Determination of the LBNF Neutrino Flux

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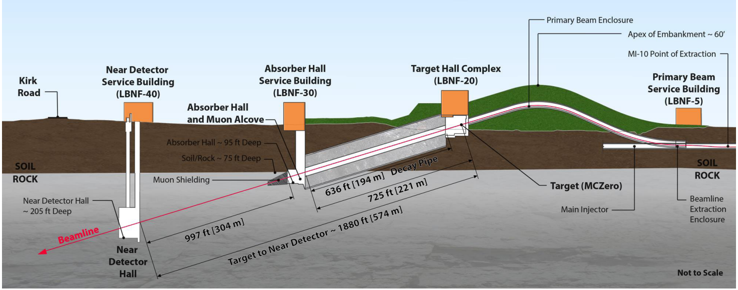
Mary Bishai (on behalf of LBNF/DUNE)
Brookhaven National Lab

1. The LBNF Beamline
2. Flux Modeling and Uncertainties
3. Near Detector(s) Flux Measurements
4. Muon Monitors
5. Summary

Overview of the LBNF Beamline

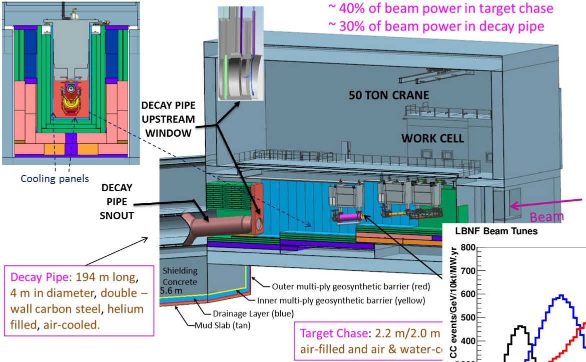


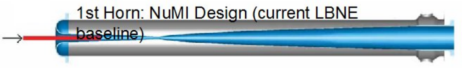
- **Primary proton beam 60-120 GeV**
- **Initial 1.2 MW beam power, upgradable to 2.4 MW**
- **Embankement allows target complex to be at grade**
- **Wide-band beam (on-axis) based on NuMI design with tunable energy spectrum.**
- **Decay pipe: 194m x 4m diameter, He filled**

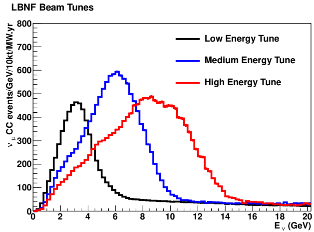
ND default: 574 m from target, FD: 1300 km

The LBNF Reference Design (up to 2015)

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







LBNF has switched to CPV optimized focusing design with 3 horns

Optimization of flux for Physics: CP Violation

- **The 2015 CD1R reference design for LBNF/DUNE is a NuMI-like movable target (segmented rectangular graphite fins with water cooling $\approx$ 1m long) and 2 modified NuMI horns 6.6m apart**
- **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).**
- **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.**

Optimization of flux for Physics: CP Violation

Laura Fields

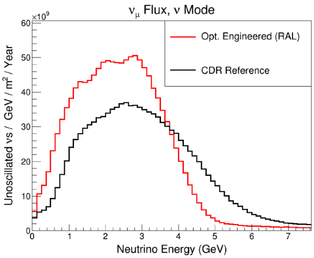
Optimized horn design with 297kA current :

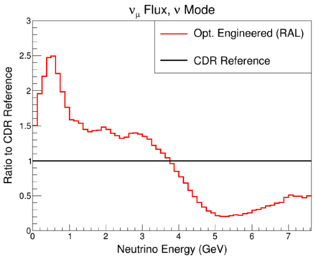
Parameter	Value		Parameter	Value
Horn A Length (mm)	2218		Horn A F1 (% of length)	53
Horn A R1 (mm)	43		Horn A OC Radius (mm)	369
Horn A R2 (mm)	33			
Horn B Length (mm)	3932		Horn C Length (mm)	2184
Horn B R1 (mm)	159		Horn C R1 (mm)	284
Horn B R2 (mm)	81		Horn C R2 (mm)	131
Horn B R3 (mm)	225		Horn 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

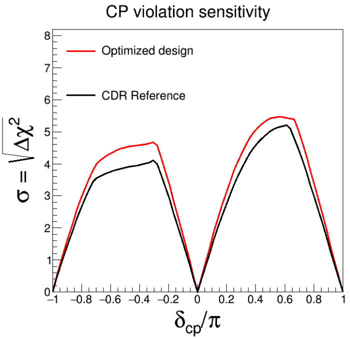
Optimized target is 4λ (2m C) with $\sigma_{\text{beam}} = 2.7$mm, $E_p \sim 110$ GeV

Optimization of flux for Physics: CP Violation

Laura Fields







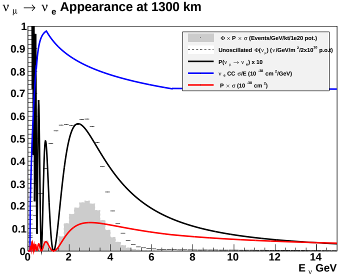
Computationally advanced optimization techniques = significant gain in flux and CPV sensitivity from *many* small changes

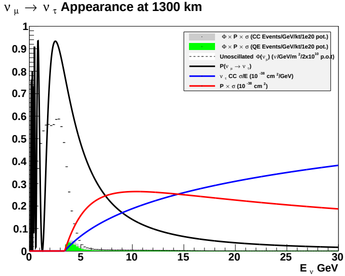
Gain in sensitivity ≡ 70% increase in FD mass

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:



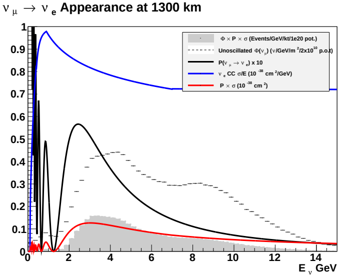


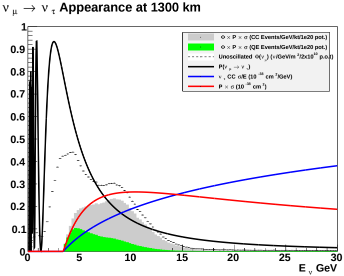
$\nu_\mu \to \nu_e$ 290 events $\quad$ $\nu_\mu \to \nu_\tau$ 60 events
in 40 ktons, 1 year at 1.2 MW

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





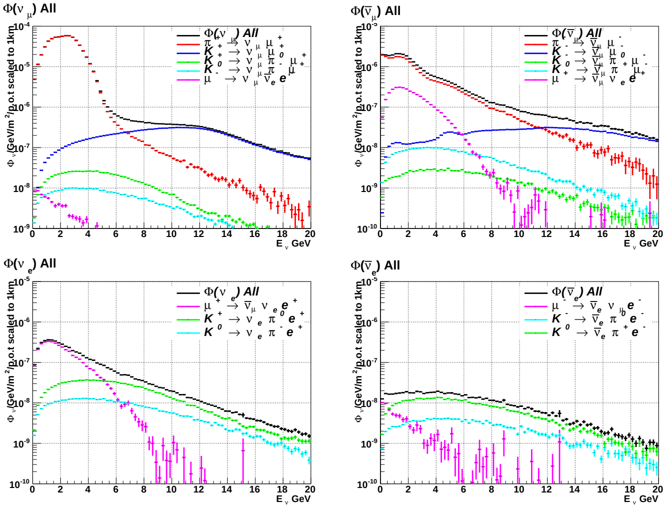
$\nu_\mu \rightarrow \nu_e$ 330 events $\quad$ $\nu_\mu \rightarrow \nu_\tau$ 700 events
in 40 ktons, 1 year at 1.2 MW

Increase ν_τ appearance 10x!!!

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

Flux components at near and far

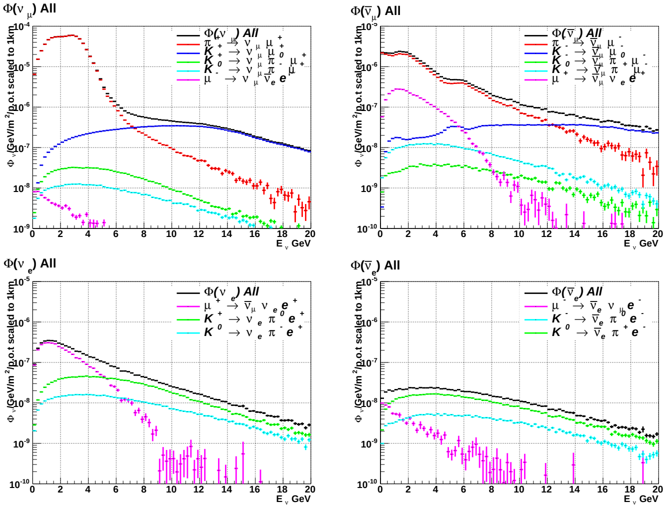
ND 570



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

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Summary

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:

$$w_{\mathrm{HP}} = \frac{f_{\mathrm{Data}}(x_F, p_T, E)}{f_{\mathrm{MC}}(x_f, p_T, E)} \qquad f = E\frac{d^3\sigma}{dp^3}$$

  - 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

Flux Modeling Uncertainties

PPFX Package

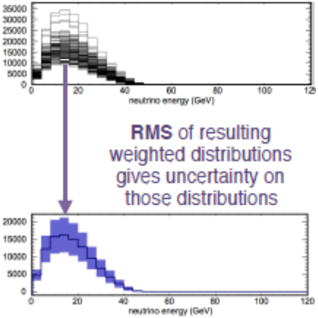
- **Uncertainties** on the external data constraints are propagated to uncertainties on our flux and other simulated distributions using a "**Many-Universes**" method:

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

$$w = e^{-L\rho(\sigma_{\text{Data}}-\sigma_{\text{MC}})}\left(\prod_{\substack{\text{reweightable}\\\text{interactions}}} \frac{f_{\text{Data}}(x_F,p_T,E)}{f_{\text{MC}}(x_f,p_T,E)}\right)$$

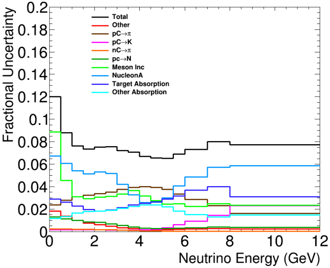
We also store many (~1000) weights constructed from **data cross sections varied according to their uncertainties** (taking into account correlations)

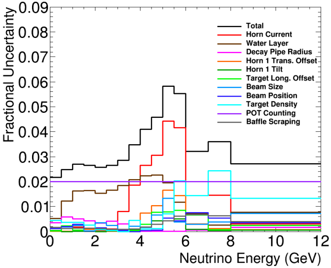
For interactions **uncovered by data, large (40%) are assumed**, correlated with neighboring bins



Flux Modeling Uncertainties

L. Fields and A. Bashyal





Hadron Prod. Uncertainties

NA49 dateset 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

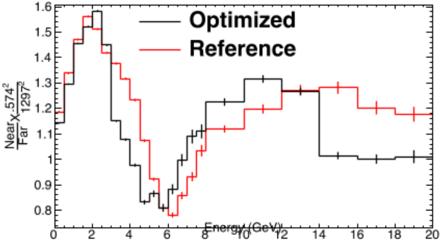
Detailed focusing uncertainties based on the NuMI experience in MINERνA.

Used CPV optimized design with simplified 2 horns.

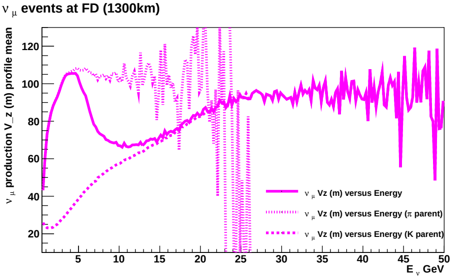
Need to use engineered 3 horn design

Near to Far Extrapolation

Simple ratio of far spectrum/near spectrum:



Neutrino parent decay location in decay pipe:



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

Near to Far Extrapolation

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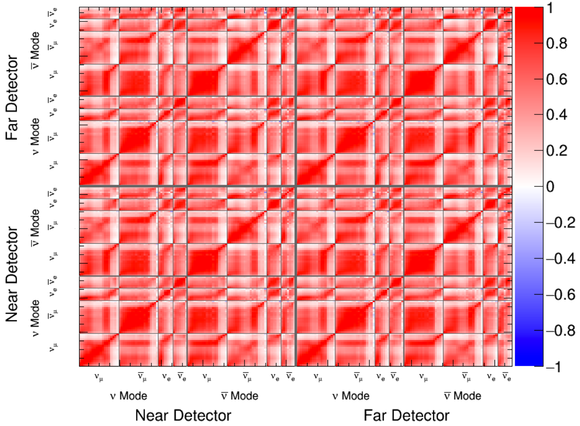
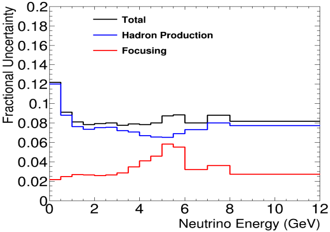
To correctly relate near to far fluxes - need to use a correlation matrix:

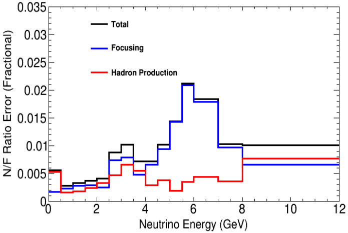


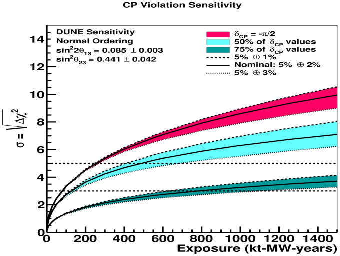
Flux correlation matrix comes from simulation and is highly correlated

Uncertainty on ND flux prediction



Residual uncertainty at FD





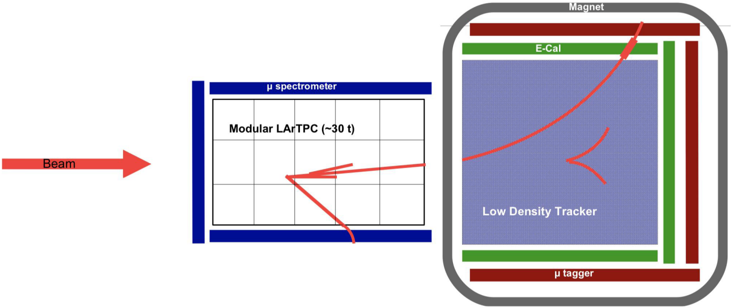
How well do we actually trust the simulation to correctly estimate the uncertainties on near → far extrapolation?

Near Detector Flux Measurement Strategies

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

The DUNE Near Detector Concept

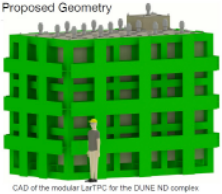
An unmagentized LArTPC with a low density tracker embedded in a large magnet with EM sampling calorimeters surrounded by muon spectrometers

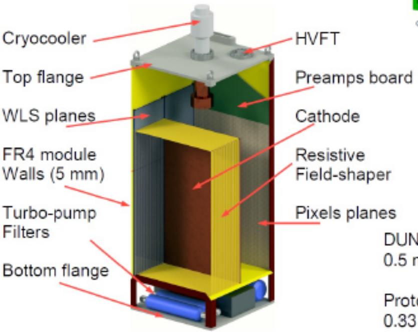


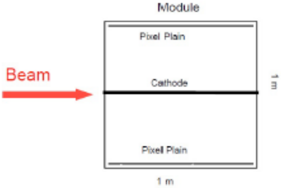
Expect 2.5×10^5 neutrino interactions/ton Ar/1e20 POT at 574m

LArTPC concept

ArgonCube







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

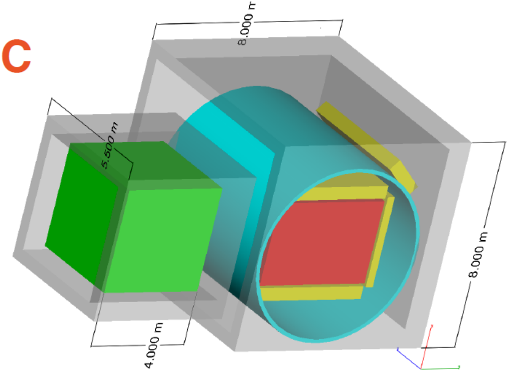
Allows for high statistics measurements on Ar and ND/FD detector systematics constraints

Magnetized GArTPC for central tracker

HP GAr TPC

- Magnet (0.5T)
- LAr
- TPC_{hpg}
- EM Cal ($20X_o$)
- Steel ($4\lambda_o$)

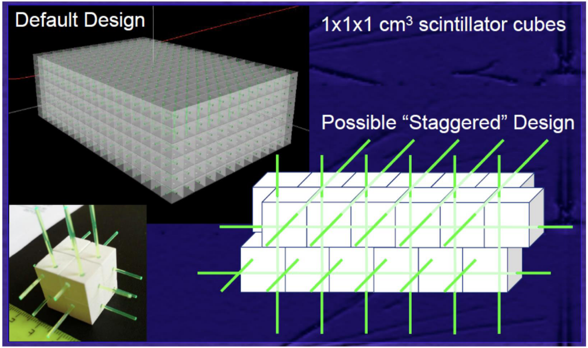
LAr:
with 2 X 2 m FV
~ 7 X_o annulus
~ 1.25 λ_o annulus



GArTPC allows for precision measurement of ν-Ar vertex activity

3D Scintillator Tracker

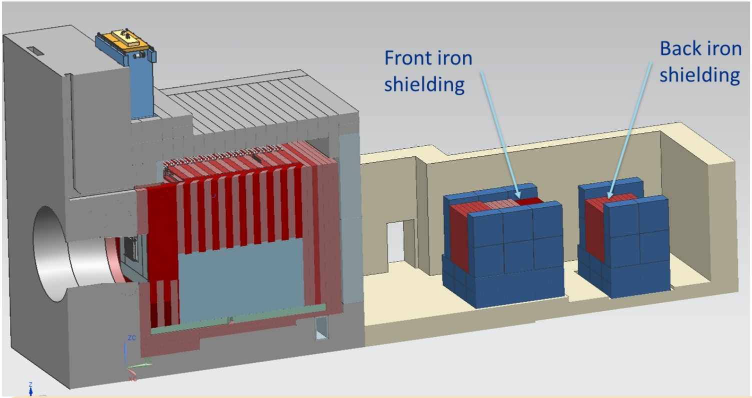
3DST



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 $\pi^0\gamma\gamma$.

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*

Correlation between neutrino and muon spectrum

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- **Muon Monitors**
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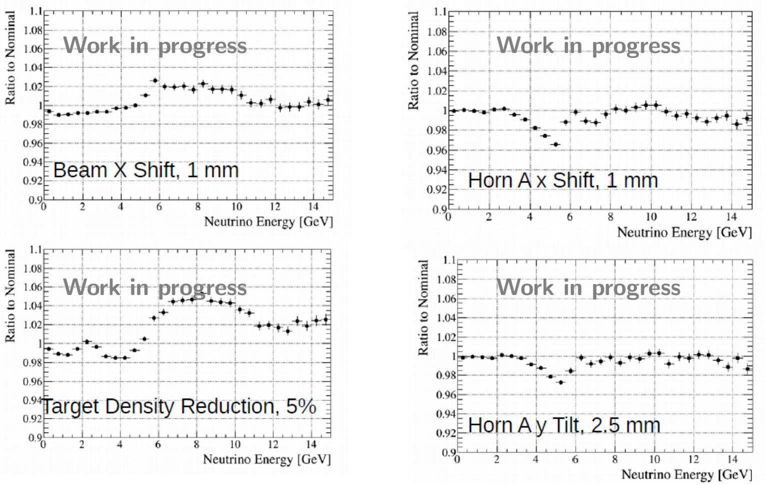
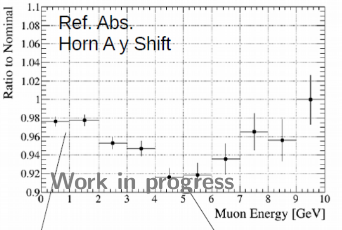
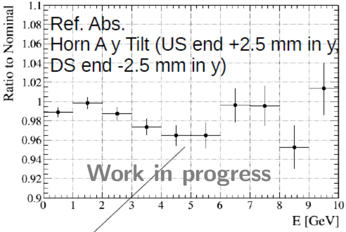
ν Spectrum Changes



Correlation between neutrino and muon spectrum

μ Spectrum Changes





Reduction in total flux

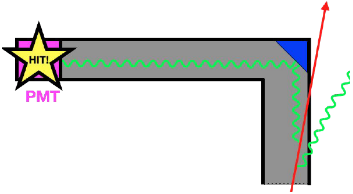
Shape changes at max near 5 GeV

Changes are v. small - need novel detector concepts

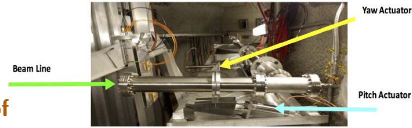
Muon Monitor Technologies under R&D

- **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:

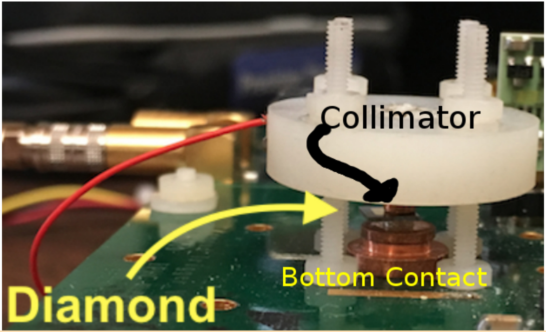


Prototype in NuMI beamline:



Currently only ionization detectors included in the beam design.

Ionization detector: Diamond Detector Prototyoe



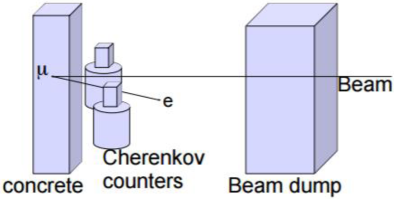
Use polycrystal chemical vapor deposition (pCVD) diamond - detects ionizing radiation when a large voltage potential (1V per m of thickness) is applied across two sides of the diamond. Diamond is radiation hard.

pCVD detector prototype installed in NuMI during 2018 shutdown.

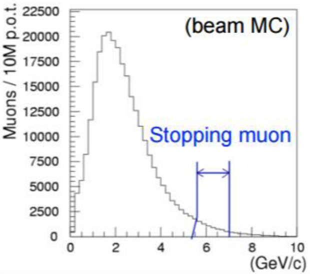
Stopped Muon Concept

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

Strategy



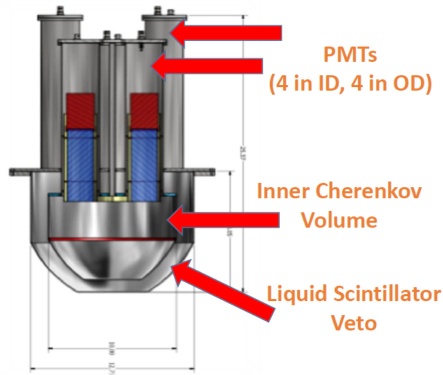
- Counting the decay electrons from muons stopping at the wall of μ-pit
- Measuring spatial and time distributions of events



- 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 wide-band beam with tunable capabilities $\Rightarrow$ requires beam flux/spectrum measurements over a large range of energies.**
- **Very high intensity beams (MW class) are needed $\Rightarrow$ 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 $\Rightarrow$ 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.**