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Neutrinos from a pion beam line: nuPIL

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Neutrinos from a pion beam line: nuPIL

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Abstract. We describe a novel configuration for a neutrino beam line that can simultaneously support both long and short baseline experiments .The neutrino beams originate from pions that are first focused by a magnetic horn, as in a conventional neutrino beam. However, in the case of nuPIL, the horn is followed by a magnetic lattice that is used to select the pion charge and then transports the pions in a production straight. This produces extremely pure neutrino and anti-neutrino beams, while minimizing the amount of beam power that is transported underground for the long-baseline physics program. This configuration greatly simplifies the civil construction leading to a large cost reduction. The principles of the design of nuPIL are presented, together with tracking results and the resulting neutrino flux. The potential of the facility for CP-violation searches, in the framework of the DUNE experiment, is discussed and compared to that of an optimized beam from LBNF.

1. Introduction

LBNF-DUNE is a project based at Fermilab which will allow for precision studies of neutrino oscillations, especially for CP violation in the leptonic sector [1]. The baseline neutrino beam follows the conventional approach, where a high-energy proton beam hits a target, producing pions collected by a system of horns and then decay in a decay pipe. The LBNF 4 m-diameter and 204 m-long decay pipe points toward detectors placed at the Sanford Underground Research Facility (SURF) in South Dakota, about 1300 km away, so the tunnel is tilted with a vertical angle of 5.8 deg to maximize the flux at the detector. Radiation safety requires that the surrounding earth needs to be shielded by about 6 m of concrete surrounding the pipe, which therefore requires an excavation of at least 16 m in diameter. Furthermore, since all forward going particles can enter the decay tunnel, an inevitable background signal is created at the detector by neutrinos produced from kaon, wrong-sign pion and muon decays.

A different approach to neutrino beam production, the use of a pion beam line, is described in this paper. The primary proton beam hits the target and a horn focuses the resulting pions. These pions are then transported in a 5.8 deg beam line bend and then either injected into a beam line (composed of large bore quadrupoles or of straight scaling Fixed Field Alternating Gradient (FFAG) magnets [3]) or directly into a decay pipe. In this approach, the pions would go through a charge selection process in the bend, providing a cleaner neutrino beam at the detector. Furthermore, the engineering complexity of the decay pipe is also lessened, since the remaining high energy protons would not be bent. The "spent" proton beam remains at surface level which allows for a relatively simple surface beam absorber and simplifies the radiation safety issues in the decay tunnel. Instrumentation can also be installed, giving the possibility to

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have access to an in situ measurement of the pion flux. Finally, the wrong sign pions could be collected in, and extracted from, the bending section and could be used in another facility (i.e. nuSTORM [2]).

The design of a pion beam line with large aperture separate function magnets (dipoles and quadrupoles) [4] was studied and shows that the transport of such a large momentum spread beam is problematic, especially in the bending section. The use of scaling FFAG magnets [3, 5] can increase the momentum acceptance. This paper will present the preliminary results of an FFAG design for the nuPIL concept.

2. Lattice design

Among many developed solutions, one (called Lattice 11) is presented in this paper. It is a bending beam line composed of scaling FFAG magnets with a 5.8 deg bend and a decay pipe similar to the LBNF baseline scenario. The layout of the FFAG bend is presented in Fig. 1. First, a dispersion creator is used to adjust the dispersion (null after the horn) to a suitable value. Second, an optics matching section is used in order to minimize the divergence of the beam at the entrance of the decay pipe, while completing the required 5.8 degrees of bend.

A pion distribution coming from a nuSTORM horn [6] has been tracked in the FFAG bend. The momentum distribution of the pions at different points in the lattice simulation (decays turned off) is presented in Fig. 2. The surviving particles have been used to compute the resulting neutrino flux and anti-neutrino flux at the far detector (see Fig. 3 and 4). The DUNE CP violation sensitivity is presented in Fig. 6. The signal to background ratios for the baseline and for nuPIL lattice 11 are shown in Fig. 5.

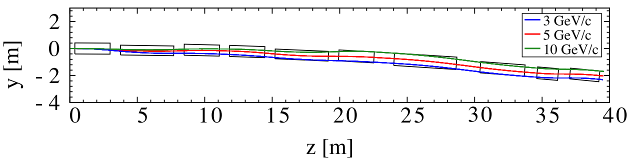

Figure 1. Layout of the lattice 11 bend. The horn is at z = 0, and the decay pipe starts at $z = 39\,\text{m}$.

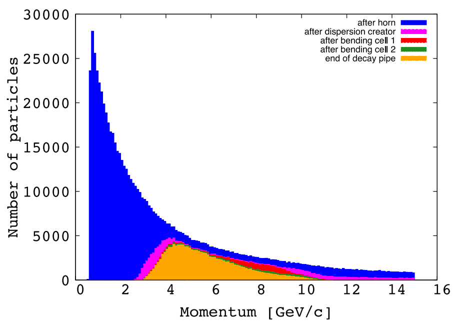

Figure 2. Momentum distribution of the pions from the nuSTORM horn at different places, with pion decay turned off in the simulation.

The nuSTORM horn is not optimized for lattice 11. A single horn optimization using a genetic algorithm has been performed with a carbon target in order to maximize the number of pions in the 6D acceptance of the lattice 11 bend. An increase of 38% in flux is achieved (see Fig. 7).

3. Conclusion

The nuPIL concept can deliver a clean neutrino beam for long-baseline neutrino experiments. The configuration shown here can be extended so that it could simultaneously provide beam for long-baseline and short-baseline experiments. Preliminary results with this nuPIL configuration are very encouraging. A more detailed study is needed and a design with a straight decay beam line is under development.

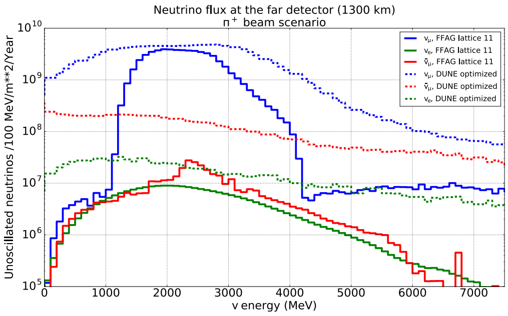

Figure 3. Neutrino flux at far detector with nuSTORM horn in nupil (plain lines) and for the LBNF 2-horn optimized solution (dotted line).

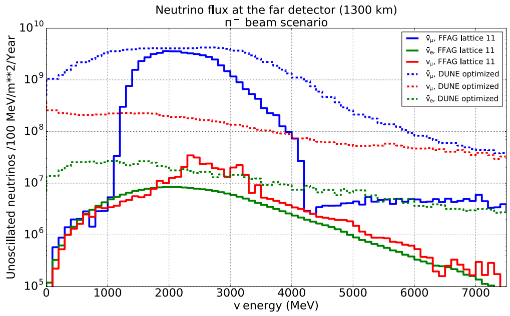

Figure 4. Anti-neutrino flux at far detector with nuSTORM horn in nupil (plain lines) and for the LBNF 2-horn optimized solution (dotted line).

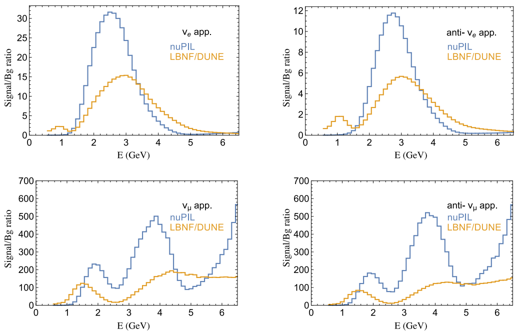

Figure 5. Signal/background ratio in LBNF/DUNE (yellow) and nuPIL (blue).

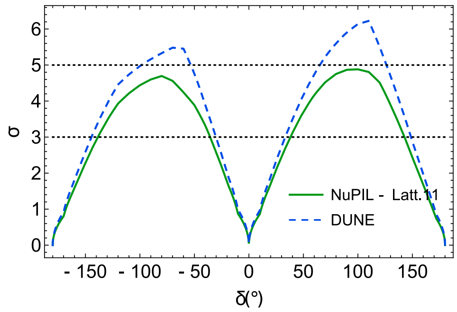

Figure 6. CP violation sensitivity for LBNF/DUNE (dotted blue) and nuPIL (plain green).

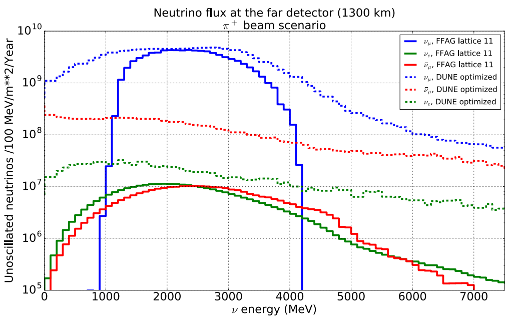

Figure 7. Neutrino flux at far detector with carbon target optimized horn (pions π^+ only).

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