Study of the Neutrino Magnetic Moment with the NOvA Near Detector

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The NuMI Off-Axis ν_e Appearance (NOvA) Experiment

The main science goal of NOvA is to observe the oscillation of ν_μ to ν_e which leads to goals such as:

1. Precision measurements for θ_{23} and Δm^2_{32}
2. Place constraints on δ_{CP}
3. Place constraints on neutrino mass ordering
4. **Study other exotic processes**

[1]

NOvA is a long baseline experiment with a Near Detector (ND) and Far Detector (FD). This work exclusively uses the ND located 1 km downstream from the NuMI target.

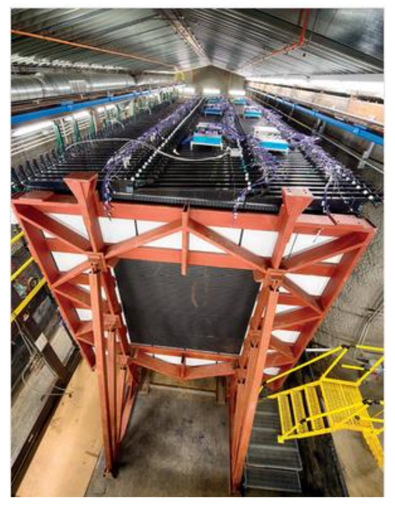

Figure 1: Beam-eye view of the NOvA Near Detector (Image credit: Fermilab Visual Media Services)

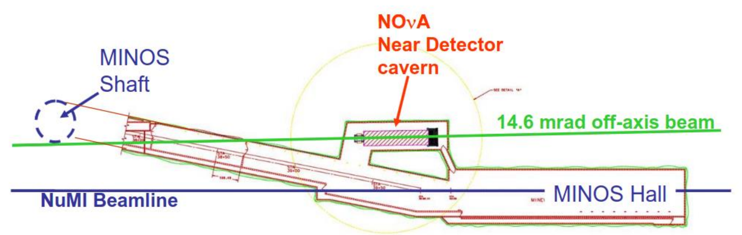

Figure 2: Top-down view of the ND in relation to the NuMI beamline and MINOS hall. The ND is about 1 km from the NuMI target and receives a nearly pure ν_μ beam [1].

Neutrino Magnetic Moment (nuMM)

- Neutrinos are observed to be electrically neutral which aligns with Standard Model (SM) predictions
- It is known that some extension to the SM is required by the existence of neutrino masses
- Application of higher order perturbative effects to a minimal extension on the SM allows neutrinos to acquire non-zero electromagnetic properties
  - Occurs through effective coupling with a photon

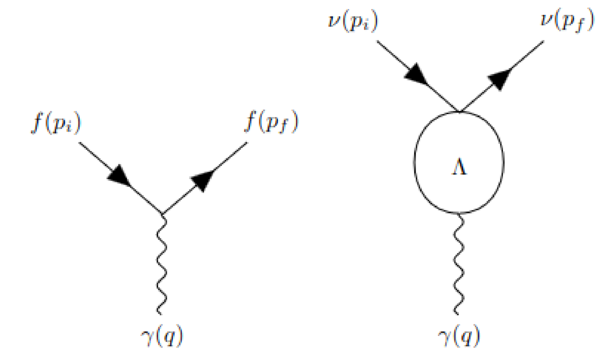

Figure 3: Diagram for first order coupling of a fermion directly with a photon (left) compared to higher order effective coupling to one loop between a neutrino and photon (right). Λ represents the vertex function which contains the interaction information for the blob [2].

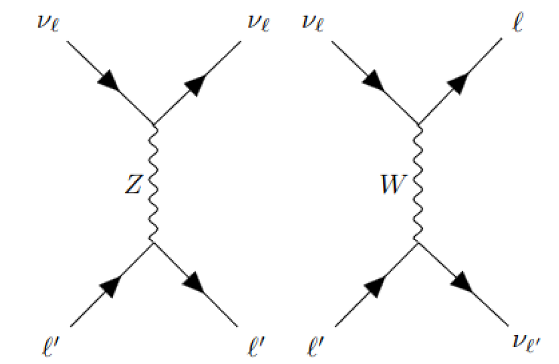

Figure 4: Example lowest order Feynman diagrams for SM v-on-e scattering. ℓ' in this process would be the electron [4].

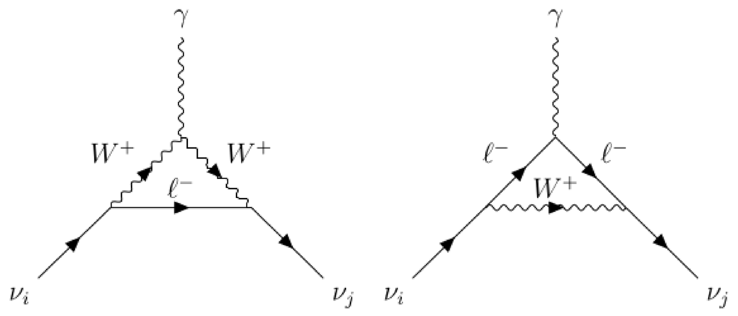

Figure 5: Example Feynman diagrams for higher order v-on-e scattering resulting in a nuMM. The process can vary depending on the theoretical framework utilized, these were used in [3].

Analysis Process: v-on-e Scattering

v-on-e scattering is the most sensitive and widely used process for studying the neutrino magnetic moment because of the differential cross section dependencies and it is purely leptonic [2]

$$\frac{d\sigma_{\nu_\ell e}}{dT_e} = \left(\frac{d\sigma_{\nu_\ell e}}{dT_e}\right)_{SM} + \left(\frac{d\sigma_{\nu_\ell e}}{dT_e}\right)_{MAG}$$

Equation 1: Components for the differential cross section for v-on-e scattering to one loop corrections. T_e is the recoil kinetic energy of the scattered electron [2].

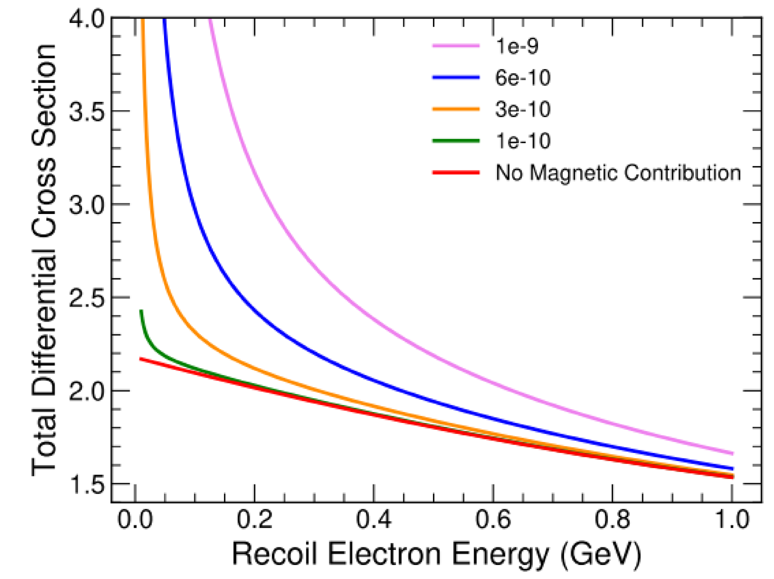

Figure 6: Differential cross section for v-on-e scattering with respect to T_e and for different values for the neutrino magnetic moment. The red, flat like represents the SM contribution only and the other lines include SM + MAG contributions.

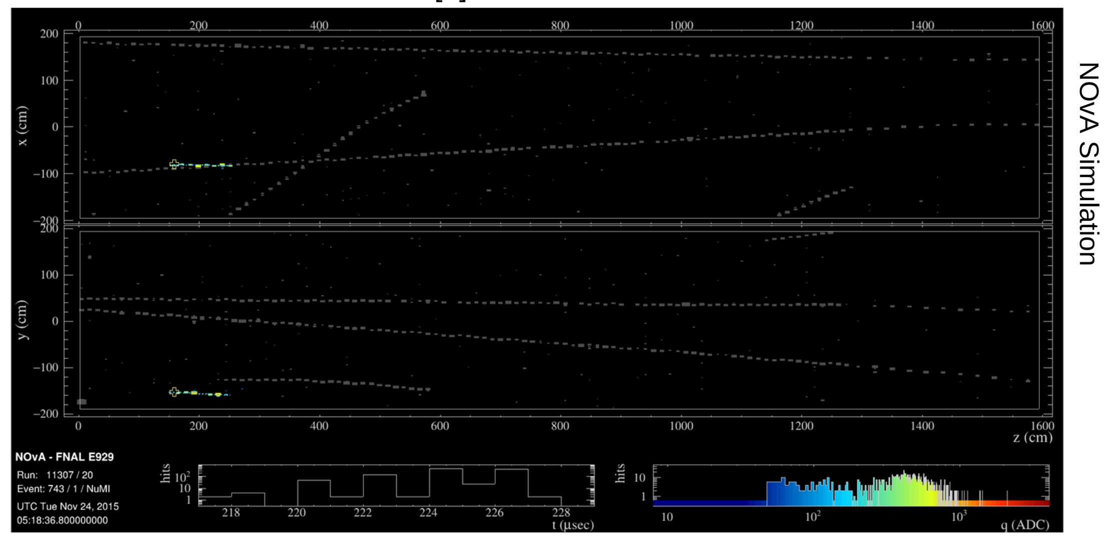

Figure 7: Sample simulation event display for a v-on-e scattering event.

Signal is observed as an excess of events (particularly at low recoil electron energy) which deviates from SM predictions

Event Selection Method

- Our signal is an enhancement over the SM prediction for v-on-e scattering
- Nominal signal is single electron energy 0.5 to 5 GeV
  - Select well-contained and well - reconstructed showers
  - Nothing else in event
  - Focus on low energy where most magnetic moment enhancement appears
    - Reduced lower bound on electron energy from 0.5 to 0.3 GeV
- Main (irreducible) background is from SM v-on-e scattering
  - Consider additional backgrounds from 2p2h and ν_eCC QE events (small compared to SM v-on-e)

Cutflow Method:

Preselection
↓
Volume Constraint
↓
Single Particle
↓
Limit Energy
↓
Apply Neural Network
↓
Forward Going

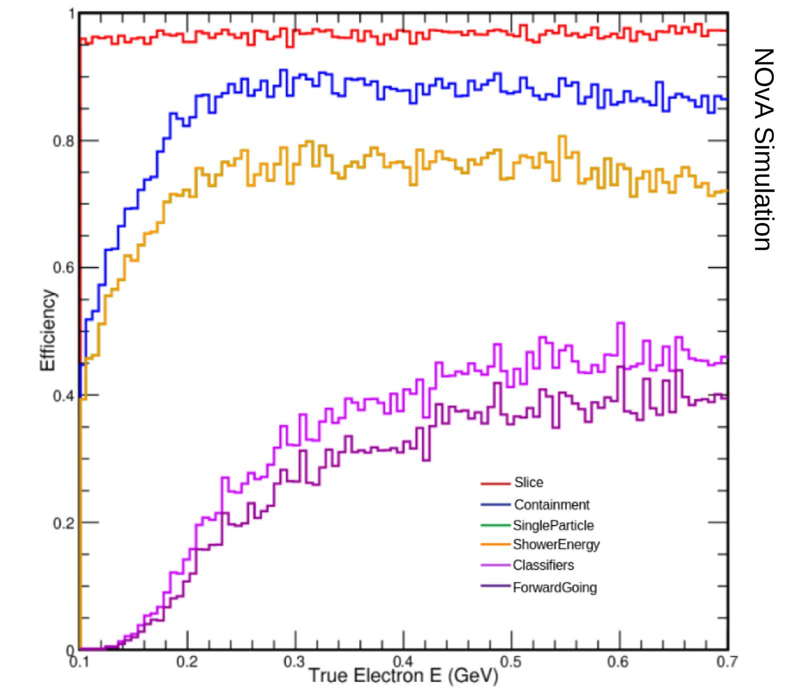

Figure 8: Simulation-based efficiency study to determine an appropriate lower bound energy value to validate down to.

Detector Uncertainty	+8.2% / -10.3%
Flux Uncertainty	+/- 8.1%
Statistical Uncertainty	+/- 2.6%
Total Background Prediction	1432 +/- 38 (stat) +118/-147 (det) +/- 116 (flux)

Table 1: Uncertainties affecting the background prediction and the total background prediction with the associated uncertainties. Only the shift up in uncertainty matters for the nuMM prediction, as we are looking for an observed excess.

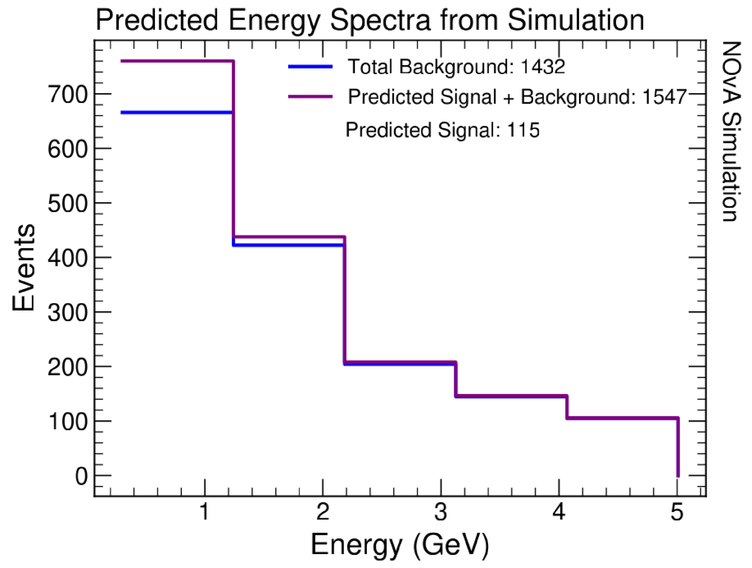

Figure 9: Predicted electron energy for signal + background and background only spectra from NOvA simulations

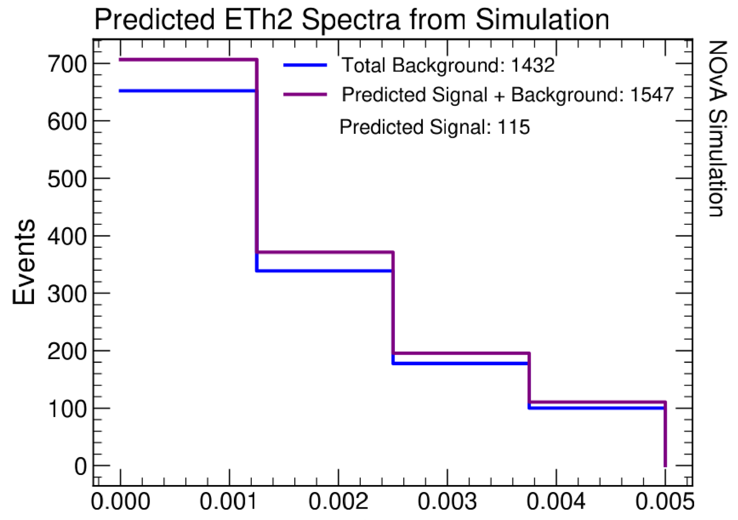

Figure 10: Predicted signal + background and background only spectra with respect to $E\theta^2$ using NOvA simulations

Note: $E\theta^2$ is defined by the reconstructed electron energy and the angle of the electron with respect to the beam -- it describes the forward-going nature of the signal.

90% CL Sensitivity Predictions

Experiment	Year	90% CL Result (x 10^{-9} μ_B)
MiniBooNE	2008	< 1.27
CHARM II	1995	< 3.0
LSND	1993	< 0.68
BNL-E-0734	1990	< 0.85

Table 2: Prior direct measurements for the nuMM. $\mu_B = e\hbar / 2m_e$ is the Bohr magneton.

To predict NOvA sensitivity for analysis of 2.42E21 POT of FHC data:

- Utilize an Asimov
- Approximate spectra as Gaussian and assume no signal events observed

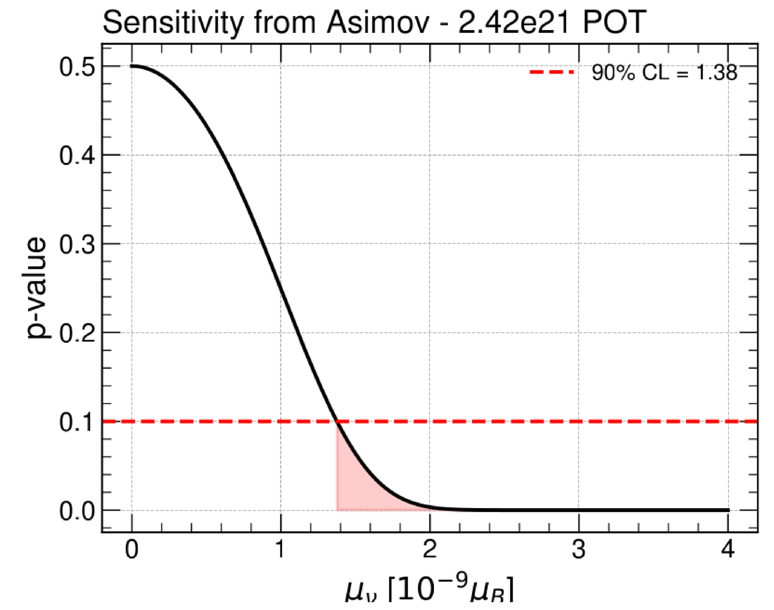

Figure 11: Sensitivity predictions for full range of electron energy (0.3 to 5 GeV). The *p*-value at 0.1 correlates to the nuMM value prediction at 90% confidence level (CL).

The prediction for the upper bound on NOvA's sensitivity is <1.38 x 10^{-9} μ_B.

Next we split the electron spectrum into a signal and sideband region, optimizing the shower energy using the expected 90% CL sensitivity. The new signal region requires 0.3 GeV < E_{shower} < 1.43 GeV, with a sideband at 1.43 GeV < E_{shower} < 5.0 GeV

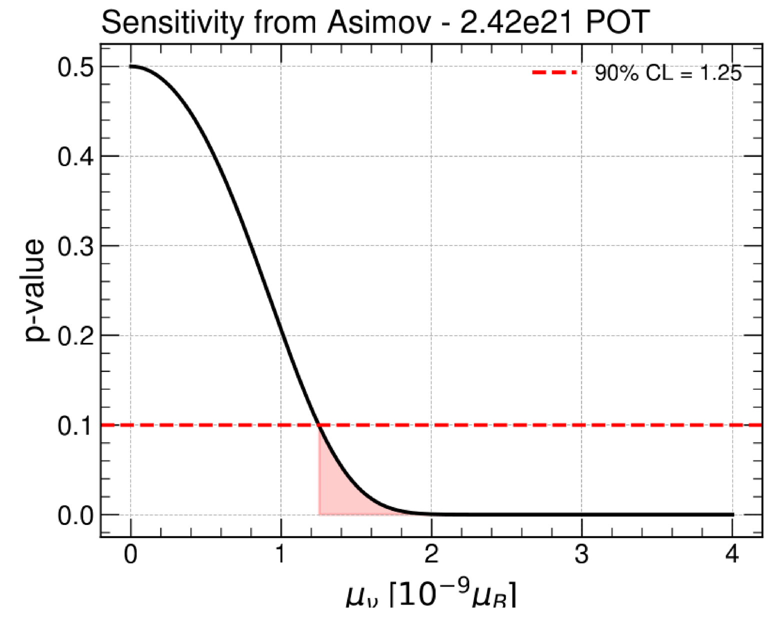

Figure 12: Sensitivity predictions applying the update signal region energy requirement (0.3 to 1.43 GeV). The *p*-value at 0.1 correlates to the nuMM value prediction at 90% confidence level (CL).

The prediction for the upper bound on NOvA's sensitivity is now <1.25 x 10^{-9} μ_B.

Continuing Work

- Signal region validation studies have been performed with 10% of the available data, reviewed by collaboration
- Analysis of full dataset coming soon!
- Future work focuses on improving low energy reconstruction to try to improve efficiency in the region where this signal is most accessible

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