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Limits on $p \to \mu + \pi^0$ decay from a DUNE-like experiment

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Abstract

We derive the the expected background to proton decay in large underground DUNE-like neutrino detector and introduced, for the first time in this kind of analysis, the experimentally confirmed oscillations of atmospheric neutrinos. We also determine the effect of neutrino cross-section tuned with MineBooNE data. Considering a 40 kton detector with efficiency 45%, our analysis leads to an error band in the lower limit for the proton lifetime sensitivity, τ/B, from 7.9×10^{33} years to 1.1×10^{34} years at 90% C.L.. These numbers can be compared with the current mode dependent experimental limits $\tau > 10^{31} - 7.7\times10^{33}$ years at 90% C.L.. More details in https://arxiv.org/abs/1704.03927.

Introduction

The quest of finding proton decay is fully related with atmospheric neutrinos since they consist the main background to the most probable decay channels. Recent results from SK 2017 [1] shown 2 candidates to p-decay in the channel,

$$p \to \mu^+ + \pi^0, \tag{1}$$

where a background of $\to 0.87$ events was expected. This implied in 22% probability of saw the signal and not a fluctuation of background and reduced the limit for p-decay to $\frac{\tau}{\beta} = 7.7\times10^{33}$ years. The DUNE experiment will be sensitive to this specific decay channel too. In [2] an extensive calculation was performed for the most probable decay channels. It is clear from that work that the main source of background to detect the proton decay is the (anti)neutrino reaction:

$$\nu_l + n \to \mu^- + \Delta^+ \to p + \mu^- + \pi^0; \qquad \bar{\nu}_l + p \to \mu^+ + \Delta^0 \to n + \mu^+ + \pi^0\,. \tag{2}$$

Our goal is to include in the calculation of the background to Equation. (1) physical effects that we think cannot be disregarded and that are not present in the literature for a argon based neutrino detector. They are:

- Neutrino-nucleon resonant cross-section for neutral pion production tuned to MiniBooNE [3] data,
- The Standard Neutrino Oscillations.

In what follows we describe such features, include it in the background calculation and find the limits for proton decay in a DUNE-like detector within such assumptions.

Proton decay kinematics

If the protons are at rest, then μ and π_0 must be back-to-back. Generally, protons can have some initial momenta before decay, which we assume or order of $p_p = 250$ MeV. Four-momenta conservation combined with the momentum resolution, $\delta p_\mu/p_\mu \approx 18\%$, leads to $278 \le p_\mu \le 696$ MeV and $299 \le E_\mu \le 703$ MeV. The neutral pion generates an EM shower, $\pi^0 \to \gamma\gamma \to e^+e^- + e^+e^-$, which resolution is $\frac{\sigma(E)}{E} \approx 3\%\sqrt{E(\mathrm{GeV})}$. Hence, as $|p_\mu| = |p_\pi|$, the neutral pion emission energy must be in the interval $360 \le E_{\pi^0} \le 620$ MeV. Such kinematic cuts constrain the number of events from Equation (2) that counts for the background.

Cross-sections for $\nu + N \to N' + \mu + \pi^0$

To take into account events due to Equation. (2) we use the *Fogli and Nardulli* model to calculate the exclusive single neutral pion resonant production cross-section. This model reproduced the results from the old Bubble Chamber experiments [4]. We apply this model also to the MiniBooNE data [3]. The results can be seen in In Figure (1), left panel. The fits are related by a factor 1/2. In right panel we show the resulting cross section after apply the kinematic cuts defined previously. These are the cross-sections that we effectively need.

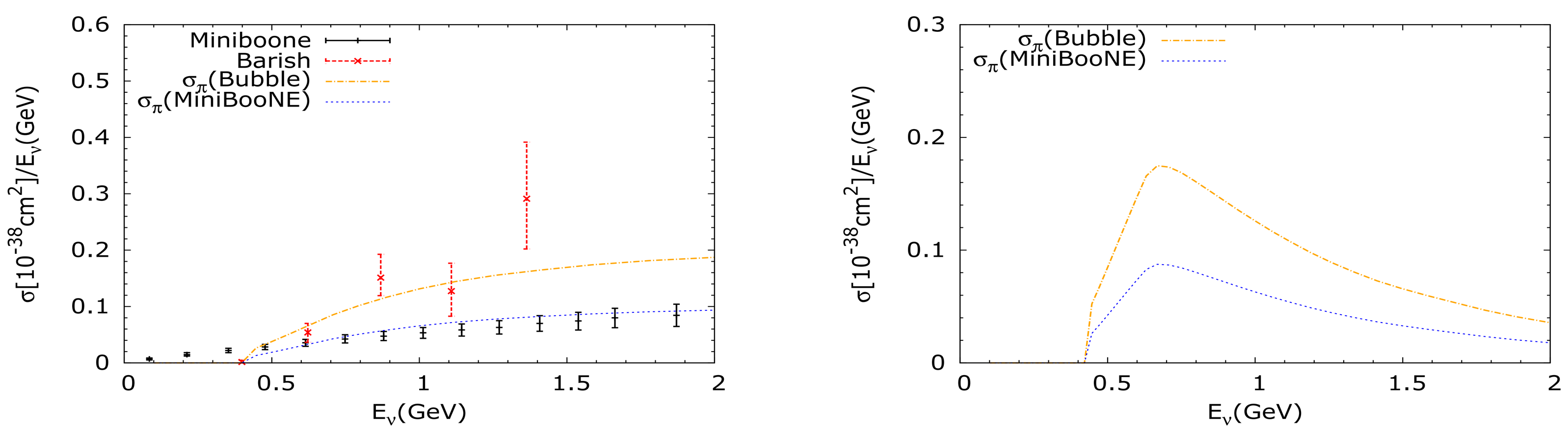

Figure 1: *Left Panel:* Our results for the neutrino-nucleon resonant neutral pion production cross-section from *Fogli and Nardulli* model applied to both Bubble and MineBooNE data sets. *Right Panel:* The same cross-sections when the kinematic cuts are applied.

Standard neutrino oscillations

To include the full 3-neutrino oscillation probability we solve the Schroedinger-like equation for the three neutrino time evolution Hamiltonian, including the standard matter potential due to CC interactions between neutrinos and electrons inside the Earth [5]. We adopt the values of $\Delta m^2_{21} = 7.4\times10^{-5}$ eV^2, $\Delta m^2_{31} = 2.47\times10^{-3}$ eV^2, $\theta_{12} = 33.36^0$, $\theta_{13} = 8.66^0$, $\theta_{23} = 40.00^0$. $N_e(r)$ is the electron density profile of the Earth from PREM model. The resulting probabilities are shown in Figure (2) and are necessary to take into account the right number of muon neutrinos that reaches the detector.

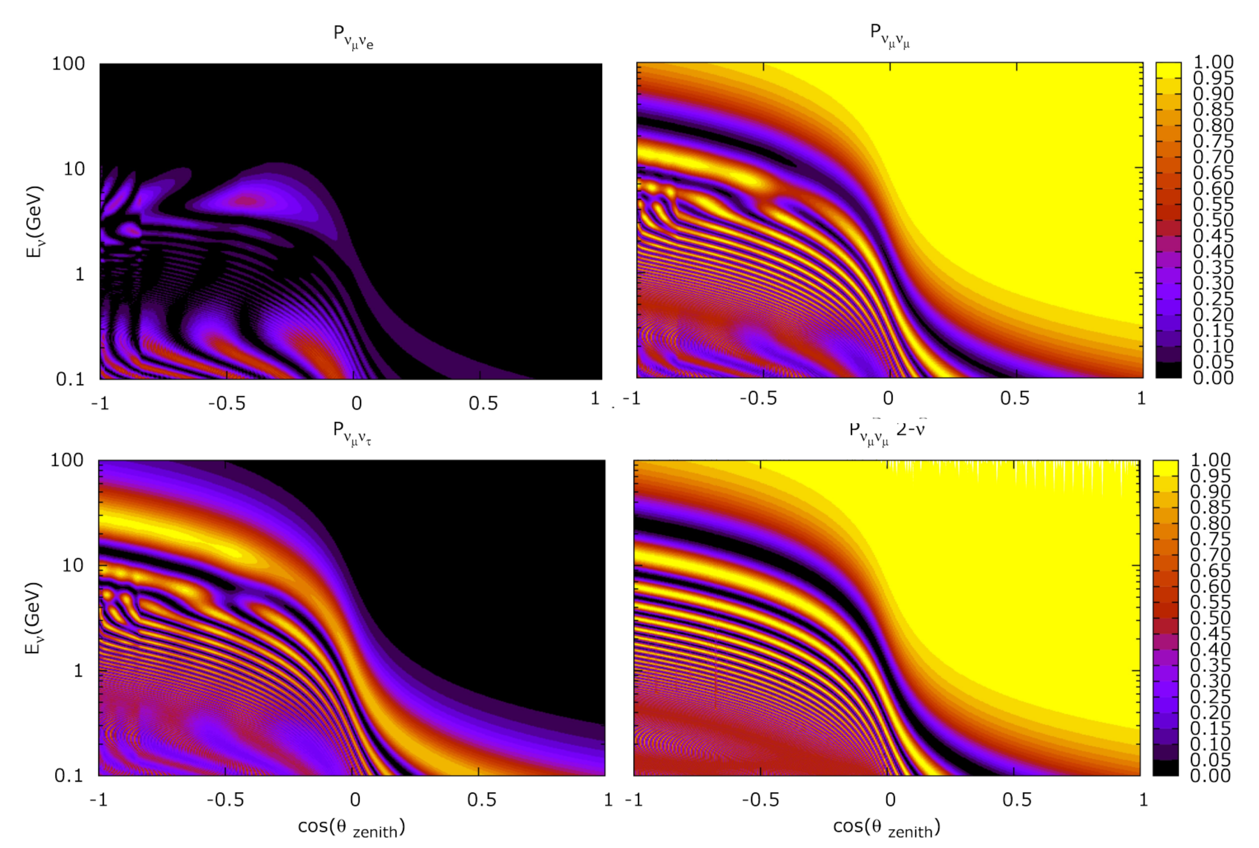

Figure 2: Oscillograms for $P_{\nu_\mu\nu_\alpha}$ as function simultaneously of $\cos(\theta_{\mathrm{zenith}})$ and neutrino energy.

Background Calculation

The number of atmospheric neutrino events is the integral of the product of differential cross-section with atmospheric neutrino flux and oscillation probability, which leads to:

$$N_{\nu_\mu} = n_{\mathrm{targets}} \times \epsilon \times t \times \sum_{\bar\nu,\nu}\int_{x_0}^{1} dx \int_{-1}^{1} d\cos(\theta_\nu)\int_0^{2\pi} d\phi_\nu \int_{E_{\nu,0}}^{E_{\nu,f}} dE_\nu \int_{E_{l,0}}^{E_{l,f}} dE_l \,\times$$
$$\times\left[\Phi_{\nu_\mu}(E_\nu,\theta_\nu,\phi_\nu)\times P_{\nu_\mu\to\nu_\mu} + \Phi_{\nu_e}(E_\nu,\theta_\nu,\phi_\nu)\times P_{\nu_e\to\nu_\mu}\right]\times\frac{d\sigma(\nu+N\to N'+\mu+\pi^0)}{dE_\nu dE_l}, \tag{3}$$

where t=10 years, and the atmospheric neutrino flux are obtained from Ref. [6]. An overall factor of 38% is introduced to count only the neutral pions that emerge from Δ decay within the desired energy interval. Finally, muon and pion must to be back-to-back, which leads to the angular window, $\delta\mathcal{A} = \delta\mathcal{A}_\mu + \delta\mathcal{A}_{\pi^0} = [\theta_{\max}(1+\cos(\theta_{\max}))]/[4\pi]$. The resulting background as a function of $\delta\theta_{max}$ and uncertainty in muon momentum are shown respectively in the left and right panels of Figure (3). We compare it with SK [7] results and also with the predictions from [2].

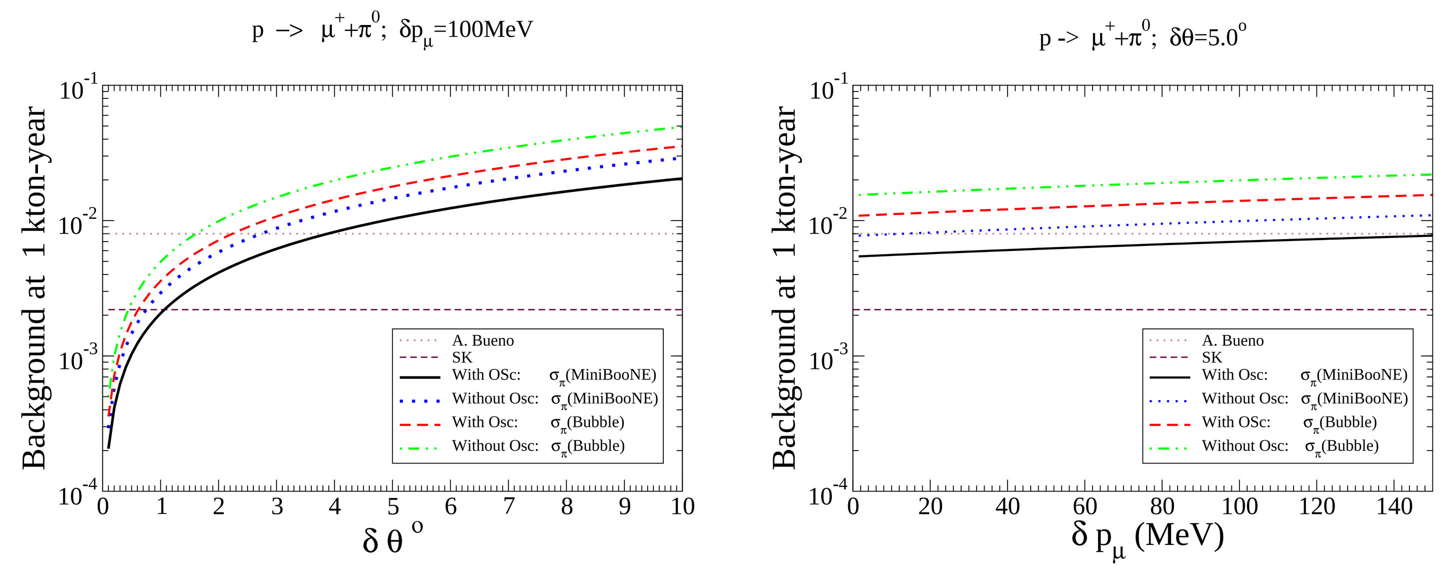

Figure 3: Effect of neutrino oscillations and cross-section model on the background to $p \to \mu + \pi^0$. *Left Panel:* As function of angular uncertainty. *Right Panel:* As function of muon momentum resolution.

Limits on $p \to \mu + \pi^0$

The Poisson distribution $P(n,\lambda)$ gives the probability of measure n events having a expectation value λ. For a given value of background b, the expected signal S necessary to reach of 90% C.L., that means $\alpha = 0.1$, is given by [2],

$$\frac{\sum\limits_{n=0}^{n_0} P(n, b+S)}{\sum\limits_{n=0}^{n_0} P(n,b)} = \alpha = 0.1, \qquad \text{where} \qquad P(n,\lambda) = \frac{e^{-\lambda}(\lambda)^n}{n!}. \tag{4}$$

Here n_0 is the integer number closest to b. Once $S(T\epsilon)$ is known from Equation. (4), the limit on proton lifetime should be written as [2]:

$$\frac{\tau}{B}(\mathrm{years}) > \frac{2.7\ 10^{32}}{\mathrm{S(T}\times\epsilon)}\times \mathrm{T}\times\epsilon, \tag{5}$$

where 2.7×10^{32} is the number of protons in one kton of ^{40} Ar and B is the branching ratio to the channel $p \to \mu^+ + \pi^0$. Note that only the effective exposure is in practice relevant. In Figure. (4) we show our predictions for the sensitivity limit on proton lifetime as a function of exposure and overall efficiency.

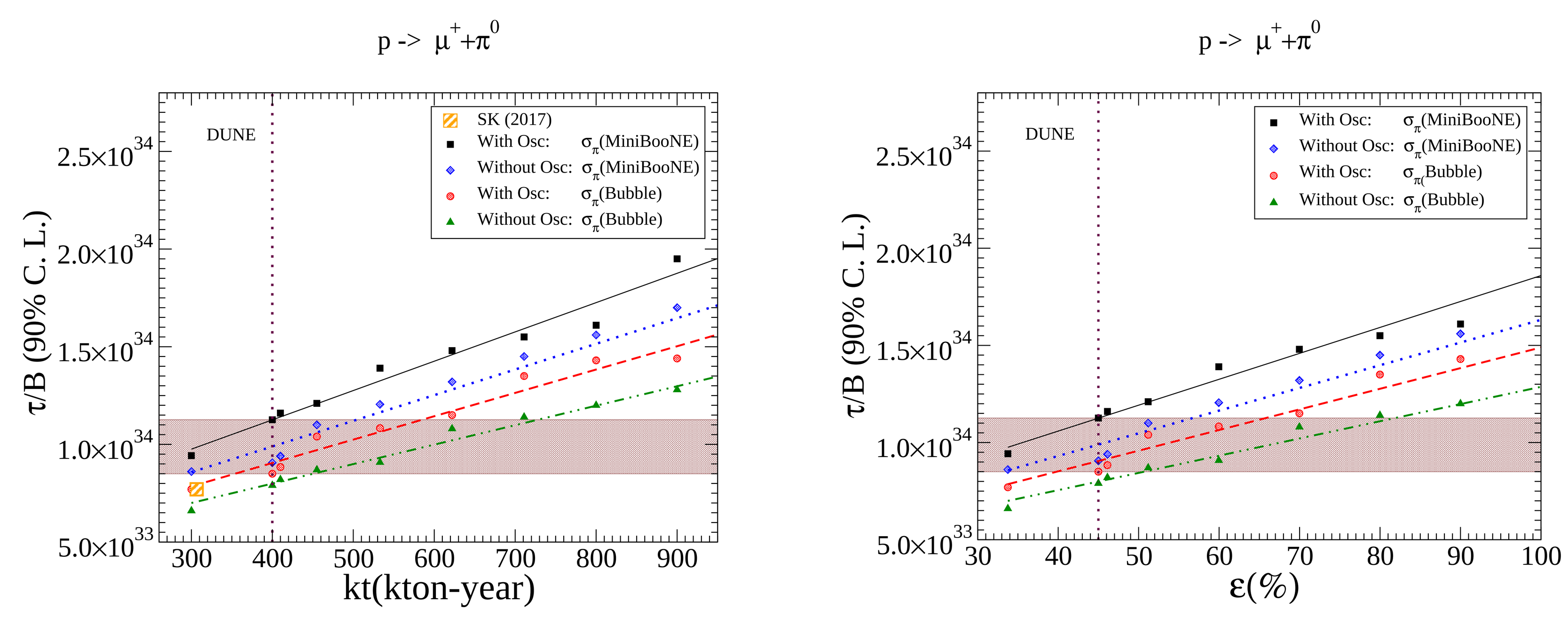

Figure 4: *Left Panel:* Our predictions for the sensitivity limit on τ/B as a function of exposure. *Right Panel:* The same as function of the overall efficiency for a fixed exposure of 400 kton-yr.

Conclusions

We found that the pion resonant cross-section tuned with MiniBooNE data reduces the background when compared with old bubble data at least 57%. However, due to fluctuations in such small background, a reduction on it does not imply a strictly proportional increment of proton lifetime expectation. Also, $\sigma_\pi(\mathrm{MiniBooNE})$ cross-section improve proton lifetime sensitivity limit in $13-33\%$ and the inclusion of standard oscillations enhance such limit in $\approx 5-24\%$ when comparing to the present limit of proton decay [**?**]. Combined, such features reduced background by a factor of 2.4. For a realistic detector of 40 kton taking data for 10 years, we obtained a range in sensitivity limit of proton lifetime of $7.9\times10^{33} \le \tau/\mathrm{B} \le 1.1\times10^{34}$ s. Hence, DUNE should be competitive to SK in this specific channel, and can play an important rule in the determination of limits on proton life-time.

References

[1] K. Abe. et. al. Phys. Rev. D95, 012004(2017)

[2] A. Bueno, Z. Dai, Y. Ge, M. Laffranchi, A. J. Melgarejo, A. Meregaglia, S. Navas and A. Rubbia, JHEP **0704**, 041 (2007) [hep-ph/0701101].

[3] A. A. Aguilar-Arevalo *et al.* [MiniBooNE Collaboration], Phys. Rev. D **81**, 092005 (2010) [arXiv:1002.2680 [hep-ex]].

[4] S. J. Barish *et al.*, Phys. Rev. D **19**, 2521 (1979).

[5] S. P. Mikheyev and A. Y. Smirnov, Prog. Part. Nucl. Phys. **23**, 41 (1989).
L. Wolfenstein, Phys. Rev. D **17**, 2369 (1978).

[6] M. Honda, T. Kajita, K. Kasahara, S. Midorikawa and T. Sanuki, Phys. Rev. D **75**, 043006 (2007) [astro-ph/0611418].

[7] M Ikeda *et al.*, Super-Kamiokande Collaboration, G. Santucci Talk at NNN2015.