CHALLENGES AND OPPORTUNITIES FOR THE USE OF BEAM STROBOSCOPY IN NEUTRINO OSCILLATIONS

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CHALLENGES FOR NEUTRINO OSCILLATIONS IN DUNE

Neutrino oscillation probability

what we want:

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

- In an ideal neutrino oscillation experiment we measure the flux of neutrinos before and after oscillations as a function of true neutrino energy and obtain the oscillation probability parameters.

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what we wish

we observed:

$$N(E_\nu) = \Phi(E_\nu) \times \sigma(E_\nu) \times \epsilon(E_\nu)$$

- We would observe a neutrino interaction rate which depends on the beam flux, cross sections and detector acceptance. Unfortunately there is a high degree of uncertainty in the cross section component.

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$$N(E_\nu) = \Phi(E_\nu) \times \sigma(E_\nu) \times \epsilon(E_\nu)$$

what we measure:

$$N(E_{reco}) = \int \Phi(E_\nu) \times \sigma(E_\nu) \times \epsilon(E_\nu) \times \mathbf{D}(E_\nu \to E_{reco}) dE_\nu$$

- What we actually measure is a function of **reconstructed energy** connected through true neutrino energy by a smearing matrix that depends on the detector but also on neutrino interactions.

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- So what we end up with is NOT this scenario.

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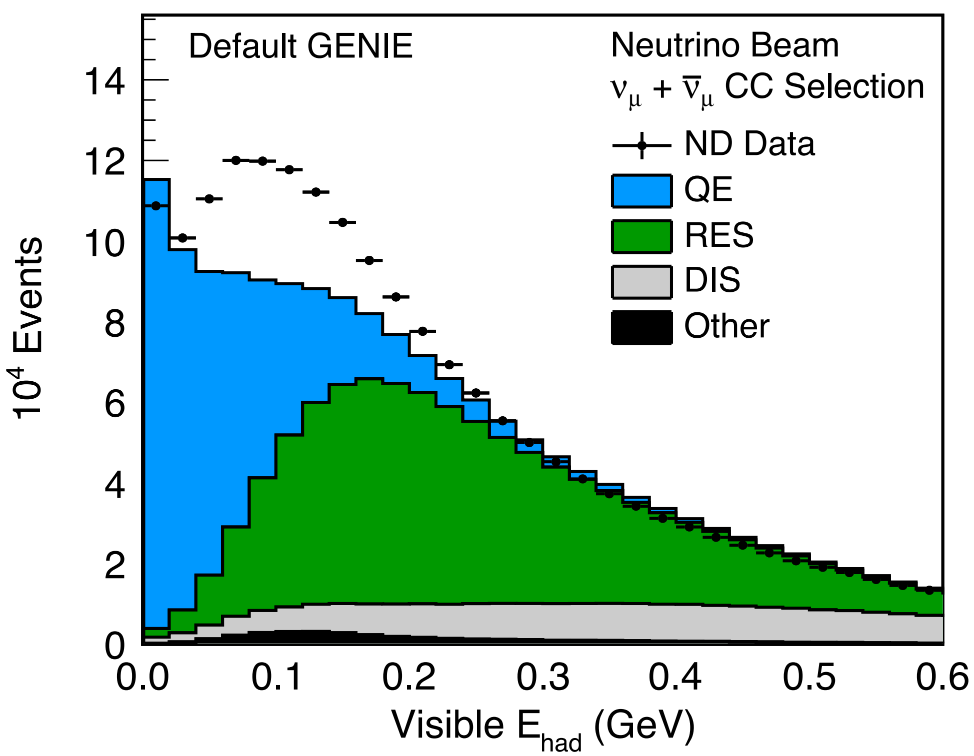
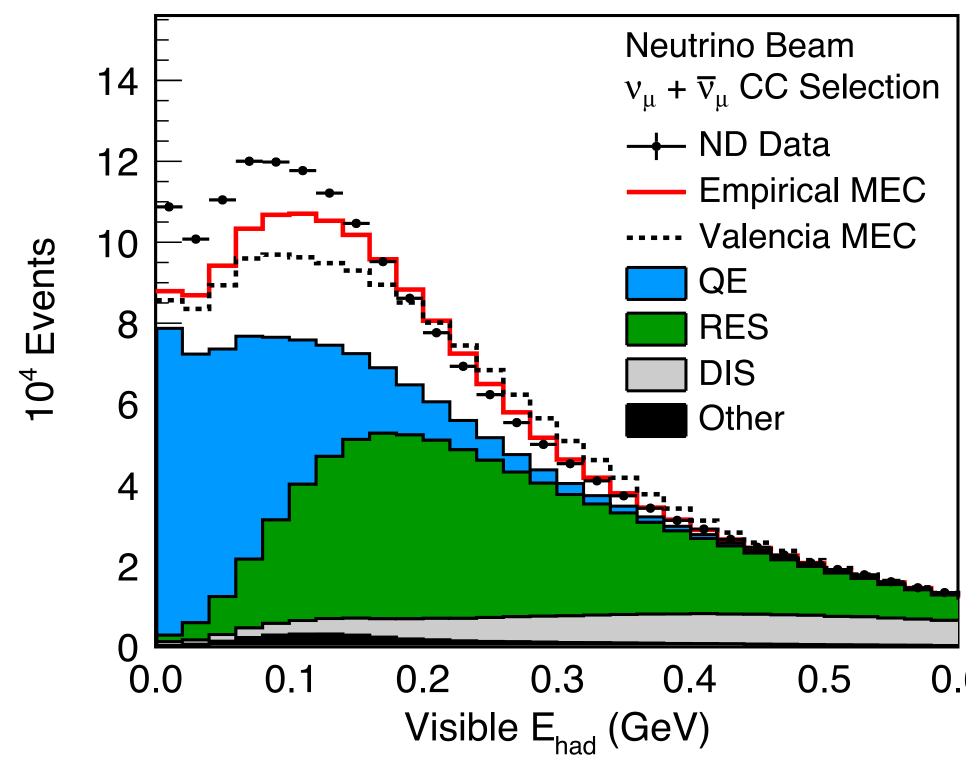
- What we actually measure does NOT neatly factorize because of the dependence on true energy. However techniques that allow disentangling neutrino flux and cross sections do aid in constraining the uncertainties.

CHALLENGES FOR NEUTRINO OSCILLATIONS IN DUNE

- One aspect that cannot be emphasized enough is the level of uncertainty on the neutrino interaction models.





- As in other experiments, NOvA found that the default neutrino interaction simulation was missing multi-nucleon processes. Current models for MEC (2p2h) still will not match NOvA's data.

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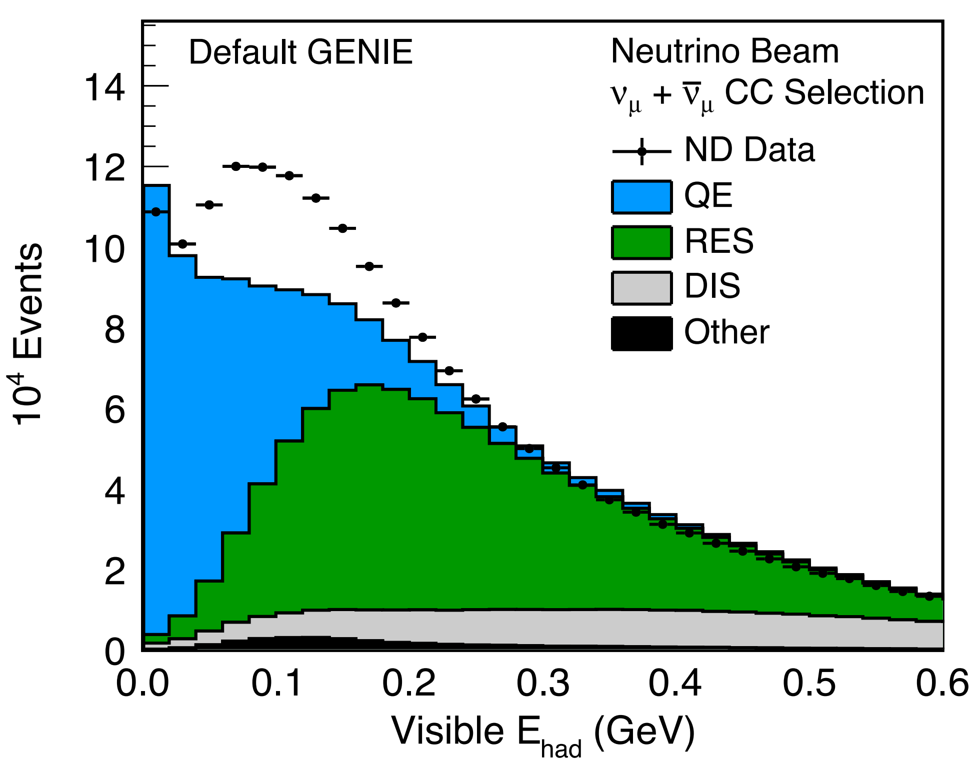

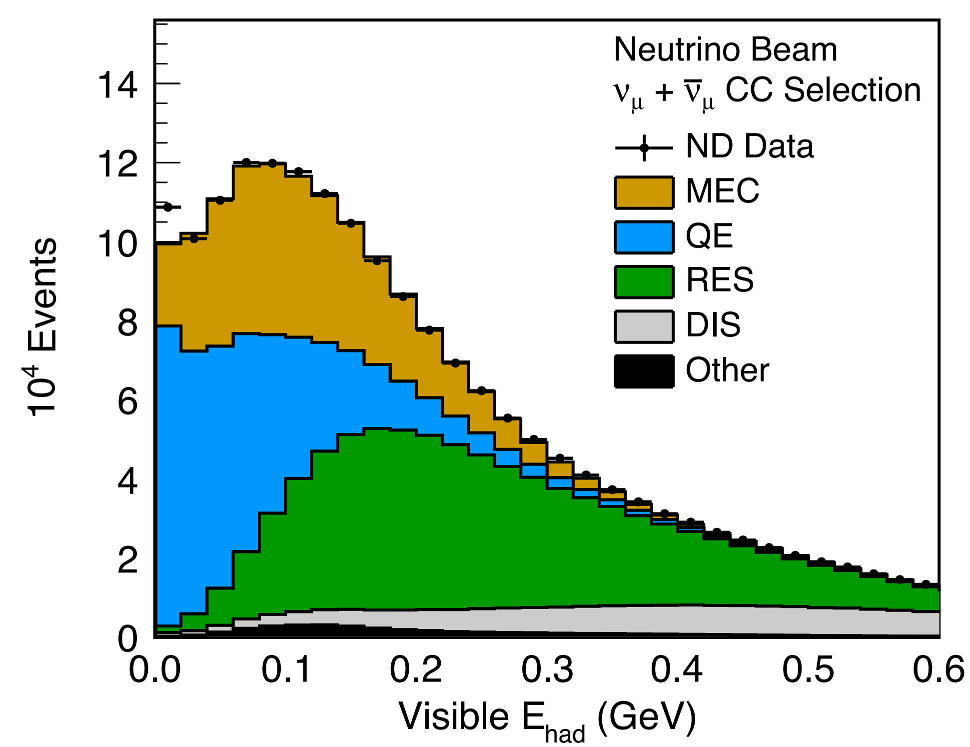

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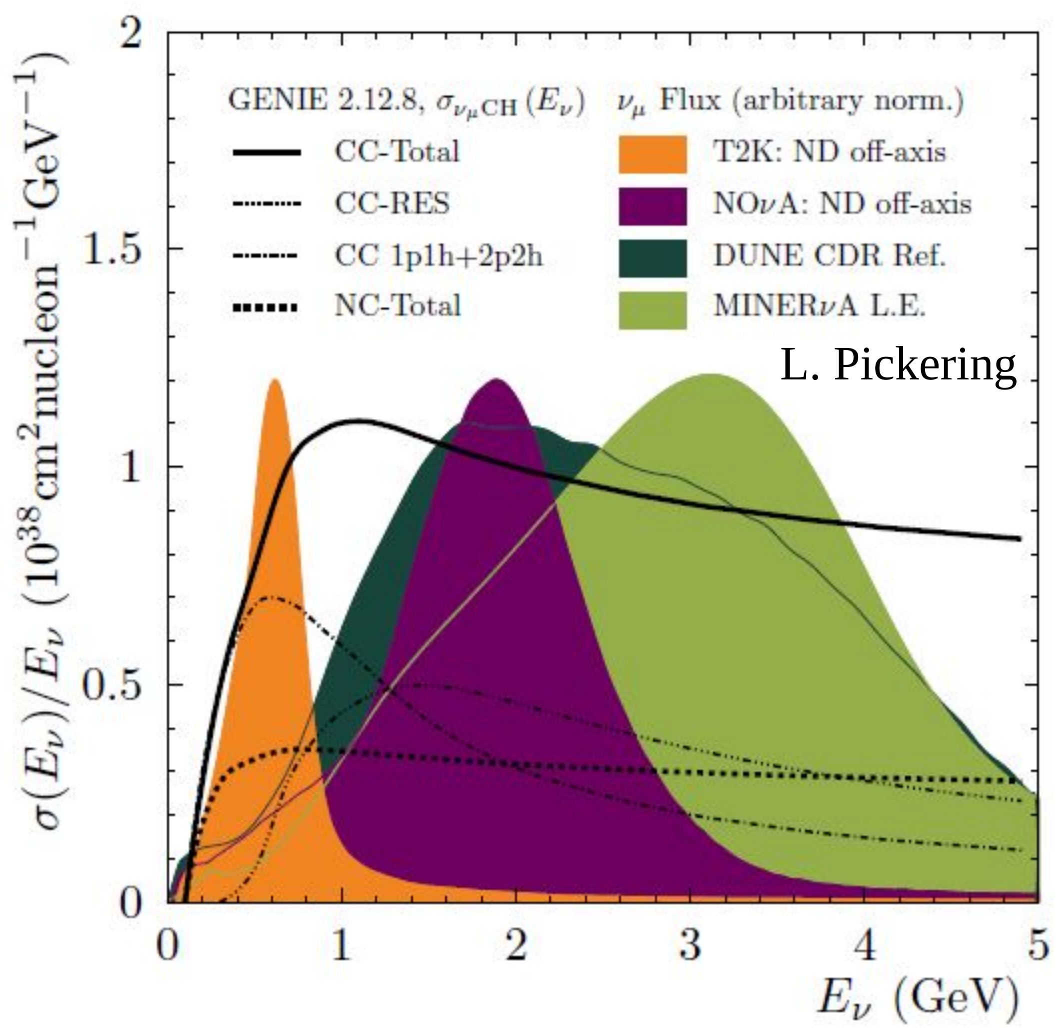
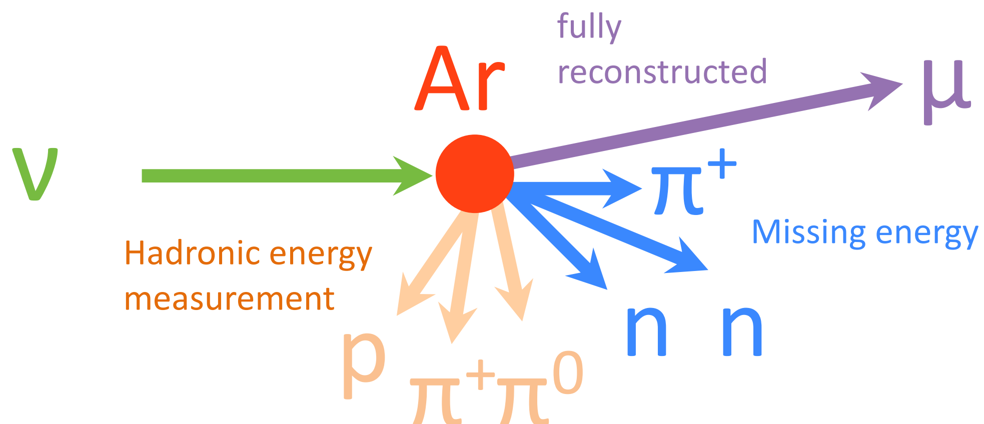
CHALLENGES FOR NEUTRINO OSCILLATIONS IN DUNE

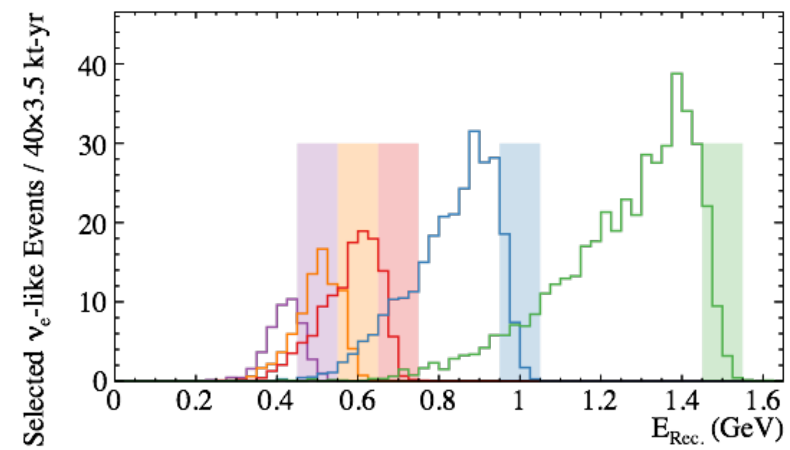
- Enormous amount of work has gone into characterizing the effects of uncertainties on DUNE using experience from current running neutrino experiments.
- However, DUNE's flux sits in an energy regime with a different mix of neutrino interaction modes where QE, RES and DIS are all significant.
- Also argon is a bigger, more complex nucleus than any of the previous oscillation experiments has used.
- We are bound to have important disagreements in the neutrino interaction modeling of these.



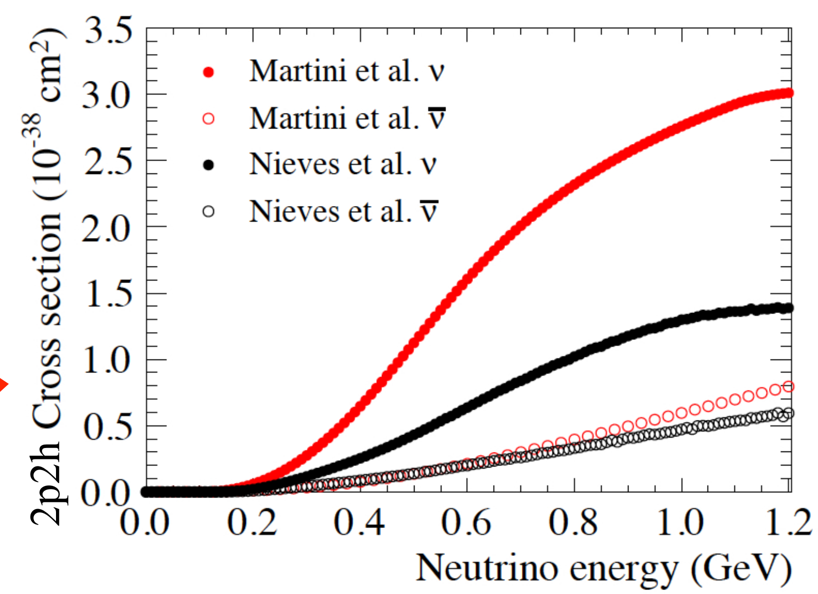
CHALLENGES FOR NEUTRINO OSCILLATIONS IN DUNE

The E Measurement Problem *M. Wilking*





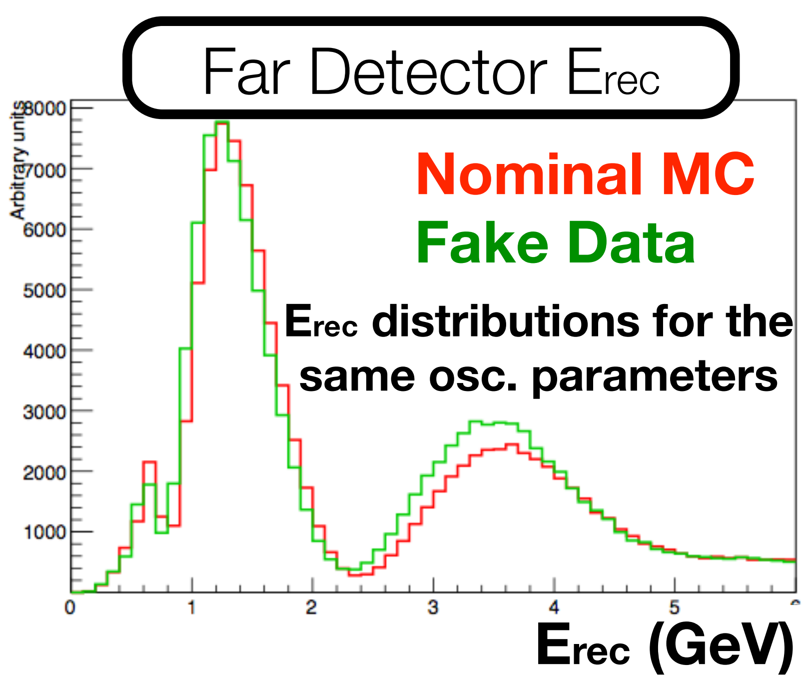
- Typically, E_ν is “measured” via the observed final state
  - However, the final state is subject to **missing energy** (e.g. neutrons) & **nuclear effects**
  - This causes smearing of E_{rec} relative to E_{true} (typically feed-down)
- E_{rec} ➜ E_{true} translation depends on **poorly understood neutrino interaction models**
  - 1p1h, 2p2h, npnh, RPA, pion production, FSI, multi-pi transition region, DIS, etc.

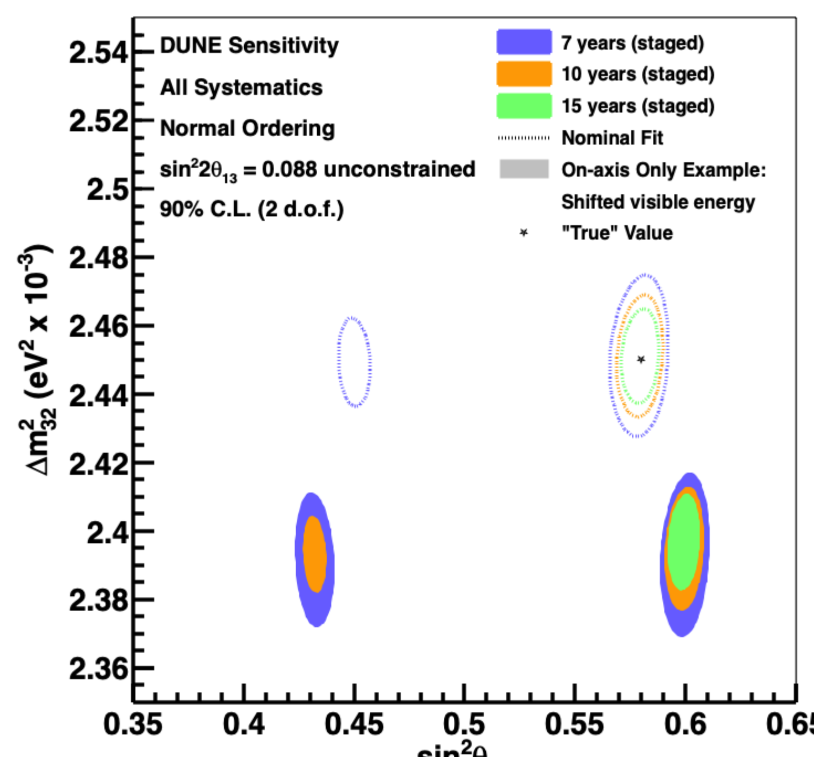


➤ Not done with the challenges :-(

OPPORTUNITIES IN NEUTRINO OSCILLATIONS IN DUNE

- The collaboration has spent significant effort in developing a ND concept that mitigates many of these concerns. The main lesson from these efforts is that demonstrating reduction of uncertainties in models that might be wrong is NOT enough.
- It is important to show what happens in the nightmare scenarios where you make the wrong assumption about the model. These studies are key.

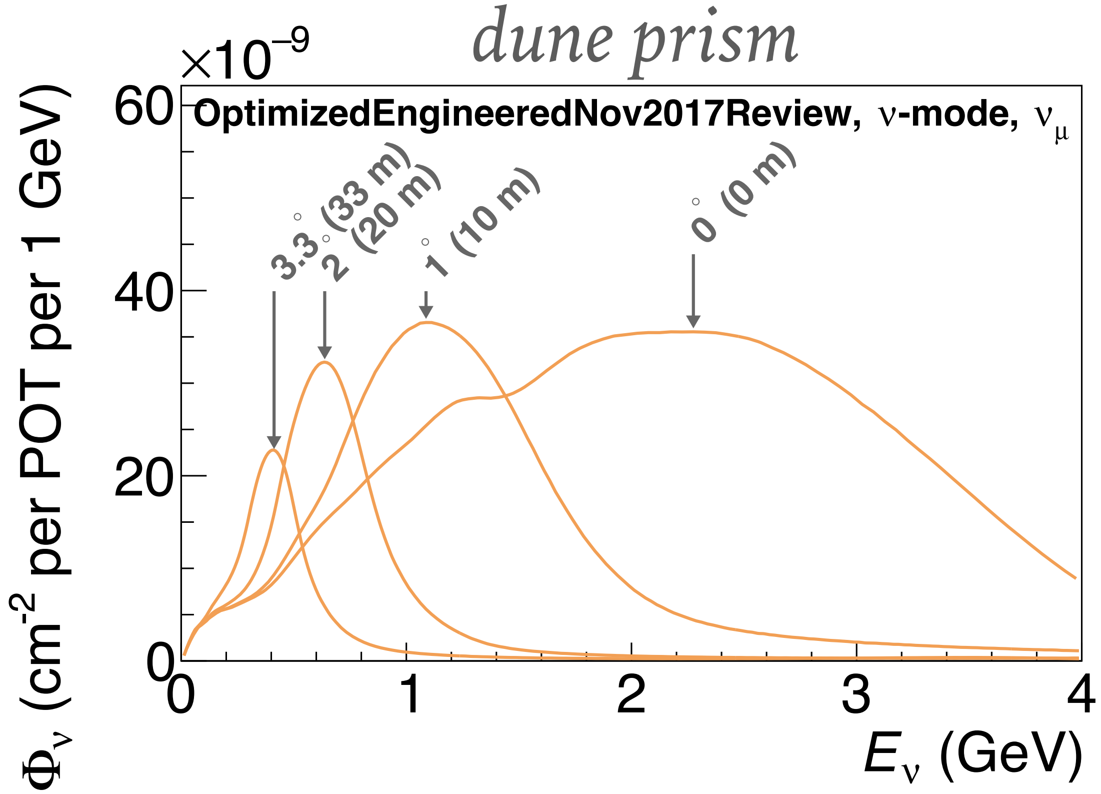




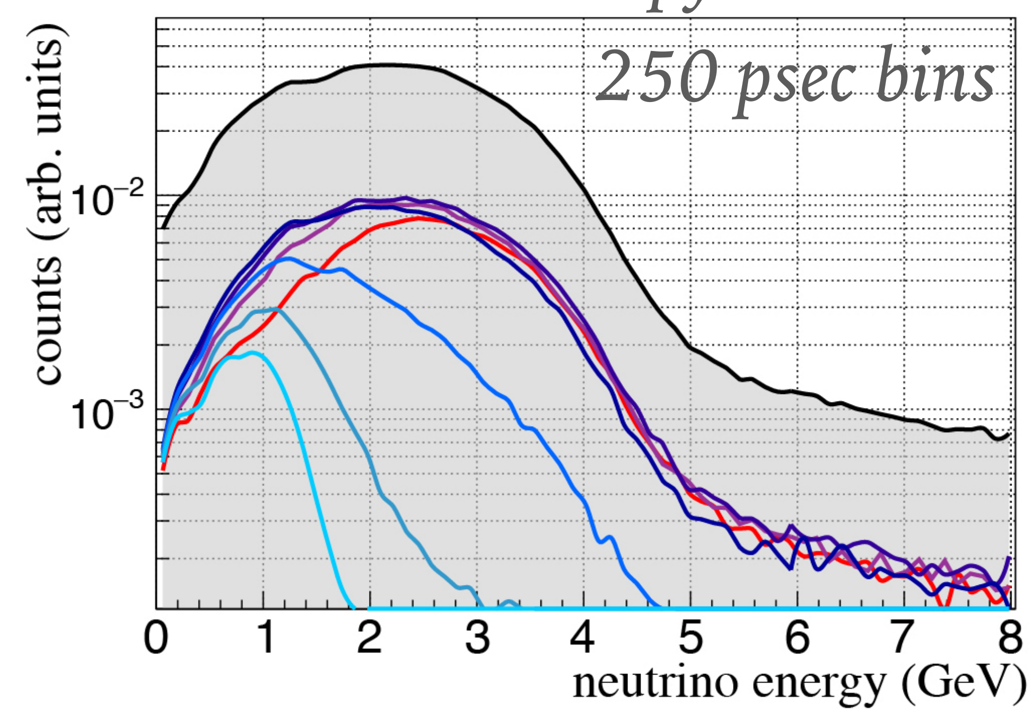
OPPORTUNITIES FOR BEAM TIMING IN DUNE

- The DUNE PRISM concept has already demonstrated that there is value in adding information about multiple flux components to the mix of information to nail down the underlying modeling.

dune prism



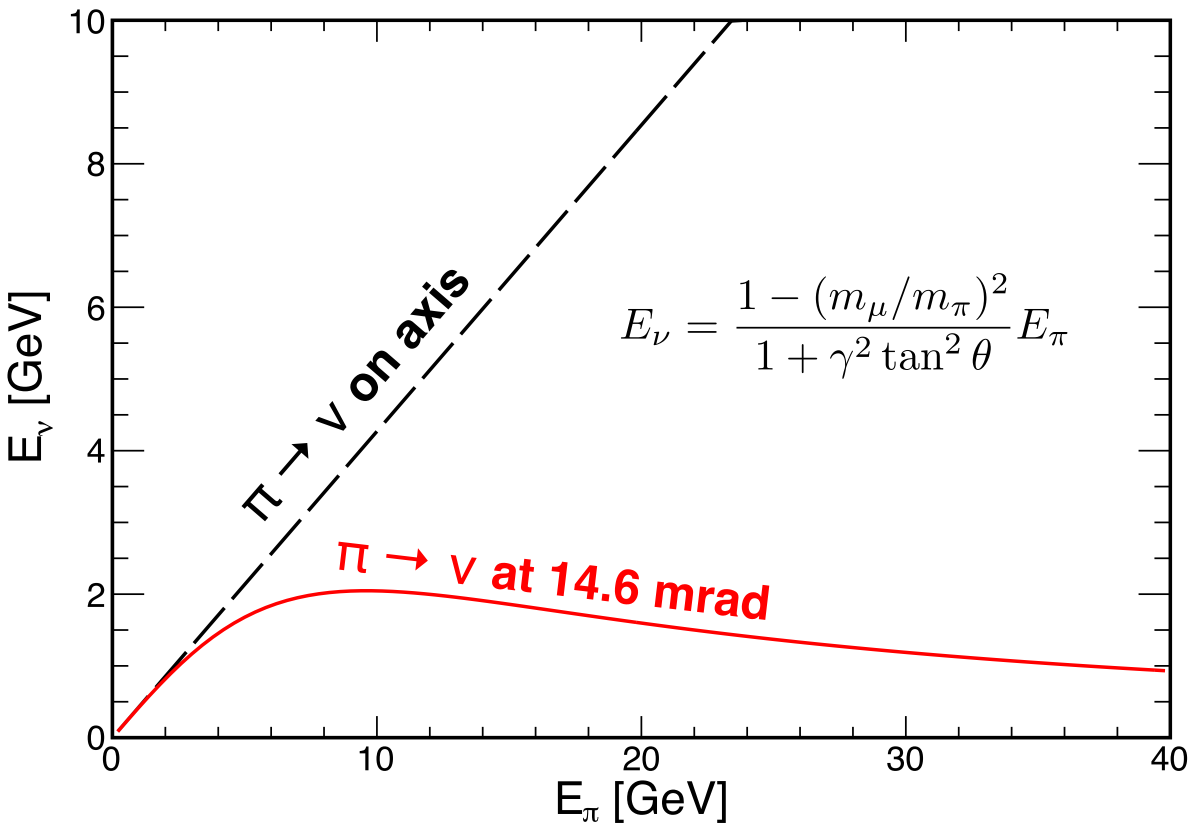
stroboscopy

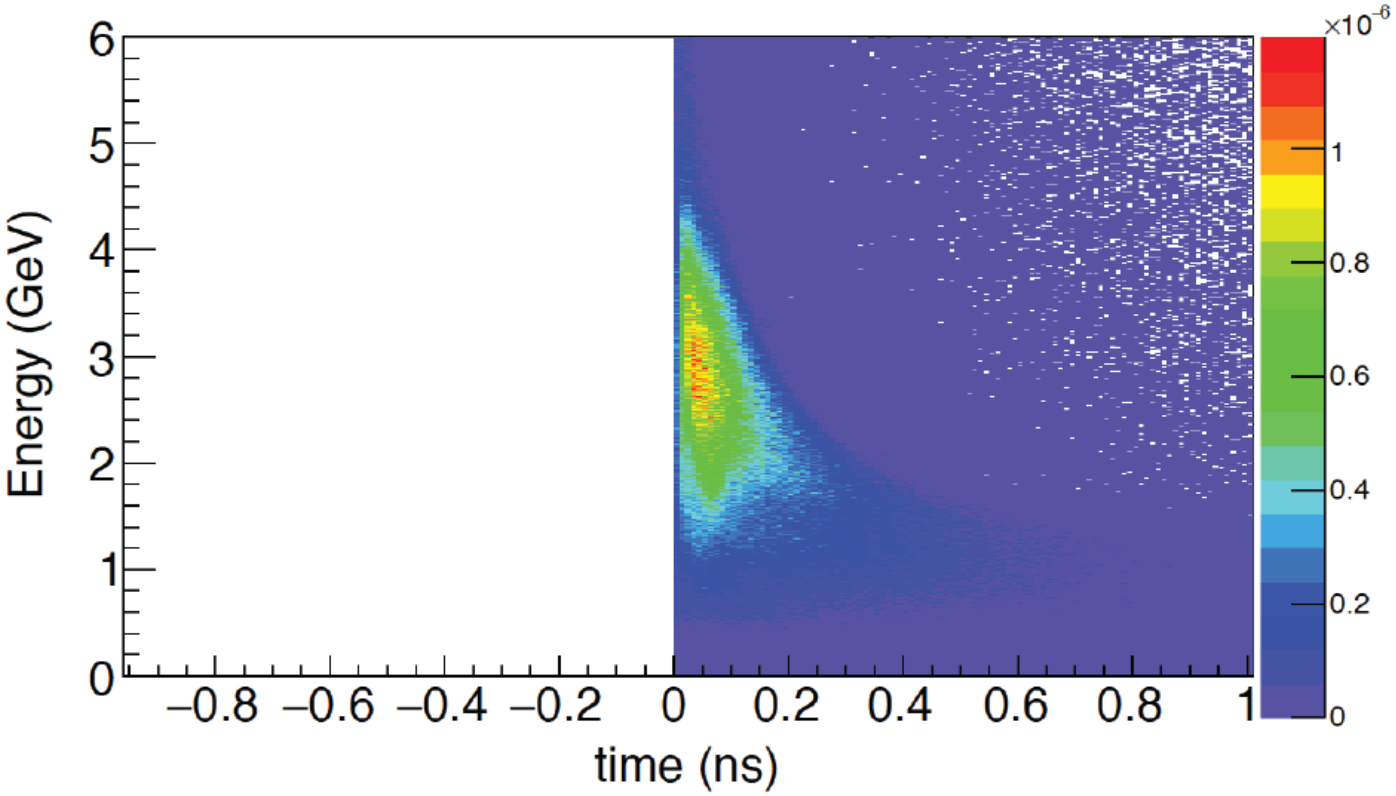


- The same kind of studies that have been valuable to make the case for DUNE PRISM could be used here. These would need to happen within DUNE.
  - Low energy reach is useful if it has sufficient statistics.

OPPORTUNITIES FOR BEAM TIMING IN DUNE

- DUNE PRISM relies on off-axis fluxes to sum over pion energies thus selecting spectra peaked at different energies.





- In principle beam spectroscopy is orthogonal to this as it is instead relying on pion momentum to select neutrino energy.
    - It is important to understand if this is the only effect.

This complementarity could make the combination a powerful concept in disentangling flux uncertainties.

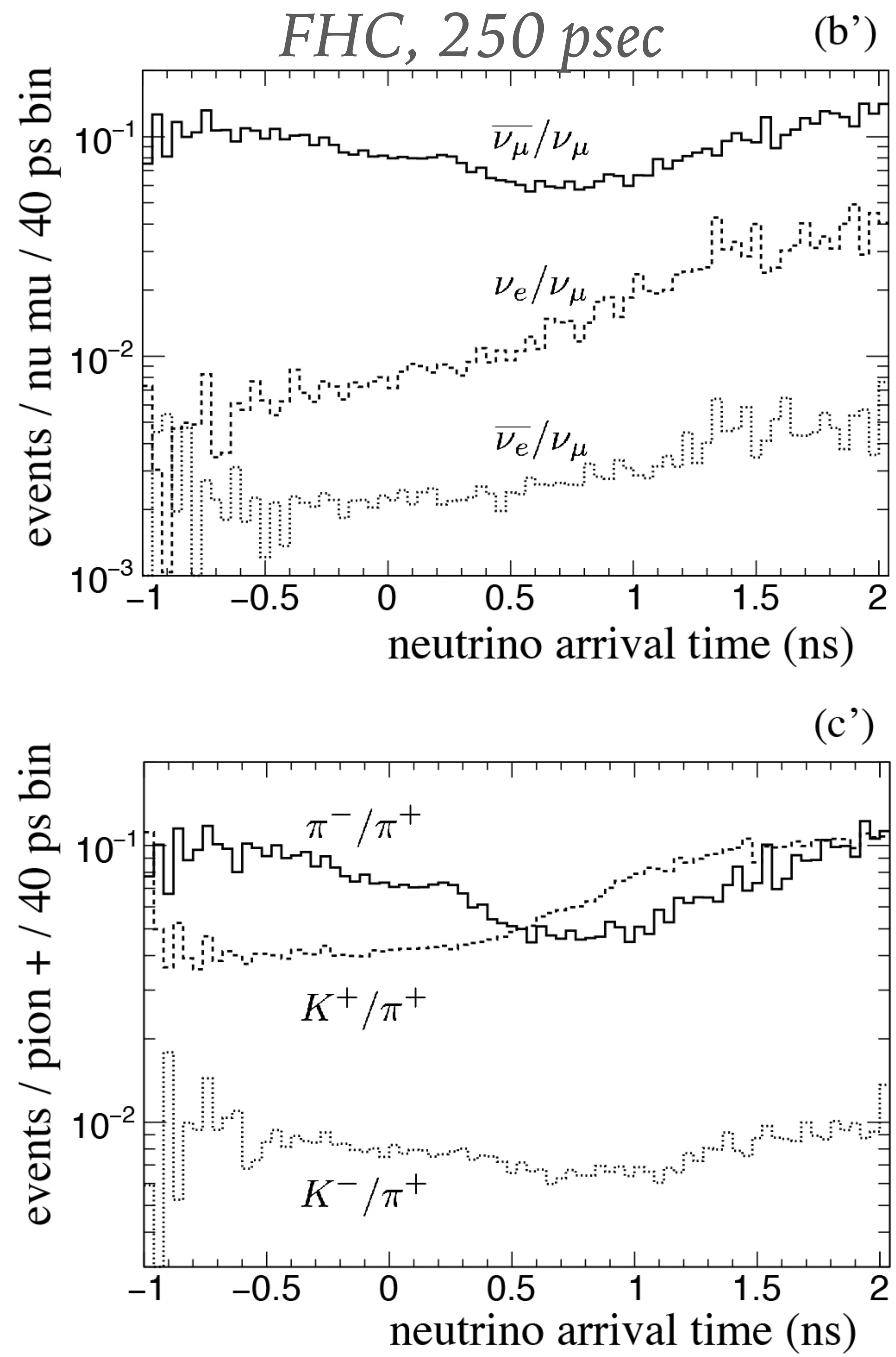
OPPORTUNITIES FOR BEAM TIMING IN DUNE

- There are a number of uncertainties that the DUNE PRISM scheme is most sensitive to:
  - Efficiency correction, geometrical efficiency correction, flux systematic uncertainties.
  - In particular for the latter, those that might affect off-axis/on-axis differently, eg focusing vs proton position and horn current.
  - Additionally, it might sensitive to a few other things yet to be studied: interactions in the decay pipe, drain hole in the decay pipe, fringe fields.
- Opportunity to understand if some of these can be mitigated by doing a timing cross check.

Do we expect to see this effect off-axis? That would be valuable

OPPORTUNITIES FOR BEAM TIMING IN DUNE

- As it was done in the case of MiniBooNE a handle on the pion/kaon ratio would be very useful to the collaboration.
- This could be a unique component of what can be done with the beam slicing concept.
  - Flavor ratios might be well measured down to few percent level but not as function of true energy.



OPPORTUNITIES FOR BEAM TIMING IN DUNE

Uses of DUNE-PRISM Samples *M. Wilking*

1. **Identify** cross section mis-modeling that can produce biased oscillation parameter measurements
   - By looking off-axis (changing the E_ν spectrum), we can identify mis-modeling problems that are not apparent on-axis
2. **Overcome** cross section mis-modeling problems (2 approaches):
   a) **Standard approach**: Develop a cross section model that can describe the near detector data
      - The bar is now much higher due to samples taken at many different neutrino energy spectra

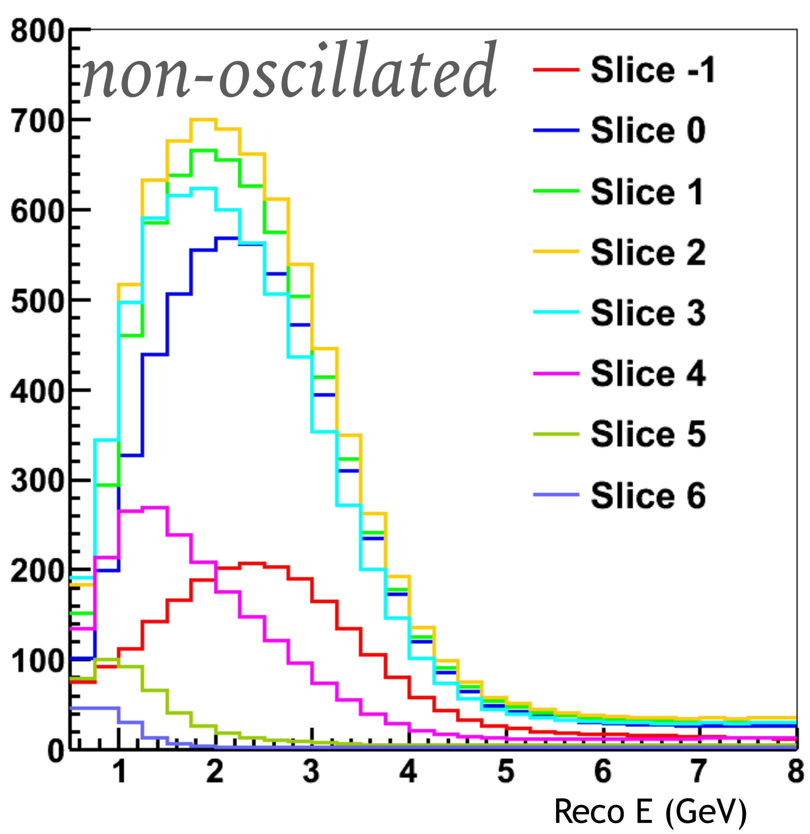
   b) **Data-driven approach**: Take linear combinations of off-axis measurements to produce a FD prediction composed of ND data
      - Any unknown cross section effects are directly incorporated into the far detector spectrum prediction

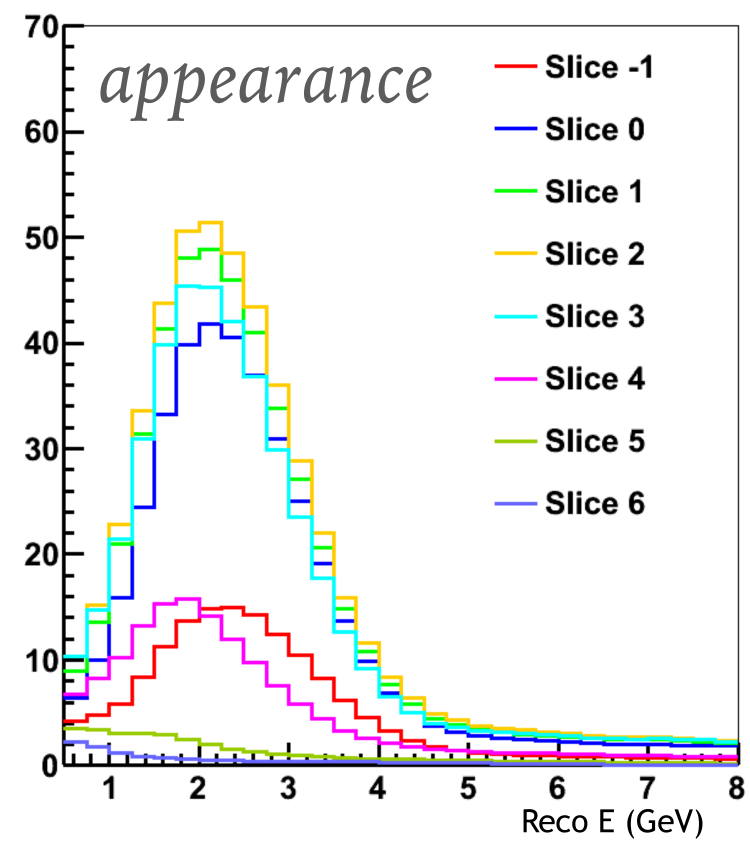
- Approaches for beam stroboscopy would be similar to these. I'll note that 1 and 2a requires significant and lengthy head-scratching whereas 2b might be less applicable if the resulting spectra overlay does not cover enough of the phase space with sufficient stats.

OPPORTUNITIES FOR BEAM TIMING IN DUNE

- We have seen the first disappearance and appearance spectra per slice.

E. Worcester

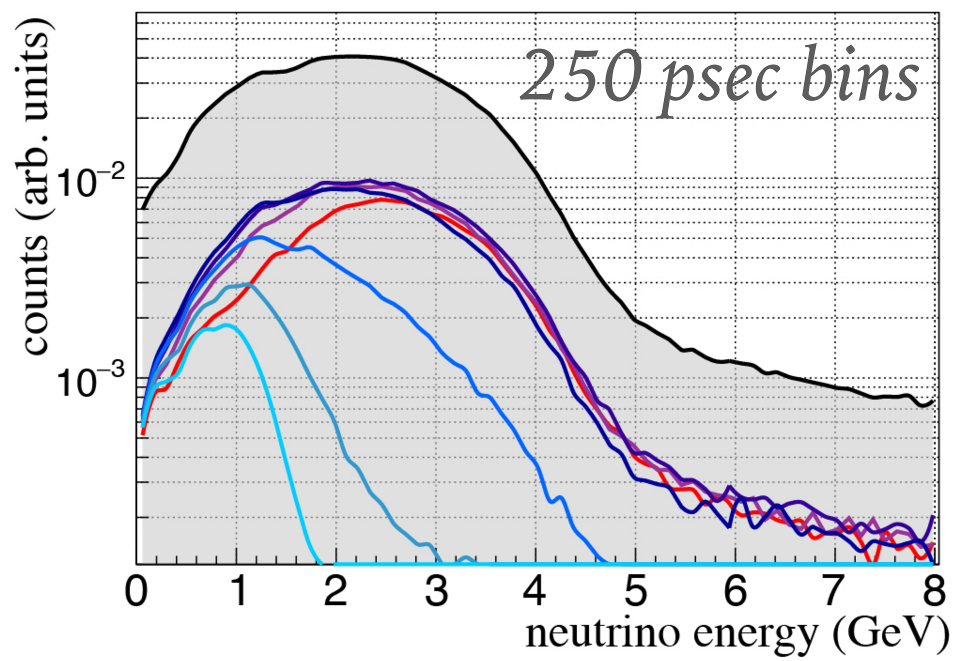




- Channeling Elizabeth: *Quantifying impact on sensitivity is hard and will require DUNE LBL analysis with full suite of systematics and clever use of mock data.*
  - Globes studies can help indicate where the sensitivity to CP is coming from and might helpful in optimizing bin slices but not much more than that.

CHALLENGES FOR BEAM TIMING IN DUNE

- As it has been done in DUNE PRISM, the uncertainties of the method will need to be characterized.



stroboscopy

- One one hand this method will be less sensitive to relative acceptance issues as it is comparing fluxes in the same detector position. It also does not rely on the off-axis flux.
- On the other hand issues like beam/bunch timing are new and will need sensible guesses as to how well things can be know. Also, is the difference in time coming just from pion momentum selection or are there geometric effects at play as well?

The key will be in understanding the underlying potential uncertainties of the method.

CHALLENGES FOR BEAM TIMING IN DUNE

- Ultimately, to show complementarity/value, we will want to create a study that shows something that could go unnoticed by DUNE ND/PRISM but would show up with this method.
  - This will need a detailed understanding of the complementarity.
- Feasibility of this method for the ND seems ok.
  - However using say timing in the muon catcher components vs the main volume of detector might expose you to additional acceptance uncertainties. Needs to be studied.
- Feasibility of this method for the FD still has to be demonstrated. Potential avenues seem to be: dual phase detector or upgrade to future modules.
  - The benefit to the analysis is not obvious and must be thought through. It is possible that doing multiple ND/FD experiments (as if they were on-axis+different off-axis angles) and combining them might have some additional power (not obvious from Globes study, perhaps because of stats at low end?), but the key will be what uncertainty or potential mis-modeling are you mitigating.

OPEN QUESTIONS

- Is the mechanism for the energy selection by time coming only for the meson momentum?
- What are the uncertainties this method is most sensitive to?
- Does it work off-axis?
- How do the event counts in the lower energy slice compare to the most off-axis positions in DUNE PRISM (in straw man run plan)?
- What uncertainty would a pion/kaon (or other flavor) ratio measurement have with this method?
- What is the benefit of this method in the Far Detector?