Study of the Neutrino Magnetic Moment with the NOνA Near Detector

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Introduction

Neutrino Overview

Neutrinos are a coherent superposition of mass (ν_1, ν_2, ν_3) and flavor (ν_μ, ν_e, ν_τ) eigenstates

$\implies$ Neutrinos can oscillate between different flavor and mass states

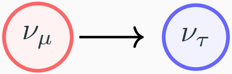

Figure 1: After propagating some distance, a neutrino observed to be in the μ flavor state can be observed to be in the τ flavor state.

Some Current Neutrino Questions Are...

1. What are the precise values for the mixing angles?
    - Angle of rotation between flavor basis and mass basis, see Figure 2 for an example of a mixing angle for two flavor mixing
2. What are the precise values for the mass squared splittings?
    - Unclear which mass state is the heaviest, see Figure 3
3. What is the value of the CP violating phase?
    - $\delta_{\text{CP}} = 0$ rad indicates ν and $\bar{\nu}$ oscillate in the same way
4. **Are neutrinos Dirac or Majorana fermions?**

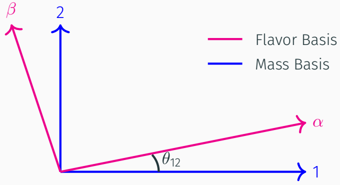

Figure 2: Two flavor mixing.

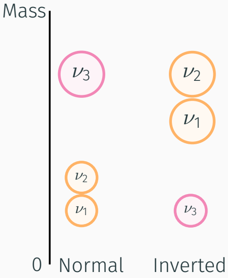

Figure 3: Mass state ordering.

The NuMI Off-axis ν_e Appearance (NOνA) Experiment

Figure 4: Location of NOνA Near Detector at Fermilab and Far Detector in Ash River, Minnesota. The FD is 810.5 km from Fermilab [2].

Broad goal of NOνA is to observe the oscillation of ν_μ to ν_e leading to science goals including [2]:

1. Precision measurement for θ_{23} and Δm^2_{32}
2. Place constraints on δ_{CP}
3. Place constraints on neutrino mass ordering

The NOνA Near Detector (ND)

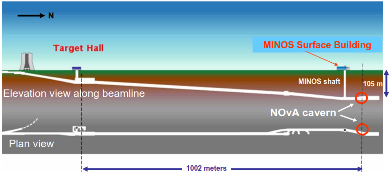

Figure 5: Side view (top) and plan view (bottom) of NOνA cavern in relation to MINOS and the NuMI Target Hall [2].

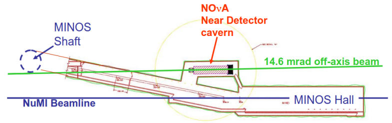

Figure 6: Top-down view of NOνA ND in relation to the NuMI beamline and MINOS hall. The ND is $\sim$1 km from the NuMI target [2].

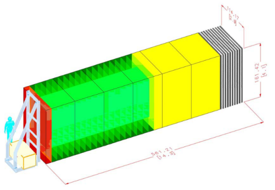

Figure 7: ND sections [2].

1. Red = veto region
2. Green = fiducial region
3. Yellow = shower containment region
4. 10, 0.1 m thick steel plates form a muon catcher region

Project Goal

Measure the magnetic moment for a muon neutrino using NOνA Near Detector data

Neutrino Magnetic Moment (νMM) Theory

Overview

- Neutrinos are observed to be electrically neutral and should be according to the Standard Model (SM)
- SM also predicts neutrinos to be massless so it is known there must be some extension to account for neutrino masses
- A minimal extension of the SM also allows neutrinos to have a non-vanishing magnetic moment
- Arises at the quantum level
  - Same source as the anomalous magnetic moment for the electron!
- νMM behaves differently for Dirac or Majorana neutrinos

Interaction

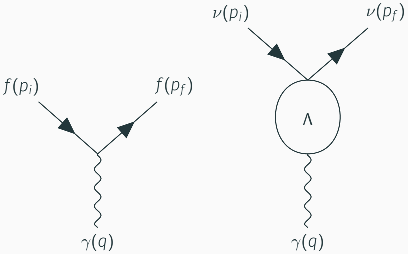

Figure 8: Coupling of a fermion with a photon (left) and coupling of a neutrino with a photon through higher order expansion with the blob encasing the vertex function, Λ (right) [3].

Coupling to a real photon gives physical meaning to the form factors contained in Λ

- $\mathbb{f}_Q(0) = q$
- $\mathbb{f}_M(0) = \mu$
- $\mathbb{f}_E(0) = \epsilon$
- $\mathbb{f}_A(0) = \mathbb{a}$

$\implies$ From quantum loop effects, we get μ which is the νMM [3]

νMM

νMM consists of a 3x3 matrix of values denoted by μ_{ij}

- $i = j$ representing diagonal terms
- $i \neq j$ representing transition terms

	Dirac	Majorana
$i = j$	$\approx 3.2 \times 10^{-19} \left(\frac{m_i}{eV}\right) \mu_B$	None
$i \neq j$	Negligible	$\approx \frac{-3ieG_F}{16\sqrt{2}\pi^2}(m_i + m_j)\Sigma_{\ell=e,\mu,\tau} \, \mathrm{Im}[U^*_{\ell i} U_{\ell j}] \frac{m^2_\ell}{m^2_W}$

[4]

νMM Analysis

Analysis Method: ν-on-e Scattering

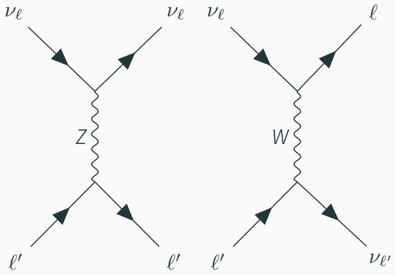

Figure 9: Examples of tree-level contributions for neutrino-lepton scattering according to the SM mediated through the exchange of either a *W* or *Z* boson. ℓ represents any charged lepton. For neutrino-electron scattering, the lepton would be an electron [5].

ν-on-e Scattering Cross Section

The differential cross section for ν-on-e scattering to one loop is

$$\frac{\mathrm{d}\sigma_{\nu_\ell e^-}}{\mathrm{d}T_e} = \left(\frac{\mathrm{d}\sigma_{\nu_\ell e^-}}{\mathrm{d}T_e}\right)_{SM} + \left(\frac{\mathrm{d}\sigma_{\nu_\ell e^-}}{\mathrm{d}T_e}\right)_{MAG}$$

T_e = recoil kinetic energy of the electron

$$\boxed{\begin{aligned} \left(\frac{\mathrm{d}\sigma_{\nu_\ell e^-}}{\mathrm{d}T_e}\right)_{Mag} &\propto \frac{1}{T_e} \\ \left(\frac{\mathrm{d}\sigma_{\nu_\ell e^-}}{\mathrm{d}T_e}\right)_{SM} &\propto {T_e}^2 \end{aligned}}$$

$\implies$ **Excess of events at low T_e, deviating from SM, is our νMM signal** [3]

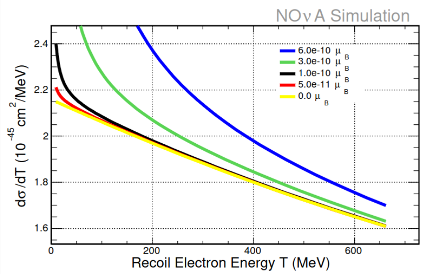

Figure 10: Example of how the differential cross section changes with T_e. Plot from [6], yellow line indicates no magnetic contribution.

NOνA Coverage for νMM

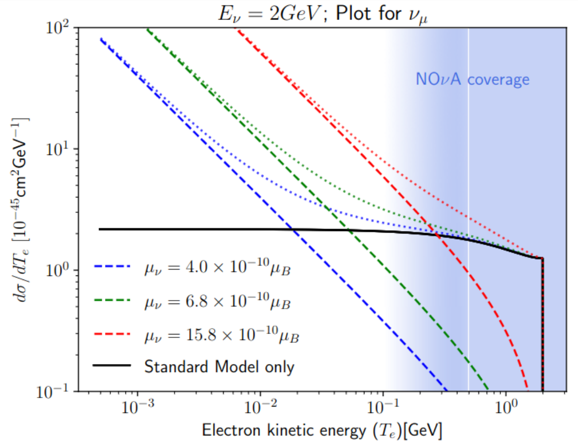

Figure 11: Plot of how the differential cross section changes with T_e on a log-log scale for different values of νMM. This is the same idea as the plot on the previous slide but this time includes the region that NOνA is sensitive to. Plot from [7].

Other Experiments

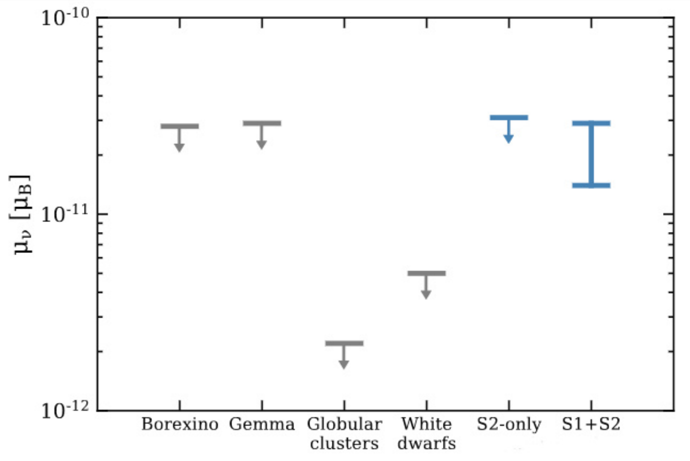

Figure 12: Upper limits on ν_μ from other experiments. These are indirect measurements from solar neutrinos while this work is focusing on making a direct measurement. Plot from [8].

Analysis Method Overview

- Build on prior work done by Biao Wang (Southern Methodist University [6], University of Iowa) and Robert Kralik (University of Sussex)
- Utilize various cuts in order to extract the νMM signal out of the background
- Signal is a well reconstructed, single, final state electron
- Main background includes ν-on-e scattering events consistent with the SM
- Additional background includes:
    - ν_μ CC interactions
    - ν_e CC interactions
    - NC interactions as π^0 can be misidentified as electrons

Other Applications for the Event Selection

1. Near Detector (ND) Group
    - Generated event selection criteria
    - νMM analysis is currently using a cut flow generated by the ND group
    - The signal for the ND group is ν-on-e scattering, which is part of our background
2. Light Dark Matter (LDM) Group
    - The background for the LDM group contains both ν-on-e scattering as well as νMM events

Simulation Details

Enhanced ν-on-e sample:

- Only ν-on-e and νMM samples
- Needs to be scaled to match full SM background
  - $\text{scale} = 3.70 \times 10^{20} / 1.72 \times 10^{24}$
  - Matching POT = background POT * scale

Full SM background sample:

- 1.39×10^{21} POT

*POT = protons on target

Example Event Selection Plots: Pre-Selection Only

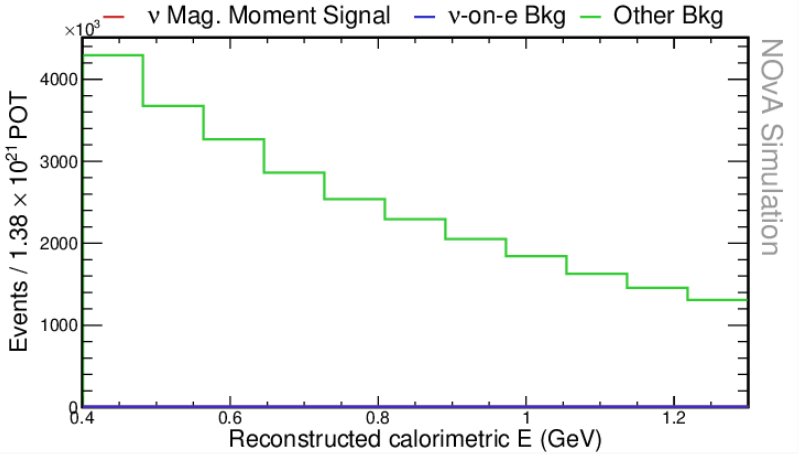

Figure 13: Plot showing νMM signal, ν-on-e background, and all other background with respect to the reconstructed electron energy. No cuts have been applied, only pre-selection criteria so the signal and ν-on-e are dominated by other background.

Example Event Selection Plots: Pre-Selection Only

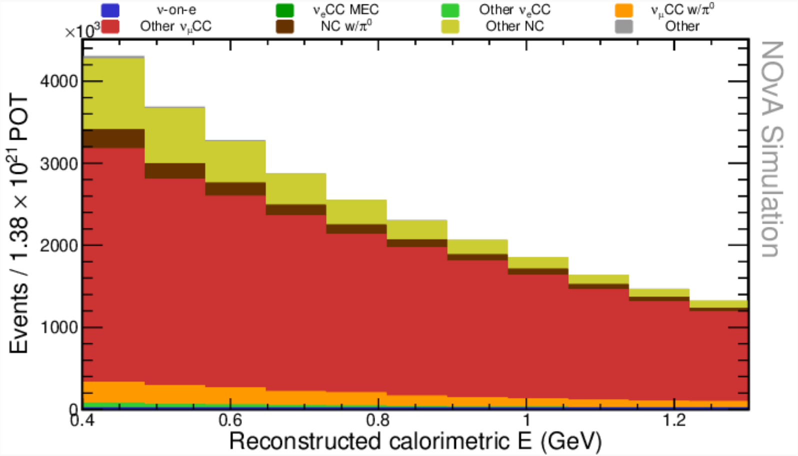

Figure 14: Plot showing the background breakdown for the event selection after applying only preselection criteria. The event selection is dominated by ν_μ CC events, NC events, and NC events containing a π^0.

Example Event Selection Plots: End of Cut Flow

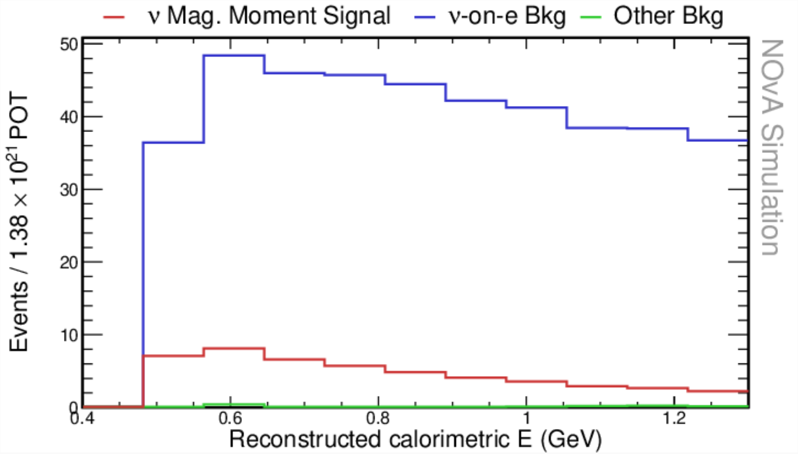

Figure 15: Same plots as the initial one, this time having applied the entire cut flow to decrease background and improve νMM signal. Now the dominant background is ν-on-e scattering, however this is a well understood process.

Next Steps

- Optimize cut flow for νMM analysis
- Gain a more complete understanding of the systematic uncertainties for this analysis

Long term:

- Obtain collaboration permission to look at data
- Get a result for the value of the neutrino magnetic moment

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Review of particle physics.
Progress of Theoretical and Experimental Physics, 2022(8):083C01, 08 2022.

[2] D. S. Ayres et al.
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[3] Carlo Giunti and Alexander Studenikin.
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[4] Studenikin Alexander.
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Journal of Physics: Conference Series, 718(6):062076, may 2016.

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[5] Oleksandr Tomalak and Richard J. Hill.
Theory of elastic neutrino-electron scattering.
Physical Review D, 101(3), February 2020.

[6] Biao Wang.
Muon-neutrino electron elastic scatting and a search for the muon-neutrino magnetic moment in the nova near detector, 2017.

[7] Robert Kralik.
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[8] XENON1T Collaboration.
Excess electronic recoil events in xenon1t.
Physical Review D, 102(7), October 2020.

Questions?

Backup

Relation Between Flavor and Mass States: PMNS Mixing Matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

PMNS Mixing Matrix: Standard Parameterization

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 1 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13} e^{-i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

with $c_{ij} = \cos_\theta ij$ and $s_{ij} = \sin\theta_{ij}$ where $i, j = 1, 2, 3$

Off-Axis

- Both the ND and FD are 14.6 mrad off axis from the beam
- ND off-axis design is a result of the FD being off-axis since the ND is a control for the FD and therefore needs to be as identical as possible
- Motivation for FD to be off axis is to generate a narrow neutrino energy spectra to increase flux and enhance background rejection at the FD [2]
- This choice is more important for the FD since it has an inherently lower flux than the ND

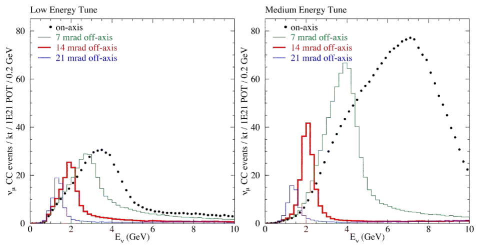

Figure 16: Number of ν_μ charged current events as a function of neutrino energy in the FD for various off-axis angles with and on-axis as reference [2].

Interaction

Assuming Lorentz and electromagnetic gauge invariance Λ is given by

$$\Lambda_\mu(q) = \mathbb{f}_Q(q^2)\gamma_\mu - \mathbb{f}_M(q^2) i\sigma_{\mu\nu}q^\nu + \mathbb{f}_E(q^2)\sigma_{\mu\nu}q^\nu\gamma_5 + \mathbb{f}_A(q^2)(q^2\gamma_\mu - q_\mu \not{q})\gamma_5,$$

Coupling to a real photon such that the four-momentum of the photon is zero, $q = 0$ gives physical meaning to the form factors

- $\mathbb{f}_Q(0) = q$
- $\mathbb{f}_M(0) = \mu$
- $\mathbb{f}_E(0) = \epsilon$
- $\mathbb{f}_A(0) = \mathbb{a}$

$\implies$ From quantum loop effects, we get μ which is the νMM [3]

Experimental Observables

Assuming the electron is at rest in the lab frame,

1. Kinetic energy of the recoil electron, T_e
2. Recoil angle with respect to the neutrino beam, χ

$$T_e \leq \frac{2E_\nu^2}{2E_\nu + m_e}$$

$$\cos\chi = \frac{E_\nu + m_e}{E_\nu}\left(\frac{T_e}{T_e + 2m_e}\right)^{1/2}$$

[3]

Normalized Plot for Pre-Selection Criteria

To ensure that we do have a signal since it is so suppressed, we can normalize the plot

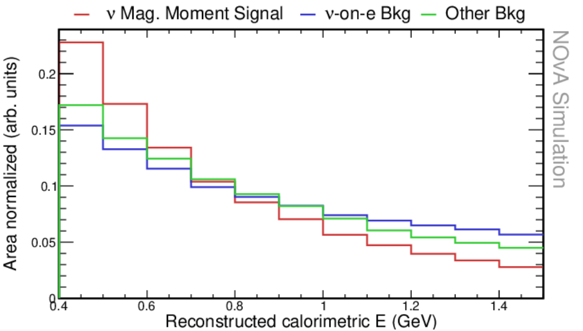

Figure 17: There is both a νMM signal and ν-on-e background. They just are not visible prior to the cut flow without normalizing.