Short and long baseline sensitivities with νPRISM

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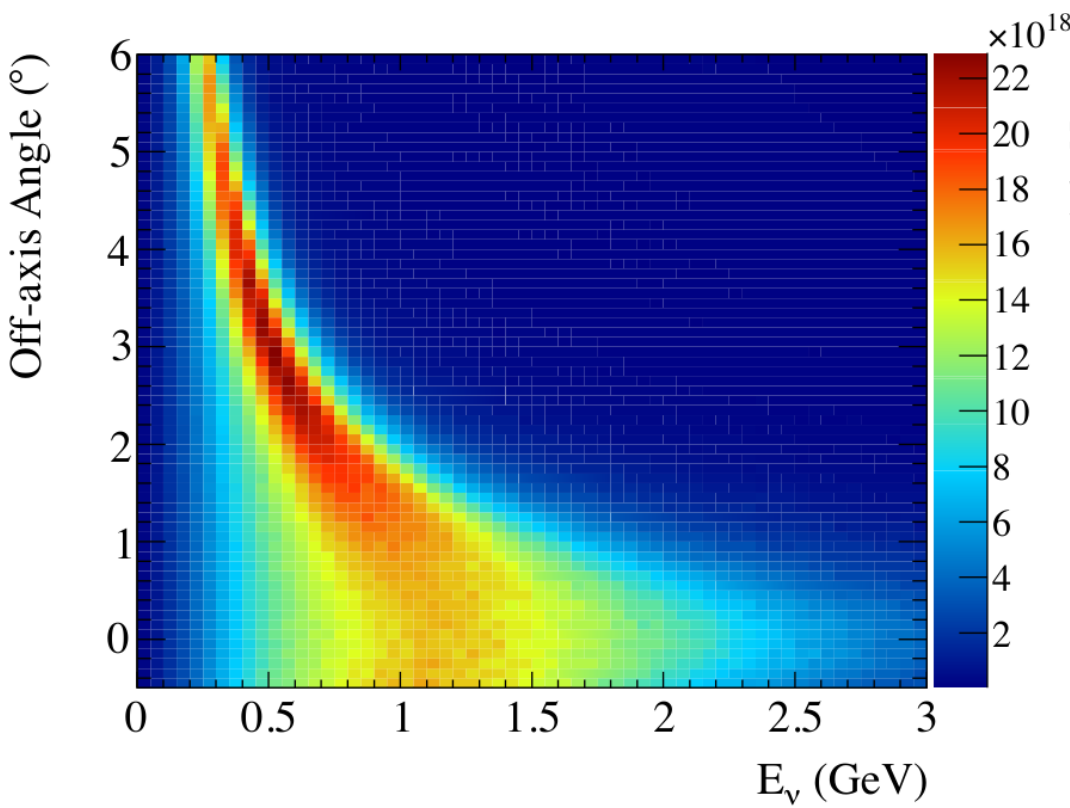
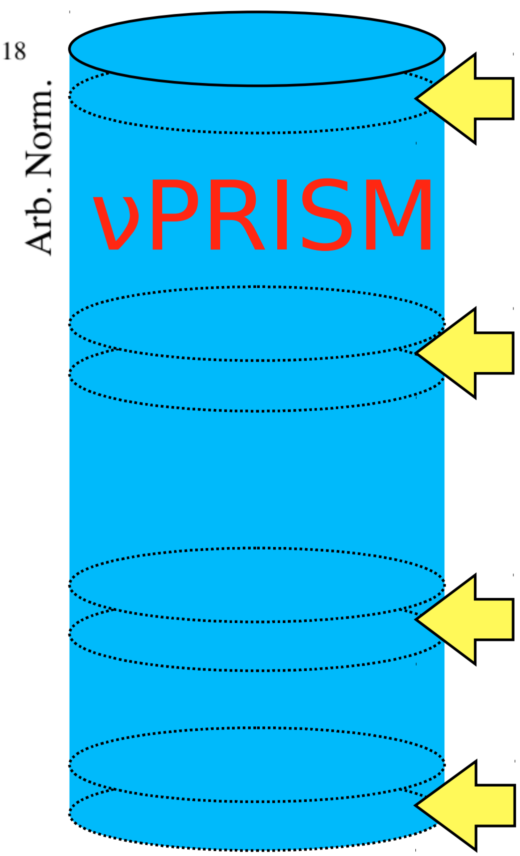
5^{th} Open Hyper-K Meeting

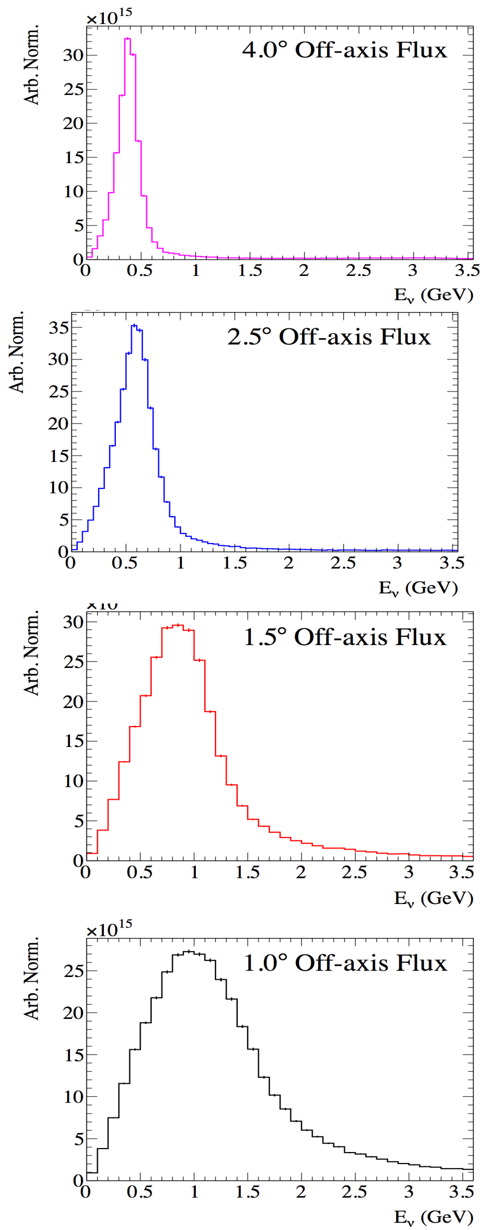
July 22^{nd} 2014

νPRISM Concept

- Different off-axis angles see different neutrino fluxes



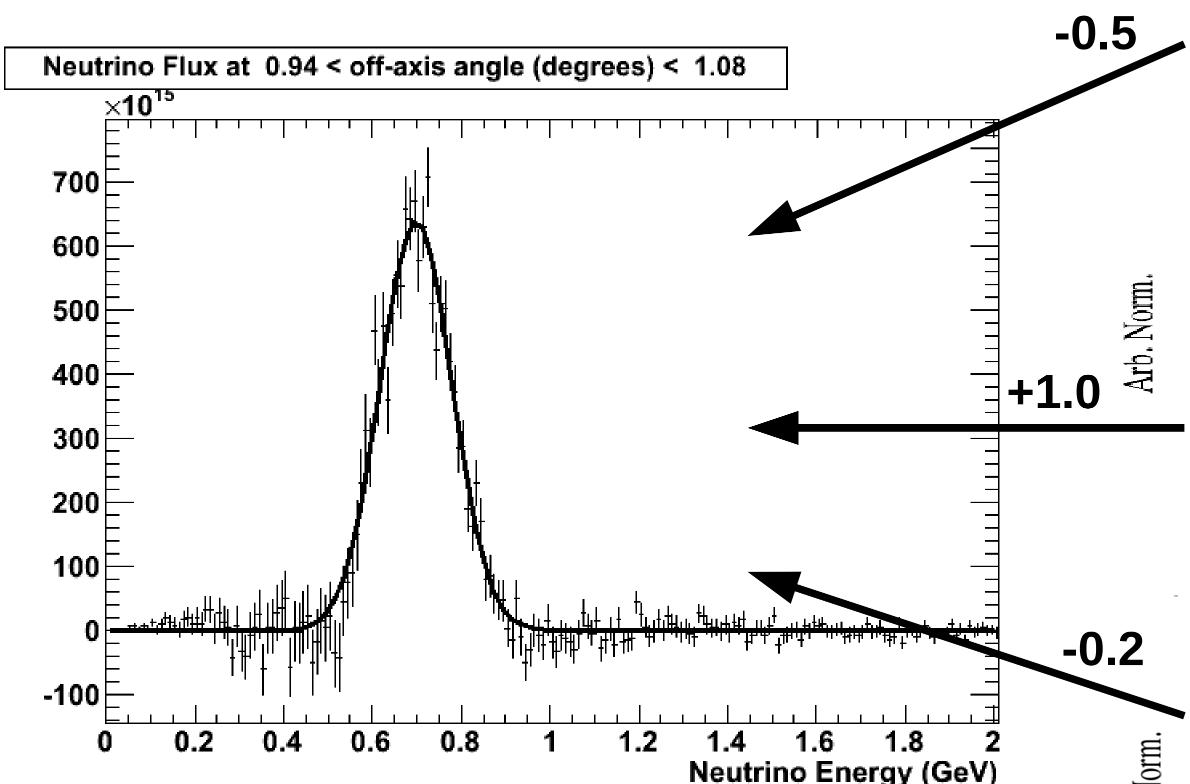


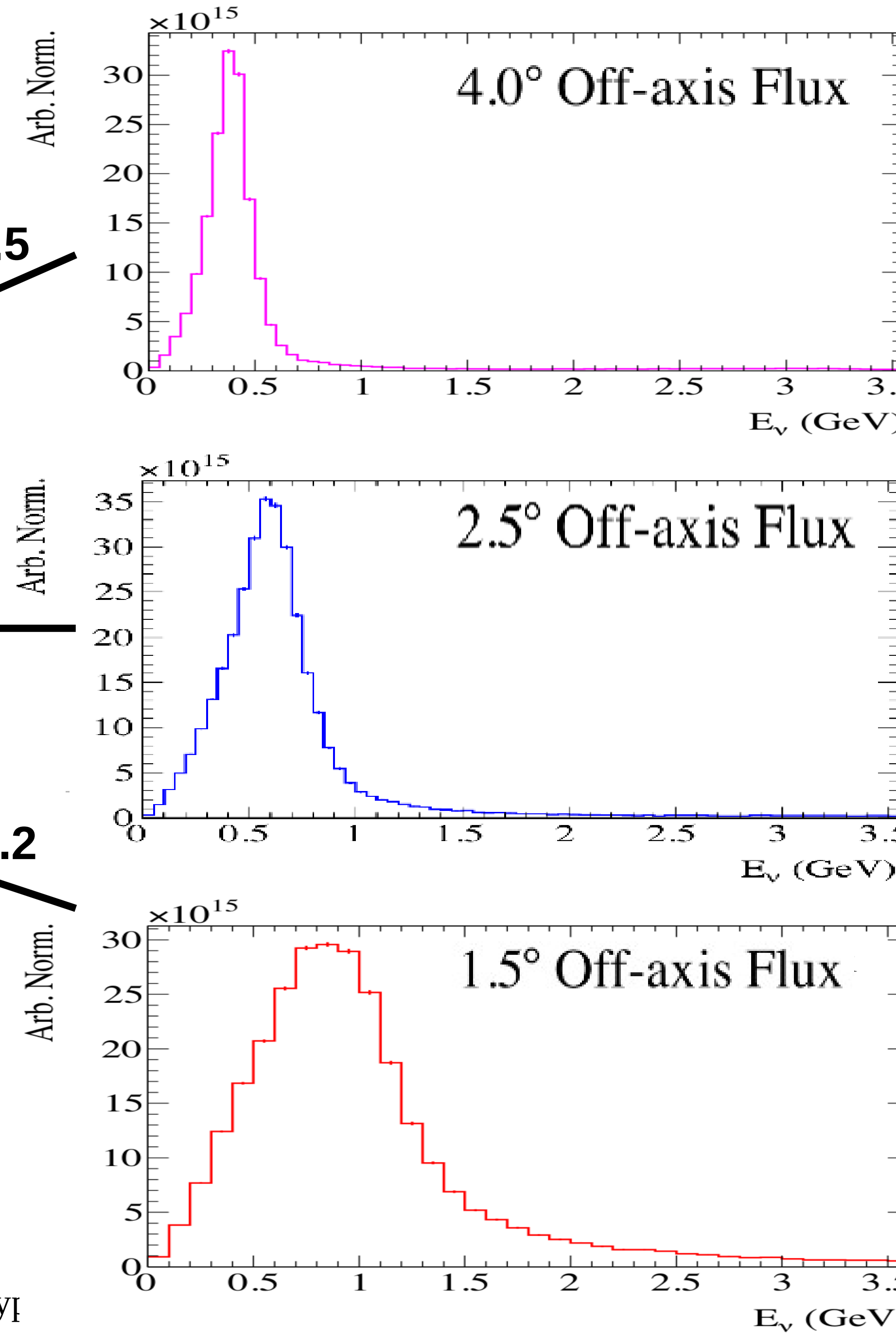


- Further off-axis → Narrower energy distribution, lower peak energy

Gaussian beams

- Can combine angular slices to create desired neutrino flux

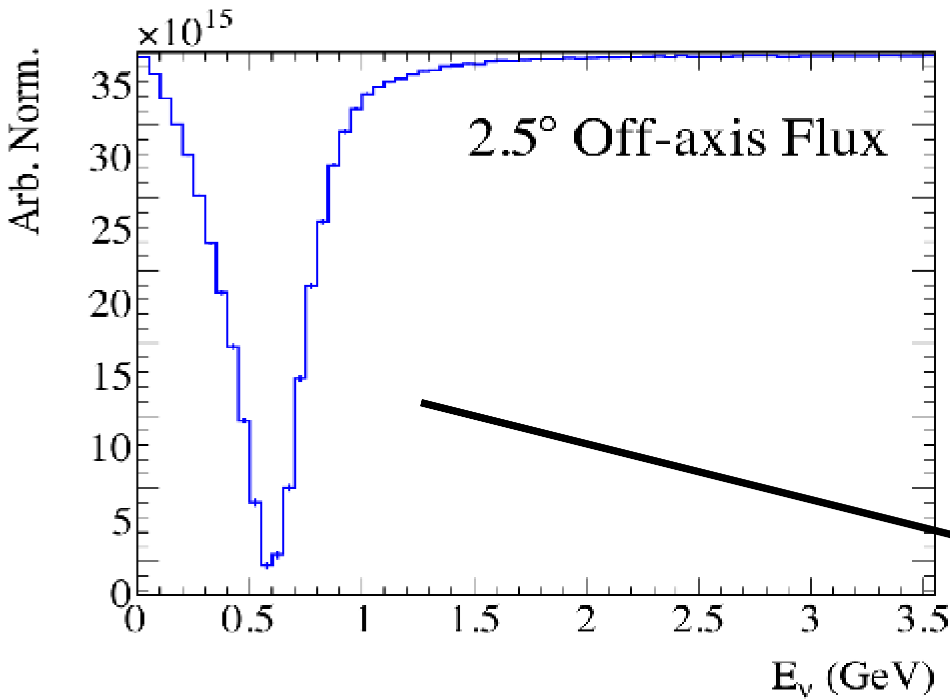


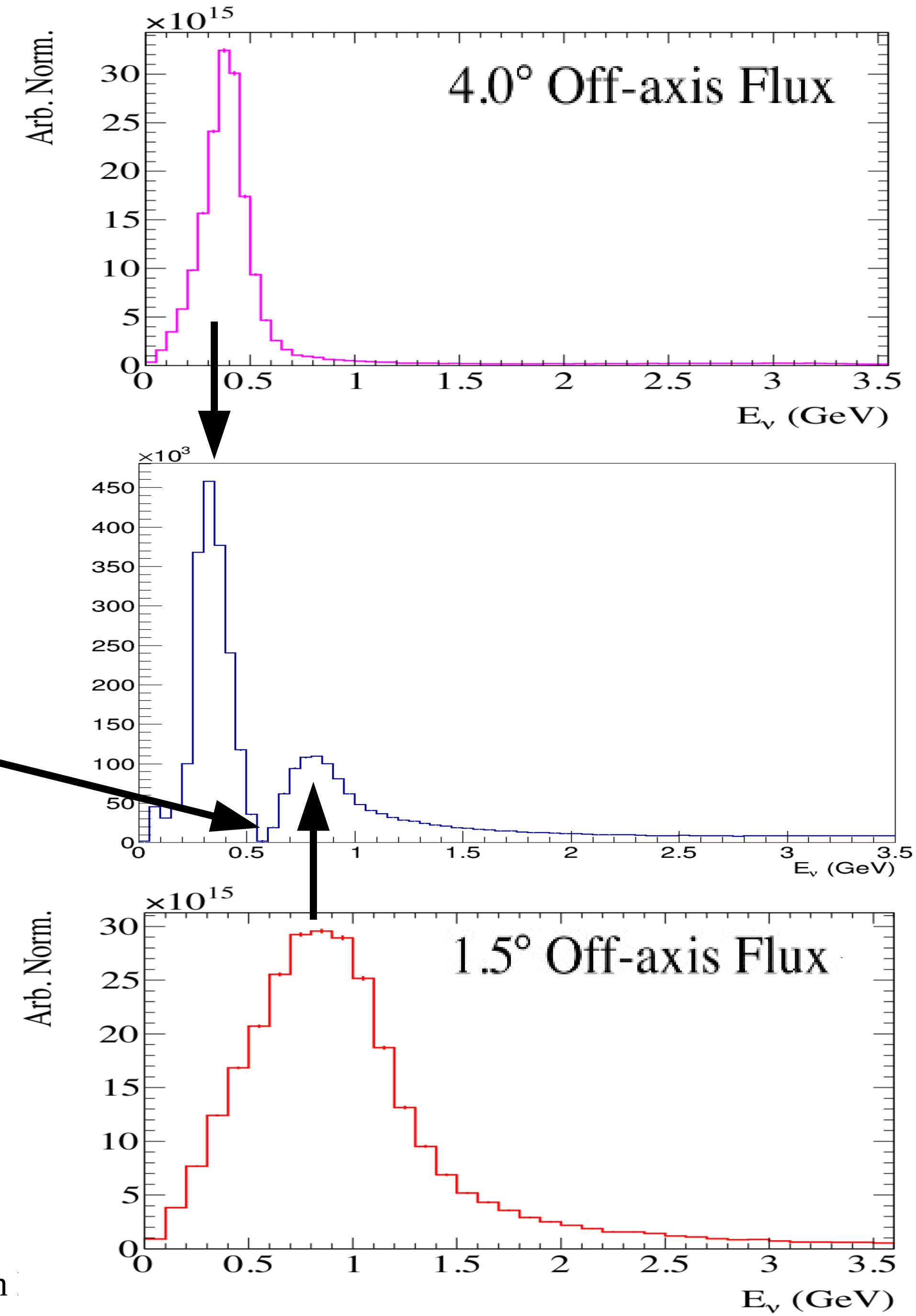


- Build a Gaussian neutrino flux!

Oscillated beam

- Can combine different angular slices to recreate the oscillated SK spectrum

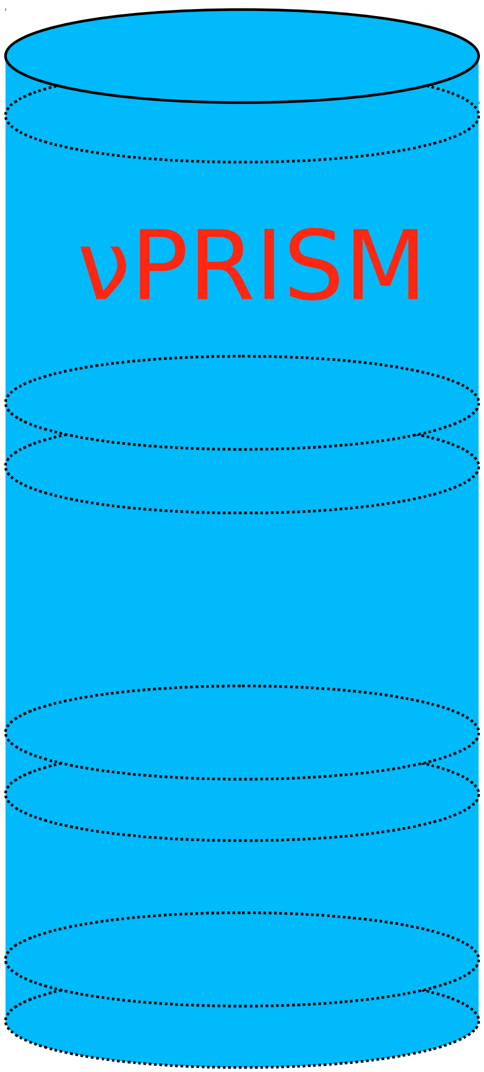




- 4° and 1.5° flux give the low and high energy peaks at SK
- Subtract the 2.5° flux to create the oscillation dip

νPRISM Design

- Baseline design used in the oscillation studies



- 3m radius inner detector
- 52.5m tall – spanning 1-4 degrees off axis
- 1km from neutrino target

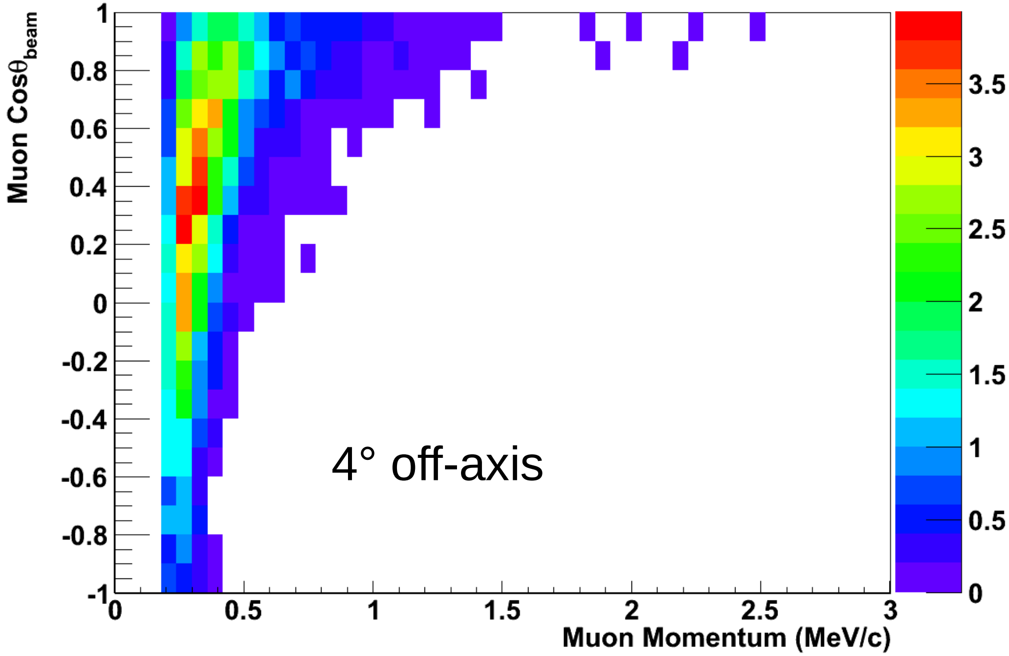
- νPRISM-lite:
  - Instrument 14m movable cylinder
  - Take data at different off-axis angles over run
  - Studies assumes 4.5 x 10^{20} POT in each off-axis slice of νPRISM

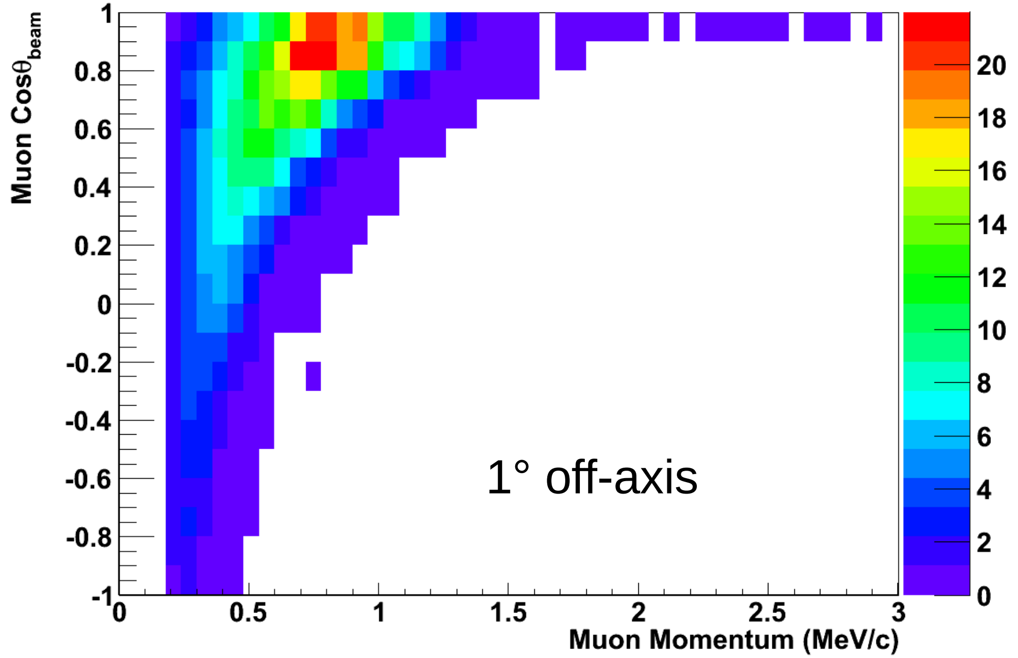
ν_μ Disappearance Analysis

- Event selection
- νPRISM predicted SK spectrum
- Systematic uncertainties
- Statistical uncertainties
- Oscillation fit
- Effect of multi-nucleon events

Event Selection

- Same event selection as at SK:
  - Single ring
  - Muon-like
  - Fully contained in fiducial volume

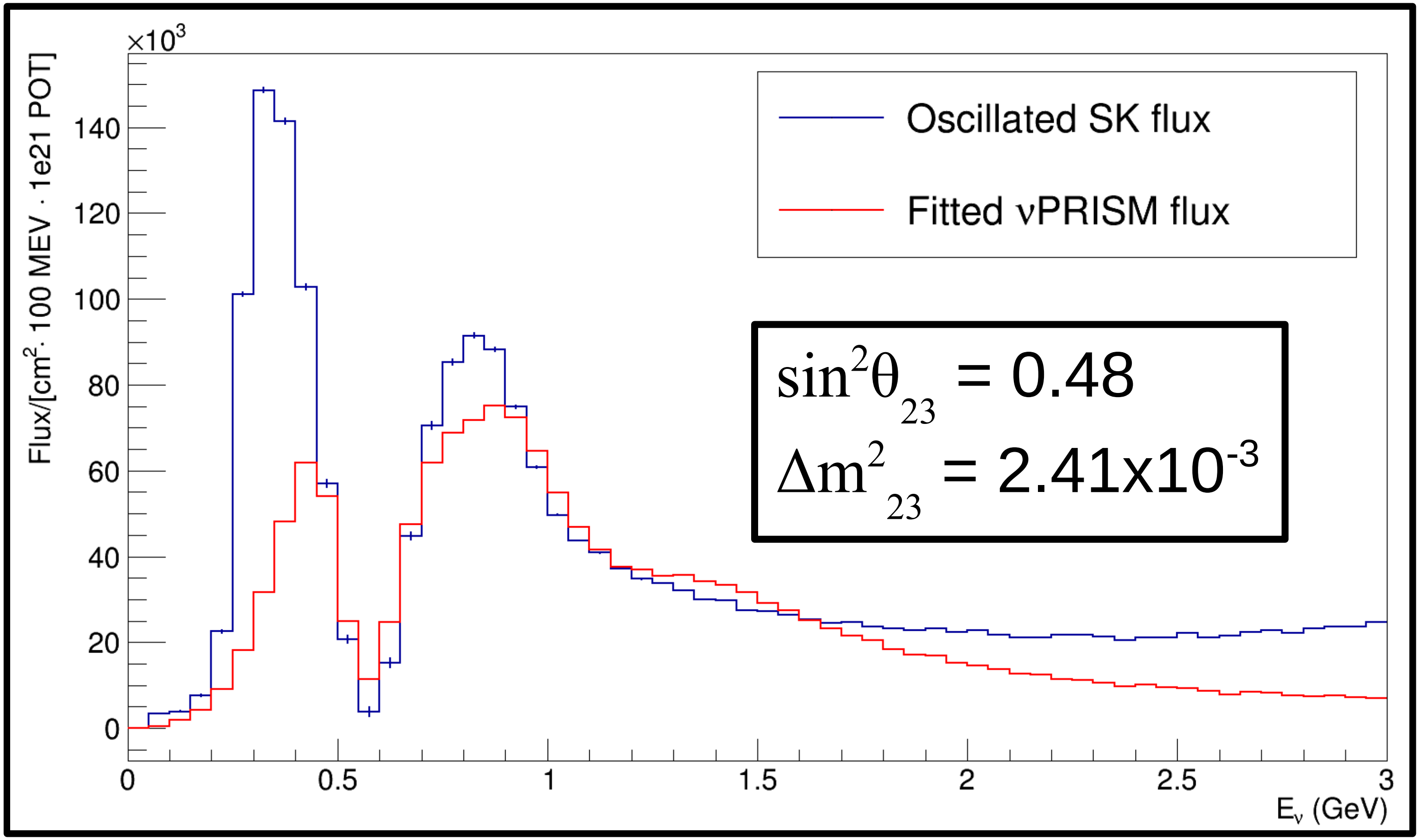




- Record the off-axis angle of the interaction, using the reconstructed vertex position

SK prediction

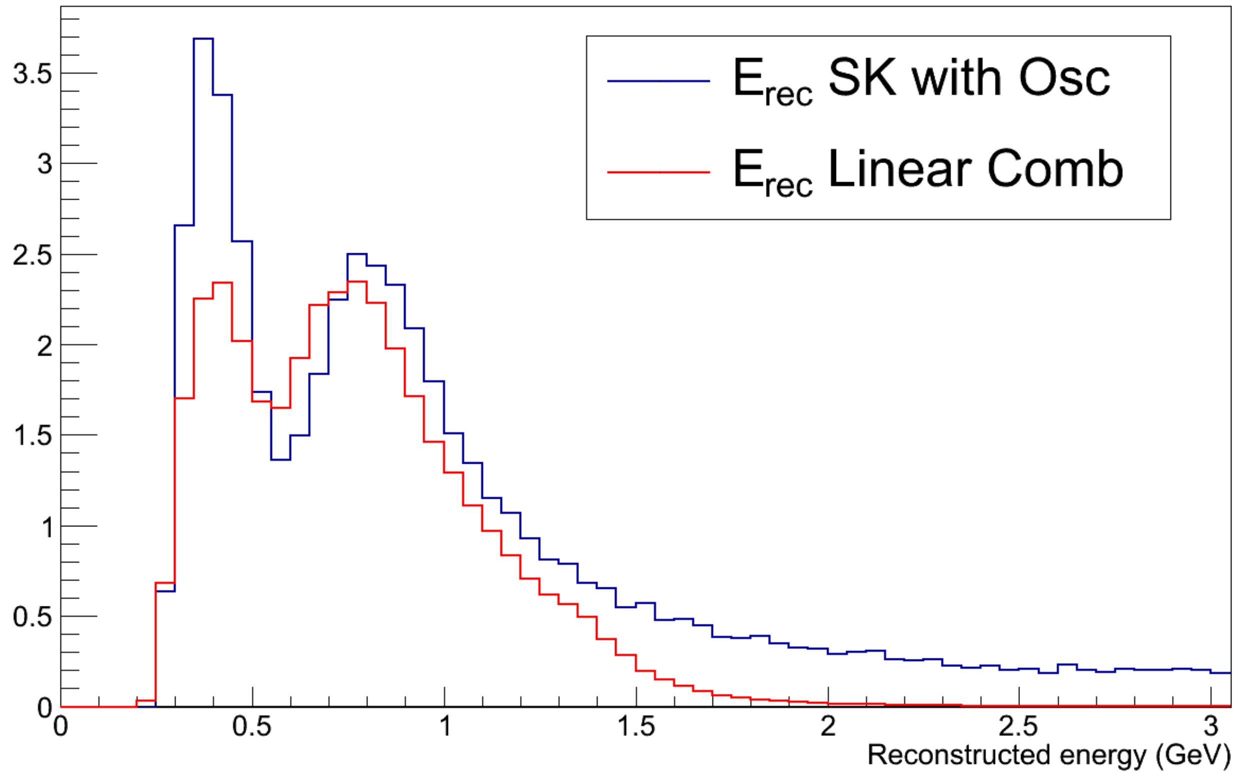
- Use νPRISM technique (linear combinations) to create the SK neutrino flux assuming a given set of oscillation parameters



- Provides a set of weights for the different off-axis slices of νPRISM

SK prediction

- Apply these weights to the selected events in each off-axis slice of νPRISM
- Now looking at reconstructed neutrino energy - events smeared into oscillation dip by nuclear effects and energy resolution



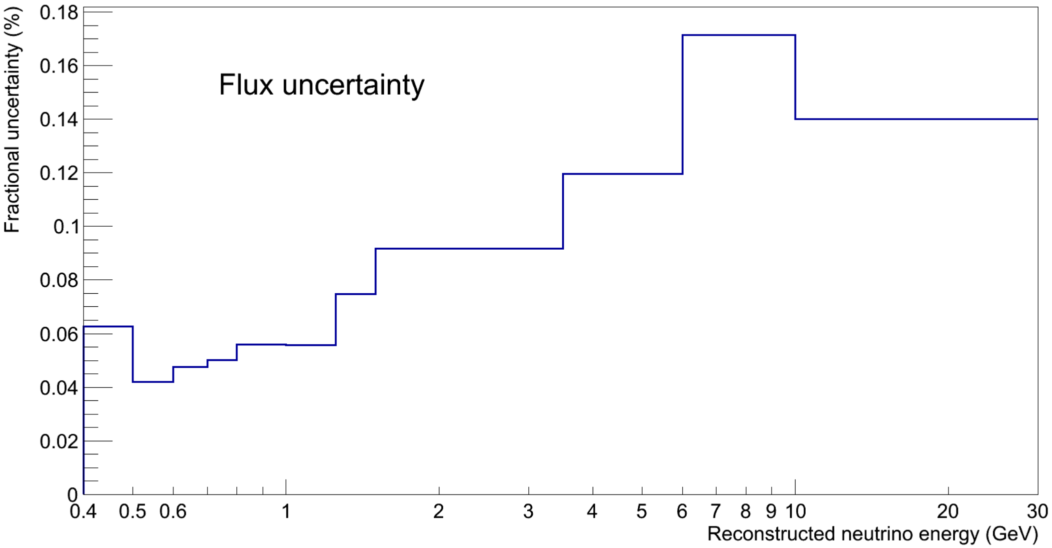
- To νPRISM data:
  - Background subtraction
  - Efficiency correction
  - Addition of selected SK background
- Introduce some model dependence

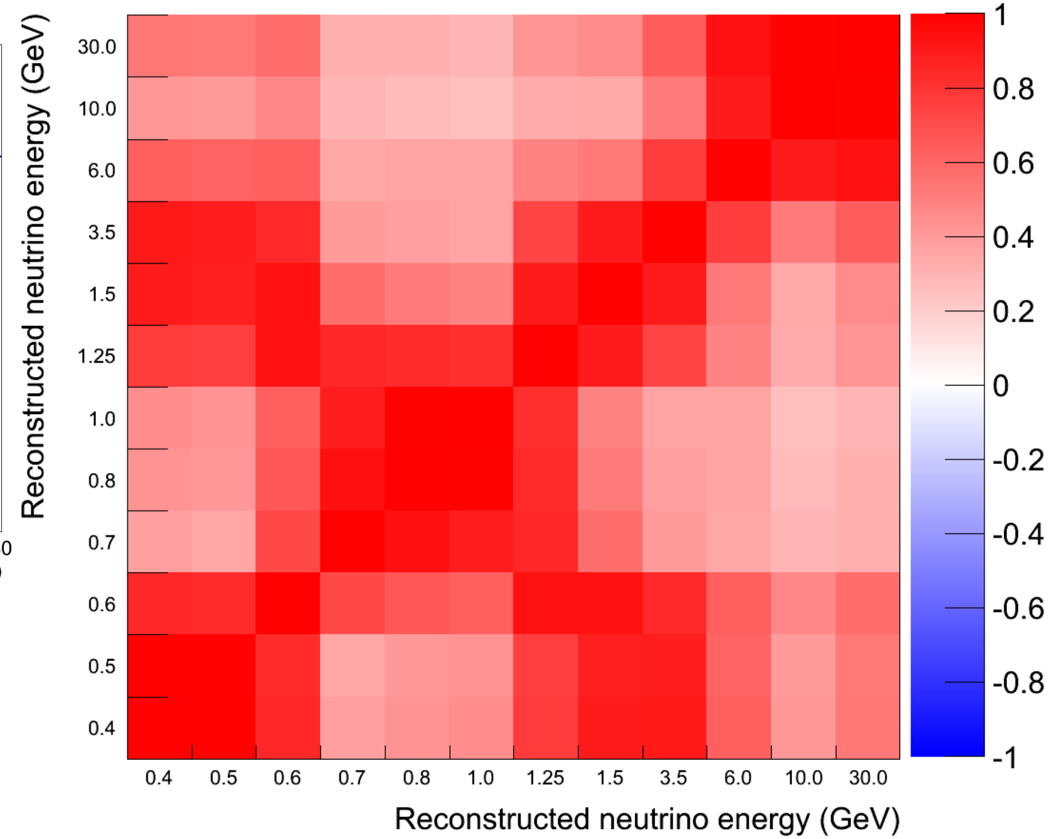
Systematic uncertainties

- Every correction made to the νPRISM prediction is calculated from our nominal MC – all are constant corrections
- To calculate systematic uncertainties:
  - Apply a variation to the νPRISM and SK MC
  - Changes number of selected events at both detectors
  - Apply corrections (from the unvaried, nominal MC)
  - Calculate change in the νPRISM prediction
  - Use this to calculate fractional covariance matrix for νPRISM prediction
- This analysis takes flux and cross section uncertainties into account
  - Conservative detector systematics coming soon!

Flux uncertainty

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

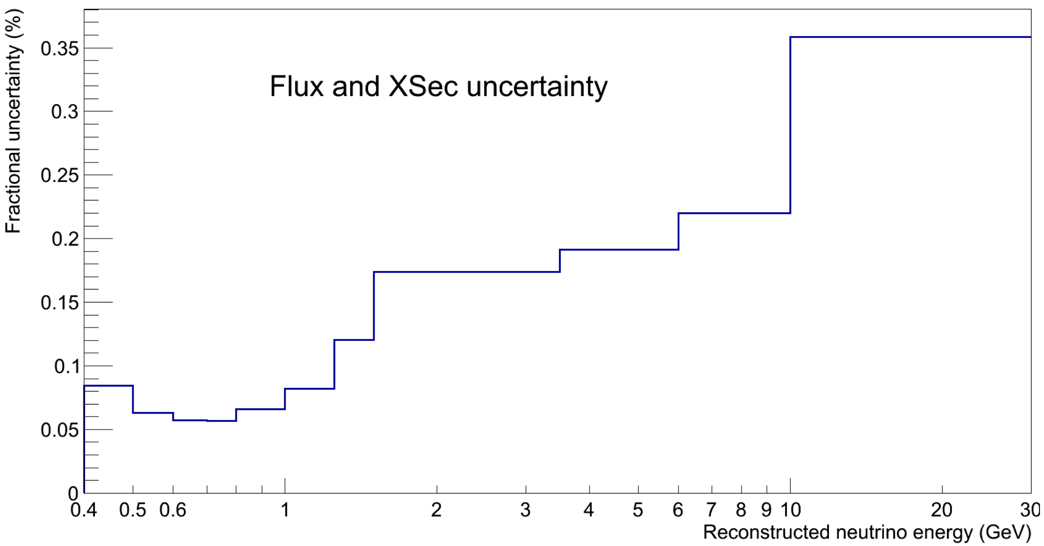


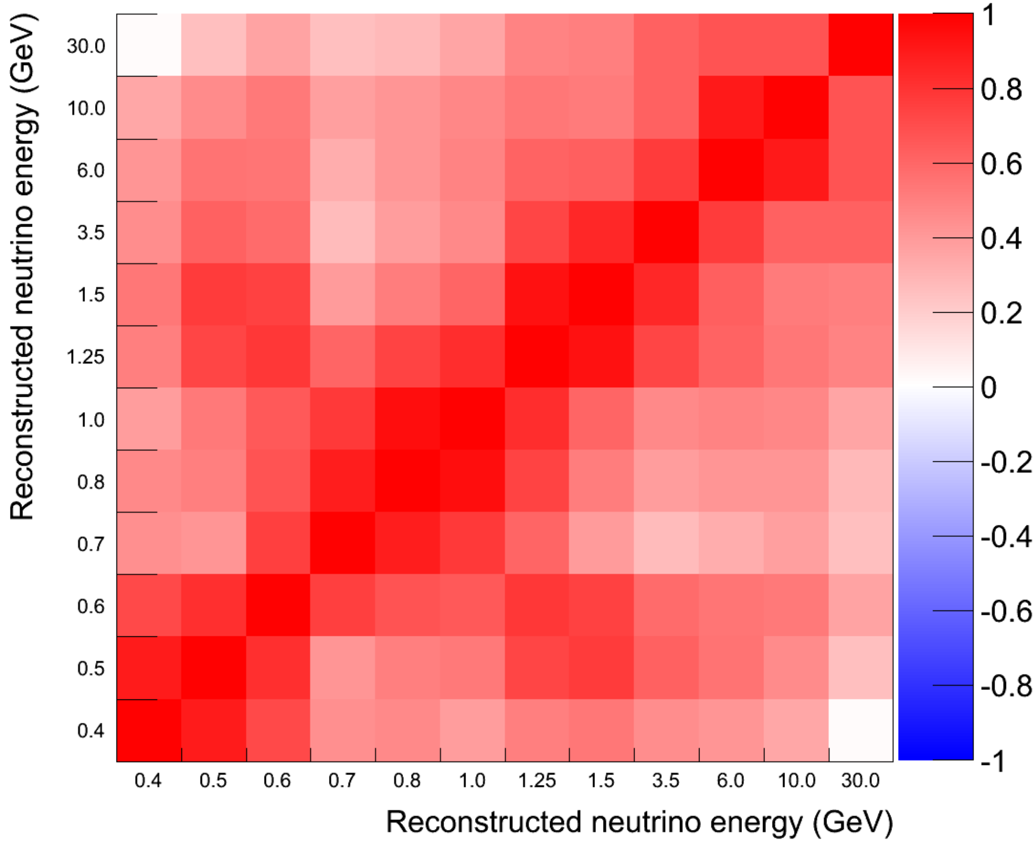


- Larger errors at high energy – no νPRISM events
- Error at oscillation dip around 4-5%

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

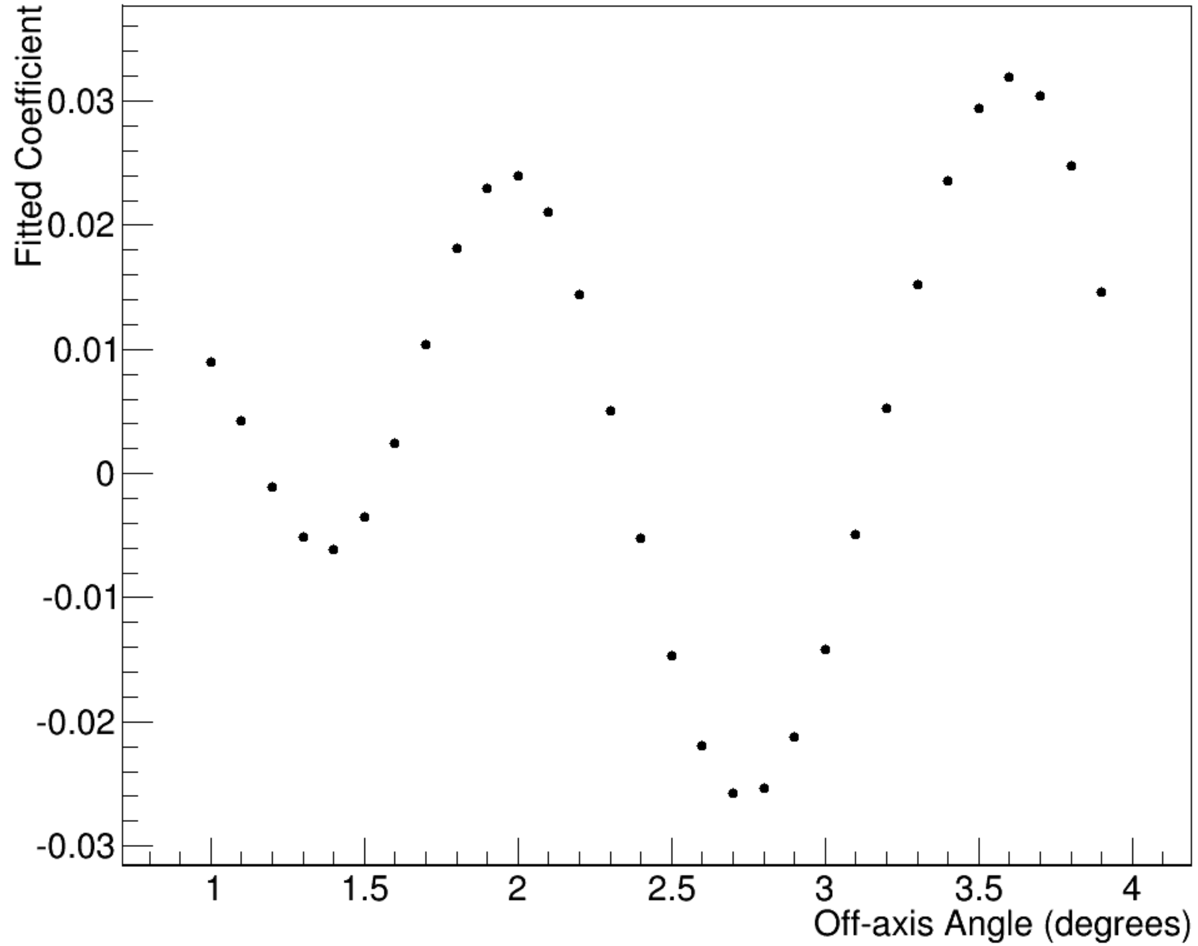




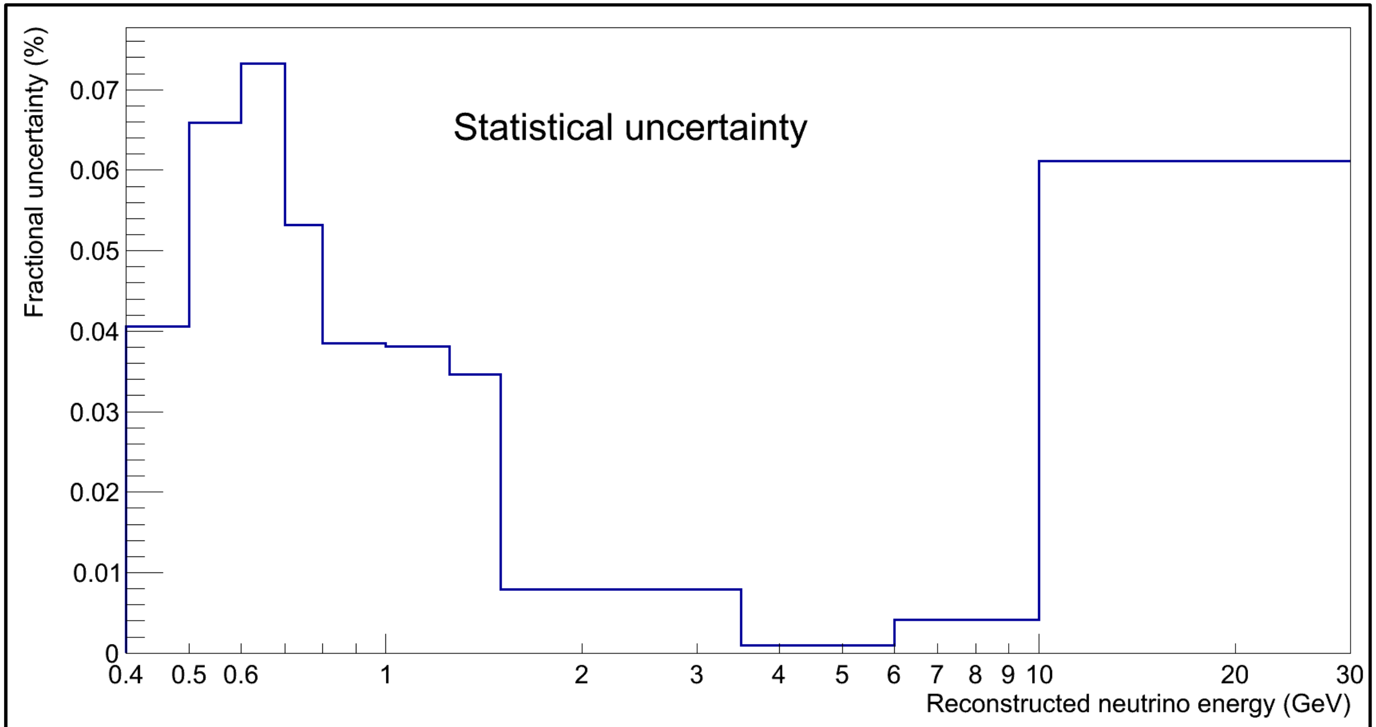
- Combined flux and cross section uncertainty around 5% at the oscillation dip

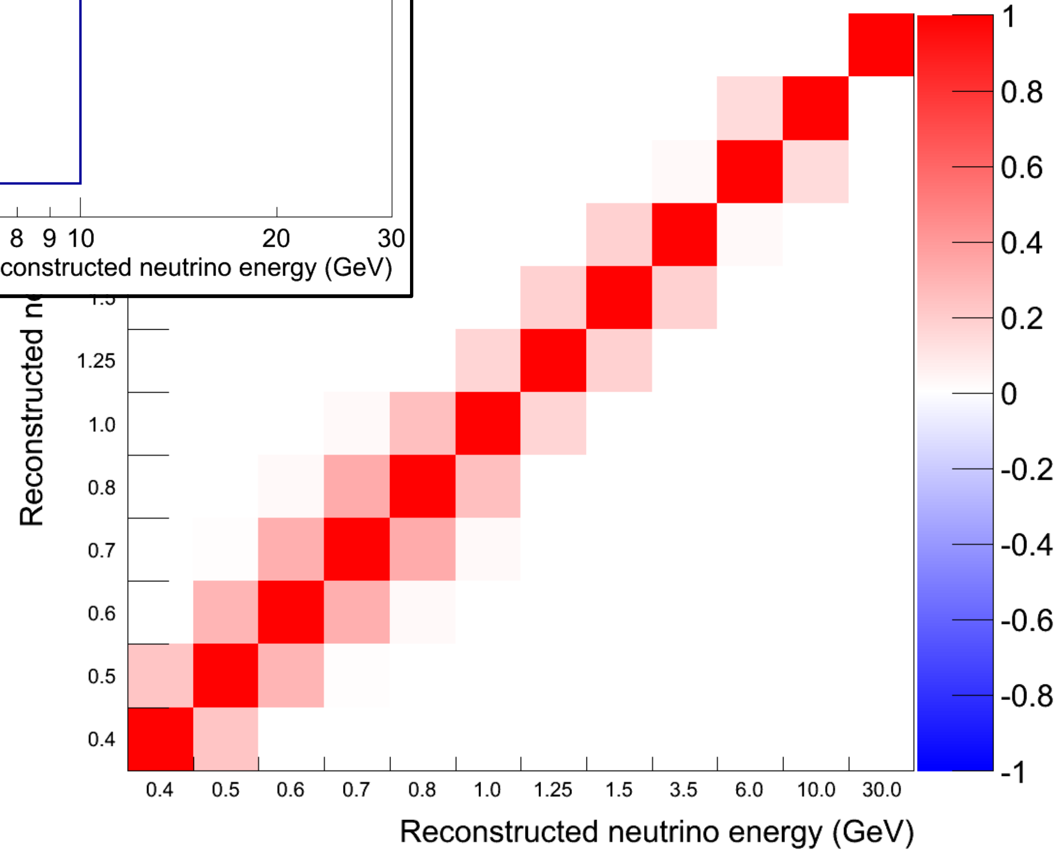
Statistical uncertainties

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



Statistical uncertainties

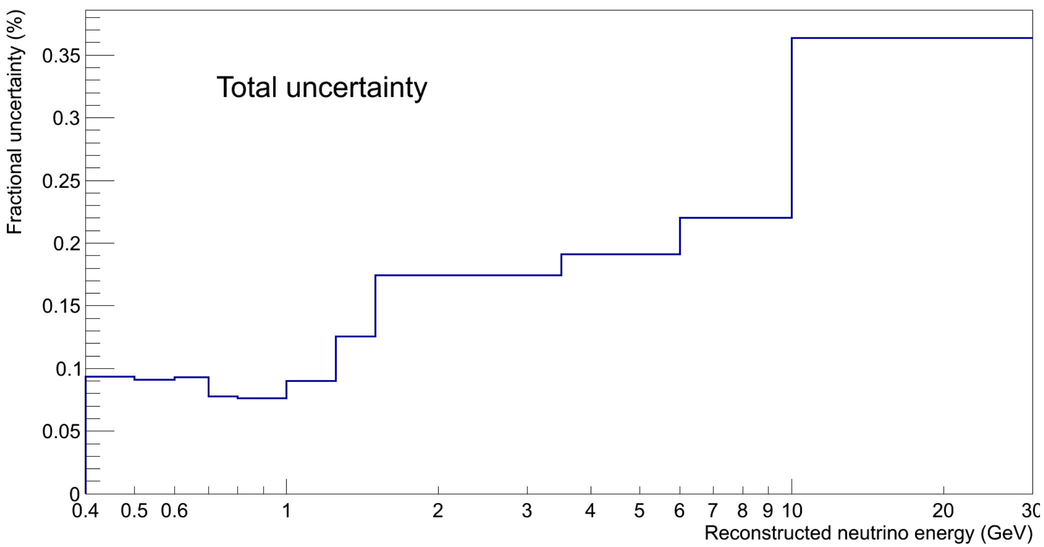


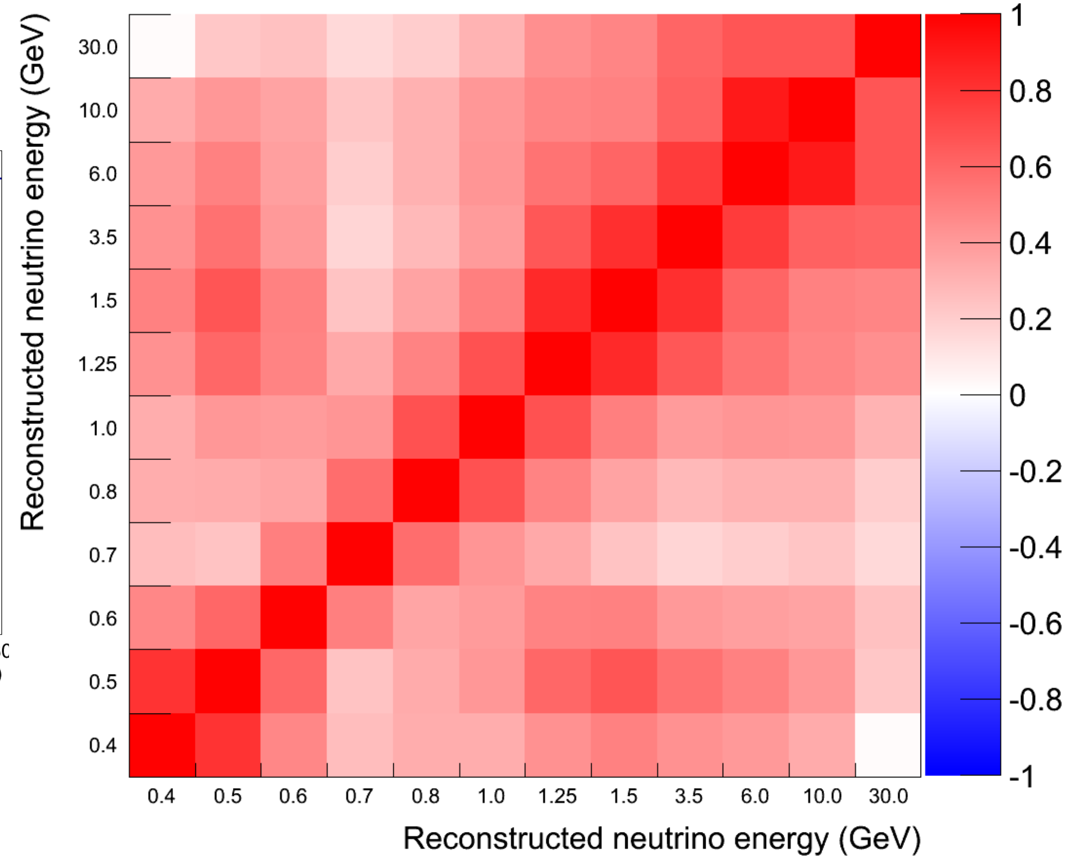


- Uncertainty maximal in oscillation dip – subtracting distributions to get zero events
- Statistical uncertainty ~7% in oscillation dip

Total uncertainty

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



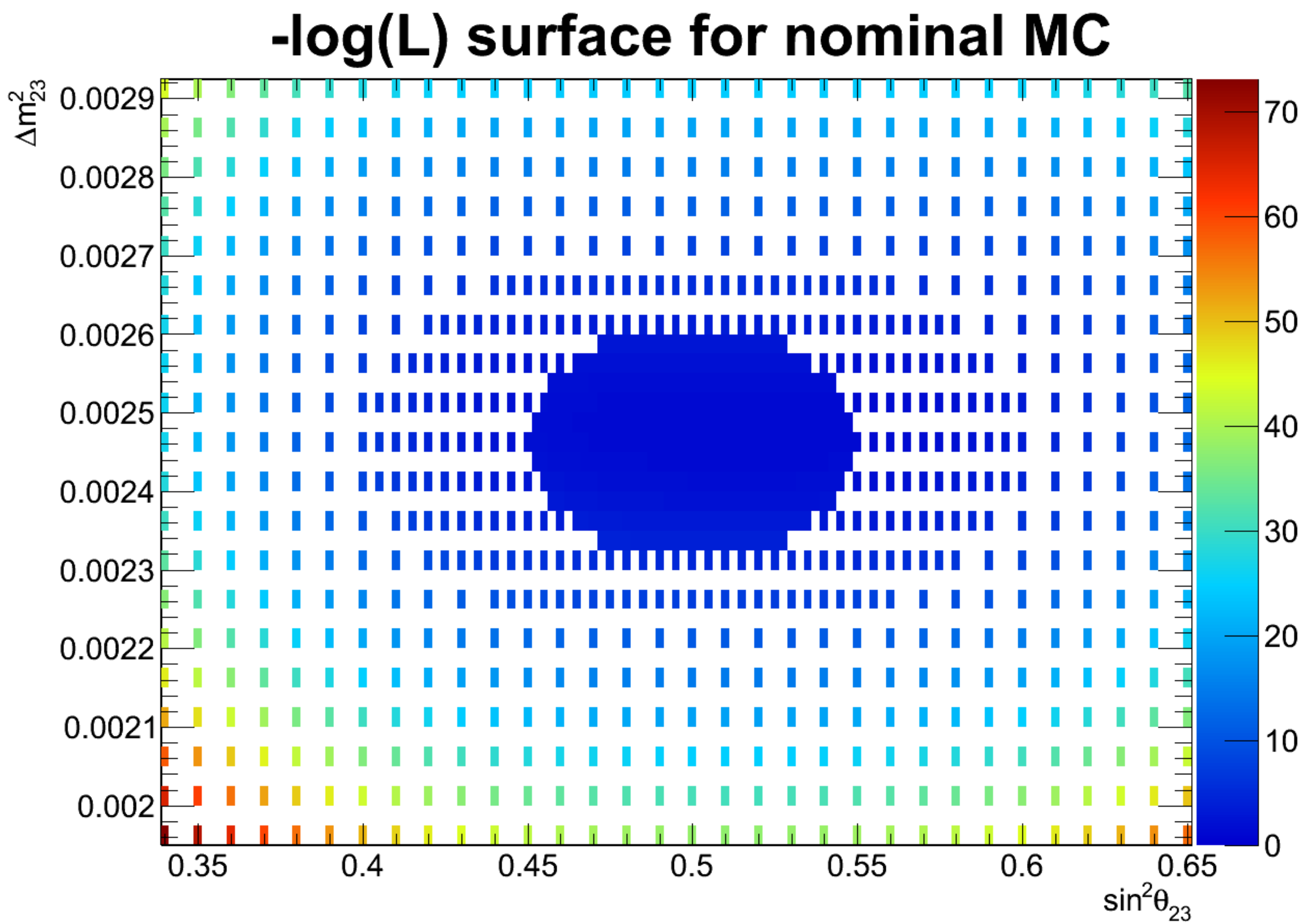


- Total uncertainty is <10% at oscillation peak
- ~7% statistical, 6% systematic

Oscillation fit

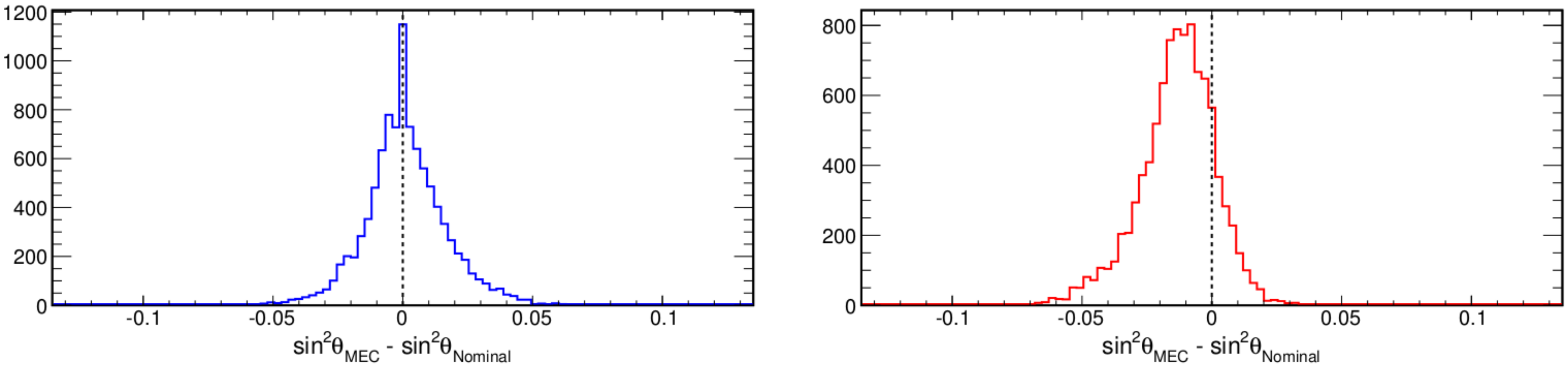
- Calculate covariance matrix and νPRISM prediction for various points in θ_{23} and Δm^2 phase space

- Use Simple Fitter to calculate likelihood (L)
- Plot - ln(L) for all points in θ_{23} and Δm^2
- Minimum bin gives best fit oscillation parameters



Multi-Nucleon effect

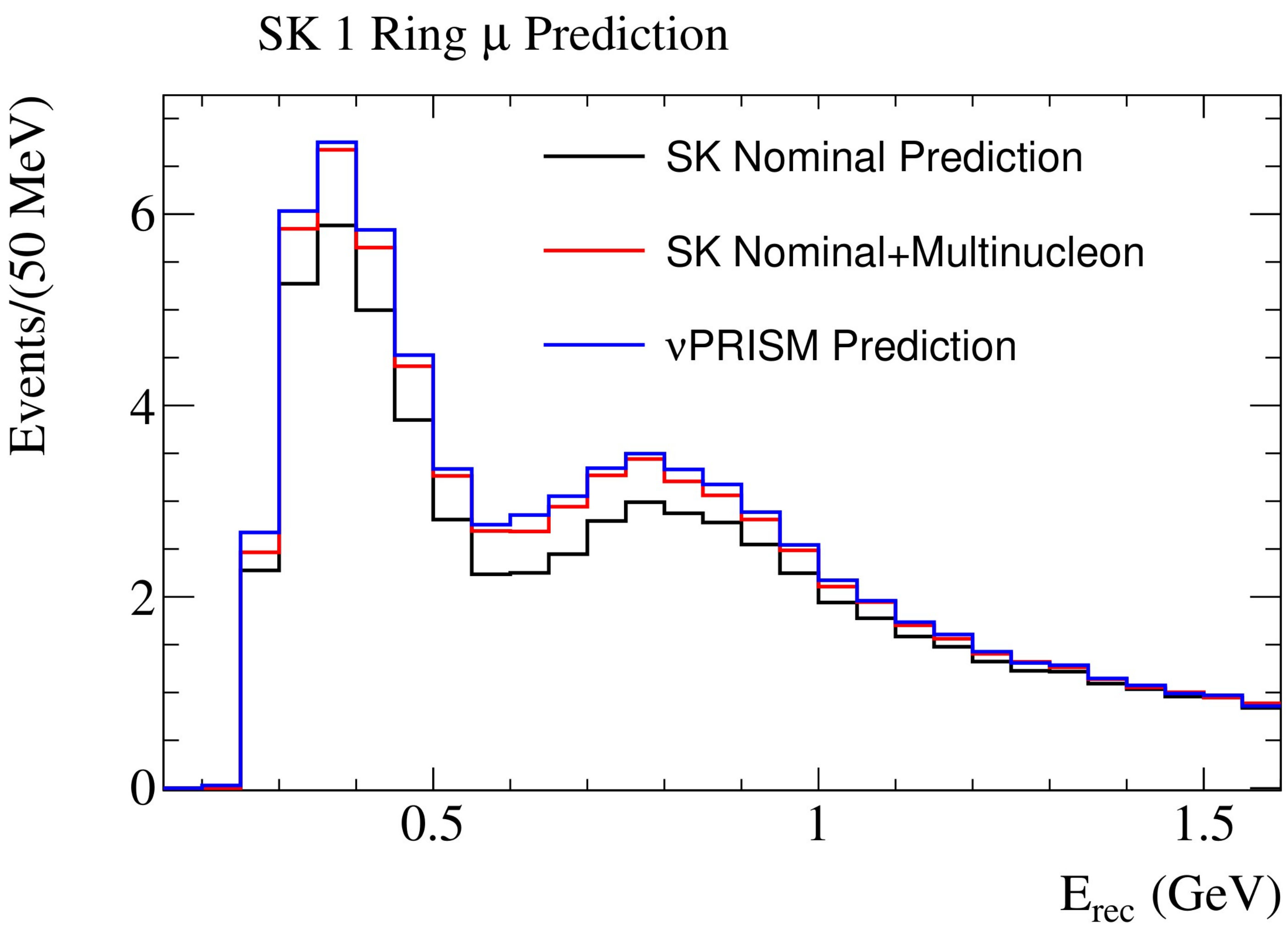
- Add meson exchange current (MEC) interactions to the same νPRISM and SK fake data sets, using Nieves and Martini models
- Re-calculate νPRISM prediction of SK distribution - do not change any of the corrections!
- Find the best fit oscillation point for each fake data set – compare to best fit point without MEC



- Plots above show the result of the same analysis performed by T2K
- Using Nieves' MEC prediction on left, Martini mock up on right
- Both show ~3.5% spread, with a bias in the Martini case

Multi-Nucleon example

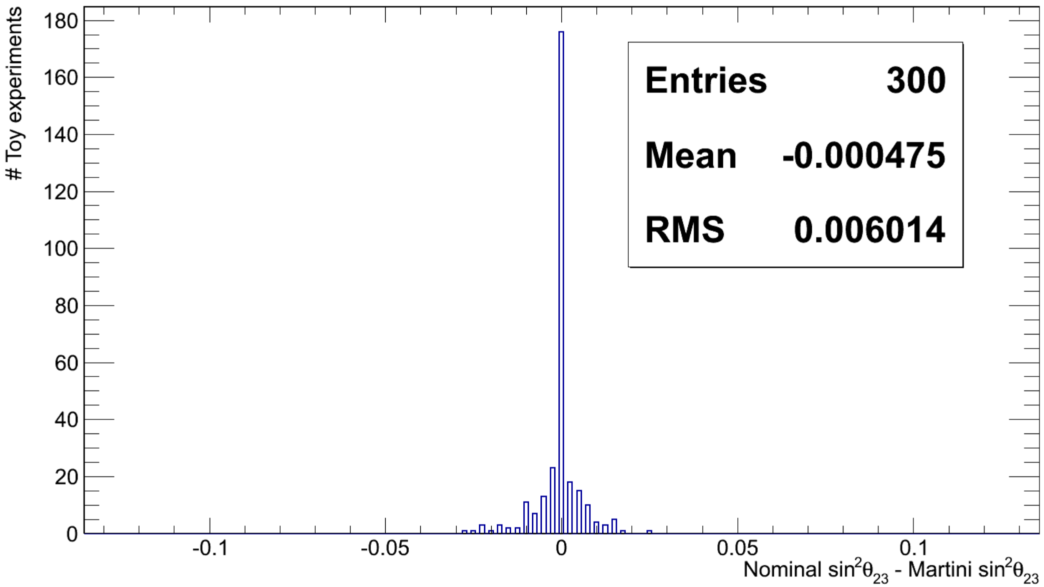
- Add multi-nucleon events to the nominal MC to make fake data

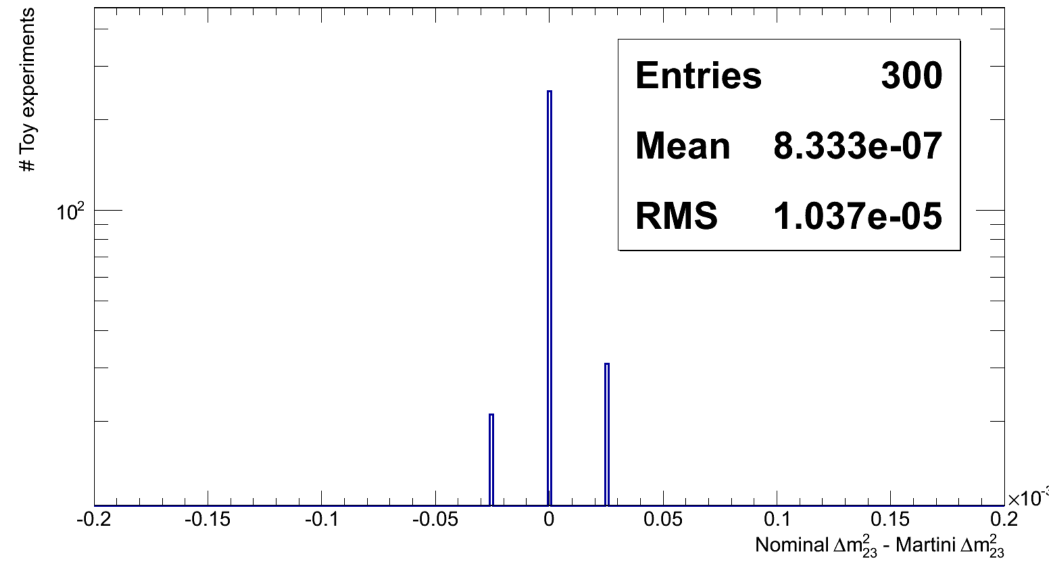


- See νPRISM prediction still reproduces oscillated SK spectrum when multi-nucleon events are present

Martini MEC result

- Look at effect of adding MEC events to 300 fake data sets

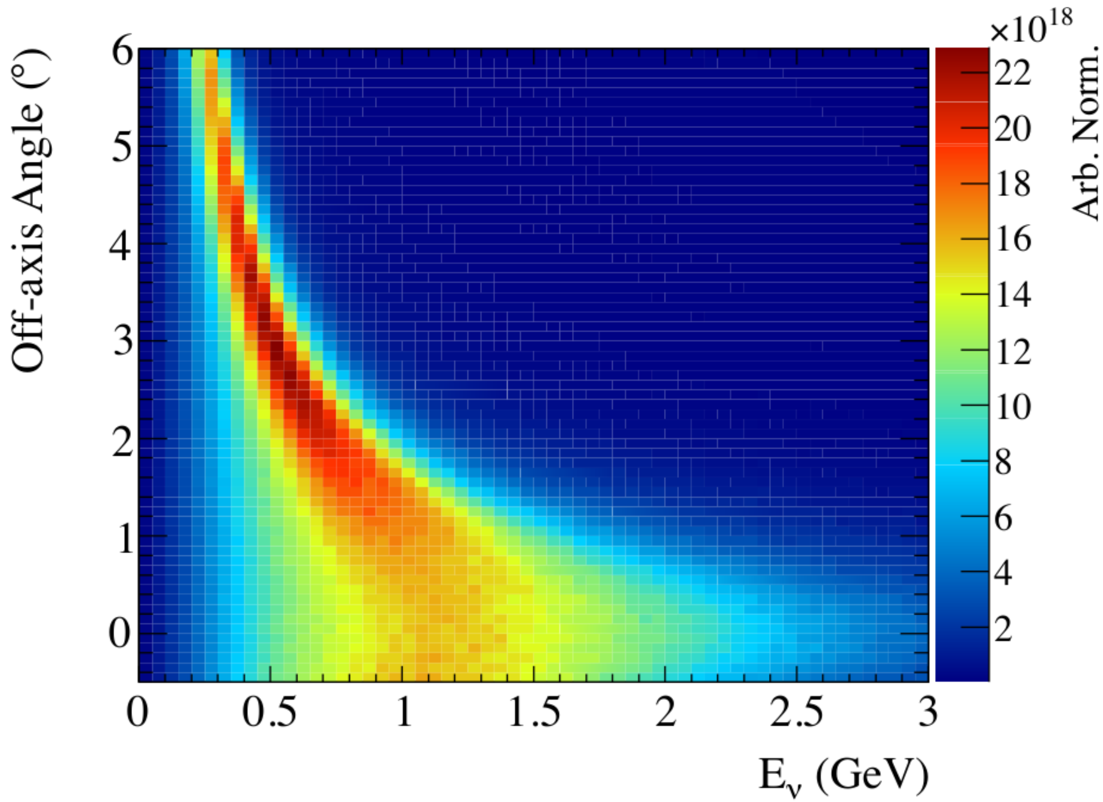


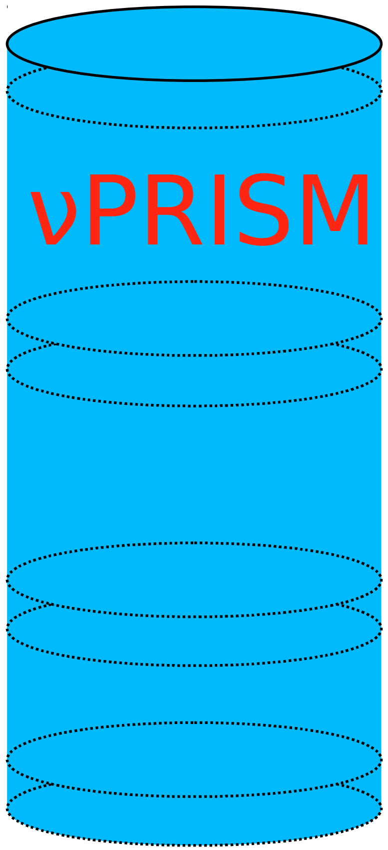


- Much smaller RMS in θ_{23} (left) and Δm^2 (right) than in T2K analysis
- No bias seen in θ_{23} plot
- νPRISM will provide the first data driven constraint on the effect of multi-nucleon events in oscillation measurements

Short baseline physics

- νPRISM provides a unique opportunity for short baseline oscillation searches





- Can create Gaussian neutrino beams with energies from 500MeV – 1 GeV
- Study the energy dependence of oscillations with a known ν energy!

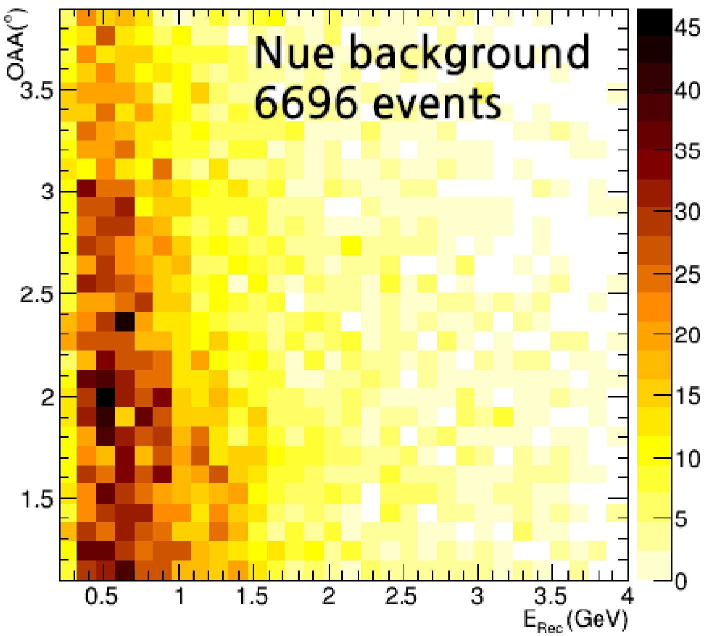
ν_e appearance sensitivity

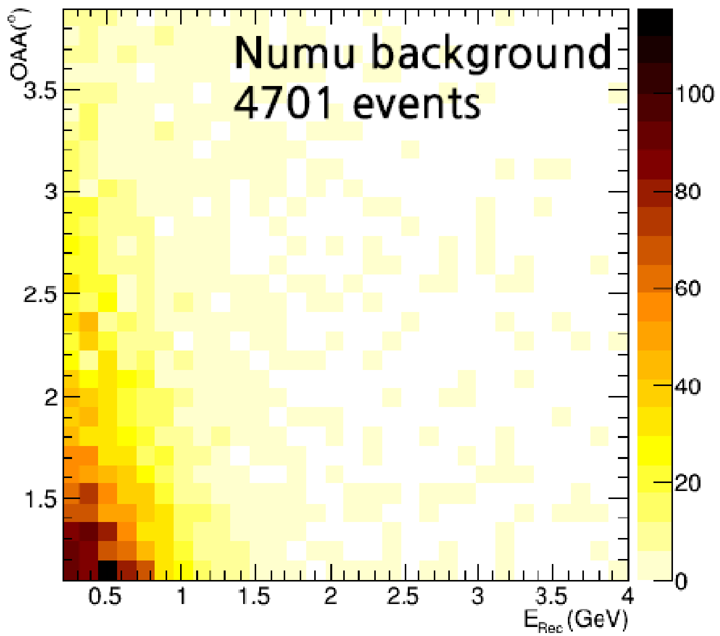
- Studied the νPRISM sensitivity for the ν_e appearance case in the 3 + 1 sterile model – J. Caravaca, J. Vo, S. Bordoni, F. Sánchez
- A shape + rate analysis performed in reconstructed neutrino energy and off-axis angle space
- Flux and cross section uncertainties taken into account
- χ^2 test used to determine the allowed regions of parameter space

- A conservative approach:
  - Using full flux and cross section uncertainties
  - Just use raw off-axis angle
  - Using SK reconstruction efficiencies and fiducial volume cuts
  - No combined ν_e / ν_μ fit

ν_e selection

- Require > 2m between the reconstructed vertex position and the wall of νPRISM (dWall)
- Require > 200MeV of visible energy
- Require > 3.2m distance to the νPRISM wall in the lepton direction (toWall)





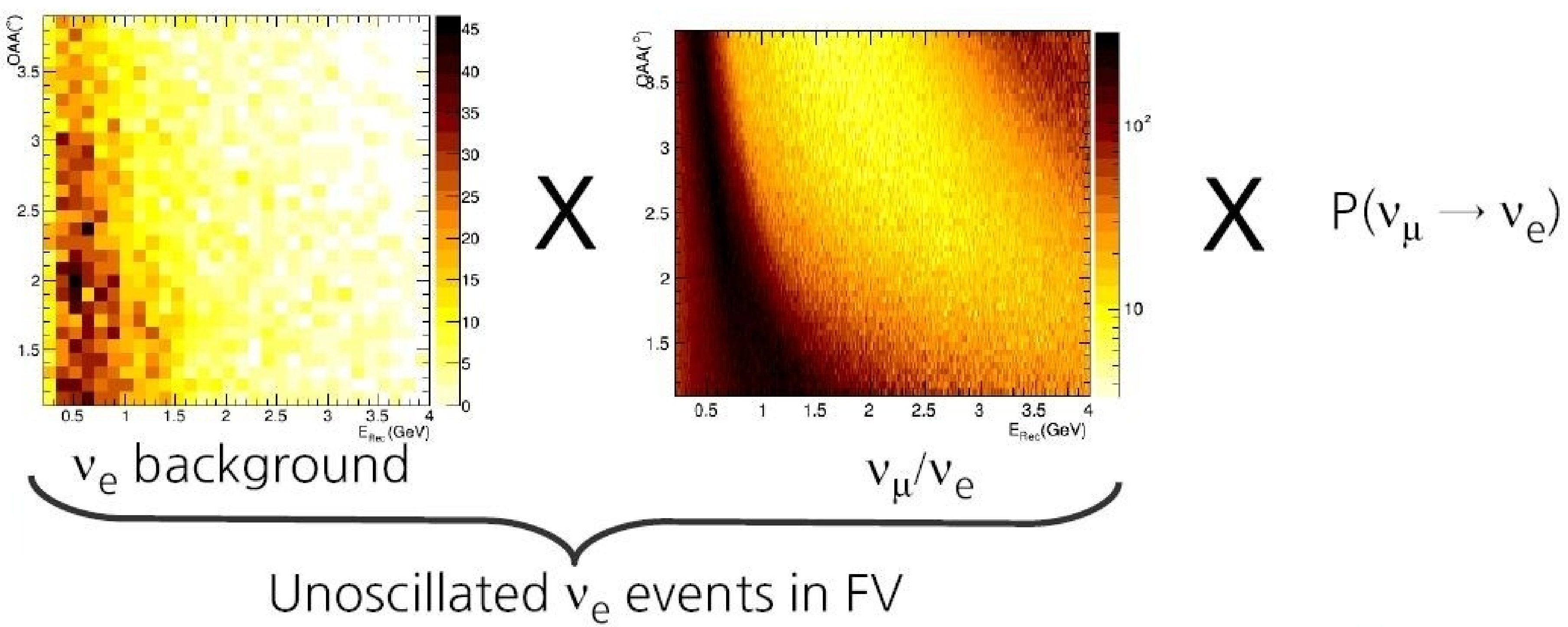
Purities with 4m (NEW)
numu = 36.2%
numub = 1.5%
nue = 58.8%
nueb = 3.5%
Total = 11396 events

ν_e signal template

- Take selected ν_e background events
- Reweight to the ν_μ flux
- Apply the 3 + 1 oscillation probability

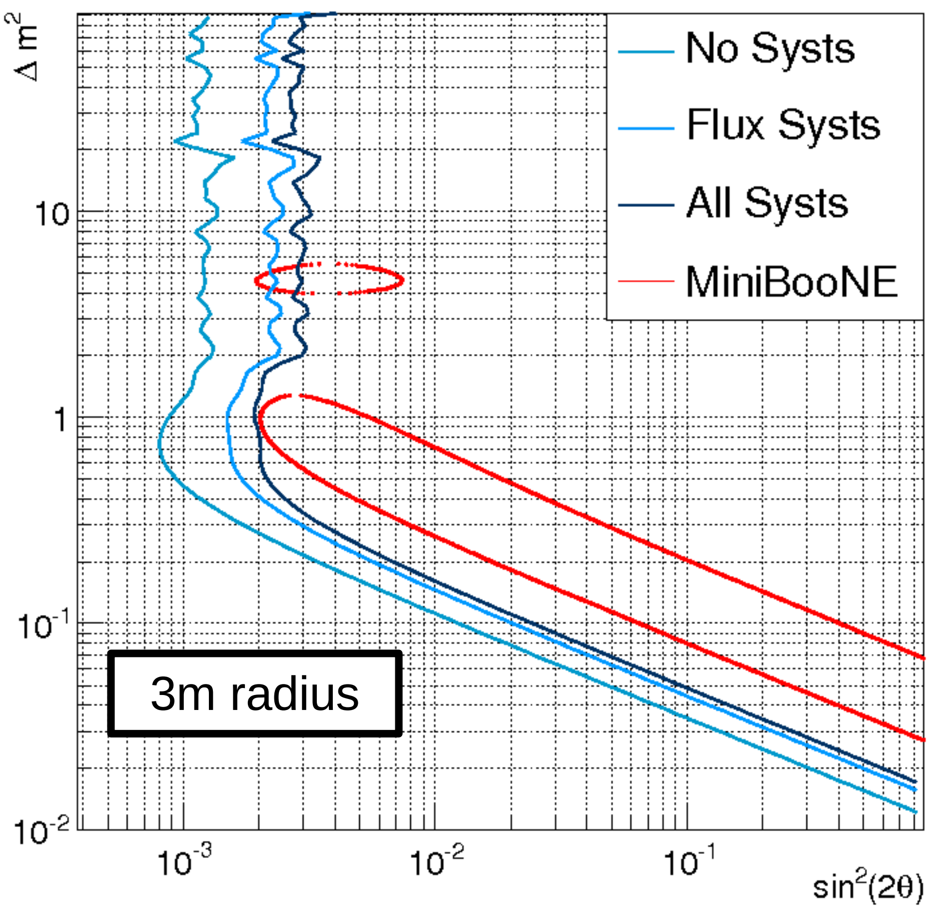
$$P(\nu_\mu \to \nu_e) = P(\nu_e \to \nu_\mu) = 4|U_{e4}|^2|U_{\mu4}|^2 \sin^2\left(1.27\,\Delta m^2_{41}\frac{L}{E}\right)$$

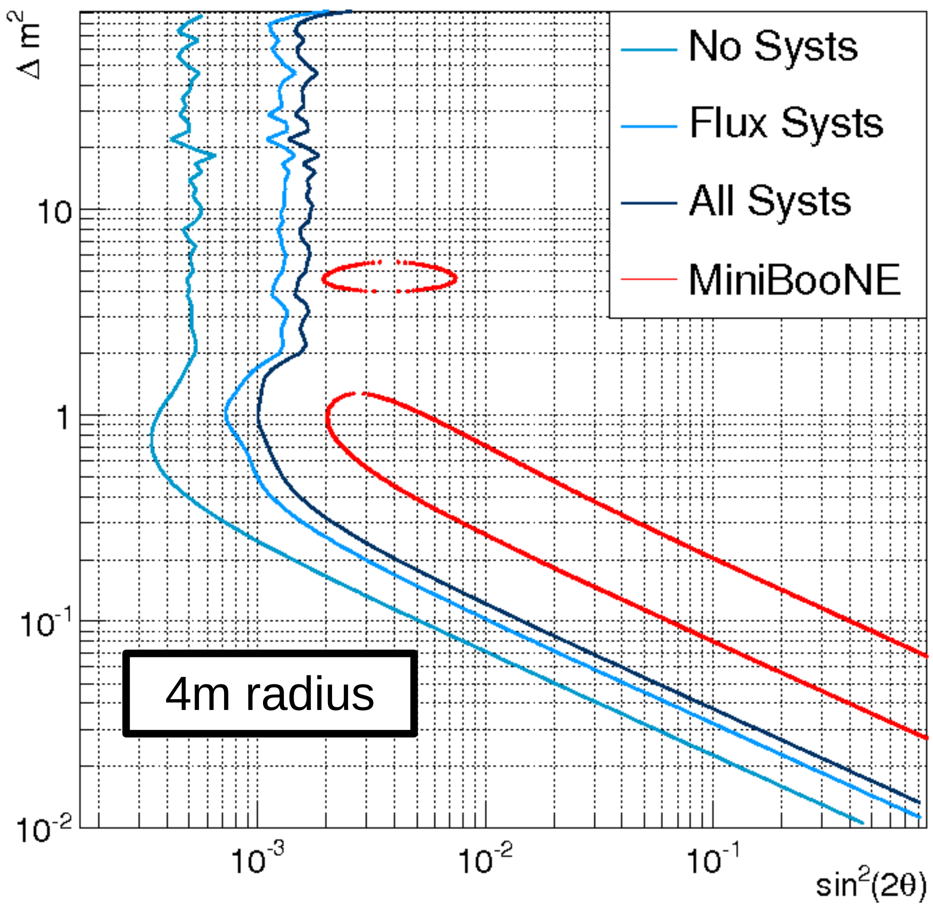
$$\sin^2(2\theta_{e\mu}) = 4|U_{e4}|^2|U_{\mu4}|^2$$



Final sensitivities

- ν_e fiducial volume cut is harsh – reduces statistics considerably
- Show two cases – 3m radius νPRISM and 4m radius

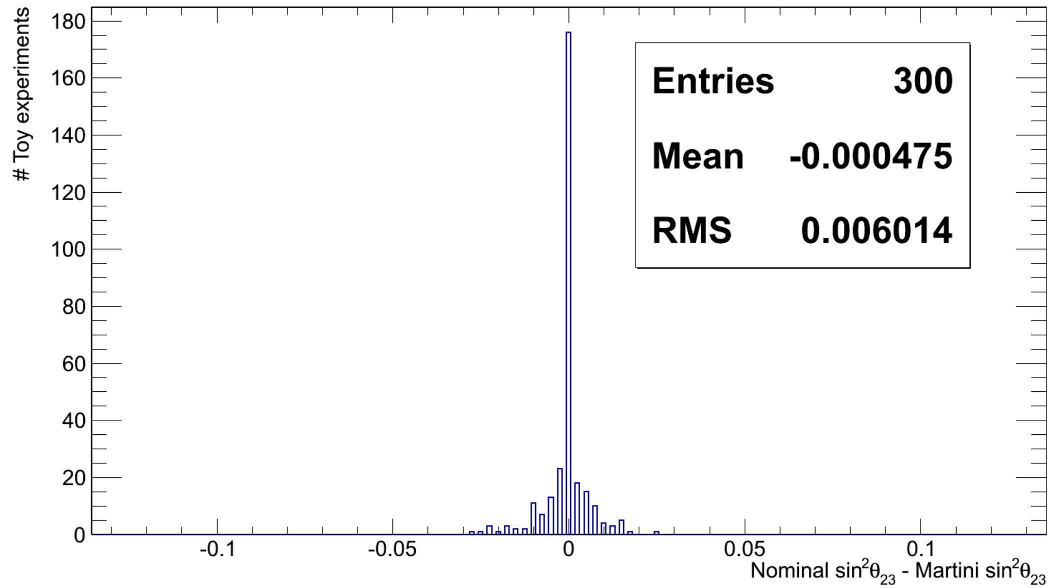


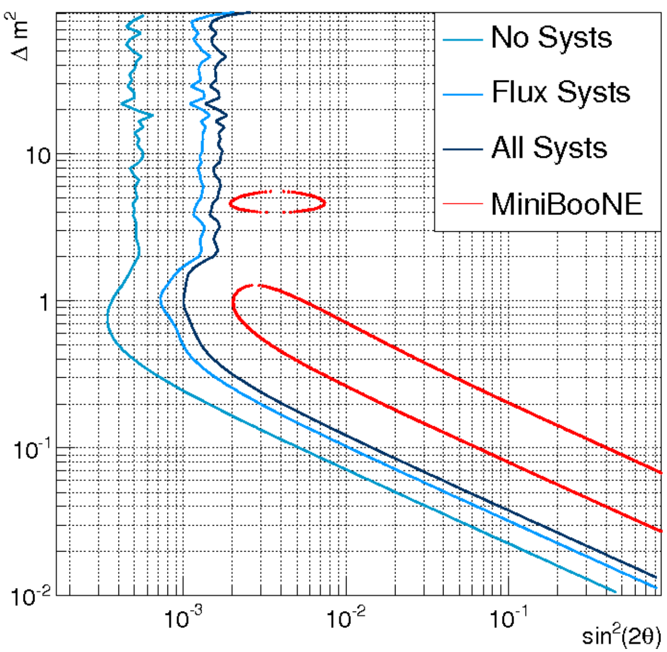


- Majority of MiniBooNe allowed region is covered in both cases
- Larger radius (or better FV cuts) greatly increases sensitivity

Summary

- νPRISM gives direct information about the neutrino energy
- Can remove bias from unknown nuclear effects
- νPRISM will also reduce the effect of all cross section uncertainties



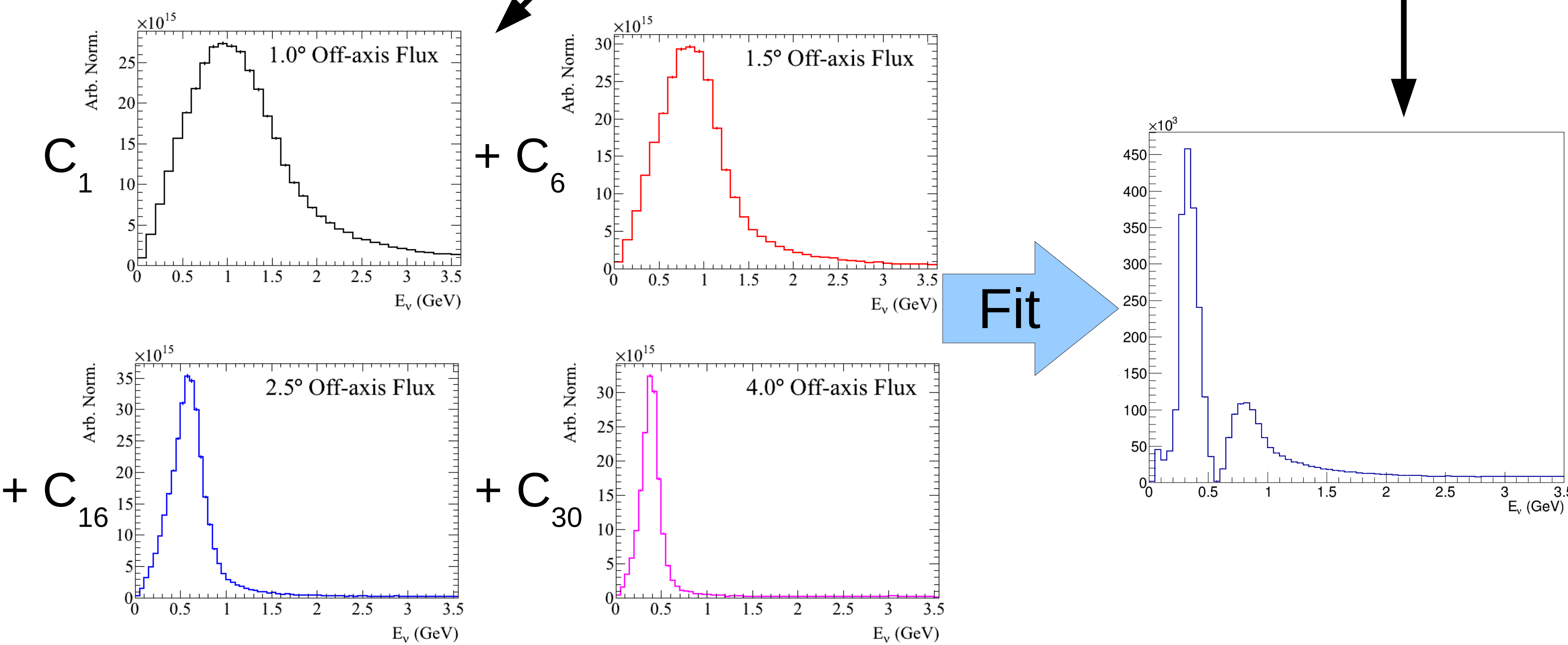


- Can perform short baseline oscillation searches as function of neutrino energy
- Conservative analysis
- νPRISM can exclude the MiniBooNe allowed region for a 3 + 1 sterile neutrino model

Backup slides

Building the oscillated flux

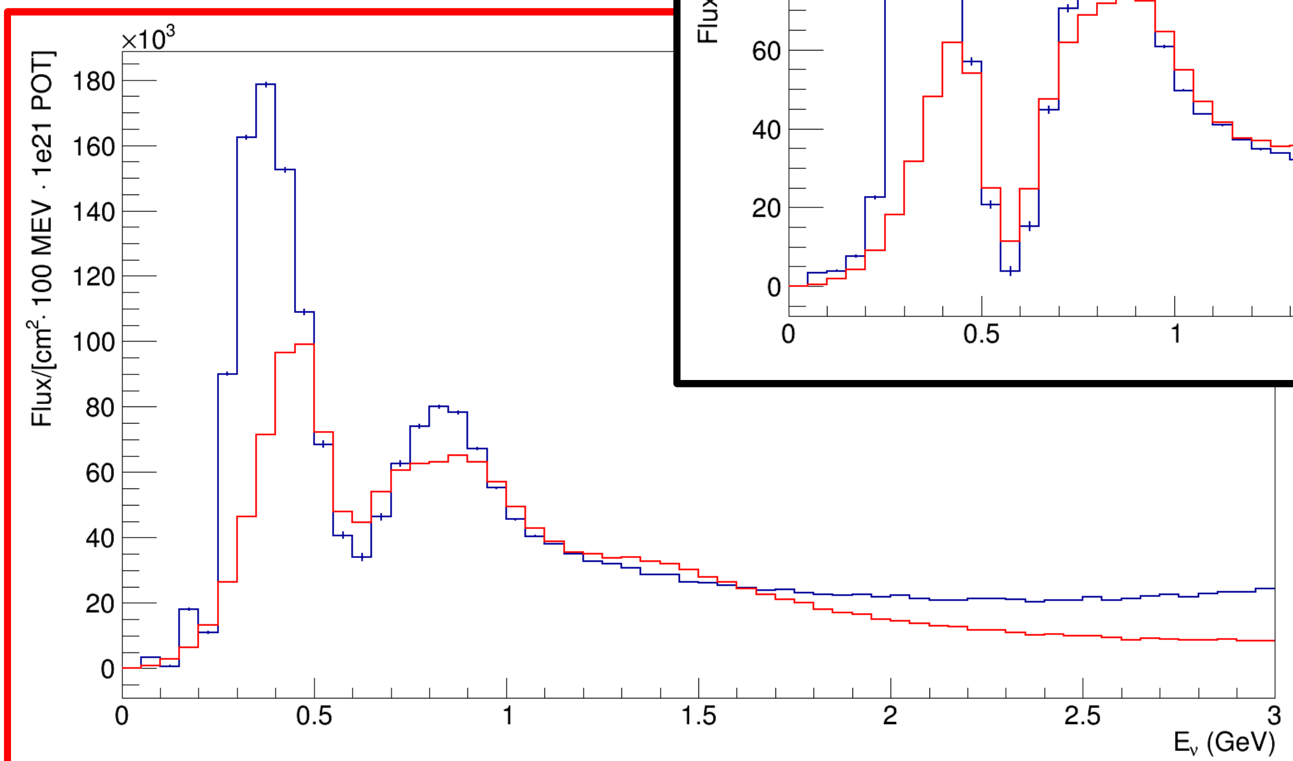
- All based on simulated neutrino flux at SK and νPRISM
- Slice νPRISM into 30 slices of 0.1 degree – assign each a weight
- MINUIT χ^2 fit between sum of weighted νPRISM slices and oscillated SK flux

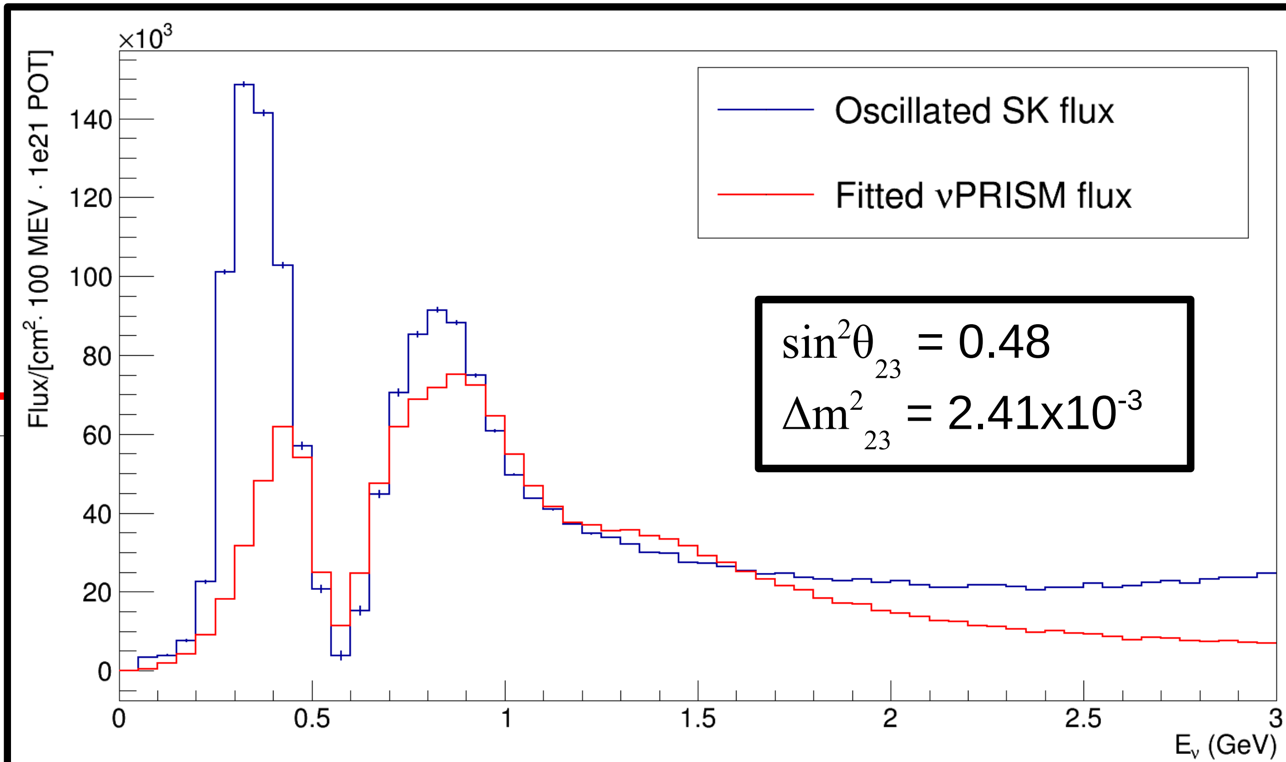


Building the oscillated flux

- Perform fit for all combinations of oscillation parameters used in the oscillation fit

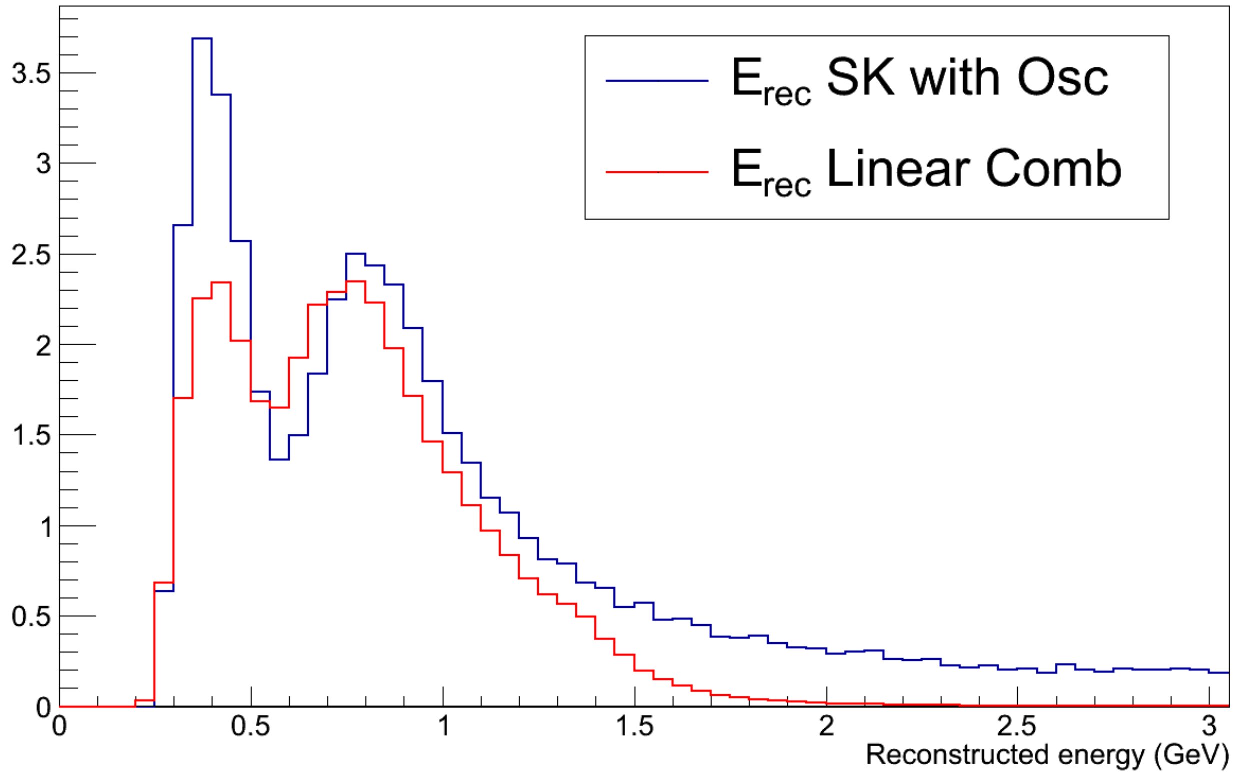
$\sin^2\theta_{23} = 0.61$
$\Delta m^2_{23} = 2.56\text{x}10^{-3}$





- Get a set of 30 C_i coefficients for each pair of oscillation parameters

Additive correction



- Final step – additive correction
- Subtract selected SK spectrum from νPRISM prediction
- Add this difference to the νPRISM prediction
- If our MC exactly reproduces nature, νPRISM prediction will exactly match selected SK spectrum

νPRISM corrections

- Every correction made to the νPRISM prediction is calculated from our nominal MC – all are constant corrections
- These corrections potentially introduce model dependence
- To calculate systematic uncertainties:
  - Apply a variation to the νPRISM and SK MC
  - Changes number of selected events at both detectors
  - Apply corrections (from the unvaried, nominal MC)
  - Calculate difference between selected SK events and νPRISM prediction
  - Use this to calculate fractional covariance matrix for νPRISM prediction

Flux uncertainty

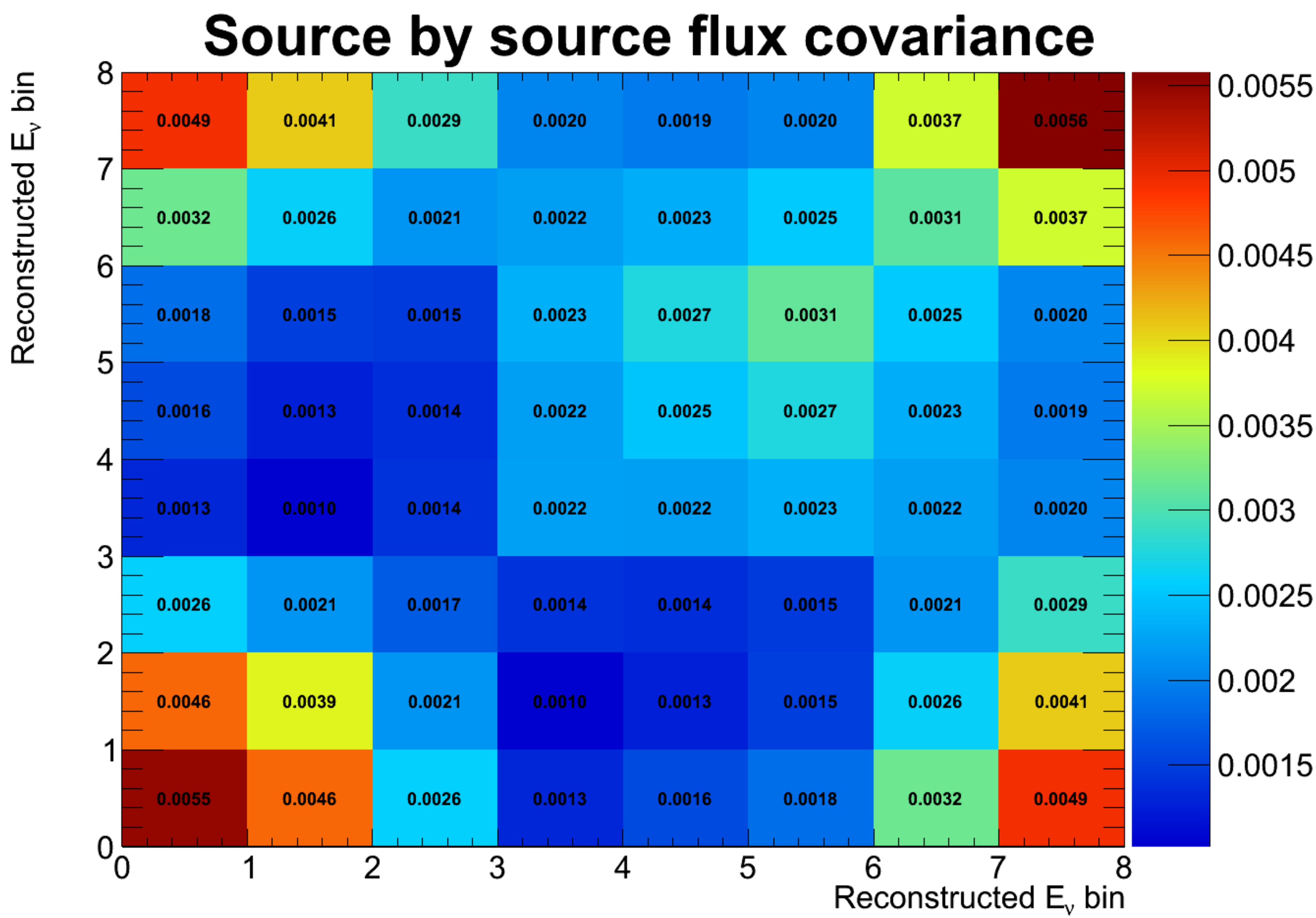
- Flux uncertainties come from 26 sources
  - Proton beam alignment
  - Hadron production
  - Etc.
  - Expect to be independent of one another

- Can calculate a flux covariance matrix in two ways:
  - From each source separately, then combine in quadrature
  - Apply variation from each source at the same time and calculate a covariance for the entire flux uncertainty in one step

- These should give the same answer

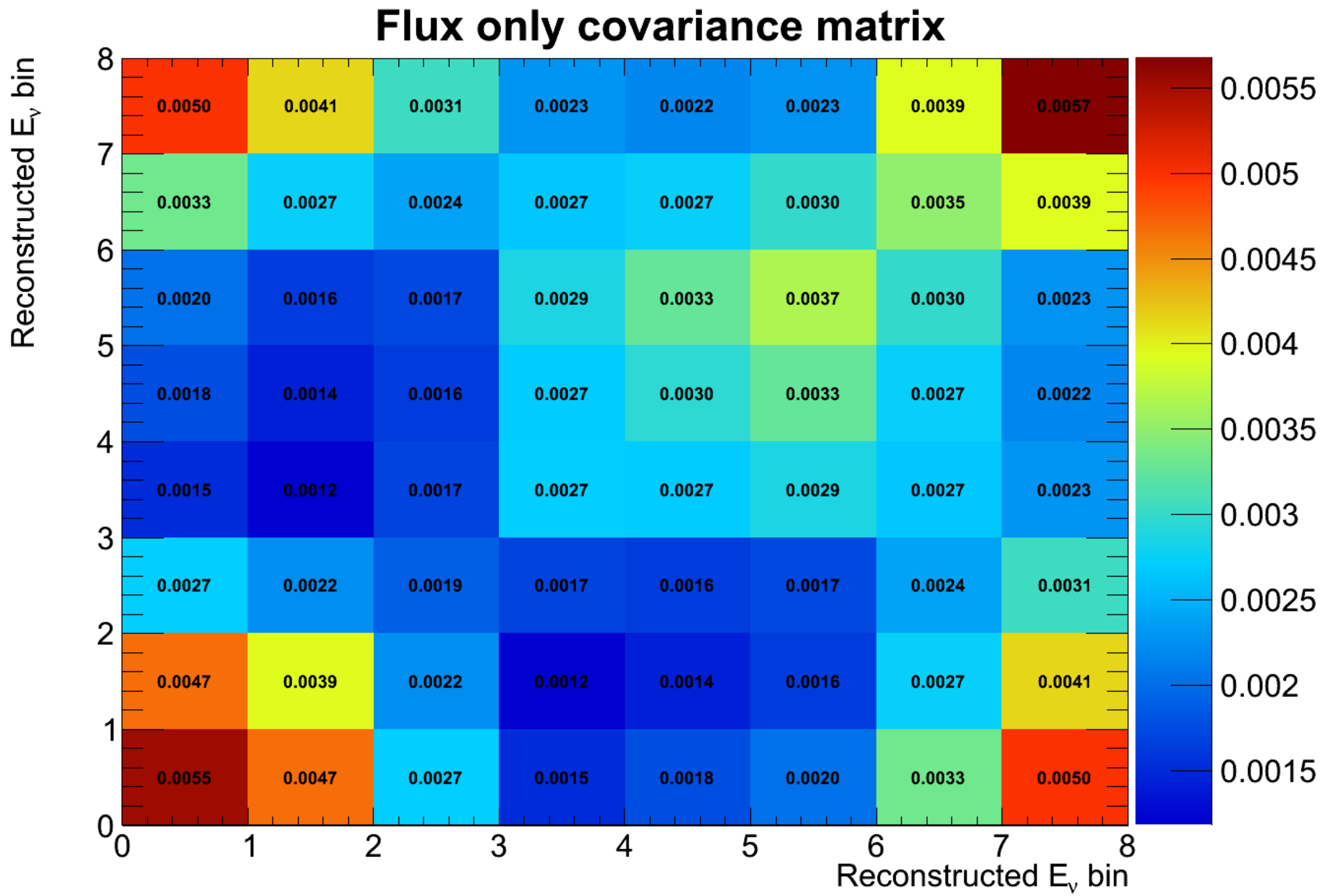
Separate sources

- Oscillation analysis performed using 12 uneven bins in reconstructed neutrino energy – the 8 shown cover 0 – 3 GeV



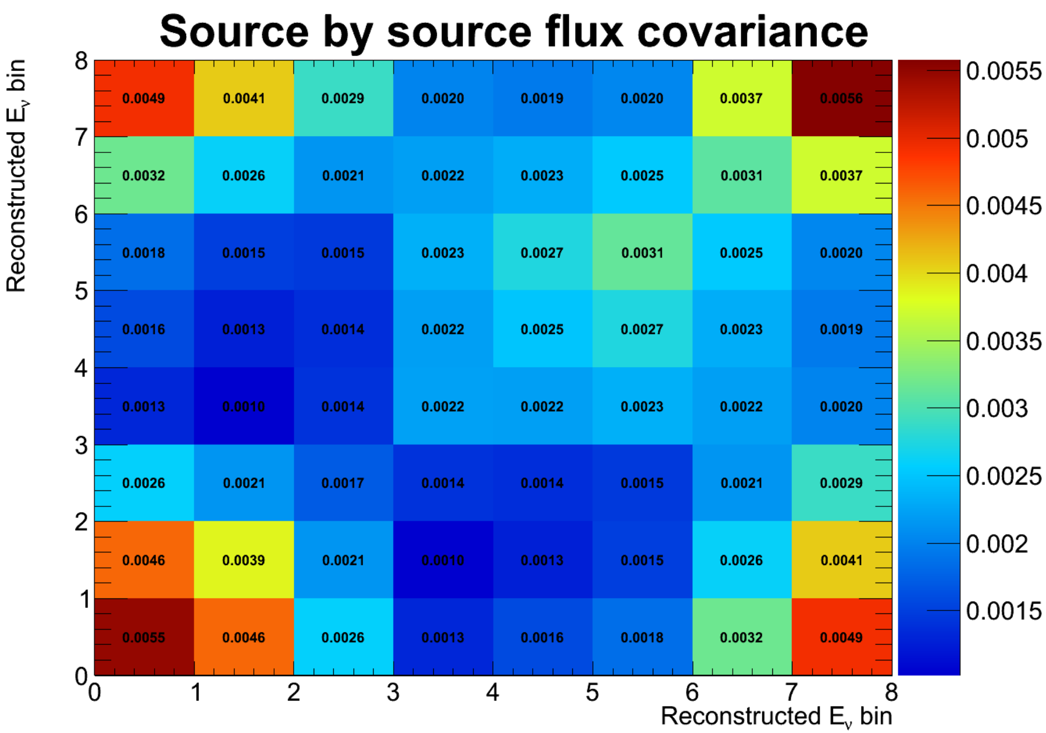
Simultaneous variation

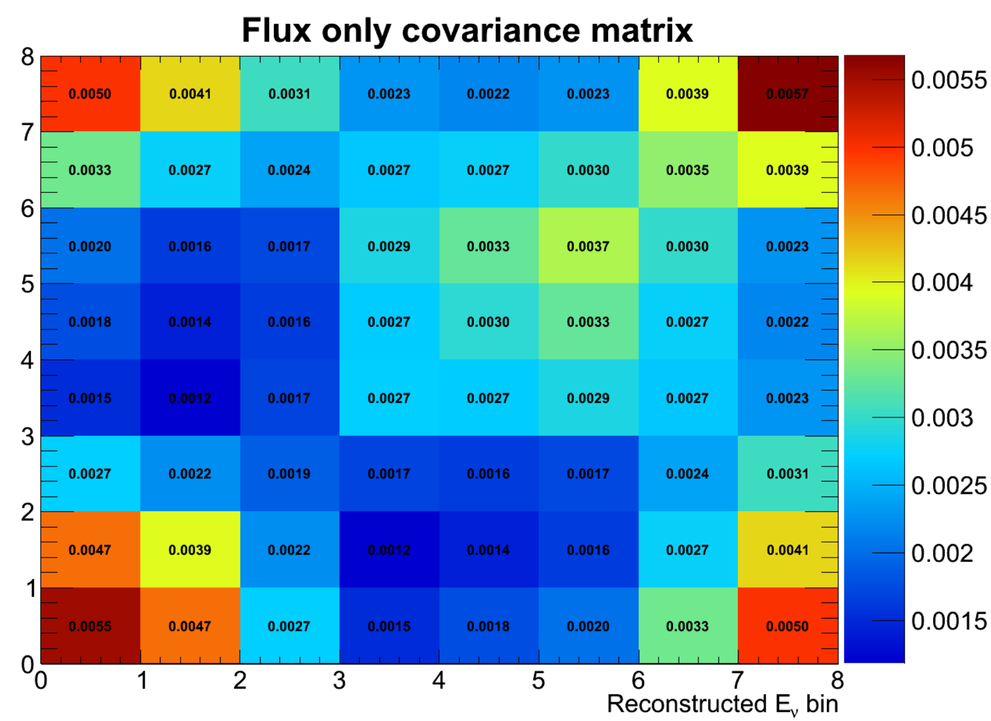
- Larger errors at high and low energy – no νPRISM events
- Error at oscillation dip (bin 3) around 5%



Comparing flux uncertainty

- Source by source matrix on left, simultaneous matrix on right

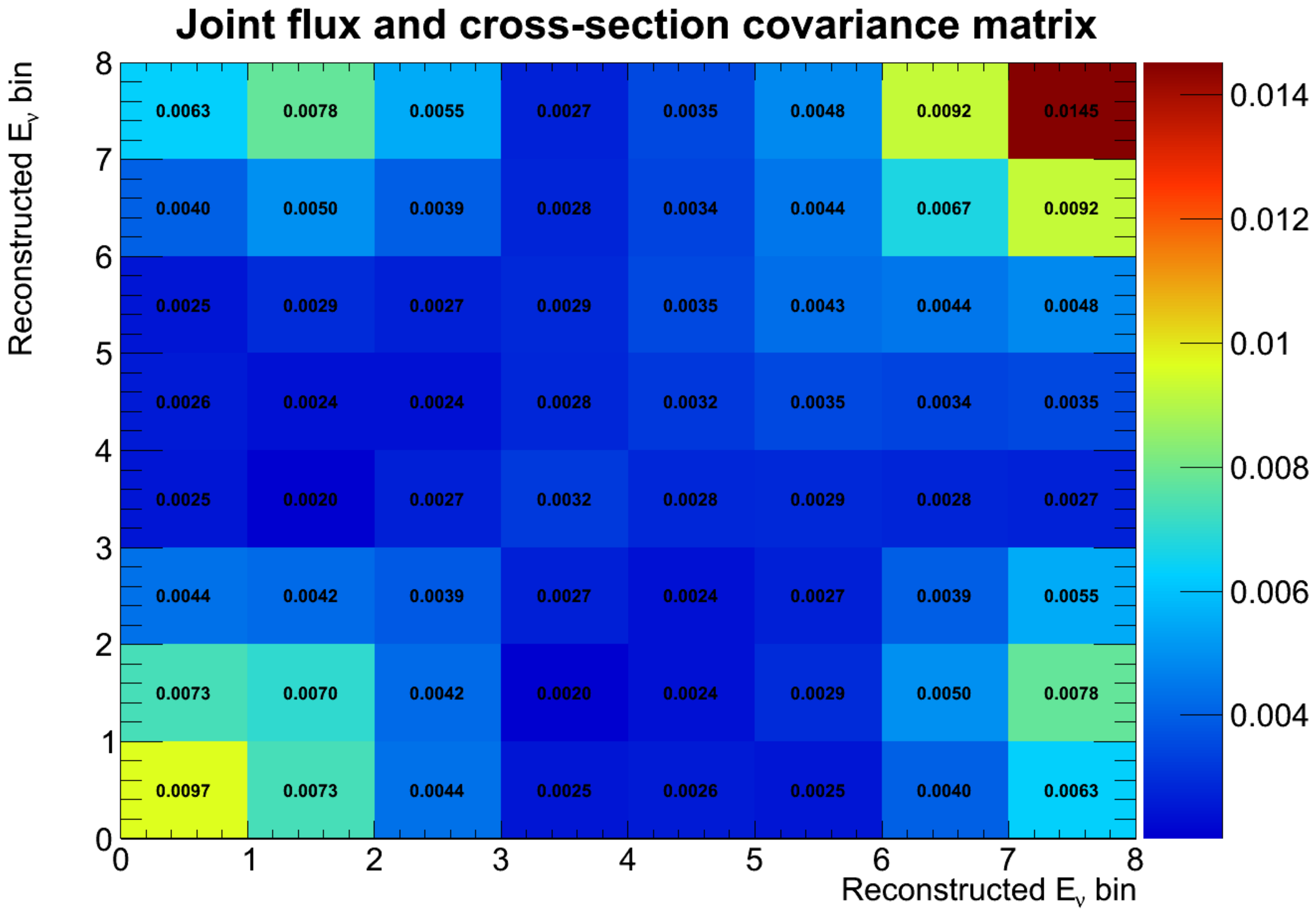




- Very good agreement between the two methods
- Confident flux uncertainties are being applied correctly

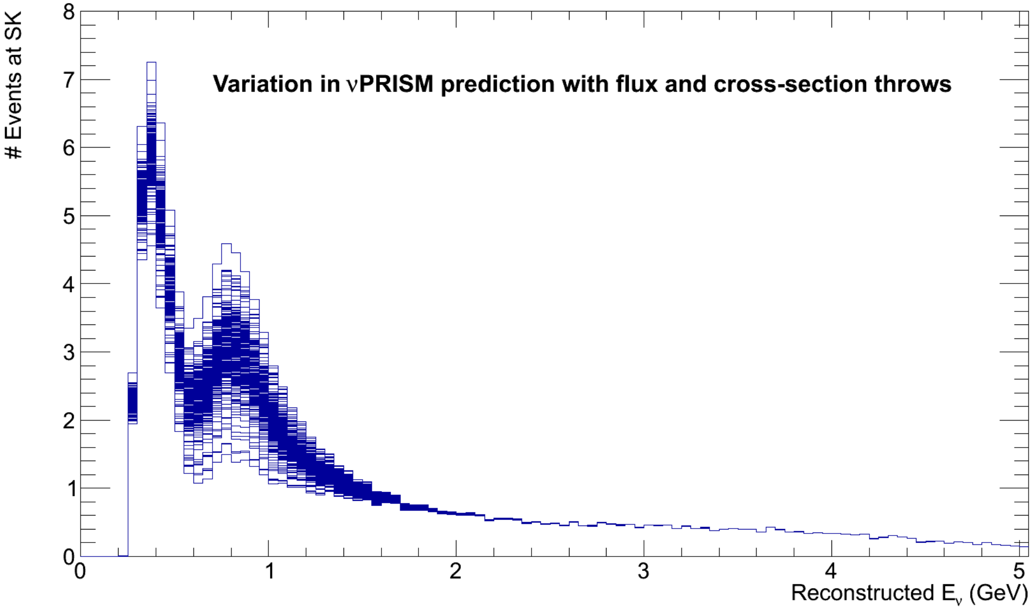
Flux and cross section

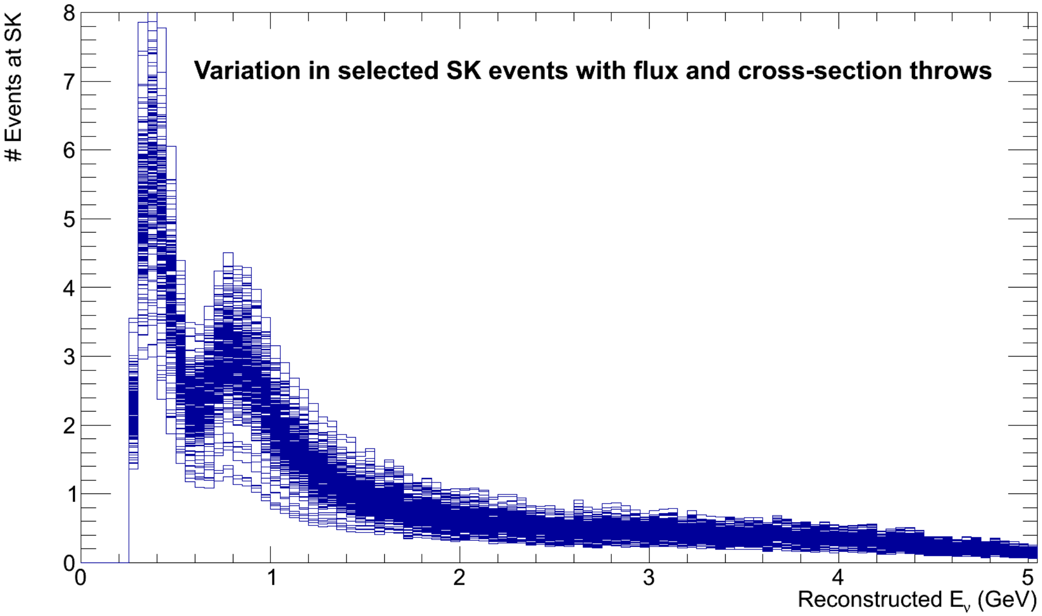
- When varying flux and cross section simultaneously the uncertainty in bin 3 (600 – 700 MeV) is 5.7%



Systematic throws

- Look at fake data throws of both flux and cross section uncertainties



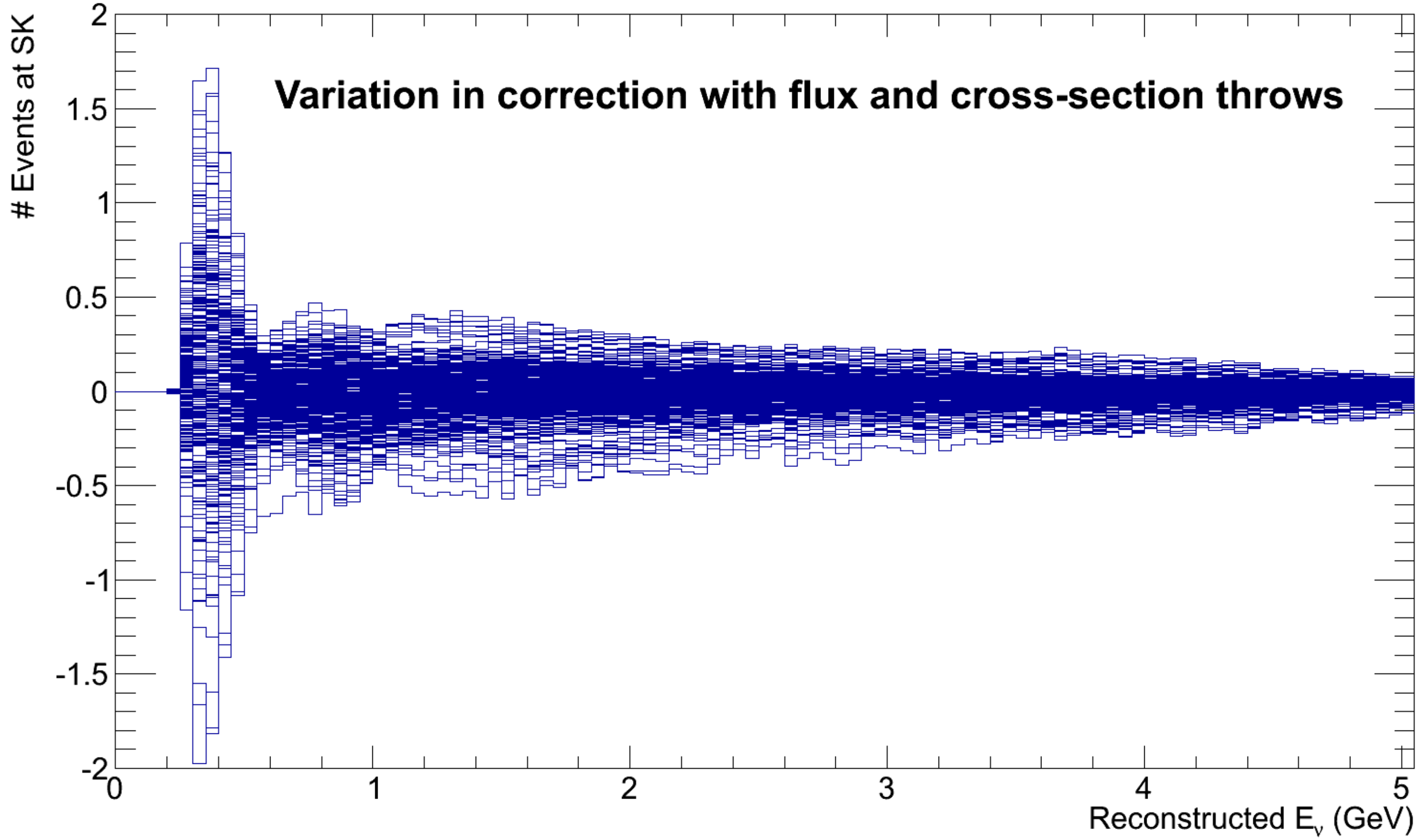


- Plots show all 300 throws of the νPRISM prediction (left) and selected SK events (right)

- νPRISM - very few events at low or high energy, little variation
- In oscillation region variations similar at SK and νPRISM
- Spectra are ~Gaussian distributed about the central value

Systematic throws

- Plot difference between selected SK events and νPRISM prediction for each throw

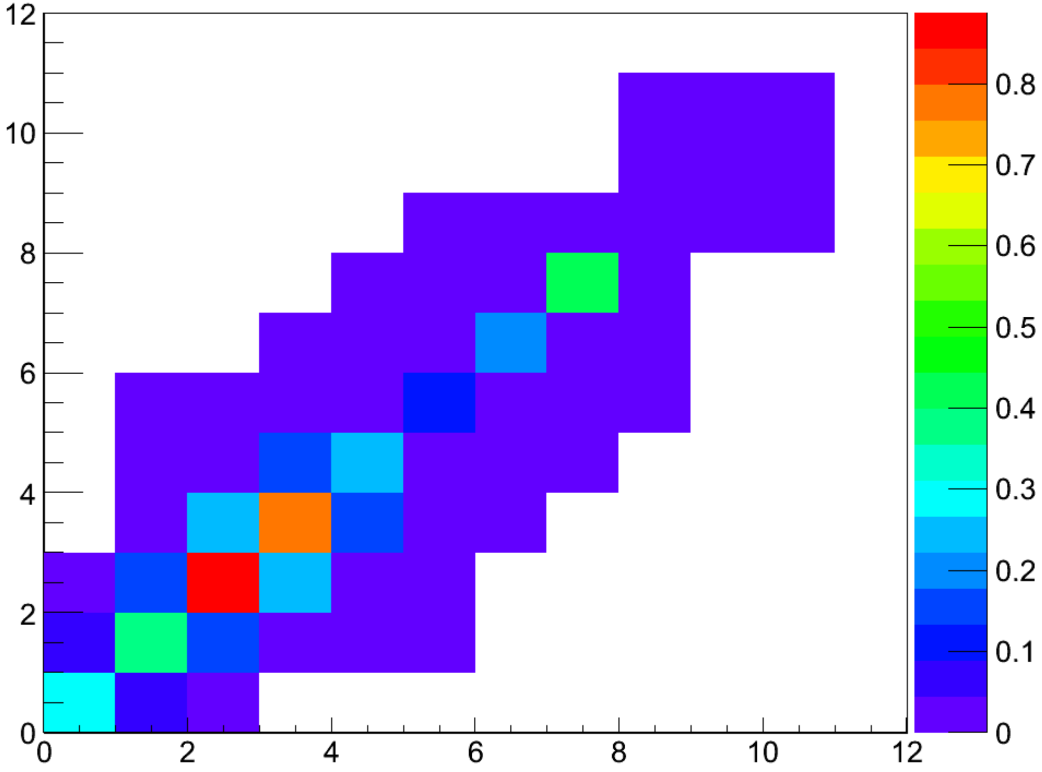


- Most of spectrum shows less than 0.5 event difference between SK and νPRISM prediction
- Systematic uncertainties are cancelling between the two detectors

Statistical uncertainties

- Potential to be large due to linear combination
- Original error matrix on right

  - almost 100% uncertainty



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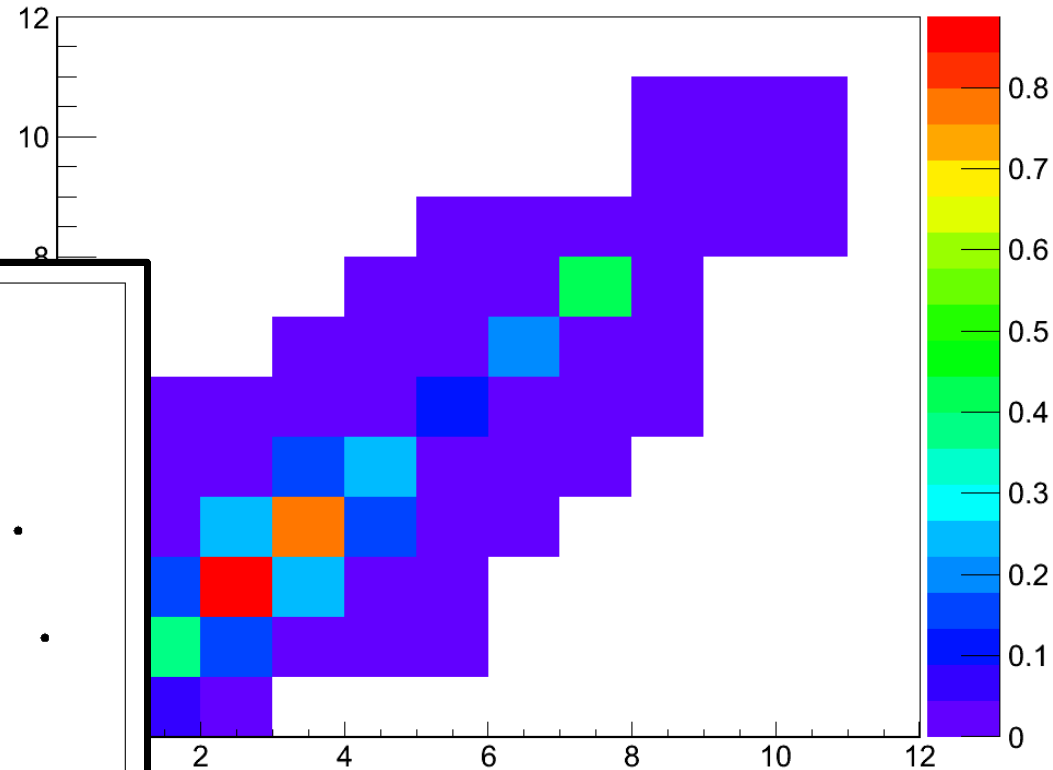
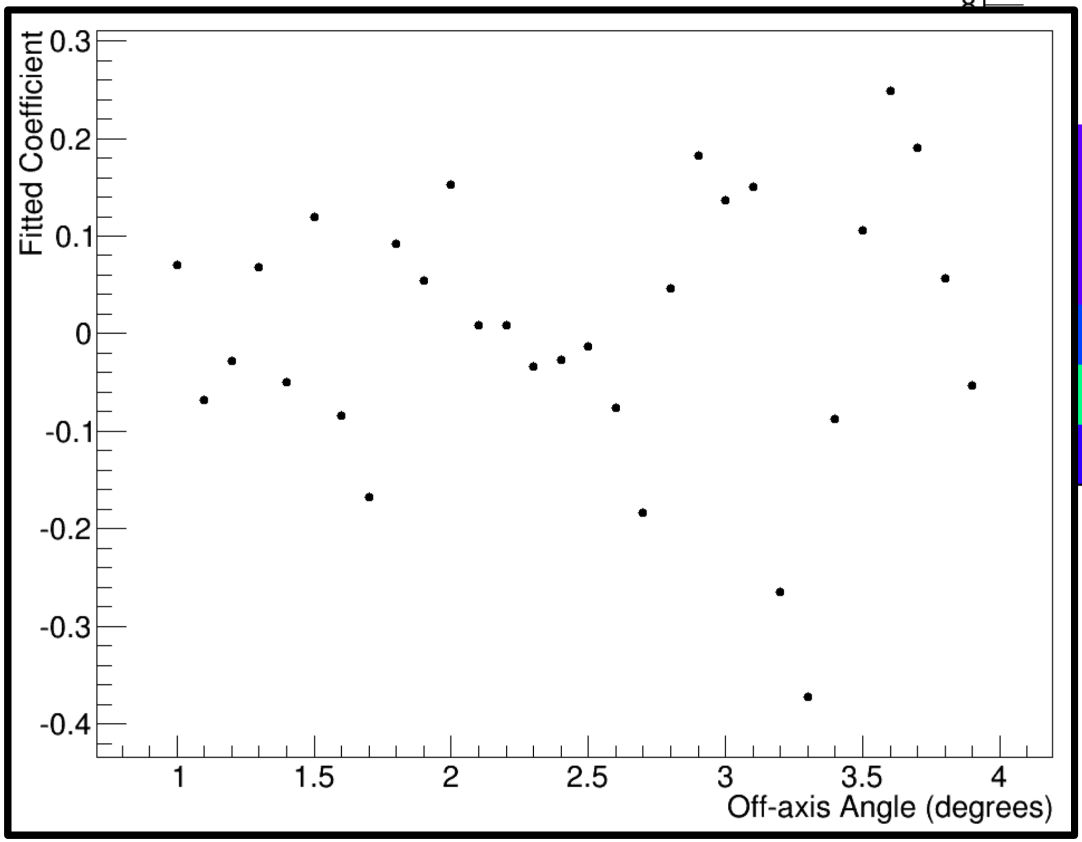
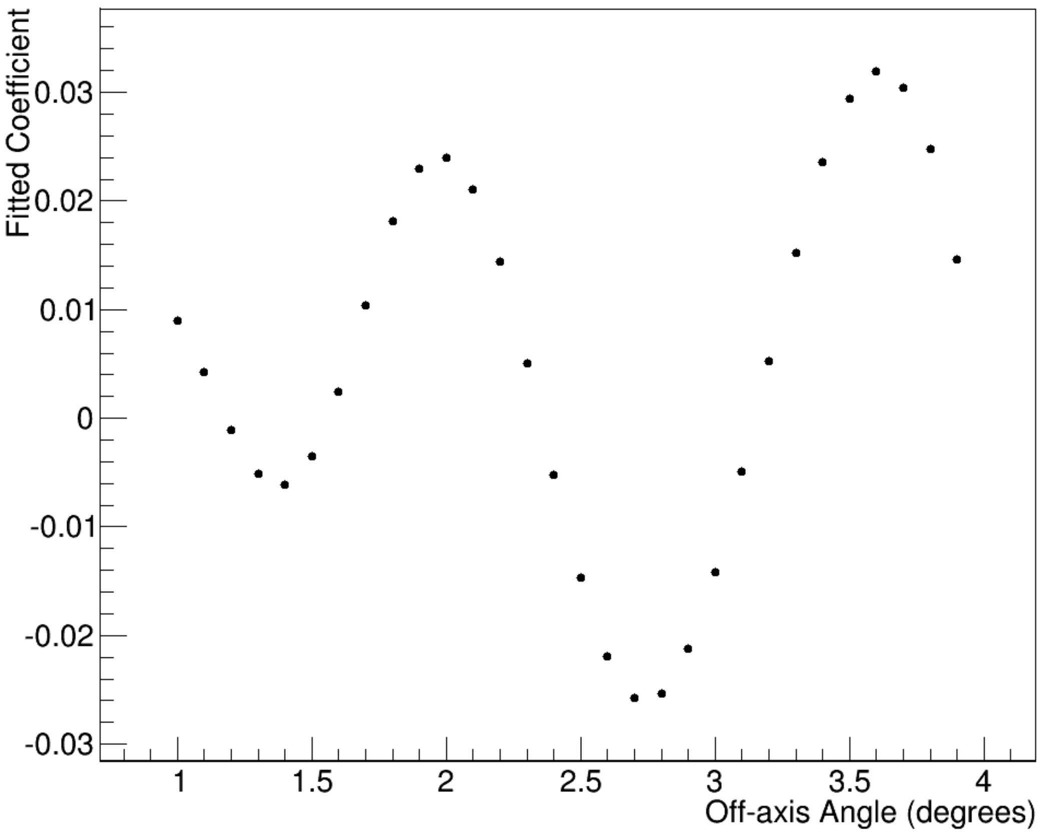




- Fit coefficients:
  - Rapidly varying
  - Relatively large

Statistical uncertainties

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



Statistical uncertainties

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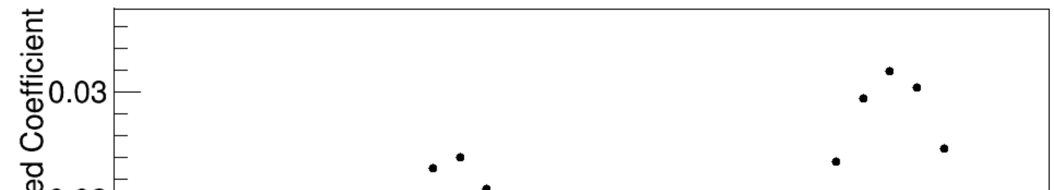
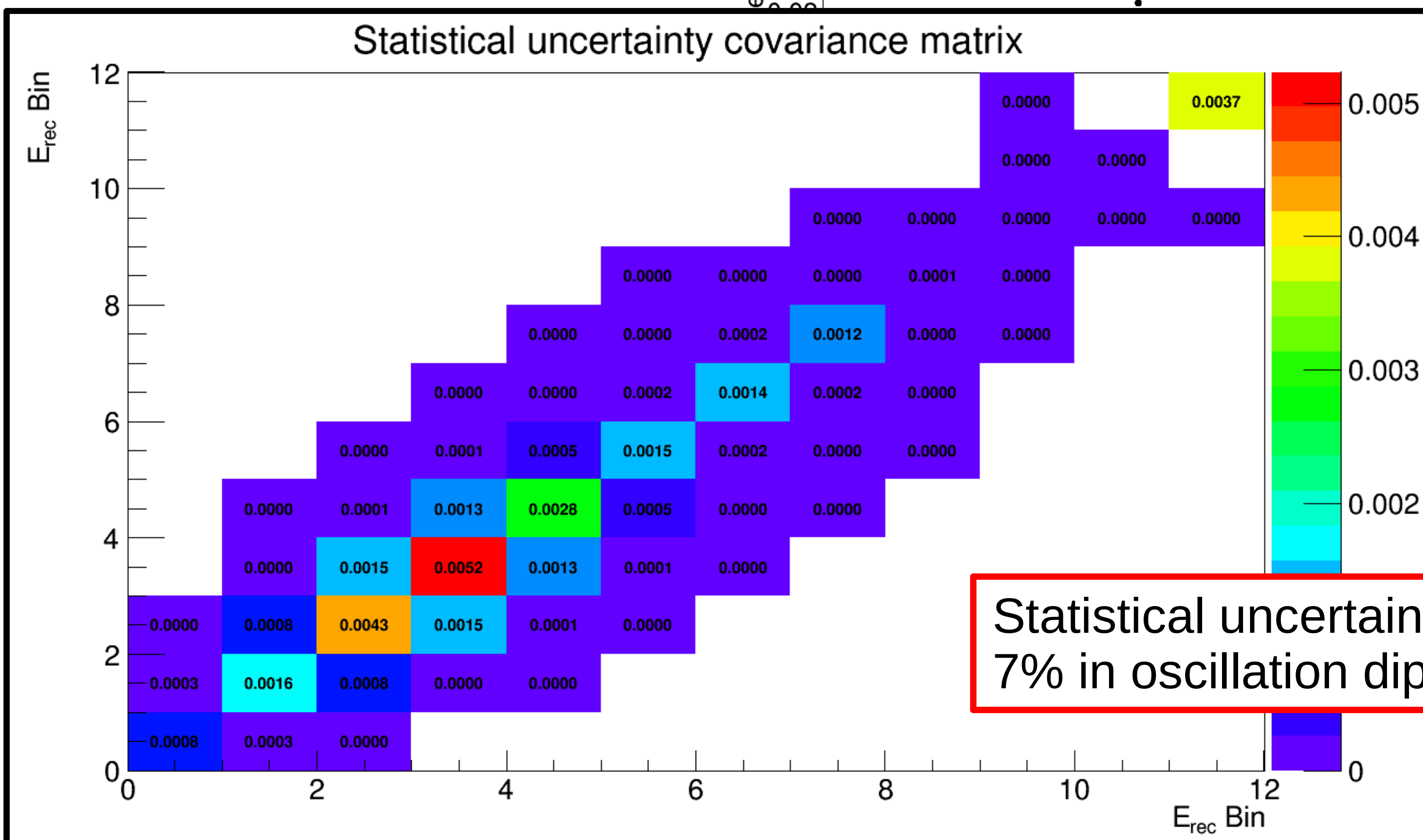
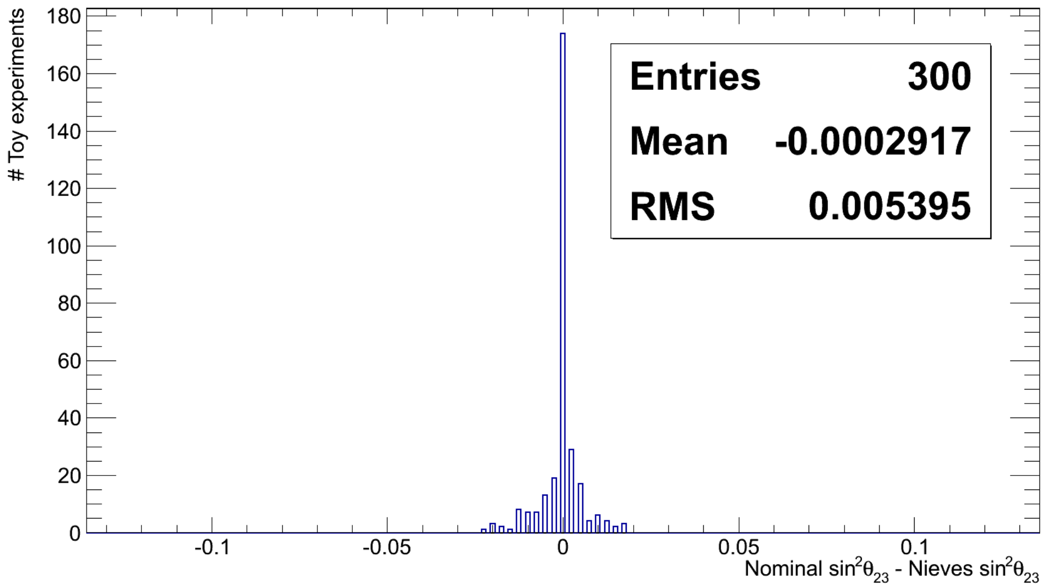


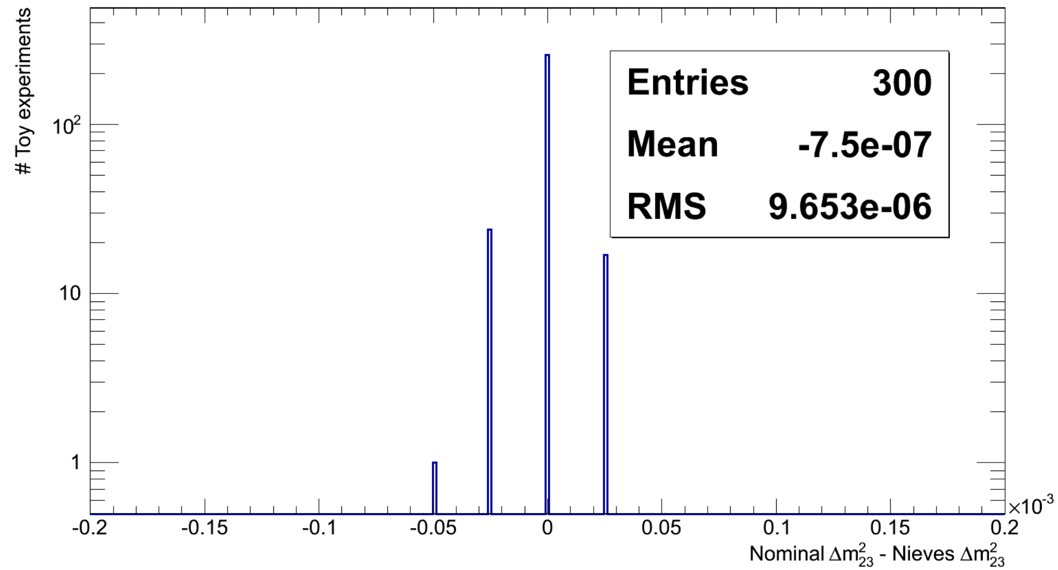


Statistical uncertainty around 7% in oscillation dip

Nieves' result

- Look at the difference in best fit oscillation parameters between the nominal MC and the MC with additional Nieves MEC events





- Much smaller RMS in θ_{23} (left) and Δm^2 (right) than in T2K analysis
- Large spike at 0 difference in both plots

ν_e systematic errors

- Use cross section and flux uncertainty throws to construct covariance matrix
- Each element corresponds to a single bin in the reconstructed energy and off-axis angle space