Application of Precision Time Structure in On-Axis Neutrino Beams

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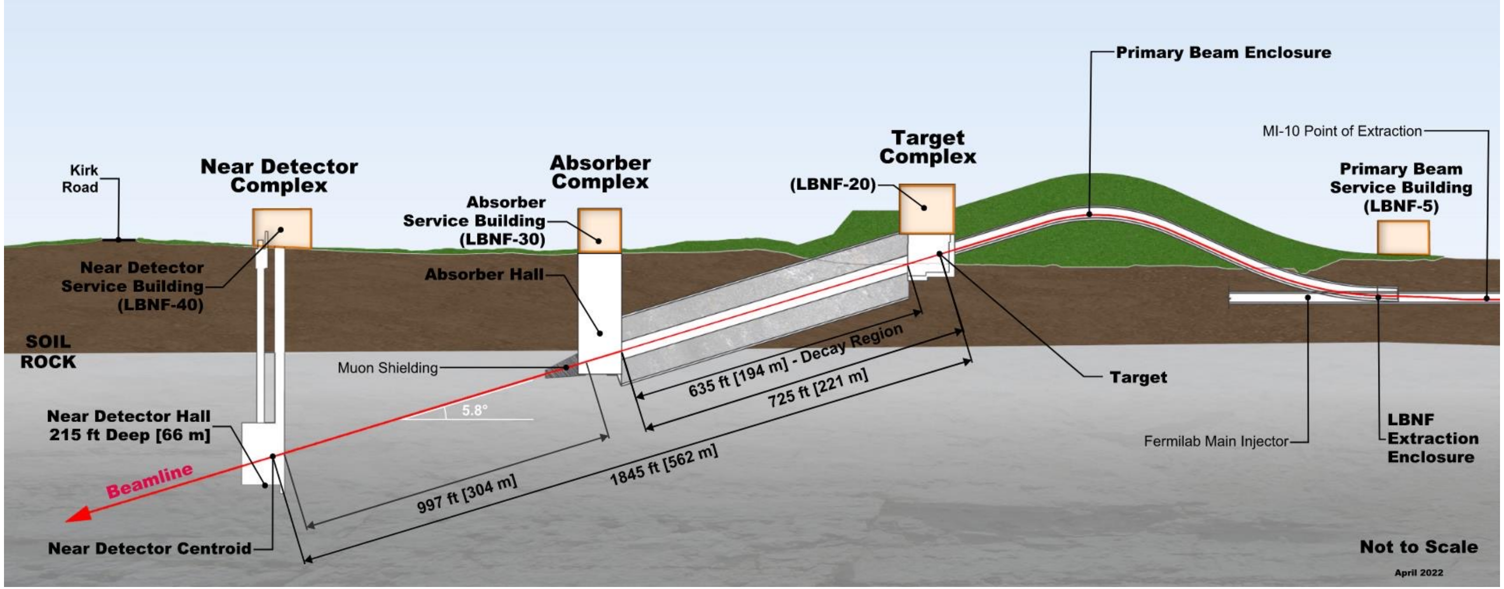
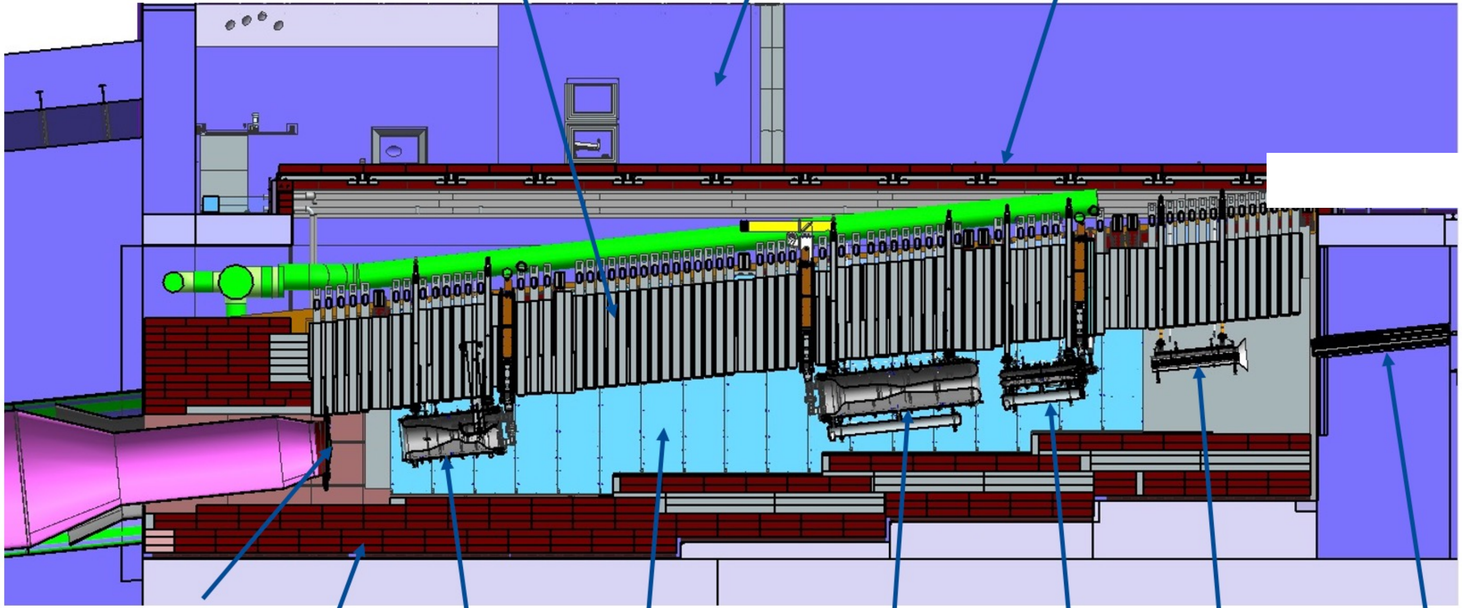
Fermilab

LBNF Beamline



- Proton beam extracted from Fermilab's Main Injector in the range of 60 – 120 GeV every 0.7 – 1.2 sec with pulse duration of 10 μs
- Protons per cycle:
  - -1.2 MW era: 7.5×10^{13}
  - -2.4 MW era: $(1.5\text{-}2.0) \times 10^{14}$

Target Hall Shield Pile Layout – Optimized Design



Removable Steel Shielding

Work Cell

Sealed Hatch Covers

Decay Region Upstream Window

Steel Shielding

Horn C

Cooling Panels

Horn B

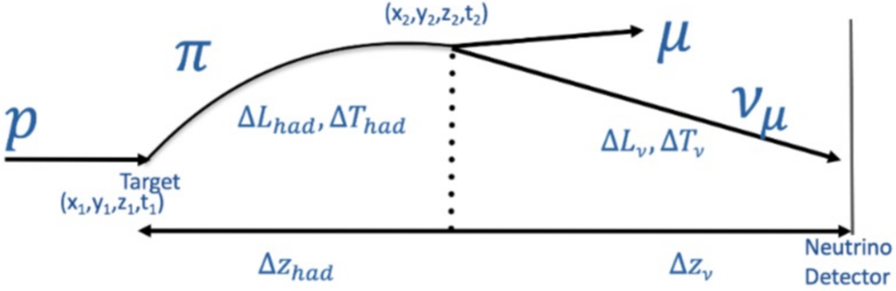
Horn A with Target

Baffle

Primary Beam Window Assembly

Neutrino Beam Timing

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



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

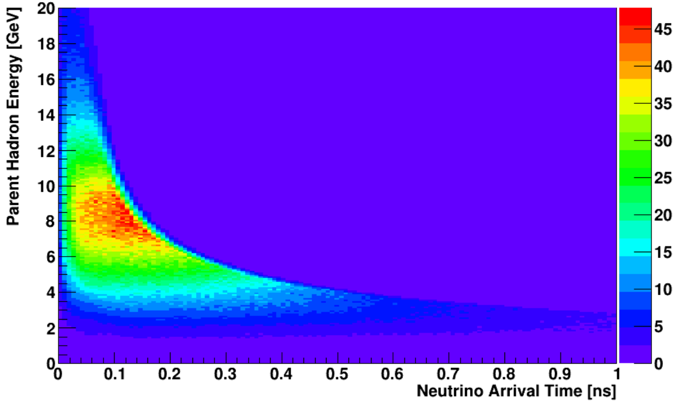
$$T_A^{prompt} = \Delta z/c = (\Delta z_{had} + \Delta z_{\nu})/c$$

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

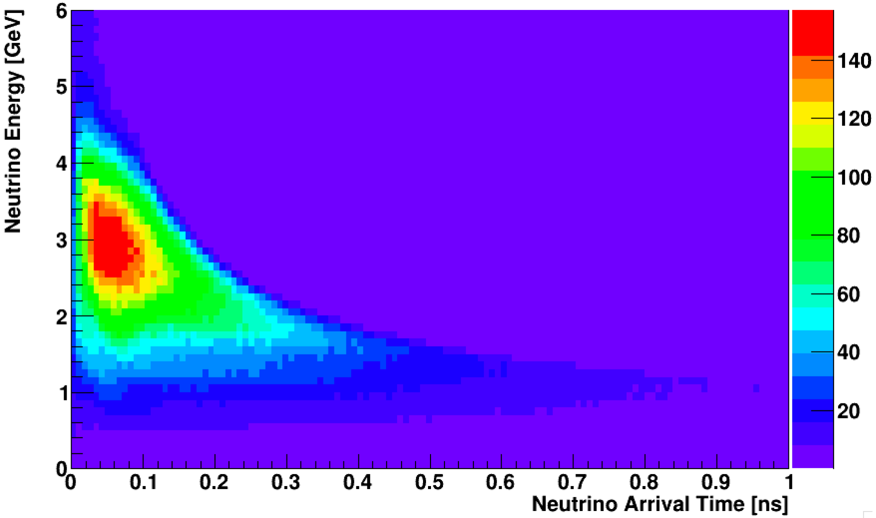
For $\Delta \mathrm{L}_{\nu} \approx \Delta \mathrm{z}_{\nu}$

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

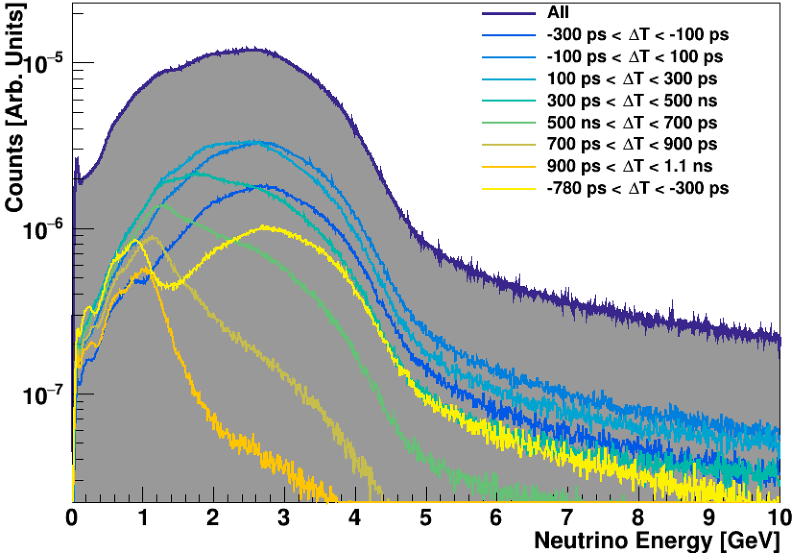
Arrival time difference between neutrinos from relativistic hadrons and neutrino from hadron of energy E:



Neutrinos at Near Detector



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

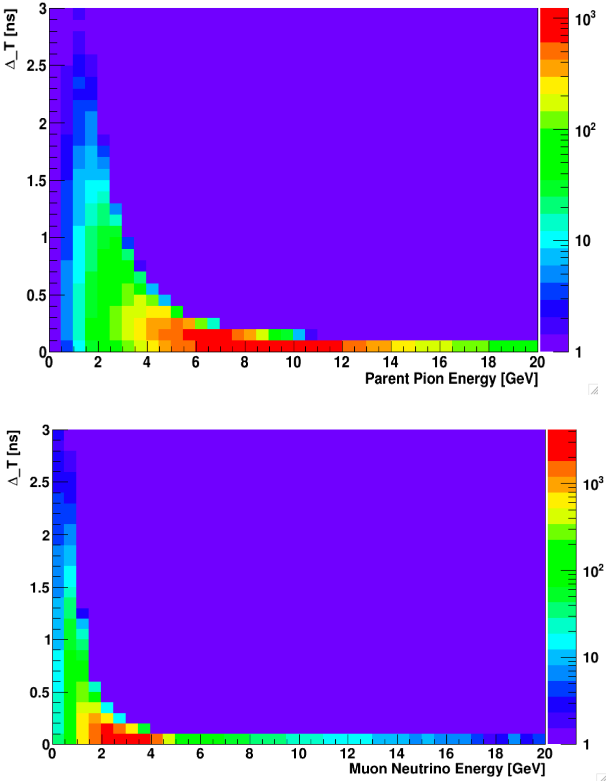


Simulation of neutrino energy distribution (the outer dark blue envelope), overlaid with fluxes corresponding to increasingly later binned time cuts, assumes 250 ps bunch width, 100 ps detector timing in 200 ps bins at the Near Detector

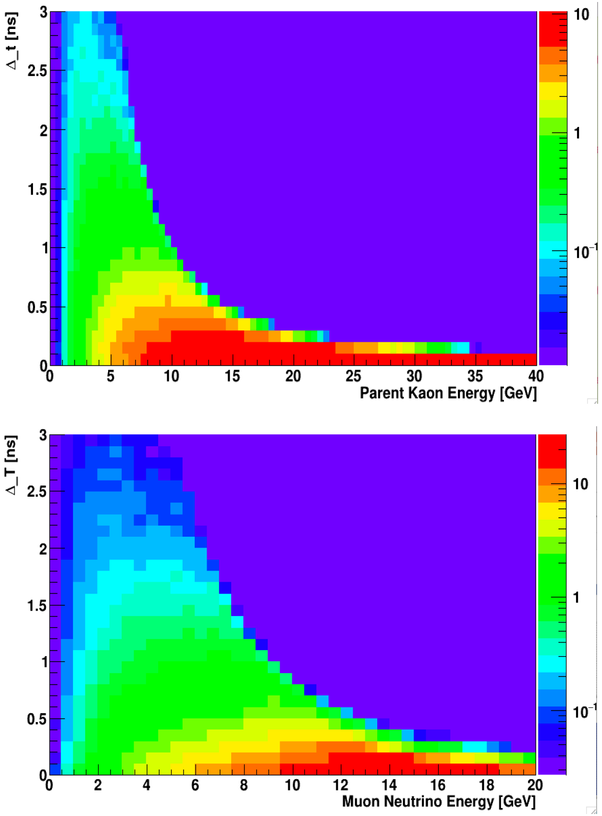
Both plots are made in Forward Horn Current Mode

Neutrinos at Near Detector

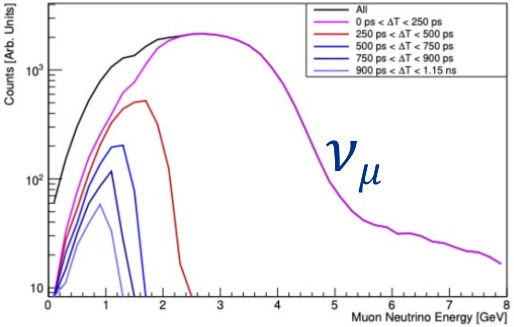
$P+C \rightarrow \pi^{+} \rightarrow \nu\mu$



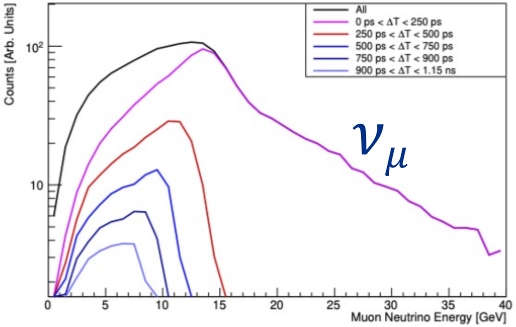
$P+C \rightarrow K^{+} \rightarrow \nu\mu$



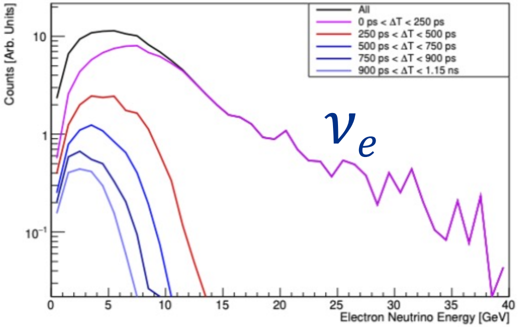
Timing to Separate Out Neutrino Family Types, Parent Hadron Components



Parent hadron: pion only

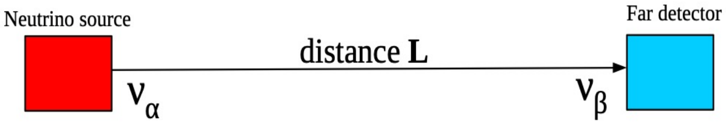


Parent hadron: kaon only



Parent hadron: kaon only

Motivation



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

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

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

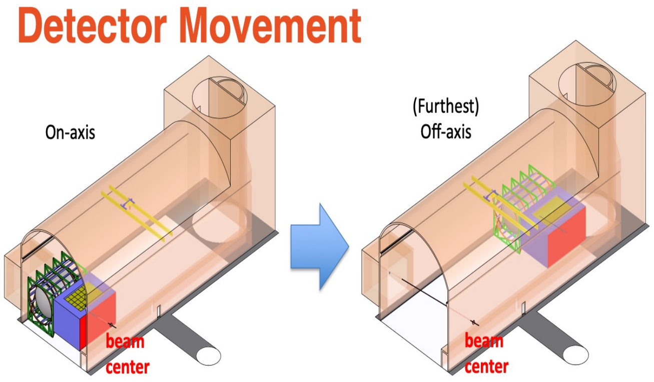
- Want to measure oscillation probability
- Instead measure neutrino interaction rate N
- N depends on flux, cross-section, detector acceptance
- Need to deconvolve initial neutrino flux & reaction cross sections, detector effects – each energy dependent

- Neutrino energy spectra different at Near & Far Detectors, 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 & FD were literally identical, flux differences mean no cancellation b/w ND & FD

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

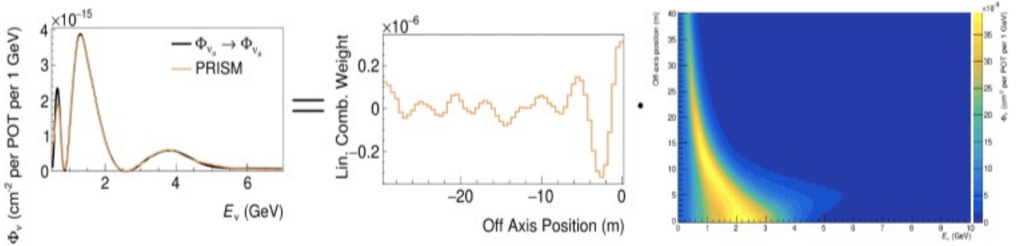
- Allows to make cross-section measurements in different energy distributions:
  - same detector
  - same target material as FD



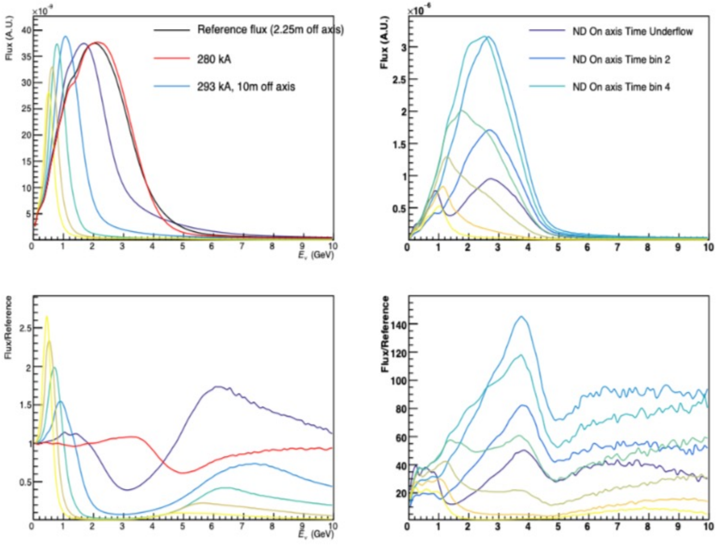
- **But application limited to ND**

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

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



PRISM Complementarity of Stroboscopic Approach



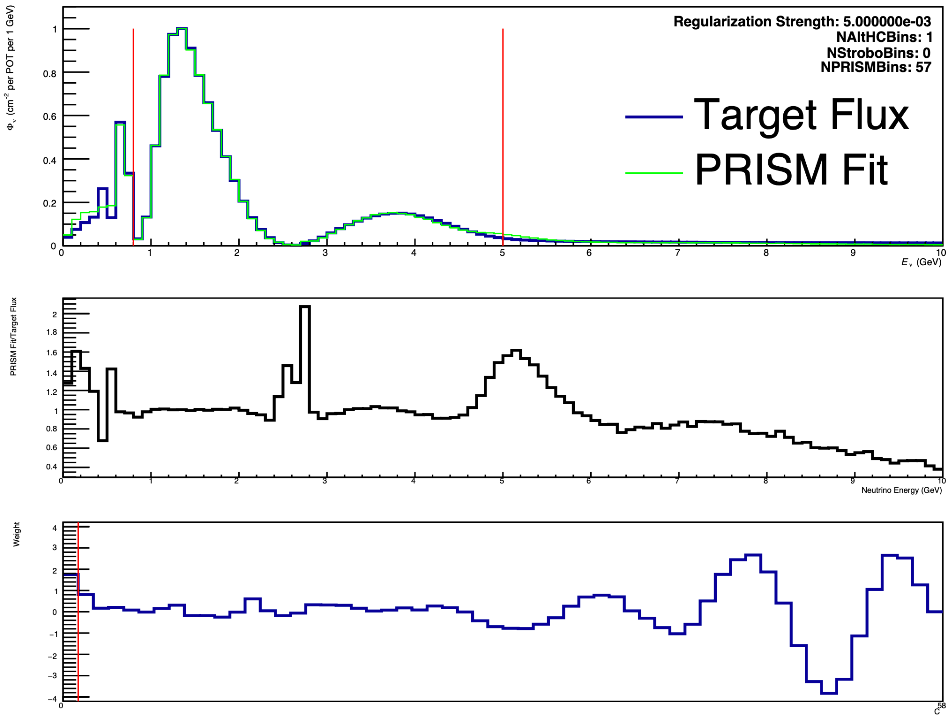
Flux components at Near Detector to perform PRISM fits

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

Top right: Stroboscopic fluxes

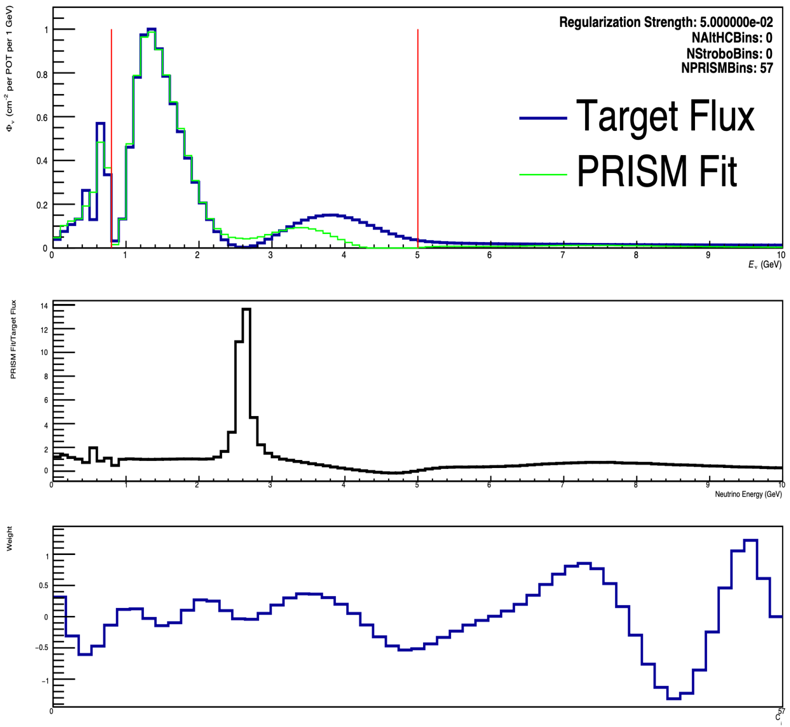
Bottom left: Ratio of the PRISM fluxes and the 280kA flux to reference flux

Bottom right: Ratio of the stroboscopic fluxes to reference flux

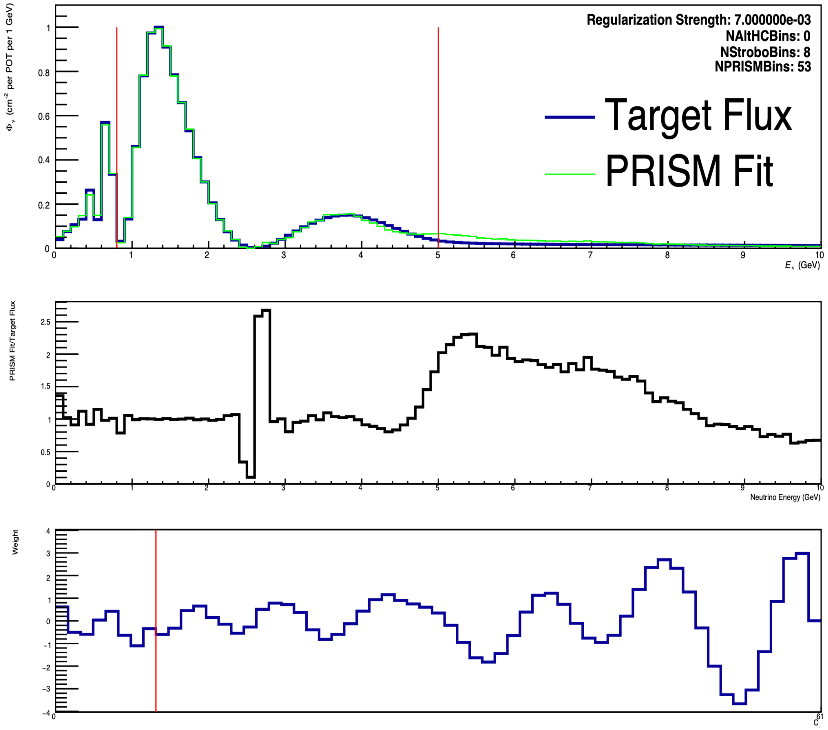


Default PRISM fit with PRISM on and off-axis fluxes and altHC flux

PRISM Complementarity of Stroboscopic Approach



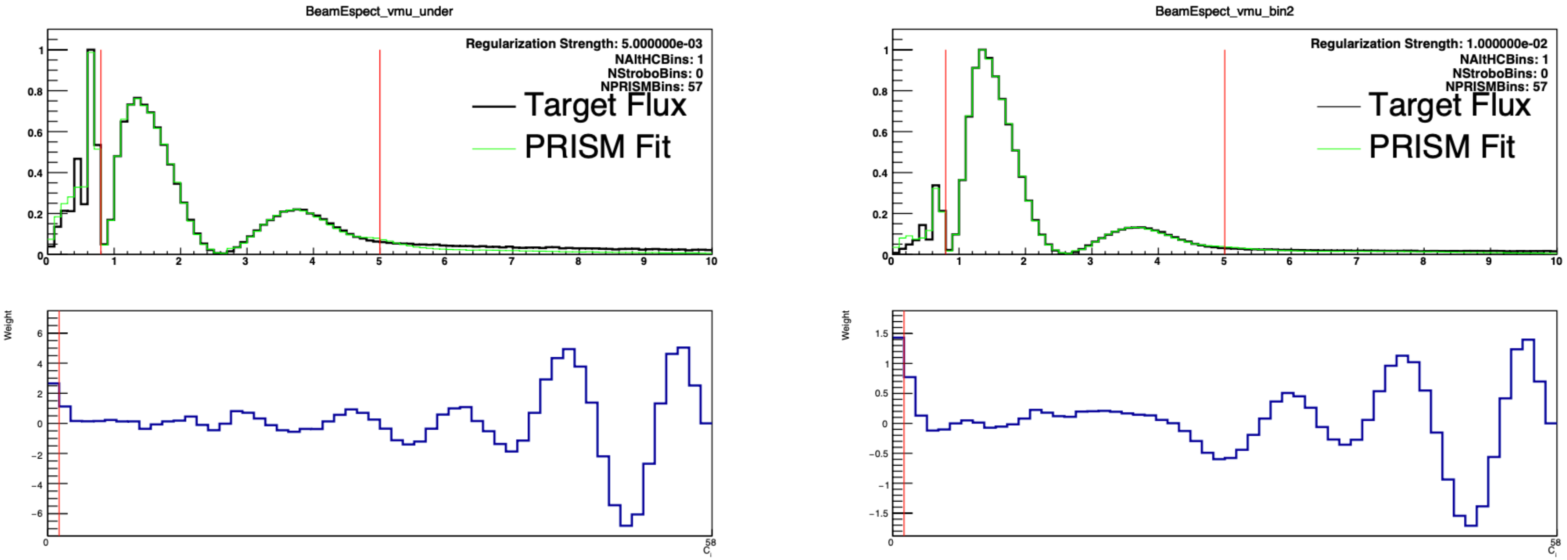
PRISM fit with PRISM on and off-axis fluxes only, no altHC flux



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



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

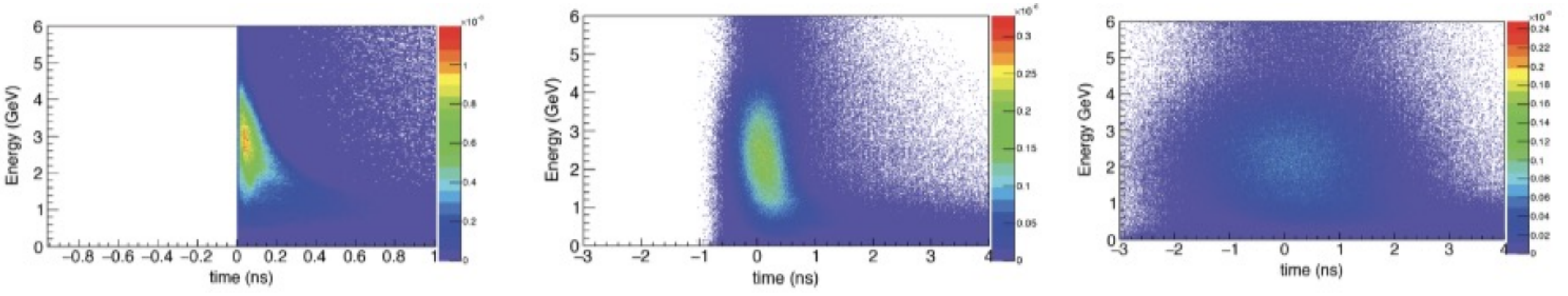
Application of stroboscopic approach requires:

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

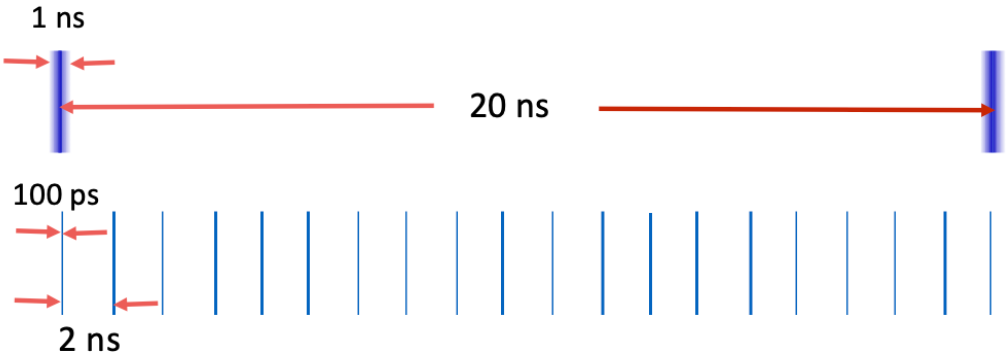


- Energy and time correlation of neutrinos becomes smeared when proton bunch has a non-zero time-width
- At ~1 ns bunch lengths typical of Fermilab neutrino facilities, correlation b/w timing and energy is mostly washed out except for a small, low-statistics tail

Creation of Shorter Proton Bunches

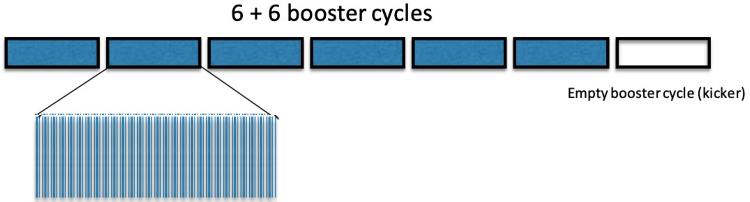
Re-bunching beam proposed in: https://arxiv.org/pdf/1904.01611.pdf

O(1) ns bucket every 20 ns → O(100) ps bucket every 2 ns

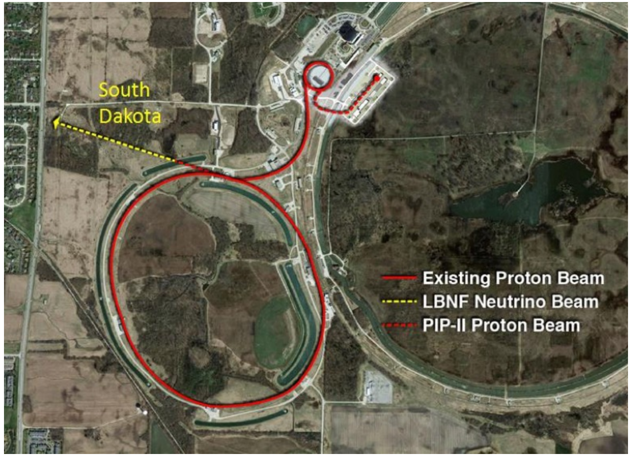


- Superimpose a higher frequency harmonic on top of bunch structure: 10xharmonic, going from 53.1 MHz to 531 MHz
- Total number of protons stays same
- Requires adding a Superconducting RF Cavity

Creation of Shorter Proton Bunches



- Recycler and Main Injector(MI) rings are 7 X diameter of Booster
- Recycler accumulates Booster protons in 6/7 of its circumference (504/588) RF buckets. An 84 buckets gap is left for Kicker to direct beam to target
- MI accelerates protons from Recycler from 8 GeV to 120 GeV, after which Kicker directs them onto neutrino target



•10x re-bunching (531 MHz) proposed in MI, after acceleration

•Advantage: re-bunching at a fixed energy

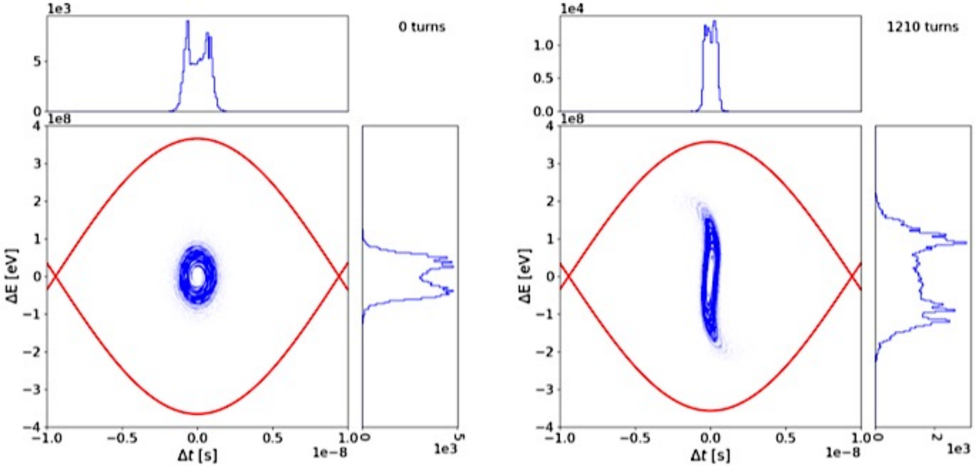
•Adiabatically ramping down the existing 53 MHz cavity and ramping up of a single 531 MHz SRF cavity

Addition of a new cavity, however, require 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

Longitudinal phase distribution with (right) &

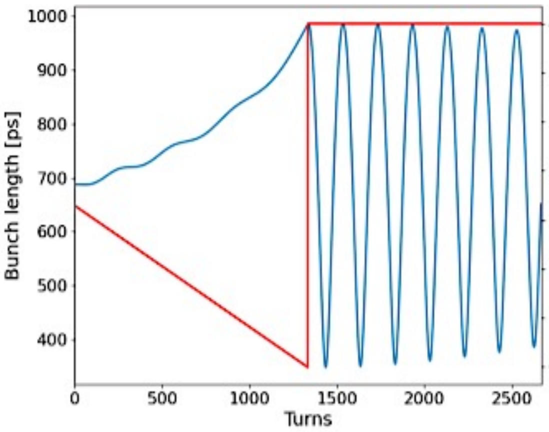
without (left) bunch rotation with simulated data generated with BLonD

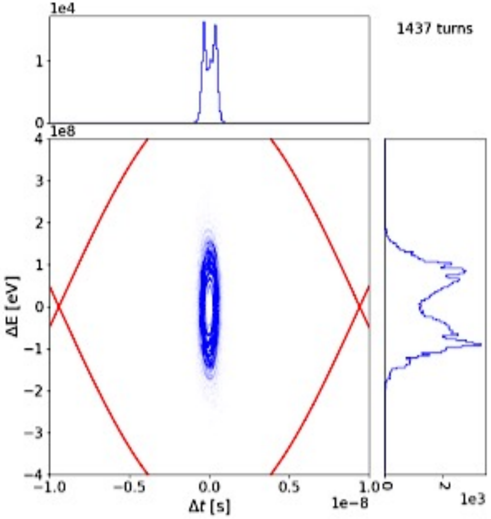
Creation of Shorter Proton Bunches

- Use bunch rotation at MI to create Narrow Bunches

Snap Bunch Rotation in MI:

Minimal bunch length of 350 ps occurs ~ 1437 revolution



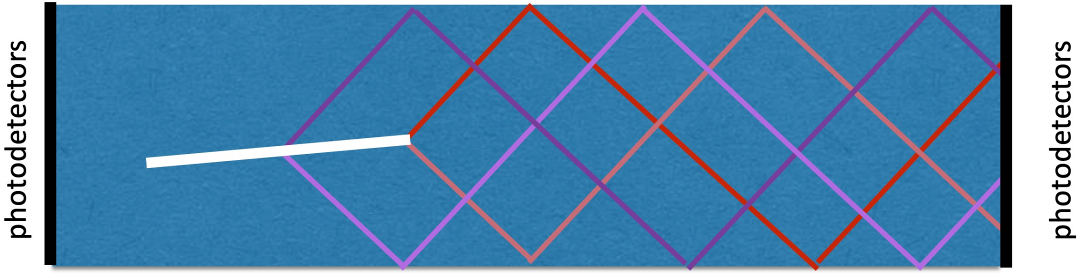


- Longitudinal phase distribution with bunch rotation (left)
- RF voltage modulation (left)

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

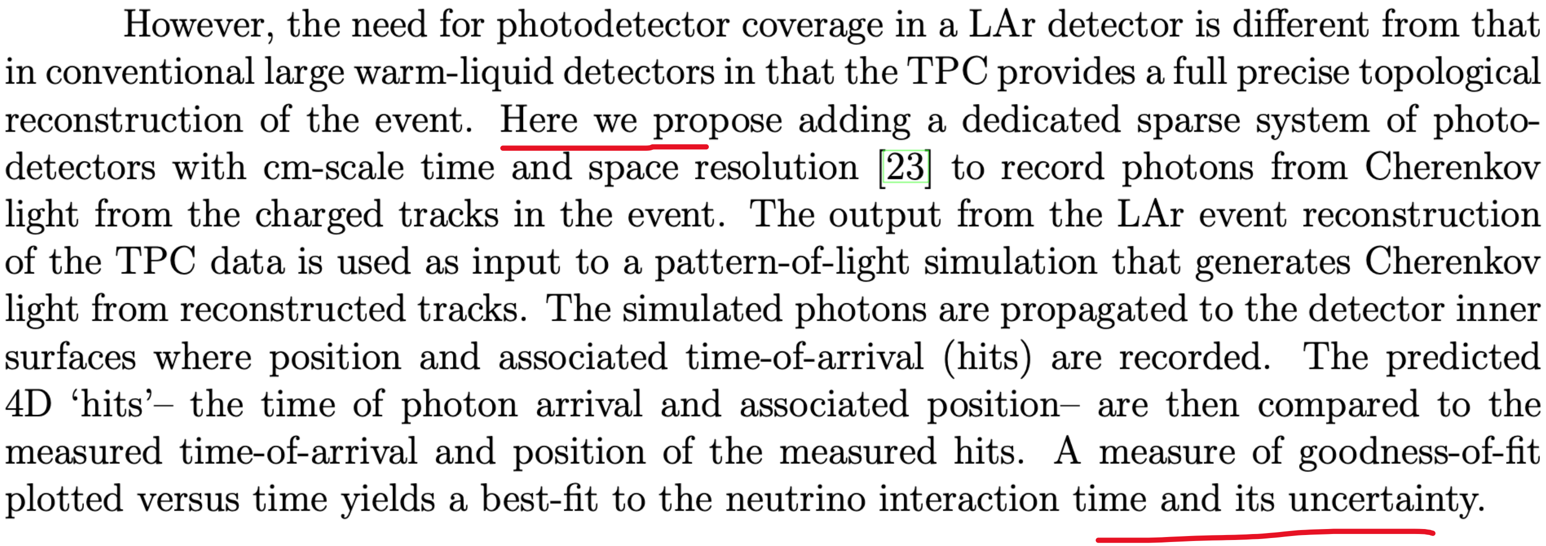


- From electron TPC data, liquid Argon-based detectors can precisely re-construct each event in space
- It is possible to use reconstructed track from electron drift to simulate detected time and position of Cherenkov photons emitted by some or all charged particles
- Only one parameter, neutrino event time needs to be fitted for, in comparison of 4D-coordinates of simulated photons and measured photons
- For 50-100 ps precision timing in liquid Argon, prompt light must be detected precisely, and Cherenkov light at visible wavelengths has properties required
- One option for photodetection - mirror top, bottom, sides, and place photodetectors on end caps

Outside scope of current ECA proposal

Detectors with fast timing

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



However, the need for photodetector coverage in a LAr detector is different from that in conventional large warm-liquid detectors in that the TPC provides a full precise topological reconstruction of the event. Here we propose adding a dedicated sparse system of photodetectors with cm-scale time and space resolution [23] to record photons from Cherenkov light from the charged tracks in the event. The output from the LAr event reconstruction of the TPC data is used as input to a pattern-of-light simulation that generates Cherenkov light from reconstructed tracks. The simulated photons are propagated to the detector inner surfaces where position and associated time-of-arrival (hits) are recorded. The predicted 4D 'hits'– the time of photon arrival and associated position– are then compared to the measured time-of-arrival and position of the measured hits. A measure of goodness-of-fit plotted versus time yields a best-fit to the neutrino interaction time and its uncertainty.

Outside scope of current ECA proposal

ANNIE Detector

- ANNIE can provide a first demonstration of stroboscopic approach on neutrinos from BNB beam

- Energy of BNB spectrum skews towards the low end, there is a broader tail of low-energy neutrinos

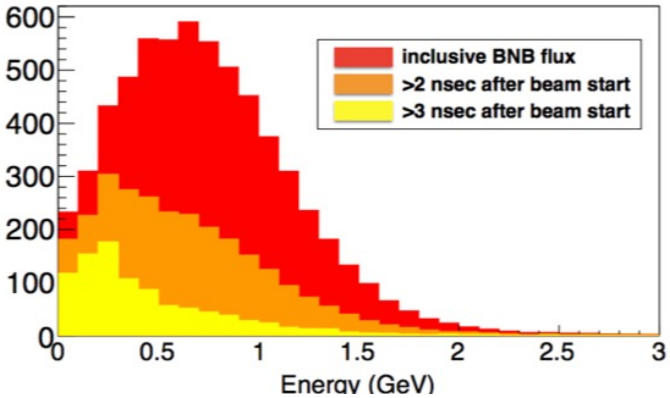
- Detecting time-slicing effect should be possible, even with 1 ns bunches, however a smaller bunch length is better

- **Motivates applying bunch rotation in Booster**

- ANNIE is running with LAPPDs deployed into neutrino beam by 2022

- Effort to synchronize ANNIE detector to BNB beam with the time resolution of ~300 ps is currently missing

- White Rabbit system can provide time precision down to less than a ns over many kilometers



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

Tools developed in completing synchronization will be able to be used for future experiments with fast timing in detectors

Advantages

- With application of stroboscopic approach, PRISM Near Detector program can be further enhanced with a fast Near Detector.
- Stroboscopic approach also 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
- ANNIE is equipped with Large Area Picosecond Photodetectors (LAPPDs) → better vertex reconstruction, improved background rejection
- With tools developed for time synchronization, precision timing can be applied to future oscillation experiments with fast detectors - there is an excellent opportunity here to think about fast timing for LAr-TPCs