E61: The J-PARC Intermediate Water Cherenkov Detector

Mike Wilking
Stony Brook University
EPS-HEP
July 6th, 2017

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NuPRISM

TITUS

E61: The J-PARC Intermediate Water Cherenkov Detector

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How to Measure Neutrino Oscillations

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

$$ND(\nu_\mu) = \boxed{\Phi(E_\nu) \times \sigma(E_\nu, A)} \times \epsilon_{ND}$$
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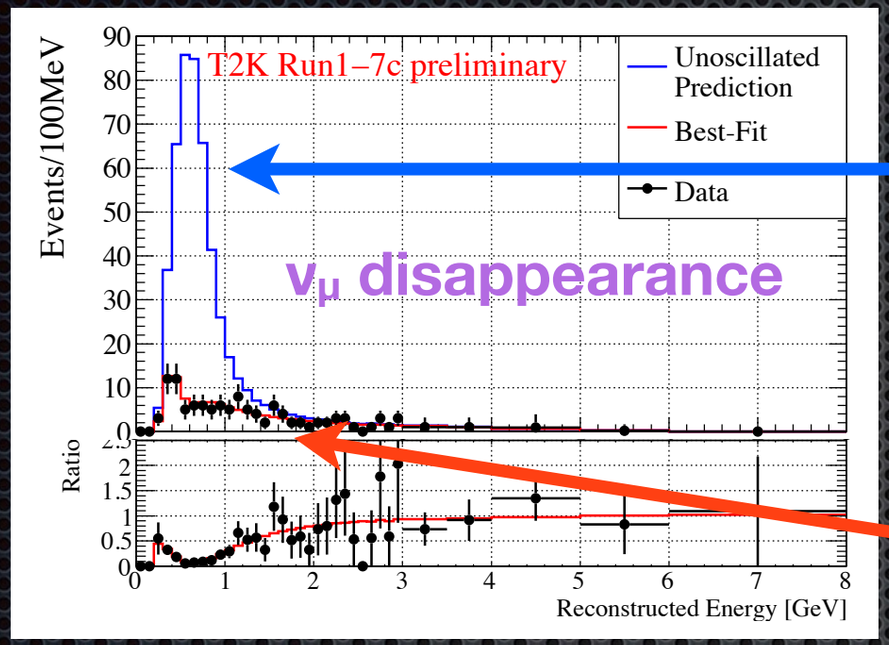
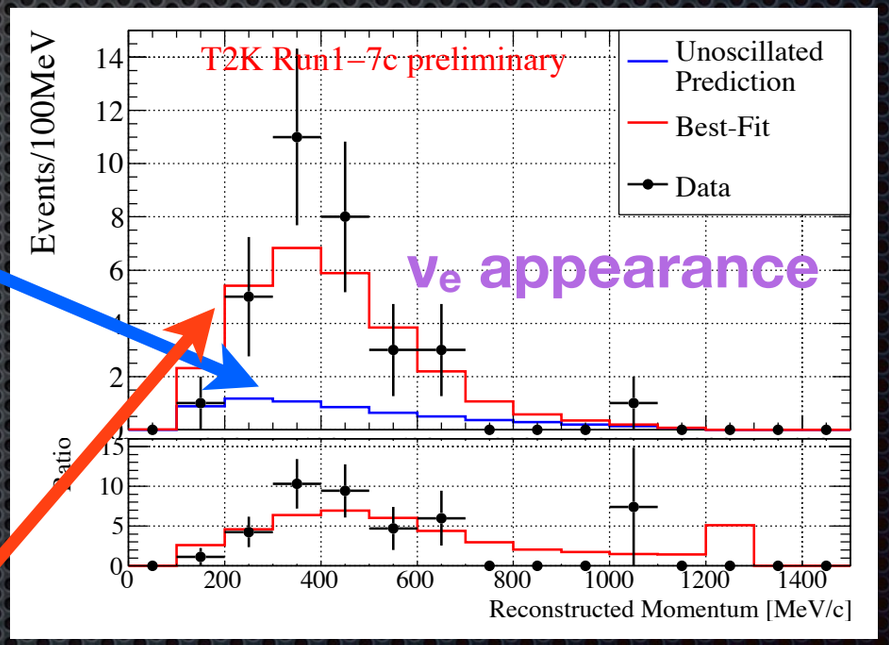


Near Detector Measures:
- ν_μ energy spectrum
- Small ν_e component

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



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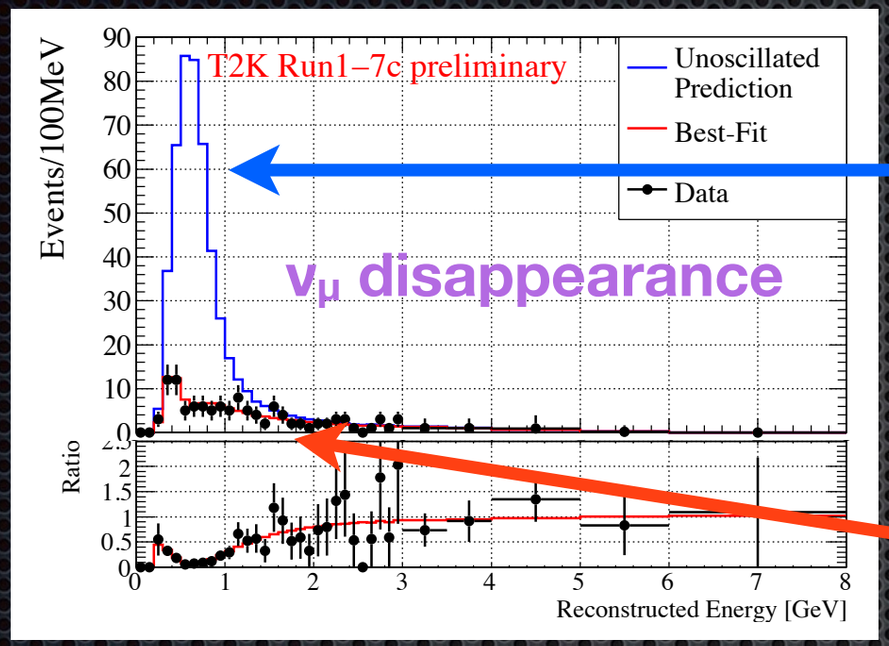

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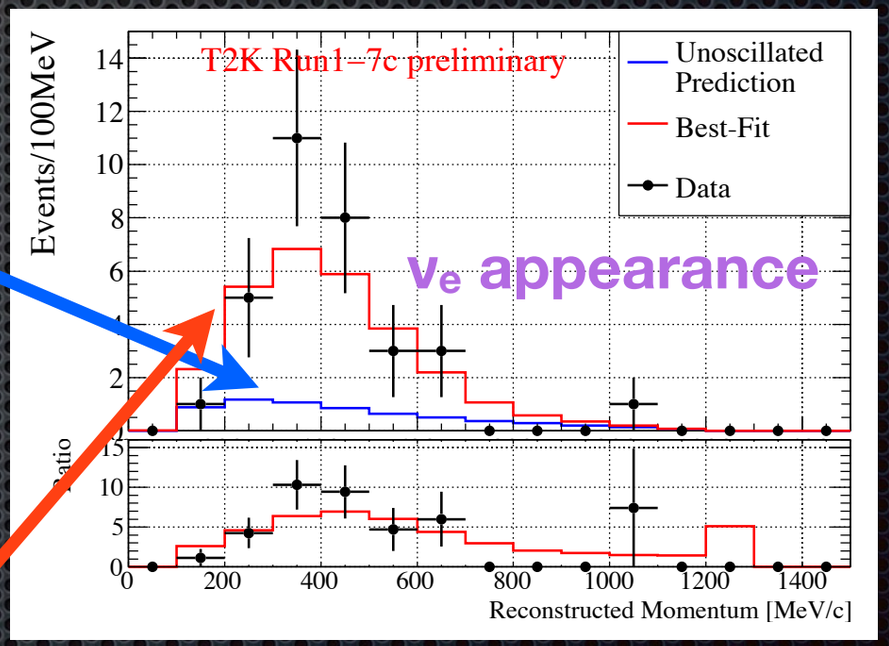
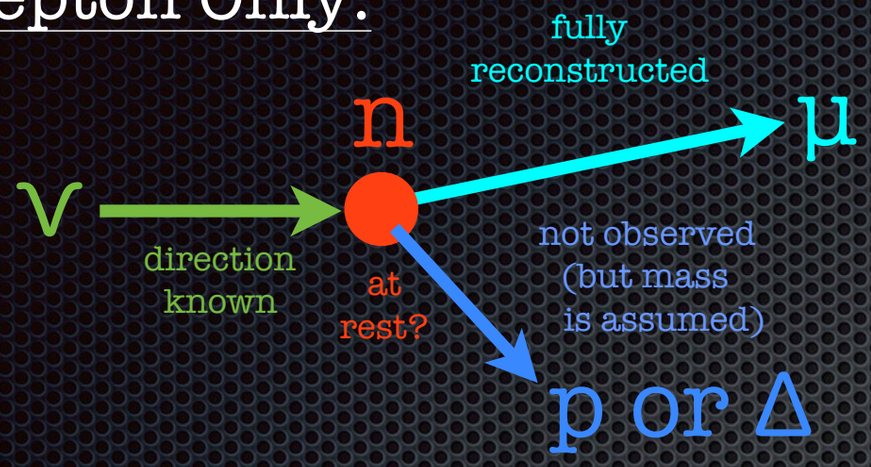


- E_{true} ➜ E_{rec} migration matrix is (quite) non-diagonal! (next slides)
- Several important cross section uncertainties will not cancel

Measuring E_ν

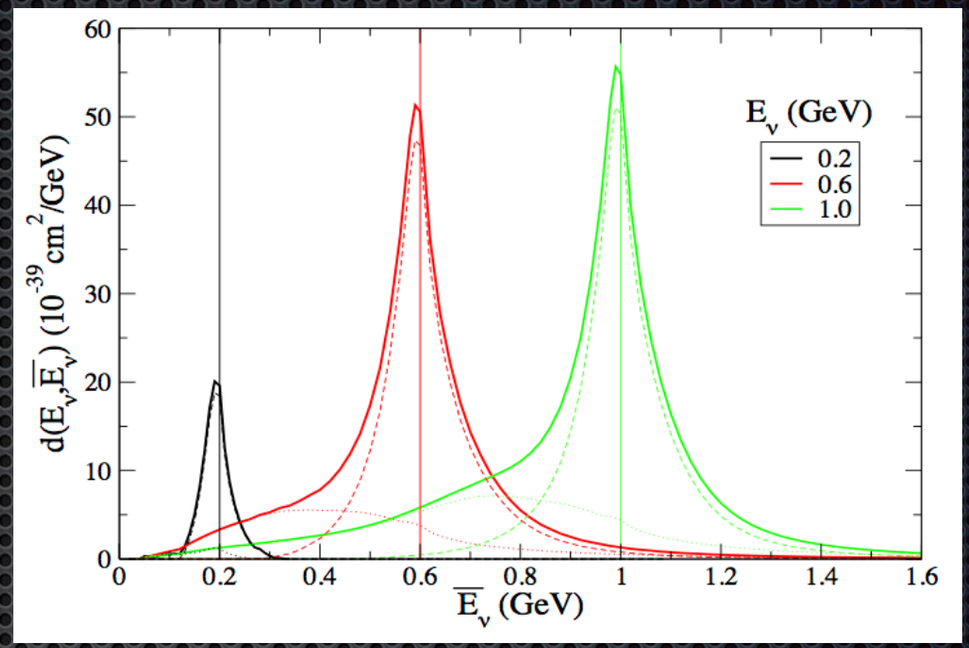
Martini et al. arXiv:1211.1523

Lepton Only:



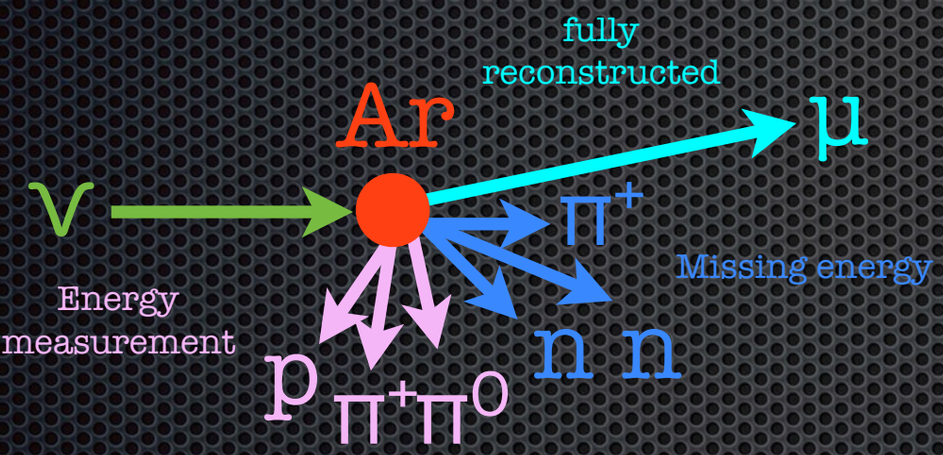
Must assume mass of recoiling hadron(s)

Problematic! due to Multi-nucleon interactions



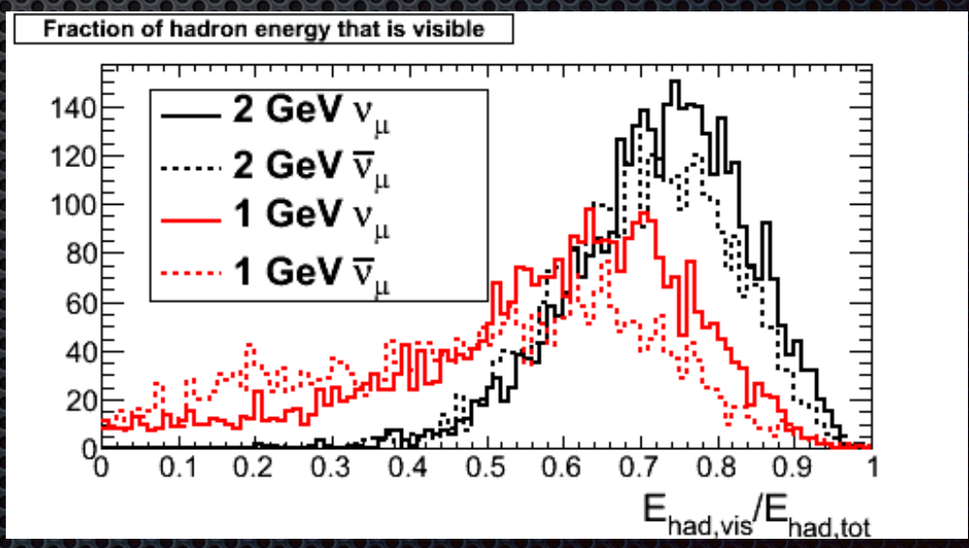
Lepton + Hadronic Energy:

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

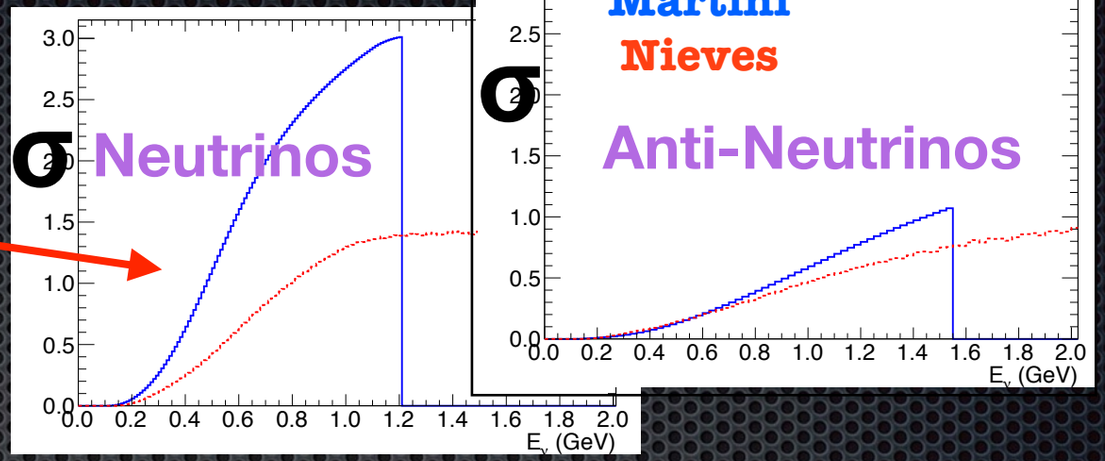
(True deposited hadronic energy)/
(True initial hadronic energy)

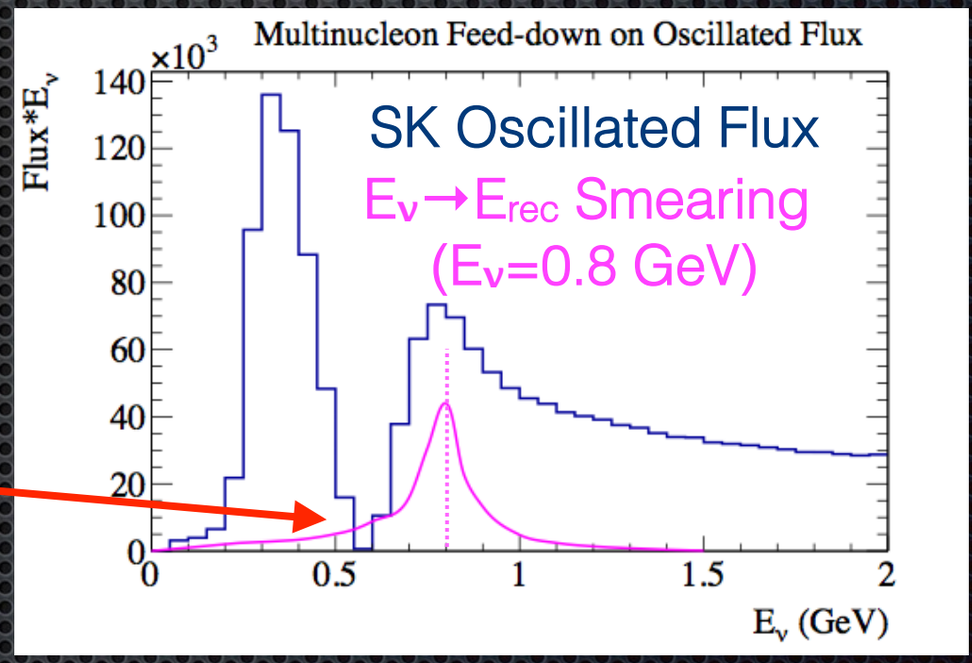
- Both effects lead to underestimating the neutrino energy (feed down)
- Need to calibrate both leptonic (e & μ) & hadronic energy scales and shapes (e.g. long E_{rec} tails)

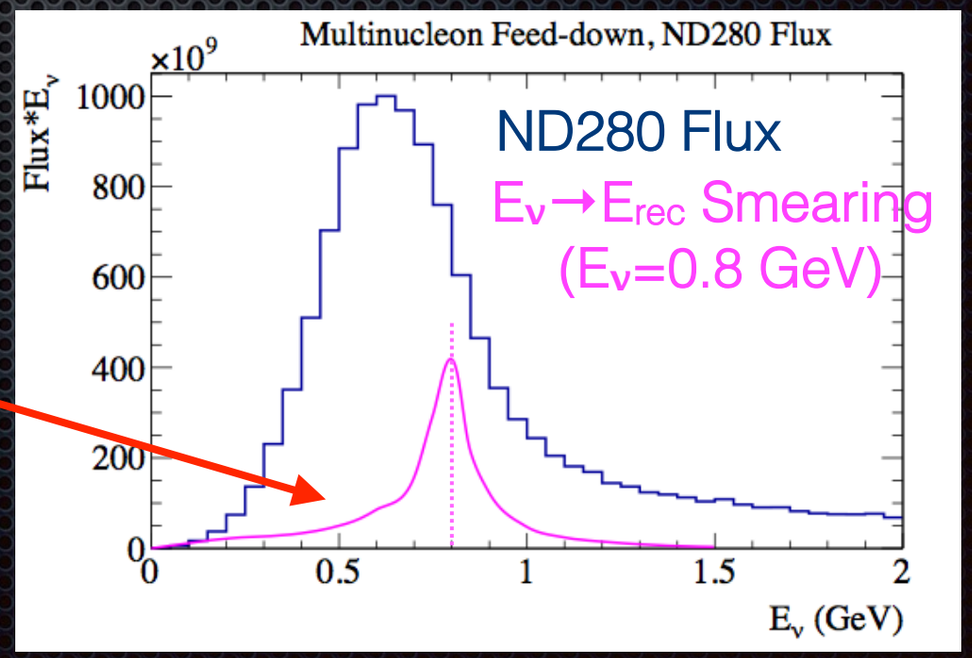
E_ν Feed Down

- 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

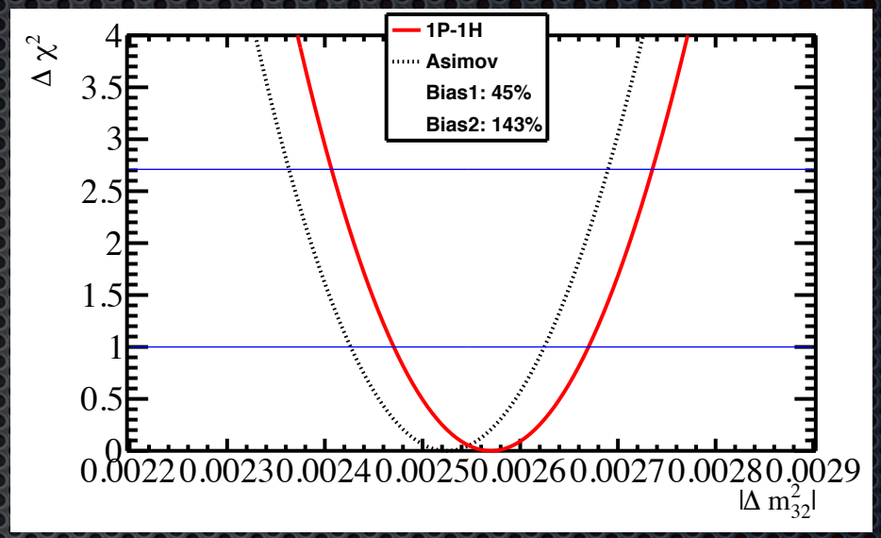


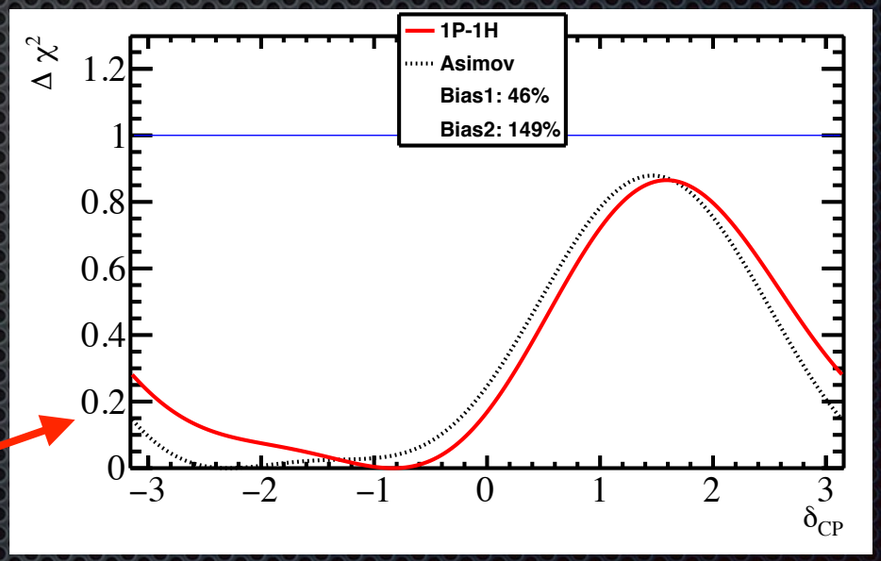


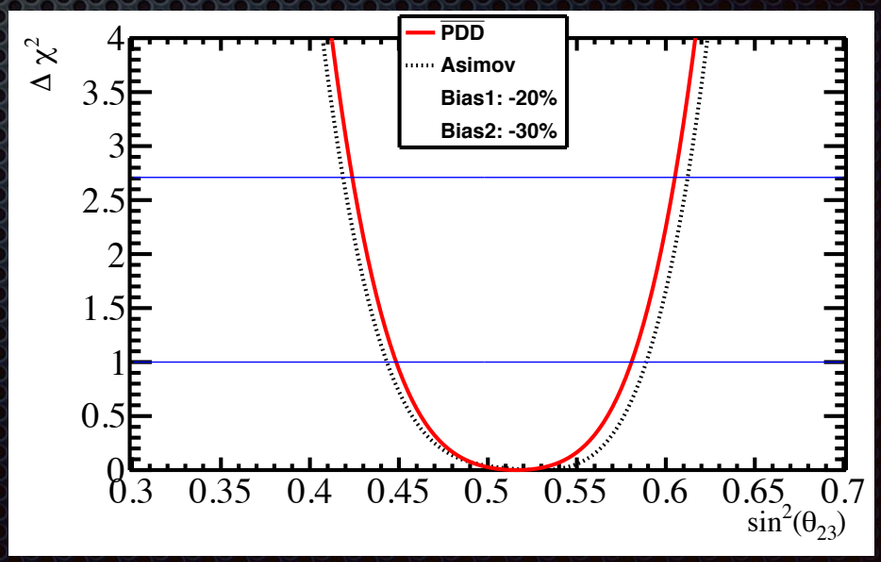


Fake Data Studies

- 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



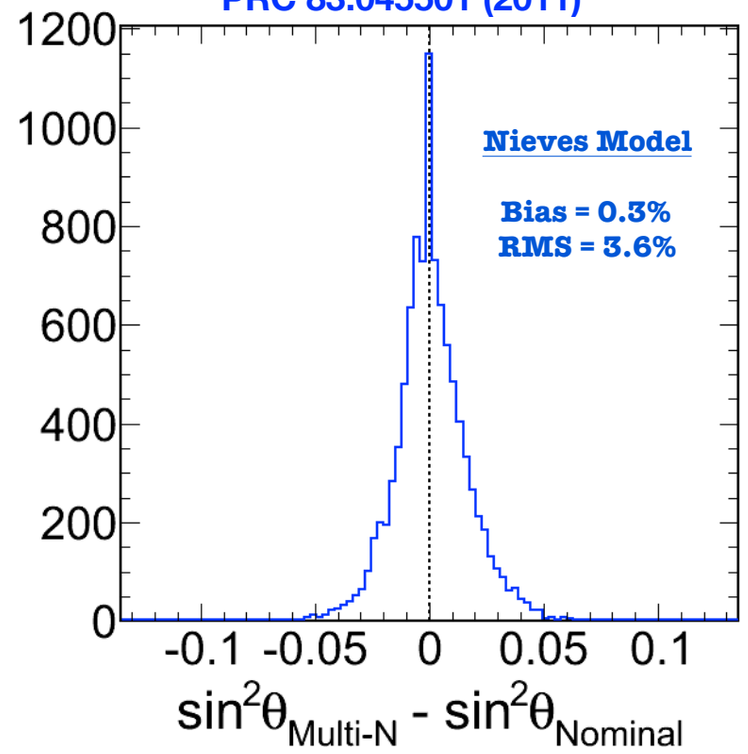




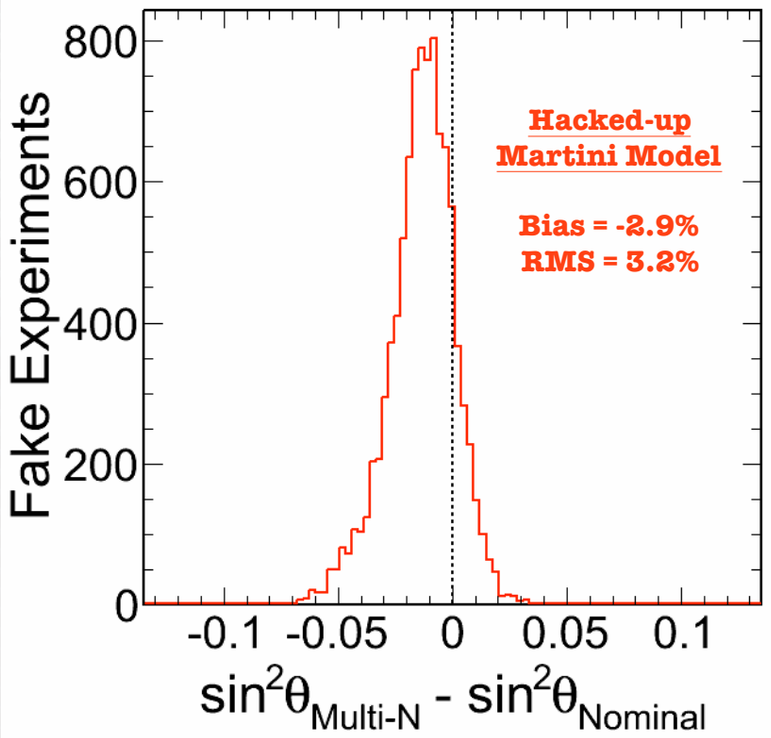
Example Fake Data Study

- 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

J. Nieves, I. Ruiz Simo, and M. J. Vicente Vacas,
PRC 83:045501 (2011)

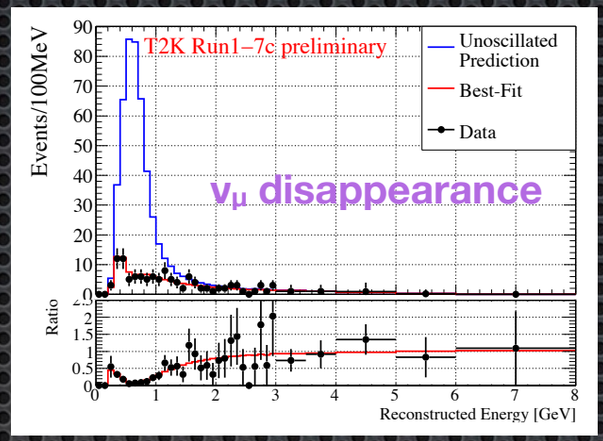


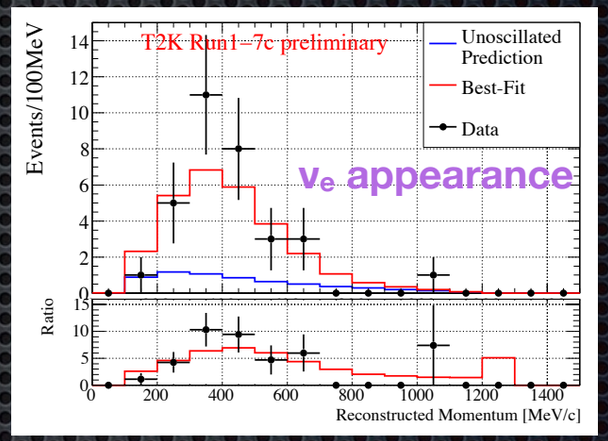
M. Martini, M. Ericson, G. Chanfray, and J. Marteau
PRC 80:065501 (2009)

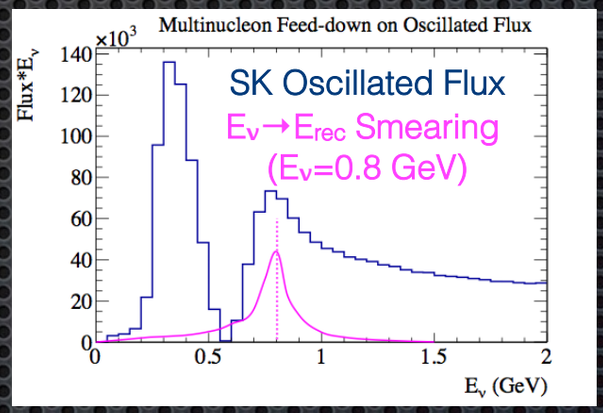


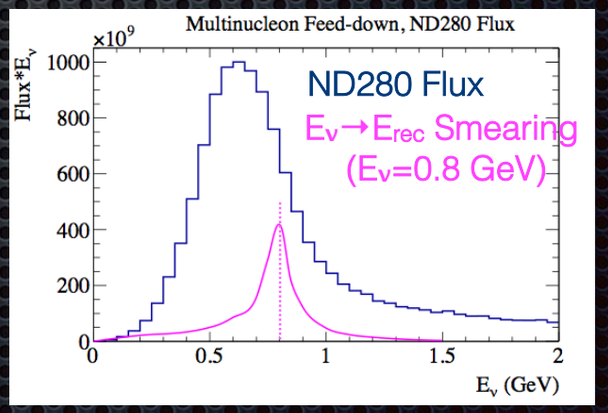
Summary of Cross Section Model Difficulties for Conventional Near Detectors

1. If your **fluxes are different** at the near and far detectors
   - …they will be, due to oscillations
2. Then you can introduce **cross section parameters** that are:
   A. **Important** at the **far** detector
   B. **Largely degenerate** at the **near** detector
3. This produces 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)



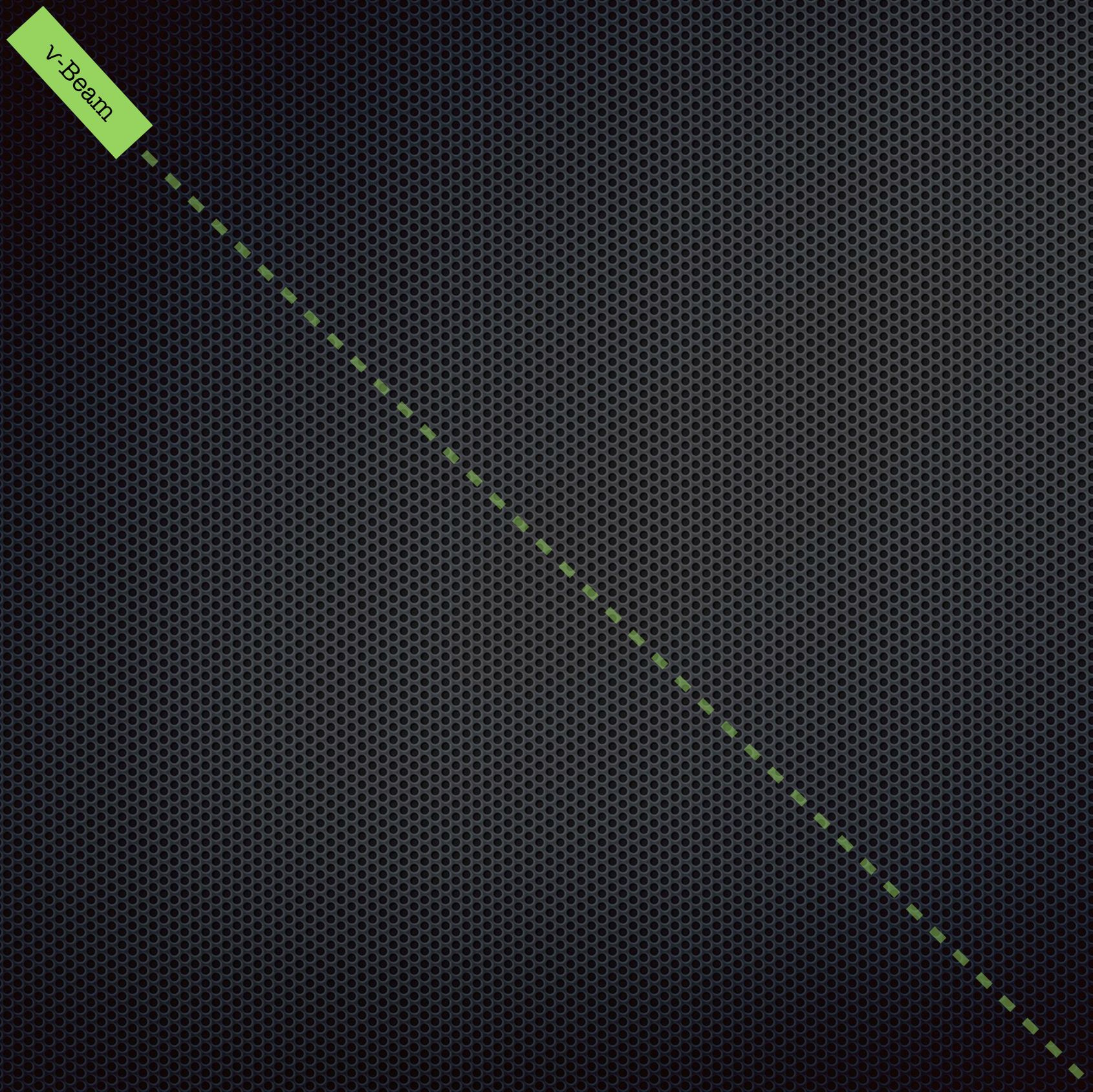






This problem goes away if we can measure $E_{true} \rightarrow E_{rec}$ experimentally

E61 Detector Concept



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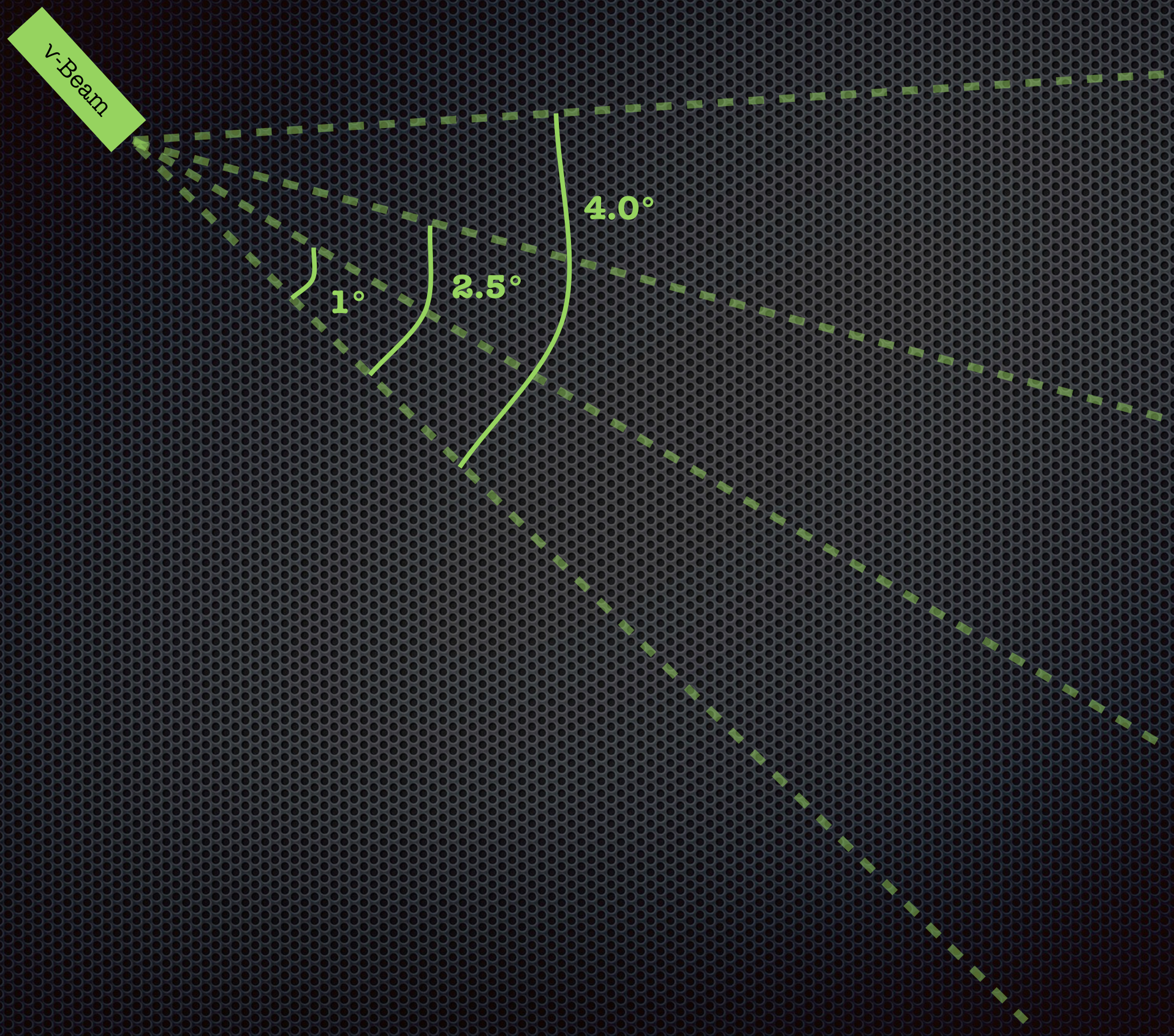

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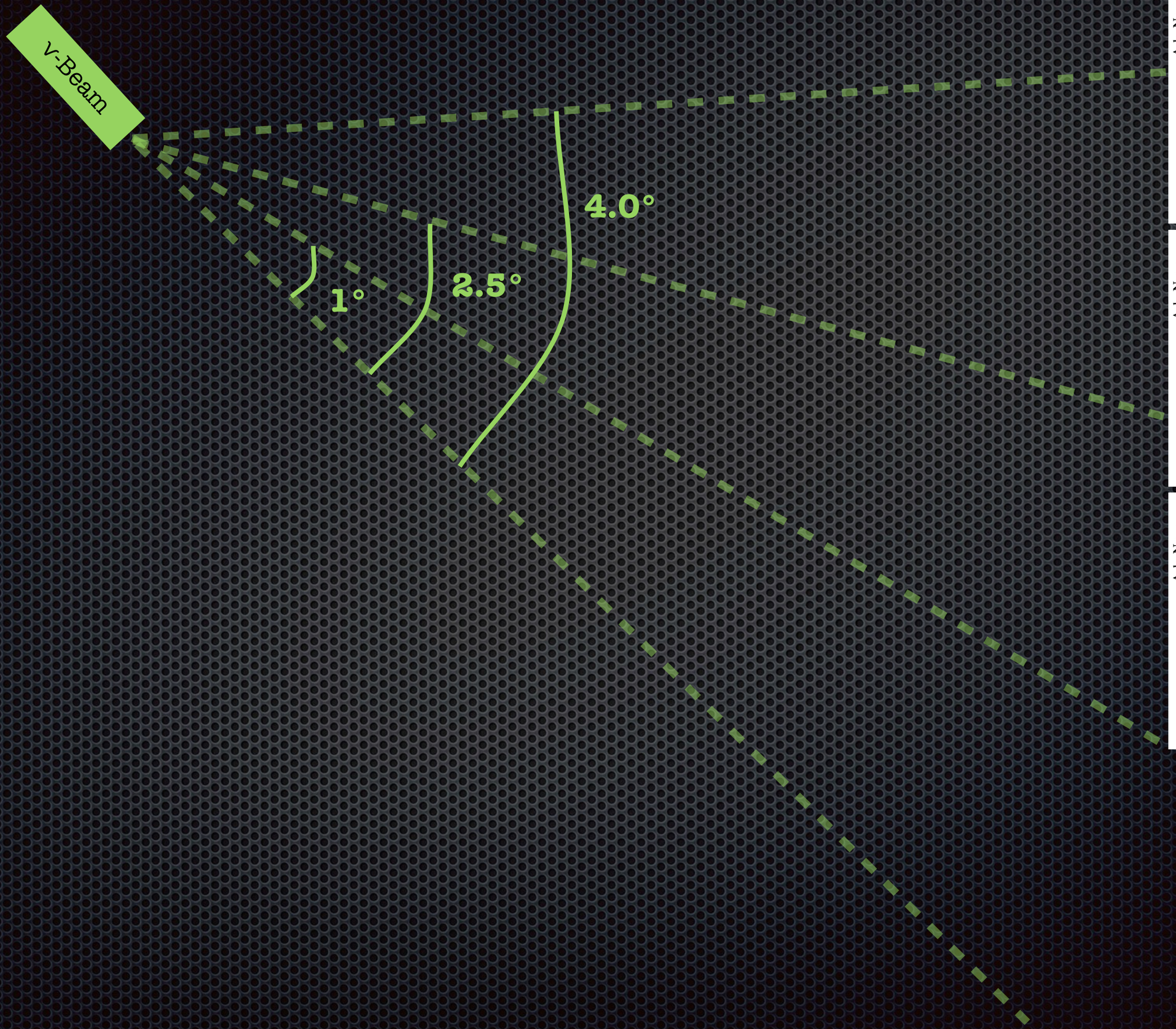

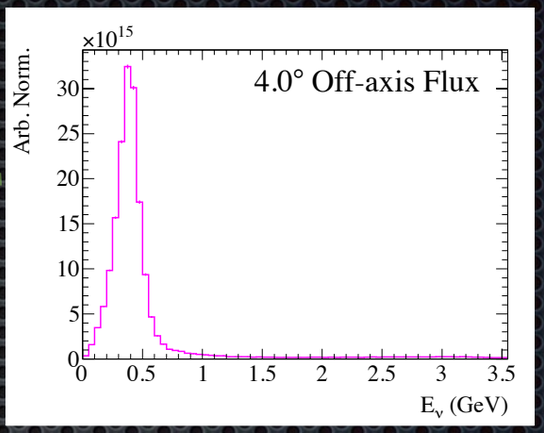

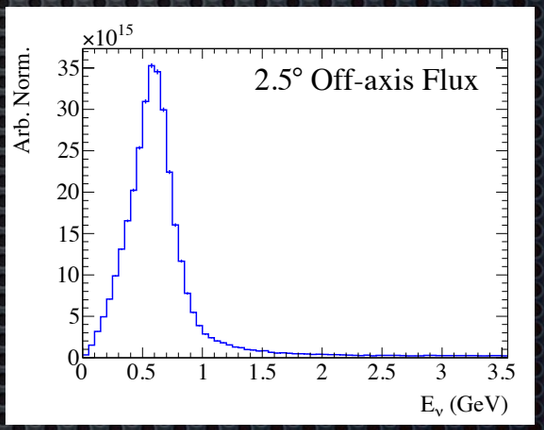

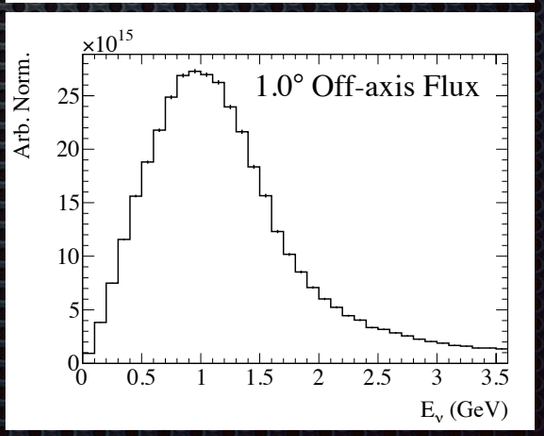

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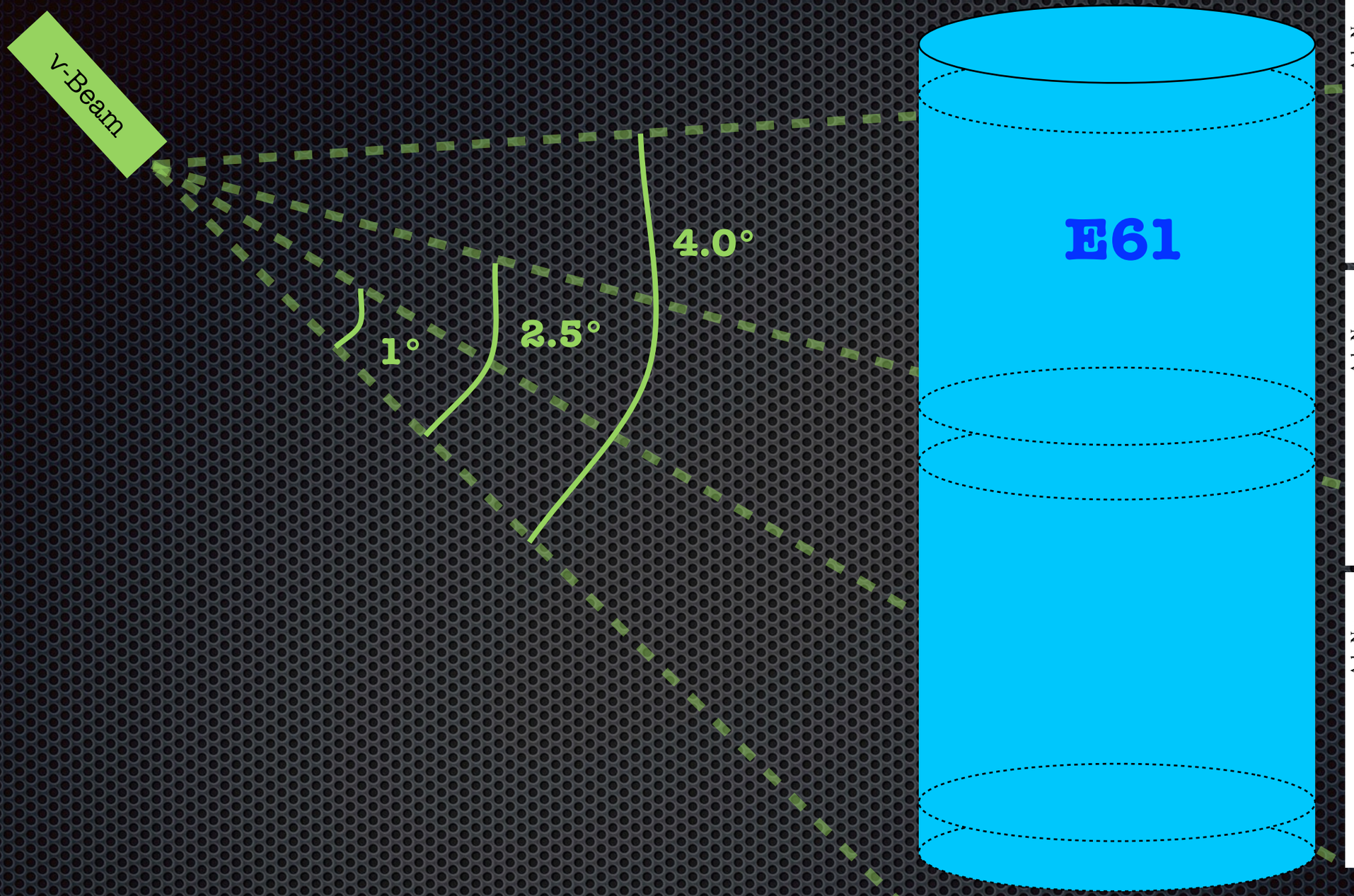

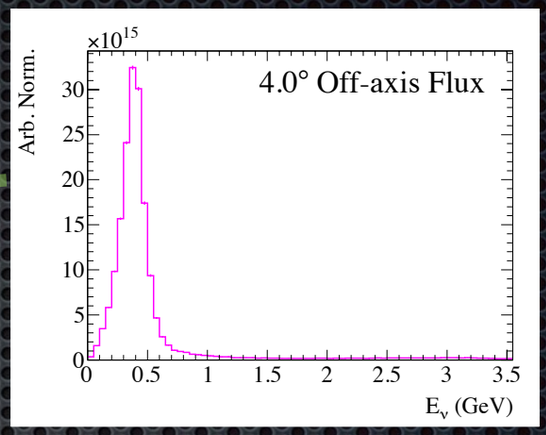

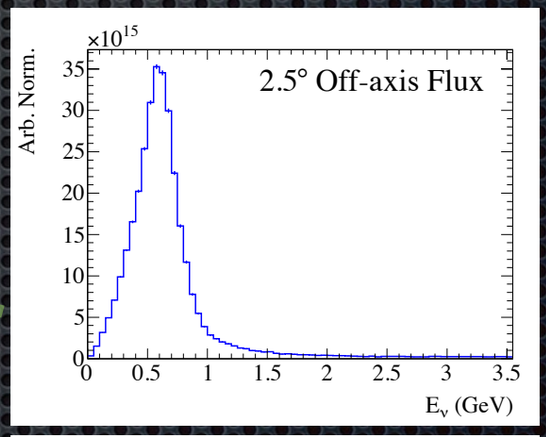

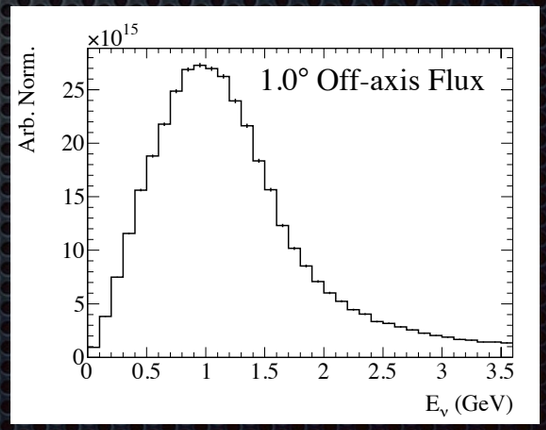

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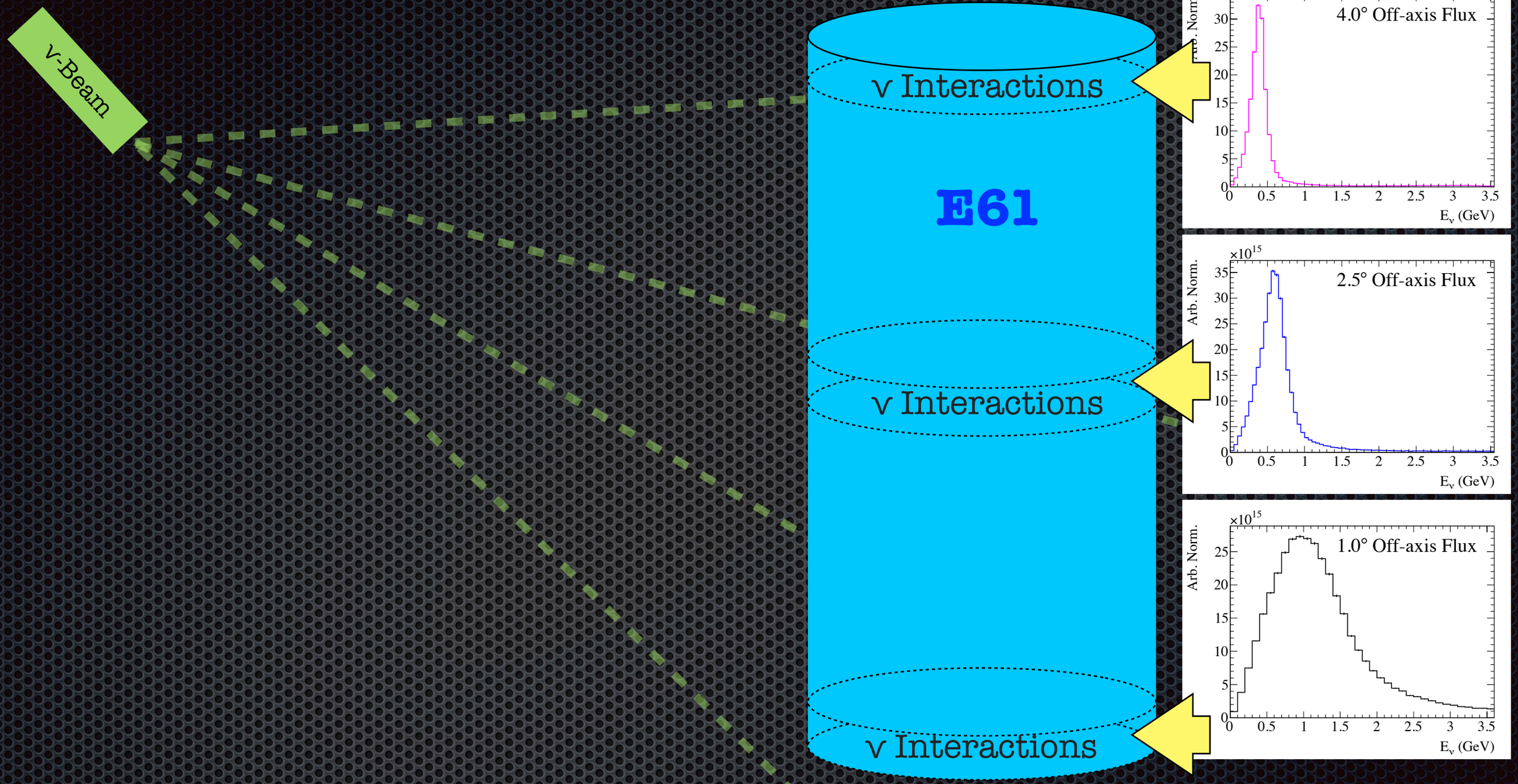
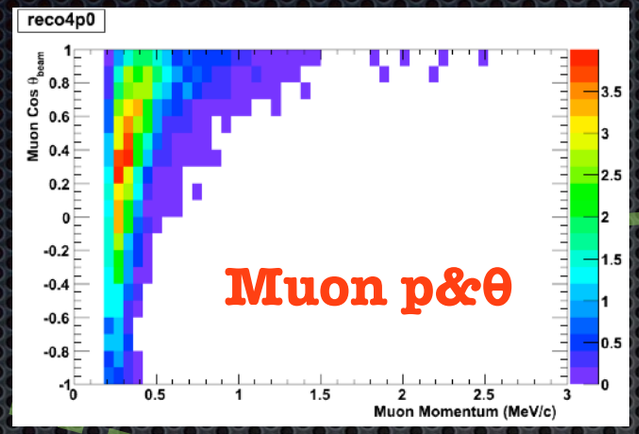
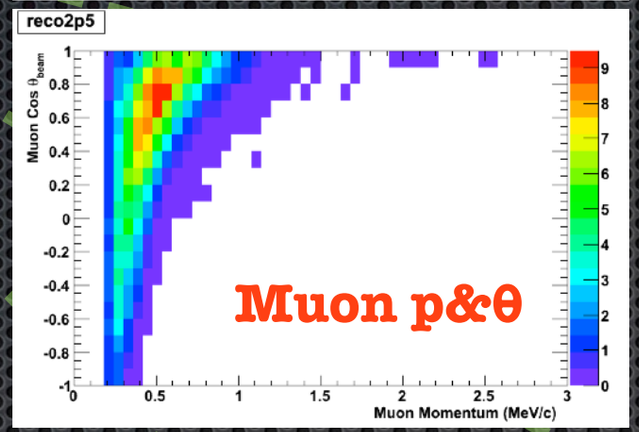
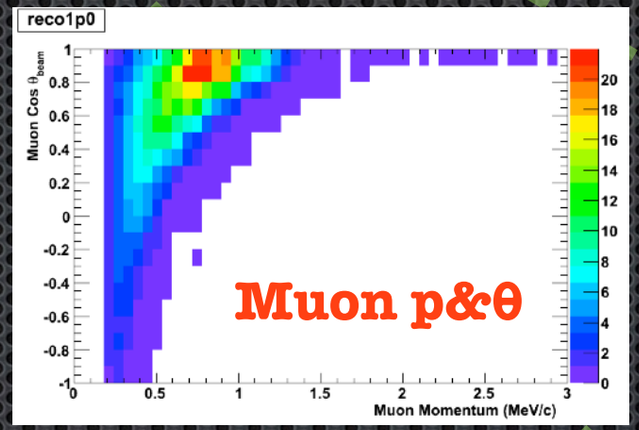


E61 Detector Concept

ν-Beam







ν Interactions

E61

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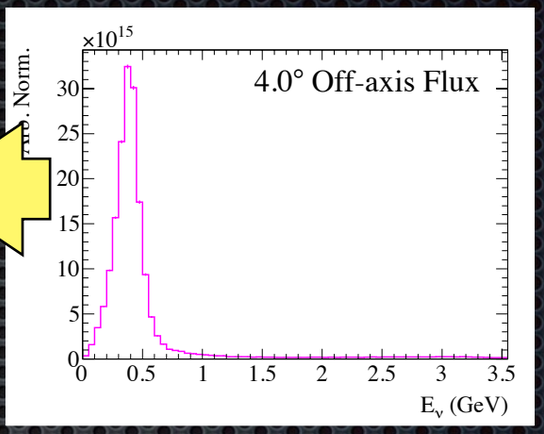
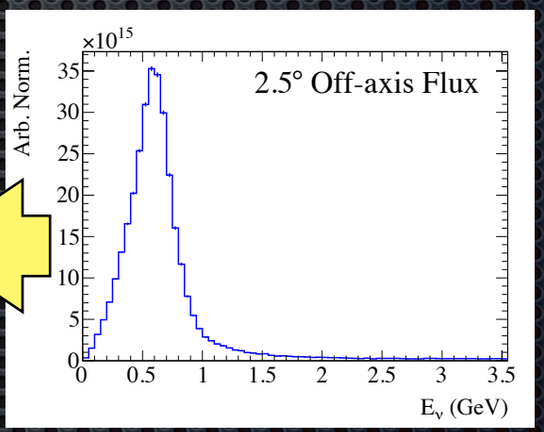
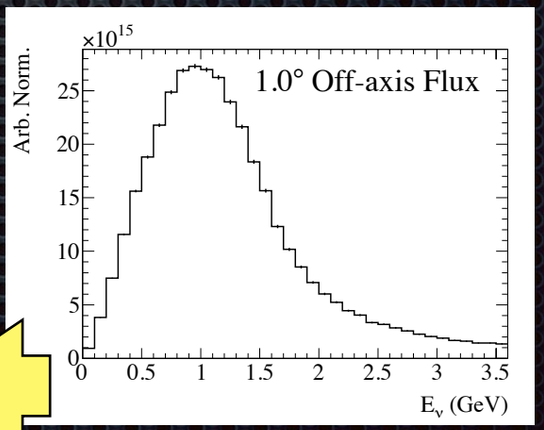






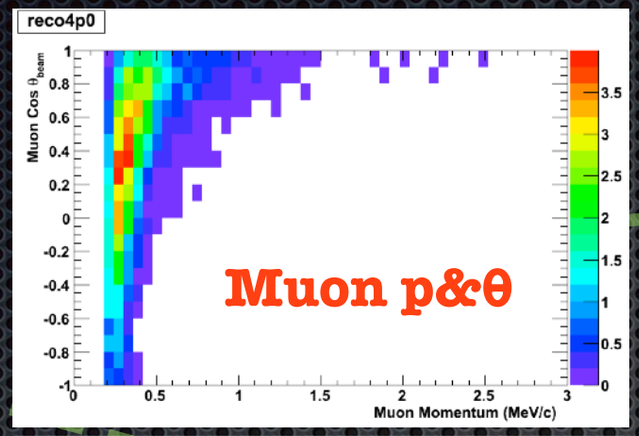
E61 Detector Concept

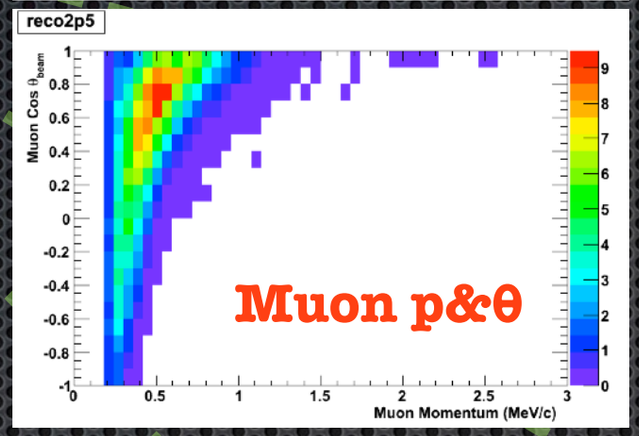
-0.5 *

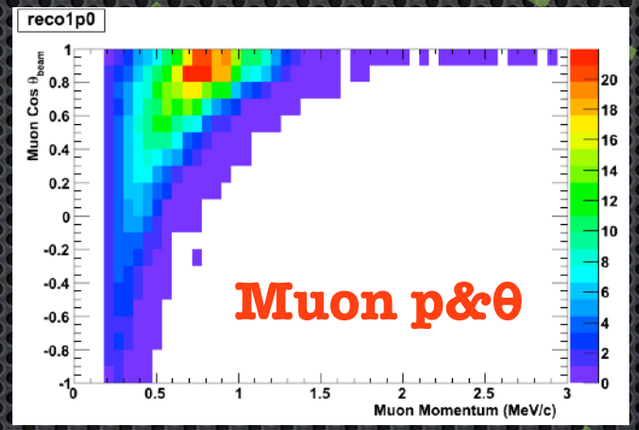
+1.0 *

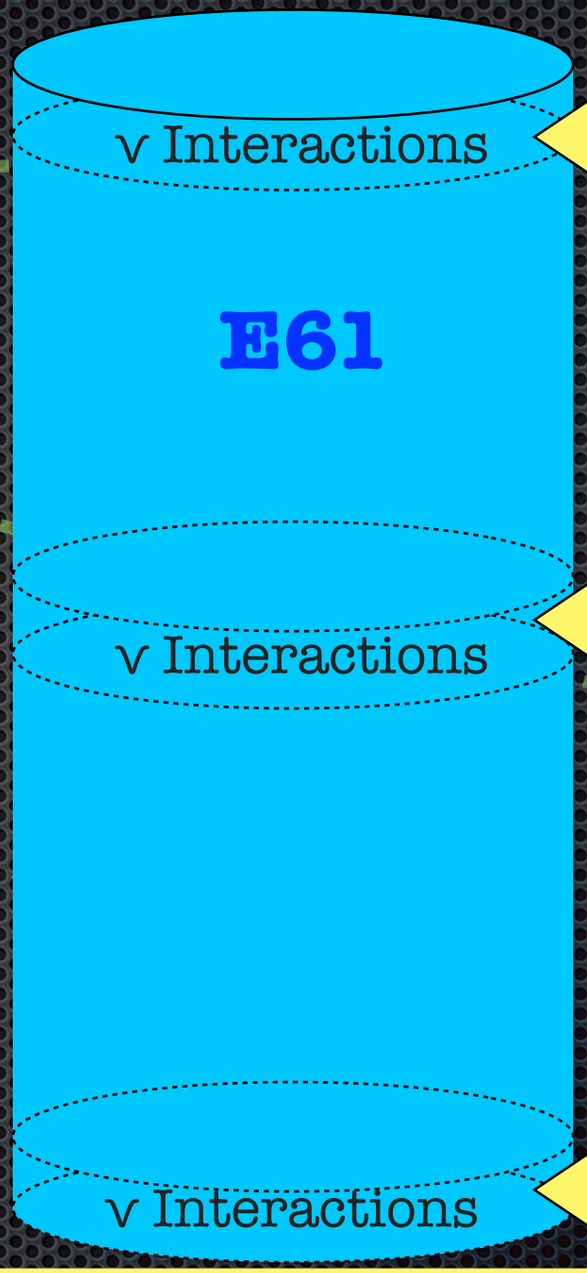
-0.2 *

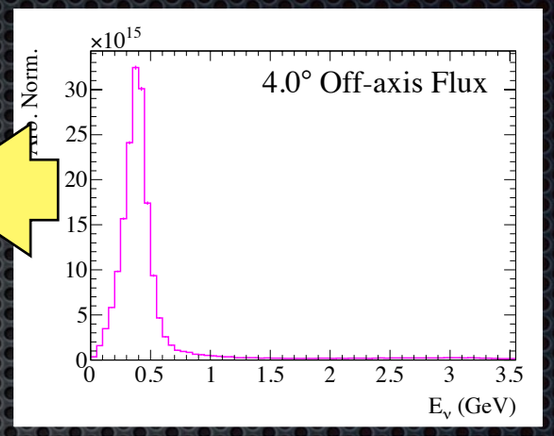
Take linear combinations!

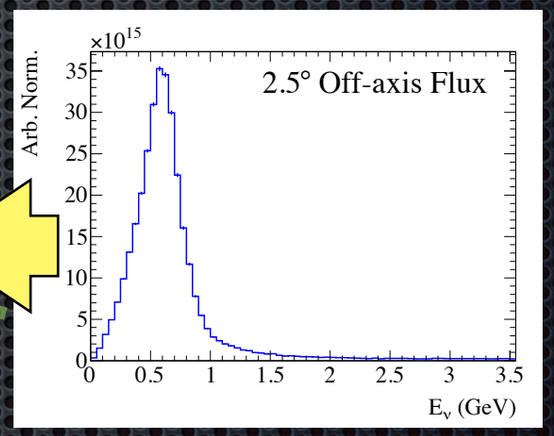


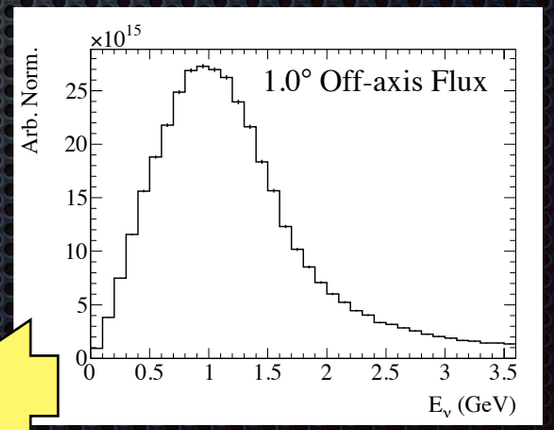












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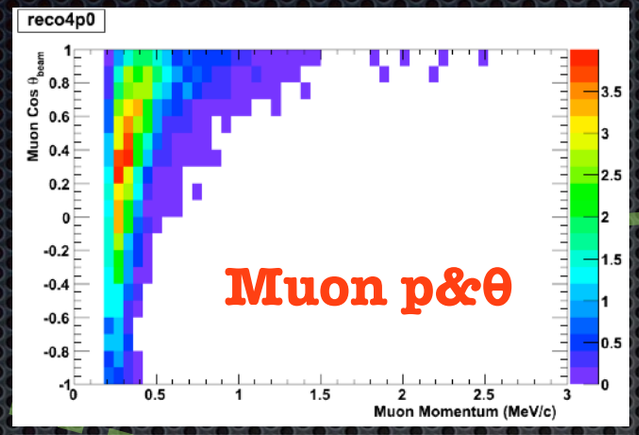
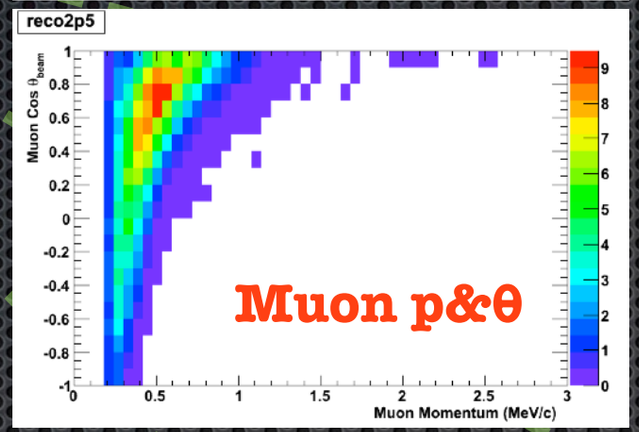
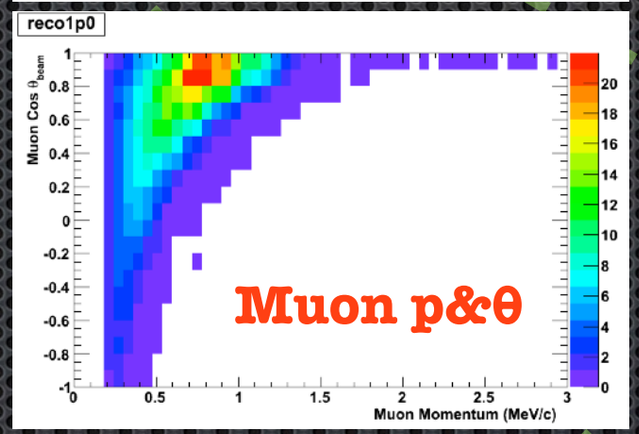
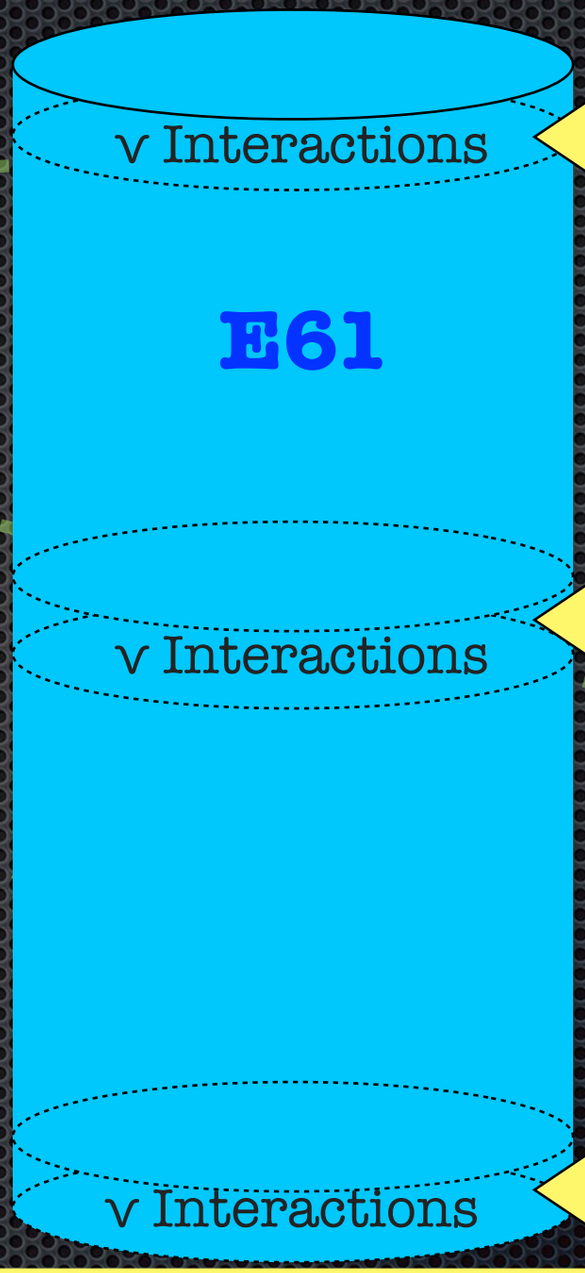
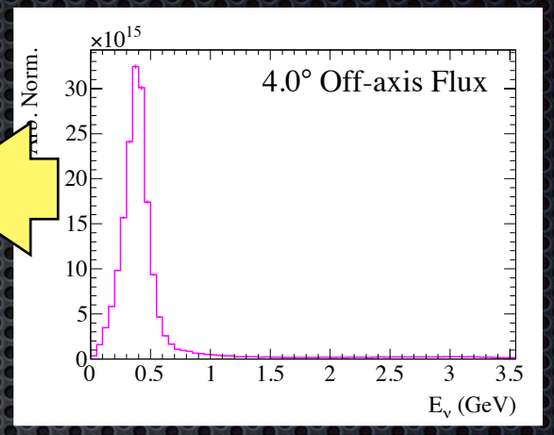
Take linear combinations!

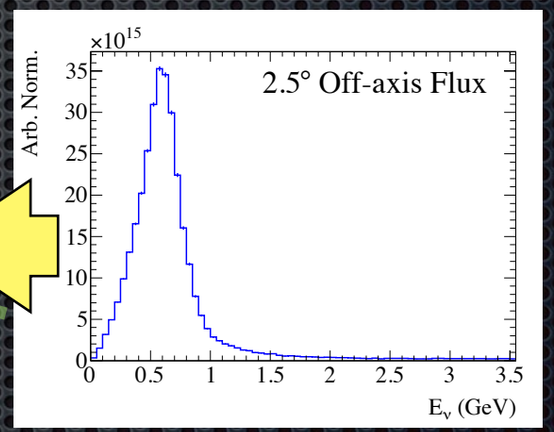


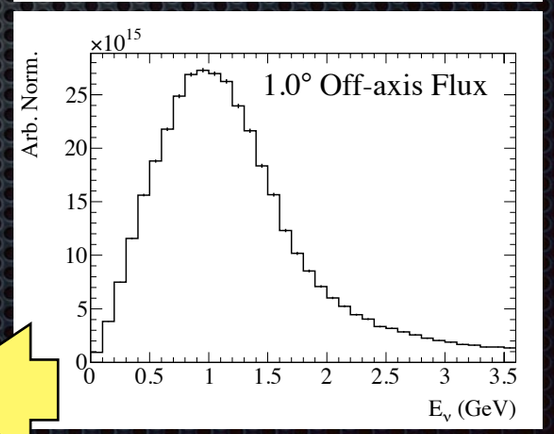


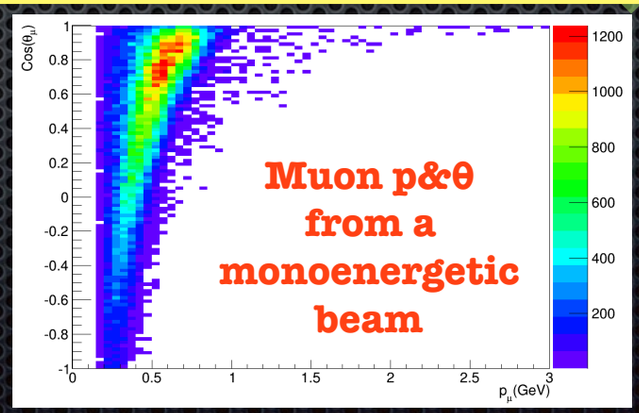


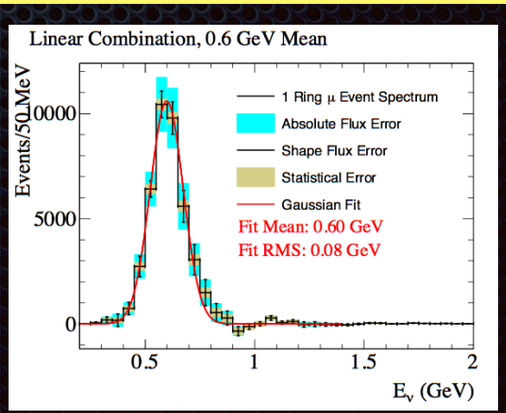












E61 Detector Concept

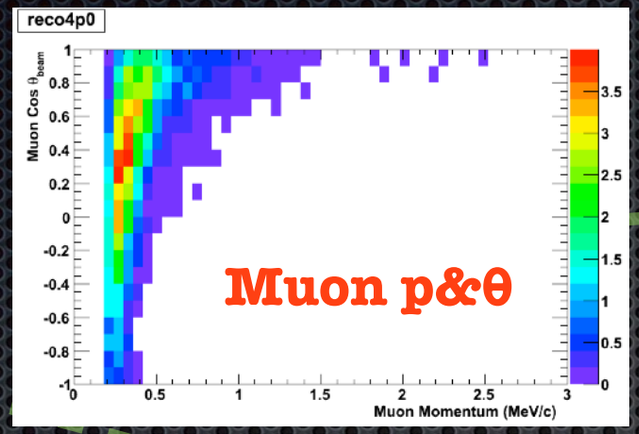
-0.5 *

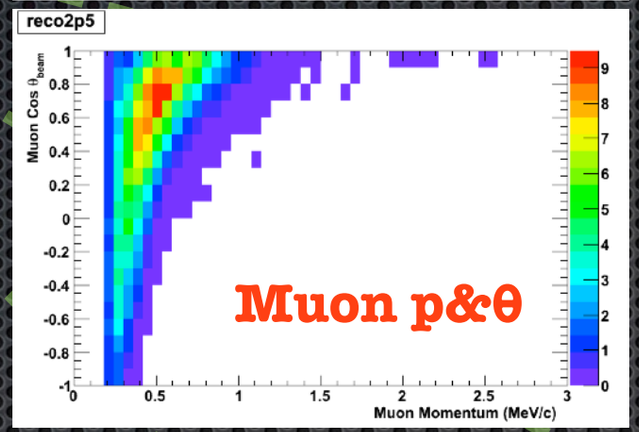
+1.0 *

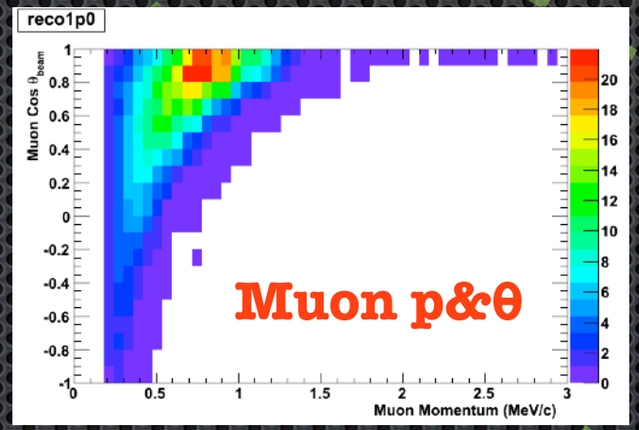
-0.2 *

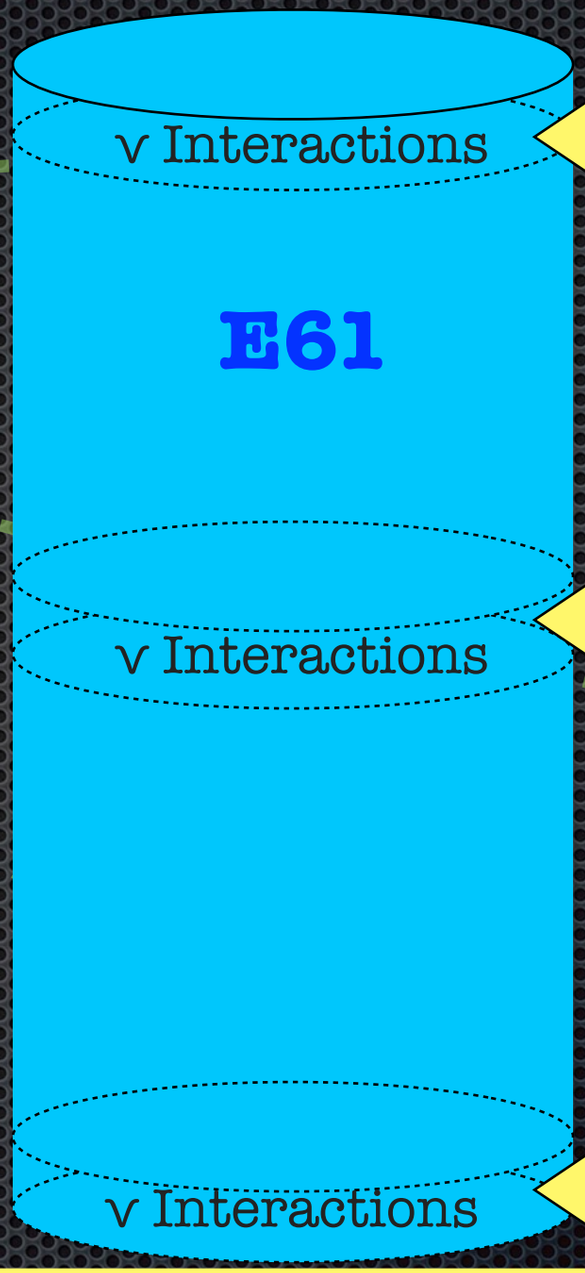
Take linear combinations!

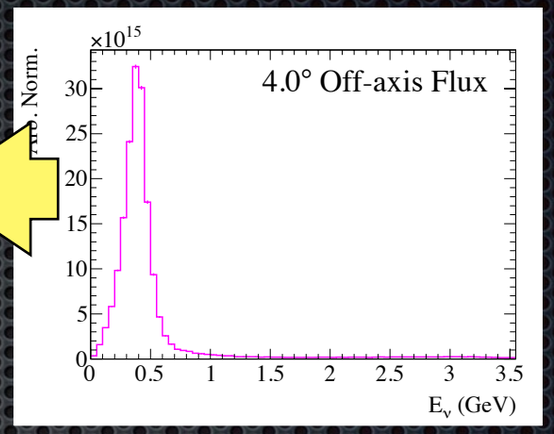
600 MeV Monoenergetic Beam using 60 slices in off-axis angle

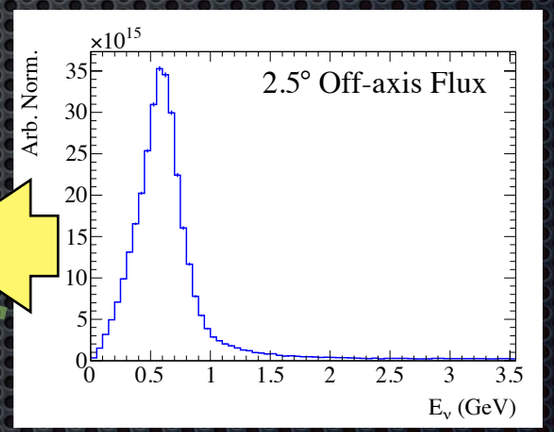


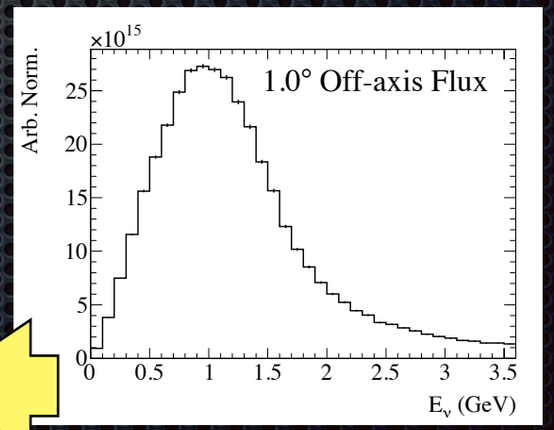


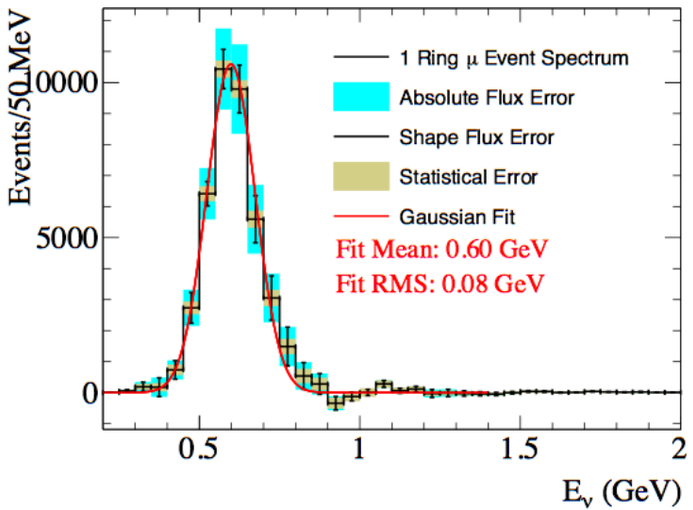


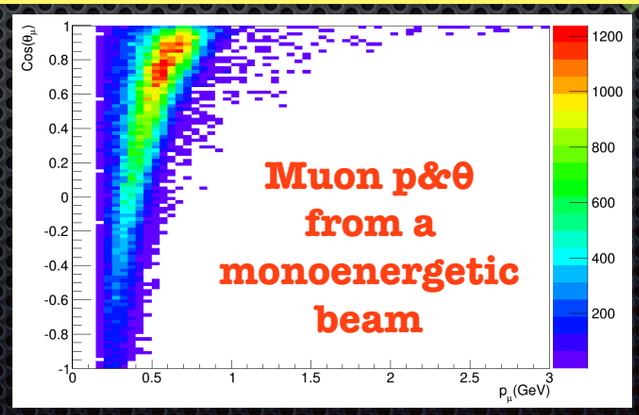


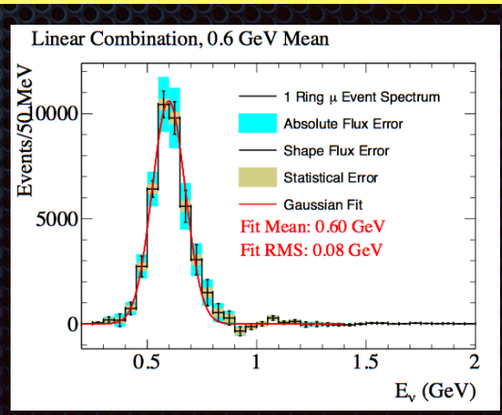




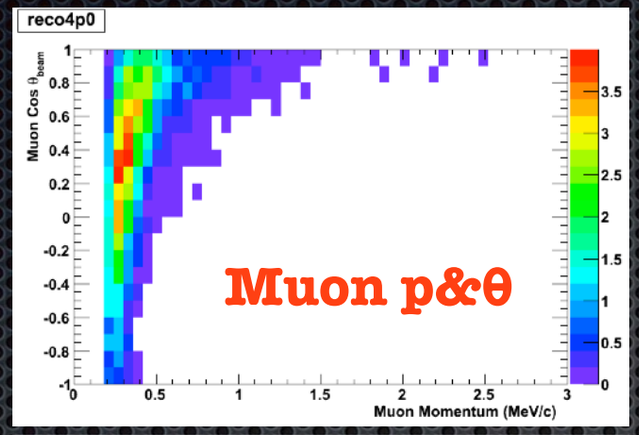


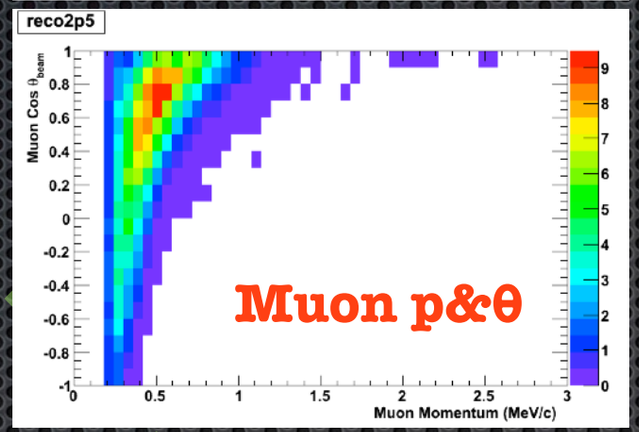


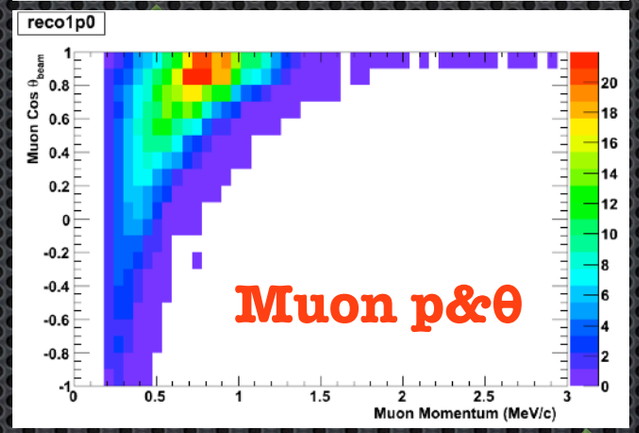


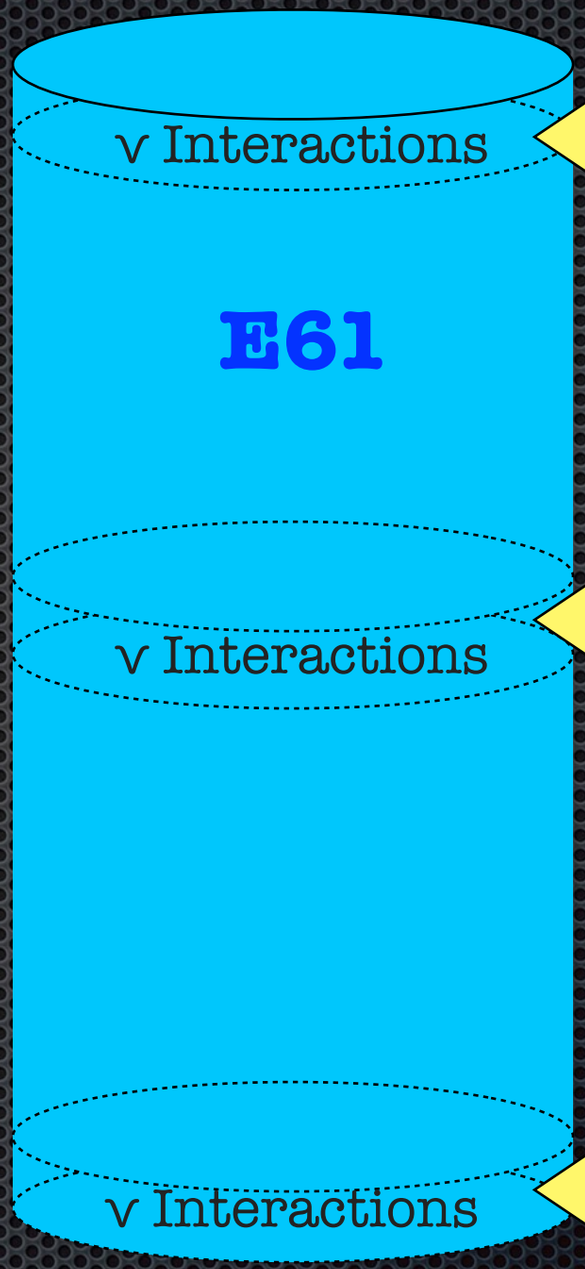


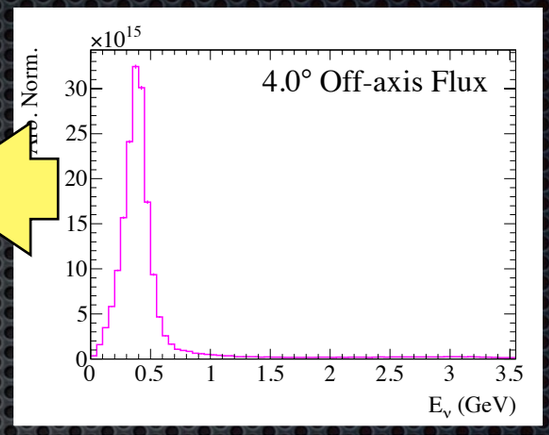
E61 in an Oscillation Experiment

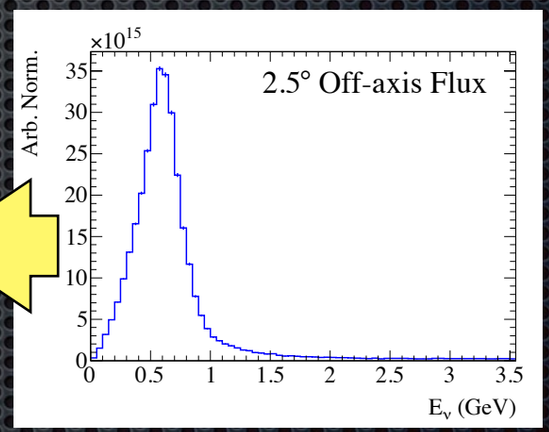


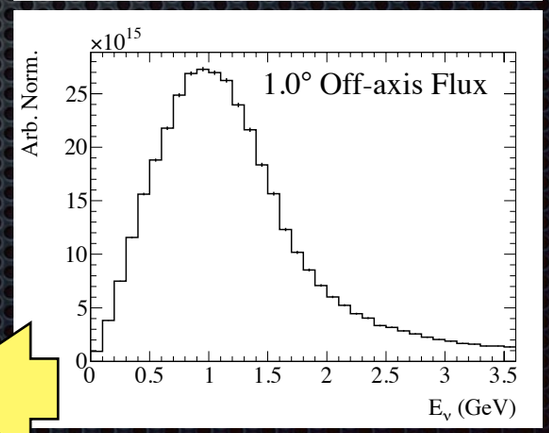












E61 in an Oscillation Experiment

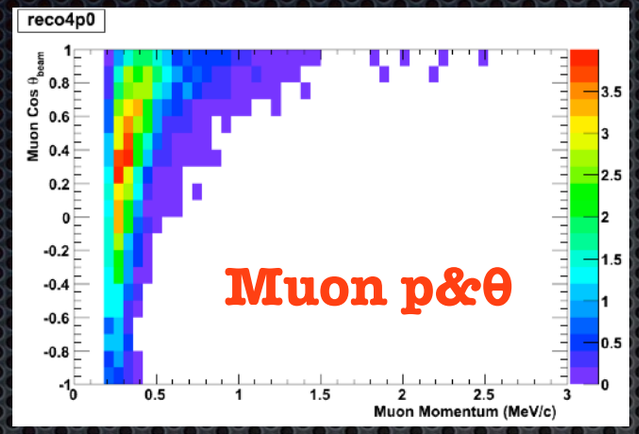
ν-Beam

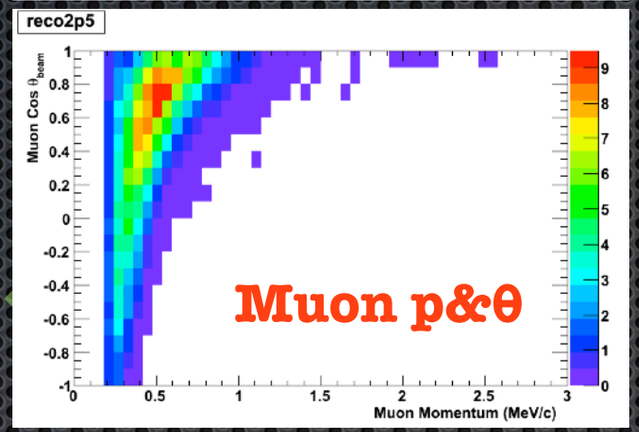
+1.0*

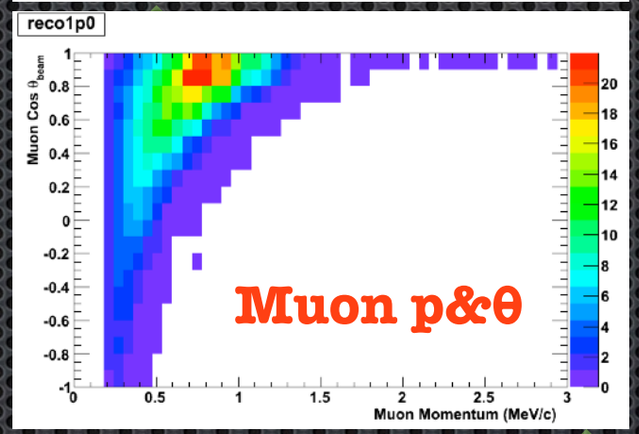
-0.8*

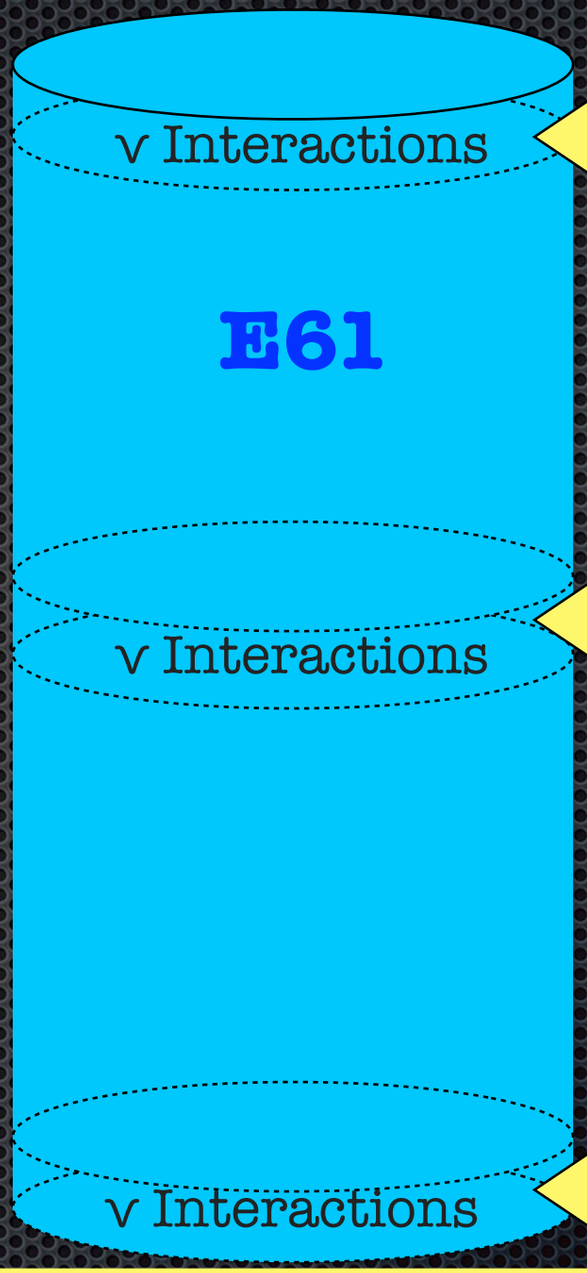
+0.2*

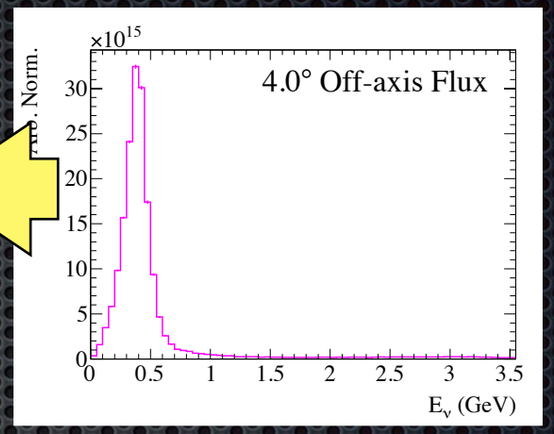
Take different linear combinations!

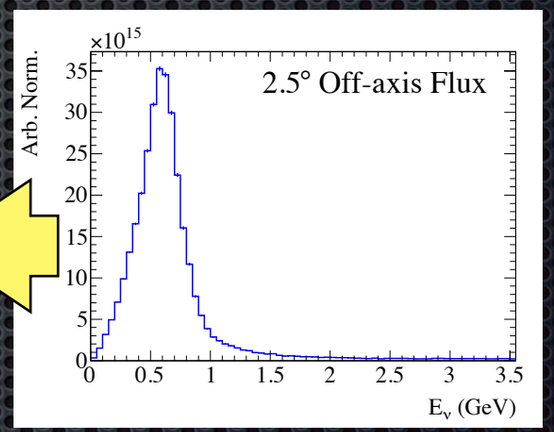


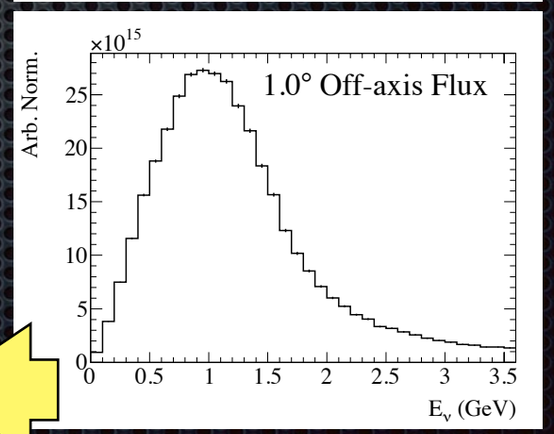












E61 in an Oscillation Experiment

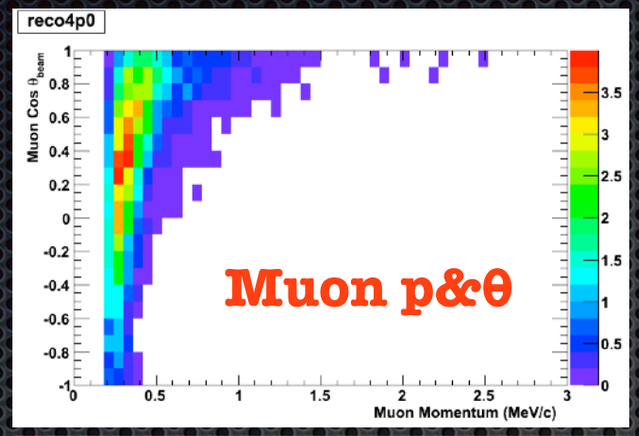
ν-Beam

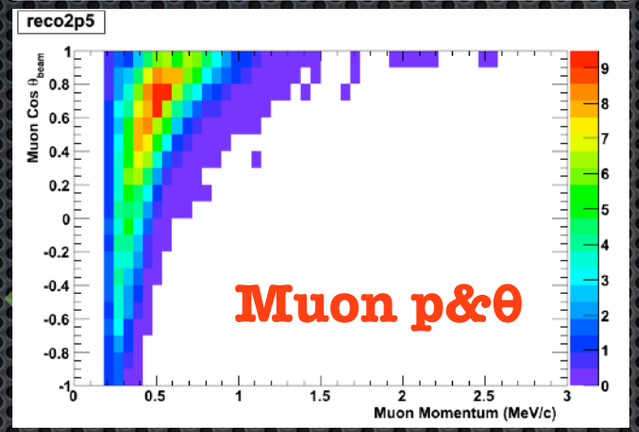
Take different linear combinations!

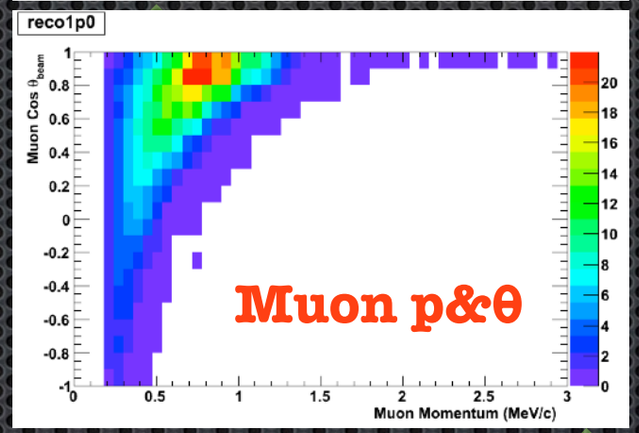
+1.0*

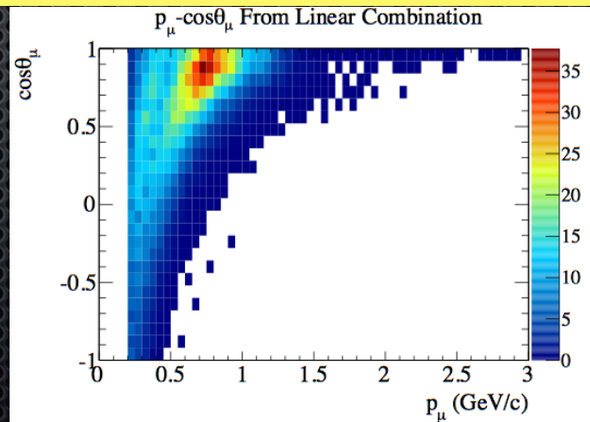
-0.8*

+0.2*







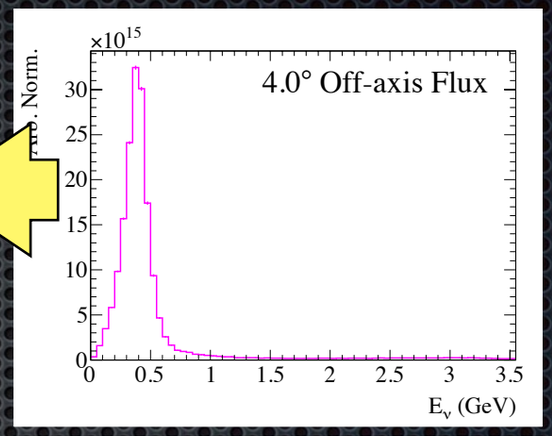


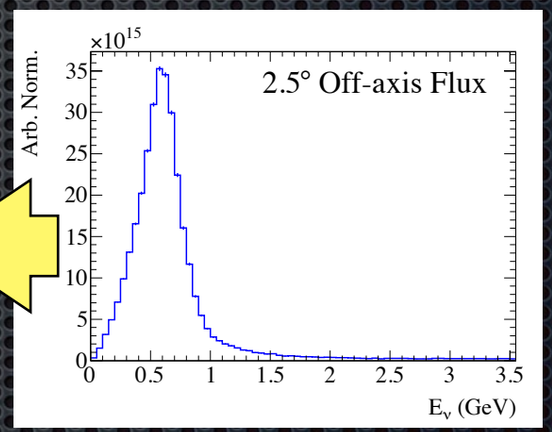
ν Interactions

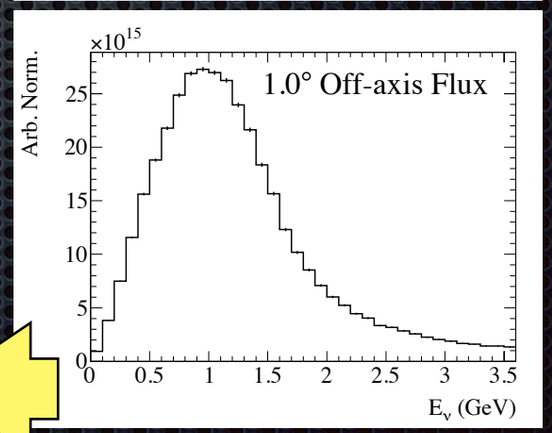
E61

ν Interactions

ν Interactions

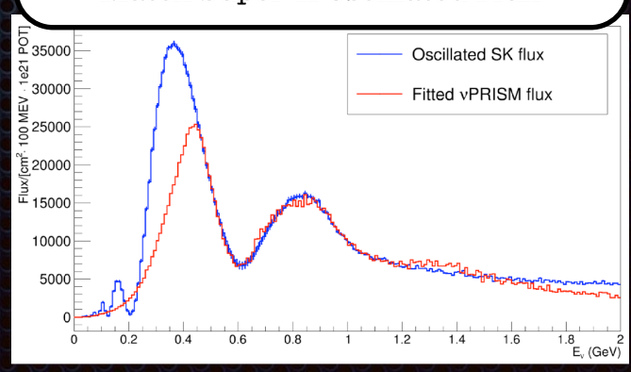






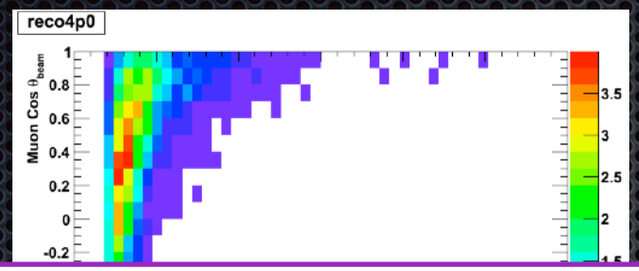
Measured oscillated p&θ spectrum in a near detector!

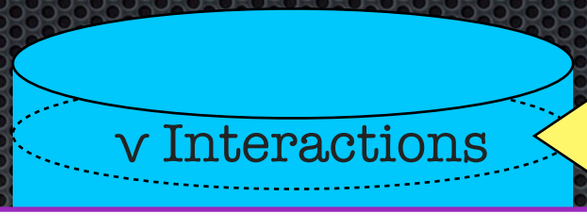
Match Super-K Oscillated Flux

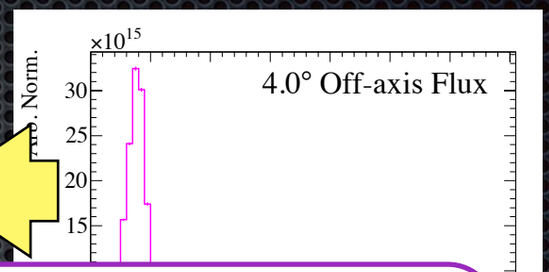


E61 in an Oscillation Experiment

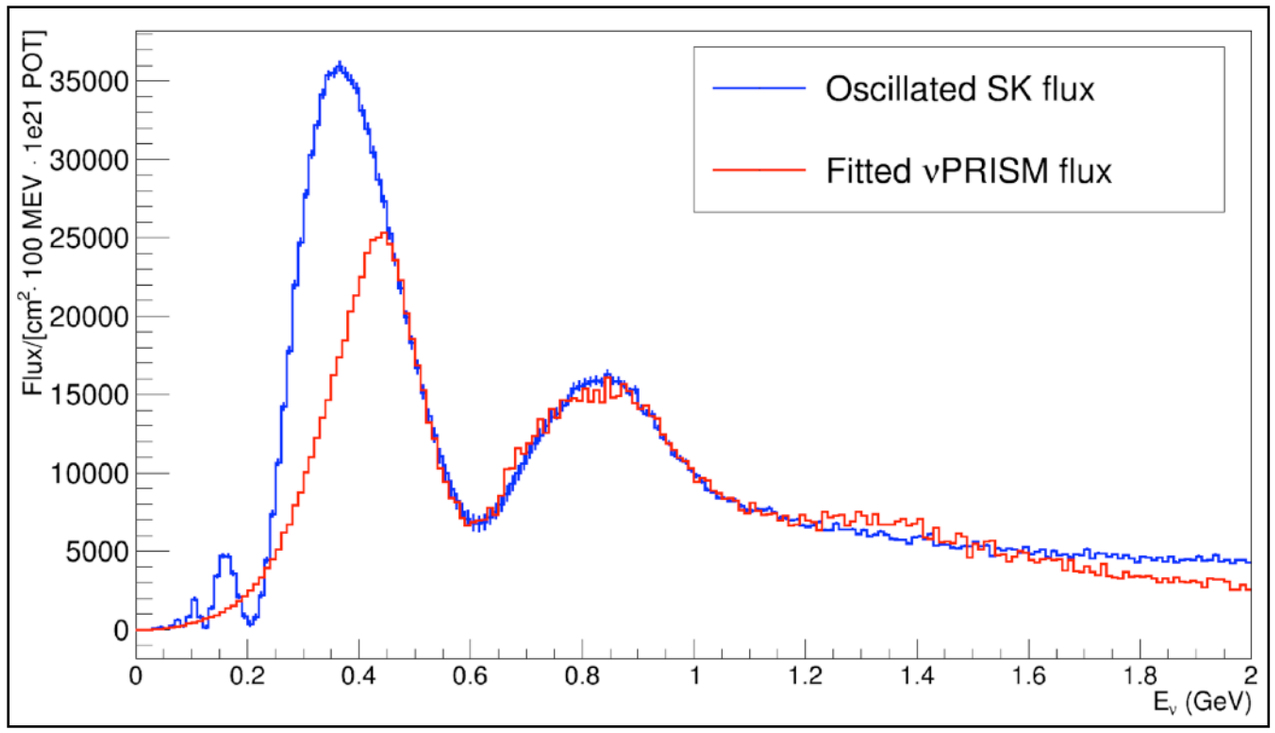
+1.0*



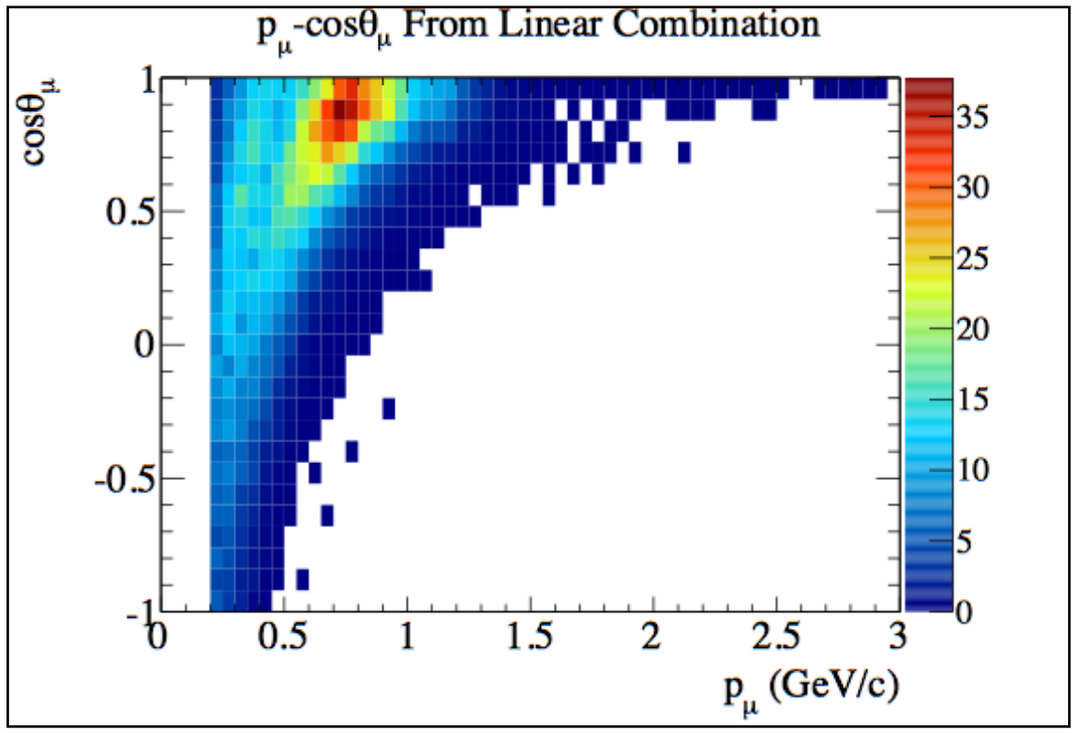


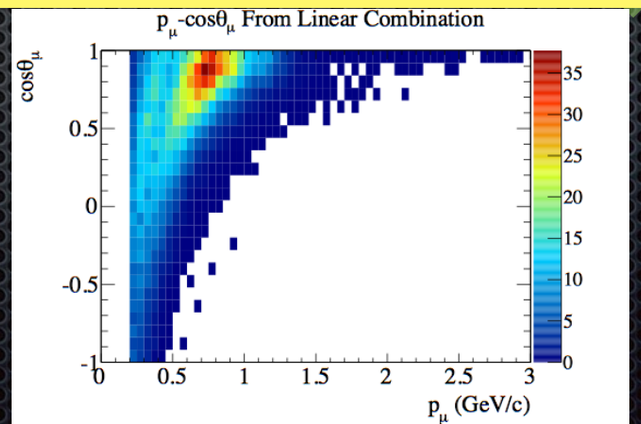


Oscillated Flux Produced at the Near Detector!



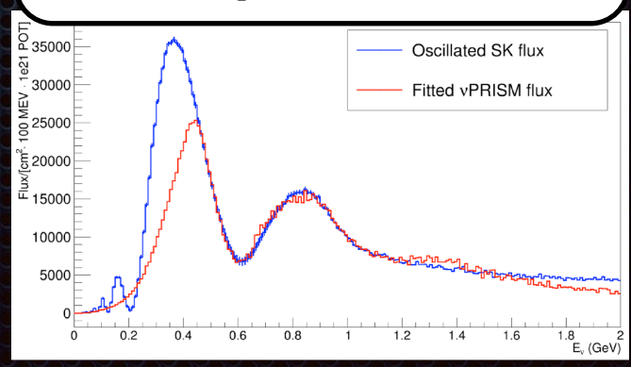
Oscillated p&θ Measured at the Near Detector!





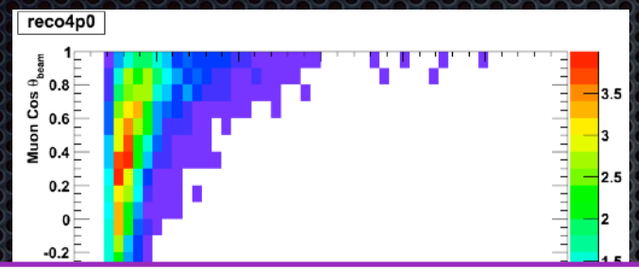
Measured oscillated p&θ spectrum in a near detector!

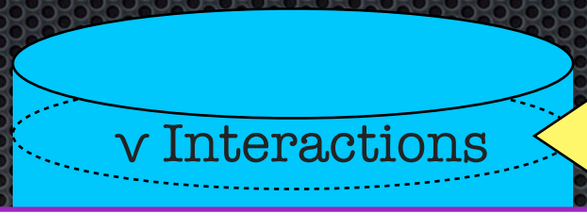
Match Super-K Oscillated Flux

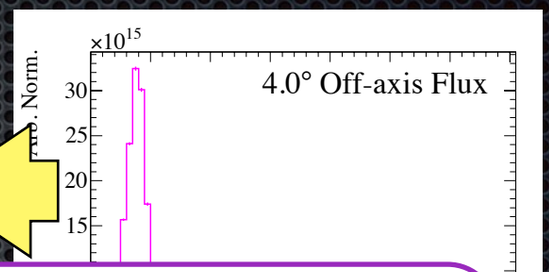


E61 in an Oscillation Experiment

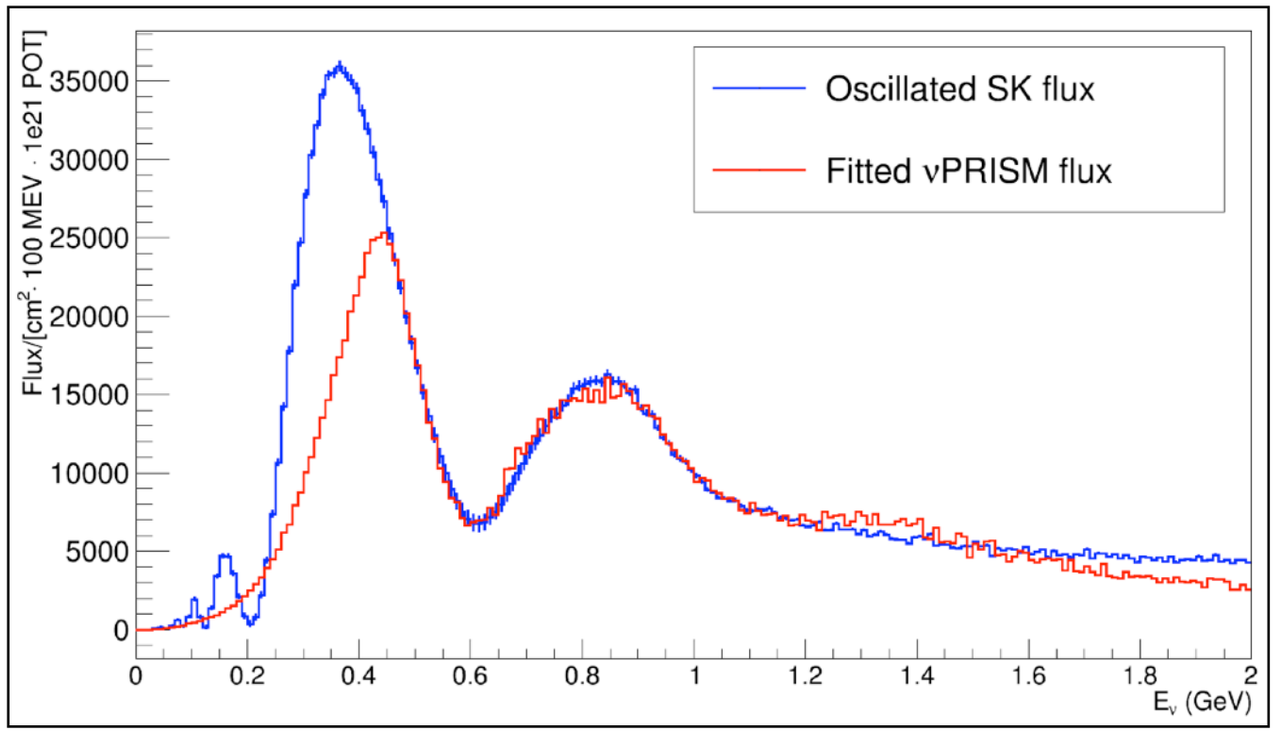
+1.0*



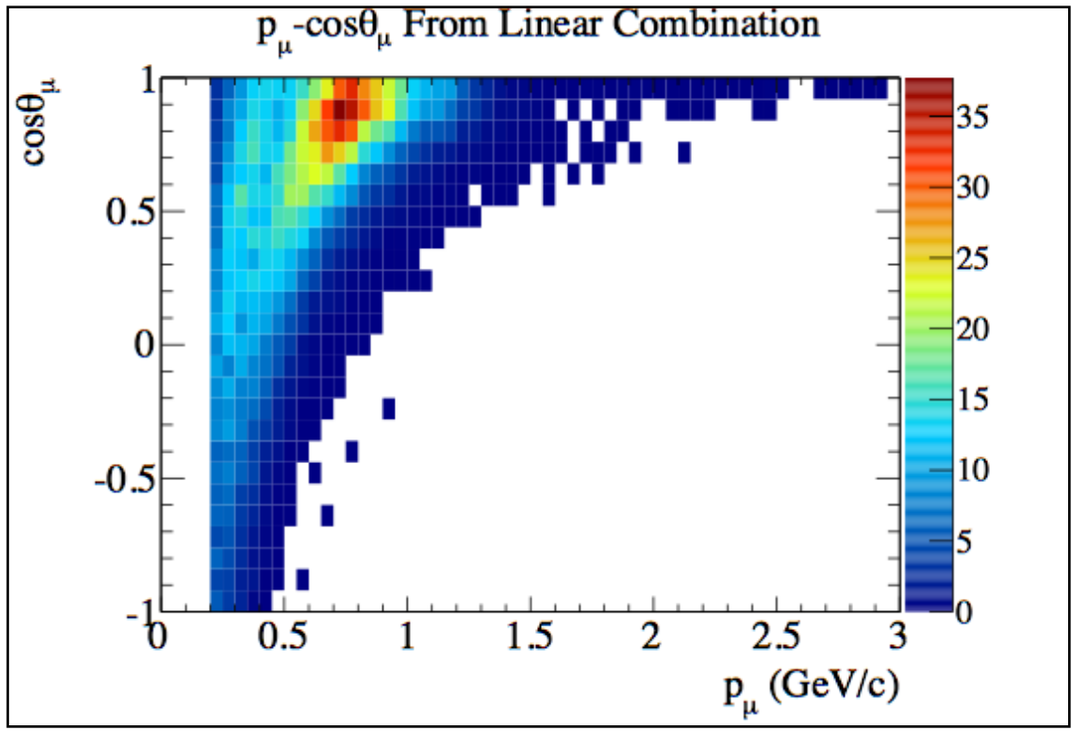




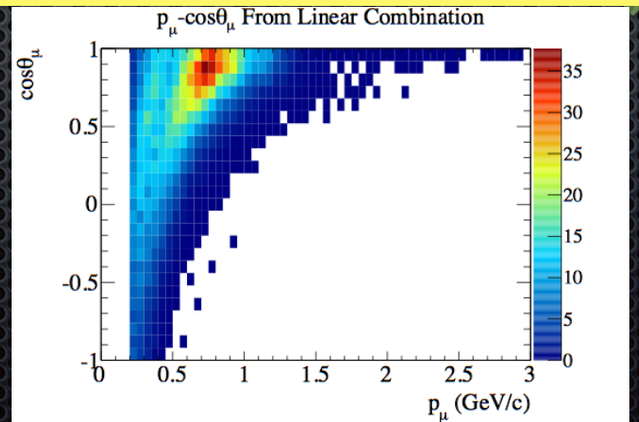
Oscillated Flux Produced at the Near Detector!



Oscillated p&θ Measured at the Near Detector!

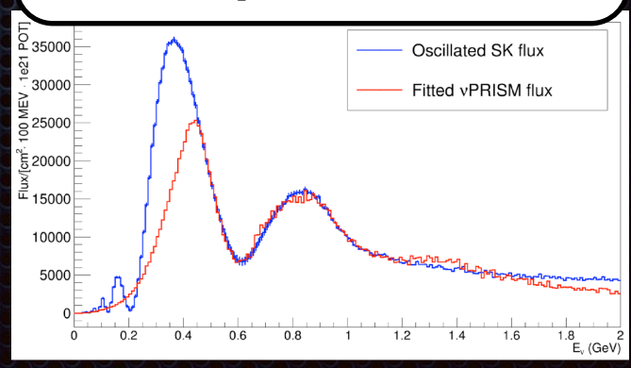


This technique is robust against existing fake data studies

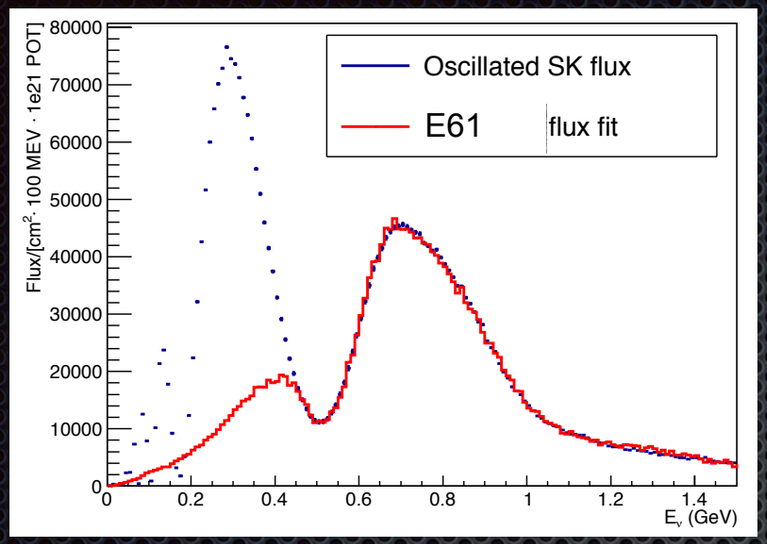


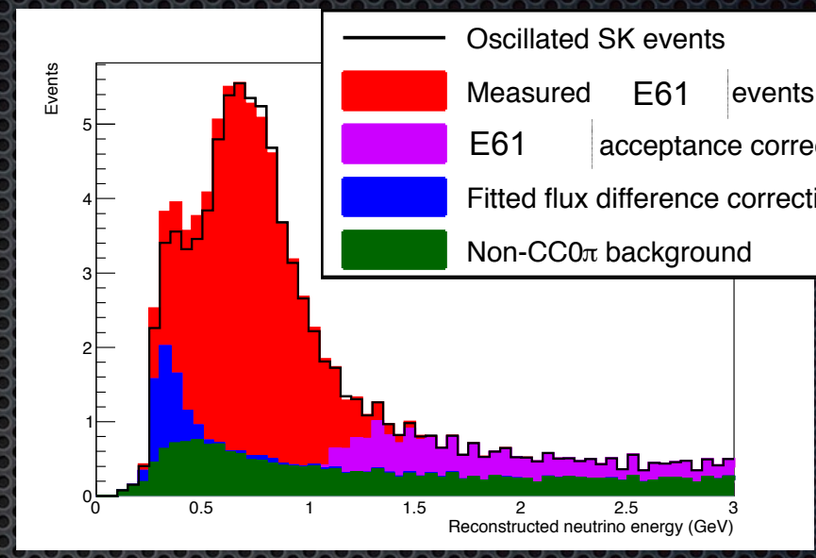
Measured oscillated p&θ spectrum in a near detector!

Match Super-K Oscillated Flux

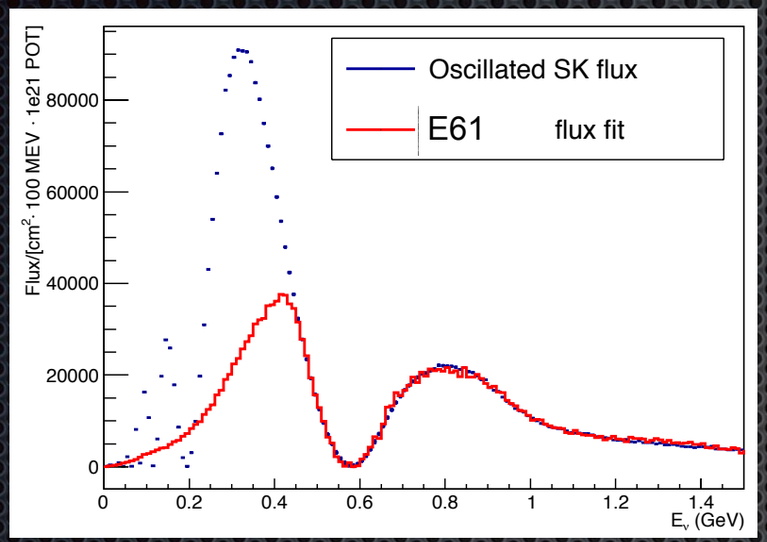


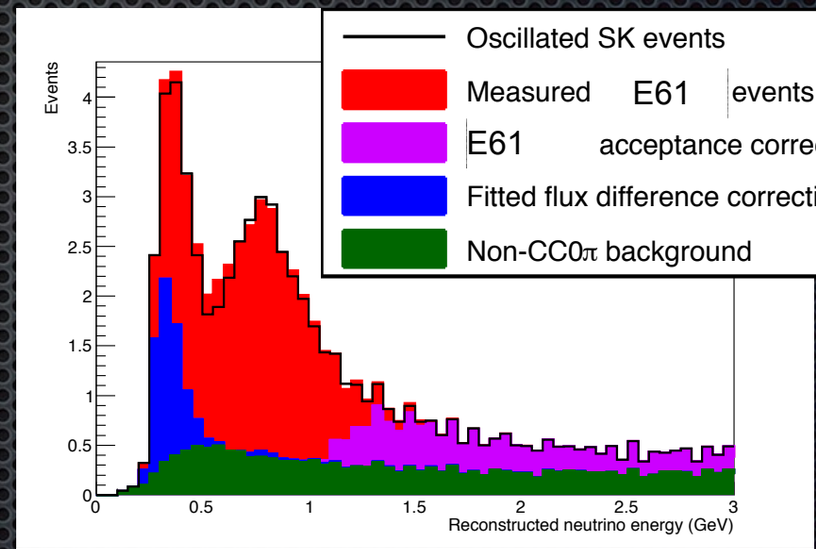
“Oscillations” in a Near Detector

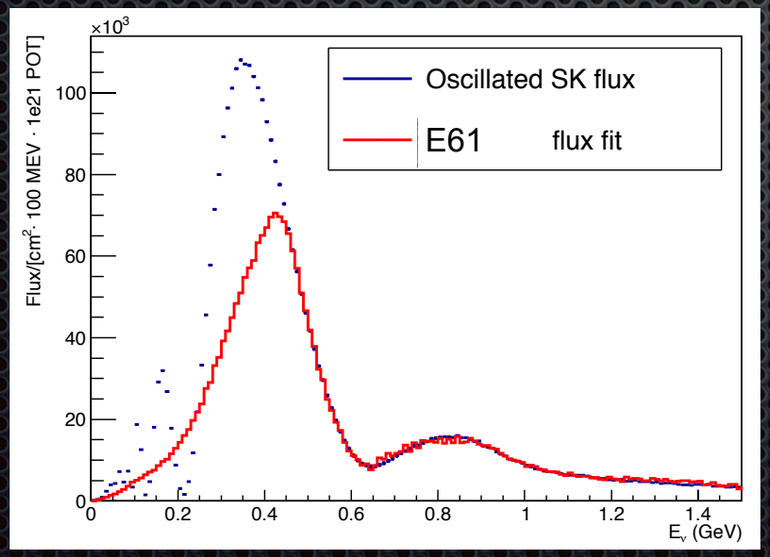


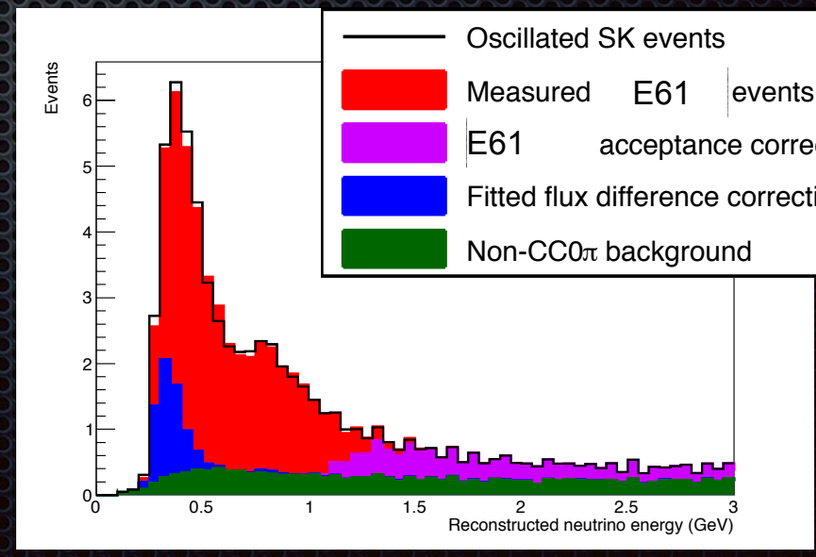


- Red region is directly measured by E61
- Blue region is flux difference correction
- Green is SK non-CC0π background
- Partially cancels with already-subtracted E61 CC0π background
- Magenta is acceptance correction
- (geometric muon acceptance)
- SK prediction is largely from directly measured component



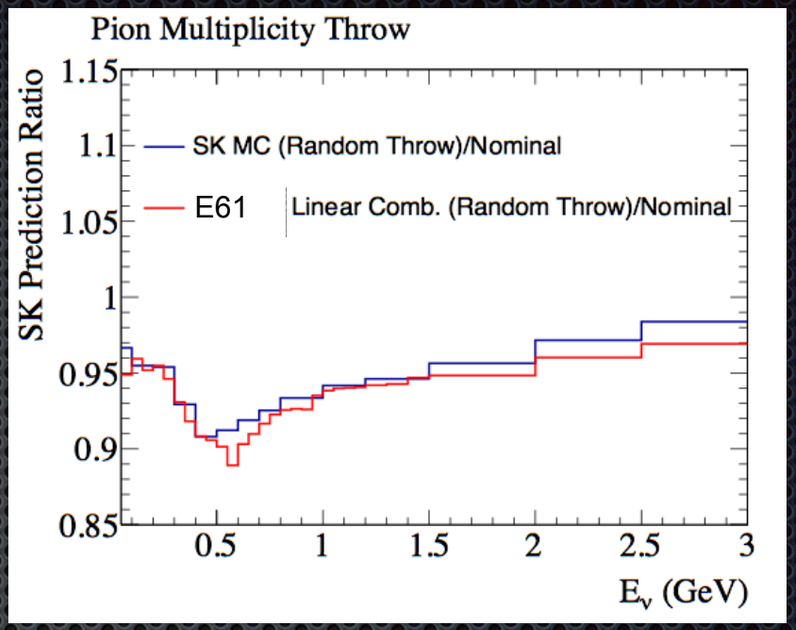


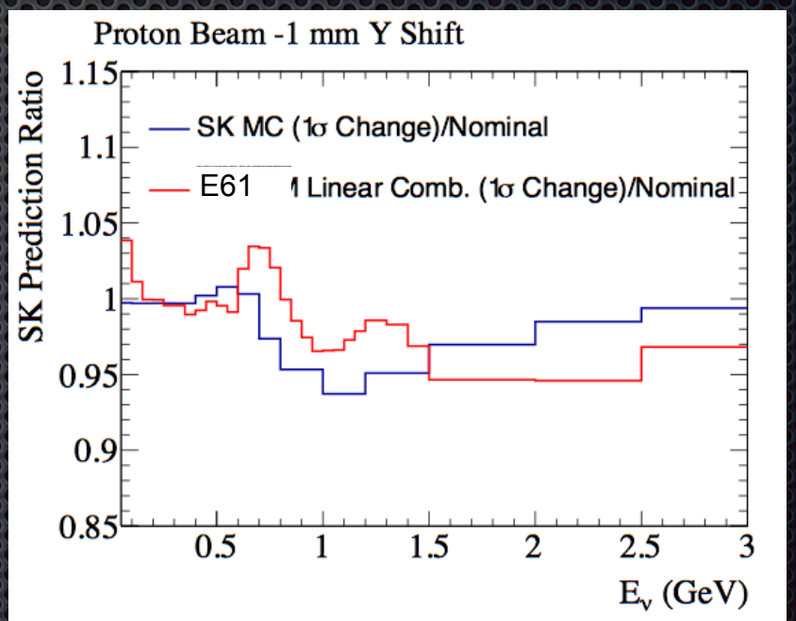


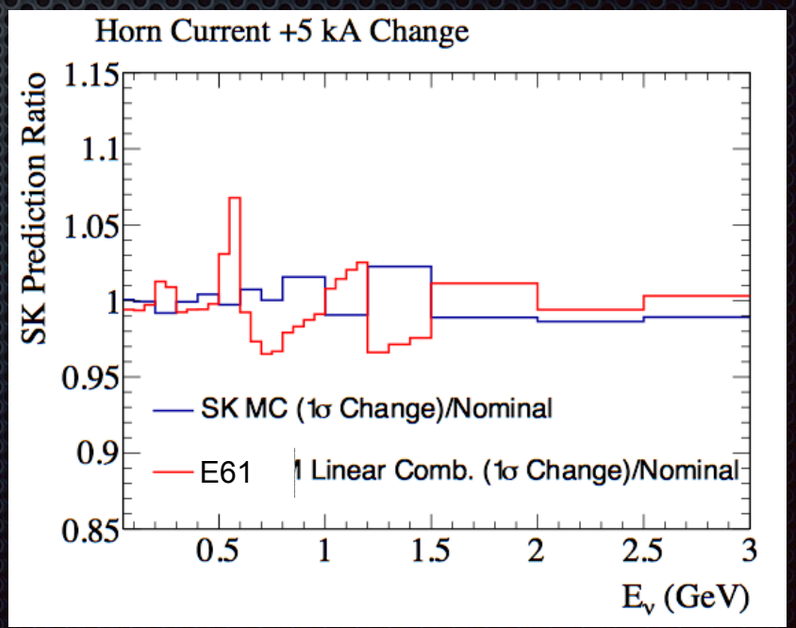


Beam Uncertainties

- Haven't we just replaced **unknown cross section errors** with **unknown flux errors**?
  - Yes! But only relative flux errors are important!
  - Significant cancelation between E61 and far detector variations
- **Normalization uncertainties will cancel** in the E61 analysis
  - Cancelations persist, even for the E61 linear combination
  - **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
  - Horn current, beam direction, alignment, etc.
- For T2K, beam uncertainties do not significantly contribute to the ν_μ disappearance sensitivity

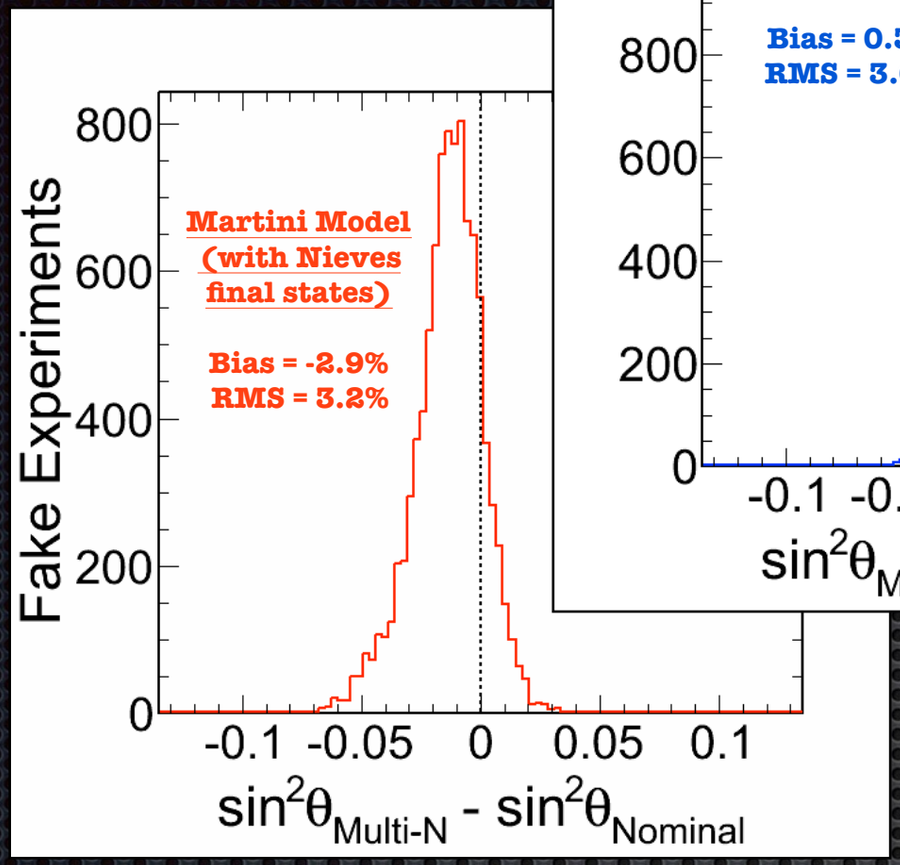


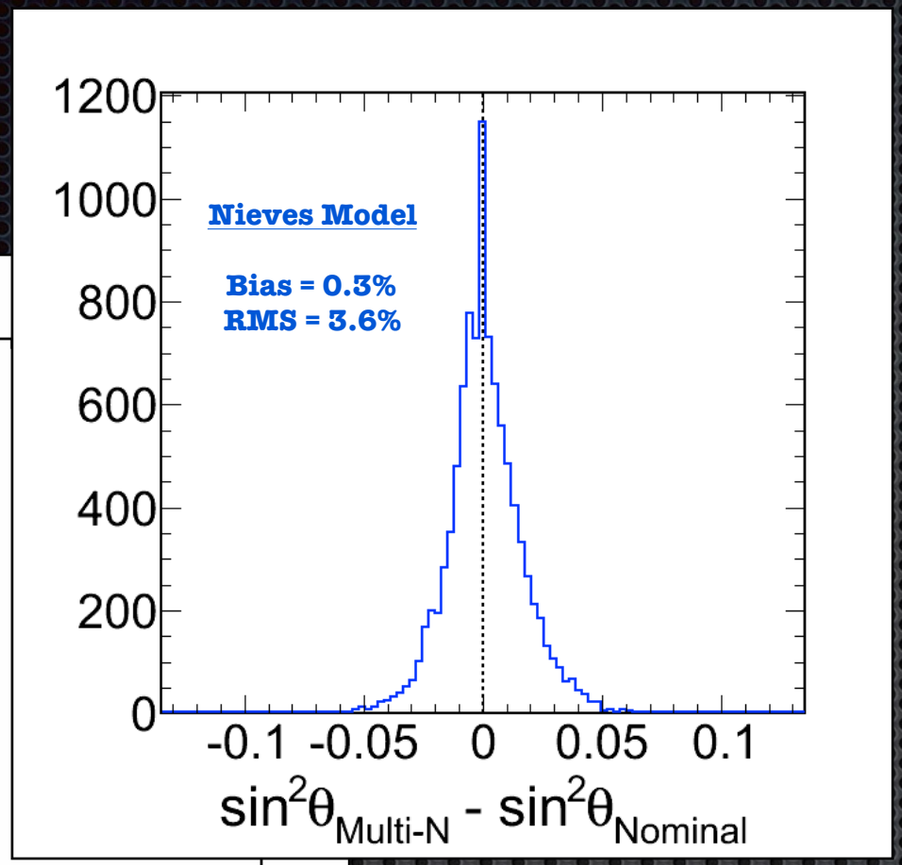




E61 ν_μ Disappearance Constraint

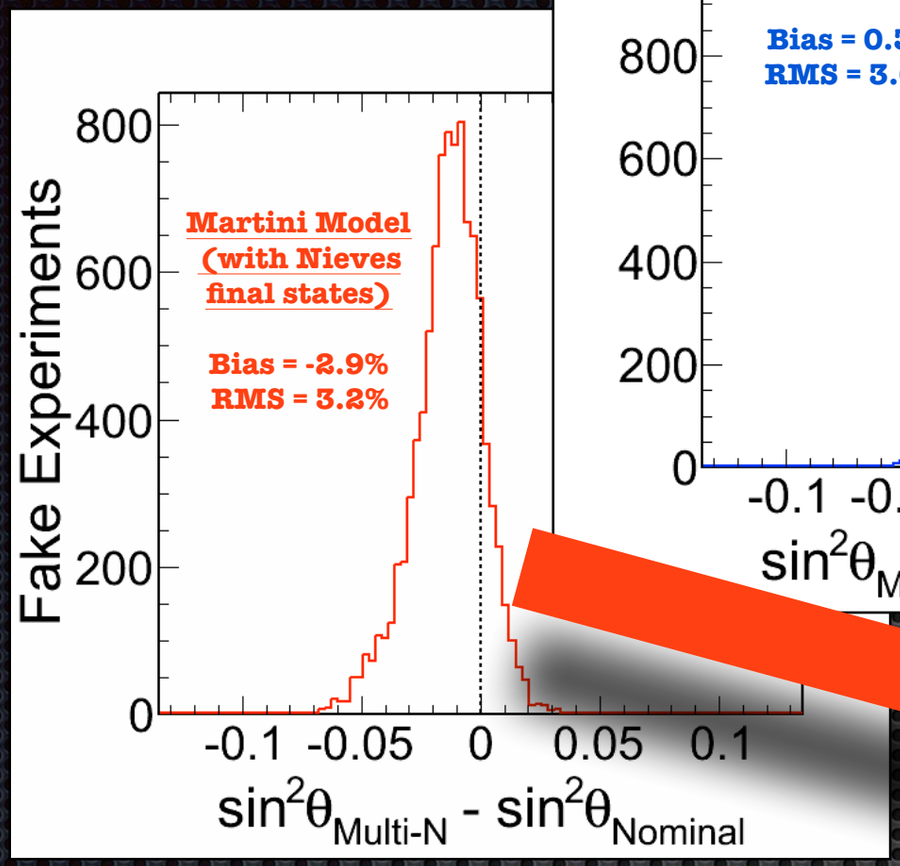
Standard T2K Analysis

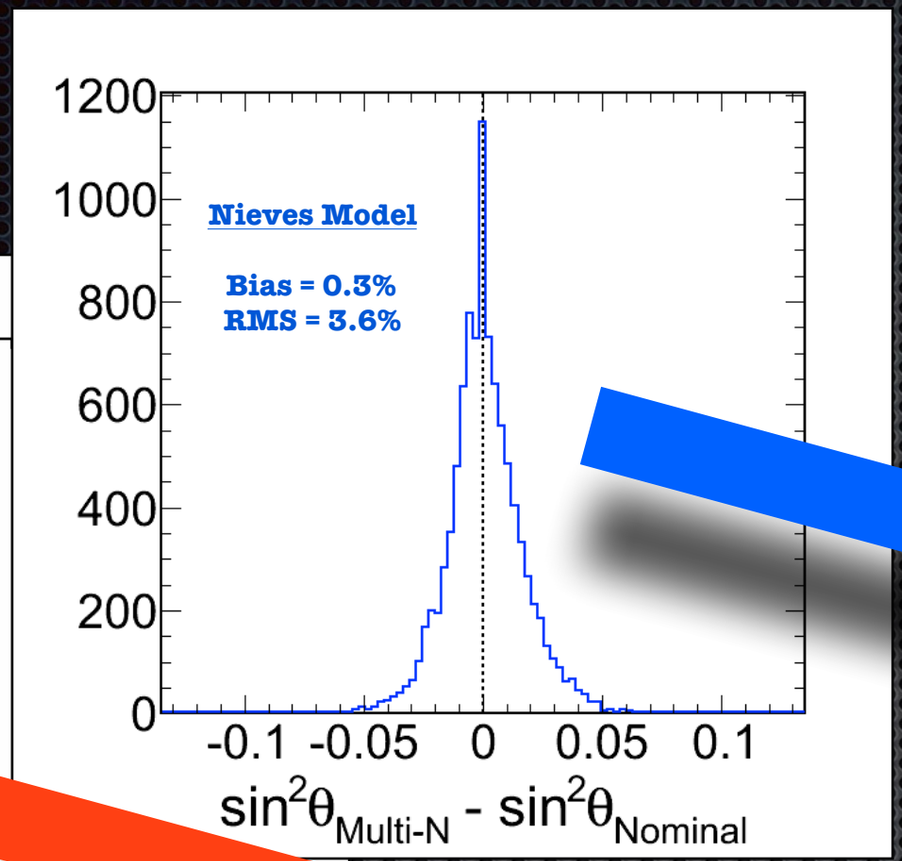




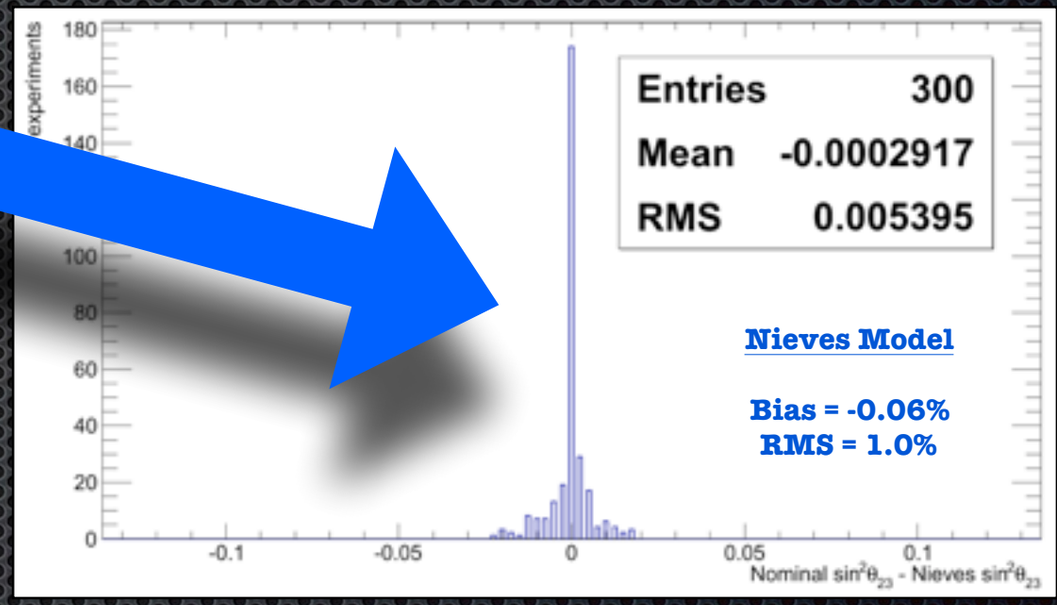
E61 ν_μ Disappearance Constraint

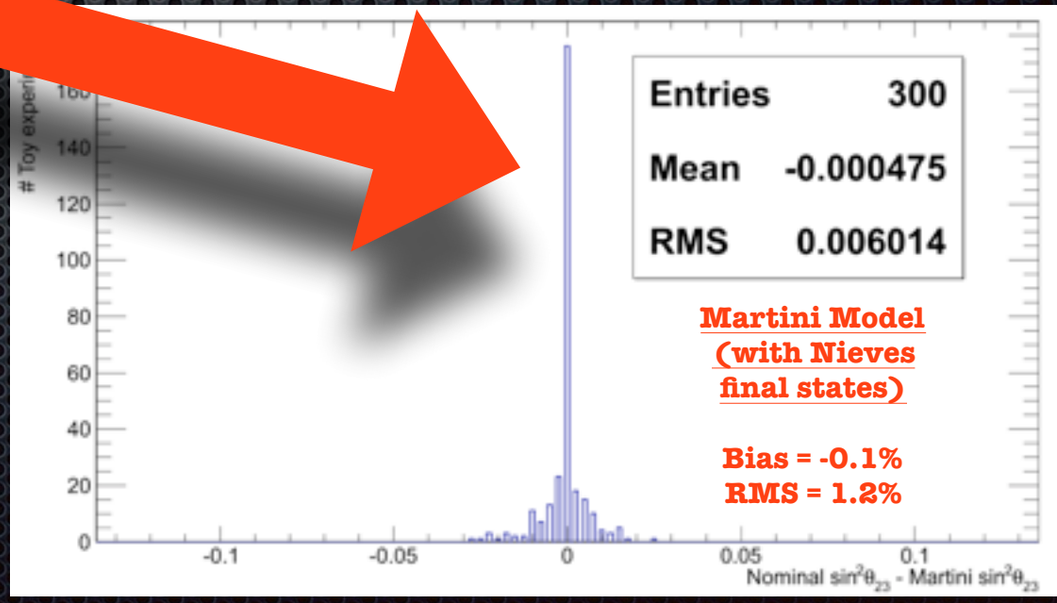
Standard T2K Analysis





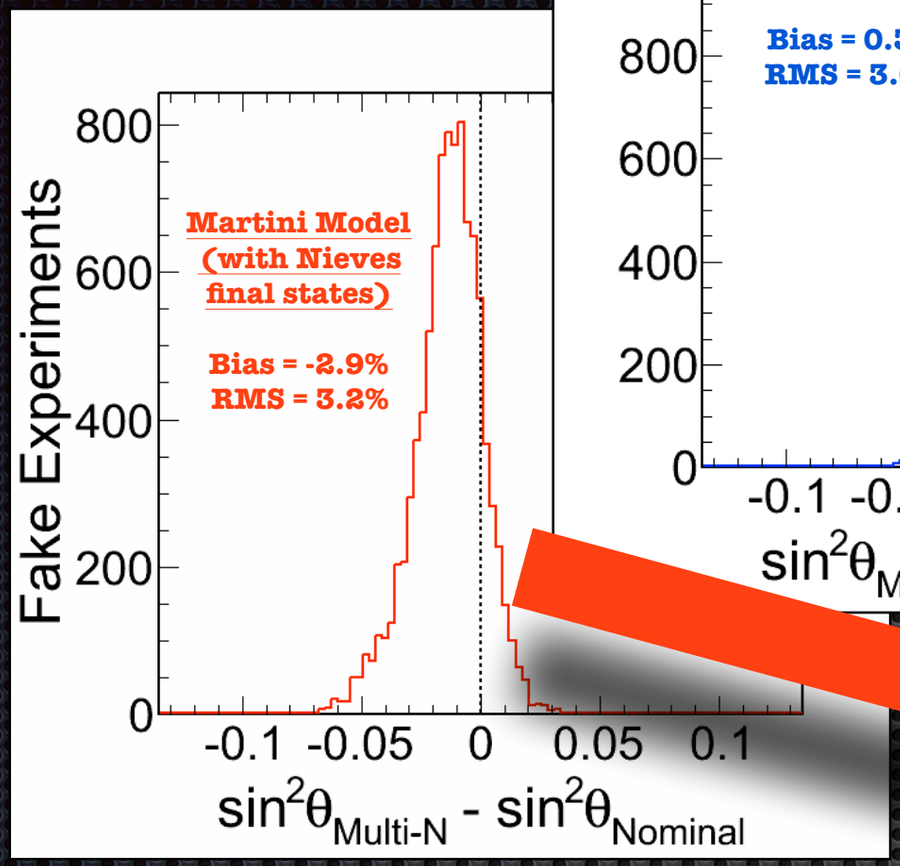
E61 Analysis

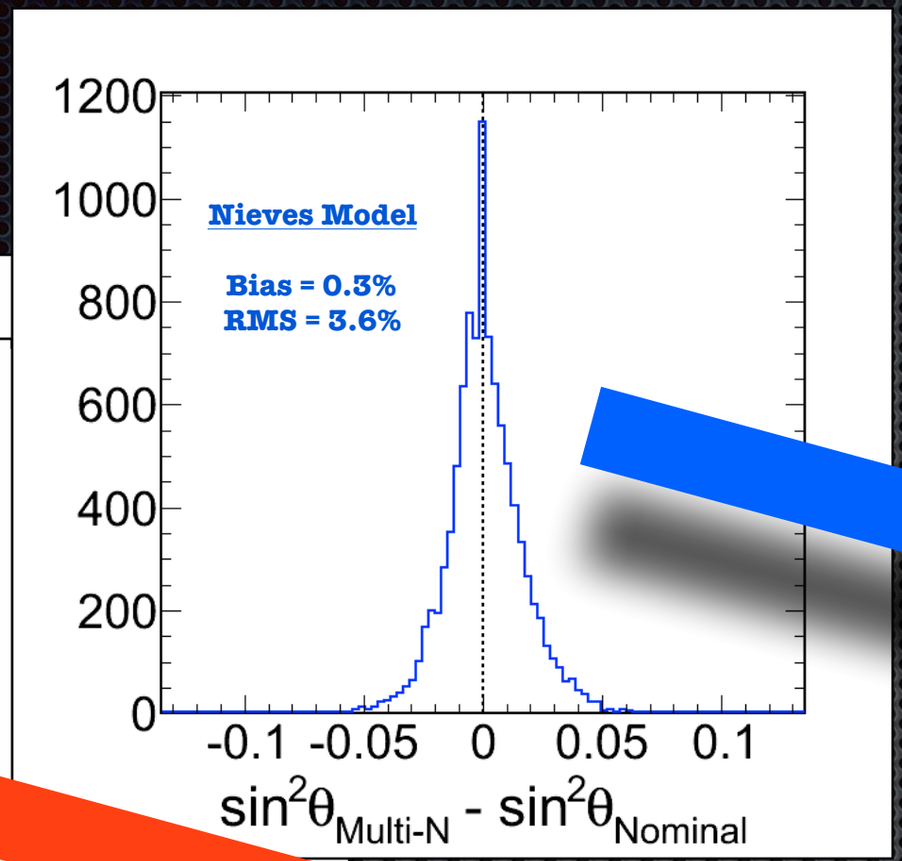




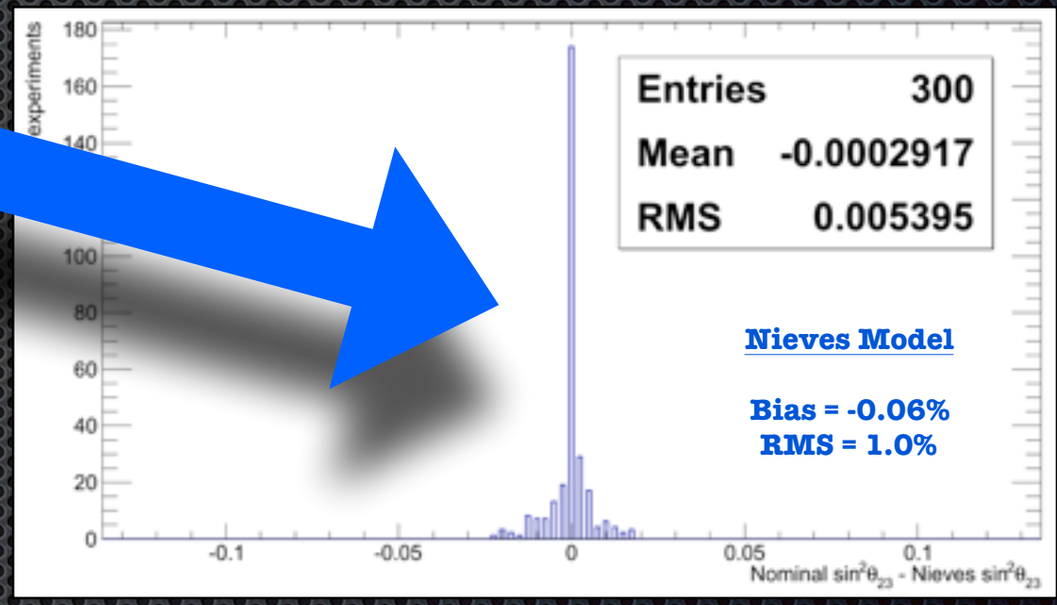
E61 ν_μ Disappearance Constraint

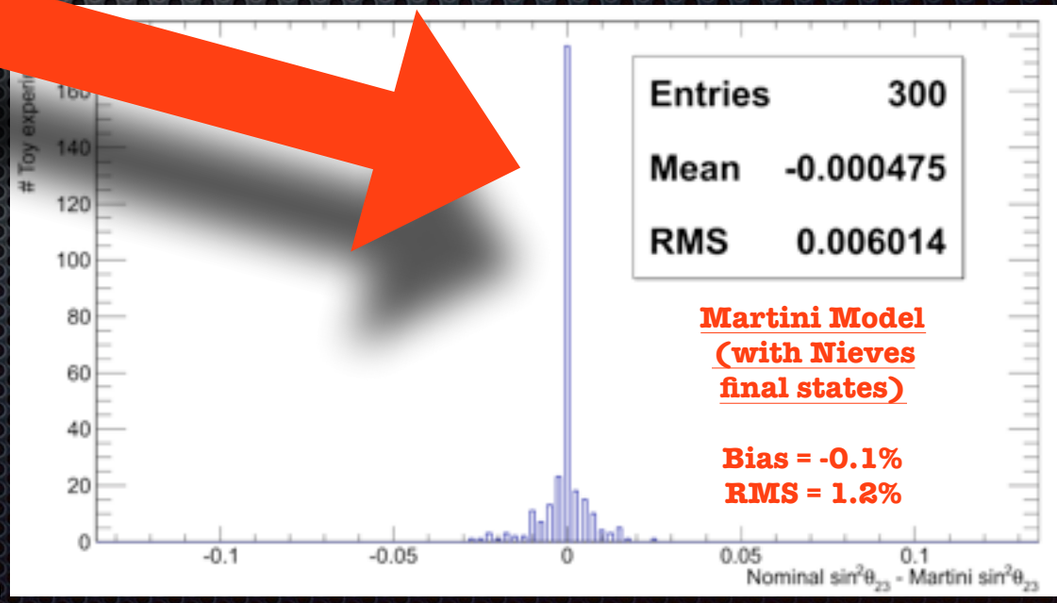
Standard T2K Analysis





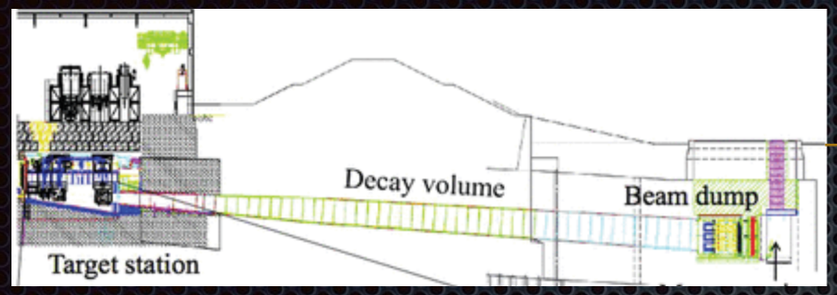
E61 Analysis



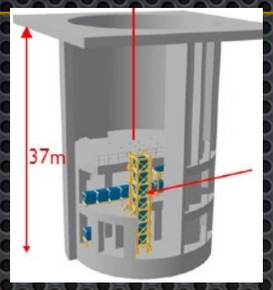


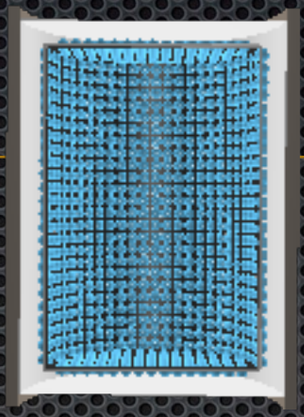
- Fake data studies show the bias in θ_{13} is reduced from **4.3%/3.6%** to **1.2%/1.0%**
- More importantly, this is now based on a **data constraint**, rather than a model-based guess
- Expect the E61 constraints to get significantly better as additional constraints are implemented (very conservative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

A Phased Approach



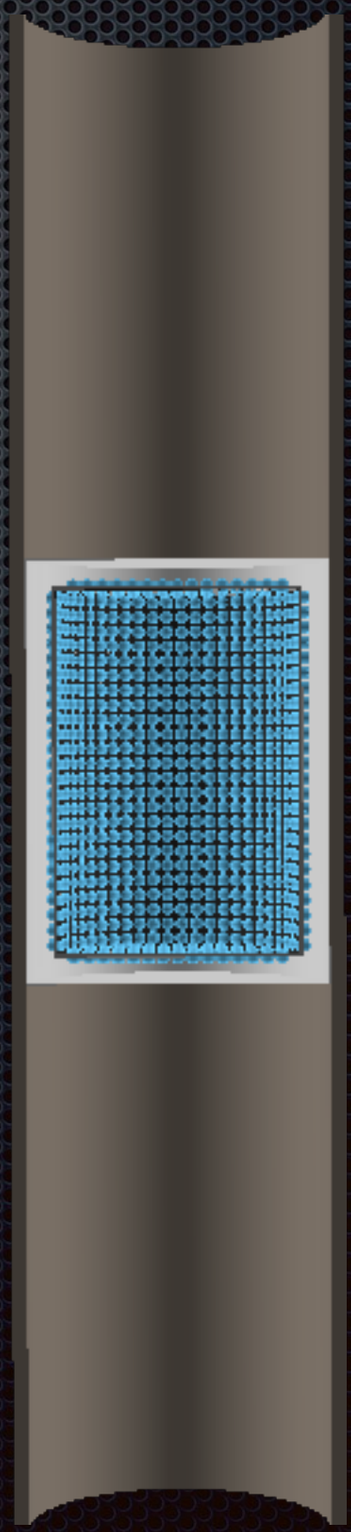
INGRID & ND280





Phase 0

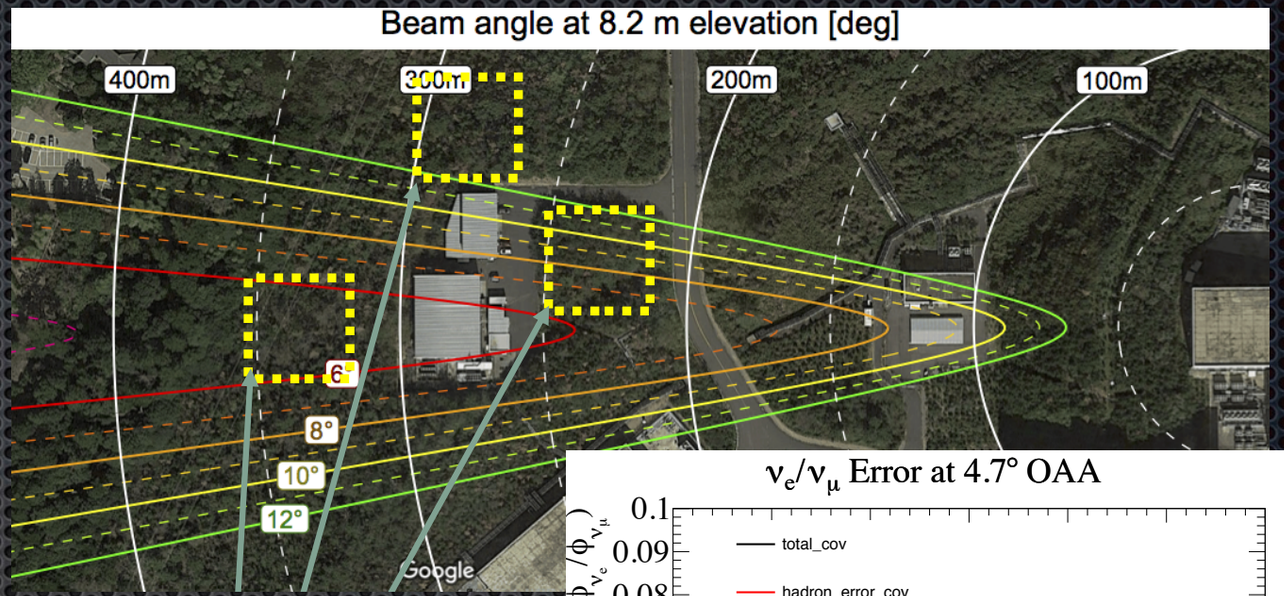
Phase 1



- Phase 1
  - Moveable instrumented detector, placed in a ~50 m deep pit, ~1 km away from the neutrino target
- Phase 0
  - Instrumented portion of phase 1 is placed in a water tank near ND280
  - Physics goal: measure $\sigma(\nu_e)/\sigma(\nu_\mu)$ to ~3% precision
  - Can demonstrate detector performance & calibration precision
  - Provides a test detector for Hyper-K R&D

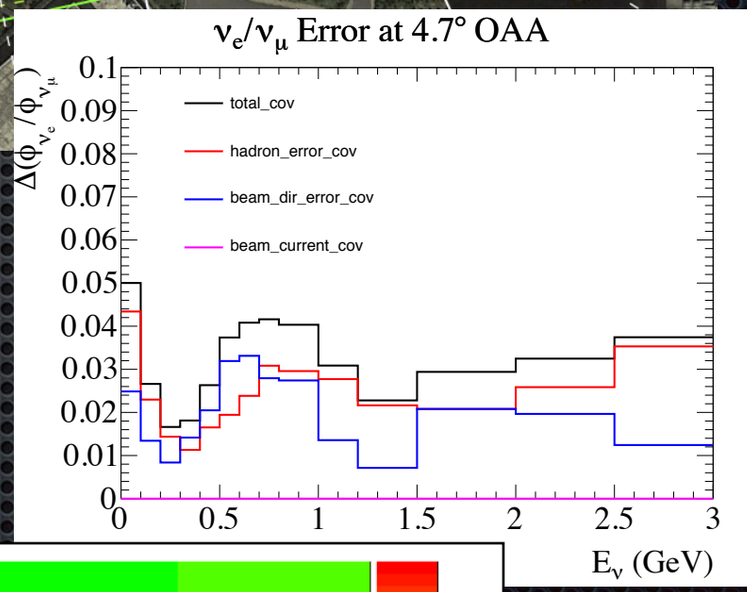
Phase 0 $\sigma(\nu_e)/\sigma(\nu_\mu)$ Measurement

- The best $\sigma(\nu_e)/\sigma(\nu_\mu)$ measurements have ~20% errors
  - Theoretical uncertainty at 3% level
    - Default uncertainty for osc. experiments, and already significant for δ_{CP}

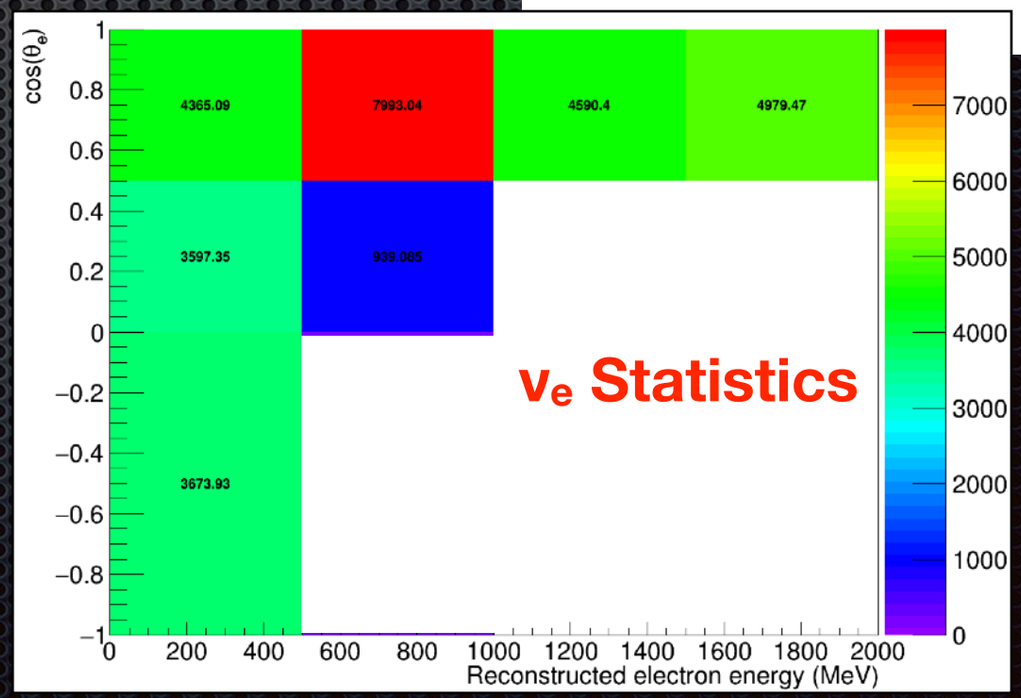


- Nice overview given by Kevin McFarland at NuINT 2 weeks ago: https://meetings.triumf.ca/indico/event/6/session/2/contribution/78

ν_e/ν_μ Flux Ratio Uncertainties:

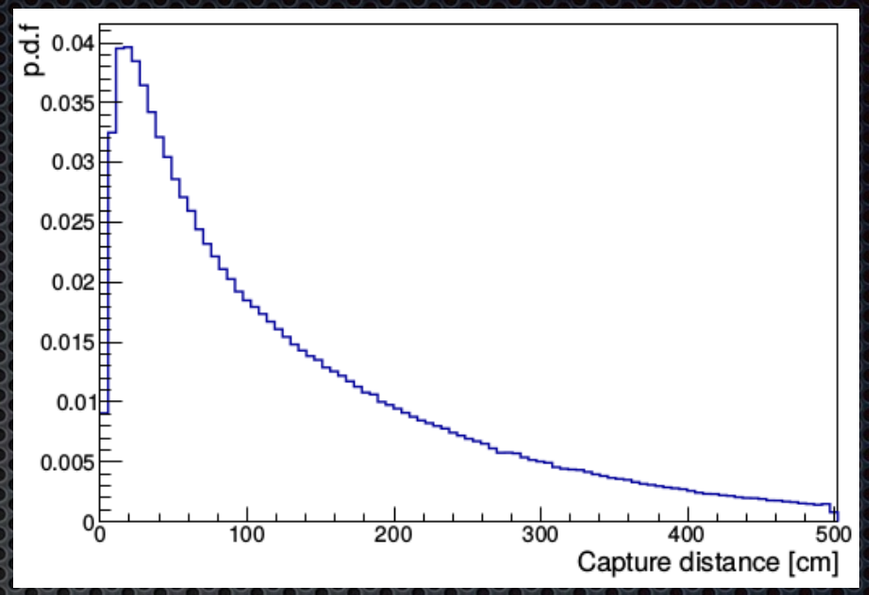


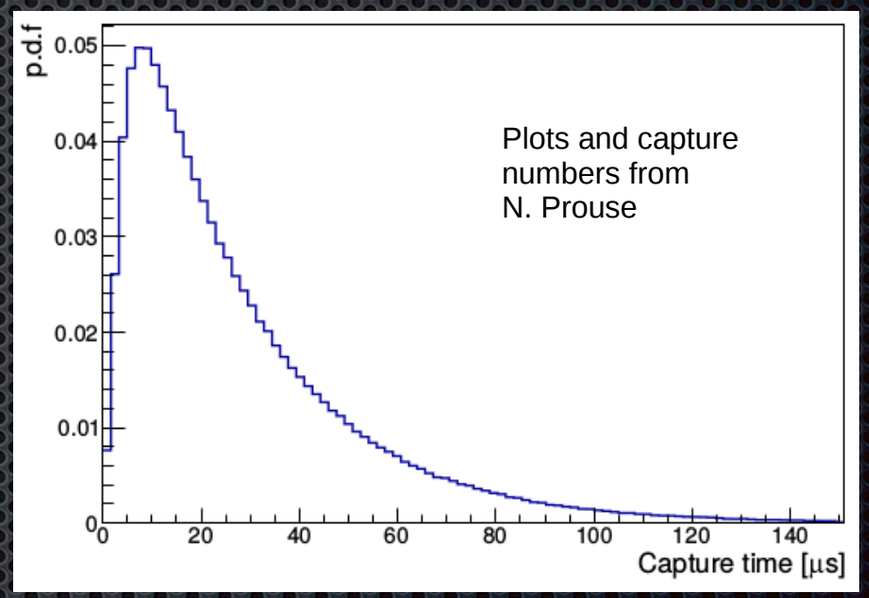
- ν_e/ν_μ Flux ratio uncertainties grow at larger off-axis angles due to increase in ν_e from kaon decay
  - Few percent uncertainties up to ~8°
- Expect to make a few percent measurement of $\sigma(\nu_e)/\sigma(\nu_\mu)$ in several ν_e kinematic bins



Gd Loading

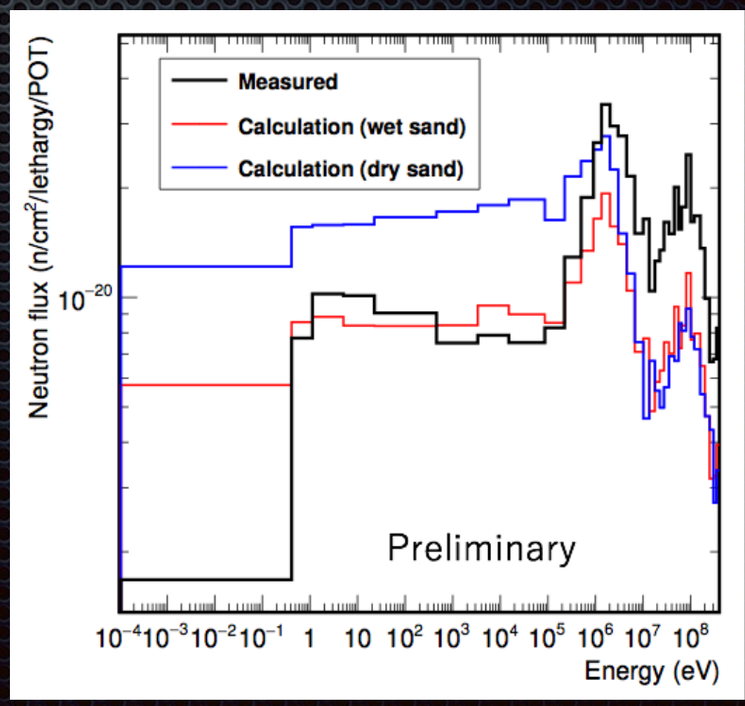
- Aim to load E61 with Gd to study n-capture
- Super-K will soon be loaded with Gd
  - Some separation of ν/anti-ν may be possible
  - But, to utilize this information for high-energy analysis, must constrain neutron emission/capture
- Phase 1 can measure neutron capture rate as a function of E_ν and muon kinematics (Hyper-ANNIE?)
- Phase 0 can provide initial constraints, and is an important demonstrator for Phase 1
  - 93% of muons in the FV capture in the Phase 0 detector (88% Gd, 12% H)
- Extensive studies are underway
  - Simulation and reconstruction tools
  - Studies of radioactive backgrounds and external neutron signals



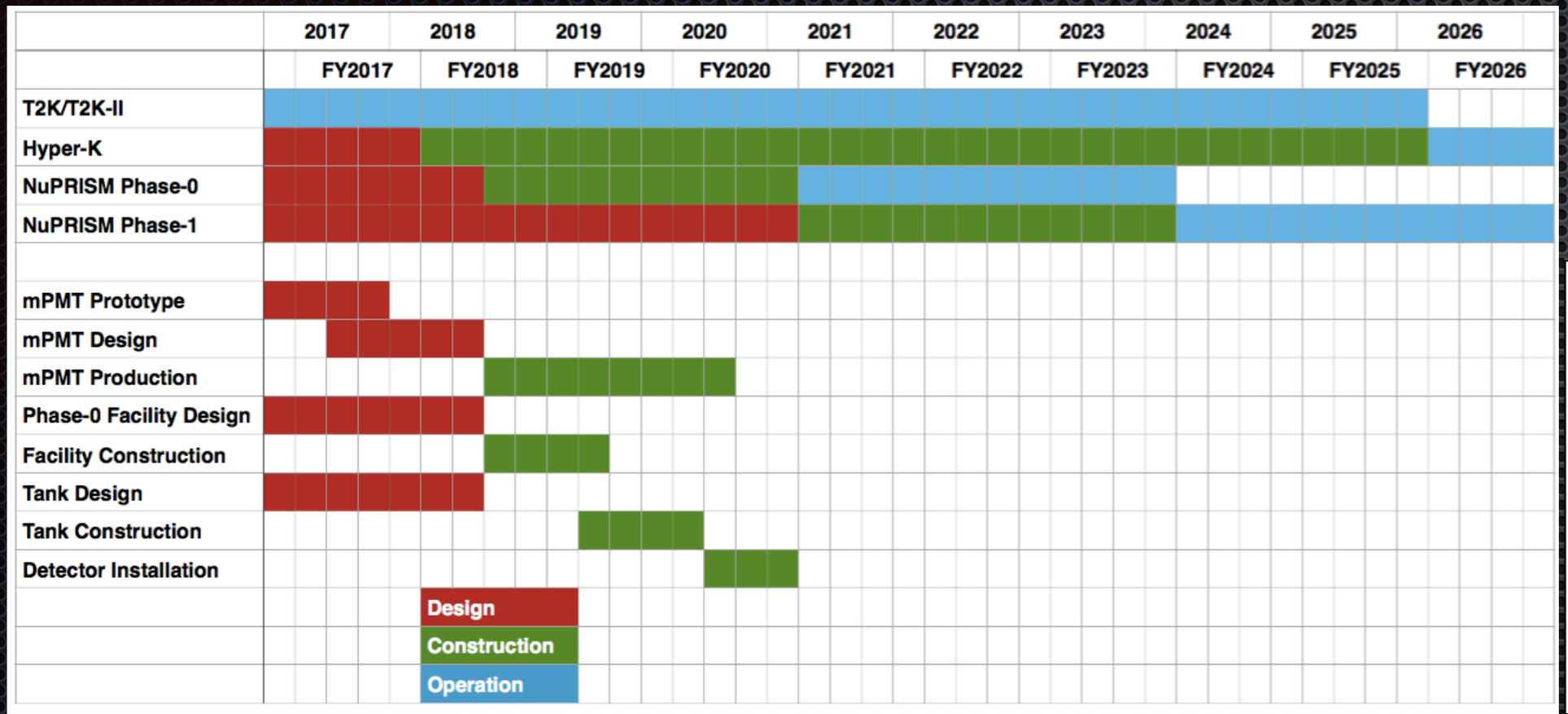


Plots and capture numbers from N. Prouse

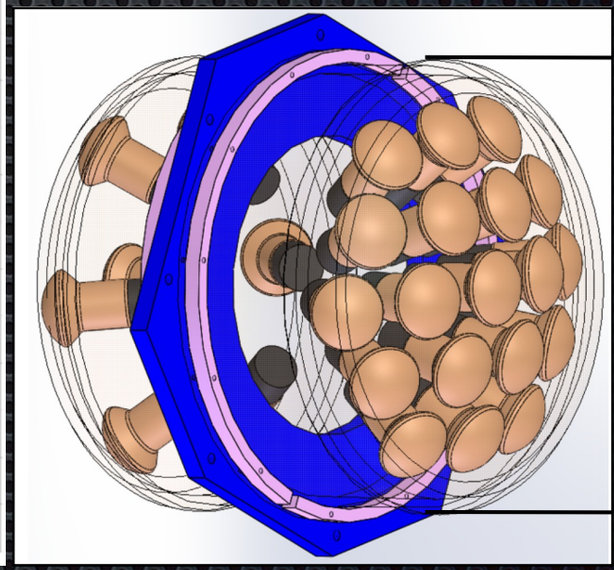
Neutron flux measurements at ND280:



Status & Timeline



Extensive mPMT R&D is underway



- E61 was granted Stage-1 approval in July, 2016
  - A Technical Design Report is under development for Stage-2 (final) approval in 2018
- Phase 0 start is driven by mPMT development & production
  - Plan to take at least 2 years of beam data in Phase 0
- Aim to begin Phase 1 ~3 years after Phase 0 start
  - Data taking over the last 2-3 years of T2K-II run

Summary

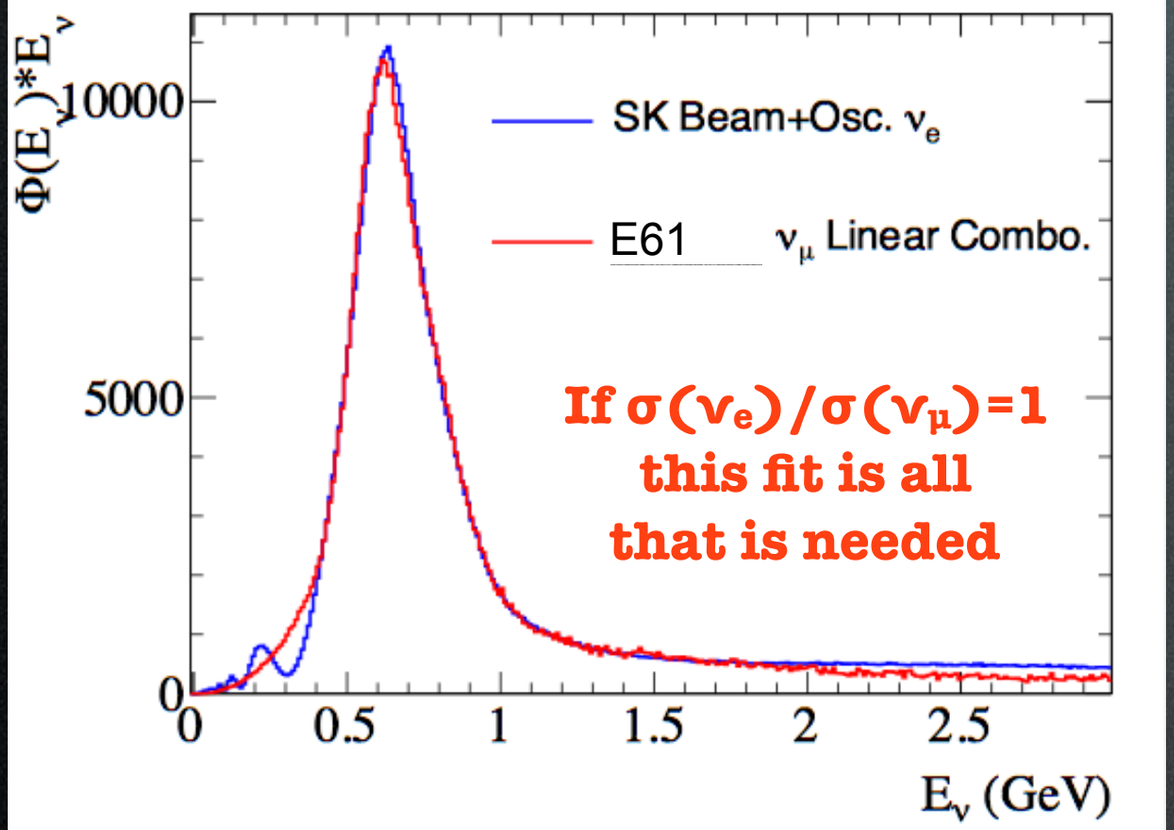
- Long-baseline neutrino oscillation experiments are beginning to face limitations due to cross section uncertainties
  - Poorly understood “feed down” can bias oscillation parameter measurements
    - …due to very different near & far detector ν_e & ν_μ fluxes
- The E61 experiment (Phase 1) at J-PARC can provide an experimental solution to $E_{rec} \rightarrow E_{true}$ problem
  - Phase 0 can make a precise measurement of $\sigma(\nu_e)/\sigma(\nu_\mu)$
    - Also a demonstrator for Phase 1, and hardware test detector for Hyper-K
- Variety of other measurements: n-Gd capture rates, sterile neutrino search, and a rich cross section program with mono-energetic beams

Supplement

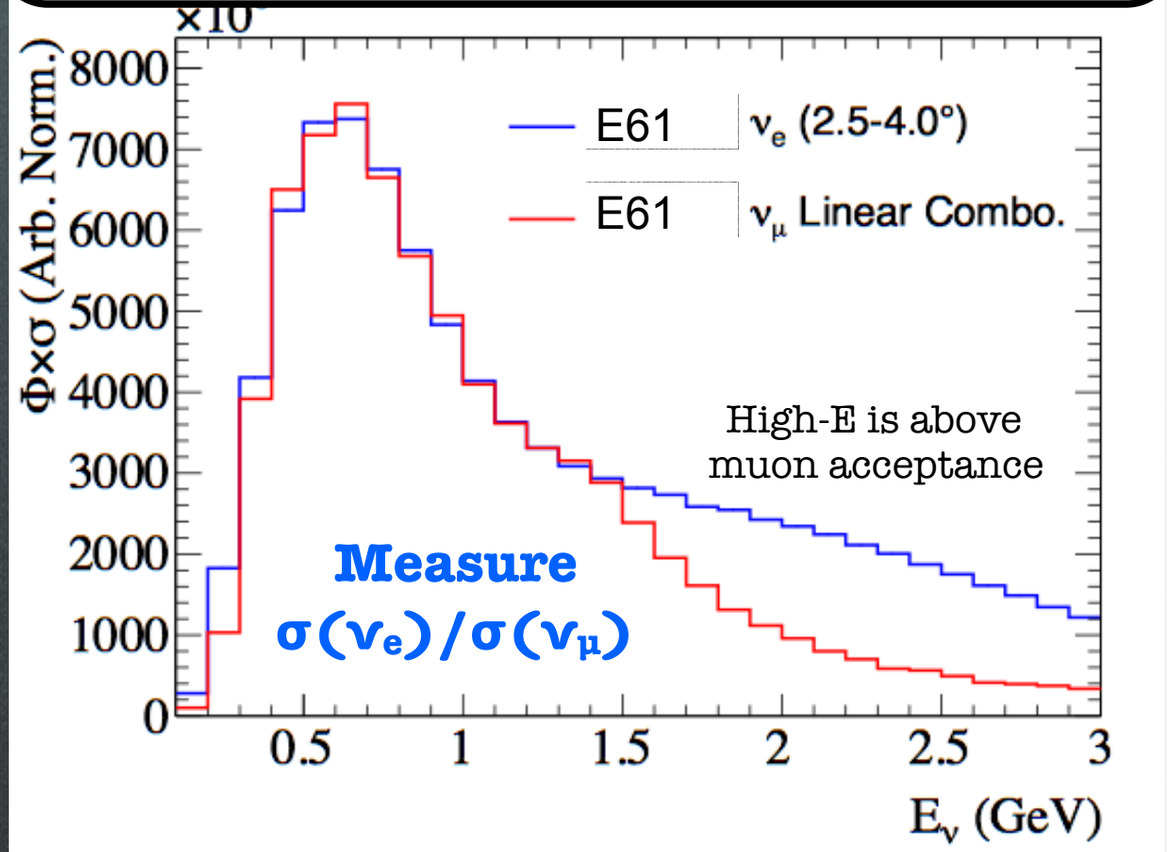
Phase 1 ν_e Appearance (CPV)

3 step approach:

Step 1: Measure **Super-K ν_e** response with **E61 ν_μ**



Step 2: Measure **E61 ν_e** response with **E61 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 E61 to measure $\sigma(\nu_e)/\sigma(\nu_\mu)$
  - Constrains the $\sigma(\nu_e)/\sigma(\nu_\mu)$ uncertainty
- Step 3 uses the slice of E61 in the far detector direction to measure NC backgrounds with the same energy spectrum as the far detector (reduces background systematics)