νPRISM:
Analysis overview

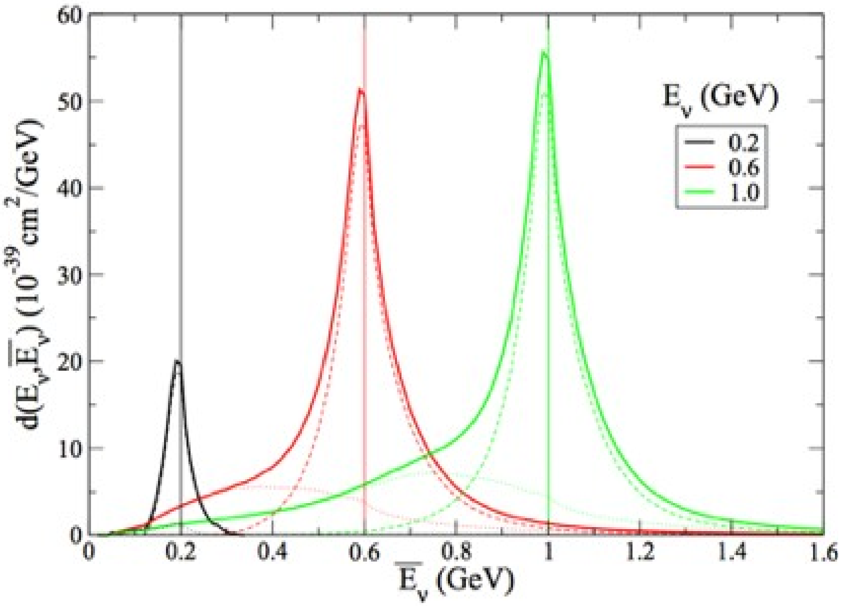
Mark Scott for the νPRISM collaboration
6th open Hyper-K meeting
30th Jan 2015 - IPMU

Overview

- Analysis updates:
  - Mono-chromatic neutrino beams (Mark Hartz)
  - Sterile neutrino analyses (John Vo, Stefania Bordoni, Federico Sanchez)
  - Muon neutrino disappearance analysis
- Electron neutrino, anti-neutrino and cross section analyses progressing, but nothing to report today
- More details at the νPRISM meeting on Sunday

Motivation for mono-chromatic Beams

- The modelling of multi-nucleon reactions, pion absorption, the nuclear initial state, etc., introduce uncertainties on:
  - The absolute normalization of the cross section for CC events with only visible leptons
  - The relationship between the lepton (or other final state) kinematics and the neutrino energy (important for oscillation measurements)
- Measuring the effect of nuclear effects on the final state kinematics is challenging in a conventional beams due to the width of the neutrino spectrum
- Ideally, a monochromatic neutrino beam would allow one to study how nuclear effects contribute to the final state particle distributions
- We can make "mono-chromatic" neutrino beams in nuPRISM



Martini et. al.
Phys.Rev. D87 (2013) 013009

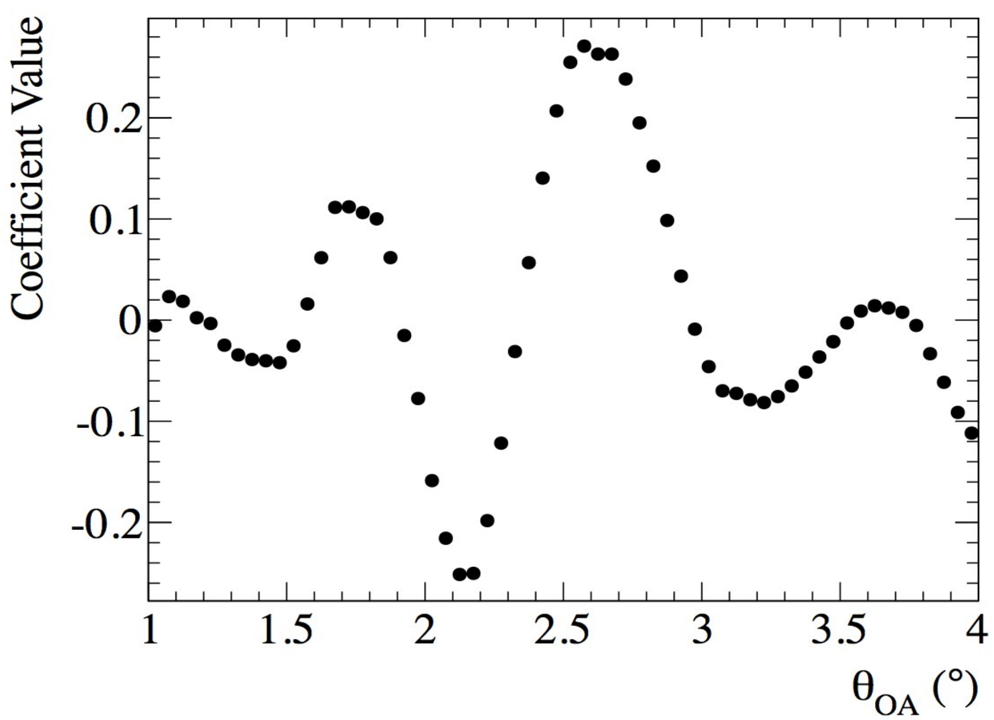
Mono-chromatic Beams with nuPRISM

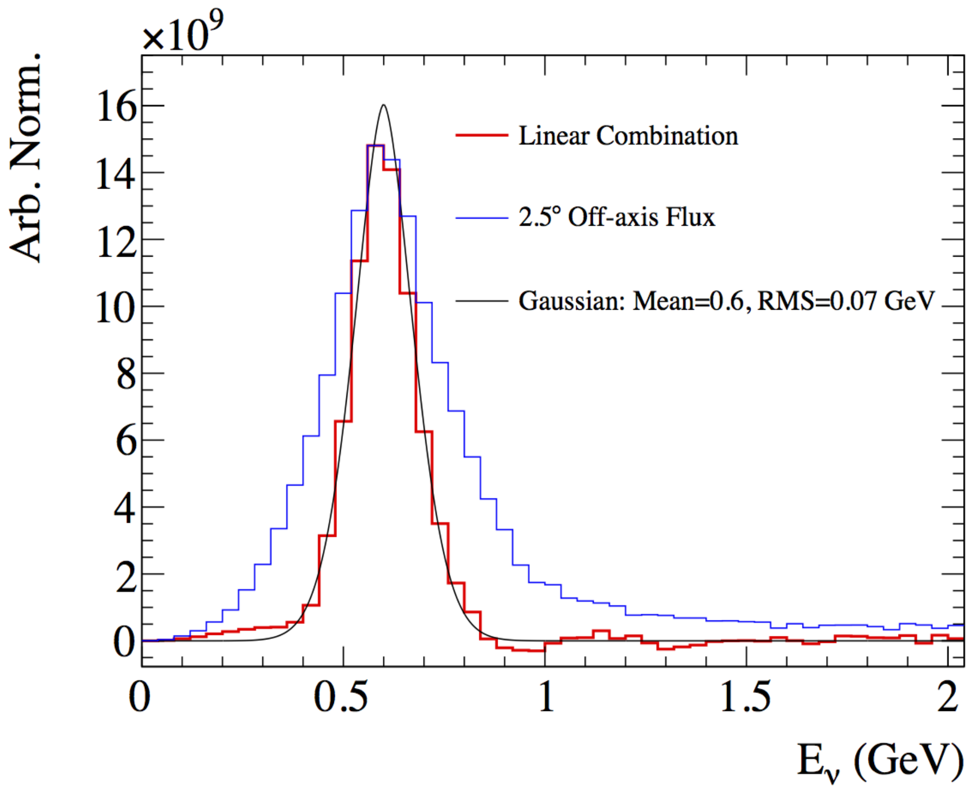
- Using the linear combination method, we can produce Gaussian beams with widths significantly less than an off-axis spectrum peaked at the same energy

$$G(E_\nu;\mu,\sigma)=\sum_{i=1}^{\#\text{ of Off-axis bins}} c_i\varphi_i(E_\nu)$$

- Here the c_i are chose to give the desired mean μ and width σ of the Gaussian
- In practice, the range of μ that can be achieved is limited by the range of peak energies in the off-axis fluxes that nuPRISM observed, ~0.4-1.2 GeV
- The width of the mono-chromatic beam, σ, is limited by the level of statistical and systematic error that can be propagated in the linear combination

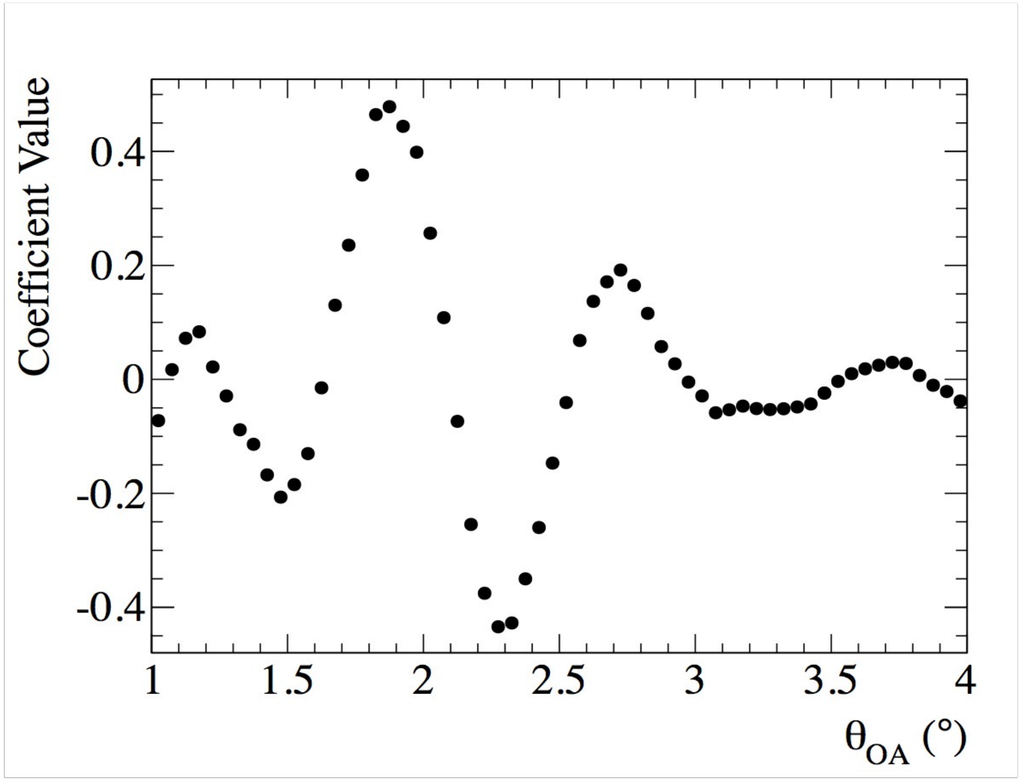
The 600 MeV Gaussian Beam

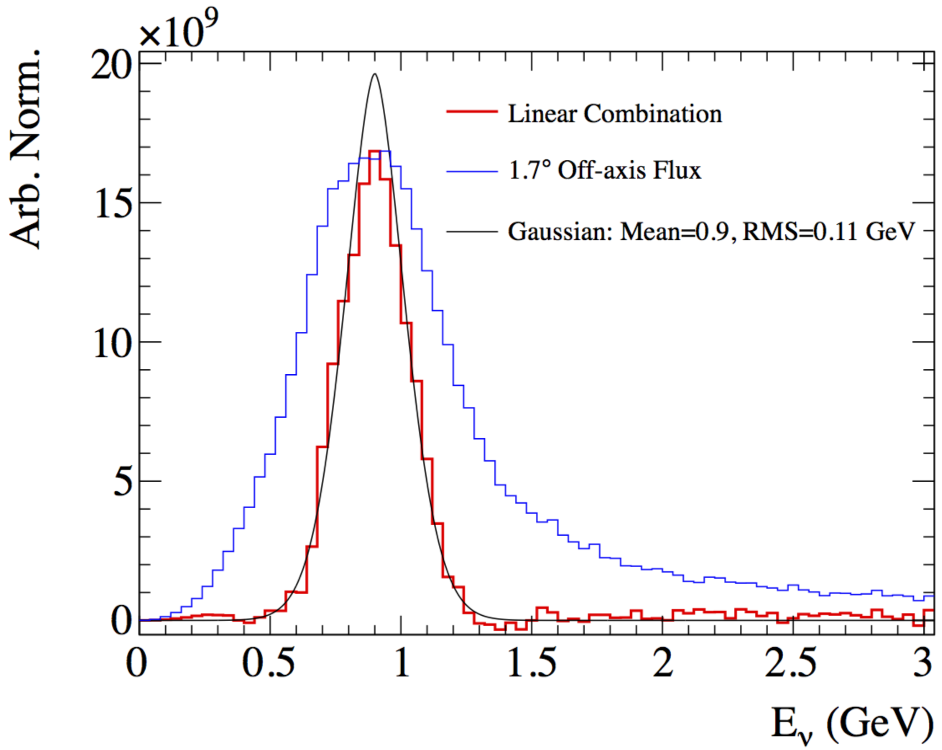




- The choice of coefficients on the left produces the red spectrum on the right
  - Coefficients take the 2.5 degree off-axis flux and subtract of the high and low energy tails
- The red spectrum has a mean of 600 MeV and a width of 70 MeV
- For comparison the 2.5 degree off-axis flux is shown in blue

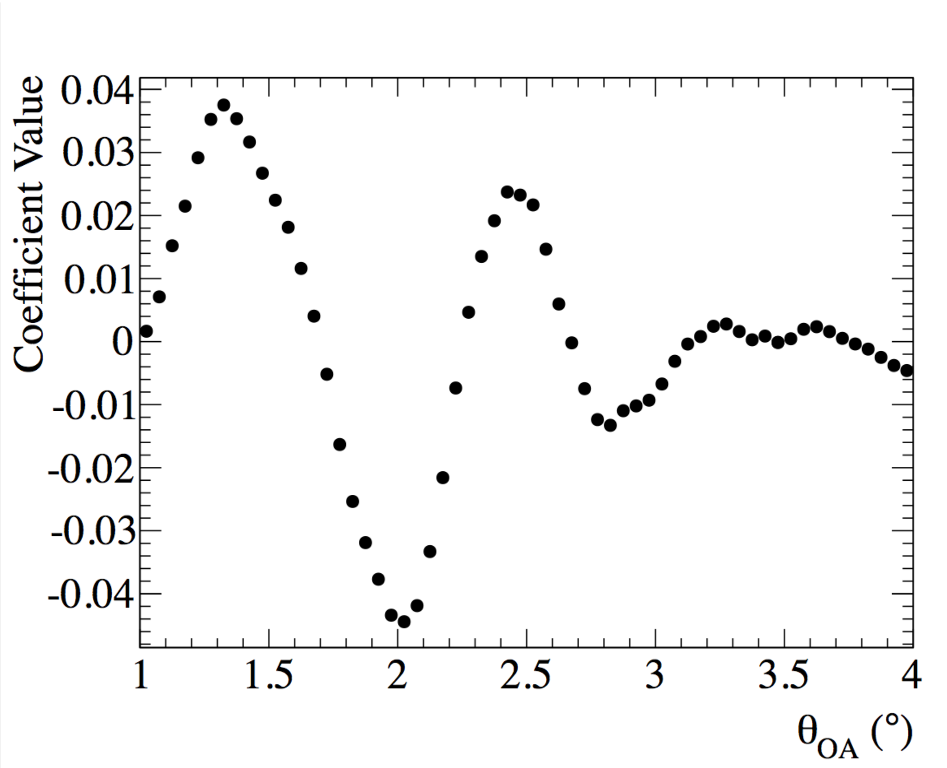
The 900 MeV Gaussian Beam

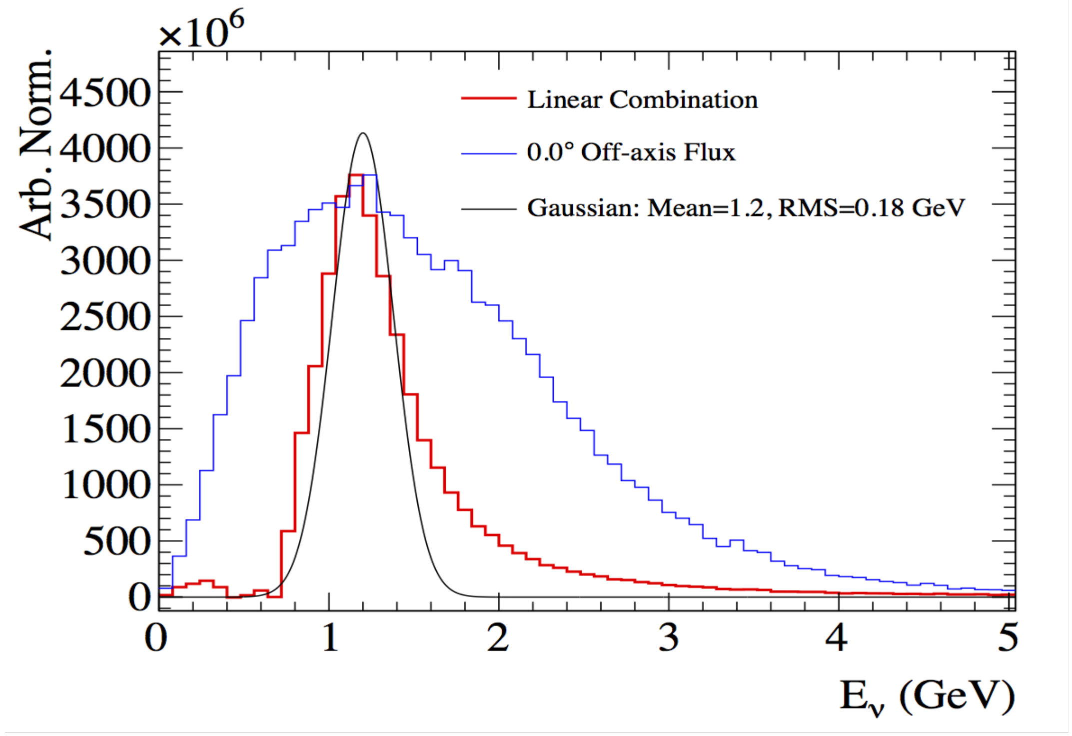




- The choice of coefficients on the left produces the red spectrum on the right
- The red spectrum has a mean of 900 MeV and a width of ~120 MeV
- For comparison the 1.7 degree off-axis flux is shown in blue

The 1200 MeV Gaussian Beam



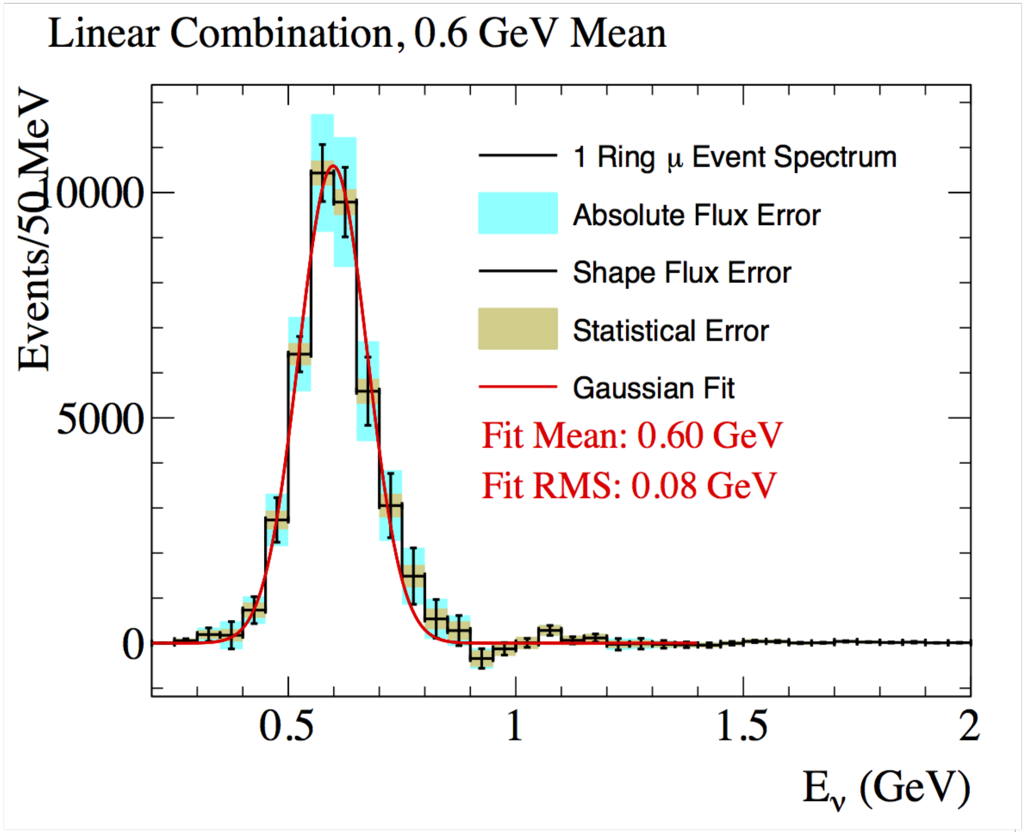


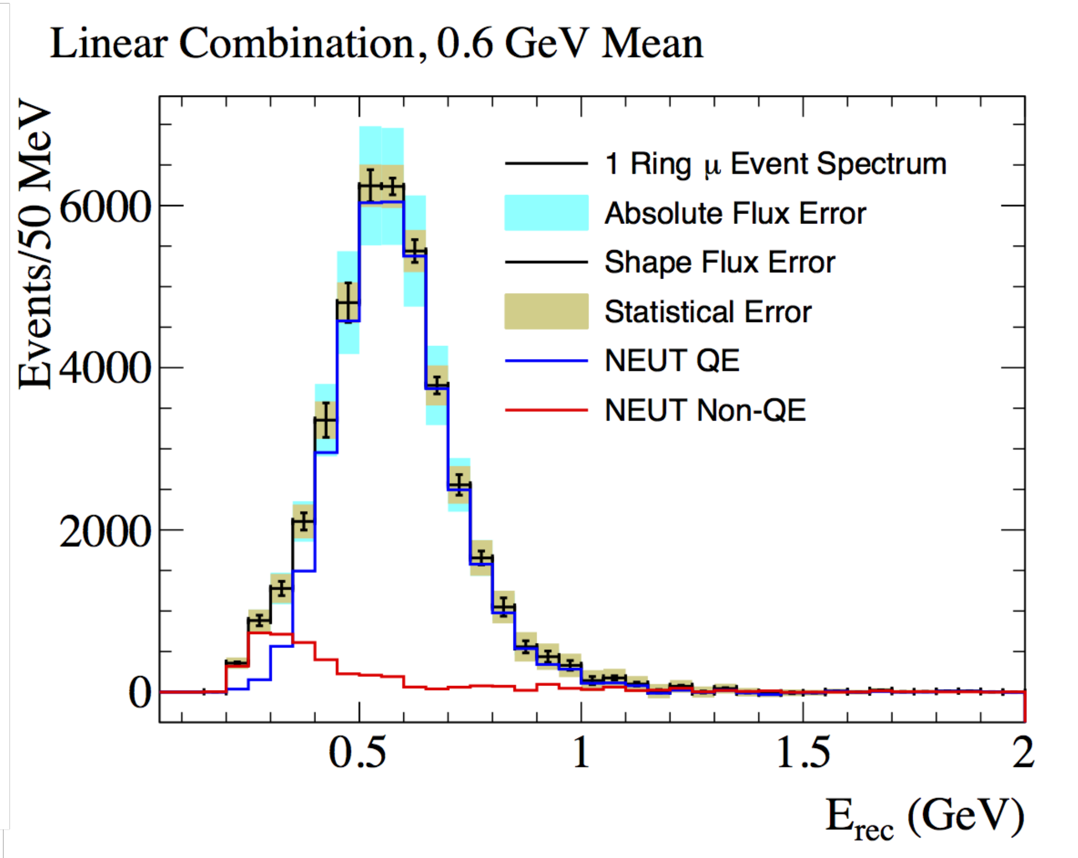
- The choice of coefficients on the left produces the red spectrum on the right
- The red spectrum has a long high energy tail compared to a Gaussian distribution, but it is still significantly smaller than the on-axis flux (blue)

Observable and Systematic Study

- To test the “mono-chromatic” beams, we look at the reconstructed energy distribution of single muon ring candidates
  - The nuPRISM simulation of single muon ring candidates is used to simulate event rates in each off-axis bin
  - The coefficients for the monochromatic beams are applied
- We apply the flux systematic uncertainties and statistical uncertainty for 4.5e20 protons on target

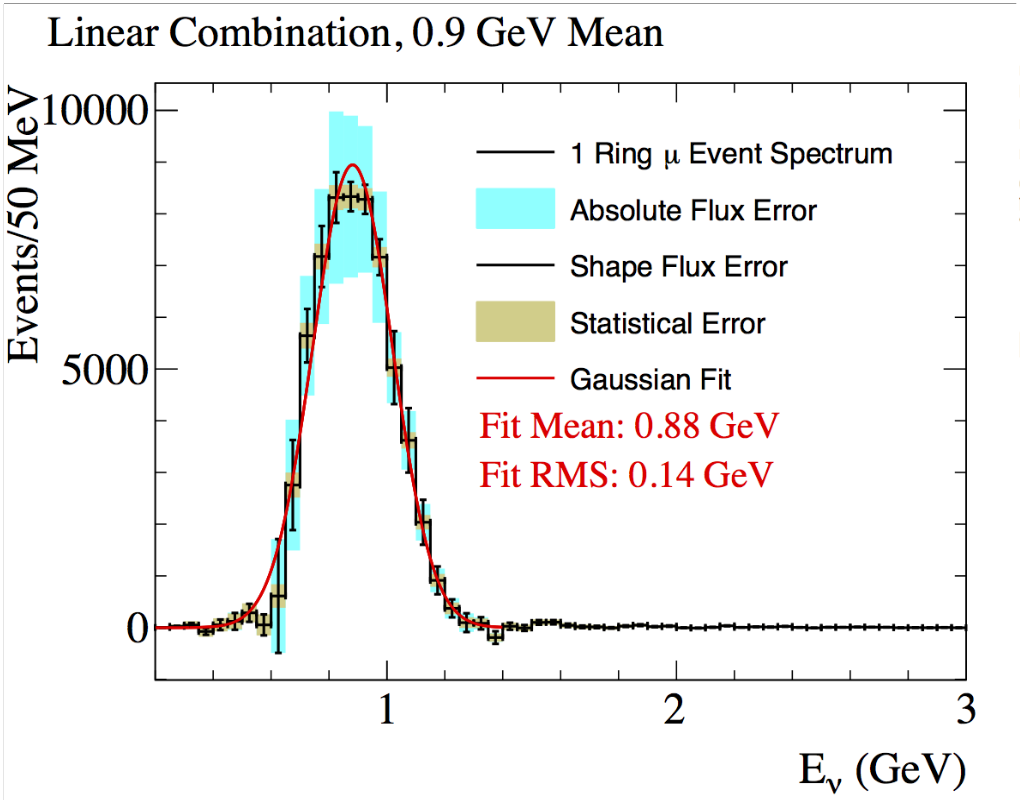
600 MeV Gaussian Beam

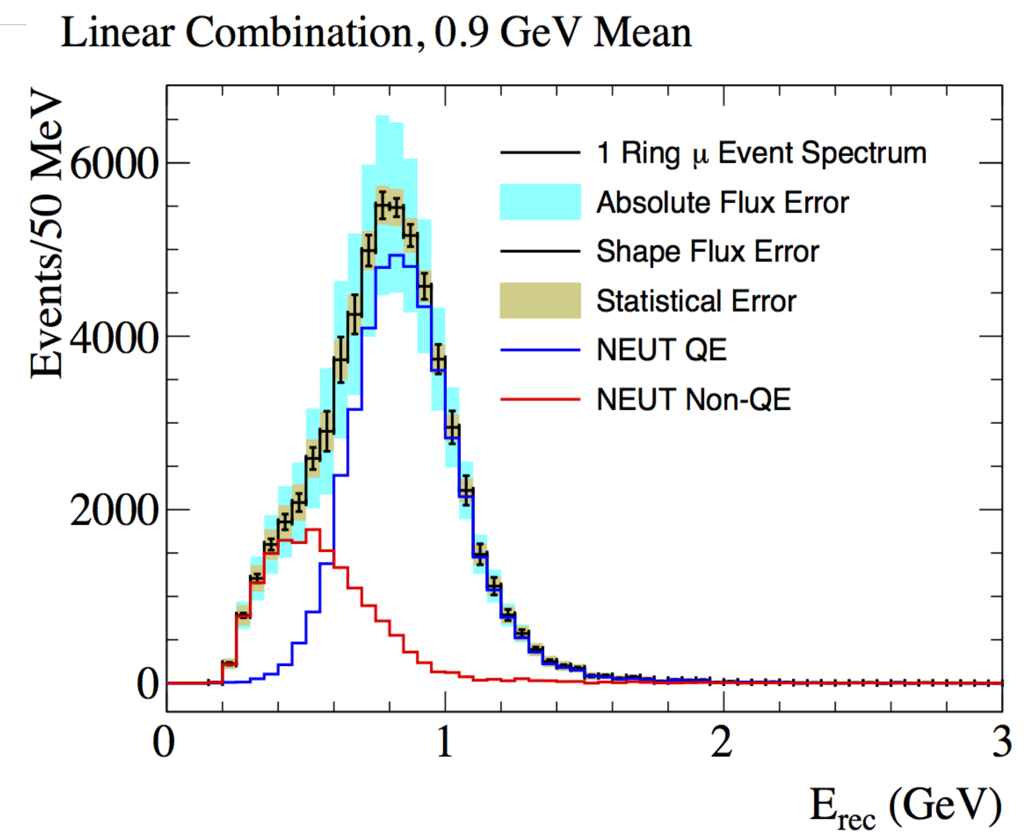




- The true neutrino energy distribution (left) now shows the expected flux and statistical errors
- The reconstructed energy distribution is shown on the right with the breakdown between true QE (blue) and true non-QE (red) events
  - The non-QE contribution is small in NEUT 5.1.4.2 at 600 MeV because they only come from processes related to the production of a Delta resonance

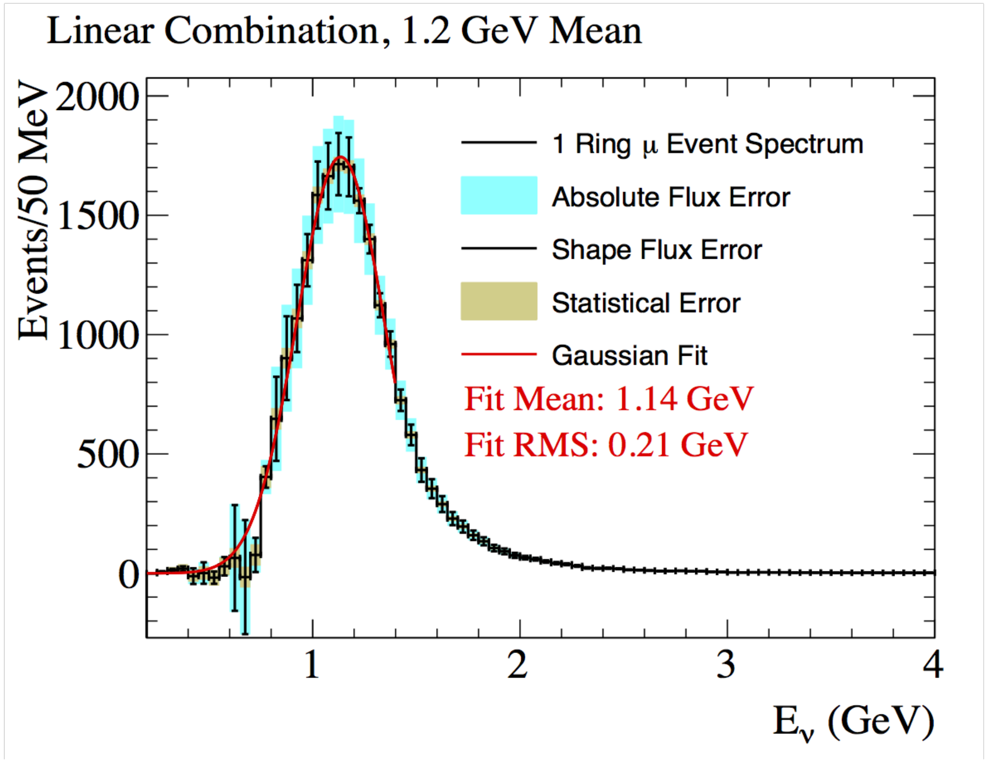
900 MeV Gaussian Beam

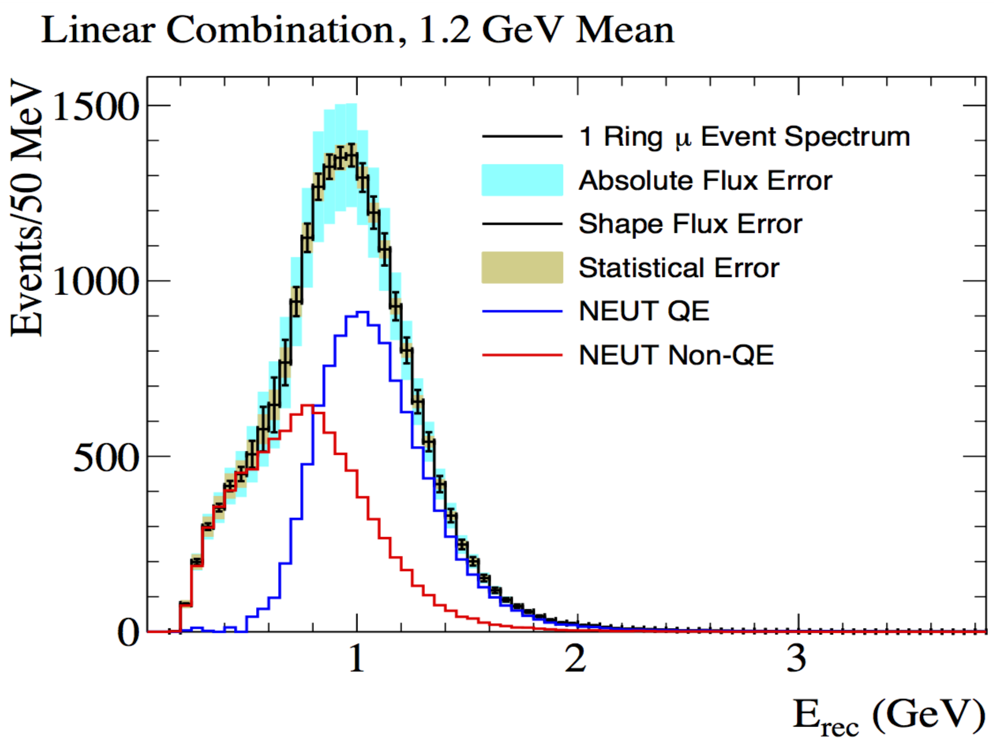




- The true neutrino energy distribution (left) - large flux error around 500 MeV from the horn current uncertainty, under study
- The reconstructed energy distribution is shows a clear excess of non-QE events at low reconstructed energy that is well below the statistical or flux systematic variations

1200 MeV Gaussian Beam





- The true neutrino energy distribution (left) - large flux error around 500 MeV from the horn current uncertainty, under study
- The reconstructed energy distribution is shows a clear excess of non-QE events at low reconstructed energy that is well below the statistical or flux systematic variations
- Some of the efficiency at high reconstructed energy is falling off due to the muon momentum acceptance

Conclusion on Mono-chromatic beams

- The nuPRISM linear combination method can be used to make mono-chromatic beams that are much narrower than the neutrino spectra at individual off-axis angles in the J-PARC beam
- The beams can be peaked at 400-1200 MeV
- The minimization of the beam width in energy is balanced against the propagated systematic and statistical errors in the linear combination
- With the monochromatic beams, the low reconstructed energy tails from nuclear effects can be observed, even accounting for flux systematic uncertainties
- Studies will be updated to include systematic uncertainties on the reconstruction efficiencies

Last Short-Baseline Sterile studies for nuPRISM

JOHN VO, STEFANIA BORDONI, FEDERICO SÁNCHEZ

Institut de Física d'Altes Energies IFAE

EXCELENCIA SEVERO OCHOA

Introduction

- We started doing two kind of analyses:

1. **ν_e-only analysis:** considering only the expected signal (ν_e^{signal}).
2. **RATIO (ν_e/ν_μ) analysis**: considering the ratio between the expected signal (ν_e^{signal})and the amount of *the expected ν_μ candidates*.

- The steps we follow are:

1) Select the ν_e candidates (background), binning in the reconstructed energy (E_{REC}) and off-axis angle (OAA)
2) Multiply it for the $\left(\frac{\nu_\mu}{\nu_e}\right)$ flux ratio: $\#\,\nu_\mu^{unoscillated} = \#\,\nu_e \times \frac{\Phi_{\nu_\mu}}{\Phi_{\nu_e}} = \Phi_{\nu_e} \times \varepsilon_e \times \sigma_e \times \frac{\Phi_{\nu_\mu}}{\Phi_{\nu_e}} = \Phi_\mu \times \varepsilon_e \times \sigma_e$
3) Apply the Oscillation probability: $\nu_e^{signal} = \#\,\nu_\mu^{unoscillated} \times P_{\nu_\mu \to \nu_e}(\theta, \Delta m^2)$
4) Compute the sensitivity maps with the chi square: $\chi^2 = \left(\nu_e^{signal}\right)^T \times V^{-1} \times (\nu_e^{signal})$

Outline

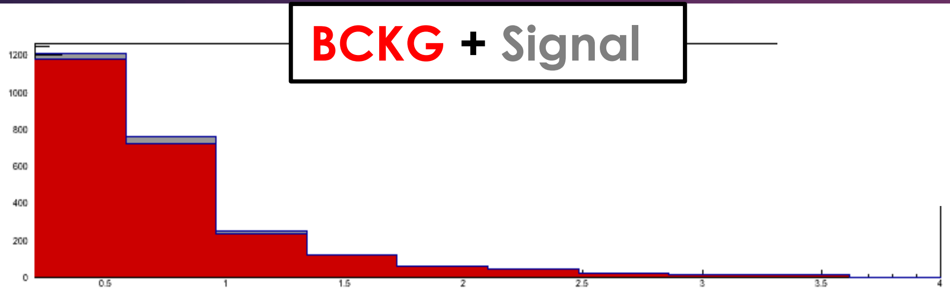
- We are only showing $\boldsymbol{\nu_e}$**-only analysis** results in this talk:
  A. First of all,we will show the signal and background distributions for the 4.6×10^{20} p.o.t.
  B. We will show the LoI sensitivity results, where we used the MiniBooNE ANTINUE contours*.
  C. Then we will show the same results but with MiniBooNE Nue contours, to stablish a clearer comparison.
  D. We will present the signal and background distributions for the HK statistics (1.56×10^{22}) and the sensitivity plots, both for NUE and ANTINUE MiniBooNE contours.
  E. Conclusions and outlook

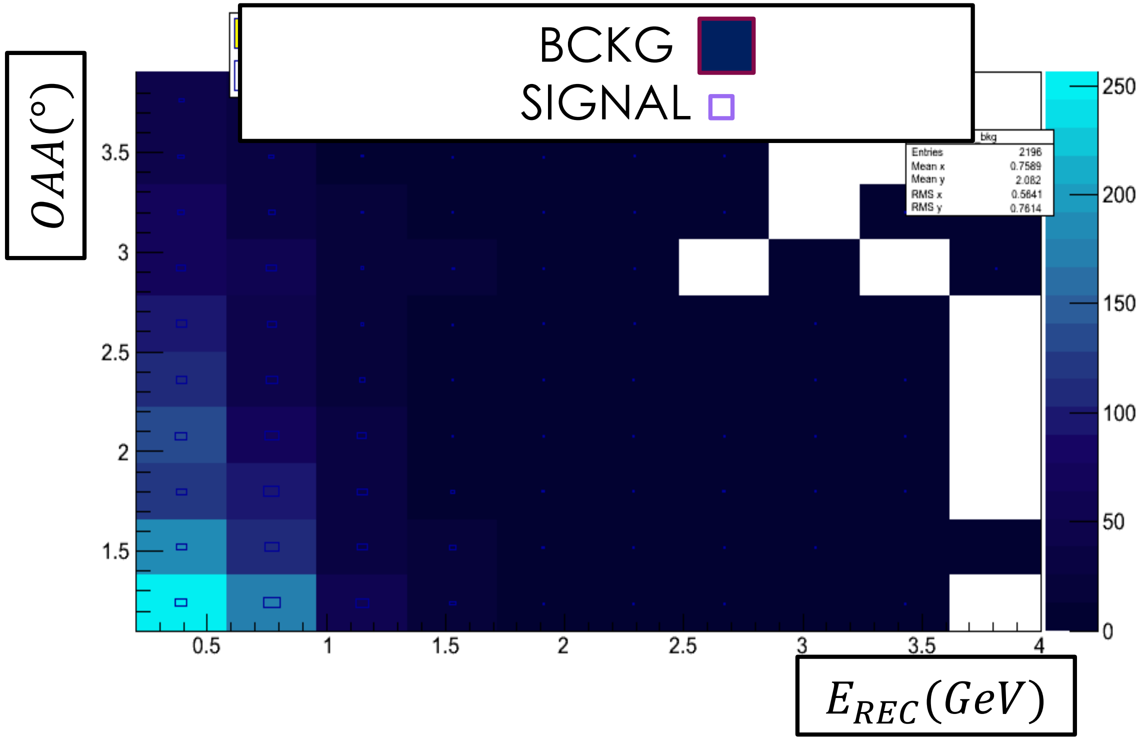
*: this choice was made due to the fact that at 3σ C.L. MiniBooNE NUE mode contours were not constraining the lower $\sin^2(2\theta)$ region. Since we are just presenting 90% C.L., we decided to move also to the MiniBooNE NUE mode results.

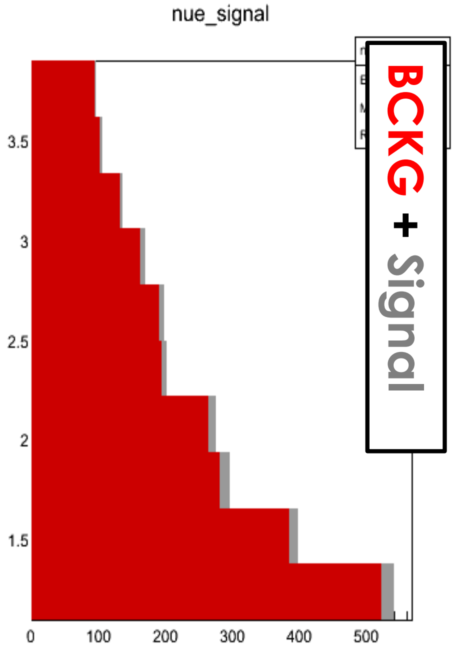
Signal and BCKG distributions

3m case

$4.6 \cdot 10^{20}$ p.o.t







BCKG = 2326
Signal = 86

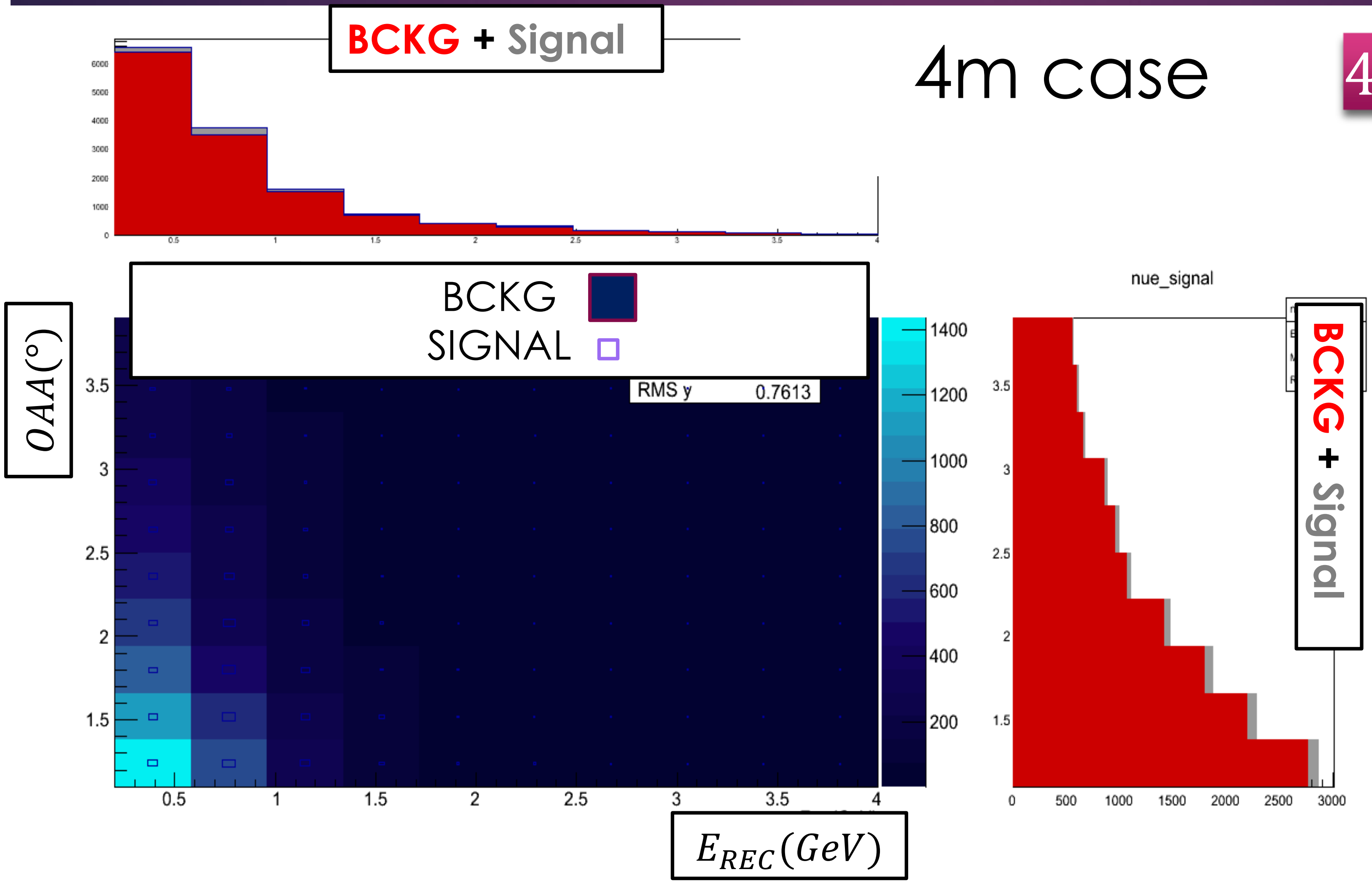
Background Composition:

$\#(CC\nu_e) = 1018$ (~48%)
$\#(CC\nu_\mu) = 1308$ (~52%)

Signal and BCKG distributions

4m case

$4.6 \cdot 10^{20}$ p.o.t



BCKG = 12901
Signal = 466

Background Composition:

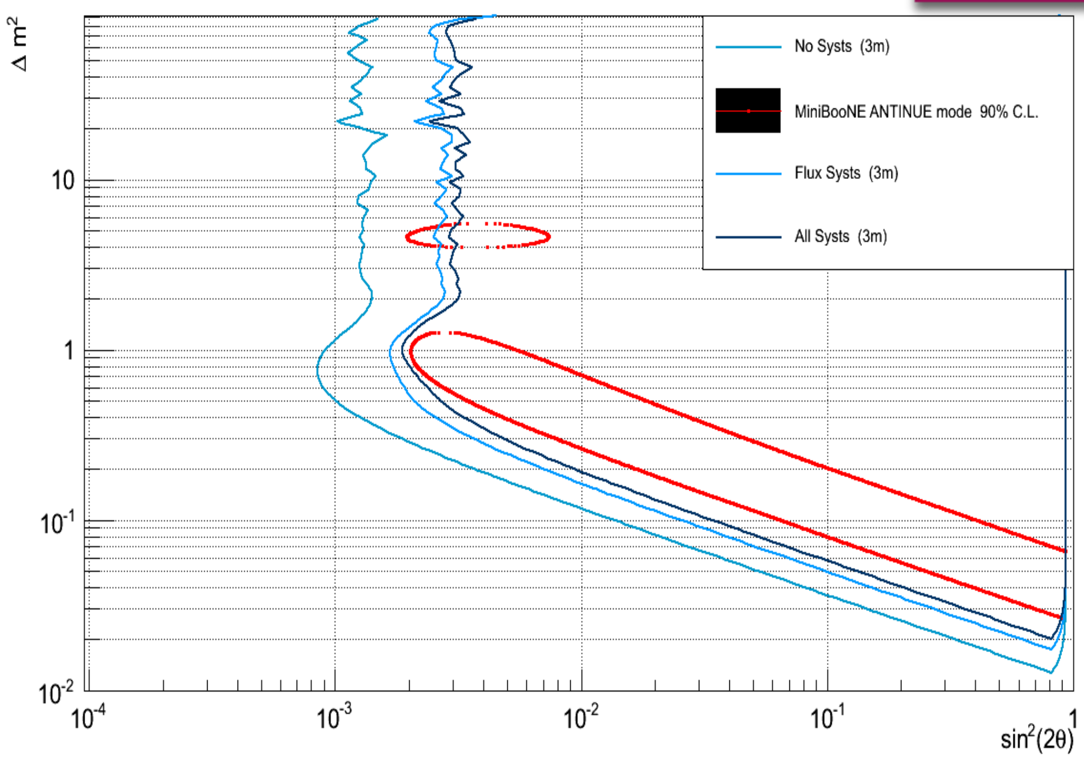
$\#(CC\nu_e) = 6162$ (~48%)
$\#(CC\nu_\mu) = 6739$ (~52%)

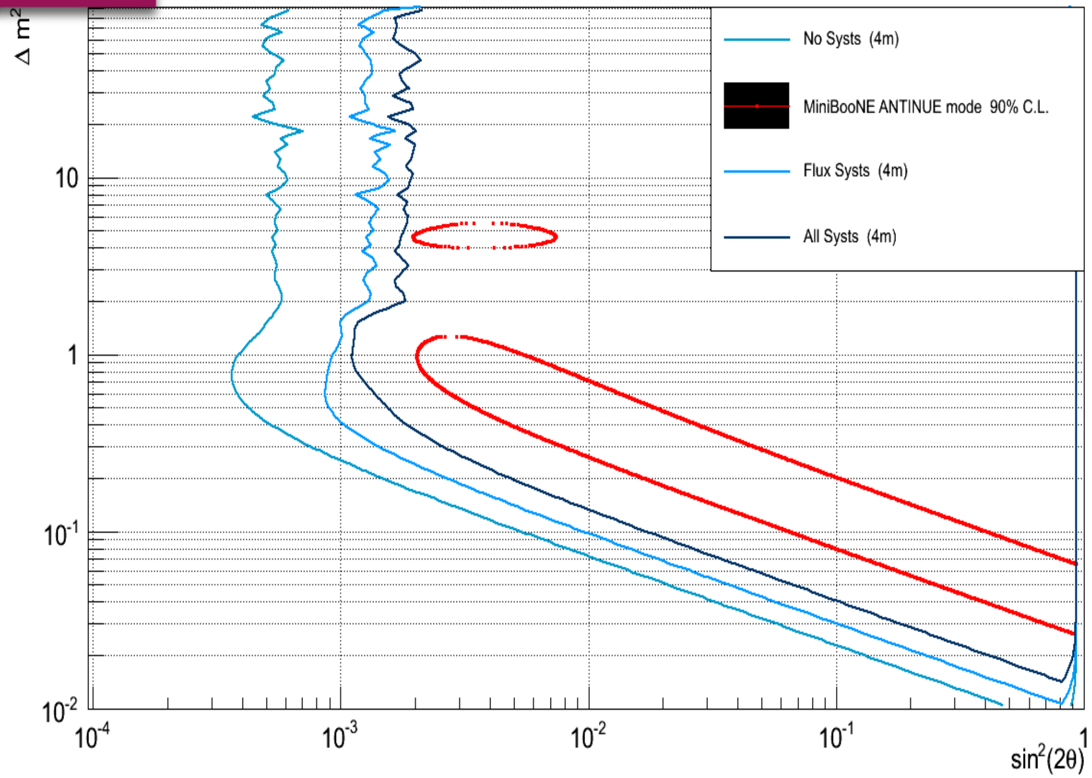
Sterile Sensitivity Maps (LoI Results)

3m case

$4.6 \cdot 10^{20}$ p.o.t

4m case





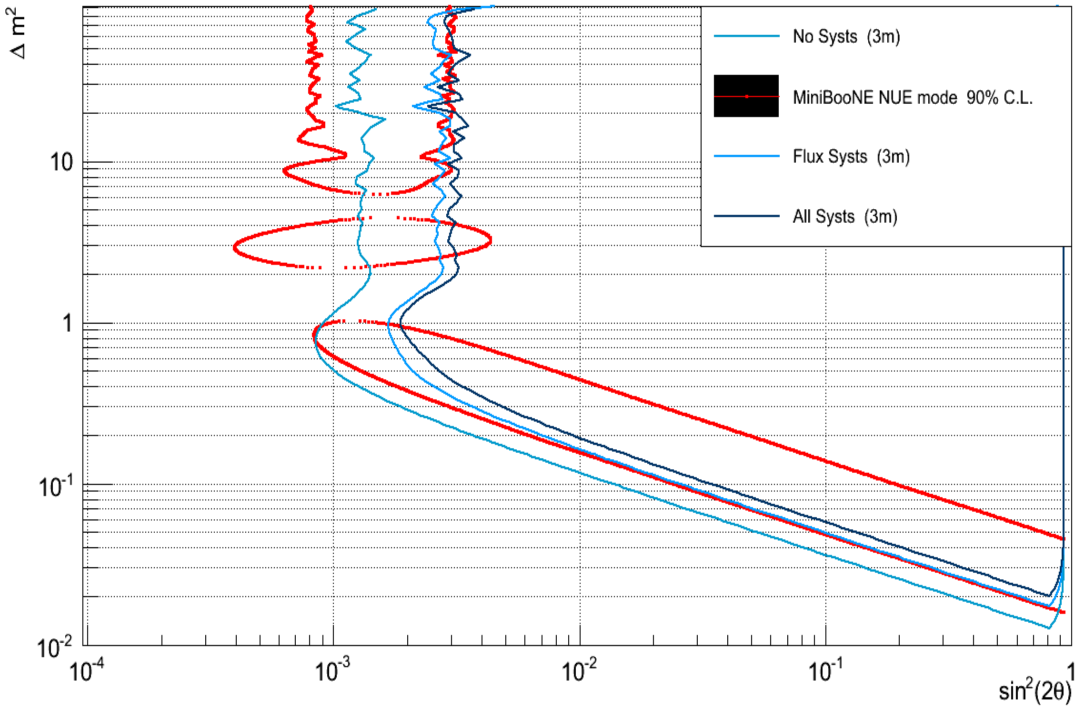
MiniBooNE AntiNUE mode 90% C.L. contours

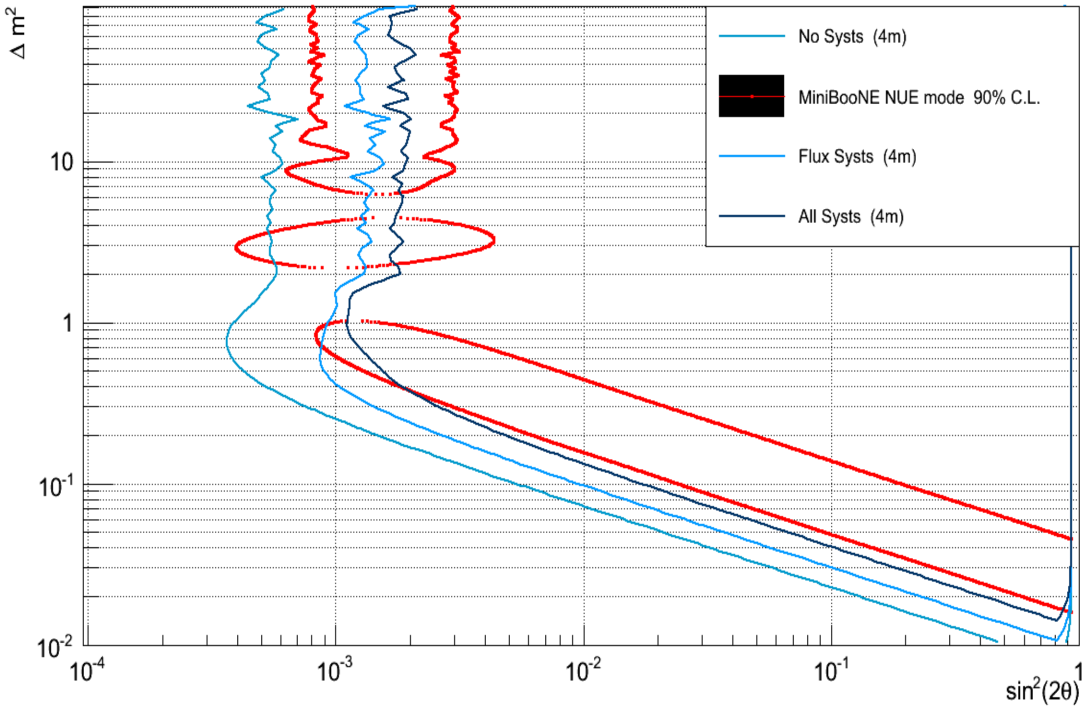
Sterile Sensitivity Maps (MiniBooNE Nue mode contours)

3m case

$4.6 \cdot 10^{20}$ p.o.t

4m case





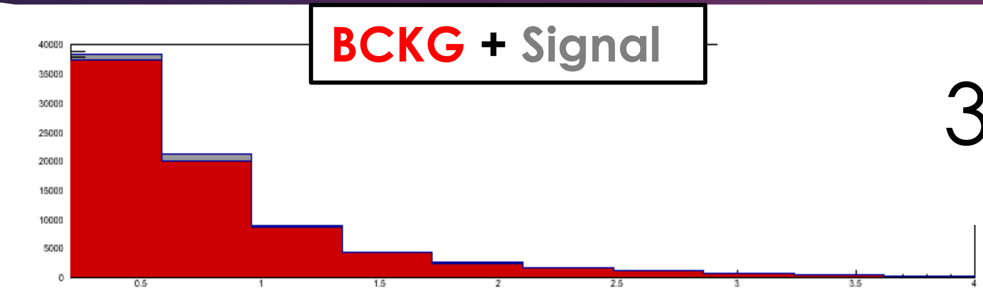
MiniBooNE NUE mode 90% C.L. contours

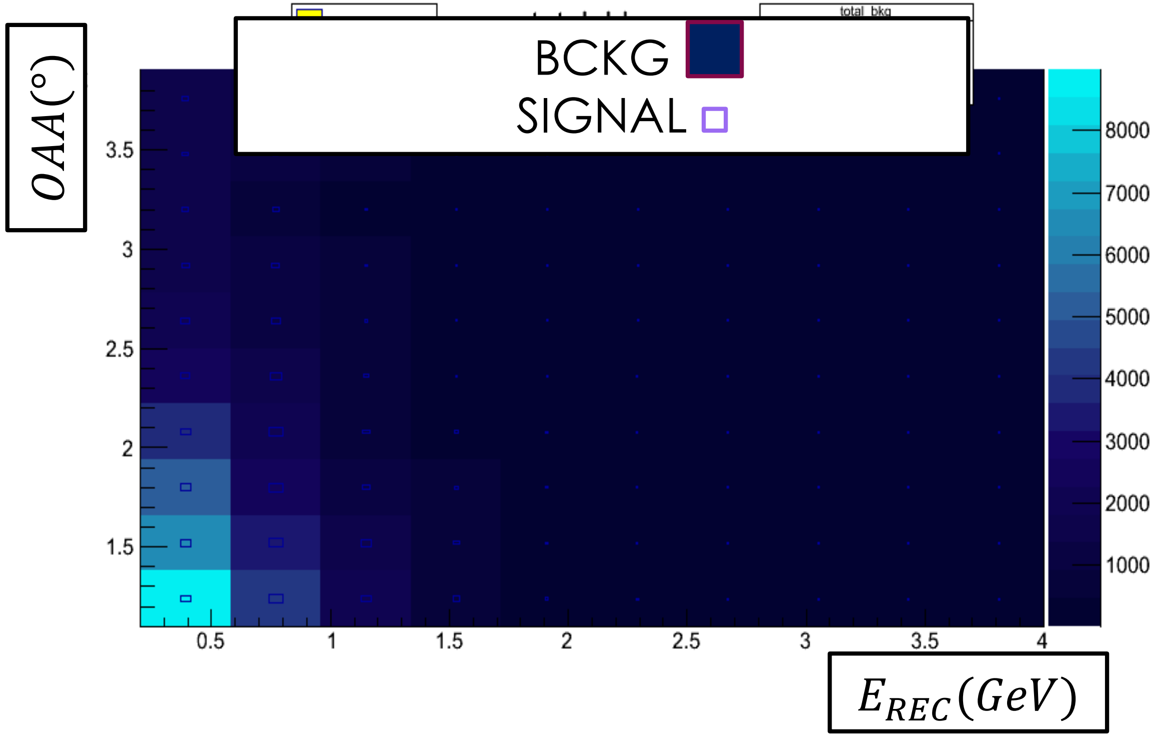
Hyper-Kamiokande Sterile Sensitivity Maps

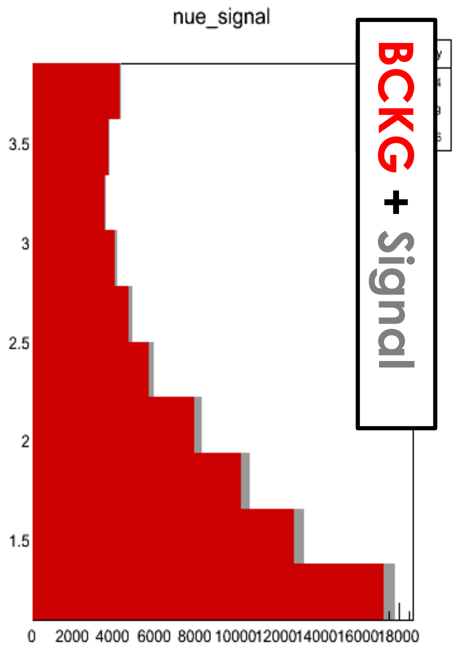
Signal and BCKG distributions (HK statistics)

3m case

$1.56 \cdot 10^{22}$ p.o.t







BCKG = 74237
Signal = 2610

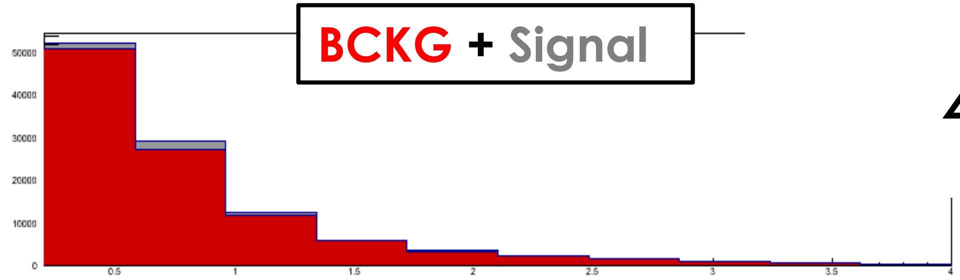
Background Composition:

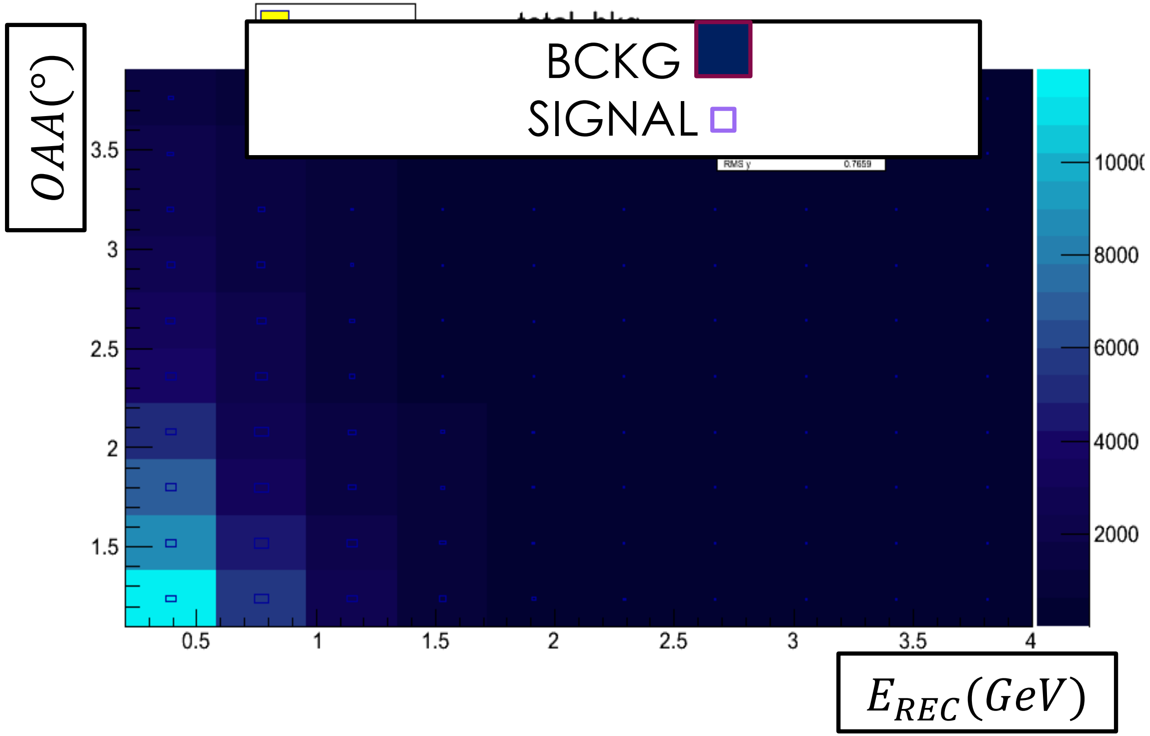
$\#(CC\nu_e) = 34684$ (~47%)
$\#(CC\nu_\mu) = 39552$ (~53%)

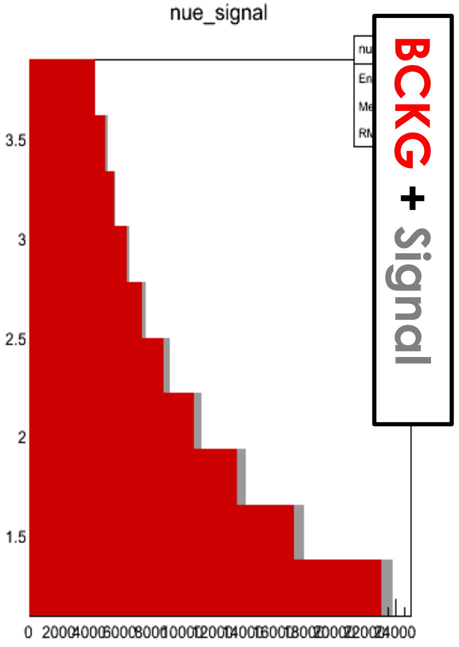
Signal and BCKG distributions (HK statistics)

$1.56 \cdot 10^{22}$ p.o.t

4m case







BCKG = 102071
Signal = 3662

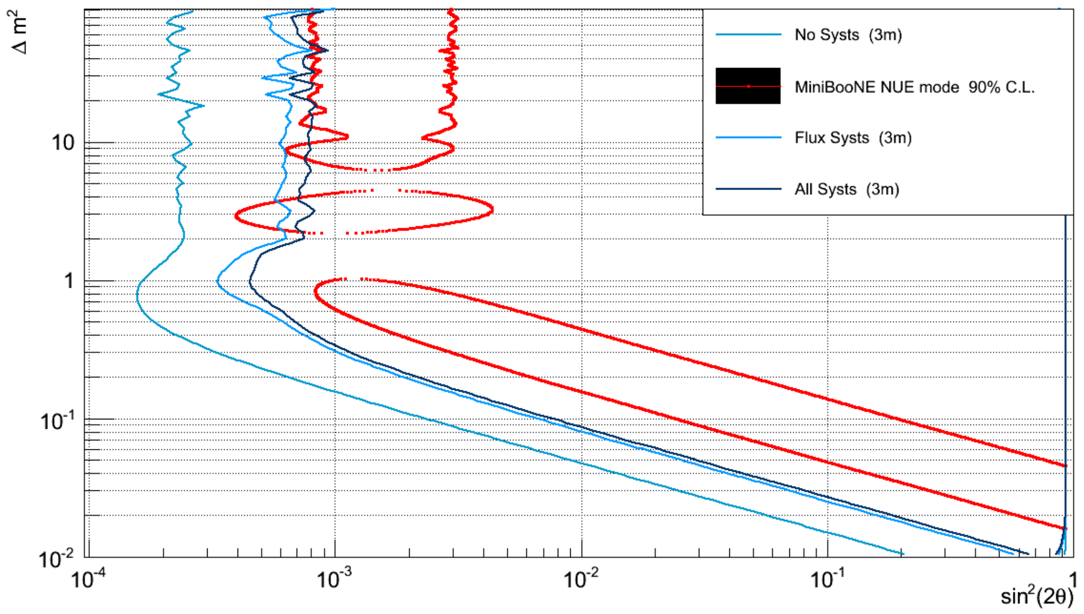
Background Composition:

$\#(CC\nu_e) = 48393$ (~47%)
$\#(CC\nu_\mu) = 53678$ (~54%)

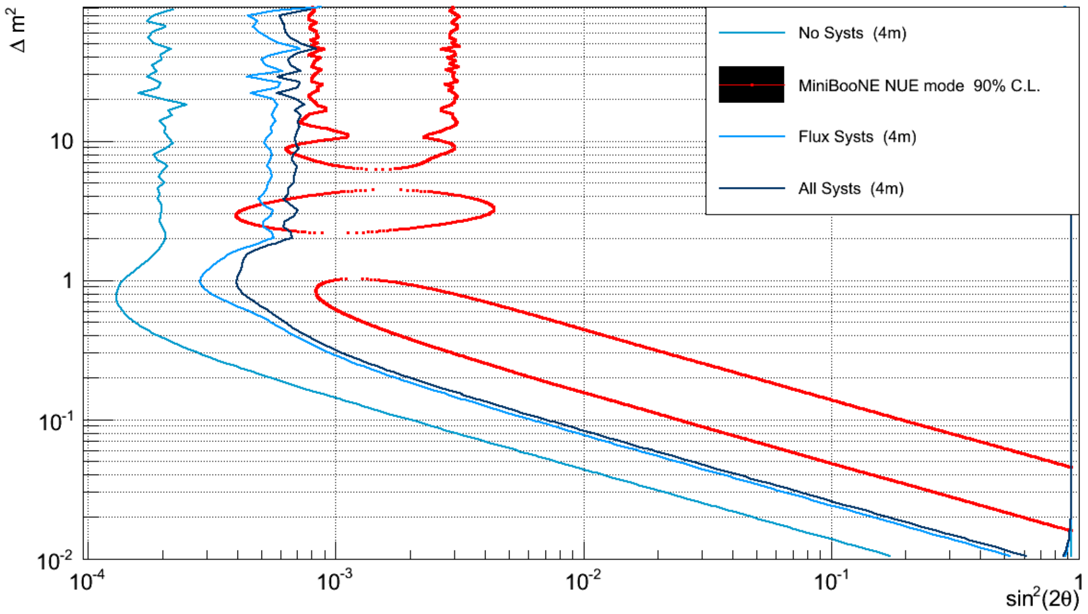
HK statistics Sterile Sensitivity Maps (MiniBooNE Nue mode contours)

$1.56 \cdot 10^{22}$ p.o.t

3m case



4m case



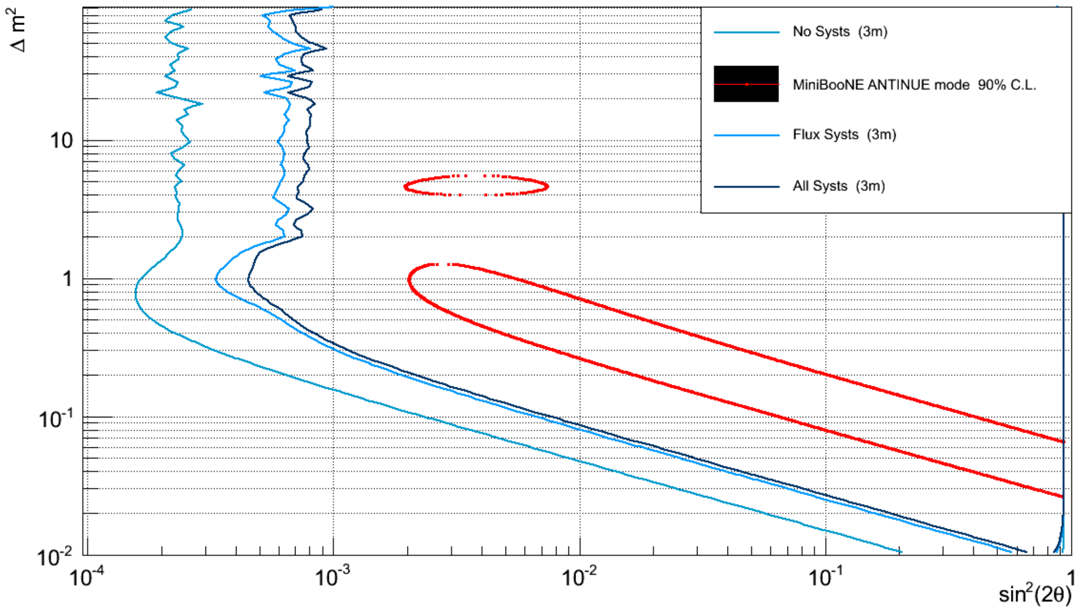
MiniBooNE NUE mode 90% C.L. contours

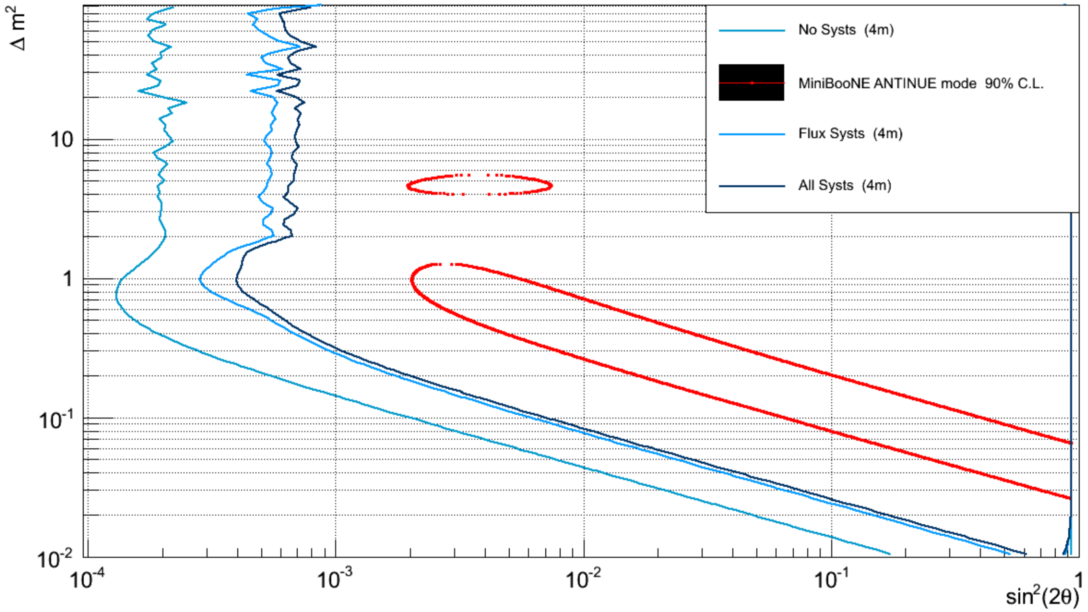
HK statistics Sterile Sensitivity Maps (MiniBooNE Nue mode contours)

3m case

$1.56 \cdot 10^{22}$ p.o.t

4m case





MiniBooNE NUE mode 90% C.L. contours

Conclusions

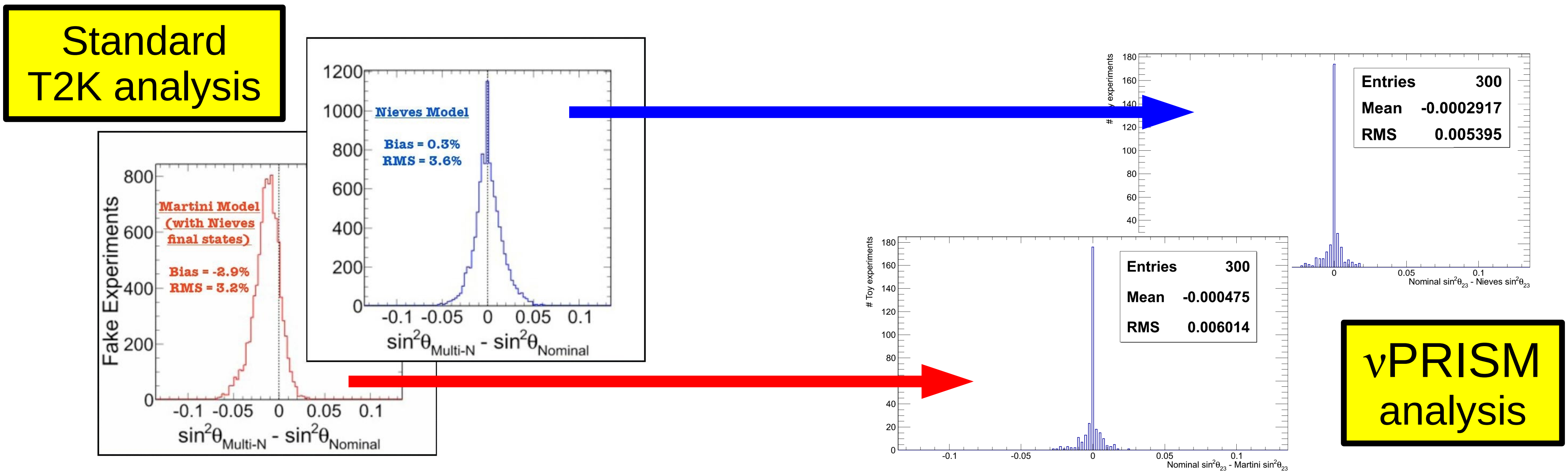
- Several sensitivity studies at 90% C.L. have been presented considering **different sizes** of the inner detector radius and **different exposures**.
  1. With our current p.o.t ($4.6 \cdot 10^{20}$):
     1. We can cover half the region (4m) of the MiniBooNE results in the NUE mode due to the fact that it extends the lower $\sin^2(2\theta)$ → **Control of the systematics** is crucial to improve our sensitivities.
     2. We can almost fully cover the MiniBooNE ANTINUE mode (both 3m and 4m).
  2. With HK statistics ($1.56 \cdot 10^{22}$ p.o.t):
     1. We can almost fully cover it in the NUE mode (both 3 and 4m) → Control of the systematics is crucial to improve our sensitivities, specially for the 3m case.
     2. In the ANTINUE mode, we can fully cover it by far (both 3 and 4m).

Other studies ongoing

- We are working in the field of **reducing the systematics**:
  1. For that purpose, we are trying to calculate how ND280 constraints would improve the sensitivity results (we plan to apply a flat reduction factor in the systematics based on the 2013 oscillation analyses results).
  2. We are also working on the ν_e and ν_μ combination options, trying to construct a bigger covariance matrix that take into account correlations coming from both contributions at the same time. Also, we keep on researching in the RATIO analyses taking advantage of events with similiar energy and off-axis angle.
  3. We started doing studies about the impact of the BINNING in the correlations, and so, how is the impact on the systematics.
- We will present a review of these ongoing studies at the **nuPRISM meeting on Sunday**

ν_μ disappearance analysis status

- Previously - νPRISM disappearance analysis unaffected by unknown nuclear model
- Incomplete MC model did not change the fitted oscillation parameters



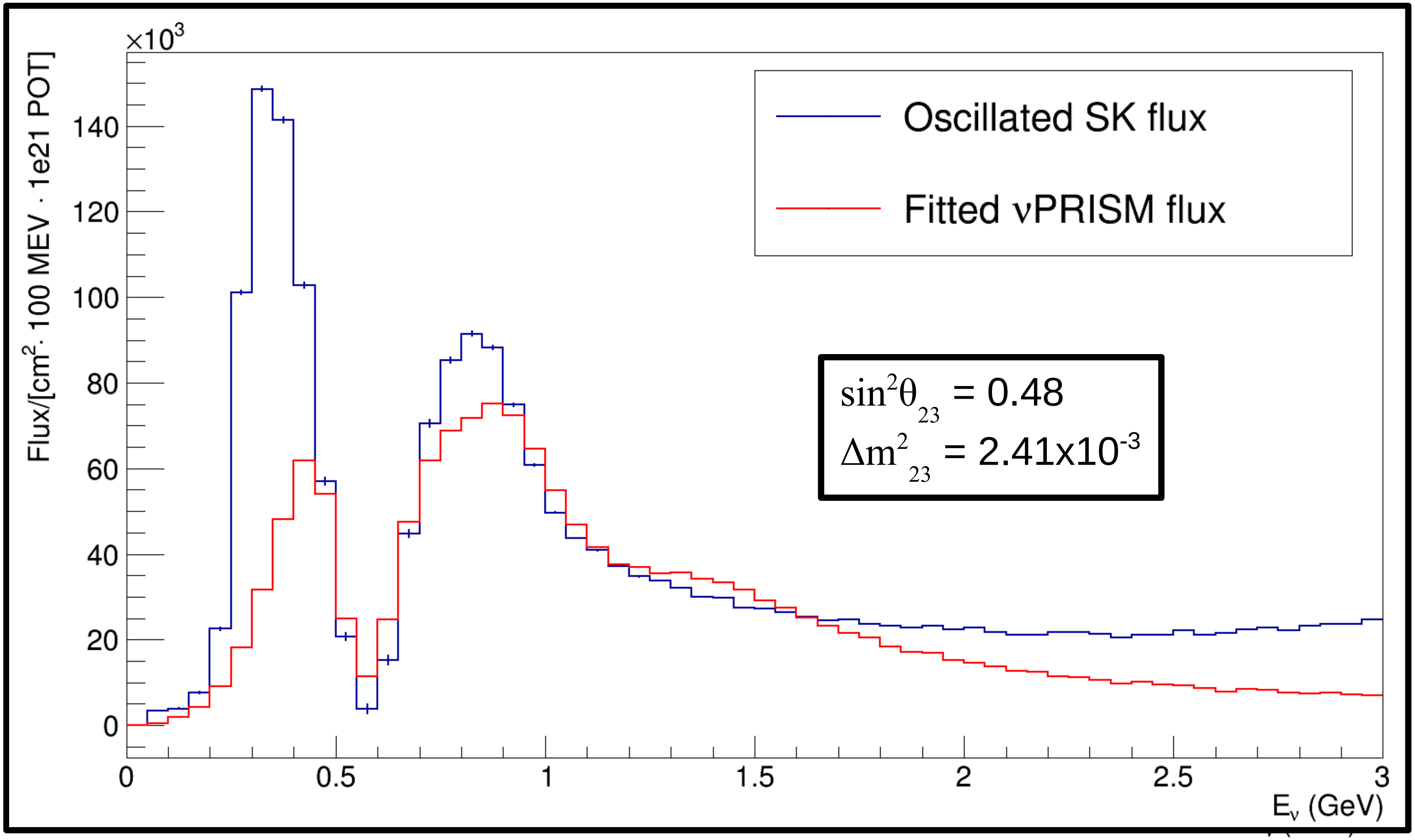
- Bug found in statistical uncertainty calculation
  - scaled down number of events at νPRISM by factor of 40

Does this affect the previous analysis?

- Not much:
  - Only effect was to increase statistical uncertainty by factor of 6.3 ($\sqrt{40}$)
- Insensitivity to nuclear effects still valid
- Only the disappearance analysis used this code, nothing else affected

What can we do with this?

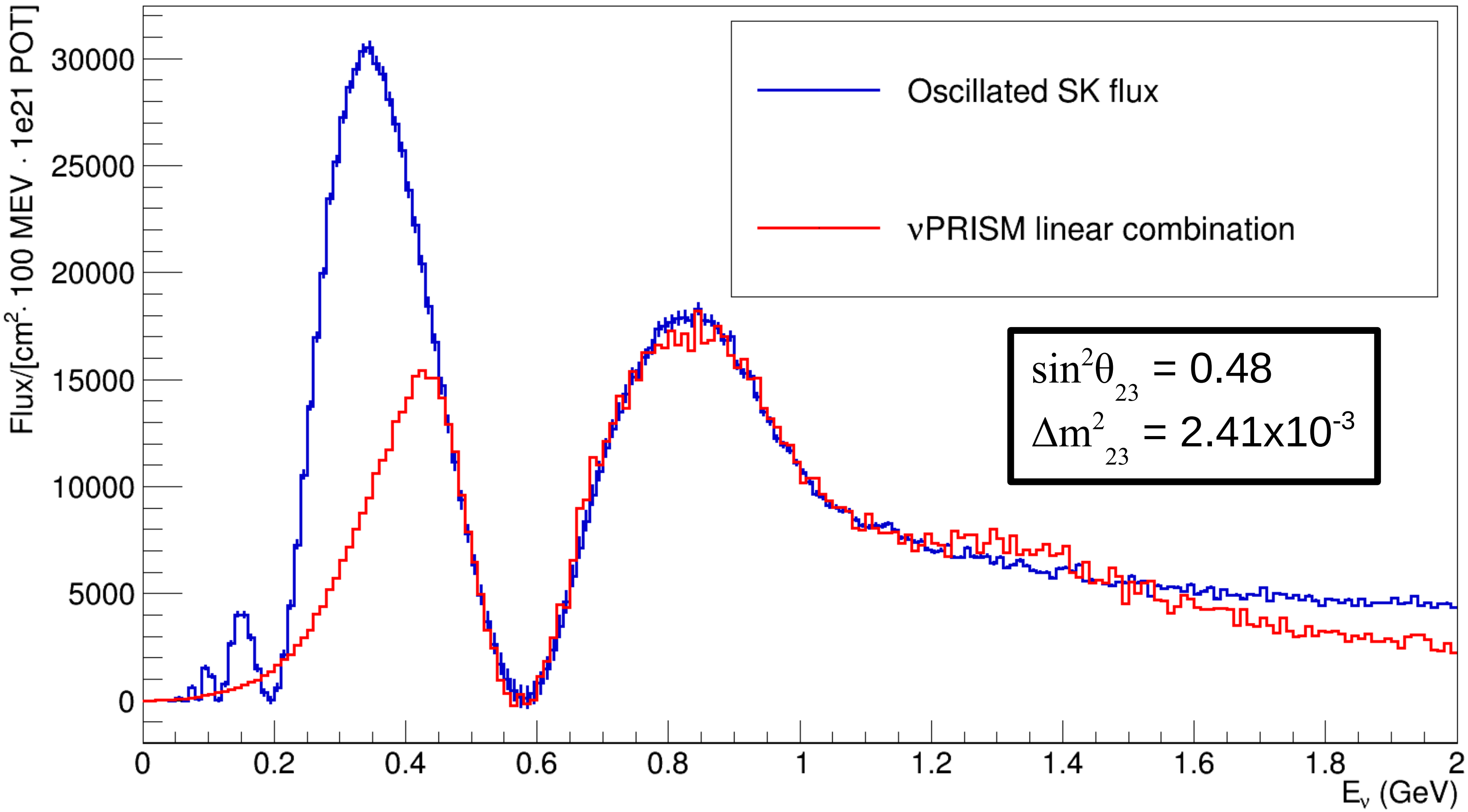
- Make better flux fits!
- Previously, large statistical uncertainty limited how well we could fit the oscillated SK flux



νPRISM

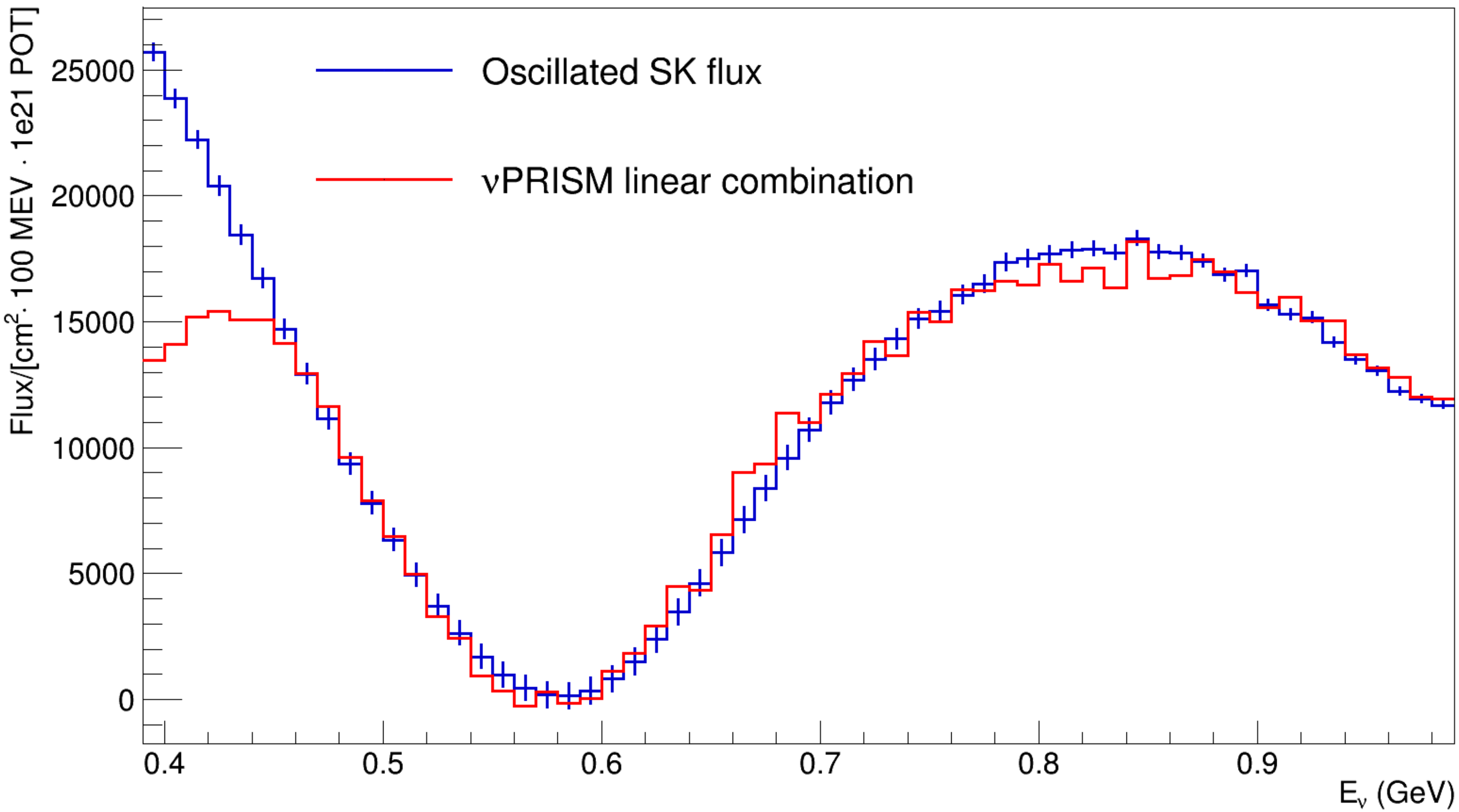
What can we do with this?

- Make better flux fits!
- Previously, large statistical uncertainty limited how well we could fit the oscillated SK flux
- Now we can do much better



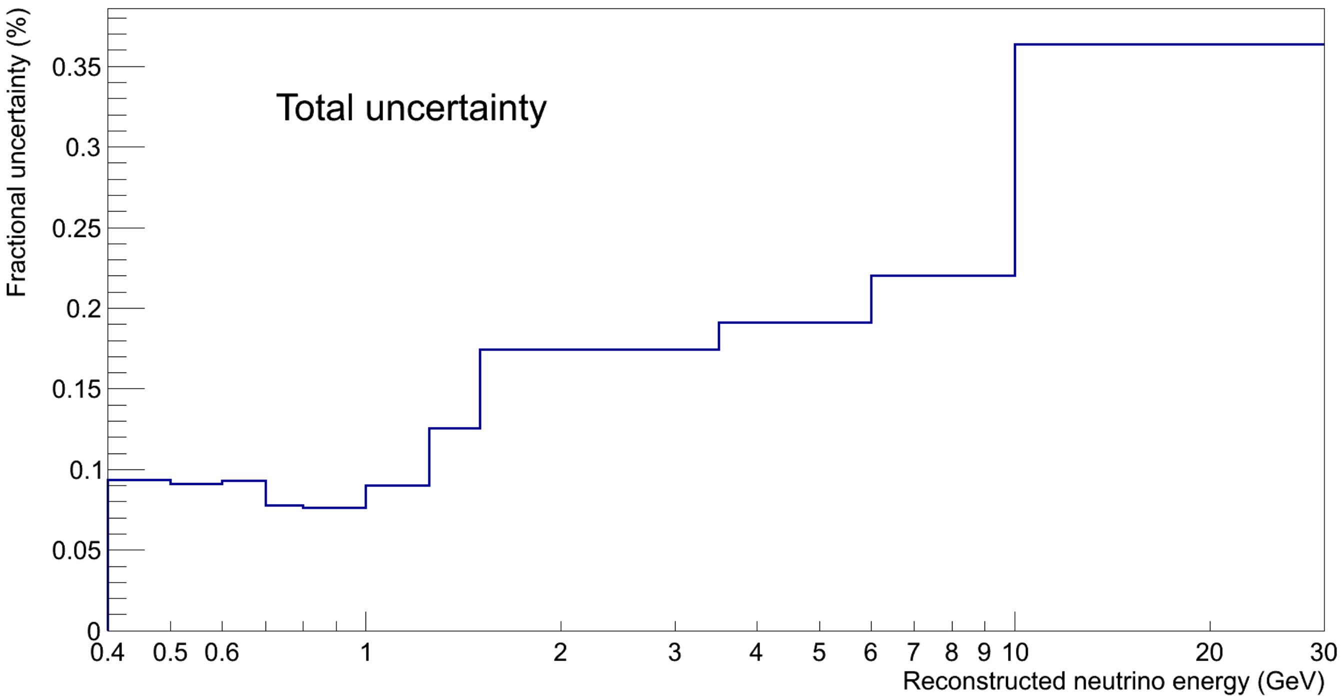
What can we do with this?

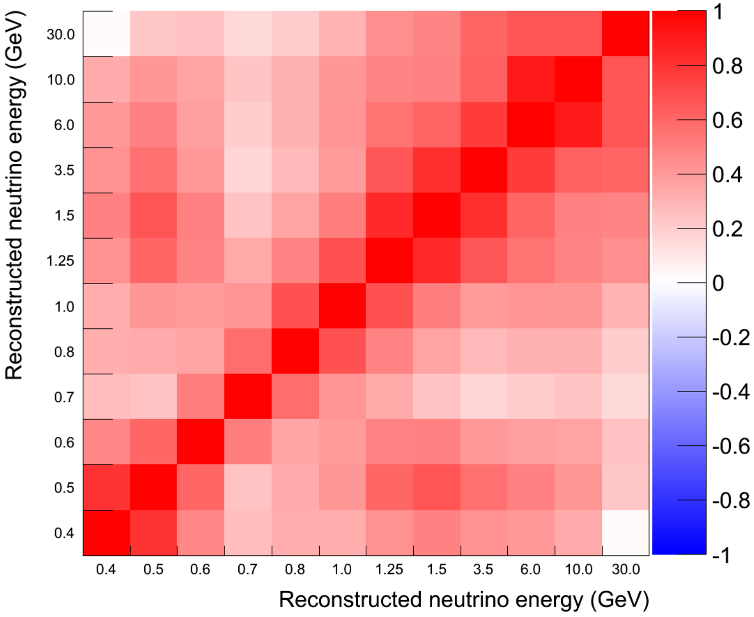
- Make better flux fits!
- Previously, large statistical uncertainty limited how well we could fit the oscillated SK flux
- Now we can do much better



Previous analysis uncertainty

- Total uncertainty on the predicted event spectrum at SK, including statistical and systematic sources

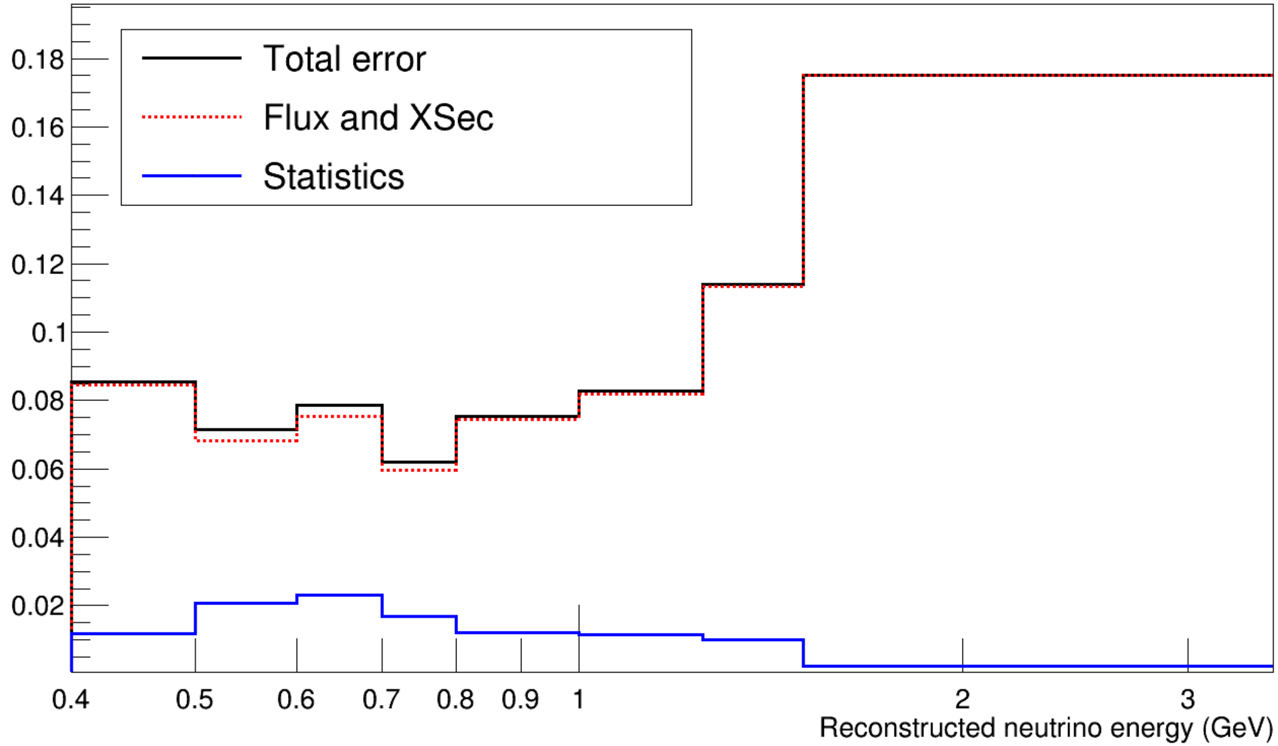


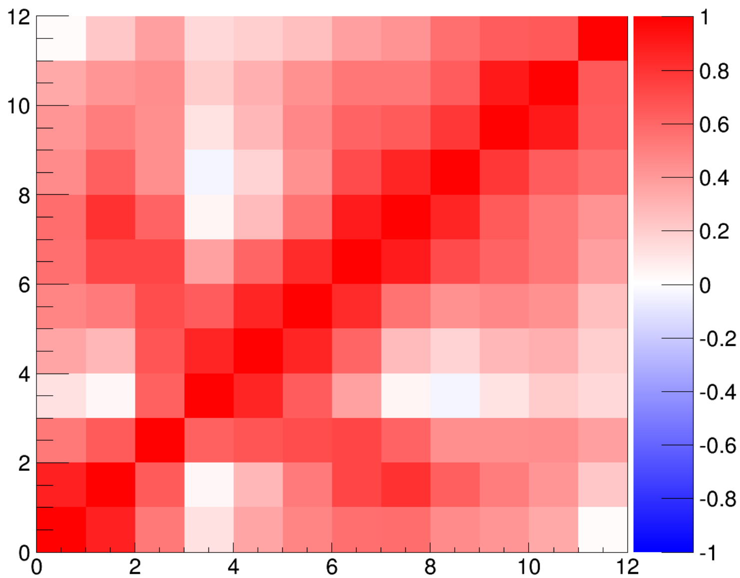


- Total uncertainty is <10% at oscillation peak
- ~7% statistical, 6% systematic

New uncertainties

- At oscillation point: $\sin^2\theta = 0.5$, $dm^2 = 2.41e^{-3}$
- Total uncertainty in oscillation dip < 8%





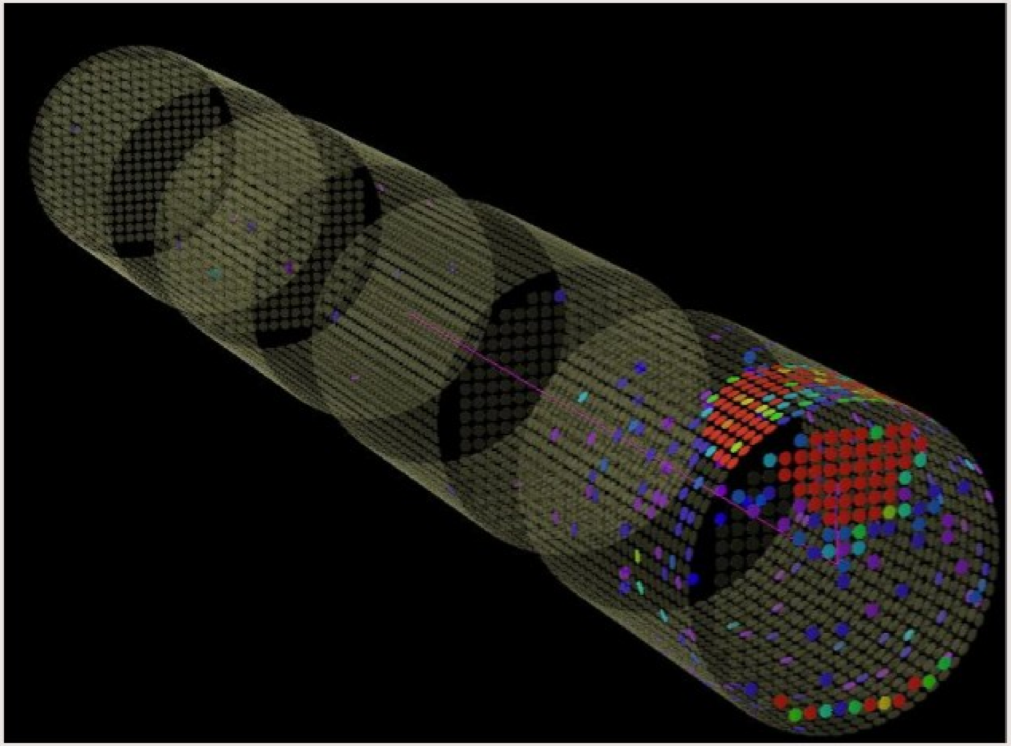
- Correlation matrix very similar shape to previous analysis
- Statistical uncertainty dropped, but flux uncertainty increased – expected (see backup slides)

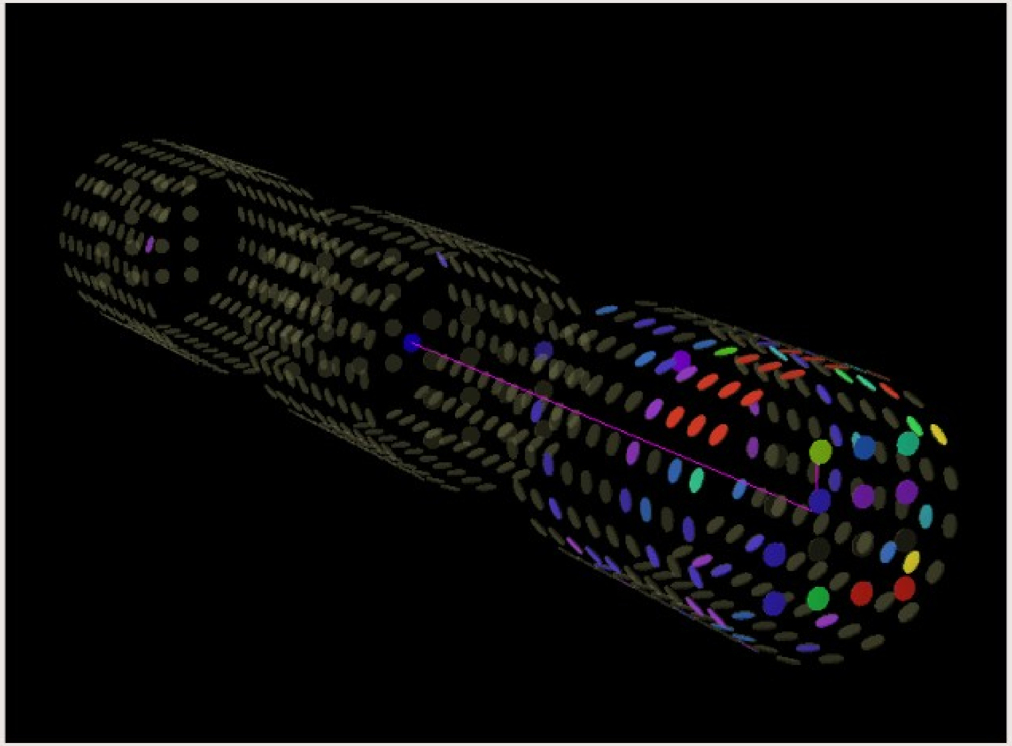
Current work

- Working to create full detector simulation using WCSim and fiTQun – see talks at the νPRISM meeting for more details
- Majority of work performed by two Co-op students at TRIUMF – Alex Lam and Carl Rethmeier
- Current status:
  - νPRISM detector geometry present in old version of WCSim
  - Can vary detector size, number of compartments, PMT coverage, PMT type
  - Have generated fiTQun scattering table with νPRISM geometry
  - Transformation from νPRISM coordinate system (z-axis along neutrino beam) to WCSim/fiTQun coordinates (z-axis along centre of detector)
  - Code to extract reconstructed and true information from fiTQun

WCSim

- Example of two extreme νPRISM configurations in WCSim



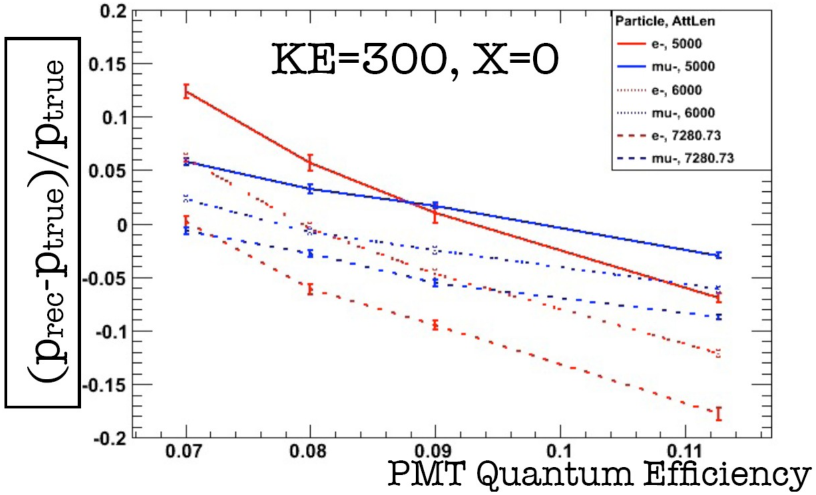


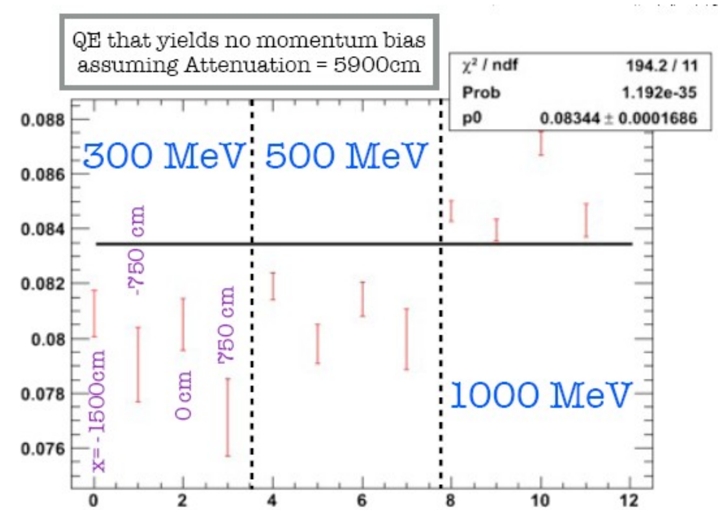
Radius = 0.127m (10inch diameter)
Percent Coverage = 60%
nSections = 4
SectionHeight = 8.0m
SectionGap = 4.0m

Radius = 0.254m (20inch diameter)
Percent Coverage = 20%
nSections = 3
SectionHeight = 10.0m
SectionGap = 7.5m

fiTQun

- fiTQun tuned to SK geometry in WCSim by Mike W.





- The WCSim SK tuned values were expected to be valid for all geometries - Super-K, Hyper-K, νPRISM, TITUS
- However, if the PMTs are changed, retuning may be necessary
- Alex found that running WCSim with some type of 8” PMT required a much higher QE (>50% larger)
- Mike is studying the QE and angular acceptance of these PMTs to determine how different they are from the Super-K 20” PMTs
- Will have rapid progress in the near future

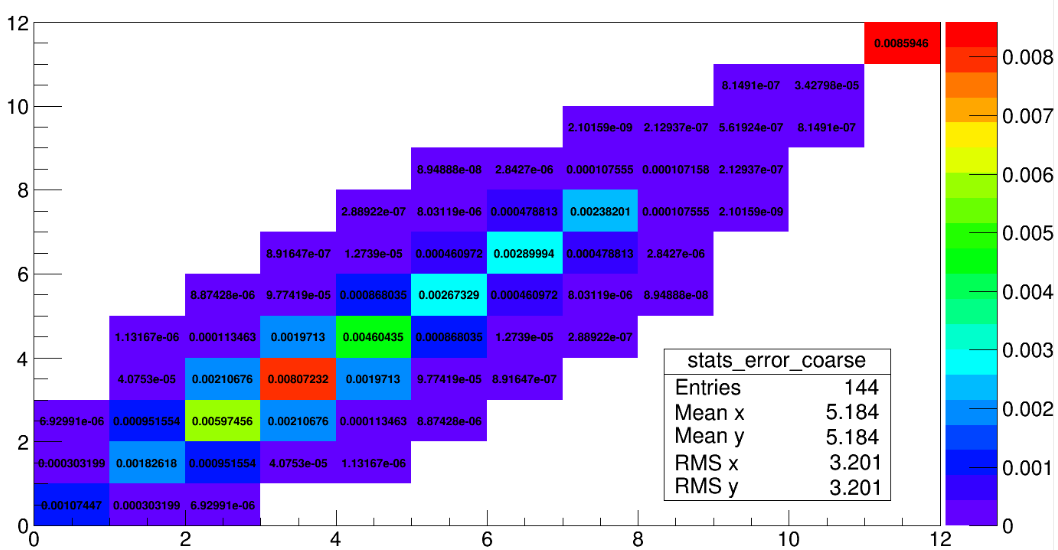
Summary

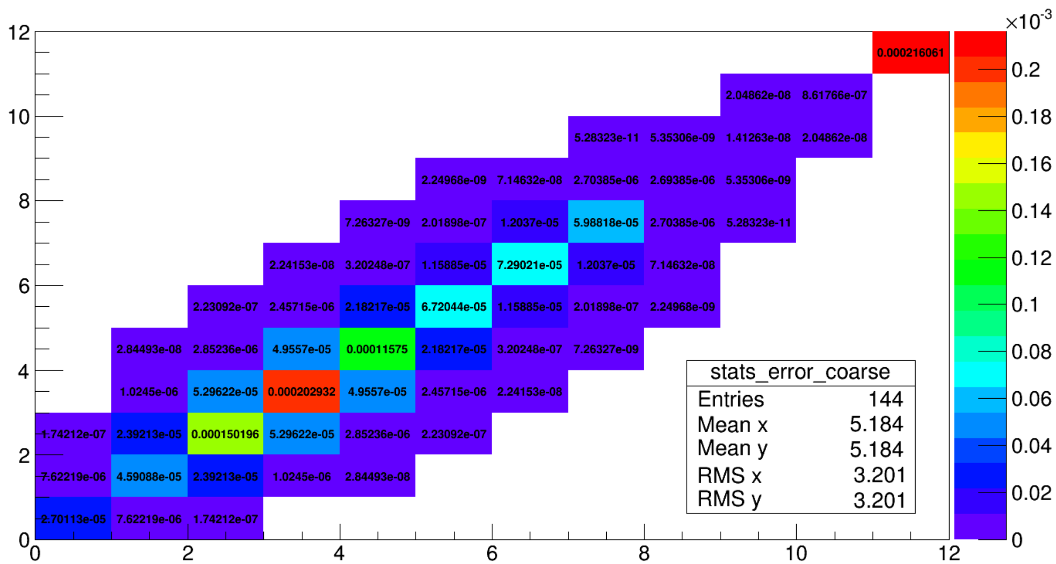
- Disappearance fits no longer constrained by statistical uncertainty – analysis is systematics limited
- νPRISM simulation and reconstruction work ongoing – expect working version of software soon
- First Gaussian neutrino beams produced with flux and cross-section systematics
  - Clear power to separate models!
  - Working to include reconstruction systematic uncertainties
- νPRISM sterile analysis improving

Backup slides

Validating the bug fix

- Ran analysis code with 'flux_mass_correction_factor' set to its current value and set to 1

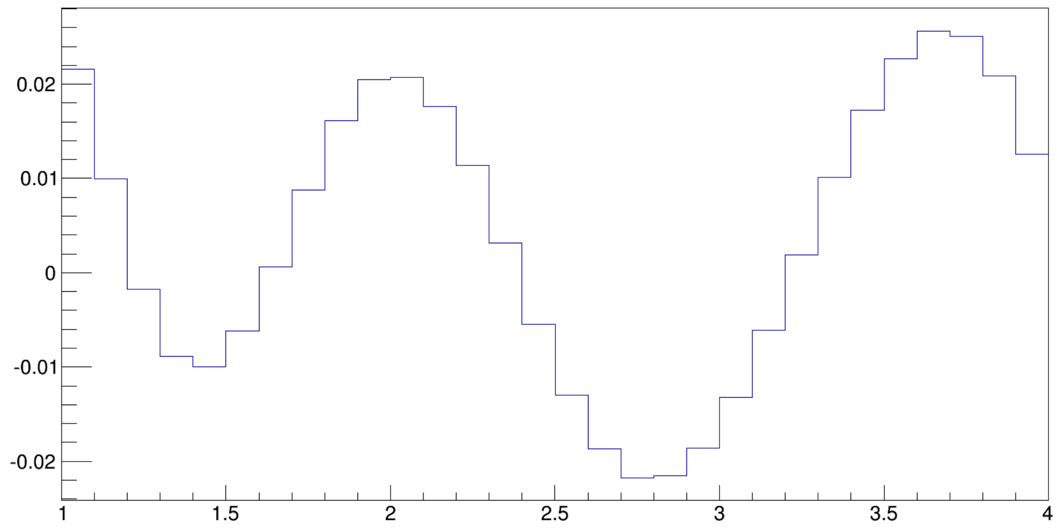


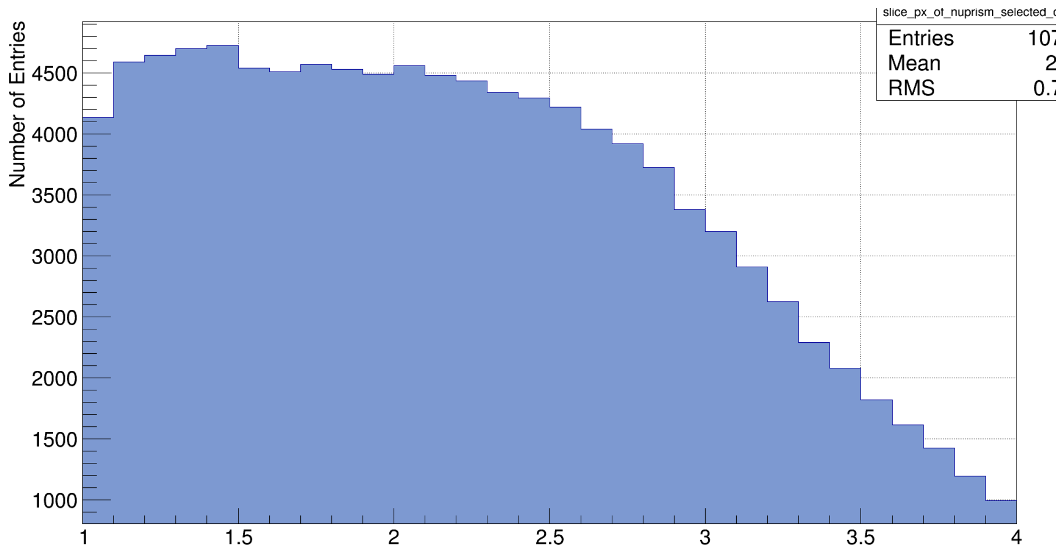


- Statistical uncertainty covariance matrix
- Buggy code on top, fixed code beneath
- In buggy code see statistical uncertainty of 8.8% in largest bin
  - Roughly same size as in analysis presented at last T2K meeting
  - Difference due to different oscillation parameters
- In fixed code, uncertainty ~1.4%
- 1.4*6.3 = 8.8, as expected

Validating the bug fix 2

- Calculated naïve statistical uncertainty for 500-600MeV reconstructed energy bin by hand





- Flux fit coefficients versus off-axis angle on top
- Selected nuPrism events versus off-axis angle on bottom
- N_Events = Sum over oaa bins (NSelected * Coefficient)
- Error^2 = Sum over oaa bins (NSelected * Coefficient^2)

- N_Events = 220
- Error = 4.8
- Fractional error = 2.2%

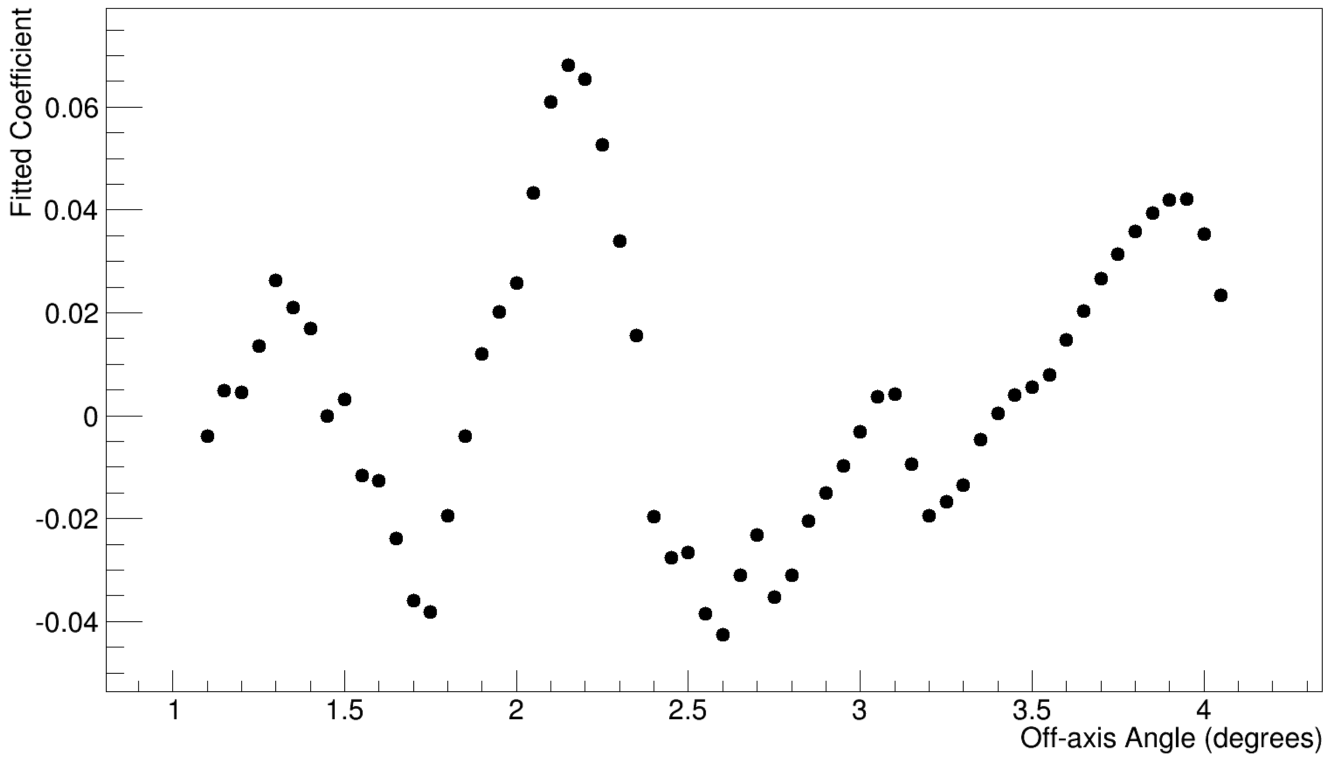
Validating the bug fix 3

- Calculated naïve statistical uncertainty for 500-600MeV reconstructed energy bin by hand - 2.2% fractional statistical uncertainty
- Also calculated same uncertainty using c++ – almost exact agreement with above results
- Analysis code gave uncertainty of 1.2% for this bin
  - Analysis applies corrections, so do not expect identical numbers
  - Only change to code was to remove scaling number – all previous statistical variation validation (Poisson throws) still valid

νPRISM

New coefficients

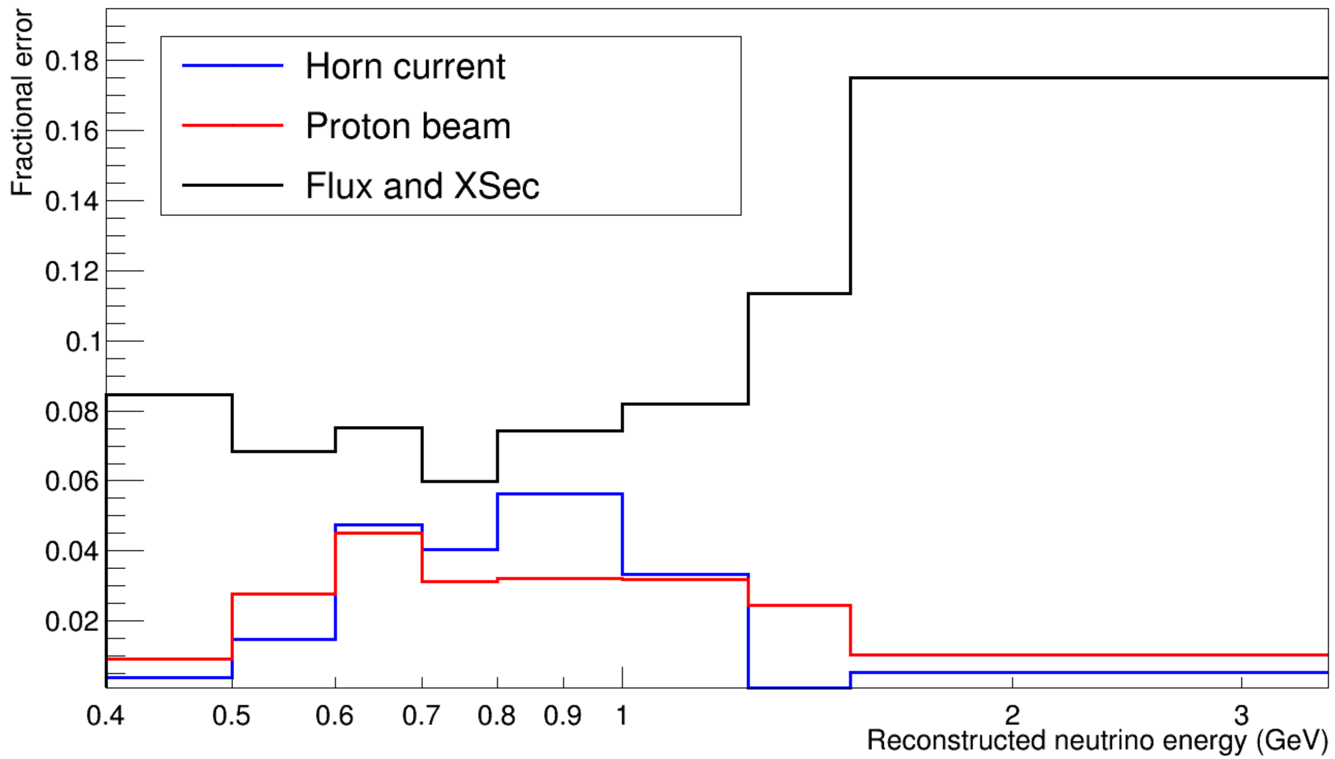
- Coefficients not as smooth as before
- Built on previous work to improve fit



- Fit from 450MeV – 1200MeV
- Use 10MeV bins in chi-squared calculation
- Use 60 off-axis parameters
- Smooth with denominator = 0.01

Flux systematics

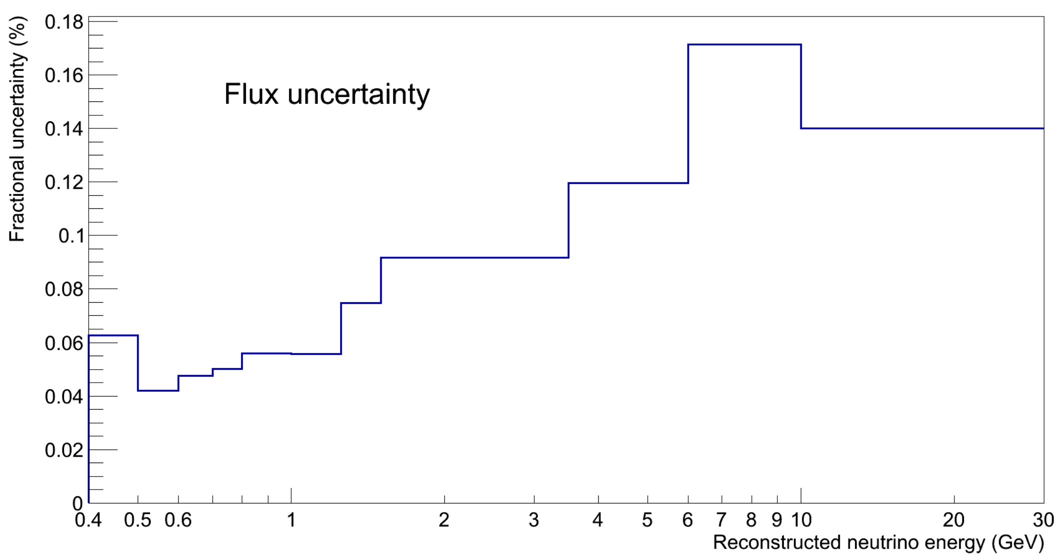
- Flux uncertainty increased from 5% to 7% at oscillation dip
- Largely driven by proton beam and horn current uncertainties

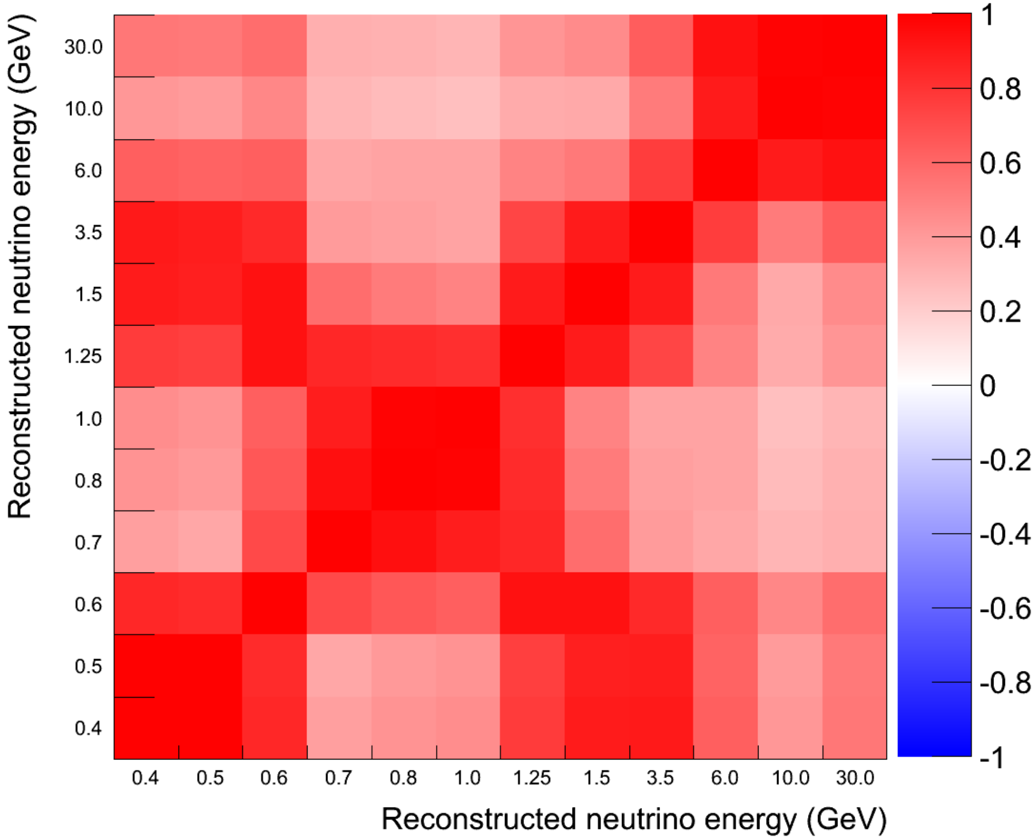


- Not unexpected:
  - More variation between neighbouring coefficients
  - Systematics that effect off-axis angle flux have bigger effect

Old flux uncertainty

- Flux uncertainties calculated in same ways as for T2K, evaluated at 1km
- Fractional error on left, correlation matrix on right

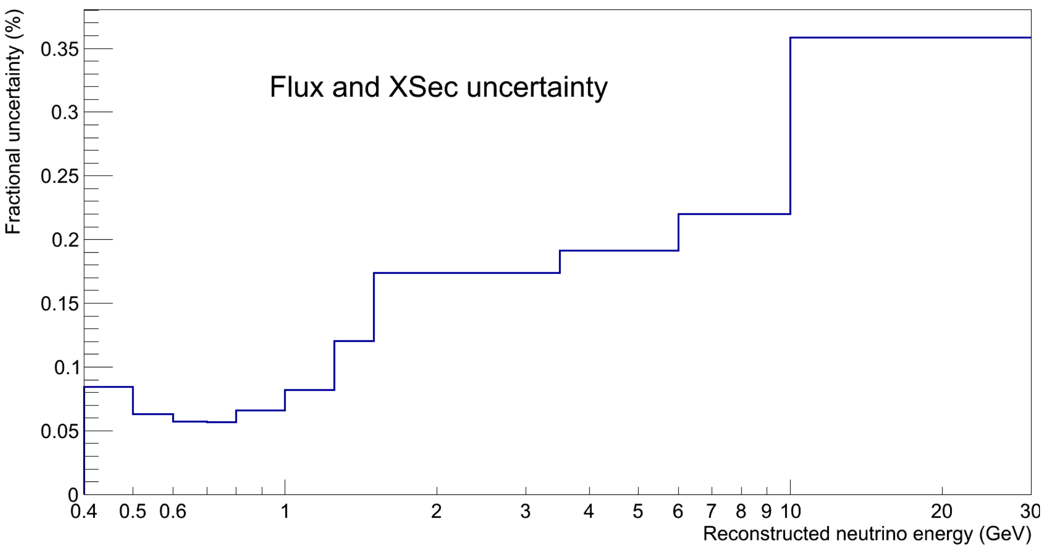


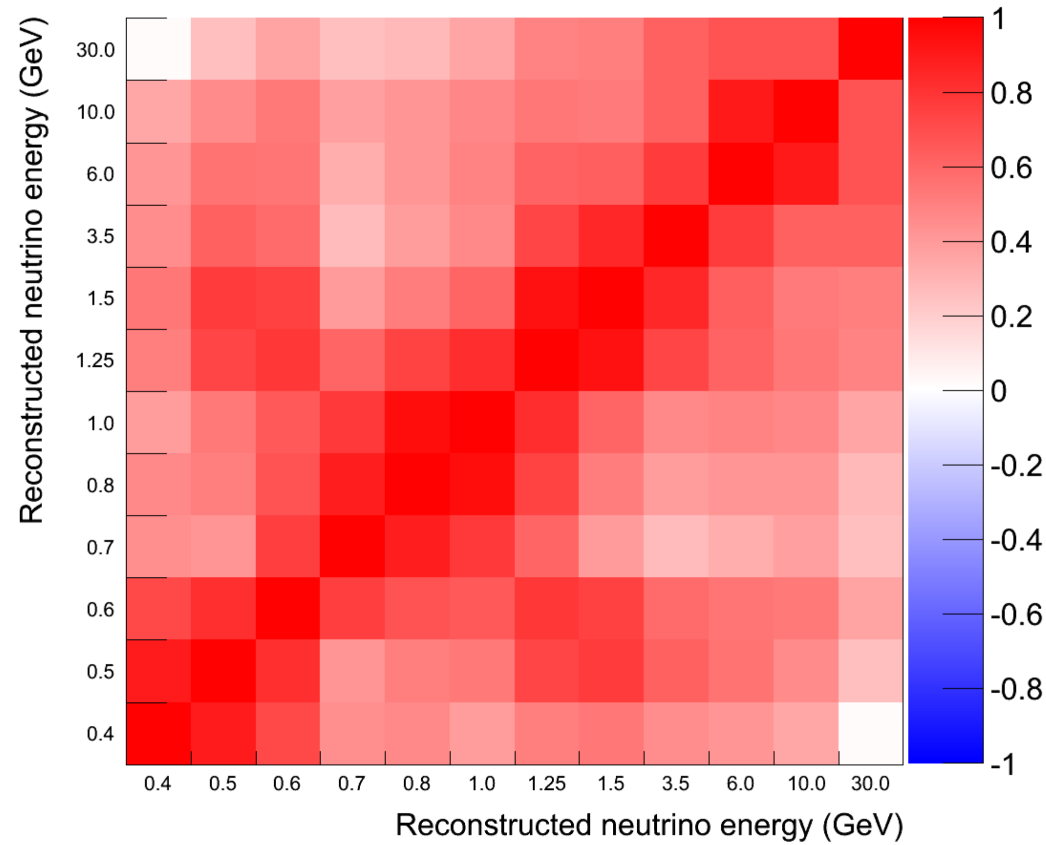


- Larger errors at high energy – no νPRISM events
- Error at oscillation dip around 4-5%

Old flux and Xsec uncertainty

- Xsec uncertainties should largely cancel at νPRISM – amount of cancellation depends on how well flux combination matches SK flux
- Need to throw flux and cross section uncertainties together

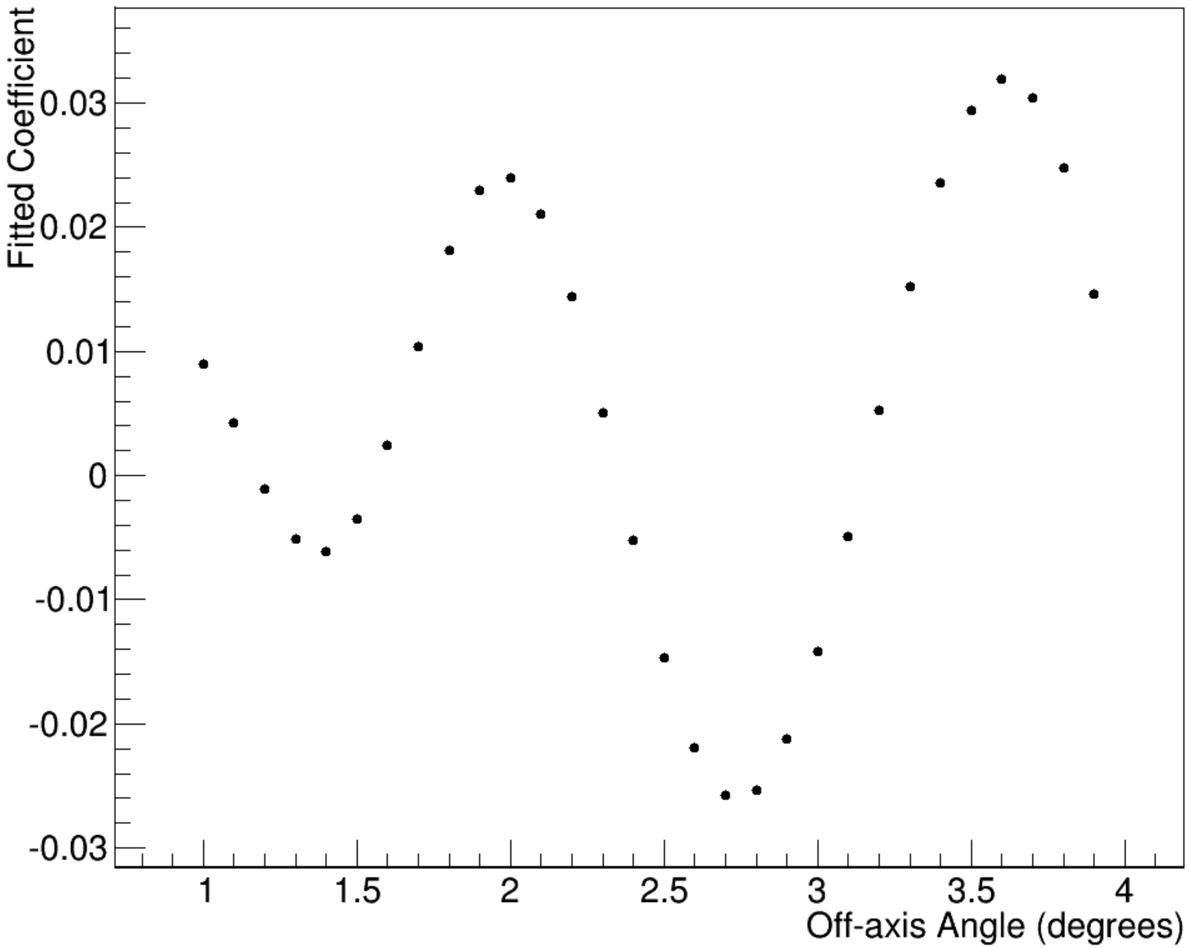




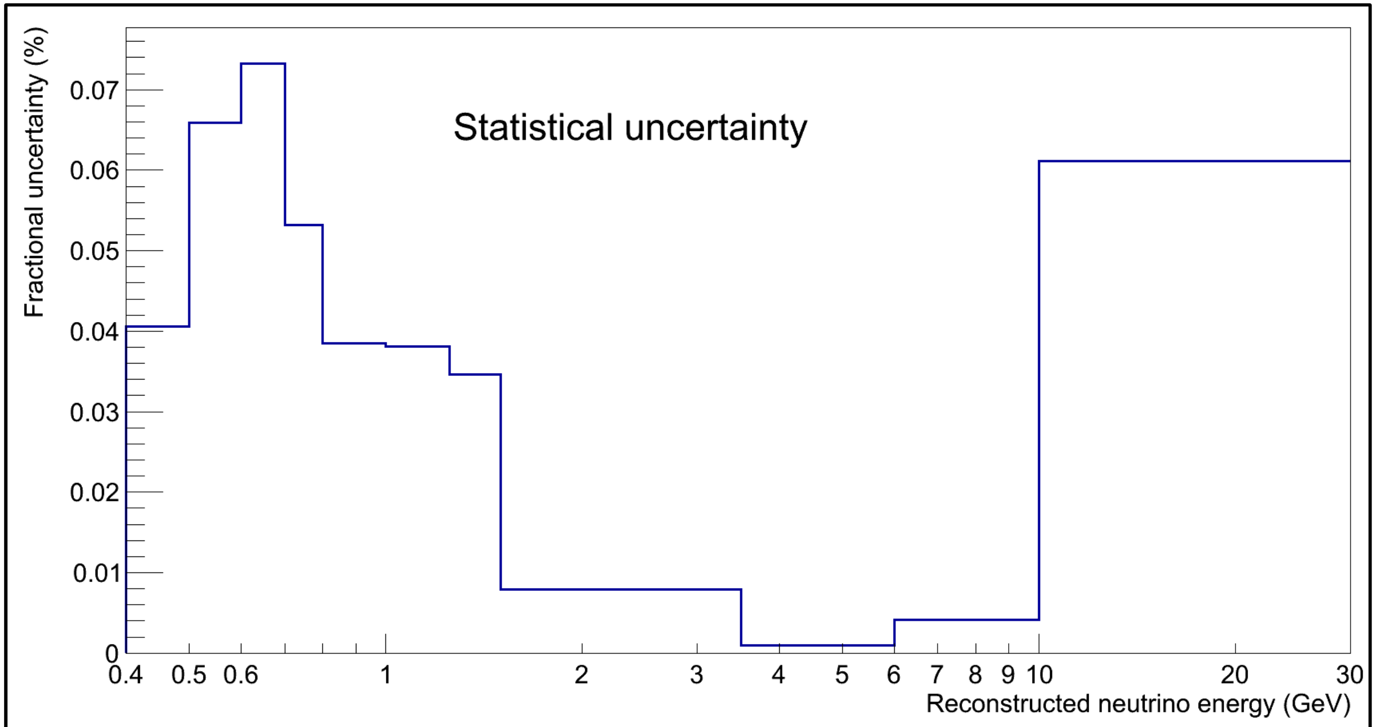
- Combined flux and cross section uncertainty around 5% at the oscillation dip

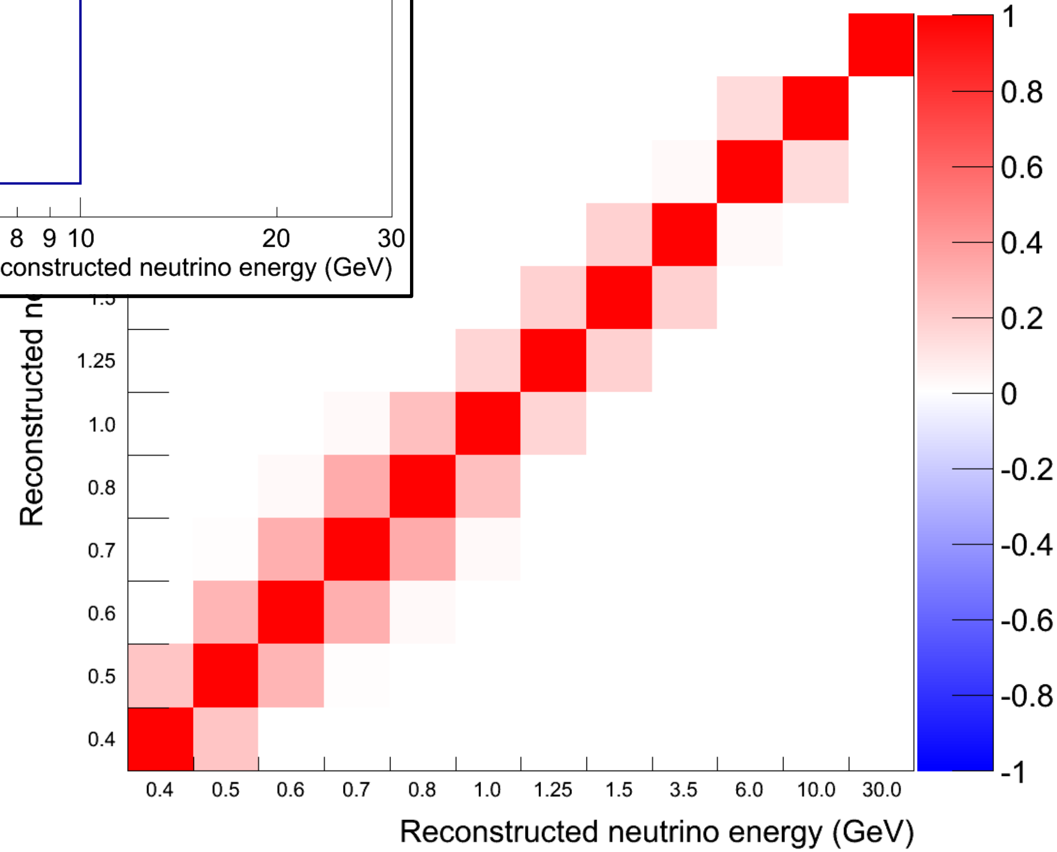
Old coefficients

- Smooth linear combination – variations in neighbouring slices cancel out to large extent



Old statistical uncertainties





- Uncertainty maximal in oscillation dip – subtracting distributions to get zero events
- Statistical uncertainty ~7% in oscillation dip