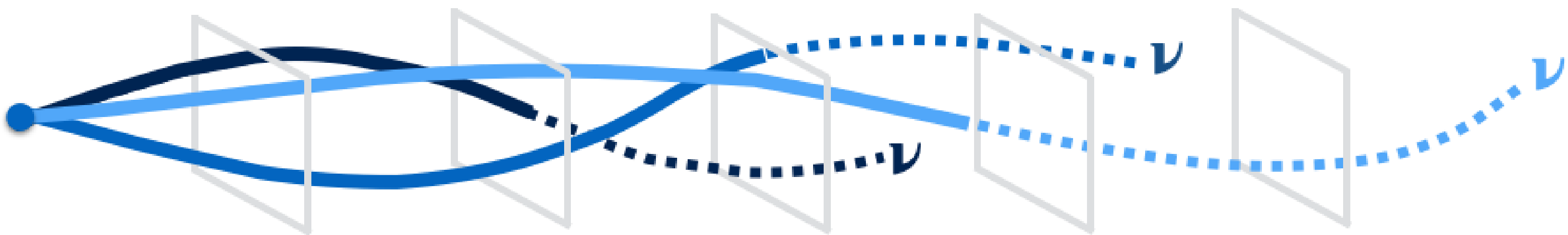


Physics with Precision Time Structure in On-Axis Neutrino Beams

Matt Wetstein

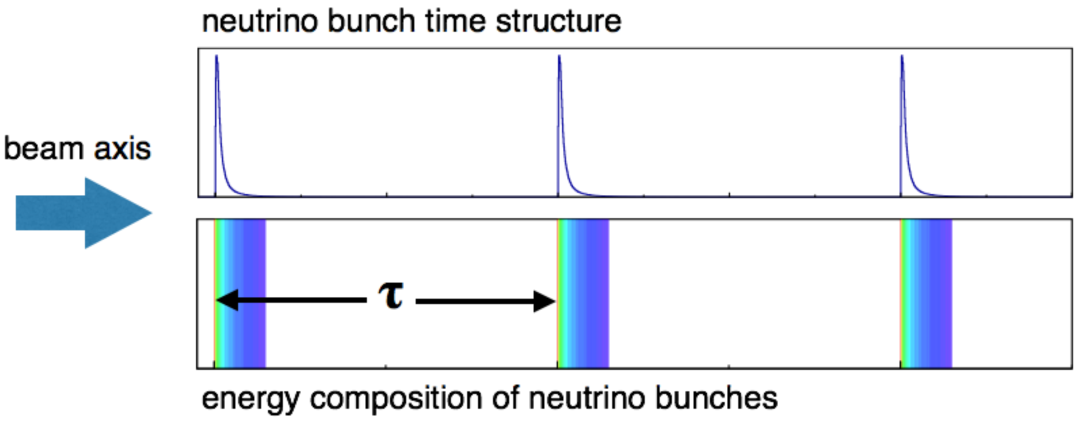
June 5, 2025

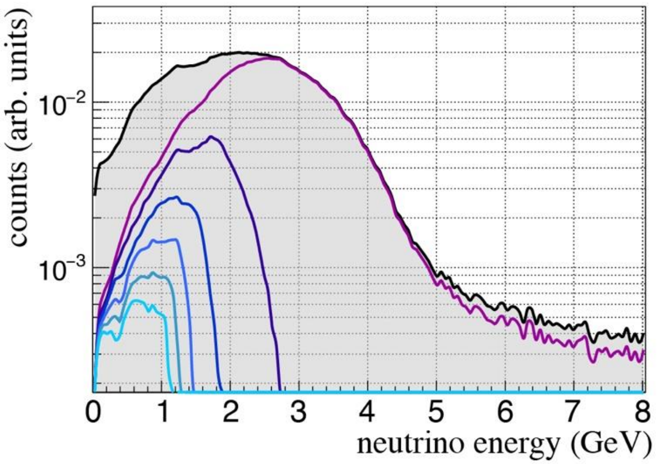
STATE

annie

Introduction

- Neutrinos beams have an intrinsic time structure imprinted on them by the accelerators used to produce them
- The relative arrival time of neutrino with respect to the bunch correlates with the neutrino energy, parent hadron, and flavor
- Timing in neutrino beams could therefore provide a strong experimental handle to help understand and reduce beam systematic uncertainties on flux, cross section, and energy reconstruction in DUNE
- It may also provide a new handle in searching for new physics





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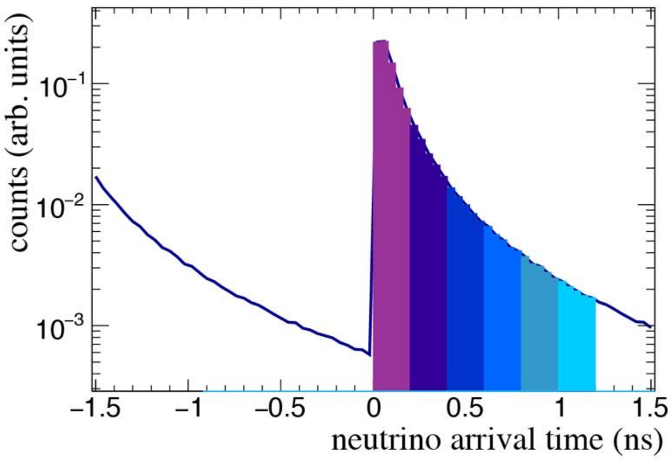
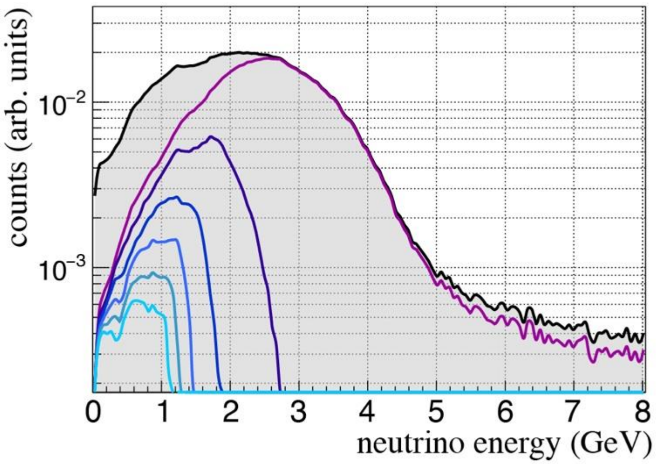
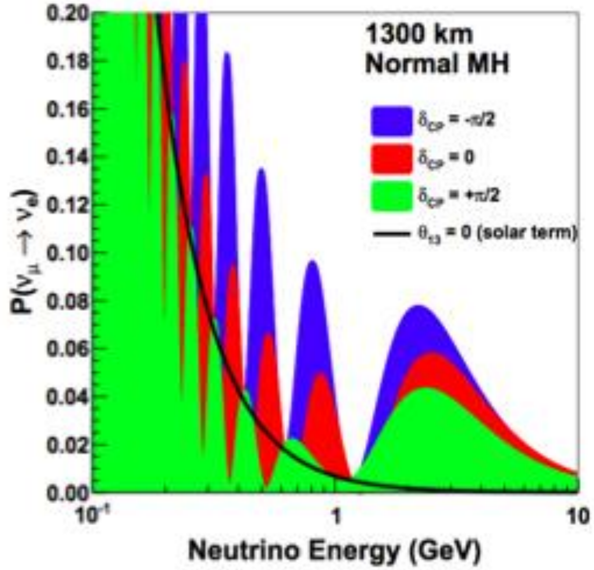
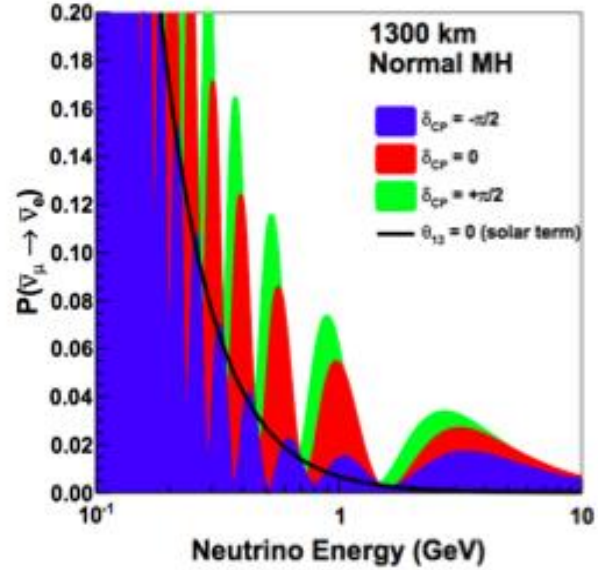
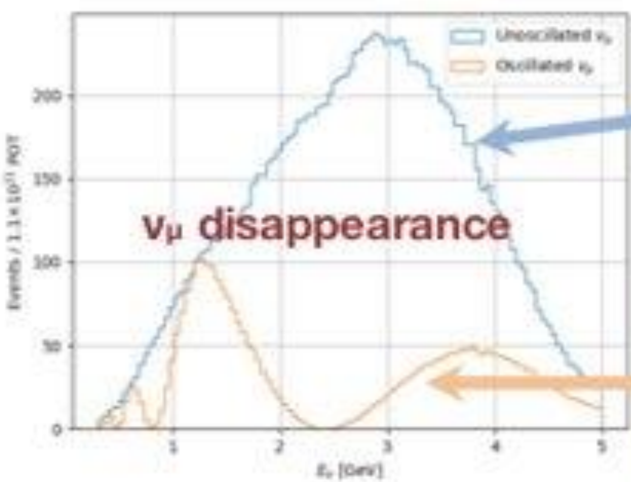




Neutrino oscillations are energy dependent

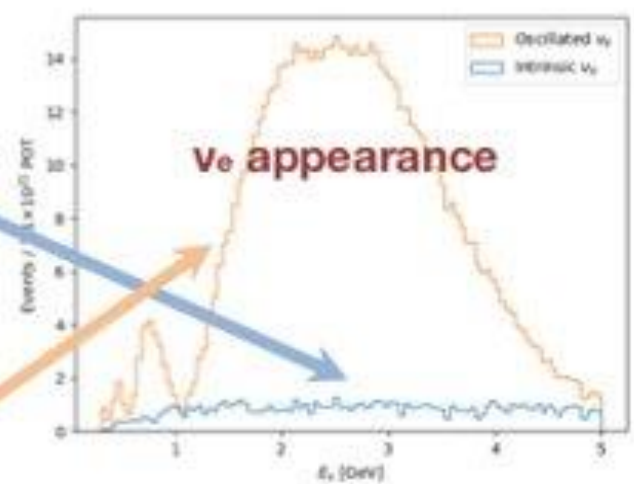




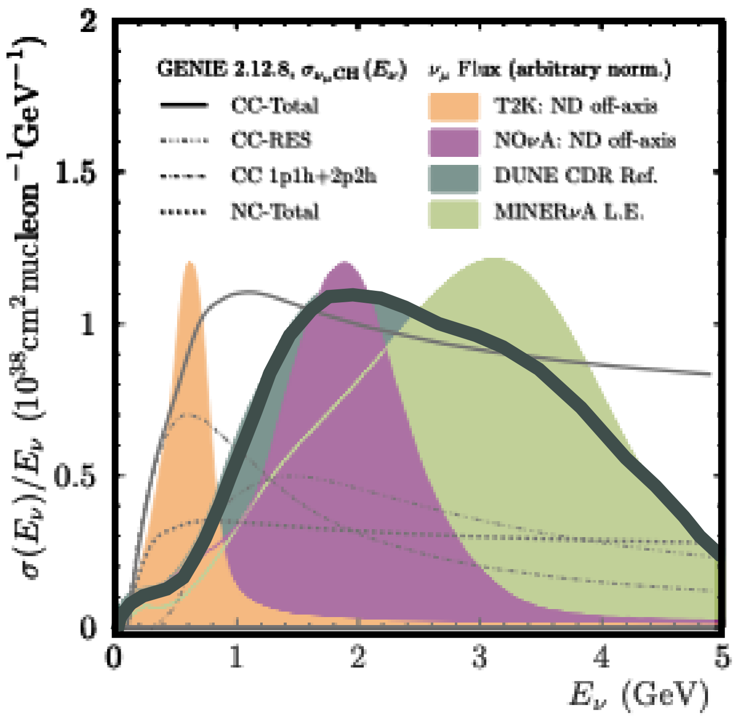


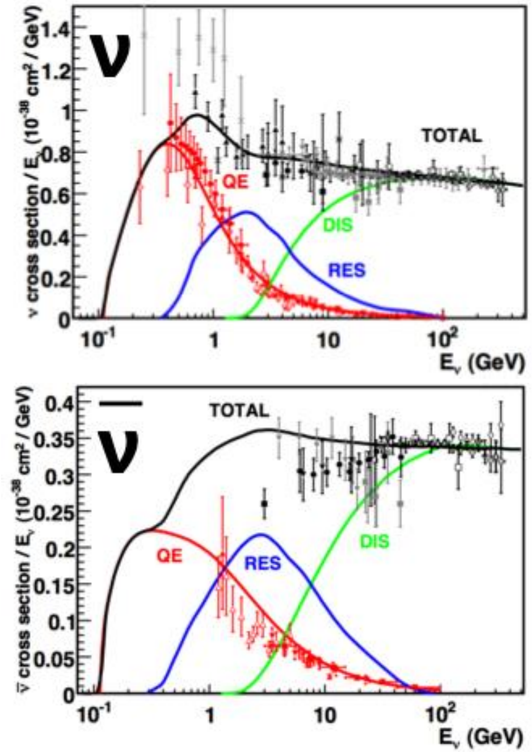
Near Detector Measures:
- Large ν_μ component
- Small ν_e component

Far Detector Measures:
- Osc. ν_μ component
- Osc. ν_e component



LBNF covers a wide range of energies





- This is advantageous because it enables shape fitting of the oscillation spectrum over a wide range
- It is also presents a challenge: it must rely on accurate reconstruction of neutrino energy and knowledge of the beam composition

Neutrino rates are cross section (and detector) dependent
…and sensitive to nuclear effects

- We do not always directly measure primary interactions. Neutrino scatters are often subject to Final State Interactions (FSI)
- Multiple combinations of primary interaction + FSI can yield final states with degenerate experimental signatures
- Missing energy can be carried away by undetected particles (e.g. neutrons)
- Argon is a particularly large and complex target nucleus

Systematics do not entirely cancel between near and far

$$R(\mathbf{k}) = \sum_{i}^{\text{process}} \sum_{j}^{\text{target}} \int_{E_{min}}^{E_{max}} \underbrace{\overbrace{\phi(E_\nu) \times \sigma_i(E_\nu,k) \times \varepsilon(k) \times N_j}^{\text{Near Detector}} \times P_{\nu a \to \nu b}(E_\nu)}_{\text{Far Detector}} \; dE_\nu$$

- Energy dependent cross sections are sampled by a very different energy spectrum in the far detector than that of the near detector
- The DUNE Prism working group has shown that it is possible to tune the cross sections and flux model to achieve data-Monte Carlo near detector agreement and get the oscillation measurement *wrong*

The importance of adding multi-dimensional constraints

If we can identify reconstruction-independent observables that allow us to select different energy spectra within the same beam…

…Then we have multiple constraints with which to disentangle flux and cross-section uncertainties

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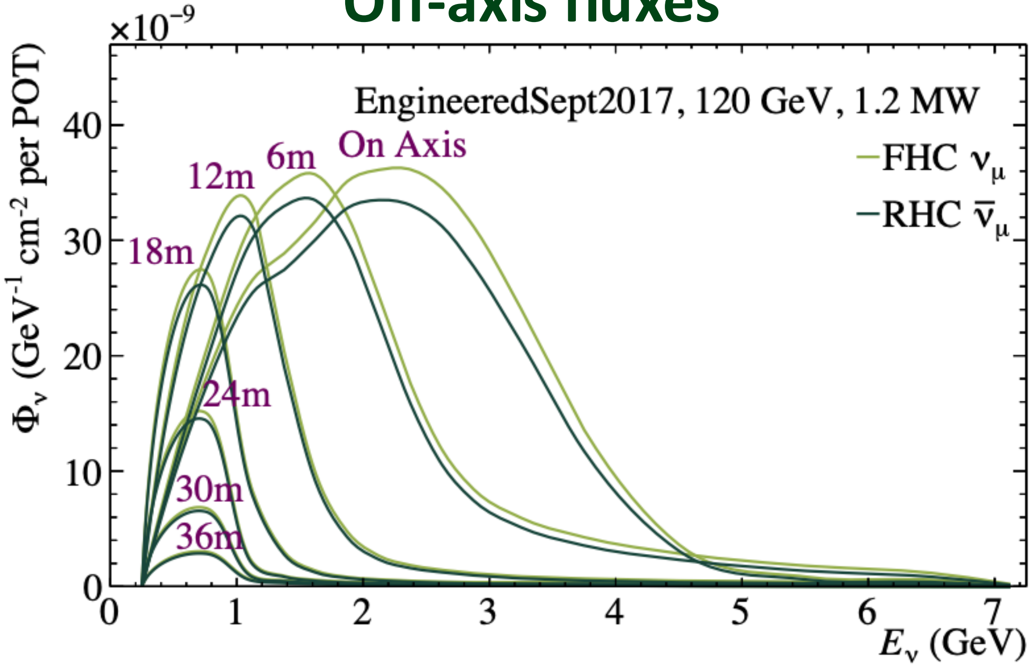
Off-axis fluxes



DUNE has already recognized this and placed a priority on DUNE-Prism, which explores the LBNF near neutrino flux at different off-axis angles

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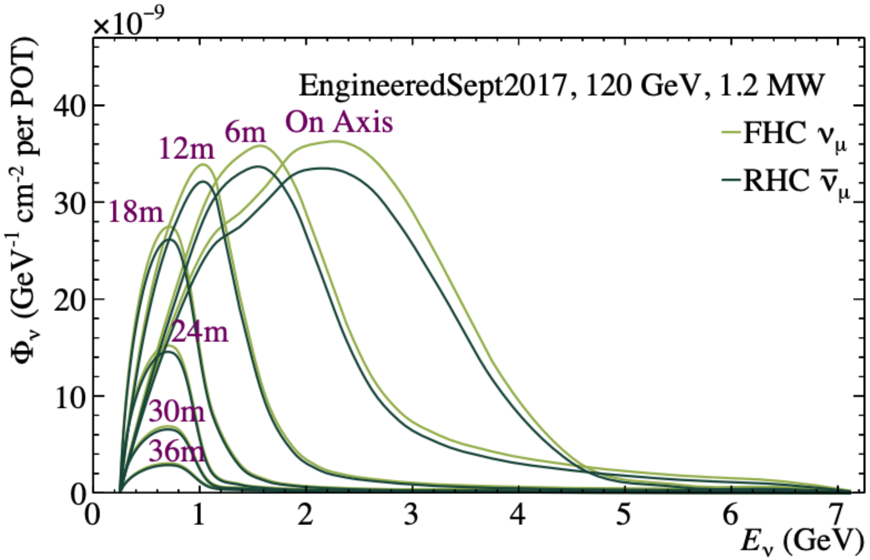

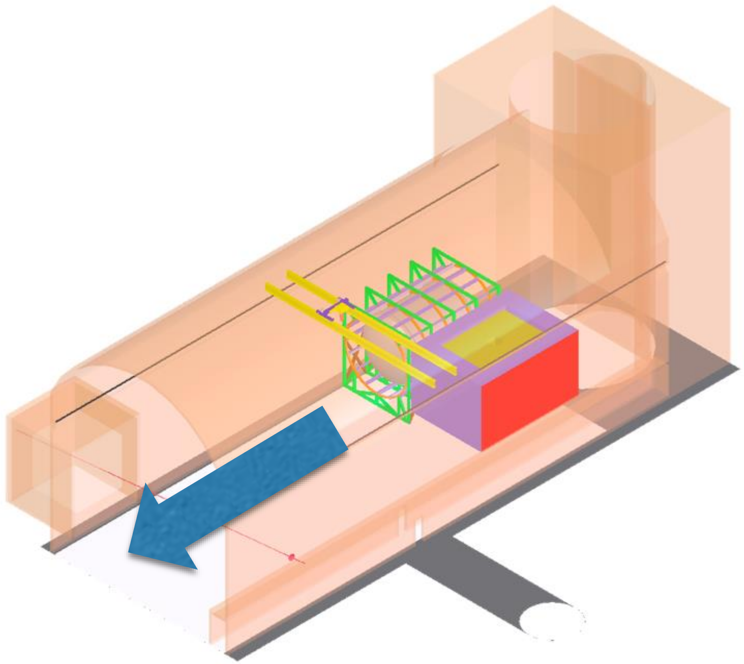

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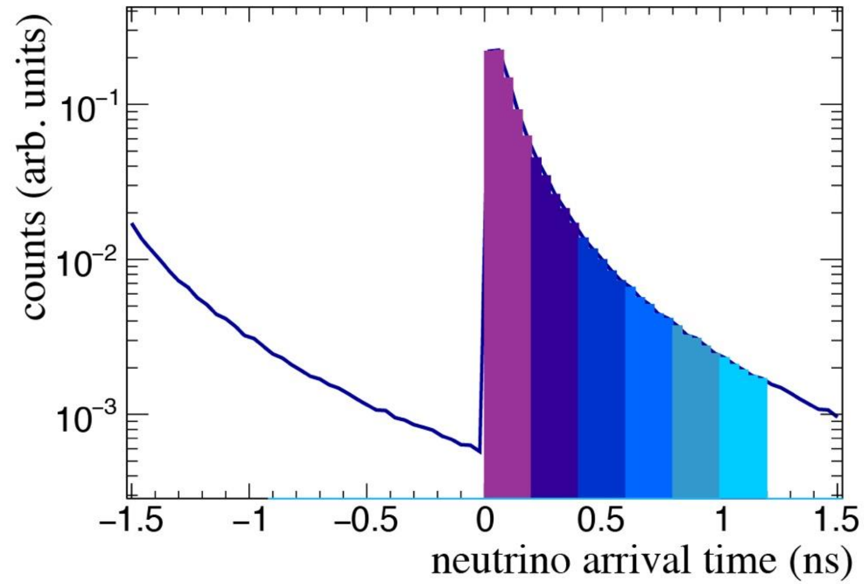
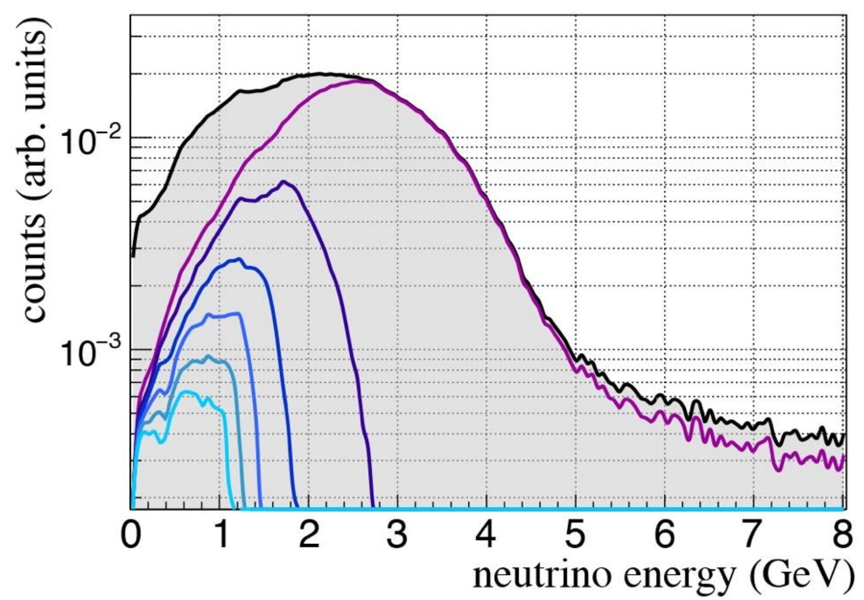
Time-Slicing of Neutrino Fluxes

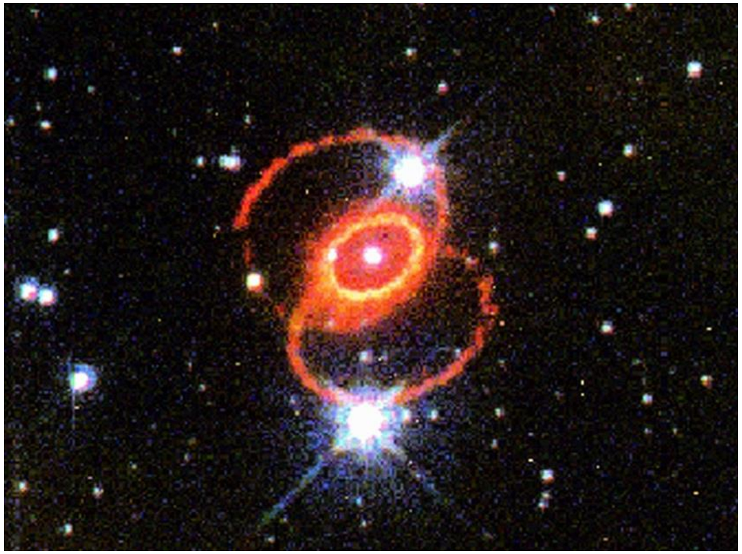
Basic Timing Concept

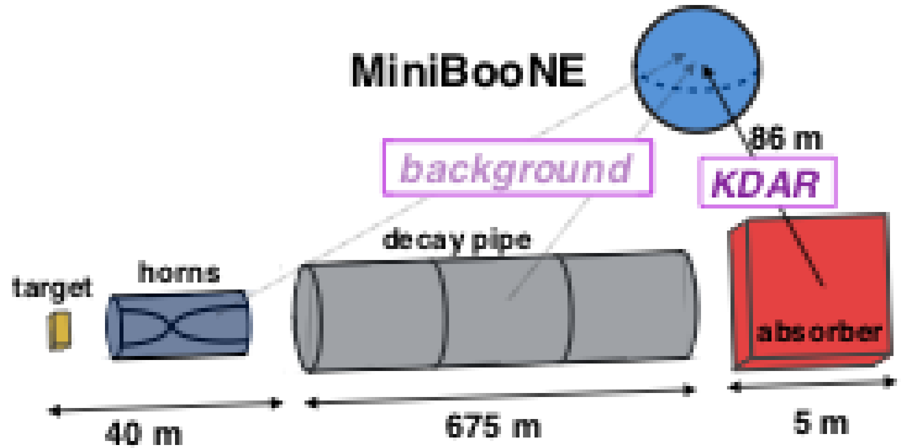
- Precision timing can be used to measure the arrival time of neutrinos with respect to the rest of the bunch
- Later neutrinos tend to have lower energies due to the correlation between neutrino energy and the velocity of the parent hadron
- This allows one to select different flux spectra based on timing
- All of these fluxes co-exist within a single on-axis detector





Prior Efforts on Timing



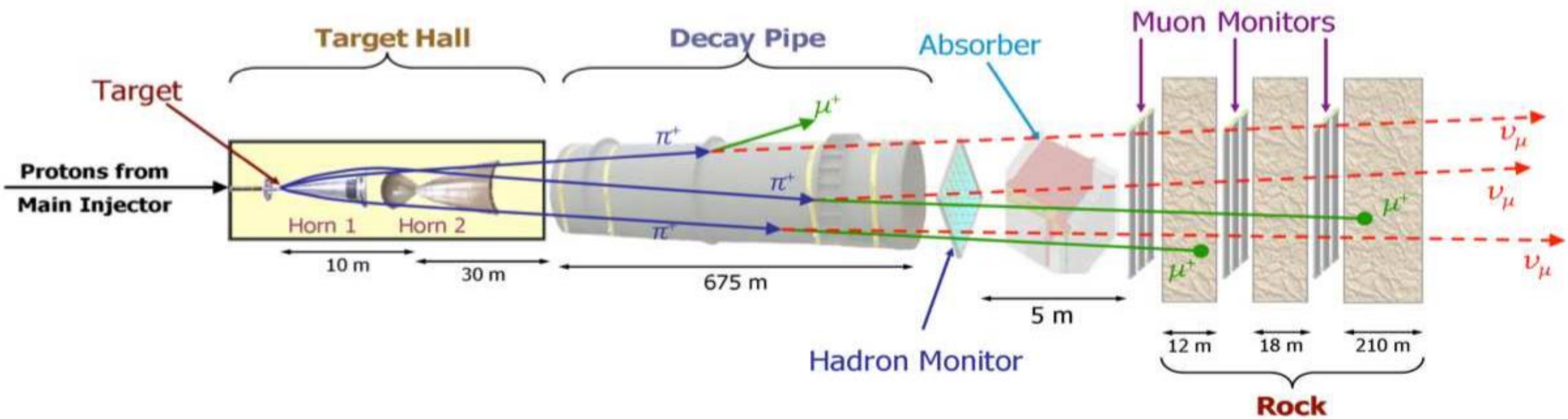


- M Goldhaber suggested that neutrino arrival times could be used in the analysis of SN1987a 10.1142/S0217751X03017154
- MINOS demonstrated precision timing with the sub-structure of NUMI in their neutrino time-of-flight paper https://arxiv.org/abs/1408.6267
- MiniBooNE recently published a stopped Kaon analysis based on arrival time with respect to the bunch. https://arxiv.org/abs/1801.03848
- MiniBooNE also explored the idea of selecting different energy spectra Melanie L Novak, Bucknell (2002)

- Proton beams collide with a target, producing pions and kaons
- These hadrons are selected by sign and momentum and focused by a series of magnetic horns

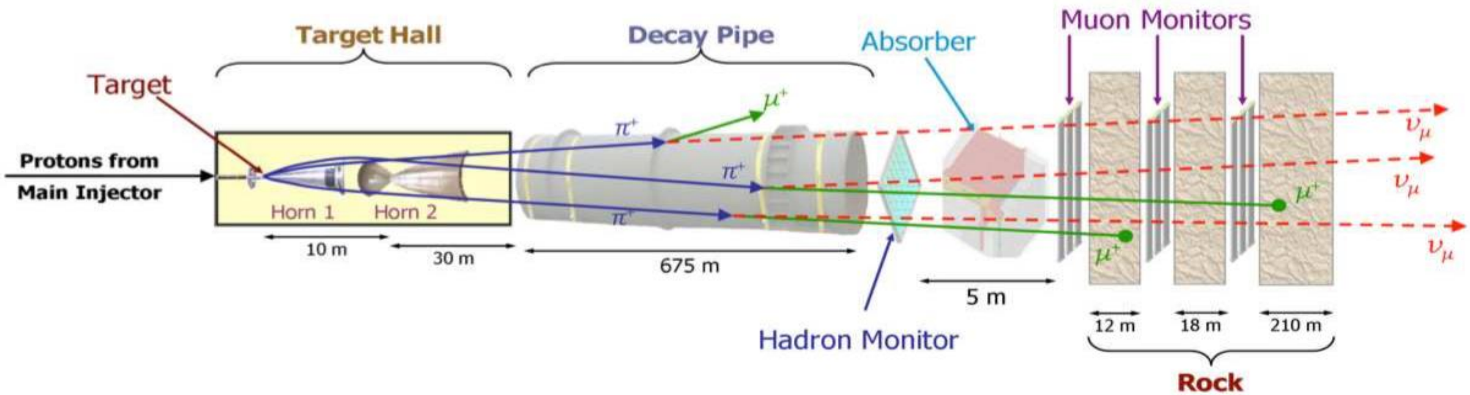
- The hadrons decay into muons and ν_μ's with a strongly forward directionality.
- An intrinsic background or ν_e's originates from early-decay of the muons. An additional wrong-sign component originates from hadrons not rejected by the magnetic horns.

The final kinematics of the neutrinos are driven by hadron kinematics & decay time



Kinematics of the Neutrino Timing

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

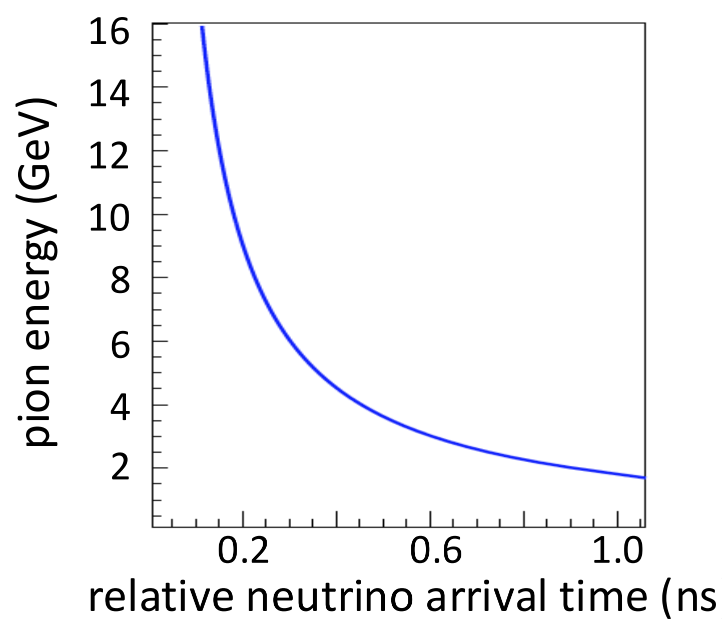


$$\Delta t(E) = \tau(E)[1-\beta(E)]$$

$$\Delta t(E) = (\gamma\tau_0)[1-\sqrt{(1-1/\gamma^2)}]$$

$$\Delta t(E) \rightarrow \tau_0 \quad \text{as} \quad \gamma \rightarrow 1$$

$$\Delta t(E) \rightarrow \tau_0/2\gamma \quad \text{for} \quad \gamma >> 1$$



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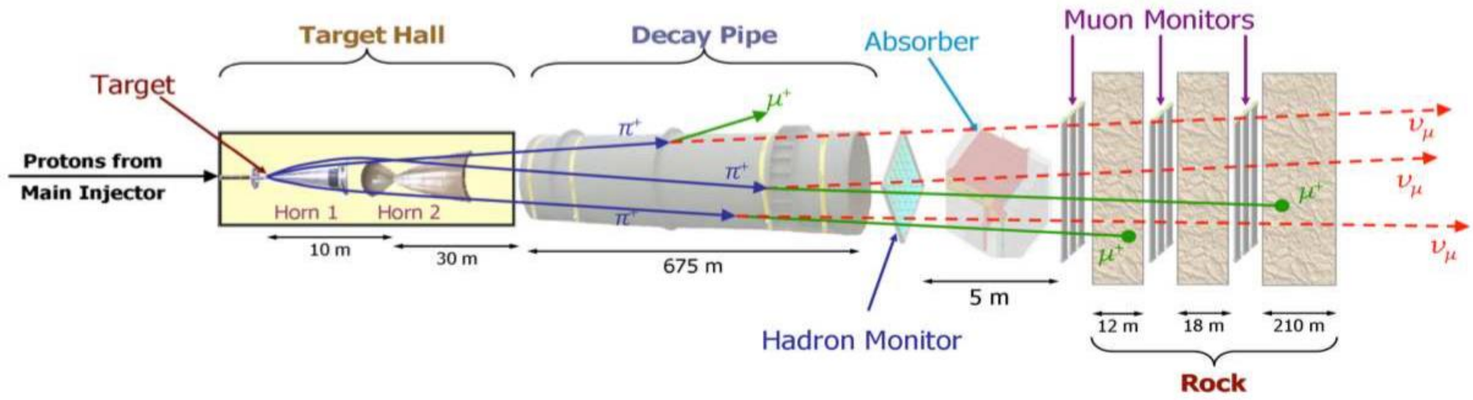

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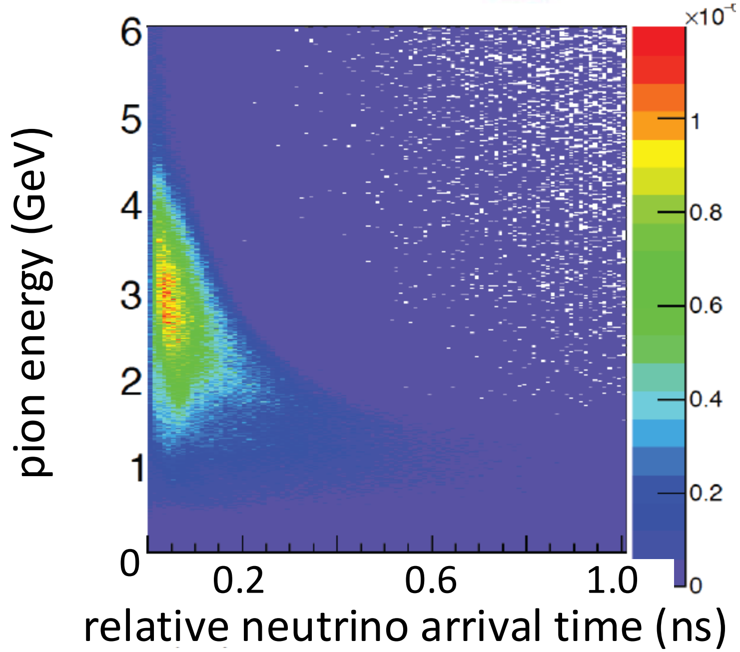


Characteristic Timescales/Limiting Factors

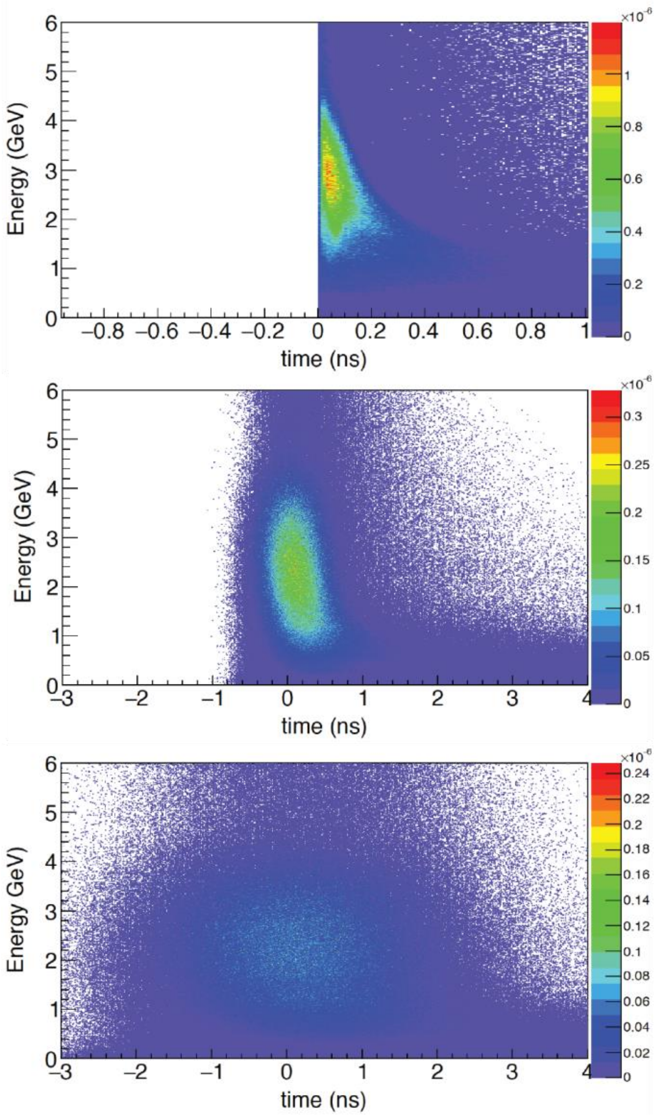
Stroboscopic techniques require sufficiently short bunch sizes

- If all hadrons are produced at the same time, the different neutrino energies will stratify over roughly ~1 nsec
- This effect starts to wash out if the proton beam width or detector resolutions exceed a nsec
- The current Fermilab RF structure is not designed to deliver proton bunches much shorter than 1 nsec.

infinitesimal proton bunch

200 psec smearing

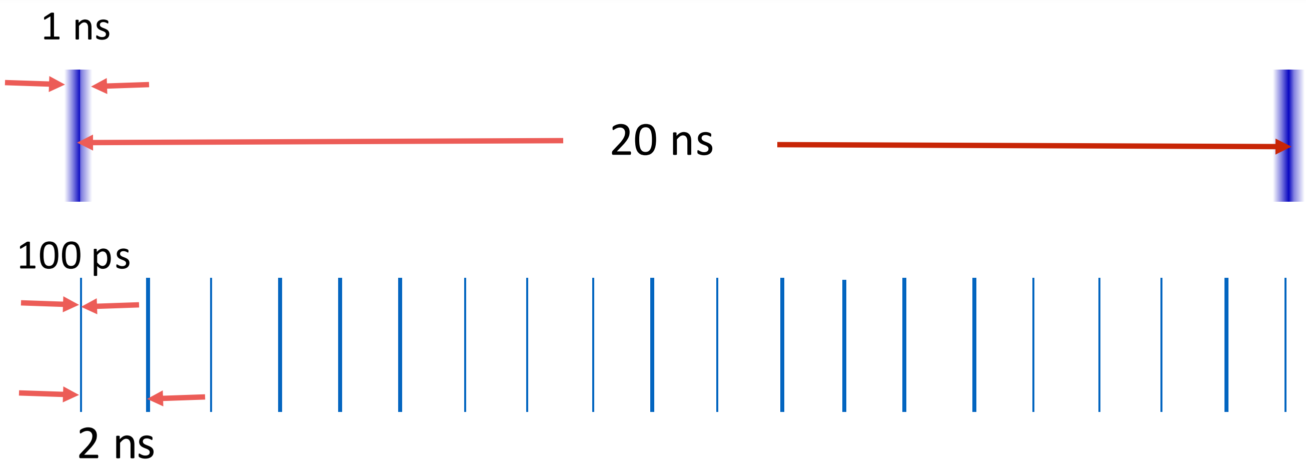
1 nsec smearing



Rebunching the Beam

- Compressing the existing proton bunches in time in not feasible
- However, imposing a higher frequency harmonic on top of the bunch structure would be compatible with FNAL accelerator operation.
- The 10x harmonic, going from 53.1 MHz to 531 MHz, has a particularly advantageous relationship between bunch size and spacing
- The total number of protons is preserved, just “reorganized”

53.1 MHz → 531 MHz
O(1) ns bucket every 20 ns → O(100) ps bucket every 2 ns



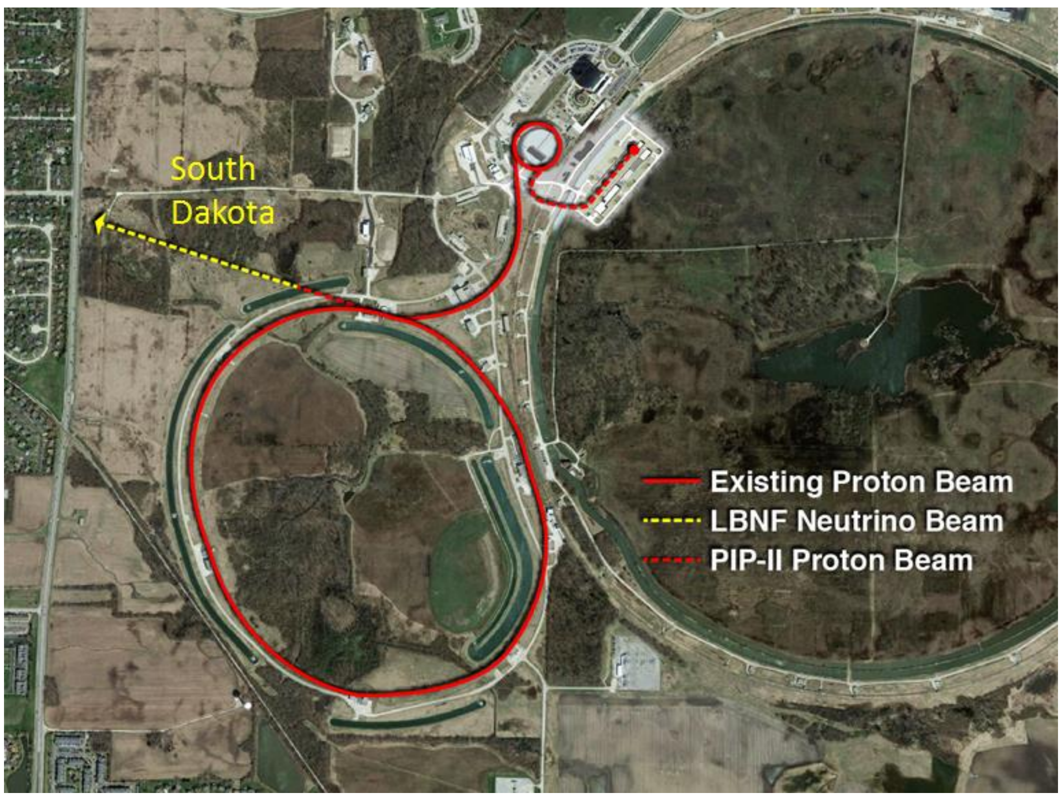
PRECISION TIMING IN BEAM DELIVERY

Artwork by Sandbox Studio, Chicago with Ana Kova

Intro: Delivering Protons on Target

6 + 6 booster cycles

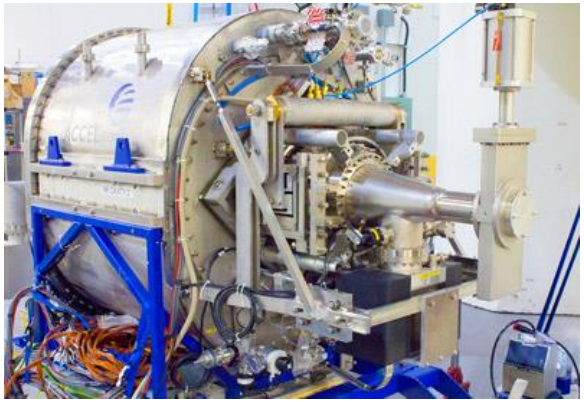
Empty booster cycle (kicker)

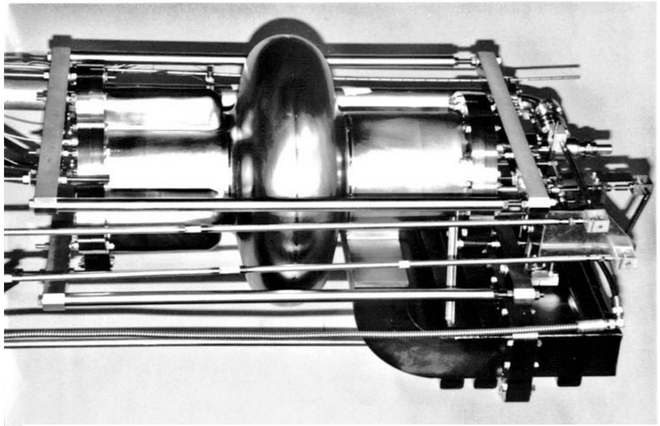


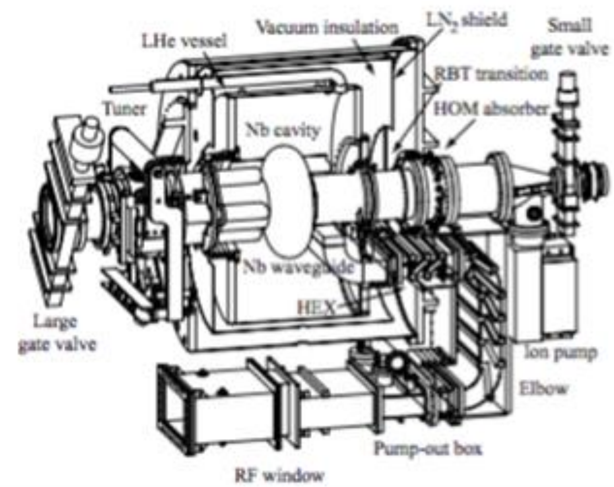
- The Recycler and Main Injector (MI) rings are 7 times the diameter of the Booster
- The Recycler accumulates Booster protons in 6/7 of its circumference (504/588) RF buckets. An 84 bucket gap is left for the Kicker to direct the beam to the target
- The Main Injector accelerates the protons from the Recycler from 8 GeV to 120 GeV, after which the Kicker directs them onto the neutrino target
- The typical MI cycle time is 1.2 s with a typical spill length of 11 microseconds

Adding a Superconducting RF Cavity

- Rebunching could be achieved with the addition of just 1 or 2 superconducting RF (SRF) cavities
- There is a commercially available SRF cavity that closely matches our needed expectations: The Cornell B Cavity:
  - 500 MHz (versus 531 MHz)
  - Well tested in the field
  - Large aperture
- Feasible to implement, would be first MI cryomodule



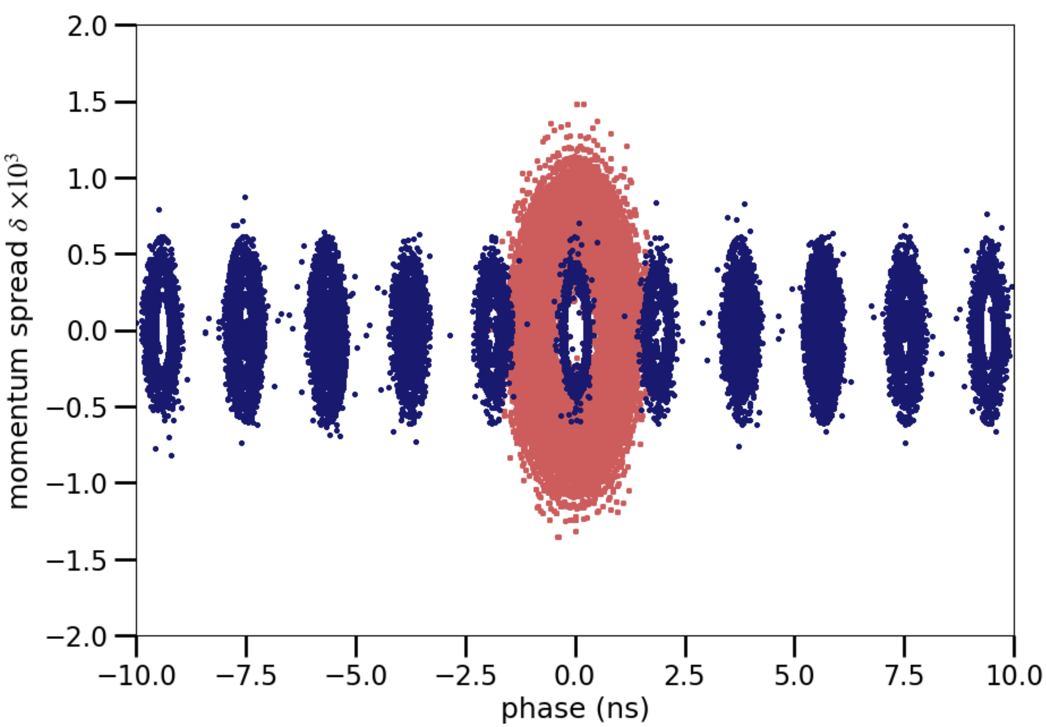




RF Simulation

A realistic, multi-particle simulation was performed to study the following properties of the rebunching procedure:

- ramp-down/ramp-up functions for rebunching at a higher frequency
- the final time structure/RMS time widths of the 531 MHz bunches



- The resulting rebunched structure is promising
- Typical 531 MHz bunches have an RMS of around 200 ps
- These bunches have sharp edges and substructure, which could be measured by RF monitors and exploited for better extracting time information

Evan Angelico, Sergei Nagaitsev

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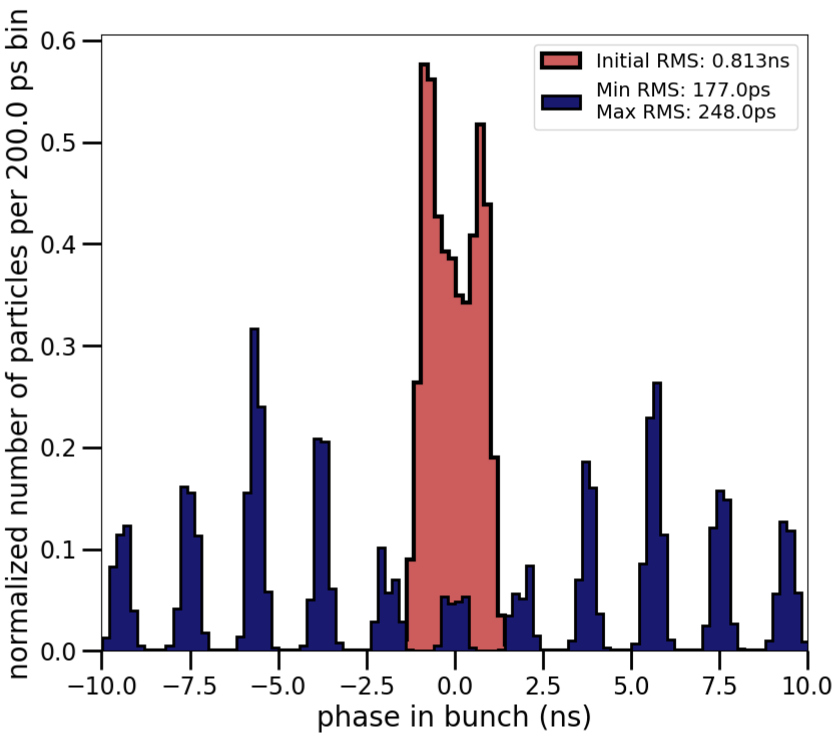

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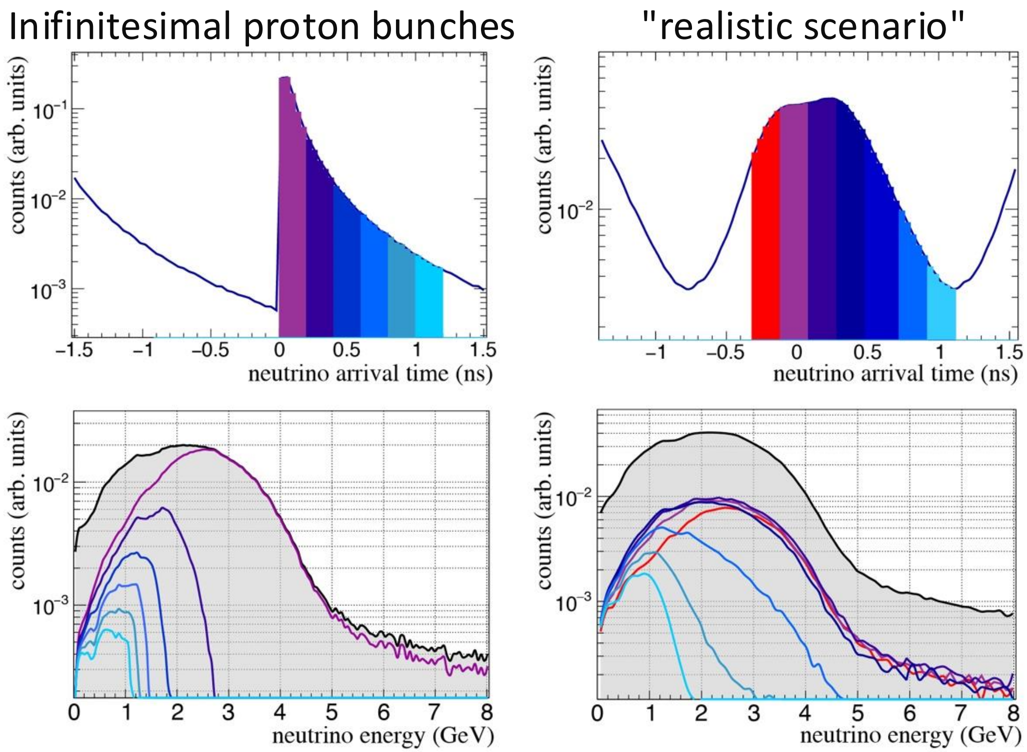
Time slicing in a more realistic scenario

Even with
- a realistic simulation of the 531 MHz rebunched time structure
- an additional 100 ps Gausian to account for detector affects
- the effects of pileup between the bunches

it is still possible to select isolated, lower energy flux bins



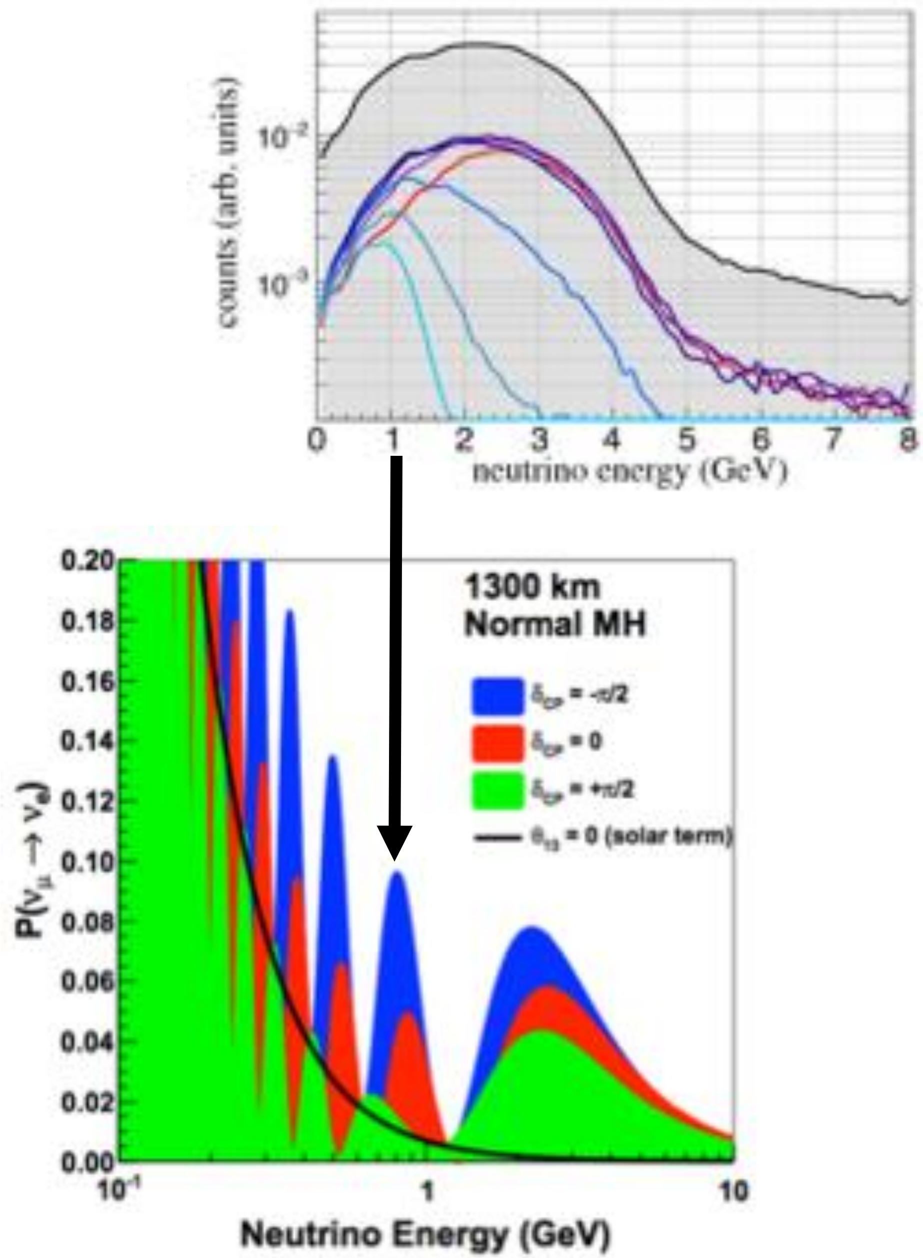
Putting Together a Physics Program

The second maximum

Time slicing in the far detector
is particularly advantageous as it can

- select a more pure sample of neutrinos from the second maximum
- suppress “feed down” from higher energy backgrounds
  - Resonant pion production
  - Deep Inelastic Scattering
- Suppress downward migration of reconstructed energy from higher energy interactions

Being able to fit both maxima would place strong constraints on oscillation parameters



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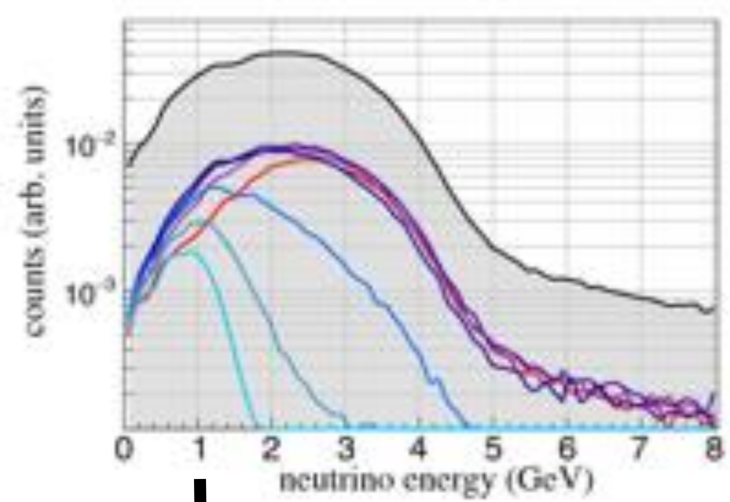
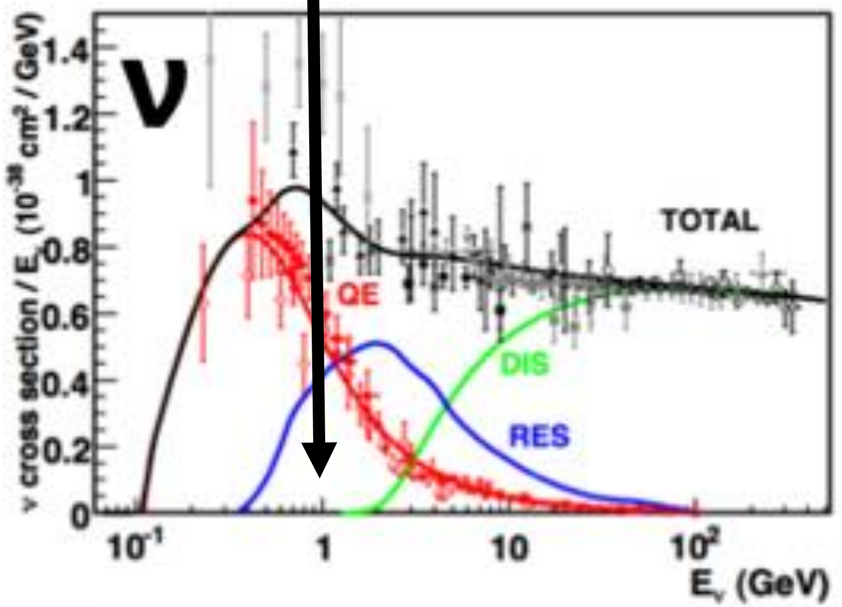
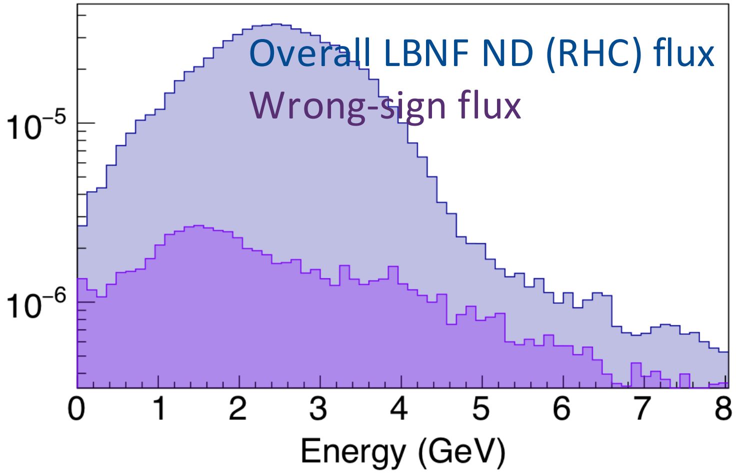




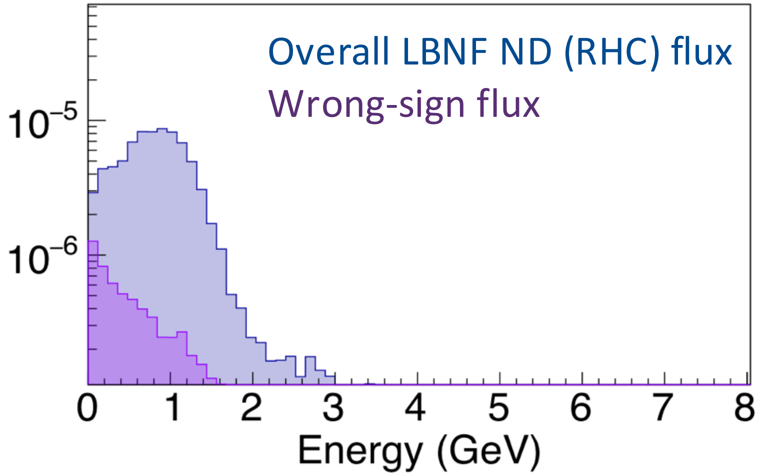
Separating different components of the beam

- The relative normalization and ***shape*** of the different components of the neutrino flux (wrong-sign, intrinsic ν_e , K/π) evolve differently and in deterministic ways with respect to the timing cuts
- Fitting in multiple time slices greatly constrains the fit to the overall flux

time slice from -0.3 to –0.1 ns



time slice from 0.9 to 1.1 ns



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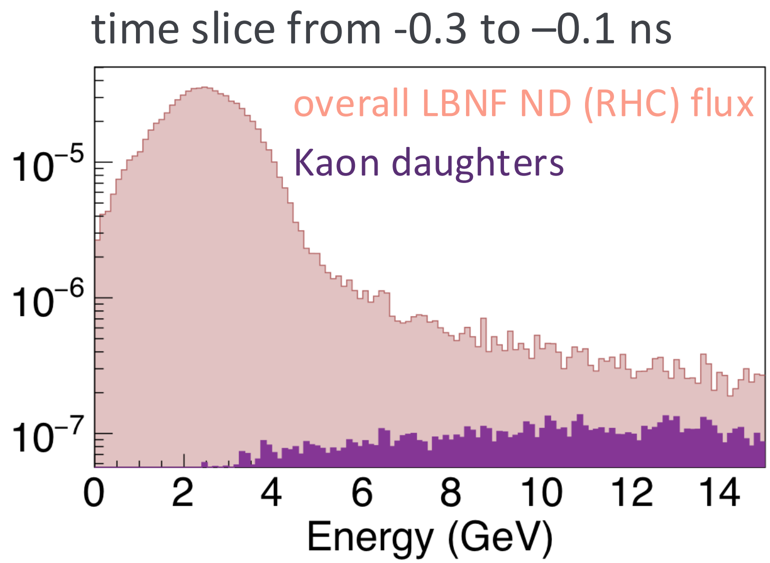

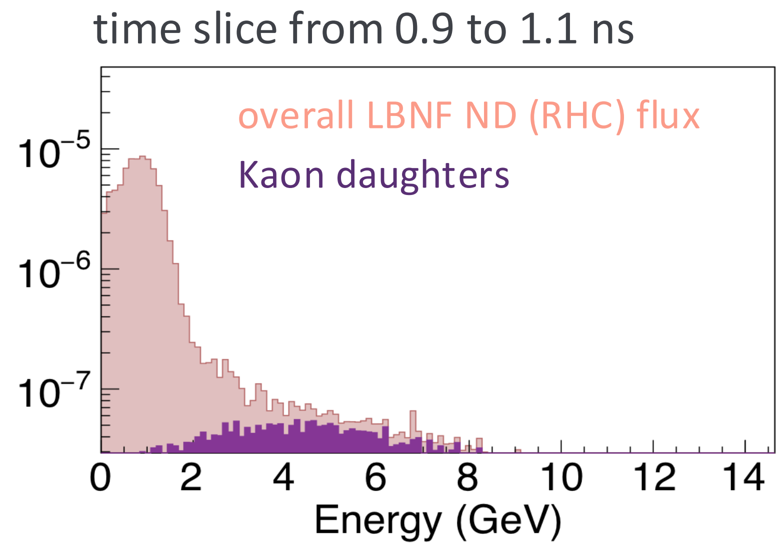

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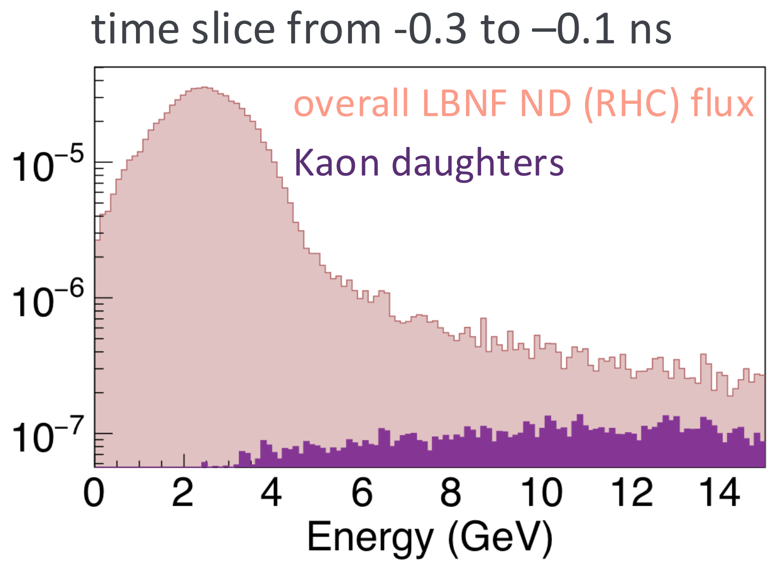
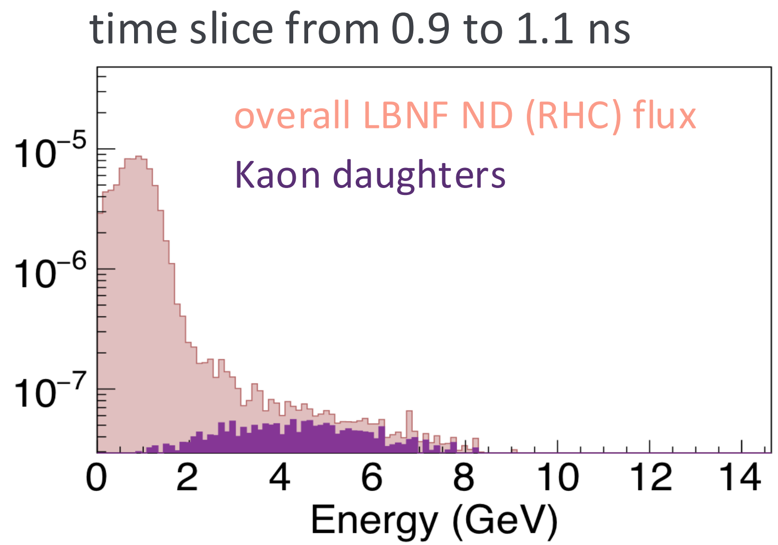
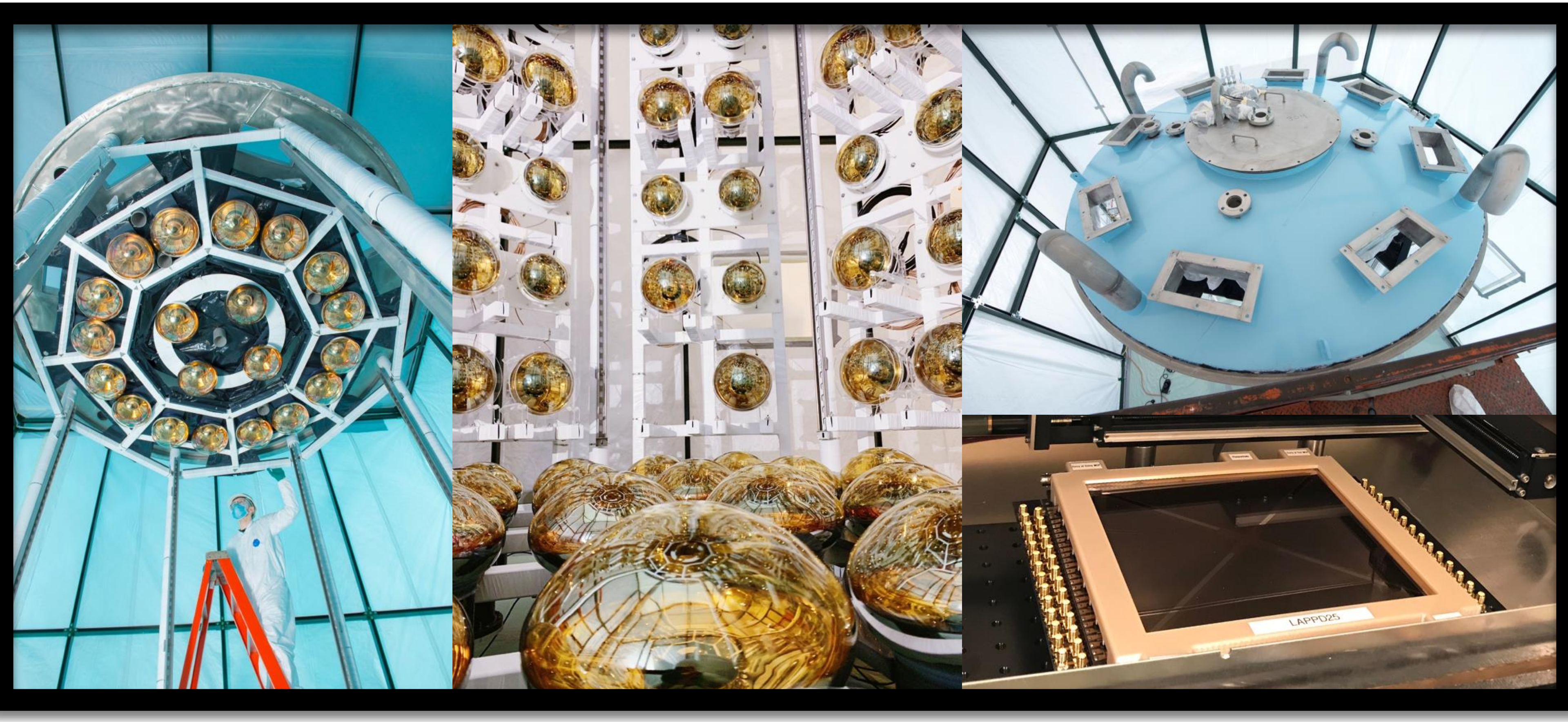




- Imagine having to fit the flux model to a 2-d grid of spectra binned in off-axis angle *and* time slice!

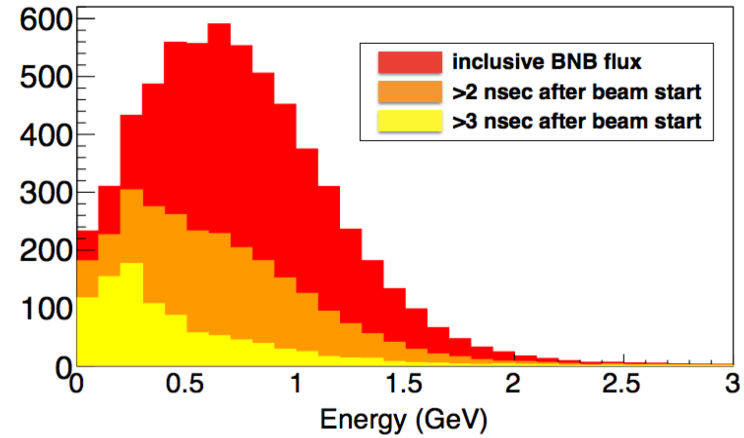
…Also Dark Sector Searches/N-body decays?

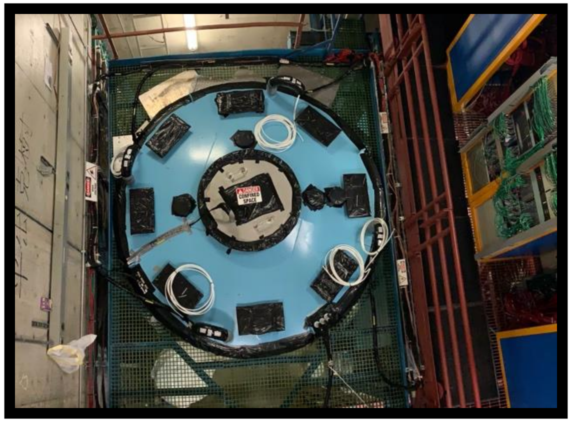
Towards a Measurement in ANNIE

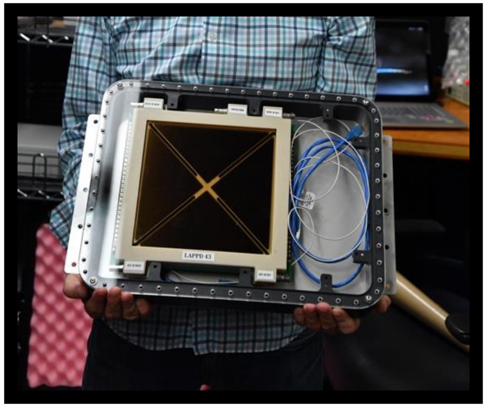


The Opportunity

- ANNIE can provide a first demonstration of this technique on neutrinos from the BNB
- The ANNIE detector has the needed time resolution
- Because the energy of the BNB spectrum skews towards the low end, there is a broader tail of low-energy neutrinos
- Thus. detecting the time-slicing effect should be possible, **even with 1 ns bunches**







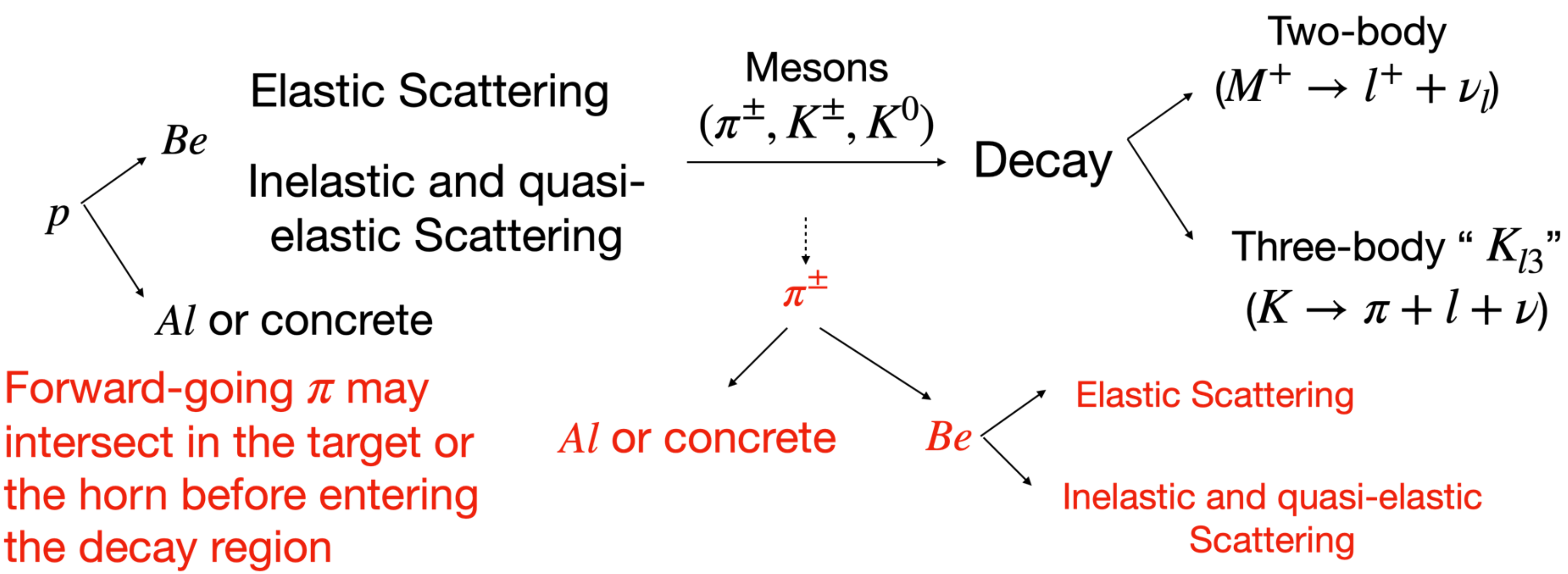
Credit: Dr. Marvin Ascensio Sosa (ISU)

Reproducing Earlier Studies

Simulation made with **G4BNB** developed for SBND.

The G4BNB is based on the MiniBoone flux simulation.

MC flow:



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Simulation made with **G4BNB** developed for SBND.

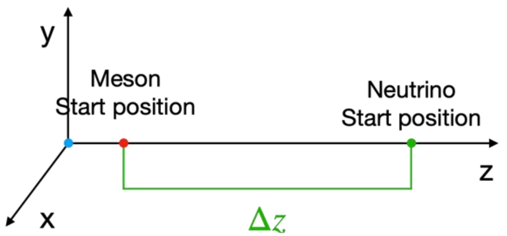
Possible Opportunity:

Dark Sector/New Physics Searches?

the decay region

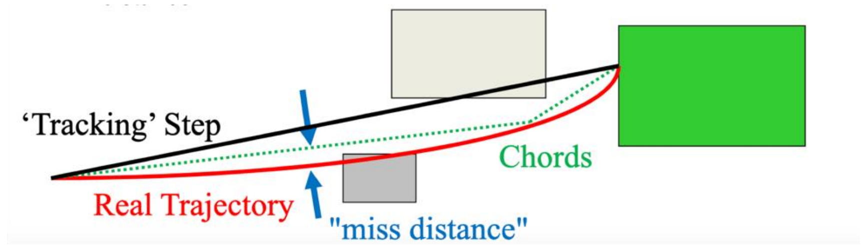
Scattering

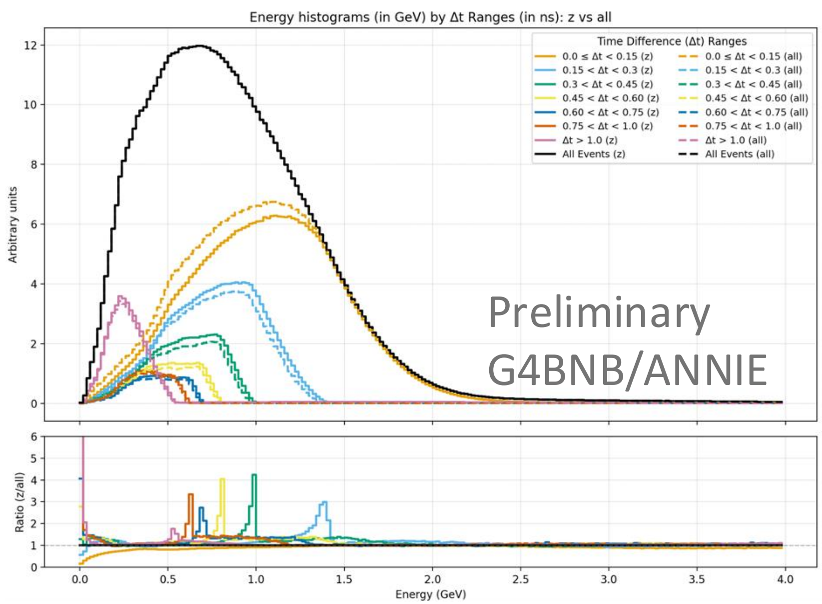
Reproducing Earlier Studies

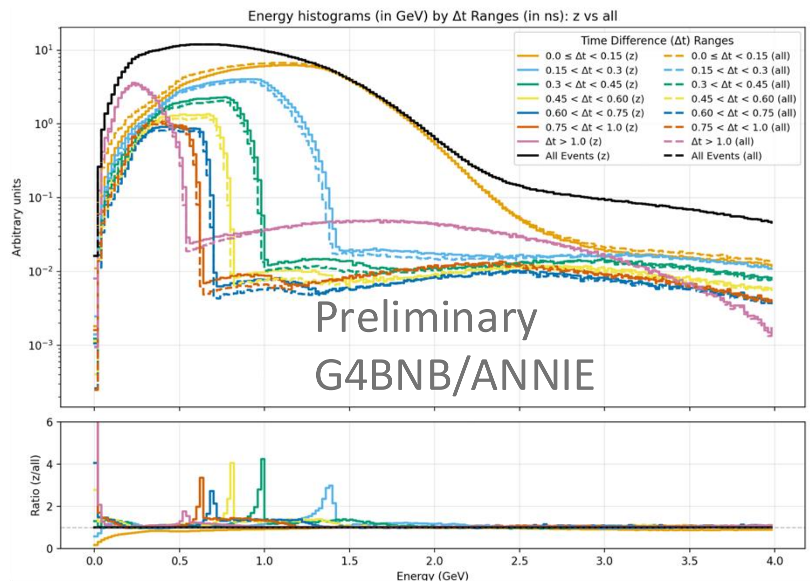


Only z axis were considered

VS



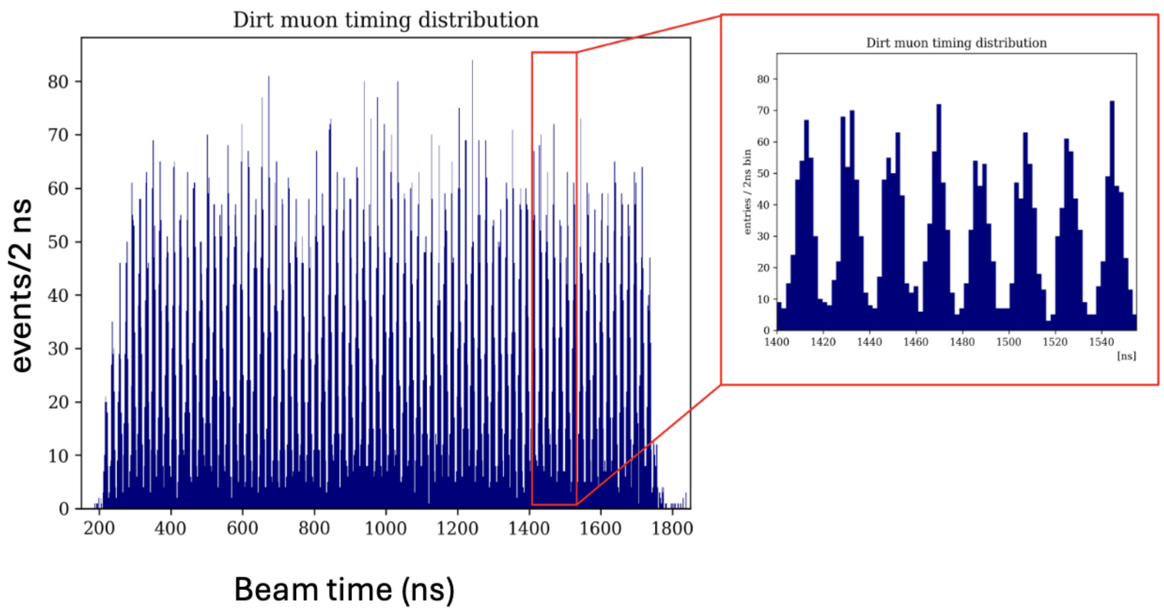




Dashed histogram with curved trajectory.

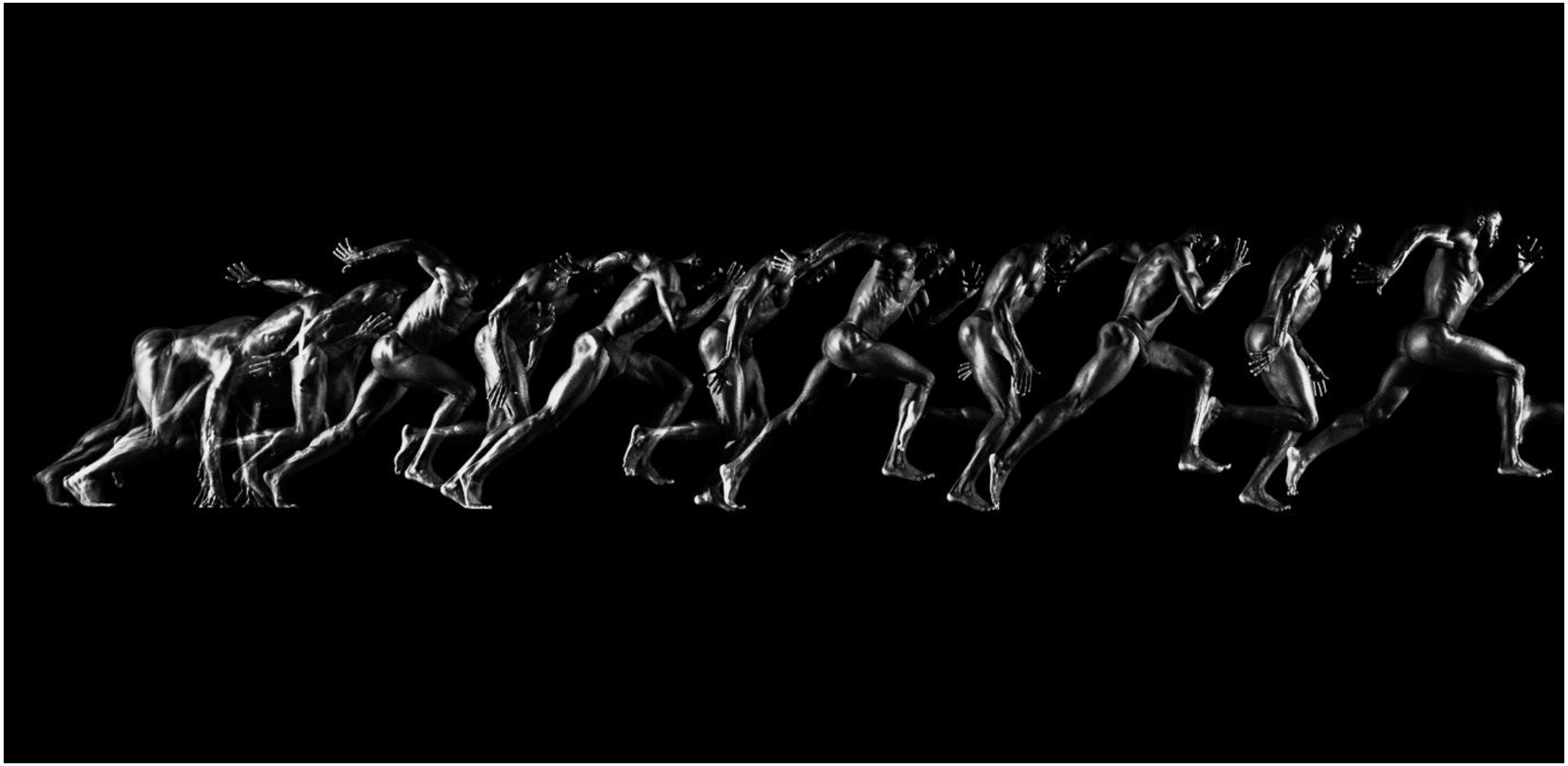
Direct Measurement

- ANNIE can already resolve the sub-structure of the beam with conventional PMTs
- The LAPPD group has reproduced a first-pass version with LAPPDs



- Work is underway to improve use of reference Beam-RF signal to better sync ANNIE to the bunch-by-bunch accelerator timing
- Getting T0 right also requires track reconstruction for proper TOF-corrections…this is also underway!

6. Conclusions



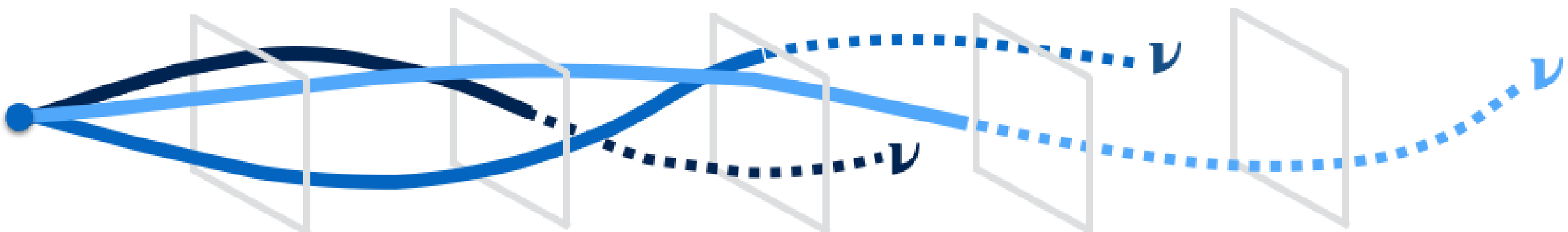
Conclusions

- Precision timing could be used to select different beam fluxes based on neutrino arrival time, due to the correlation between the energy of the beam neutrinos and the velocities of the parent hadrons.
- The ability to select different fluxes is a powerful capability for constraining complicated and correlated systematic uncertainties on flux, cross sections, and neutrino energy. This is important for guarding against unknown unknowns and in searching for new physics
- This technique has some interesting and complementary aspects to off-axis techniques, like those of DUNE Prism and would thus strengthen the DUNE program
- The rebunching technology in delivering beam is potentially compatible with exsiting accelerator plans for DUNE
- Timing in the Near Detector may be achievable within the framework of the current design.
- Timing in the DUNE far detectors is not likely for the current 1st and 2nd modules but could be incorporated in later installations
- New technological capabilities often bring new physics reach in areas that weren't originally planned. Continued thinking about precision timing is worthwhile
- This idea is new and there is much work ahead to establish it's feasibility and cost-benefit.
- We welcome feedback from the community in establing the feasibility and cost-benefits of this technique and look forward to the discussions!

Workshop on Precision Time Structure in On-Axis Neutrino Beams

Fermilab November 2-3 2019

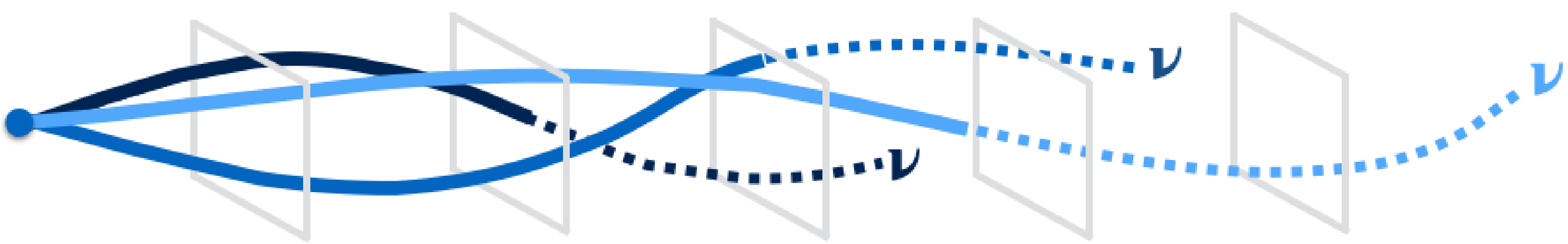
https://indico.fnal.gov/event/21409/



PHYS REV D 100, 032008 (2019) https://arxiv.org/abs/1904.01611

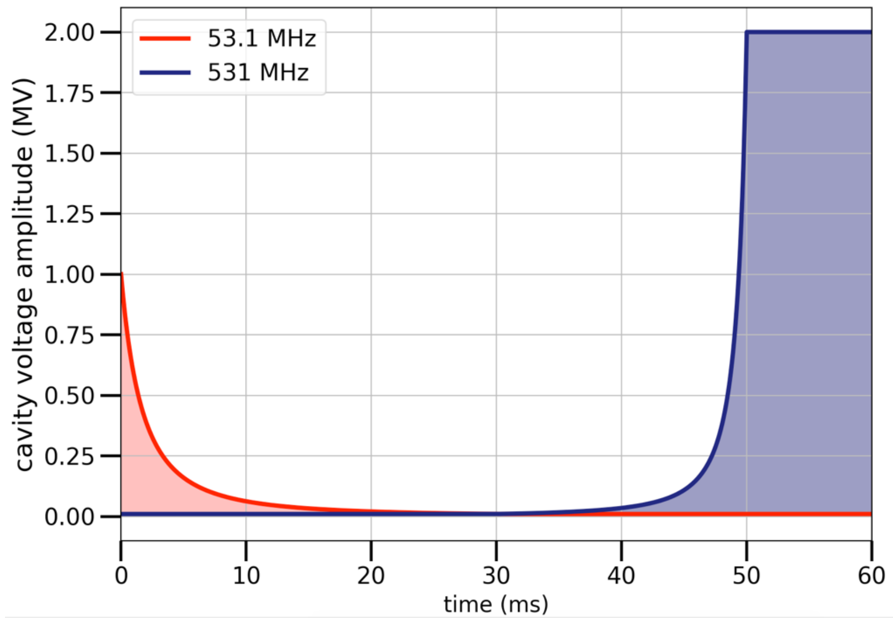
Thank you!

Backups



Execution of the Rebunching

- The 10x rebunching (531 MHz) would happen in the MI, *after* the acceleration phase
- This has the advantage that the rebunching is applied at a fixed energy and will only require 1-2 RF cavities
- The process of rebunching consists of adiabatically ramping down the existing 53 MHz cavity and ramping up of a single 531 MHz SRF cavity



- The proposed rebunching process aims to add no more than 60 ms on to the present MI cycle. We estimate a loss of no more than 5% POT due to this increase in cycle time
- There may be clever ways to recoup duty-cycle losses

Timing and Far Detection: LAr-TPCs

- **Detection of Cherenkov light emission in liquid argon** - Antonello, M. *et al.* Nucl. Instrum. Meth. A516 (2004) 348-363
- **Index of refraction, Rayleigh scattering length, and Sellmeier coefficients in solid and liquid argon and xenon** - Grace, Emily *et al.* Nucl. Instrum. Meth. A867 (2017) 204-208 arXiv:1502.04213 [physics.ins-det]
- Refractive Indices of the Condensed Inert Gases - Sinnock, A.C. et al. Phys.Rev. 181 (1969) 1297-1307
- Seidel, G.. Rayleigh scattering in rare-gas liquids - 2002. Nucl. Instrum. Methods Phys. Res., Sect.,A489,189
- Bideau-Mehu, A.. Measurement of refractive indices of neon, argon, krypton and xenon in the 253.7 140.4 nm wavelength range. dispersion relations and estimated oscillator strengths of the resonance lines - 1981. J. Quant. Spectrosc. Radiat. Trans.,25,395

Timing and Far Detection: LAr-TPCs

- The optical properties of Liquid Argon detectors are very similar to those of water
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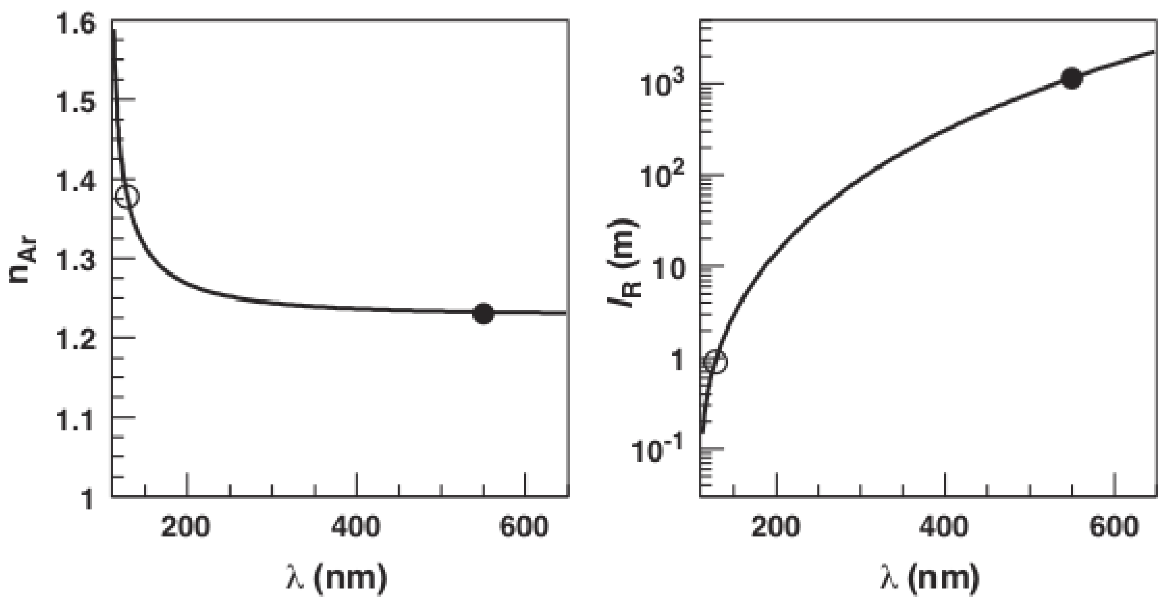
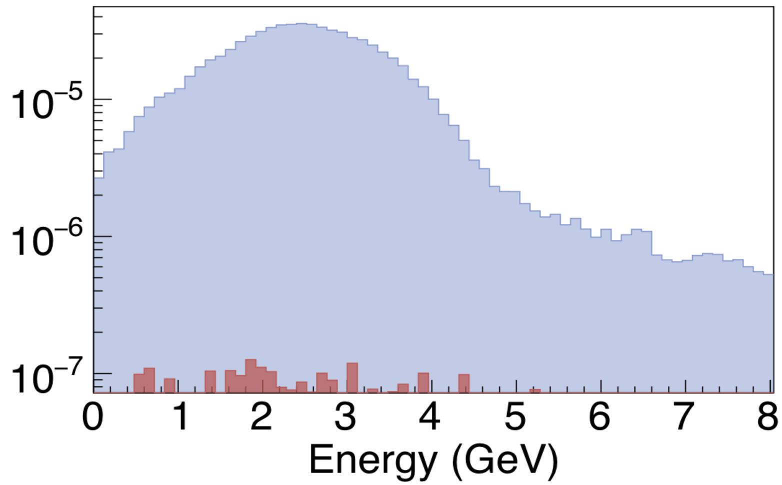
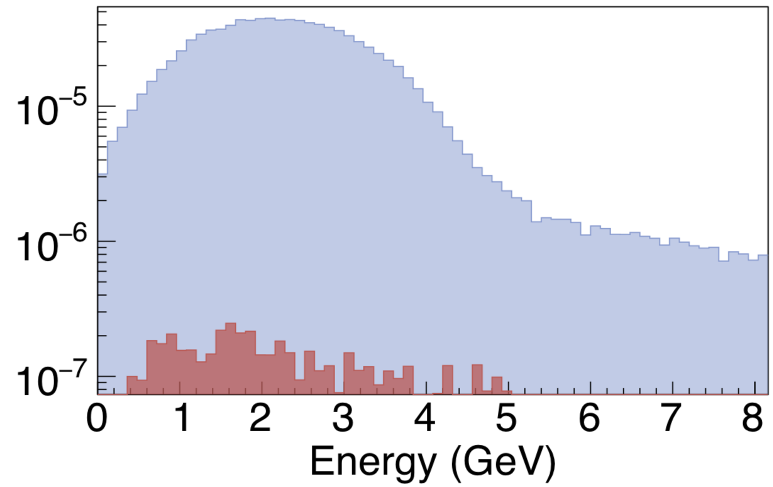


Intrinsic Nuebar Contamination (RHC)

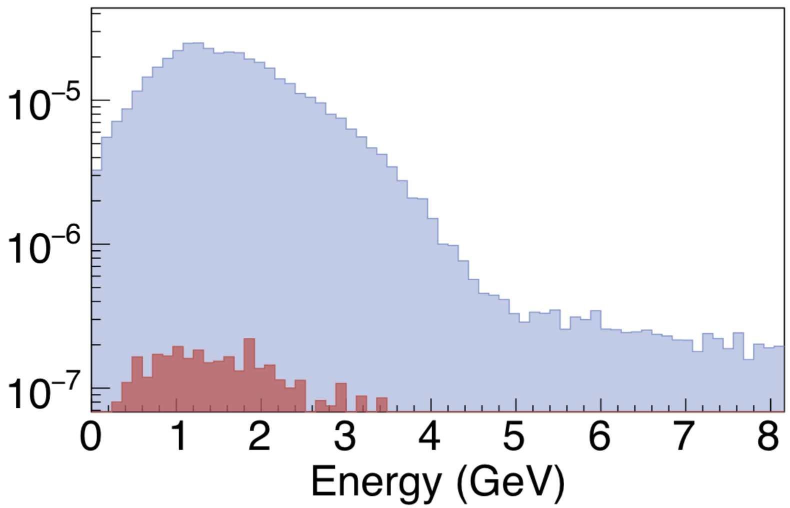
Slice 0: -0.3 to –0.1 ns



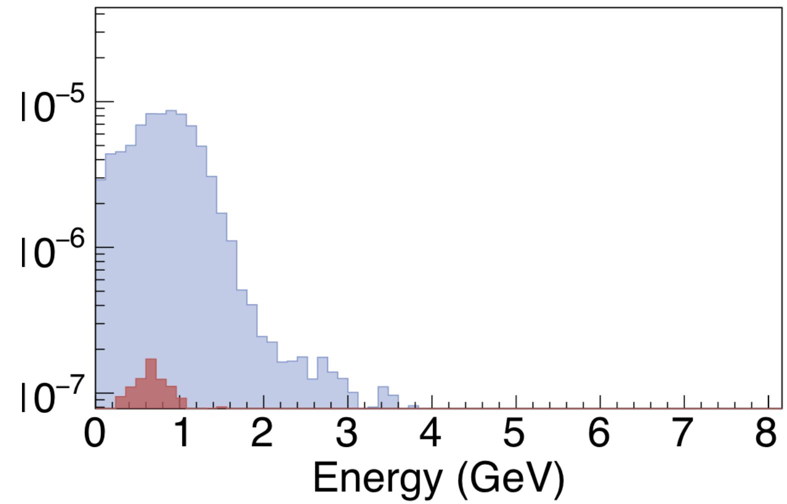
Slice 2: 0.1 to 0.3 ns



Slice 4: 0.5 to 0.7 ns

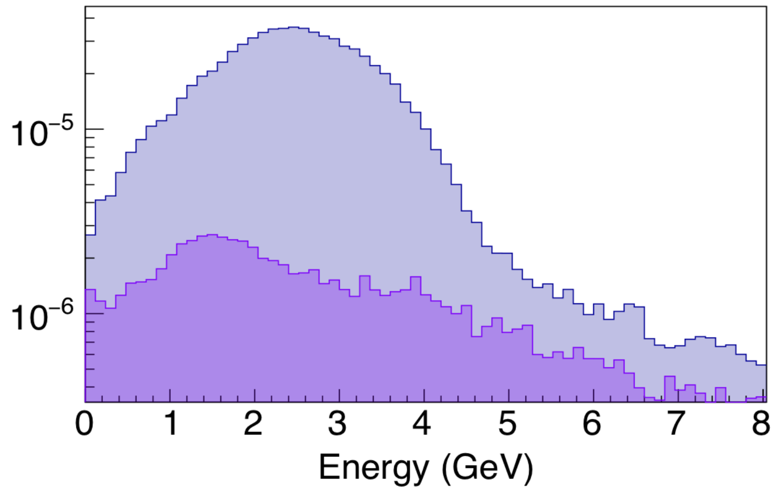


Slice 6: 0.9 to 1.1 ns

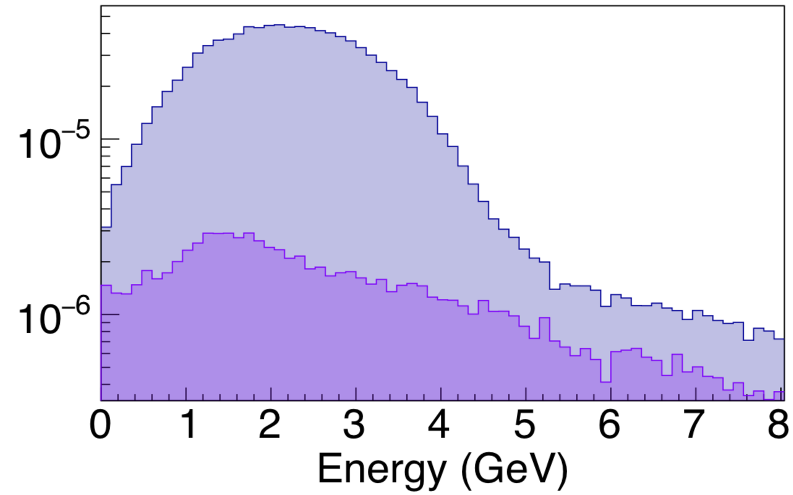


Wrong Sign Contamination (RHC)

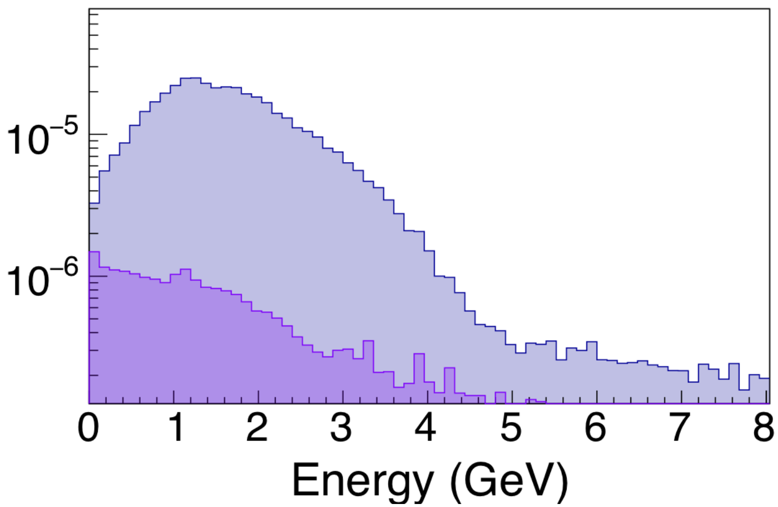
Slice 0: -0.3 to –0.1 ns



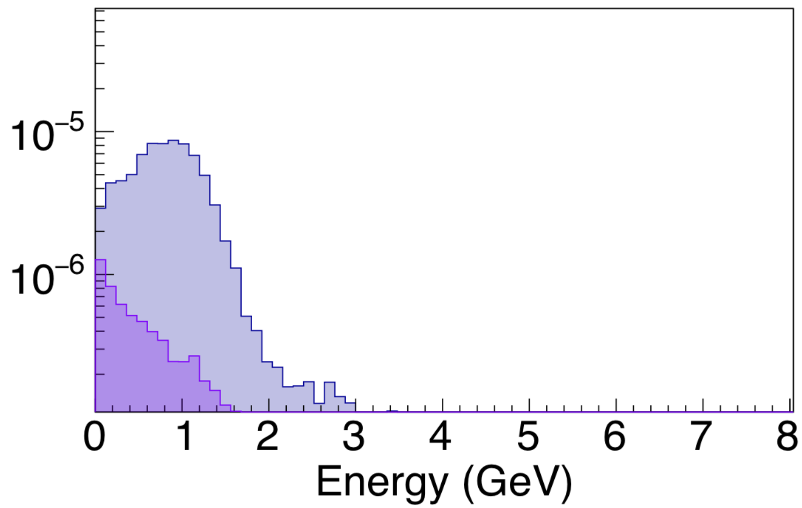
Slice 2: 0.1 to 0.3 ns



Slice 4: 0.5 to 0.7 ns

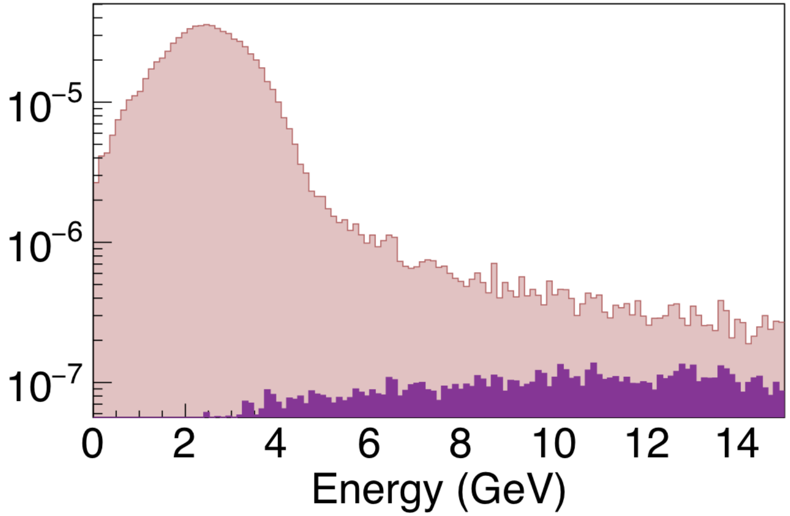


Slice 6: 0.9 to 1.1 ns

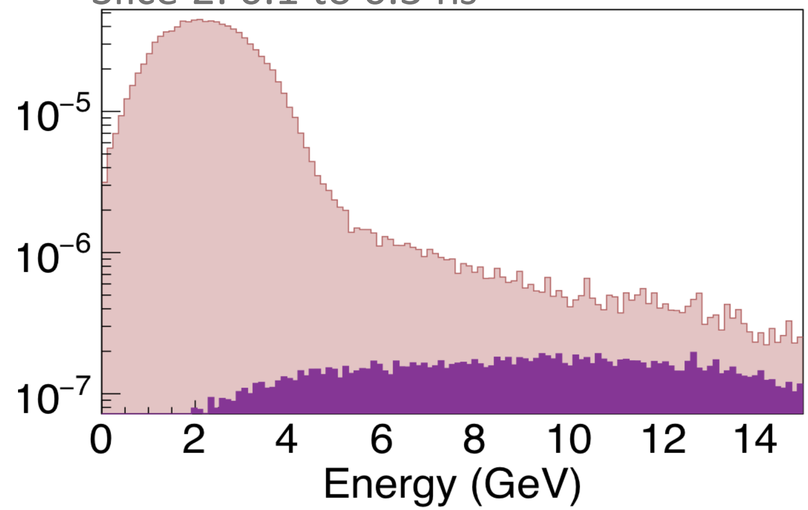


K^- component(RHC)

Slice 0: -0.3 to –0.1 ns



Slice 2: 0.1 to 0.3 ns



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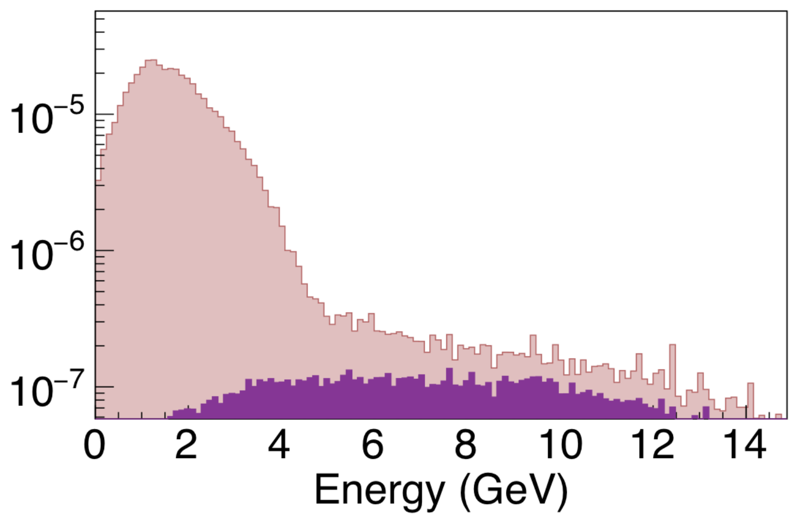

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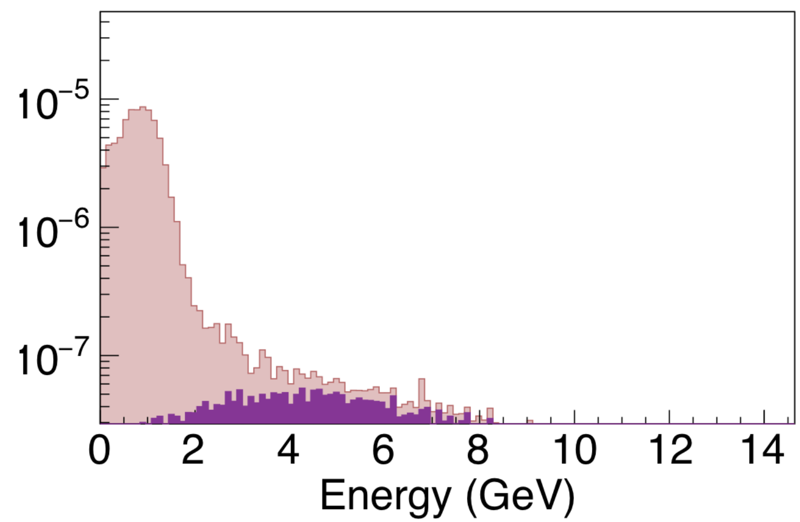
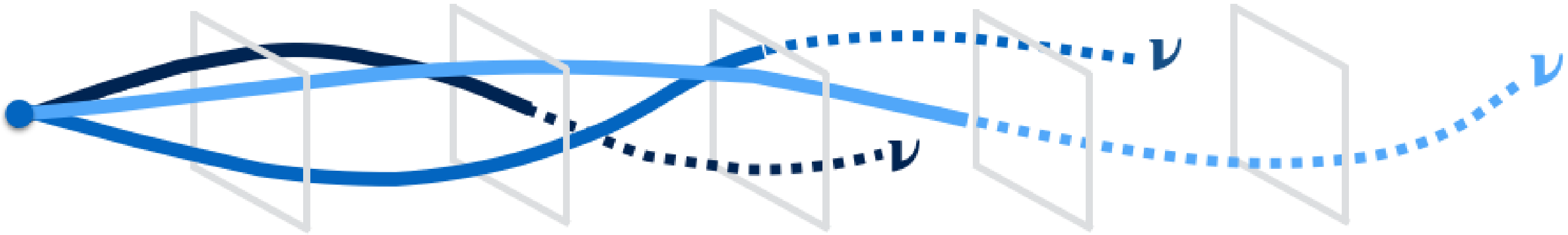


Additional Motivations Slides



Motivations: Neutrinos and the Big Questions

- Why are neutrinos so light?

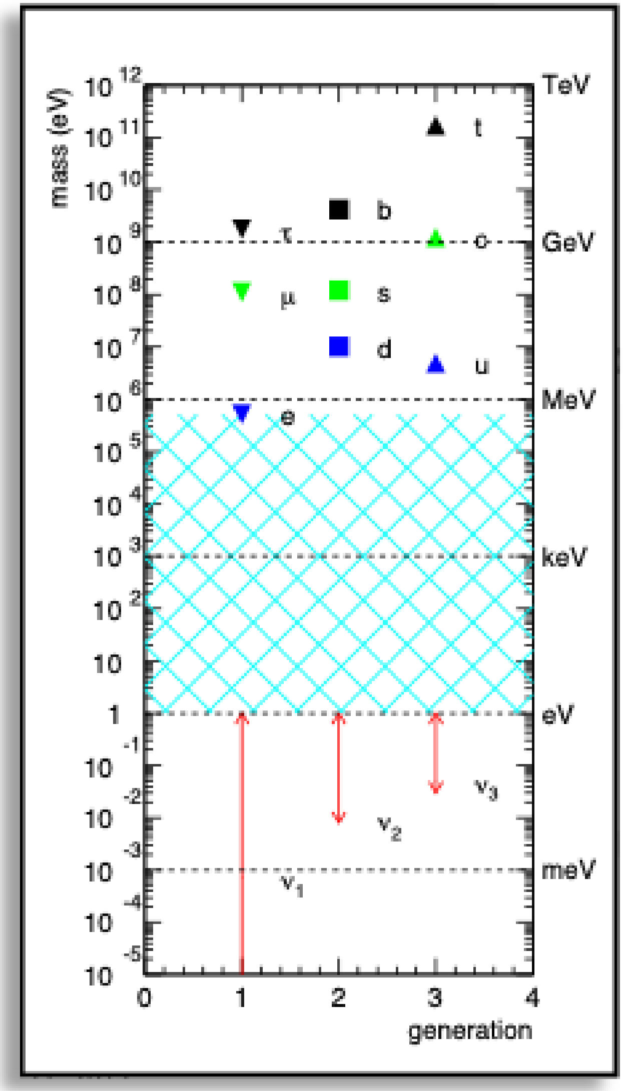
  Alternative (non-Higgs) mechanism

- Are neutrinos their own anti-particles (Majorana)?

  Seesaw mechanism

- Are neutrinos CP violating? How much?

  Possible explanation for matter/anti-matter asymmetry



Motivations: Neutrinos and the Big Questions

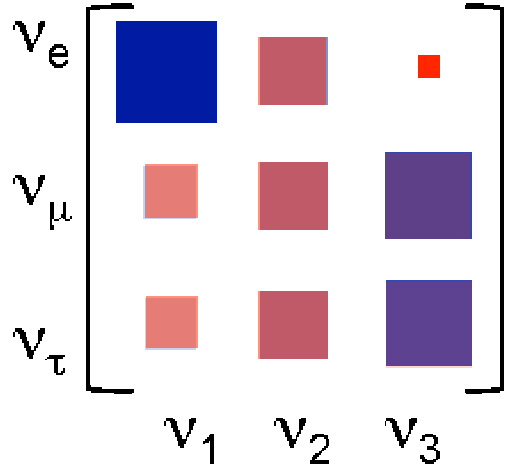
The flavor states which govern how neutrinos interact, are a quantum superposition of the mass states, which govern how they propagate in time

Motivations: Precision Neutrino Oscillometry

$$\begin{bmatrix} \nu_\mathrm{e} \\ \nu_{\boldsymbol{\mu}} \\ \nu_{\boldsymbol{\tau}} \end{bmatrix} = \begin{bmatrix} \mathrm{U}_{\mathrm{e}1} & \mathrm{U}_{\mathrm{e}2} & \mathrm{U}_{\mathrm{e}3} \\ \mathrm{U}_{\boldsymbol{\mu}1} & \mathrm{U}_{\boldsymbol{\mu}2} & \mathrm{U}_{\boldsymbol{\mu}3} \\ \mathrm{U}_{\boldsymbol{\tau}1} & \mathrm{U}_{\boldsymbol{\tau}1} & \mathrm{U}_{\boldsymbol{\tau}1} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix} =$$

Motivations: Precision Neutrino Oscillometry

$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} =$$



$$\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix} =$$

PMNS Matrix: Pontecervo, Maki, Nakagowa, Sakata

Motivations: Precision Neutrino Oscillometry

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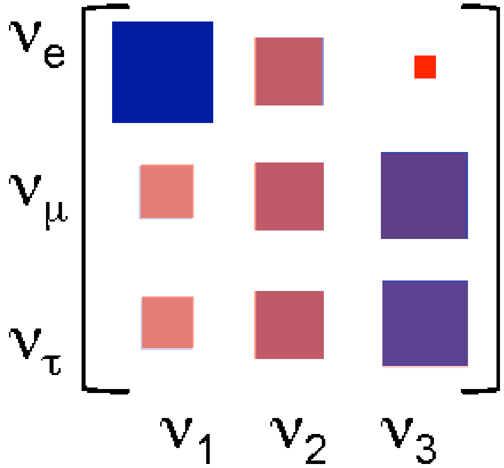

$$\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix} =$$

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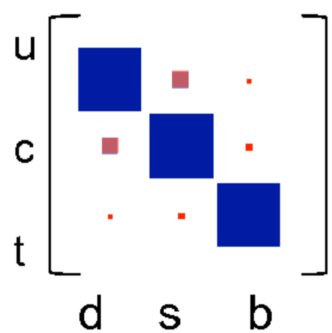


CKM Matrix

Motivations: Precision Neutrino Oscillometry

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 1} & U_{\tau 1} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix} =$$

$$\underbrace{\begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{\text{"atmospheric"}} \underbrace{\begin{bmatrix} c_{13} & s_{12} & s_{13}e^{-i\delta_{cp}} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta_{cp}} & 0 & c_{13} \end{bmatrix}}_{\text{"reactor"}} \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix}}_{\text{"solar"}}$$

Motivations: Precision Neutrino Oscillometry

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 1} & U_{\tau 1} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix} =$$

$$\begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} c_{13} & s_{12} & s_{13}e^{-i\delta_{cp}} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta_{cp}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix}$$

"atmospheric" "reactor" "solar"

$\theta_{12} = 45 \pm 3°$
$|\Delta m^2_{12}| = 2.52 \pm 0.04 \times 10^{-3}\ eV^2$

$\theta_{13} = 8.5 \pm 0.15°$
$|\Delta m^2_{13}| = 2.52 \pm 0.04 \times 10^{-3}\ eV^2$

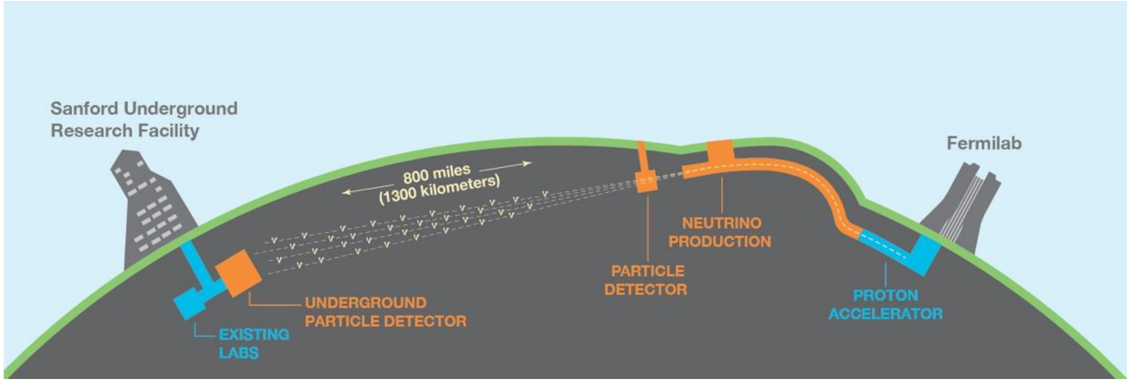
$\theta_{23} = 33.6 \pm 0.8°$
$|\Delta m^2_{23}| = 7.5 \pm 0.18 \times 10^{-5}\ eV^2$

δ_{cp} = ???? mass hierarchy????

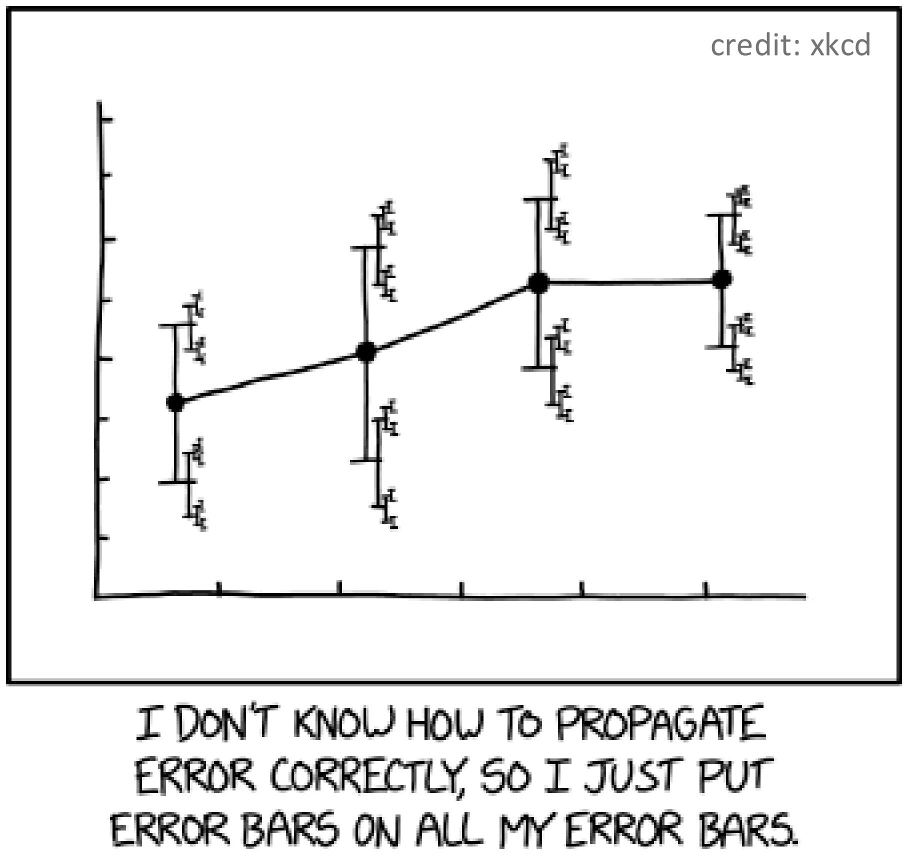
DEEP UNDERGROUND NEUTRINO EXPERIMENT

- Fermilab and the worldwide neutrino community are building a world class neutrino beamline and cutting edge neutrino detectors to make neutrino oscillation measurements at unprecedented levels of precision
- High among the goals of DUNE, the observation and measurement of CP violation in the neutrino sector
- LBNF/DUNE represents the transition from statistics limited oscillations measurements to a new era of systematics limitations
- Given the high priority of DUNE, anything we can do to control systematics and protect against "unknown unknowns", the better

More handles on systematic uncertainties, also means more sensitivity to possible new physics: non-standard interactions, non-standard oscillation



2. Limiting Systematics on DUNE



Neutrino rates are cross section (and detector) dependent

For a given set of kinematic variables **k**, the event rate R(**k**) is given by

$$R(\mathbf{k}) = \sum_{i}^{\text{process}} \sum_{j}^{\text{target}} \int_{E_{min}}^{E_{max}} \boldsymbol{\phi}(E_{\boldsymbol{\nu}}) \text{ x } \boldsymbol{\sigma}_i(E_{\boldsymbol{\nu}},\mathbf{k}) \text{ x } \boldsymbol{\varepsilon}(\mathbf{k}) \text{ x } N_j \text{ x } P_{\boldsymbol{\nu}a \rightarrow \boldsymbol{\nu}b}(E_{\boldsymbol{\nu}}) \; dE_{\boldsymbol{\nu}}$$

Neutrino rates are cross section (and detector) dependent

E_{reco}, $\mathbf{p}_{\mu}$, E_{had}, etc

For a given set of kinematic variables **k**, the event rate R(**k**) is given by

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what we detect

what we want to measure!!

- We want to measure the oscillation probability, but we actually detect the rates of events defined by a set of specific experimental observable.

Neutrino rates are cross section (and detector) dependent

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what we detect

flux

cross sections

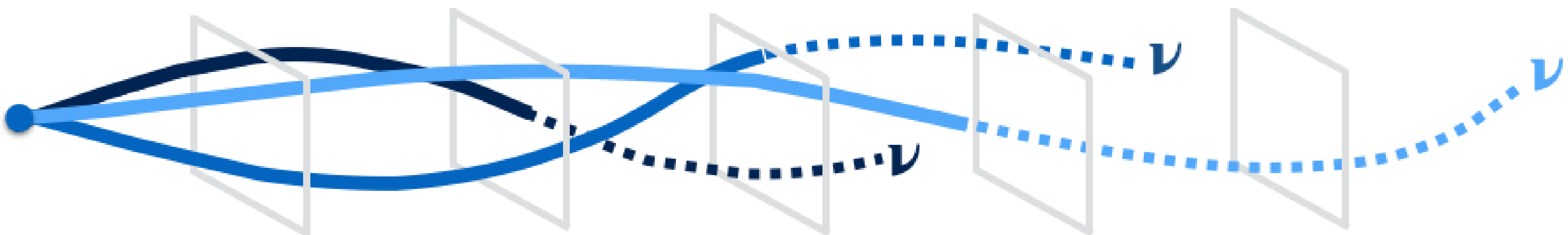
detector effects

(efficiency /number of targets)

what we want to measure!!

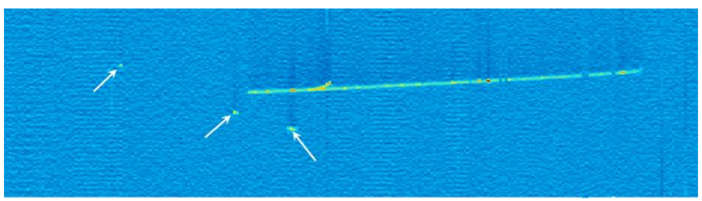
- We want to measure the oscillation probability, but we actually detect the rates of events defined by a set of specific experimental observables
- In between what we want to measure and what experimentally detect, we need to deconvolve the initial neutrino flux and reaction cross sections (as well as detector affects), which are themselves energy dependent.

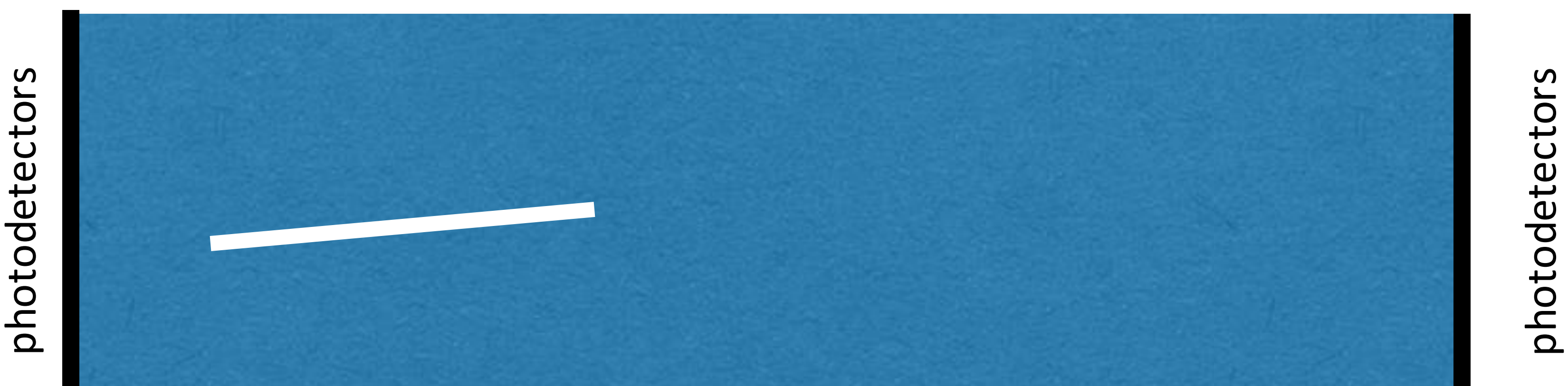
Timing in LAr-TPCs/DUNE



Timing and Far Detection: LAr-TPCs

- The optical properties of Liquid Argon detectors are very similar to those of water
- Cherenkov light *in combination* with the reconstructed track from electron drift could provide an excellent handle for establishing T_0 of the vertex
- One option for photodetection - mirror the top, bottom, sides, and place photodetectors on the end caps





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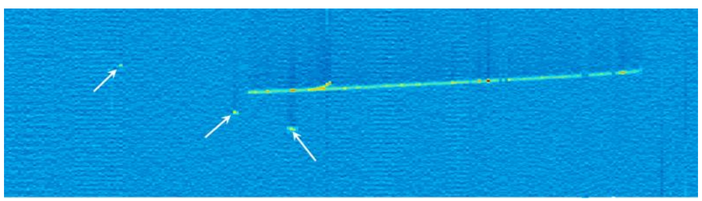

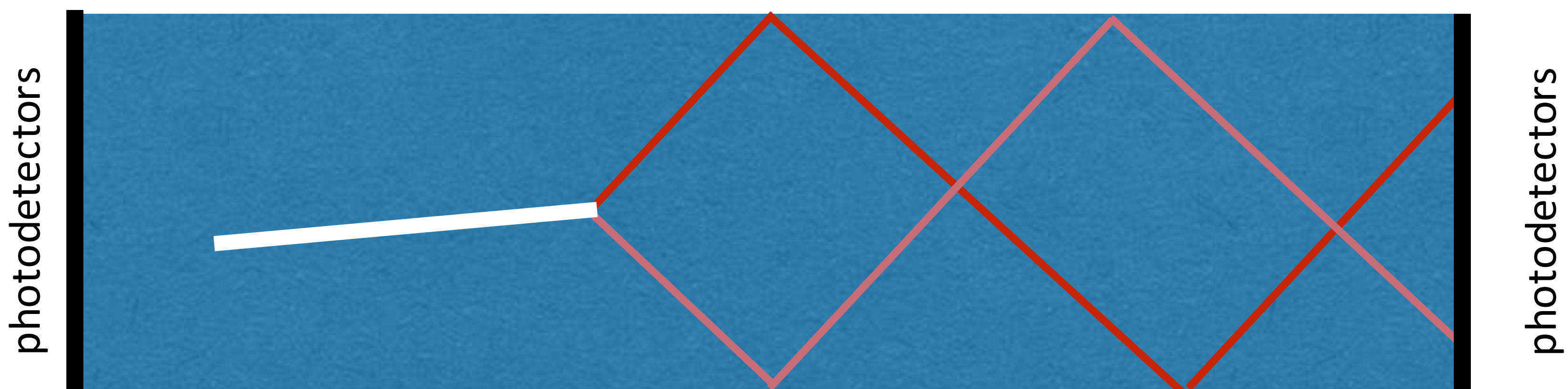

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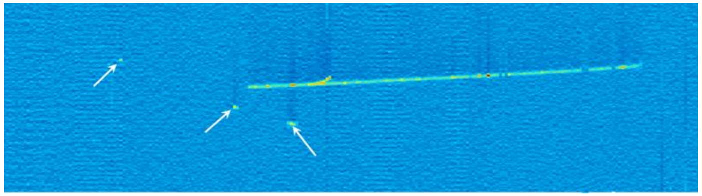

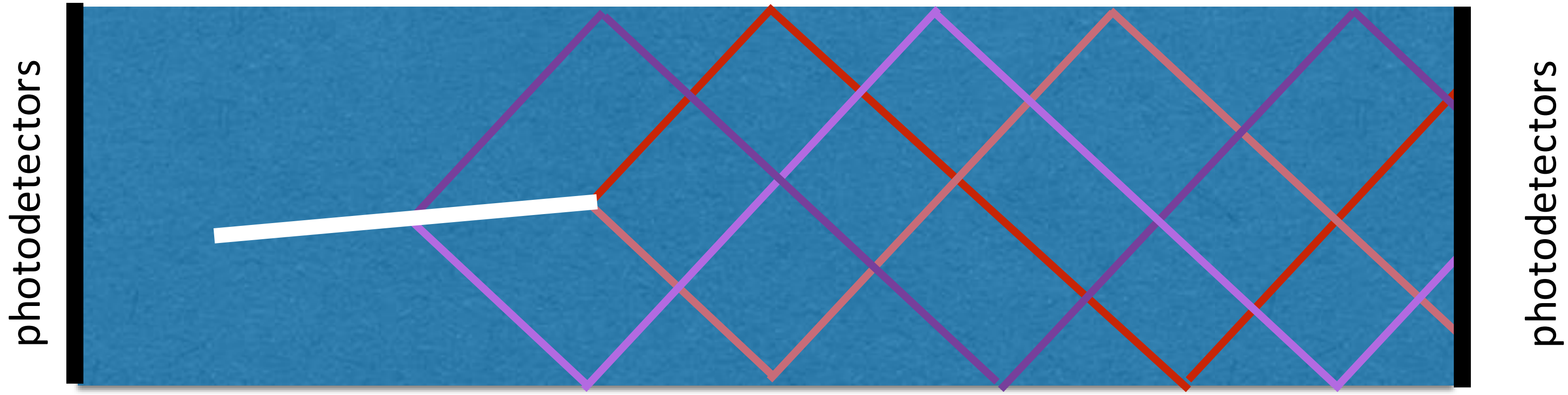

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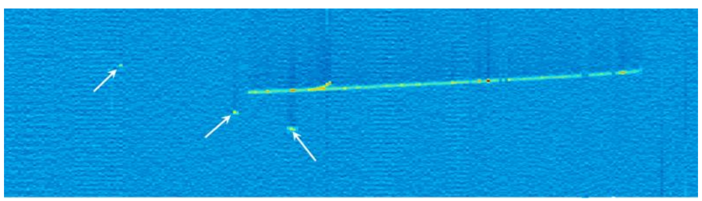
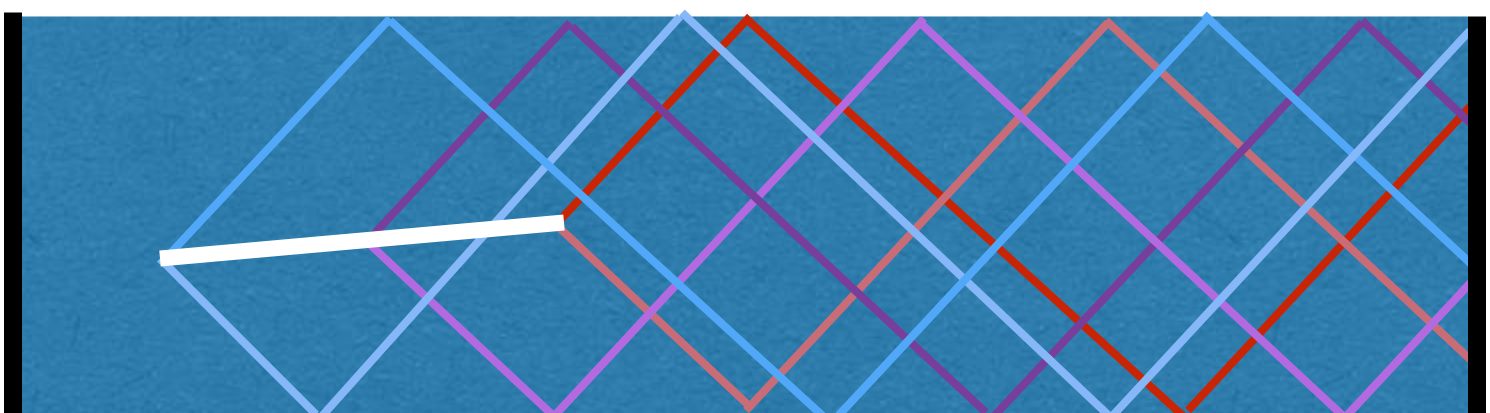


photodetectors



photodetectors

Timing and Far Detection: LAr-TPCs

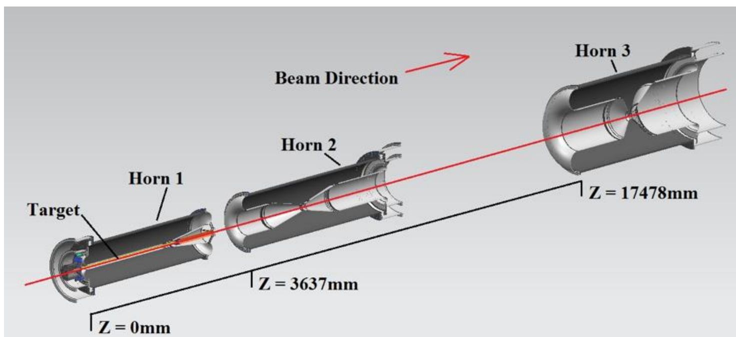
- The optical properties of Liquid Argon detectors are very similar to those of water
- Cherenkov light *in combination* with the reconstructed track from electron drift could provide an excellent handle for establishing T_0 of the vertex
- One option for photodetection - mirror the top, bottom, sides, and place photodetectors on the end caps
- Far detector synchronization with the beam RF is challenging but not so far from the level of precision available in commercial GPS technology
- A 1ps over 1km white rabbit system is currently being commissioned at the FNAL test-beam

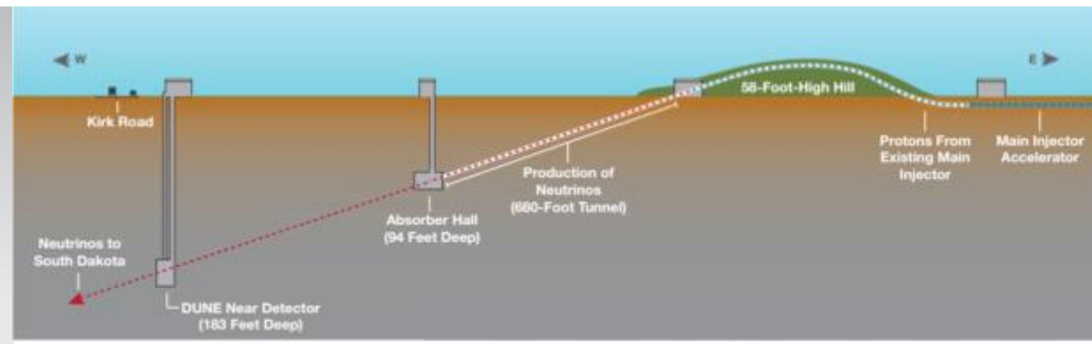
- There is broad interest in the community in thinking about the future, beyond the first LAr-TPC modules in DUNE
- In two weeks there will be a meeting to discuss some of these forward thinking ideas
- This is an excellent opportunity to start thinking about fast timing in LAr-TPCs
- It is also an excellent opportunity to think about complementary technologies such as Theia
  - A water-based neutrino detector as a possible candidate for the fourth module in Homestake
  - Key technological elements of Theia include the addition of water based liquid scintillator and advanced, high resolution photodetection
  - Because fast timing is an inherent part of the Theia concept, it is an excellent candidate for time-slicing in the far detector.

Realistic Flux Simulation

https://home.fnal.gov/~ljf26/DUNEFluxes/

- Optimized 3-Horn Design presented at the October 2017 Beam Optimization Review (used in the DUNE TDR)
- Timing information is included in the ntuples
- All simulated protons hit the target at the same time





- We convoluted the proton hit times with the timing of the emergent bunch structure from the accelerator simulations
- We also added 100 psec Gaussian smearing to account for plausible, albeit ambitious detector capabilities
- We also added in the effects of pileup from the previous bunches