Determination of the LBNF Neutrino Flux

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Mary Bishai (on behalf of LBNF/DUNE)  
Brookhaven National Lab

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Overview of the LBNF Beamline

- Primary proton beam 60-120 GeV
- Initial 1.2 MW beam power, upgradable to 2.4 MW
- Embankement allows target complex to be at grade
- Wide-band beam (on-axis) based on NuMI design with tunable energy spectrum.
- Decay pipe: 194m x 4m diameter, He filled

ND default: 574 m from target, FD: 1300 km
The LBNF Reference Design (up to 2015)

Initial conceptual design was of a *tunable wide-band* NuMI-style focusing:

- Decay Pipe: 194 m long, 4 m in diameter, double-wall carbon steel, helium filled, air-cooled.
- Target Chase: 2.2 m/2.0 m air-filled and air & water-cooled.

LBNF has switched to CPV optimized focusing design with 3 horns.
The 2015 CD1R reference design for LBNF/DUNE is a NuMI-like movable target (segmented rectangular graphite fins with water cooling \( \approx 1 \text{m long} \)) and 2 modified NuMI horns 6.6m apart.

In Sep 2017 LBNF adopted a focusing design with 3 horns optimized using a genetic algorithm with the physics parameter to be measured (CPV sensitivity) used to gauge fitness.

Target geometry is optimized at the same time, as well as proton beam energy with realistic Main Injector power profile (1.03 MW at 60 GeV to 1.2 MW at 120 GeV).

Limits on horn current, diameter and length are imposed based on experience with T2K and NuMI horn manufacturing.

Limits on horn separation imposed based on size of target chase.
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#### The LBNF Beamline

**Flux Modeling and Uncertainties**

**Near Detector(s)**

**Muon Monitors**

**Summary**

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**Optimization of flux for Physics: CP Violation**  
Laura Fields

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**Optimized horn design with 297kA current:**

![Optimized horn design](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horn A Length (mm)</td>
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<td>Horn A F1 (% of length)</td>
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<td>Horn A R1 (mm)</td>
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<td>Horn B Position (mm)</td>
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<td>Horn C OC Radius (mm)</td>
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<td></td>
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<td>Horn C Position (mm)</td>
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</table>

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**Optimized target is 4λ (2m C) with \( \sigma_{beam} = 2.7\,\text{mm} \), \( E_p \sim 110\,\text{GeV} \)**
Optimization of flux for Physics: CP Violation

Laura Fields

Computationally advanced optimization techniques = significant gain in flux and CPV sensitivity from many small changes

Gain in sensitivity ≡ 70% increase in FD mass
Tunability of Beam with 2015 NuMI-like Design

NuMI-like reference design could be tuned to higher energy to observe $\nu_\mu \rightarrow \nu_\tau$ with high statistics.

2015 two horn optimized design $E_p = 66$ GeV:

- **$\nu_\mu \rightarrow \nu_e$** Appearance at 1300 km
- **$\nu_\mu \rightarrow \nu_\tau$** Appearance at 1300 km

$\nu_\mu \rightarrow \nu_e$ 290 events $\quad \nu_\mu \rightarrow \nu_\tau$ 60 events

in 40 ktons, 1 year at 1.2 MW
NuMI-like reference design could be tuned to higher energy to observe $\nu_\mu \rightarrow \nu_\tau$ with high statistics.

LBNF target -2m from horn 1, NuMI focusing 230 kA, horns 17m apart

$\nu_\mu \rightarrow \nu_e$ Appearance at 1300 km

$\nu_\mu \rightarrow \nu_\tau$ Appearance at 1300 km

$\nu_\mu \rightarrow \nu_e$ 330 events
in 40 ktons, 1 year at 1.2 MW

Increase $\nu_\tau$ appearance 10x!!!

Increase high energy $\nu_e$ appearance - good for NSI/Sterile searches
Flux components at near and far

Baseline scaled to 1km from middle of decay channel
Flux components at near and far

Baseline scaled to 1km from middle of decay channel
PPFX Package

- PPFX is a package that was developed to correct the MINERvA flux simulation to ‘match’ external hadron production data, e.g. NA49:
- How the external data constraint works in practice:
  - Complete information about cascades leading to a neutrino is recorded for each proton on target and stored in the flux tuples
    - Including interaction materials and ancestor kinematics
  - In MINERvA analyses, neutrino events are weighted by:

\[
w_{HP} = \frac{f_{\text{Data}}(x_F, p_T, E)}{f_{\text{MC}}(x_F, p_T, E)} \quad f = E \frac{d^3\sigma}{dp^3}
\]

- Weights are applied for incident protons \(12 < E_p < 120\) GeV/c, scaled by Fluka and checked by comparing to NA61 pC @ 31 GeV [Phys. Rev. C84 (2011)034604]
- Weights for events with multiple interactions in the ancestor chain are the product of the weight for each interaction
PPFX Package

- **Uncertainties** on the external data constraints are propagated to uncertainties on our flux and other simulated distributions using a “Many-Universes” method:

- For each event, in addition to the central value weights we have discussed:

\[
    w = e^{-LP(\sigma_{\text{Data}} - \sigma_{\text{MC}})} \left( \prod_{\text{reweightable interactions}} \frac{f_{\text{Data}}(x_F, p_T, E)}{f_{\text{MC}}(x_F, p_T, E)} \right)
\]

We also store many (∼1000) weights constructed from data cross sections varied according to their uncertainties (taking into account correlations)

For interactions uncovered by data, large (40%) are assumed, correlated with neighboring bins

RMS of resulting weighted distributions gives uncertainty on those distributions
Flux Modeling Uncertainties

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Muon Monitors Summary

Hadron Prod. Uncertainties

NA49 dataset used to constrain
\( pC \rightarrow \pi^\pm, K^\pm, n(p)X \)

Pion production by neutrons from data (assuming isospin symmetry
Nucleon incident interactions not covered by data

Focusing Uncertainties

Detailed focusing uncertainties based on the NuMI experience in MiNER\( \nu \)A.
Used CPV optimized design with simplified 2 horns.
Need to use engineered 3 horn design
Near to Far Extrapolation

Simple ratio of far spectrum/near spectrum:

Neutrino parent decay location in decay pipe:

$$\pi/K$$ decay kinematics and decay channel geometry are primary reason for strange shape of F/N ratio
Near to Far Extrapolation

To correctly relate near to far fluxes - need to use a correlation matrix:

Flux correlation matrix comes from simulation and is highly correlated.
How well do we actually trust the simulation to correctly estimate the uncertainties on near → far extrapolation?
# Near Detector Flux Measurement Strategies

<table>
<thead>
<tr>
<th>Technique</th>
<th>Flavor</th>
<th>Absolute Normalization</th>
<th>Relative flux (\Phi(E_\mu))</th>
<th>Near Detector Requirements</th>
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<tr>
<td>NC Scattering</td>
<td>(\nu_\mu)</td>
<td>2.5%</td>
<td>(\sim 5%)</td>
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<td></td>
<td>(\nu_\mu e^- \rightarrow \nu_\mu e^-)</td>
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<td>(\theta_e) Resolution</td>
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<td>(e^-/e^+) Separation</td>
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<td>Inverse muon decay</td>
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<td>(\theta_\mu) Resolution</td>
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<td>2-Track ((\mu+X)) Resolution</td>
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<td>(\mu) energy scale</td>
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<td>CC QE</td>
<td>(\nu_\mu)</td>
<td>3 - 5%</td>
<td>5 - 10%</td>
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<td>(\nu_\mu n \rightarrow \mu^- p)</td>
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<td>(p) Angular resolution</td>
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<td>(Q^2 \rightarrow 0)</td>
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<td>(p) energy resolution</td>
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<td>CC QE</td>
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<td>10%</td>
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<td>(\bar{\nu}_\mu p \rightarrow \mu^+ n)</td>
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<td>Back-Subtraction</td>
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<td>(Q^2 \rightarrow 0)</td>
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<td>(\nu_\mu)</td>
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<td>(\mu^-) vs (\mu^+)</td>
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<td>(E_\mu)-Scale</td>
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<td>Low-(E_{H\text{ad}}) Resolution</td>
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<tr>
<td>Low-(\nu_0)</td>
<td>(\bar{\nu}_\mu)</td>
<td>2.0%</td>
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<td>(\mu^-) vs (\mu^+)</td>
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<td>(E_\mu)-Scale</td>
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<td>Low-(E_{H\text{ad}}) Resolution</td>
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<tr>
<td>Low-(\nu_0)</td>
<td>(\nu_e/\bar{\nu}_e)</td>
<td>1-3%</td>
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<td>(e^-/e^+) Separation ((K^0_L))</td>
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<td>CC</td>
<td>(\nu_e/\nu_\mu)</td>
<td>&lt;1%</td>
<td>(\sim 2%)</td>
<td>(e^-) ID &amp; (\mu^-) ID</td>
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<td>(p_e/p_{\mu}) Resolution</td>
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<tr>
<td>CC</td>
<td>(\bar{\nu}<em>e/\bar{\nu}</em>\mu)</td>
<td>&lt;1%</td>
<td>(\sim 2%)</td>
<td>(e^+) ID &amp; (\mu^+) ID</td>
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<td>(p_e/p_{\mu}) Resolution</td>
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<tr>
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<td>(\bar{\nu}<em>\mu/\nu</em>\mu)</td>
<td>(\sim 2%)</td>
<td>(\sim 2%)</td>
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<td>(p_{\mu}) Resolution</td>
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<td></td>
<td>(E_{H\text{ad}}) Resolution</td>
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</table>
An unmagentized LArTPC with a low density tracker embedded in a large magnet with EM sampling calorimeters surrounded by muon spectrometers.

Expect $2.5 \times 10^5$ neutrino interactions/ton Ar/1e20 POT at 574m.
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Summary

LArTPC concept

ArgonCube

Cryocooler
Top flange
WLS planes
FR4 module
Walls (5 mm)
Turbo-pump
Filters
Bottom flange
HVFT
Preamps board
Cathode
Resistive
Field-shaper
Pixels planes

DUNE ND modules: 1.0 x 1.0 x 2.0 m^3.
0.5 m drift length
Prototype modules 0.67 x 0.67 x 1.8 m^3.
0.33 m drift

Allows for high statistics measurements on Ar and ND/FD detector systematics constraints
Magnetized GArTPC for central tracker

HP GAr TPC

- Magnet (0.5T)
- LAr
- TPC_{hpg}
- EM Cal (20X_{0})
- Steel (4\lambda_{0})

LAr:
- with 2 x 2 m FV
- \sim 7 X_{0} annulus
- \sim 1.25 \lambda_{0} annulus

GArTPC allows for precision measurement of ν-Ar vertex activity
Improved beam flux measurements (for example using low-ν method and CC QE) on a lighter target and when combined with GArTPC allows for measurement of $\pi^0 \gamma\gamma$. 

**3DST**

- Default Design
- 1x1x1 cm³ scintillator cubes
- Possible “Staggered” Design
High intensity makes it difficult to measure $\mu$ spectrum accurately. With a 2.4 MW beam, the absorber thickness is too large to sample the lower energy muons. But these systems play an essential role in monitoring flux stability.
Correlation between neutrino and muon spectrum

ν Spectrum Changes

- Beam X Shift, 1 mm
  - Work in progress

- Horn A x Shift, 1 mm
  - Work in progress

- Target Density Reduction, 5%
  - Work in progress

- Horn A y Tilt, 2.5 mm
  - Work in progress
Correlation between neutrino and muon spectrum

\( \mu \) Spectrum Changes

- Ref. Abs. Horn A y Shift
- Work in progress
- Reduction in total flux
- Shape changes at max near 5 GeV

Changes are v. small - need novel detector concepts
Muon Monitor Technologies under R&D

- **Array of ionization detectors:** Measures muon beam center and intensity. Spill by spill monitoring of beam stability. Both diamond and silicon under study.

- **Threshold gas Cherenkov detector (R&D):** Uses signal intensity at different gas pressure and angles to extract rough muon spectrum.

- **Stopped muon counters (R&D):** separate stations with steel shielding in between could measure muon flux at several energies. Better measurement of beam flux spectrum and composition.

Currently only ionization detectors included in the beam design.
Ionization detector: Diamond Detector Prototype

Use polycrystal chemical vapor deposition (pCVD) diamond - detects ionizing radiation when a large voltage potential (1V per m of thickness) is applied across two sides of the diamond. Diamond is radiation hard.

pCVD detector prototype installed in NuMI during 2018 shutdown.
Stopped Muon Concept

Strategy

- Counting the decay electrons from muons stopping at the wall of $\mu$-pit
- Measuring spatial and time distributions of events

• Energy loss of muons in the beam dump
• Range of electrons in the concrete

We can measure muons of $5.2\sim7.0\text{GeV/c}$ by counting the decay electrons

From K. Hiraide, Muon monitor using the decay electrons, NBI2003 Workshop

Muon Monitors

Summary
Prototypes being commissioned with cosmics.
The next generation of long-baseline experiments requires determination of the flux at the 1-2% level.

LBNF is a wide-band beam with tunable capabilities ⇒ requires beam flux/spectrum measurements over a large range of energies.

Very high intensity beams (MW class) are needed ⇒ challenging near detector designs. Difficult to keep the same technology near and far. For LBNF/DUNE the near detector could be a gas tracker using an Ar target to match the liquid Argon TPC far detector.

Focusing uncertainties dominate the residual uncertainties in the near to far extrapolation at LBNF/DUNE ⇒ determination of the hadron production from the target is necessary but not sufficient for a-priori calculations of the neutrino flux. Do we need a spectrometer following the horns?

Measurements of the muon flux after the absorber is difficult but necessary to monitor the tertiary beam stability. R&D is ongoing on new technologies.