PROCEEDINGS OF SCIENCE

Neutrino trident production at near detectors

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In this talk we discuss the potential to measure neutrino trident production at future and current neutrino experiments. We revisit the full calculation of the process and address recently used approximations, showing the expected rates at various near detectors. Backgrounds are studied and shown to have very distinct kinematics to the trident signal.

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1. Introduction

Neutrino oscillation experiments often rely on flux and cross section measurement at near detectors. The large statistics at these facilities makes them ideal to study neutrino interactions. Provided backgrounds are kept under control, searches for rare scattering processes, such as neutrino trident production, are a feasible goal of current and future neutrino oscillation experiments and can be unique probes of new physics [1, 2]. Neutrino trident scattering is the production of a pair of charged leptons by a neutrino in the Coulomb field of a nucleus or nucleon. This process is dominated by the coherent and diffractive regimes, where scattering happens off the whole nucleus and off the individual nucleons, respectively. In the Standard Model (SM), this process receives contributions from the Charged Current (CC), Neutral Current (NC) or a combination of the two. To this date, only the NC+CC process $\nu_\mu \to \nu_\mu \mu^+ \mu^-$ has been measured at CHARM-II [3], CCFR and NuTeV. The measurements are all within one sigma of the SM prediction.

Future LAr near detectors will, for the first time, offer the opportunity to measure other channels with e^+e^- and $e^\pm\mu^\mp$ in the final state. In addition, the energy range of future oscillation experiments like DUNE can provide the best limits on light new physics, such as the anomaly-free abelian extension of the SM with $L_\mu - L_\tau$ charges [2].

2. Cross section

Early computations of this process provide the first calculation of the total cross section and distributions [4]. We follow the method in these references and adapt our formalism to address the Equivalent Photon Approximation (EPA) performed in recent literature [5]. By explicitly calculating the contributions from longitudinally and transversely polarised photons, we are able to show where the EPA falls short. In our treatment, the full cross section can be obtained via the following formula

$$\frac{\mathrm{d}^2\sigma_{\nu \mathrm{X}}}{\mathrm{d}Q^2\mathrm{d}\hat{s}} = \frac{1}{32\pi^2}\frac{1}{\hat{s}\,Q^2}\left[h_{\mathrm{X}}^{\mathrm{T}}(Q^2,\hat{s})\,\sigma_{\nu\gamma}^{\mathrm{T}}(Q^2,\hat{s}) + h_{\mathrm{X}}^{\mathrm{L}}(Q^2,\hat{s})\,\sigma_{\nu\gamma}^{\mathrm{L}}(Q^2,\hat{s})\right], \tag{2.1}$$

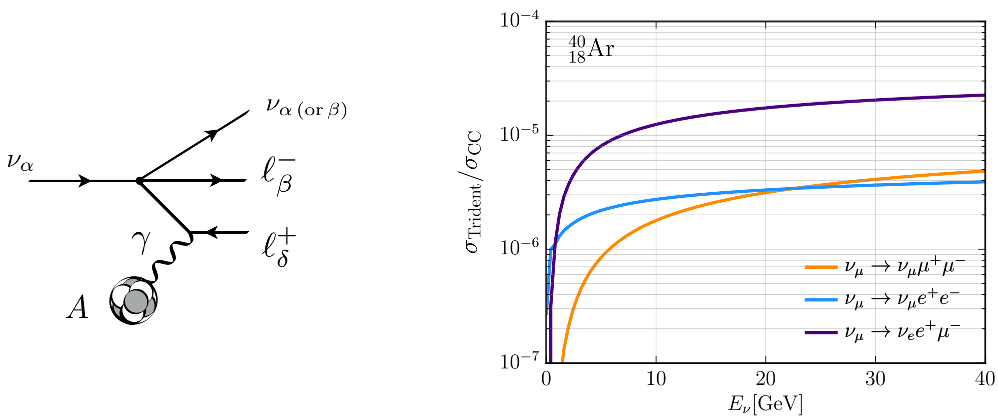

Figure 1: Left: One of the contributions to neutrino trident production in the SM. **Right:** The coherent trident cross section normalised by the CC cross section on ^{40}Ar for a ν_μ beam.

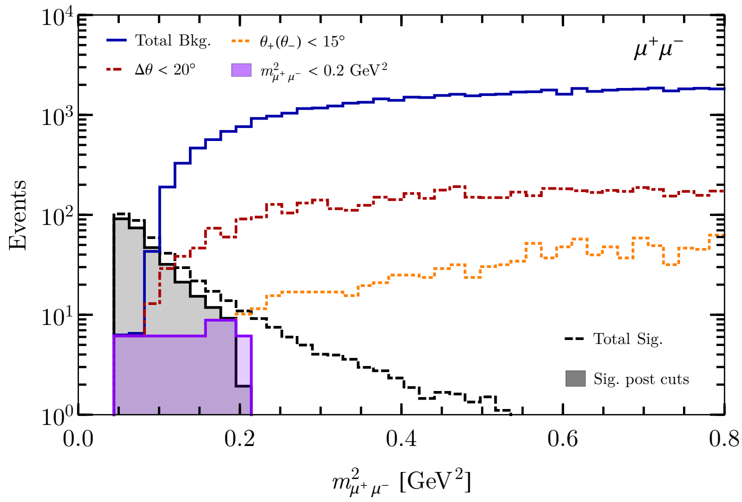

Figure 2: The trident signal and the expected background as a function of the muon candidate $m^2_{\mu^+\mu^-}$ at the DUNE near detector for neutrino mode. Consecutive cuts are applied on the background sample until the purple histogram is obtained.

where $h_{\rm X}^{\rm T(L)}(Q^2, \hat{s})$ are the flux functions of transverse (longitudinal) photons from the hadronic target X, and $\sigma_{\nu\gamma}^{\rm T(L)}(Q^2, \hat{s})$ the neutrino-photon cross sections. This formalism allows us to compute the neutrino-photon cross sections, and convolve them with the analytical expressions for the flux functions (given in [1]). We find the EPA approximation to perform particularly bad at low neutrino energies for all channels, and to overestimate the cross section for trident production of electron pairs and of mixed charged leptons. In the EPA, the typical momentum transfer Q^2 to the hadronic system is expected to be small. Whilst this is ensured by the nuclear form factor in the coherent regime, it is no longer true in the diffractive one. Furthermore, the presence of the lepton propagator in this process can lead to significant deviations from the $1/Q^2$ pole structure assumed in the EPA, leading to an overestimation of electron channels when performing the EPA.

The coherent cross section on an ^{40}Ar nucleus is shown on the right panel of Fig.1. It is interesting to note that the cancellation between NC and CC leads to a reduction of the cross section by 40% in the $\mu^+\mu^-$ channel.

3. Rates and backgrounds

Using our calculation, we compute the expected trident rate at various current and future neutrino detectors. Our results are for future LAr detectors are shown in Tab.1 assuming 100% efficiency. Despite the large number of events expect at the LAr module of the DUNE near detector, backgrounds will likely present the biggest challenge in this measurement. To address this issue, we have performed a background analysis at the generator level using GENIE for all background reactions that may mimic the trident signal. For the signal, we developed our own dedicated Monte Carlo (MC) for neutrino trident production in the DUNE ND. The largest backgrounds are expected to come from mis-identification, especially for $\mu^\pm/\pi^\pm$ and e/γ, which we assume to happen 10% and 5% of the time, respectively. The largest backgrounds for $\mu^+\mu^-$ tridents come from CC1$\pi^\pm$, where a muon is produced alognside a charged pion. The most important features for background

Channel		SBND	DUNE ν	DUNE $\overline{\nu}$
$e^{\pm}\mu^{\mp}$	coh	10	2993	2307
	dif	1	391	299
$e^{+}e^{-}$	coh	6	1007	800
	dif	0.2	64	49
$\mu^{+}\mu^{-}$	coh	0.4	286	210
	dif	0.3	143	108

Channel	$\mathbf{N}_{\mathrm{B}}^{\mathrm{misID}}$	$\mathbf{N}_{\mathrm{B}}^{\mathrm{kin}}$	$\varepsilon_{\mathrm{sig}}^{\mathrm{coh}}$
$e^{\pm}\mu^{\mp}$	$84,502$ $(25,050)$	228 (56)	0.61 (0.61)
$e^{+}e^{-}$	$21,2014$ $(62,850)$	$3,388$ $(2,115)$	0.48 (0.47)
$\mu^{+}\mu^{-}$	$1,345,960$ $(399,000)$	18 (5)	0.66 (0.67)

Table 1: Left: Coherent and diffractive trident events at different LAr experiments assuming 100% efficiency. **Right:** Number of backgrounds expected for neutrino (antineutrino) mode at the DUNE ND before ($N_{\mathrm{B}}^{\mathrm{misID}}$) and after ($N_{\mathrm{B}}^{\mathrm{misID}}$) kinematical cuts, and signal efficiencies $\varepsilon_{\mathrm{sig}}^{\mathrm{coh}}$ for coherent tridents.

reduction in this channel are the collimated nature of muon pair in the trident process, the small angles with respect to the beam, the small invariant mass and the lack of hadronic activity. It should be noted, however, that the presence of a coherent contribution to ν_{μ}CC1$\pi^{\pm}$ gives rise to a large fraction of events with no hadronic activity and to forward signatures. Nevertheless, we show that a substantial amount of background reduction can be achieved with the use of simple kinematical cuts, as shown in Fig.2. The final cut on invariant mass is most crucial, and the experimental resolution on this quantity will play a crucial role in suppressing backgrounds. Our findings are similar for $e^{+}e^{-}$ and $e^{\pm}\mu^{\mp}$ channels, where π^{0} production and single gamma processes in NC and CC interactions are the leading backgrounds. In our analysis, $e^{+}e^{-}$ tridents present the biggest challenge, with $S/B \sim 30\%$.

4. Conclusions

The neutrino trident scattering cross section was calculated and shown to be largely sensitive to the charged lepton mass. This renders the EPA approximation inappropriate for this process. Our background analysis shows that the distinct kinematics of trident can be used to reduce backgrounds and paves the way for future experimental work. The DUNE near detector will have a unique opportunity to measure $e^{+}e^{-}$ and $e^{\pm}\mu^{\mp}$ trident channels for the first time.

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