

# Measurement of the neutrino magnetic moment at the NOvA experiment

Technical note

Robert Kralik<sup>1</sup>

<sup>1</sup>University of Sussex, Brighton, UK

January 3, 2024

## Abstract

This is the abstract

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## 47 **1 Introduction**

48 Main motivations for the analysis. Briefly mention that there was a previous study by Biao,  
49 what were the results there and what limitations (or maybe talk about this in the Experimental  
50 overview?).

51 Maybe briefly mention the overview of the theory and experimental overview.

## 52 **2 Literature review**

### 53 **2.1 Theoretical overview**

54 (TO DO: *Go over the theoretical overview and make it better*)

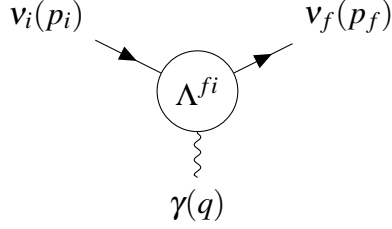


Figure 1: Effective coupling of neutrinos with one photon electromagnetic field.

## 2.2 Electromagnetic properties of the neutrino

In the standard model, neutrino can have electromagnetic interaction only at a higher order of the perturbative expansion of the interaction - from loop diagrams. *(TO DO: To be more specific, neutrinos can only have charge radius in standard model. Any other electromagnetic interactions must come from beyond standard model theories)*

In the one photon approximation, electromagnetic interactions of a neutrino field  $v_k(x)$ ,  $k \in \{1, \dots, N\}$ , for  $N$  neutrino mass states, can be described by an effective interaction Hamiltonian [1]

$$\mathcal{H}_{em}^{(v)}(x) = \sum_{k,j=1}^N \bar{v}_k(x) \Lambda_{\mu}^{kj} v_j(x) A^{\mu}(x). \quad (1)$$

*(TO DO: describe here what is lambda and everything else in the equation. Also mention figure 1)*

The amplitude of neutrino-to-neutrino interaction for **Dirac** neutrinos is

$$\langle v_f(p_f) | j_{\mu}^{(v)}(x) | v_i(p_i) \rangle = e^{i(p_f - p_i)x} \bar{u}_f(p_f) \Lambda_{\mu}^{fi}(p_f, p_i) u_i(p_i), \quad (2)$$

where  $p_f$  and  $p_i$  are the final and initial four momentums respectively and  $u/\bar{u}$  are the solutions to the Dirac equation for a free particle. We take into account possible transitions between different mass states  $v_i$  and  $v_f$  [1]. *(TO DO: also describe what is j)*

The vertex function  $\Lambda_{\mu}^{fi}(p_f, p_i)$  is generally a matrix and in the most general case it can be written in terms of linearly independent products of Dirac matrices ( $\gamma$ ) and four momentum of the photon ( $q = p_f - p_i$ ):

$$\Lambda_{\mu}^{fi}(p_f, p_i) = \mathbb{F}_1^{fi}(q^2) q_{\mu} + \mathbb{F}_2^{fi}(q^2) q_{\mu} \gamma_5 + \mathbb{F}_3^{fi}(q^2) \gamma_{\mu} + \mathbb{F}_4^{fi}(q^2) \gamma_{\mu} \gamma_5 + \mathbb{F}_5^{fi}(q^2) \sigma_{\mu\nu} q^{\nu} + \mathbb{F}_6^{fi}(q^2) \varepsilon_{\mu\nu\rho\gamma} q^{\nu} \sigma^{\rho\gamma}, \quad (3)$$

where  $\mathbb{F}_i^{fi}(q^2)$  are six Lorentz invariant form factors. For  $f = i$  they are called "diagonal" and for  $f \neq i$  "transition form factors" [1].

Applying conditions of hermiticity ( $\mathcal{H}_{em}^{(v)\dagger} = \mathcal{H}_{em}^{(v)}$ ) and of conservation of the current (continuity equation:  $\partial^{\mu} j_{\mu}^{(v)}(x) = 0$ ), we can rewrite the vertex function as *(TO DO: maybe describe why we would want to apply these conditions)*

$$\Lambda_{\mu}^{fi}(q) = (\gamma_{\mu} - q_{\mu} \not{q} / q^2) \left[ \mathbb{F}_Q^{fi}(q^2) + \mathbb{F}_A^{fi}(q^2) q^2 \gamma_5 \right] - i \sigma_{\mu\nu} q^{\nu} \left[ \mathbb{F}_M^{fi}(q^2) + i \mathbb{F}_E^{fi}(q^2) \gamma_5 \right], \quad (4)$$

66 where  $\mathbb{F}_Q^{fi}, \mathbb{F}_M^{fi}, \mathbb{F}_E^{fi}$  and  $\mathbb{F}_A^{fi}$  are hermitian matrices representing the real charge, dipole magnetic,  
 67 dipole electric and anapole neutrino form factors. In coupling with a real photon ( $q^2 = 0$ ) these  
 68 become the neutrino charge and magnetic, electric and anapole moments [1].

For antineutrinos the form factors are transformed as:

$$\bar{\mathbb{F}}_\Omega^{fi} = -\mathbb{F}_\Omega^{if} = -\left(\mathbb{F}_\Omega^{fi}\right)^* \quad \Omega = Q, M, E, \quad (5)$$

$$\bar{\mathbb{F}}_A^{fi} = \mathbb{F}_A^{if} = \left(\mathbb{F}_A^{fi}\right)^*. \quad (6)$$

69 (TO DO: *maybe describe what does this mean?*)

In case of **Majorana neutrinos**, the general expression for the vertex function in terms of charge, magnetic, electric and anapole form factors looks the same as for Dirac neutrinos. (TO DO: *so does that mean that the interaction amplitude can be written in the same way for both Dirac and Majorana neutrinos?*) However, since Majorana antineutrinos are the same particle as Majorana neutrinos, from eq.5,6 we can see that:

$$\mathbb{F}_\Omega^M = -\left(\mathbb{F}_\Omega^M\right)^T \quad \Omega = Q, M, E, \quad (7)$$

$$\mathbb{F}_A^M = \left(\mathbb{F}_A^M\right)^T. \quad (8)$$

70 Therefore the Majorana charge, magnetic and electric form factor matrices are antisymmetric and  
 71 the anapole form factor matrix is symmetric. This means that Majorana neutrino doesn't have any  
 72 diagonal charge and dipole magnetic and electric moments, but it can have transition charge and  
 73 magnetic and electric moment [1]. (TO DO: *Explain why is this worth mentioning or remove it if*  
 74 *it's not*)

75 [NuMMBasicsAndAstro\_2022.pdf] One of the most important astrophysical consequences of  
 76 neutrino non-zero effective magnetic moments is the neutrino helicity change  $\nu_l \rightarrow \nu_R$  with the  
 77 appearance of nearly sterile right-handed neutrinos  $\nu_R$ . In general, this phenomena can proceed in  
 78 three different mechanisms:

- 79 1. the helicity change in the neutrino magnetic moment scattering on electrons (or protons and  
 80 neutrons),
- 81 2. the neutrino spin and spin-flavour precession in an external magnetic field, and
- 82 3. the neutrino spin and spin-flavour precession in the transversally moving matter currents or  
 83 in the transversally polarized matter at rest

84 For completeness note that the important astrophysical consequence of nonzero neutrino mil-  
 85 licharges is the neutrino deviation from the rectilinear trajectory. (TO DO: *find out if this is the*  
 86 *same thing that IceCube describes in their paper*)

### 2.2.1 Neutrino electric and magnetic dipole moments

Evaluating the one loop diagrams in the minimal extension of the standard model (TO DO: *should I mention here what actually do I mean by the minimal extension of SM? probably this: "introduction of three right-handed neutrinos"*) with right handed (Dirac) neutrinos gives us the first approximation of the electric and magnetic moments ( $q^2 = 0$ ):

$$\left. \begin{array}{l} \mu_{kj}^D \\ i\varepsilon_{kj}^D \end{array} \right\} \simeq \frac{3eG_F}{16\sqrt{2}\pi^2} (m_k \pm m_j) \left( \delta_{kj} - \frac{1}{2} \sum_{l=e,\mu,\tau} U_{lk}^* U_{lj} \frac{m_l^2}{m_W^2} \right), \quad (9)$$

where  $m_k, m_j$  are the neutrino masses and  $m_l$  are the masses of charged leptons which appear in the loop diagrams. Higher order electromagnetic corrections were neglected, but those can also have a significant contribution [1]. (TO DO: *ok, so what does that mean? Does that mean that this equation is not actually correct or that it's the higher/lower limit? or something else?*)

(It can be seen that) There are no diagonal electric moments ( $\varepsilon_{kk}^D = 0$ ) and the diagonal magnetic moments are approximately

$$\mu_{kk}^D \simeq \frac{3eG_F m_k}{8\sqrt{2}\pi^2} \simeq 3.2 \times 10^{-19} \left( \frac{m_k}{\text{eV}} \right) \mu_B, \quad (10)$$

where  $\mu_B$  is the Bohr magneton [1].

The transition magnetic moments are suppressed with respect to the largest of the diagonal magnetic moments by at least a factor of  $10^{-4}$  due to the  $m_W^2$  in denominator and the transition electric moments are even smaller than that due to the mass difference [1]. Therefore an experimental observation of a magnetic moment larger than in eq.10 would indicate physics beyond the minimally extended standard model [2].

Majorana neutrinos can be obtained by either adding a  $SU(2)_L$  Higgs triplet, or right handed neutrinos together with a  $SU(2)_L$  Higgs singlet (TO DO: *is this also considered a minimally extended SM? or is this the only way to get Majorana neutrinos? Most likely the former - from nuElmagInt2015.pdf: the absence of Higgs triplets, without which it is not possible to have Majorana mass terms.*). If we neglect the Feynman diagrams which depend on the model of the scalar sector (TO DO: *what does that mean for the result?*), the magnetic and electric dipole moments are

$$\mu_{kj}^M \simeq -\frac{3ieG_F}{16\sqrt{2}\pi^2} (m_k + m_j) \sum_{l=e,\mu,\tau} \text{Im} [U_{lk}^* U_{lj}] \frac{m_l^2}{m_W^2}, \quad (11)$$

$$\varepsilon_{kj}^M \simeq \frac{3ieG_F}{16\sqrt{2}\pi^2} (m_k - m_j) \sum_{l=e,\mu,\tau} \text{Re} [U_{lk}^* U_{lj}] \frac{m_l^2}{m_W^2}. \quad (12)$$

These are difficult to compare to the Dirac case, due to possible presence of Majorana phases in the PMNS matrices, but it is clear that they have the same order of magnitude as Dirac transition dipole moments. However, the neglected model dependent contributions can enhance the transition dipole moments [1]. (TO DO: *but how much?*)

It is possible [2] to obtain "natural" upper limits on the size of neutrino magnetic moment by calculating its contribution to the neutrino mass by standard model radiative corrections. For Dirac

neutrinos the radiative correction induced by neutrino magnetic moment, generated at an energy scale  $\Lambda$ , to the neutrino mass is generically

$$m_\nu^D \sim \frac{\mu_\nu^D}{3 \times 10^{-15} \mu_B} [\Lambda (\text{TeV})]^2 \text{ eV}. \quad (13)$$

102 So for  $\Lambda \simeq 1 \text{ TeV}$  and  $m_\nu \lesssim 0.3 \text{ eV}$  the limit becomes  $\mu_\nu^D \lesssim 10^{-15} \mu_B$ . This applies only if the new  
103 physics is well above the electroweak scale ( $\Lambda_{EW} \sim 100 \text{ GeV}$ ). It is possible to get Dirac neutrino  
104 magnetic moment higher than this limit, for example in frameworks of minimal super-symmetric  
105 standard model, by adding more Higgs doublets, or by considering large extra dimensions [1].

The limit for Majorana neutrino magnetic moment is less stringent, due to the antisymmetry condition from eq.7 and considering  $m_\nu \lesssim 0.3 \text{ eV}$  can be expressed as

$$\mu_{\tau\mu}, \mu_{\tau e} \lesssim 10^{-9} [\Lambda (\text{TeV})]^{-2} \quad (14)$$

$$\mu_{\mu e} \lesssim 3 \times 10^{-7} [\Lambda (\text{TeV})]^{-2} \quad (15)$$

which is shown in the flavour basis, which relates to the framework used previously as

$$\mu_{ij} = \sum_{\alpha\beta} \mu_{\alpha\beta} U_{\alpha i}^* U_{\beta j}, \quad \alpha, \beta \in \{e, \mu, \tau\}. \quad (16)$$

106 This limits imply, that if a magnetic moment  $\mu \gtrsim 10^{-15} \mu_B$  would be measured, it is plausible  
107 neutrinos are Majorana fermions and the scale of lepton violation would be well below the con-  
108 ventional see-saw scale [2].

## 109 2.3 Measuring neutrino magnetic moment

110 *(TO DO: Need to add some general description of the measurements)*

### 111 2.3.1 Effective neutrino magnetic moment

What we measure in experiments is an effective "flavour" magnetic moment, which is influenced by mixing of "mass" magnetic moments (and electric moments) and oscillations. In the ultrarelativistic limit this is

$$\mu_{\nu_l}^2(L, E_\nu) = \sum_j \left| \sum_k U_{lk}^* e^{-i\Delta m_{kj}^2 L/2E_\nu} (\mu_{jk} - i\varepsilon_{jk}) \right|^2. \quad (17)$$

112 What is called the effective magnetic moment (often just magnetic moment) therefore contains  
113 contributions from both the neutrino magnetic and electric moment [1].

For antineutrinos, the effective magnetic moment is *(TO DO: maybe I should just combine these two equations to avoid overcrowding)*

$$\mu_{\bar{\nu}_l}^2(L, E_\nu) = \sum_j \left| \sum_k U_{lk}^* e^{+i\Delta m_{kj}^2 L/2E_\nu} (\mu_{jk} - i\varepsilon_{jk}) \right|^2. \quad (18)$$

114 So the only difference is in the phase induced by neutrino oscillations.

For experiments with baselines short enough for neutrino oscillations to not develop ( $\frac{\Delta m^2 L}{2E_\nu} \ll 1$ ), such as the NOvA ND, the effective magnetic moment can be expressed as

$$\mu_{\nu_l}^2 \simeq \mu_{\bar{\nu}_l}^2 \simeq \sum_j \left| \sum_k U_{lk}^* (\mu_{jk} - i\varepsilon_{jk}) \right|^2 = \left[ U (\mu^2 + \varepsilon^2) U^\dagger + 2 \text{Im} (U \mu \varepsilon U^\dagger) \right]_{ll'}, \quad (19)$$

115 which is independent of the neutrino energy and of the source to detector distance.

116 It is important to mention, that since the effective magnetic moment depends on the flavour  
117 of the studied neutrino, it is different for different types of neutrino experiment. Also the solar  
118 neutrino experiments need to include the effect of the solar matter on the neutrino oscillations.  
119 Therefore the reports on the value (or upper limit) of the effective neutrino magnetic moment are  
120 not directly comparable between different types of neutrino experiments.

### 121 2.3.2 Neutrino-on-electron elastic scattering

The most sensitive method to measure neutrino magnetic moment is the low energy elastic scattering of (anti)neutrinos on electrons [1]. This interaction has two observables, the recoil electron's kinetic energy ( $T_e$ ) and the recoil angle with respect to the incoming neutrino beam ( $\theta$ ). From simple  $2 \rightarrow 2$  kinematics we can get

$$(P_\nu - P_{e'})^2 = (P_{\nu'} - P_e)^2, \quad (20)$$

$$m_\nu^2 + m_e^2 - 2E_\nu E_{e'} + 2E_\nu p_{e'} \cos \theta = m_{\nu'}^2 + m_e^2 - 2E_{\nu'} m_e. \quad (21)$$

Using the energy conservation

$$E_\nu + m_e = E_{\nu'} + E_{e'} = E_{\nu'} + T_e + m_e \Rightarrow E_{\nu'} = E_\nu - T_e \quad (22)$$

we get

$$E_\nu p_{e'} \cos \theta = E_\nu E_{e'} - E_{\nu'} m_e = E_\nu (T_e + m_e) - (E_\nu - T_e) m_e = T_e (E_\nu + m_e), \quad (23)$$

$$\cos \theta = \frac{E_\nu + m_e}{E_\nu} \sqrt{\frac{T_e^2}{E_{e'}^2 - m_e^2}} = \frac{E_\nu + m_e}{E_\nu} \sqrt{\frac{T_e^2}{T_e^2 + 2T_e m_e}}. \quad (24)$$

And finally we get

$$\cos \theta = \frac{E_\nu + m_e}{E_\nu} \sqrt{\frac{T_e}{T_e + 2m_e}}. \quad (25)$$

Electron's kinetic energy is kinematically constrained by

$$T_e \leq \frac{2E_\nu^2}{2E_\nu + m_e}. \quad (26)$$



Considering  $E_\nu \sim \text{GeV}$ , we can approximate  $\frac{m_e^2}{E_\nu^2} \rightarrow 0$  and in the small angle approximation we get from eq.25

$$T\theta^2 \cong 2m_e \left(1 - \frac{T_e}{E_\nu}\right) < 2m_e. \quad (27)$$

In the ultrarelativistic limit, the neutrino magnetic moment changes the neutrino helicity, turning active neutrinos into sterile (**TO DO: this is a very strong statement and it probably need a bit more backing up**). Since the SM weak interaction conserves helicity we can add the two contribution to the neutrino on electron cross section incoherently [1]:

$$\frac{d\sigma_{\nu_l e^-}}{dT_e} = \left(\frac{d\sigma_{\nu_l e^-}}{dT_e}\right)_{\text{SM}} + \left(\frac{d\sigma_{\nu_l e^-}}{dT_e}\right)_{\text{MAG}}. \quad (28)$$

The standard model contribution can be expressed as [1]:

$$\left(\frac{d\sigma_{\nu_l e^-}}{dT_e}\right)_{\text{SM}} = \frac{G_F^2 m_e}{2\pi} \left\{ (g_V^{\nu_l} + g_A^{\nu_l})^2 + (g_V^{\nu_l} - g_A^{\nu_l})^2 \left(1 - \frac{T_e}{E_\nu}\right)^2 + \left((g_A^{\nu_l})^2 - (g_V^{\nu_l})^2\right) \frac{m_e T_e}{E_\nu^2} \right\}, \quad (29)$$

where the coupling constants  $g_V$  and  $g_A$  are different for different neutrino flavours and for antineutrinos. Their values are:

$$g_V^{\nu_e} = 2\sin^2\theta_W + 1/2, \quad g_A^{\nu_e} = 1/2, \quad (30)$$

$$g_V^{\nu_{\mu,\tau}} = 2\sin^2\theta_W - 1/2, \quad g_A^{\nu_{\mu,\tau}} = -1/2. \quad (31)$$

122 For antineutrinos  $g_A \rightarrow -g_A$ .

123 Using expressions 25 and 27 we can also derive [3] cross sections with respect to  $\cos\theta$ ,  $\theta^2$   
 124 and  $T\theta^2$ : (**TO DO: I don't think these equations are actually valid. We've been using some**  
 125 **approximations and therefore I don't think these equations work for any theta dependence**)

$$\begin{aligned} \left(\frac{d\sigma_{\nu_l e^-}}{d\cos\theta}\right)_{\text{SM}} &= \frac{2G_F^2 E_\nu^2 m_e^2 \cos\theta (E_\nu + m_e)^2}{\pi \left((E_\nu + m_e)^2 - E_\nu^2 \cos^2\theta\right)^2} \\ &\quad \left\{ (g_V^{\nu_l} + g_A^{\nu_l})^2 + (g_V^{\nu_l} - g_A^{\nu_l})^2 \left(1 - \frac{2m_e E_\nu \cos^2\theta}{(E_\nu + m_e)^2 - E_\nu^2 \cos^2\theta}\right)^2 + \right. \\ &\quad \left. \left((g_A^{\nu_l})^2 - (g_V^{\nu_l})^2\right) \frac{2m_e^2 \cos^2\theta}{\left((E_\nu + m_e)^2 - E_\nu^2 \cos^2\theta\right)} \right\}, \quad (32) \end{aligned}$$

$$\left(\frac{d\sigma_{\nu_l e^-}}{d\theta^2}\right)_{\text{SM}} = \frac{G_F^2 m_e^2}{\pi \left(\theta^2 + \frac{2m_e}{E_\nu}\right)^2} \left\{ (g_V^{\nu_l} + g_A^{\nu_l})^2 + (g_V^{\nu_l} - g_A^{\nu_l})^2 \left(\frac{\theta^2}{\theta^2 + \frac{2m_e}{E_\nu}}\right)^2 + \right. \\ \left. \left( (g_A^{\nu_l})^2 - (g_V^{\nu_l})^2 \right) \frac{2m_e^2}{E_\nu^2 \left(\theta^2 + \frac{2m_e}{E_\nu}\right)} \right\}, \quad (33)$$

$$\left(\frac{d\sigma_{\nu_l e^-}}{dT\theta^2}\right)_{\text{SM}} = \frac{G_F^2 E_\nu}{4\pi} \left\{ (g_V^{\nu_l} + g_A^{\nu_l})^2 + (g_V^{\nu_l} - g_A^{\nu_l})^2 \left(\frac{T\theta^2}{2m_e}\right)^2 + \right. \\ \left. \left( (g_A^{\nu_l})^2 - (g_V^{\nu_l})^2 \right) \frac{m_e}{E_\nu} \left(1 - \frac{T\theta^2}{2m_e}\right) \right\}. \quad (34)$$

The neutrino magnetic moment contribution is **(TO DO: include derivation from [4])** [1]:

$$\left(\frac{d\sigma_{\nu_l e^-}}{dT_e}\right)_{\text{MAG}} = \frac{\pi\alpha^2}{m_e^2} \left(\frac{1}{T_e} - \frac{1}{E_\nu}\right) \left(\frac{\mu_{\nu_l}}{\mu_B}\right)^2, \quad (35)$$

126 where  $\alpha$  is the fine structure constant.

Analogically to previous, we can also express this cross section in  $\cos\theta$ ,  $\theta^2$  and  $T\theta^2$ :

$$\left(\frac{d\sigma_{\nu_l e^-}}{d\cos\theta}\right)_{\text{MAG}} = \frac{2\pi\alpha^2 (E_\nu + m_e)^2 (E_\nu + m_e)^2 - E_\nu^2 \cos^2\theta - 2m_e E_\nu \cos^2\theta}{m_e^2 \cos\theta \left((E_\nu + m_e)^2 - E_\nu^2 \cos^2\theta\right)^2} \left(\frac{\mu_{\nu_l}}{\mu_B}\right)^2, \quad (36)$$

$$\left(\frac{d\sigma_{\nu_l e^-}}{d\theta^2}\right)_{\text{MAG}} = \frac{\pi\alpha^2}{m_e^2} \frac{\theta^2}{\left(\theta^2 + \frac{2m_e}{E_\nu}\right)} \left(\frac{\mu_{\nu_l}}{\mu_B}\right)^2, \quad (37)$$

$$\left(\frac{d\sigma_{\nu_l e^-}}{dT\theta^2}\right)_{\text{MAG}} = \frac{\pi\alpha^2}{4m_e^4} \frac{T\theta^2}{\left(1 - \frac{T\theta^2}{2m_e}\right)} \left(\frac{\mu_{\nu_l}}{\mu_B}\right)^2. \quad (38)$$

The magnetic moment contribution exceeds the standard model contribution for low enough  $T_e$  [1]:

$$T_e \lesssim \frac{\pi^2 \alpha^2}{G_F^2 m_e^3} \left(\frac{\mu_\nu}{\mu_B}\right)^2 \simeq 2.9 \times 10^{19} \left(\frac{\mu_\nu}{\mu_B}\right)^2 [\text{MeV}], \quad (39)$$

127 which does not depend on the neutrino energy and makes neutrino experiment sensitive to lower  
 128 energetic neutrinos more sensitive to the neutrino magnetic moment. **(TO DO: this is probably not**  
 129 **about sensitivity to lower energetic neutrinos but to lower energetic electron, isn't it?)**

## 130 **2.4 Experimental overview**

131 *(TO DO: Create a story for the experimental overview. Point out what is the hole in the current*  
132 *knowledge that NOvA can fill up)*

## 2.5 Direct muon (anti)neutrino magnetic moment measurements

### 2.5.1 NOvA (Biao's thesis)

- $\nu_\mu$  only
- Only comparing total event counts - 25 events observed and 23.78 expected
- Put an upper limit (90% C.L.) of  $\mu_{\nu_\mu} < 1.58 \times 10^{-9} \mu_B$  with 10.9% systematic uncertainty on the standard model background
- Used  $3.62 \times 10^{20}$  POT of data ( $6.74 \times 10^{23}$  POT for MC) with  $T\theta^2 < 0.003 \text{ GeV} \times \text{Rad}^2$ ,  $0.3 < T < 0.9 \text{ GeV}$

### 2.5.2 MiniBooNE

- $\nu_\mu$  only
- Observed excess of events (seems a bit too high)

### 2.5.3 E734 at the Alternating Gradient Synchrotron (AGS) of the Brookhaven National Laboratory

- Both  $\nu_\mu$  and  $\bar{\nu}_\mu$
- $\mu_{\nu_\mu} < 8.5 \times 10^{-10} \mu_B$

### 2.5.4 LSND

## 2.6 Direct electron (anti)neutrino magnetic moment measurements

## 2.7 Solar neutrino magnetic moment measurements

### 2.7.1 XENONnT

First results published in arXiv:2207.11330[5] on 22 July 2022.

- 5.9 tonne dual-phase liquid xenon TPC dark matter detector
- Region Of Interest is (1,140) keV
- Very low background ( 5 times lower than XENON1T)
- Tritium excluded as the potential background (also in XENON1T)
- No excess found - XENON1T excess excluded with  $4\sigma$
- The 90% C.L. upper limit on solar neutrinos with an "enhanced" magnetic moment is  $\mu_{\nu_{sol}} < 6.3 \times 10^{-12} \mu_B$ , the strongest non-astronomical limit so far (see fig.2)

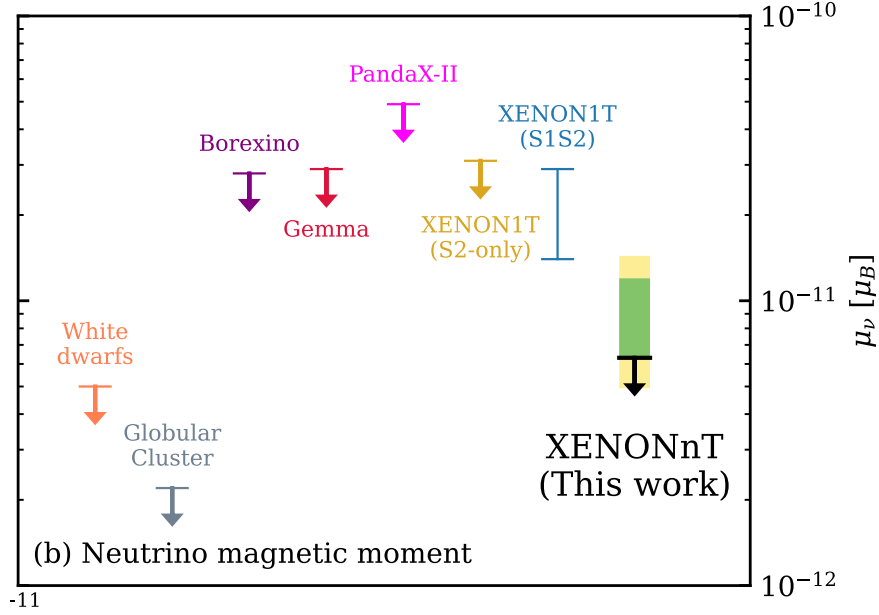


Figure 2: 90% C.L. upper limit on solar neutrinos with an enhanced magnetic moment.

Amir Khan used[6] XENONnT's results and derived limits on electromagnetic properties for the three SM neutrino flavours (see fig.3). For  $\nu_\mu$  they

## 2.7.2 XENON1T

## 2.7.3 BOREXINO

Should be  $\mu_{\nu_e} < 2.8 \times 10^{-11} \mu_B$  [BorexinoLimit2017.pdf]

## 2.7.4 GEMMA

Should be  $\mu_{\nu_{eff}} < 2.9 \times 10^{-11} \mu_B$ . [GemmaLimits2013.pdf]

## 2.8 Other

### 2.8.1 LHC Forward Physics Facilities

Preliminary sensitivity studies for future experiments (namely for FLArE and FASERv2)

- LHC's Forward Physics Facilities study high energy (TeV) neutrinos of all flavours from the ATLAS interaction point.
- Large opportunity to study tau neutrinos in more detail

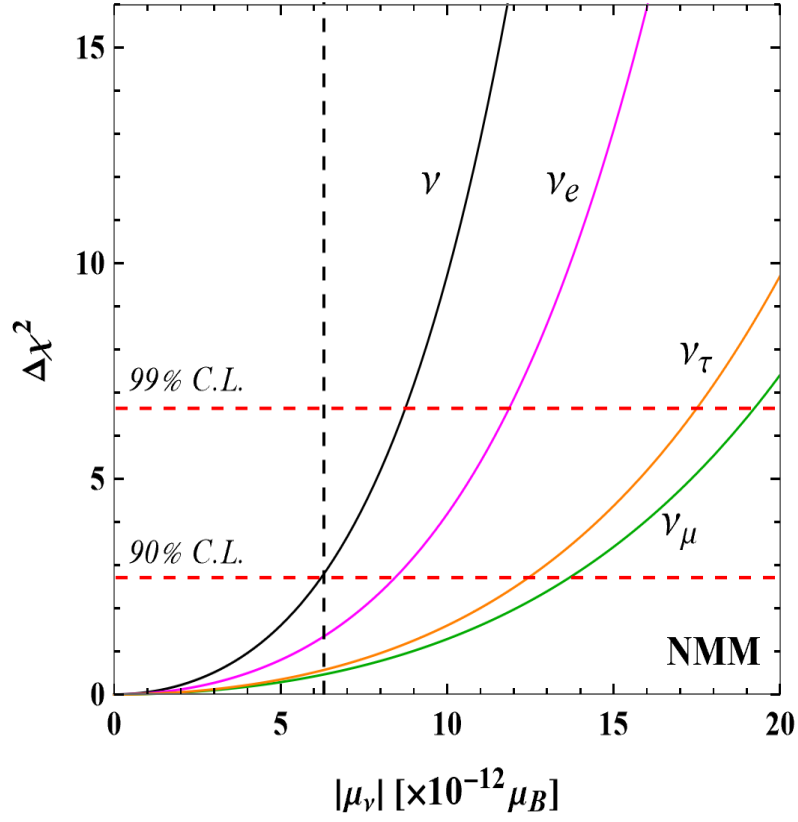


Figure 3: One-dimensional  $\Delta\chi^2$  distribution with 90% and 99% C.L. boundaries of neutrino magnetic moments. The distribution in black corresponds to the effective flavor independent magnetic moment

## 2.9 Astrophysics

[NuMMBasicsAndAstro\_2022.pdf] Neutrino electromagnetic processes that could be studied/observed in astrophysics

- Neutrino radiative decay

- Decay of heavier neutrino flavour into a lighter neutrino and a photon

- "The neutrino radiative decay has been constrained from the absence of decay photons in studies of the solar, supernova and reactor (anti)neutrino fluxes, as well as of the spectral distortions of the cosmic microwave background radiation."

- Less stringent than the plasmon decay into a  $\nu$ - $\bar{\nu}$  pairs

- Plasmon decay to neutrino-antineutrino pair

- "For constraining neutrino electromagnetic properties, and obtaining upper bounds on neutrino magnetic moments in particular, the most interesting process is the plasmon decay into a neutrino-antineutrino pair [11]"

- Plasmon decay frees the energy from the stars plasma in form of neutrinos that escape and therefore speeds up the star cooling

- "observed properties of globular cluster stars provides new upper bounds on the effective neutrino magnetic moment  $\mu_{ef} \leq (1.2 - 2.6) \times 10^{-12} \mu_B$  that is valid for both cases of Dirac and Majorana neutrinos."

- Transition of neutrino helicities  $\nu_L \rightarrow \nu_R$  from active to sterile neutrinos

- Supernovas would cool much faster - not observed for 1987A by Kamioka II and IMB, constraining Dirac neutrino mag. moment

### 3 Analysis overview

(**TO DO: Describe the motivations for this analysis**) What are we trying to achieve? Are we aiming for purity or efficiency?

Trying to select  $\nu$ -on-e events with low electron recoil energies.

What are we going to do with these events afterwards?

Are we just going to compare the event counts of signal and background (and possibly correct the background based on some other "sideband" selection?), or are we doing a fit to some spectra - either electron energy, angle or ETh2.

Describe what I'm talking about in this section (datasets, weights, selection, resolution, fitting framework).

Describe already here that we're dividing the signal/background into four due to ... Here on forward I'm going to describe the differences between these (definitions, weights, signal def, systematics. What is the same: event selection and binning. They're joint together in the fitting framework, where the  $\nu_e$ CC MEC and the other backgrounds are simply summed together and scaled together. The  $\nu$ -on-e background (also called the irreducible background by the LDM analysis) is treated/scaled separately.

*Should I describe the NOvA Near Detector here? Specifically its capabilities for detecting electrons?*

#### 3.1 Datasets and Event Reconstruction details

For this analysis we are using the near detector samples with a standard Production 5.1 reconstruction. To tackle low number of  $\nu$ -on-e and  $\nu_e$ CC MEC events (after full selection) in the nominal simulation sample, and to increase speed and lower the computation costs of each study, we are using the following samples for the signal and background components, for the nominal prediction as well as systematically shifted.

(**TO DO: Find out what data sample we're using and write out the data POT**) For data we are only planning to unveil them after fully approved by the collaboration and we will be using the following data sample...

Yiwen has already looked at data for the following samples and the results are here...

Should I mention the POT counting here or somewhere else? - I think I should mention with each separate sample if the POT has to be rescaled or not.

The use of the samples can be briefly summarised as follows:

Signal	Enhanced $\nu$ -on-e sample
$\nu$ -on-e background	Enhanced $\nu$ -on-e sample
$\nu_e$ CC MEC background	Enhanced $\nu_e$ CC MEC sample
Other background	Flat sumdecaf

Table 1: Overview of simulation samples used.



## Enhanced $\nu$ -on-e sample

Created by Wenjie Wu (was it just him or also Yiwen?) to do ... and fully described in the technote [7]. Using the overlayed and filematched samples for consistency.

We only have the selected few systematics definitions because ...

Describe the differences

- Missing cross section parameters - unable to use cross section weights or so
- Special mode for nu-on-e elastic scattering 10005

List all the nu-on-e sample definitions used is on table 2.

---

### Nominal:

prod\_caf\_R20-11-25-prod5.1reco.g\_nd\_genie\_N1810j0211a\_nonswap\_fhc\_nova\_v08\_full\_v1\_nuone\_overlay

### Systematically shifted samples:

prod\_caf\_R20-11-25-prod5.1reco.g\_nd\_genie\_N1810j0211a\_nonswap\_fhc\_nova\_v08\_full\_calibup\_v1\_nuone\_overlay

prod\_caf\_R20-11-25-prod5.1reco.g\_nd\_genie\_N1810j0211a\_nonswap\_fhc\_nova\_v08\_full\_calibdown\_v1\_nuone\_overlay

prod\_caf\_R20-11-25-prod5.1reco.g\_nd\_genie\_N1810j0211a\_nonswap\_fhc\_nova\_v08\_full\_ckvup\_v1\_nuone\_overlay

prod\_caf\_R20-11-25-prod5.1reco.g\_nd\_genie\_N1810j0211a\_nonswap\_fhc\_nova\_v08\_full\_ckvdown\_v1\_nuone\_overlay

prod\_caf\_R20-11-25-prod5.1reco.g\_nd\_genie\_N1810j0211a\_nonswap\_fhc\_nova\_v08\_full\_lightlevelup\_v1\_nuone\_overlay

prod\_caf\_R20-11-25-prod5.1reco.g\_nd\_genie\_N1810j0211a\_nonswap\_fhc\_nova\_v08\_full\_lightleveldown\_v1\_nuone\_overlay

---

Table 2: SAMWEB definitions for the  $\nu$ -on-e samples.

## Enhance $\nu_e$ CC MEC sample

Created by Yiwen Xiao [7] to tackle the low statistics of the  $\nu_e$ CC MEC background events and subsequently large and unphysical cross section weights.

List all the nueCC MEC sample definitions used. Do this after creating the filematched definitions maybe?

## Near detector flat summed decaf sample

What are the cuts used for the DeCAF sample? Why was it created? What is the effect of these cuts?

---

---

**Nominal:**

prod\_flatsumdecaf\_R20-11-25-prod5.1reco.g\_nd\_genie\_N1810j0211a\_nonswap\_fhc  
\_nova\_v08\_full\_v1\_g4rwgt\_respin\_batch2\_filematchedSystematics

**Systematically shifted samples:**

prod\_flatsumdecaf\_R20-11-25-prod5.1reco.e\_nd\_genie\_N1810j0211a\_nonswap\_fhc  
\_nova\_v08\_full\_calibdown\_v1\_batch2\_filematchedSystematics\_calibdown\_v1

---

---

Table 3: SAMWEB definitions of the other background samples. THIS IS JUST A PLACEHOLDER!

241 There's also 3 flavour concats - what are those? there are both numu and nue and they're for  
242 the ND... What are the cuts used to create these?

243 Should I include here also why did I choose to use the decafs instead of cafs? Maybe just point  
244 to my talks where I show the plot how much faster it is and that it doesn't matter much for the  
245 result. Maybe discuss how different the result would be if I used cafs instead of decafs...

List all the flat sumdecaf definitions used.

---

---

**Nominal:**

prod\_flatsumdecaf\_R20-11-25-prod5.1reco.g\_nd\_genie\_N1810j0211a\_nonswap\_fhc  
\_nova\_v08\_full\_v1\_g4rwgt\_respin\_batch2\_filematchedSystematics

**Systematically shifted samples:**

prod\_flatsumdecaf\_R20-11-25-prod5.1reco.e\_nd\_genie\_N1810j0211a\_nonswap\_fhc  
\_nova\_v08\_full\_calibdown\_v1\_batch2\_filematchedSystematics\_calibdown\_v1

---

---

Table 4: SAMWEB definitions of the other background samples. First figure out what definitions should I use

## 247 3.2 Analysis weights

248 (*TO DO: Describe why do we use weights*) What are the weights we are using and why?

249 To correct for known deficiencies in simulation of neutrino flux or cross sections we apply  
250 weights calculated for each event.

251 Table 5 shows what CAFAna weights are used to simulate what signal/background sample.

### 252 PPFX weight

253 ana::kPPFXFluxCVWgt [8] (*TO DO: What does this do (one sentence ish).*)

Signal	Flux and neutrino magnetic moment weights
$\nu$ -on-e background	Flux and radiative correction weights
$\nu_e$ CC MEC background	Flux and cross section weights
Other background	Flux and cross section weights

Table 5: Overview of CAFAna weights applied to each analysis sample.

### Prod5.1 GSF XSec weight

ana: :kXSecCVWgt2020GSFProd51 (TO DO: Find the reference: possibly Maria's docdb:53336 together with the official 2020 XSec tuning technote docdb:43962.)

(TO DO: Briefly describe what does this do. Also mention Yiwen's talk/technote about the large XSec weights that made her create an enhanced nueCC MEC sample.)

We are only using the for the background since we assume that the cross section for the signal is perfect. Also there are not weights for this kind of interaction.

### Radiative correction weight

(TO DO: Why are we doing this? (reference Yiwen's talk/technote).)

Mention here where did I get the original GENIE cross section from (reference Yiwen's talk or technote, plus the original paper that was used).

(TO DO: Write out the actual version of the weight. Including the original and the corrected XSec constants)

Say that we are not using the third part of the correction because it is tiny and it makes no difference. (tried and tested)

(TO DO: correct the equation) Calculated as

$$weight_{\text{Radiative Corr.}} = \left. \frac{d\sigma_{\nu\text{-on-e}}}{dy} \right|_{\text{Radiative Corr.}} / \left. \frac{d\sigma_{\nu\text{-on-e}}}{dy} \right|_{\text{GENIE 3}} ; y = \frac{E_e - m_e}{E_\nu} \quad (40)$$

### 3.2.1 Neutrino magnetic moment signal as a weight

(TO DO: What does this do and why does it work? Reference the theory part as to why is the magnetic moment signal simply a rescaling of the GENIE cross section.)

Using the same tree-level cross section from GENIE as in the rad. corr. weight.

(TO DO: Write the name of the weight in CAFAna/nuone namespace and where it is located)

(TO DO: correct the equation) Calculated as

$$weight_{\nu \text{ Mag. Moment}} = \left. \frac{d\sigma_{\nu\text{-on-e}}}{dy} \right|_{\nu \text{ Mag. Moment}} / \left. \frac{d\sigma_{\nu\text{-on-e}}}{dy} \right|_{\text{GENIE 3}} ; y = \frac{E_e - m_e}{E_\nu} \quad (41)$$

### 3.3 Event selection

*Should this be a separate section or is it all right to keep it here? It will have a lot of plots...*

(**TO DO: Define the signal of the NuMM. Reference the NuMM weight description above**) The signal of the neutrino magnetic moment analysis is just a reweighted signal of the  $\nu$ -on-e analysis from the near detector group. We are using the same event selection as the near detector group.

(**TO DO: Decide and explain what signal definitions we're using (kIsVtxContained VS Fiducial volume)**) What is the signal and all the background samples definition? Difference between using kIsVtxCont and the fiducial volume. Is there a fundamental difference or preference? Or does it just depend on me? The results/counts are quite different...

Signal	kMode== 10005 && NDNuoneFiducial
$\nu$ -on-e background	kMode== 10005 && NDNuoneFiducial
$\nu_e$ CC MEC background	!(kMode== 5 && kElInFinState && NDNuoneFiducial) && (kIsCC && kIsNue && kMode == 10)
Other background	!(kMode== 5 && kElInFinState && NDNuoneFiducial)    !(kIsCC && kIsNue && kMode == 10)

Table 6: Overview of signal and background definitions. Mode 10005 denotes  $\nu$ -on-e events, while mode 5 denotes all electron scattering events, including inverse muon decay interactions. That is why we had to add a requirement of an electron in the final state. Mode 10 denotes all MEC events. (**TO DO: Check that the definitions are correct from the code.**)

(**TO DO: Add the link to the LDM group's technote and say what's different (or maybe do this after we discuss the cuts?)**) Currently we are using the exact same selection as is used by the ND group [7] and very similar to the Light Dark Matter analysis (cite their technote).

Pre-selection cuts include basic quality cuts (**TO DO: describe the basic quality cuts that are implied from the preselection cuts**). They also remove the obvious  $\nu$ CC interactions by requiring that the length of the longest prong is  $< 800$  cm, number of planes crossed by the longest prong is  $< 120$ , and the summed number of cells for all prongs in the slice is  $< 600$ . In pre-selection we also include a cut on the time difference between the mean times of the "current" slice and of the slice closest in time, which should be  $> 25$  ns. This ensures that ... (**TO DO: describe why do we need the closest slice cut with reference to Yiwen's talk and technote**).

(**TO DO: Add the DeCAF cuts description here - might describe them already when introducing the decaf samples, not sure yet**)

(**TO DO: Describe what does the fiducial cut do**) We require that the reconstructed vertex is contained within the following volume:  $-185 < V_{tx_X} < 175, -175 < V_{tx_Y} < 175, 95 < V_{tx_Z} < 1095$  cm.

To ensure all the energy is contained within the detector and to remove events originating outside of the detector (rock muons), we require that the extreme positions of hits for all prongs in the slice are within the following volume:  $-190 < \min_X, \max_X < 180, -180 < \min_Y, \max_Y < 190, 105 < \min_Z, \max_Z < 1275$  cm

To selection events with a single particle we require that the fraction of energy contained in the most energetic shower is  $> 0.8$ , that the summed energy of all cells (above threshold and within  $\pm 8$  planes from the vertex) outside of the most energetic shower is  $< 0.02$  GeV, and that the distance between the vertex and the start of the primary shower is  $< 20$  cm.

(TO DO: discuss the energy cut, should this be removed? What is the effect on the event count? Why was this included in the first place (the identifiers are not as strong for lowere energies - is this true though? - also there are further unexplored backgrounds that would need to be further studied and explore. Maybe depends on where would we move the cut...)) The calorimetric energy of the primary shower is required to be within  $0.5 < E_{cal} < 5$  GeV.

We are using two event classifiers based on convolution neural network that were developed specifically to identify  $\nu$ -on-e interactions. The first one (NuoneID) is trained to select  $\nu$ -on-e events and the second one (Epi0ID) is trained on the events passing the NuoneID to reject the  $\pi^0$  background. Our selection requires that NuoneID  $> 0.73$  and that Epi0ID  $> 0.92$ .

(TO DO: reference theory for the kinematics of nuone scattering) We require that the product of reconstructed energy of the primary shower and the square of its angle from the Z axis is  $E_{cal}\theta^2 < 0.005 \text{ GeV} \times \text{rad}^2$ .

(TO DO: Add plots of distributions of the event selection variables with two columns. LHS shows no cuts applied and RHS shows all previous cuts applied)

Using the many plots below that show the effect of each of the cuts on the signal and all background events. (For signal we are showing NuMM=...)

(TO DO: Get the correct table below and describe it) The final event count and efficiency of each of the cuts is shown on the table ... Table ... shows the dissemination of background into the individual components.

Selection	$\nu$ Mag. Moment signal			$\nu$ -on-e background			Other background		
	$N_{sig}$	$\epsilon^{N-1}$	$\epsilon$ (%)	$N_{IBkg}$	$\epsilon^{N-1}$	$\epsilon$ (%)	$N_{Bkg}$	$\epsilon^{N-1}$	$\epsilon$ (%)
No Cut	263.39	100	100	3,352.43	100	100	9.19E+6	100	100
DeCAF cuts	73.53	27.92	27.92	2,332.75	69.58	69.58	9.19E+6	100	100
Closest Slice Time	71.57	97.34	27.17	2,275.86	97.56	67.89	8.79E+6	95.72	95.72
Preselection	71.57	100	27.17	2,271.24	99.80	67.75	8.30E+6	94.42	90.38
Fiducial	70.86	99.01	26.90	2,248.47	99.00	67.07	6.80E+6	81.92	74.03
Containment	68.49	96.65	26.00	2,090.35	92.97	62.35	5.65E+6	83.13	61.54
Single Particle Req.	58.47	85.37	22.20	1,754.08	83.91	52.32	5.83E+5	<b>10.31</b>	6.34
Energy Cut	35.33	60.43	13.41	1,280.94	73.03	38.21	4.48E+5	76.97	4.88
NuoneID	28.08	79.49	10.66	888.69	69.38	26.51	17384.6	<b>3.88</b>	0.19
Epi0ID	21.45	76.39	8.14	708.96	79.78	21.15	10740.7	61.78	0.12
<b>etheta2</b>	<b>18.83</b>	<b>87.80</b>	<b>7.15</b>	<b>638.39</b>	<b>90.05</b>	<b>19.04</b>	<b>65.92</b>	<b>0.61</b>	<b>0.00072</b>
No Energy Cut	29.03		11.02	726.66		21.68	112.03		0.0012

Table 7: Event selection cutflow table

(TO DO: Add a discussion of possible improvements on the event selection on its limitations - mostly for the analysis review committee) From here we can see that ... Maybe what can be

improved is... This can likely be improved upon by specifically selection low energy events and removing the cut on the reconstructed shower energy.

### 3.4 Resolution and binning

The electron energy and angle distributions and resolutions. Are we going to fit in E, Th, or ETh2? Is there something else?

Show plots of Reco V True for both energy and angle. (Should I show it with or without the energy cut?). Also show the resolution plots.

### 3.5 Systematic uncertainties

Plots showing combined uncertainties for signal and backgrounds. Maybe also some interpolations. Table of systematic uncertainties on the event count.

#### Normalization systematics

Should we include normalization systematics? Would that make any difference? There's a POT scaling uncertainty which is very small (find out exactly how small).

In the fitting experiment normalization uncertainties would probably not make any difference whatsoever, but in the counting experiment they might be important?

#### Neutrino flux systematics

Using the PCA vs using the PPFX universes+beam transport separately. Plots of energy showing shifts for signal and backgrounds separately

Selection	Background				
	All	$\nu_e$ CC	$\nu_\mu$ CC	NC	Other
No Cut	9.19E+06	2.41E+05	6.29E+06	2.66E+06	0
DeCAF Cuts	9.19E+06	2.41E+05	6.29E+06	2.66E+06	0
Closest Slice Cuts	8.79E+06	2.31E+05	6.03E+06	2.53E+06	0
Preselection	8.30E+06	2.30E+05	5.55E+06	2.52E+06	0
Fiducial	6.80E+06	1.88E+05	4.50E+06	2.12E+06	0
Containment	5.65E+06	1.70E+05	3.46E+06	2.02E+06	0
Single Particle Req.	5.83E+05	2.26E+04	3.93E+05	1.67E+05	0
Energy Cut	4.48E+05	1.43E+04	3.21E+05	1.13E+05	0
NuoneID	1.74E+04	3.92E+03	7.20E+03	6.26E+03	0
Epi0ID	1.07E+04	3.08E+03	4.45E+03	3.21E+03	0
<b>etheta2</b>	<b>65.92</b>	<b>50.81</b>	<b>1.90</b>	<b>13.20</b>	<b>0</b>
No Energy Cut	112.03	72.46	9.85	29.72	0

Table 8: Event selection cutflow table for background components

[to do]: understand differences with ND and 3F methods

This is mainly a normalization. Discuss how to use the fact that  $\nu$ -on-e events can be used (and are used) to constraint the beam uncertainty. Would the counting experiment still be valid then? Maybe if we made another sideband sample...

### Detector systematics

Plots of energy showing shifts for signal and backgrounds separately

### Cross section systematics

Only for the non  $\nu$ -on-e background. Assuming the  $\nu$ -on-e events (including the signal events) are precisely known.

Plots of energy showing shifts for signal and backgrounds separately

## 3.6 Fitting framework

How does the fitting framework work? It's based on the framework developed by Mu Wei for the Light Dark Matter analysis (ref.) which was developed together (is this fair?). Basic description of the framework.

Also this framework is used for both LDM and NuMM together. It is trivial to simply switch between including the NuMM or LDM in it. This was done to save space in creating predictions since our backgrounds are exactly the same (or at least they should be...). Theoretically this could be separated into two difference frameworks.

- `<NDPredictionSingleElectron>` Prediction class which holds the LDM as a special 2-D spectrum (not used for NuMM), and NuMM,  $\nu$ -on-e background,  $\nu_e$ CC MEC background and other background as simple 1-D spectra. Also scaling each spectra by...
- `<NDPredictionSystSingleElectron>` class derived from `PredictionInterp` that takes in the `NDPredictionSingleElectron` and applies systematic shifts to it. Includes the interpolation/extrapolation between the systematic shifts.
- `FitVariables` and what do they do
- Fitter which does exactly what... What are the parameters of the fit? What are the results/outputs?

## 4 Results / Fake data studies

[to do]: talk about the shape-only versus normalisation-only strategies for the differential versus single-bin analyses.

I think it might be a good idea to talk about this already in the analysis overview section.

I need to also discuss fake data studies. Should I talk about this now? Probably

## 4.1 Counting experiment

Single bin analysis - total numbers of signal and backgrounds predicted. Possible background corrections and its effect on the background uncertainties.

## 4.2 Binned experiment

Plots showing delta chi2 for stats and systs separately. Plot showing the chi2 with limits. Maybe talk about using different binning and variables and the effect.

Also need to somehow quantify the various fitter settings, like different seeding values, different range of profiling. Should I talk about Feldman-Cousins?

### 4.2.1 Sensitivities and limits

## 5 Conclusion

Report the limit with its uncertainty.

Very briefly discuss differences with current world limit and how the techniques differ.

Very briefly summarise expectations for future measurements.

## References

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