Study of the Neutrino Magnetic Moment with the NOνA Near Detector

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The NuMI Off-Axis ν_e Appearance (NOνA) Experiment

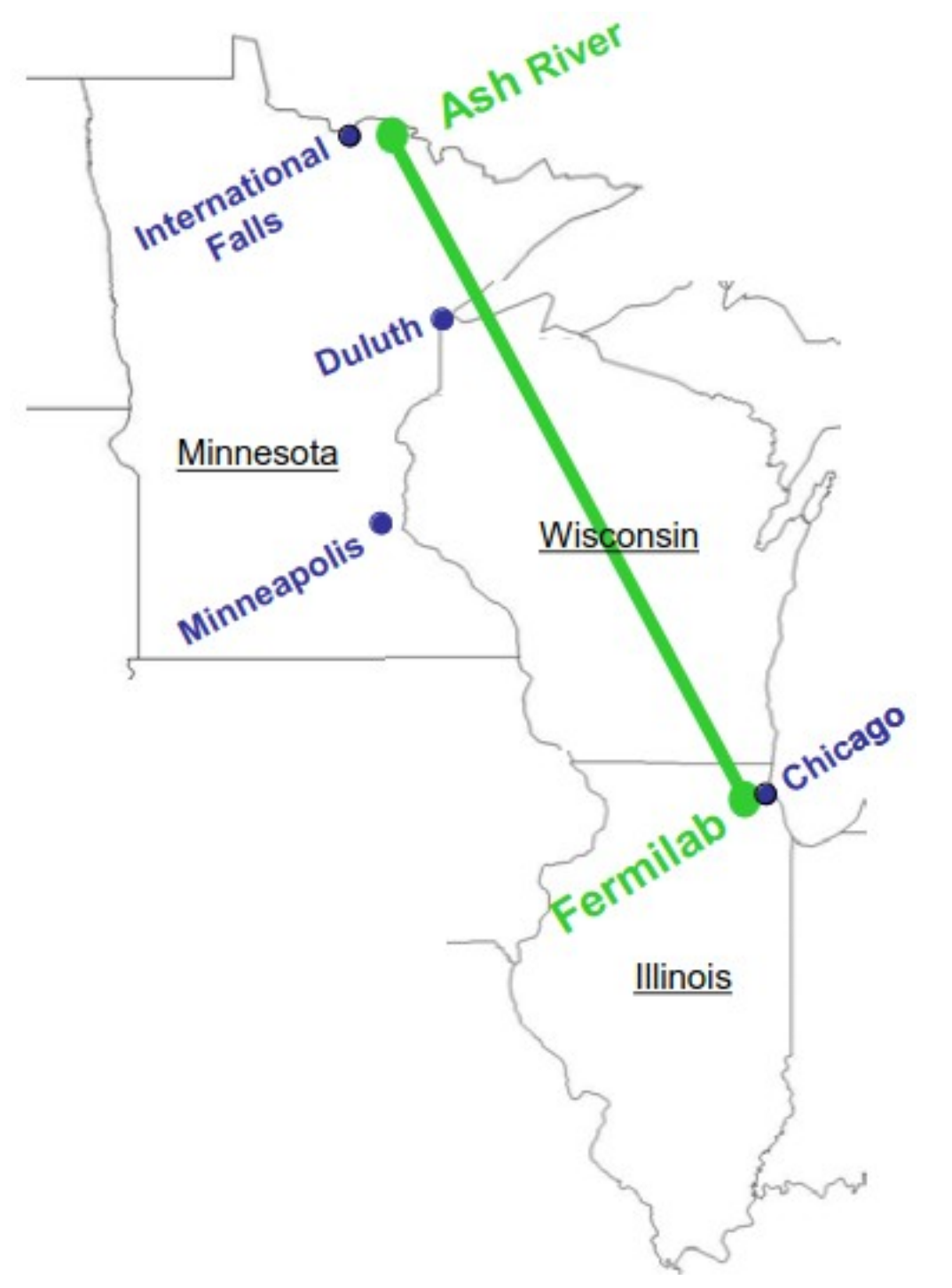

Figure 1: Location of the NOνA Near Detector at Fermilab and Far Detector in Ash River, Minnesota. The Far Detector is about 810.5 km from Fermilab [1].

From [1], NOνA will observe the oscillation of ν_μ to ν_e which will allow for goals including but not limited to:

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

The focus for this work is the Near Detector (ND)

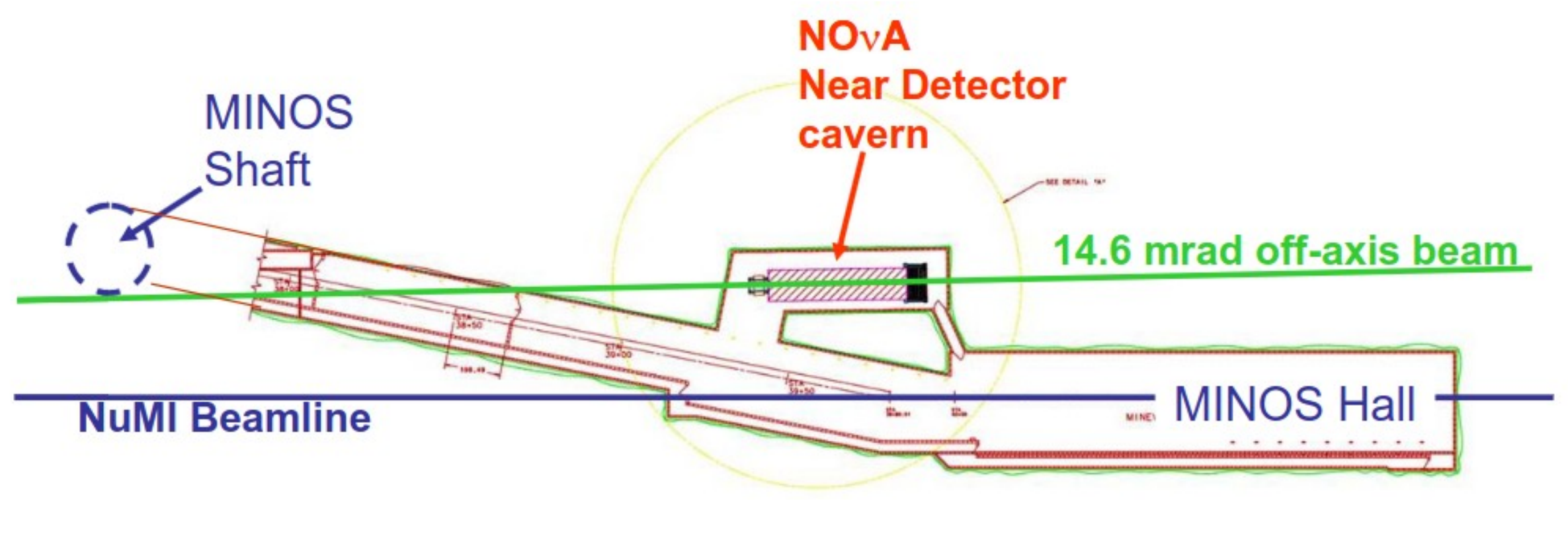

Figure 2: Top-down of the NovA ND in relation to the NuMI beamline and MINOS hall. The ND is about 1 km from the NuMI target [1].

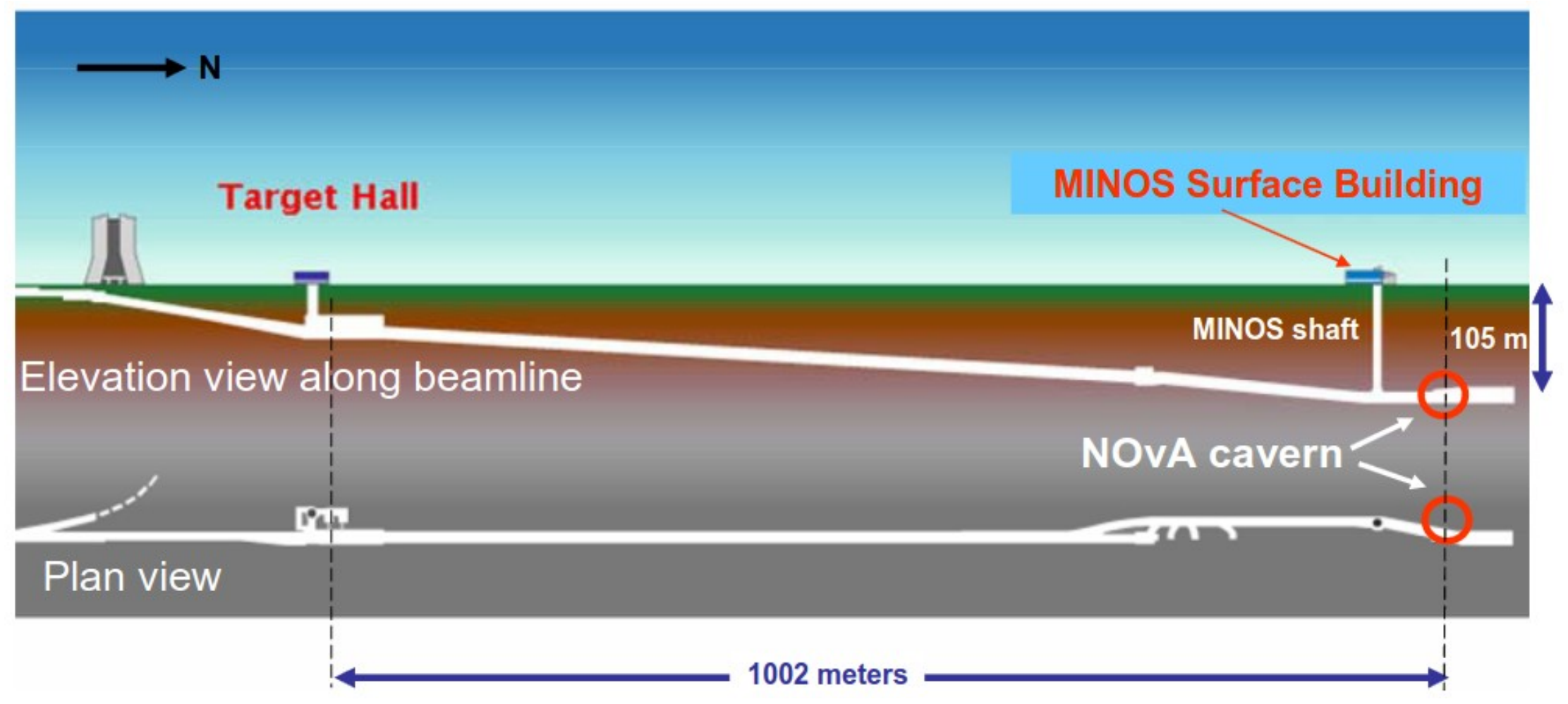

Figure 3: Side view (top) and plan view (bottom) of the NovA cavern in relation to MINOS and the NuMI target hall [1].

Neutrino Magnetic Moment (νMM) Background

- Neutrinos are observed to be electrically neutral which aligns with Standard Model (SM) predictions
- Extenstion to the SM is known to be required as it predicts neutrinos to be massless, which they are not
- Minimal extension to the SM also allows neutrinos to have a non-vanishing magnetic moment arising at the quantum level
- νMM behaves differently for Dirac or Majorana neutrinos

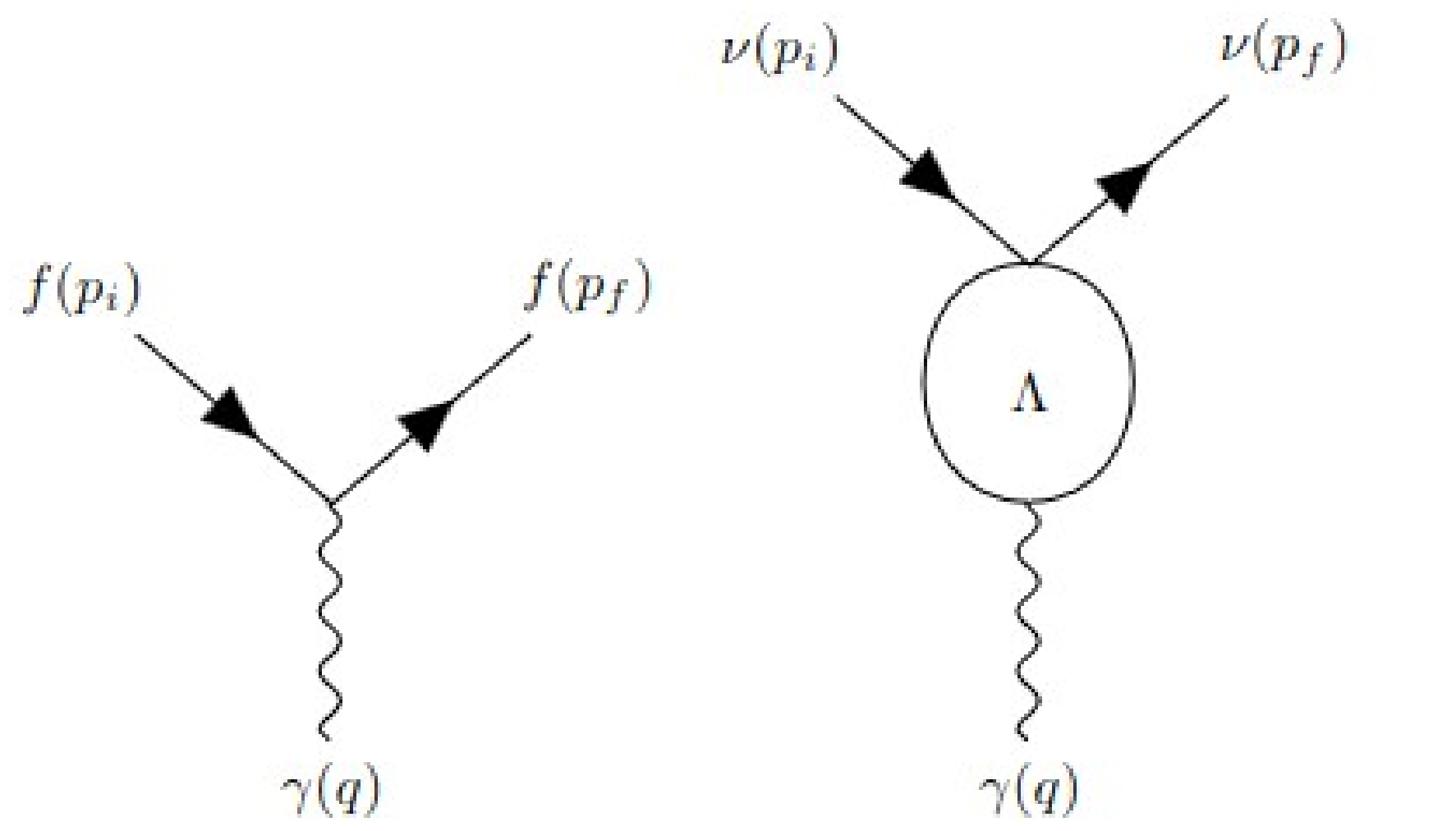

Figure 4: First order coupling of a fermion with a photon (left) and higher order coupling to one loop of a neutrino with a photon (right). **Λ** represents the vertex function which contains the interaction information for the blob [2].

Λ contains form factors which take on physical meaning when coupling with a real photon occurs:

1) $\mathbb{f}_Q(0) = q$
3) $\mathbb{f}_E(0) = \epsilon$
2) $\mathbb{f}_M(0) = \boldsymbol{\mu}$
4) $\mathbb{f}_A(0) = \mathbb{a}$

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

Figure 5: νMM denoted by μ_{ij} where i=j represents diagonal moments and i≠j represents transition moments. Behavior differs for Dirac or Majorana neutrinos and the Majorana value is much smaller than the Dirac value [3].

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Analysis Process: ν-on-e Scattering

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

*T_e = recoil kinetic energy of the scattered electron

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

$$\left(\frac{\mathrm{d}\sigma_{\nu_\ell e}}{\mathrm{d}T_e}\right)_{\mathrm{SM}} = \frac{G_F^2 m_e}{2\pi}\left((g_V^{\nu_\ell} + g_A^{\nu_\ell})^2 + (g_V^{\nu_\ell} - g_A^{\nu_\ell})^2\left(1 - \frac{T_e}{E_\nu}\right)^2 + [(g_A^{\nu_\ell})^2 - (g_V^{\nu_\ell})^2]\frac{m_e T_e}{E_\nu^2}\right) \quad \propto \mathbf{T_e^2 + T_e}$$

$$\left(\frac{\mathrm{d}\sigma_{\nu_\ell e}}{\mathrm{d}T_e}\right)_{\mathrm{MAG}} = \frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T_e} - \frac{1}{E_\nu}\right)\left(\frac{\mu_{\nu_\ell}}{\mu_B}\right)^2 \quad \propto \frac{\mathbf{1}}{\mathbf{T_e}}$$

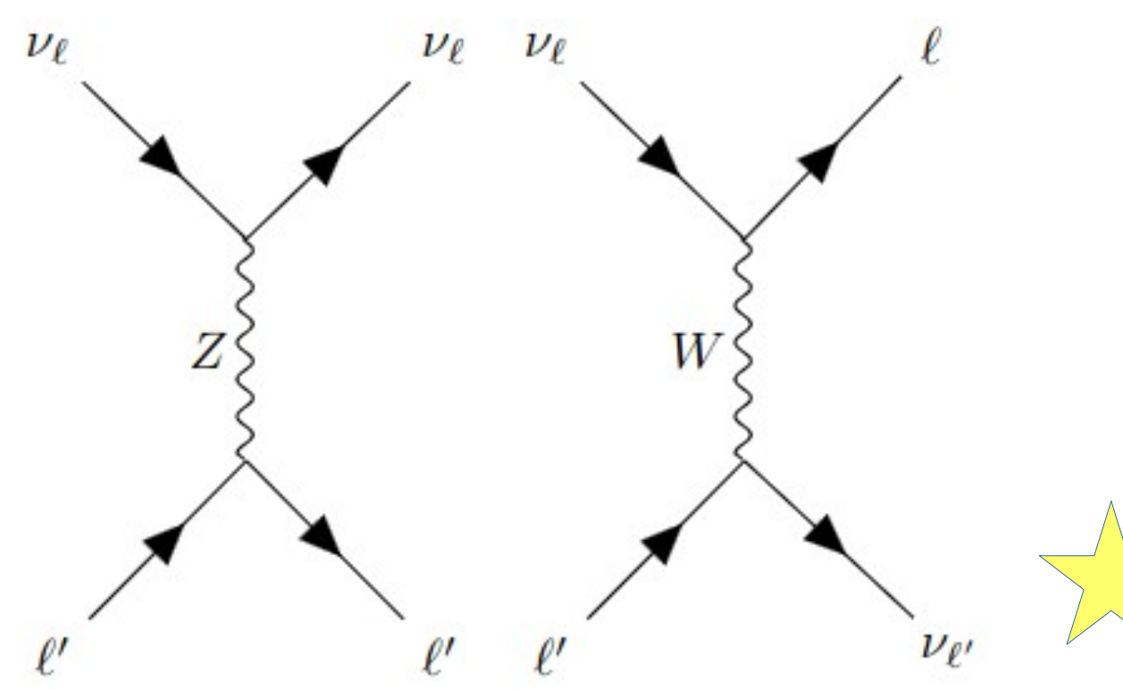

Figure 6: Example lowest order Feynma diagrams for **ν**-on-e scattering where ℓ' in this process would be an electron [4].

νMM signal is an excess of events at low T_e, deviating from SM predictions

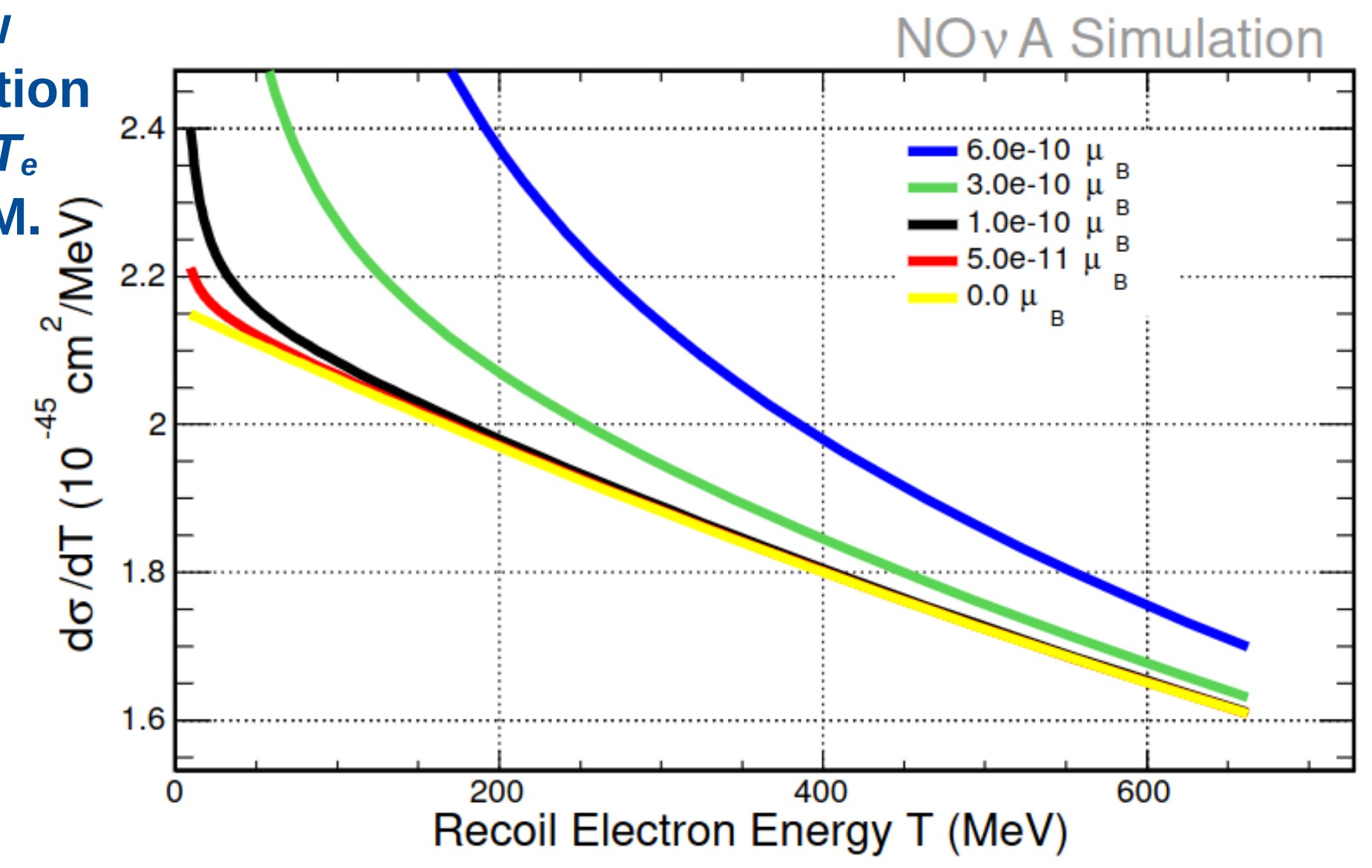

Figure 7: Example of how the differential cross section changes with respect to T_e for various values of **ν**MM. The yellow line indicates only SM contribution, no magnetic. Plot from [5].

Analysis Method

- Utilize various cuts in order to extract νMM signal from the background
- Signal: Well reconstructed, single, final state electron
- Main background: ν-on-e scattering events consistent with the SM
- Other backgrounds: ν_μ and ν_e charged current interactions, neutral current interactions

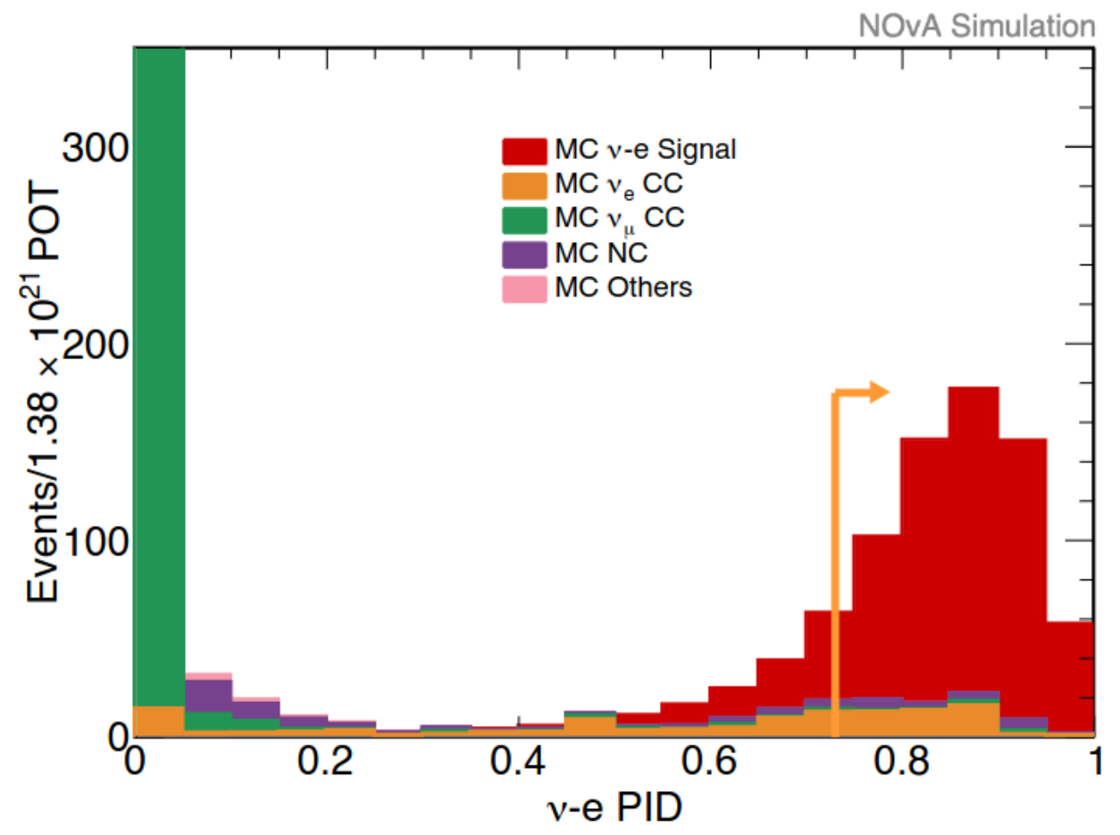

Figure 8: Two CNNs were used to help separate signal from background. The first is to identify **ν**-on-e scattering events. This plot is from the Near Detector group, [6], and they have applied a cut around 0.75 to show that electrons identified in events at a confidence above this threshold are most likely from their nu-on-e signal.

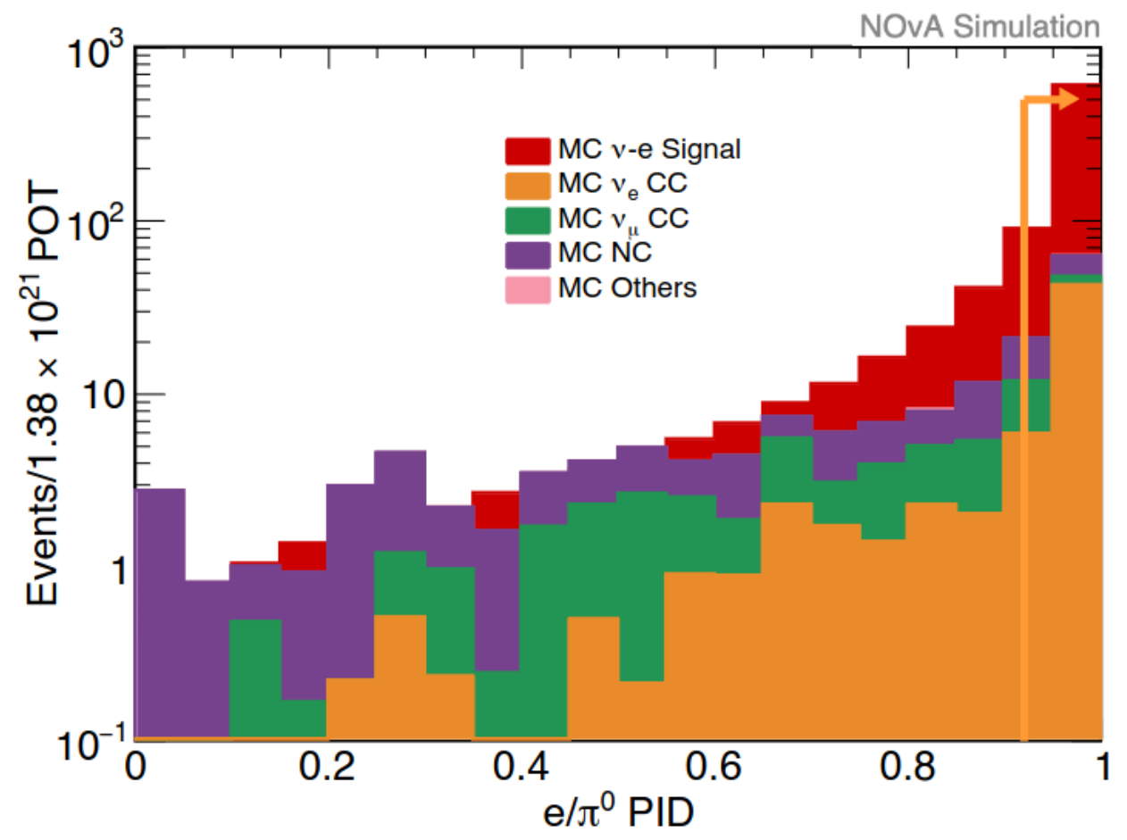

Figure 9: The other CNN applied rejects events that are identified to contain a π^0, as π^0 can be misidentified as electrons. This plot is again from the Near Detector group, [6], and they have placed a cut around 0.9 to show that events above this threshold most likely have a π^0 and should be removed.

Next Steps

- Optimize cut flow
- Gain a more complete understanding of the systematic uncertainties
- Obtain collaboration permission to look at data

The efficacy of the cut flow chain is seen in the following plots:

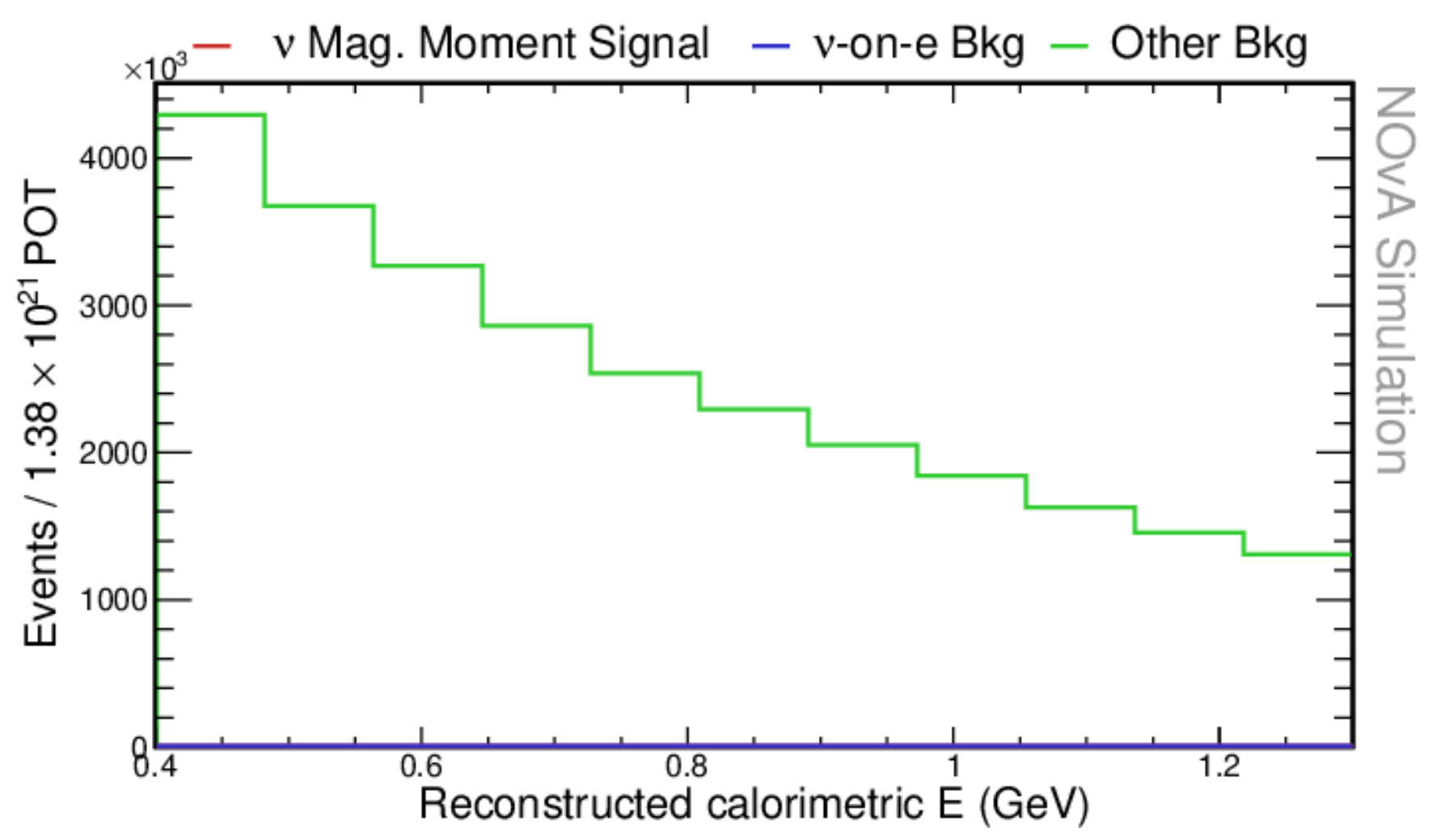

Figure 10: Event selection plotted with respected to reconstructed electron energy. No cuts applied, only pre-selection criteria. Plot is completely dominated by background.

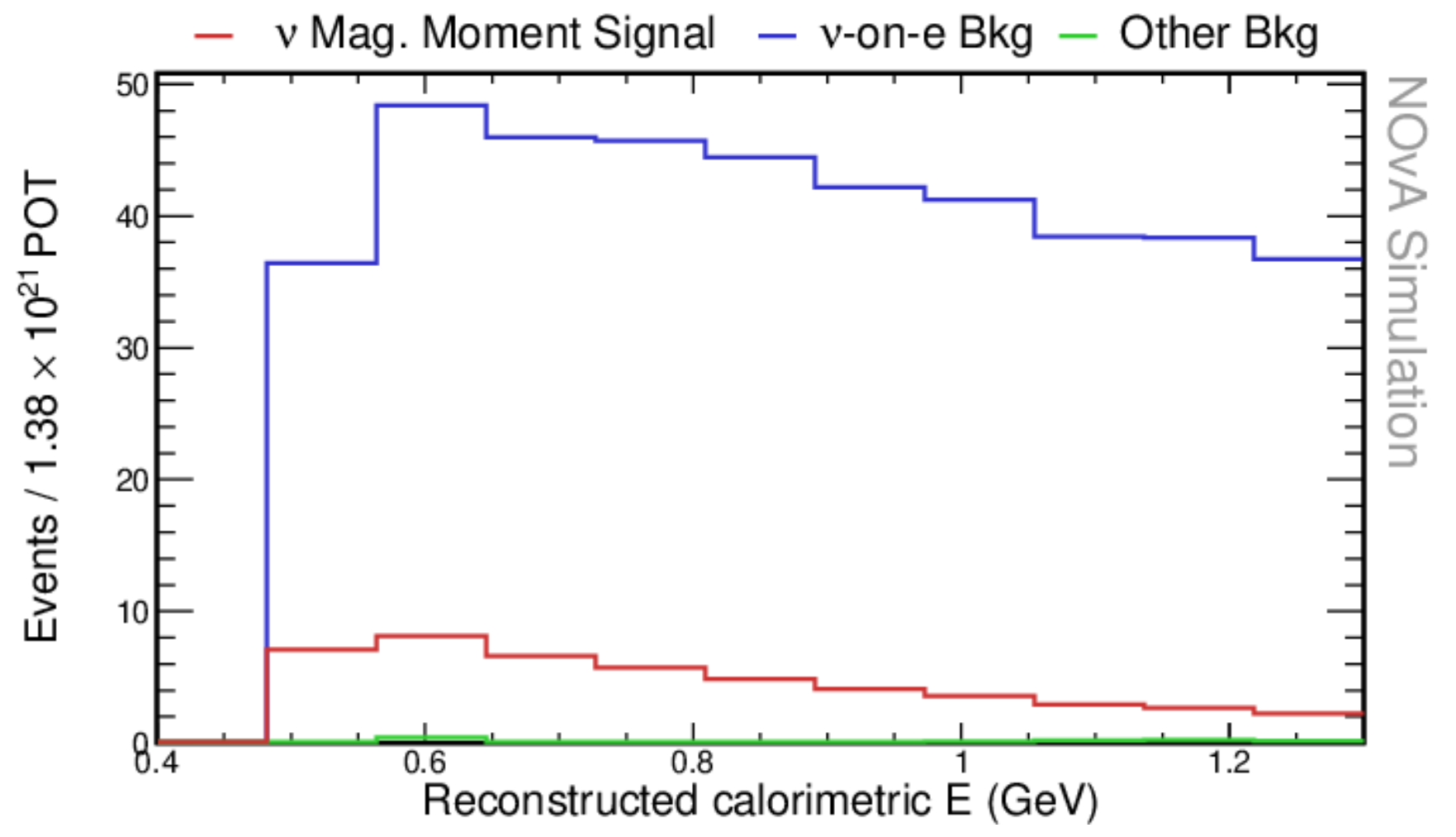

Figure 11: Same event selection but with pre-selection criteria applied plus the entire cut flow. The other background has been mostly elimiated and the **ν**MM signal has emerged. The dominant background is SM **ν**-on-e scattering, which is a well understood process

References

1. D. S. Ayres et al. *The NovA Technical Design Report.* 10 2007.
2. Carlo Giunti and Alexander Studenikin. *Neutrino electromagnetic interactions: a window to new physics.* 2015
3. Alexander Studenikin. *Status and perspectives of neutrino magnetic moments*. Journal of Physics: Conference Series, 781(6):062076, may 2016.
4. Oleksandr Tomalak and Richard J. Hill. *Theory of elastic neutrino-electron scattering.* Physical Review D, 101(3), feb 2020.
5. Biao Wang, *Muon-neutrino electron elastic scattering and a search for the muon-neutrino magnetic moment in the nova near detector.* 2017.
6. Yiwen Xiao. *Measurement of Neutrino-electron Elastic Scattering in the NovA Near Detector.* APS April Meeting, April 2023, talk.

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