Constraining Neutrino Magnetic Moments at the FPF

Roshan Mammen Abraham

Department of Physics, Oklahoma State University

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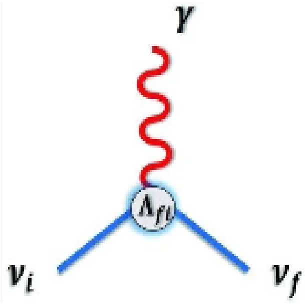
Based on

- arXiv:2109.05032, A. Ismail, S. Jana, and R. Mammen Abraham
- In preparation, S. Foroughi-Abari, Y.-D. Tsai, and R. Mammen Abraham

Neutrino Magnetic Moments

- Neutrino mixing parameters have been measured with incredible precision in recent years.
- **Electromagnetic properties of neutrinos can also be used to probe new physics**.
- SM predicts a very small value for the active neutrino transition magnetic moments for Majorana neutrinos, $\sim 10^{-23}\mu_B$.
- The minimally-extended SM with right-handed neutrinos can acquire a diagonal magnetic moment proportional to their mass, $\mu_\nu^D \sim 10^{-19}(\frac{m_\nu}{1\text{ev}})\mu_B$.
- These predictions are **several orders of magnitude smaller than the present experimental and astrophysical upper bounds**, motivating our study of NMM using LHC neutrinos.

Neutrino Magentic Moments - Experimental Signature



$$\mathcal{L}_{dipole} \sim \mu_\nu^{if} \bar{\nu}^i \sigma^{\mu\nu} \nu^f F_{\mu\nu}$$

A striking experimental signature of the magnetic moment operator is an electron recoiling. Incoming active neutrinos interact with the electrons in the target atom causing the electron to recoil. We consider two cases:

- Final state neutrino, ν_f is the same as the incoming active neutrino species, ν_i.
- ν_f is a Heavy Neutral Lepton (HNL) a.k.a sterile neutrino, N_R.

Neutrino Magnetic Moments - Cross-Section Expression

A characteristic feature of neutrino magnetic moment interaction is an enhancement in signal cross-section at low recoil energies, $d\sigma/dE_{rec} \sim 1/E_{rec}$

For the scattering $\nu_\alpha e^- \longrightarrow \nu_\alpha e^-$ we have,

$$\frac{d\sigma}{dE_{rec}} = \frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{E_{rec}} - \frac{1}{E_\nu}\right)\left(\frac{\mu_{\nu_\alpha}}{\mu_{\mathrm{B}}}\right)^2$$

and for $\nu_\alpha e^- \longrightarrow N_R e^-$

$$\frac{d\sigma}{dE_{rec}} = \alpha\,(\mu_\nu^\alpha)^2\,\left[\frac{1}{E_{rec}} - \frac{1}{E_\nu} + M_N^2\frac{E_{rec} - 2E_\nu - M_e}{4E_\nu^2 E_{rec} M_e} + M_N^4\frac{E_{rec} - M_e}{8E_\nu^2 E_{rec}^2 M_e^2}\right].$$

So if we have a **source of neutrinos and a detector with sufficiently low energy thresholds** then we can study neutrino magnetic moments. FPF!!!

Backgrounds

Before we study the prospects at FPF we have to reduce the backgrounds.

- Muon-induced backgrounds: Muons can emit photons through bremsstrahlung which subsequently undergo pair conversion. If one of the resulting $e^{\pm}$ is missed, the event would mimic our neutrino-electron scattering process. With timing, however, these events could be associated with the accompanying muon and vetoed.
- ν-induce backgrounds: The dominant background is ν interactions where only an e recoils. This is both NC interactions for all flavors, and CC interaction for ν_e only. We use differences in kinematic distributions to reduce this background.

Detectors at FPF

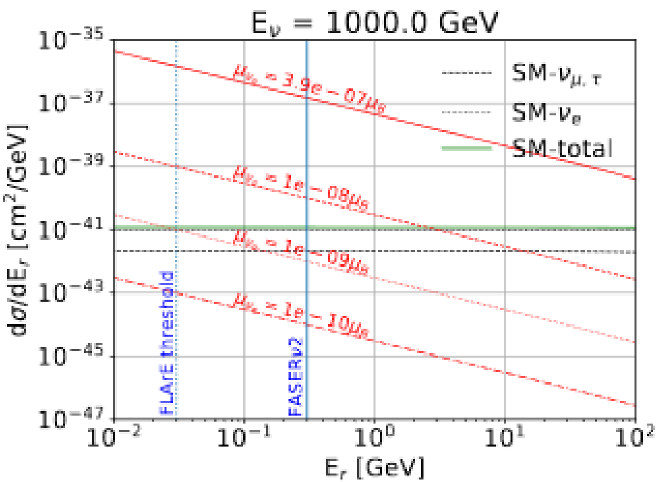
At the FPF we focus on the following detectors:

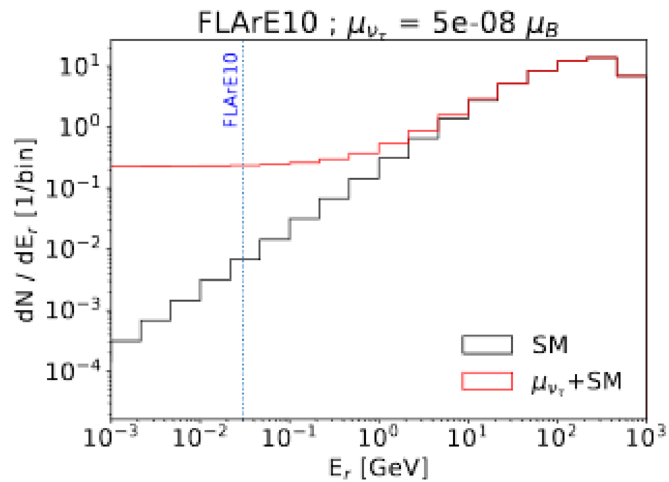
- FASERν2 : 0.5 m x 0.5 m x 2 m tungsten detector with a mass of 10 tonnes, and $E_{th} = 300$MeV.
- FLArE : Liquid argon detector with $E_{th} = 30$MeV and dimensions
  - 1 m x 1 m x 7 m with a mass of 10 tonnes.
  - 1.6 m x 1.6 m x 30 m with a mass of 100 tonnes.

With a lower energy threshold we expect FLArE to be more sensitive.

Active Neutrino Magnetic Moment

$$\nu_\alpha e^- \longrightarrow \nu_\alpha e^-$$





Left: The SM background has a flat distribution but the NMM contribution is enhanced at low recoil energies. **Right:** Expected number of SM and μ_{ν_τ} + SM events at FLArE10.

Active Neutrino Magnetic Moment

We employ a simple cut and count analysis with *cuts* corresponding to $E_{thresh} < E_{rec} < 1$ GeV.

Detector	SM backgrounds		$\mu_{\nu_e} = 5 \cdot 10^{-8} \mu_B$		$\mu_{\nu_\mu} = 5 \cdot 10^{-9} \mu_B$		$\mu_{\nu_\tau} = 5 \cdot 10^{-8} \mu_B$	
	no cuts	cuts	no cuts	cuts	no cuts	cuts	no cuts	cuts
FASERν2	86	0.1	142	11.5	9.5	0.8	3.8	0.3
FLArE-10	51	0.1	97	24.1	7.3	1.9	4.0	1.0
FLArE-100	332	1.0	704	177.4	56.4	15.0	39.1	9.8

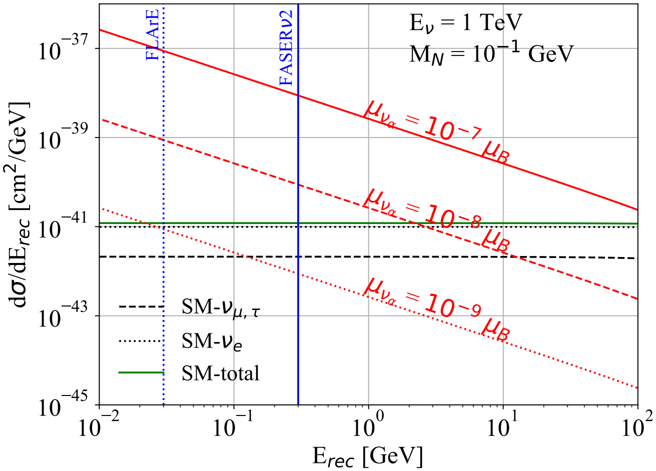
Bounds on μ_{ν_α}:

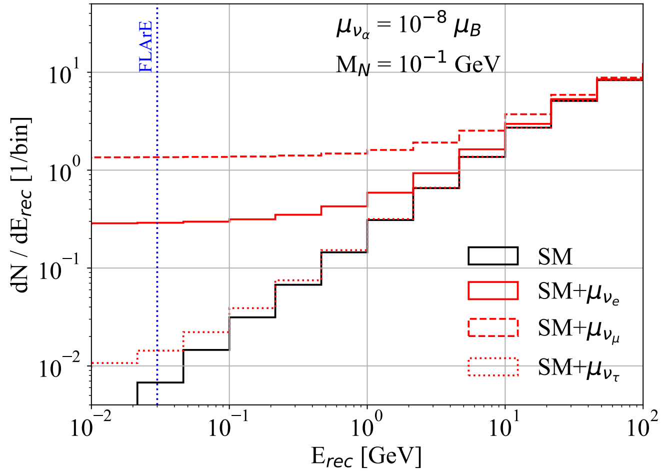
Detector	μ_{ν_e} $(10^{-8} \mu_B)$	μ_{ν_μ} $(10^{-9} \mu_B)$	μ_{ν_τ} $(10^{-7} \mu_B)$
FASERν2	2.2	8.4	1.3
FLArE-10	1.5	5.5	0.75
FLArE-100	0.62	2.1	0.26

DONUT bounds are at $\mu_{\nu_\tau} < 3.9 \times 10^{-7} \mu_B$. FLArE-100 can do an order of magnitude better.

Active to Sterile Neutrino Transition Magnetic Moment

$$\nu_\alpha e^- \longrightarrow N_R e^- \quad ; \quad \mathcal{L}_{dipole} \supset \frac{1}{2}\mu_\nu^\alpha \bar{\nu}_L^\alpha \sigma^{\mu\nu} N_R F_{\mu\nu}$$





Qualitatively it is the same as before so we can employ a similar cut and count analysis. But **sterile neutrinos can undergo decays**.

Active to Sterile Neutrino Transition Magnetic Moment

The decay length of N_R in the lab frame is given by
$l_{decay} = \frac{16\pi}{\mu_\nu^2 M_N^4}\sqrt{E_N^2 - M_N^2}$, where E_N = energy of the outgoing N_R.

l_{prompt} = minimum decay length for the decay vertex to appear displaced, and hence distinguishable from the production vertex.

- $l_{decay} > l_{detector}$: N_R decays outside the detector and the decay vertex is not observable.
- $l_{prompt} < l_{decay} < l_{detector}$: The decay vertex is sufficiently displaced from the production vertex and results in "double-bang" events.
- $l_{decay} < l_{prompt}$: The decay occurs promptly, leading to an electron and photon appearing to be produced at the same point.

Active to Sterile Neutrino Transition Magnetic Moment

Of the possible signatures above, we focus on those with a single electron track emerging from the production vertex, **with no other nearby activity in the detector**.

We discard events where the N_R decays promptly, which could have different backgrounds than the ones we consider.

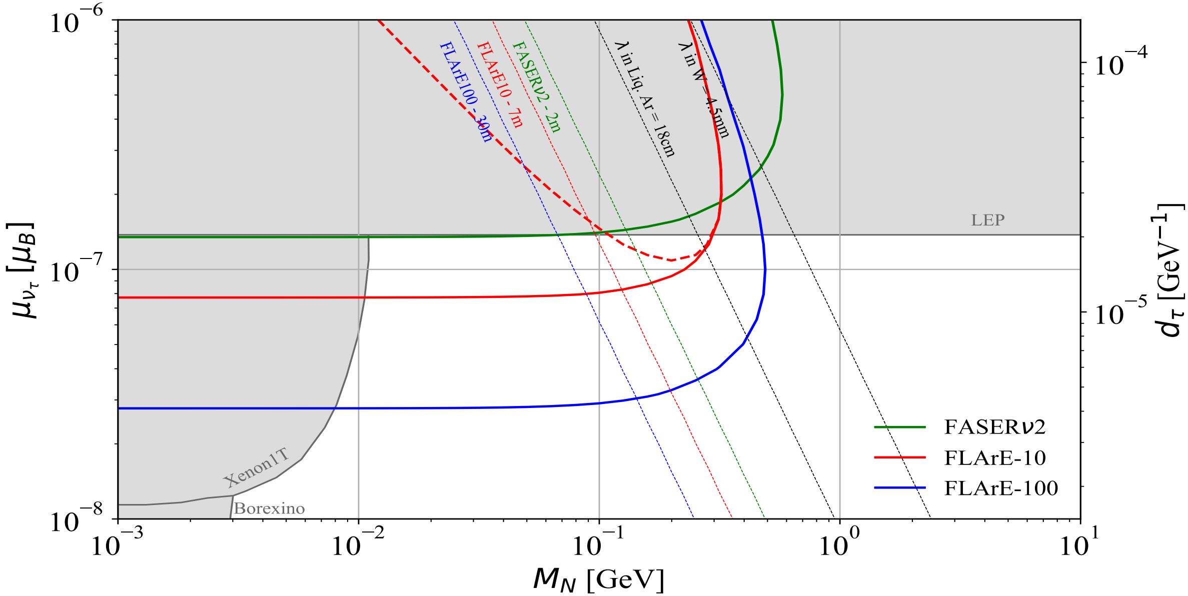
We take l_{prompt} to be the mean free path λ for pair production by the photon in the detector material: $\lambda = 4.5$ mm (18 cm) for FASERν2 (FLArE).

Loose (strong) cuts correspond to $E_{thresh} < E_{rec} < 10$ (1) GeV.

Detector	SM backgrounds			$\mu_{\nu_e} = 10^{-7}\mu_B$			$\mu_{\nu_\mu} = 10^{-8}\mu_B$			$\mu_{\nu_\tau} = 10^{-7}\mu_B$		
	no cuts	loose	strong	no cuts	loose	strong	no cuts	loose	strong	no cuts	loose	strong
FASERν2	86	2.5	0.1	480	134.1	39	30	8.6	2.5	12.7	3.6	1.0
FLArE-10	51	2	0.1	320.5	144	79.6	22.3	10.4	5.9	13.1	5.9	3.3
FLArE-100	332	15	1.0	2285	1037	575.7	165.1	78.2	44.6	126.1	57.2	31.8

Active to Sterile Neutrino Transition Magnetic Moment

$l_{decay} \sim \frac{1}{\mu_\nu^2 M_N^4}$

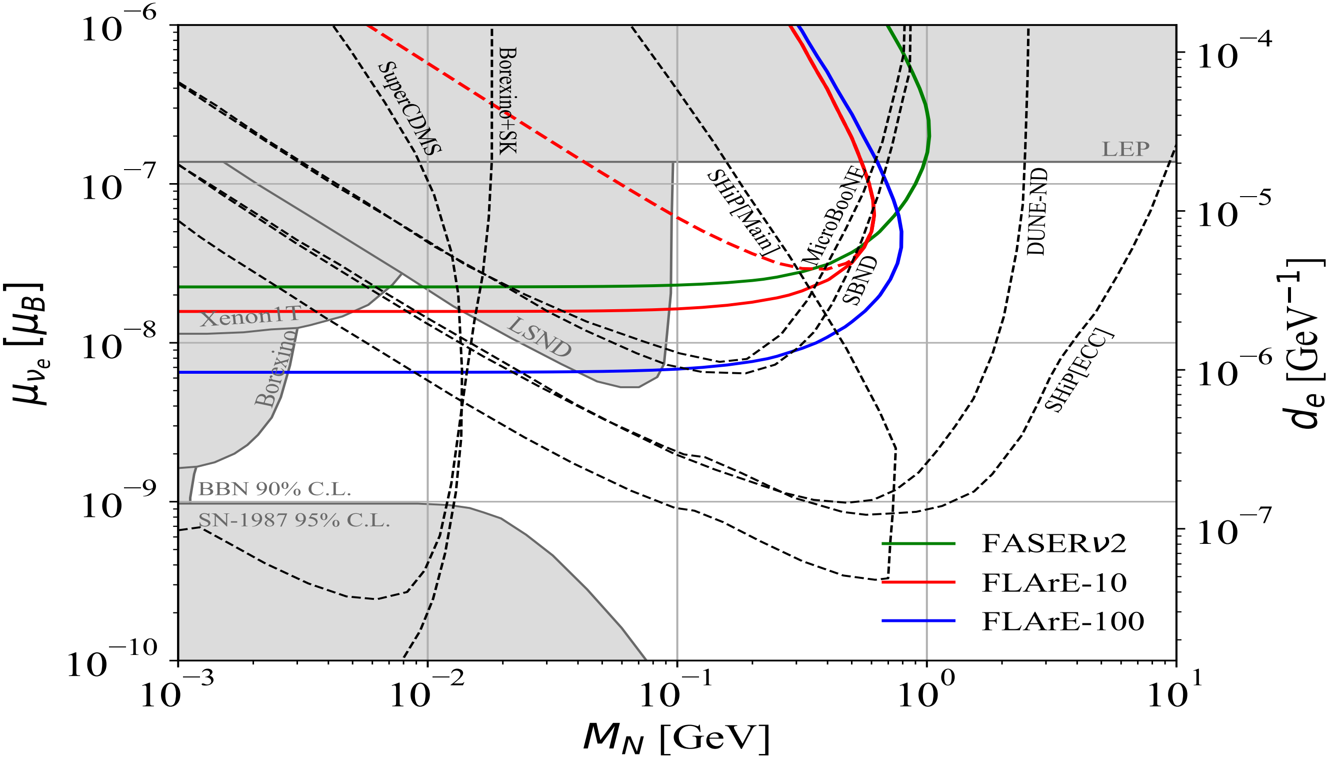


The colored dotted lines show $l_{deacy} = l_{detector}$ for various detectors assuming $E_N = 100$ GeV, and the black dotted lines show $l_{decay} = \lambda$ in various detector materials. The red dashed line is from considering only double bang events at FLArE-10.

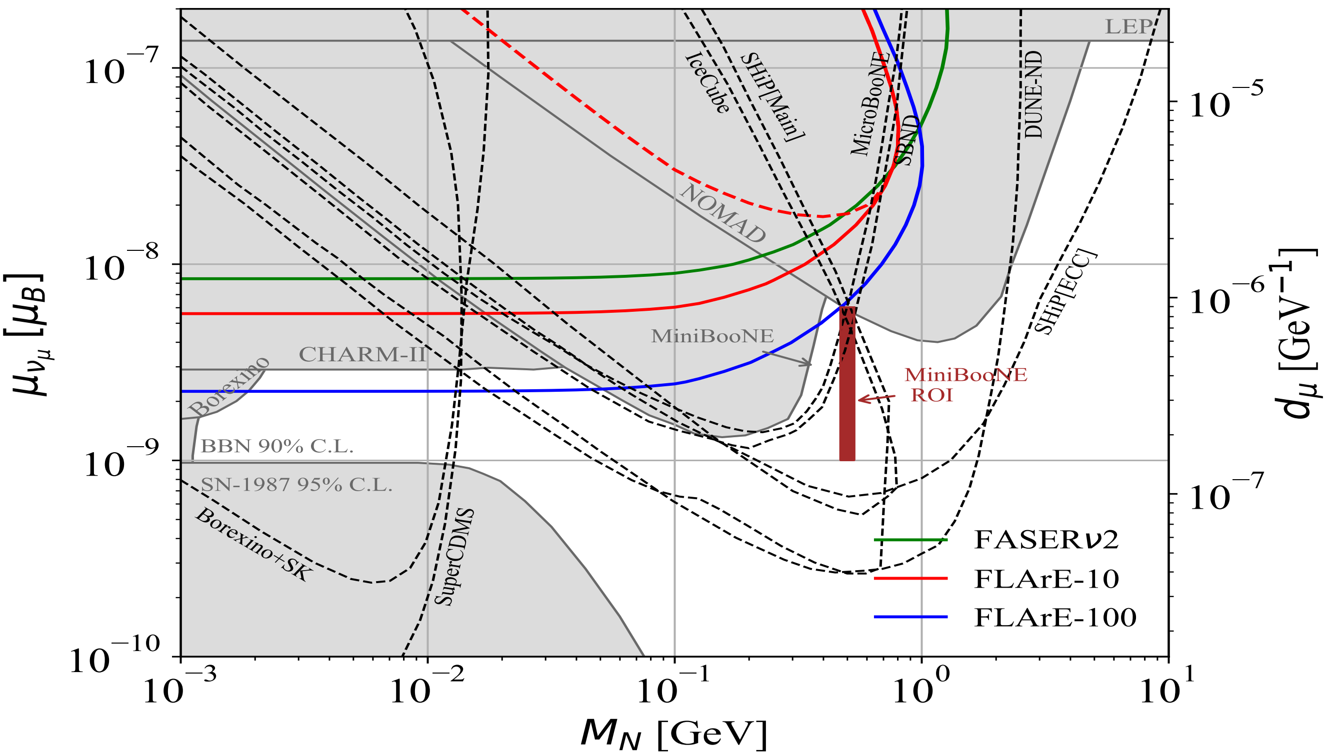
Summary

- The existence of nonzero neutrino magnetic moments is implied by neutrino masses.
- It is important to search for magnetic moments that could be larger than the typical expectation given by the neutrino mass scale.
- The intense beam of ν's, and detectors with low energy thresholds and timing capabilities make FPF suited for such searches.
- FASERν2, FLArE-10 can constrain active tau neutrino magnetic moment to $\sim 10^{-7}\mu_B$, and FLArE-100 to $\sim 10^{-8}\mu_B$, an order of magnitude better than DONUT.
- Highly competitive bounds on active to sterile neutrino transition moments are also obtained at FPF.

Global picture: μ_{ν_e}



Global picture: μ_{ν_μ}



Backup slides

Global picture: μ_{ν_τ}