Determination of the LBNF Neutrino Flux

NuInt 2018, 15-19 October 2018, Gran Sasso Science Institute, Italy

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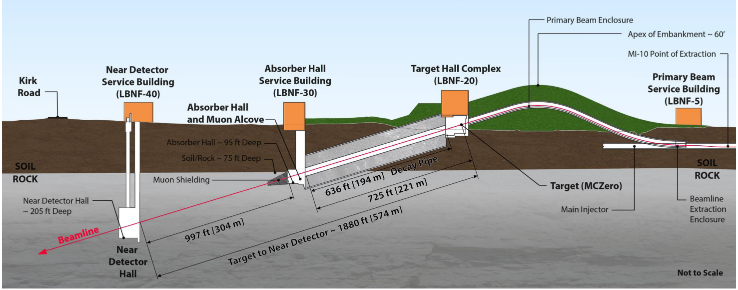
Brookhaven National Lab

Overview of the LBNF Beamline

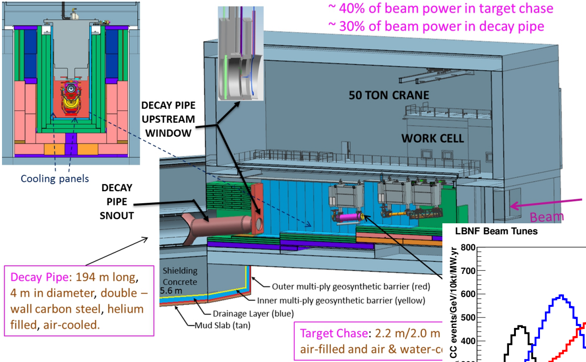


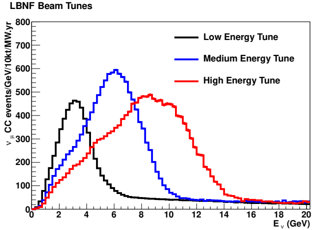
- Primary proton beam 60-120 GeV
- Initial 1.2 MW beam power, upgradable to 2.4 MW
- Embankement allows target complex to be at grade
- Wide-band configurable beam (on-axis) optimized for CP Violation sensitivity
- Decay pipe: 194m x 4m diameter, He filled

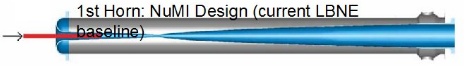
ND default: 574 m from target, FD: 1297 km

The LBNF Reference Design (up to 2015)

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

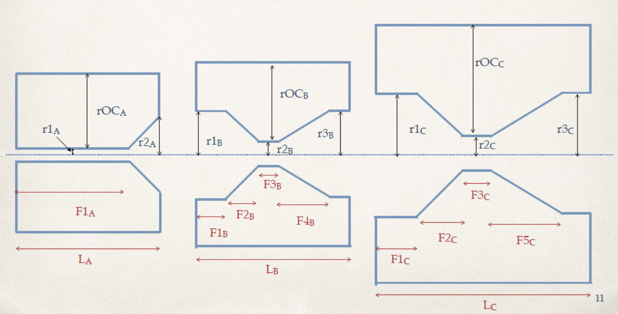






LBNF has switched to CPV optimized focusing design with 3 horns

- **In Sep 2017 LBNF adopted a focusing design with 3 horns optimized using a *genetic algorithim* 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).**



Optimization of flux for Physics: CP Violation

Laura Fields

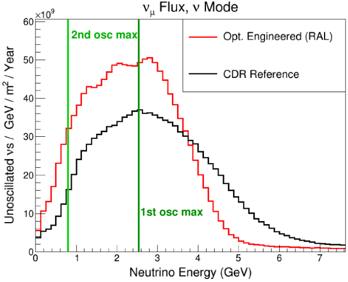
Optimized horn design with 297kA current :

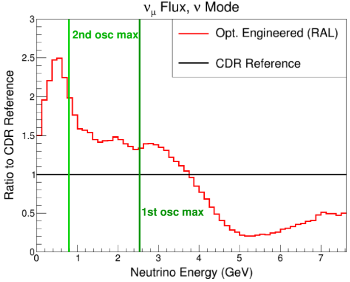
Parameter	Value		Parameter	Value
Horn A Length (mm)	2218		Horn A F1 (% of length)	53
Horn A R1 (mm)	43		Horn A OC Radius (mm)	369
Horn A R2 (mm)	33			
Horn B Length (mm)	3932		Horn C Length (mm)	2184
Horn B R1 (mm)	159		Horn C R1 (mm)	284
Horn B R2 (mm)	81		Horn C R2 (mm)	131
Horn B R3 (mm)	225		Horn C R3 (mm)	362
Horn B F1 (% of length)	31		Horn C F1 (% of length)	20
Horn B F2 (% of length)	22		Horn C F2 (% of length)	9
Horn B F3 (% of length)	2		Horn C F3 (% of length)	7
Horn B F4 (% of length)	16		Horn C F4 (% of length)	35
Horn B OC Radius (mm)	634		Horn C OC Radius (mm)	634
Horn B Position (mm)	2956		Horn C Position (mm)	17806

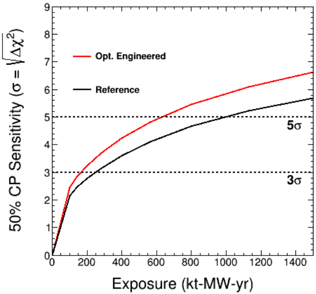
Optimized target is 4λ (2m C) with $\sigma_{\mathrm{beam}} = 2.7$mm, $E_p \sim 110$ GeV

Optimization of flux for Physics: CP Violation

Laura Fields







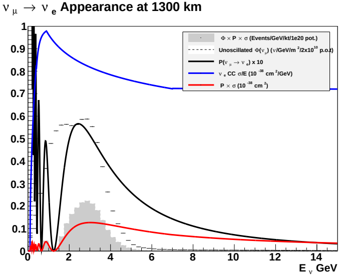
Computationally advanced optimization techniques = significant gain in flux and CPV sensitivity from *many* small changes

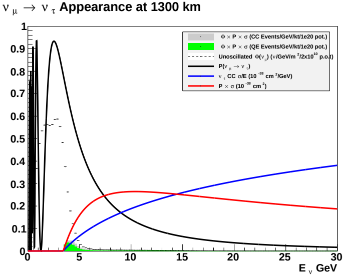
Gain in sensitivity ≡ 70% increase in FD mass for goal of ≥ 3σ CPV sensitivity over 75% of δ_{cp} values.

Tunability of Beam with 2015 NuMI-like Design

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

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



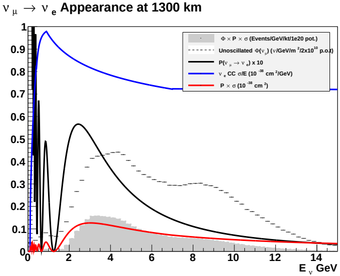


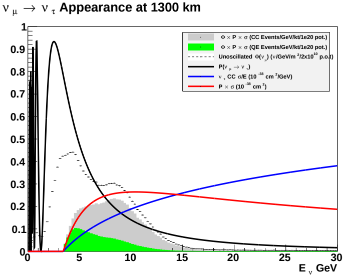
$\nu_\mu \to \nu_e$ 290 events **$\nu_\mu \to \nu_\tau$ 60 events**
in 40 ktons, 1 year at 1.2 MW

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.

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





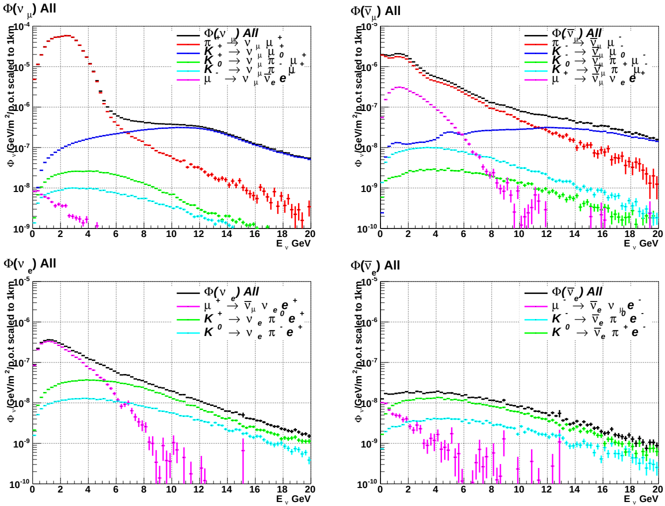
$\nu_\mu \rightarrow \nu_e$ 330 events **$\nu_\mu \rightarrow \nu_\tau$ 700 events**
in 40 ktons, 1 year at 1.2 MW

Increase ν_τ appearance 10x !! Potential for large ν_τ data set.

Increase high energy ν_e appearance - good for NSI/Sterile searches

Flux components at near and far

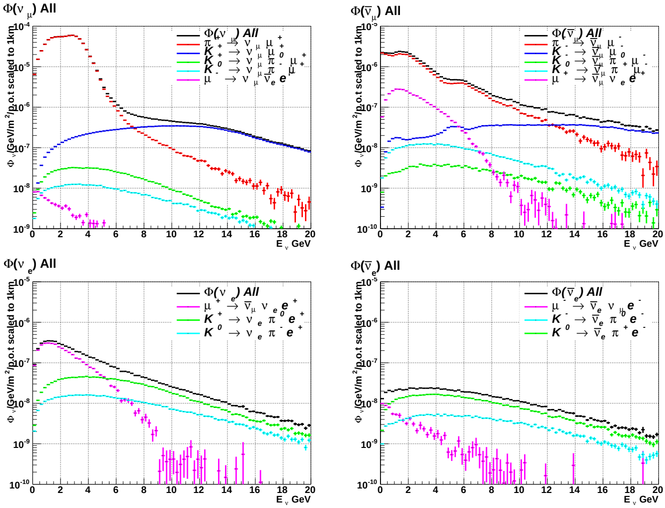
ND 570



Baseline scaled to 1km from middle of decay channel

Flux components at near and far

FD 1300km

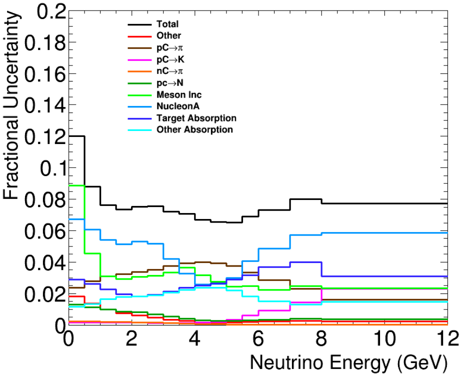


Baseline scaled to 1km from middle of decay channel

Flux Modeling Uncertainties at ND

The main sources of flux modeling uncertainties are:

- **Hadron production uncertainties:** **driven by uncertainities in the hadron interaction models used to estimate hadron distributions exiting the target (prior to focusing) as well as secondary and tertiary interactions of hadrons with beamline material. Fully evaluated for LBNF/DUNE using the ppfx package developed for MINERνA.**
- **Focusing uncertainties:** **Dominated by horn material, geometry and magentic field modeling as well as target geometry and density. Alignment of the neutrino beamline elements can also have large impact on ν flux. Includes proton counting uncertainities. These uncertainties are assessed by simulating individual effects in Geant 4 and combining.**
- **Other beamline uncertainties:** **Primarily uncertainties on the distribution of passive material in the beamline: for e.g. impact of Nitrogen in the target chase, decay pipe window thickness...etc. Experience with NuMI indicates these are subdominant**

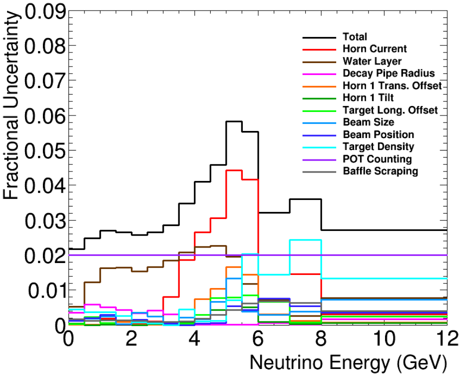


Hadron Prod. Uncertainties

NA49/MIPP/older datasets 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

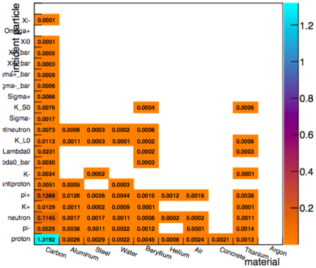


Focusing Uncertainties

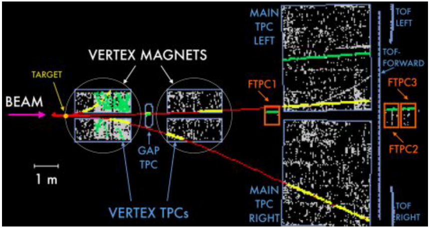
Detailed focusing uncertainties based on the NuMI experience in MINERνA. Detailed estimates for both 2015 NuMI-like design and CPV optimized design with simplified 2 horns.

Ongoing program with NA61/SHINE

DUNE collaborators active in the hadron production measurements at NA61



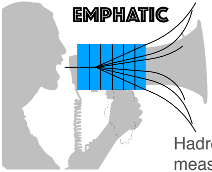
Beamline interactions per ν in ND



Event display from NA61

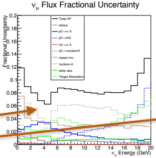
- **2016 dataset:** π^+ C/Be at 60 GeV, p$^+$ C,Be at 120 GeV, p$^+$ C,Al,Be at 60 GeV. Currently under analysis.
- **2017 dataset:** π^+ Al at 60 GeV,π^+ Al at 60 GeV,π^- C at 60 GeV, p$^+$ C,Be at 120 GeV, p$^+$ C at 90 GeV.

EMPHATIC at Fermilab



A new hadron production experiment for improved neutrino flux predictions

Hadron production measurements to reduce flux uncertainties from secondary and tertiary interactions in the neutrino production target



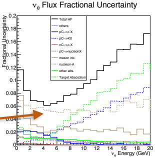
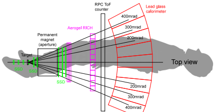
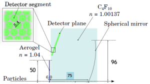
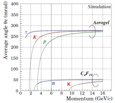
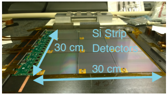


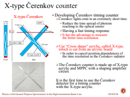
Table-top-sized experiment

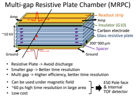




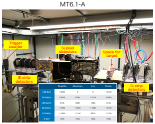


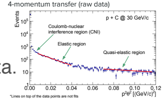






2 week-long test run this past January already collected useful data.





See posters by J. Paley, M. Pavin & T. Vladisavljevic, and T. Sugimoto!

A Spectrometer for Hadron Flux Measurements in LBNF?

Proposal by Laura Fields at Fermilab:

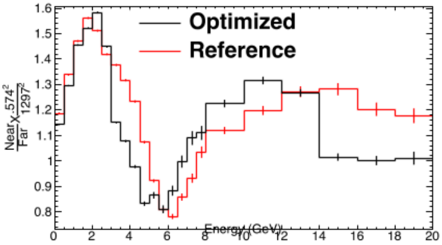
The LBNF Spectrometer is a concept for a thick-target hadron production measurement after the focusing horns. It would involve a replica of the LBNF target and horns in an external beamline at Fermilab. In addition to hadron production in the target, the spectrometer would also measure hadron production and absorption in the horns and the effects of the magnetic fields in the horns.

Detector technology is always challenging

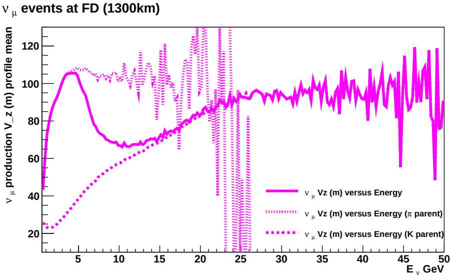
Need to get more people interested and involved to succeed

Near to Far Extrapolation

Simple ratio of near spectrum/far spectrum:



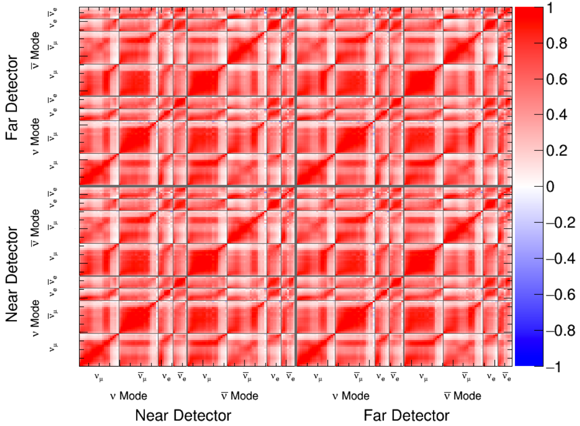
Neutrino parent decay location in decay pipe:



π/K decay kinematics and decay channel geometry are primary reason for strange shape of N/F ratio

Near to Far Extrapolation

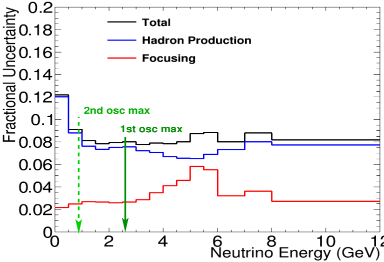
To correctly relate near to far fluxes - need to use a correlation matrix:



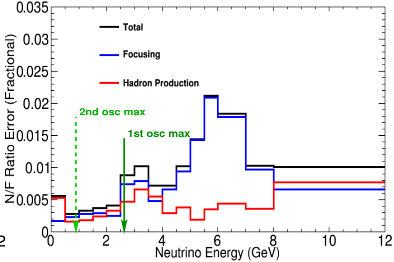
Flux correlation matrix comes from simulation and is highly correlated

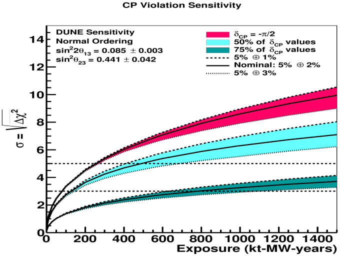
FD Flux Determination Uncertainities

Uncertainty on FD flux prediction



Residual uncertainty on flux at FD





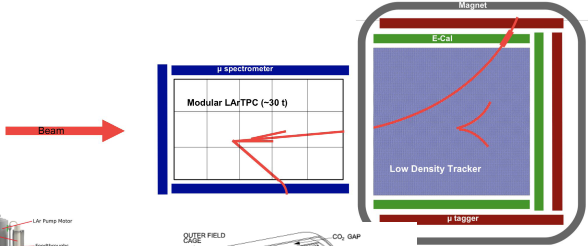
How well do we actually trust the simulation to correctly estimate the uncertainties on near $\rightarrow$ far extrapolation?

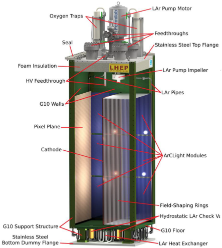
Near Detector Flux Measurement Strategies

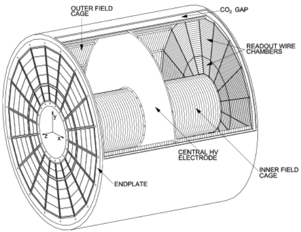
Technique	Flavor	Absolute normalization	Relative flux $\Phi(E_\nu)$	Near Detector requirements
NC Scattering $\nu_\mu e^- \to \nu_\mu e^-$	ν_μ	2.5%	$\sim 5\%$	e ID θ_e Resolution e^-/e^+ Separation
Inverse muon decay $\nu_\mu e^- \to \mu^- \nu_e$	ν_μ	3%		μ ID θ_μ Resolution 2-Track (μ+X) Resolution μ energy scale
CC QE $\nu_\mu n \to \mu^- p$ $Q^2 \to 0$	ν_μ	$3-5\%$	$5-10\%$	D target p Angular resolution p energy resolution Back-Subtraction
CC QE $\overline{\nu}_\mu p \to \mu^+ n$ $Q^2 \to 0$	$\overline{\nu}_\mu$	5%	10%	H target Back-Subtraction
Low-ν_0	ν_μ		2.0%	μ^- vs μ^+ E_μ-Scale Low-E_{Had} Resolution
Low-ν_0	$\overline{\nu}_\mu$		2.0%	μ^- vs μ^+ E_μ-Scale Low-E_{Had} Resolution
Low-ν_0	$\nu_e/\overline{\nu}_e$	1-3%	2.0%	e^-/e^+ Separation (K_L^0)
CC	ν_e/ν_μ	<1%	$\sim$2%	e^- ID & μ^- ID p_e/p_μ Resolution
CC	$\overline{\nu}_e/\overline{\nu}_\mu$	<1%	$\sim$2%	e^+ ID & μ^+ ID p_e/p_μ Resolution
Low-ν_0/CohPi	$\overline{\nu}_\mu/\nu_\mu$	$\sim$2%	$\sim$2%	μ^+ ID & μ^- ID p_μ Resolution E_{Had} Resolution

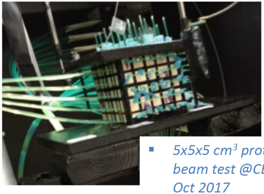
The DUNE Near Detector Concept

An unmagentized LArTPC with followed by a low density tracker embedded in a large $\sim$ 0.5T magnet with EM sampling calorimeters.









- *5x5x5 cm^3 prototype beam test @CERN, Oct 2017*

Segmented LArTPC **ALICE-like GArTPC** **3D scint**

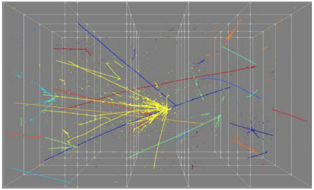
DUNE ND Capabilities

LArTPC: Allows for high statistics measurements on Ar and ND/FD detector systematics constraints. With 25 ton FV $\Rightarrow$ 37M CC ν_μ interactions/year (1MW beam)

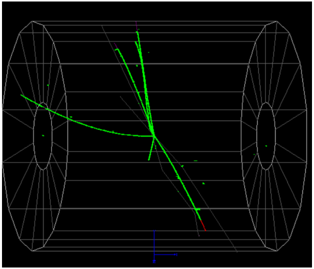
GArTPC: allows for precision measurement of ν-Ar vertex activity using Ar-CH_4. Low treshold improves low-ν on Ar. Could allow for different gas mixtures (H???).

3DST: Increases interaction statistics in magenetized volume $\sim$ 6 t fiducial mass $\Rightarrow$ 9M ν_μ events/yr. Beam flux measurements on a lighter target. Contain EM showers from $\nu - e$ scattering when combined with ECAL ($\sim$ 1000 events/yr).

Challenge: how to integrate with GArTPC.

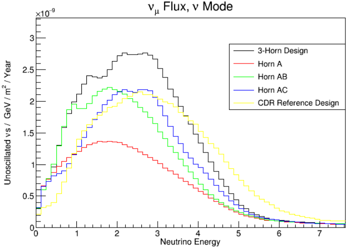


ND LArTPC simulation

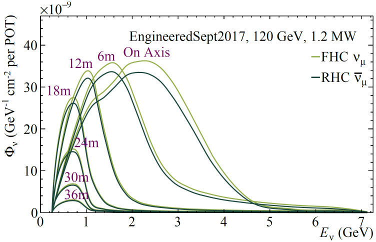


ND GArTPC simulation

Beam tunes and DUNE-PRISM Constraints



ν_μ **flux different horn configs**

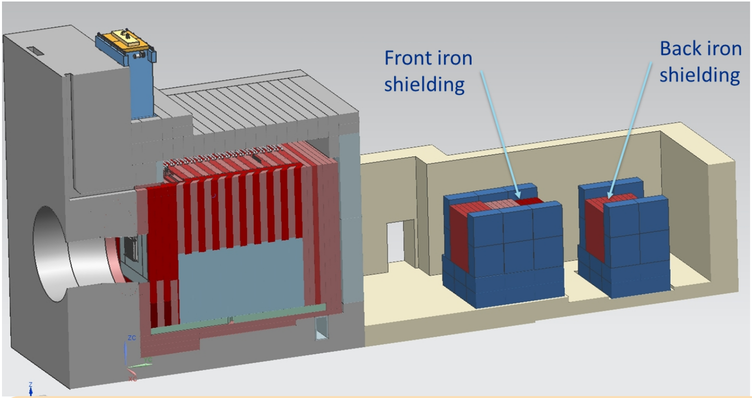


$\nu_\mu / \bar{\nu}_\mu$ **off-axis fluxes at ND**

More flux and focusing constraints could be obtained by combining information from ND off-axis measurements (DUNE-PRISM) and varying on-axis beam tunes (with varying horn current for e.g.). Studies are under way.

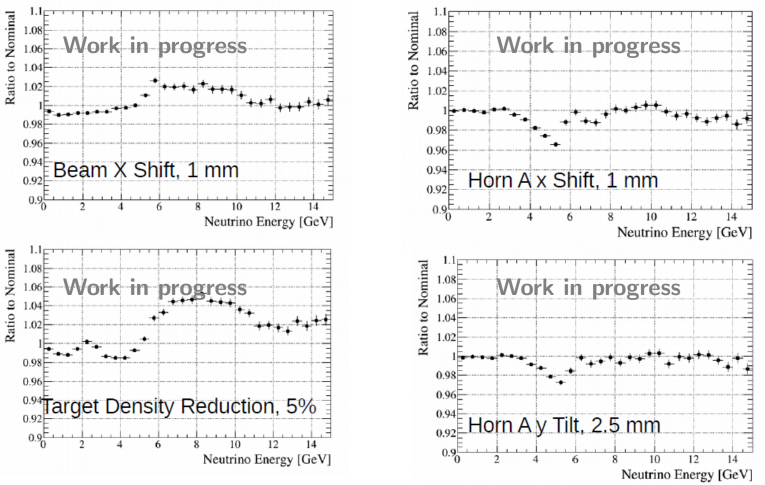
Muon Beam Monitors

Layout of Muon Alcove and Shielding



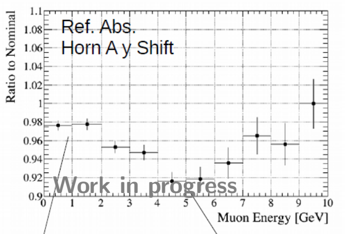
High intensity makes it difficult to measure μ spectrum accurately. With a 2.4 MW beam, the absorber thickness is too large to sample the lower energy muons. But these systems play an essential role in monitoring *flux stability*

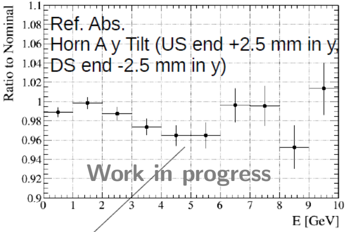
ν Spectrum Changes



Correlation between neutrino and muon spectrum

μ Spectrum Changes





Reduction in total flux

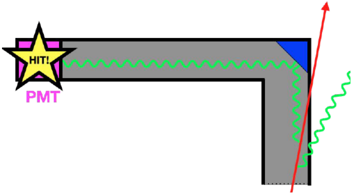
Shape changes at max near 5 GeV

Changes are v. small - need novel detector concepts

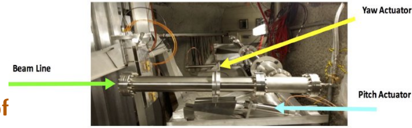
Muon Monitor Technologies under R&D

- **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.**

Gas Cherenkov counter concept:

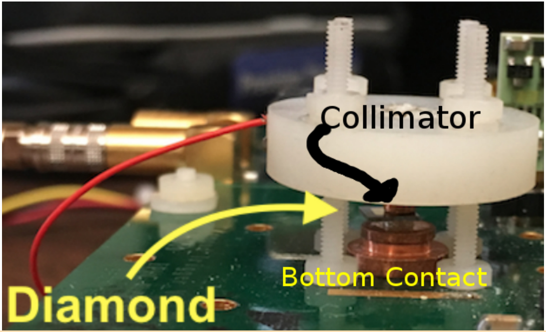


Prototype in NuMI beamline:



Currently only ionization detectors included in the beam design.

Ionization detector: Diamond Detector Prototyoe



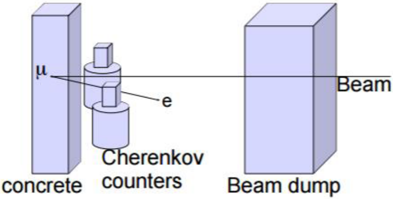
Use polycrystal chemical vapor deposition (pCVD) diamond - detects ionizing radiation when a large voltage potential (1V per m of thickness) is applied across two sides of the diamond. Diamond is radiation hard.

pCVD detector prototype installed in NuMI during 2018 shutdown.

Stopped Muon Concept

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

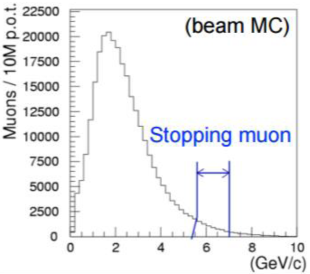
Strategy



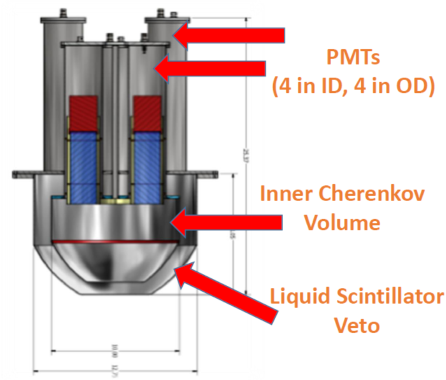
- Counting the decay electrons from muons stopping at the wall of μ-pit
- Measuring spatial and time distributions of events

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

We can measure muons of
5.2~7.0GeV/c
by counting the decay electrons



Stopped Muon Prototype



Prototypes being commissioned with cosmics.

Summary and Conclusions

- **The next generation of long-baseline experiments requires determination of the flux at the 1-2% level.**
- **LBNF is a configurable wide-band beam ⇒ 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 concept is a combination of many different technologies**
- **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.**