

Exploring the Potential of Short-Baseline Physics at Fermilab

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We study the capabilities of the short baseline neutrino program at Fermilab to probe the unitarity of the lepton mixing matrix. We find that the Fermilab program can improve the sensitivity to non-unitary parameter $|\alpha_{21}|$ by about one order of magnitude. Motivated by the future DUNE experiment, we have also analyzed the potential of a liquid Argon near the detector in the LBNF beamline. This will substantially improve the current sensitivity of non-unitarity.

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1. The short-baseline program at Fermilab

The neutrino oscillation program at Fermilab occupies a central role in neutrino physics experimentation [1, 2]. Here we aim to study the physics capabilities of the short baseline neutrino program to probe beyond standard model physics associated with the non-unitarity of the lepton mixing matrix. We have also studied the perspectives of the DUNE liquid Argon near the detector to further improve this sensitivity. For a more detailed discussion of the subject (including NSI and sterile neutrino), please refer to the original reference [3]. We studied two configurations:

- (1) The Fermilab Short Baseline Neutrino Experiment (SBNE). This experiment consists of three detectors: the Short Baseline Neutrino Detector (SBND), with a baseline of 0.11 km, the μ BooNE detector, with a baseline of 0.47 km, and the ICARUS detector, whose baseline is 0.6 km. Their size and characteristics are described in the SBNE proposal [4].
- (2) The DUNE near detector: The Long-Baseline Neutrino Facility (LBNF) will need a near detector to achieve its main goals. Such detector will receive the highest-intensity neutrino beam in the world sitting at a distance of around 600 meters. The design of such a detector is still under discussion.

For our simulation of SBN, we used the configuration provided by [5]. For the DUNE near detector, we re-scaled the usual DUNE far detector provided by Globes [6]. Since we are interested in a zero-distance effect, the flux shape and cross section uncertainties are important. In order to take them into consideration we used the following χ^2 function

$$\chi^2 = \sum_{O=1}^3 \sum_{i=1}^{N_{\text{bin}}} \left(\frac{N_{iO}^{\text{exp}} - (1-a-a_{iO})N_{iO}^{\text{th}} - (1-b-b_{iO})N_{iO}^{\text{bg}}}{\sqrt{N_{iO}^{\text{exp}}}} \right)^2 + \chi_{\text{SYS}}^2, \quad (1.1)$$

where χ_{SYS}^2 contain Gaussian priors for the uncertainties parameters a, b, a_i, b_i with uncorrelated errors σ . a_i and b_i wrap all the uncertainties in the shape of the detected spectrum, including cross-section. N_{iO}^{exp} is the total number of events assuming standard physics. $N_{iO}^{\text{th}}, (N_{iO}^{\text{bg}})$ is the expected number of signal (background) events in non-unitarity of experiment O .

2. Sensitivity to New Physics

Non-Unitarity effects can be described by modifying the (unitary) mixing matrix U by its non-unitary version $U_{\text{Non-Unit}} = \alpha.U$, where α is a triangular matrix ($\alpha_{ij} = 0$ if $j > i$) that contains the violations of unitarity generated by the existence of heavy neutrino states. At short distances, the neutrino flux is modified by non-oscillatory transitions $\nu_\mu \rightarrow \nu_e$ resulting in an electron neutrino flux of $\phi_e^{\text{Non-Unit}} \sim \phi_e^0 + |\alpha_{21}|^2 \phi_\mu^0$, where ϕ_a^0 are the flux of neutrinos $a = e, \mu$ in the unitary case.

Hence, short-baseline experiments can constrain $|\alpha_{21}|$ if fluxes and cross-sections are known to some degree. In Fig. 1 we plotted this sensitivity by assuming overall normalization error of 10% and shape error of 1%. Notice that the high statistics of LBNF provides one order of magnitude better sensitivity over the SBN. Nevertheless, both improve current limit from NOMAD $|\alpha_{21}|^2 < 7 \times 10^{-4}$ [7]. The most limiting factor to probe non-unitarity in a near detector lies in knowing the shape of the neutrino flux/cross-section with high precision.

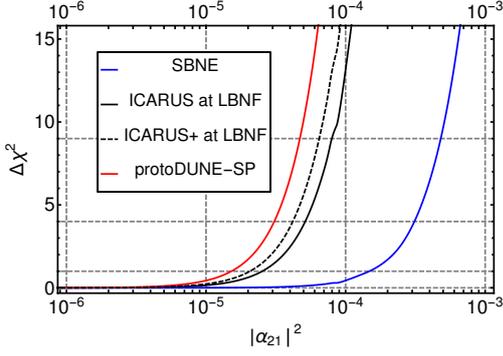


Figure 1: Sensitivity of each configuration assumed: SBN experiment (blue), ICARUS at LBNF (black-solid), ICARUS+ at LBNF (black-dashed) and protoDUNE-SP (red). All of them are assumed to be located at 600 m from the neutrino source and running for 3.5 years in the neutrino and 3.5 in the anti-neutrino mode.

The DUNE collaboration plan to predict the flux from the muons and hadron-production responsible for the neutrino beam [1], while precise theoretical calculations of the neutrino cross-section is an ongoing debate. In Fig. 2 we present the change in the sensitivity on $|\alpha_{21}|^2$ at 90% C. L. when varying the detector's Baseline and the shape-spectrum error.

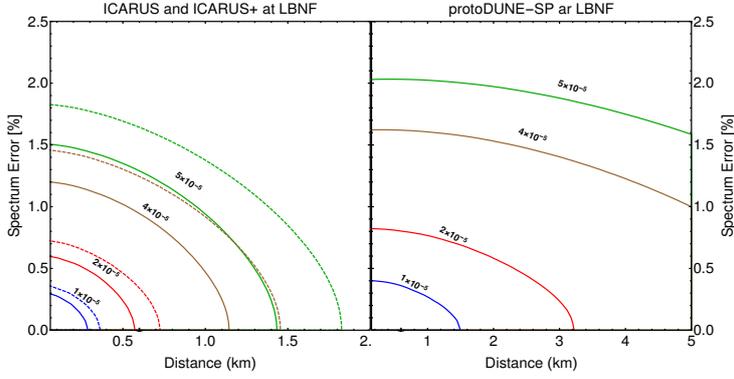


Figure 2: **Left:** 90% C.L. sensitivity to $|\alpha_{21}|$ for ICARUS (solid line) and ICARUS+ (dashed line). **Right:** 90% C.L. protoDUNE-SP sensitivity for various combinations of spectrum error. Lines correspond to $|\alpha_{21}|^2 < 10^{-5}$ (blue), 2×10^{-5} (red), 4×10^{-5} (brown) and 5×10^{-5} (green).

3. Discussion and conclusion

We looked into the potential capabilities of the SBN program and the near detector of the DUNE experiment to probe non-unitarity. We obtained that it is possible to improve current bounds depending on how well the systematics of the neutrino beam is controlled. If the shape of the spectrum is known at few %, the DUNE near detector could improve the bound on $|\alpha_{21}|$ by one order of magnitude.

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