Measuring the Muon Flux of Neutrino Beams with a Novel Gas Cherenkov Detector

by

Peter S. Madigan

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Reviewed by:

Professor Alysia Marino, Advisor, Physics Professor John Cumalat, Honors Council Representative, Physics Professor Juan Restrepo, Applied Mathematics

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Madigan, Peter S. (B.S., Engineering Physics)

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Thesis directed by Professor Alysia Marino

The Deep Underground Neutrino Experiment is a future long-baseline neutrino experiment that plans to make measurements of neutrino oscillation parameters. This experiment will require accurate estimates of the neutrino fluxes through the near and far detectors; however, these estimates rely heavily on Monte-Carlo models of hadronic interactions. In order to verify these Monte-Carlo flux estimates with physical data, the by-product muon beam can be observed using modest detectors. These measurements of the muon flux can then be used in conjunction with hadronic models to constrain predictions of the neutrino flux. In order to perform measurements of the muon flux of the future Deep Underground Neutrino Experiment, a muon monitoring system will be implemented. As part of this muon monitoring system, a novel Cherenkov detector will perform measurements of the muon beam spectrum and divergence. This thesis describes the research and development efforts to determine this detector design's capabilities that are currently being undertaken at the University of Colorado Boulder and at the Fermi National Accelerator Lab in Illinois.

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Contents

Chapter

| 1 | Intro | oduction | 1 |
|----------|-------|--|----|
| | 1.1 | Neutrinos and the Standard Model | 2 |
| | | 1.1.1 The Standard Model | 2 |
| | | 1.1.2 Neutrinos | 3 |
| | 1.2 | The Deep Underground Neutrino Experiment and the Long Baseline Neutrino Facility | 6 |
| | | 1.2.1 The Physics Goals of DUNE | 7 |
| | | 1.2.2 The Long Baseline Neutrino Facility | 8 |
| 2 | The | Gas Cherenkov Muon Detector | 13 |
| | 2.1 | Cherenkov radiation | 13 |
| | 2.2 | Cherenkov detectors | 15 |
| | 2.3 | Gas Cherenkov detector design | 17 |
| | 2.4 | Cosmic muon testing | 20 |
| | | 2.4.1 Data collection | 21 |
| | | 2.4.2 Simulation | 24 |
| | | 2.4.3 Results | 29 |
| 3 | The | NuMI Beam | 30 |
| | 3.1 | Overview | 30 |
| | 3.2 | Simulating the NuMI Beam | 34 |

| | 3.3 | Detect | cor performance | 40 |
|---|-----|---------|--|----|
| | 3.4 | Extrac | cting the muon flux | 43 |
| | | 3.4.1 | Simulating Cherenkov response | 44 |
| | | 3.4.2 | Fitting Cherenkov yield to muon E v. θ distribution | 45 |
| 4 | Con | clusion | and Future Work | 50 |

Bibliography

52

v

Figures

Figure

| 1.1 | A summary of the the particles in the SM. All known matter is composed of quarks | |
|-----|--|----|
| | (red) and leptons (blue). Forces between matter are mediated by the gauge bosons | |
| | (orange). The scalar Higgs boson (grey) gives mass to the other particles. \ldots . | 2 |
| 1.2 | Probability of measuring flavor α and α' using a two-flavor approximation. This | |
| | approximation is useful in both visualization of neutrino oscillation and performing | |
| | basic calculations of neutrino mixing | 5 |
| 1.3 | An diagrammatic overview of a neutrino beam production chain. A proton beam | |
| | is accelerated into a fixed target, producing various hadrons. These are focused | |
| | and sign-selected by magnetic horns. The hadrons are allowed to decay, producing | |
| | primarily muons and neutrinos. A hadron absorber is used to collect un-decayed | |
| | hadrons. Muons penetrate farther than other products, passing through the hadron | |
| | absorber into the subsequent concrete and rock | 9 |
| 1.4 | From [1]. Diagram of the Near Site facilities. A 58-ft hill must be built in order to | |
| | angle the beam downward towards the far detector in South Dakota | 10 |
| 1.5 | From [2]. Example LArTPC track of a ν_e interaction producing a p and e using a | |
| | GEANT4 simulation | 12 |
| 2.1 | From [3]. The geometric relationship between a particle's velocity v , the medium's | |
| | refractive index n, and the Cherenkov angle θ_C is $\cos(\theta_C) = 1/\beta n$. The z-axis is | |

defined here as the direction of the particle's momentum, and t is an arbitrary time. 14

| 2.2 | The muon phase space that the Cherenkov detector can theoretically collect light | |
|-----|--|----|
| | from while aligned with the muon beam, assuming various values of angular accep- | |
| | tance θ_A and a chamber pressure of 1 atm | 18 |
| 2.3 | The current design for the gas Cherenkov muon monitors to be used in DUNE. | |
| | They consist of a radiating chamber, a flat mirror, and an extended optics chamber | |
| | (partially shown) | 19 |
| 2.4 | A cosmic event is triggered by the coincidence of light from two scintillating blocks. | |
| | A trigger causes the readout from the PMT to be stored. | 21 |
| 2.5 | An example oscilloscope waveform from a flagged event while testing with an Argon- | |
| | filled chamber with a corrected internal pressure of 0.843 atm. The gaussian fit is | |
| | overlaid in red | 23 |
| 2.6 | GEANT4 simulation geometry consisting of two steel tubes (white), a gas-filled | |
| | chamber (brown), and a thin mirror (white). Also shown in this diagram is a single | |
| | simulated muon (blue) and the produced Cherenkov light (green). The scintillating | |
| | bars (shown in purple) are only used as a reference | 25 |
| 2.7 | From [4]. (Left) The cosmic ray spectrum at sea-level. (Right) The characteristic | |
| | cosmic muon angular distribution for various energies. \ldots \ldots \ldots \ldots \ldots \ldots | 26 |
| 2.8 | (Left) The approximation of the cosmic muon momentum that was generated. (Right) | |
| | The \cos^2 angular distribution generated with the scintillator-trigger generation method. | 27 |
| 2.9 | (Left) Simulation results for the expected number of photons reaching the photode- | |
| | tector without the optics chamber. Approx. 7% of cosmic muons produce light | |
| | that reaches the photodetector. (Right) The simulated angular photon yield for the | |
| | cosmic prototype. The 60-cm optics chamber reduces the angular acceptance to | |
| | < 120 mrad | 28 |
| 3.1 | From [5]. Overview of the NuMI accelerator chain at Fermilab. | 31 |

| 3.2 | From [5]. Diagrammatic top-view of the area downstream of the decay pipe, showing | |
|------|---|----|
| | the hadron monitor, absorber, and the muon alcoves. | 32 |
| 3.3 | Prototype gas Cherenkov detector installed in muon alcove 2 of the NuMI beam | |
| | shown with actuator settings and angles | 33 |
| 3.4 | Photograph of the prototype gas Cherenkov detector installed in muon alcove 2 taken | |
| | from the entrance of alcove 2. The gas ionization muon monitors can be seen in the | |
| | upper right. Picture taken by Geoffrey Mills of LANL | 34 |
| 3.5 | The initial muon energies of muons reaching alcoves 1 (upper-right), 2 (lower-left), | |
| | and 3 (lower-right) separated by muon parent as simulated by g4numi. The upper- | |
| | left plot shows the original muon energy at the decay point | 35 |
| 3.6 | The spatial distribution of the muon beam flux at alcove 1 (top-right), 2 (lower-left), | |
| | and 3 (lower-right) as simulated by g4numi | 36 |
| 3.7 | The muon E v. θ distribution in alcove 2 as simulated by g4numi | 37 |
| 3.8 | Example fit for the 2 GeV to 2.5 GeV energy slice of the E v. θ muon distribution in | |
| | alcove 2. The fitting parameters here correspond to those in eq. 3.1 where p0 $\rightarrow A$ | |
| | and $p1 \rightarrow \sigma$ | 37 |
| 3.9 | Comparison of the Monte Carlo muon distribution and fits to the Monte Carlo muon | |
| | distribution with various values of n . See equation 3.1 for the functional form | 38 |
| 3.10 | Final muon fit for angular muon fit parameters. Left, the parameter $A(E)$ fit to the | |
| | form in equation 3.2 where $p0 \rightarrow A_E$ and $p2 \rightarrow \sigma_E$; center, the parameter $\sigma(E)$ fit | |
| | to equation 3.3 where $p0 \rightarrow A_{\sigma}$; and right, the muon spectrum in alcove 2 | 39 |
| 3.11 | The integrated gas Cherenkov signal normalized by the alcove 2 muon monitor at | |
| | various pressures and horn currents. This data set was collected in March 2014 | 40 |
| 3.12 | Correlation between the integrated gas Cherenkov signal (GC) and POT for two | |
| | different pressure settings. Also shown is the gas ionization muon monitor signal, | |
| | for comparison. | 41 |

| 3.13 | The normalized Cherenkov stability accounting for signal loss and POT. Also shown | |
|------|--|----|
| | is a gaussian fit to these data | 42 |
| 3.14 | The results from a scan across detector yaw and detector pressure. A strong, | |
| | Cherenkov-like signal is apparent | 43 |
| 3.15 | Diagram of muon variables. The θ and ϕ variables are the azimuthal and latitudinal | |
| | angles of the muon momentum, respectively | 45 |
| 3.16 | Monte Carlo simulation of the Cherenkov yield at various detector pressures and | |
| | angles using a realistic muon distribution (described in Section 3.2). Each point | |
| | represents 10^4 simulated muons | 46 |
| 3.17 | (Left) The realistic Monte Carlo muon distribution used to generate a fake dataset. | |
| | (Right) The reconstructed muon distribution based on the fit described in Section 3.4.2. | 49 |
| 3.18 | Ratio of the rebuilt muon distribution to the original muon distribution. The muon | |
| | distribution agrees within approx. 20% in all bins. | 49 |

Chapter 1

Introduction

I will present the research that has been done in the past year and a half to develop a gas Cherenkov muon monitor for the future Deep Underground Neutrino Experiment (DUNE). This includes research performed with a prototype detector to observe the cosmic muon spectrum in Boulder, Colorado, simulations of prototype detectors and the muons generated by NuMI at Fermilab, and a test simulation that presents a plan for extracting the muon flux from the detector signal. The work done as part of this thesis provides promising results for the future and will inform the continued development of these detectors.

Chapter 1 contains a basic introduction to neutrino physics and an overview of DUNE. This provides the context for my work. Chapter 2 presents a brief discussion of how Cherenkov detectors have been used previously and how the particular design of the gas Cherenkov muon monitor for DUNE fits into this framework. This chapter also describes the testing that has been done using cosmic rays. Chapter 3 introduces the NuMI beam at Fermilab and the prototype detector that has been installed in the NuMI beam, including the detector performance over the past year and a half. Finally, this chapter also lays out the framework and preliminary Monte Carlo results for extracting the muon beam kinematics from the Cherenkov detector signal. Chapter 4 concludes with a brief summary and suggestions for future work on gas Cherenkov muon detectors.



Figure 1.1: A summary of the particles in the SM. All known matter is composed of quarks (red) and leptons (blue). Forces between matter are mediated by the gauge bosons (orange). The scalar Higgs boson (grey) gives mass to the other particles.

1.1 Neutrinos and the Standard Model

Neutrinos are nearly-massless neutral particles that interact weakly with matter. Being the second-most abundant particle in the universe after the photon, neutrinos are a necessary part of any search for a "theory of everything." This section will give a brief introduction to the Standard Model (SM) of particle physics and to the role neutrinos have played in particle physics.

1.1.1 The Standard Model

The SM of particle physics is a theoretical framework of particle physics that has been developed by many physicists over the past half-century and is widely regarded as one of the greatest achievements of physics [6]. In this framework (Figure 1.1), high-energy interactions are viewed as exchanges of force particles (i.e., photons, gluons, etc.) between matter particles (quarks or leptons). The three forces of nature that are involved in high-energy interactions correspond to integer-spin gauge bosons – the strong force from the gluon, the electromagnetic force from the photon, and the weak force from the W and Z bosons. The fundamental fermions, or half-integer spin particles, of the SM are grouped into three families each containing two quark types and two lepton types. Quarks (u, d, c, s, t, and b) interact through the strong force, weak force, and electromagnetic force. The leptons $(e, \mu, \tau, \text{ and } \nu)$ have a charged type (known as the electron e, the muon μ , and the tau τ) and a neutral type (known as a neutrino ν), and they do not interact through the strong force. The charged leptons interact through both the weak and electromagnetic forces. As a consequence of their neutrality, neutrinos do not interact with the electromagnetic force, interacting only through the weak force. Additionally, the neutrinos have three "flavors" – each corresponding to a charged lepton type. For example, the neutrino that is produced in association with an electron is the electron-flavored neutrino ν_e . The interaction range of the weak force is reduced by the large masses of the W and Z bosons. Combined, the lack of charge and short interaction range of the weak force allow neutrinos to pass through light-years of matter without interacting.

In addition to these fundamental particles of matter, the SM predicts the existence of conjugate matter, commonly called antimatter. These antiparticles interact through the same forces and possess the same mass as their counterparts; however, they have the opposite charge. For neutrinos, the antineutrino is more complicated. Because neutrinos are neutral, they have the potential to be their own antiparticle, or a Majorana particle. Current searches for neutrinoless double beta decay hope to determine if neutrinos are Majorana particles.

1.1.2 Neutrinos

Pauli's original introduction of a neutral particle (the neutrino) to explain the missing energy in nuclear β -decays was built upon by E. Fermi into a full theory of β -decay in which a neutron decays into a proton and an electron-neutrino pair [7]. From the 1940s–1970s, a full theory of the weak interaction was developed using neutrinos as neutral, massless particles with flavors corresponding to the charged leptons. This theory was largely successful in describing various nuclear reactions and made a prediction for the number of neutrinos produced in the fusion chain of the sun. However, Raymond Davis' experiment in the 1960s measured the solar neutrino flux and observed a flux of about 2–3 times less than this prediction [7]. This led to what was known as the Solar Neutrino Problem. Gribov and Pontecorvo were the first to explain this result using a mixing theory based on the previously observed mixing of the K^0 meson [7]. Their theory suggested that a significant fraction of the ν_e neutrinos had changed into another flavor in the space between the core of the sun and the Earth. Since Davis' experiment was only sensitive to electron neutrinos, the neutrinos that changed flavors were not observed, producing an apparent solar neutrino deficit. As a consequence of the mechanism proposed by Gribov and Pontecorvo, neutrinos must have a non-zero mass – a feature not in the previous models of particle physics. Additional neutrino measurements from nuclear reactors, atmospheric interactions, and man-made neutrino beams have supported the theory of neutrino flavor mixing [8].

In the current form of this theory, each neutrino flavor state $|\nu_{\alpha}\rangle$ can be expressed as a superposition of the neutrino mass states $|\nu_i\rangle$ in the form

$$|\nu_{\alpha}\rangle = \sum_{i=1}^{3} U_{\alpha i}^{*} |\nu_{i}\rangle, \qquad (1.1)$$

where U is the unitary matrix known as the PMNS mixing matrix [7, 9]. In a weak interaction, a neutrino is produced in a flavor eigenstate; however, as the mass eigenstates are vacuum energy eigenstates, the time evolution of the state obeys the Schrödinger equation. This time evolution introduces a different phase for each mass component

$$|\nu_{\alpha}\rangle = \sum_{i=1}^{3} U_{\alpha i}^{*} e^{-im_{i}^{2}L/2E} |\nu_{i}\rangle, \qquad (1.2)$$

assuming that the neutrino is highly relativistic and where L is the distance the neutrino travels and E is the neutrino energy. If the difference between these masses is zero, i.e., massless neutrinos or one neutrino mass, the phase difference disappears and the probability of flavor α changing into flavor α' , $P(\nu_{\alpha} \rightarrow \nu_{\alpha'})$, becomes $\delta_{\alpha\alpha'}$ at any distance. However, if there is a difference between the neutrino masses, the $P(\nu_{\alpha} \rightarrow \nu_{\alpha'})$ becomes

$$P(\stackrel{(-)}{\nu}_{\alpha} \rightarrow \stackrel{(-)}{\nu}_{\alpha'}) = \delta_{\alpha\alpha'} - 4\sum_{i>j} \Re \left[U^*_{\alpha i} U_{\alpha' i} U_{\alpha j} U^*_{\alpha' j} \right] \sin^2 \left(\Delta m^2_{ij} \frac{L}{4E} \right)$$

$$+ 2\sum_{i>j} \Im \left[U^*_{\alpha i} U_{\alpha' i} U_{\alpha j} U^*_{\alpha' j} \right] \sin^2 \left(\Delta m^2_{ij} \frac{L}{2E} \right)$$

$$(1.3)$$

for relativistic neutrinos ν_{α} and antineutrinos $\bar{\nu}_{\alpha}$ [9] and where $\Delta m_{ij}^2 = m_i^2 - m_j^2$. For many purposes, a two-flavor approximation can be used, simplifying the above expression. Figure 1.2



Figure 1.2: Probability of measuring flavor α and α' using a two-flavor approximation. This approximation is useful in both visualization of neutrino oscillation and performing basic calculations of neutrino mixing.

shows the probability of measuring ν_{α} as a function of distance and energy in this two-flavor approximation. From equation 1.3, the L/E-scales of neutrino oscillation can be determined by the neutrino mass differences.

In the full 3-flavor mixing model, the mixing matrix U, is expressed in the form

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{bmatrix} \times \begin{bmatrix} \cos \theta_{13} & 0 & \sin(\theta_{13})e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin(\theta_{13})e^{i\delta_{CP}} & 0 & \cos \theta_{13} \end{bmatrix} \times \begin{bmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$
(1.4)

The angles θ_{ij} are known as the mixing angles and determine mass composition of the flavor eigenstates. Additionally, if U is a complex matrix, as is allowed in the SM, a complex CPviolating phase δ_{CP} can be introduced. CP-violation is the violation of CP-symmetry, which is the symmetry under charge conjugation C (exchanging a particle with its antiparticle) and parity conjugation P (flipping the spatial coordinates). An example of this CP-violation can be seen when the oscillation probability is expressed in the form

$$P(\stackrel{(-)}{\nu}_{\mu} \rightarrow \stackrel{(-)}{\nu}_{e}) = \sin^{2}(\theta_{23})\sin^{2}(2\theta_{13})\sin^{2}(\Delta m_{32}^{2}L/4E) + \cos^{2}(\theta_{23})\sin^{2}(2\theta_{13})\sin^{2}(\Delta m_{21}^{2}L/4E) + J\cos(\delta_{CP})\cos(\Delta m_{32}^{2}L/4E) \mp J\sin(\delta_{CP})\sin(\Delta m_{32}^{2}L/4E),$$
(1.5)

where J is the Jarlskog invariant defined as $J = \Im \left[U_{\mu 3} U_{e 2} U_{\mu 2}^* U_{e 3}^* \right]$ [10]. This form reveals an oscillation probability difference of

$$\Delta P_{\nu_{\mu} \to \nu_{e}, \bar{\nu}_{\mu} \to \bar{\nu}_{e}} = 2J \sin\left(\delta_{CP}\right) \sin\left(\Delta m_{32}^{2}L/4E\right), \tag{1.6}$$

between neutrino and antineutrino oscillations in vacuum. This suggests that if $\delta_{CP} = 0$ or J = 0, there will be no difference in neutrino and antineutrino oscillations in vacuum; however, in the case that $\delta_{CP} > 0$ and $J \neq 0$, the symmetry between neutrinos and antineutrinos is broken.

Additional matter effects introduce oscillation differences between neutrinos and antineutrinos; however, this intrinsic CP-violation has yet to be observed in the lepton sector. Quark CP-violation has been observed, but due to the limited mixing between quark types, is not large enough to explain the matter–antimatter asymmetry of the observable universe. The potential for lepton CP-violation to explain the matter–antimatter asymmetry makes its discovery a primary goal of current neutrino oscillation experiments.

1.2 The Deep Underground Neutrino Experiment and the Long Baseline Neutrino Facility

Neutrino flavor oscillation is an attractive explanation of the experimental results showing neutrino appearance and disappearance, and many of the parameters that determine neutrino oscillation have been measured; however, the remaining parameters may offer unique insight into the nature of neutrinos and physics outside the SM. The Deep Underground Neutrino Experiment

Table 1.1: Current best-fit values for the known neutrino oscillation parameters [8]. The observed non-zero values of θ_{ij} suggest that $J \neq 0$ and that CP-violation could be observed in neutrino oscillations.

| $\sin^2 2\theta_{12}$ | 0.846 ± 0.021 | Fit from KamLAND, solar, SBL, and accelerator data |
|-----------------------|---|---|
| Δm_{21}^2 | $7.53 \pm 0.18 \times 10^{-5} \text{ eV}^2$ | Fit from KamLAND, solar, SBL, and accelerator data |
| $\sin^2 2\theta_{23}$ | $1.000 \pm \frac{0.001}{0.018}$ | T2K measured value assuming normal hierarchy |
| Δm_{32}^2 | $2.44 \pm 0.06 \times 10^{-3} \text{ eV}^2$ | PDG fit, sign unknown |
| $\sin^2 2\theta_{13}$ | $9.3 \pm 0.8 \times 10^{-2}$ | PDG average |
| $\delta_{ m CP}/\pi$ | $1.39 \pm {0.38 \atop 0.27}$ | PDG best fit, 2σ range assuming normal hierarchy |

(DUNE) supported by the Long-Baseline Neutrino Facility (LBNF) will make precision measurements of the remaining oscillation parameters; specifically, DUNE/LBNF will measure the θ_{13} and θ_{23} mixing angles, the δ_{CP} CP- violating phase, and the sign of Δm_{13}^2 . Additionally, the secondary physics program at LBNF could point to physics beyond the SM through proton decay and could contribute to models of stellar evolution by observing a neutrino flux originating from a core–collapse supernova.

1.2.1 The Physics Goals of DUNE

Currently, measurements of θ_{12} , θ_{23} , and Δm^2 have been made, but are not predicted by the SM. The best measurements of these values are shown in Table 1.1, where the mixing angles are expressed as their related oscillation parameters $\sin^2 2\theta_{ij}$. DUNE plans to make precision measurements of θ_{13} and θ_{23} , along with measurements of δ_{CP} and the sign of Δm_{13}^2 . These measurements will complete the mixing matrix U and will determine the mass hierarchy of neutrinos.

DUNE will have the ability to make a supernova-neutrino flux measurement if any nearby supernova occur during its lifetime. A core-collapse supernova releases on the order of 10^{57} neutrinos [11], of which the flux and flavor development carries information about the dynamics of this violent phenomenon. A measurement of this development from a nearby supernova, would both provide interesting astrophysical neutrino results as well as provide an early-warning for other supernova observatories [2].

Additionally, the DUNE far detector will be versatile enough to observe more than just

neutrino-based events; in particular, DUNE will be sensitive to proton decays and will be able to place a new lower limit on the proton lifetime. Proton decays and baryon number conservation play an important role in many Grand Unified Theories (GUTs) beyond the SM and could play a role in explaining the matter-antimatter asymmetry of the universe [2]. If DUNE were to observe proton decay, it would be a clear sign of physics beyond the SM.

1.2.2 The Long Baseline Neutrino Facility

LBNF will consist of a multi-Megawatt ν_{μ} -beam, a beam monitoring system, a small near neutrino detector, and a massive far neutrino detector. The Near Site facilities at Fermilab, Illinois will house the source of the beam, the beam monitoring system, and a near neutrino detector. The Far Site facilities will be 800 miles away in Lead, South Dakota and 4800 feet under ground in the Sanford Underground Research Facility (SURF). It will consist of a multi-kiloton liquid argon time projection chamber (LArTPC) with photon detection capabilities and the associated cryogenic systems.

The Near Facilities Fermilab is the largest national laboratory devoted to high-energy physics (HEP) in the United States. Built in 1969 [12], Fermilab has been home to a number of important discoveries, such as the discoveries of the top quark, bottom quark, and the tau neutrino, and was the site of the famous Tevatron particle accelerator. Since then, Fermilab has been an important facility in accelerator-based neutrino physics with a number of neutrino programs (MiniBooNE, NO ν A, MINER ν A, MINOS, among others [12]). However, in order for the Fermilab proton beam to produce the multi-Megawatt neutrino beam required for DUNE, some modification of the current facilities must be made.

The current design for the LBNF beamline will use a 60-120 GeV proton beam [2] from the Main Injector synchrotron at Fermilab. Dipole and quadrupole magnets will be used to focus the proton beam onto a carbon target [2]. Collisions between the high-energy protons and the carbon nuclei produce a number of secondary particles (predominantly π with some K). These secondary



Figure 1.3: An diagrammatic overview of a neutrino beam production chain. A proton beam is accelerated into a fixed target, producing various hadrons. These are focused and sign-selected by magnetic horns. The hadrons are allowed to decay, producing primarily muons and neutrinos. A hadron absorber is used to collect un-decayed hadrons. Muons penetrate farther than other products, passing through the hadron absorber into the subsequent concrete and rock.



Figure 1.4: From [1]. Diagram of the Near Site facilities. A 58-ft hill must be built in order to angle the beam downward towards the far detector in South Dakota.

particles are focused by a series of magnetic horns into a roughly parallel beam, which is allowed to decay. The magnetic horns are designed to be used with either a positive or negative current, producing either a neutrino or an antineutrino beam. In the decay pipe, the primary two-body decay mode of pions and kaons produces equal quantities of ν_{μ} and μ . The exact geometry of this 200-m long, 4-m wide decay pipe can be optimized to produce the neutrino spectrum desired for DUNE. A large hadron absorber filters out the remaining hadrons after the decay pipe, leaving a beam of mostly muon neutrinos, which continue on to the near and far detectors, and muons, which largely penetrate through the absorber and into the subsequent earth [2]. A simplified version of this production chain is shown in Figure 1.3.

After the absorber, the Absorber Hall will house a muon monitoring system to aid in precision measurements of neutrino flux. Figure 1.4 shows a schematic of the Near Site facilities, including the target facility, decay pipe and Absorber Hall. The simple decay of pions and kaons produces predictable neutrino and muon fluxes; however, these fluxes depend on the initial pion and kaon kinematics. By observing the muon flux immediately after the absorber, DUNE can determine the pion and kaon kinematics and therefore determine the neutrino flux. The muon monitoring system will consist of three types of muon detectors: a gas Cherenkov threshold-differential detector, an array of gas ionization detectors or diamond detectors, and a series of stopped-muon detectors. The gas Cherenkov detectors that will be implemented are the main focus of this thesis.

Beyond the muon monitoring system, a relatively small near neutrino detector will be placed in order to determine the neutrino flux and flavor-composition at the beam source. The details of this detector design are currently under evaluation; however, the detector design will observe (with higher statistics than the far detector) neutrino-nucleon interactions of the neutrino beam [2]. This will provide information about the beam make-up and will be able to measure neutrino crosssections.

<u>The Far Facilities</u> The LBNF Far Site will be located in the Sanford Underground Research Facility (SURF) in Lead, South Dakota. SURF is an underground research facility in the former Homestake Mine [13]. LBNF will share SURF with other low-background experiments, such as LUX and the Majorana Demonstrator [13].

The LBNF Far Detector will consist of four 10-kiloton, linearly-placed cryostats filled with liquid argon, instrumented with wire grids and scintillation detectors, and filtration and cryogenic systems designed to maintain the liquid argon. The LArTPC uses a series of cathode planes and anode wire planes to produce a relatively uniform electric field within the liquid argon. After a neutrino interacts with an argon nucleus, the produced charged particles pass through the argon, ejecting electrons. These electrons are collected on the anode wire planes. The signal produced can then be used to create accurate three-dimensional particle tracks (Figure 1.5). Additionally, this detector design performs particle identification (PID) through unambiguous measurements of energy loss dE/dX [2]. In addition to producing ionized electrons, liquid argon produces scintillation light in association with high-energy events, which can be collected with wavelength-shifting fibers to produce a fast trigger signal for non-accelerator events [2]. The high sensitivity of this detector design is critical for fulfilling DUNE's physics goals.



Figure 1.5: From [2]. Example LArTPC track of a ν_e interaction producing a p and e using a GEANT4 simulation.

Chapter 2

The Gas Cherenkov Muon Detector

The secondary beam of muons produced in standard neutrino beams is produced in an almost 1:1 ratio of $\mu : \nu_{\mu}$. Moreover, the kinematics of the neutrino beam are largely determined through the two-body decays of $\pi \to \mu + \nu_{\mu}$ and $K \to \mu + \nu_{\mu}$ and the initial pion and kaon distributions. In the meson rest frame, the muon and neutrino are produced isotropically, conserving momentum and energy, and the system can be solved analytically. Given information about the muon distribution in the lab frame, the kinematics of the original meson beam as well as the neutrino beam can be determined. As this thesis will demonstrate, one way to determine this muon distribution is by using a gas Cherenkov detector.

This chapter covers the design, function, and testing of a unique Cherenkov detector design. In Section 2.1, the phenomenon of Cherenkov radiation is briefly introduced. Section 2.2 covers the historical design and implementation of different Cherenkov detectors, including the information that can be extracted from these designs. Then in Section 2.3, the design and expected performance of the gas Cherenkov detector to be implemented in LBNF is discussed. Finally, Section 2.4 describes the cosmic muon prototype testing that has been done at the University of Colorado, as a means to confirm the observation of Cherenkov light with this detector design.

2.1 Cherenkov radiation

In P. Cherenkov's Nobel Prize winning paper [3], he discusses the discovery of a unique form of radiation produced by high-speed particles. According to this paper, the characteristics of this



Figure 2.1: From [3]. The geometric relationship between a particle's velocity v, the medium's refractive index n, and the Cherenkov angle θ_C is $\cos(\theta_C) = 1/\beta n$. The z-axis is defined here as the direction of the particle's momentum, and t is an arbitrary time.

radiation that led to the discovery of this new phenomenon were incompatible with the theories of luminescence that existed at the time. These properties were: a continuous spectrum, no decay parameter, parallel polarization, and a distinct forward intensity. Luminescence, however, is a process that results in a discrete spectrum, a decay parameter, perpendicular polarization, and a spatially symmetric intensity distribution [3]. The difference in properties of this new form of radiation from those of luminescence hinted at an underlying mechanism that was wholly different.

Tamm and Frank's theory of fast-moving electrons [14] explained the phenomena as highenergy charged particles traveling through a medium with a velocity $\beta \geq 1/n$, where β is ratio of the particle velocity to the speed of light in vacuum and n is the index of refraction of the material, i.e. at a speed greater than the speed of light in the medium. At this superluminal velocity, the EM wave produced by the charged particle at each point does not propagate forward ahead of the particle (with a velocity greater than β) but instead propagates at the slower velocity of 1/n. This causes the EM wave to destructively interfere in every direction other than the one given by the characteristic Cherenkov angle θ_C [3]. Figure 2.1 shows the geometric relationship between β , n, and θ_C . As a consequence of this interference, Cherenkov light is produced in a forward traveling cone, known as a Cherenkov cone. Using the relativistic energy of a particle given by $E = \gamma mc^2$ and an understanding that the Cherenkov threshold occurs at $\beta_t = 1/n$, there will be a threshold energy of $E_t = m/\sqrt{(1-n^{-2})}$. Additionally, the number and wavelength of photons emitted through the Cherenkov mechanism is related to the energy of the radiating particle [14], which can be used as a rough estimate of the particle's velocity β .

2.2 Cherenkov detectors

The unique properties of Cherenkov radiation provide a powerful tool for building particle detectors that accurately measure particle velocity and can be used for particle identification (PID). Additionally, Cherenkov detectors are also used as fast particle counters or tracking detectors for event reconstruction [8], which recreates the paths of particles in a high-energy interaction. Cherenkov-based particle detectors exploit the aspects of Cherenkov radiation, producing particle detectors that are blind to neutral particles and can make precise measurements of β . Usually combined with a method of measuring particle momentum (most commonly a calorimetric measurement or magnetic deflection), Cherenkov detectors are often implemented as accurate means of PID within HEP experiments. A measurement of both the velocity and momentum of a particle provides a measurement of the particle's rest mass, which is unique for a particle species. Cherenkov detectors are unable to determine the charge sign of a particle, but tracking methods can provide a clear measurement of the sign via the curvature of the particle's path in a magnetic field [8].

Most Cherenkov detector designs can put into three categories, each of which exploit different characteristics of Cherenkov radiation: threshold Cherenkov detectors, differential Cherenkov detectors, or ring-imaging Cherenkov (RICH) detectors. However, all of the designs require two features: a volume containing a Cherenkov radiator with a known n and a method of detecting the emitted photons [8]. Additionally, many designs incorporate optics in order to enhance or discriminate the Cherenkov signal.

<u>Threshold Cherenkov detectors</u> Threshold Cherenkov detectors count the photon emission of particles traveling through the radiating medium to determine the velocity β for a passing particle. Usually, no selection is made for the Cherenkov angle θ_C ; instead, light from a large angular range is focused onto one or two photodetectors [15]. These detectors are most commonly

designed with a long chamber containing a radiating gas or liquid followed by a spherical mirror to focus Cherenkov light onto a photodetector. Depending on spatial considerations of detector placement, optics can be used to focus the light to a photodetector that is displaced from the chamber or off-axis and at an angle from the chamber [16].

These detectors have high photon detection efficiencies that depend strongly on the refractive index of the radiating medium [15]. The medium within the detector is chosen with a refractive index to differentiate between particles of importance to the experiment [16]. However, analysis of the number of detected photons is needed in order to make an accurate measurement of the velocity β [15, 17]. These detectors have a large phase space acceptance, which is best suited to detect the wider-angle secondary particles in an interaction [17].

Differential Cherenkov detectors Differential Cherenkov detectors exclusively detect photons from specific Cherenkov angles. They incorporate selective optics that allow only photons produced at a desired Cherenkov angle θ_C to reach the photodetector [17]. Most designs consist of a radiating chamber followed by a mirror to reflect photons towards the photodetector; however, a collimator is usually placed between the mirror and photodetector in order to reduce the total photons to those with a specific Cherenkov angle [15]. By nature, this allows for accurate measurements of velocity; however, this sharply reduces the acceptance angle of the detectors, as the accuracy of the velocity measurement is inversely proportional to the size of the accepted angular phase-space region [17]. The reduction in acceptance angle limits the number of photons available and makes differential detectors inherently inefficient compared to other HEP detectors. However, they are commonly used in large signal situations, such as PID for intense particle beams [15].

<u>Ring-imaging Cherenkov detectors</u> One of the more recent developments in Cherenkov detectors has been the invention of ring-imaging Cherenkov (RICH) detectors that determine β from a measurement of the radius of the Cherenkov cone produced by the particle. As mentioned previously, Cherenkov radiation produces a cone of light; when striking a surface, such as the inner wall

of a RICH detector, the photons in the Cherenkov cone form a distinctive ring. Rebuilding images of Cherenkov rings requires the use of either an array of photodetectors or a photodetector that is sensitive to the spatial distribution of photons [17]. Using designs with relatively large radiators and optical enhancements, RICH detectors can have the higher efficiencies required in order to create 2D images of Cherenkov rings. These detectors then measure β through measurements of the Cherenkov rings' radii, without sacrificing phase space acceptance [17].

Implementations of Cherenkov detectors Cherenkov detectors have come to be an important aspect in a number of HEP experiments. Threshold Cherenkov detectors have been utilized in the Belle detector [16] as part of the PID system for the observation of B-meson decays. In this detector, PID is performed using a combination of measurements from tracking chambers, threshold Cherenkov detectors, time-of-flight counters, and calorimeters. RICH detectors were implemented as part of the DELPHI detector [18], the BABAR detector [19], and the LHCb detector [20], all using Cherenkov detectors a means of PID. The SNO [21] and SuperK [22] detectors were primarily RICH detectors that used large tanks of purified D_2O and H_2O , respectively, and large photodetector arrays. Cherenkov detectors continue to be proposed as parts of new HEP experiments [2, 23]; however, they have yet to be used in muon beams.

2.3 Gas Cherenkov detector design

The gas Cherenkov muon detector design to be implemented in the LBNF beam line combines the abilities of a threshold Cherenkov counter and a differential Cherenkov detector by utilizing a pressurized gas system, a narrow angular acceptance, and a positioning mount. The pressurized gas system is used to create a radiating medium with a controlled index of refraction. By adjusting the density of the radiating material, the Cherenkov threshold of the detector is changed. This not only provides a sharp cutoff in energy acceptance, but also a change in the angular distribution of the Cherenkov photons emitted by a charged particle. A small angular acceptance of the Cherenkov detector reduces the photon yield from particles outside of a narrow region of phase space, as shown



Figure 2.2: The muon phase space that the Cherenkov detector can theoretically collect light from while aligned with the muon beam, assuming various values of angular acceptance θ_A and a chamber pressure of 1 atm.



Figure 2.3: The current design for the gas Cherenkov muon monitors to be used in DUNE. They consist of a radiating chamber, a flat mirror, and an extended optics chamber (partially shown).

in Figure 2.2. By scanning the gas Cherenkov detector through angles relative to the beam line, the detector maps out a Cherenkov profile across pressure and angle. This profile can later be used to extract a charged particle momentum and angular distribution of the incoming beam.

The proposed detector design is pictured in Figure 2.3. The 26-in Argon-filled radiating chamber is placed directly into the beam and produces the Cherenkov light. A small, 5-cm flat mirror is positioned to reflect Cherenkov light traveling parallel to the radiating chamber into the optics tube. The 5-m optics tube serves to reduce the angular acceptance with a small collimator located approx. halfway down-tube and allows the sensitive photomultiplier tube to be located outside of the intense radiation of the beam. A high-pressure window is placed between the photomultiplier and the optics chamber to reduce the difficulties associated with maintaining vacuum and high-pressures across electronics ports. Additionally, after pressure testing a prototype, the design includes a reinforced T-section to enable an internal pressure range from 0 atm to 30 atm. A layer of light-absorbing flocking is inserted along the optics chamber and radiating chamber to limit reflections and light contributions from scintillation and transition radiation.

Some of the unique and useful characteristics of this detector include radiation hardness, insensitivity to neutral backgrounds, and strong angular dependence of the signal. The radiation hardness of the detector comes from the use of a noble gas (Argon) as the radiating medium, which can be flushed and replaced by fresh gas as needed, and from the use of a long optics chamber, which limits the photomultiplier tube's direct exposure to the muon beam. By relying on Cherenkov radiation as the signal, the detector limits the introduction of backgrounds due to uncharged particles. Finally, the strong angular dependence due to the long optics chamber and the directional nature of Cherenkov radiation provides a signal that is highly dependent on the angular distribution of the muon beam. Based on this design, the detector can be expected to cover a muon energy range from 0.8 GeV into the TeV range — the upper limit depending on the quality of vacuum maintained [24] and far above the expected muon energies from a 120-GeV proton beam. Additionally, the long optical tube and collimator give this design an angular acceptance of approximately 4 mrad.

2.4 Cosmic muon testing

In order to test this design, a small prototype detector was built at the University of Colorado Boulder. This detector was used to observe the cosmic muon flux and provide a proof of concept for this detector design. The cosmic muon flux is relatively well-known [8] and provides a cheap and easily-accessible muon source for testing of the muon detector design. To reduce the expense and mobility issue associated with the full-scale detector design, this prototype was scaled back to have a shorter radiating chamber of 60 centimeters and a shorter optics chamber of 60 cm. Additionally, a dark box was used instead of an isolated PMT chamber to exploit the materials available at the University of Colorado. The prototype was also not subjected to pressure testing, limiting the internal pressure range to be 0-2 atm. However, as a proof of concept, the prototype does not require the full pressure capabilities. Based on this reduced design, the prototype can be expected to observe muons of energies greater than 3 GeV with an angular acceptance of approximately 30 mrad. For reference, the mean cosmic muon energy is approx. 4 GeV and the vertical flux is approx. 110 (m² s sr)⁻¹ [8].



Figure 2.4: A cosmic event is triggered by the coincidence of light from two scintillating blocks. A trigger causes the readout from the PMT to be stored.

2.4.1 Data collection

In order to trigger on cosmic muons, a data acquisition system outlined in Figure 2.4 is used. In this system, two 1-cm scintillator blocks are attached to photomultiplier tubes. Whenever a relativistic, charged particle passes through one of these scintillator blocks, scintillation light is produced isotropically. This light is collected by a reflective Aluminum layer surrounding the block and reaches the photomultiplier within a few nanoseconds. The output signals from the photomultipliers are converted into a logic signal using a discriminator. These two logic signals can then be used as a trigger for the Cherenkov detector readout using an AND logic gate. Additionally, an amplifier is used for the Cherenkov detector output to enable higher Cherenkov photosensitivity. The four output channels (Cherenkov photomultiplier, upper scintillator photomultiplier, lower scintillator photomultiplier, and the logic trigger) are viewed on an oscilloscope and can be saved to an ASCII data format.

After some initial testing of this system, stray electronics noise was contributing to the oscillo-

scope waveforms. The vast majority of which was discovered to be the result of the photomultipliers picking up radio communications. This was mitigated by wrapping the readout photomultiplier tube with aluminum foil. Additionally, this tube was wrapped with μ -metal in order to reduce magnetic fields within the tube and improve the photodetector response.

A python analysis program is then used to extract information in these waveforms. This program calculates the extreme values, integral, FWHM integral, pulse timing, and pulse width. Additionally, it uses a gaussian fitting routine as pulse finding method. Figure 2.5 shows an example pulse with the gaussian fit. This fit is not used as a means of extracting accurate estimates of the pulse height and width, but rather it allows further analysis to quickly throw out empty waveforms. The analysis program also flags potential muon events using a simple machine learning algorithm. This algorithm compares the values of the waveform maximum, integral, width, and gaussian fit values to a set of internal value ranges. If the one of the values of a particular waveform fall within the corresponding bound, the waveform receives one flag. If the waveform has more than a set number of flags, then that waveform is flagged as a potential event candidate. In order to determine these internal bounds, the program is run in "LEARN" mode. While in this mode, for every flagged event, the waveform and fit is displayed and the user is queried if the current waveform should be classified. Based on the user's response, the internal bounds are updated. If the event's maximum, integral, width, or gaussian fit values disagree with the bounds and the user has marked the waveform as an event, the bounds that disagree are relaxed with a weighted average of the event's value and the current bound. Likewise, if the values agree with the bounds and the user has marked the waveform as not an event, the conflicting bounds are made stricter using the same weighted average. This process is repeated until the mis-identification rate is acceptable. After training the internal bounds on approximately 5000 waveforms, this algorithm mis-identifies approx. 1.2% of waveforms.



Figure 2.5: An example oscilloscope waveform from a flagged event while testing with an Argonfilled chamber with a corrected internal pressure of 0.843 atm. The gaussian fit is overlaid in red.

2.4.2 Simulation

As part of the effort to determine the functionality of this prototype and future Cherenkov detector designs, computer simulations can be used to determine hard-to-calculate performance characteristics of the detector, e.g. photon collection efficiency. By using Monte Carlo methods, computer simulations can give accurate predictions of detector characterizations. For this thesis, a stand-alone GEANT4 [25] detector simulation was developed. GEANT4 is a well-known and widely-used simulation suite specifically designed for the simulation of high-energy particles. It relies on Monte Carlo methods and an extensive collection of physics libraries to produce realistic simulations of physics processes. The previous efforts of C. Pitcher [26] and B. Schlitzer have provided a basic GEANT4 framework for the simulation of the gas Cherenkov detector.

The geometry of the simulation can be seen in Figure 2.6. This geometry is a reduction of the full detector to the essential features: a radiating chamber, an optics chamber, a mirror, a photodetector, and a variable-density gas. Each of these materials have adjustable optical properties, which are set to mimic the properties of the detector components. The steel cylindrical volumes have a reflectivity reduced to 1% to imitate the dark flocking. The aluminum mirror is set to a polished reflectivity according to CRC handbook [27], and the chamber lengths, widths, and thicknesses correspond to the true detector values according to the specification sheets. The simulation also only uses electromagnetic processes such as scattering and Bremsstrahlung and the optical processes of Cherenkov radiation, absorption, and Rayleigh scattering, in order to reduce runtimes. Additional processes, such as scintillation of Argon and transition radiation, could contribute to the overall signal; however, due to the non-directional nature of these processes, they are unlikely to contribute a significant background and are not included in the current simulation.

The simulation allows flexibility in the chamber pressure, muon beam, and detector orientation with respect to the muon beam. The variable index of refraction of the chamber is modeled using the formula

$$n(P) = 1 + \frac{P'}{P_{\text{STP}}}(n_{\text{STP}} - 1)$$
 (2.1)



Figure 2.6: GEANT4 simulation geometry consisting of two steel tubes (white), a gas-filled chamber (brown), and a thin mirror (white). Also shown in this diagram is a single simulated muon (blue) and the produced Cherenkov light (green). The scintillating bars (shown in purple) are only used as a reference.



Figure 2.7: From [4]. (Left) The cosmic ray spectrum at sea-level. (Right) The characteristic cosmic muon angular distribution for various energies.

found in [28], where P is the chamber pressure, P_{STP} is 100 kPa, and n_{STP} is the STP refractive index of the gas. The muon beam energy and angular distributions were developed as a composite of the cosmic muon spectrum that are described in [4, 8]. Figure 2.7 shows the muon spectra that are reviewed in [4]. The combined muon spectrum approximation is characterized by a flat energy spectrum for low muon energies, a -2.7 power law for large muon energies, and a mean muon energy of 4 GeV. The probability density function of this is a piecewise

$$f(E;\mu) = \begin{cases} (0.764553)\mu^{-1}, & m_{\mu}c^{2} < E < (0.823529)\mu \\ (0.452627)\mu^{1.7}E^{-2.7}, & (0.823529)\mu \le E \end{cases}$$
(2.2)

where μ is the mean muon energy of 4 GeV and m_{μ} is the muon mass. This form is a crude, but useful means of simulating expected photon yields for the detector. In order to generate the spatial distribution of muons, the simulation mimics a scintillator trigger method as is described in Section 2.4.1. In order to simulate this triggering method, a muon momentum vector is randomly generated according to the muon energy and angular distribution mentioned above in a square region 1 cm above the detector. This muon is then extrapolated to the z-location of the bottom of the detector. If this muon enters a square region the size of the lower scintillator, the simulation



Figure 2.8: (Left) The approximation of the cosmic muon momentum that was generated. (Right) The \cos^2 angular distribution generated with the scintillator-trigger generation method.

declares this a hit and runs this event using this muon momentum and spatial location; otherwise, the simulation continues to generate new muons until a hit is found. Figure 2.8 shows the simulated muon momentum (left) and angular (right) distributions.

Using this simulation, some of the expected characteristics of the detector performance can be determined. Figure 2.9 shows both the angular acceptance (right) and the expected photon yield per muon event (left). This simulation suggests that with the optics chamber, this prototype detector has an angular acceptance of < 120 mrad. In addition, the triggering method reduces the available muon angles to < 250 mrad. The simulation produces Cherenkov light that reaches the photodetector in approx. 7% of simulated muons without the optics chamber. This rate is significantly reduced by the optics chamber to approx. 3.5% of simulated muons.



Figure 2.9: (Left) Simulation results for the expected number of photons reaching the photodetector without the optics chamber. Approx. 7% of cosmic muons produce light that reaches the photodetector. (Right) The simulated angular photon yield for the cosmic prototype. The 60-cm optics chamber reduces the angular acceptance to < 120 mrad.

Table 2.1: Results from the cosmic muon testing. The percentages below come from the cosmic detector without the optics chamber due to low signal while using the optics chamber.

| | (i 00 00 i |
|---------------------|--|
| Dark rate sample | $1.9 \pm 0.2 (\text{stat.}) \pm 1.2 (\text{sys.})\%$ |
| $< 0.017 { m atm}$ | $2.4 \pm 0.2 (\text{stat.}) \pm 1.2 (\text{sys.})\%$ |
| 0.843 ± 0.017 atm | $4.9 \pm 0.4 (\text{stat.}) \pm 1.2 (\text{sys.})\%$ |
| | |

Chamber pressure (atm) | Rate (percent of triggers flagged as potential Cherenkov events)

2.4.3 Results

Using the data collection system described in Section 2.4.1, data were collected using Argon at 0.843 atm and < 0.017 atm. Additionally, a dark rate sample was taken by blocking the photomultiplier face using black paper. A summary of the results from these tests can be found in Table 2.1. We observe a statistically significant 2.5% excess of flagged events at 0.843 atm compared to < 0.017 atm, suggesting a pressure dependent signal. Additional charged cosmic rays (in the form of electrons and nucleons) contribute a background flux of approx. 1 and 10%, resp. However, due to the considerable energy required for a proton to produce Cherenkov light and the short range of electrons in steel, these backgrounds are unlikely to contribute to the observed signal by more than 0.1% of triggers. The proton background could inflate the number of triggers by up to 5%, which would change the observed rate by only -0.2% and would not affect the excess in flagged events.

Due the low trigger rate and low efficiency of the detector, the exposure time required to create a statistically significant dataset is on the order of 1–2 days. This long exposure time limits the feasibility of using this prototype detector to measure the cosmic spectrum. Photon collection inefficiency is inherent in the detector design, and thus single muon events do not produce enough light to characterize this detector. A more intense muon source, such as a muon test beam or a running neutrino beam, will confirm directionality in the detector response and act as a confirmation of Cherenkov light.

Chapter 3

The NuMI Beam

Fermilab's NuMI (Neutrinos at the Main Injector) beam facility provides a neutrino beam for a number of neutrino oscillation experiments. This beam also provides an intense neutrino beam to test new technologies for particle detection. In particular, the secondary muon beam offers a muon beam comparable to the future LBNF beam. For this reason, a prototype gas Cherenkov detector has been installed in this muon beam and has been operating for the past year and a half.

This chapter gives an overview of the NuMI beam line, including a brief description of the accelerator, target, and decay chain in Section 3.1. This section also describes the data acquisition from the prototype detector. Section 3.2 discusses the efforts to simulate the NuMI muon beam. In Section 3.3, data from the past year and a half is examined to determine the detector's performance and stability. Finally, Section 3.4 explains the current muon flux extraction techniques and presents results from a toy Monte Carlo simulation of a realistic muon distribution.

3.1 Overview

The Neutrinos at the Main Injector (NuMI) neutrino beam at Fermilab has and continues to provide neutrinos for a number of high-energy neutrino experiments, including MINOS+, MINER ν A, and NO ν A, since its construction in 2005 [29]. NuMI uses Fermilab's Booster and Main Injector (MI) to produce an intense neutrino beam from a fixed target. The beam monitoring instrumentation provides information about the beam's condition on a spill-by-spill basis. The current instrumentation can be used to test and calibrate prototype detectors, which could eventually



Figure 3.1: From [5]. Overview of the NuMI accelerator chain at Fermilab.

contribute to beam analysis and monitoring.

Figure 3.1 gives an overview of the NuMI beam at Fermilab. The MI extracts protons from Fermilab's Booster facility where they are accelerated from 8 GeV to 120 GeV. The MI has the capability to accelerate protons to 150 GeV, however 120 GeV is optimal for neutrino production [5]. Two toroidal beam monitors are used to determine the number of protons on target (POT). These are calibrated using a high-precision current source to an accuracy of 0.5%. The beam is accelerated in 1.6 μ sec batches with 53 MHz bunch spacing [5]. A method called "slip-stacking" is used to increase the beam intensity by doubling the protons in two of the batches. The beam is then extracted from the MI and focused into a 1-mm beam spot on the graphite NuMI target [30]. The beam is directed 3° downward into the Earth towards the MINOS Far Detector in the Soudan mine.

The resulting particles (mostly pions and kaons) pass through two magnetic horns, which are used to focus and sign-select the produced hadrons. These hadrons are allowed to decay in



Figure 3.2: From [5]. Diagrammatic top-view of the area downstream of the decay pipe, showing the hadron monitor, absorber, and the muon alcoves.

a 675-m (length) by 1-m (radius) steel decay pipe. Since a large portion of the beam consists of pions and kaons, the $\pi \to \nu_{\mu} + \mu$ and $K \to \nu_{\mu} + \mu$ decays dominate the resulting neutrino beam; however, other decays contribute a small ν_e background [30]. Depending on the charge of hadrons that are selected, the beam can be run in either ν_{μ} - or $\bar{\nu}_{\mu}$ -mode. An aluminum-core steel absorber is located at the end of the decay pipe to absorb the remaining *p*-beam power and un-decayed hadrons. Just before the absorber is a gas-ionization chamber array hadron monitor, which is used to monitor the beam spot and target integrity [5]. Finally, the absorber is surrounded by large concrete blocks to absorb low-energy neutrons. At this point, the neutrino beam consists almost entirely of neutrinos and muons.

After the absorber, three muon monitoring alcoves are positioned along the beam line, shown in Figure 3.2. Each of these alcoves house a gas-ionization muon monitor which are used to monitor the two dimensional profile and intensity of the beam. The increasing mass of concrete and rock between the monitors and absorber enable the monitors to observe different energies of the remaining muon beam. Testing that was performed on these monitors shows a linear response to the muon flux up to at least 2.5×10^{13} POT [5].

Installed in muon alcove 2 is a full-size gas Cherenkov detector prototype, the design of which is described in Section 2.3. This detector is installed on a platform that places the face of the



Figure 3.3: Prototype gas Cherenkov detector installed in muon alcove 2 of the NuMI beam shown with actuator settings and angles.



G. Mills, LANL

Figure 3.4: Photograph of the prototype gas Cherenkov detector installed in muon alcove 2 taken from the entrance of alcove 2. The gas ionization muon monitors can be seen in the upper right. Picture taken by Geoffrey Mills of LANL.

radiating chamber at the beam center and is equipped with two linear actuators that enable the detector to be rotated, see Figure 3.3. A gas and DAQ system have been installed in the alcove that allow remote control of the waveform acquisition, actuator settings, PMT voltage, and chamber pressure. Figure 3.4 shows the installed Cherenkov detector in muon alcove 2.

3.2 Simulating the NuMI Beam

Simulations of the NuMI beam provide a means of determining detector parameters, optimizing beam designs, and determining the expected neutrino flux. For this thesis, simulations of the NuMI beam will provide an approximate muon distribution in each of the NuMI alcoves. This will then be used as a proof of concept for the extraction of a muon flux described in Section 3.4.



Figure 3.5: The initial muon energies of muons reaching alcoves 1 (upper-right), 2 (lower-left), and 3 (lower-right) separated by muon parent as simulated by g4numi. The upper-left plot shows the original muon energy at the decay point.

The standard NuMI beam simulation uses FLUGG, which combines the particle simulation of FLUKA (well known for its physics accuracy [31]) and the geometry of GEANT4. The beam geometry has been changed and optimized during NuMI's operation in order to compliment the physics programs of the experiments using the neutrino beam. Currently, the beam design (and corresponding simulation geometry) is known as the medium energy NO ν A configuration. This configuration involves the adjustment of second horn's position and the use of the NOvA target; however, no downstream adjustments have been made [5]. For this thesis, 100 previously generated neutrino flux files using this configuration and a horn current of 0 kA are used to approximate the horn-off neutrino beam, totaling to 5×10^7 simulated POT.

The flux files generated contain kinematic and parent particle information for each simulated neutrino. To simulate the secondary muon beam, the muon distribution has to be extracted from these neutrino flux files. The kinematic information of the neutrino and its parent are combined



Figure 3.6: The spatial distribution of the muon beam flux at alcove 1 (top-right), 2 (lower-left), and 3 (lower-right) as simulated by g4numi.

in the 2-body case to recreate the muon kinematics. This new muon list can be re-simulated in the GEANT4 simulation (g4numi) and tracked to the muon alcoves. Figure 3.5 shows the initial muon energies of muons that reach alcove 1, 2, and 3. Unlike previous simulations of the muon flux [32, 33], the active area of the alcove is expanded to 100% of the 4.84 m² muon alcove area. The spatial muon flux is shown in Figure 3.6.

In order to speed up further Monte Carlo simulations of the detector response, a fit to the muon distribution can be made. To produce a fit of the muon distribution, shown in Figure 3.7, the angular distribution is assumed to be of the form

$$f(\theta, E) = A(E)\theta e^{-(\theta/\sigma(E))^n},$$
(3.1)



Figure 3.7: The muon E v. θ distribution in alcove 2 as simulated by g4numi.



Figure 3.8: Example fit for the 2 GeV to 2.5 GeV energy slice of the E v. θ muon distribution in alcove 2. The fitting parameters here correspond to those in eq. 3.1 where p0 $\rightarrow A$ and p1 $\rightarrow \sigma$.



Figure 3.9: Comparison of the Monte Carlo muon distribution and fits to the Monte Carlo muon distribution with various values of n. See equation 3.1 for the functional form.

where both A and σ are functions of the muon energy E. An example of the fit is shown in Figure 3.8. The E v. θ distribution is then sliced into cross-sections of 0.5 GeV. Figure 3.10 shows the best-fit parameters as a function of the muon energy. As shown, the parameters are fit to the forms

$$A(E) = A_A E e^{-\sqrt{E/\sigma_A}}$$
(3.2)

and

$$\sigma(E) = \sqrt{\frac{A_{\sigma}}{1 + E/m_{\mu}}}.$$
(3.3)

The parameter n in equation 3.1 was determined by comparing the g4numi Monte Carlo distribution to a large random sample from n = 1/2, 1, 2, shown in Figure 3.9. Overall, n = 1 provided the best approximation to the simulated distribution. The final results of the fit is summarized in table 3.1.

| Function | Best fit values | χ^2/ndf |
|-------------|---|-----------------------|
| A(E) | $A_A = 8.4 \pm 0.5 \times 10^4 \; (\text{GeV mrad})^{-1}$ | 56.3/76 |
| | $\sigma_A = 2.84 \pm 0.15 \mathrm{GeV}$ | |
| $\sigma(E)$ | $A_{\sigma} = 6.77 \pm 0.12 \times 10^3 \text{ mrad}^2$ | 157.9/77 |
| | | |

Table 3.1: Fit results of the muon distribution in alcove 2 with no horn current, using the fitting method described in Section 3.2.



Figure 3.10: Final muon fit for angular muon fit parameters. Left, the parameter A(E) fit to the form in equation 3.2 where $p0 \rightarrow A_E$ and $p2 \rightarrow \sigma_E$; center, the parameter $\sigma(E)$ fit to equation 3.3 where $p0 \rightarrow A_{\sigma}$; and right, the muon spectrum in alcove 2.



Figure 3.11: The integrated gas Cherenkov signal normalized by the alcove 2 muon monitor at various pressures and horn currents. This data set was collected in March 2014.

3.3 Detector performance

The prototype gas Cherenkov detector installed in alcove 2 has been exposed to the beam for more than two and a half years while the data acquisition (DAQ) system was set up. This DAQ system provided a limited data set during horn current scans in March 2014 and, recently, has been storing waveforms every few seconds since January 2015. From January to July, the horn currents were nominally stable at 200 kA. In July, the main strip-line of the horn failed and the beam was run for about a month with no horns. During this time, a gas Cherenkov pressure and detector angle scan was performed. The combined data provides a window into the *in-situ* detector performance in a variety of beam conditions. This section will summarize some of the data coming from this prototype detector during the horn current scans from March 2014, the time stability since January 2015, and the results from the pressure and angle scans in July.

Figure 3.11 plots the horn current against the normalized gas Cherenkov signal, taken during the horn current scan in March 2014. Here, the Cherenkov signal relative to the muon monitor



Figure 3.12: Correlation between the integrated gas Cherenkov signal (GC) and POT for two different pressure settings. Also shown is the gas ionization muon monitor signal, for comparison.

signal increases for decreasing horn current. As the horn current decreases, less low-energy hadrons are focused into the decay pipe. The reduction in the number of low-energy hadrons produces a muon beam that is of a higher energy, smaller divergence, and smaller total flux. Combined, these result in an increased gas Cherenkov to muon monitor signal ratio for lower horn currents. Figure 3.12 shows the linearity of the Cherenkov signal against POT, from March 2014. Within the 5–6% variation in POT shown in these plots, the detector response is linear within approx. 1%. The gas ionization response is also shown, for reference.

Figure 3.13 shows the relative stability of the Cherenkov signal during the stable operating conditions from March 25 to April 18, 2015. Shown is the total variance of the normalized and adjusted Cherenkov signal. During this time period, the detector signal showed an approx. %1/day signal loss, potentially due to contamination of the argon gas from an imperfect chamber seal. The signal reduction is currently being studied to determine a cause. However after adjusting for this signal loss, the Cherenkov signal is gaussian distributed with $\chi^2/ndf = 112.7/111$ and with a stability of $\sigma = 0.01\%$.

A yaw and pressure scan performed in July 2014 while the horns were not operating, shown in Figure 3.14, shows a distinctive Cherenkov-like signal. The results of this scan show a characteristic angle of peak response that increases as the chamber pressure increases. Additionally, the response increases with pressure due to the increased photon production in a higher refractive index and



Figure 3.13: The normalized Cherenkov stability accounting for signal loss and POT. Also shown is a gaussian fit to these data.



Figure 3.14: The results from a scan across detector yaw and detector pressure. A strong, Cherenkov-like signal is apparent.

the decreased Cherenkov threshold. At higher pressures, the detector effectively observes a larger fraction of the muons in the alcove. The pressure-dependence of the detector response suggests that the dominant signal comes from Cherenkov light produced by the beam.

3.4 Extracting the muon flux

From the pressure and angular scans (Figure 3.14), the integrated Cherenkov detector signal is a measurement of the total yield of photons Y from a collection of muons at a particular pressure P and detector angle Θ . In order to extract information on the beam distribution, the total photon yield is approximated as

$$Y(P,\Theta) = \int_0^\infty \int_0^\pi \bar{y}(E,\theta;P,\Theta) \left(\frac{d^2N}{d\theta dE}\right)_\mu d\theta dE, \qquad (3.4)$$

where \bar{y} is the average number of photons detected per muon with energy and angle (E, θ) at a chamber pressure and angle (P, Θ) and $(d^2N/d\theta dE)_{\mu}$ is the muon distribution. Practically, this form can be expressed as

$$Y(P,\Theta) \approx \sum_{i,j} \bar{y}(P,\Theta)_{ij} N_{\mu,ij}, \qquad (3.5)$$

where the muon energies and angles are binned and indexed via i and j, respectively.

For example, a single muon that passes through the detector with energy and angle (E, θ) can be placed in a bin (α, β) where $E_{\alpha} < E < E_{\alpha+1}$ and $\theta_{\beta} < \theta < \theta_{\beta+1}$. In this case, the muon distribution is $N_{\mu,ij} = \delta_{i\alpha}\delta_{j\beta}$ and equation 3.5 simplifies to $Y(P, \Theta) \approx \bar{y}(P, \Theta)_{\alpha,\beta}$, which is (on average) true.

3.4.1 Simulating Cherenkov response

The average photon yield of a detector pressure and angle can be determined with a test beam which provides a well characterized muon beam. However, installing a detector in a test beam and paying for exposure time can be slow and expensive and is beyond the scope of this thesis, so simulations are used to approximate these values. The simulation discussed in Section 2.4.2 was updated for this purpose.

The original gas Cherenkov simulation used the small prototype geometry, but in order to simulate the realistic response of the full size detector, this geometry was changed to include the 5-m optics chamber and the cosmic-trigger-based muon generation was removed. Two muon simulation methods were developed for simulating the full detector: the first being a uniform distribution and the second being the direct simulation of a list of muons. The direct simulation method was not used for this thesis due to the inefficiency of the muons generated. The uniform distribution produces muons uniformly across a 15-cm circle before the detector face. The 707-cm² area allows for approx. 10° of detector rotation before introducing errors due to the finite area of generation.

To simulate the average photon yield, a uniform distribution of muons of kinetic energy E between 0 GeV and 20 GeV with θ between 0 mrad and 100 mrad is tracked though the detector. The muons are generated uniformly in ϕ ; see Figure 3.15 for a basic diagram defining these parameters. A total of 4.2×10^8 muons were simulated across 20 gas pressures (0.5 atm, 1 atm, ..., 10 atm)



Figure 3.15: Diagram of muon variables. The θ and ϕ variables are the azimuthal and latitudinal angles of the muon momentum, respectively.

and 21 detector angles $(-5^{\circ}, -4.5^{\circ}, ..., 5^{\circ})$. Binning the results from these simulations into equal divisions of 2 GeV and 10 mrad in E, θ space, this amounts to an average of 9.1×10^3 simulated muons per bin per detector pressure and angle. The expected number of photons that reach the photodetector per simulated muon is much less than 1 for all detector pressures and angles, so the number of photons per bin used to calculate the average photon yield is substantially less than the number of simulated muons. On average, the number of photons that reach the photodetector per bin is on the order of 200, which is the current limiting factor in the precision of the simulation.

In order to test the reliability of the extraction method described in Section 3.4, the muon distribution generated in Section 3.2 is used to produce an expected Cherenkov yield for the pressures and angles simulated above. The resulting yield is shown in Figure 3.16 for 10⁴ muons per pressure and angle. The photon yield as a function of the detector pressure and angle qualitatively agrees well with the data from the NuMI prototype pressure and angle scans performed in July. Notably, the same characteristic Cherenkov angle is present, along with an increasing peak signal with respect to pressure.

3.4.2 Fitting Cherenkov yield to muon E v. θ distribution

The Monte Carlo data produced in Section 3.4.1 can be used with equation 3.5 to perform a χ^2 -fit for the total photon yield based on the muon distribution and the simulated average photon



Figure 3.16: Monte Carlo simulation of the Cherenkov yield at various detector pressures and angles using a realistic muon distribution (described in Section 3.2). Each point represents 10^4 simulated muons.

yields. ROOT's [34] built-in MINUIT fitting package [35] is used to perform the minimization.

The GEANT4 simulation of the detector response produces an *n*-tuple with each row containing information about a single generated muon. The contained information includes the initial position and momentum of the muon, the number of photons generated, and the number of photons that reach the photodetector. Additionally, the simulation stores the wavelength, initial and final positions, and time delay of each photon that reaches the photodetector. This is more than enough information to calculate the realistic yield and theoretical average yield for a detector configuration.

The yield Y is calculated as

$$Y(P,\Theta) = \frac{N_{\gamma}}{N_{\mu}} \bigg|_{P,\Theta}, \qquad (3.6)$$

where N_{γ} is the total number of photons that reach the detector and N_{μ} normalizes by the number of simulated muons at P, Θ . The normalization removes the dependence of the yield on the number of simulated muons. The average yield \bar{y} is calculated as

$$\bar{y}(P,\Theta)_{ij} = \frac{n_{\gamma,ij}}{n_{\mu,ij}}\Big|_{P,\Theta},\tag{3.7}$$

where i, j corresponds to the muon energy and angle bin as described in Section 3.4.1, $n_{\gamma,ij}$ is the total number of photons that reach the detector from bin i, j and $n_{\mu,ij}$ normalizes by the number of simulated muons in bin i, j at P, Θ .

The form of equation 3.5 is then used to fit for the underlying muon distribution $N_{\mu,ij}$, assuming a distribution described by equation 3.1, based on the observed photon yield. The combined statistical Monte Carlo errors (from the simulated total yield Y and the simulated average yields \bar{y}) used for the calculation of the χ^2 can be found to be

$$\sigma(P,\Theta) = Y(P,\Theta) \times \left(\frac{1}{\sqrt{N_{\gamma}}} + \frac{1}{\sqrt{n_{\gamma}}} + \frac{1}{\sqrt{n_{\mu}}} \right) \Big|_{P,\Theta},$$
(3.8)

where n_{γ} is the total number of photons detected from the uniform muon distribution at P, Θ and n_{μ} is the total number of uniform muons generated at P, Θ . The χ^2 best fit method is not accurate if the values are not gaussian distributed, so simulated pressures and angles where $N_{\gamma} < 100$ are removed from the fit.

| | Parameter | Best fit value | Original value |
|---|--------------|--|---|
| | A_A | $13.6 \pm 1.6 \; (\text{GeV mrad})^{-1}$ | $8.4 \times 10^4 \; (\text{GeV mrad})^{-1}$ |
| - | σ_A | $5.2 \pm 0.7 \text{ GeV}$ | 2.84 GeV |
| | A_{σ} | $6.72 \pm 0.18 \times 10^3 \text{ mrad}^2$ | $6.77 \times 10^3 \mathrm{\ mrad}^2$ |
| | | | |

Table 3.2: Photon yield fit results from the fake Monte Carlo data-set.

| $\chi^2/\mathrm{ndf} = 465.875/263$ | | | | | | |
|---|-----------------------------|---|--|---|---|---|
| Covariance matrix Correlation matrix | | | | | | |
| $ \begin{array}{c} 2.4177 \\ -1.0955 \\ -267.61 \end{array} $ | -1.0955 0.5051 115.92 | $\begin{array}{c} -267.61 \\ 115.92 \\ 33858 \end{array} \right)$ | | $ \left(\begin{array}{c} 1\\ -0.99138\\ -0.93534 \end{array}\right) $ | $ \begin{array}{r} -0.99138 \\ 1 \\ 0.88642 \end{array} $ | $\begin{array}{c} -0.93534 \\ 0.88642 \\ 1 \end{array} \right)$ |

Table 3.2 summarizes the results from this fit. The fit parameter A_A in this fit differs by a normalization factor from the A_A used in Section 3.2. The factor includes the detector efficiency, number of simulated muons, and muon generation area and would be needed if the detector was expected to make a measurement of the absolute muon flux. Since the detector will likely only be used for a relative muon flux measurement, this factor was not calculated for this data. The σ_A fit parameter disagrees with the original value by more than 3σ , however this large disagreement is not reflected in the comparison of the fake muon distribution and the reconstructed distribution, given in Figure 3.18. This disagreement in value that is not apparent in the muon distribution might arise through the strong correlation between the fit parameters. The final parameter, A_{σ} determines the divergence of the muon distribution. The extraction method was able accurately fit to this value to within 3%. In the comparison of muon distributions, the reconstructed muon distribution agrees with the original distribution to within 20% for all bins above 2 GeV. Below this, $n_{\gamma} < 100$ and so the χ^2 -fit should not be used in this region.



Figure 3.17: (Left) The realistic Monte Carlo muon distribution used to generate a fake dataset. (Right) The reconstructed muon distribution based on the fit described in Section 3.4.2.



Figure 3.18: Ratio of the rebuilt muon distribution to the original muon distribution. The muon distribution agrees within approx. 20% in all bins.

Chapter 4

Conclusion and Future Work

This thesis has presented the research that has been done to develop a gas Cherenkov muon monitor for the future DUNE. This has involved developing simulations of various muon sources and the detector response along with prototype work done in Boulder, Colorado and in the NuMI beam at Fermilab. In this work, the Cherenkov signal in the prototype detectors was confirmed and a plan for extracting a muon flux from the Cherenkov signal has been shown to be viable.

The cosmic muon prototype detector that was built and tested in Boulder was able to demonstrate a pressure-dependent signal from cosmic muons; however, due to inherent inefficiencies in the detector design, creating a substantial dataset proved to be difficult. That said, continued work using the detector without an optics chamber and at varying azimuthal angles could provide a second confirmation of the directional nature of the detector signal. Additionally, this prototype could be useful in determining the detector response to background radiation, such as fast-electrons, by exposure to well-known radioactive sources. The mobility of this detector also would enable it to be quickly installed in a muon test beam to verify Monte Carlo simulations of the average photon yield.

The work done to simulate and characterize the muon flux of the NuMI beam will likely prove useful in the prototype testing of the other muon monitors for DUNE and could be used by other NuMI-based experiments. This simulation work is just a beginning, however — simulations of the muon flux with a horn current will be required for future testing of this prototype detector. Additionally, the functional forms of equation 3.1, 3.2, and 3.3 that were used to fit the Monte Carlo data could be improved. While the described fits produce a similar distribution for Monte Carlo simulations of the Cherenkov detector, in order to expect an accurate result from the fit described in Section 3.4 to real data, the functional form should be grounded in a theory of muon scattering, such as in [36].

Finally, the extraction method outlined in this thesis was able to reconstruct a fake muon distribution to within 20% of the original distribution; however for DUNE, the detector should be able to rebuild the distribution to within 5%. This may be achievable with the current extraction method by using a larger Monte Carlo data-set to predict the average photon yield of muons. Additionally, the current fixed-width binning of the simulation limits the resolution of the reconstructed muon distribution. Based on Monte Carlo simulations, the binning could be redistributed to better reflect the alcove muon distribution and reduce the inaccuracy due to binning errors. The extraction method has also yet to be applied to a real dataset. The prototype Cherenkov detector installed in NuMI has provided data that will be used to test this method in a real muon beam.

Ultimately, the goal of the muon flux measurements performed by this detector is to constrain the neutrino flux of a neutrino beam. While the promising results of this thesis suggest that a muon flux can be measured with this detector, continued work is needed to improve on the methods described in this thesis and to relate measurements of the muon flux to the neutrino beam.

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