# On the influence of a nonzero magnetic dipole moment of the neutrino for the trident processes in the DUNE ND.

Andrés Castillo, for the DUNE collaboration

Universidad Sergio Arboleda

DEEP UNDERGROUND NEUTRINO EXPERIMENT

## Study

Neutrino electromagnetic form factors have significant effects in the lepton-antilepton pair's production through neutrino-nucleus scattering $\nu_\mu X \to \nu_\mu l^+ l^- X$, or "tridents." Tridents are a sensitive probe in the search for new neutral currents. The Deep Underground Neutrino Experiment (DUNE) with the near detector will employ an 84-ton LarTPC to observe these dileptons events via dilepton production channels $l^+l^-$: $\mu^+\mu^-$ and $e^+e^-$ or $\mu^\pm e^\mp$.

- Our studies include: computed and simulated interaction cross-section for tridents with the additional neutral current contribution from the neutrino-magnetic moment (NMM).
- Analyses of cross-sections for coherent and diffractive regimes in the trident production of $\mu^+\mu^-$ channels.
- Kinematical distributions from NMM (coherent and diffractive scenarios) and SM, using the $\nu_\mu$ flux on DUNE ND.

## Tridents topology and matrix element

The new contribution for the trident amplitude for a coherent $(\mathrm{X}=\mathrm{c})$ or diffractive $(\mathrm{X}=\mathrm{D})$ scattering takes the form

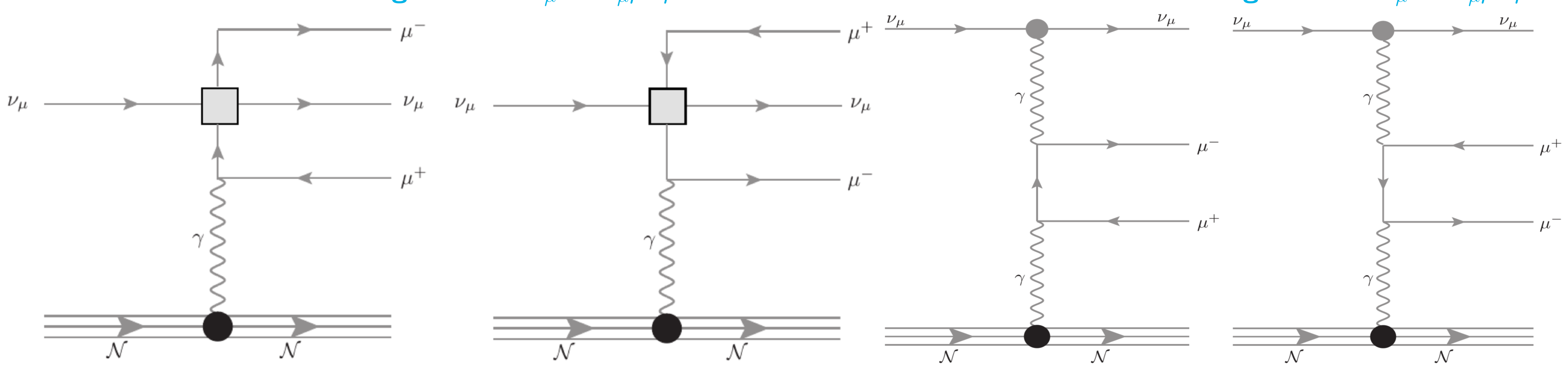
$$\mathcal{M}_{NMM} = -eL^\mu_{NMM}(\{p\},q)\,\frac{g_{\mu\nu}}{q^2}\,\mathrm{H}^\nu_{\mathrm{X}}(P,P')\,,$$

$\{p\}$ is the collection of all 4-momentum for leptons, $P, P'$ and $q$ are the on-shell and off-shell 4-momentums for the hadronic part. The NC neutrino vertex incorporates a EM form factor $\Gamma$, changing the matrix element by

$$L^\mu \equiv \frac{[\bar{u}(p_2)\Gamma^\tau(q'^2)u(p_1)]}{q'^2} \times \bar{u}(p_4)\left[\gamma_\tau \frac{1}{(\not{q}-\not{p}_3-m_3)}\gamma^\mu - \gamma^\mu \frac{1}{(\not{p}_4-\not{q}-m_4)}\gamma_\tau\right]v(p_3)$$

$q'$ is the photon 4-momentum, in the neutrino-neutrino vertex. We consider only magnetic and electromagnetic form factors $\Gamma^\tau(q^2) = \sigma_{\lambda\rho}q^\rho\left[F_M(q^2) + iF_E(q^2)\right]$. We call this scenario the NMM model.

**Effective induced diagrams for $\nu_\mu \to \nu_\mu \mu^- \mu^+$.** **NMM induced diagrams for $\nu_\mu \to \nu_\mu \mu^- \mu^+$**




$\mathrm{H}^\nu_{\mathrm{X}}(P,P')$ is the total hadronic amplitude in two scenarios: **Coherent regime** or the scattering of a neutrino off heavy nucleus (with $F_N(q^2)$ the EM nuclear form factor)

$$\mathrm{H}^{\alpha\beta}_N = 4P_\alpha P_\beta\left[F_N(q^2)\right]^2\,,$$

. **Diffractive regime** or the scattering of a neutrino off individual nucleons (with electric and magnetic form factors $G_E^{p(n)}(q^2)$ and $G_M^{p(n)}(q^2)$) where

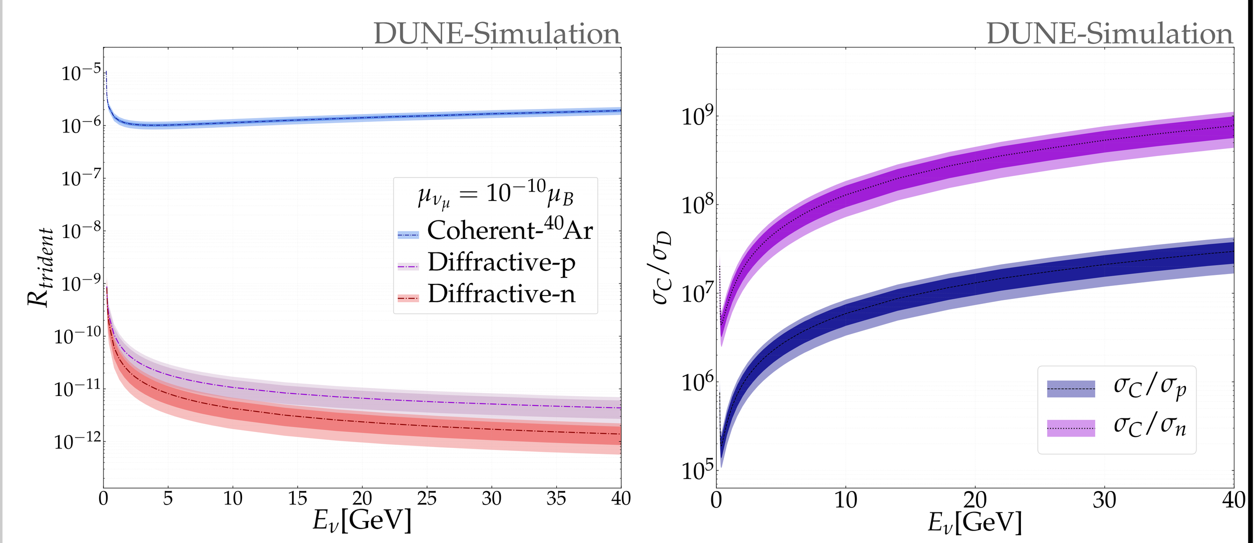
$$\mathrm{H}^{\alpha\beta}_{p(n)} = 4P^\alpha P^\beta\left(\frac{4m^2_{p(n)}\left[G_E^{p(n)}(q^2)\right]^2}{q^2+4m^2_{p(n)}} + \frac{q^2\left[G_M^{p(n)}(q^2)\right]^2}{q^2+4m^2_{p(n)}}\right) + g^{\alpha\beta}q^2\left[G_M^{p(n)}(q^2)\right]^2.$$

**Square matrix element facts**:

- At leading order $(m^2_\nu \to 0)$, there are non-interference effects with neutral and charged currents of SM channels ($Z$ and $W^\pm$ bosons have been integrated out).
- Diagonal terms in the diffractive regime vanish at leading order.
- The square matrix element for both regimes depends on the square effective neutrino-magnetic moment $\mu^2_{\nu_\mu} = |F_M|^2 + |F_E|^2$ $(F_M, F_E \in \Re)$
- Effective neutrino-magnetic moment for $\nu_\mu$ has been constrained in the LSND experiment with a upper limit of $\mu_{\nu_\mu} < 6.8 \times 10^{-10}\mu_B$ and BOREXINO with $\mu_{\nu_\mu} < 1.9 \times 10^{-10}\mu_B$, both at $90\%$ C.L..

## Cross section analyses

Ratios for different regimes of $\sigma(\nu_\mu X \to \nu_\mu \mu^+ \mu^- X)$



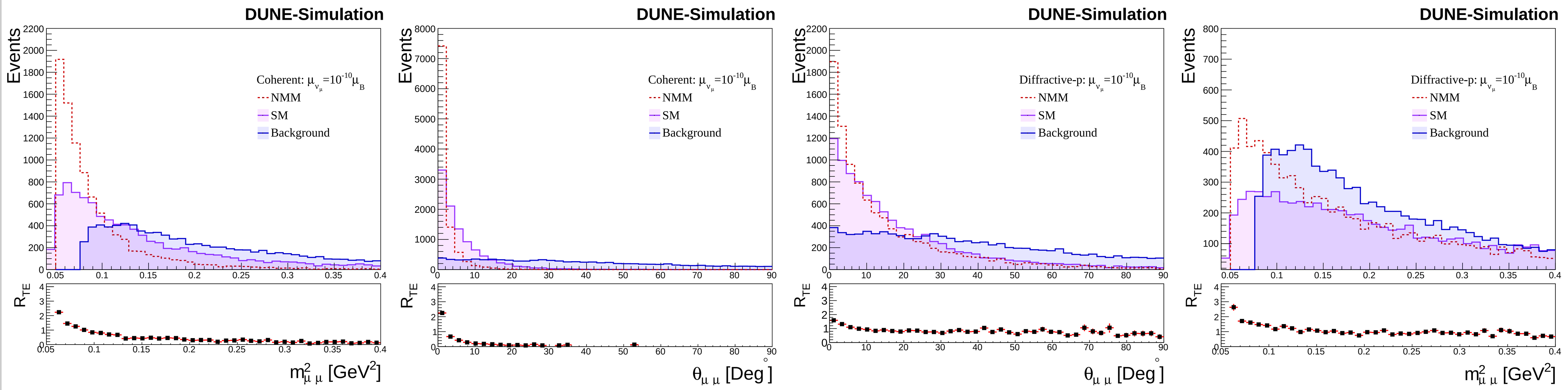

(Left) $R_{trident} \equiv \sigma_X^{NMMM}/\sigma_X^{SM}$ $(\mu_{\nu_\mu} = 10^{-10}\,\mu_B)$. (Right) $\sigma_C/\sigma_D$

Contributions ratio of coherent and diffractive components for NMM.

- Cross-sections ratio for NMM and SM are less than $\sigma^D_{ref} = 10^{-5} \times \sigma^C_{SM}$ in the coherent case and $\sigma^D_{ref} = 10^{-9}\mu_B \times \sigma^D_{SM}$ in the diffractive scenario.
- Other values of cross-sections scale $\sigma^{ref}$ as $\mu^2_{\nu_\mu}/\mu^{(ref)2}_{\nu_\mu}$.
- Cross-section (coherent) affects the expected SM rates within DUNE-ND uncertainties ( $25\%$) when $\mu_{\nu_\mu}$ $10^{-7}\mu_B$ (value ruled out by BOREXINO studies).
- Diffractive cross sections are 5-10 orders of magnitude smaller than coherent cross sections. Values are in the band uncertainties for coherent cross-section.
- Shaded bands indicate $1\sigma$ and $2\sigma$ uncertainties of the cross-sections. Uncertainties come from form factors, higher-order EW corrections, and nuclear models.

## Kinematical distributions

Dimuon invariant mass $m^2_{\mu\mu}$ and separation angle $\theta_{\mu\mu}$ distributions for coherent (Right) and diffractive (Left) components. Each distribution plots the ratio $R_{TE}$ between NMM trident events and SM trident events. We use the experimental allowed value $\mu_{\nu_\mu} = 10^{-10}\,\mu_B$ (Borexino limit at 95 % C.L.)




- The NMM effects enhance these event distributions at low values of $m^2_{\mu\mu} < 0.1$ GeV$^2$ and $\theta_{\mu\mu} < 2°$.
- The NMM enhancement effects are more significant for coherent component than for diffractive regime.
- SM and NMM coherent dimuon tridents tend to be quite collimated, with more than $90\%$ of events having $\theta_{\mu\mu} < 20°$.
- The background is based on processes CC$1\pi^\pm$, with the muon's misidentification as charged pions.

## Future work

- We will consider the following topics of study: combined analyses with other trident channels $e^+e^-$ and $\mu^+\mu^-$, taking into account both $\nu$ and $\bar{\nu}$ modes.
- Reconstruction and background analyses for possible neutrino topology and tracks for distinctive NMM events using cuts here found.
- Sensitivity plots and exclusion limits of NMM for BSM physics.
- Implementation of new cuts from different machine learning algorithms for kinematical distributions here shown