DUNE-PRISM: A New Approach to Constraining Neutrino Interaction Uncertainties

Mike Wilking
Stony Brook University
DUNE ND Workshop
June 9th, 2017

Overview

- Reminder of limitations of single-location near detectors
  - Cross section uncertainties produce unknown
  - Determination of E_{true} ➜ E_{rec} is model dependent
- Brief reminder of NuPRISM concept (within T2K)
- DUNE-PRISM geometry and requirements
  - Signal definition choices
- Brief discussion of $\sigma(\nu_e)/\sigma(\nu_\mu)$

How to Measure Neutrino Oscillations

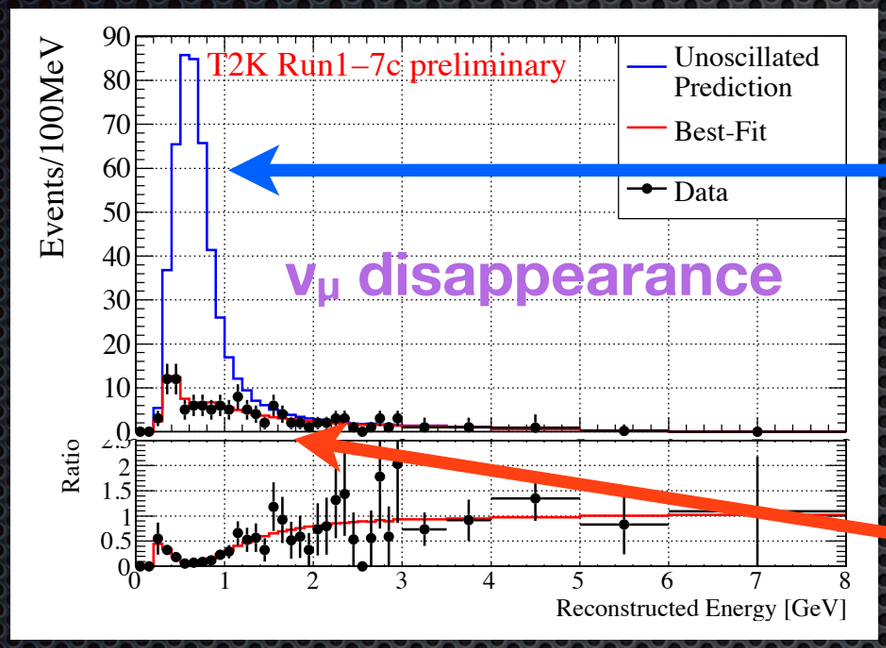
These equations are often shown at DUNE meetings:

$$ND(\nu_\mu) = \Phi(E_\nu) \times \sigma(E_\nu, A) \times \epsilon_{ND} \times M^{E_{rec}}_{E_{true}}$$

$$FD(\nu_\mu) = \Phi(E_\nu) \times \sigma(E_\nu, A) \times \epsilon_{FD} \times P_{osc} \times M^{E_{rec}}_{E_{true}}$$

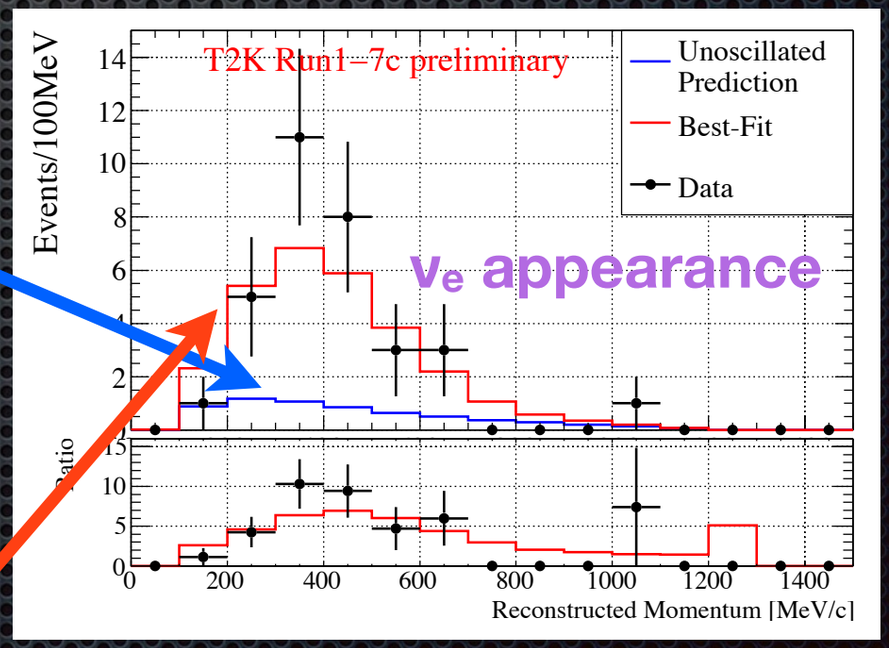
- In the case of functionally similar detectors the flux combined with the cross sections uncertainties ~~largely cancel.~~ still see **very different** E_ν fluxes (due to oscillations)

Unfortunately, "cancelation" does not work!



Near Detector Measures:
- ν_μ energy spectrum
- Small ν_e component

Far Detector Measures:
- Osc. ν_μ energy spectrum
- Large ν_e appearance signal

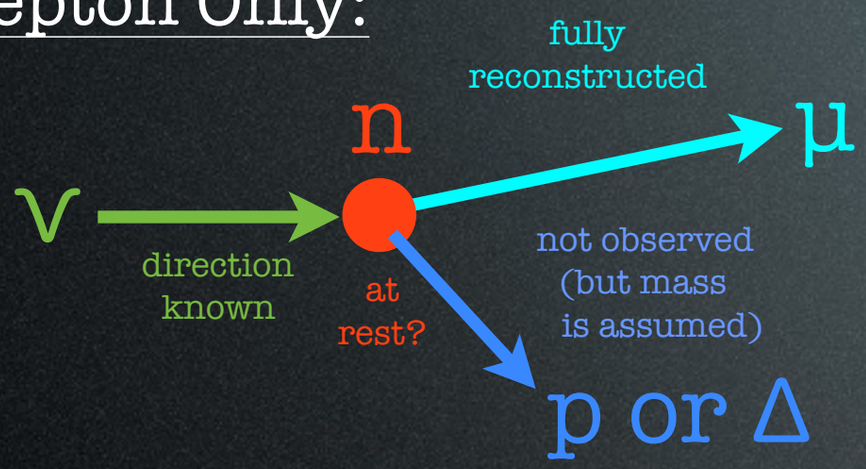


- $E_{true} \rightarrow E_{rec}$ migration matrix is (quite) non-diagonal! (next slides)
- Several important cross section uncertainties will not cancel

Measuring E_ν

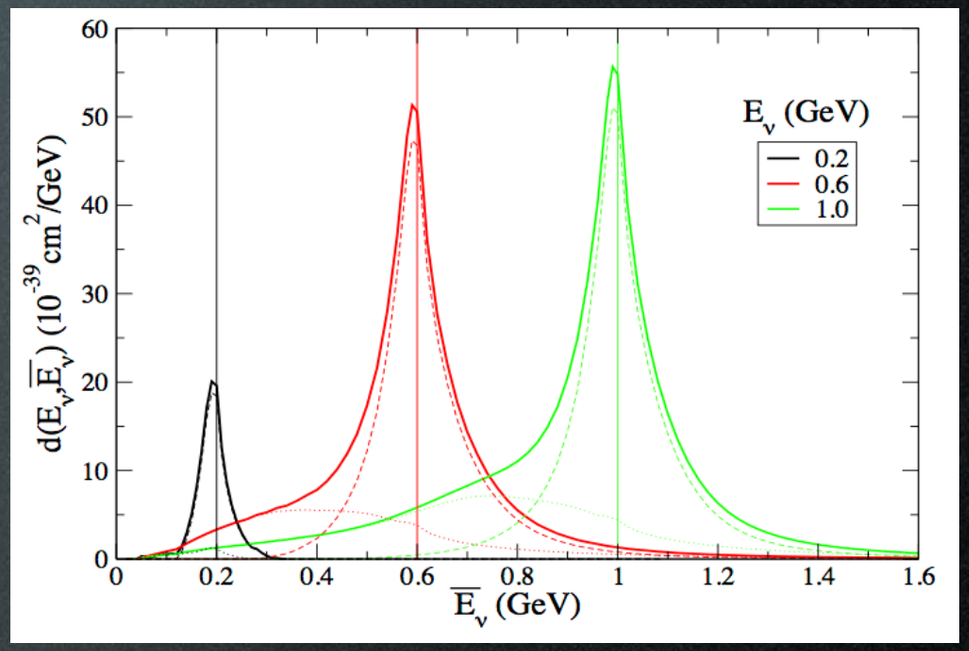
Martini et al. arXiv:1211.1523

Lepton Only:



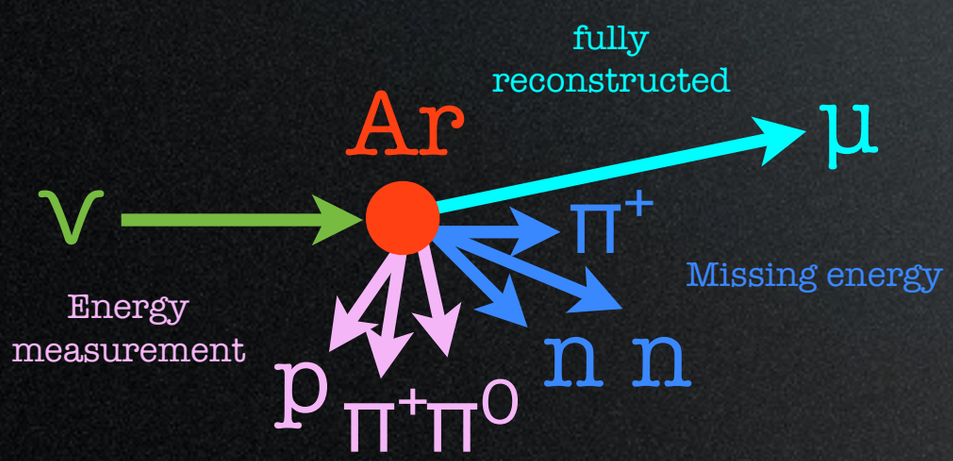
Must assume mass of recoiling hadron(s)

Problematic! due to Multi-nucleon interactions



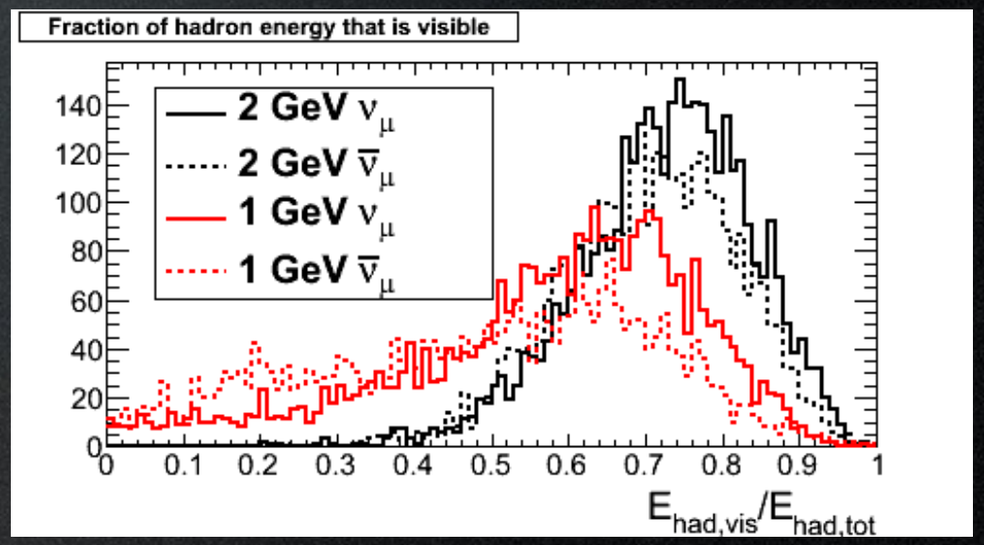
Lepton + Hadronic Energy:

http://public.lanl.gov/friedland/LBNEApril2014/LBNEApril2014talks/McGrew_LANL_Apr2014.pdf



Missing hadronic energy from n, unseen π^+, etc.

Energy loss is different for ν and anti-ν



GEANT4 Simulation of a large LAr volume

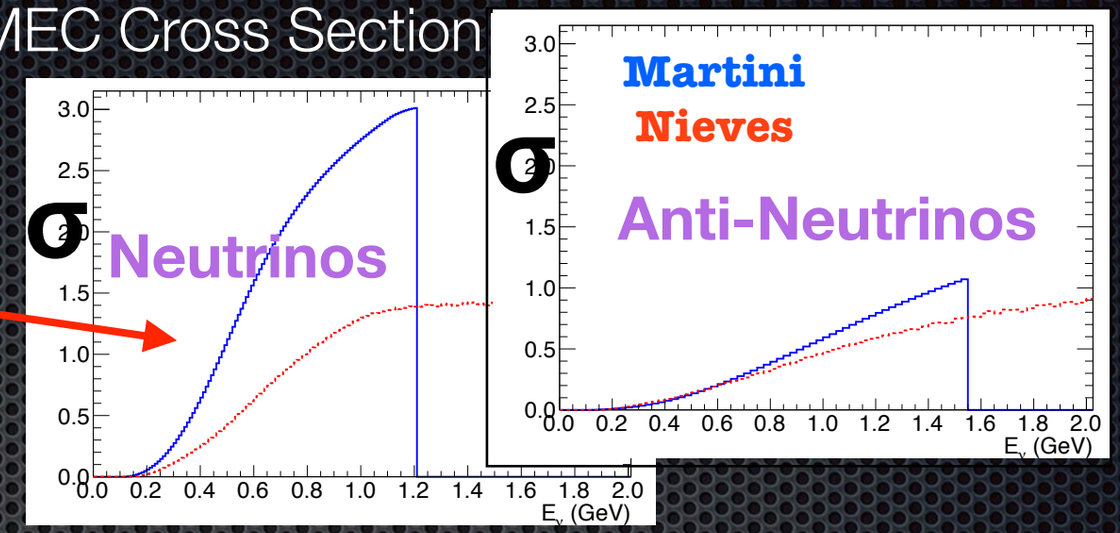
(True deposited hadronic energy)/
(True initial hadronic energy)

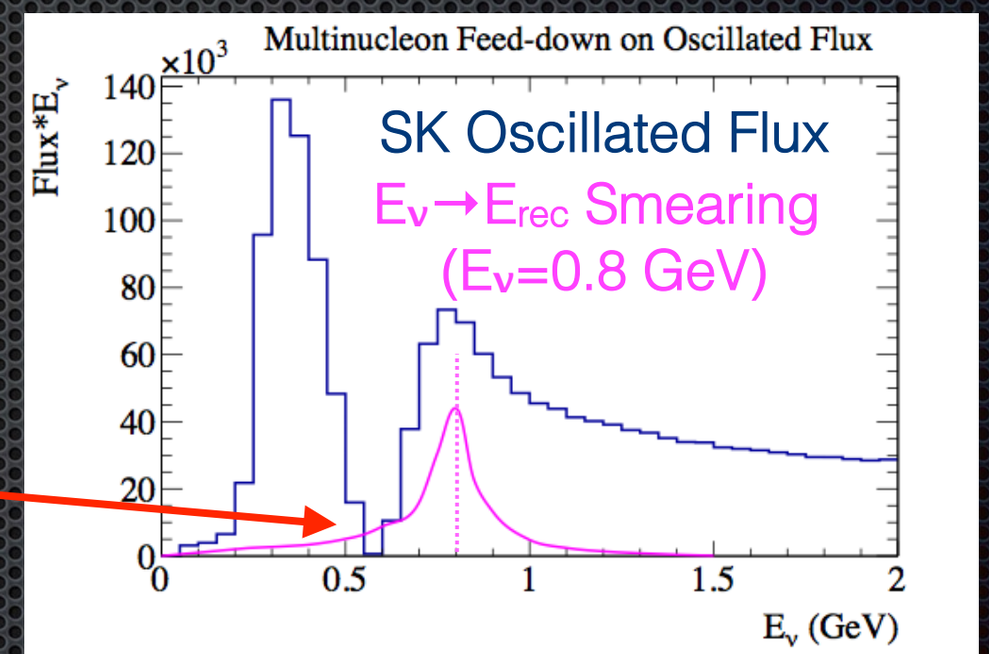
- Both effects lead to underestimating the neutrino energy (feed down)
- Need to calibrate both leptonic (e & μ) & hadronic energy scales, and energy tails

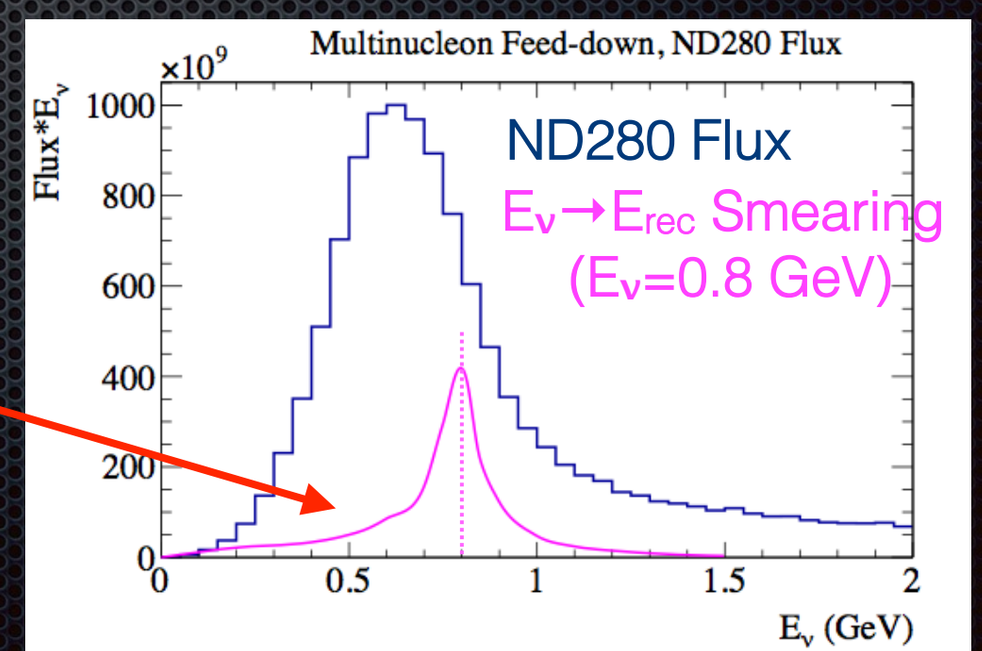
E_ν Feed Down

- Feed down & σ are poorly understood
  - Factor of ~3 disagreements in existing (effective theory) models
  - Different for ν & anti-ν
- E_ν feed down **fills in** the ν_μ disappearance dip
  - Results in **large biases** in **θ_{23}** and **Δm^2_{32}** measurements
- **Conventional near detectors lack sensitivity** to feed down tail
  - Many degenerate solutions
  - Cannot constrain effect at far detector

MEC Cross Section

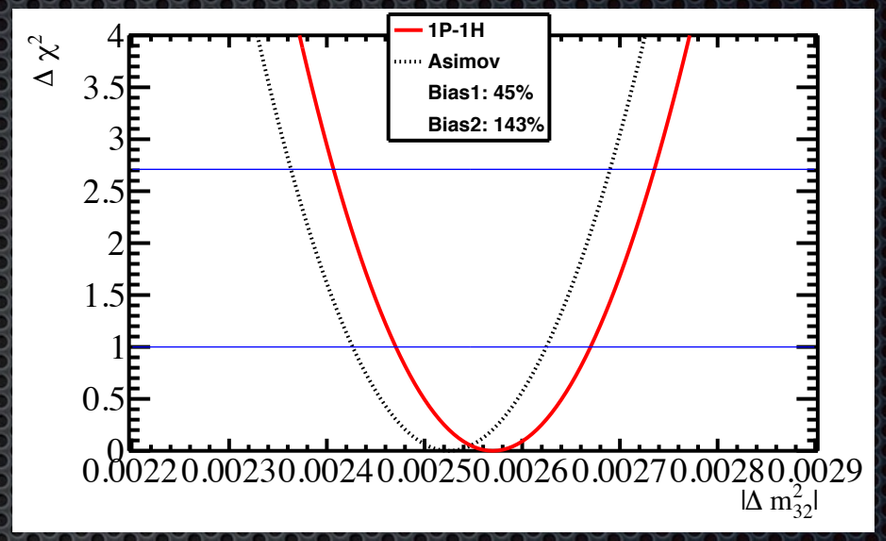


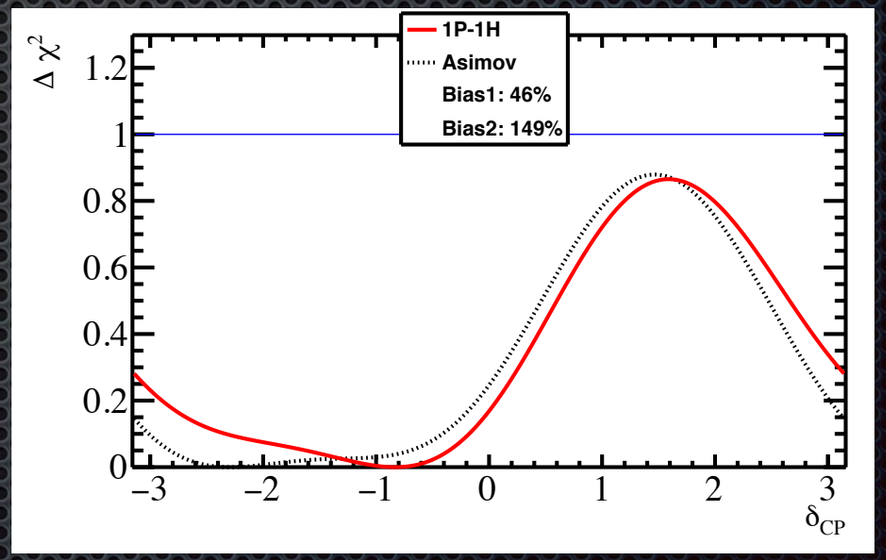


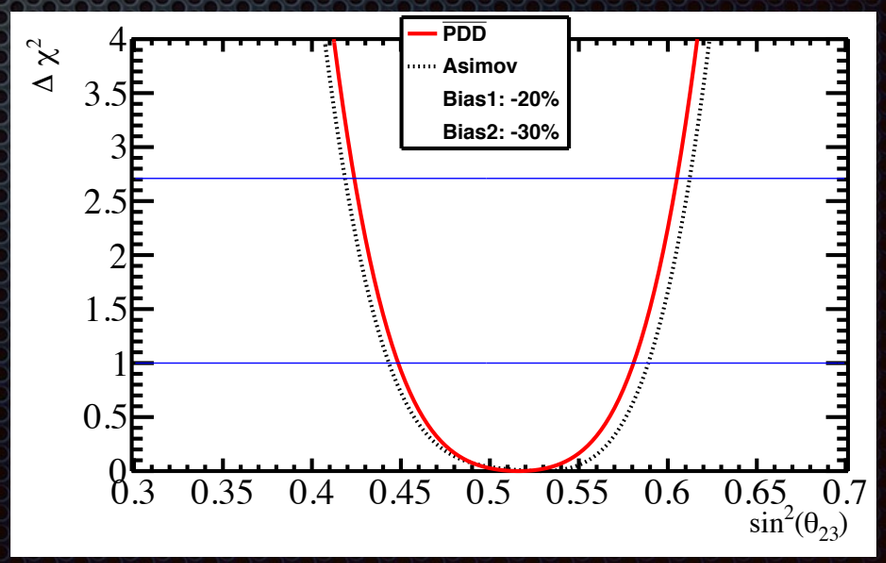


Fake Data Studies

- If we had a **model we could believe** at the sub-% level (in rate and shape), our jobs would be much easier
  - We would simply design a near detector to constrain the parameters of that model (& e.g. valor fits would provide all necessary information for decision making)
- However, our models are **not very good**
  - It is unlikely that any combination of model parameters will reproduce our data
- We can try to probe this using **fake data studies**, where the data contains features not accessible by the MC model in the fit
  - In T2K, such studies show that, even with a standard near detector constraint, **large biases occur** in the fitted oscillation parameters

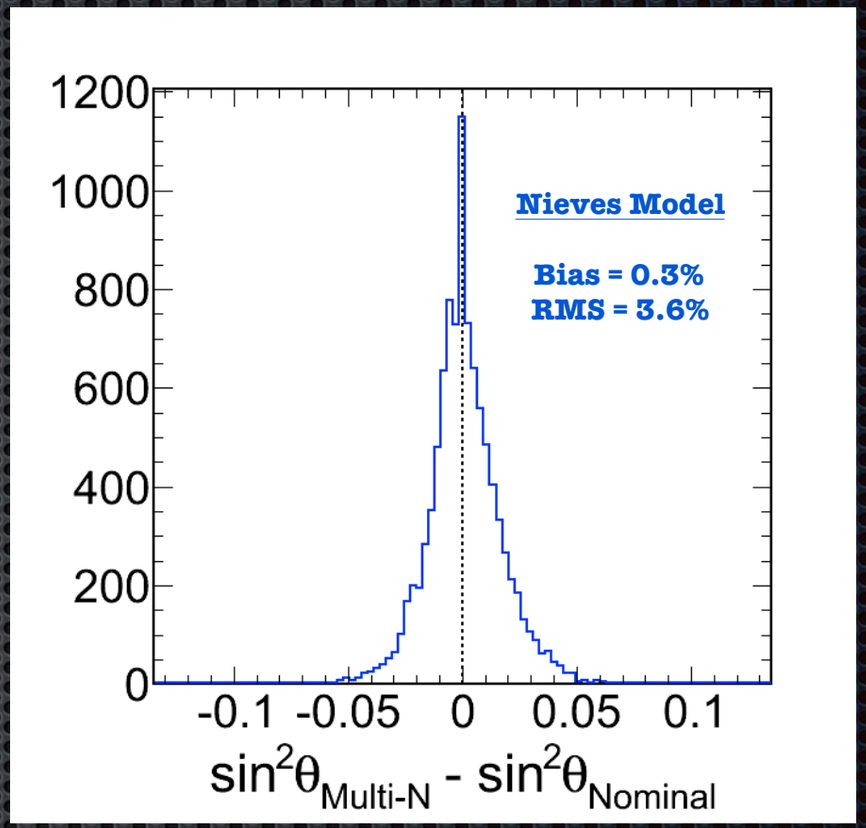


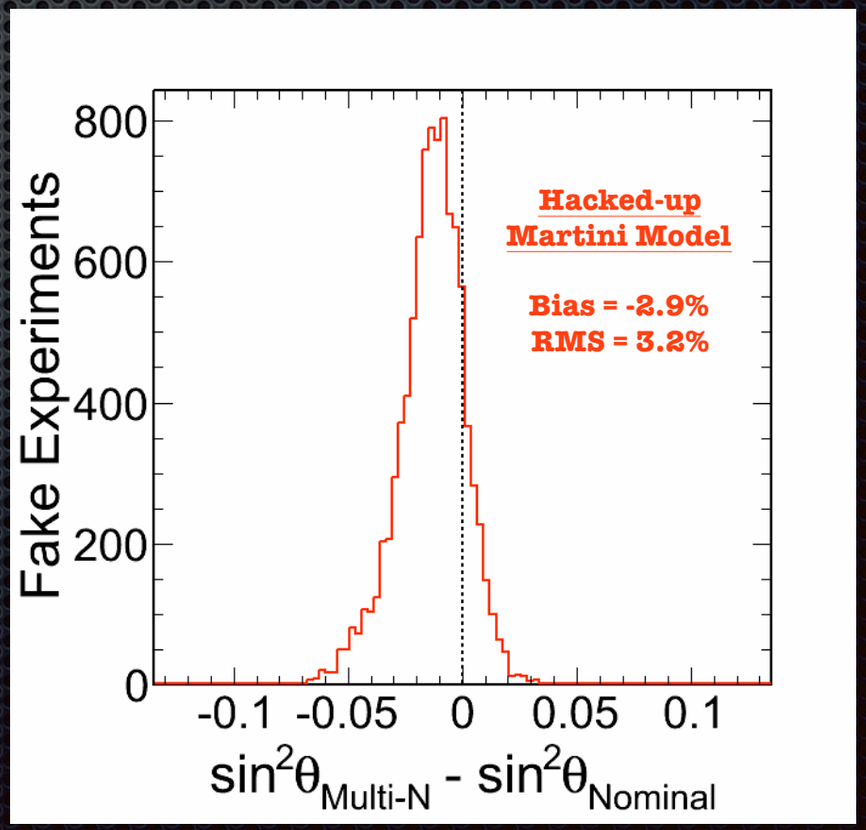




Example Fake Data Study

- Create fake data samples with flux and cross section variations
  - 2 versions: **with** and **without** multi-nucleon events (i.e. T2K 2013 model vs 2015 model)
- For each fake data set, full T2K near/far oscillation fit is performed
  - For each variation, plot difference with and without multi-nucleon events
- Resulting error on θ_{23} at the ~4% level
  - **This is would be one of the largest systematic uncertainties for T2K**
- But this is not a "real" systematic uncertainty; it is just the comparison of 2 models

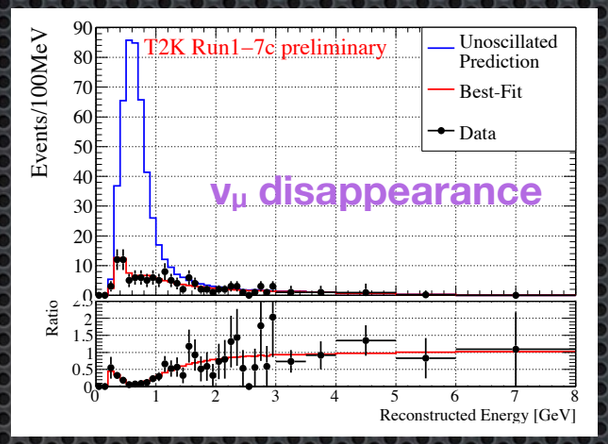


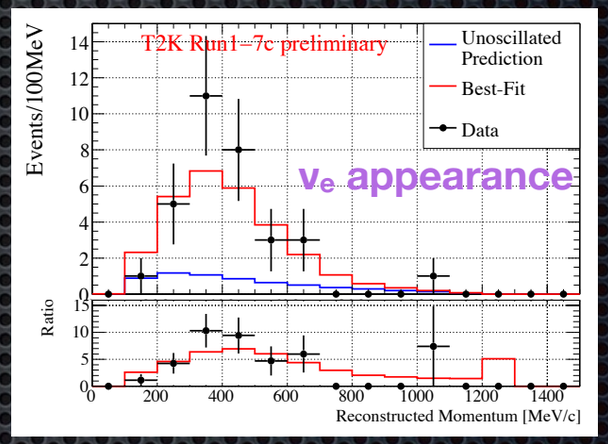


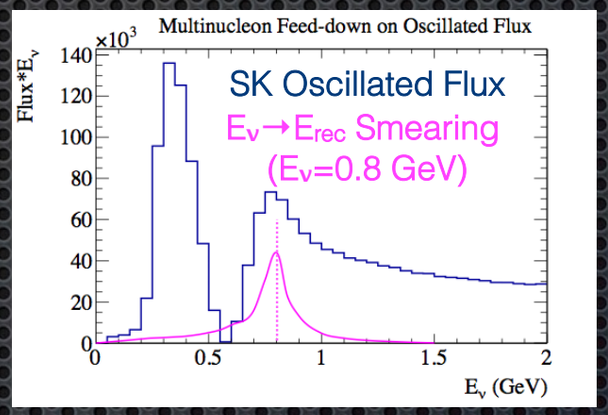
Summary of Cross Section Model Difficulties for Conventional Near Detectors

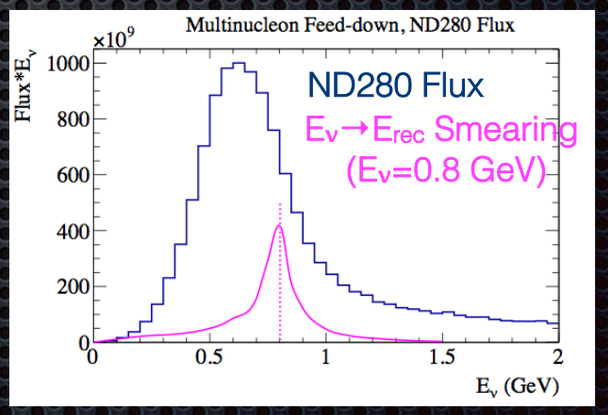
1. If your **fluxes are different** at the near and far detectors
   - …they will be, due to oscillations
2. And you introduce **cross section parameters** that are:
   A. **Important** at the **far** detector
   B. **Largely degenerate** at the **near** detector
3. Then you will have systematic errors that your near detector can no longer help with

- We already know of some such parameters, and more are likely to be introduced in the future (unknown unknowns)



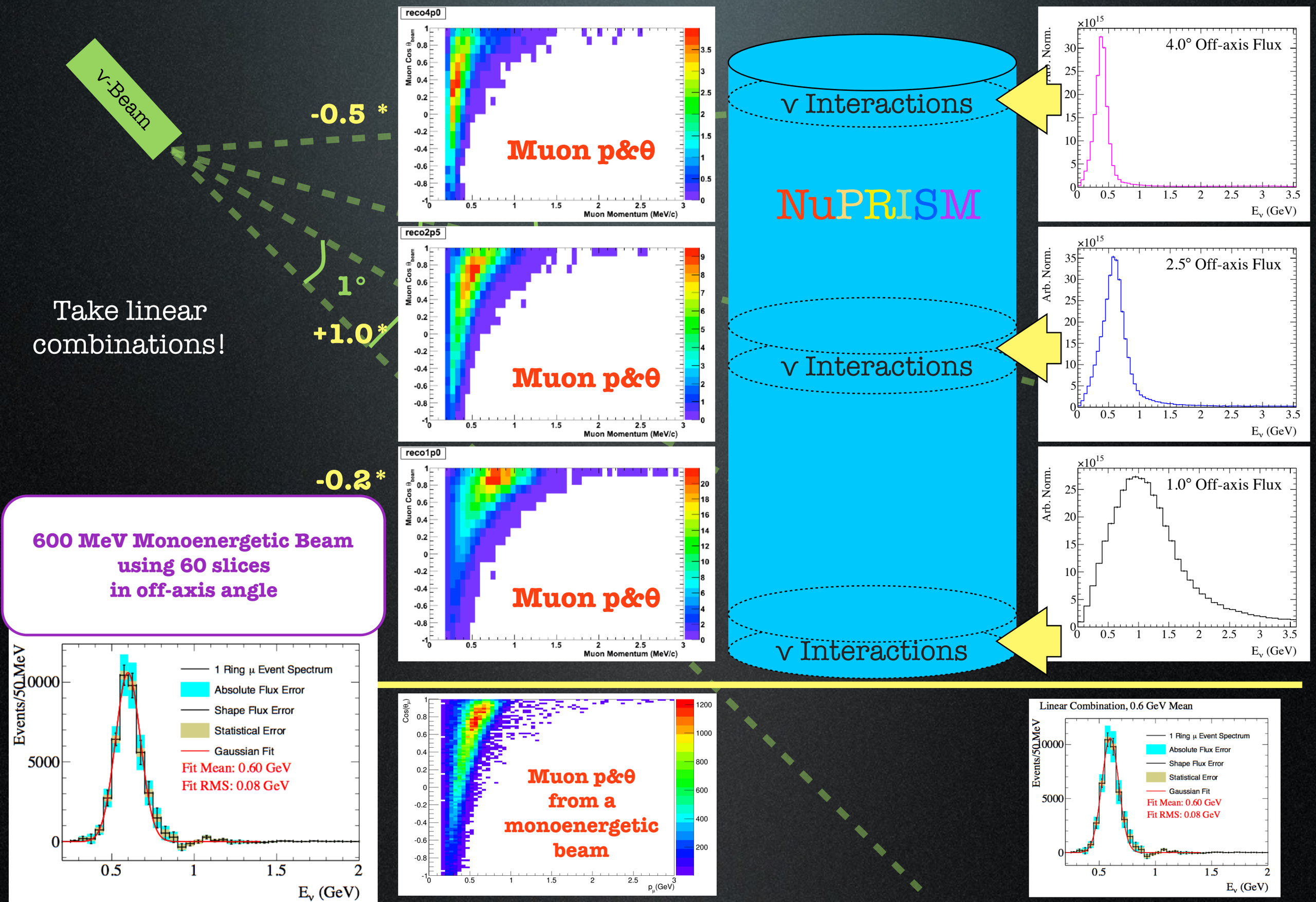




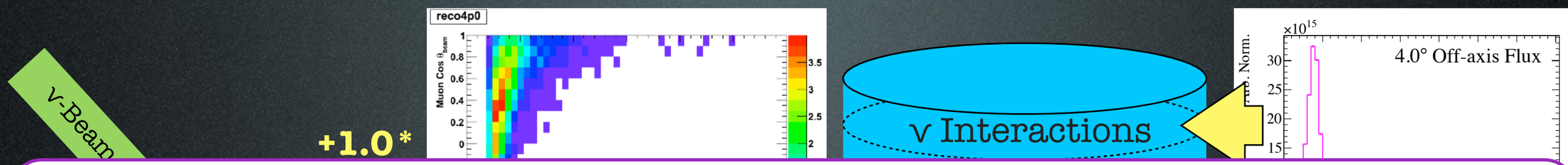


This problem goes away if we can measure $E_{true} \rightarrow E_{rec}$ experimentally

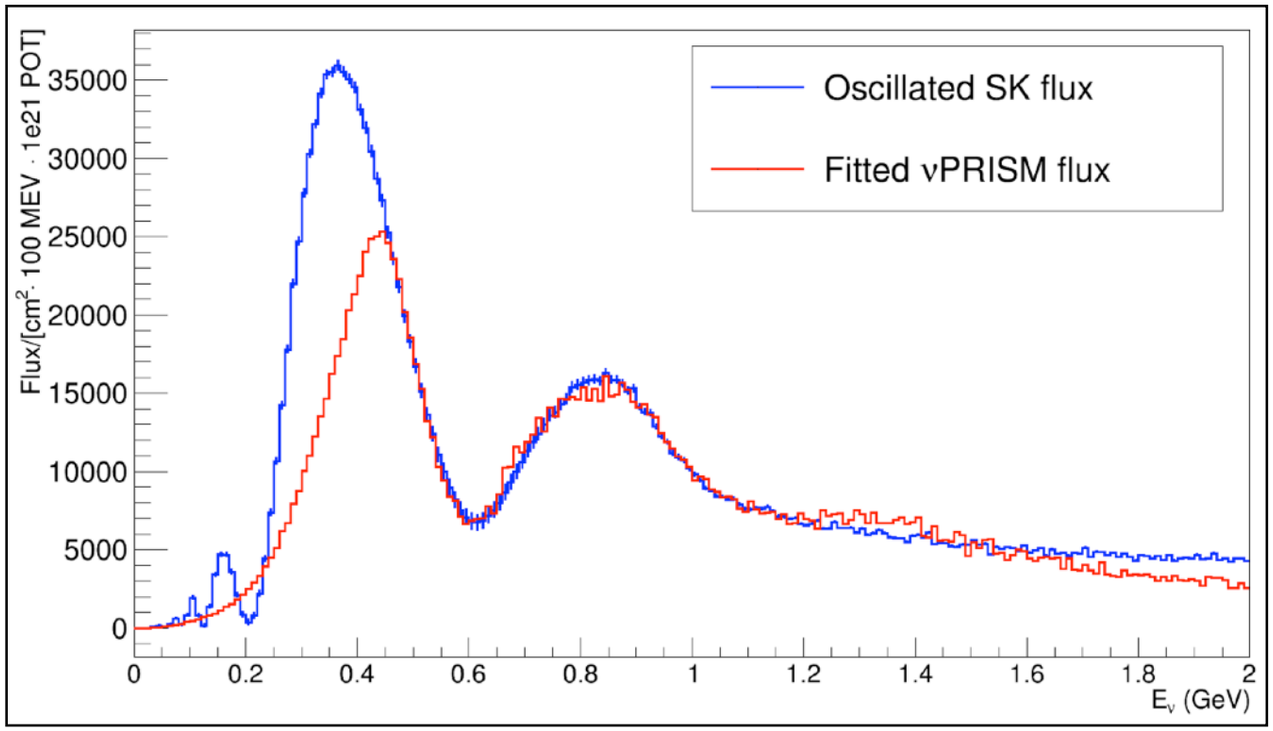
NuPRISM Detector Concept



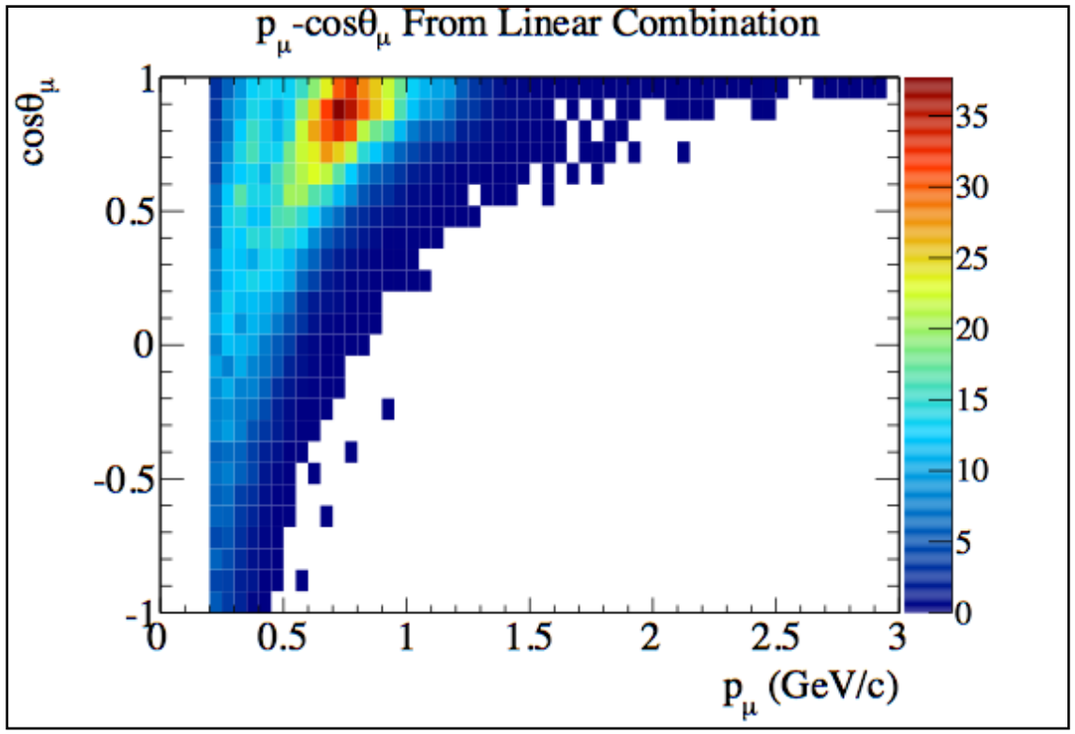
NuPRISM in Oscillation Experiments



Oscillated Flux Produced at the Near Detector!



Oscillated p&θ Measured at the Near Detector!

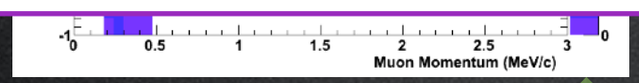


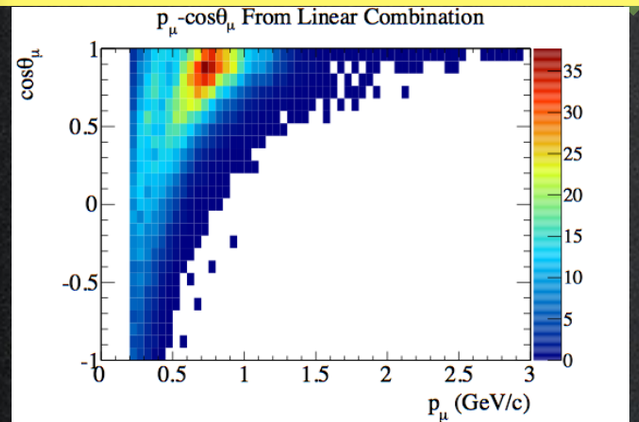
Ta

co

This technique has (so far) been robust to fake data studies

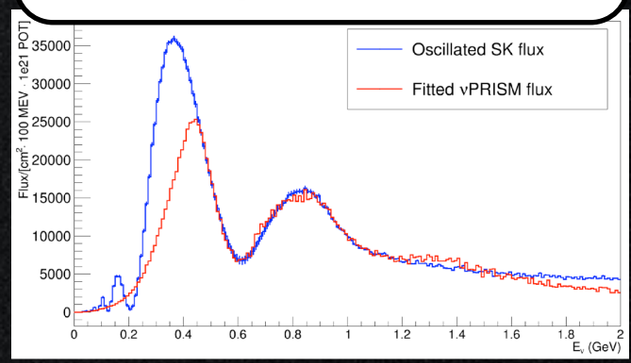
(more detailed study is underway)





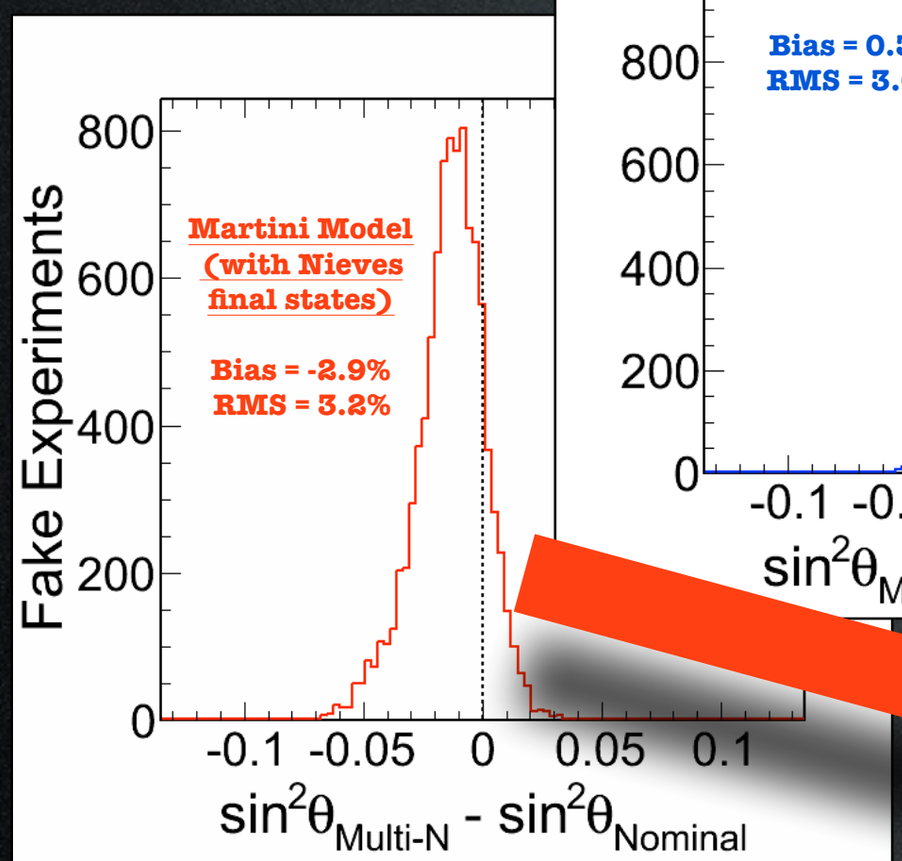
Measured oscillated p&θ spectrum in a near detector!

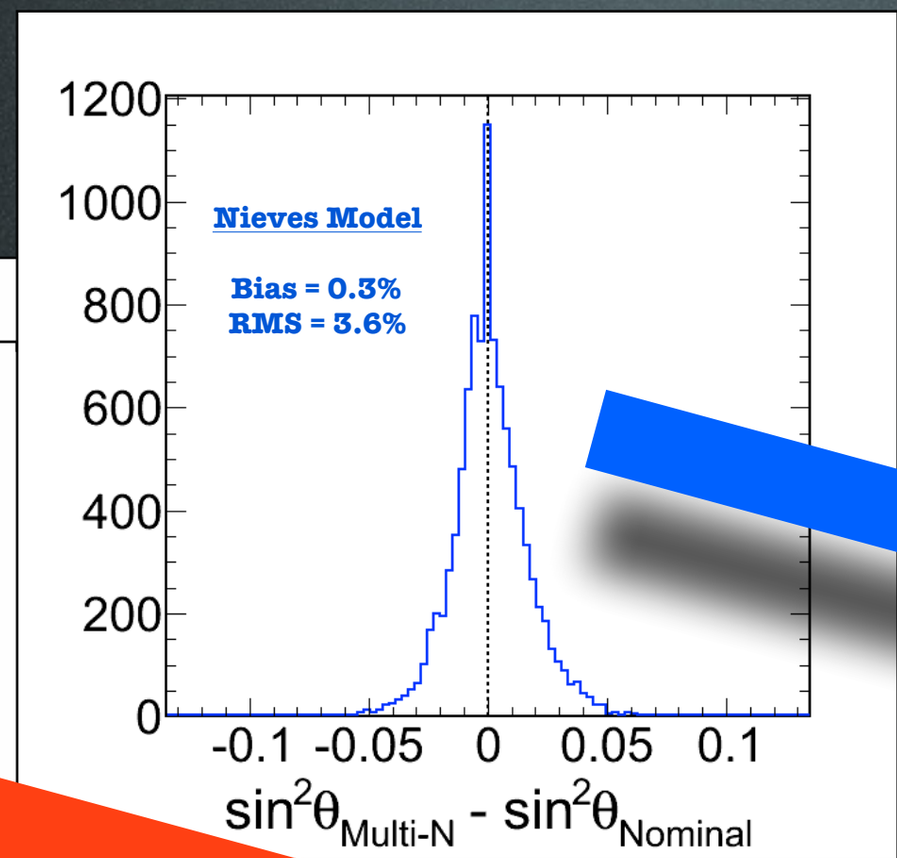
Match Super-K Oscillated Flux



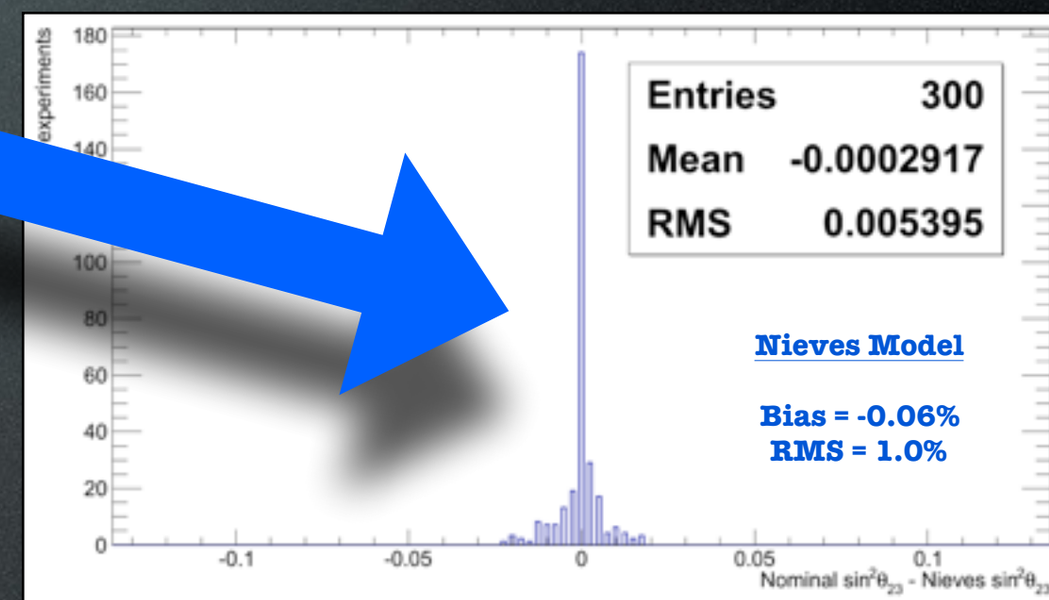
NuPRISM ν_μ Disappearance Constraint

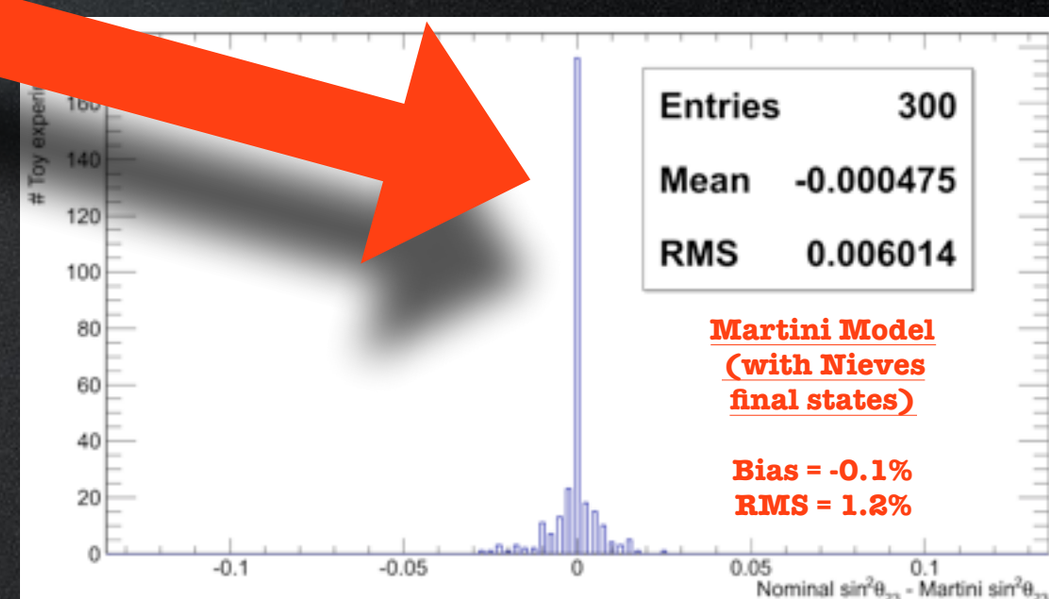
Standard T2K Analysis





NuPRISM Analysis

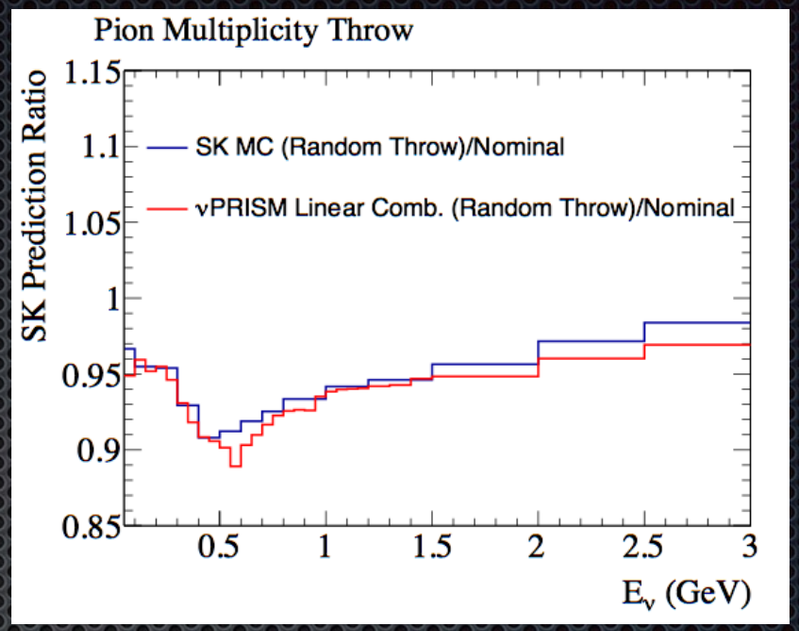


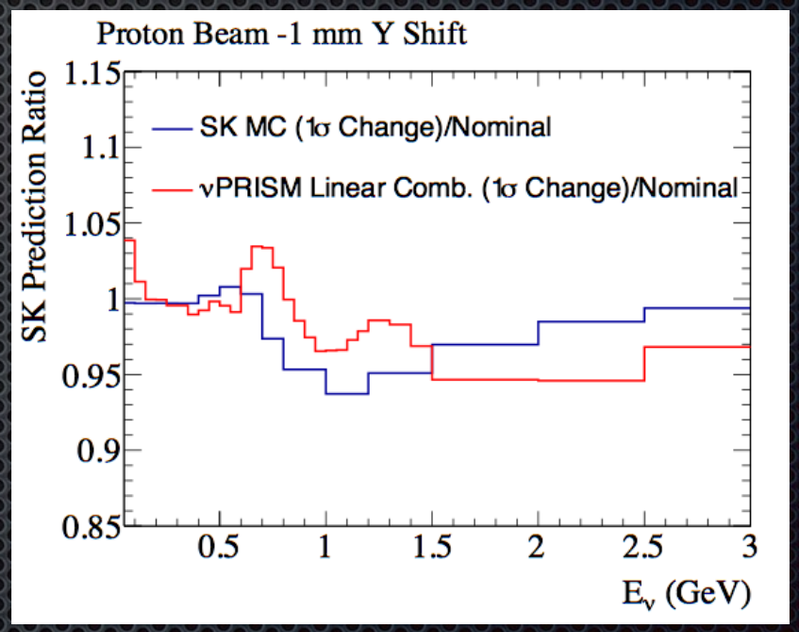


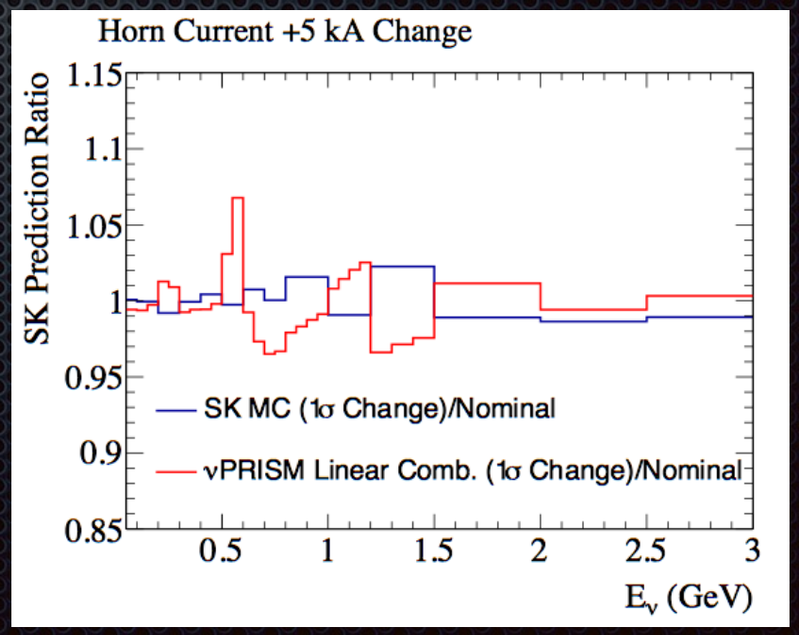
- Fake data studies show the bias in θ_{13} is reduced from **4.3%/3.6%** to **1.2%/1.0%**
- More importantly, this is now based on a **data constraint**, rather than a model-based guess
- Expect the NuPRISM constraints to get significantly better as additional constraints are implemented (very conservative errors)

Beam Uncertainties

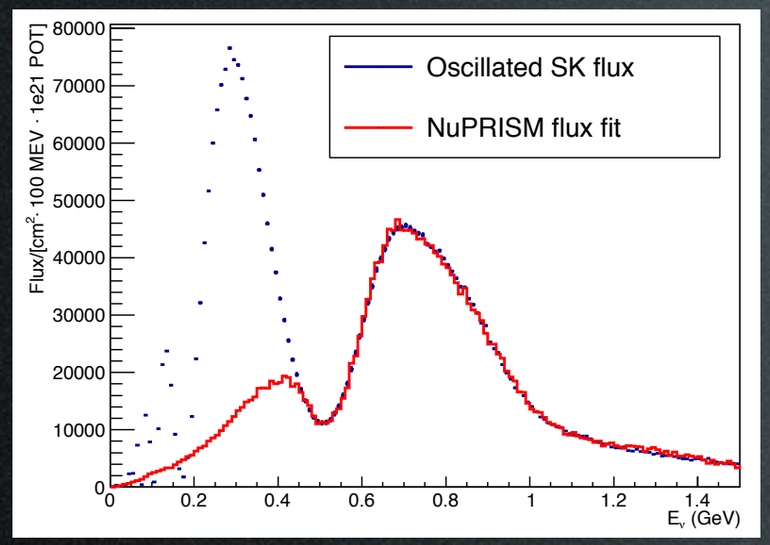
- Haven't we just replaced **unknown cross section errors** with **unknown flux errors**?
  - Yes! But only relative flux errors are important!
  - Significant cancelation between NuPRISM and far detector variations
- **Normalization uncertainties will cancel** in the NuPRISM analysis
  - Cancelations persist, even for the NuPRISM linear combination
  - **T2K without NuPRISM**: hadron prod. errors dominate; **T2K with NuPRISM**: hadron prod. errors are negligible
- Variations that affect off-axis angle shape are most important
  - Horn current, beam direction, alignment, etc.
- For T2K, beam uncertainties do not significantly contribute to the ν_μ disappearance sensitivity

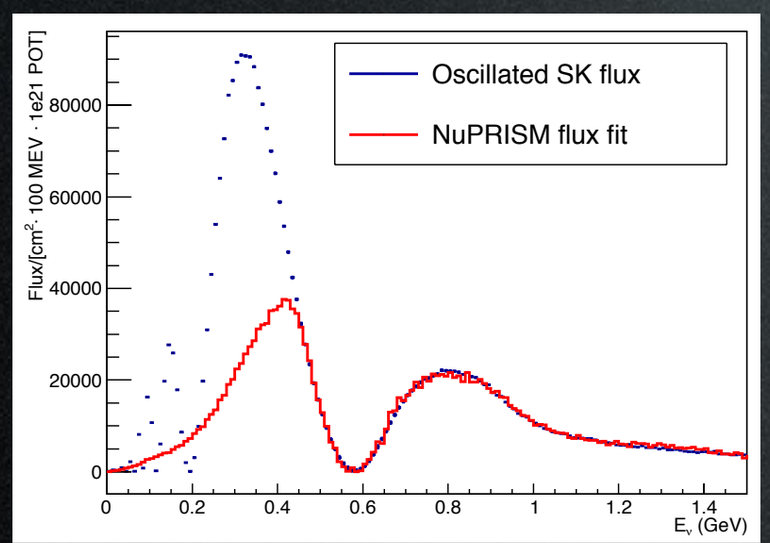


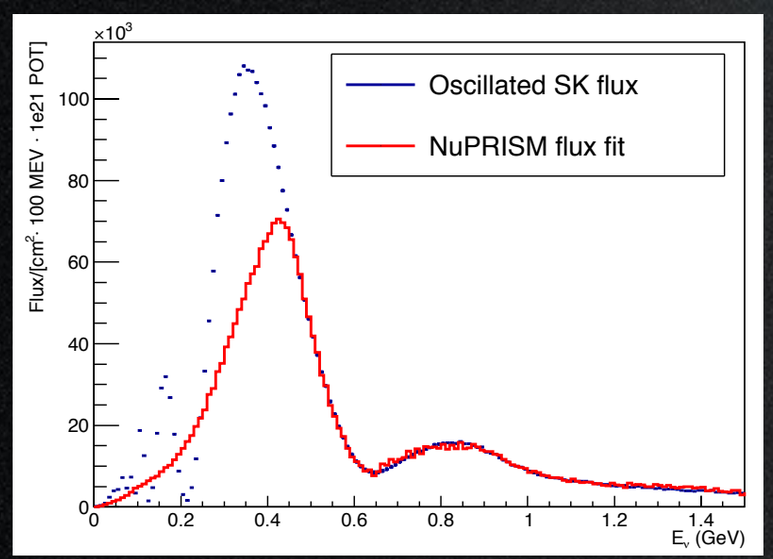




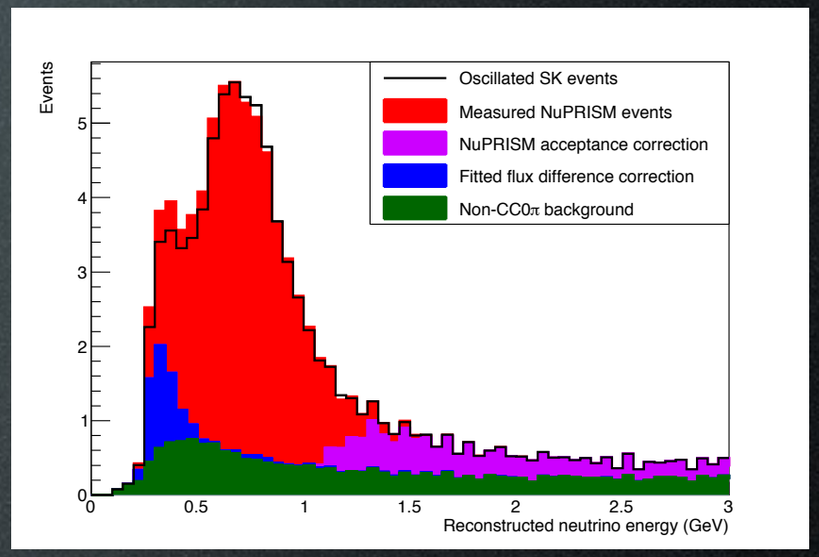
“Oscillations” in a Near Detector

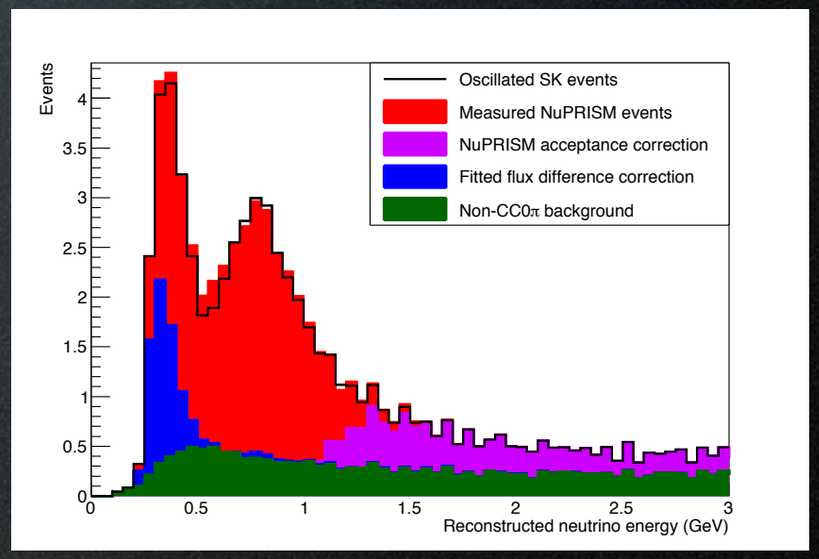


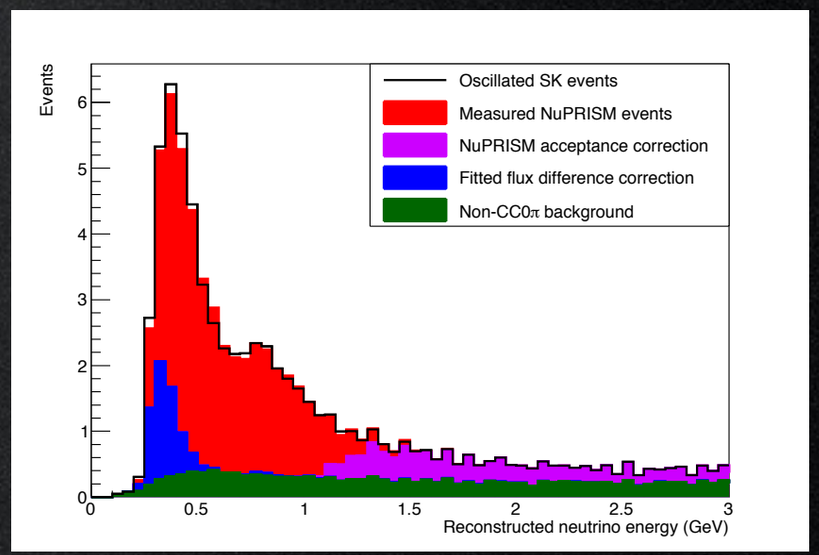




- Red region is directly measured by NuPRISM
- Blue region is flux difference correction
- Green is SK non-CC0π background
  - Partially cancels with already-subtracted NuPRISM CC0π background
- Magenta is acceptance correction
  - (geometric muon acceptance)
- SK prediction is largely from directly measured component



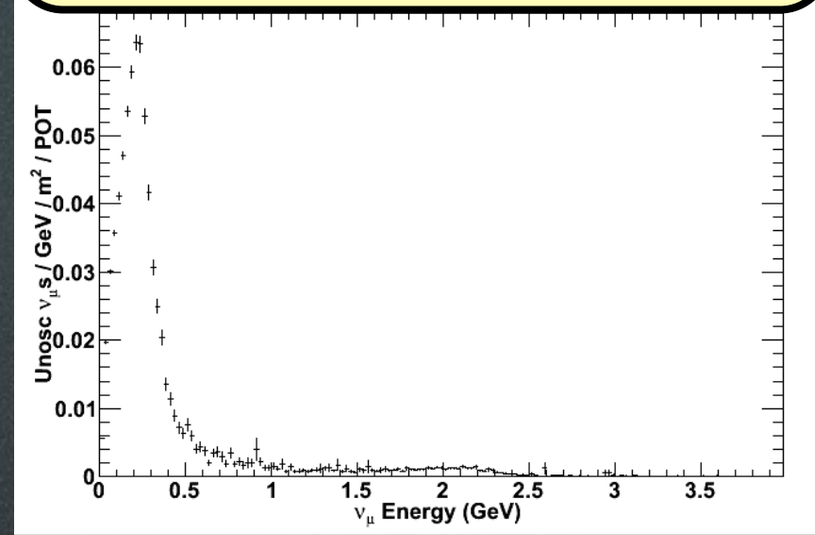




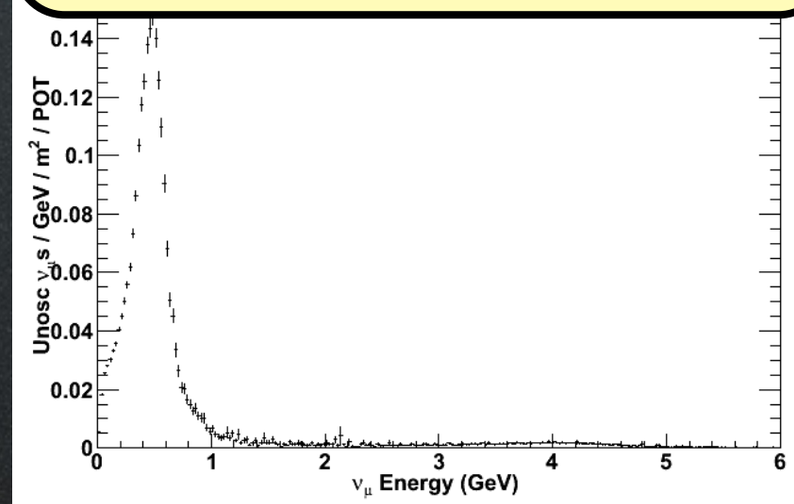
DUNE E_ν Spectra

- The DUNE beam points directly at the far detector (on-axis)
- Therefore, it is impossible to access a more on-axis E_ν spectrum
  - Higher E_ν spectra are needed to subtract high-E_ν tail
- Hence, DUNE-PRISM concept only works up to ~2.5 GeV
  - "First" oscillation maximum is at 2.5 GeV

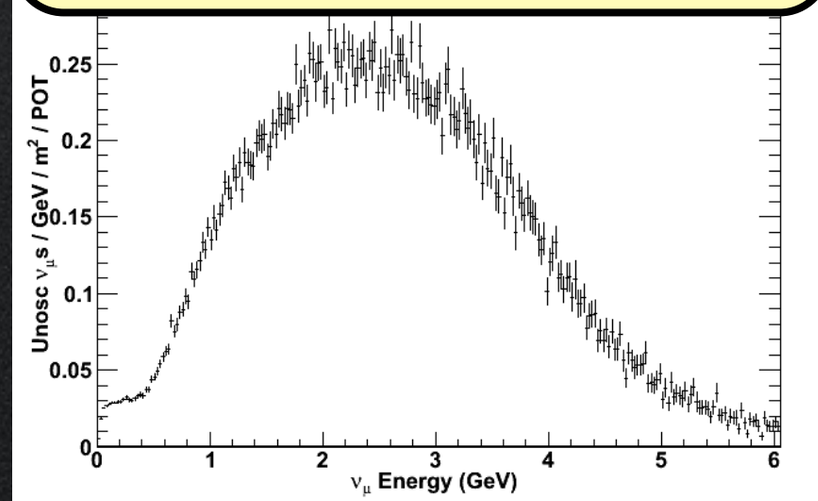
6° (105 mrad) Off-axis



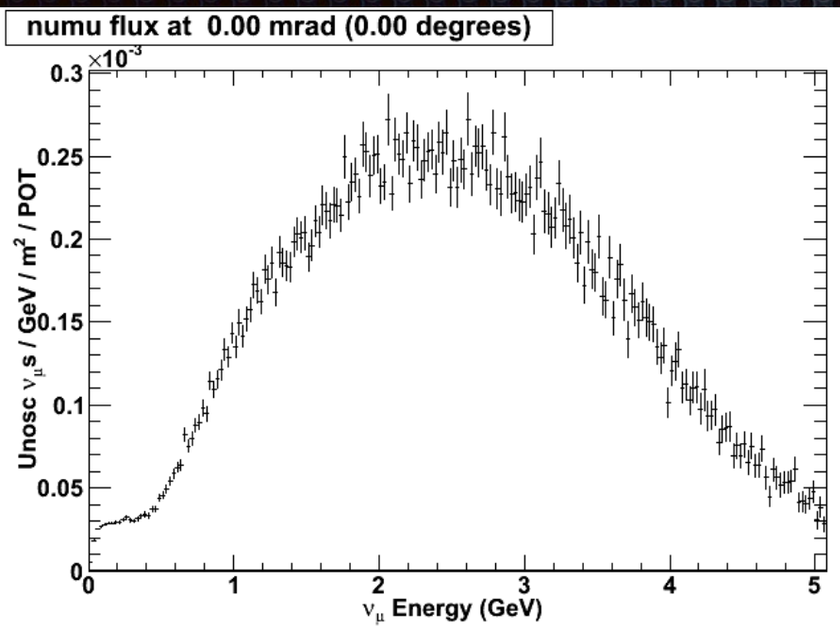
3° (52 mrad) Off-axis

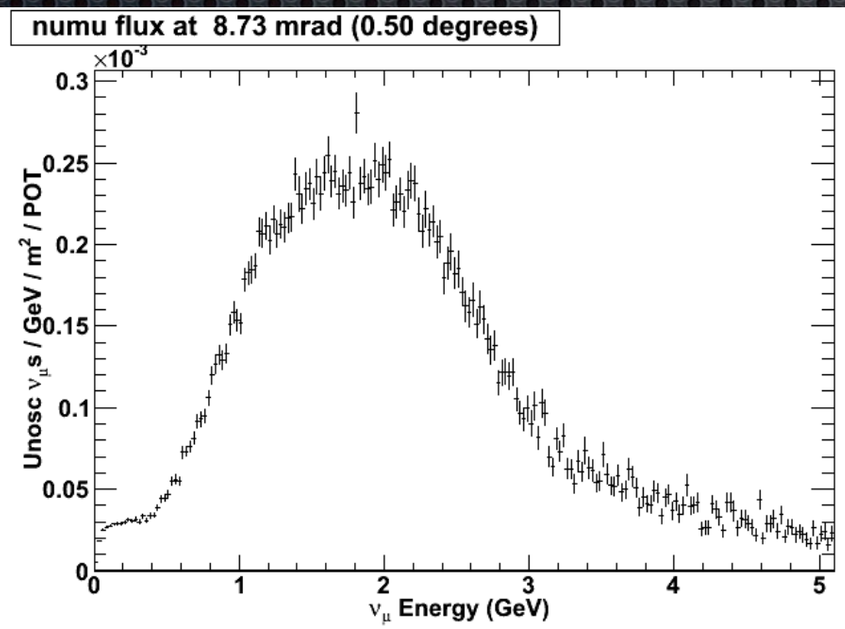


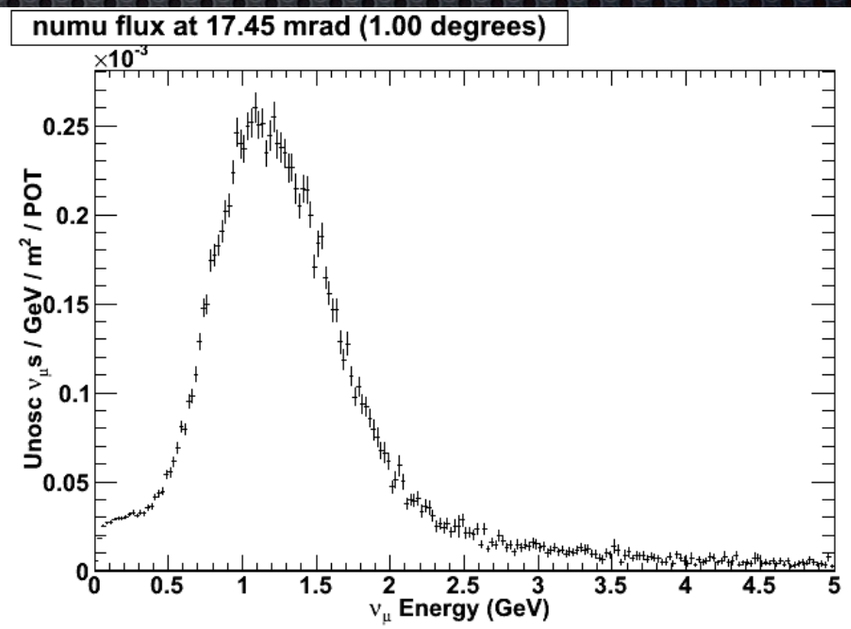
0° (0 mrad) Off-axis

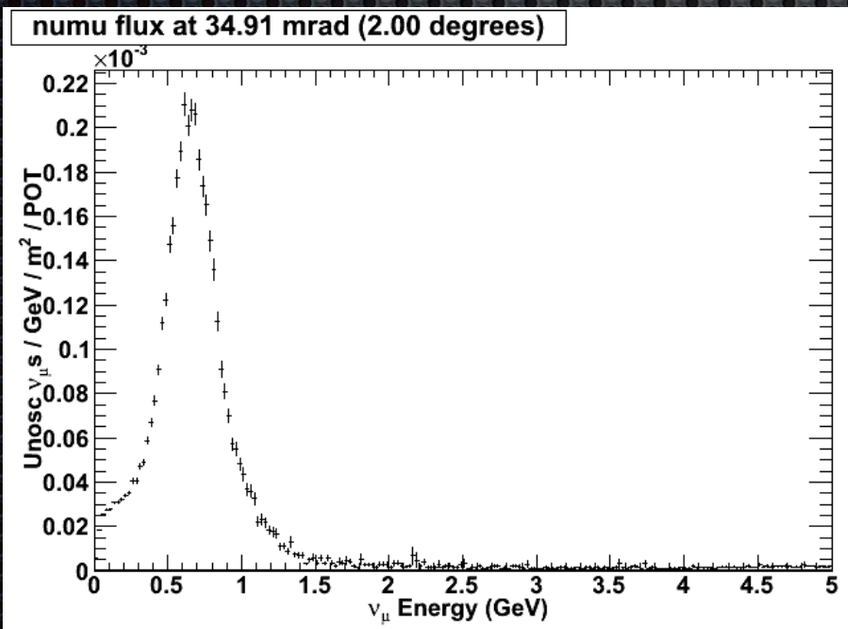


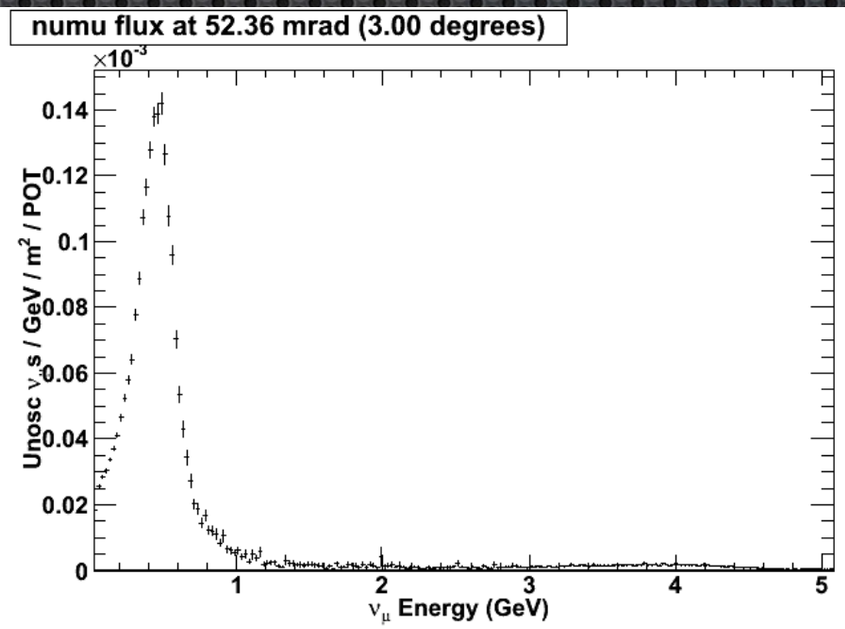
DUNE Off-Axis Fluxes

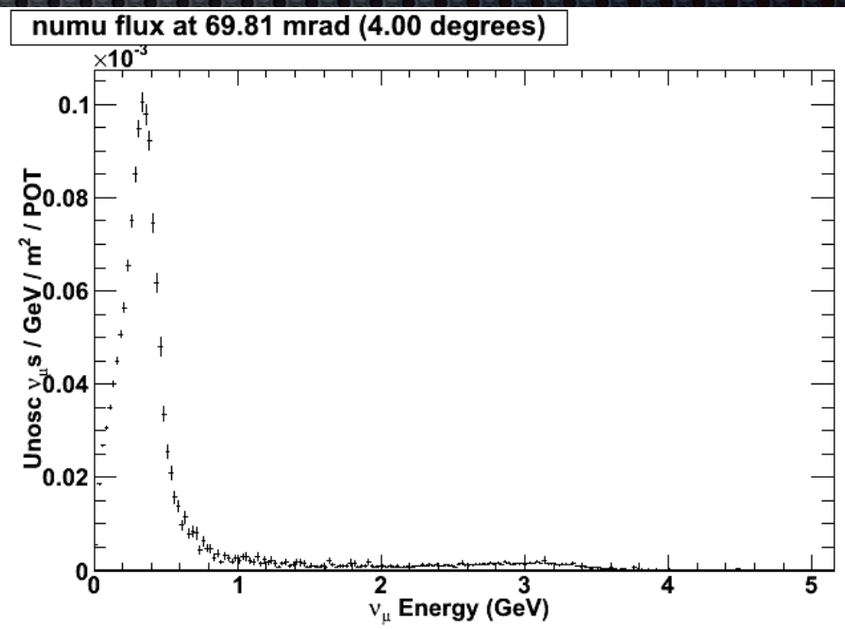






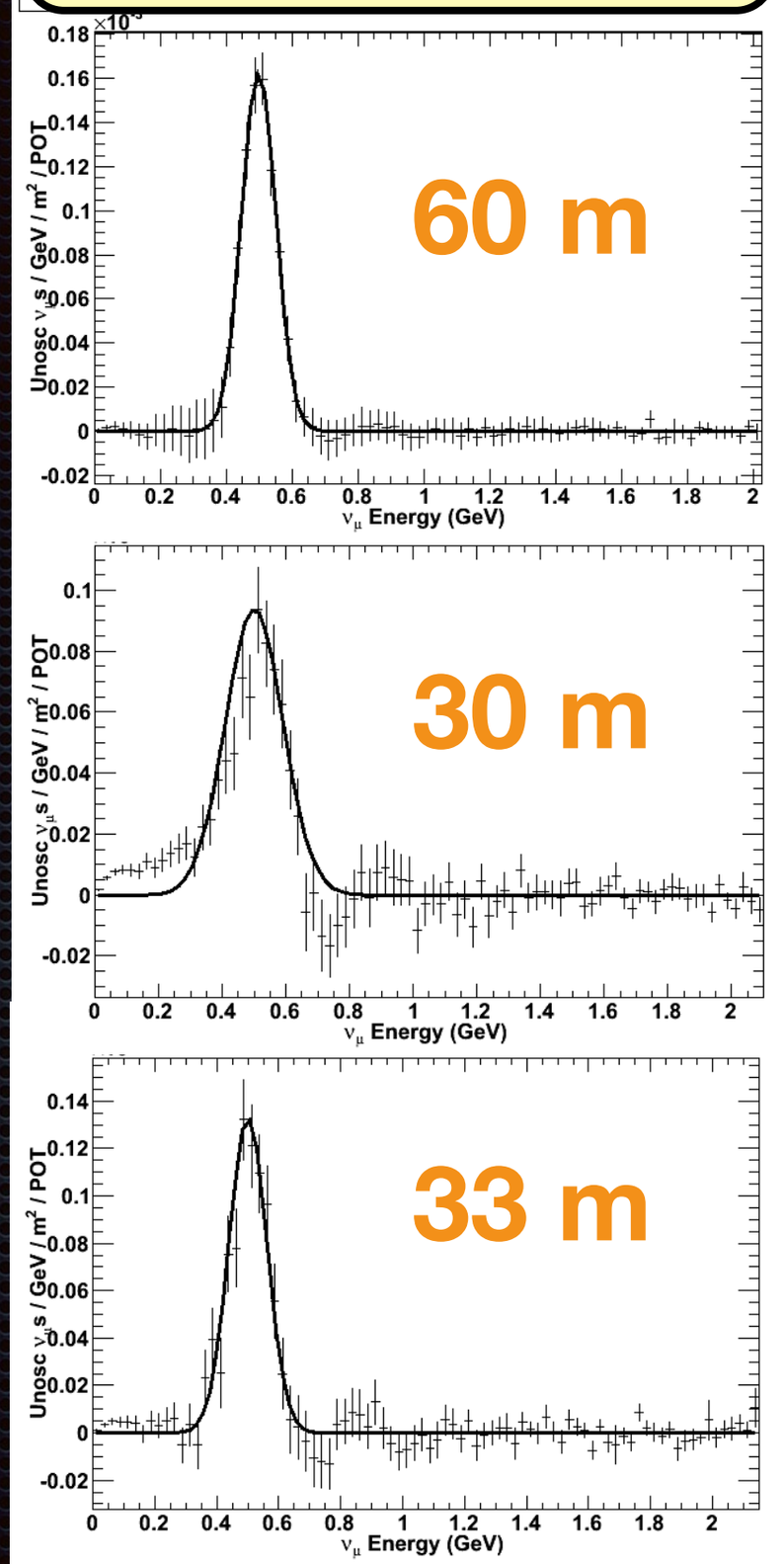




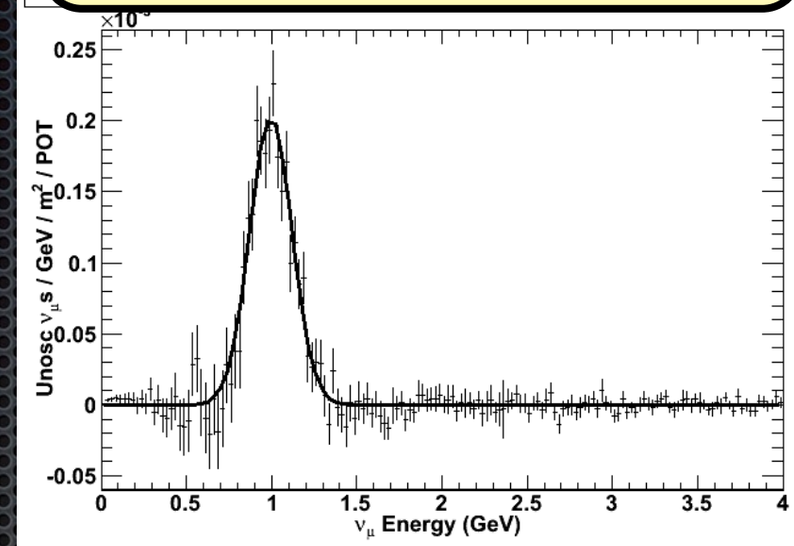


Mono-energetic Beams

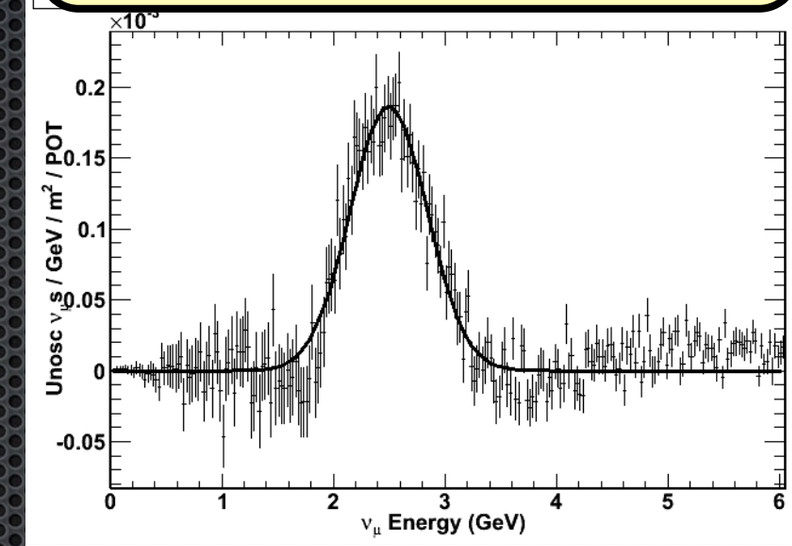
DUNE-PRISM 0.5 GeV



DUNE-PRISM 1.0 GeV

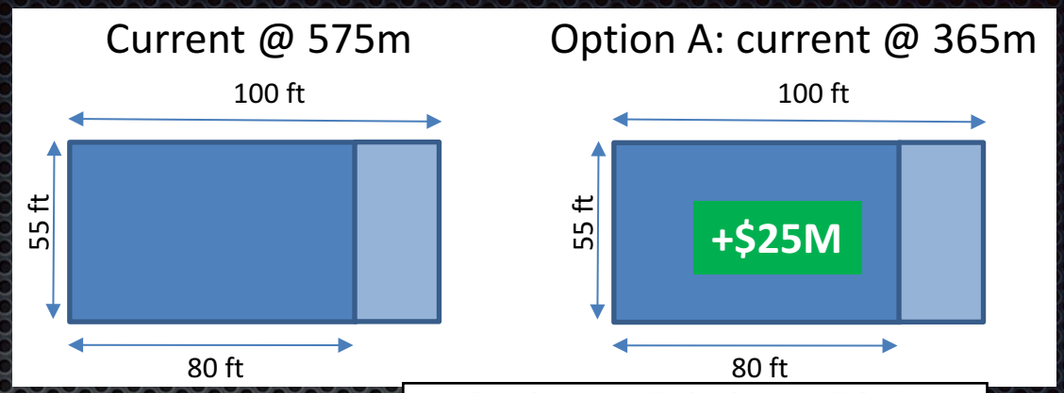


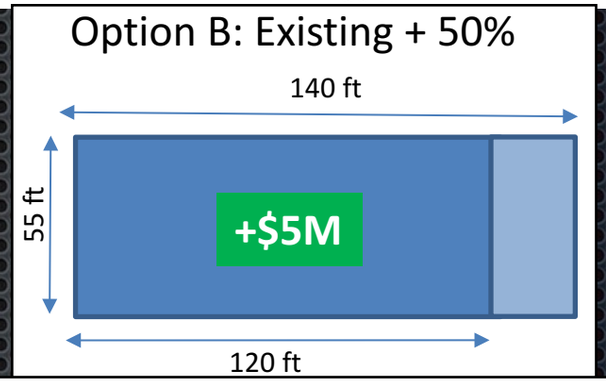
DUNE-PRISM 2.5 GeV

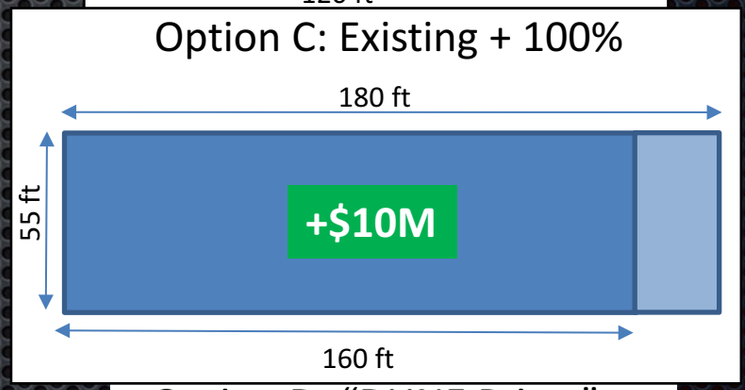


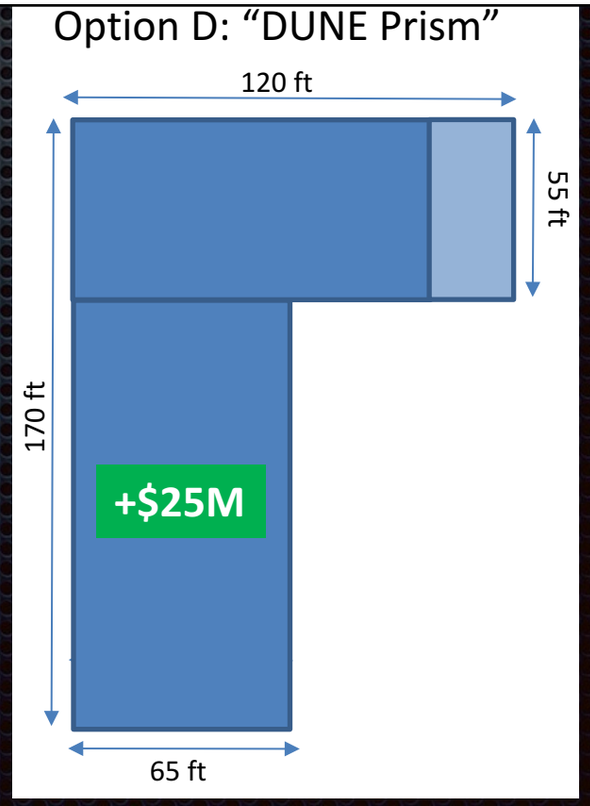
- At low energies, limited by off-axis range
  - Around 30 m limits reach to ~0.5 GeV
  - Need to fine tune based on physics required
- At high energies, begin to develop a high-side tail above 2.5 GeV
  - But some information is still available

Detector Geometry









- DUNE-PRISM can be accomplished by moving a detector vertically or horizontally
  - Vertical requires an "open cut" cavern, which may be cost prohibitive (as well as a large lift)
- ~35 m of travel required to cover 2nd osc. max
  - Less, if we just want to map out the ~1 to 2.5 GeV region (~20 m or less)
- Default option (or option B) could perhaps be sufficient if the detector is <55 ft long (what about 100 ft x 65 ft?)

Mark Thomson's talk from this morning:

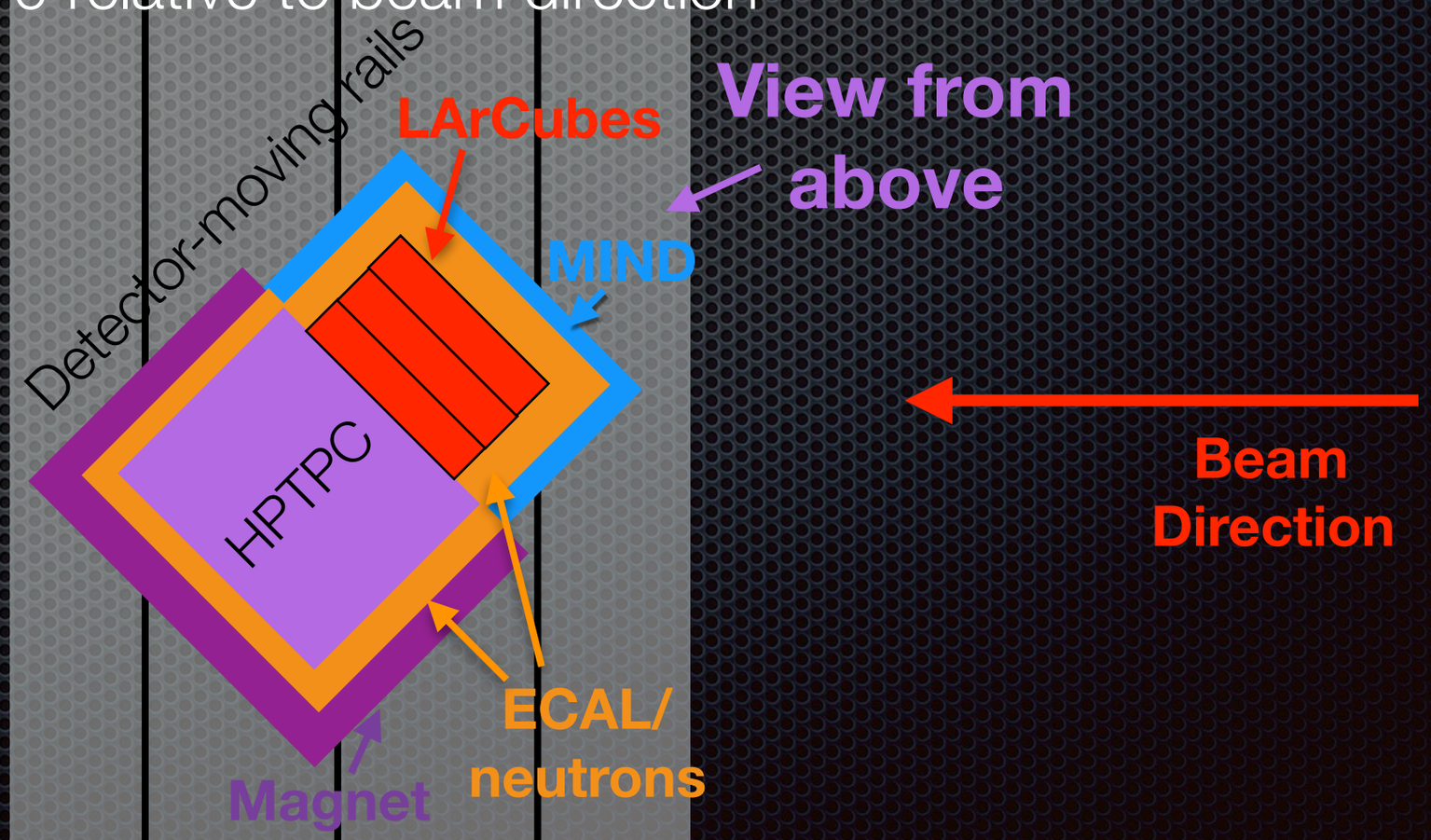
- Would need to be a very strong scientific case
- e.g. can not reach DUNE primary science goals with existing hall size

- It is unlikely that we will understand the full oscillation analysis with sufficient precision to make this case
  - However, if we make some careful fake-data studies, it may be possible to demonstrate more immunity to oscillation parameter biases

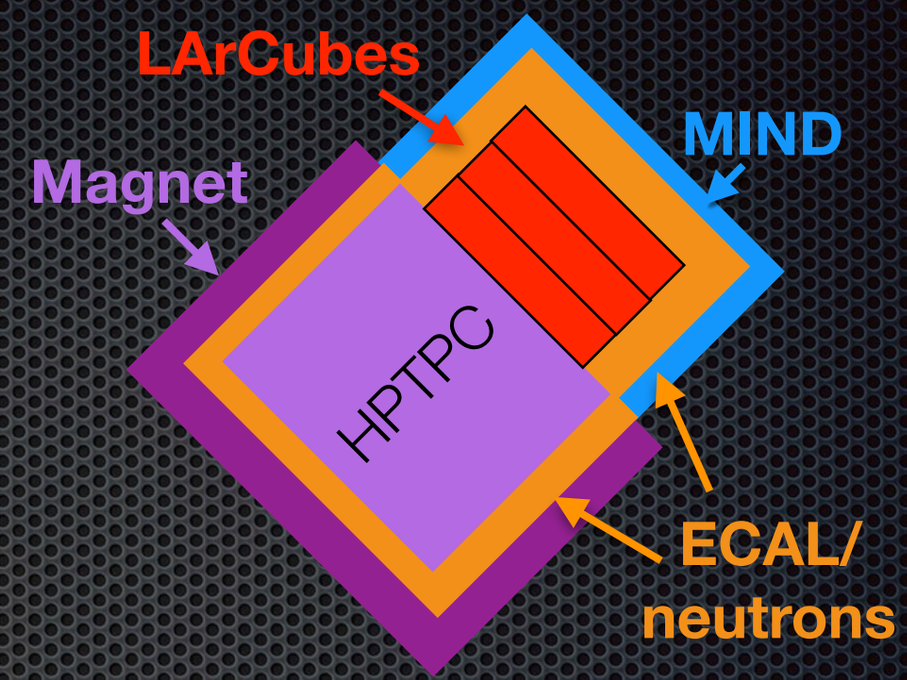
DUNE-PRISM Detector

- Elongated **LAr** cubes (e.g. **6m x 6m x 2m** in drift dimension)
  - Need to measure same signal as far detector (e.g. E_{had}; more in next slides)
- **Muon containment** in LAr likely **not possible**
  - Magnetized **Ar-HPTPC** "downstream" to measure momentum of exiting muons
- Surrounded by ECAL/neutron detection (and possibly magnetized muon system - MIND)
- For any detector option, do not align the detector with the beam direction!
  - Large coverage of muon p-θ relative to beam direction

ppt engineering drawing



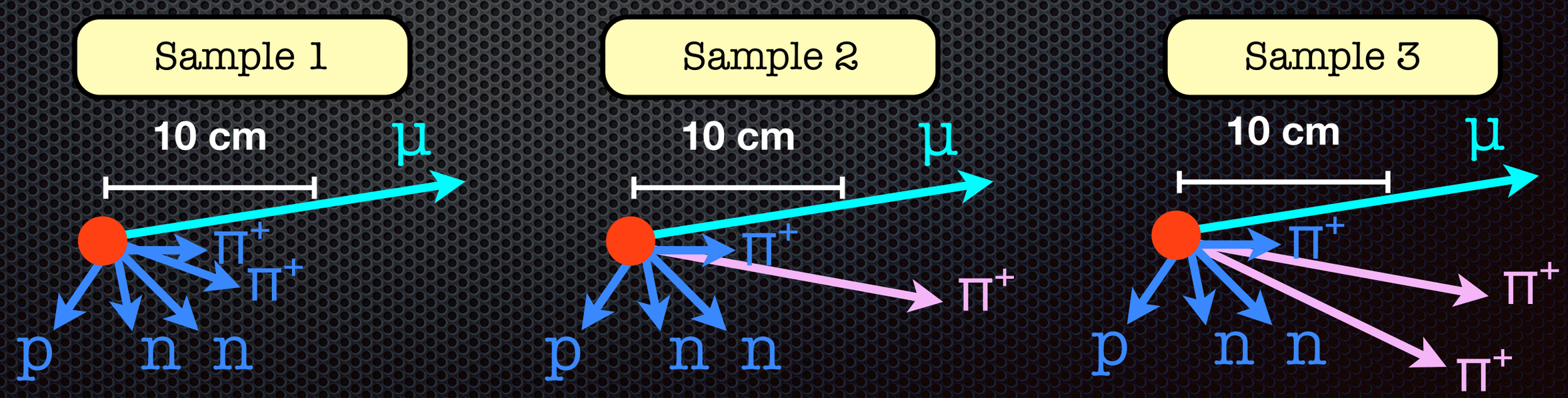
Detector Notes



- Detector is rotated to improve muon angular coverage (θ_{beam})
- **Argon cubes** need to be large enough to fiducialize
  - Must **contain hadronic energy** around vertex (~2 m)
  - 6m tall (out of page) x 6m "long" x 2m in drift direction
    - Results in a **2m x 2m x ~2m fiducial volume** in the center cube
    - Also possible to use **interactions in downstream cube in conjunction with HPTPC** (different signal, but more detail)
- **HPTPC** is ideal for measuring momentum of **LAr exiting tracks**, and to study **interaction vertices**
  - A precise understanding of "**vertex activity**" is needed to properly characterize E_{had}
  - Need to understand production of low-momentum **π^+** & **p** (missing E_{had}) with 4π coverage
  - Ideally **"wider" than LAr targets** to improve angular coverage of exiting tracks
- Is there any way to design an **ECAL** detect (fast and slow) neutrons with reasonable efficiency?
  - (free hydrogen, E resolution, fast timing…)

Signal Definition

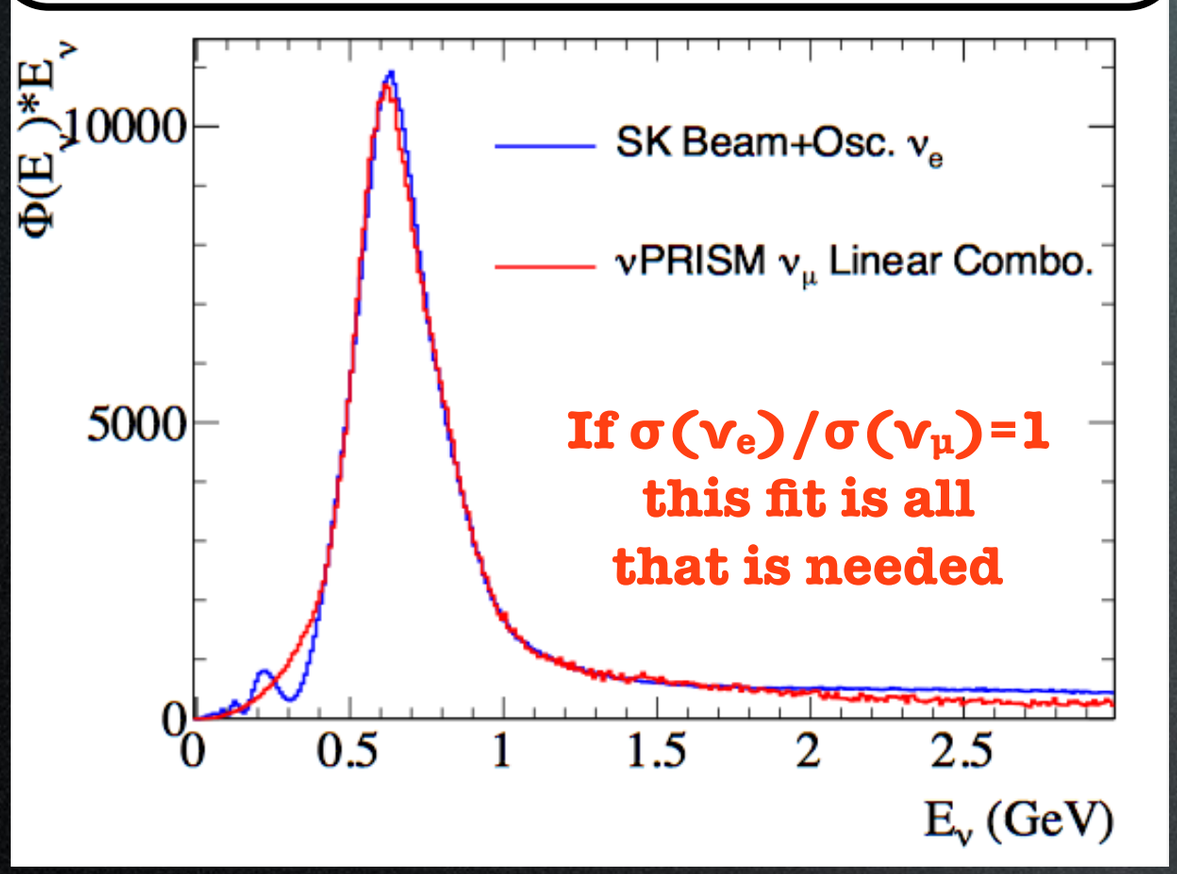
- With constrained E_ν, you have freedom to determine signal definitions (e.g. based on visible topologies)
  - No longer need to relate back to microscopic cross section
    - And variations of microscopic parameters will have little impact
- Scenario 1: Determine distributions of lepton kinematics + E_{had} for all events vs E_ν
  - At far detector, vary these templates vs E_ν for different osc. parameters
- Scenario 2: Separately perform scenario 1 for different numbers of visible charged pions (e.g. visible pion = pion track longer than 10 cm).
  - Separately fit each of these visible topology templates vs E_ν at the far detector



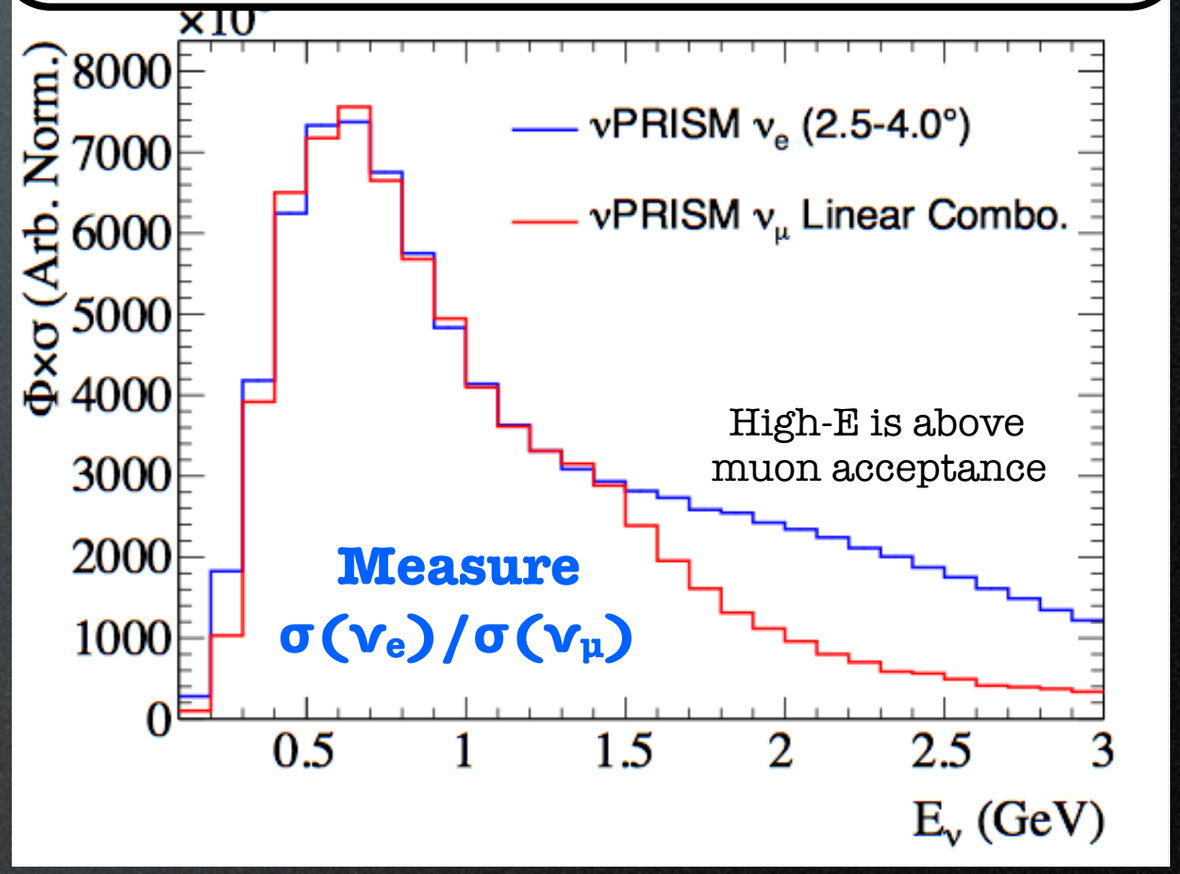
NuPRISM ν_e Appearance (CPV)

3 step approach:

Step 1: Measure **Super-K** ν_e response with NuPRISM ν_μ



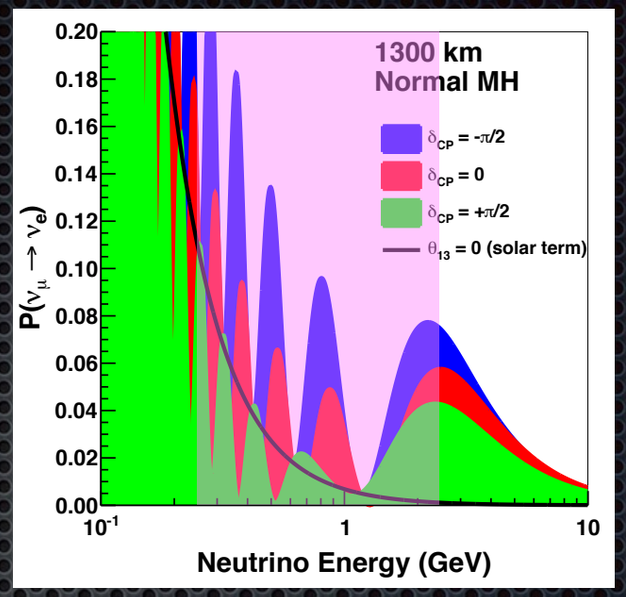
Step 2: Measure **NuPRISM** ν_e response with NuPRISM ν_μ



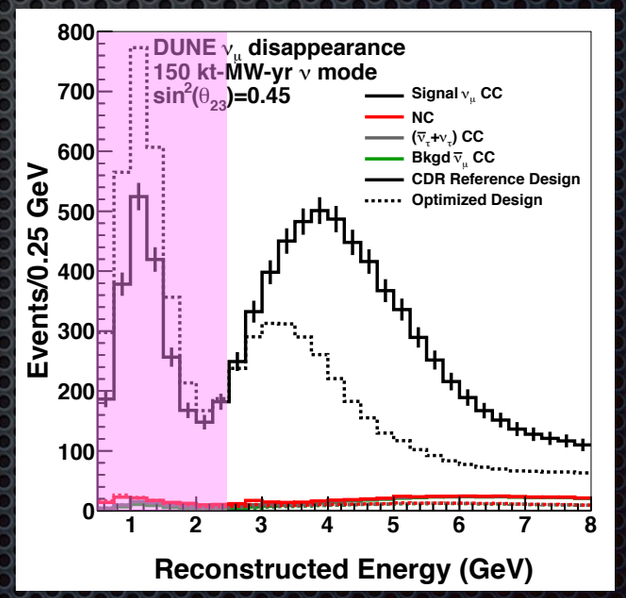
- Step 1 is the ν_e version of the ν_μ disappearance analysis
  - Reduces FSI/SI and SK detector uncertainties, and improves ND280 flux+xsec constraint
- Step 2 uses only NuPRISM to measure $\sigma(\nu_e)/\sigma(\nu_\mu)$
  - Constrains the $\sigma(\nu_e)/\sigma(\nu_\mu)$ uncertainty
- Step 3 uses the slice of NuPRISM in the far detector direction to measure NC backgrounds with the same energy spectrum as the far detector (reduces background systematics)

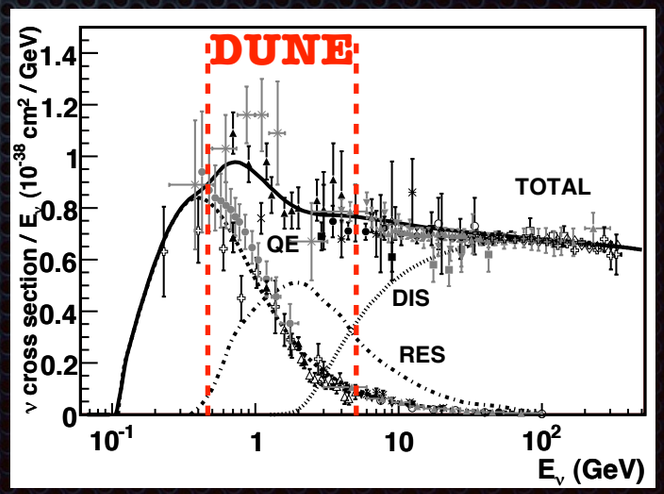
Summary

- Repeating our measurements for a variety of different energy spectra provides extremely useful information
  - e.g. can construct mono-E_ν beams and directly measure any observables vs "E_{true}"
  - **Any measurements that we were planning to make anyway will be enhanced with extra a priori energy information**
- This helps us navigate energy reconstruction in the 0.5-2.5 GeV region in a model independent way
  - i.e. where CCQE, CCRES, DIS all overlap
- A detector that can only constrain parameters of an assumed model, and cannot adequately adapt to **E_{true} ➜ E_{rec} migrations** not present in the model, can produce **large biases** in measured oscillation parameters



DUNE-PRISM Range

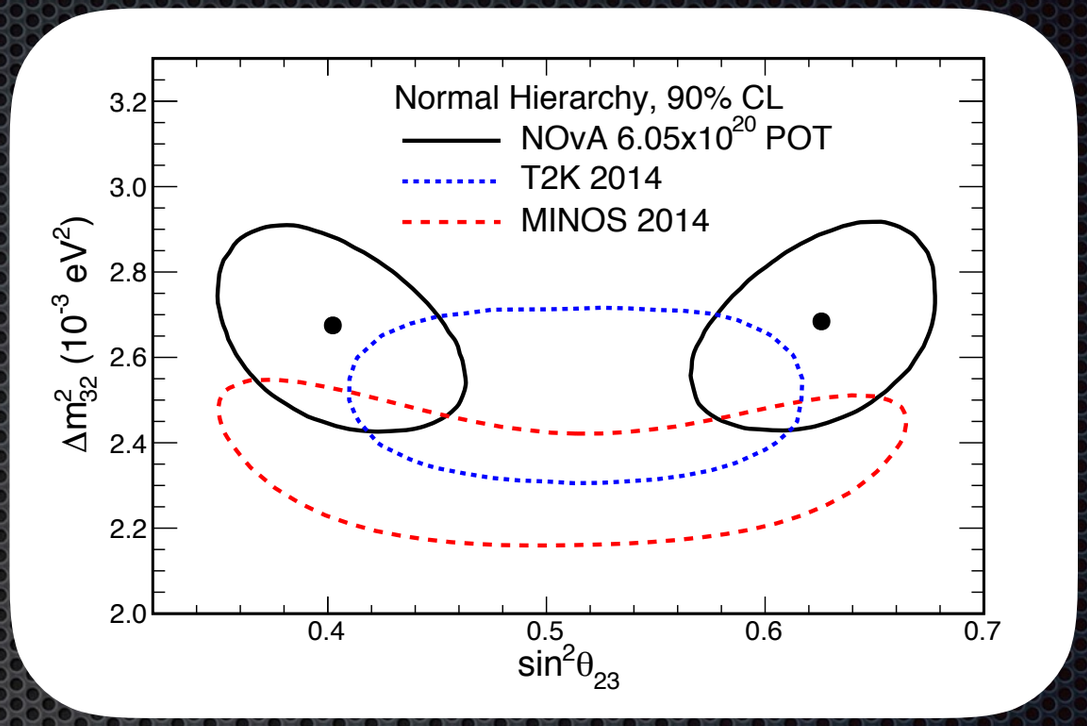


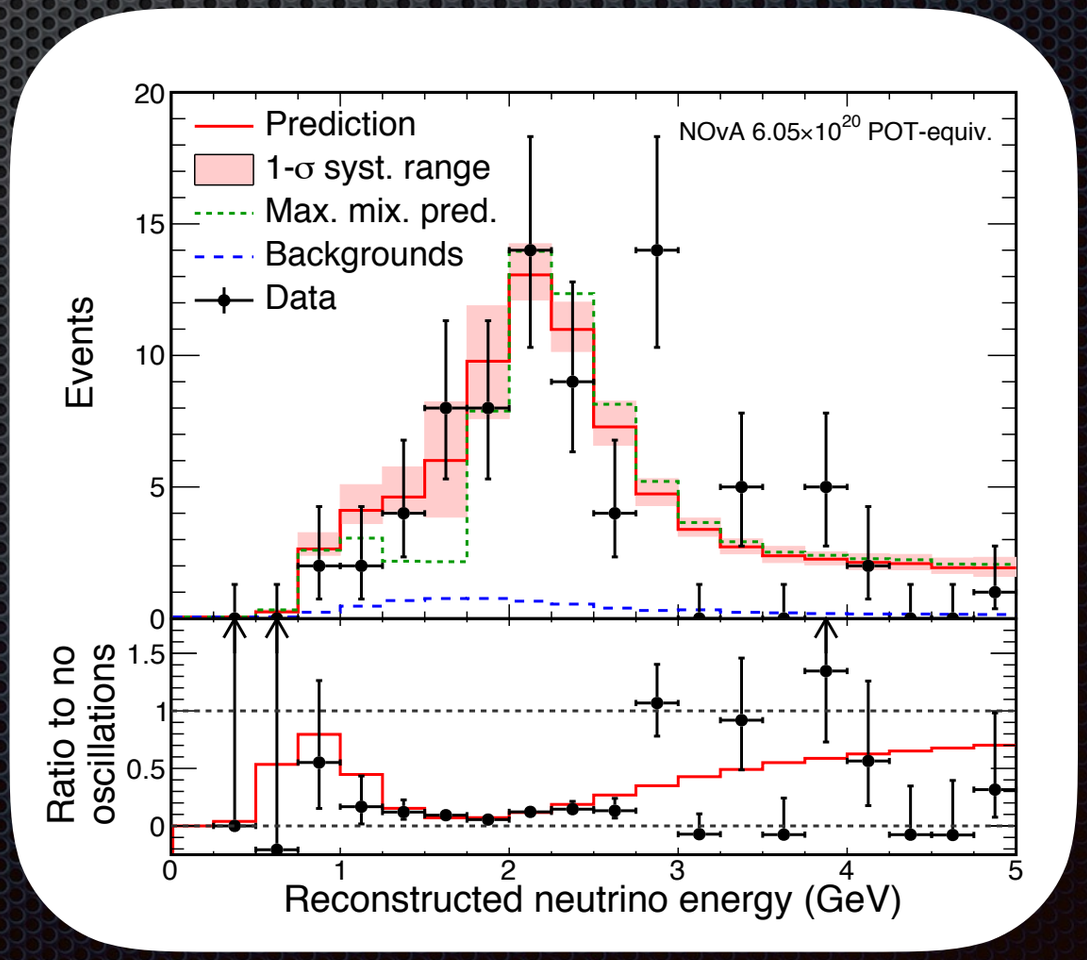


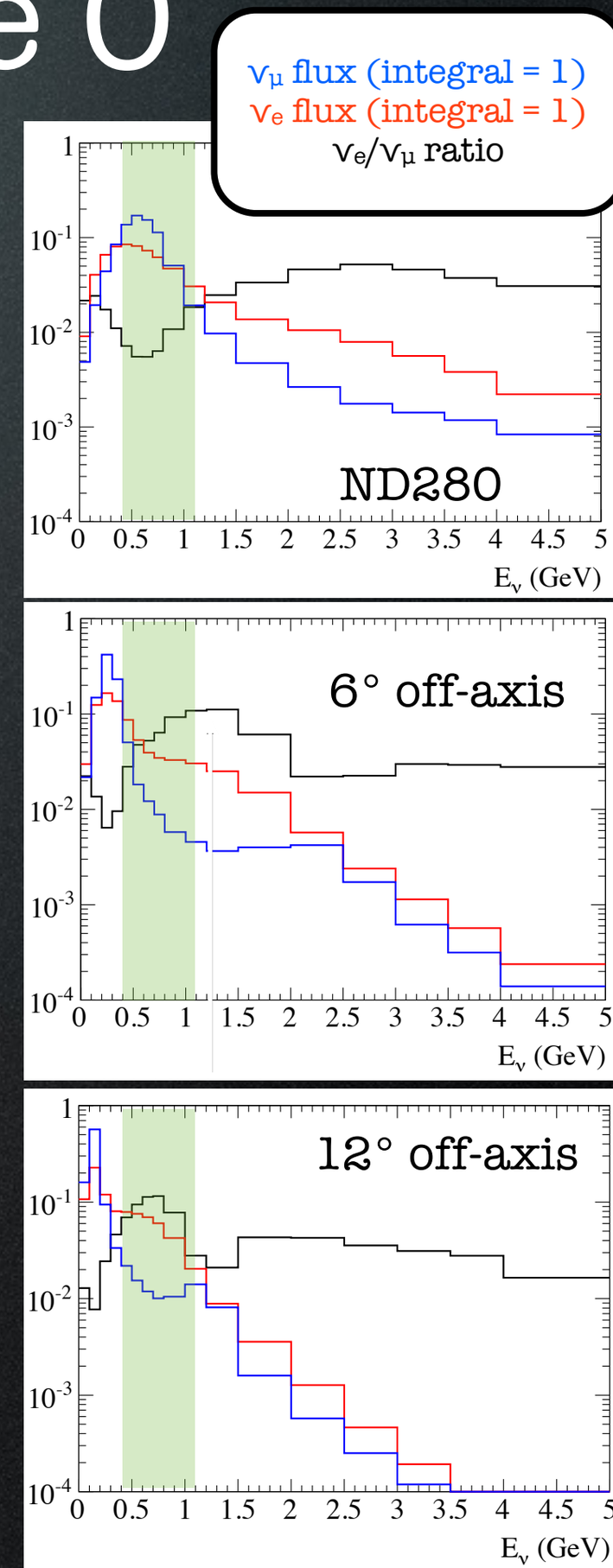
Supplement

NOvA

- These same issues are important for NOvA as well
- NOvA has reported a 2.6σ exclusion of θ_{23}=45°
  - Difference between the red and dotted-green lines
- A detailed understanding of E_ν feed down is essential to this measurement
  - Exclusion largely depends on the 1.6 GeV bin
  - Any additional feed down from higher energy bins would dilute the exclusion significance





NuPRISM Phase 0

- If KEK funds are not immediately available for excavation at a new, off-site facility, we propose a staged approach
- **NuPRISM phase 0** can conduct a high-purity measurement of **$\sigma(\nu_e)/\sigma(\nu_\mu)$**
  - The instrumented portion of the detector will be constructed, and placed **on the surface** near ND280
  - Off-axis angles of ≥6.6° are accessible
    - The flux ratio of ν_e/ν_μ grows with off-axis angle
- In addition, an easily accessible surface detector will allow access to refine detector calibration as needed
- Performance of reconstruction (PID, ring counting, etc.) can also be demonstrated