Electromagnetic Properties of Neutrinos

Magnetic moments and polarizability

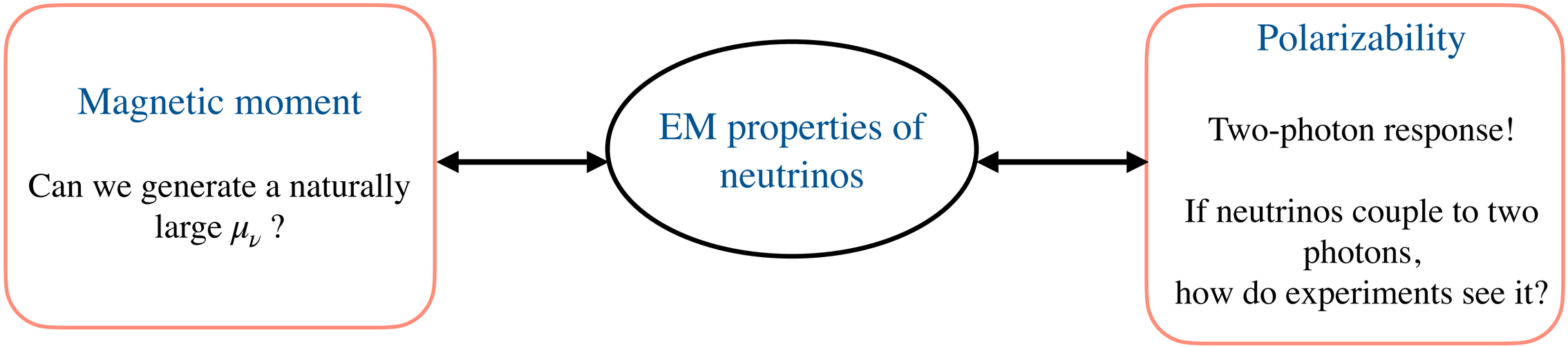
Anil Thapa



Theoretical Astroparticle and Cosmology Symposium in Texas

October 24 2026

This talk is built around the following questions



Pages, **AT**: arXiv: 2506.15777

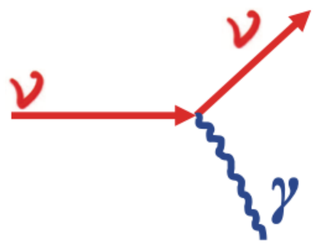
Gehrlein, Shoemaker, **AT**: arXiv: 2506.14881
Gehrlein, **AT**, Thompson: arXiv: 2512.07691

Electromagnetic properties of neutrinos

- Neutrinos are electrically neutral in the SM; they do not have direct couplings to photons.
- Radiative (loop) corrections may induce electromagnetic properties — such as charge radius and magnetic moments — of neutrinos.

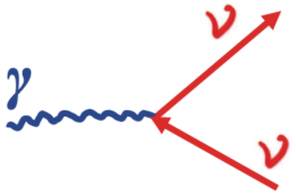
Physical processes with neutrino magnetic moments

Neutrino decay



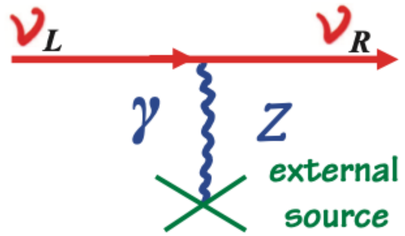
$$\Gamma_{\nu_i \to \nu_f + \gamma} = \frac{1}{8\pi}\left(\frac{m_i^2 - m_f^2}{m_i}\right)^3 \left|\mu_{fi}\right|^2$$

Plasmon decay



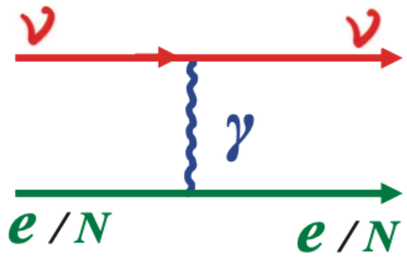
$$\Gamma_{\gamma^* \to \nu\bar{\nu}}\left(\mu_\nu\right) = \frac{\mu_\nu^2}{24\pi} Z \frac{\omega_{\mathrm{P}}^4}{\omega_\gamma}$$

Spin-flavor precession



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

Scattering



$$\left(\frac{d\sigma}{dT_e}\right)_{\mathrm{Tot}} \equiv \left(\frac{d\sigma}{dT}\right)_{\mathrm{SM}} + \left(\frac{d\sigma}{dT}\right)_{\mathrm{mag}}$$

Experimental limits on Neutrino Magnetic Moments

Method	Experiment	Limit [μ_B]	CL	Year
Reactor $\bar{\nu}_e$ EνES	Krasnoyarsk	$\mu_{\nu_e} < 2.4 \times 10^{-10}$	90%	1992
	Rovno	$\mu_{\nu_e} < 1.9 \times 10^{-10}$	95%	1993
	MUNU	$\mu_{\nu_e} < 9 \times 10^{-11}$	90%	2005
	TEXONO	$\mu_{\nu_e} < 7.4 \times 10^{-11}$	90%	2006
	GEMMA	$\mu_{\nu_e} < 2.9 \times 10^{-11}$	90%	2012
	CONUS	$\mu_{\nu_e} < 7.5 \times 10^{-11}$	90%	2022
Solar EνES	LUX-ZEPLIN (74)	$\mu_{\nu_e} < 1.5 \times 10^{-11}$ $\mu_{\nu_\mu} < 2.3 \times 10^{-11}$ $\mu_{\nu_\tau} < 2.1 \times 10^{-11}$	90%	2022
	XENONnT (71)	$\mu_{\nu_e} < 9.0 \times 10^{-12}$ $\mu_{\nu_\mu} < 1.5 \times 10^{-11}$ $\mu_{\nu_\tau} < 1.3 \times 10^{-11}$	90%	2022
	LUX-ZEPLIN (74) + PandaX-4T (78) +	$\mu_S^{\mathrm{LE}} < 7.5 \times 10^{-12}$ $\mu_{\nu_e} < 1.0 \times 10^{-11}$	90%	2023

list is not exhaustive

- The energy loss of the red giant branch in the globular cluster provides the most stringent limit of $\mu_{\mathrm{astro}} < 4.5 \times 10^{-12} \mu_B$

Viaux ++, ‘13

[see the review by Giunti, Studenikin, ’24]

Experimental limits on Neutrino Magnetic Moments

- Current experiments reach sensitivity of order $\mu_\nu \sim 10^{-11}\ \mu_B$
- Generally any extension of SM: $\mu_\nu < 10^{-19}\mu_B$
- Gap of 8 orders of magnitude

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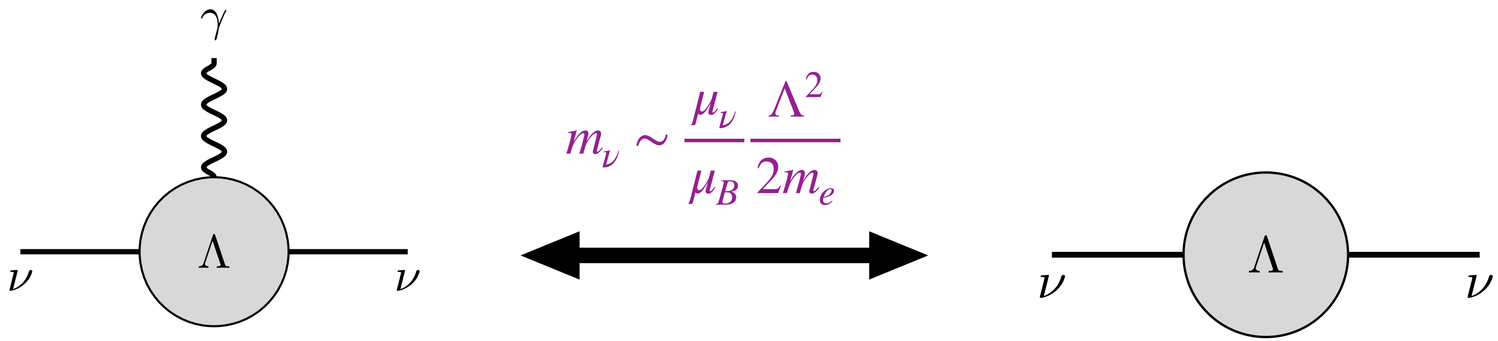
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$\mu_\nu - m_\nu$ conundrum: general argument

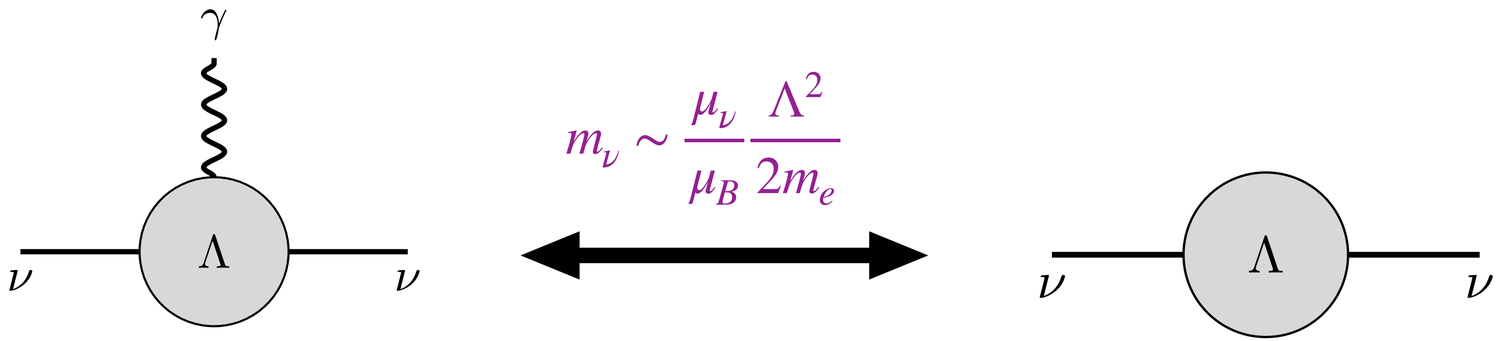
- The neutrino magnetic operator and mass are both chirality-flipping operator
- The effective vertex that generates the dipole operator (neutrino magnetic moment) in any EFT in general give rise to neutrino masses **once the photon line is removed.**



Λ is the new physics scale; mass of heavy particles running inside the loop

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Λ is the new physics scale; mass of heavy particles running inside the loop

- At least one new particle running inside the loop must be at the $\mathcal{O}$ (100) GeV scale or above

$\Longrightarrow$ leads to the naturalness bound $\mu_\nu \lesssim 10^{-19}\mu_B \left(\frac{\delta m_\nu}{0.1\ \text{eV}}\right)\left(\frac{\Lambda}{\text{TeV}}\right)^{-2}$

8 orders of magnitude smaller than current experimental reach

Mechanisms to decouple mass and magnetic moment

- **Spin Symmetry**

  Barr, Freire, and Zee (1990)
  Babu, Chang, Keung, Phillips (1992)

- **Voloshin Symmetry / $SU(2)_H$ Horizontal Symmetry**

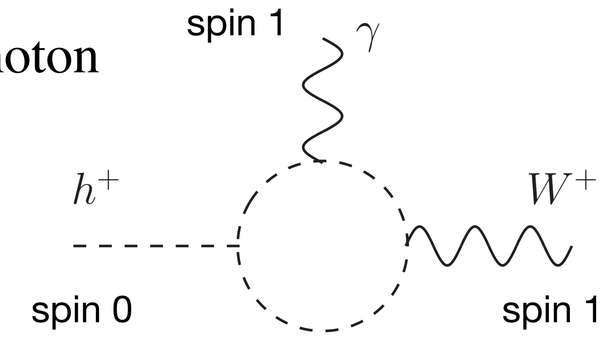
  Voloshin (1988)
  Barbari and Mohapatra (1989)
  Babu and Mohapatra (1990)
  Leurer and Marcus (1990)

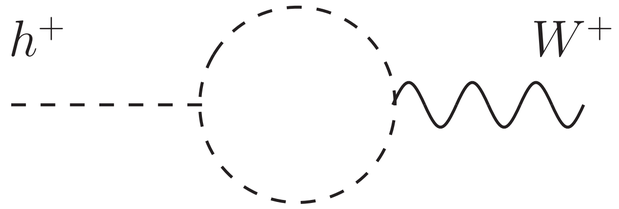
- **The proposed mechanism: $SU(2)_L$ Invariance**

  Pages, **Thapa** (2025)

Spin Suppression Mechanism

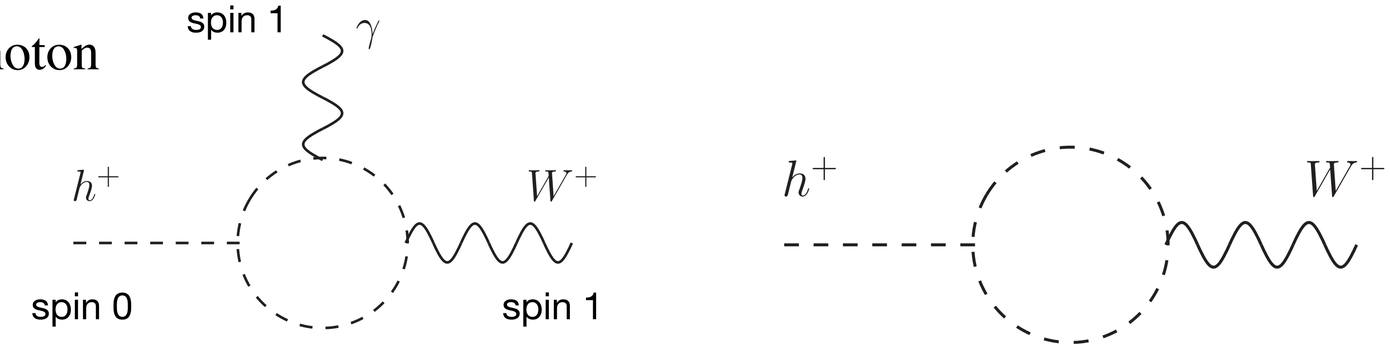
- Uses the spin quantum number of the photon



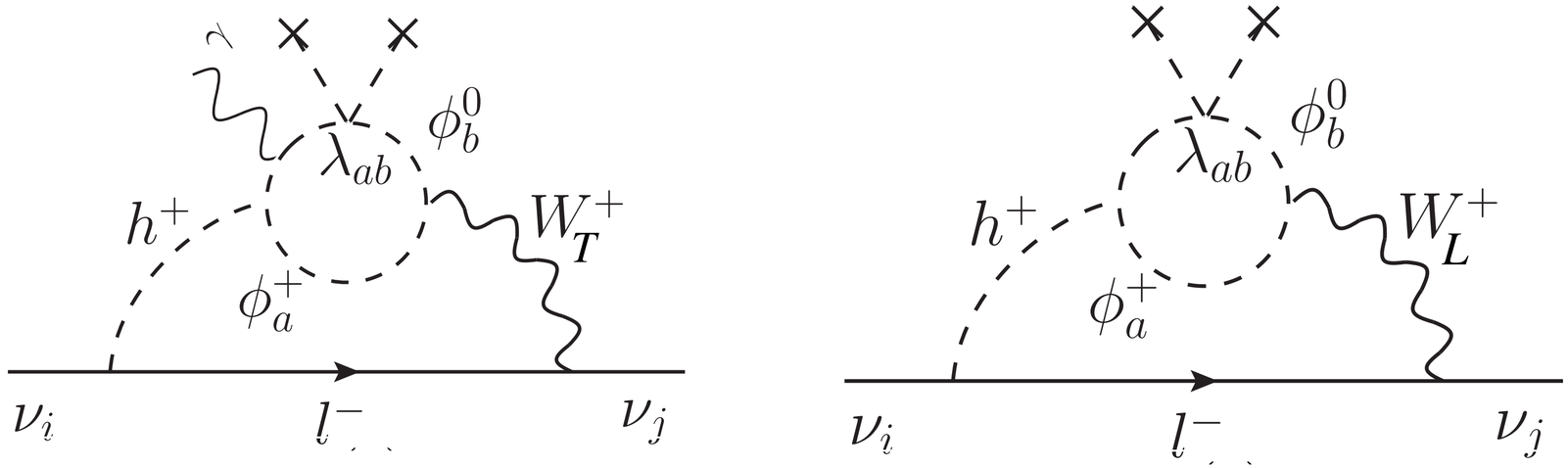


Spin Suppression Mechanism

- Uses the spin quantum number of the photon



- The original proposal uses a charged singlet h^+ (1,1,1) and three scalar doublets ϕ_a (1,2,1/2)



$$\delta m_{\nu_\mu \nu_\tau} = 0.5 \times 10^6 \text{ eV} \left(\frac{m_\tau^2}{M_W^2}\right)\left(\frac{\delta M_2^2 + \delta M_3^2}{2M^2}\right)\left(\frac{M}{\text{TeV}}\right)^2\left(\frac{\mu_\nu}{10^{-12}\mu_B}\right)$$

Barr, Freire, and Zee (1990)
Babu, Chang, Keung, Phillips (1992)

Horizontal Symmetry

- Voloshin $SU(2)_\nu$ symmetry that transforms $(\nu_R^C, \nu_L)^T$ as doublets with the transformation $\nu_L \to \nu_R^C$, $\nu_R \to -\nu_L^C$ such that **magnetic moment is invariant while mass term is not.**

$$\overline{\nu_L}\nu_R \to -\overline{\nu_L}\nu_R$$
$$\overline{\nu_L}\sigma_{\mu\nu}\nu_R F^{\mu\nu} \to +\overline{\nu_L}\sigma_{\mu\nu}\nu_R F^{\mu\nu}$$

Simplest realization in $SU(3)_L \times U(1)_X$
$\Longrightarrow \mu_\nu \lesssim 10^{-16}\mu_B$

Barbari and Mohapatra (1989)

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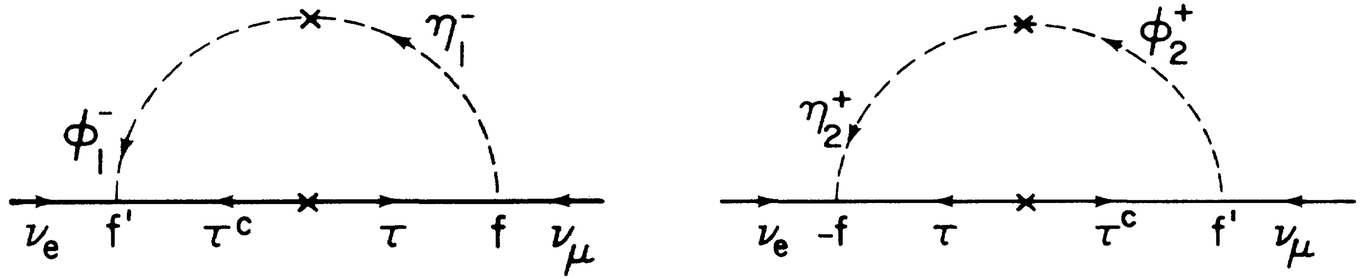
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- **Horizontal symmetry:** Based on $SU(3)_C \times SU(2)_L \times U(1)_Y \times SU(2)_H$

$$\Psi_L = \begin{pmatrix} \nu_e & \nu_\mu \\ e & \mu \end{pmatrix}_L, \Psi_R = (e \quad \mu)_R, \Psi_{3L} = \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L, \tau_R \qquad \Phi = \begin{pmatrix} \phi_1^+ & \phi_2^+ \\ \phi_1^0 & \phi_2^0 \end{pmatrix}, \phi_s = \begin{pmatrix} \phi_s^+ \\ \phi_s^0 \end{pmatrix}, \quad \eta = \begin{pmatrix} \eta_1^+ & \eta_2^+ \end{pmatrix}, \quad \sigma_a = \begin{pmatrix} \sigma_1^0 & \sigma_2^0 & \sigma_3^0 \end{pmatrix}_a$$



$$\left(\frac{\mu_{\nu_e\nu_\mu}}{10^{-12}\mu_B}\right) = 2\left(\frac{\delta m_{\nu_e\nu_\mu}}{\text{eV}}\right)\left(\frac{\text{GeV}^2}{\Delta m_\eta^2}\right)\left(\frac{m_\eta^2}{m_\phi^2} - 1\right)\log\frac{m_\eta^2}{m_\phi^2}$$

$\Longrightarrow \mu_\nu \lesssim 10^{-12}\mu_B$

Babu and Mohapatra (1990)

The proposed mechanism: $SU(2)_L$ Invariance

- The Dirac (Majorana) neutrino magnetic moment arises from **dimension-6 (dimension-7) operators**

$$C_{\nu B}\, g_1\, \bar{L}\, \tilde{H}\, \sigma^{\mu\nu}\, \nu_R\, B_{\mu\nu} \;+\; C_{\nu W}\, g_2\, \bar{L}\, \tau^a\, \tilde{H}\, \sigma^{\mu\nu}\, \nu_R\, W^a_{\mu\nu} \quad \Longrightarrow \quad \bar{\nu}_L \sigma^{\mu\nu} \nu_R F_{\mu\nu}$$

$$C_{LHB}\, g_1\, (\bar{L}^c\, \epsilon\, H)\, \sigma^{\mu\nu}\, (H^T\, \epsilon\, L)\, B_{\mu\nu} \;+\; C_{LHW}\, g_2\, (\bar{L}^c\, \epsilon\, H)\, \sigma^{\mu\nu}\, (H^T\, \epsilon\, \tau^i\, L)\, W^i_{\mu\nu} \quad \Longrightarrow \quad \bar{\nu}^c_L \sigma^{\mu\nu} \nu_L F_{\mu\nu}$$

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- Both L and H transform as doublets under $SU(2)_L$: $H \sim (\mathbf{1}, \mathbf{2}, 1/2)$ and $L \sim (\mathbf{1}, \mathbf{2}, -1/2)$

$\mathbf{2} \otimes \mathbf{2} = \mathbf{3} \oplus \mathbf{1}$ → combine to form gauge-invariant operators with B_μ and W_μ

triplet

singlet

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- Replace L with **new Fermion transforming under different representation of** $SU(2)_L$: $\mathbf{R_{1,2}}$

Search for effective vertices that **contain an invariant in the product**

$$\mathbf{R_1} \otimes \mathbf{R_2} \otimes \mathbf{3} \otimes \underbrace{\mathbf{2} \otimes \ldots\ldots \otimes \mathbf{2}}_{n}$$

$\mathbf{3} : W^i_\mu$

$\mathbf{2} : H$

but not in the product

$$\mathbf{R_1} \otimes \mathbf{R_2} \otimes \underbrace{\mathbf{2} \otimes \ldots\ldots \otimes \mathbf{2}}_{n}$$

Complete set of diagrams

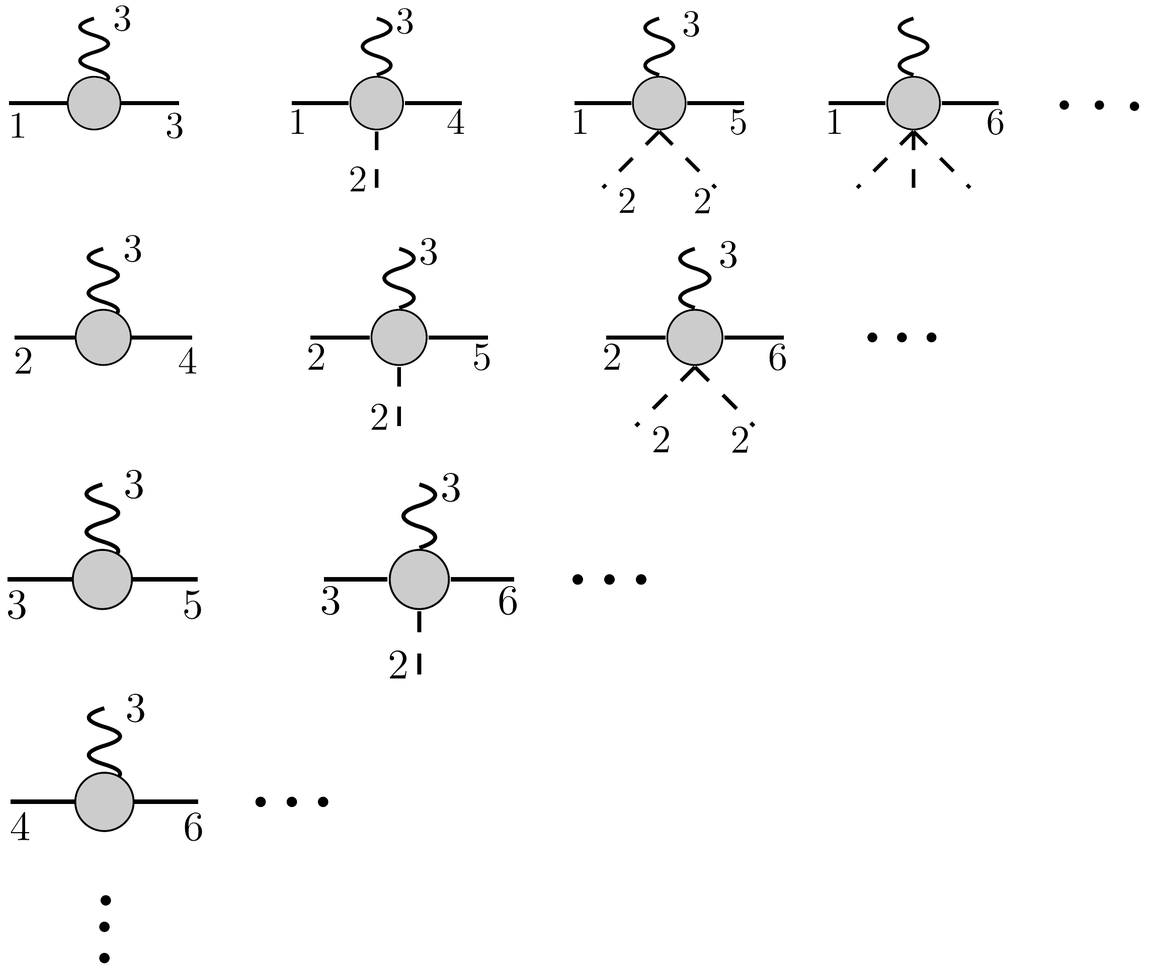
- Dipole operator **exists only for** the $SU(2)_L$ gauge bosons W_μ **but not for** the $U(1)_Y$ gauge boson B_μ
- Neutrino mass without any gauge boson attached is **group theoretically identical** to the B_μ graph

$\Longrightarrow$ vanishes due to $SU(2)_L$ gauge invariance

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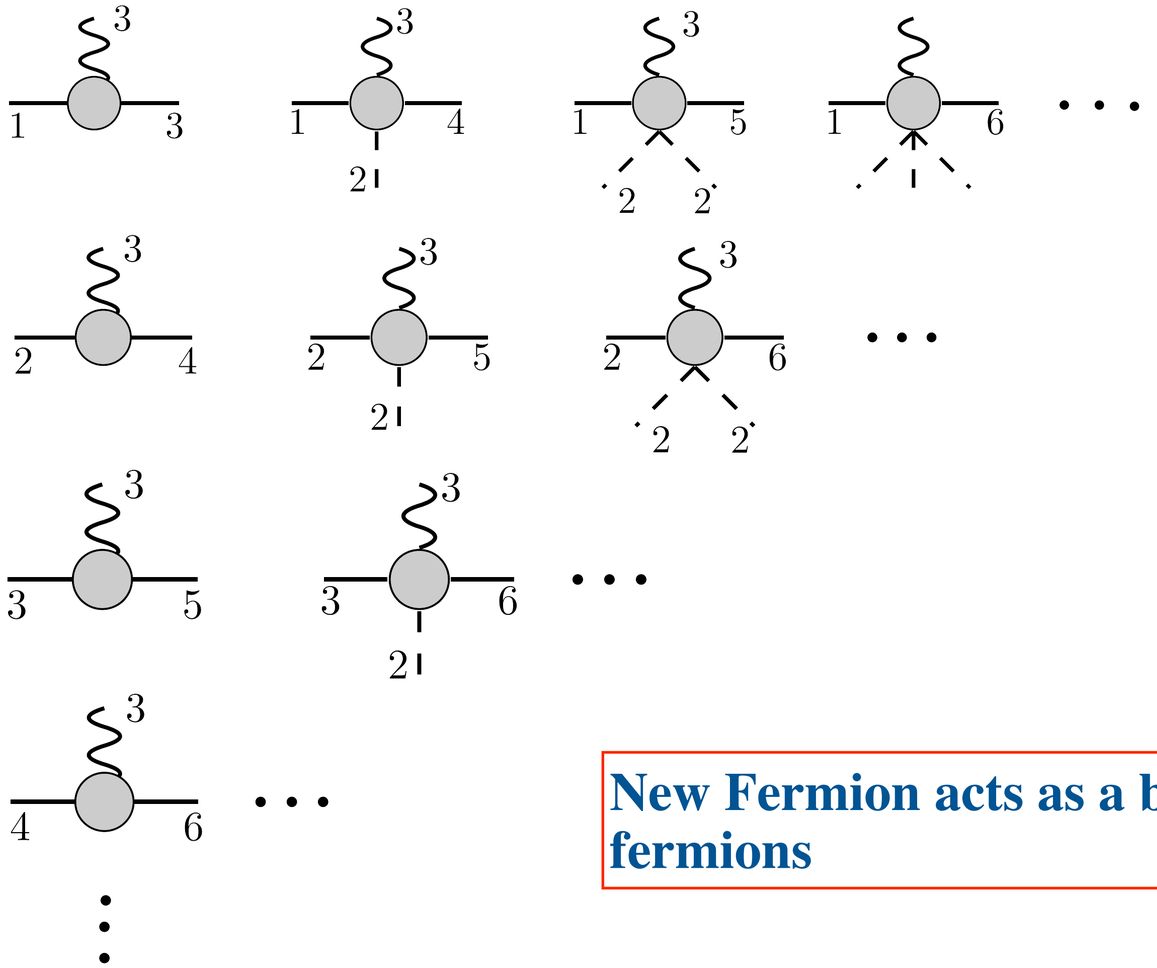
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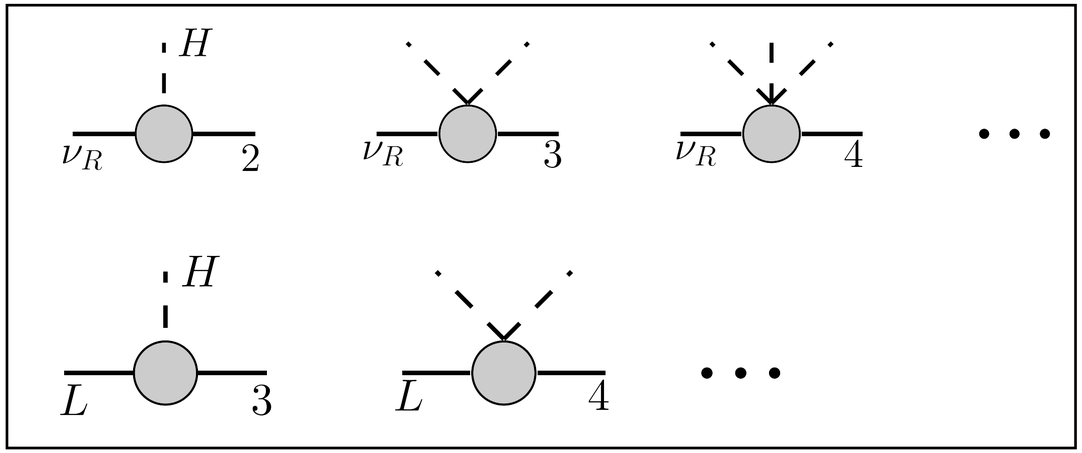


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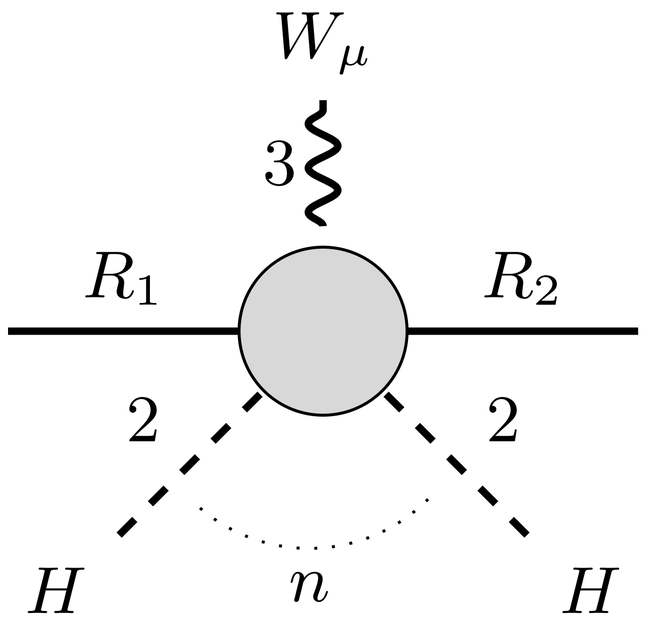


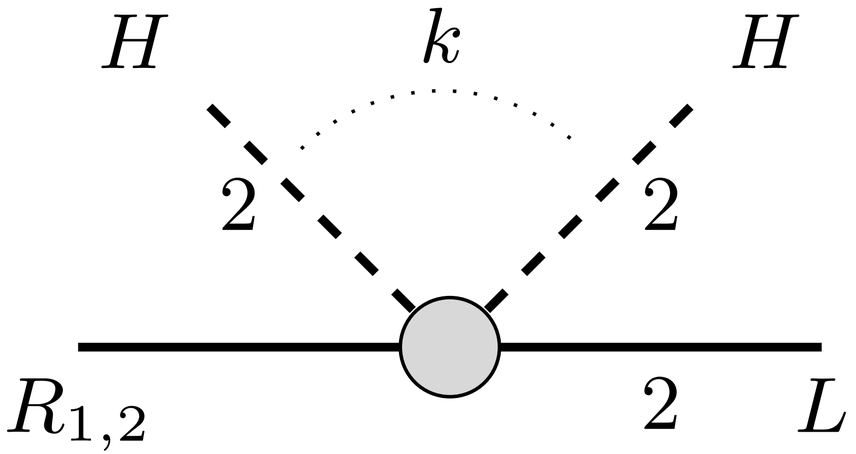
New Fermion acts as a bridge between effective vertex and SM fermions

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Condition to realize magnetic moment through W_μ together with vanishing mass contribution

$$|R_1 - R_2| - n = 2$$

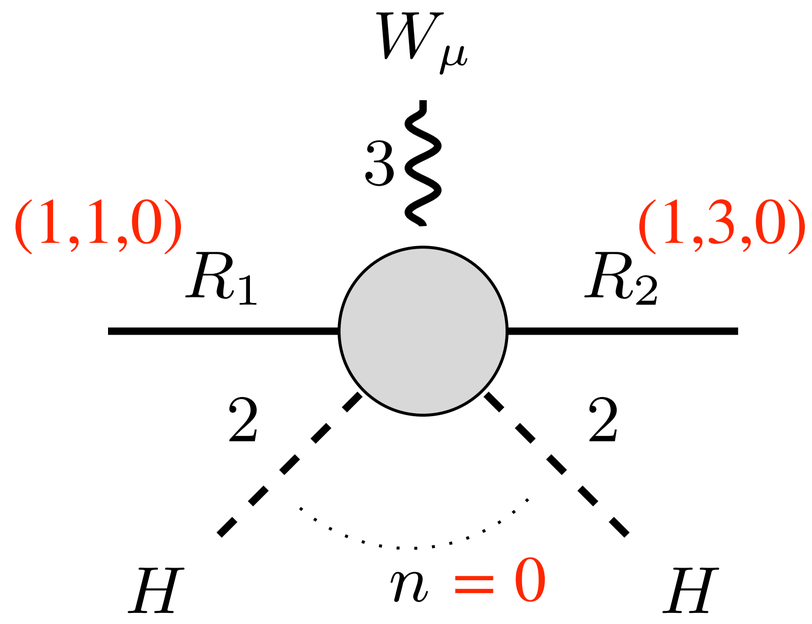
$k = R_{1,2} - 2$ to connect to L

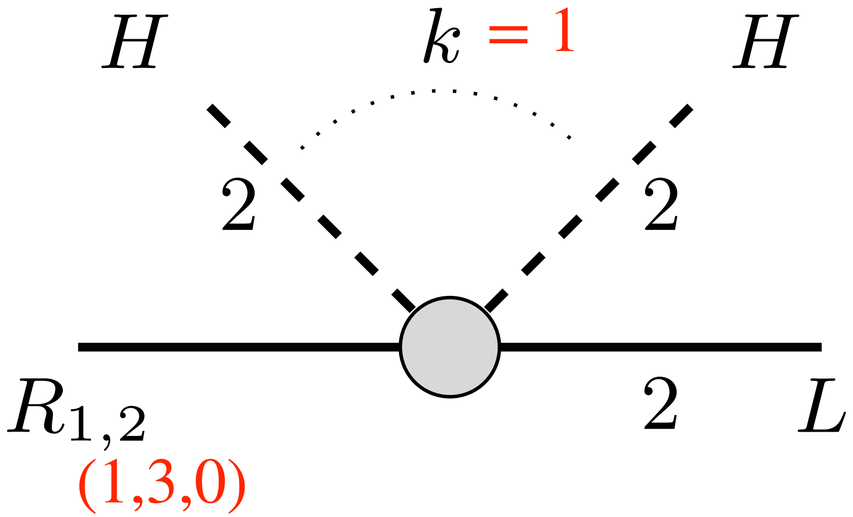
$k = R_{1,2} - 1$ to connect to ν_R

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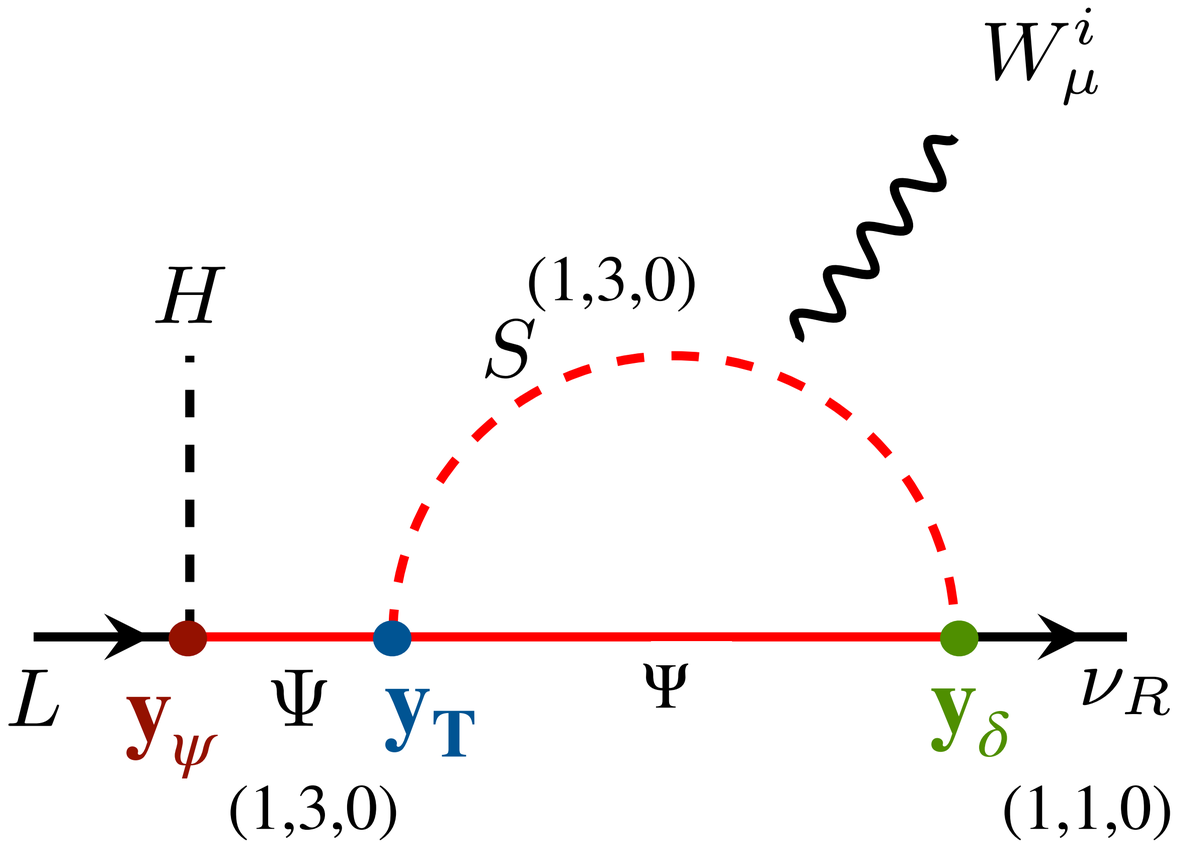
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Model for Dirac μ_ν

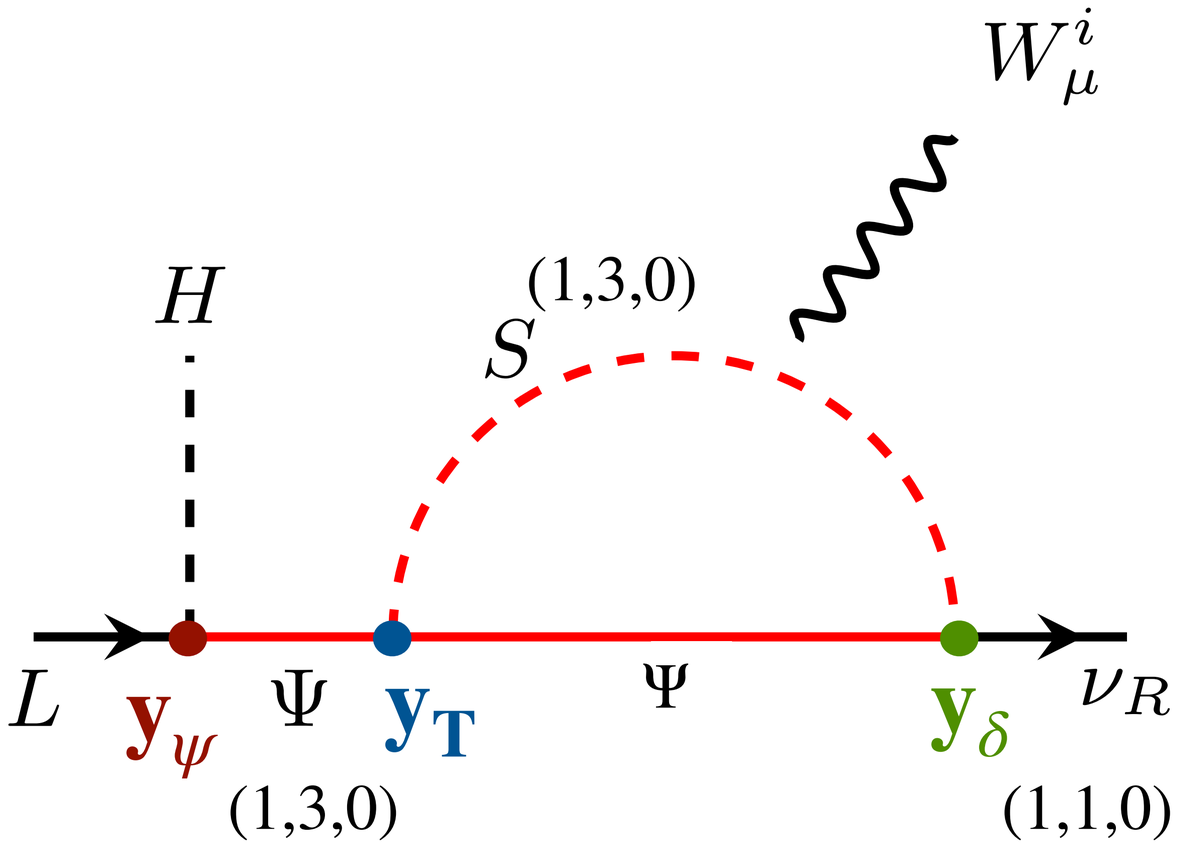


$$m_\nu^{\text{loop}} = -\frac{\mu_\nu^D}{\mu_B}\frac{|y_\Psi|^2 v^2}{4m_e}$$

For $m_\Psi, m_S \sim 1$ TeV, $\quad y_\delta, y_T \sim 1;\ y_\psi \sim 10^{-3}$

$$\Longrightarrow \mu_\nu^D \sim \mathbf{10^{-12}}\mu_B$$

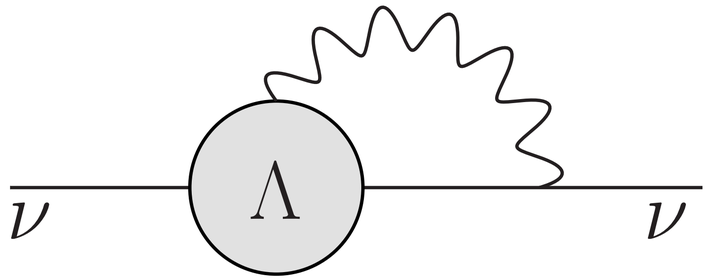
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RGE Induced Contribution:
For Dirac Magnetic moment, it leads to the bound $\mu_\nu^D \lesssim 10^{-15}\mu_B$!

[Bell et al, hep-ph/0504134]

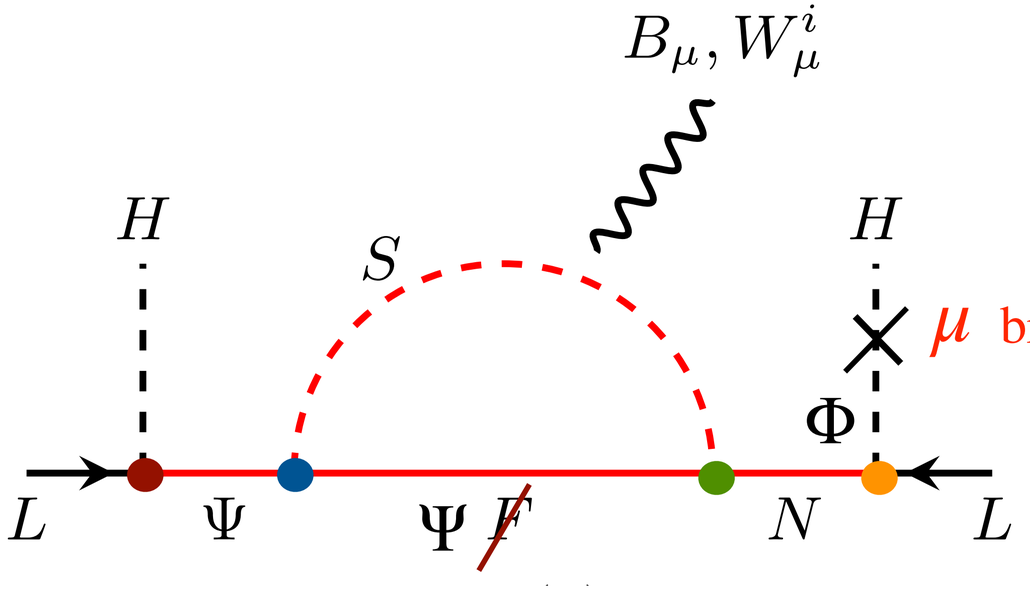
Model for Majorana μ_ν

$N_{L,R} \sim (1,1,0)$

$\Psi_{L,R} \sim (1,3,0)$

$S \sim (1,3,0)$

$\Phi \sim (1,2,1/2)$



μ breaks the lepton number

$$\frac{\mu_\nu^M}{\mu_B} = 4\, m_e v^2 C_{LHW}$$

$$C_{LHW} = \frac{y_\Psi^* y_\delta y_T y_N' \theta_{\Phi H}}{16\pi^2} \frac{m_\Psi^2 + m_S^2 \left(\log\left(m_S^2/m_\Psi^2\right) - 1\right)}{m_N (m_\Psi^2 - m_S^2)^2}$$

$$m_\nu^{\text{loop}} = -\frac{\mu_\nu^M}{\mu_B} \frac{|y_\Psi|^2 \mathrm{v}^2}{8 m_e}$$

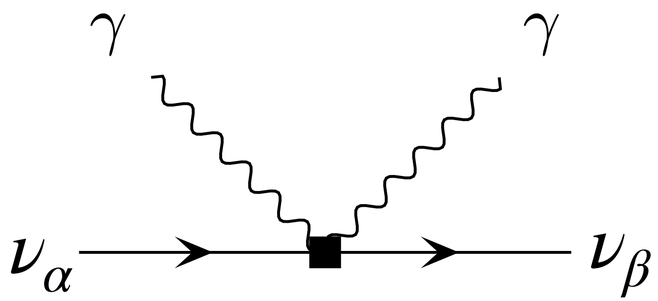
For $m_\Psi, m_S \sim 1$ TeV, $m_N \sim 100$ GeV

$y_\delta, y_T, y_N \sim 1$; $y_\Psi \sim 10^{-3}$

$$\Longrightarrow \mu_\nu^{\mathbf{M}} \sim \mathbf{10^{-12}} \mu_{\mathbf{B}}$$

Neutrino Polarizability

Instead of **one photon** (dipole), the neutrino interacts with **two photons** (polarizability)



Effective operator view

This is a **higher dimensional** interaction

$$\mathscr{L}_{\text{EFT}} = \frac{C^7}{\Lambda^3}(\bar{\nu}P_L\nu)F^{\mu\nu}\tilde{F}_{\mu\nu}$$

These operators are related to polarizability as

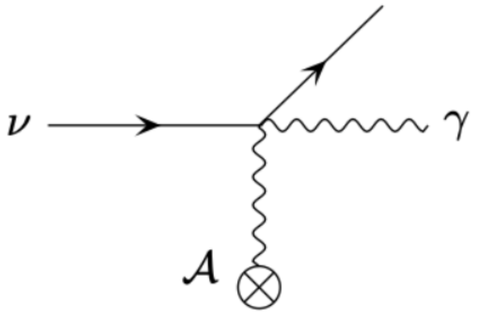
$$F_{\mu\nu}F^{\mu\nu} = \vec{B}^2 - \vec{E}^2$$

Experimental signatures?

- BSM signature in neutrino experiments through **monophoton events**
- Connection to **anomalies**: monophoton-like events are relevant to excesses such as **MiniBooNE**

Monophoton signals

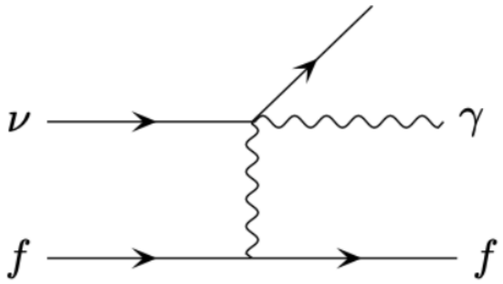
- Power of **monophoton signals at neutrino experiments** to probe polarizability
- Three kinematic regimes based on momentum transfer in $2 \to 3$ process, $q^2 = -(p_{\mathcal{N}}^{\text{out}} - p_{\mathcal{N}}^{\text{in}})^2$



Coherent

$q^2 < 0.1\ \text{GeV}^2$

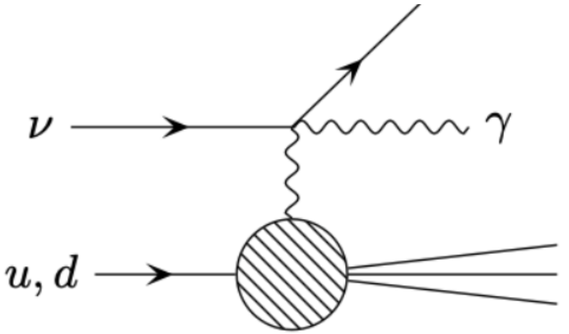
Helm form factor



Incoherent

$0.1\ \text{GeV}^2 < q^2 < 1.8\ \text{GeV}^2$

Dipole form factor



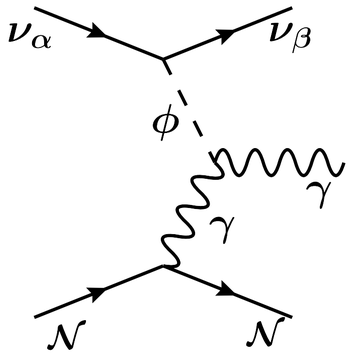
DIS

$q^2 > 1.8\ \text{GeV}^2$

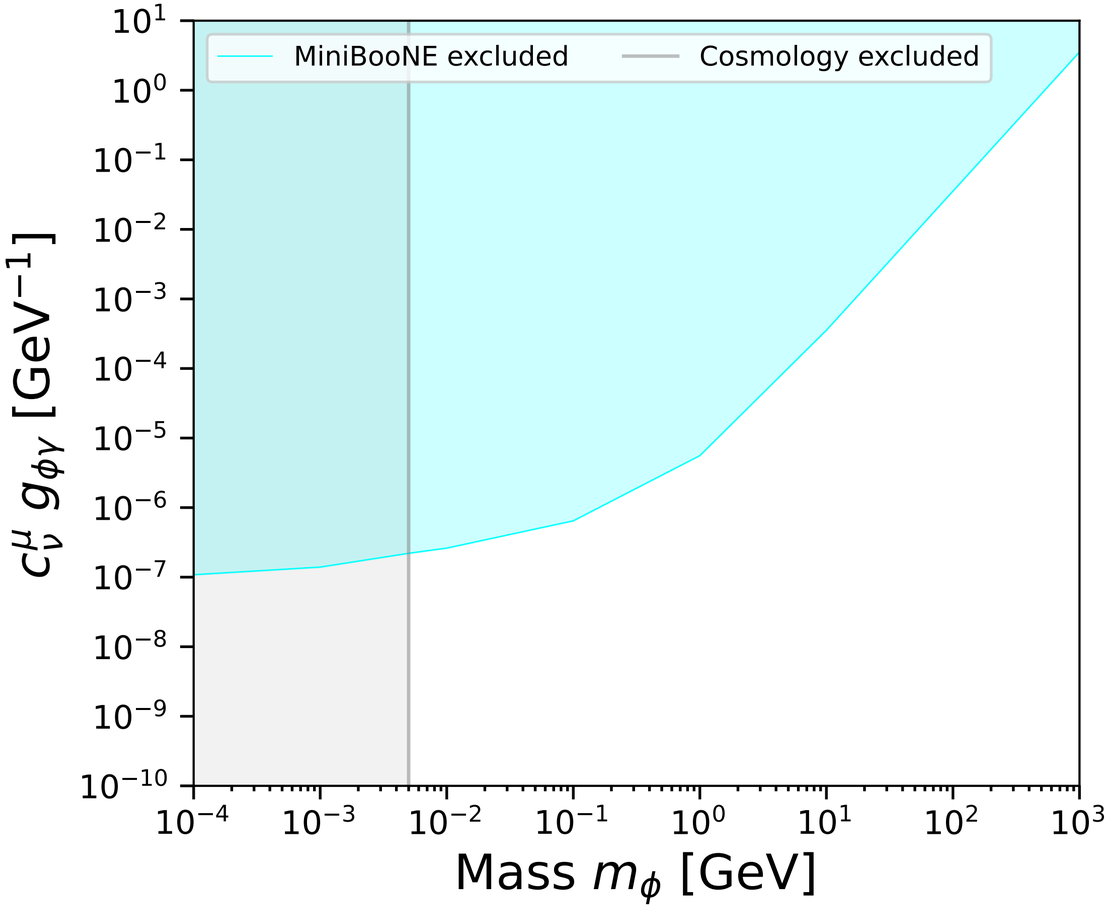
PDF of proton

- The same operator can be probed across different momentum-transfer regimes and experiments

Constraint and sensitivity

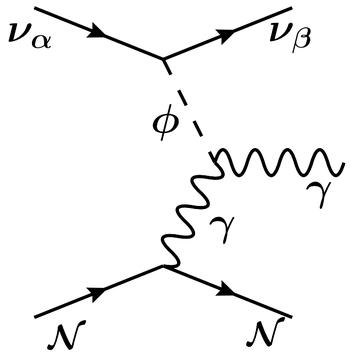


$$\frac{g_{\phi\gamma}}{4}\,\phi F^{\mu\nu}\tilde{F}_{\mu\nu} + \frac{1}{2}c_\nu^{\alpha\beta}\,(\bar{\nu}_\alpha P_L \nu_\beta)\phi$$

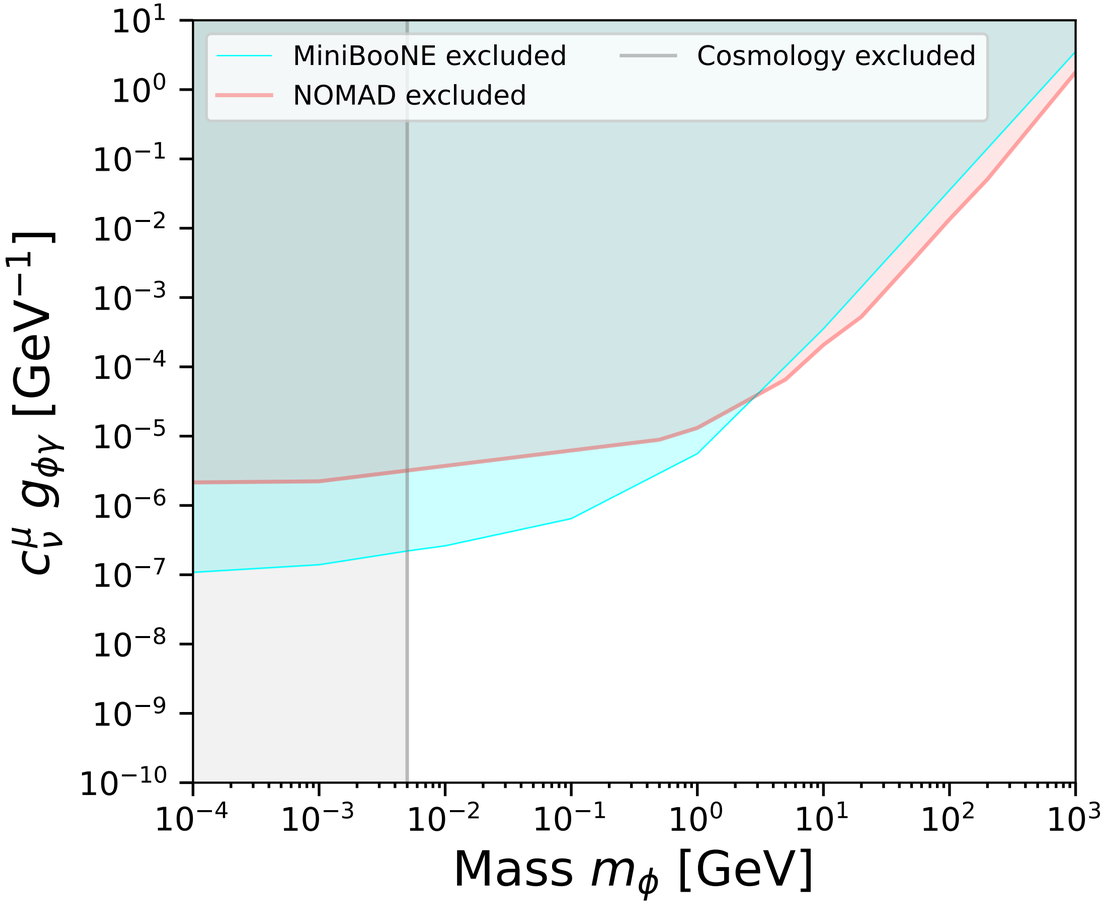


- **MiniBooNE**: Pure mineral-oil (CH_2)
- Cannot distinguish an ν_e (electron-like) signature from a single-photon events
- $\nu_\mu + \bar{\nu}_\mu$ beam flux peaks around 0.5 GeV.
- POT: 18.75×10^{20} (ν) and 11.27×10^{20} ($\bar{\nu}$)
- Energy threshold $E_\gamma > 100$ MeV
- $m_\phi > 5$ MeV from **cosmology**

Constraint and sensitivity

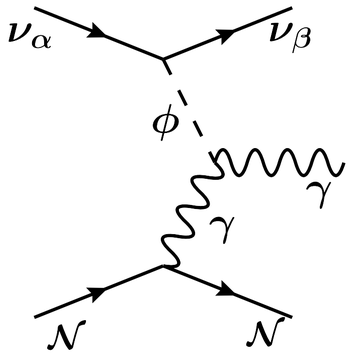


$$\frac{g_{\phi\gamma}}{4}\,\phi F^{\mu\nu}\tilde{F}_{\mu\nu} + \frac{1}{2}c_\nu^{\alpha\beta}\,(\bar{\nu}_\alpha P_L \nu_\beta)\phi$$

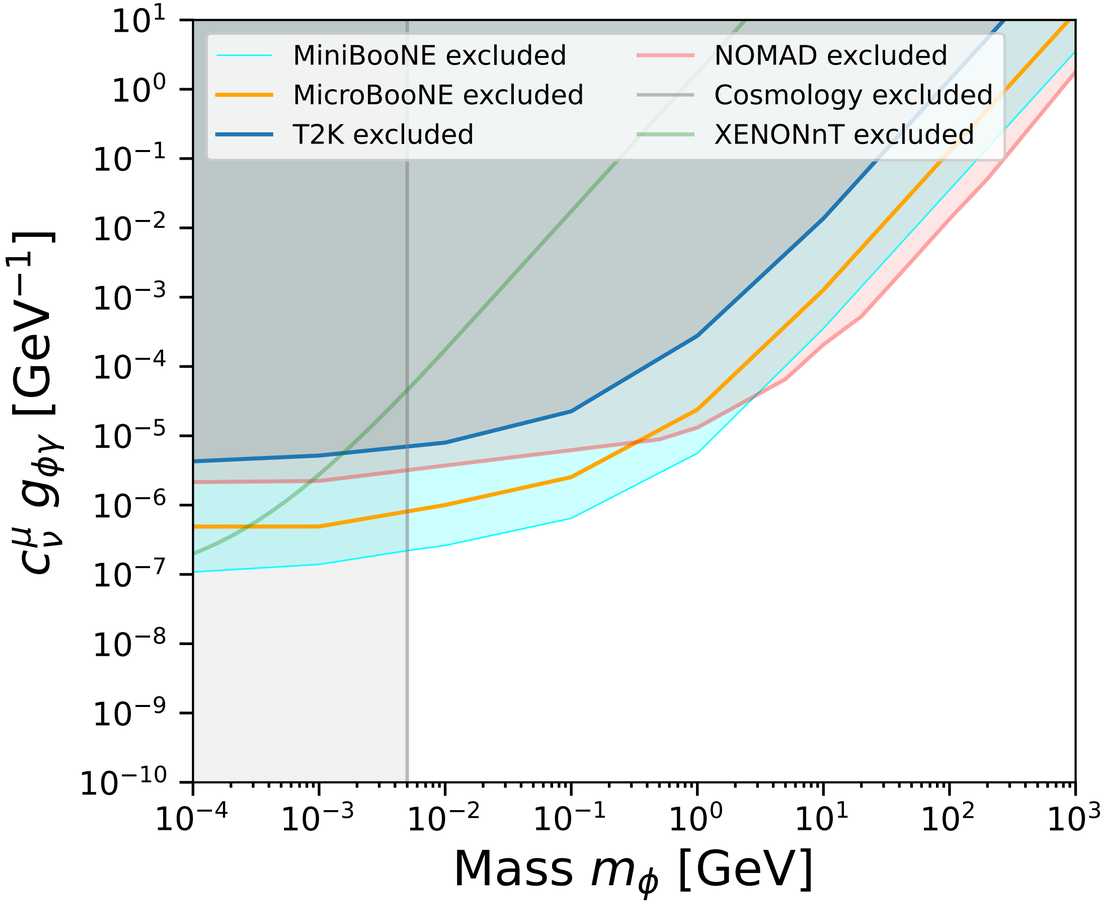


- **NOMAD**: $E_\nu = [5{,}100]$ GeV with a total exposure of 5.1×10^{19} POT.
- Used single-photon efficiency of 8 % . (arXiv: 1111.3713)
- Photon-energy-angle cut $E_\gamma[1 - \cos\theta] \leq 0.05$

Constraint and sensitivity

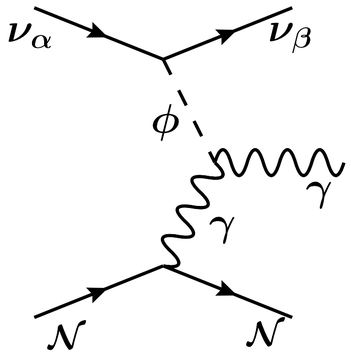


$$\frac{g_{\phi\gamma}}{4}\,\phi F^{\mu\nu}\tilde{F}_{\mu\nu} + \frac{1}{2}c_\nu^{\alpha\beta}\,(\bar{\nu}_\alpha P_L \nu_\beta)\phi$$

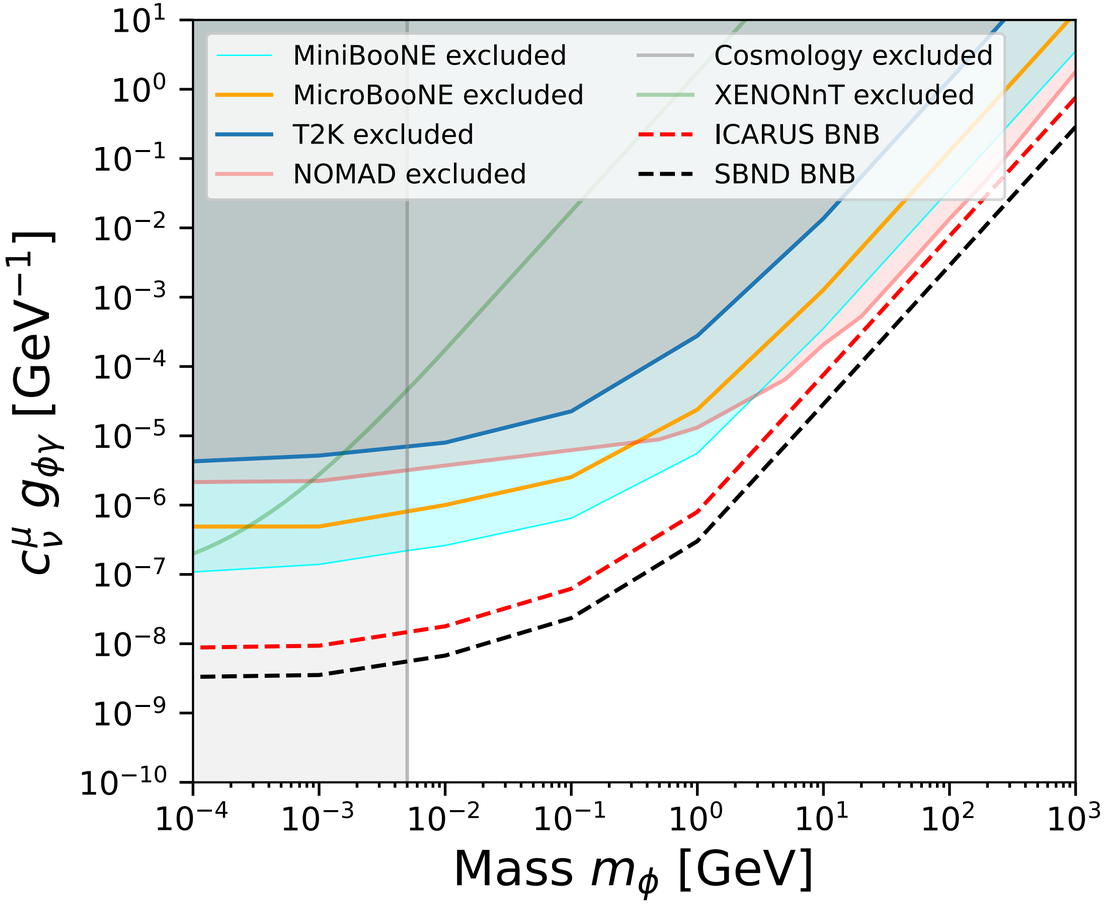


- **MicroBooNE**, **T2K**, and **XENONnT** place constraints on the model parameter space. However, these constraints are weaker than those from **MiniBooNE** and **NOMAD** constraints.

Constraint and sensitivity



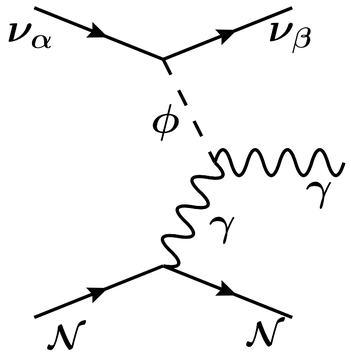
$$\frac{g_{\phi\gamma}}{4}\,\phi F^{\mu\nu}\tilde{F}_{\mu\nu} + \frac{1}{2}c_\nu^{\alpha\beta}\,(\bar{\nu}_\alpha P_L \nu_\beta)\phi$$



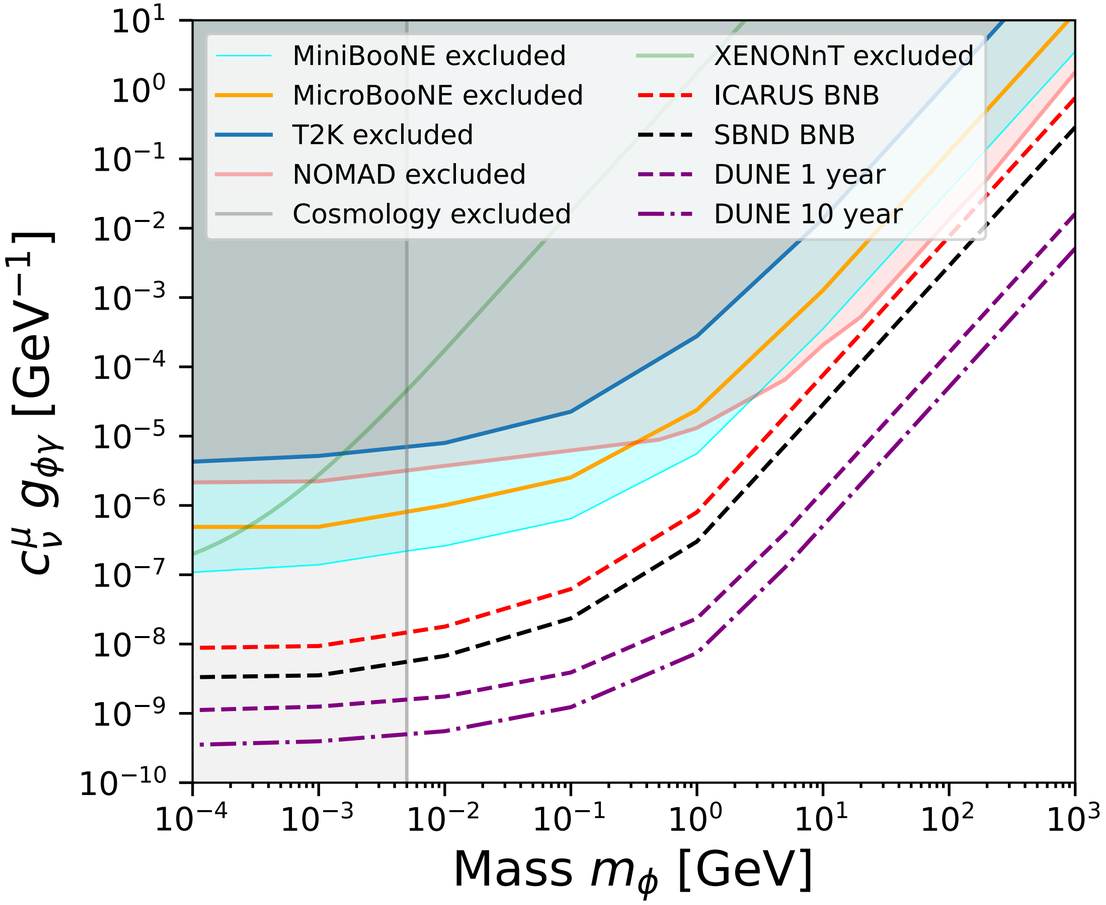
- **SBND/ICARUS**: Neither SBND nor ICARUS has performed a dedicated search for single-photon.
- We therefore treat both detectors in projected-sensitivity mode with constant photon detection efficiency of 10 % .

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Constraint and sensitivity



$$\frac{g_{\phi\gamma}}{4}\,\phi F^{\mu\nu}\tilde{F}_{\mu\nu} + \frac{1}{2}c_\nu^{\alpha\beta}\,(\bar{\nu}_\alpha P_L \nu_\beta)\phi$$

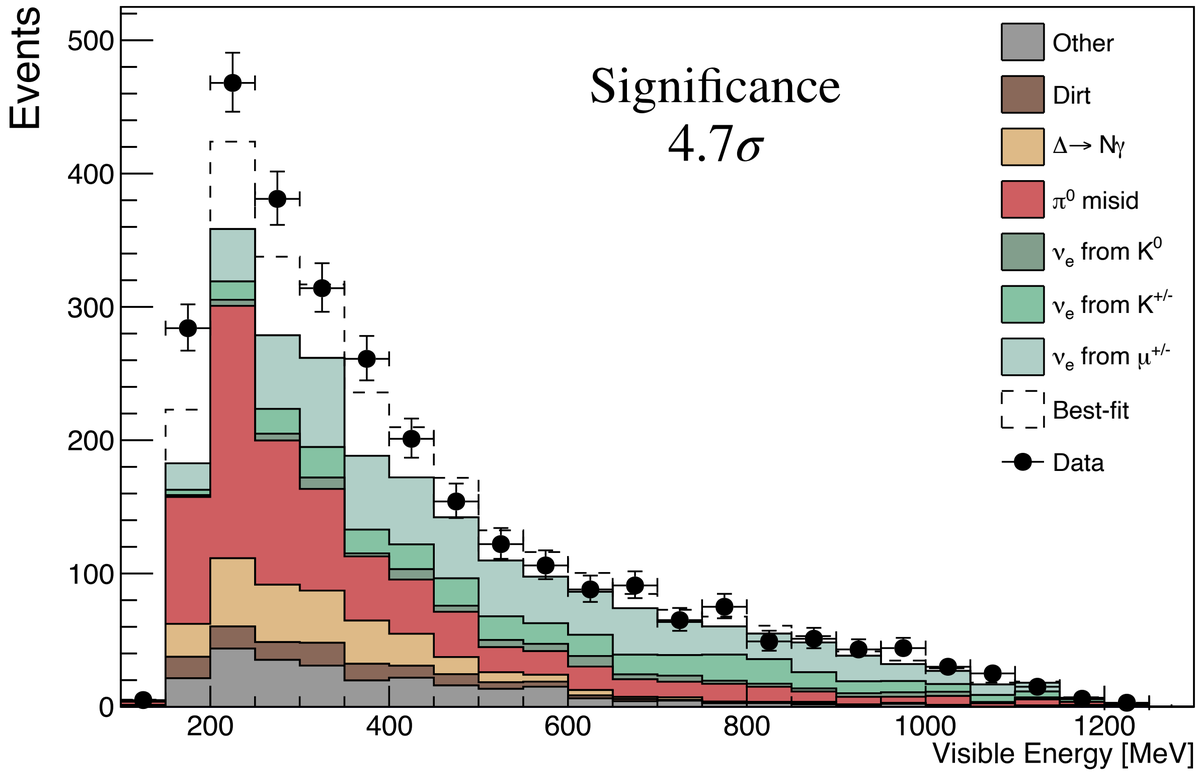




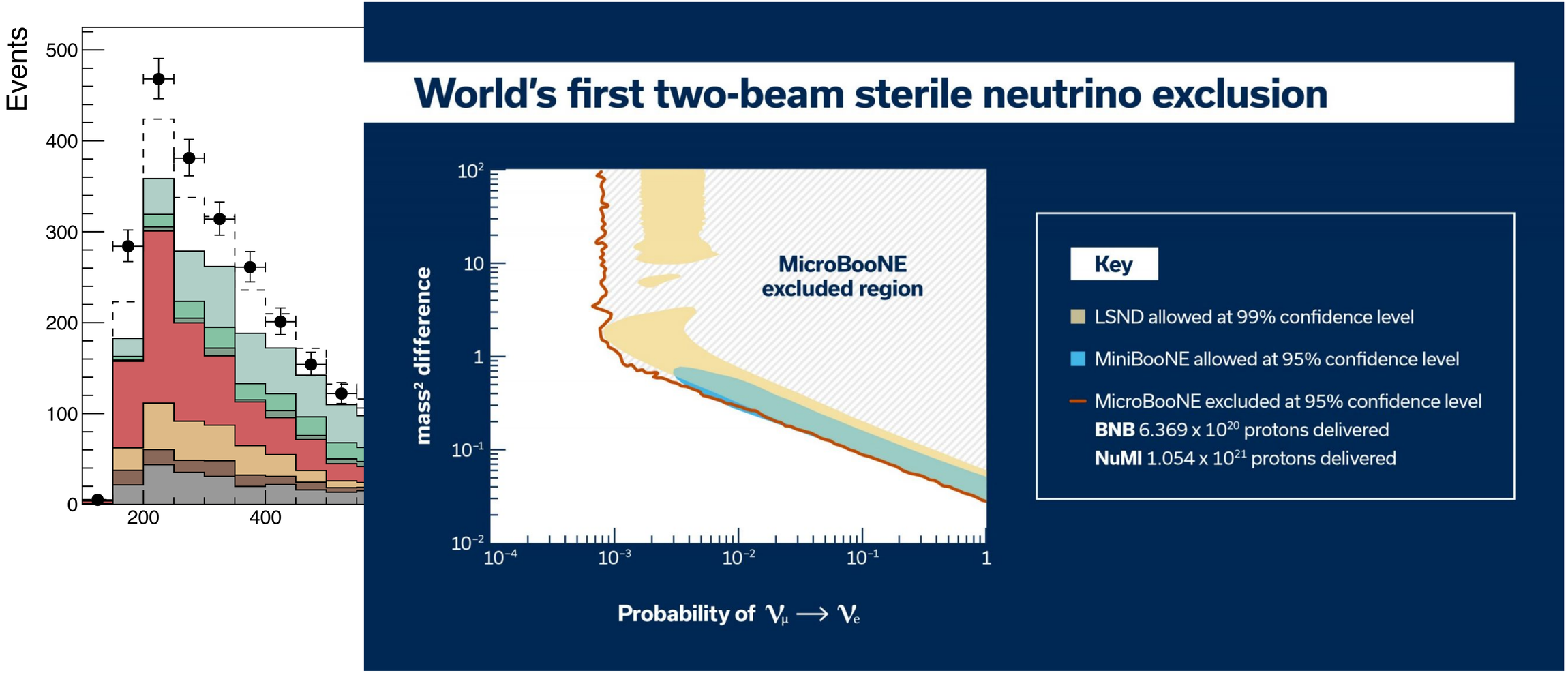
- **DUNE** will have excellent energy reconstruction.
- Ability to distinguish photons from electrons.
- An excellent probe of polarizability operators.

Gehrlein, Shoemaker, **Thapa,** ‘25

What about MiniBooNE anomaly?



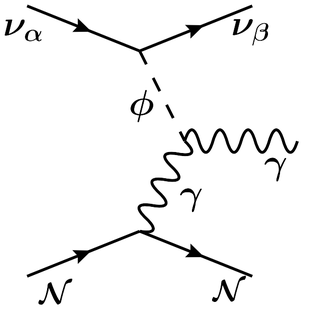
What about MiniBooNE anomaly?

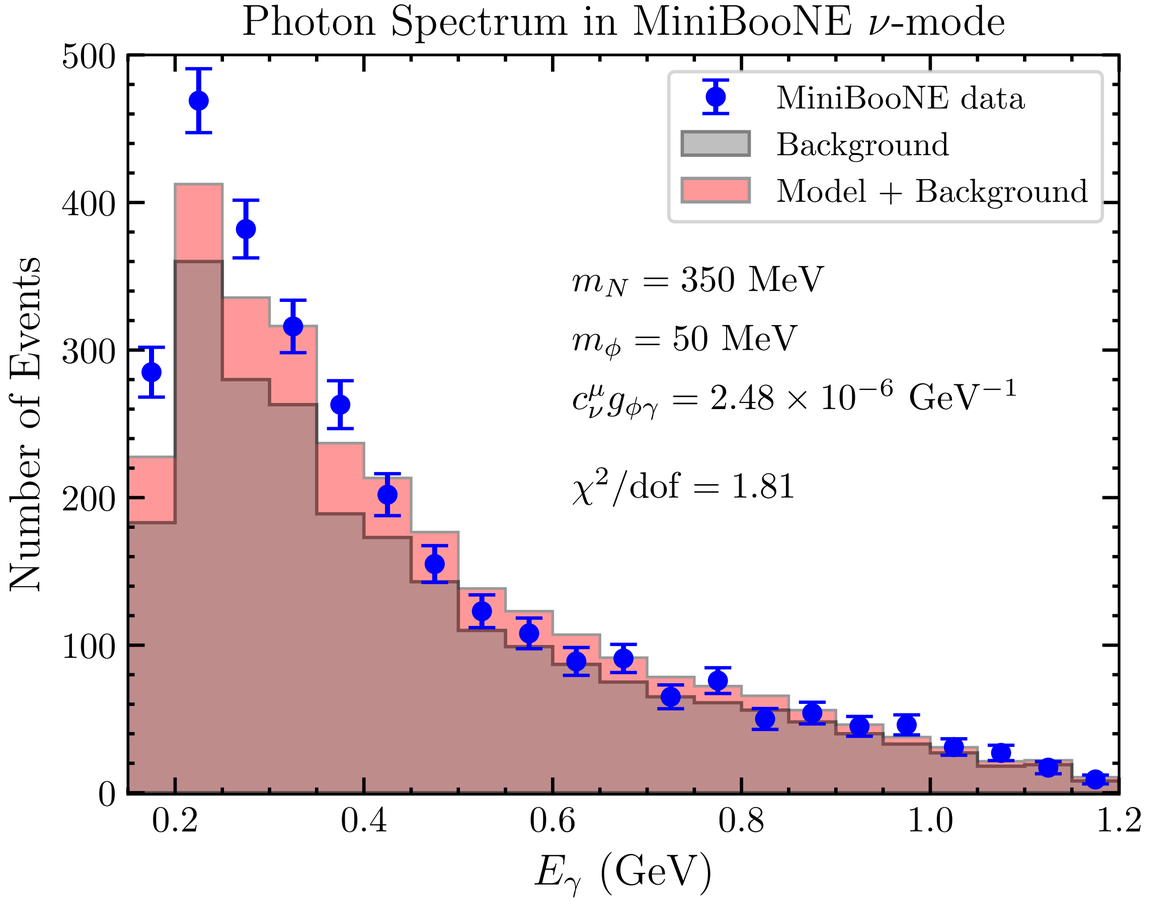


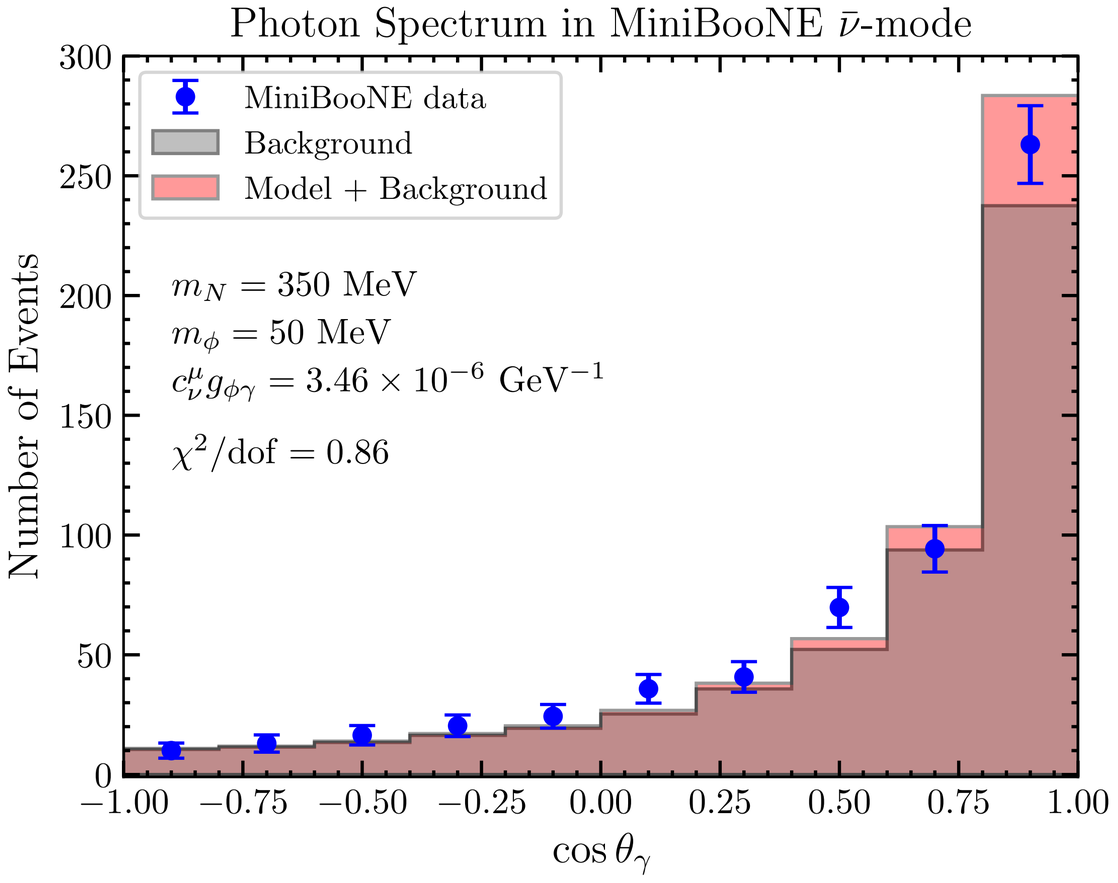
Simple sterile-neutrino oscillation explanations are under strong pressure, motivating alternative photon-like interpretations

Yes, with heavy sterile state!

$$\frac{dN}{dE_\gamma} = N_p \text{ POT} \int dE_\nu \; \epsilon(E_\gamma) \; \phi_{\text{tot}}\left(E_\nu\right) \frac{d^2\sigma}{dE_\gamma dE_\nu}$$







Gehrlein, **Thapa,** Thompson, **'25**

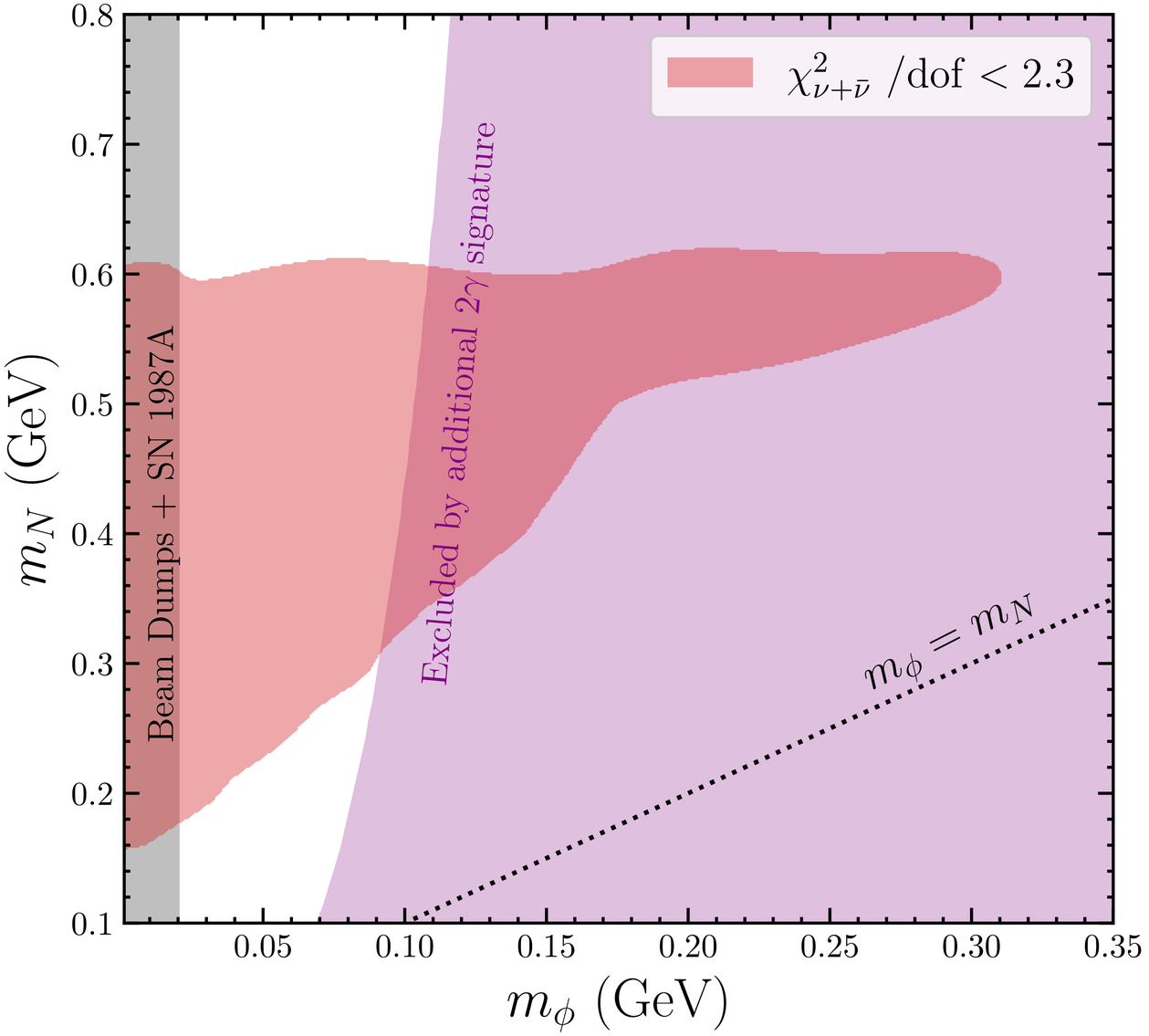
A heavy sterile state can fit both the photon-energy and angular distributions in MiniBooNE

- $m_\phi < 20$ MeV excluded by beam dumps experiments and SN 1987A
- Solution prefers m_ϕ lighter than m_N
- The allowed ranges that can provides best fit to MiniBooNE anomaly is

$$m_\phi = [20,\ 320]\ \text{MeV}$$

$$m_N = [180,\ 600]\ \text{MeV}$$

- Purple shaded region: Sterile state N decays to $N \to \nu\phi \to \nu\gamma\gamma$ inside the detector, failing single-photon selection criteria.



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Conclusion

- Neutrino electromagnetic properties provide a clean window into physics beyond the Standard Model.
- A **novel mechanism** for generating neutrino magnetic moment, in which the associated **mass contribution is forbidden by SM $SU(2)_L$ invariance** was proposed.
- Two-photon n**eutrino polarizability leads to monophoton signals,** with concrete test at current and future experiments. A **heavy sterile state** can fit the MiniBooNE excess.

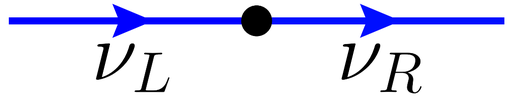
Thank you for listening

Backup Slides

Dirac vs Majorana

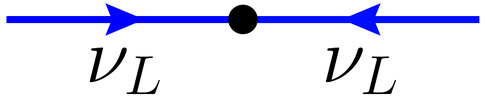
Dirac neutrinos:

Introduce ν_R to the SM $(SU(3)_C \times SU(2)_L \times U(1)_Y)$ allowing $\mathscr{L}_Y : y_\nu \bar{L} H \nu_R + h.c.$

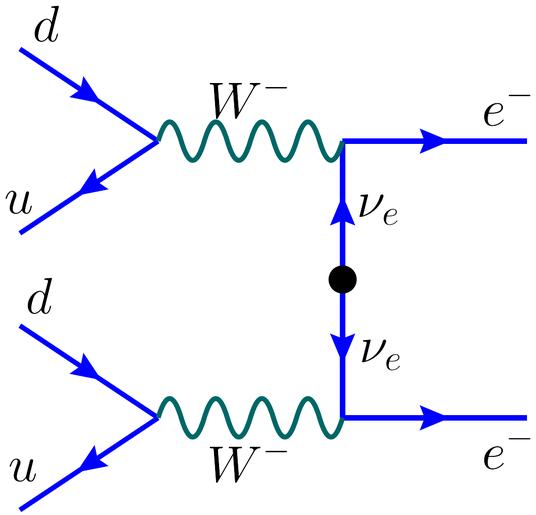


- $\nu = \nu_L + \nu_R \neq \bar{\nu}$
- $U(1)_L$ conserved
- $m_\nu = y_\nu \langle H \rangle \approx 0.1$ eV, this means Yukawa coupling $y_\nu \sim 10^{-12}$!!
- ν_R only couples to Higgs $\Longrightarrow$ difficult to measure

Majorana neutrinos:

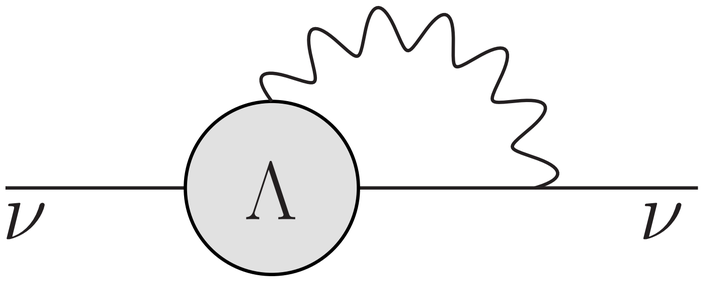


- $\nu = \nu_L + \nu_L^c = \bar{\nu}$
- $U(1)_L$ broken $\Longrightarrow$ neutrinoless double beta decay $0\nu\beta\beta$
- Weinberg operator $LLHH$ generates Majorana masses



- Oscillation experiments cannot distinguish Dirac neutrinos from Majorana neutrinos

RGE-Induced Contribution



$$C_{\nu B}\; g_1 \bar{L}\tilde{H}\sigma^{\mu\nu}\nu_R B_{\mu\nu}$$

$$C_{\nu W}\; g_2 \bar{L}\tau^a\tilde{H}\sigma^{\mu\nu}\nu_R W^a_{\mu\nu}$$

$$C_{\nu H}(\bar{L}\tilde{H}\nu_R)(H^\dagger H)$$

The RGEs for the Wilson coefficients

$$\mu\frac{d}{d\mu}C_i^6(\mu) = \frac{1}{16\pi^2}\sum_j \gamma_{ij}C_j^6(\mu)$$

- The one-loop β-function coefficients in the momentum range $v < \mu < \Lambda$

$$\gamma_{ij} = \begin{pmatrix} 3\pi(\alpha_1 - 3\alpha_2 + 4\alpha_t) & -18\pi\alpha_2 & 0 \\ -6\pi\alpha_1 & -3\pi(\alpha_1 - 3\alpha_2 - 4\alpha_t) & 0 \\ -3(4\pi)^2\alpha_1(\alpha_1 + \alpha_2) & 3(4\pi)^2\alpha_2(\alpha_1 + 3\alpha_2) & 12\lambda - 9\pi(\alpha_1 + 3\alpha_2 - 4\alpha_t) \end{pmatrix}$$

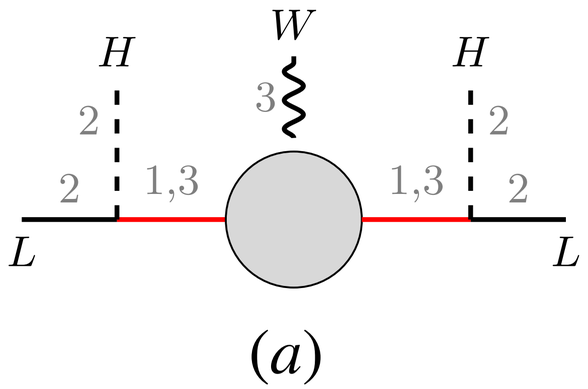
- For Dirac Magnetic moment, it leads to the bound $\mu_\nu^D \lesssim 10^{-15}\mu_B$.

[Bell et al, hep-ph/0504134]

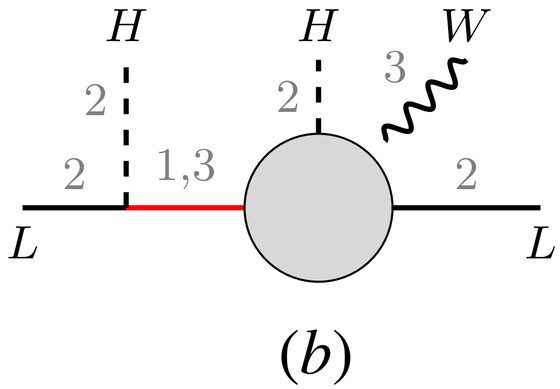
- Can do similar analysis for Majorana Magnetic moment which leads to the bound $\mu_\nu^M \lesssim 10^{-10}\mu_B$.

[Bell et al, hep-ph/0606248]

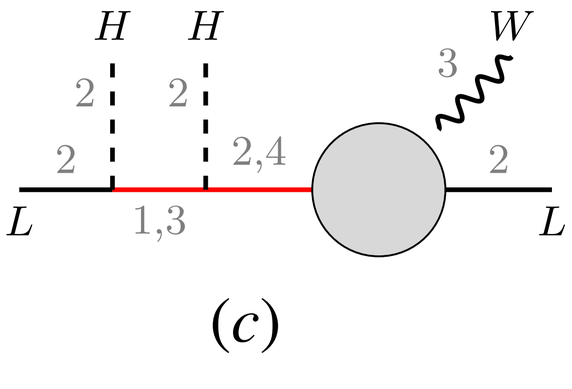
Minimal UV Realization: Majorana Magnetic moment



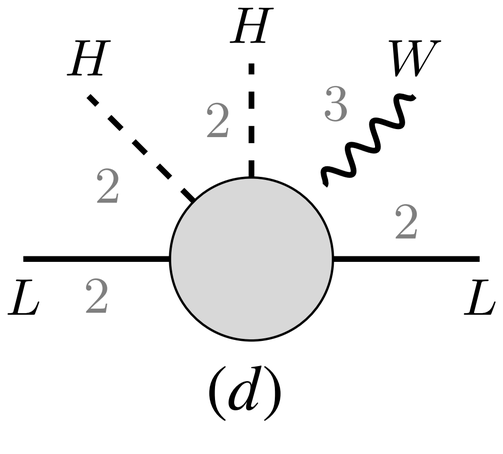
(a)



(b)



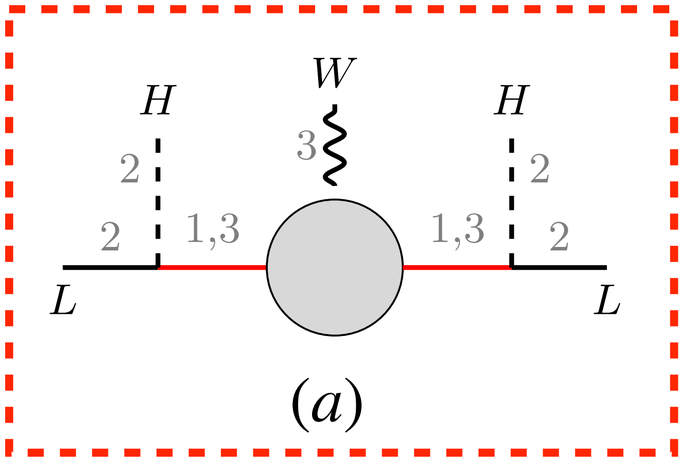
(c)



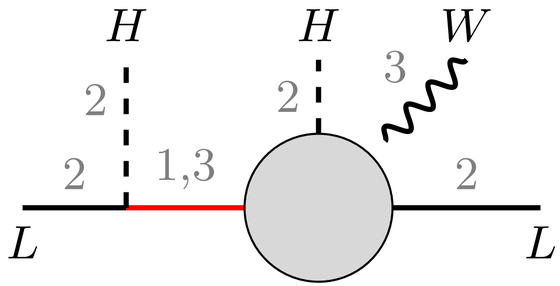
(d)

Topology	Rep. in loop	$\supset 1$	$\supset 3$
(a)	$\mathbf{1} \otimes \mathbf{1}$	✓	✗
	$\mathbf{1} \otimes \mathbf{3}$ or $\mathbf{3} \otimes \mathbf{1}$	✗	✓
	$\mathbf{3} \otimes \mathbf{3}$	✓	✓
(b)	$\mathbf{1} \otimes \mathbf{2} \otimes \mathbf{2}$	✓	✓
	$\mathbf{3} \otimes \mathbf{2} \otimes \mathbf{2}$	✓	✓
(c)	$\mathbf{2} \otimes \mathbf{2}$	✓	✓
	$\mathbf{4} \otimes \mathbf{2}$	✗	✓
(d)	$\mathbf{2} \otimes \mathbf{2} \otimes \mathbf{2} \otimes \mathbf{2}$	✓	✓

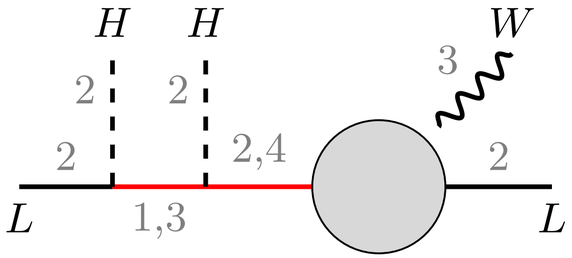
Minimal UV Realization: Majorana Magnetic moment



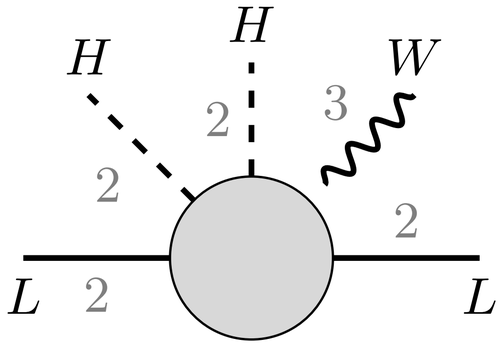
(a)



(b)



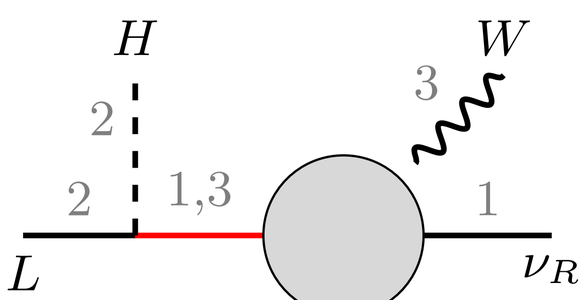
(c)

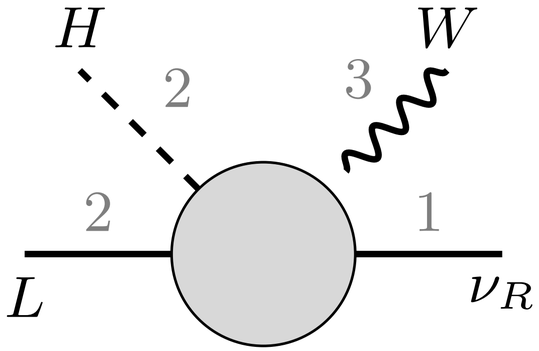


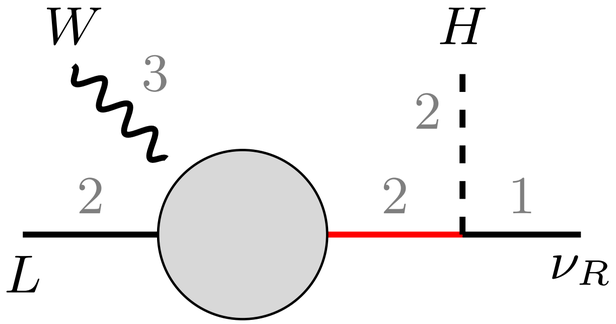
(d)

Topology	Rep. in loop	$\supset 1$	$\supset 3$
(a)	$\mathbf{1} \otimes \mathbf{1}$	✓	✗
	$\mathbf{1} \otimes \mathbf{3}$ or $\mathbf{3} \otimes \mathbf{1}$	✗	✓
	$\mathbf{3} \otimes \mathbf{3}$	✓	✓
(b)	$\mathbf{1} \otimes \mathbf{2} \otimes \mathbf{2}$	✓	✓
	$\mathbf{3} \otimes \mathbf{2} \otimes \mathbf{2}$	✓	✓
(c)	$\mathbf{2} \otimes \mathbf{2}$	✓	✓
	$\mathbf{4} \otimes \mathbf{2}$	✗	✓
(d)	$\mathbf{2} \otimes \mathbf{2} \otimes \mathbf{2} \otimes \mathbf{2}$	✓	✓

Minimal UV Realization: Dirac Magnetic moment







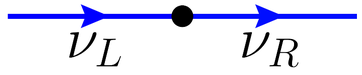
Topology	Rep. in loop	$\supset 1$	$\supset 3$
(a)	$\mathbf{1} \otimes \mathbf{1}$	✓	✗
	$\mathbf{3} \otimes \mathbf{1}$	✗	✓
(b)	$\mathbf{2} \otimes \mathbf{2} \otimes \mathbf{1}$	✓	✓
(c)	$\mathbf{2} \otimes \mathbf{2}$	✓	✓

μ_ν in BSM

Dirac neutrinos:

SM + ν_R with $\Delta L = 0$

$$\mathscr{L}_Y : y_\nu \bar{L} H \nu_R + h.c.$$



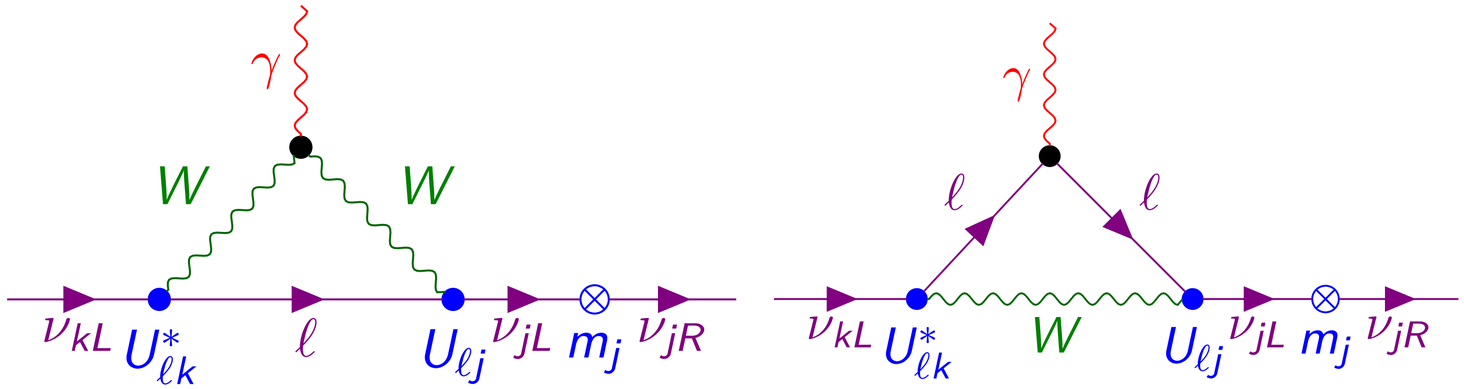
To forbid Majorana mass term for ν_R

- Effective dimension-5 operator after electroweak symmetry for Dirac neutrinos (couples LH and RH neutrinos)

$$\frac{1}{2}(\mu_\nu^D)_{\alpha\beta}\ \bar{\nu}_L^\alpha\ \sigma^{\mu\nu}\ \nu_R^\beta\ F_{\mu\nu}$$

Electromagnetic field strength tensor

- Dirac neutrinos with **diagonal** and **off-diagonal (transition)** magnetic moments



$$\mu_{kj}^D \simeq \frac{3eG_F}{16\sqrt{2}\pi^2}(m_k + m_j)\left(\delta_{ij} - \frac{1}{2}\sum_{\ell=e,\mu,\tau} U^*_{\ell k} U_{\ell j} \frac{m_\ell^2}{m_W^2}\right)$$

Suppressed by neutrino mass

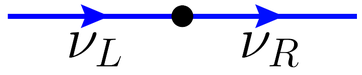
[Fujikawa, Shrock, ’80; Pal, Wolfenstein, ’82; Shrock, ’82]

μ_ν in BSM

Dirac neutrinos:

SM + ν_R with $\Delta L = 0$

$$\mathscr{L}_Y : y_\nu \bar{L} H \nu_R + h.c.$$



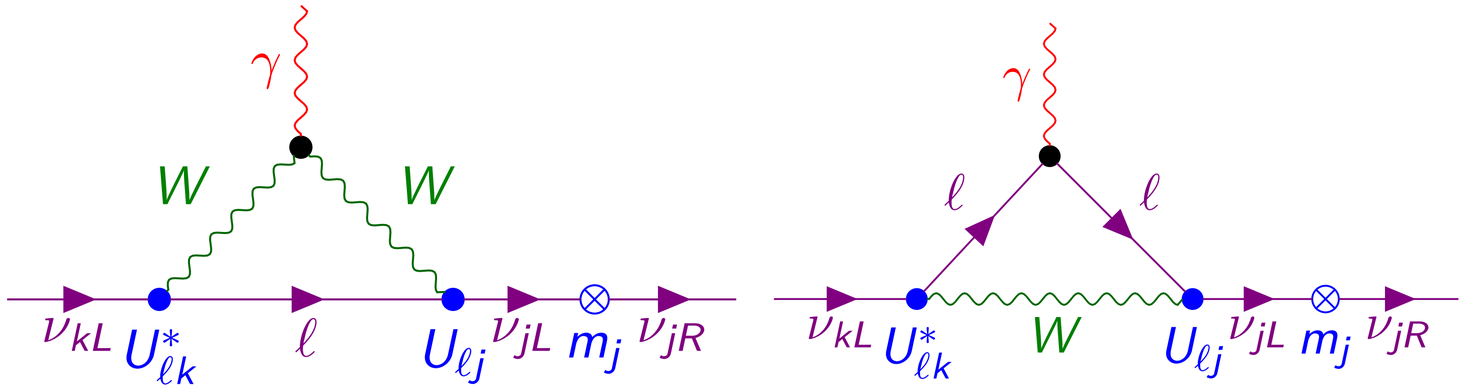
To forbid Majorana mass term for ν_R

- Effective dimension-5 operator after electroweak symmetry for Dirac neutrinos (couples LH and RH neutrinos)

$$\frac{1}{2}(\mu_\nu^D)_{\alpha\beta}\ \bar{\nu}_L^\alpha\ \sigma^{\mu\nu}\ \nu_R^\beta\ F_{\mu\nu}$$

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Suppressed by neutrino mass

Transition μ_ν are GIM suppressed

$$\mu_{kk}^D \simeq 3.2 \times 10^{-19}\mu_B \left(\frac{m_k}{\text{eV}}\right)$$

$$\mu_{\substack{kj \\ k \neq j}}^D \simeq -\,3.9 \times 10^{-23}\mu_B \left(\frac{m_k + m_j}{\text{eV}}\right) \sum_{\ell=e,\mu,\tau} U^*_{\ell k} U_{\ell j}\frac{m_\ell^2}{m_\tau^2}$$

[Fujikawa, Shrock, ’80; Pal, Wolfenstein, ’82; Shrock, ’82]

μ_ν in BSM

Left-Right Symmetric Model:

- In LRSM (based on gauge group $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$) ν_R has gauge interaction with W_R and $W_L - W_R$ mixing ($\sin\xi$) leads to magnetic moment of neutrinos



$$\mu_\nu \simeq \frac{eG_F m_\ell}{4\sqrt{2}\pi^2}\sin 2\xi$$

μ_ν in BSM

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- Same diagram without photon leads to neutrino mass!

$$\Longrightarrow \quad \mu_\nu < 10^{-16}\mu_B$$

μ_ν in BSM

Majorana neutrinos

- Effective dimension-5 operator after electroweak symmetry for Majorana neutrinos

$$\frac{1}{4}(\mu_\nu^M)_{\alpha\beta}\ \bar{\nu}^C_{\alpha L}\ \sigma^{\mu\nu}\ \nu_{\beta L}\ F_{\mu\nu}$$

Antisymmetric in flavor indices

- The magnetic moment are suppressed as in Dirac case in the minimal extension of the SM with Majorana neutrino masses

$$\mu_{kj}^M \simeq -\,7.8\times 10^{-23}\mu_B \left(\frac{m_k + m_j}{\text{eV}}\right) \sum_{\ell=e,\mu,\tau} U^*_{\ell k} U_{\ell j} \frac{m_\ell^2}{m_\tau^2}$$

Suppressed by neutrino mass [Shrock, '82]

μ_ν in BSM

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Suppressed by neutrino mass [Shrock, ’82]

Difficult to generate neutrino magnetic moment without its corresponding mass