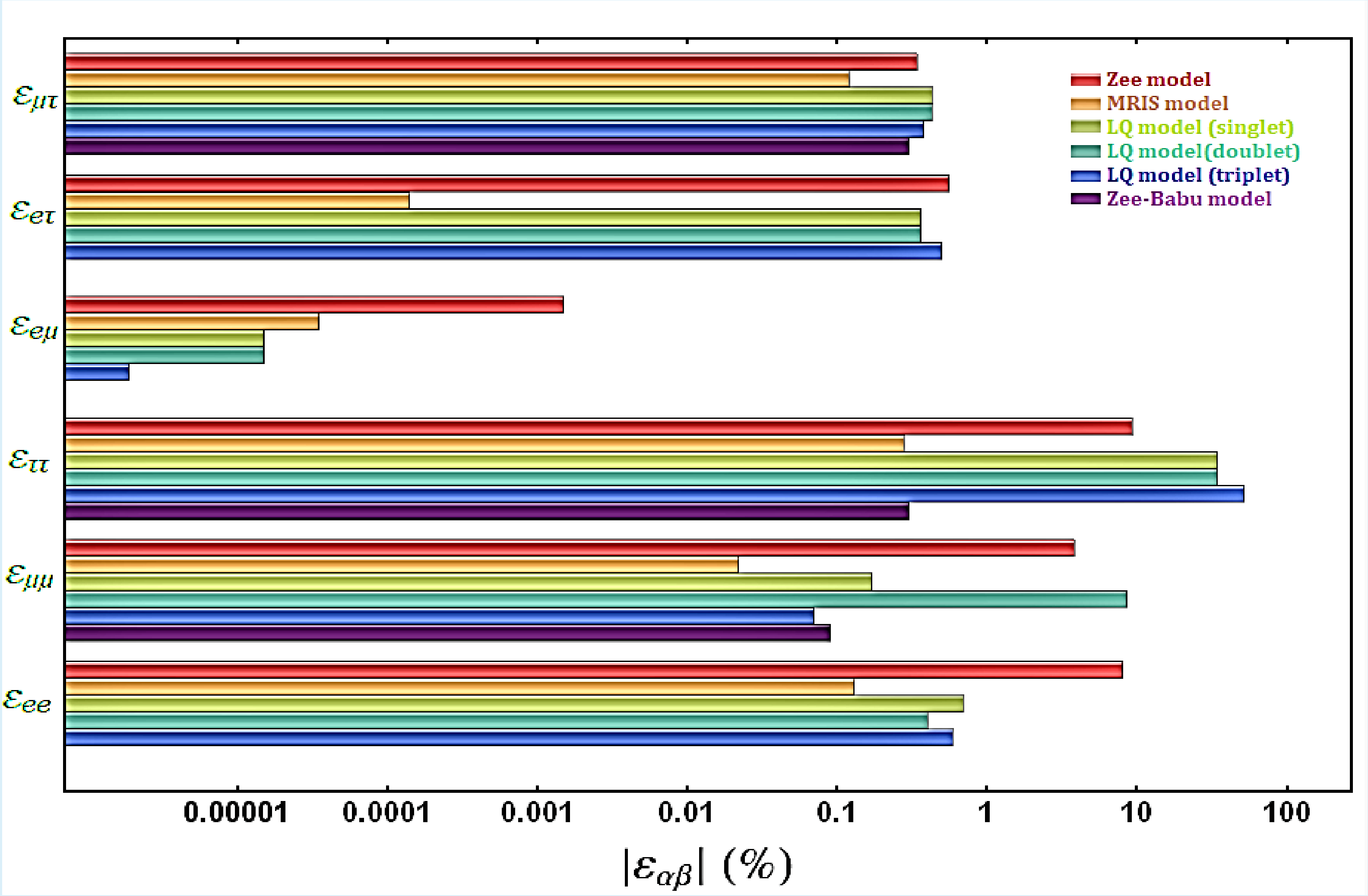
$$\boxed{\varepsilon_{\alpha\beta} \equiv \varepsilon_{\alpha\beta}^{(h^+)} + \varepsilon_{\alpha\beta}^{(H^+)} = \frac{1}{4\sqrt{2}G_F} Y_{\alpha e} Y_{\beta e}^\star \left(\frac{\sin^2\varphi}{m_{h^+}^2} + \frac{\cos^2\varphi}{m_{H^+}^2} \right)}$$

- For a benchmark value of 100 GeV masses, we have:

$$\varepsilon_{ee}^{\max} \approx 3.5\%\,, \quad \varepsilon_{\mu\mu}^{\max} \approx 5.6\%\,, \quad \varepsilon_{\tau\tau}^{\max} \approx 71.6\%$$

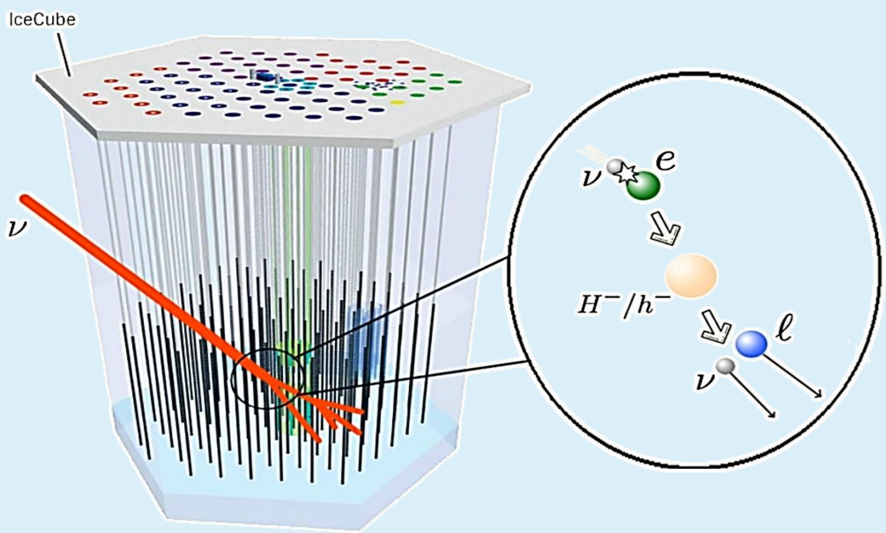
Babu, Dev, SJ, Thapa (2019)

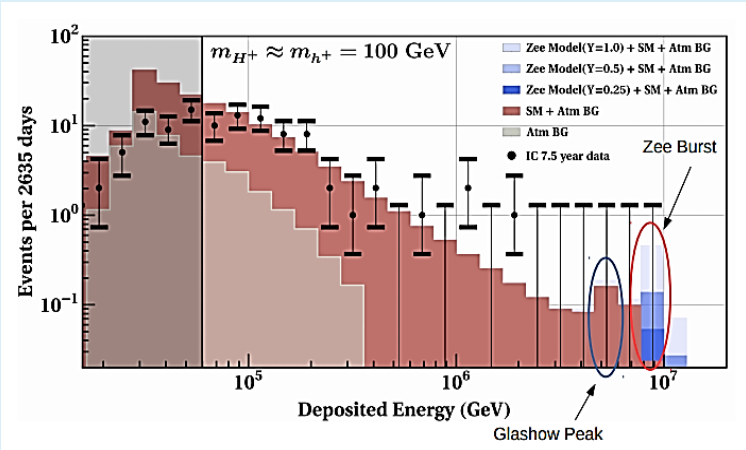
Summary of NSI in radiative models



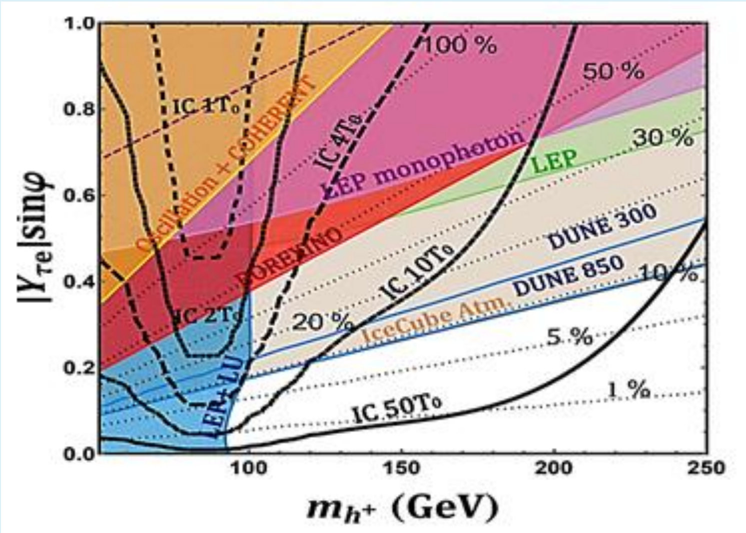
Babu, Dev, **SJ** , Thapa (2019)

Zee-Burst: A new test of NSI at IceCube





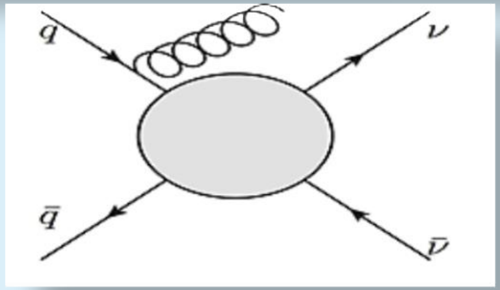
- Ultra High Energy neutrinos at IceCube can probe NSI in the Zee model
- $\overline{\nu_e} + e^- \to W^- \to$ anything has a resonant enhancement at
  $$E_\nu = \frac{m_W^2}{2m_e} = 6.3\,\mathrm{PeV} \quad \text{Glashow resonance}$$
- Since $h^\pm$ and $H^\pm$ in Zee model are allowed to be as light as 100 GeV, $\overline{\nu}_\alpha + e^- \to h^- \to$ anything is resonantly enhanced
  $$E_\nu = \frac{m_h^2}{2m_e} \simeq 9.3\,\mathrm{PeV} \quad \text{"Zee burst"}$$
- We have analyzed this possibility of "Zee burst"



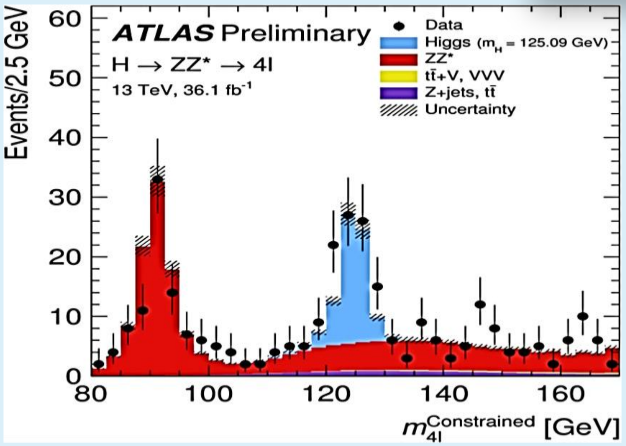
Babu, Dev, SJ , Sui (PRL' 2019)

Neutrino NSI at the LHC

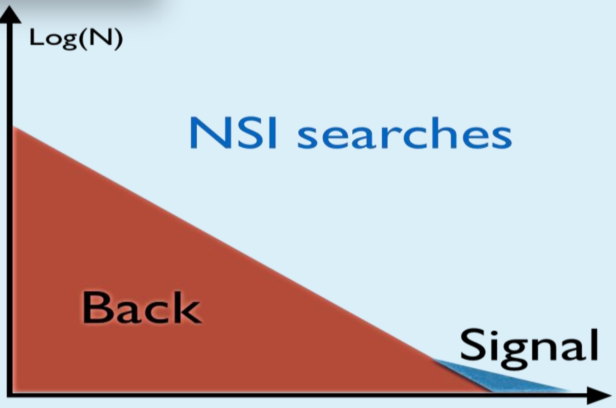
$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}\,G_F\varepsilon^{fP}_{\alpha\beta}\left(\overline{\nu}_\alpha\gamma_\rho\nu_\beta\right)\left(\overline{f}\gamma^\rho P f\right)$$



For collider studies on NSI: See
Friedland, Graesser, Shoemaker, Vecchi (2011),
Choudhury, Ghosh, Niyogi (2018),
Babu, Gonçalves, **SJ**, Machado (2020), …



vs.



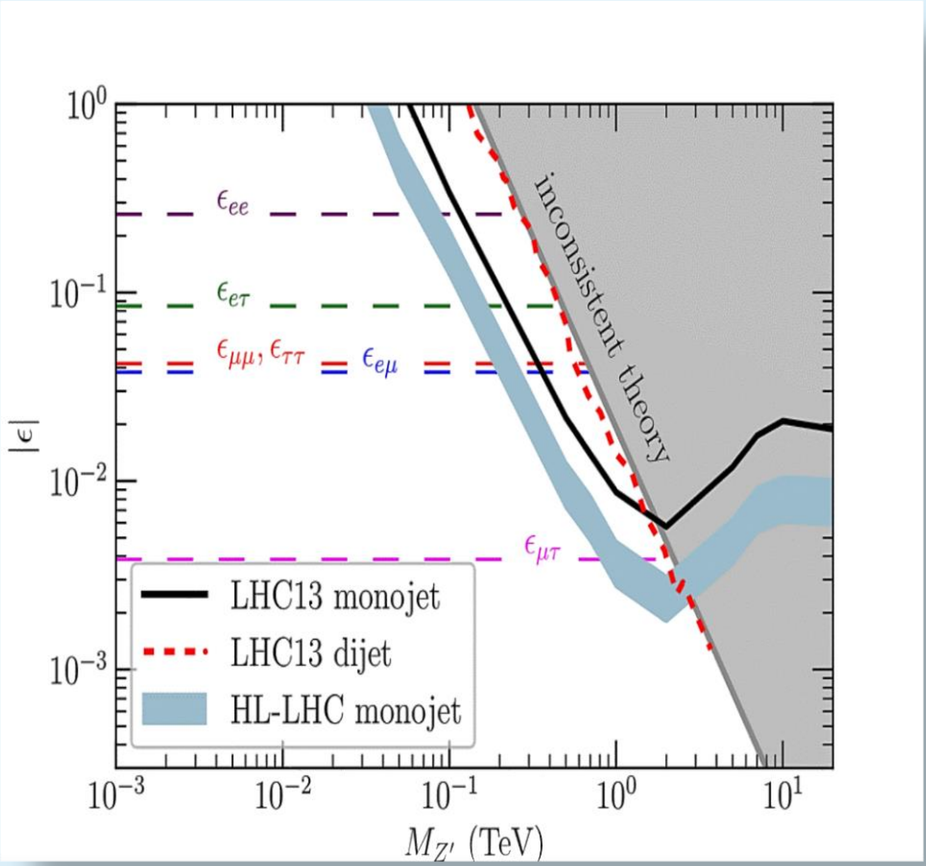
Overwhelming SM background

NSI contains both flavor-changing and flavor-diagonal interactions

Signal: small enhancement in the tail of MET distribution

Big challenge: requires precise estimation of background

From EFTs to Simplified Models



Babu, Gonçalves, **SJ**, Machado (2020)
Coloma, Esteban, Gonzalez-Garcia, Maltoni (2019)

NSIs are generally parametrized in the EFT framework as:

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}G_F\epsilon^{fY}_{\alpha\beta}\left(\bar{\nu}^\alpha\gamma_\mu\nu^\beta\right)\left(\bar{f}\gamma^\mu P_Y f\right)$$

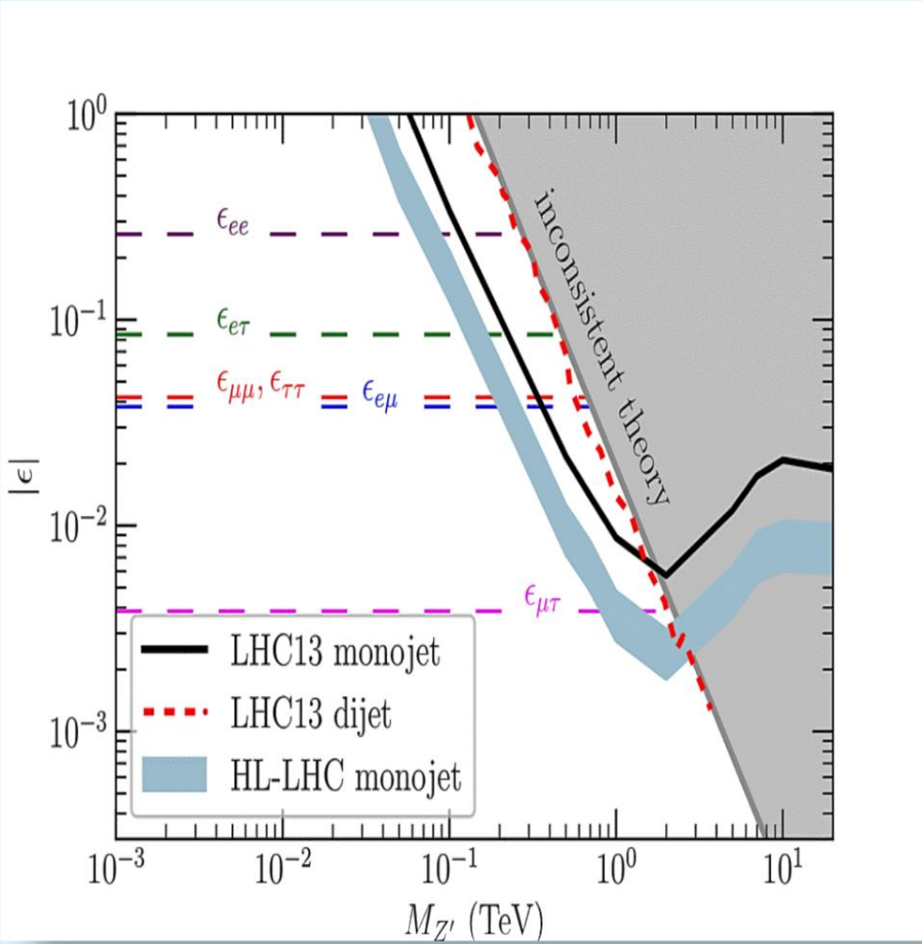
Adopting a simplified model approach, we parametrize the NSI as:

$$\mathcal{L}^{\rm Simp}_{\rm NSI} = \left(g^{\alpha\beta}_\nu\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta + g^Y_{qi}\bar{q}_i\gamma^\mu P_Y q_i\right)Z'_\mu$$

Neutrino NSIs arise in the simplified model as:

$$\epsilon^u_{\alpha\beta} = \epsilon^d_{\alpha\beta} \equiv \epsilon_{\alpha\beta} = \frac{(g_\nu)_{\alpha\beta}g^V_{u,d}}{2\sqrt{2}G_F M^2_{Z'}}$$

Validity of this EFT at the LHC



Babu, Gonçalves, **SJ**, Machado (2020)

We can identify the EFT regime for the LHC when the mass of the mediator is much above the scale of the process involved.

For any fixed ratio $\Gamma_{Z'}/M_{Z'}$, we can write the following inequality

$$|\epsilon| \leq \frac{\sqrt{3}\pi}{\sqrt{N} G_F M_{Z'}^2} \frac{\Gamma_{Z'}}{M_{Z'}}$$

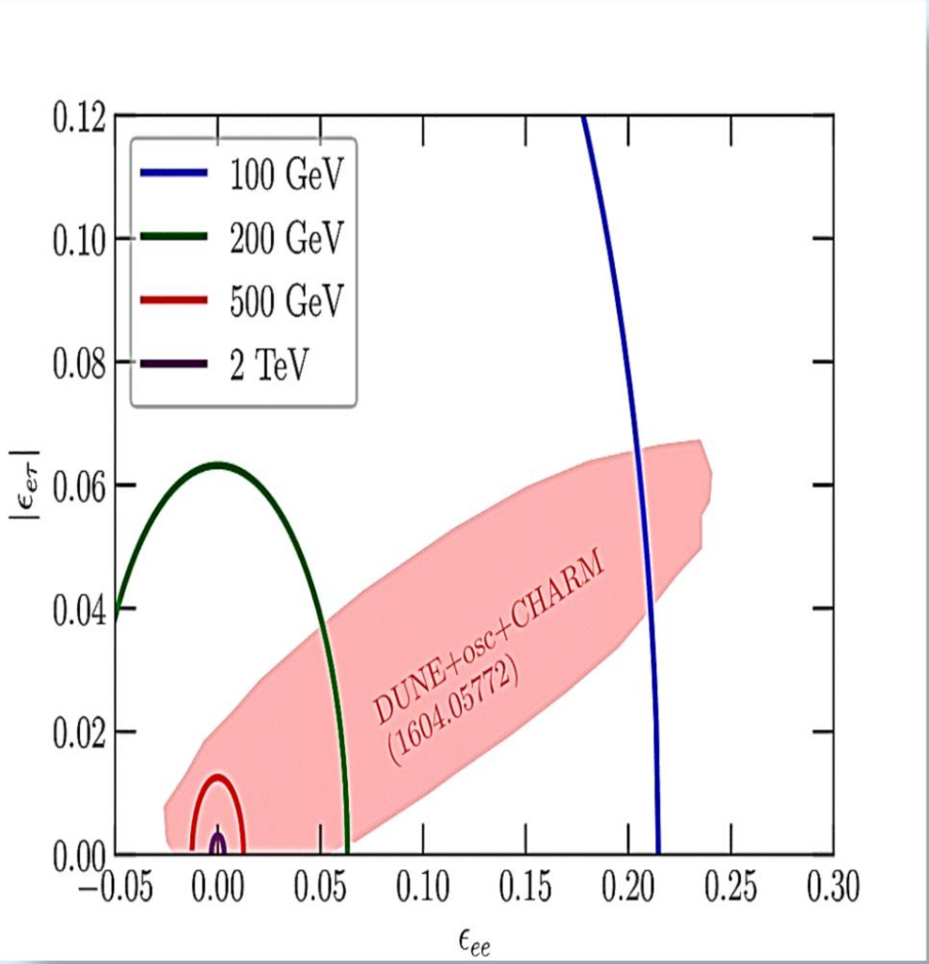
This constraint originates from the fact that the total width of the Z' should be larger than the partial widths to $q_i q_i$ and $\nu\nu$:

$$\Gamma_{Z'} \geq M_{Z'}/(24\pi)\left(g_\nu^2 + 3N\left\{\left(g_u^V\right)^2 + \left(g_d^V\right)^2\right\}\right)$$

Considering narrower Z' makes the constraint stronger, while broader Z' implies non-perturbativity

Traditional EFT analyses at the LHC using four-fermion operators will typically not be valid, at least having simple/minimal UV completions in mind.

Complementarity between LHC and neutrino experiments



Babu, Gonçalves, **SJ**, Machado (2020)
Coloma et al. (2016) , Liao et al. (2016)

Differently from the LHC, the effects of NSIs in neutrino oscillations strongly depend on the flavor structure of the NSI and the oscillation channel being studied.

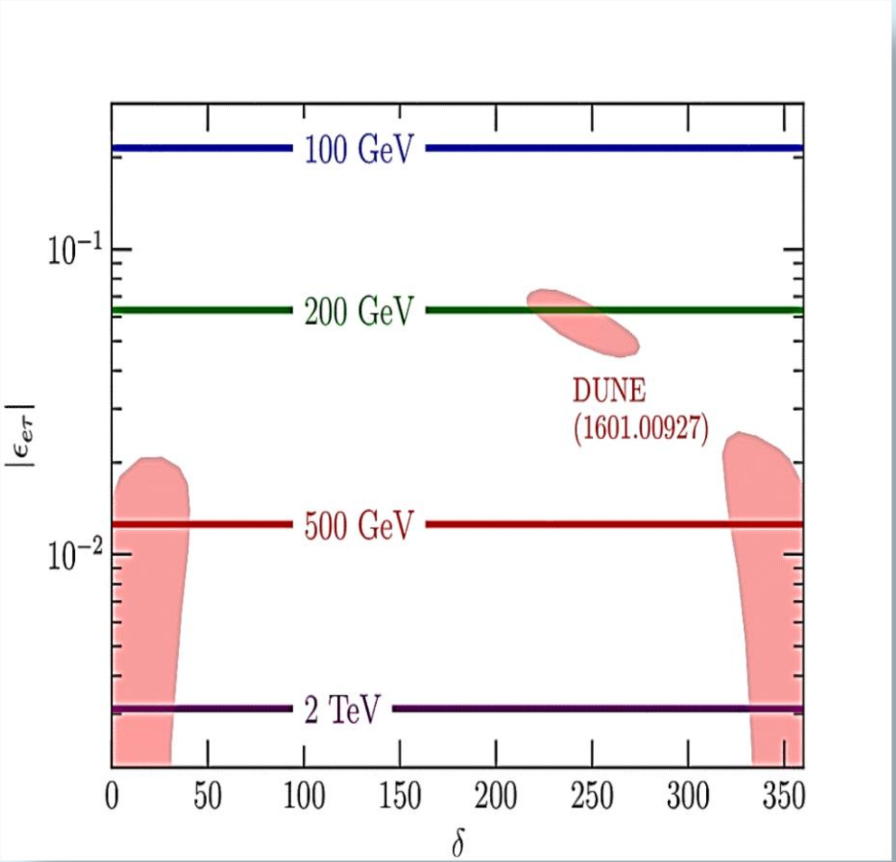
The effects of different NSIs and/or variations of the standard oscillation parameters can, in some cases, compensate each other and lead to well known degeneracies.

Disentangling those is a difficult task at neutrino facilities.

In contrast, the mono-jet signal at the LHC, does not distinguish between different choices of flavors

Besides constraining the currently allowed NSI parameter space, this feature can be further exploited to break relevant degeneracies.

Complementarity between LHC and neutrino experiments



Babu, Gonçalves, **SJ**, Machado (2020)
Coloma et al. (2016) , J. Liao et al. (2016)

*The **LHC** sensitivity displays a **strong dependence** on the **mediator mass**, but it is **free of parameter degeneracies**.*

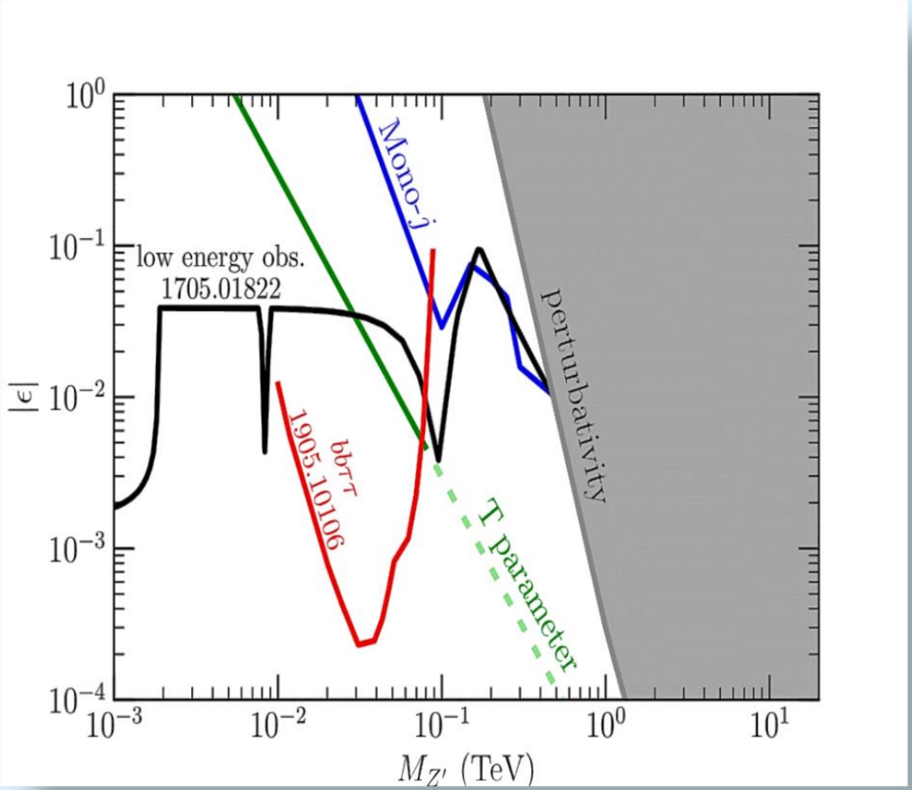
Neutrino oscillation** measurements, on the other hand, exhibit the opposite behavior: **significant degeneracies** and **no mediator mass dependence.

*The matter potential induced when neutrinos travel through a medium is not affected by a diagonal, universal contribution (as this just induces an overall phase shift on the neutrino state). On the other hand, **LHC** data is **sensitive to each and all NSI parameters independently**.*

Neutrino oscillations** are **not sensitive to axial interactions**, while **LHC** data is **sensitive to both vector and axial new physics contributions.

All these features show the synergies between oscillation measurements and collider data on probing new physics in the neutrino sector.

Towards a UV complete scenario



K.S. Babu, D. Gonçalves, **SJ**, P.A.N. Machado (2020)

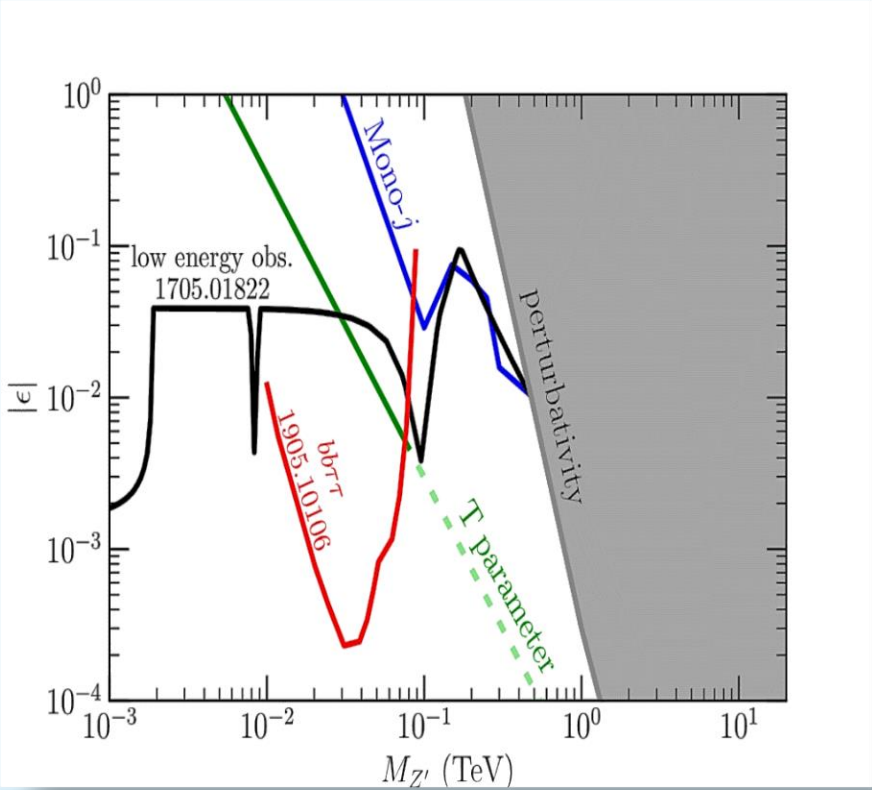
*Any **UV complete model** of neutrino NSI is expected to provide a more extensive phenomenology, especially since neutrinos are in the same $SU(2)_L$ doublet as charged leptons.*

In this UV completion the $B - L$ number is gauged, but only for the third family.

Heavy mediators are strongly constrained by LHC data.

Low mediators constrained by low-energy experiments.

Towards a UV complete scenario



Babu, Gonçalves, **SJ**, Machado (2020)
Babu, Friedland, Machado, Mocioiu (2017)
Elahi, Martin (2019)

Low energy constraints, dedicated LHC searches, and missing energy signatures provide strong constraints for different masses of the mediator.

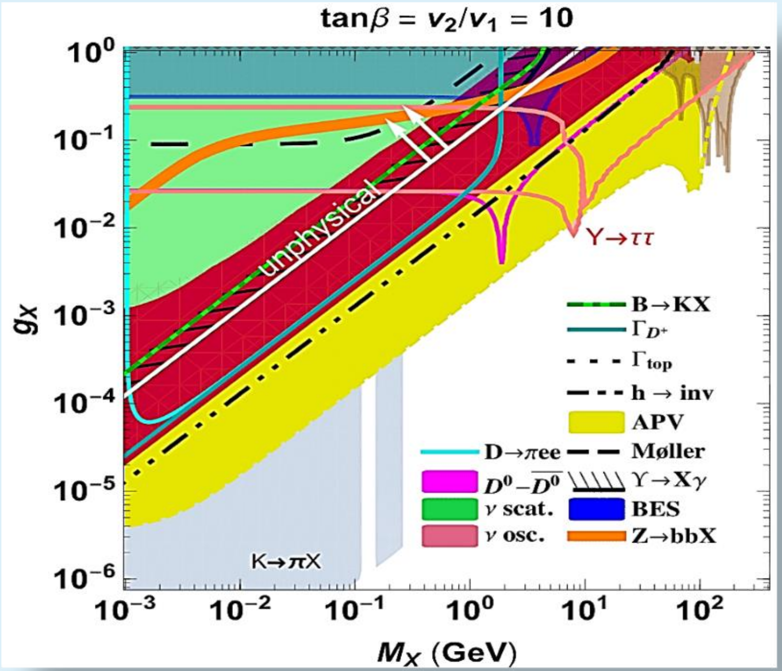
*For masses **below about 10 GeV**, low energy observables tend to dominate.*

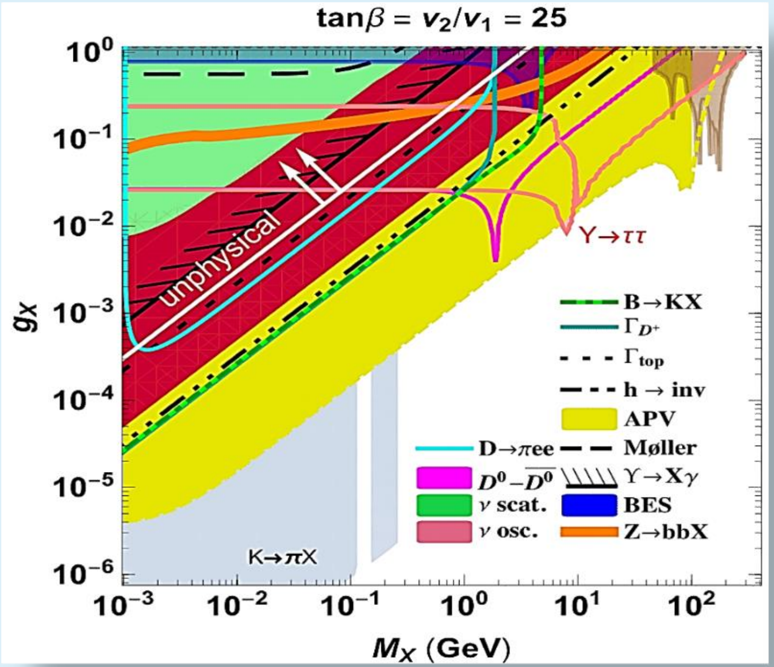
*In the intermediate regime **10 − 100 GeV**, dedicated searches for visible signatures at the LHC become more relevant.*

*Finally, from **0.1 − 1 TeV** LHC mono-jet searches, low energy observables and electroweak precision observables (up to the T parameter model dependence) play the leading role.*

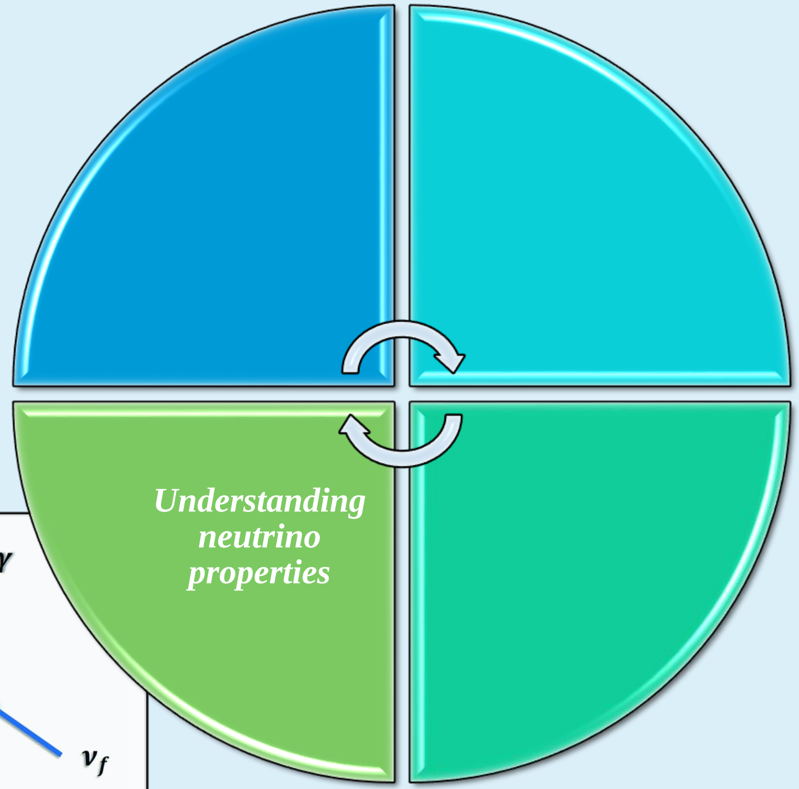
This makes manifest the complementarities among collider data, oscillation measurements, and other low energy observables.

Towards a UV complete scenario

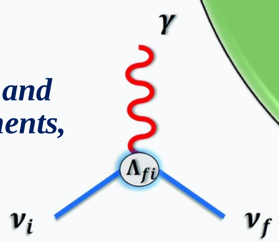




Babu, Gonçalves, **SJ**, Machado (2020)



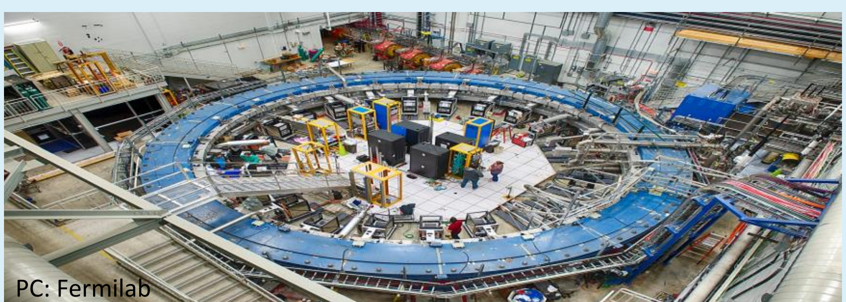
- *Neutrino magnetic and electric dipole moments, charge-radius*



Muon magnetic moment

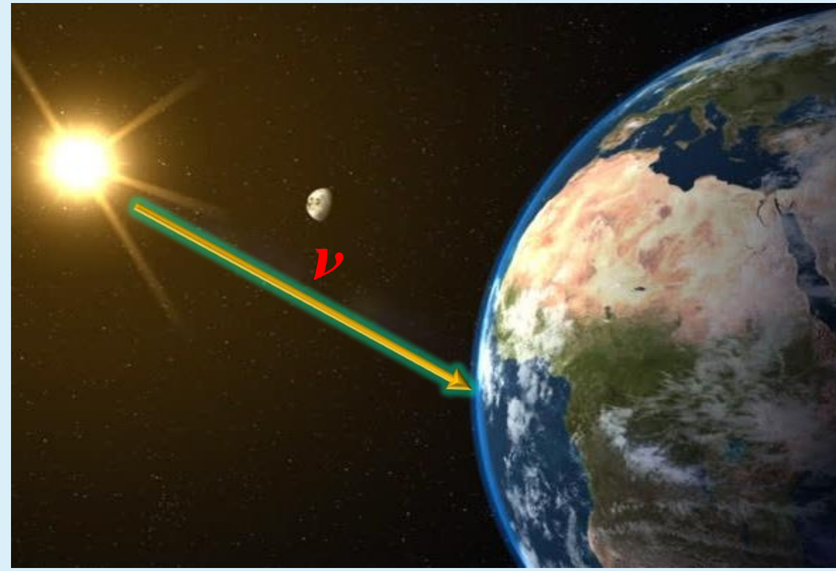
- Here, thousands of muons zip around an giant ~ 50 ft circular magnet at close to the speed of light.
- After making a few hundred laps in less than a millisecond, the muons decay and are soon replaced by another bunch.
- To understand the properties of muon: Specifically, to know about the muons' "**magnetic moment**"—

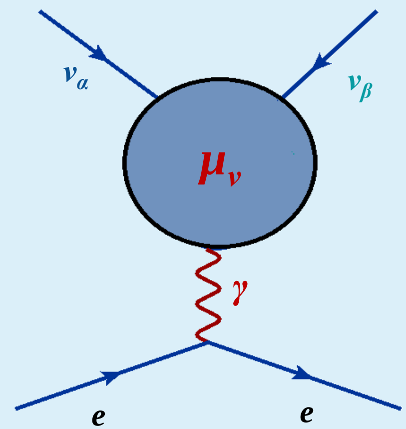
How much do they rotate on their axes in a powerful magnetic field— as they race around the magnet?

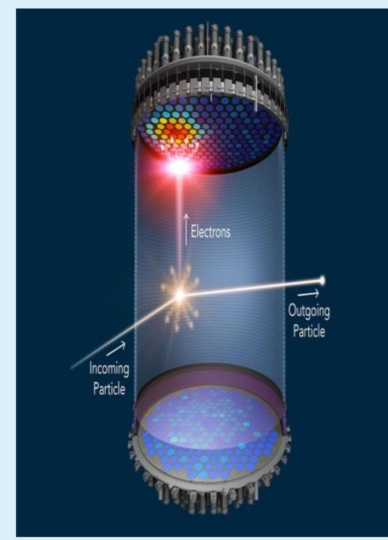


PC: Fermilab

Neutrino magnetic moment







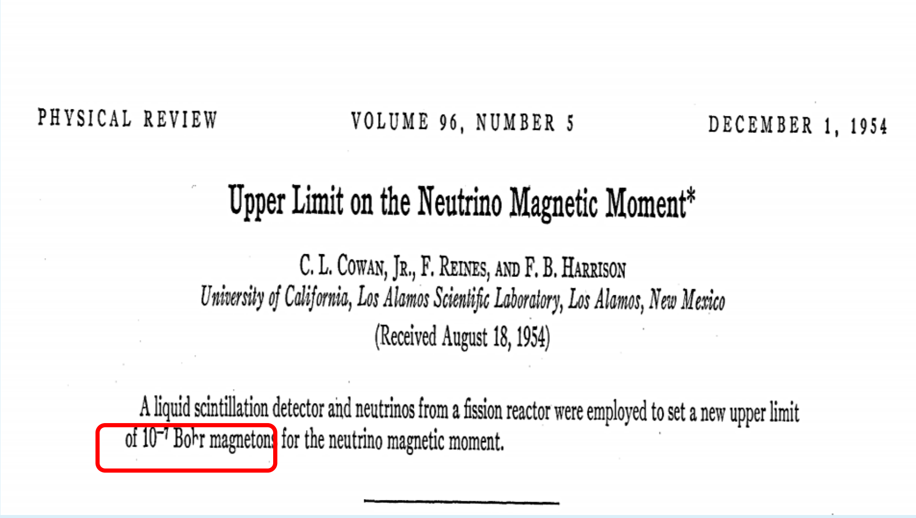
PC: XENON collaboration

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.*

Frederick Reines



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
University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico
(Received August 18, 1954)

A liquid scintillation detector and neutrinos from a fission reactor were employed to set a new upper limit of 10^{-7} Bohr magnetons for the neutrino magnetic moment.

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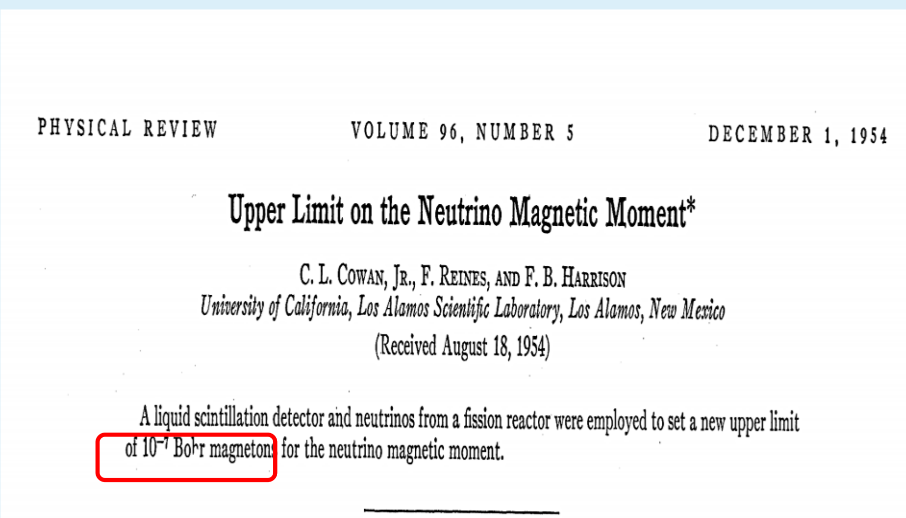

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Reactor based experiments

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

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

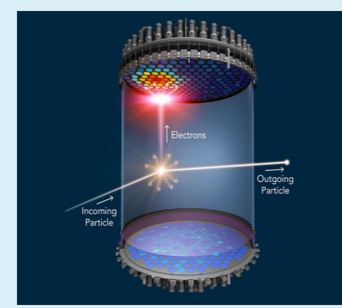
285 events observed

vs.

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

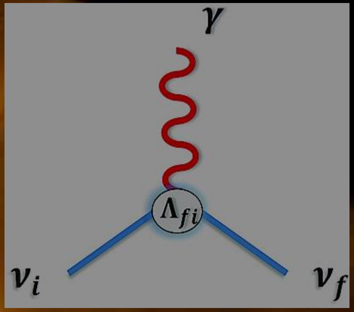
Would be a 3.5σ fluctuation

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



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

Neutrino Magnetic Moments: 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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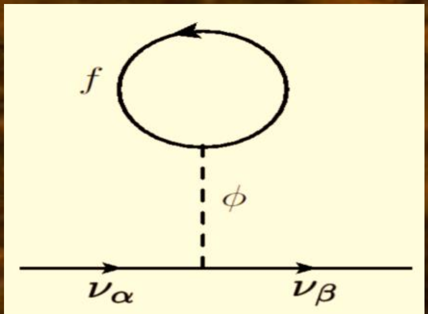
Neutrino Trapping Mechanism

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



$$\mathcal{L} \supset -\frac{y_{\alpha\beta}}{2}\overline{\nu_\alpha^c}\phi\nu_\beta - y_f \bar{f}\phi f - \frac{m_{\alpha\beta}}{2}\overline{\nu_\alpha^c}\nu_\beta - \frac{m_\phi^2}{2}\phi^2$$

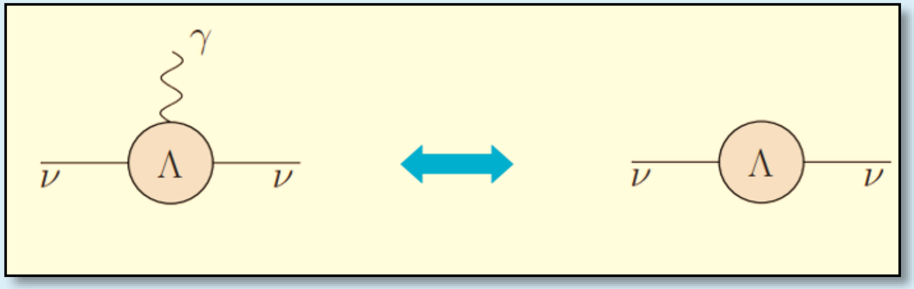
- *We closely follow the recent field theoretic evaluation of the* ***medium-dependent mass of the neutrino*** *in the presence of a light scalar that also couples to ordinary matter in illustrating our mechanism. Such interactions would provide the neutrino with a matter-dependent mass.*

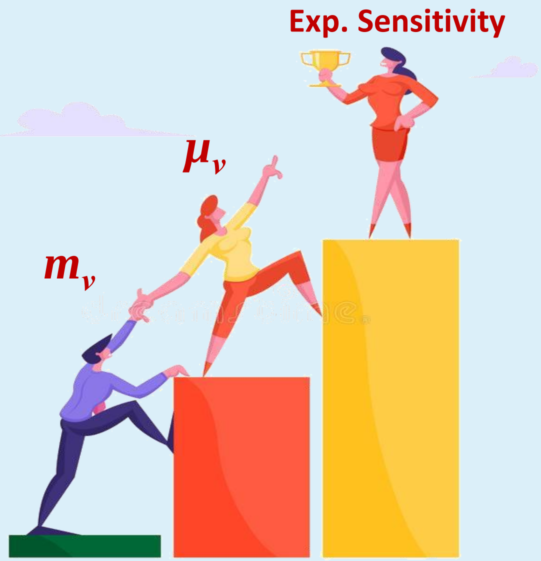
- *Phenomenological implications of this scenario, including* ***long-range force effects****, were studied and phenomenological constraints from laboratory experiments,* ***fifth force experiments****,* ***astrophysics and cosmology*** *are analyzed. [Parke et al. (2018), Smirnov et al.(2019), Babu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

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

Background courtesy: NASA

Neutrino magnetic moment – mass conundrum





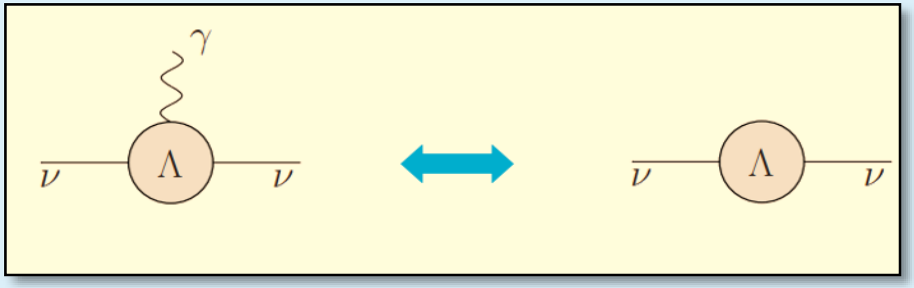
*In **the absence of additional symmetries (and without severe fine-tuning)** one would expect **neutrino masses several orders of magnitude larger than their measured values**., if $\mu_\nu \sim 10^{-11}\,\mu_B$*

*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:

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

Neutrino magnetic moment – mass conundrum



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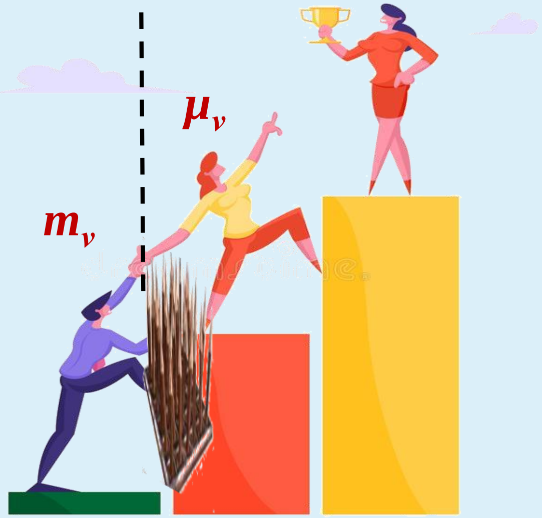


*This **magnetic moment–mass conundrum** was well recognized **three decades ago** when there was great interest in explaining **the apparent time variation of solar neutrino flux detected by the Chlorine experiment in anti-correlation with the Sun-spot activity**.*

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.

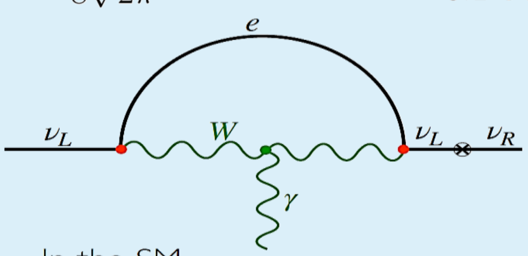
Neutrino magnetic moment – mass conundrum

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

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

K. Fujikawa and R. Shrock (1980)

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

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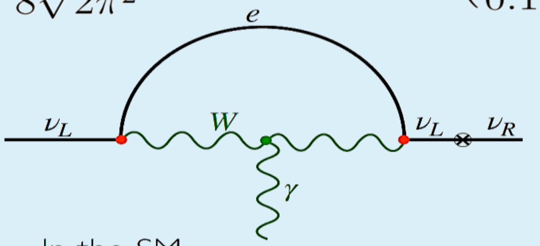

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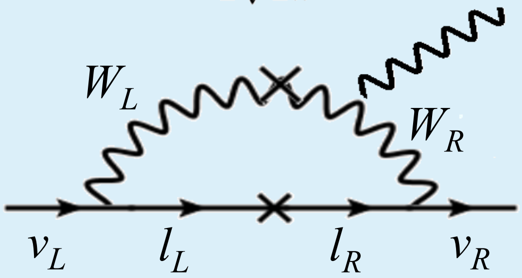
Left-Right Symmetric Model

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

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



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

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

Czakon, Gluza, Zralek (1999)

Giunti and A. Studenikin (2014)

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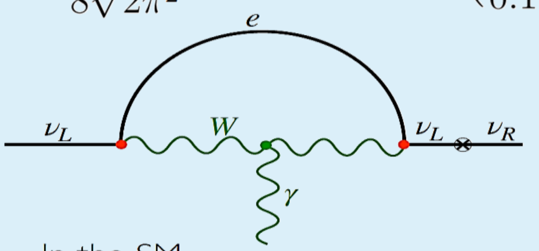

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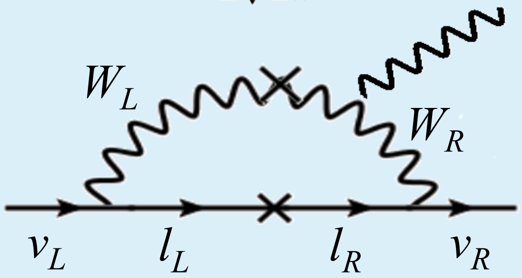

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$$\mu_\nu \sim \lambda'^2/(16\pi^2) m_\ell^2 A_\ell / M_{\tilde{\ell}}^4$$

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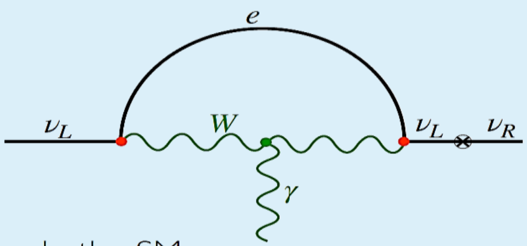

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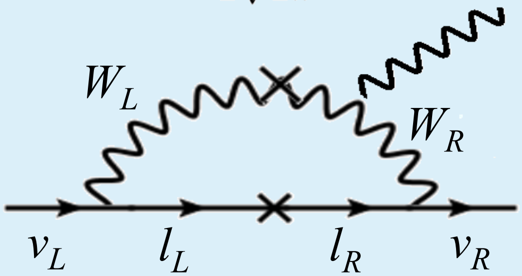

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Majorana scenario

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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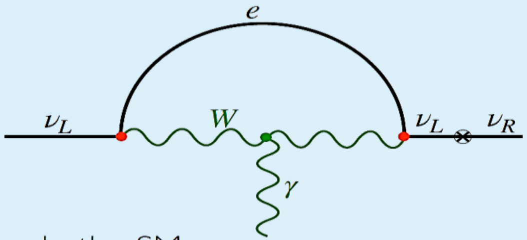

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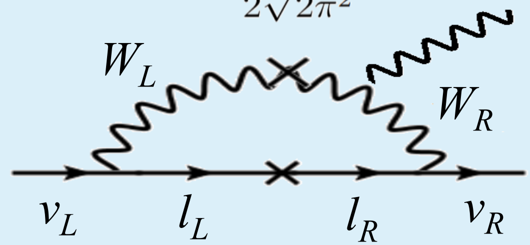

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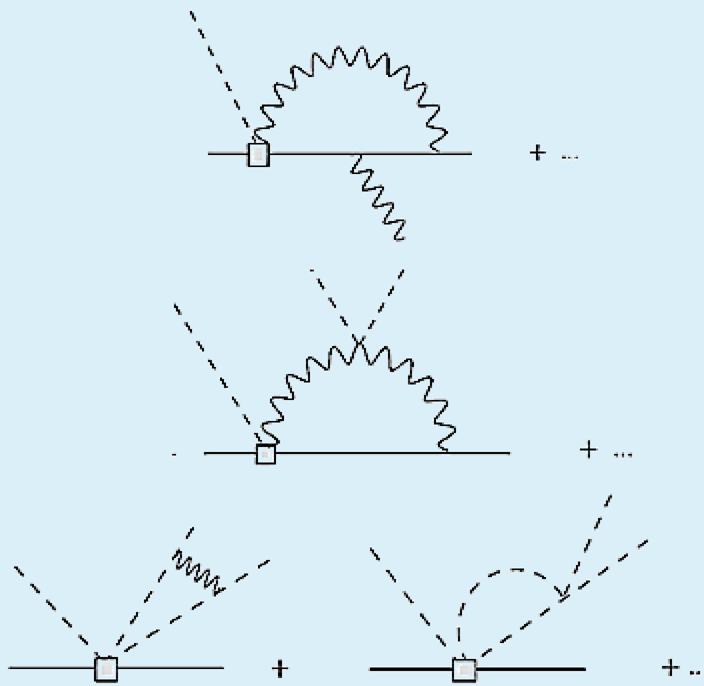
P. B. Pal and L. Wolfenstein (1982)

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

Naturalness and Dirac / Majorana NMM



$$\mathcal{O}_4^{(6)} = \bar{L}\overleftarrow{D}_\mu^\dagger \overleftarrow{D}^{\mu\ \dagger}\tilde{\phi}\nu_R$$
$$\mathcal{O}_5^{(6)} = \bar{L}\overleftarrow{D}_\mu^\dagger \tilde{\phi}\partial^\mu \nu_R$$
$$\mathcal{O}_6^{(6)} = \bar{L}\tau^a\tilde{\phi}\nu_R\,(\phi^\dagger\tau^a\phi)$$

Other n = 6 operators that one can write down are either related by the equations of motion or do not couple to $F\mu\nu$ after SSB.

$$\mathcal{L}_{\rm eff} = \sum_{n,j} \frac{C_j^n(\mu)}{\Lambda^{n-4}}\, \mathcal{O}_j^{(n)}(\mu) \; + \; \text{h.c.}$$

A neutrino magnetic moment coupling would be generated by gauge-invariant, dimension six operators that couple the matter fields to the $SU(2)_L$ and $U(1)_Y$ gauge fields

$$\mathcal{O}_1^{(6)} = g_1\bar{L}\tilde{\phi}\sigma^{\mu\nu}\nu_R B_{\mu\nu}$$
$$\mathcal{O}_2^{(6)} = g_2\bar{L}\tau^a\tilde{\phi}\sigma^{\mu\nu}\nu_R W^a_{\mu\nu}$$
$$\mathcal{O}_3^{(6)} = \bar{L}\tilde{\phi}\nu_R\,(\phi^\dagger\phi) \quad ,$$

After SSB:
$$\mathcal{O}_1^{(6)} \to \frac{v}{\sqrt{2}} g_1\bar{\nu}_L\sigma^{\mu\nu}\nu_R B_{\mu\nu}$$
$$\mathcal{O}_2^{(6)} \to g_2\frac{v}{\sqrt{2}}\bar{\nu}_L\sigma^{\mu\nu}\nu_R W^3_{\mu\nu} + \cdots$$
$$-\frac{\mu_\nu}{4}\bar{\nu}\sigma^{\mu\nu}\nu F_{\mu\nu}$$

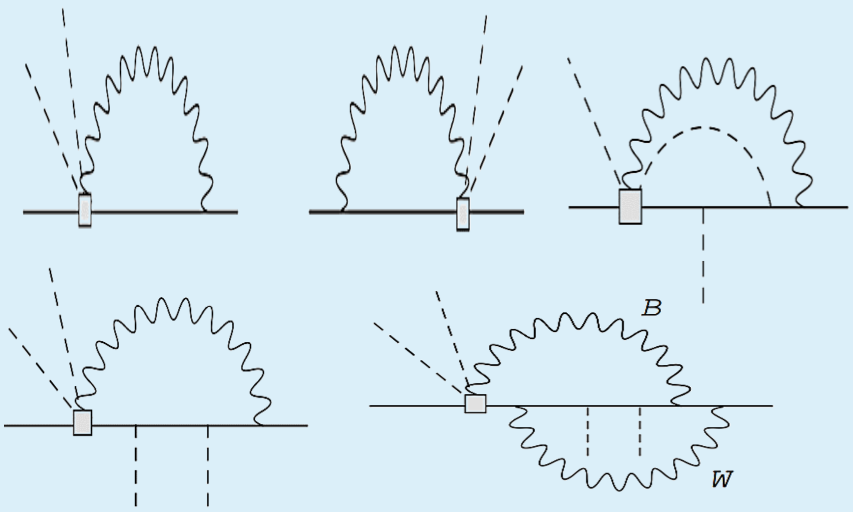
$$\frac{\mu_\nu}{\mu_B} = -4\sqrt{2}\left(\frac{m_e v}{\Lambda^2}\right)\left[C_1^6(v) + C_2^6(v)\right]$$

$$\delta m_\nu = -C_3^6(v)\frac{v^3}{2\sqrt{2}\Lambda^2}$$

$$\boxed{\frac{|\mu_\nu|}{\mu_B} \lesssim 8\times 10^{-15}\times\left(\frac{\delta m_\nu}{1\text{ eV}}\right)}$$

Bell et al. (2005)

Naturalness and Dirac / Majorana NMM



$$\frac{1}{2}\,[\mu_\nu]_{\alpha\beta}\;\overline{\nu^c}_\alpha\sigma^{\mu\nu}\nu_\beta F_{\mu\nu},$$

The neutrino magnetic moment operator must be generated by gauge invariant operators involving the $SU(2)_L$ and $U(1)_Y$ gauge field

$$\begin{aligned}[O_B]_{\alpha\beta} &= g'\,(\overline{L^c}_\alpha\epsilon H)\,\sigma^{\mu\nu}\,(H^T\epsilon L_\beta)\,B_{\mu\nu},\\ [O_W]_{\alpha\beta} &= g\,(\overline{L^c_\alpha}\epsilon H)\,\sigma^{\mu\nu}\,(H^T\epsilon\tau^a L_\beta)\,W^a_{\mu\nu}.\end{aligned}$$

$$\frac{[\mu_\nu]_{\alpha\beta}}{\mu_B} = \frac{2m_e v^2}{\Lambda^3}\left([C_B(M_W)]_{\alpha\beta} + [C_W^-(M_W)]_{\alpha\beta}\right)$$

Operators O_M are flavor symmetric, while O_B is antisymmetric

$$[O_W^\pm]_{\alpha\beta} = \frac{1}{2}\left\{[O_W]_{\alpha\beta} \pm [O_W]_{\beta\alpha}\right\}$$

$$\begin{aligned}\mathcal{L} &= \frac{C_M^{5D}}{\Lambda}O_M^{5D} + \frac{C_M^{7D}}{\Lambda^3}O_M^{7D}\\ &+\frac{C_B}{\Lambda^3}O_B + \frac{C_W^+}{\Lambda^3}O_W^+ + \frac{C_W^-}{\Lambda^3}O_W^- + \cdots\end{aligned}$$

The neutrino mass operator:

$$\begin{aligned}[O_M^{5D}]_{\alpha\beta} &= (\overline{L^c_\alpha}\epsilon H)\,(H^T\epsilon L_\beta)\\ [O_M^{7D}]_{\alpha\beta} &= (\overline{L^c_\alpha}\epsilon H)\,(H^T\epsilon L_\beta)\,(H^\dagger H)\end{aligned}$$

$$\frac{1}{2}[m_\nu]_{\alpha\beta} = \frac{v^2}{2\Lambda}\left[C_M^{5D}(M_W)\right] + \frac{v^4}{4\Lambda^3}\left[C_M^{7D}(M_W)\right]$$

$$\boxed{\begin{aligned}\mu_{\tau\mu},\mu_{\tau e} &\lesssim 10^{-9}\,[\Lambda(\mathrm{TeV})]^{-2}\\ \mu_{\mu e} &\lesssim 3\times 10^{-7}\,[\Lambda(\mathrm{TeV})]^{-2}.\end{aligned}}$$

The limit on the the magnetic moment of a Dirac neutrino is considerably more stringent than for Majorana neutrino. This is due to the different flavor symmetries involved. In the Dirac case, no insertion of Yukawa couplings is needed to convert a flavor antisymmetric operator into a flavor symmetric operator

Bell et al. (2006)

Davidson et al. (2005)

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.*

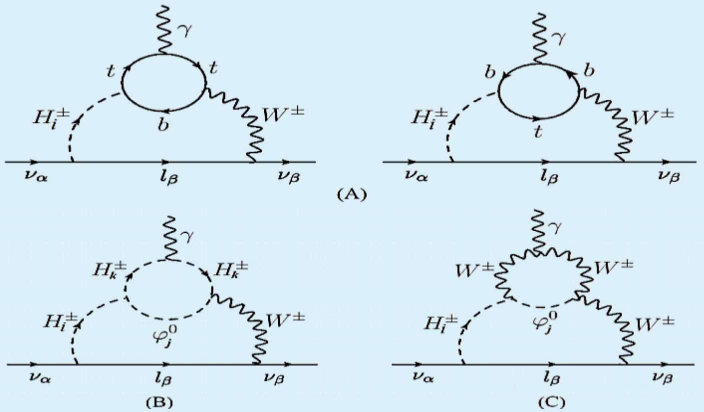
*As for its contribution to m_ν, it is well known that for **transversely polarized vector bosons, the transition from spin 1 to spin 0 cannot occur.** Only the **longitudianl mode, the Goldstone mode, would contribute to such transitions.***

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.

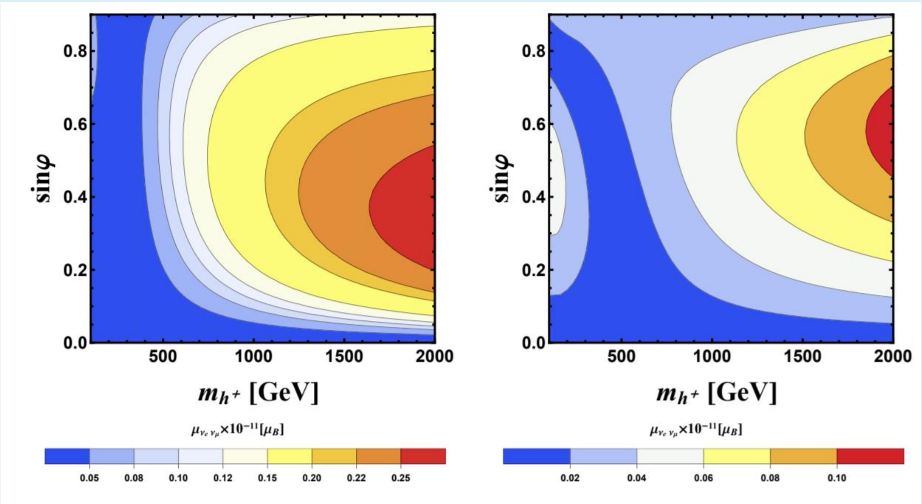
However, the contribution of two-loop graphs for the neutrino transition magnetic moments have not been quantitatively analyzed thus far.

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)

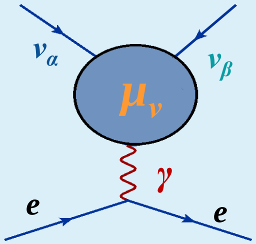


Babu, **SJ,** Lindner (2020)



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.

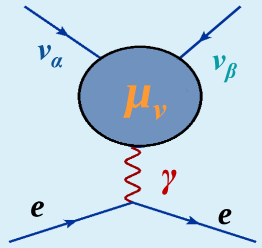
*1989: **Barbieri and R. N. Mohapatra** pointed out that its hard to implement the **Voloshin symmetry** since it does not commute with SM.*

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

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

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:

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

Higgs sector:

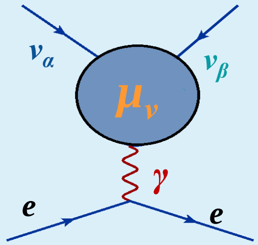
$$\begin{array}{ll}
\phi_S = \begin{pmatrix} \phi_S^+ \\ \phi_S^0 \end{pmatrix} & (2, \frac{1}{2}, 1) \\
\Phi = \begin{pmatrix} \phi_1^+ & \phi_2^+ \\ \phi_1^0 & \phi_2^0 \end{pmatrix} & (2, \frac{1}{2}, 2) \\
\eta = (\eta_1^+ \quad \eta_2^+) & (1, 1, 2) \ .
\end{array}$$

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

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

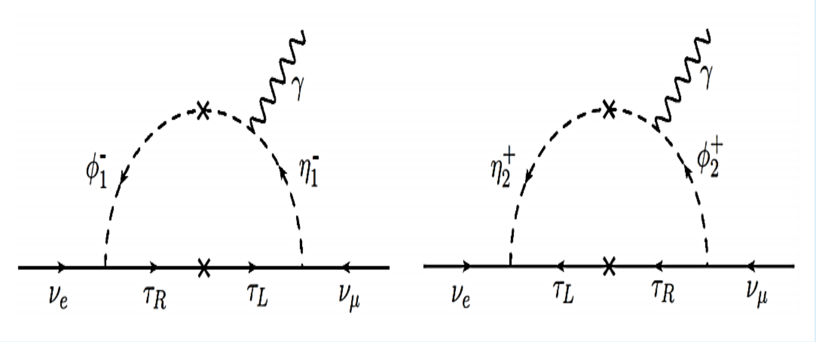


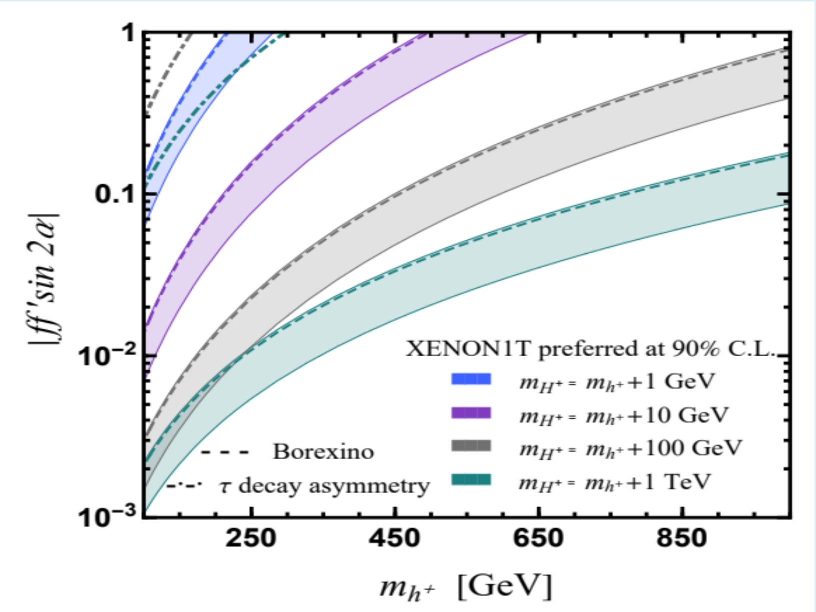
- *The Lagrangian of the model* ***does not respect lepton number****. The $SU(2)_H$ limit of the model however respects $L_e - L_\mu$ symmetry. This allows a nonzero transition magnetic moment, while neutrino mass terms are forbidden.*

- *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****.*

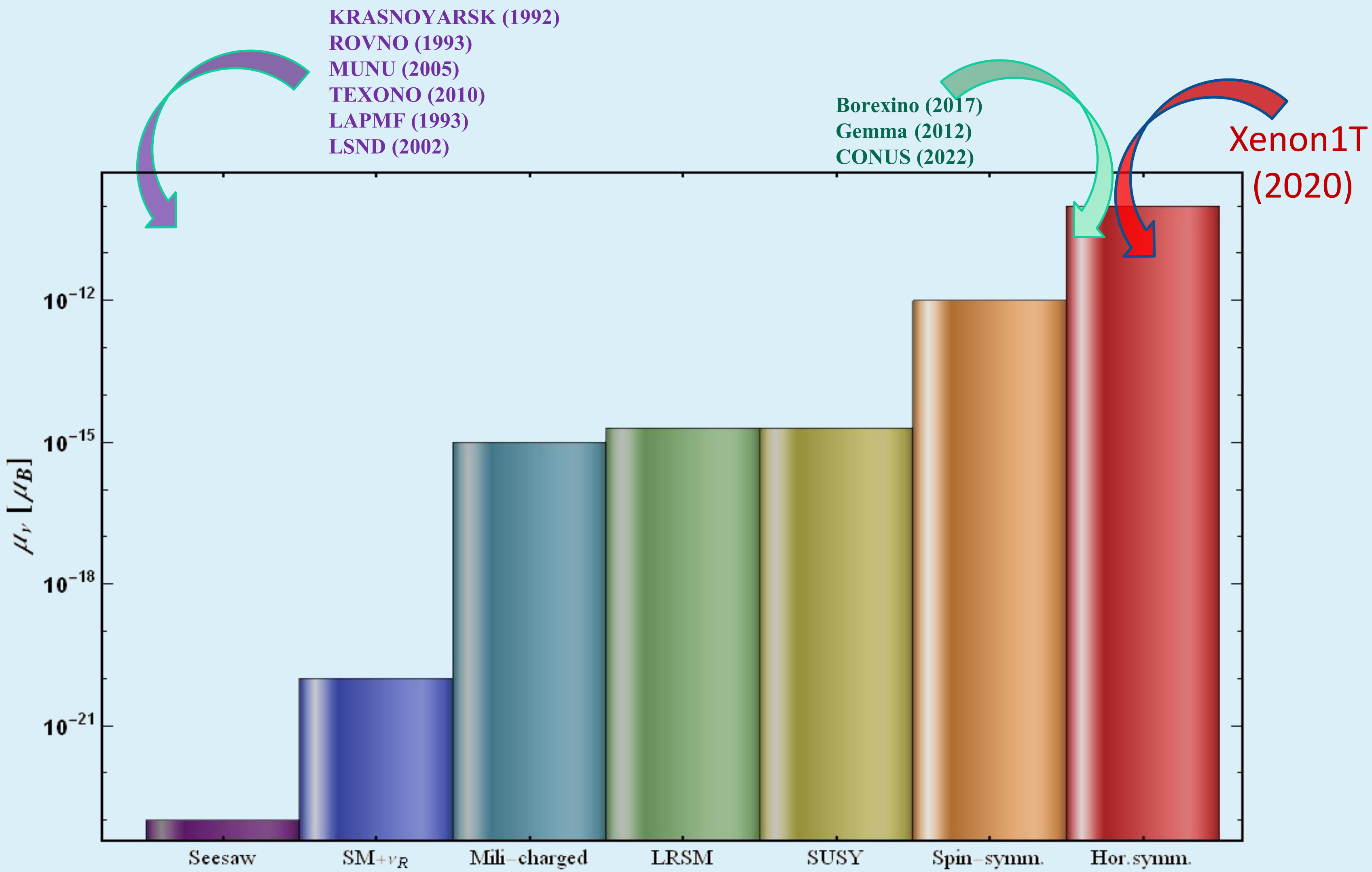
$$\mu_{\nu_e\nu_\mu} = \frac{ff'}{8\pi^2} m_\tau \sin 2\alpha \left[\frac{1}{m_{h^+}^2}\left\{\ln\frac{m_{h^+}^2}{m_\tau^2} - 1\right\} - \frac{1}{m_{H^+}^2}\left\{\ln\frac{m_{H^+}^2}{m_\tau^2} - 1\right\}\right]$$





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

Neutrino Magnetic Moment



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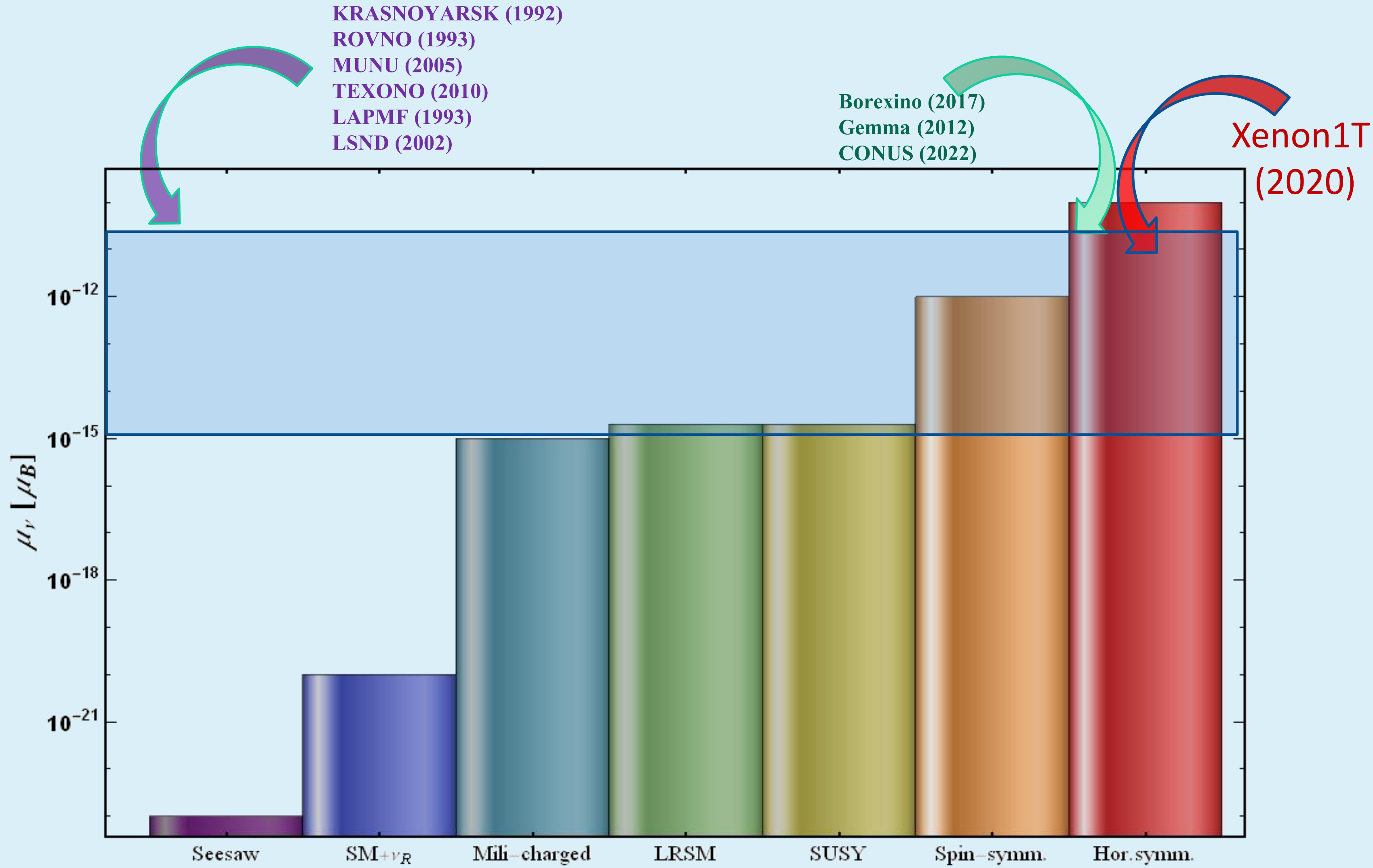
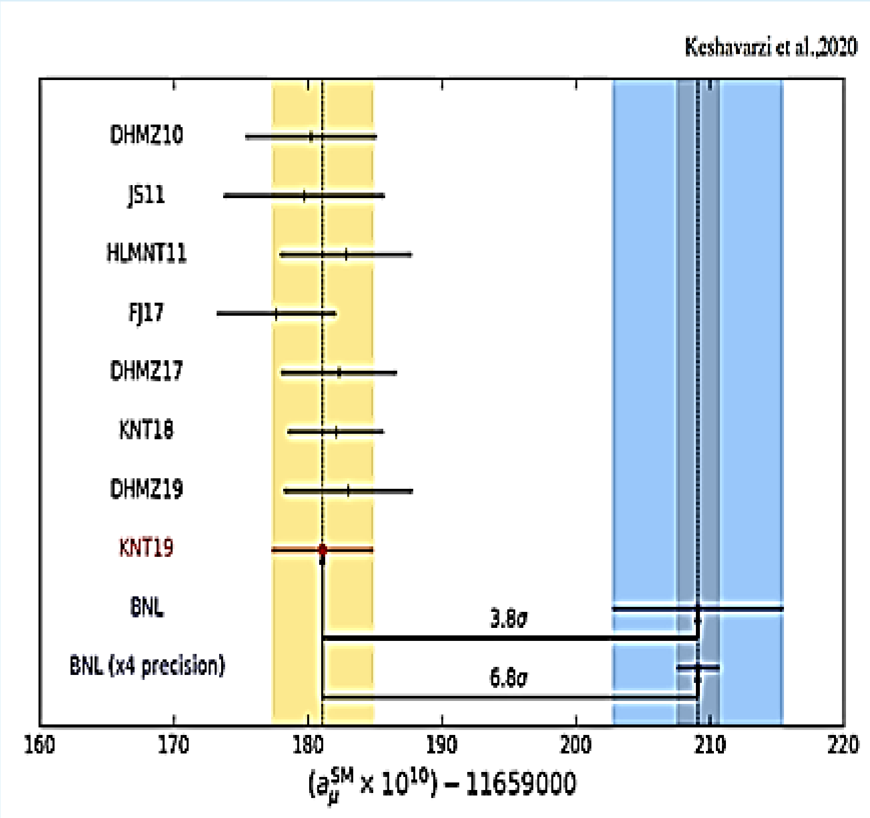
Neutrino Magnetic Moment



Babu, SJ, Lindner (2020)

Muon g-2: experimental status

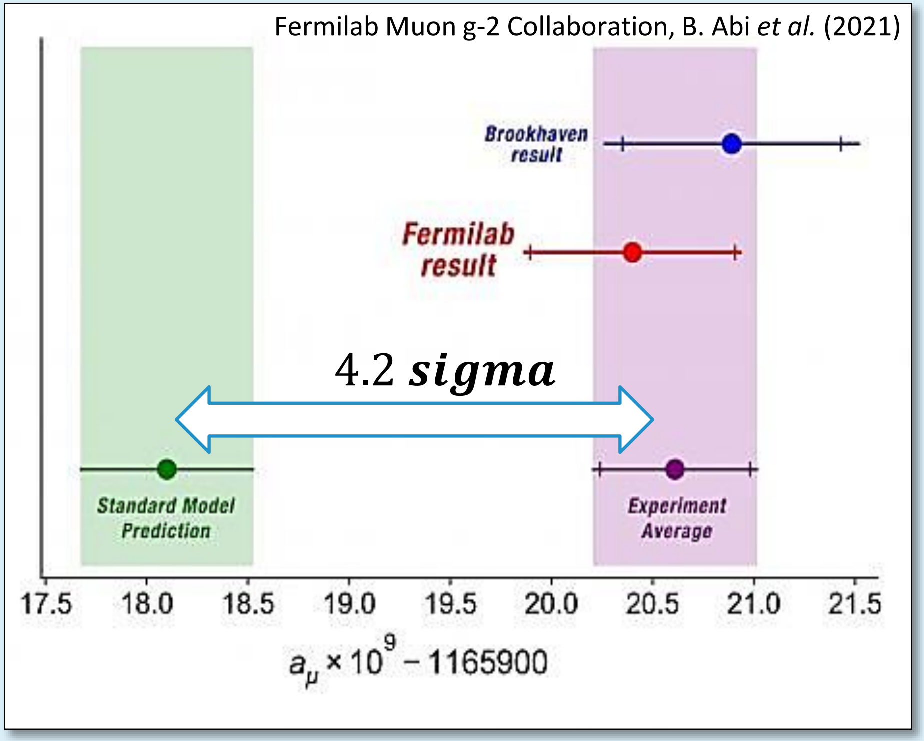
Before Fermilab muon g-2 announcement:



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

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

After Fermilab muon g-2 announcement:

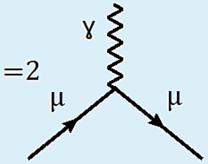


$$10^{11} a_\mu = \begin{cases} 116591810(43) & \textbf{SM} \\ 116592040(54) & \textbf{Exp} \end{cases}$$

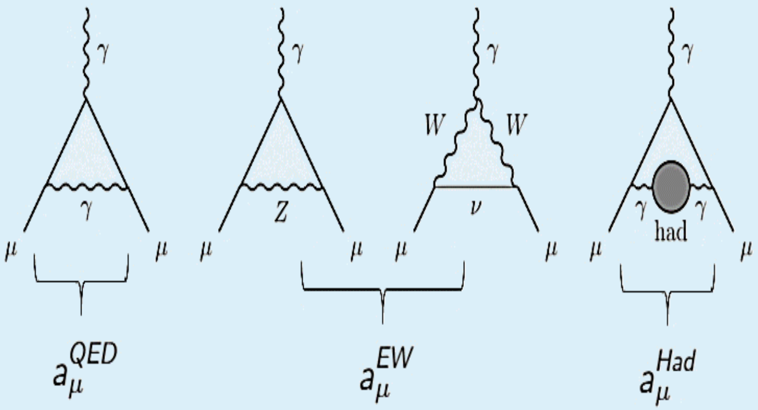
$$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 251(59) \times 10^{-11}$$

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: $a_\mu = \frac{(g-2)_\mu}{2}$

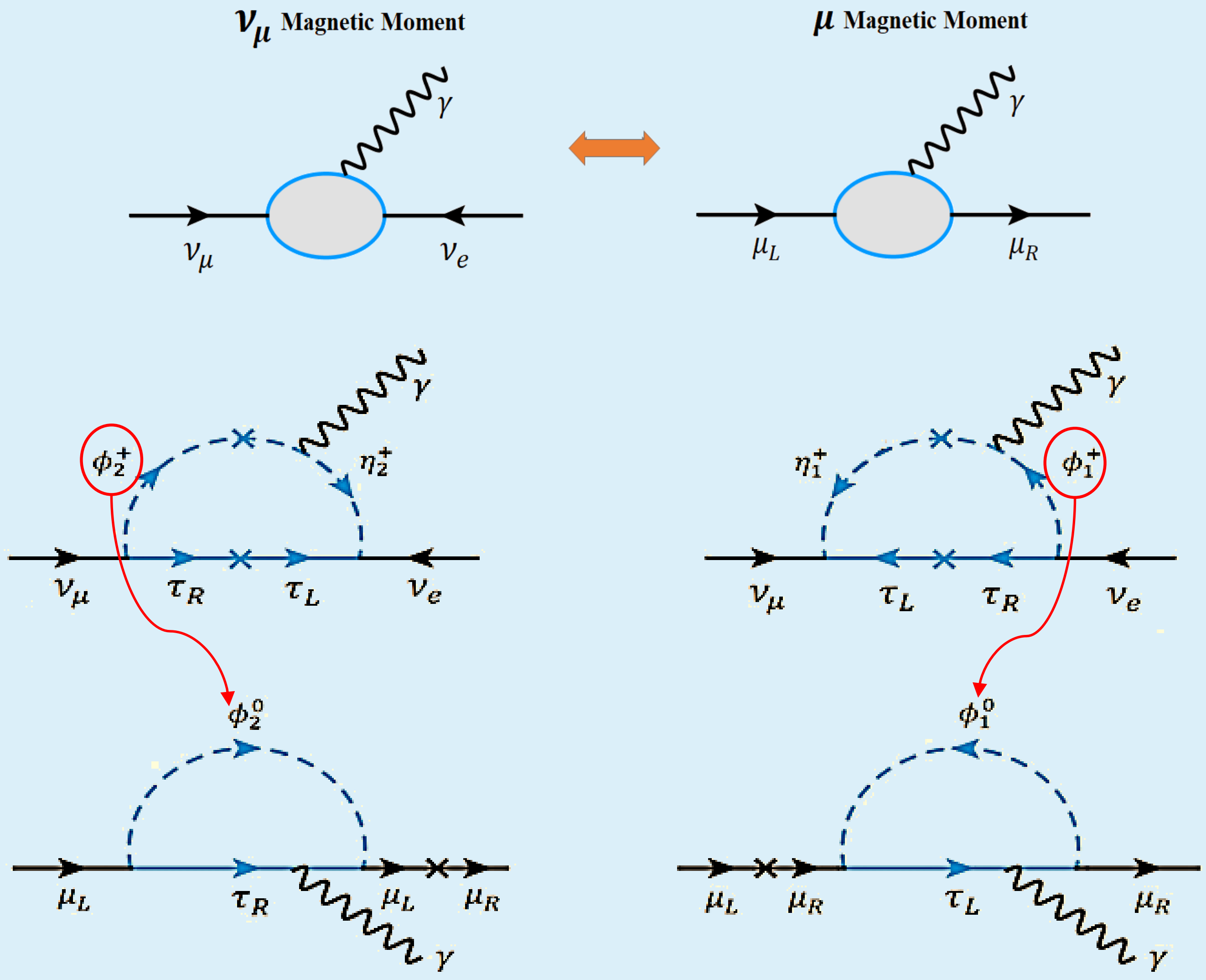


$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{Had}$$

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**

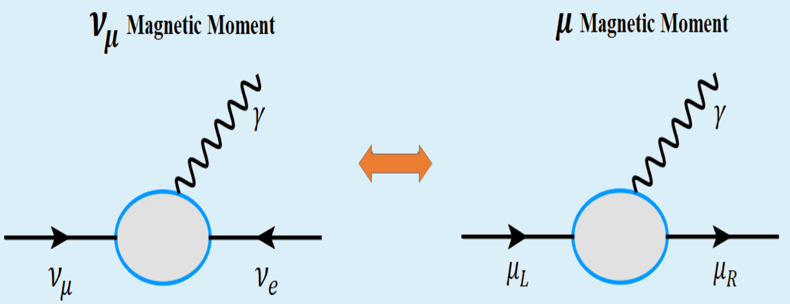
No neutrino magnetic moments in the SM!

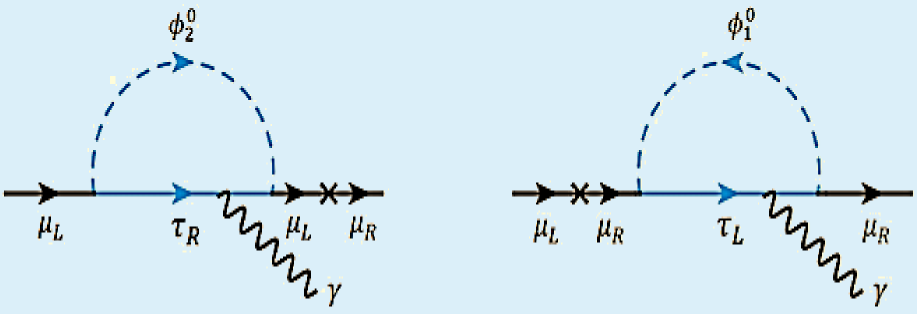
Neutrino magnetic moment – Muon g-2 Anomaly



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

Neutrino magnetic moment – Muon g-2 Anomaly





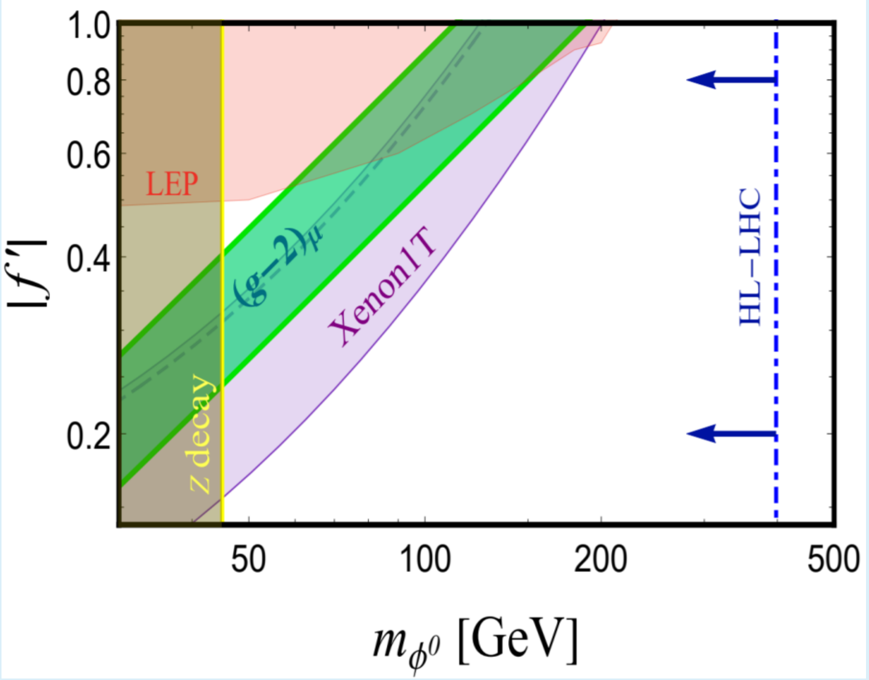
A direct correlation between the neutrino magnetic moment and muon g-2

LFV coupling without Lepton flavor violation

Outside chirality flipping

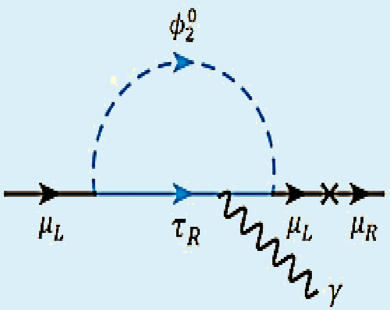
Sign and strength are automatic here, no control over it.

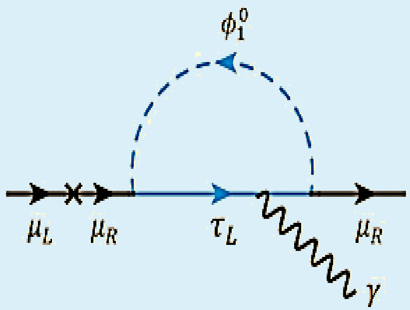
A minimal unified framework for three different components:
μ_ν , m_ν , *muon g-2*

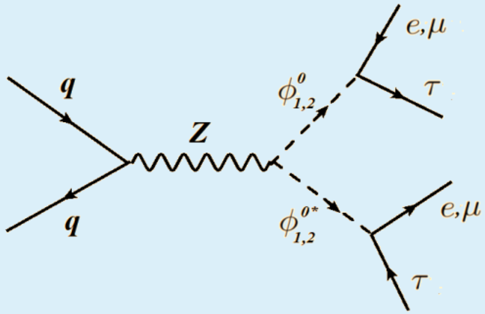


Babu, **SJ,** Lindner, Kovilakam (2021)

Neutrino magnetic moment – Muon g-2 Anomaly







Testable at the upcoming run of LHC

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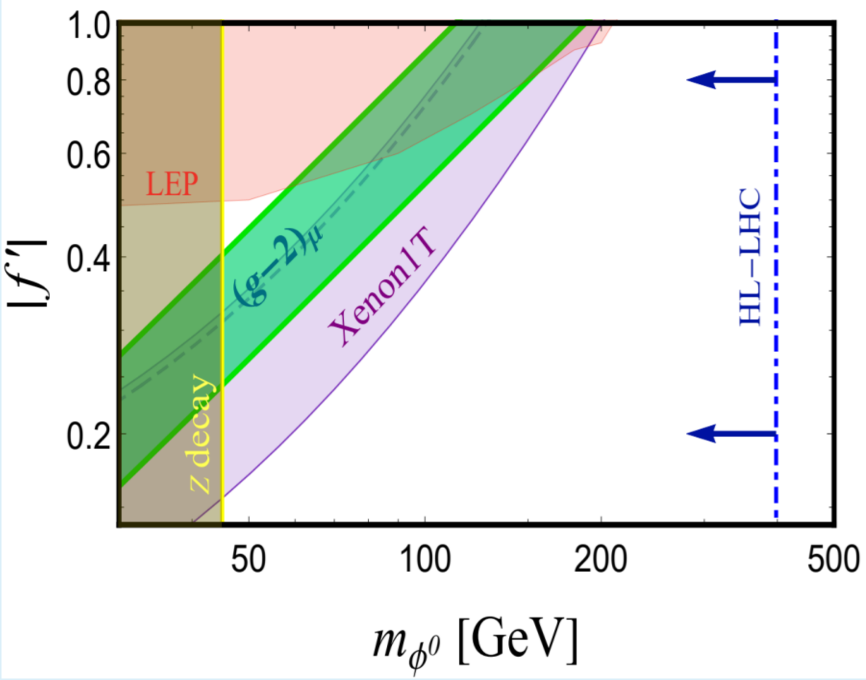
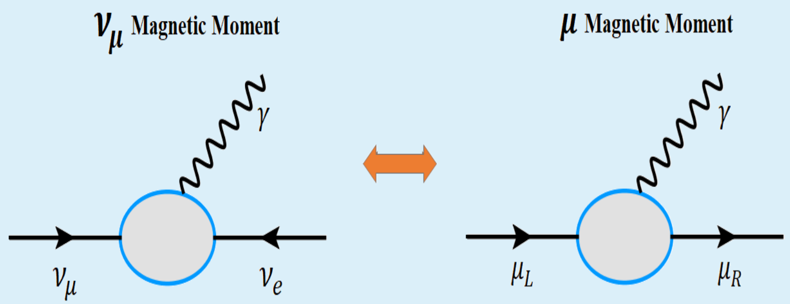


Babu, **SJ,** Lindner, Kovilakam (2021)

Neutrino magnetic moment – Muon g-2 Anomaly



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

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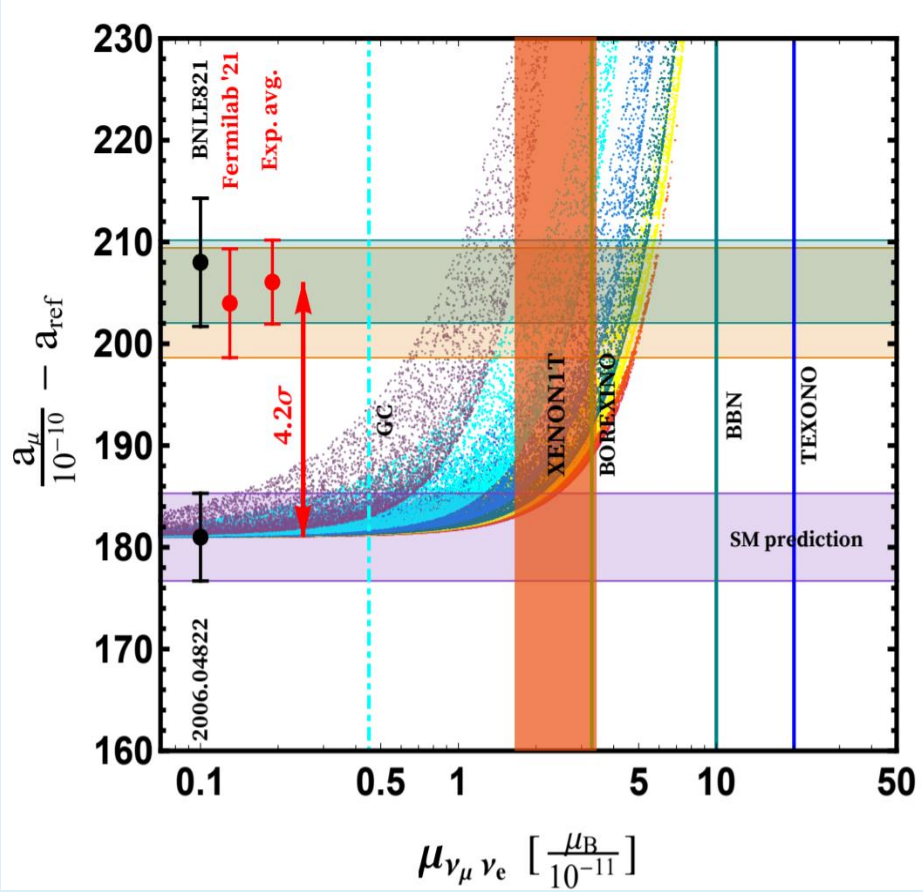
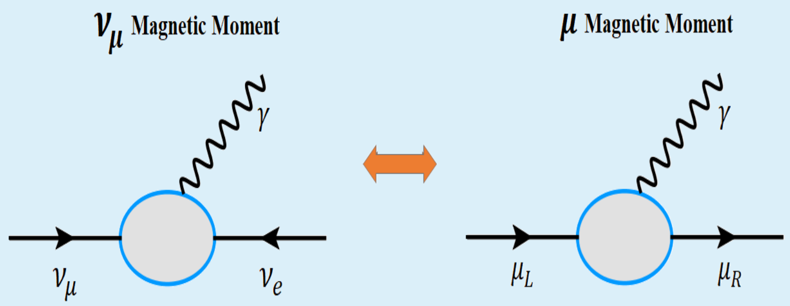
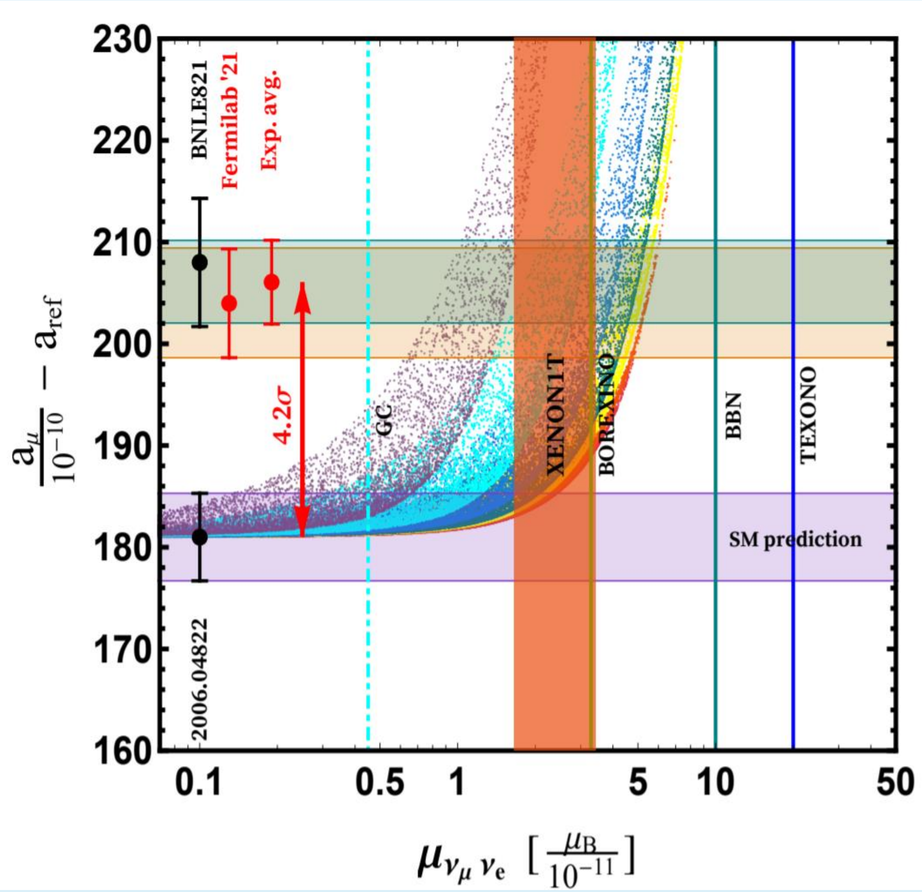
A minimal unified framework for three different components:
Large μ_ν, m_ν, *muon g-2*



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

Neutrino magnetic moment – Muon g-2 Anomaly





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

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A minimal unified framework for three different components:

Large μ_ν, m_ν, *muon g-2*

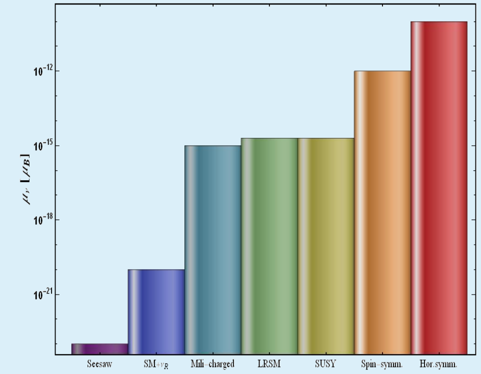
Babu, **SJ,** Lindner, Kovilakam (2021)

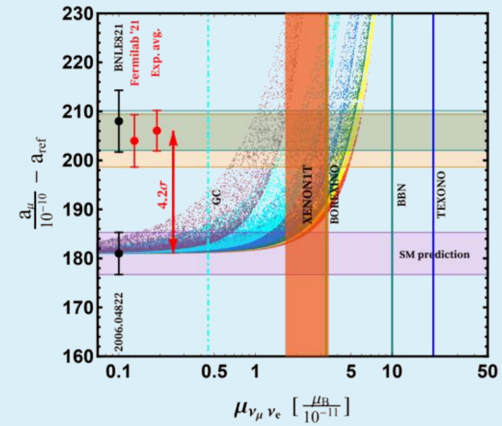
Summary

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

Neutrino trapping mechanism to evade astrophysical limit

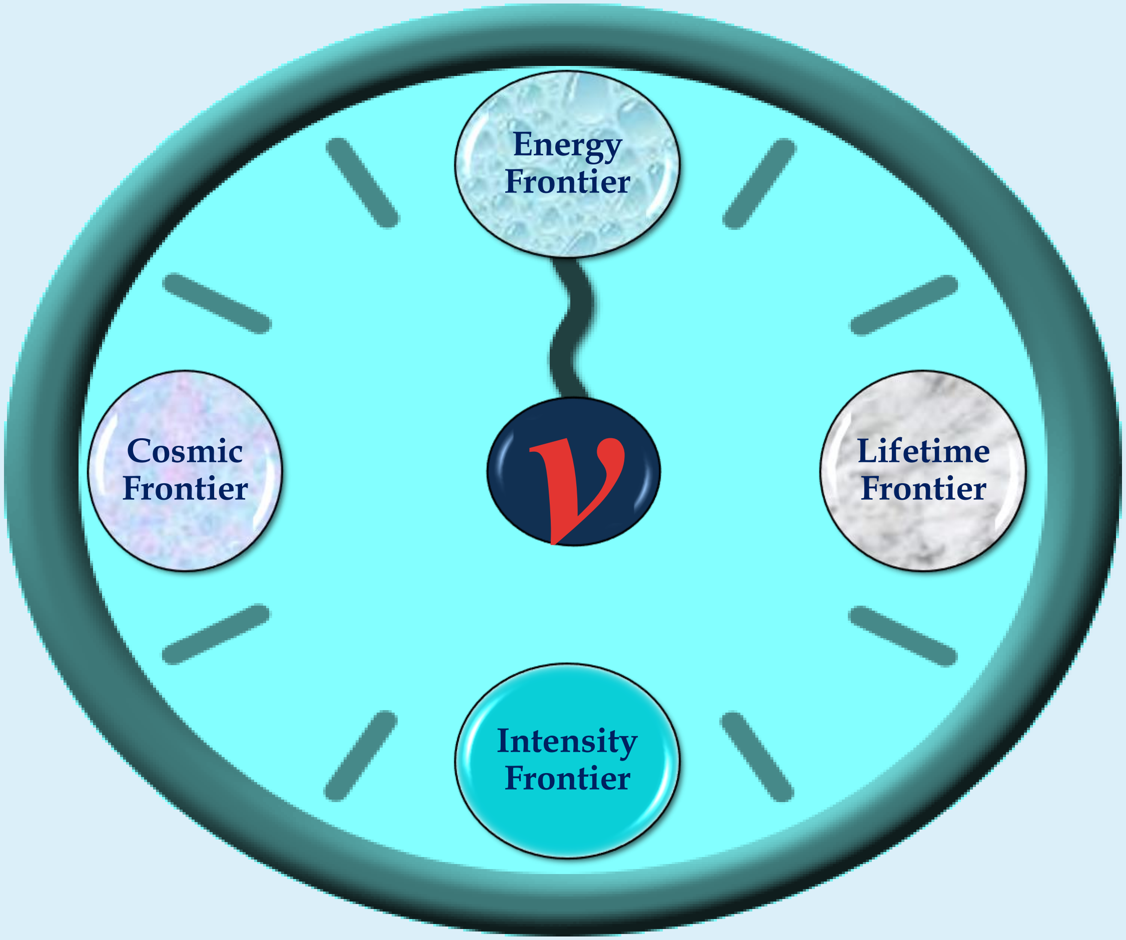
Direct correlation between μ_ν **and** ***muon g-2***





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.

Summary



Energy Frontier
Cosmic Frontier
ν
Lifetime Frontier
Intensity Frontier


Thank you!