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An absolute ν mass measurement with the DUNE experiment

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Neutrinos of all flavours with mean energies of $O(10)$ MeV are copiusly produced during a Supernova explosion. Its early stage, the so called *neutronization burst*, is characterized by the emission of a large amounth of electron neutrinos during the first $\sim$ 25 ms of the explosion, as a result of a fast neutronization of the stellar nucleus via electron capture on free protons. The presence of this sharp time structure in the electron neutrino flavor time distribution makes this channel a very powerful one, allowing large liquid argon underground detectors to provide precision measurements of the time dependence of the electron neutrino fluxes. By exploiting the time-of-flight delay experienced by massive neutrinos, we derive here a new model-independent constraints on the absolute neutrino mass attainable at the future DUNE far detector from a future supernova collapse in our galactic neighborhood. Under favorable scenarios, we found sub-eV results that are competitive with those expected for laboratory direct neutrino mass searches.

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1. Introduction

Since atmospheric neutrinos provided the first evidence of neutrino oscillations [1], hence massive neutrinos, several experiments, spread over cosmology and particle physics, are trying to measure the absolute value of neutrino mass. The most constraining upper bound on the total neutrino mass comes from cosmology, $\sum m_\nu < 0.09$ eV at 95% confidence level (C.L.) [2, 3]. Supernova (SN) explosions can be used to put independent constraints on neutrino masses by exploiting the time-of-flight delay experienced by a neutrino of mass m_ν and energy E_ν [4]:

$$\Delta t = \frac{D}{2c}\left(\frac{m_\nu}{E_\nu}\right)^2 . \tag{1}$$

This method has been already used to study neutrinos from SN1987A [5–7]. Through the detection of inverse β-decay events, $\bar{\nu}_e + p \to e^+ + n$, sensitive to $\bar{\nu}_e$ only, the current 95% C.L. upper limit at $m_\nu < 5.8$ eV [8] has been obtained. Here we want to point out the importance of the detection of the ν_e component of the SN neutrino signal, by exploiting the ν_e charged-current (CC) interactions with ^{40}Ar nuclei, $\nu_e + {}^{40}Ar \to e^- + {}^{40}K^*$ at the DUNE far detector [9, 10]. The large number of detected neutrinos and the very distinctive feature of the neutronization burst [11] will ensure a unique sensitivity to the neutrino mass signature via time delays.

2. Supernova electron neutrino emission and detection

We assumed the quasi-thermal parametrization, which is reproducing accurately the output of current numerical simulations [12–14]:

$$\Phi^0_{\nu_\beta}(t,E) = \frac{L_{\nu_\beta}(t)}{4\pi D^2}\frac{\varphi_{\nu_\beta}(t,E)}{\langle E_{\nu_\beta}(t)\rangle} , \tag{2}$$

and describing the differential flux for each neutrino flavor ν_β at a time t after the SN core bounce. Here, D is the SN distance from the Earth, $L_{\nu_\beta}(t)$ is the ν_β luminosity, $\langle E_{\nu_\beta}(t)\rangle$ the mean neutrino energy and $\varphi_{\nu_\beta}(t,E)$ is the ν_β energy distribution, defined as:

$$\varphi_{\nu_\beta}(t,E) = \xi_\beta(t)\left(\frac{E}{\langle E_{\nu_\beta}(t)\rangle}\right)^{\alpha_\beta(t)} \exp\left\{\frac{-\left[\alpha_\beta(t)+1\right]E}{\langle E_{\nu_\beta}(t)\rangle}\right\} , \tag{3}$$

where $\alpha_\beta(t)$ is a *pinching* parameter and $\xi_\beta(t)$ is a unit-area normalization factor. Input for $L_{\nu_\beta}(t)$, $\langle E_{\nu_\beta}(t)\rangle$ and $\alpha_\beta(t)$ values have been taken from Garching Core-Collapse Modeling Group [15] simulations: here we consider two SN progenitors with masses of $8.8M_\odot$ [16] and $19M_\odot$ [17]. While propagating inside the SN, neutrinos experience the Mikheyev-Smirnov-Wolfenstein (MSW) effect [18], which modifies their fluxes. At the Earth, these fluxes (Φ_{ν_e} and $\Phi_{\nu_\mu} = \Phi_{\nu_\tau} = \Phi_{\bar{\nu}_\mu} = \Phi_{\bar{\nu}_\tau} \equiv \Phi_{\nu_x}$) read as:

$$\Phi_{\nu_e} = p\Phi^0_{\nu_e} + (1-p)\Phi^0_{\nu_x} ; \tag{4}$$

$$\Phi_{\nu_\mu} + \Phi_{\nu_\tau} \equiv 2\Phi_{\nu_x} = (1-p)\Phi^0_{\nu_e} + (1+p)\Phi^0_{\nu_x} , \tag{5}$$

where Φ^0 refers to the neutrino flux produced in the SN core, in absence of oscillations (no-osc), and the ν_e survival probability p, expressed in terms of the oscillation parameters, is given by

$p = |U_{e3}|^2 = \sin^2\theta_{13}$ in Normal Ordering (NO) and $p \simeq |U_{e2}|^2 \simeq \sin^2\theta_{12}$ in Inverted one (IO). Possible non-adiabaticity effects are here neglected, while has been proved that matter effects due to Earth crossing marginally affect the sensitivity to the neutrino mass. The neutrino interaction rate per unit time and energy in the DUNE far detector is defined as:

$$R(t, E) = N_{\text{target}}\, \sigma_{\nu_e \text{CC}}(E)\, \epsilon(E)\, \Phi_{\nu_e}(t, E)\ , \tag{6}$$

where t is the neutrino emission time, E is the neutrino energy, $N_{\text{target}} = 6.03 \times 10^{32}$ is the number of argon nuclei for a 40 kton fiducial mass of liquid argon, $\sigma_{\nu_e \text{CC}}(E)$ is the CC ν_e cross-section on ^{40}Ar implemented in SNOwGLoBES [19], $\epsilon(E)$ is the DUNE reconstruction efficiency [10] and $\Phi_{\nu_e}(t, E)$ is defined in Eq. 2. The total number of expected events is given by $R \equiv \int R(t, E)dtdE$. For a SN located at $D = 10$ kpc from the Earth and neglecting Earth matter effects, assuming the $8.8M_\odot$ progenitor, R is found to be 860, 1372 and 1228 (201, 54 and 95) in no-osc, NO and IO cases, respectively, during the whole 9 s (the first 50 ms) of the SN explosion, while considering the $19M_\odot$ one, $R = 3644, 5441, 4936$ (200, 88, 120) in the same cases.

3. Neutrino mass sensitivity

Assuming massless neutrinos, we generated ~ 500 DUNE datasets for each oscillation scenario, with the time/energy information sampled following the parametrization of Eq. 6. A 10% energy resolution has been assumed [10] to smear the neutrino energy of each generated event. We assume perfect time resolution for our studies, which results to be a good approximation due to the high light yields expected in the DUNE far detector [9]. Once events are generated, we proceed with the analysis of the sensitivity to the neutrino mass. Without including any background or uncertainties on the neutrino production, propagation and interaction, the two free parameters constrained in our fit are an offset time t_{off} between the moment when the earliest SN burst neutrino reaches the Earth and the detection of the first event $i = 1$, and the neutrino mass m_ν. The fitted emission times $t_{i,fit}$ for each event i depend on these two fit parameters as follows:

$$t_{i,fit} = \delta t_i - \Delta t_i(m_\nu) + t_{\text{off}}\,, \tag{7}$$

where δt_i is the time at which the neutrino interaction i is measured in DUNE (with the convention that $\delta t_1 \equiv 0$ for the first detected event) and $\Delta t_i(m_\nu)$ is the delay induced by the non-zero neutrino mass defined in Eq. 1. By neglecting all the constant (irrelevant) factors, our likelihood $\mathcal{L}$ function [8, 20] reads as

$$\mathcal{L}(m_\nu, t_{\text{off}}) = \prod_{i=1}^{R} \int R(t_i, E_i) G_i(E)\, \mathrm{d}E\ \ , \tag{8}$$

where G_i is a Gaussian distribution with mean E_i and sigma $0.1E_i$, accounting for the energy resolution. The estimation of the m_ν fit parameter is done by marginalizing over the nuisance parameter t_{off}. For each fixed m_ν value, we minimize the following χ^2 function:

$$\chi^2(m_\nu) = -2\log[\mathcal{L}(m_\nu, t_{\text{off,best}})]\ , \tag{9}$$

where $\mathcal{L}(m_\nu, t_{\text{off,best}})$ indicates the maximum likelihood at this particular m_ν value. The final step in our analysis is the combination of all datasets for the same oscillation scenario and SN progenitor,

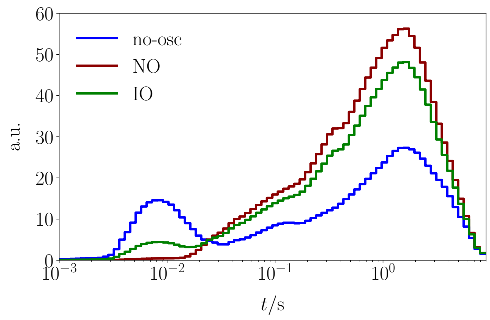

Figure 1: Expected number of ν_e events (in arbitrary units) as a function of time, obtained by an energy integration of Eq. 6. A SN distance of 10kpc is assumed. The neutronization burst results almost entirely (partially) suppressed for NO (IO).

Mass ordering	$8.8 M_\odot$ m_ν(eV)	$19 M_\odot$ m_ν(eV)
no-osc	$0.51^{+0.20}_{-0.20}$	$0.56^{+0.20}_{-0.21}$
NO	$2.01^{+0.69}_{-0.55}$	$1.65^{+0.54}_{-0.40}$
IO	$0.91^{+0.31}_{-0.33}$	$0.85^{+0.30}_{-0.25}$

Table 1: Mean and standard deviation of the 95% CL sensitivity on m_ν from a sample of DUNE SN datasets at $D = 10$ kpc, for different neutrino oscillation scenarios and SN progenitors.

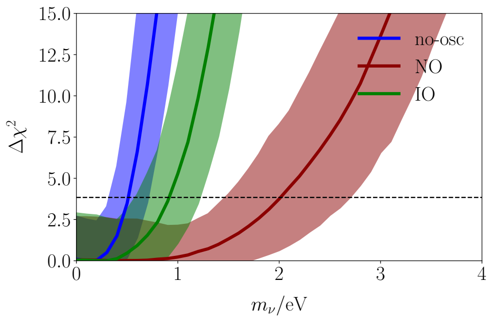

Figure 2: $\Delta\chi^2(m_\nu)$ profiles as a function of the neutrino mass m_ν for DUNE generated samples from a SN progenitor of $8.8 M_\odot$ [16], assuming massless neutrinos and a $D = 10$ kpc. The mean sensitivities and their $\pm 1\sigma$ uncertainties are shown with solid lines and filled bands, respectively. The horizontal dashed line depicts the 95% C.L.

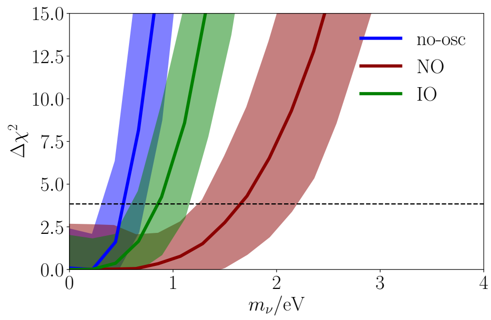

Figure 3: $\Delta\chi^2(m_\nu)$ profiles as a function of the neutrino mass m_ν for DUNE generated samples from a SN progenitor of $19 M_\odot$ [17], assuming massless neutrinos and a $D = 10$ kpc. The mean sensitivities and their $\pm 1\sigma$ uncertainties are shown with solid lines and filled bands, respectively. The horizontal dashed line depicts the 95% C.L.

to evaluate the impact of statistical fluctuations. For each m_ν, we compute the mean and standard deviation of all dataset χ^2 values. In order to estimate the allowed range in m_ν, the $\Delta\chi^2$ difference between all mean χ^2 values and the global mean χ^2 minimum is computed. The mean 95% C.L. sensitivity to m_ν is then defined as the largest m_ν value satisfying $\Delta\chi^2 < 3.84$. The $\pm 1\sigma$ uncertainty on the 95% C.L. m_ν sensitivity can be computed similarly. Results of our statistical analysis for no-osc, NO and IO cases and assuming a SN distance of $D = 10$ kpc can be seen in Figs. 2,3 and in Tab. 1, for both SN progenitors studied. In both cases, the best results have been obtained for the no-osc and IO scenarios, where the reach is below $\sim$ 1eV. Despite the largest overall event statistics expected in NO for both the SN progenitors of $8.8 M_\odot$ ($R = 1372$) and $19 M_\odot$ ($R = 5441$), its reach is the worst among the three cases. This result plainly indicates the importance of the sharp neutronization burst time structure, clearly visible in the no-osc and IO cases (Fig. 1). A more massive progenitor usually produces a higher number of events during the successive SN phases [21], but no significant change is expected in the neutronization burst, which is a nearly progenitor independent feature [11]. This emerges from Tab.1, where results for IO and no-osc do not change among the progenitors, while these can be significantly improved in NO, since in this case the sensitivity depends on the statistics collected in the entire $\sim$ 10 s of the SN neutrino emission.

4. Conclusions

The capability to detect the ν_e flux component from a core-collapse SN in our galactic neighborhood makes liquid argon detectors powerful observatories to put constraints on m_ν via time-of-flight measurements. Exploiting the signal coming from CC interactions of ν_e with ^{40}Ar nuclei and assuming a SN distance of 10 kpc, sub-eV sensitivity on the absolute value of m_ν has been obtained in DUNE for IO scenario. The sensitivity is expected to be significantly worse in NO, even if better for higher progenitors masses. The difference between the two orderings demonstrates the benefit of detecting the ν_e neutronization burst, which constitutes an important tool to constrain m_ν, giving a complementary and independent measurement to direct neutrino mass laboratory and cosmology experiments.

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