The NuPRISM Near Detector Technique for J-PARC (E61) and DUNE

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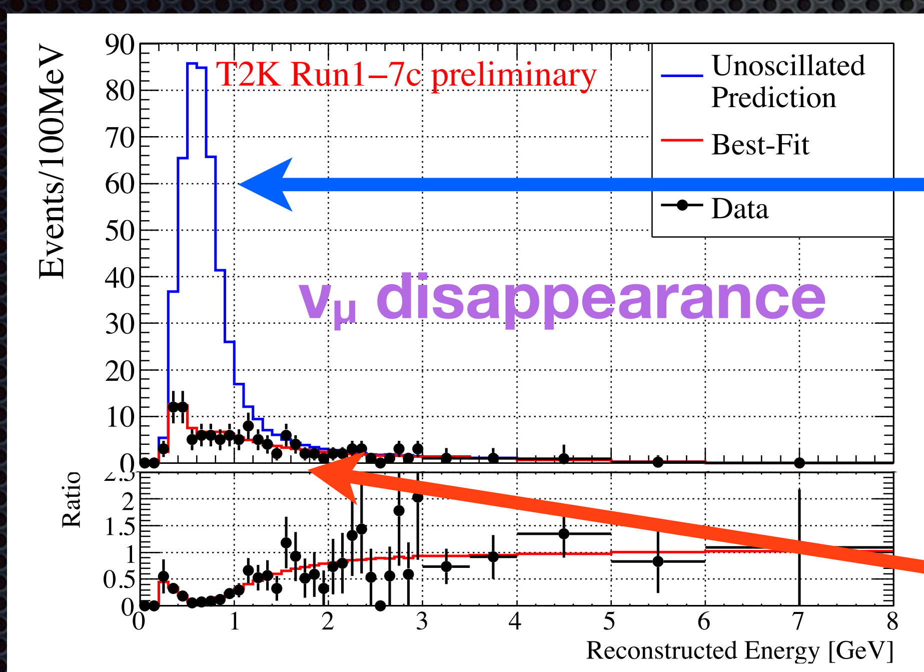
How to Measure Neutrino Oscillations

In a near/far experiment, σ uncertainties will cancel?

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

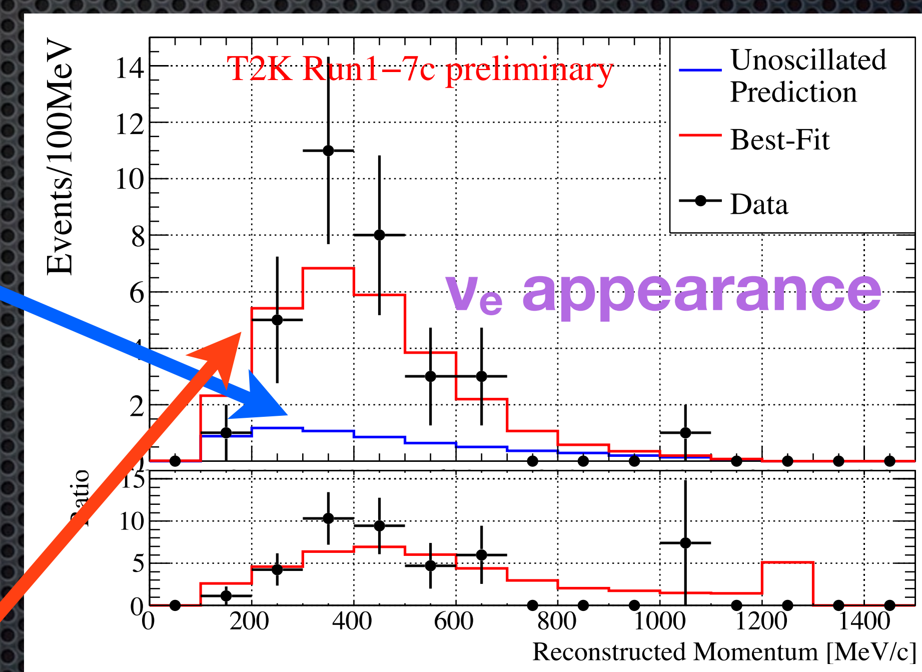
$$FD(\nu_\mu) = \Phi(E_\nu) \times \sigma(E_\nu, A) \times \epsilon_{FD} \times P_{osc} \times M^{E_{rec}}_{E_{true}}$$

Cancelations of uncertainties in both flux and cross sections are spoiled by energy migrations



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

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

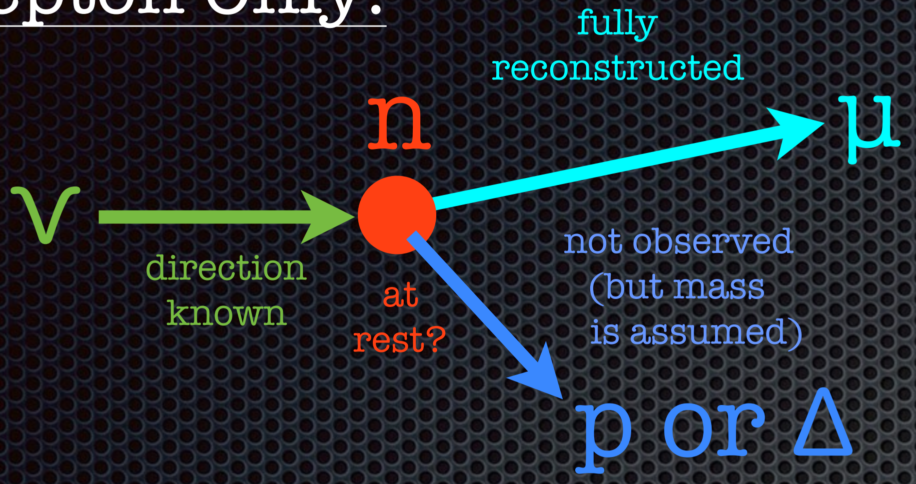


- E_{true} ➜ E_{rec} migration matrix is (quite) non-diagonal! (next slides)
- Several important cross section uncertainties will not cancel

Measuring E_ν

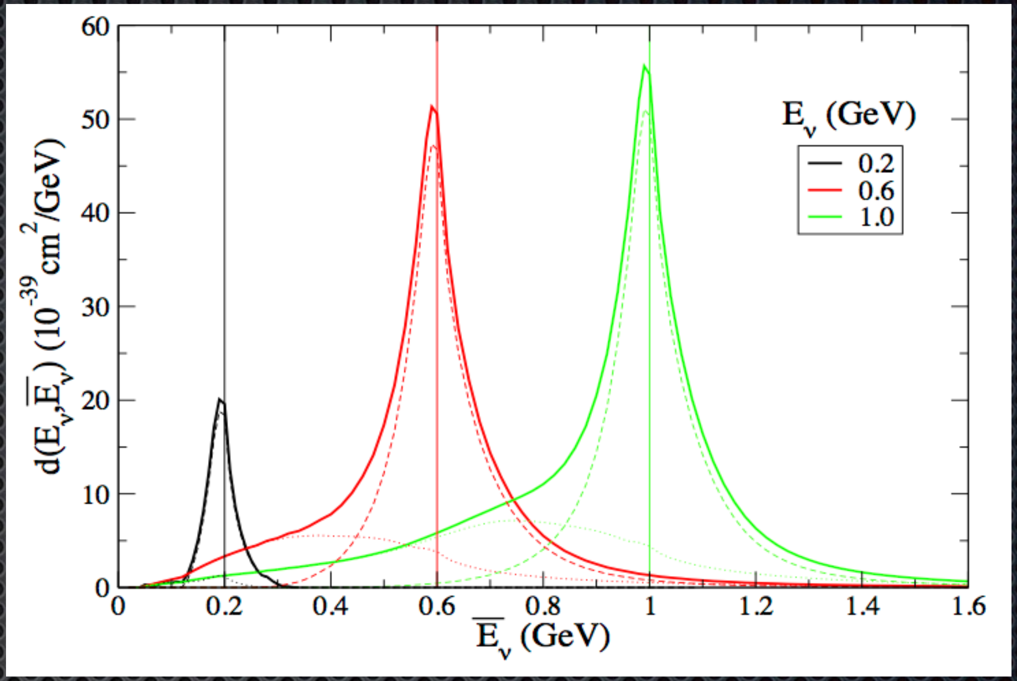
Martini et al. arXiv:1211.1523

Lepton Only:

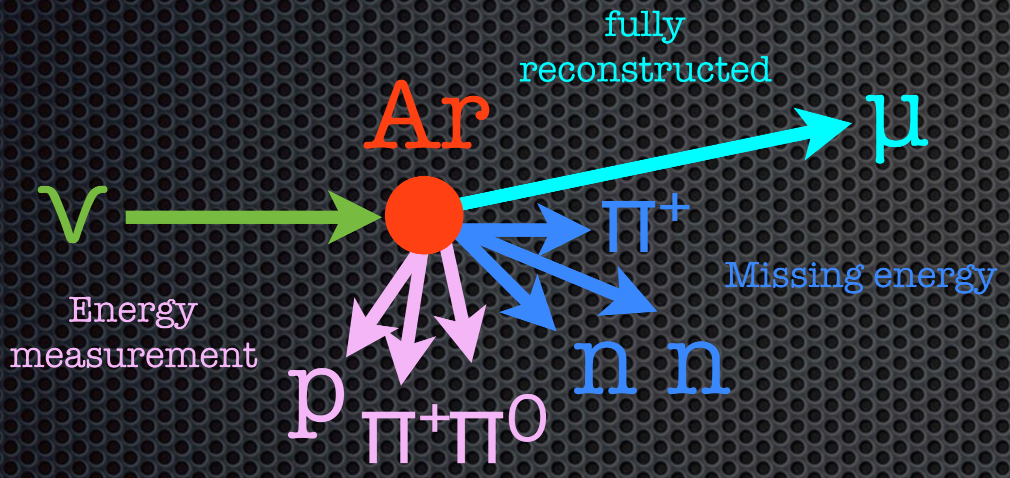


Must assume mass of recoiling hadron(s)

Problematic! due to Multi-nucleon interactions



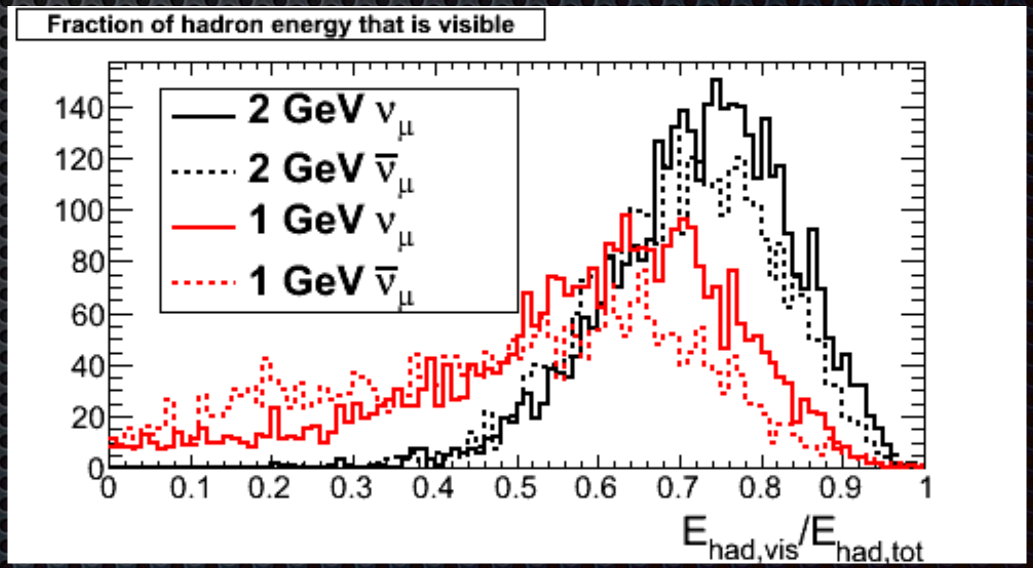
Lepton + Hadronic Energy:



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

Energy loss is different for ν and anti-ν

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



GEANT4 Simulation of a large LAr volume

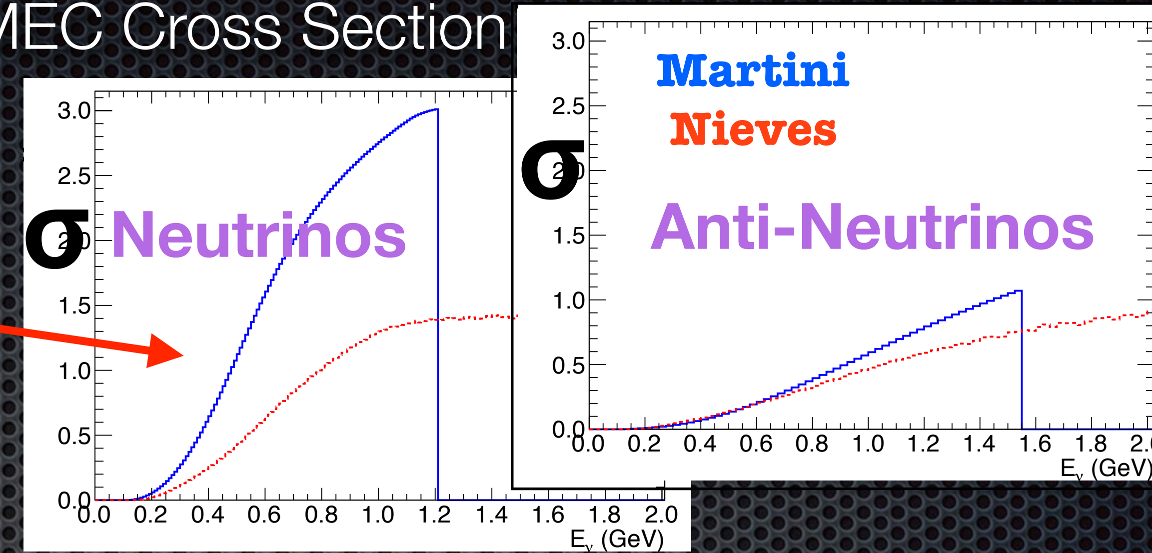
(True deposited hadronic energy)/
(True initial hadronic energy)

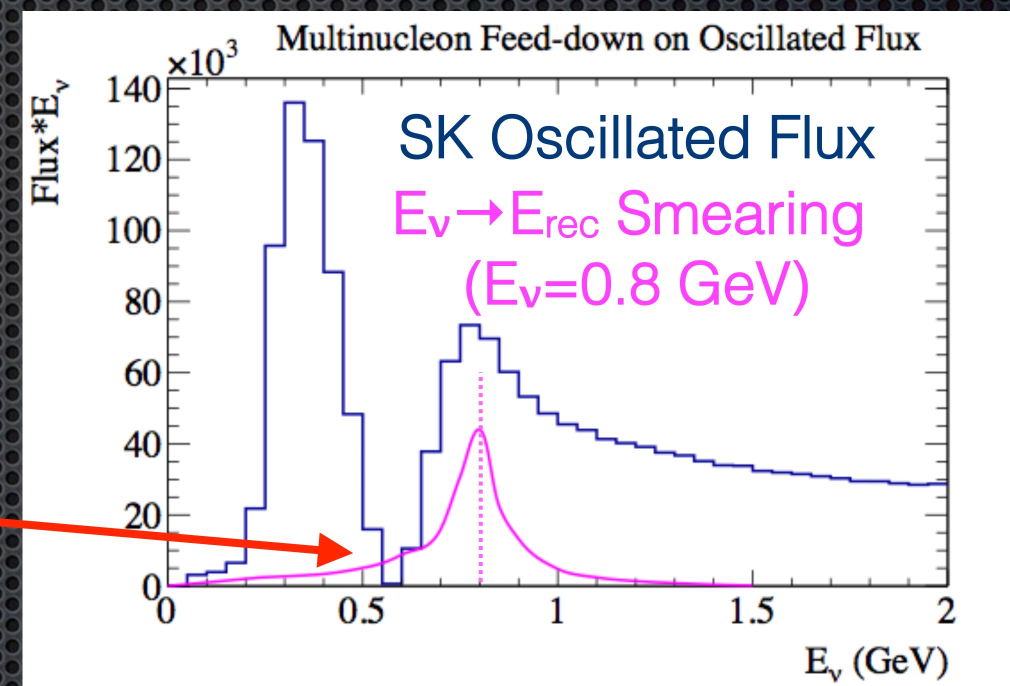
- Both effects lead to underestimating the neutrino energy (feed down)
- Need to calibrate both leptonic (e & μ) & hadronic energy scales and shapes (e.g. long E_{rec} tails)

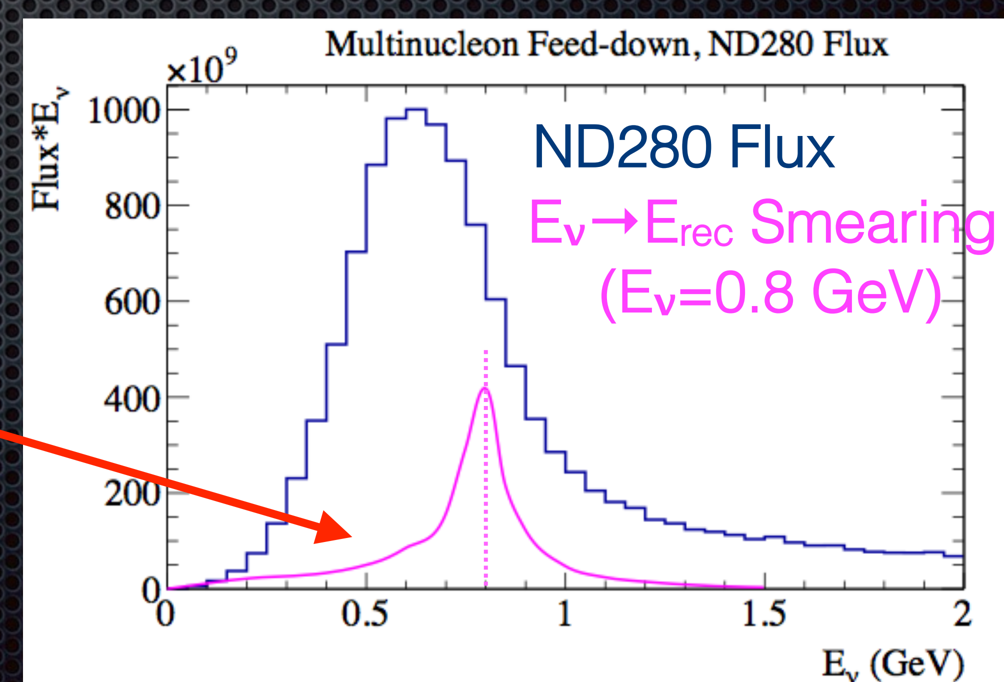
E_ν Feed Down

- 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

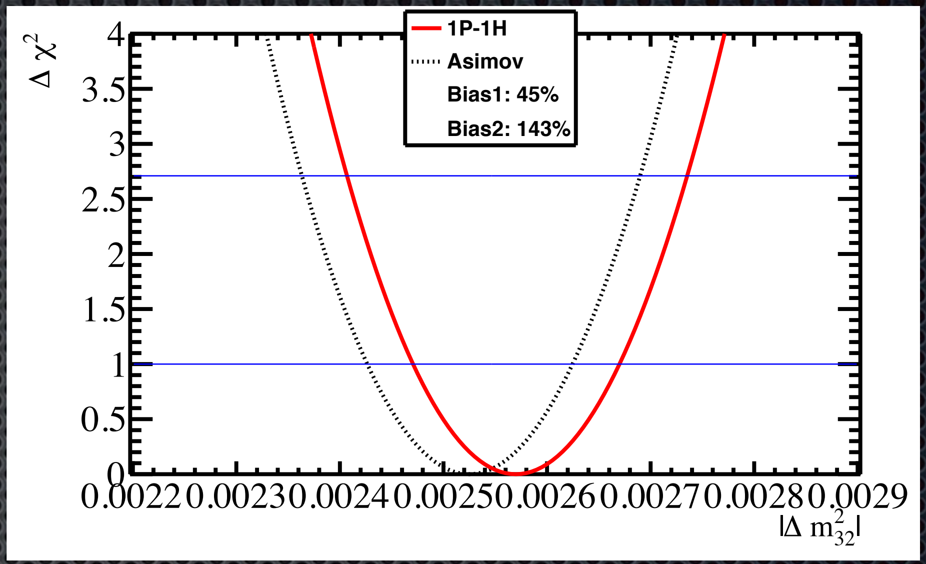


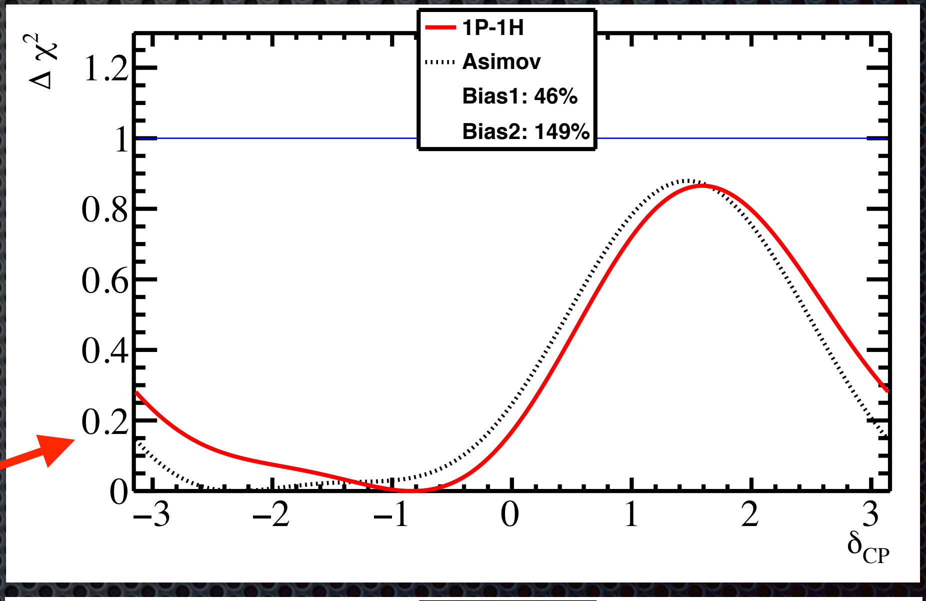


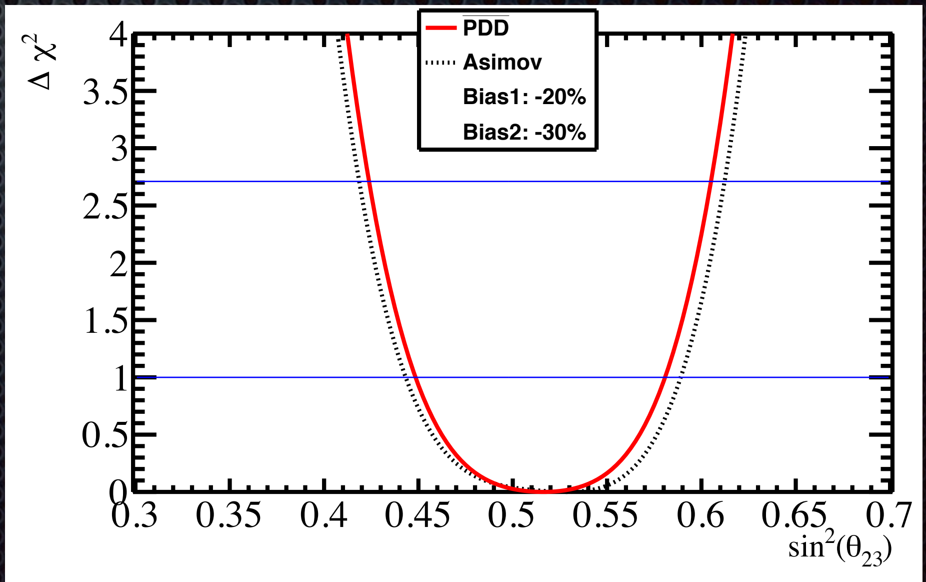


Fake Data Studies

- 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
- 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

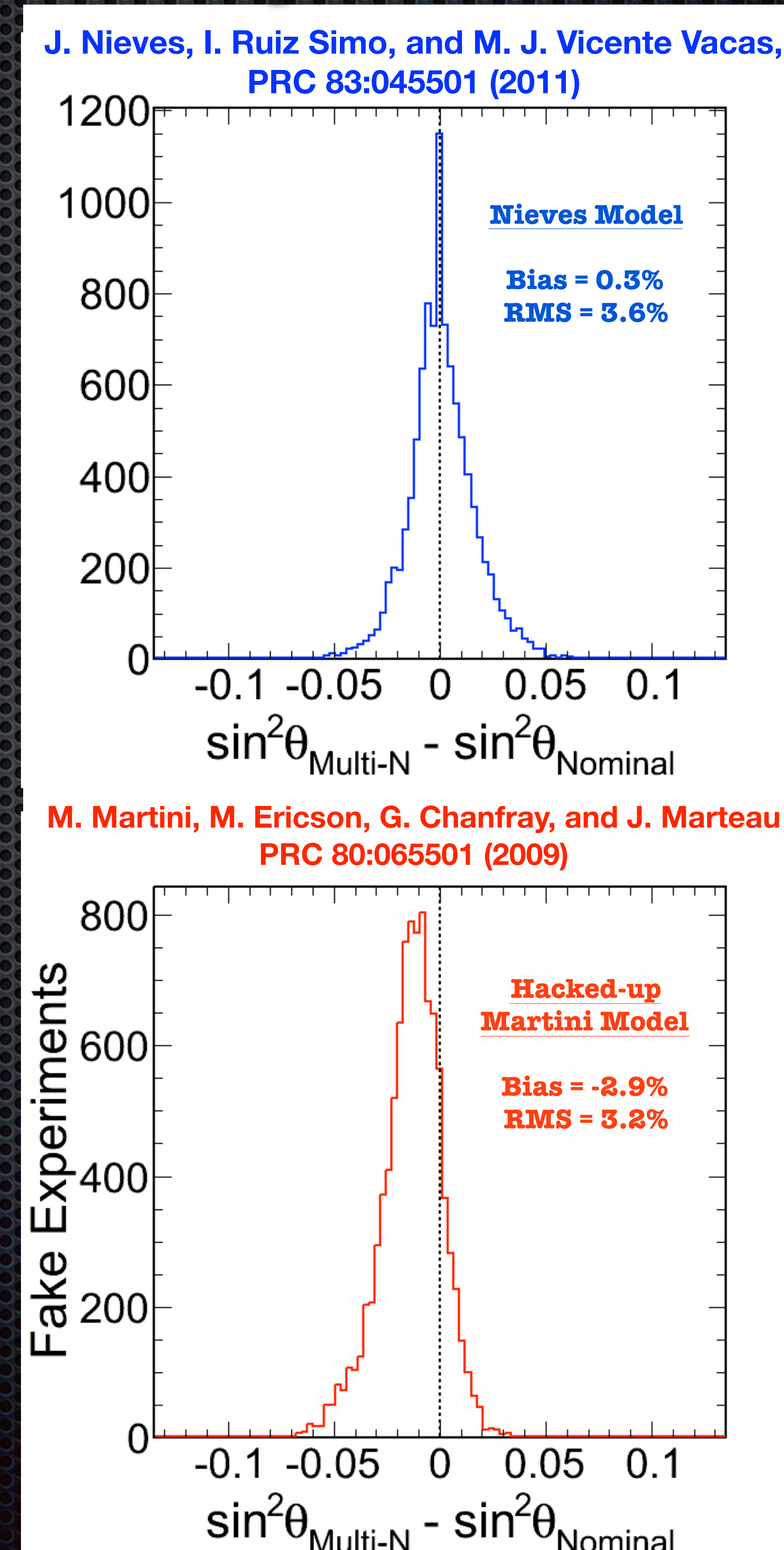




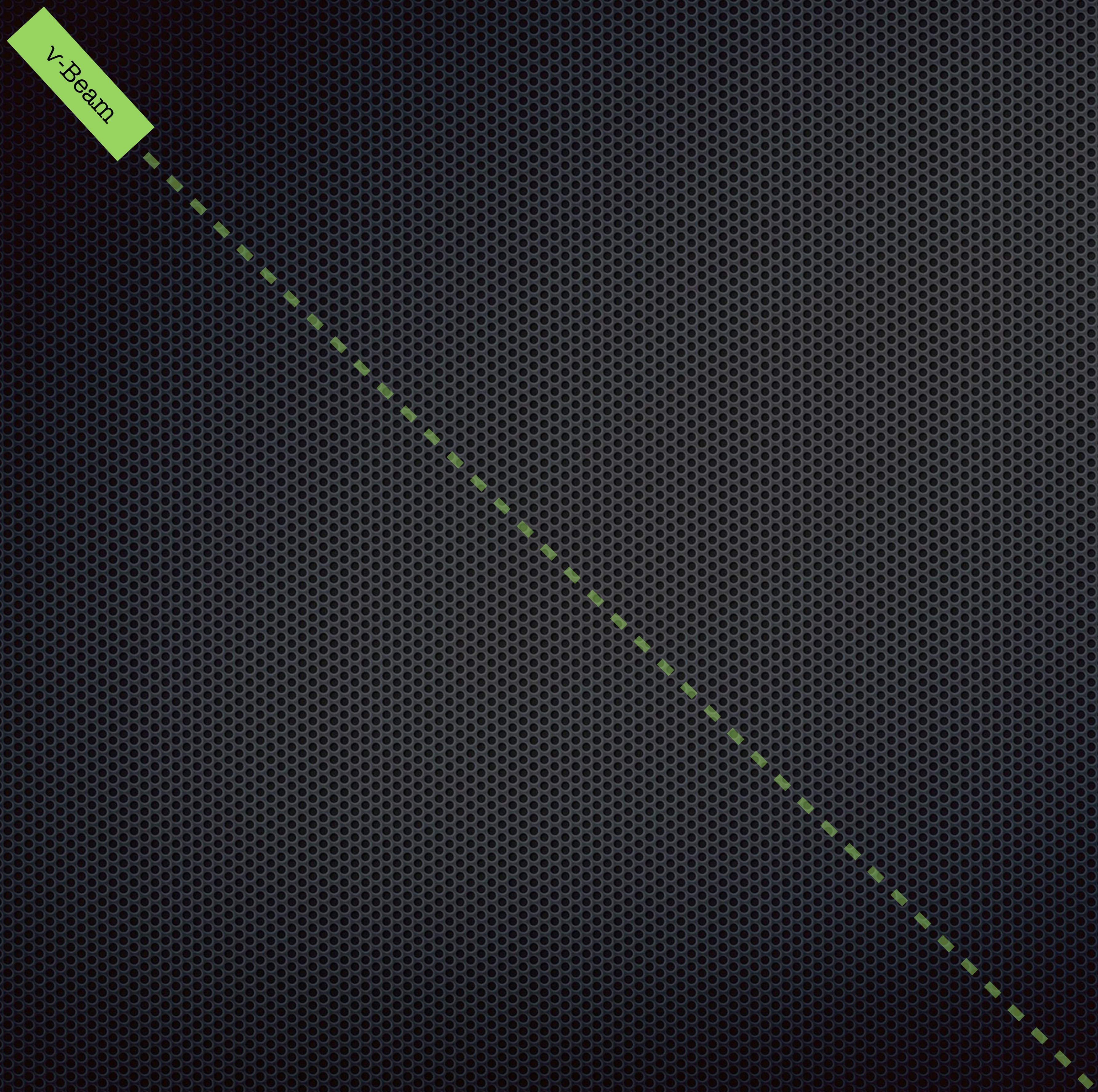


Example Fake Data Study

- 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



E61 Detector Concept



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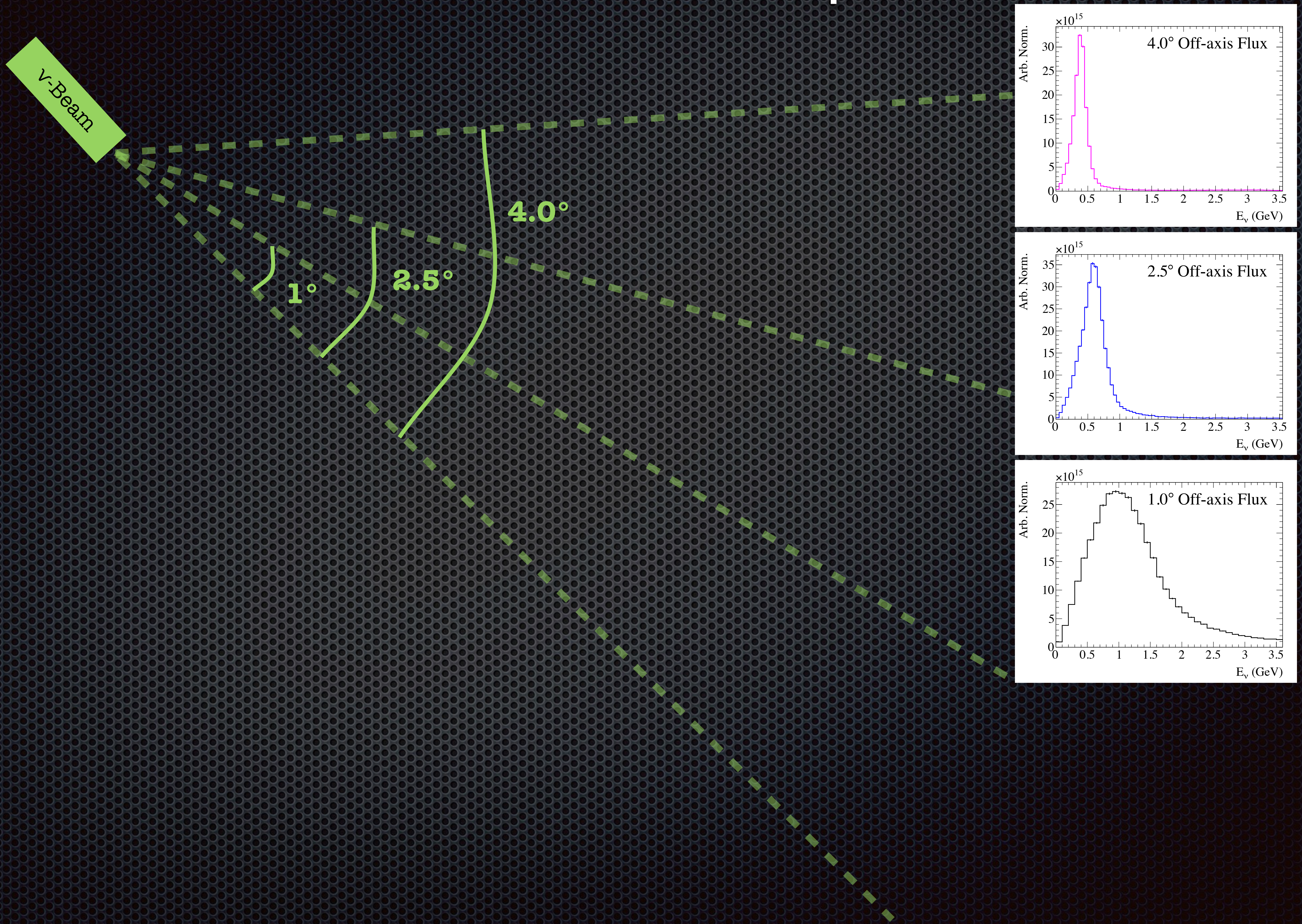

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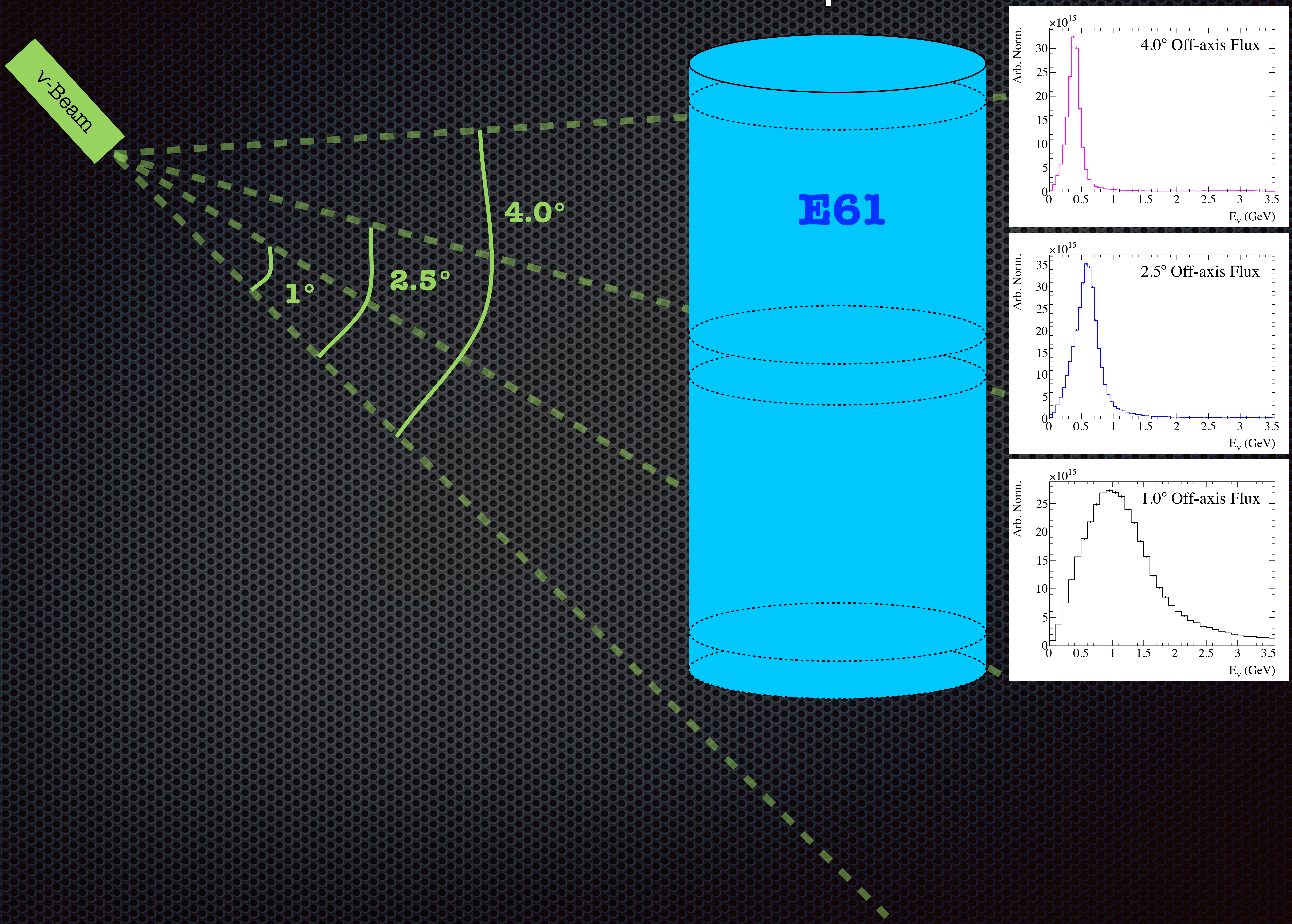

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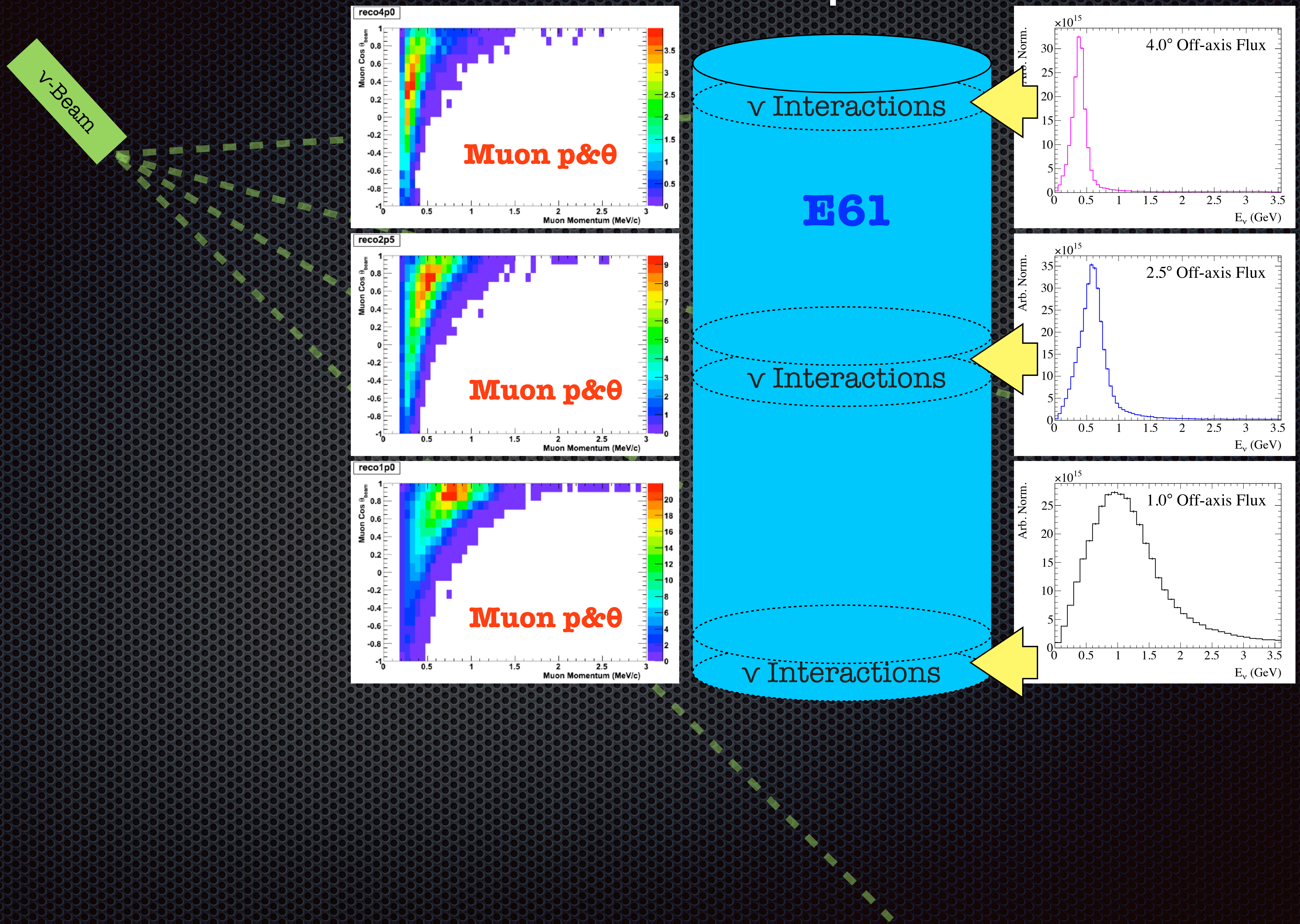

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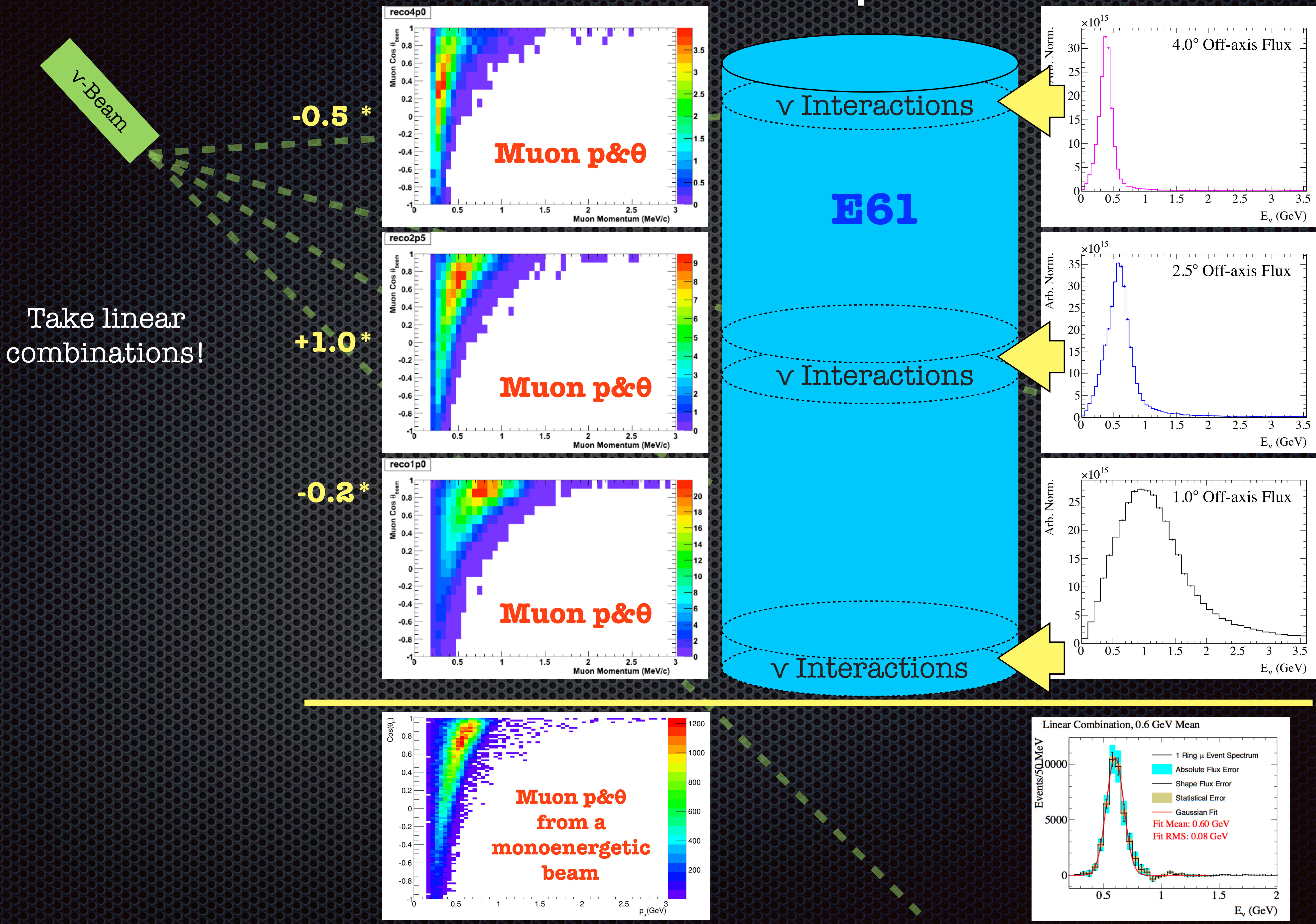

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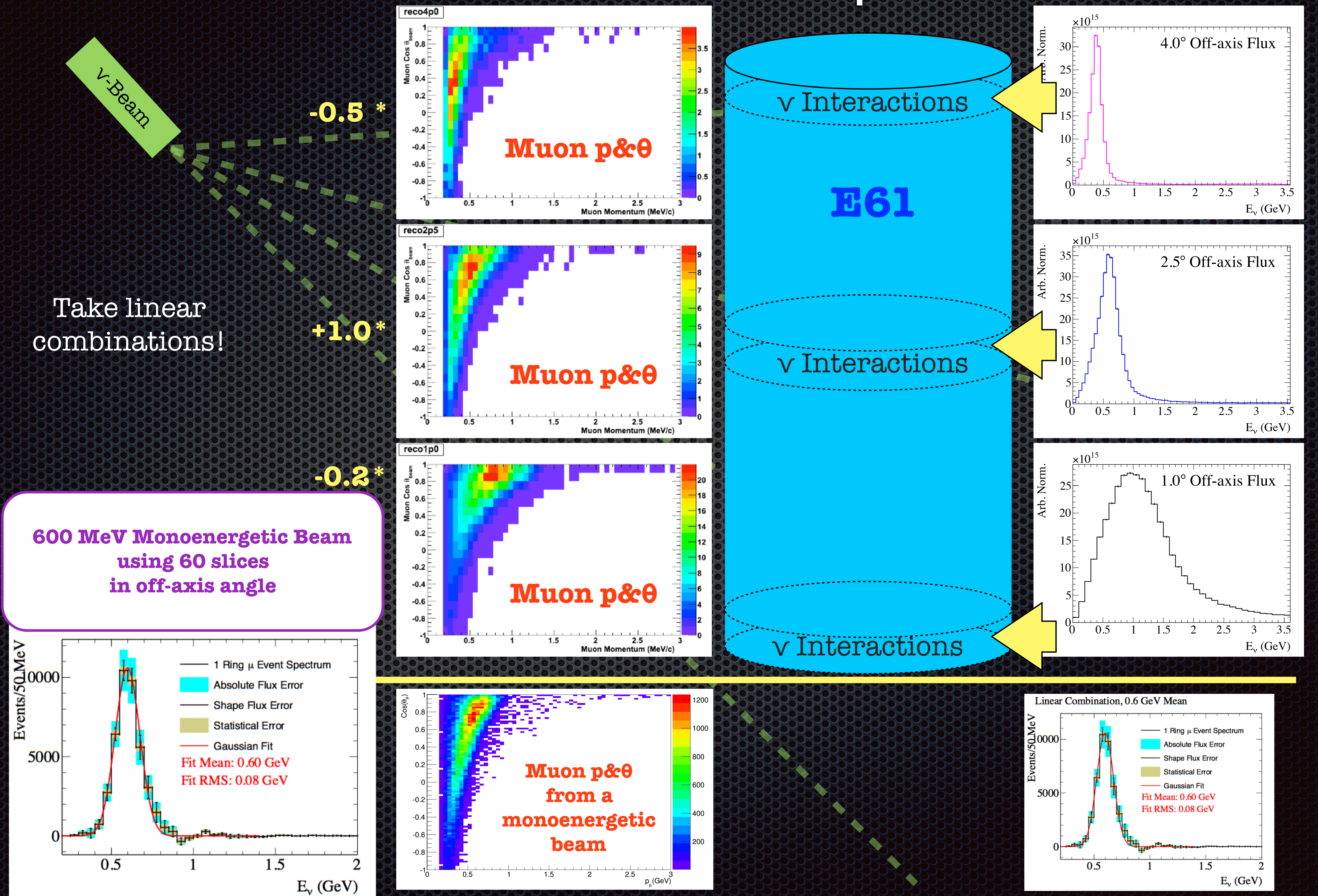
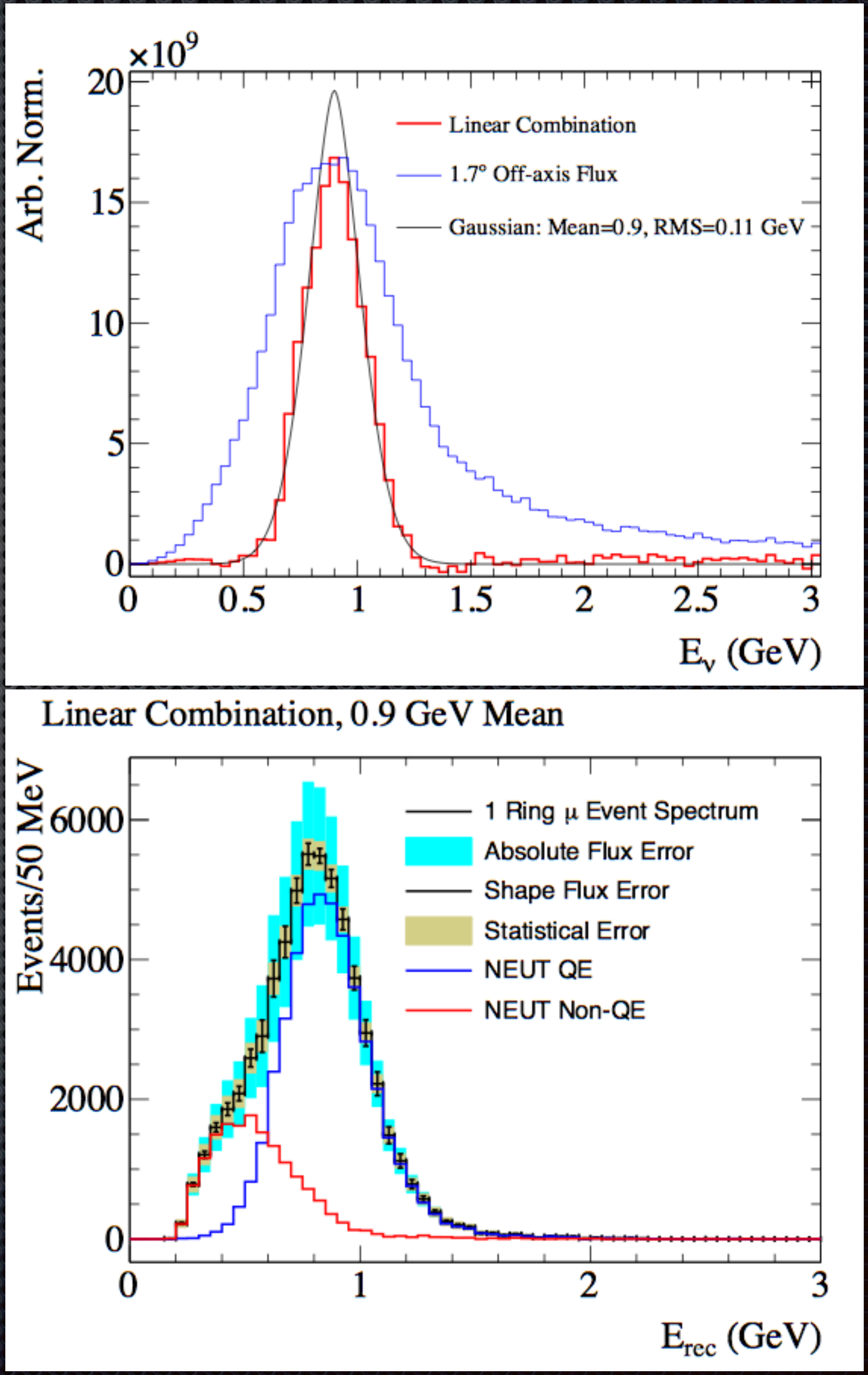
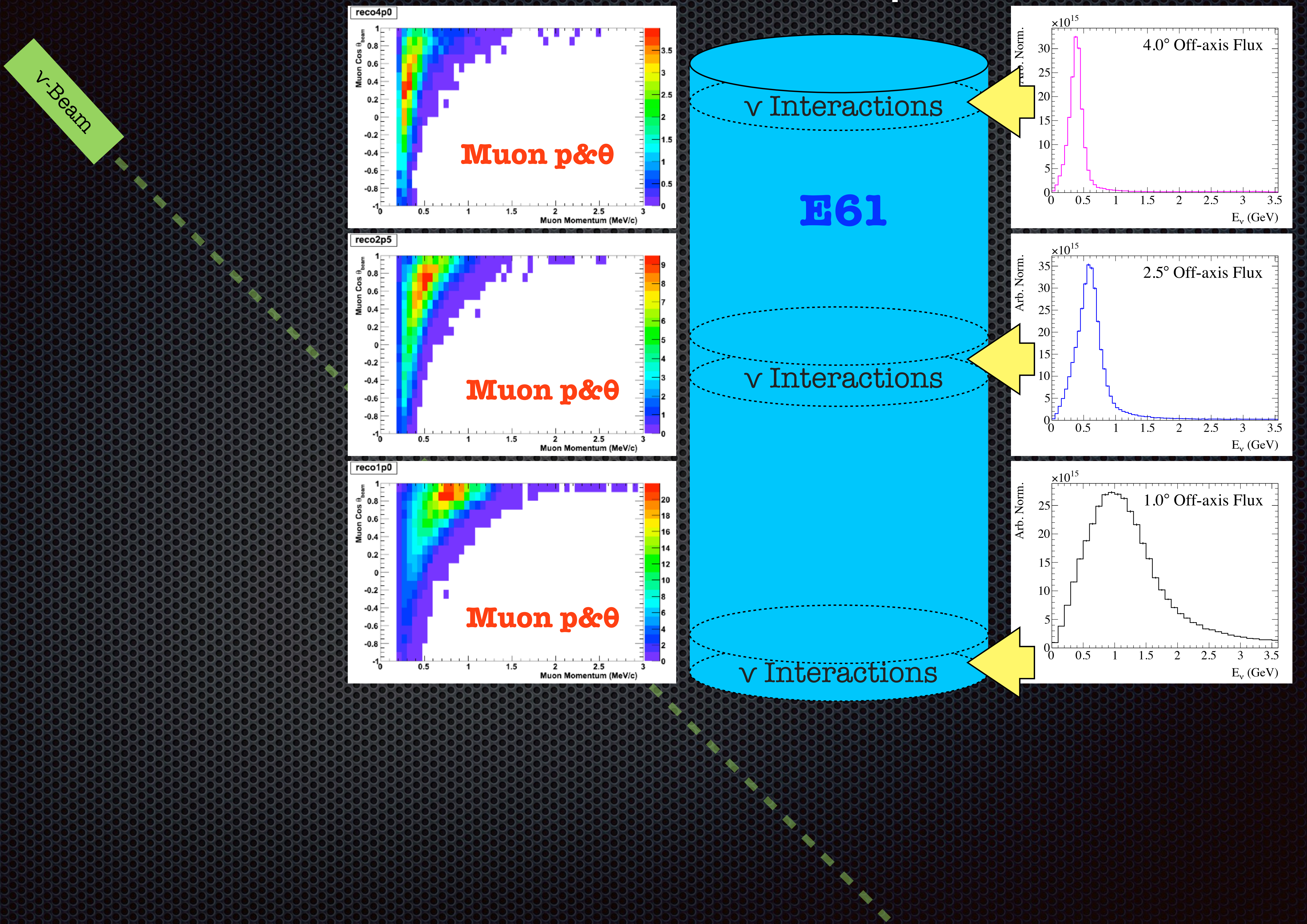


Benefits of a Monoenergetic Beam

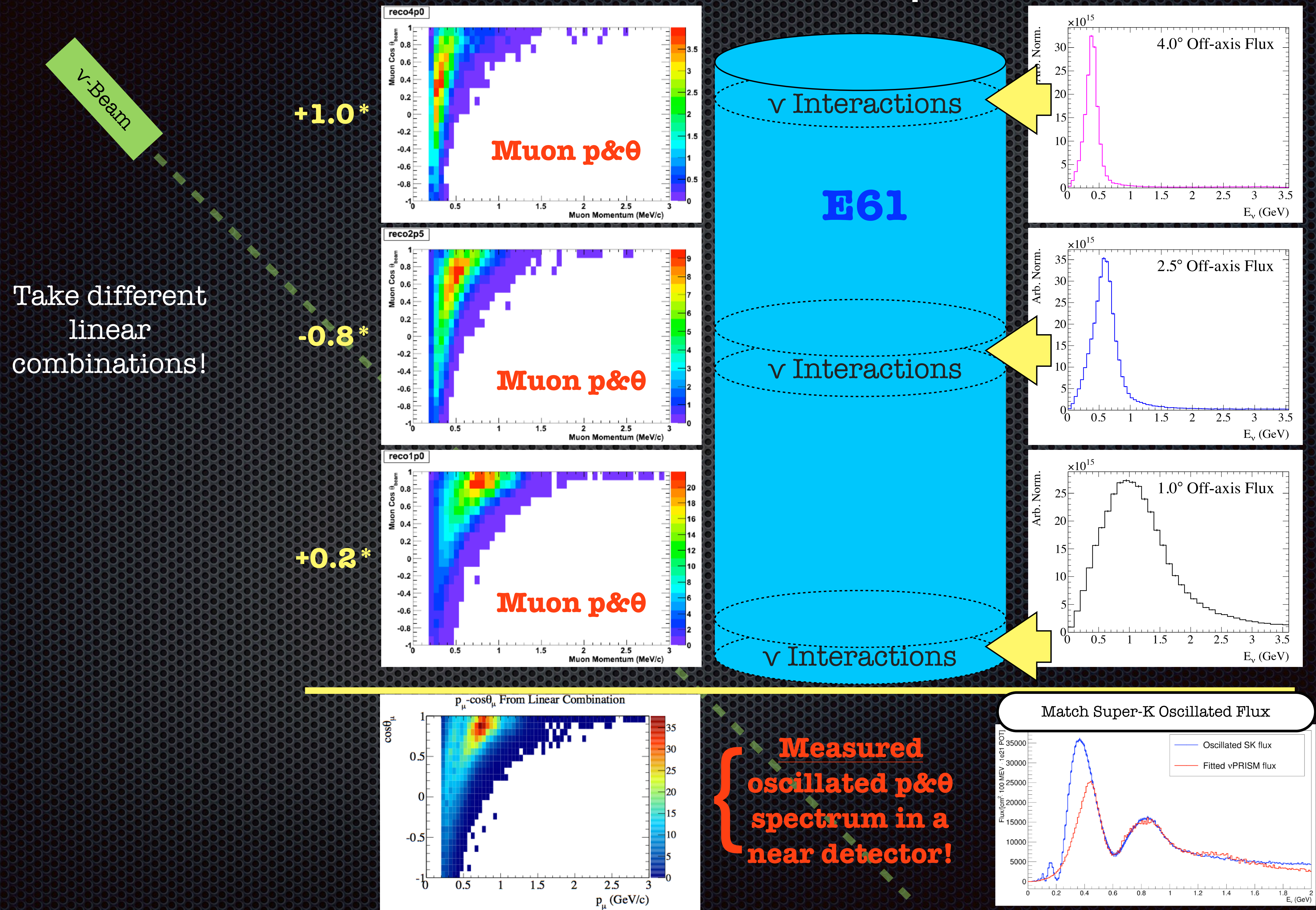
- **Fully specified initial state!**
  - Electron-scattering-like measurements with neutrinos!
- First ever measurements of **$\sigma^{NC}(E_\nu)$**
  - Much better constraints on NC oscillation backgrounds
- First ever "**correct**" measurements of **$\sigma^{CC}(E_\nu)$**
  - No longer rely on final state particles to determine E_ν
- It is now possible to **separate the various components** of single-μ events!



E61 in an Oscillation Experiment



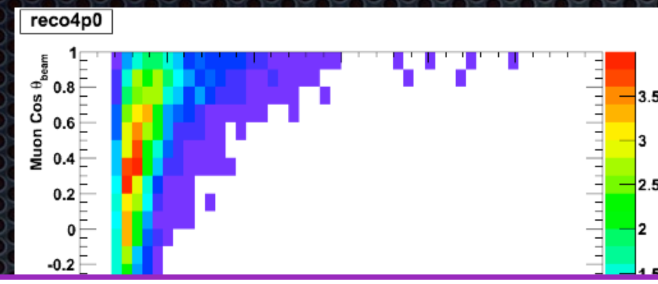
E61 in an Oscillation Experiment

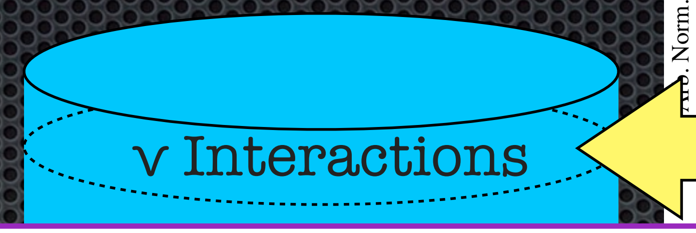


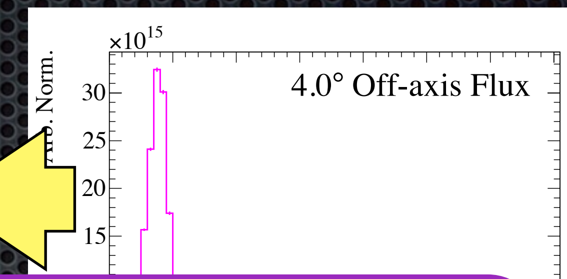
E61 in an Oscillation Experiment

ν-Beam

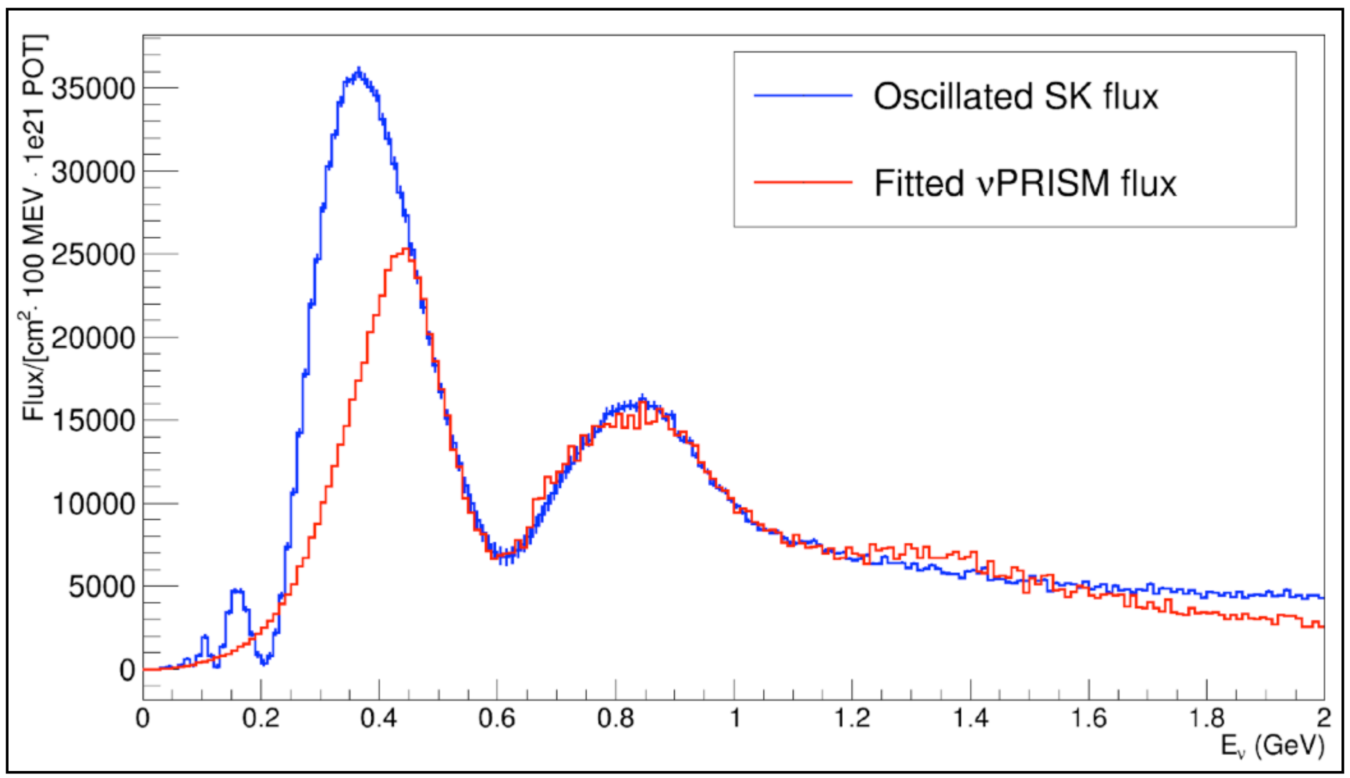
+1.0 *



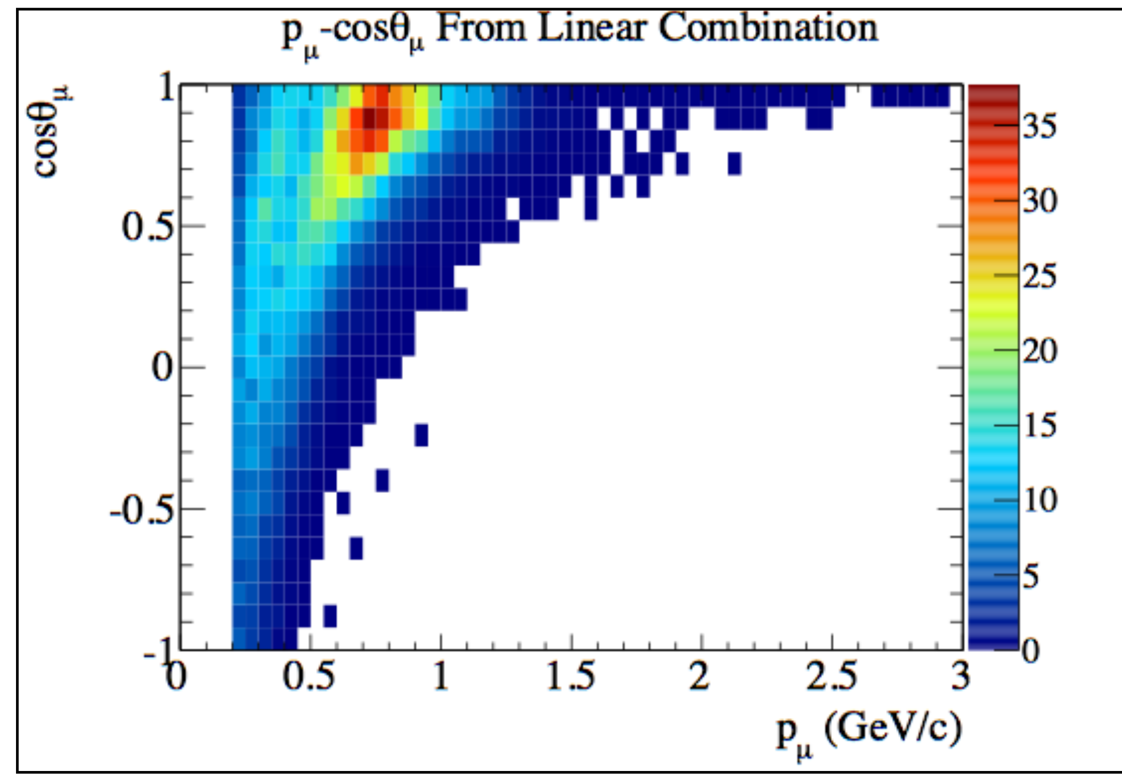


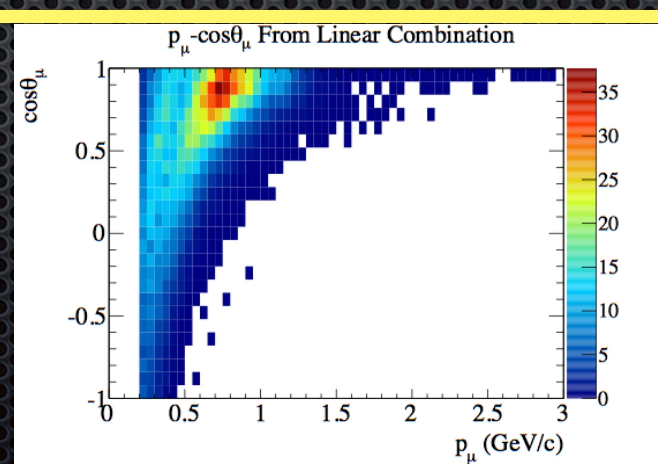


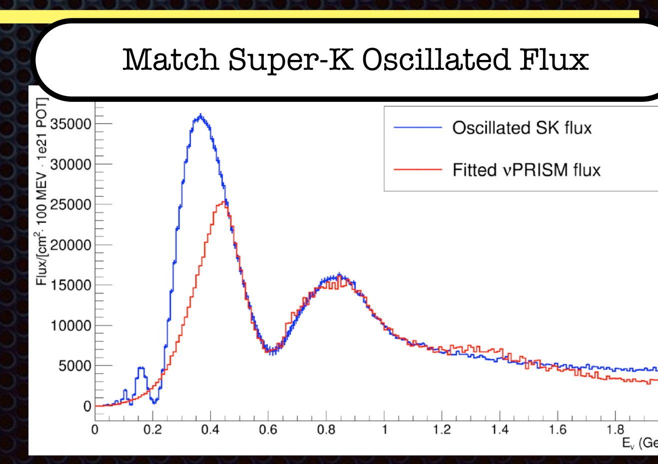
Oscillated Flux Produced at the Near Detector!



Oscillated p&θ Measured at the Near Detector!





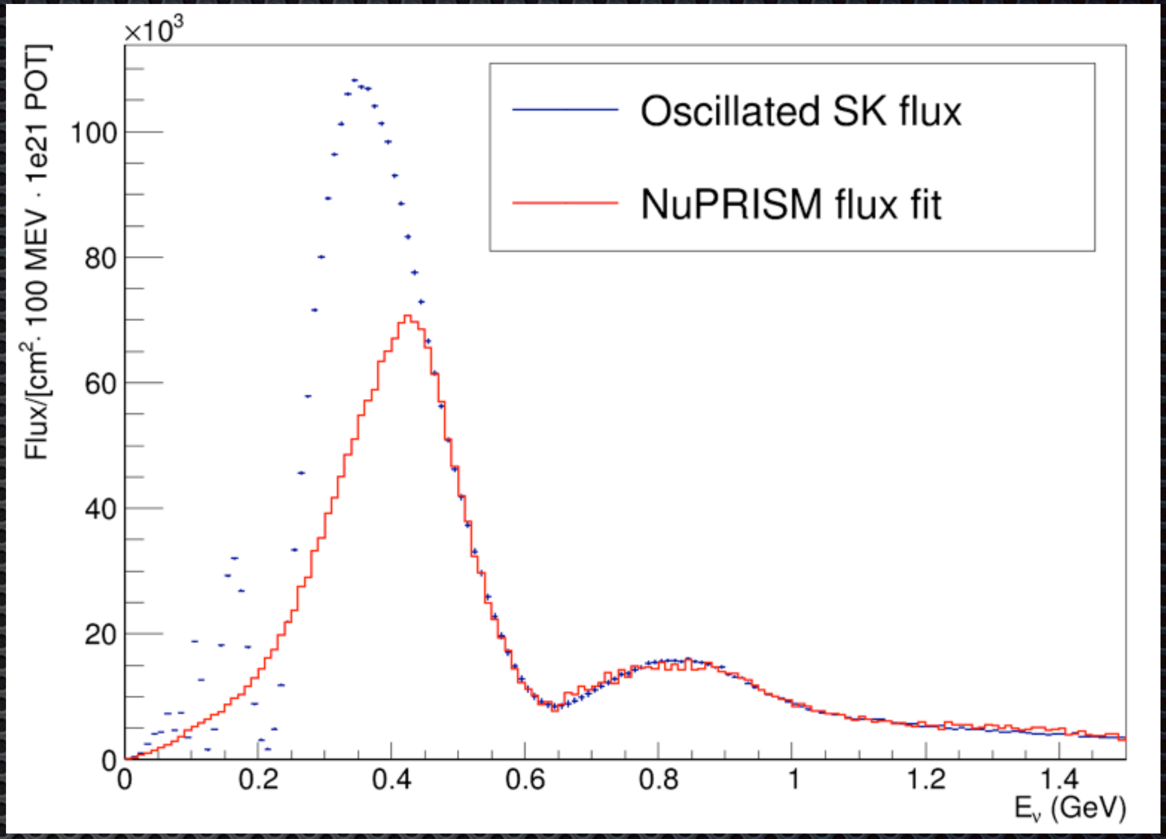


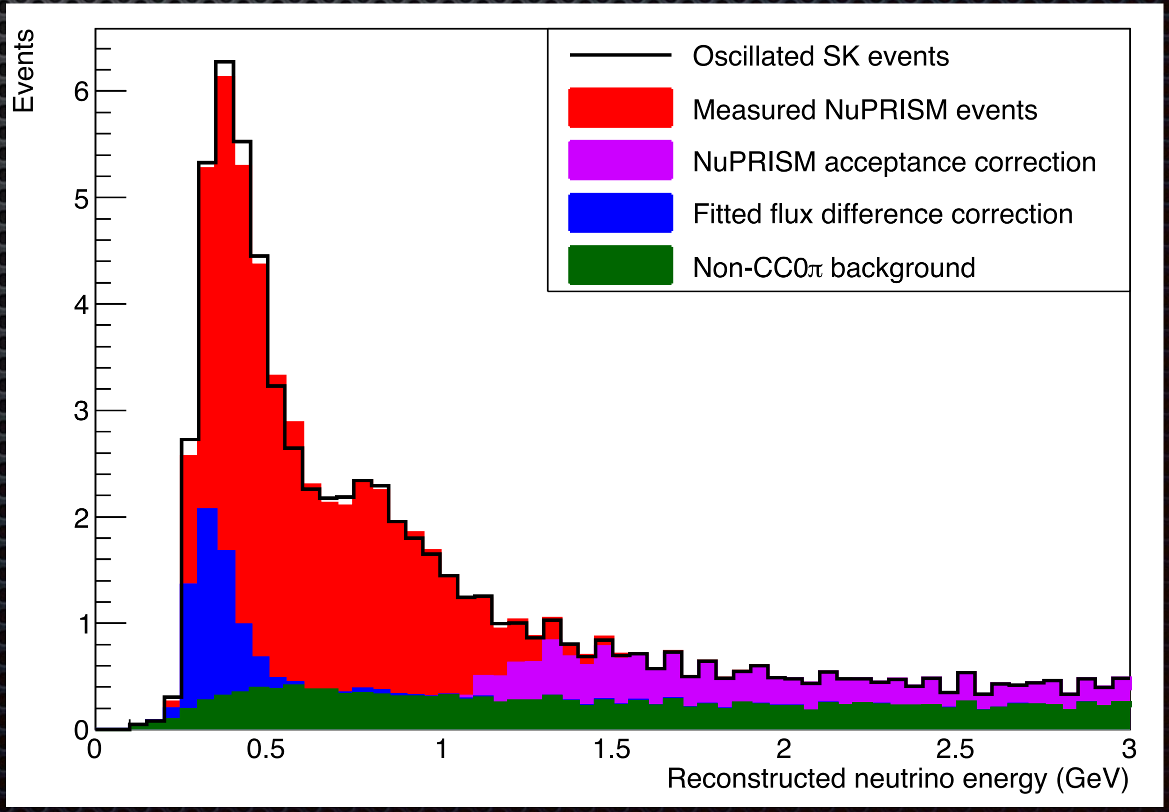
This technique is robust against existing fake data studies

Measured oscillated p&θ spectrum in a near detector!

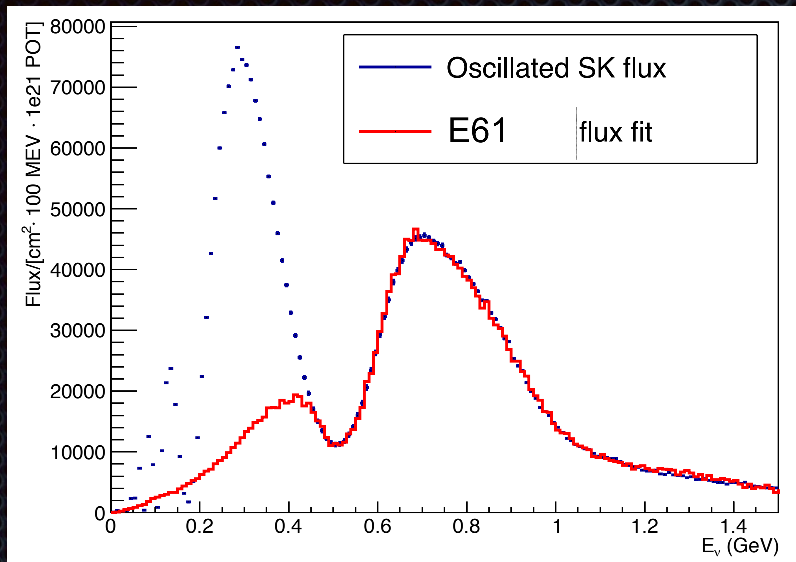
Linear Combination Technique

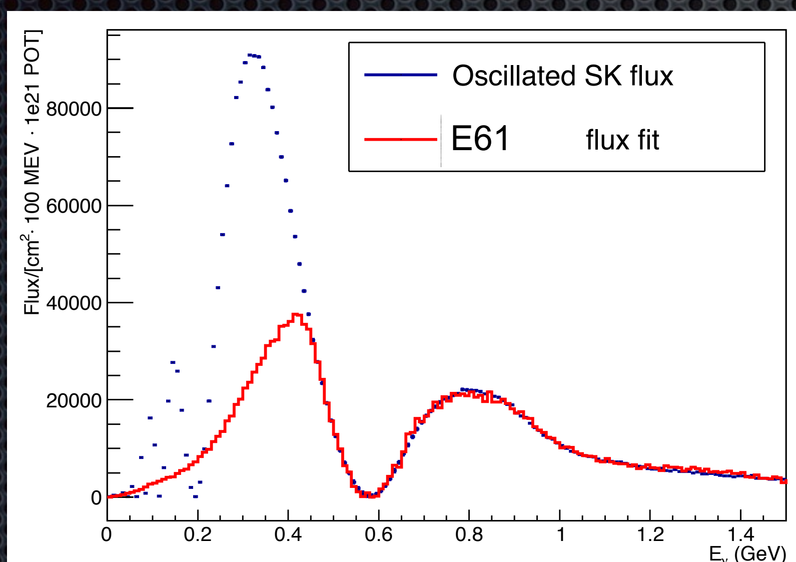
- Flux is now the same at the near and far detector
  - **Can just measure observed muon p vs θ for any oscillated flux**
- Same signal selection as used at Super-K
  - Single, muon-like ring
- **Signal events** can be defined as **all true single-ring, muon-like events**
  - A muon above Cherenkov threshold
  - All other particles below Cherenkov threshold
  - Signal includes CCQE, multi-nucleon, $CC\pi^+$, etc.
- **No need to make individual measurements of each process and extrapolate to oscillated E_ν spectrum**
  - Some corrections are needed for different detector acceptance, flux fit differences, and remaining backgrounds

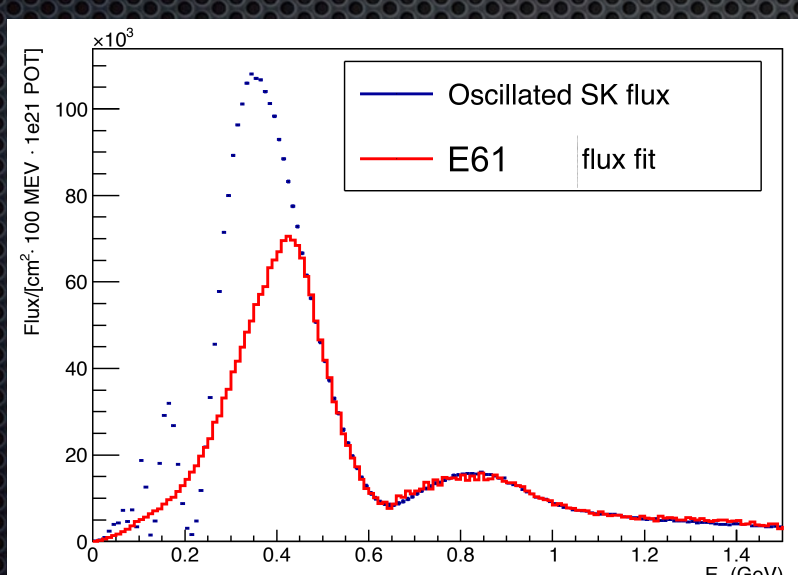




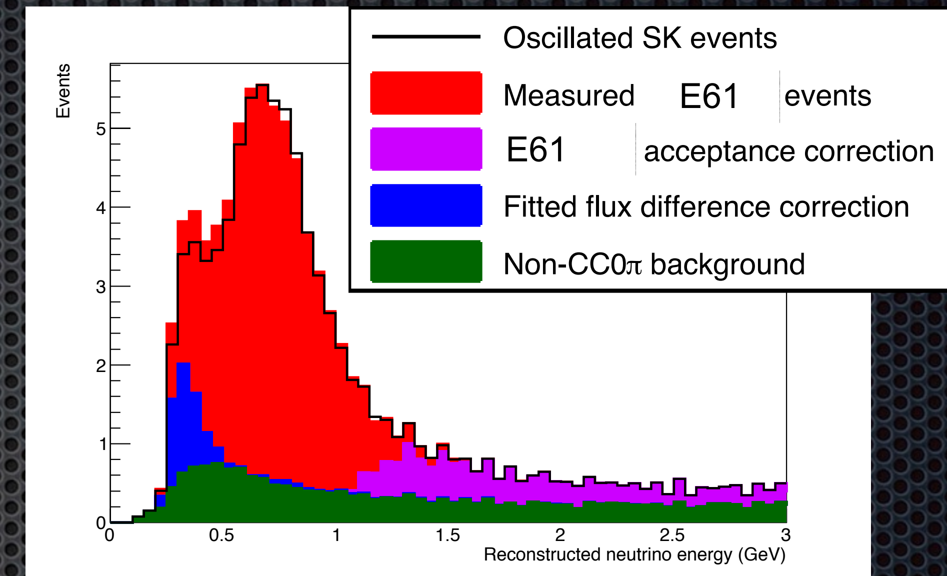
"Oscillations" in a Near Detector

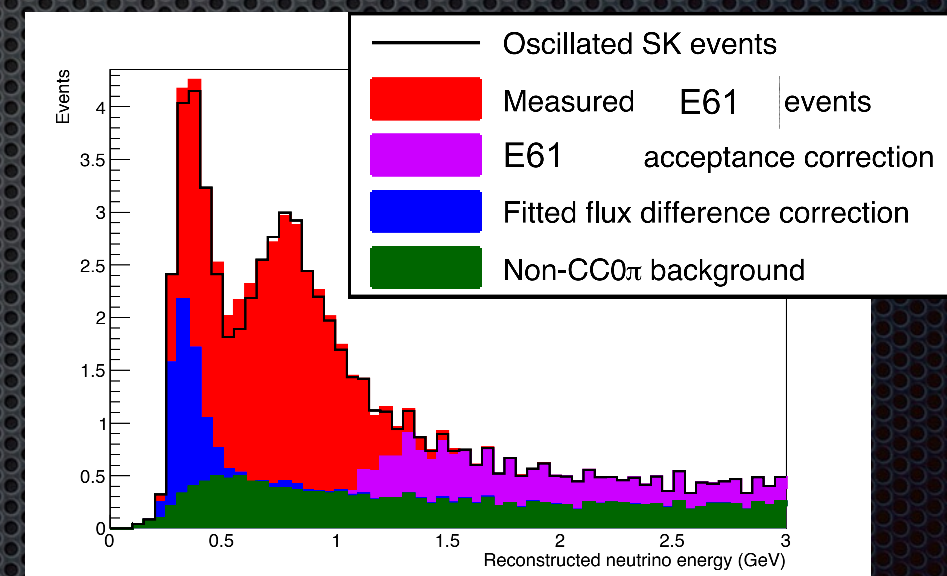


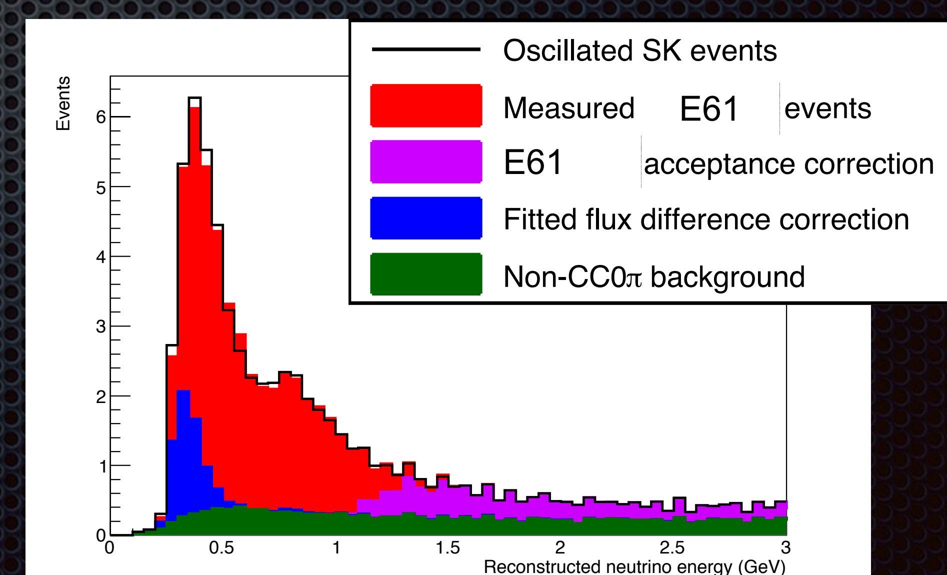




- Red region is directly measured by E61
- Blue region is flux difference correction
- Green is SK non-CC0π background
- Partially cancels with already-subtracted E61 CC0π background
- Magenta is acceptance correction
- (geometric muon acceptance)
- SK prediction is largely from directly measured component

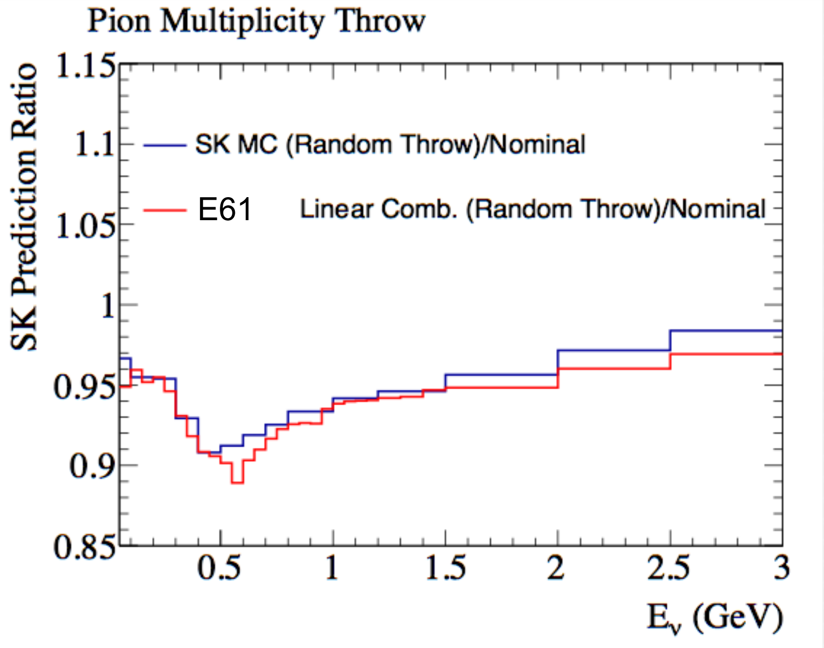


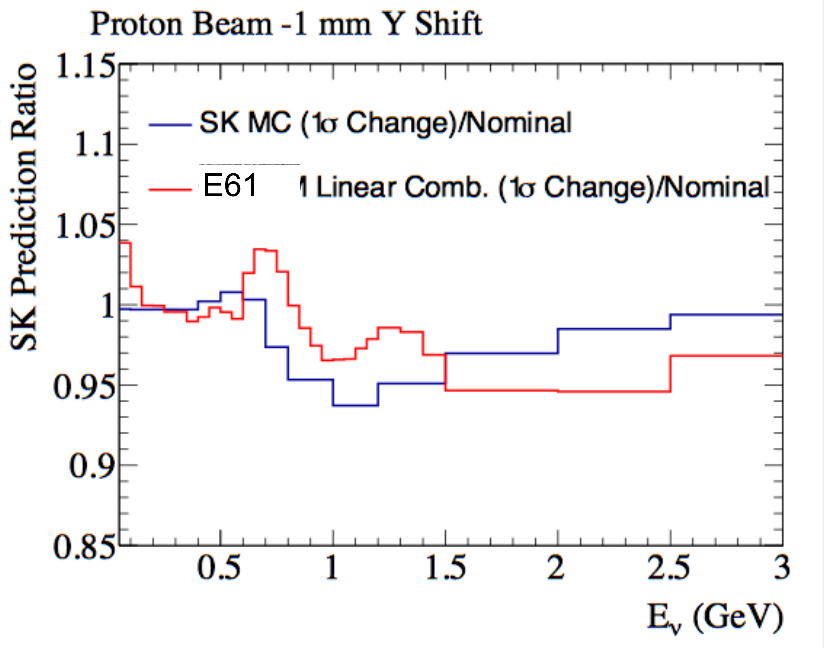


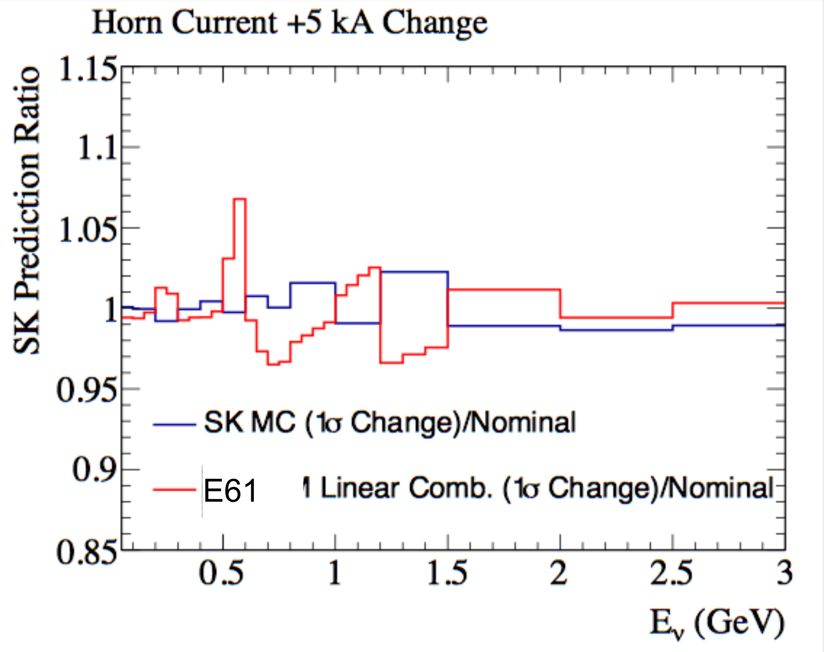


Flux Uncertainties

- Haven't we just replaced **unknown cross section errors** with **unknown flux errors**?
  - Yes! But only relative flux errors are important!
  - Significant cancelation between E61 and far detector variations
- **Normalization uncertainties will cancel** in the E61 analysis
  - This is not the case for a standard near+far analysis, due to different near/far fluxes, and energy migrations due to cross sections
  - **T2K without E61**: hadron prod. errors dominate; **T2K with E61**: hadron prod. errors are negligible
- Variations that affect off-axis angle shape are most important (although still not the dominant systematic uncertainty)
  - Horn current, beam direction, alignment, etc.

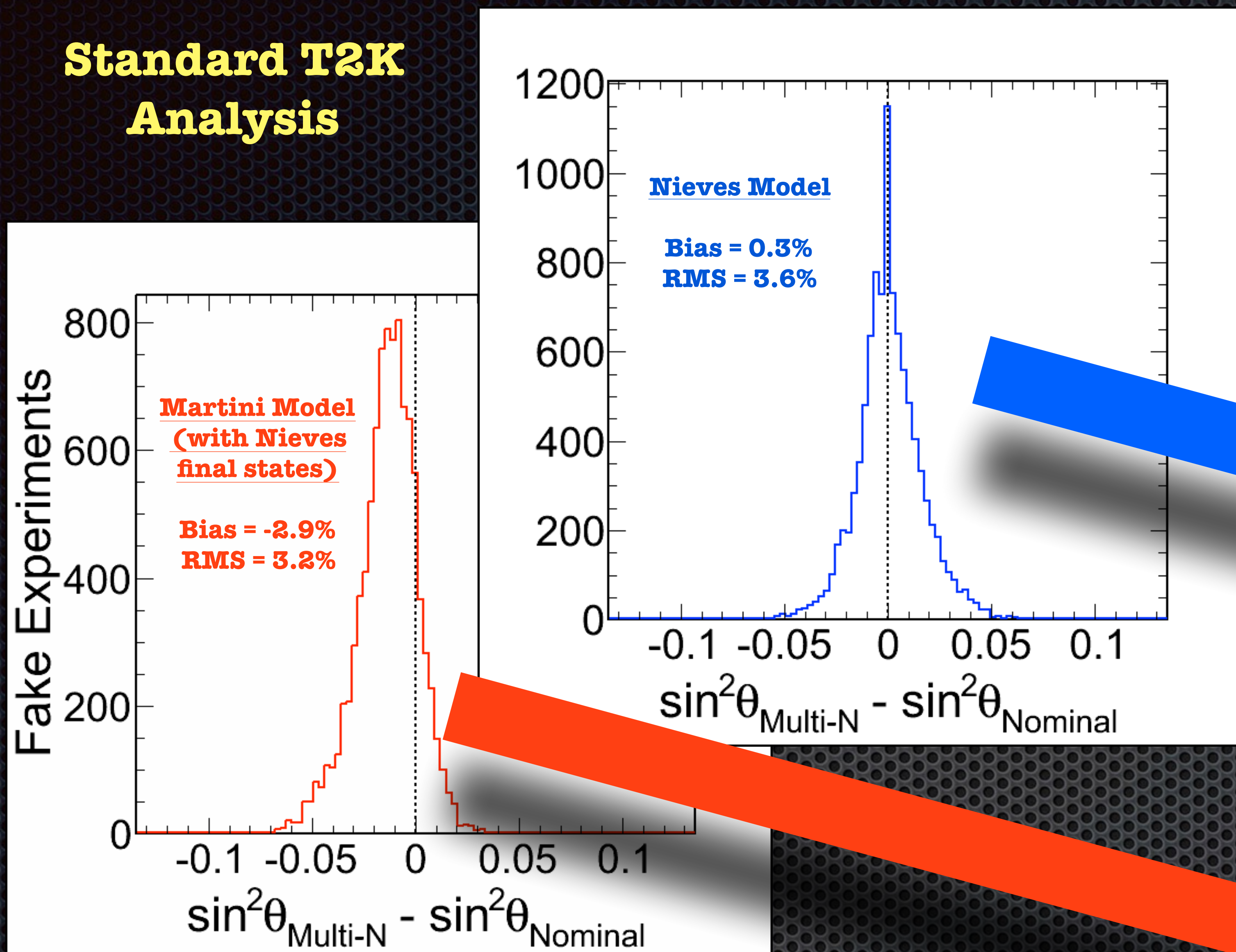




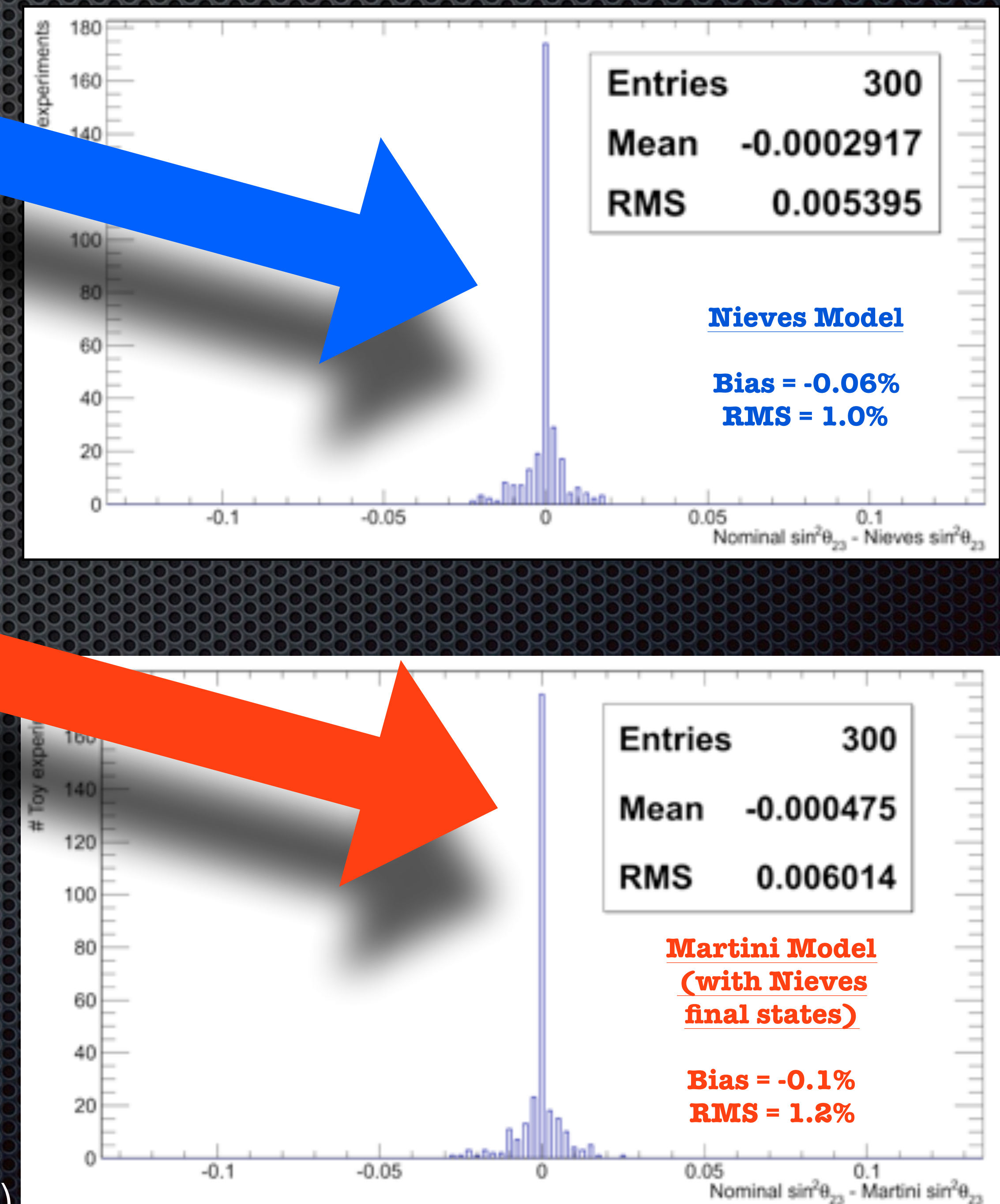


E61 ν_μ Disappearance Constraint

Standard T2K Analysis



E61 Analysis

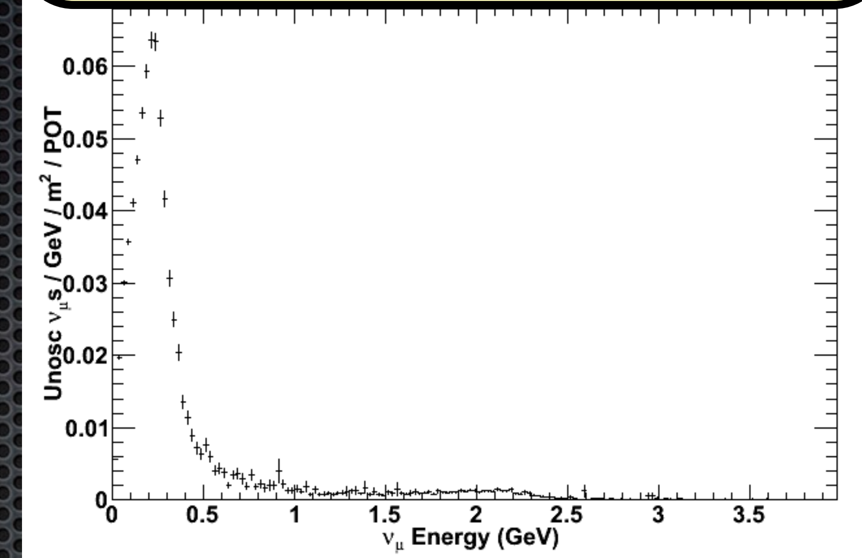


- Fake data studies show the bias in θ_{13} is reduced from 4.3%/3.6% to 1.2%/1.0%
- More importantly, this is now based on a **data constraint**, rather than a model-based guess
- Expect the E61 constraints to get significantly better as additional constraints are implemented (very conservative errors)

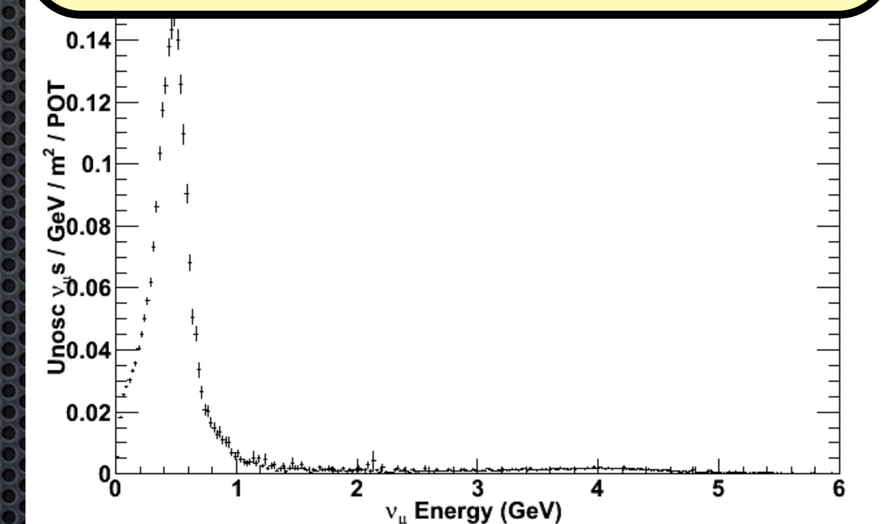
DUNE-PRISM

- The DUNE beam points directly at the far detector (on-axis)
- Therefore, it is impossible to access a higher energy E_ν spectrum at the near detector
  - Higher E_ν spectra are needed to subtract high-E_ν tail
  - “First” oscillation maximum is at 2.5 GeV
- However, the on-axis flux is broad, so it is possible to utilize to higher energy portion of the flux peak (~3.5 GeV; next slides)

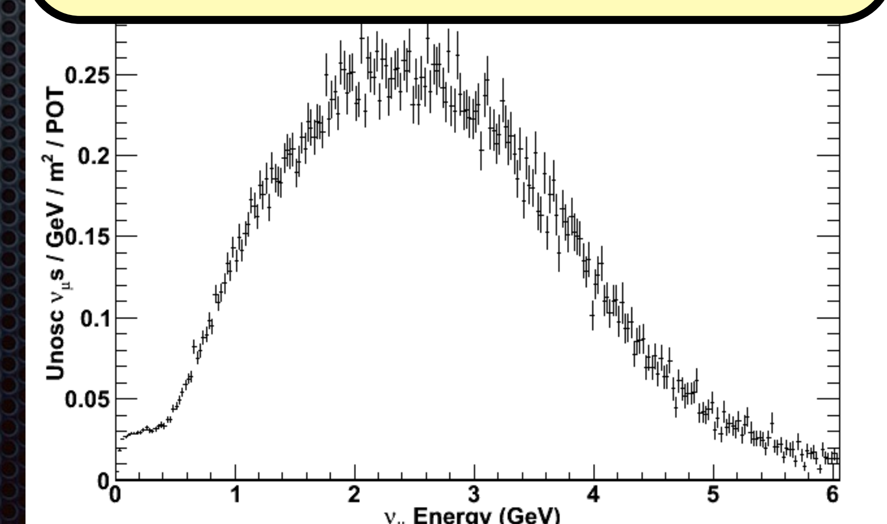
6° (105 mrad) Off-axis



3° (52 mrad) Off-axis

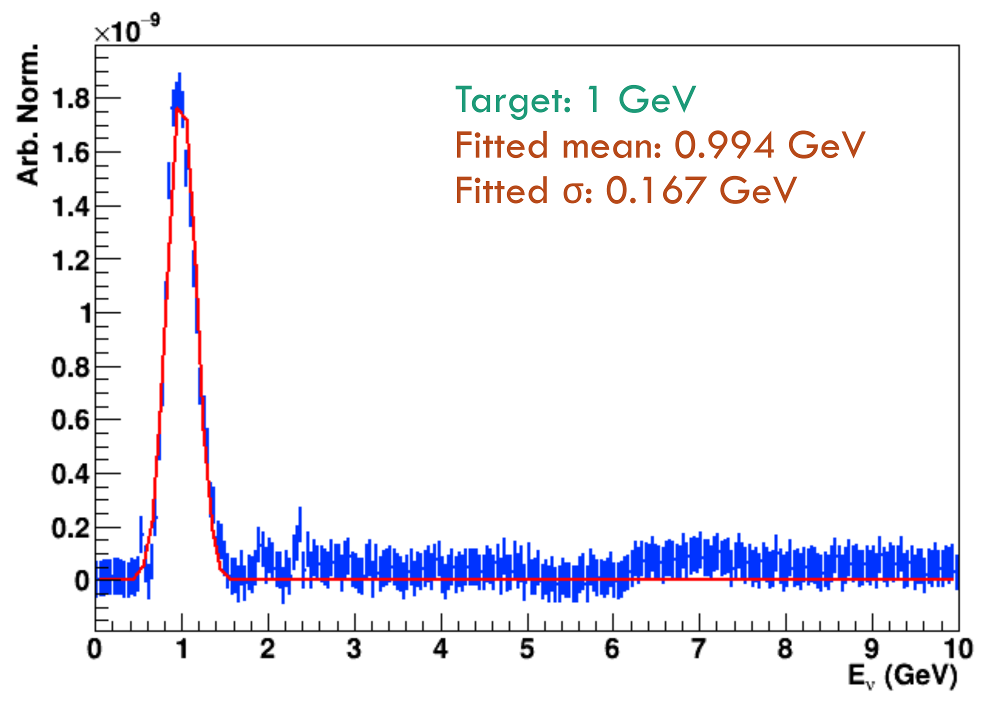


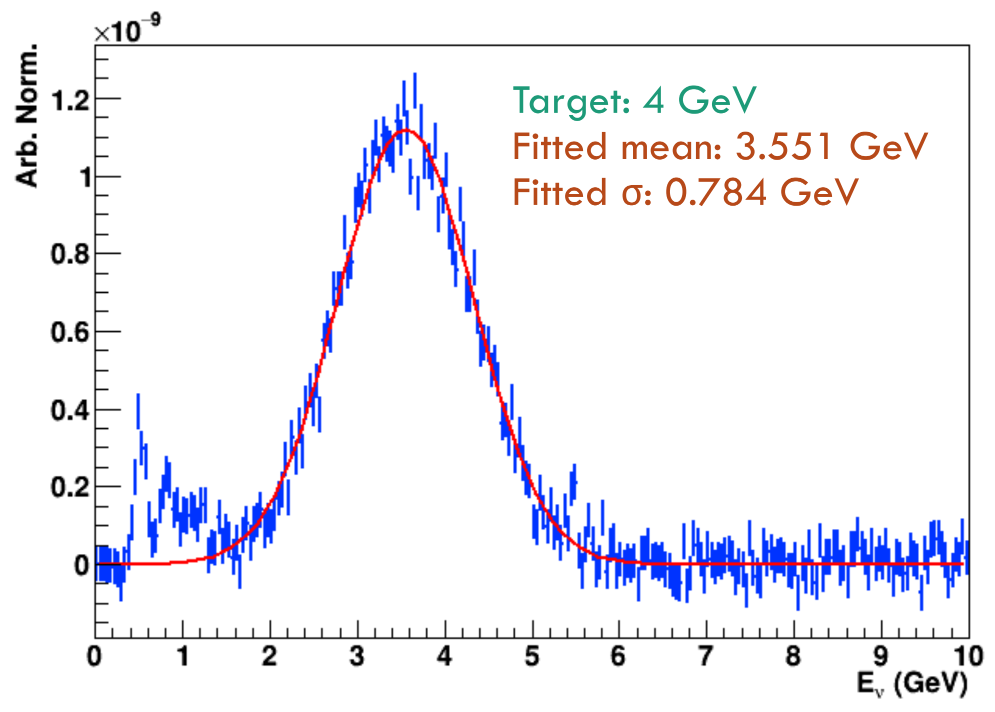
0° (0 mrad) Off-axis



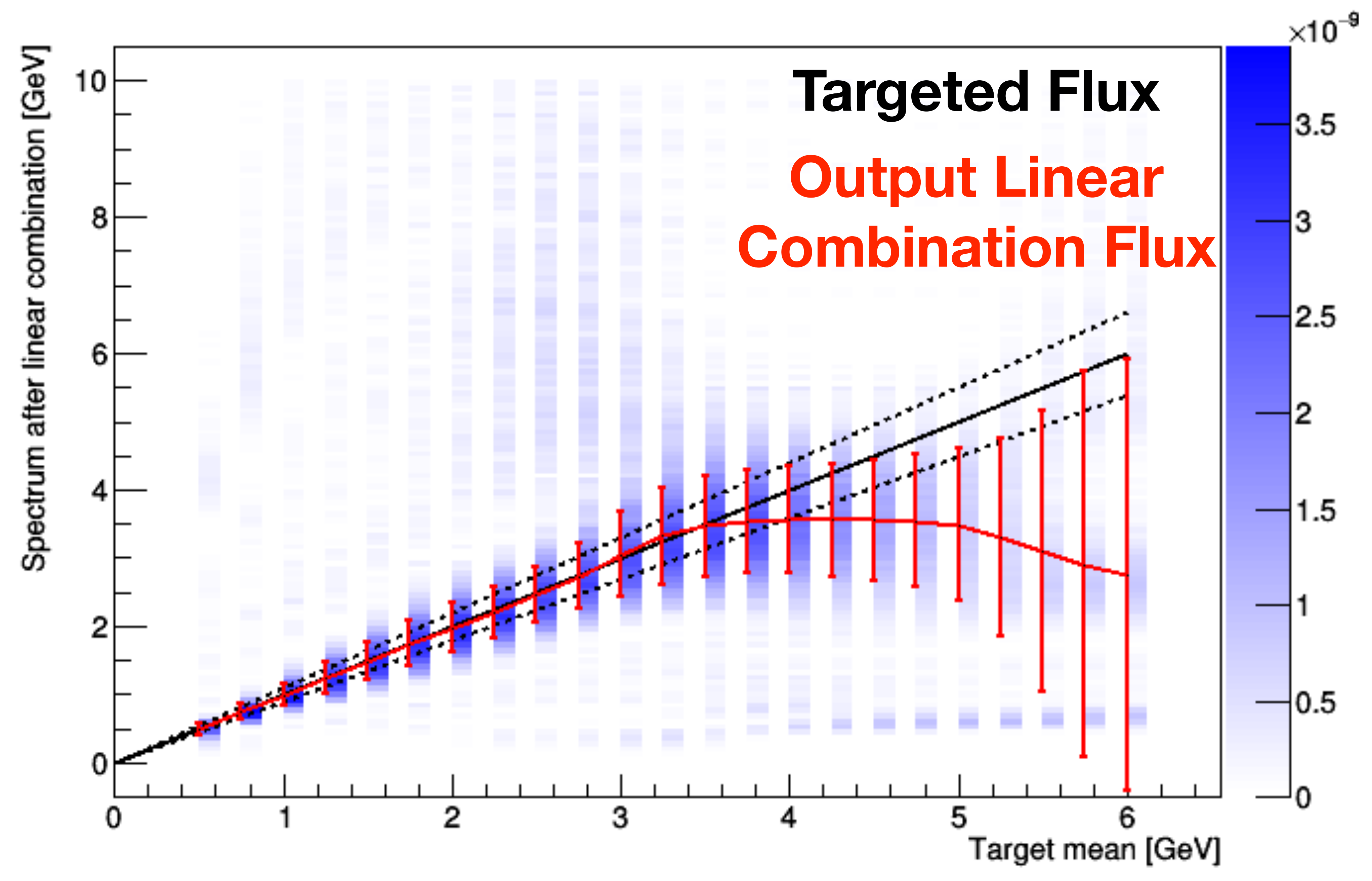
DUNE-PRISM Monoenergetic Linear Combinations

- Monoenergetic fluxes can be produced up to ~3.5 GeV
  - This is above the peak neutrino energy of the on-axis flux!
  - Good cancelation in high energy tail
- Fits begin to develop features at low energy as higher energies are attempted





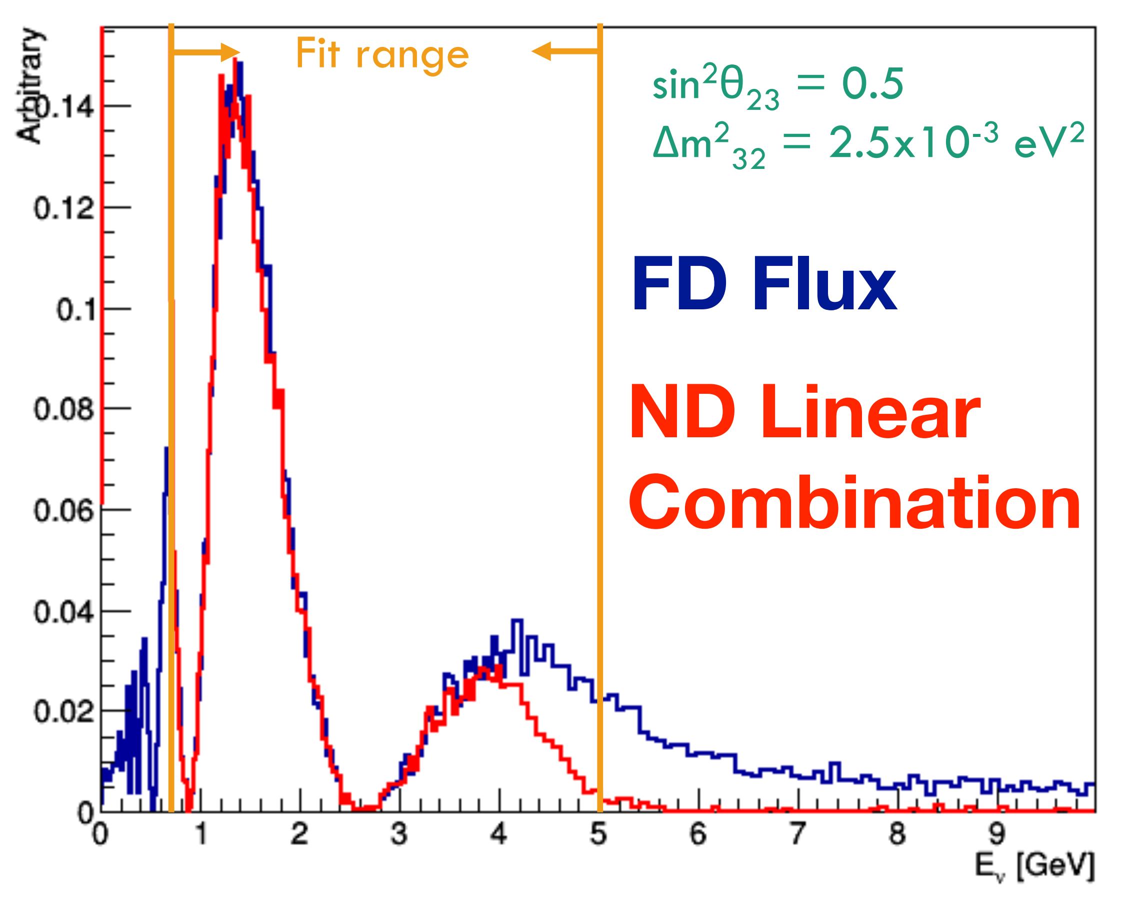
Monoenergetic Fluxes



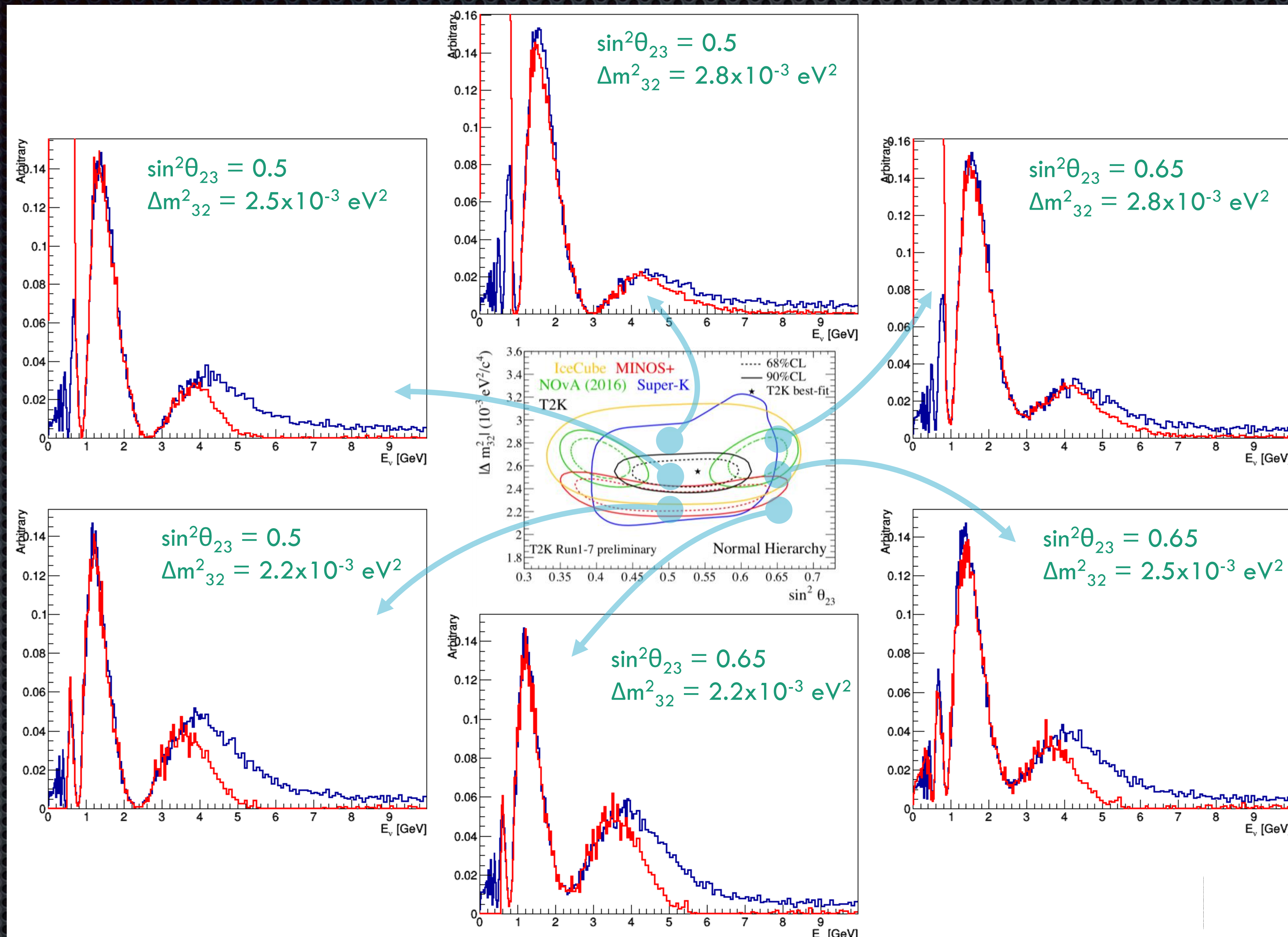
- DUNE-PRISM off-axis measurements can resolve features up to 3.5 GeV
  - The lower limit is below the 600 MeV peak of 2nd oscillation maximum

ND "Oscillated" Fluxes

- The far detector oscillated spectrum can be mostly reproduced with near detector linear combinations
  - Cannot quite cover the bump just above the oscillation maximum at 4 GeV
  - Is it still possible to point the beam slightly off-axis and slightly increase beam power?
    - just kidding; it is now too late to make major changes to the beam
- However, this is still quite promising!
  - Some residual model dependence at high energy, but DIS may be more understandable in this region
  - The poorly understood, low energy CCQE + MEC + CCpi+ region is well covered



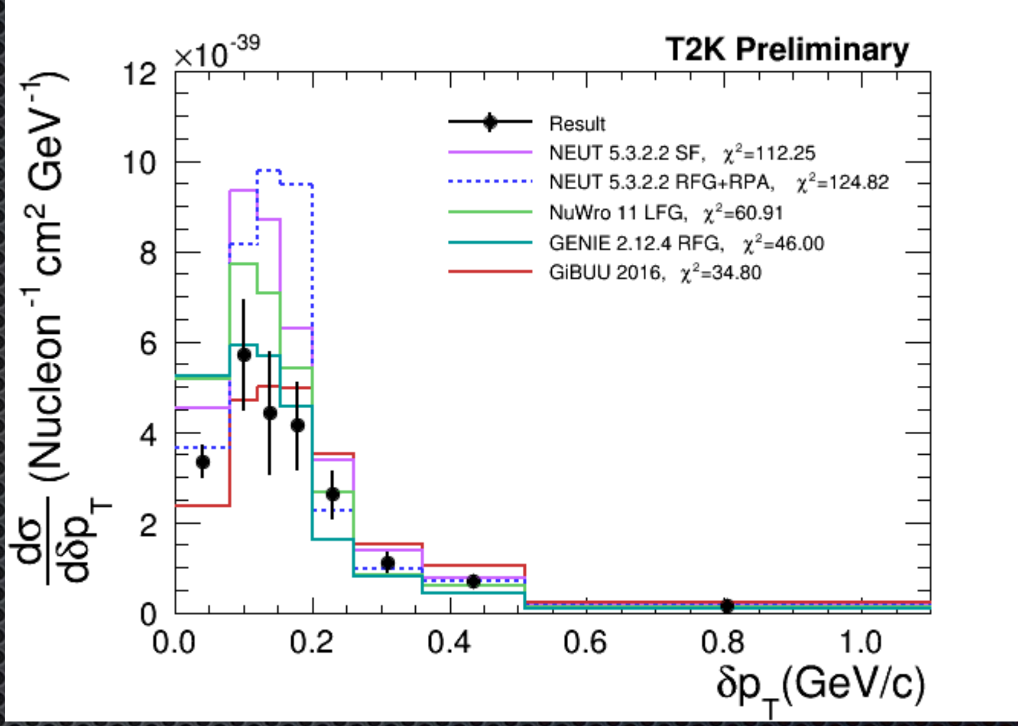
Varying the Oscillation Parameters

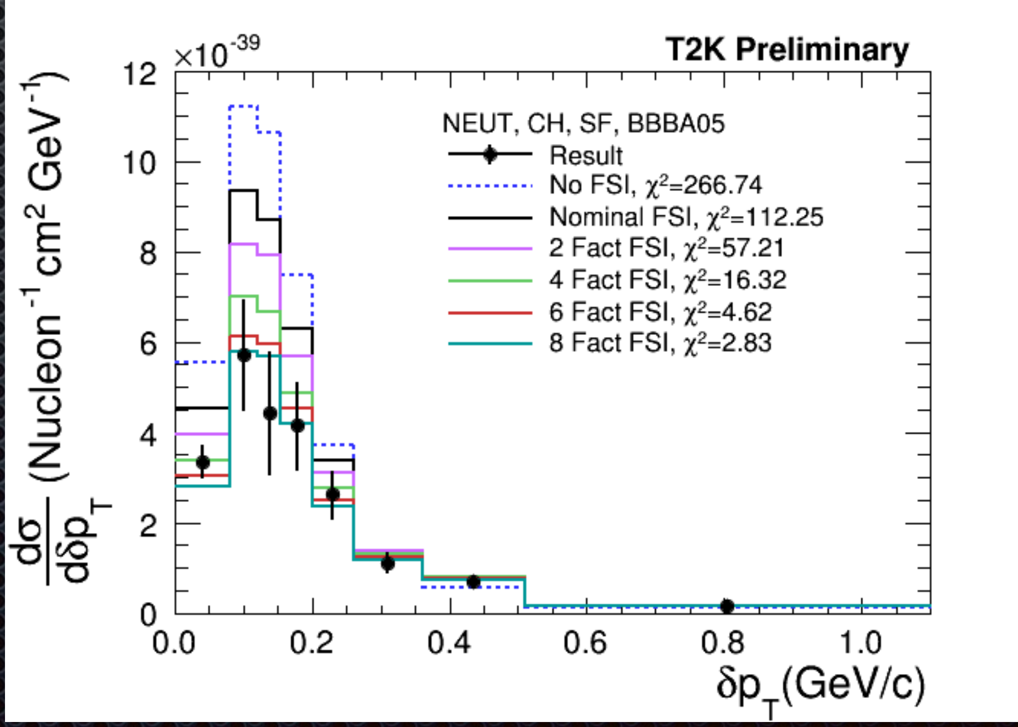


- Far detector oscillated spectrum can be mostly reproduced at the near detertor across the interesting oscillation parameter space

DUNE Fake Data Studies

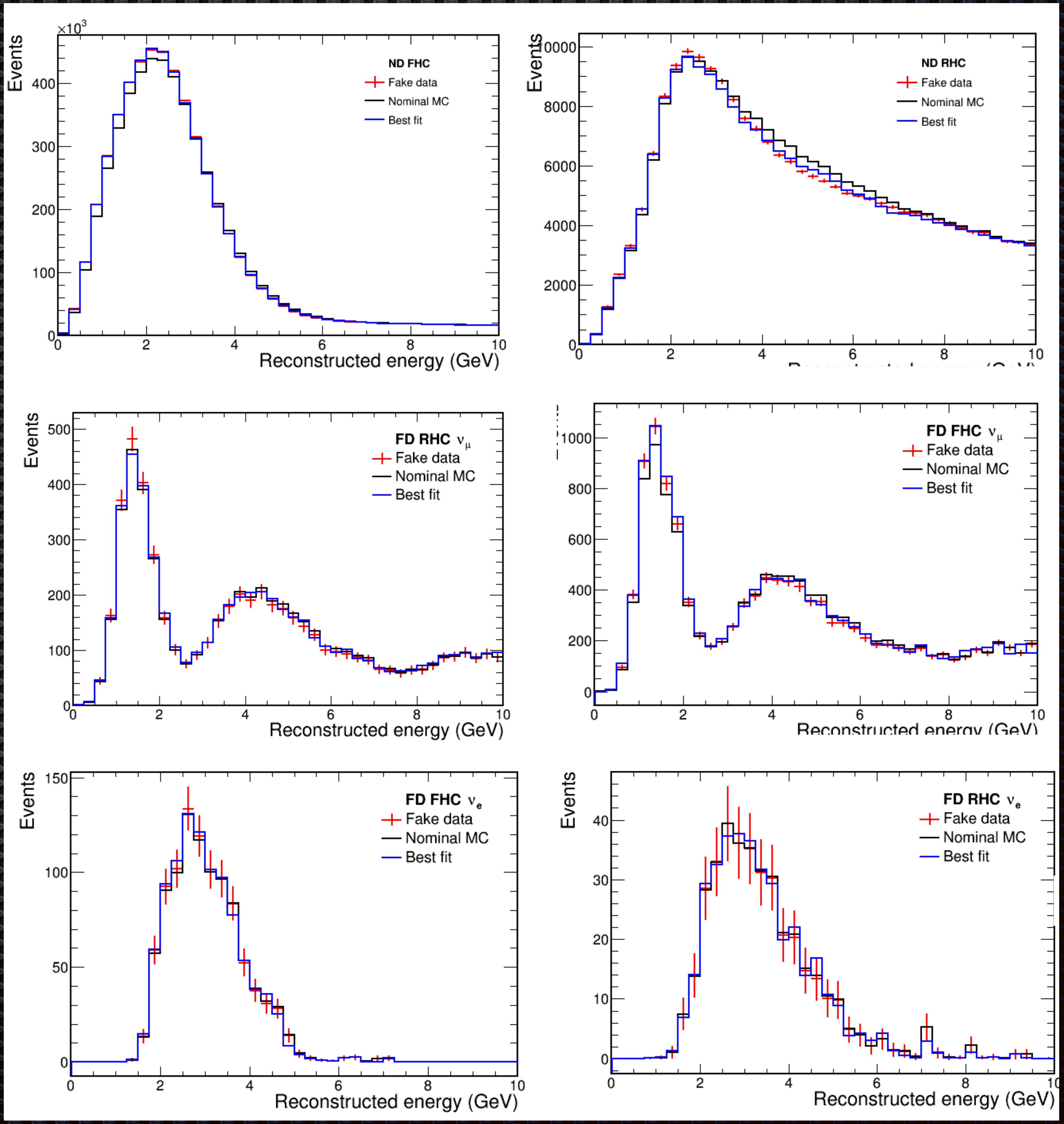
- To demonstrate the danger of trusting an incorrect cross section model, we can make fits to fake data
  - The fake data contain a modification to the cross section that the fitting model does not know about
  - The fitting framework we use is a version of CAFAna (i.e. the NOvA fitting framework)
- The hadronic final state from neutrino interactions has been less studied than the leptonic final state
- As a first example, fake data have been produced with 20% of the charged pion energy transferred to neutrons



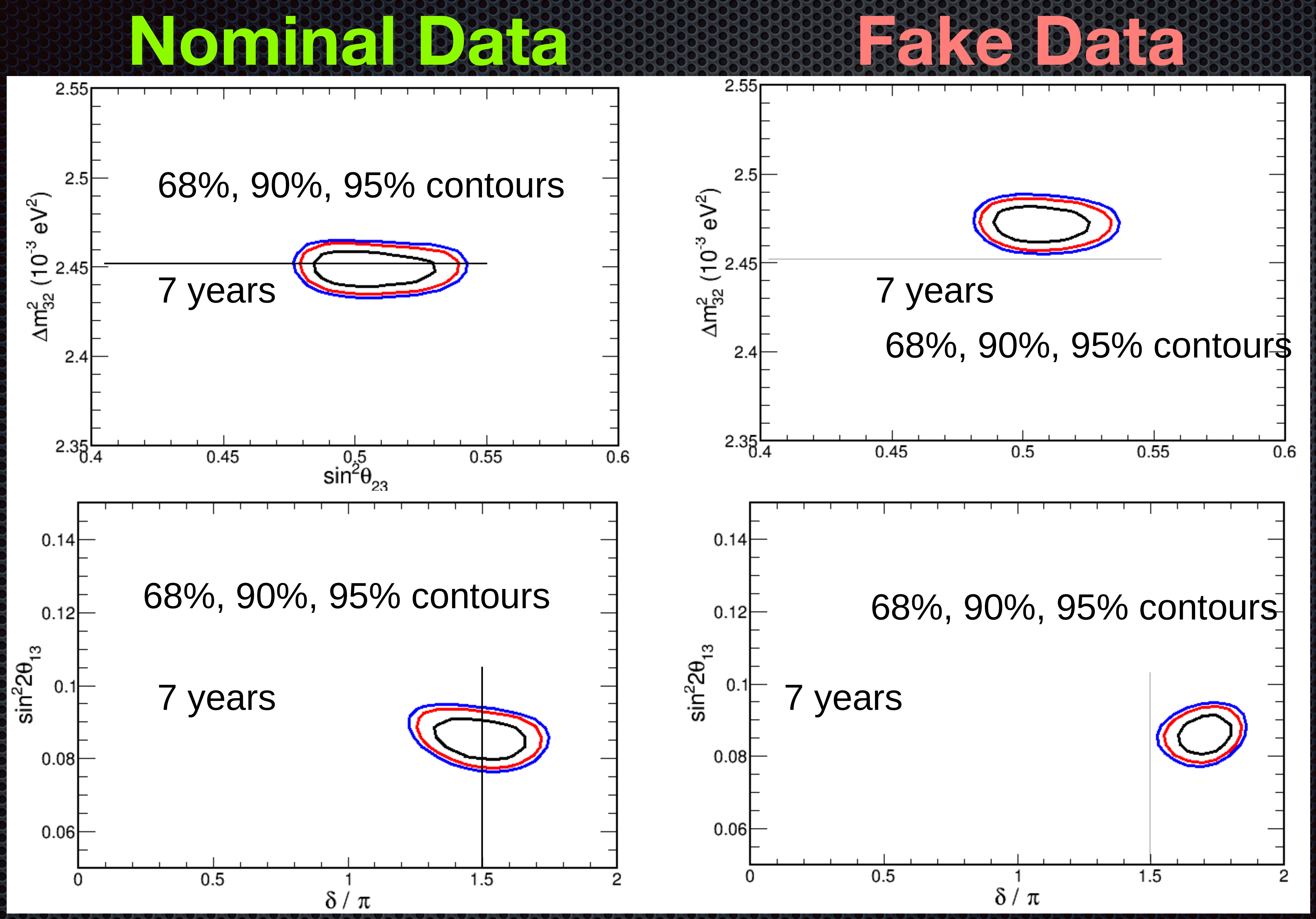


Fake Data Example

- Fake data has 20% charged pion energy converted to neutron energy
- Fit has energy scale uncertainty, and standard flux & cross section uncertainties
- Fit can reproduce fake data distributions, but at the cost of biasing the oscillation result (next slide)



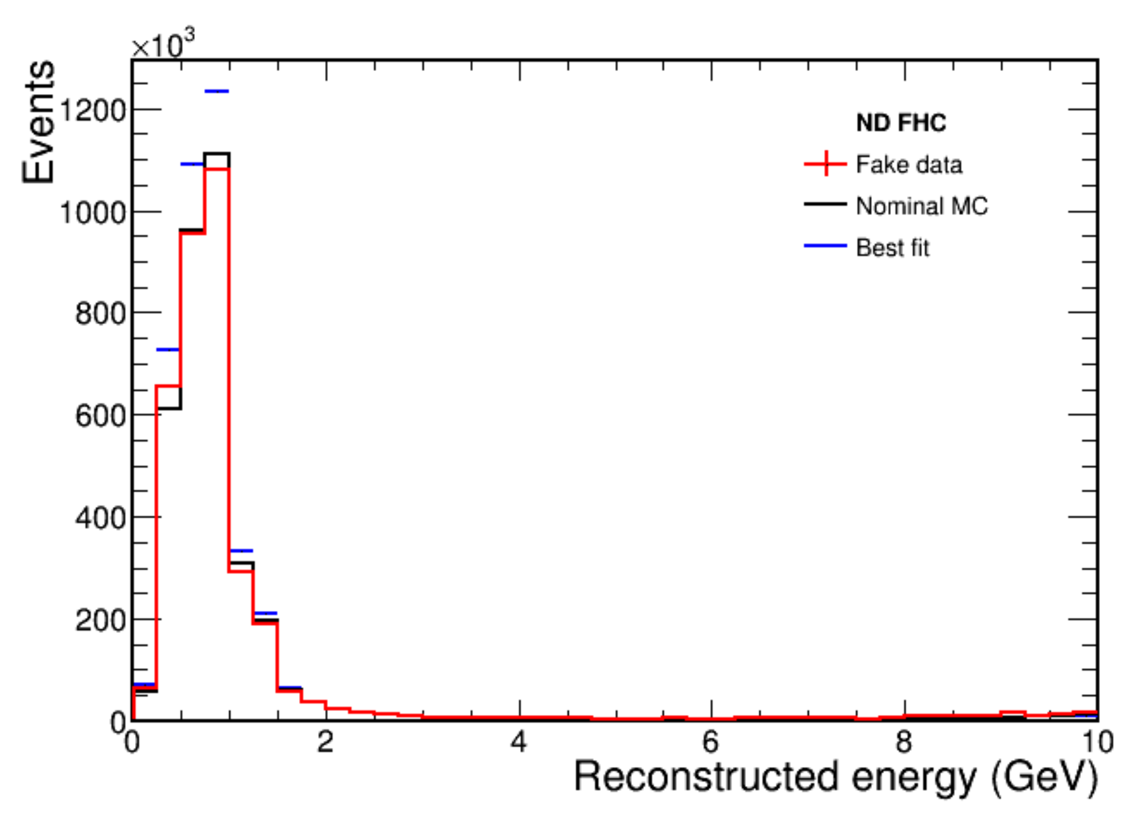
Fit Biases



- Summary: it is possible to get biased fit results if the wrong cross section model is assumed

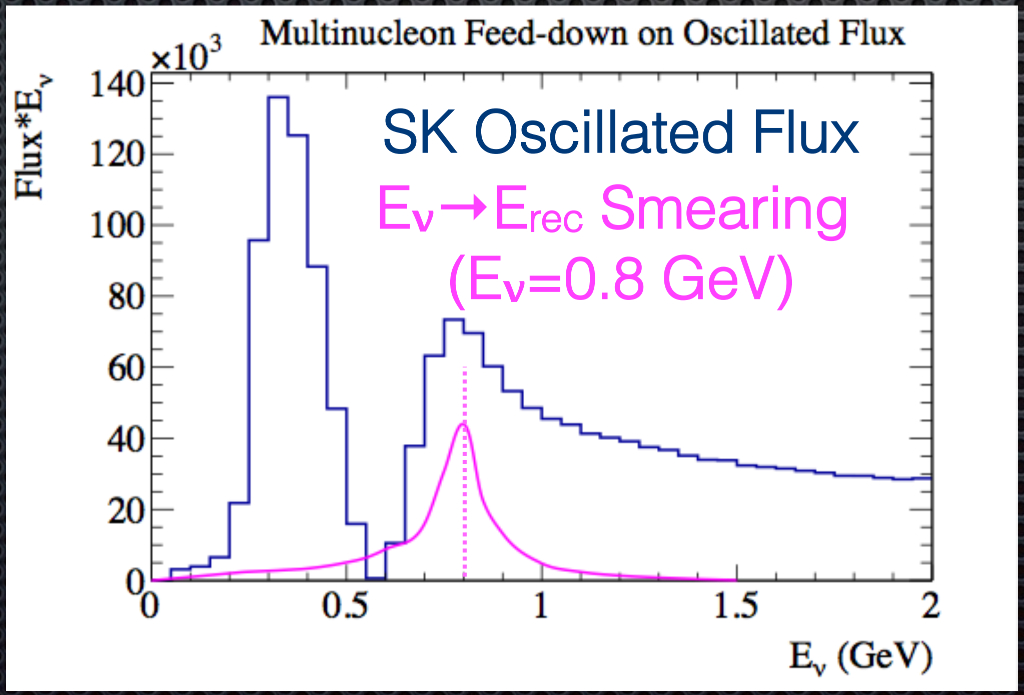
Power of Off-Axis Measurements

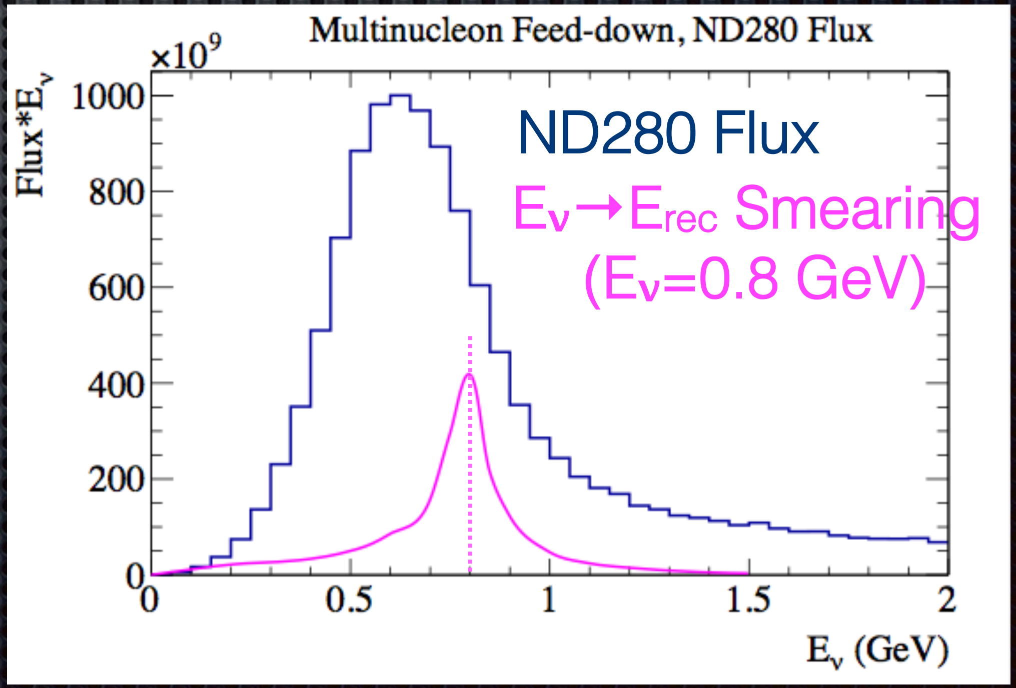
- Best fit of on-axis near detector + far detector distributions causes a problem at 1.7° off-axis
  - Now have evidence something is wrong in the model, and we may have a bias in the oscillation fit
- Next step is to demonstrate that a far detector prediction built from a linear combination of off-axis near detector measurements is insensitive to any feasible fake data sample



Role of Flux Uncertainties I

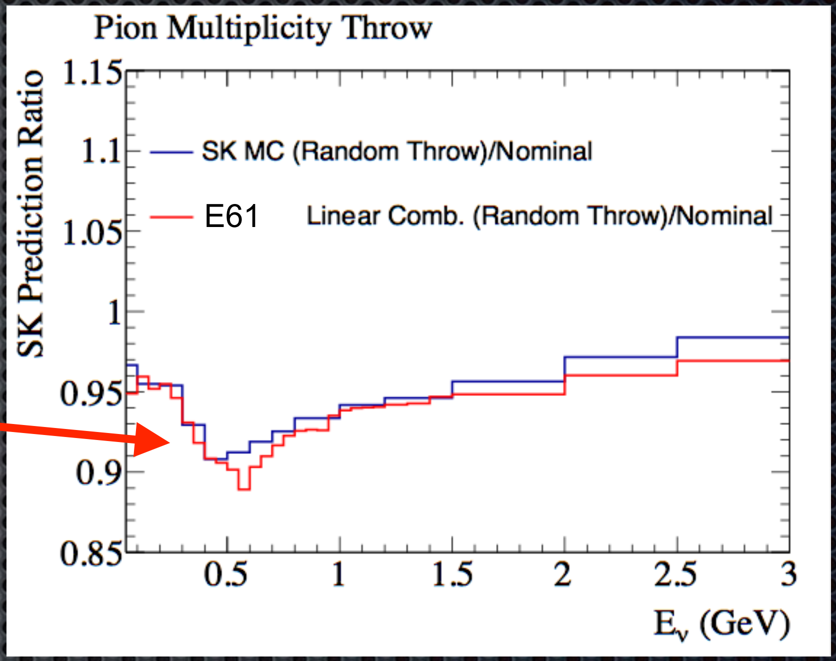
- For a standard near+far fit, flux model parameters are constrained along with cross section model parameters (as was done in the fake data study just shown)
  - The more the flux can be constrained a priori, the better these fits can disentangle flux & cross section effects (although degeneracies can still be present)
- For a standard near+far fit, flux variations, even those that are identical at the near and far detector, will produce systematic errors due to poorly understood energy migrations in the cross section model

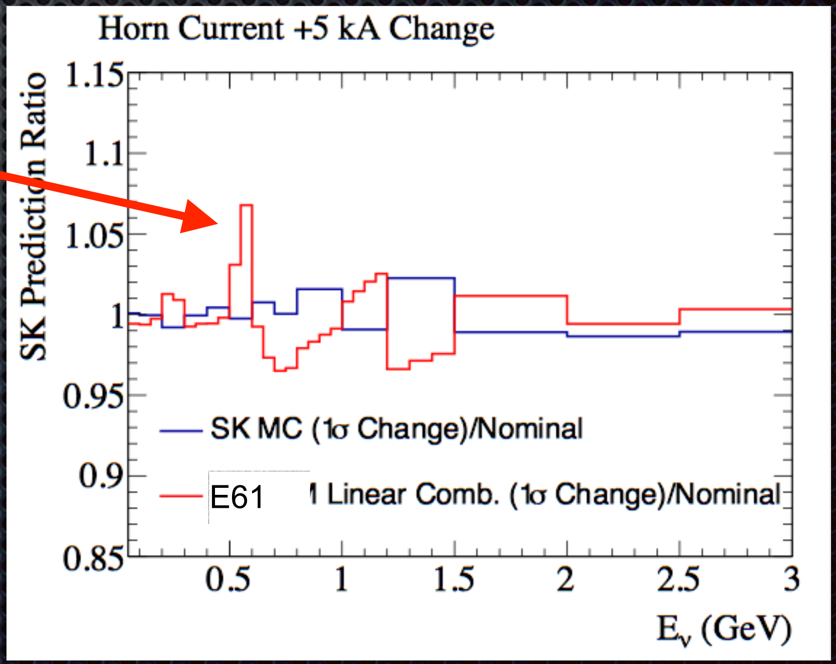




Role of Flux Uncertainties II

- Linear combinations of off-axis near detector measurements can be used to make a more robust far detector prediction
  - For flux variations that produce the same effect in the far detector and the linear combination, effects in the charged current cross section will cancel (both known and unknown)
- For E61 & DUNE-PRISM, beam optics effects become more important (but still not the dominant systematic error for E61 + T2K)
  - However, off-axis measurements also provide another dimension (beyond E_ν) with which flux and cross section effects can be disentangled





Summary

- Current neutrino oscillation experiments are beginning to face limitations due to cross section uncertainties
  - Poorly understood "feed down" can bias oscillation parameter measurements due to very different near & far detector ν_e & ν_μ fluxes
    - These effects will be enhanced by flux uncertainties, even those that produce the same fractional change at the (on-axis) near and far detector
  - For DUNE and Hyper-K, constraining these effects will be even more critical
- Making measurements at an (ideally continuous) set of off-axis angles can provide a direct constraint on $E_{true} \rightarrow E_{rec}$ and significantly reduce the dependence of oscillation parameter measurements on cross section modeling
- With extra off-axis angle information, beam optics uncertainties become more important (but still not dominant for E61 + T2K)
  - However, measurements across many off-axis angles provide an extra dimension to disentangle this and other flux effects from cross section effects