Time Slicing of Neutrino Fluxes in Oscillation Experiments at Fermilab

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Author Background

- Associate Scientist in Target Systems Department at Fermilab (November 2020 - Present)
  - Horn Monitoring System for LBNF
  - NuMI, LBNF beam simulations
  - Run-Coordinator for FY2022 accelerator operations
- Previously served as a run-coordinator and operations manager for Muon g-2 & involved in data analyses for the experiment (2015 - 2020)
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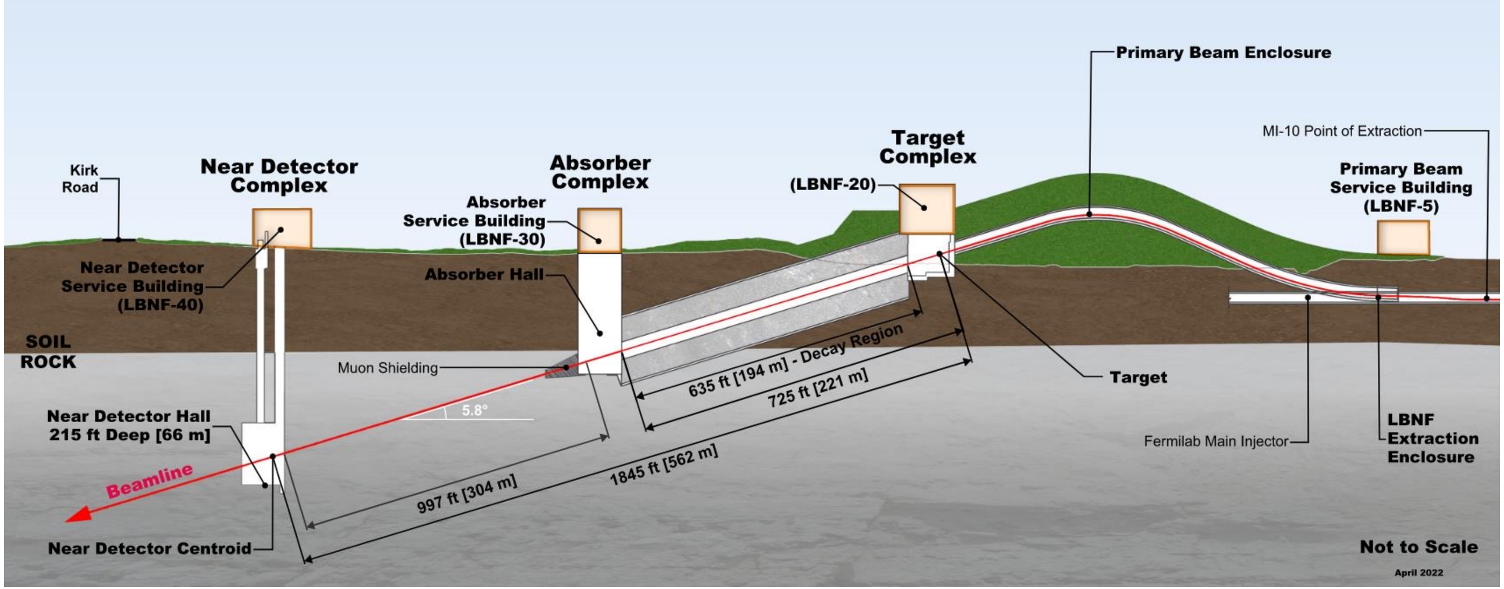
LBNF Beamline

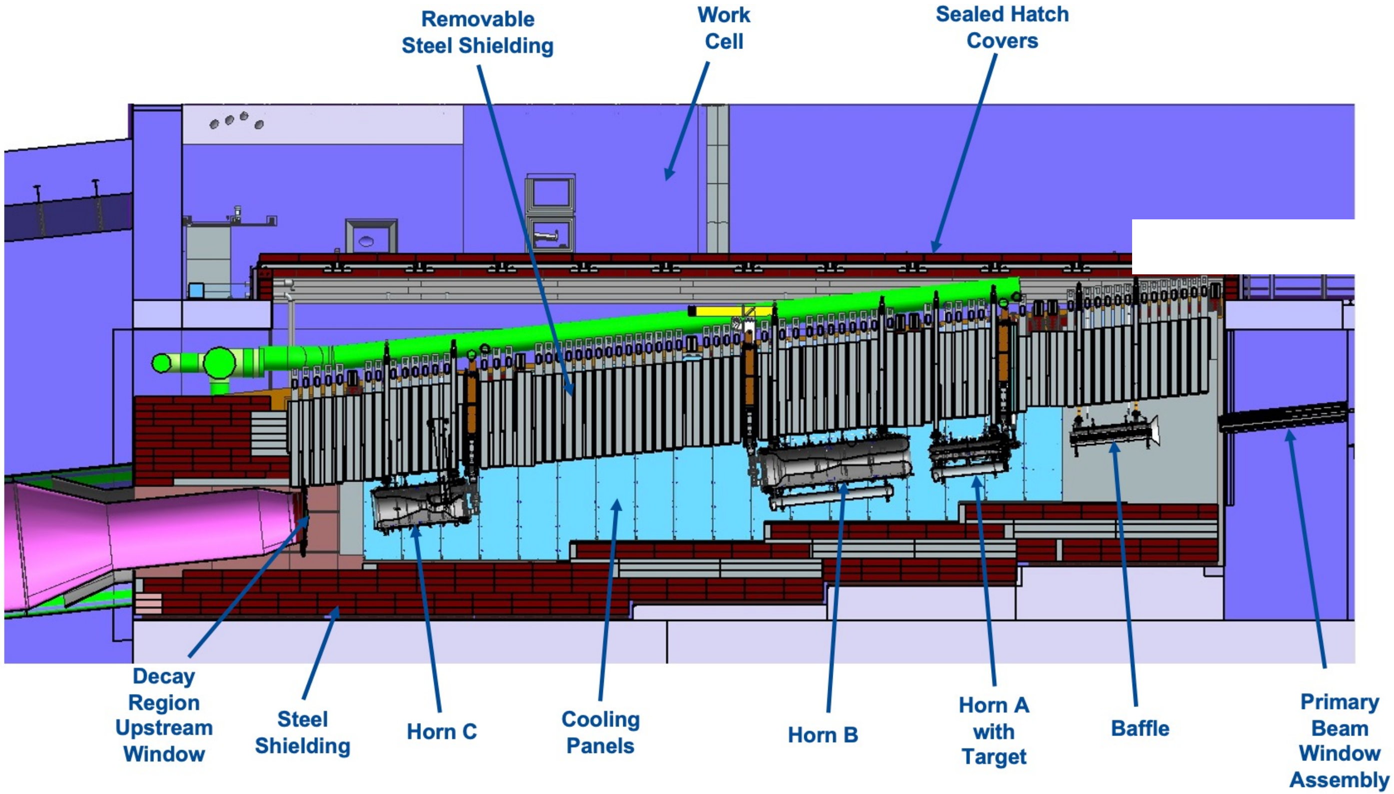


- Proton beam extracted from Fermilab's Main Injector in range of 60 – 120 GeV every 0.7 – 1.2 sec with pulse duration of 10 μs
- Protons per cycle:

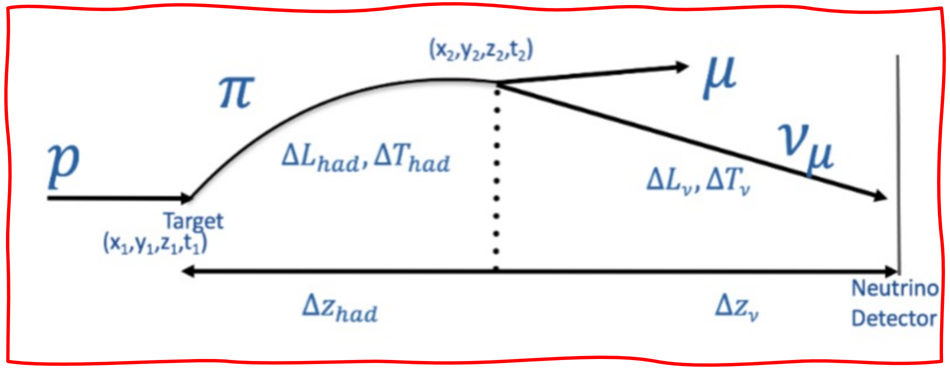
  -1.2 MW era: 7.5x10^{13}

  -2.4 MW era: (1.5-2.0)x10^{14}

Target Hall Shield Pile Layout – Optimized Design



Neutrino Beam Timing



$$T_A = \Delta T_{had} + \Delta T_\nu = (t_2 - t_1) + \Delta L_\nu / c$$

$$T_A^{prompt} = \Delta z / c = (\Delta z_{had} + \Delta z_\nu)/c$$

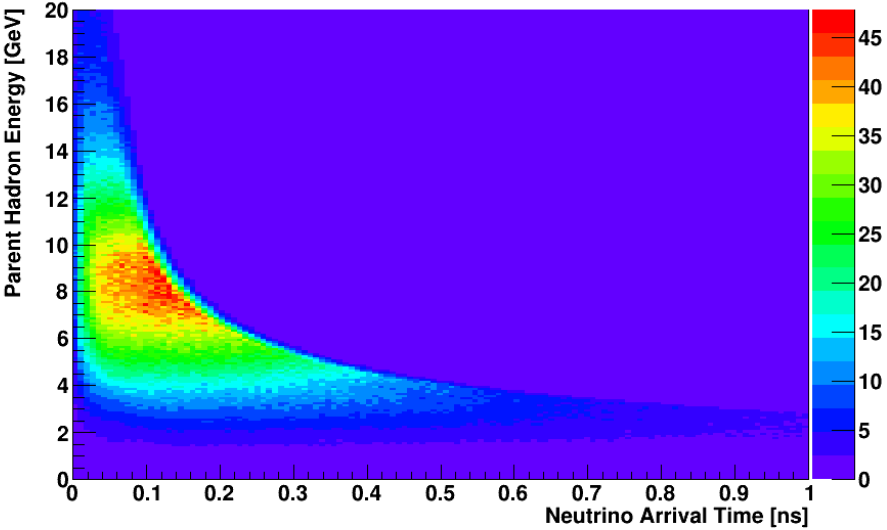
$$\Delta T_{had} = t_2 - t_1 \qquad \Delta T_\nu = \Delta L_\nu / c$$

$$\boldsymbol{Eqn1}\text{: } \Delta T = T_A - T_A^{prompt}$$
$$= \Delta T_{had} + \Delta L_\nu / c - (\Delta z_{had} + \Delta z_\nu)/c$$

For $\Delta L_\nu \approx \Delta z_\nu$

$$\boxed{\boldsymbol{Eqn2}\text{: } \Delta T \approx \Delta T_{had} - \Delta z_{had}/c}$$

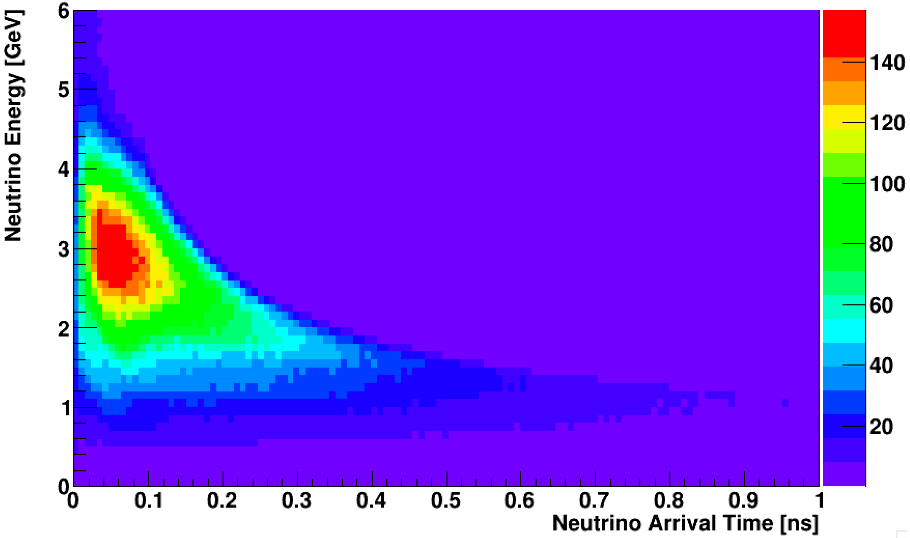
Neutrino Beam Timing



With simulated data of LBNF beam in Forward Horn Current Mode

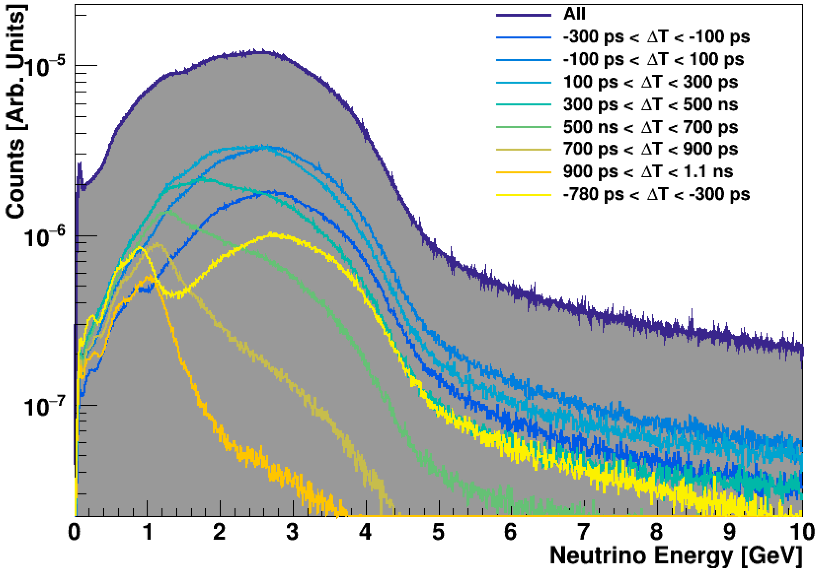
Arrival time difference b/w neutrinos from relativistic hadrons & neutrino from hadron of energy E

Neutrinos at Near Detector



Relative neutrino arrival times versus neutrino energies for all neutrinos with simulated data of the LBNF beam

Neutrinos at Near Detector

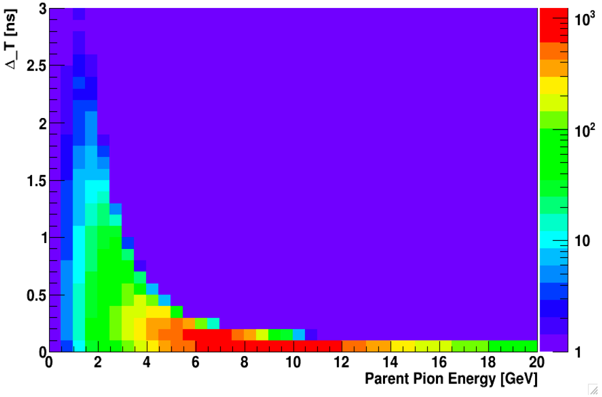


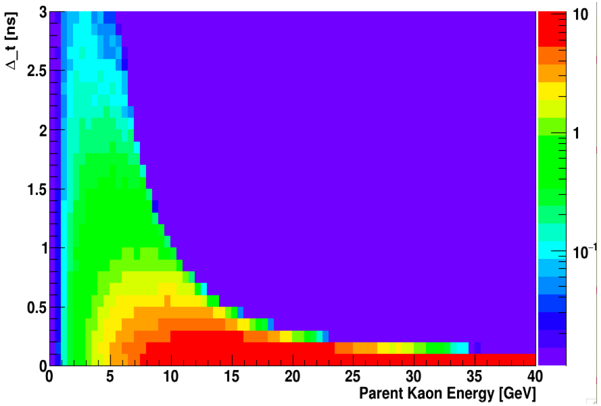
- Simulation of neutrino energy distribution (the outer dark blue envelope)
- Overlaid with fluxes corresponding to increasingly later binned time cuts
- 250 ps bunch width
- 100 ps detector timing in 200 ps bins at Near Detector

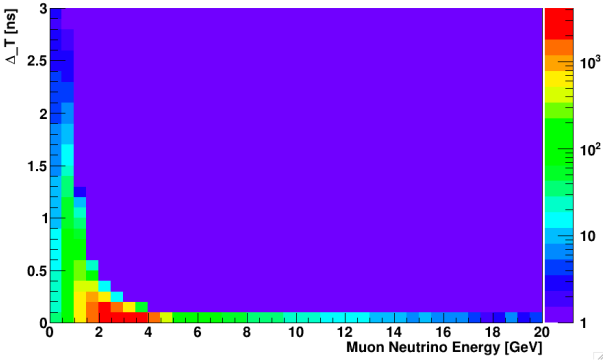
Neutrinos at Near Detector

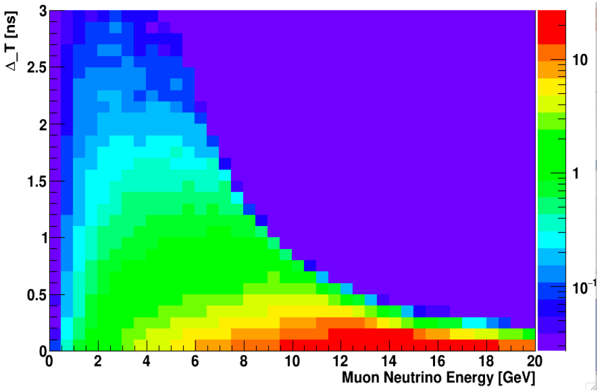
$P+C \rightarrow \pi^{+} \rightarrow \nu\mu$

$P+C \rightarrow K^{+} \rightarrow \nu\mu$

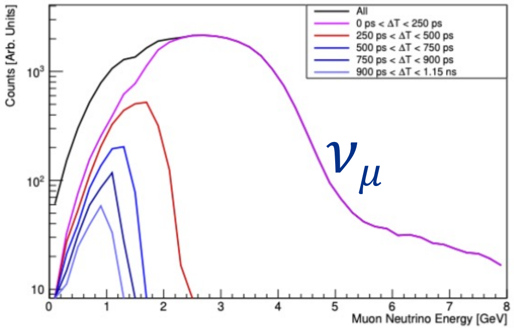




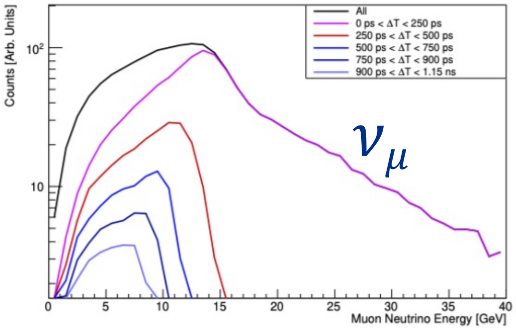




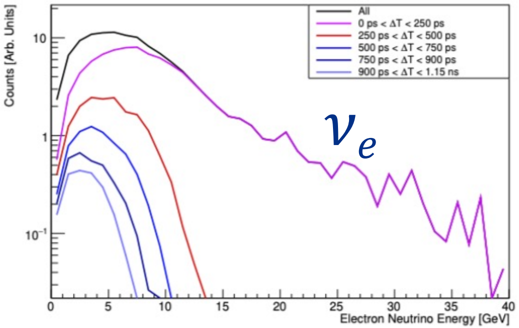
Timing to Separate Out Neutrino Family Types, Parent Hadron Components



Parent hadron: pion only



Parent hadron: kaon only



Parent hadron: kaon only

Motivation

$$P(\nu_\alpha \to \nu_\beta) = \frac{\Phi_{\nu_\beta}(E_\nu, L)}{\Phi_{\nu_\alpha}(E_\nu, 0)}$$

- Need to disentangle initial neutrino flux & reaction cross sections, detector effects – each energy dependent

Number of Near Detector events = **Flux** • **Cross section** • **Detector effects**

Number of Far Detector events = **Flux** • **Oscillation probability** • **Cross section** • **Detector effects**

- Neutrino energy spectra different at ND & FD, fluxes different due to oscillation
- Cross sections highly uncertain due to strong energy dependence
- N sensitive to nuclear effects – FSI, missing energy
- $E_{rec} \rightarrow E_{true}$ depends on poorly understood neutrino interaction models
- Even if ND and FD were the same, flux differences mean that there is no cancellation between the two

DUNE PRISM

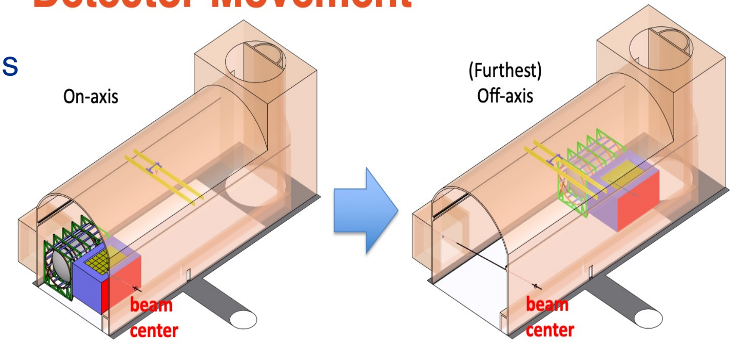
- Prismatic approaches look at full flux & sample multiple off-axis angles in same detector
  → by changing off-axis angle of detector, sample a continuously changing energy spectrum

- Allows to make cross-section measurements in different energy distributions:
  - same detector
  - same target material as FD

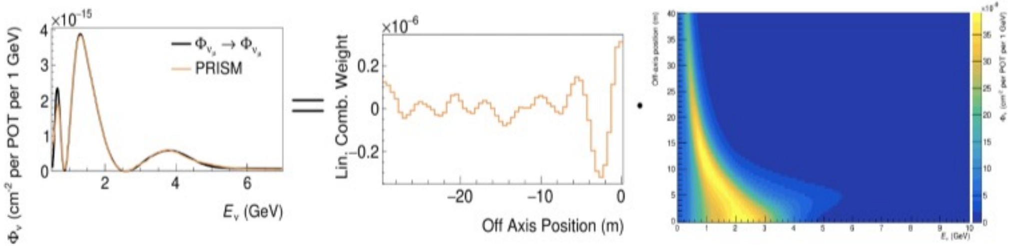
- **But application limited to ND**

- **Measure oscillated flux at the near detector**

Detector Movement

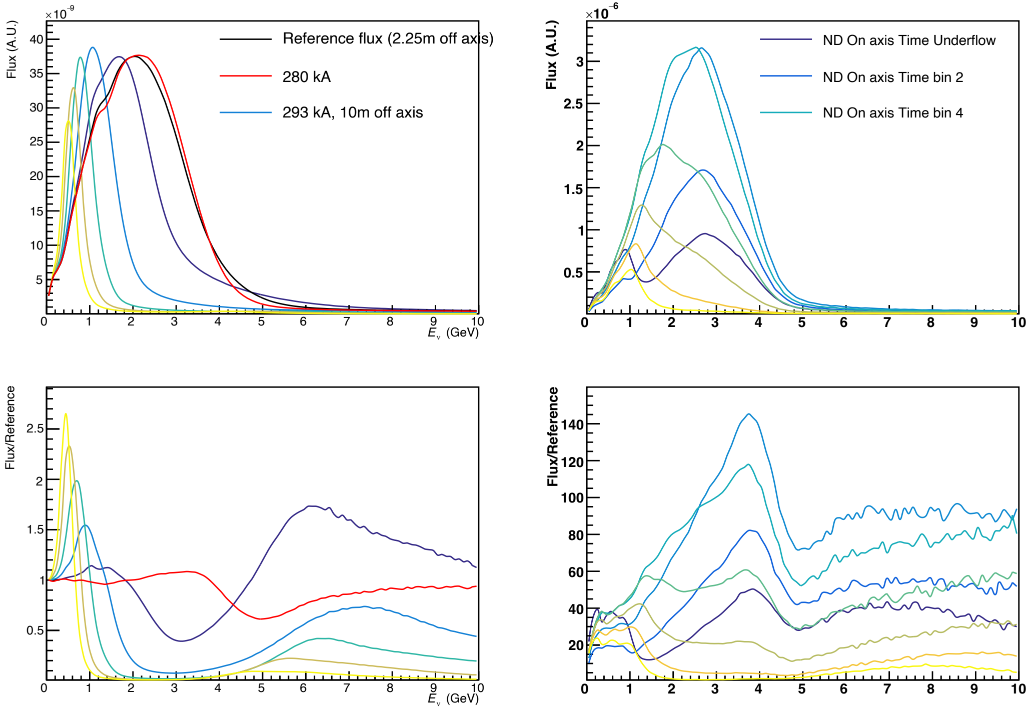


$$\vec{\Phi}^{\nu}_{\mathrm{far}} P^{\mathbf{H}}_{\mathrm{osc}} = \vec{C} \cdot \Phi^{\nu}_{\mathrm{near}}$$



PRISM Complementarity of Stroboscopic Approach

Flux components at Near Detector to perform PRISM fits



Top left: PRISM off-axis and alternate horn current (280 kA) fluxes

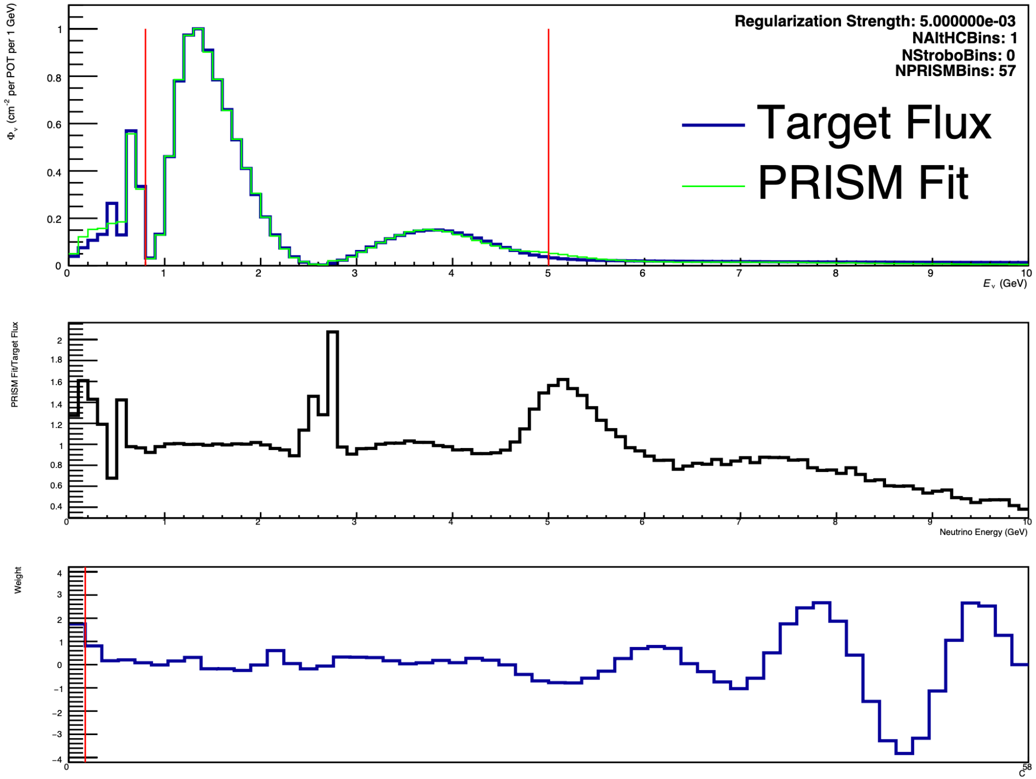
Top right: Stroboscopic fluxes

Bottom left: Ratio of the PRISM fluxes and the 280kA flux to reference flux

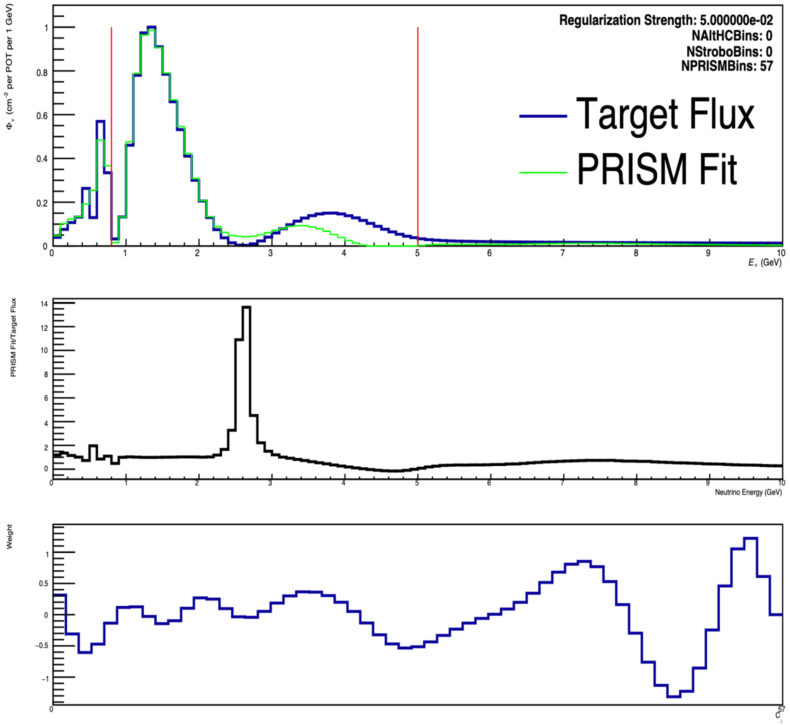
Bottom right: Ratio of the stroboscopic fluxes to reference flux

PRISM Complementarity of Stroboscopic Approach

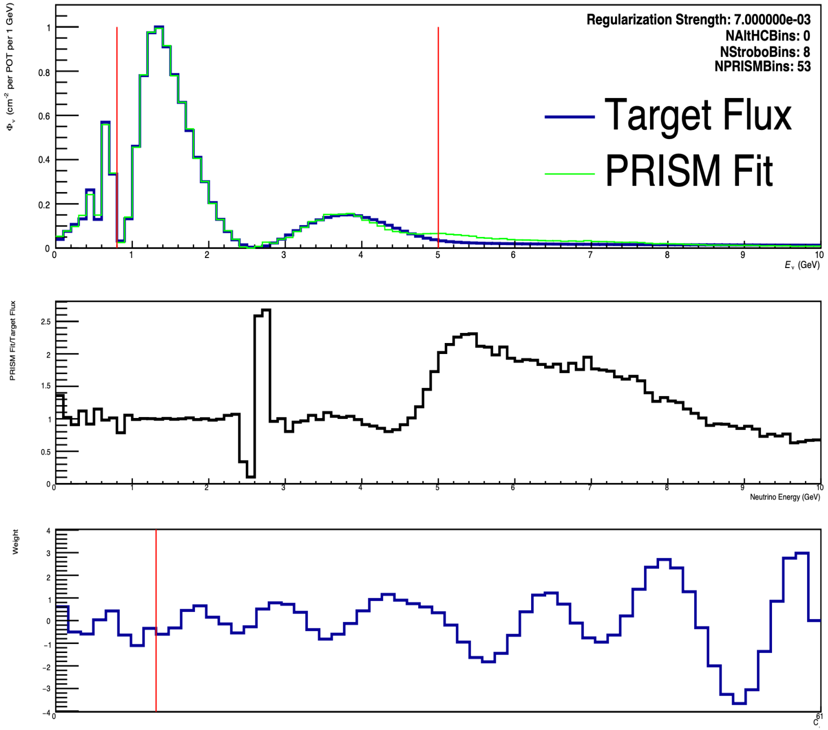
Default PRISM fit with PRISM on and off-axis fluxes and altHC flux



PRISM Complementarity of Stroboscopic Approach

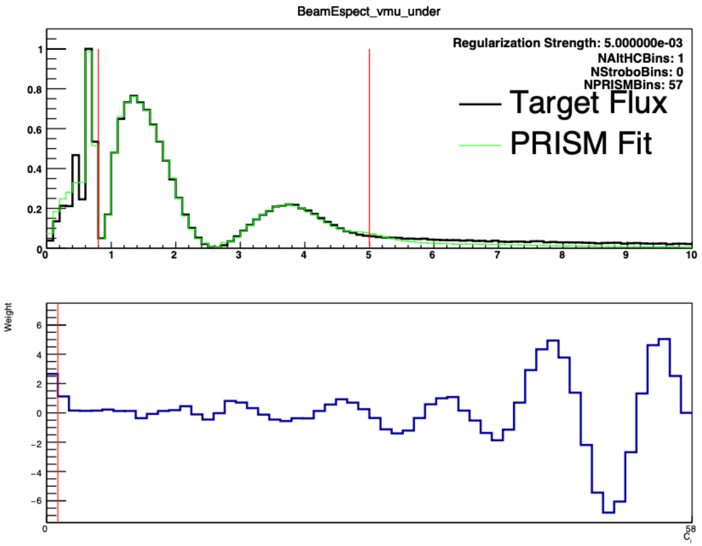


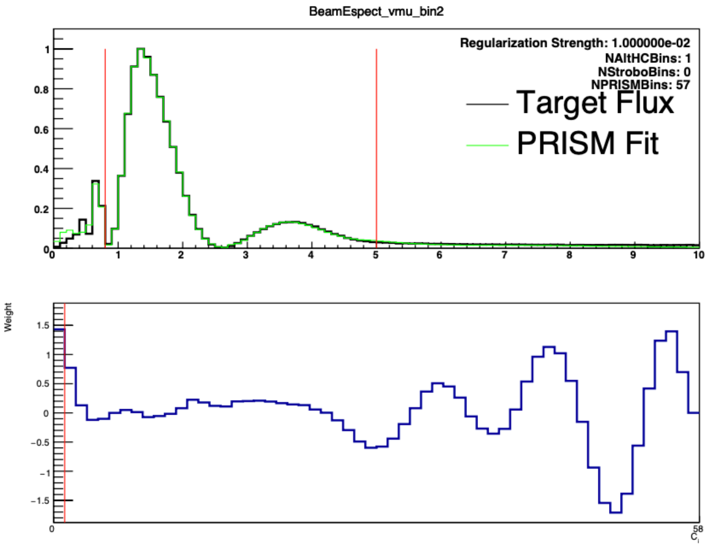
PRISM fit with PRISM on and off-axis fluxes only, no altHC flux



PRISM fit with PRISM off-axis fluxes only, stroboscopic on-axis fluxes and no altHC flux

PRISM Complementarity of Stroboscopic Approach





PRISM fits to oscillated Far Detector time bins

PRISM Complementarity of Stroboscopic Approach

A reconstruction independent observable is needed to select different energy spectrums within a beam

- One way is to do PRISM
- PRISM Near Detector program can be further enhanced with a fast Near Detector
- Stroboscopic approach can enhance PRISM's default program by providing Far Detector oscillated time slices

Application of Stroboscopic Approach

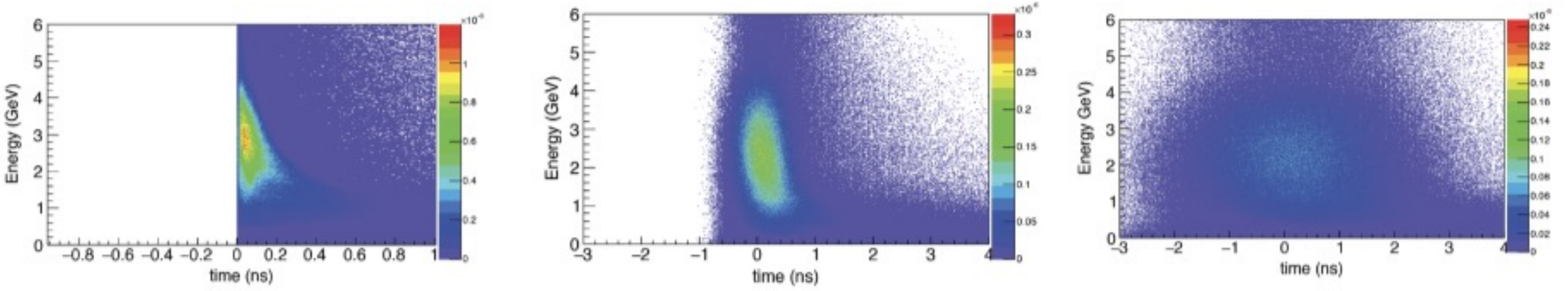
Application of stroboscopic approach requires:

Creation of short (O(100 ps)) proton bunch length

Detectors with fast timing to get equivalent time resolution

Synchronization b/w time at detector & time of bunch-by-bunch proton

Application of Stroboscopic Approach

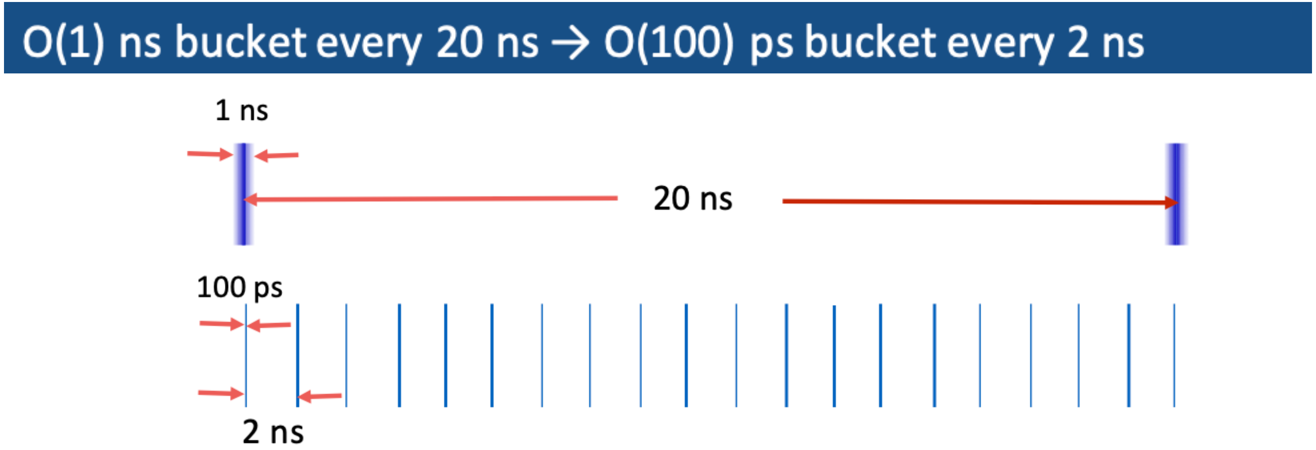


Reference: https://arxiv.org/pdf/1904.01611.pdf

- Energy and time correlation of neutrinos becomes smeared when proton bunch has a non-zero time-width
- At ~1 ns bunch lengths typical of Fermilab neutrino facilities, correlation b/w timing and energy is mostly washed out except for a small, low-statistics tail

Creation of Shorter Proton Bunches

Re-bunching beam proposed in: https://arxiv.org/pdf/1904.01611.pdf



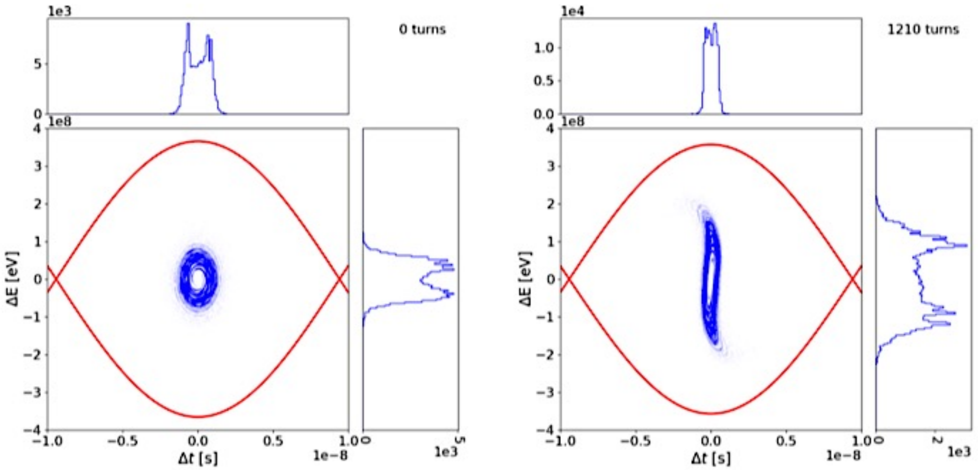
- Superimpose a higher frequency harmonic on top of bunch structure: 10xharmonic, going from 53.1 MHz to 531 MHz
- Total number of protons stays same
- Requires adding a Superconducting RF Cavity

Addition of a new cavity, requires a significant investment

Creation of Shorter Proton Bunches

- Use bunch rotation at MI to create Narrow Bunches

Adiabatic excitation of longitudinal bunch shape oscillation in MI:



Minimal bunch length of 330 ps occurs ~ 1210 revolution

Plot courtesy:
Robert Ainsworth, Fermilab

Longitudinal phase distribution with (right) &

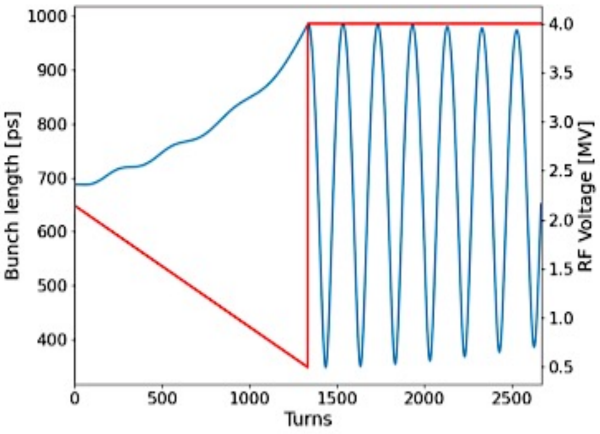
without (left) bunch rotation with simulated data generated with BLonD

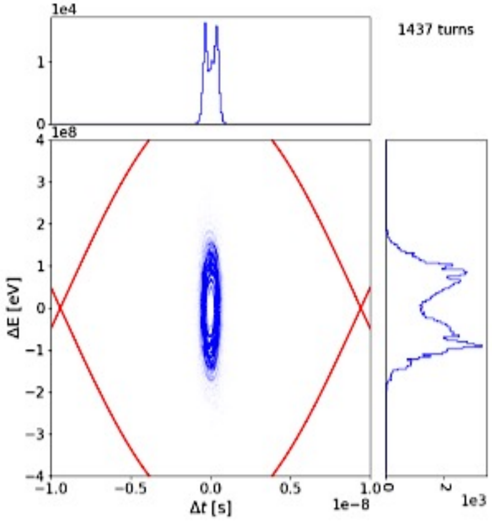
Creation of Shorter Proton Bunches

- Use bunch rotation at MI to create Narrow Bunches

Snap Bunch Rotation in MI:

Minimal bunch length of 350 ps occurs ~ 1437 revolution



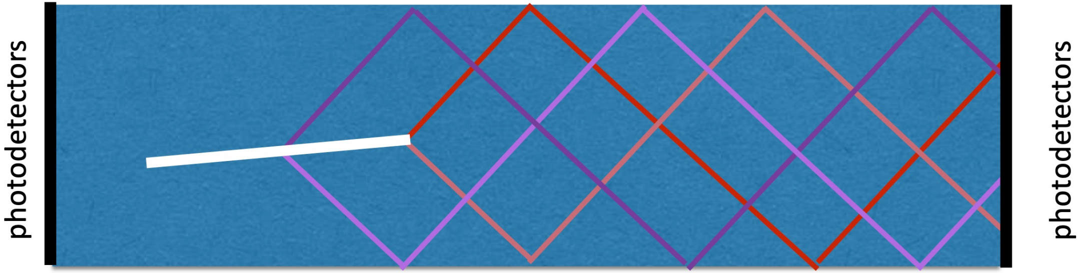


- Longitudinal phase distribution with bunch rotation (right)
- RF voltage modulation (left)

Plot courtesy:
Robert Ainsworth, Fermilab

Detectors with fast timing

- LBNF Near and Far detectors can be used to divide neutrino flux by neutrino arrival time by
- Creating short proton bunches in MI - if detectors have a time resolution like proton bunches at target
- Liquid Argon TPCs as currently conceived are slow detectors

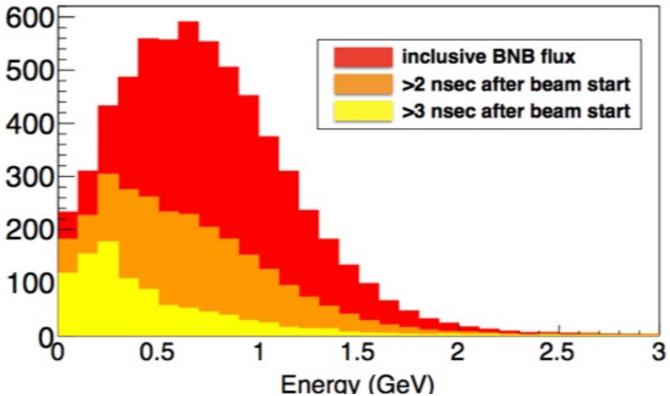


Proposed method:https://arxiv.org/abs/2004.00580

- From electron TPC data, liquid Argon-based detectors precisely re-construct each event in space
- Use reconstructed track from electron drift to simulate detected time and position of Cherenkov photons
- Only one parameter, neutrino event time needs to be fitted for
- For 50-100 ps precision timing in liquid Argon, prompt light must be detected precisely, **Cherenkov light at visible wavelengths has properties required**
- Possible option for photodetection - mirror top, bottom, sides, and place photodetectors on end caps

ANNIE Detector

- ANNIE provides a first demonstration of stroboscopic approach on neutrinos from BNB beam
- Detecting time-slicing effect should be possible, even with 1 ns bunches, however a smaller bunch length is better
- **Motivates applying bunch rotation in Booster**
- ANNIE running with LAPPDs deployed into neutrino beam by 2022
- Effort to synchronize ANNIE detector to BNB beam with time resolution of ~300 ps is currently missing
- White Rabbit system can provide time precision down to less than one ns over many kilometers

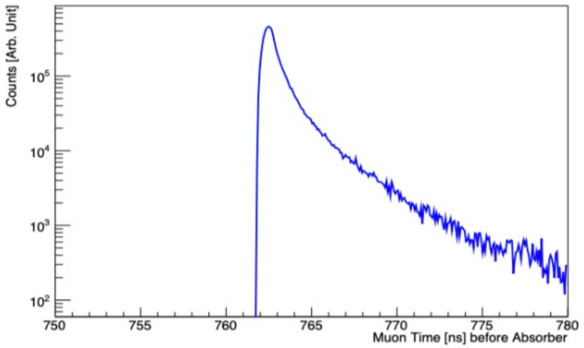


Synchronization b/w time at detector & time of bunch-by-bunch proton

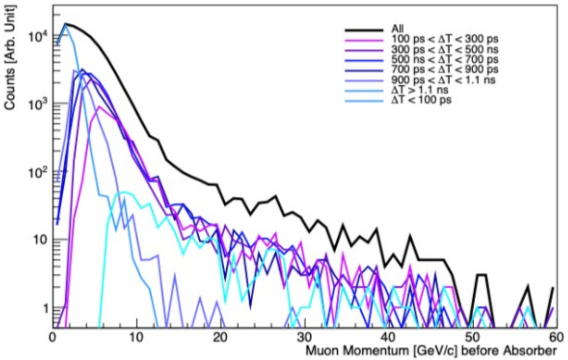
Synchronization tools will be useful for future detector experiments with fast timing

Stroboscopic Muons

- Neutrinos & muons have a similar time-energy correlation from pion decay
- Muon momentum spectra can be measured stroboscopically
- Bin muons in same time intervals as neutrinos, create muon samples to normalize neutrino flux in each time bin
- By placing muon monitors before full absorbers installed, measure muon momentum spectrum during a low-intensity run on LBNF beamline – psec timing



Muon time before absorber



Muon momenta in each time bin after absorber

Reference:https://arxiv.org/pdf/1904.01611.pdf, https://indico.fnal.gov/event/58470/

Advantages

- With stroboscopic approach, PRISM Near Detector program can be further enhanced with a fast Near Detector
- Opens possibility of using PRISM's default program by providing Far Detector oscillated time slices
- Together with precision timing in beam delivery and time synchronization tools developed, first proof of principle can be performed with ANNIE
- An excellent opportunity here to think about fast timing for LAr-TPCs

Neutrinos & muons will play a key role in future neutrino experiments

Stroboscopic techniques allow us to exploit neutrino & muon beams to their fullest potential