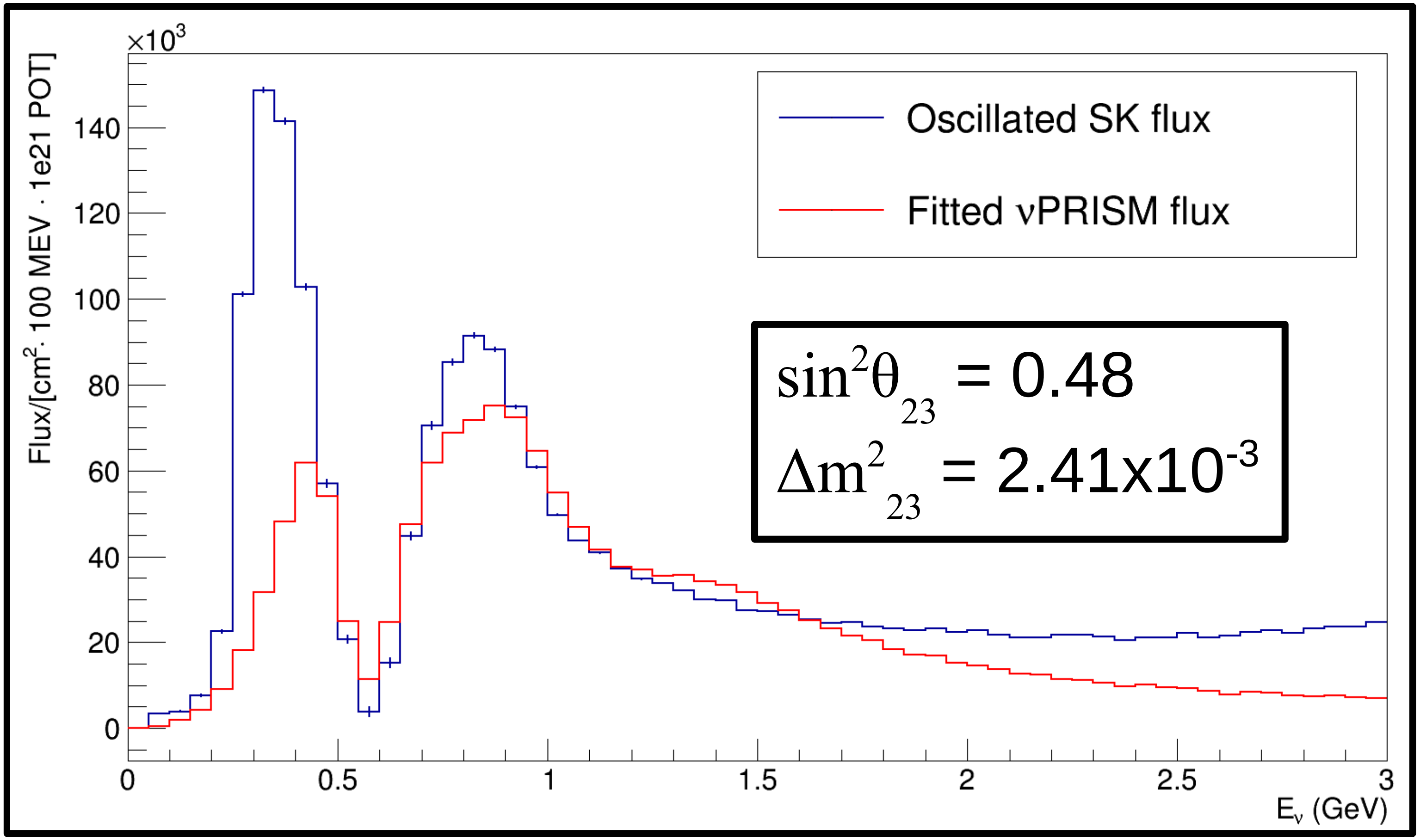
# $\nu$PRISM $\nu_\mu$ disappearance analysis

Mark Scott
2nd $\nu$PRISM workshop
July 23[nd] 2014

# Flux fit

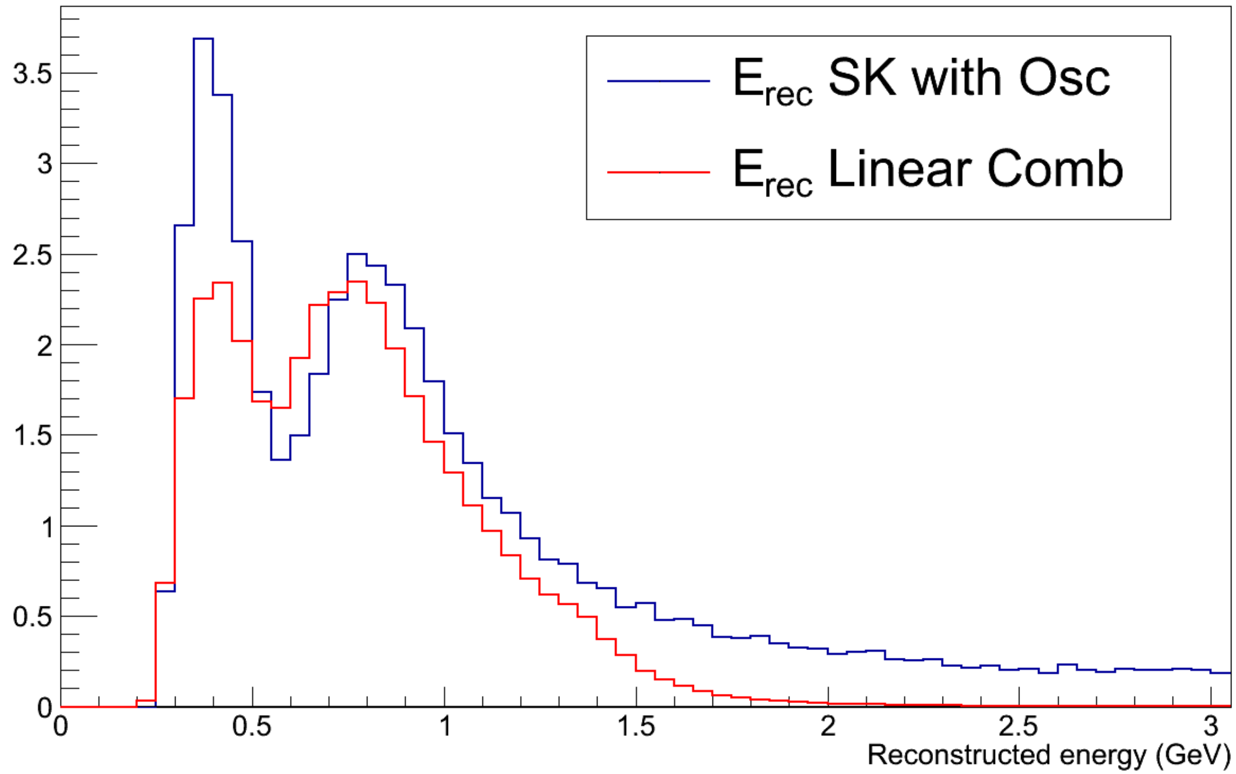
- Use νPRISM technique (linear combinations) to create the SK neutrino flux assuming a given set of oscillation parameters




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

# SK prediction

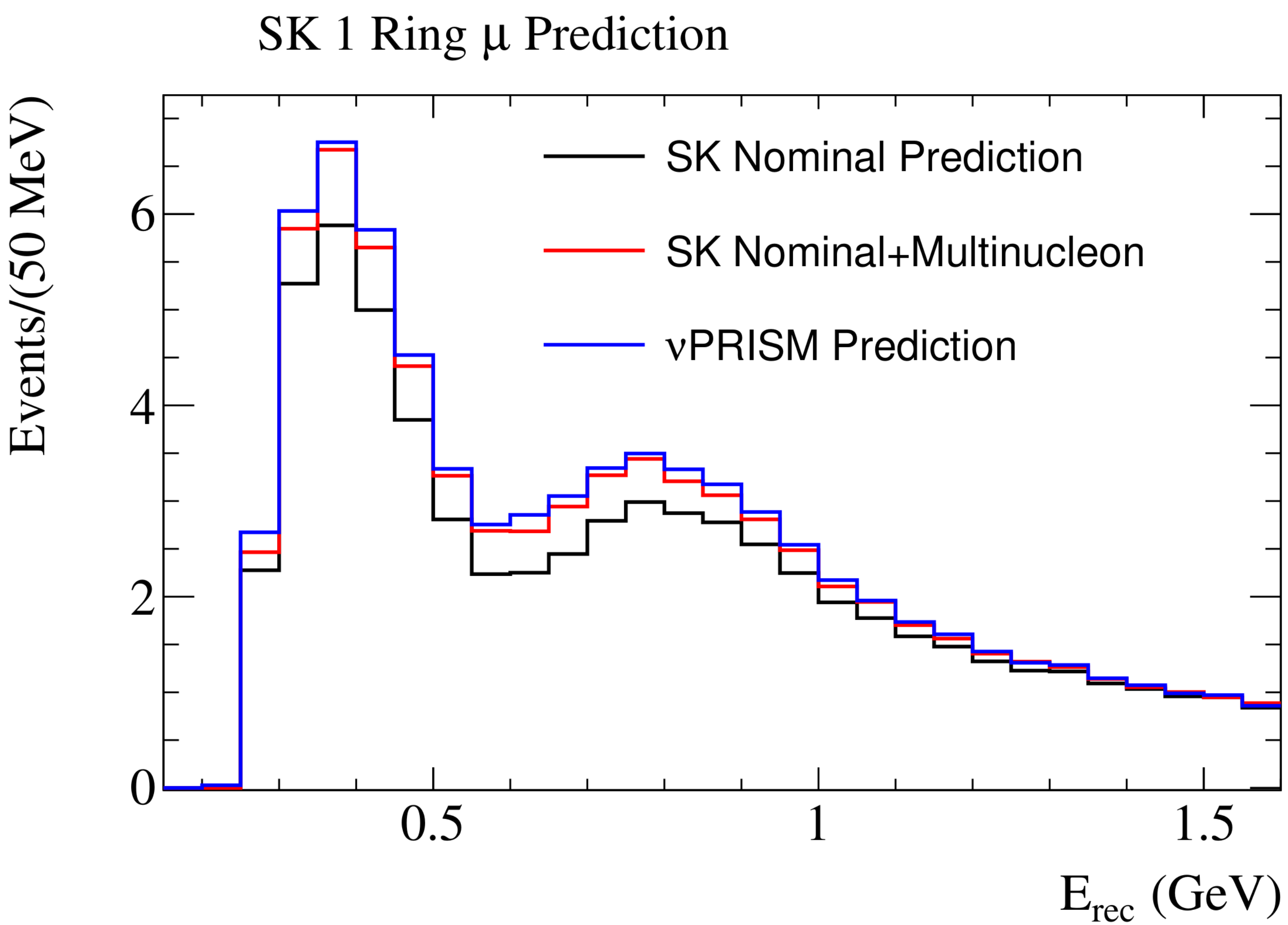
- Apply these weights to the selected events in each off-axis slice of νPRISM
- Now looking at reconstructed neutrino energy - events smeared into oscillation dip by nuclear effects and energy resolution




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

# Multi-Nucleon example

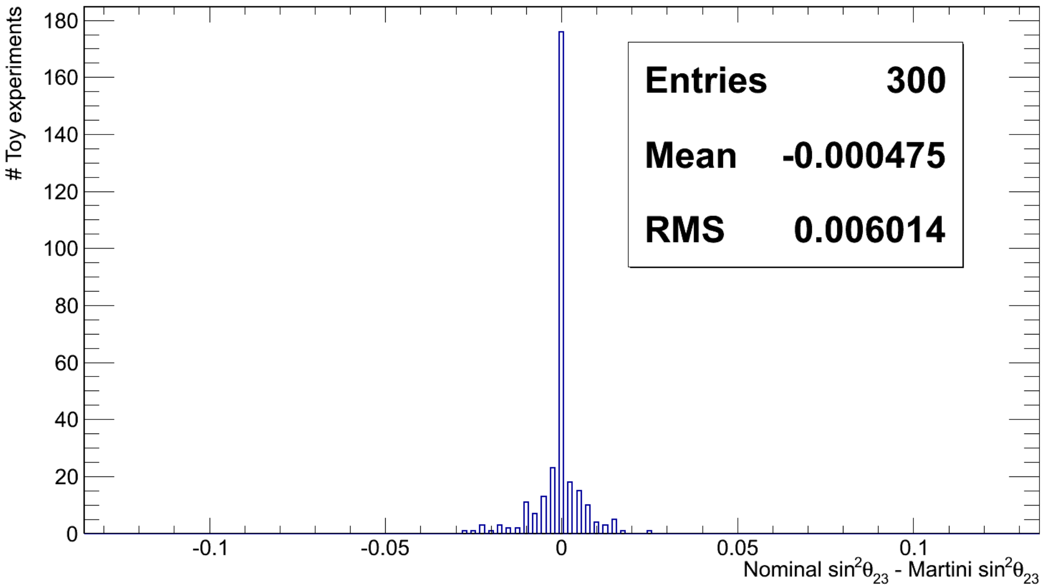
- Add multi-nucleon events to the nominal MC to make fake data

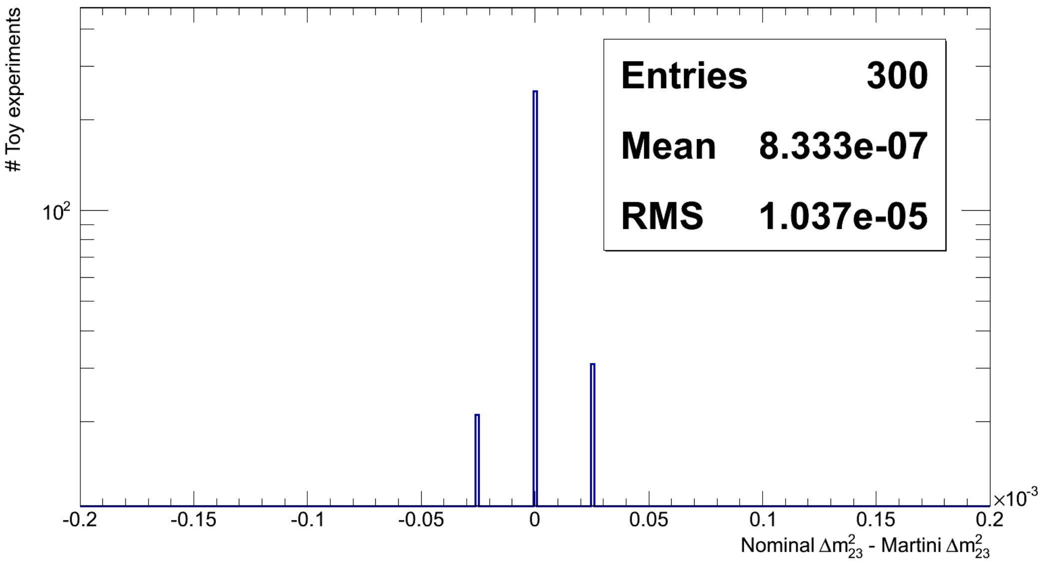



- See νPRISM prediction still reproduces oscillated SK spectrum when multi-nucleon events are present

# Martini MEC result

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




- Much smaller RMS in $\theta_{23}$ (left) and $\Delta m^2$ (right) than in T2K analysis
- No bias seen in $\theta_{23}$ plot
- The $\nu$PRISM concept is working!

# Next steps

- Need to move to full detector MC and reconstruction – See Carl's talk later today
- Perform oscillation fit in muon p-theta
- Use increased MC stats – T2K/HK sensitivity?
- Interpolate likelihood surface to find minimum – resolution not limited by discrete binning of histogram

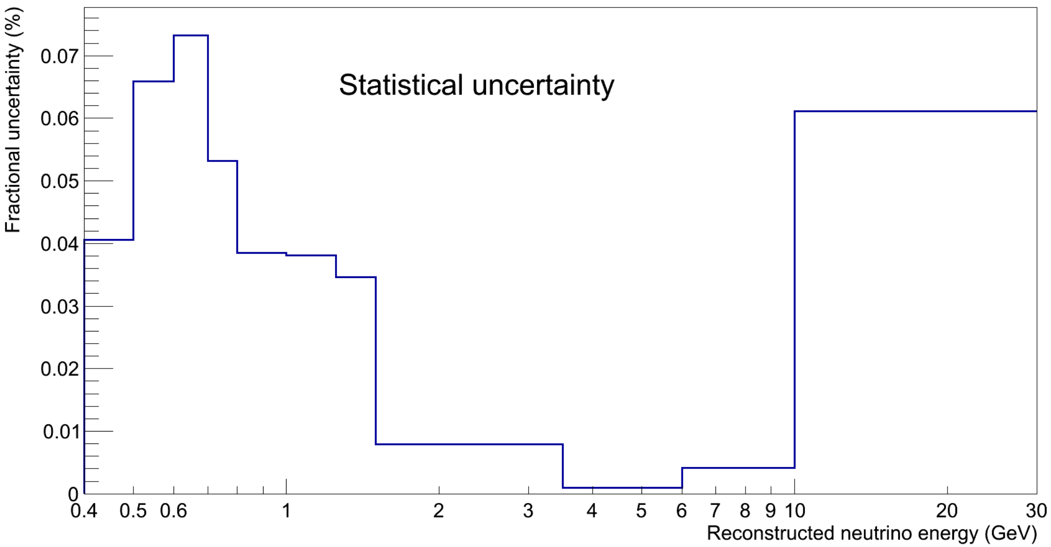
- Can we improve the flux coefficient fit?
  - Better fit → less model dependent and smaller xsec systematics
  - Balance against statistical uncertainty
- How do detector systematics screw things up?

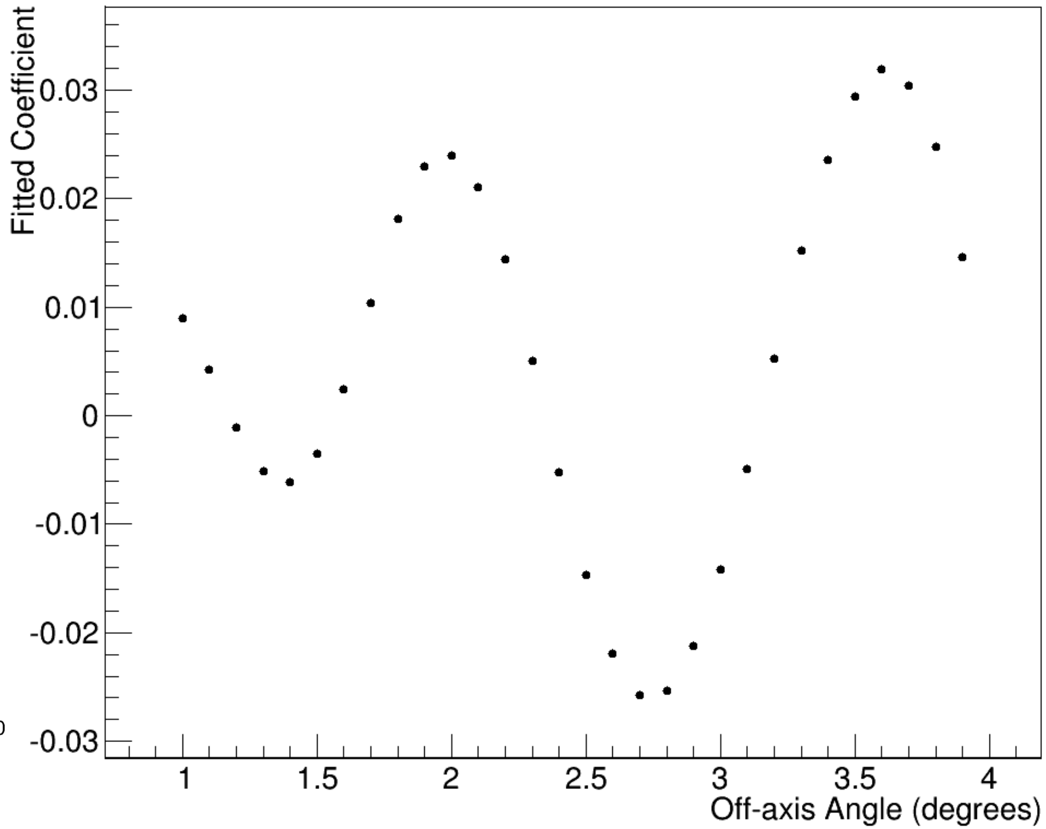
# Flux coefficient fit

- Currently smooth neighbouring coefficients:

$$\Delta\chi^2 = \left(\frac{C_i - C_{i+1}}{0.001}\right)^2$$

- Gives 7% uncertainty in SK prediction in oscillation dip



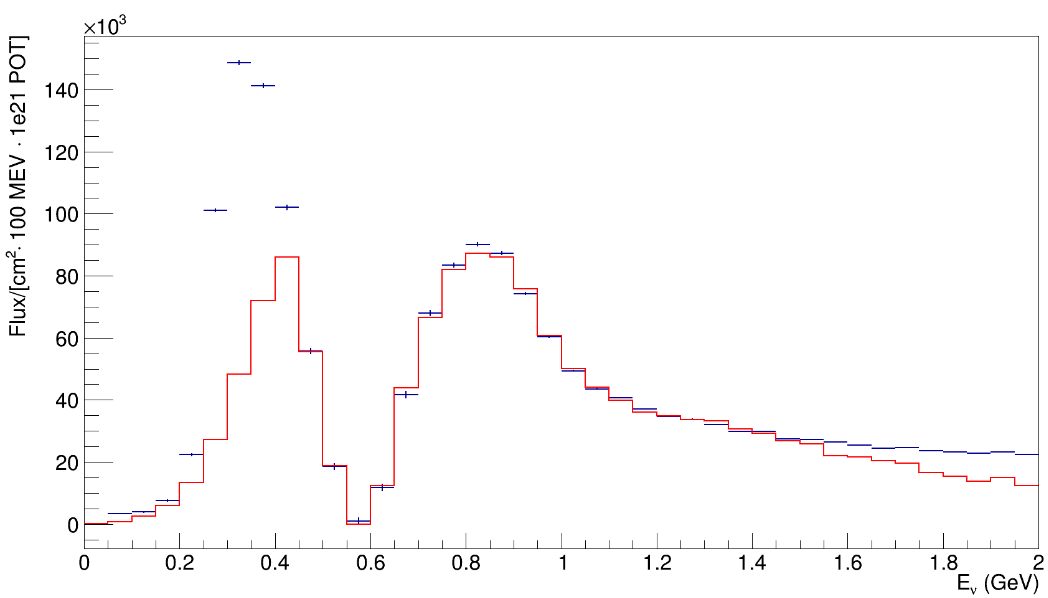



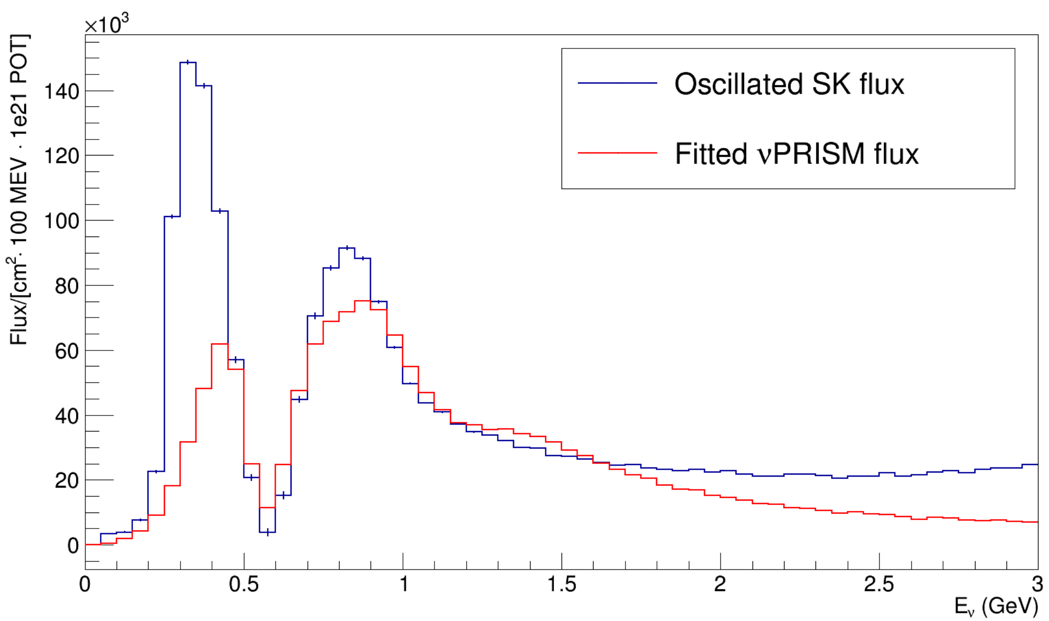
# Can we do better?

- Apply more smoothing around oscillation dip (2.5 degrees off-axis)

$$\Delta\chi^2 = \left(\frac{C_i - C_{i+1}}{0.05\cdot\left(\left|\left(o.a.a. - 2.5\right)\right| + 0.1\right)}\right)^2$$

- New fit on left, old, smooth fit on right



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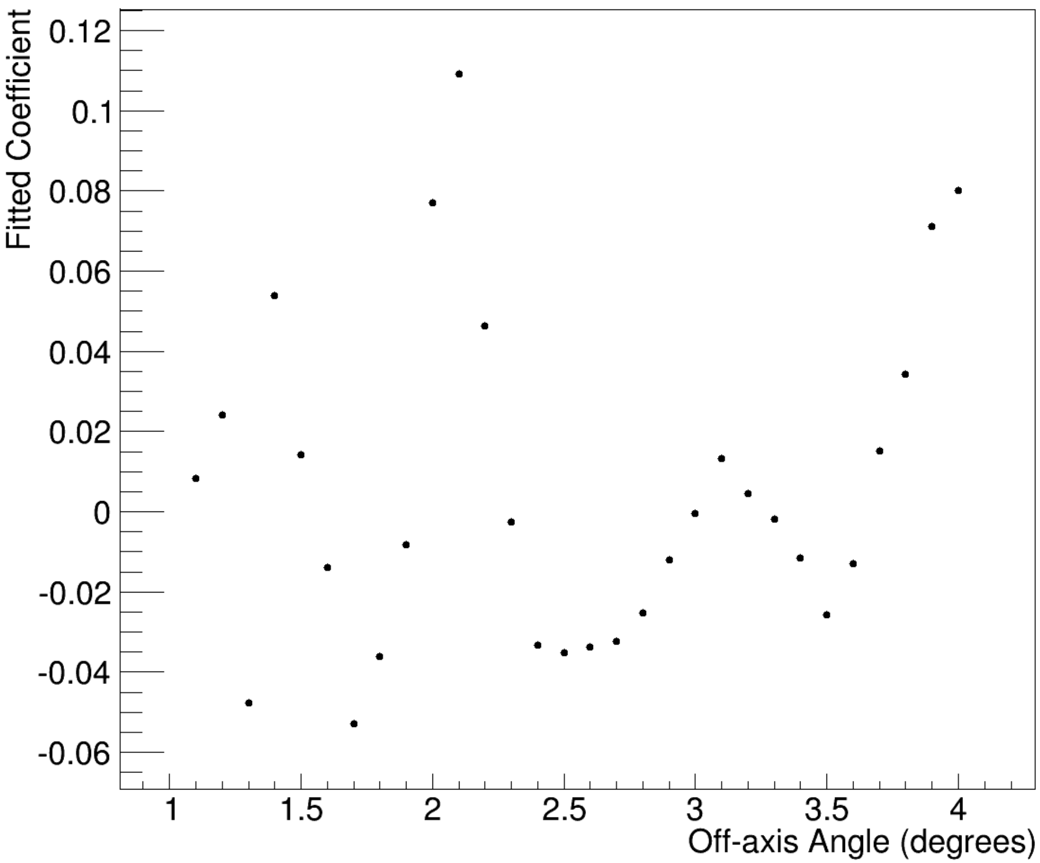
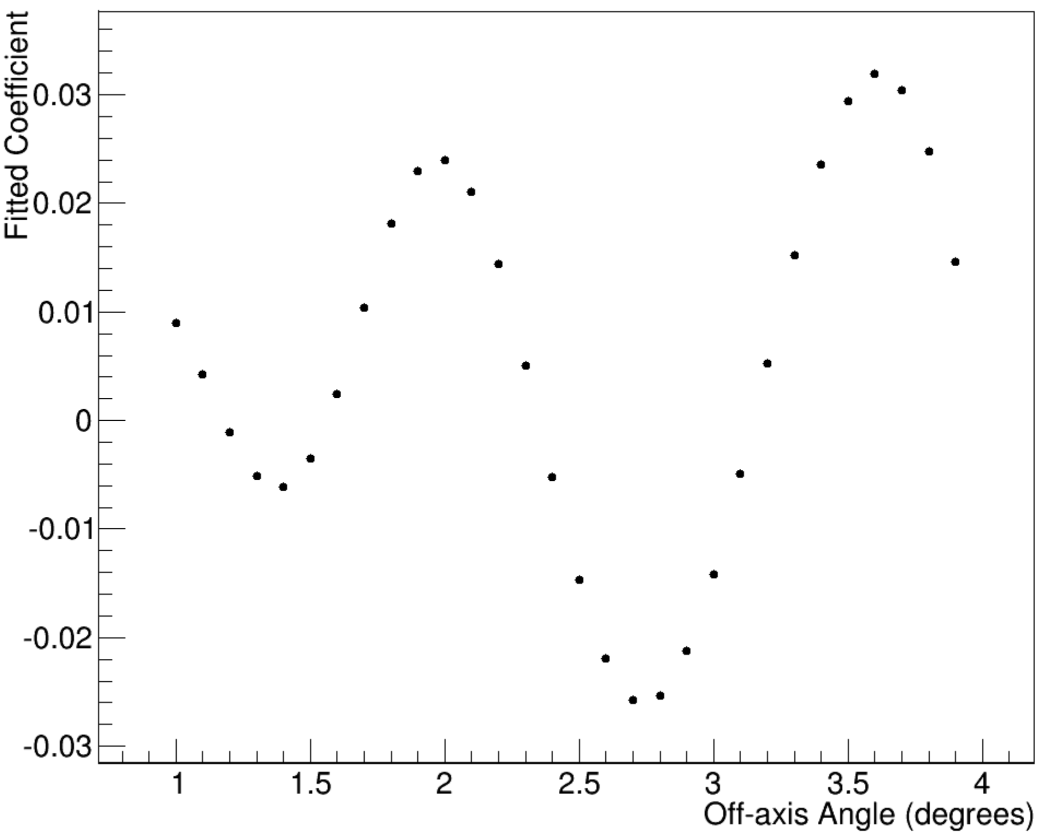
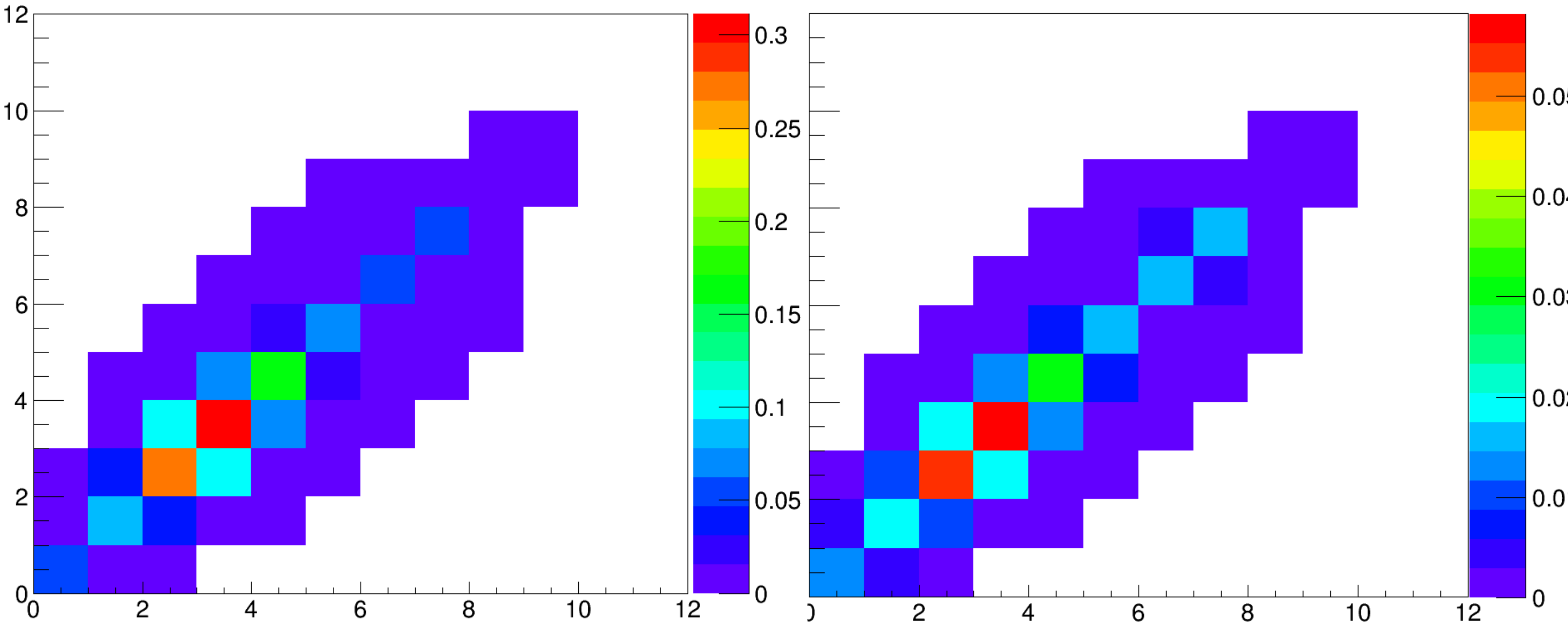


# Effect on statistical error

- Look at the statistical variance from both fits when applied to smaller sample of nuPRISM data
- New fit on left, old, smooth fit on right



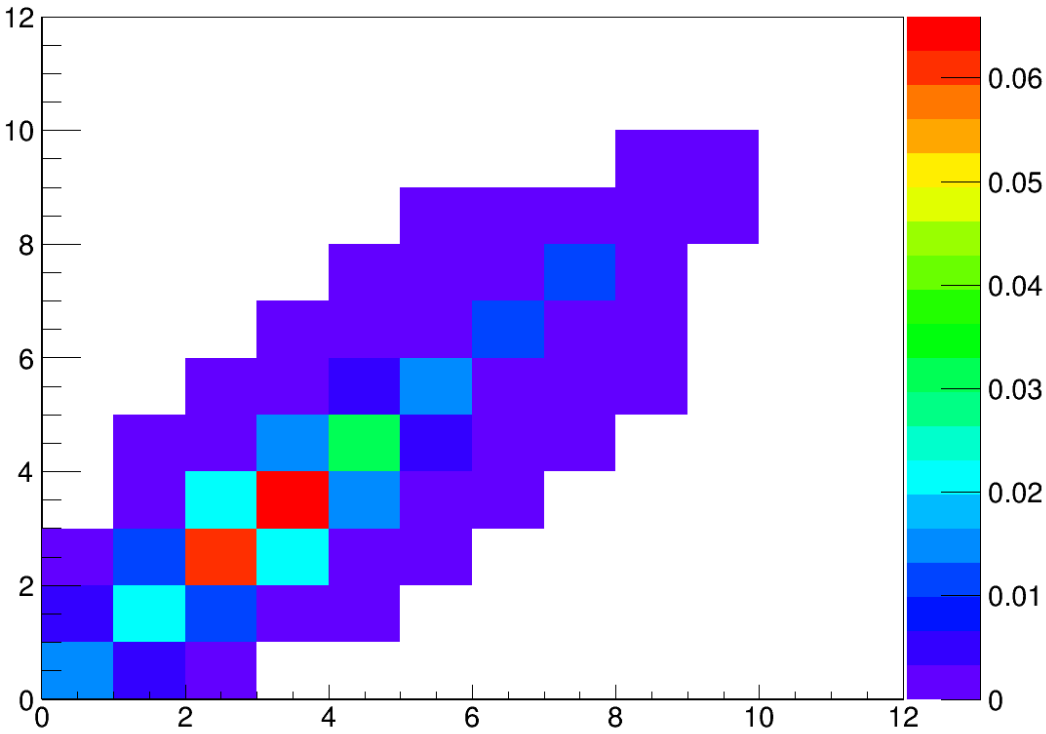

- New fit has substantially larger variance – Z axis

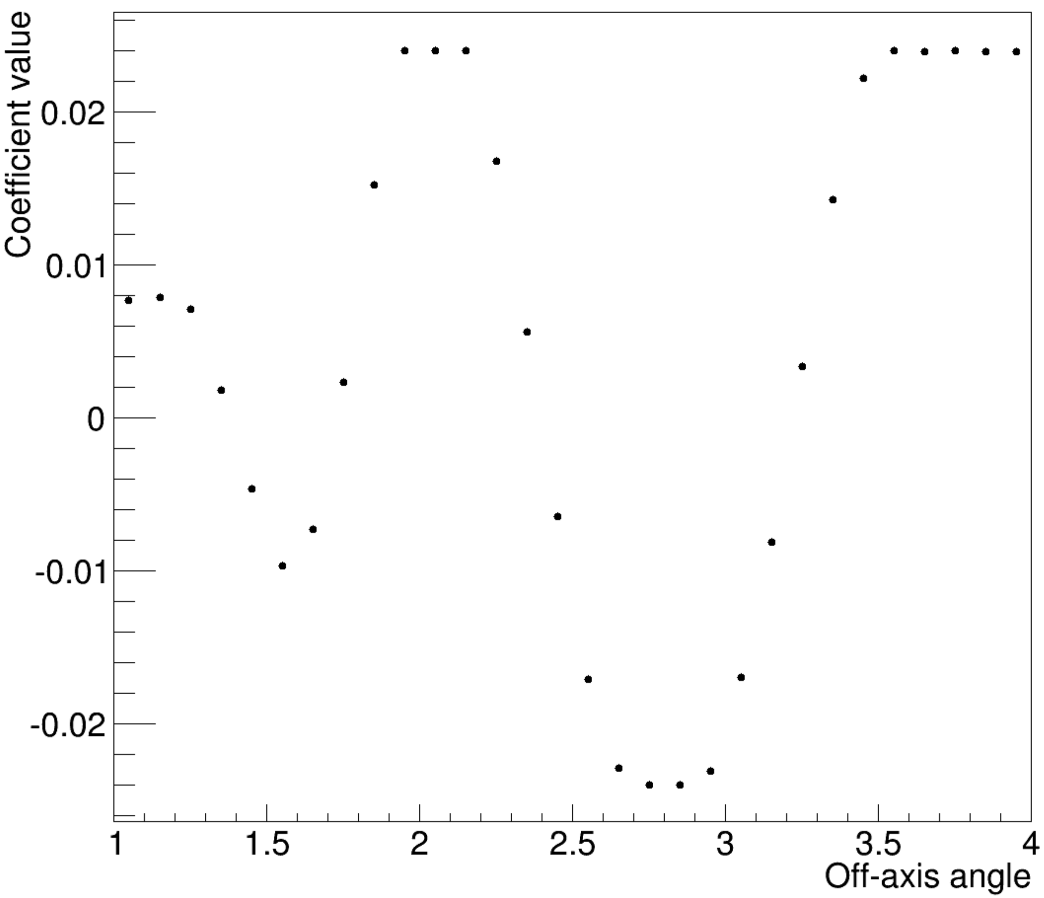
# Why did the uncertainty increase?

- New coefficients are larger?
- Coefficients are less smooth?
- This particular fit?

# Coefficient size

- Apply no smoothing function
- Large penalty term if absolute value of any coefficient > 0.023



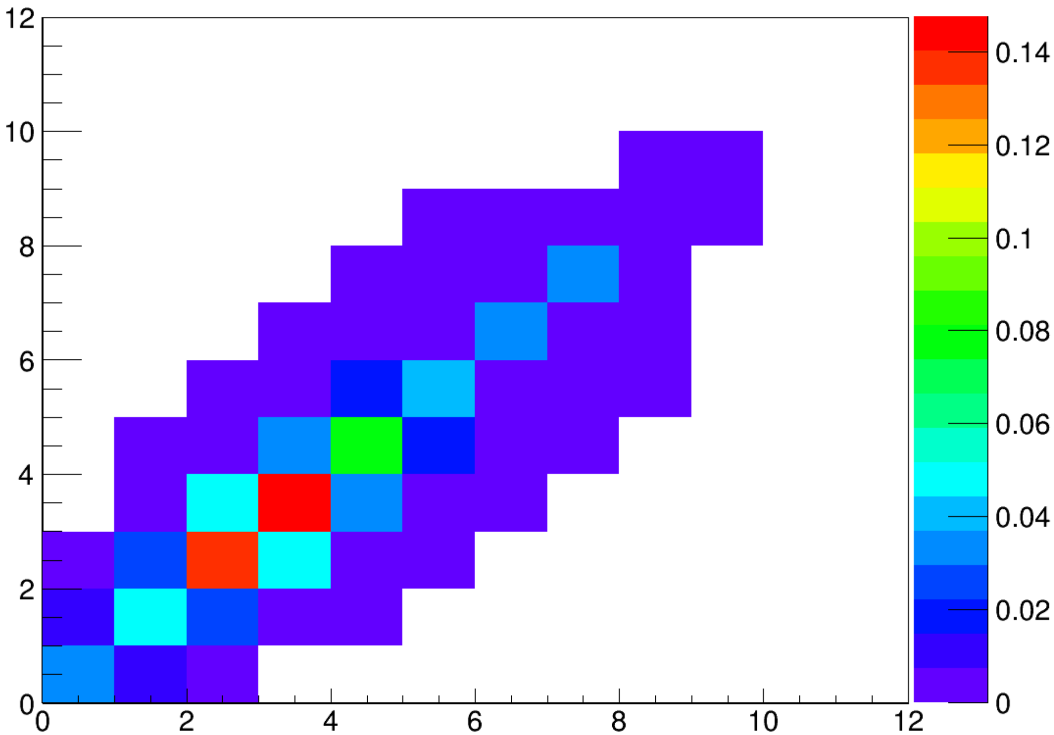



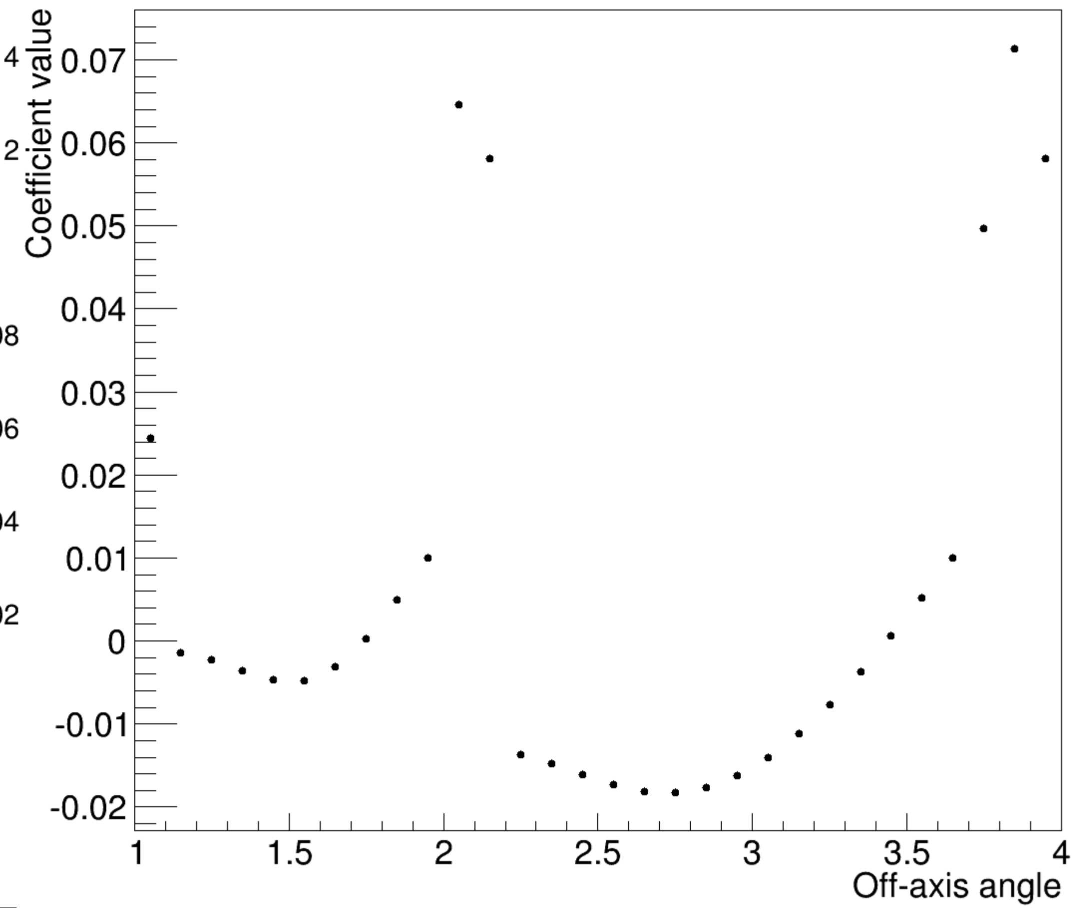

- Having small coefficients forces smoothness

- Still not as good as nominal – larger error + worse flux fit

# Coefficients smoothness

- Apply strong smoothing if coefficient is < 0.01
- Coefficients smooth over most angles, but a couple of big jumps

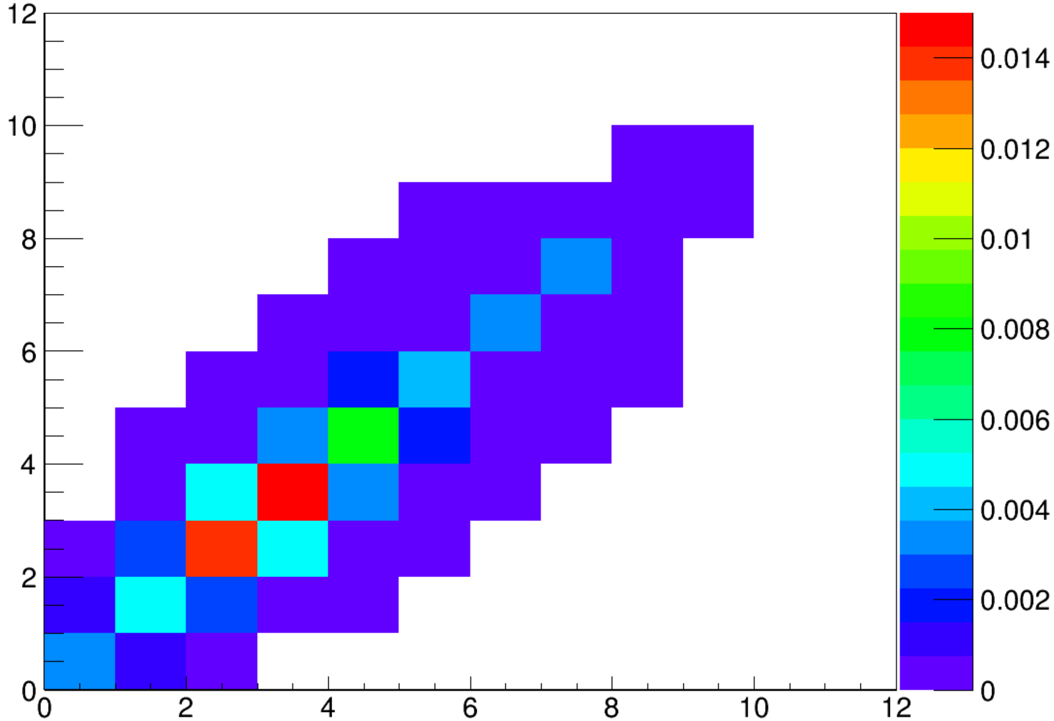


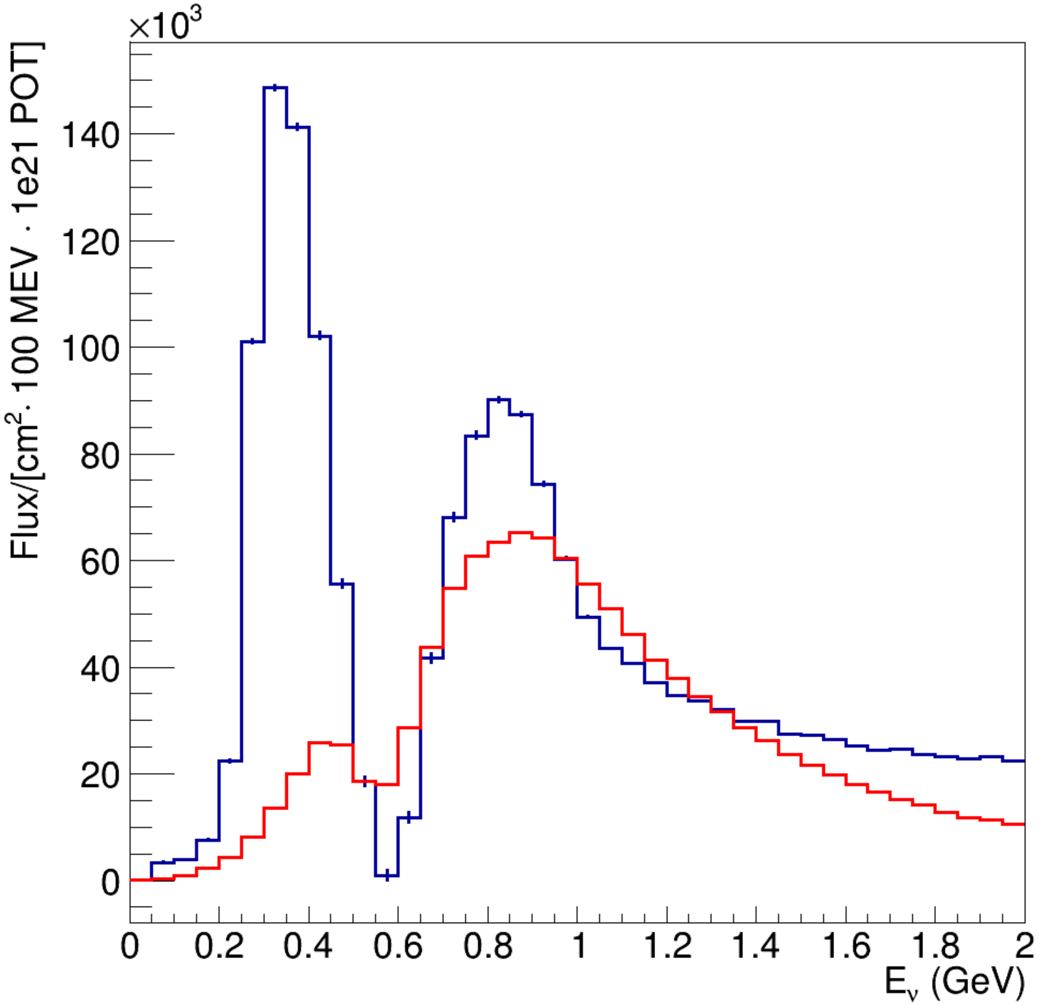




- One or two discontinuities greatly increases stats error – 0.14 c.f. 0.05 in nominal fit

# Coefficients smoothness 2

- Apply very strong smoothing for all coefficients
- Flux fit does get worse



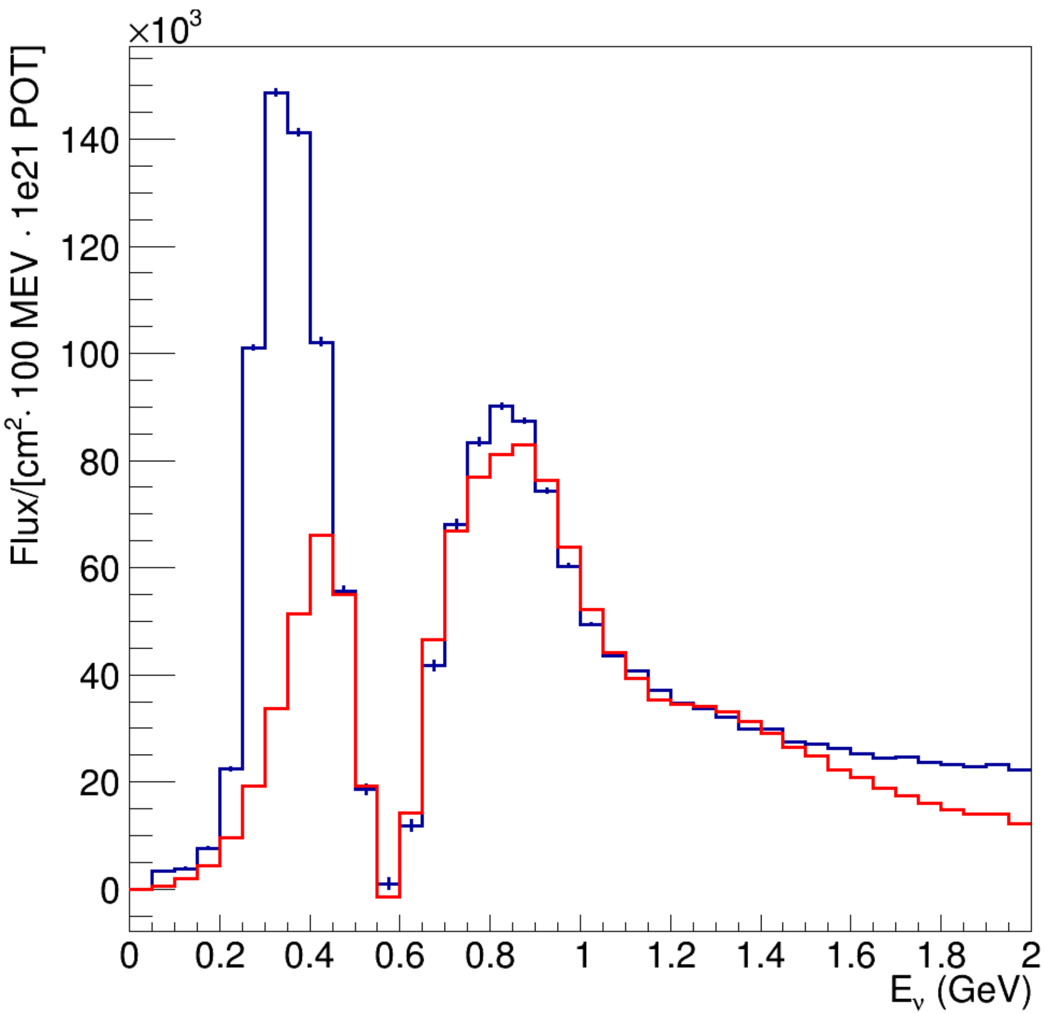

- Statistical variance 0.014, compared to 0.056 in nominal fit
- 'Smoothness' is crucial to reduce statistical uncertainty

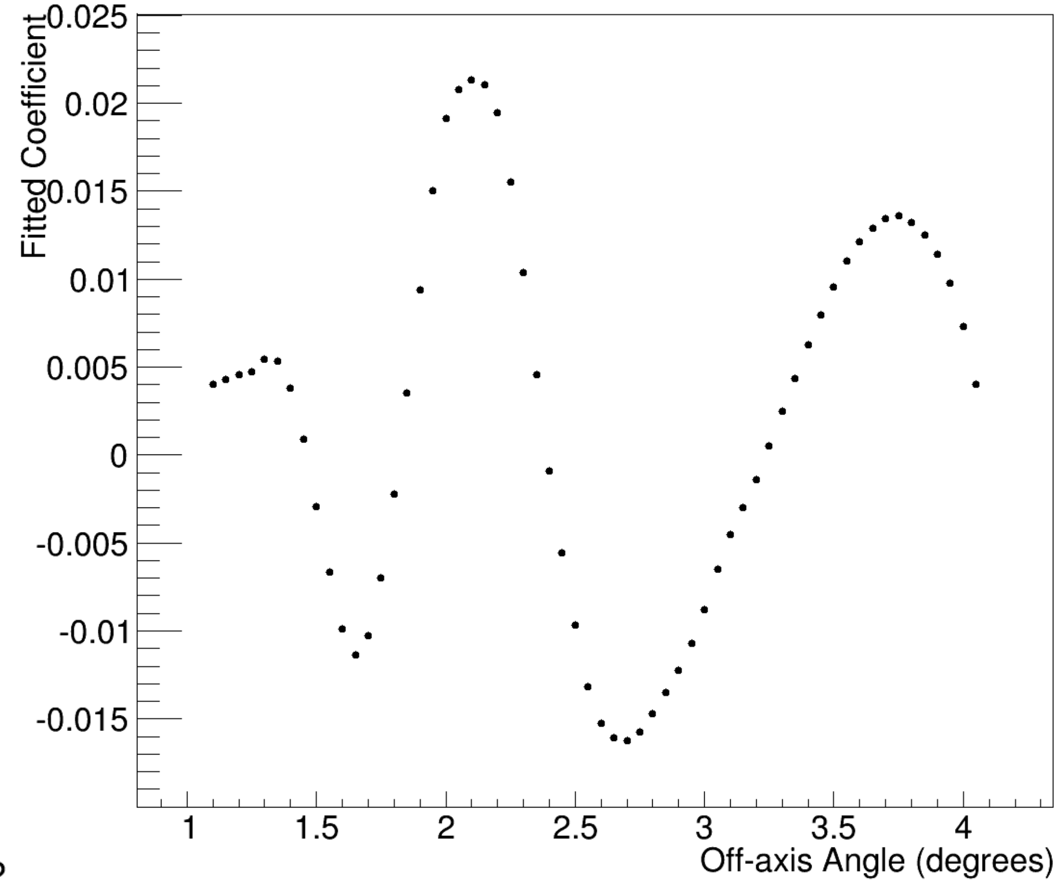
# Failed attempts...

- Tried a number of different smoothing functions to try and improve fit while retaining small statistical uncertainty
  - Small coefficients with smoothing
  - Let more on-axis slices vary more than off-axis slices (more events)
  - Only smooth negative coefficients
  - Smooth coefficients around 2.5 degrees
  - Fit 60 slices, rather than 30
  - Fit 10MeV bins in neutrino energy, rather than 50MeV bins
- All gave minor improvements in the flux fit but with significant increases in statistical uncertainty

# Best attempt

- Fit 60 slices
- Penalty term for coefficients above 0.02
- Slightly relaxed smoothing term (denom: 0.001 → 0.003)
- Fit out to 1.5 GeV, not 2 GeV in neutrino energy



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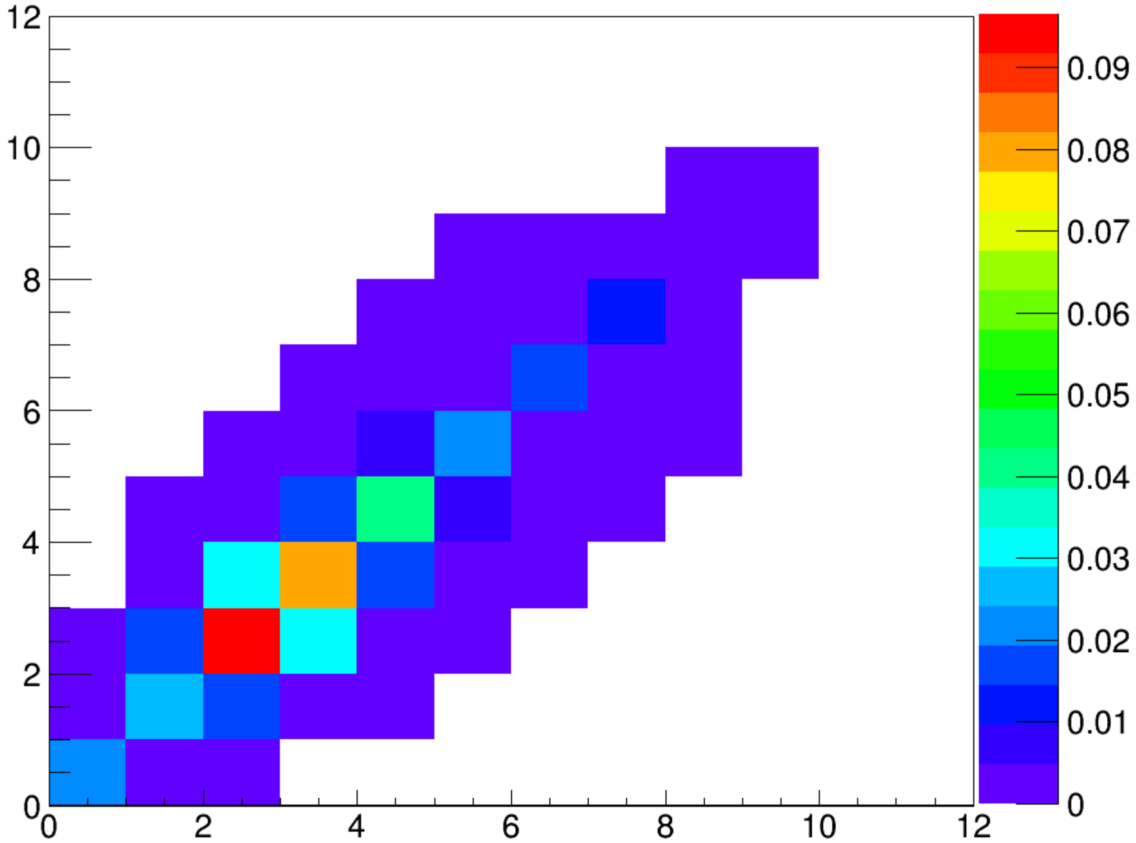



- Still gives larger statistical error
- Maybe some room for improvement still
- Don't expect much though!

# Detector systematics

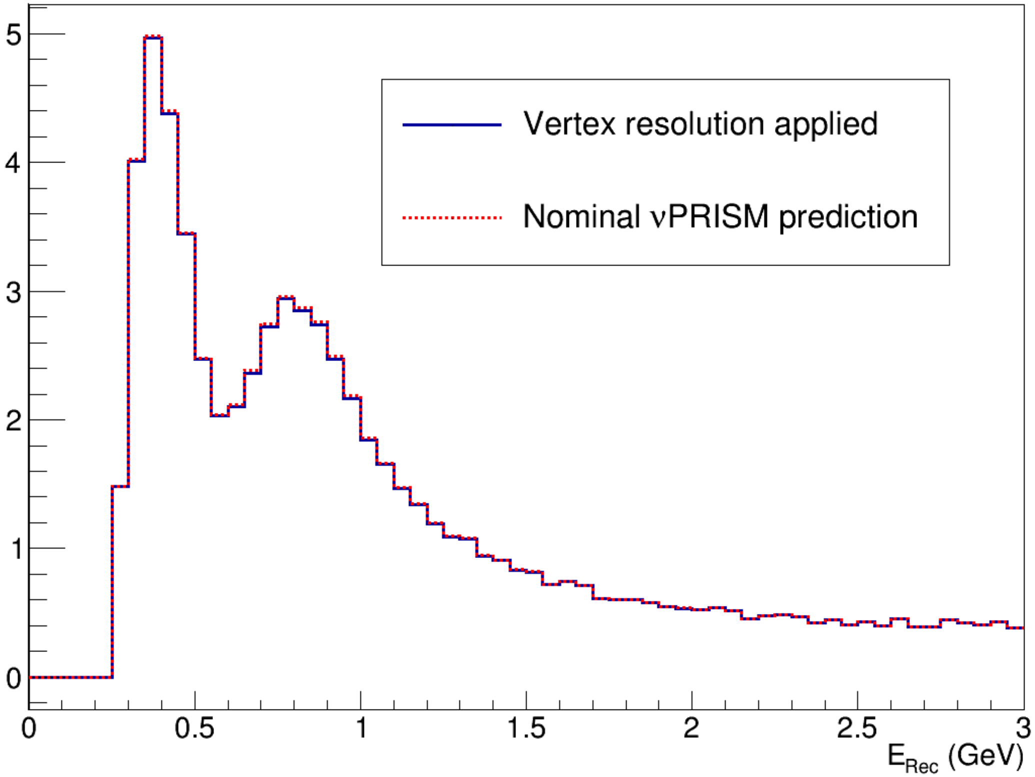
- Change to a happier topic – detector systematics

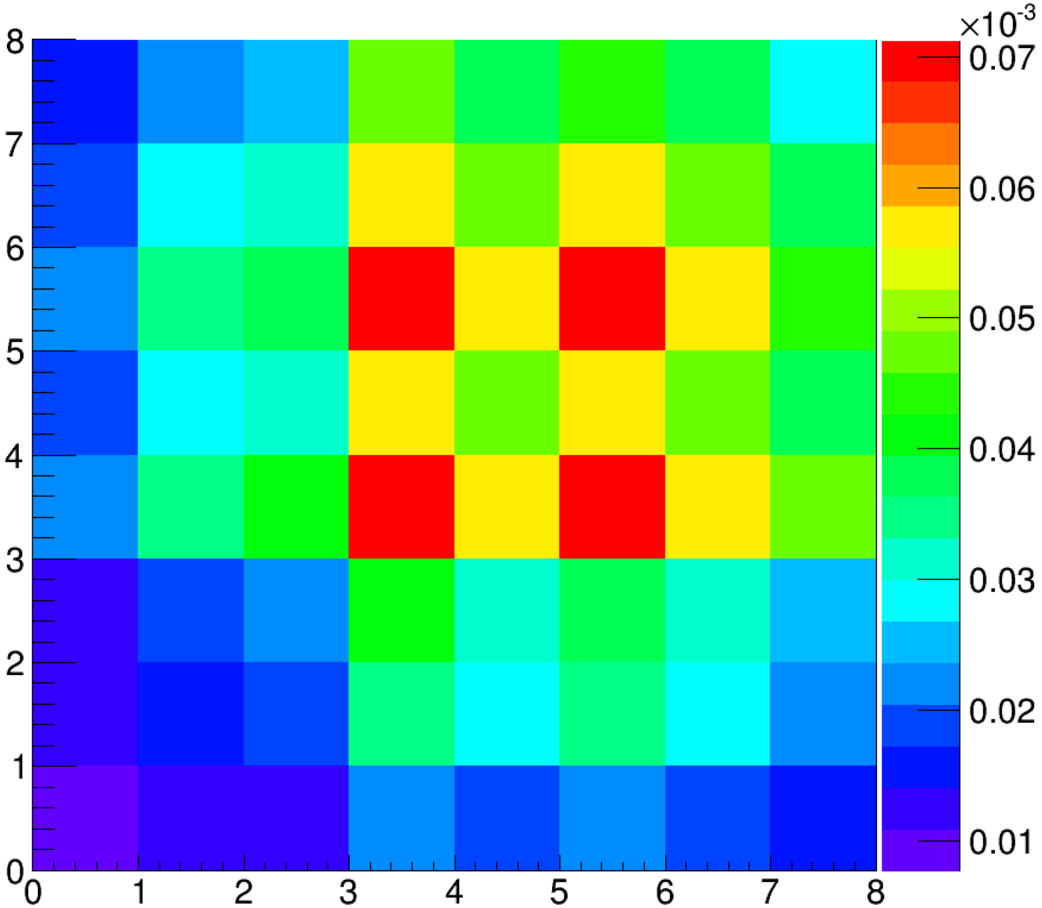
- Have started writing new package to apply detector systematic variations:
  - Vertex position bias – not studied yet, very similar to off-axis shift that is already included
  - Vertex position resolution
  - Varying detection efficiency as a function of depth
  - Varying momentum bias with depth

- Applied to reconstructed event – can calculate covariance matrix in same way as for flux and xsec systematics

# Vertex resolution

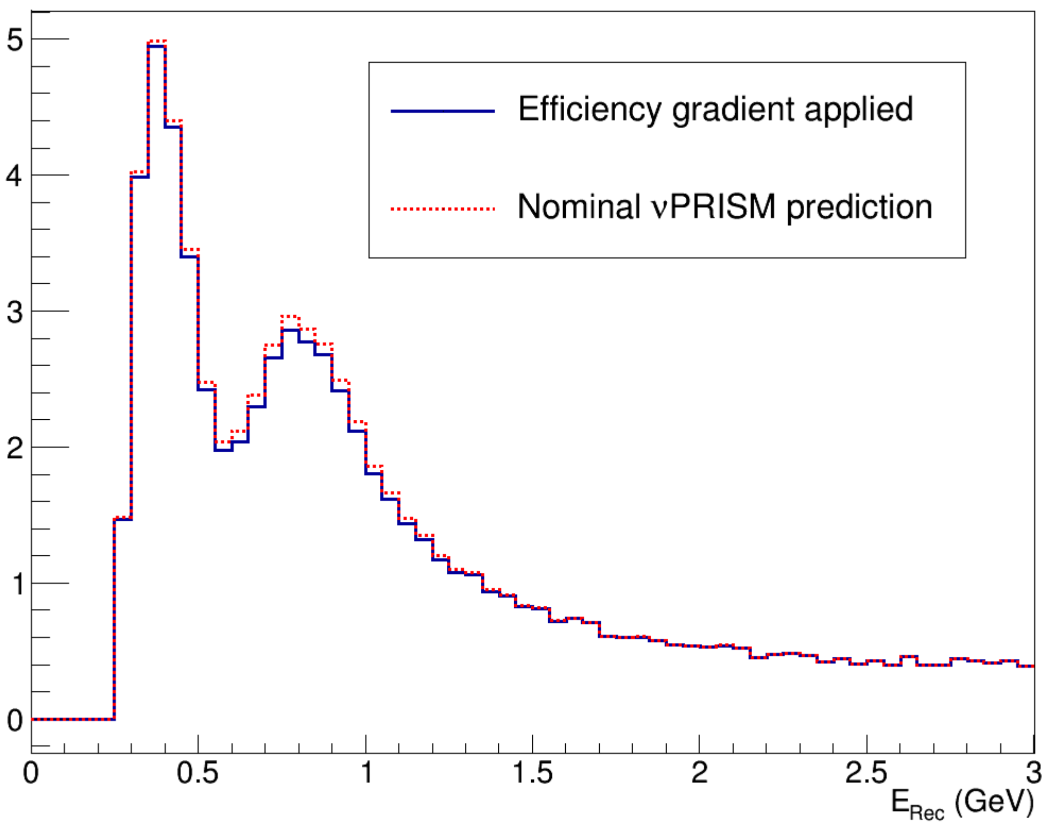
- Randomly move reconstructed vertex position
  - Distance moved is a random draw from a Gaussian with a set width (30cm)
  - Theta-Phi randomly determined

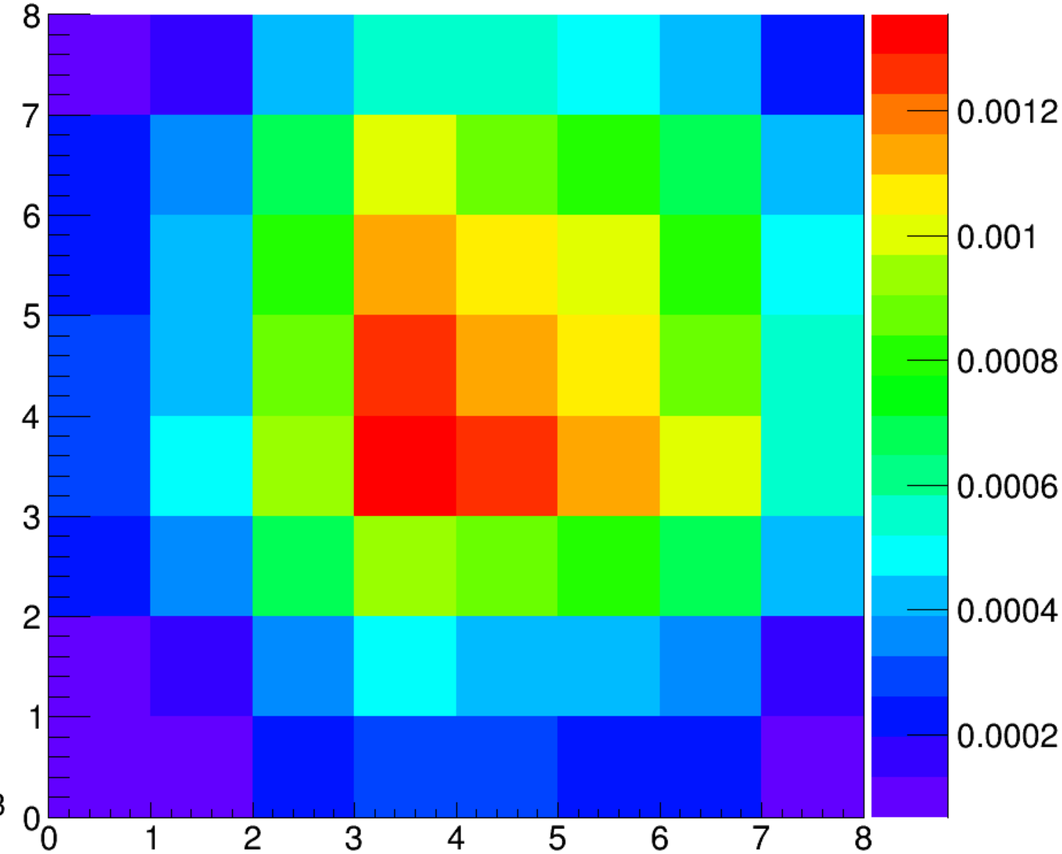


# Efficiency gradient

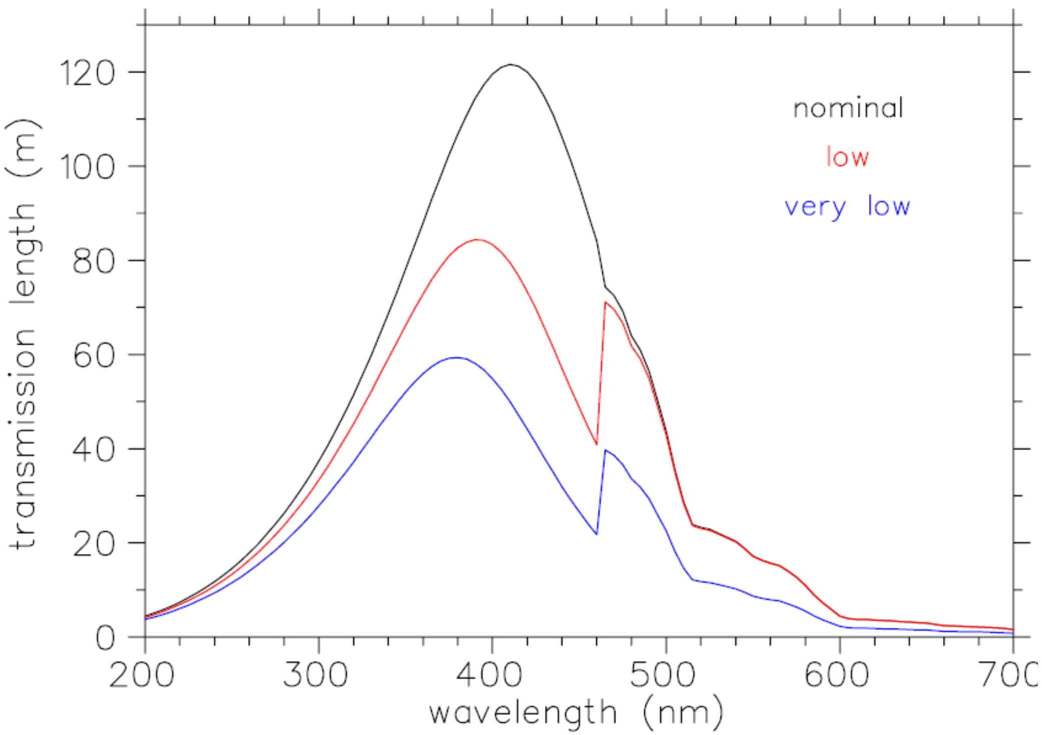
- Vary selection efficiency linearly as a function of depth
  - 100% efficient at top, 95% efficient at bottom
  - Surprisingly small effect

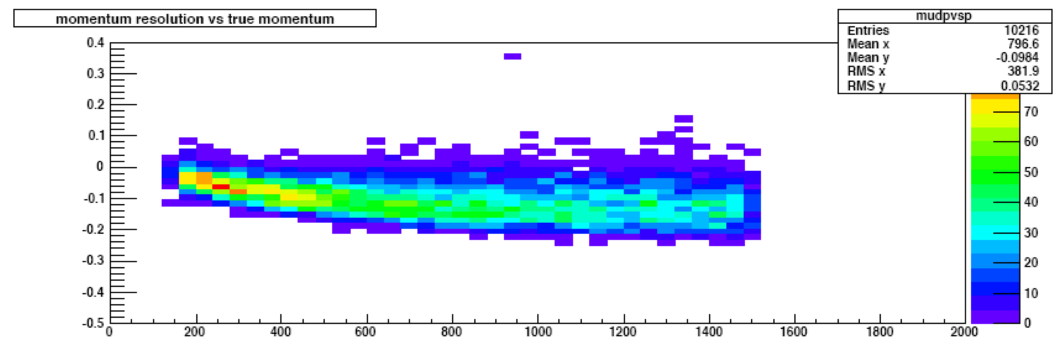


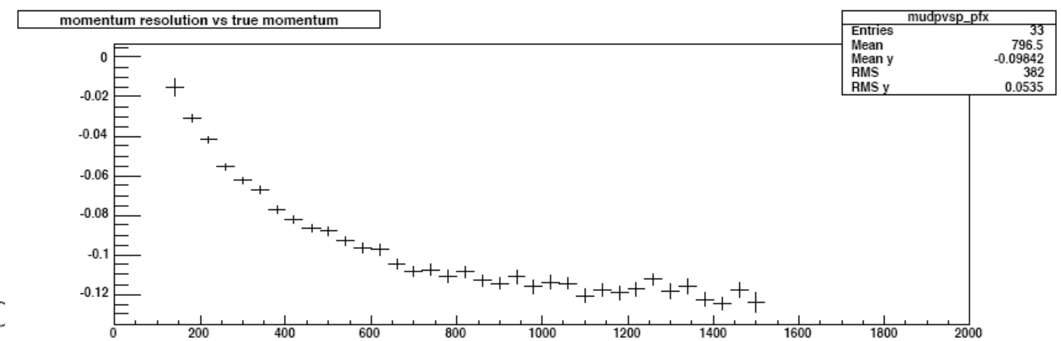



# Momentum bias

- Based on work by R. Tacik -
- http://www.t2k.org/ndup/nuprism/meetings/20140319/water



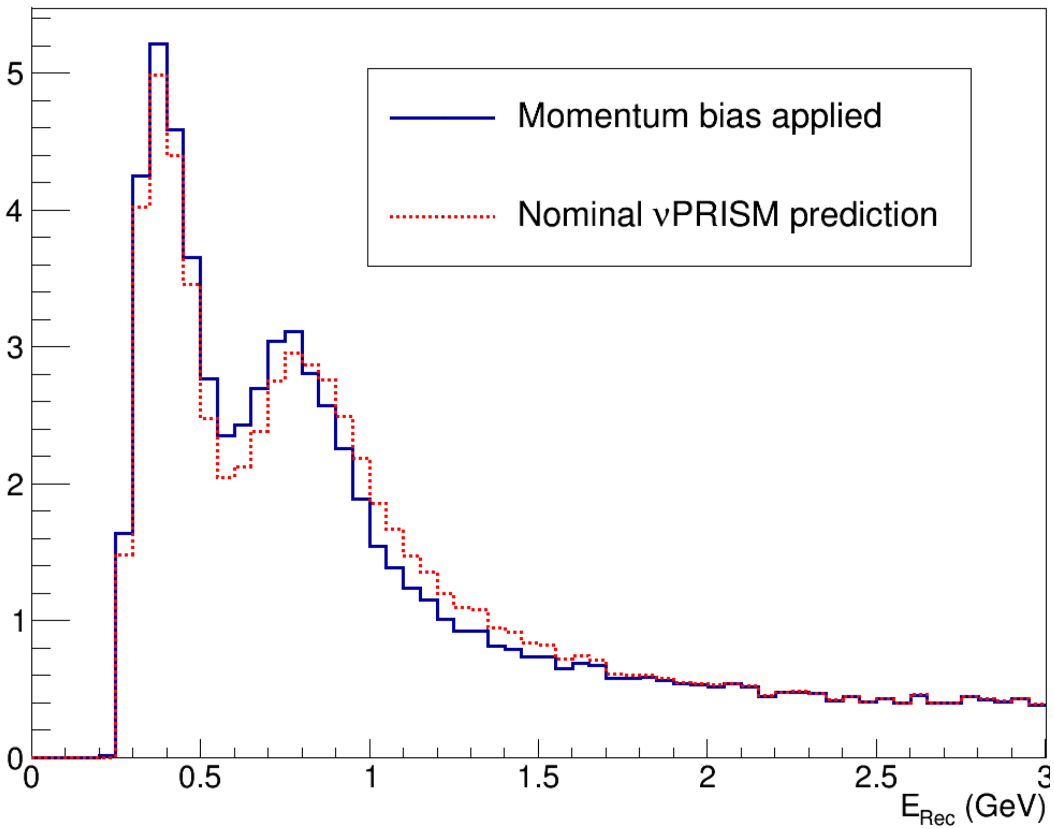



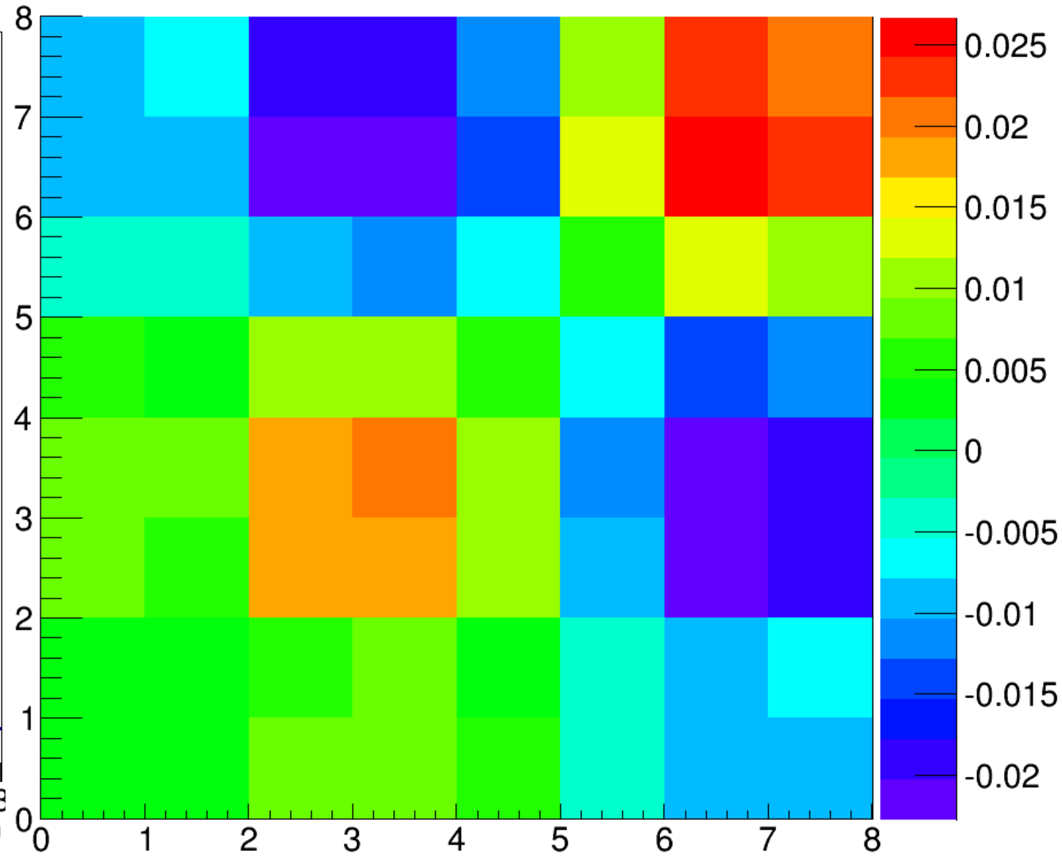




- Investigated effect of water quality on SK reconstruction
- Found no effect in vertex resolution
- Negative bias in measured muon momentum, up to 12%

# Momentum bias

- Linear momentum bias as a function of depth:
  - Nominal momentum at top, 93% of measured value at bottom



- Big effect, ~15% maximum uncertainty and anti-correlations in energy bins

# Systematics summary

- Package exists to apply systematics – will commit soon
- Initial studies show that vertex resolution will not be a problem
  - Bias' in vertex position might be though
- If a selection efficiency difference exists as a function of depth this is probably OK too
- A changing momentum bias will cause difficulties:
  - Need to check whether this is due to the bias, or the fact it changes with depth
  - Does this bias effect the oscillation parameters we extract?

- Need to perform some cross checks to make sure systematics are being applied correctly
- What other systematics should be considered?

# Summary summary

- The disappearance analysis has demonstrated that the $\nu$PRISM concept works
  - Multi-nucleon events do not affect the measurement of oscillation parameters

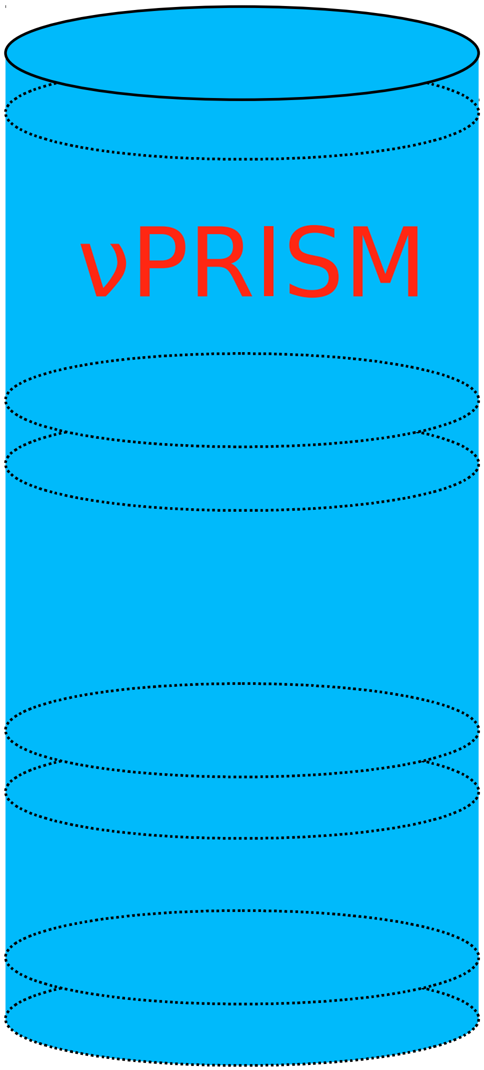
- The flux coefficient fit will be hard to improve further without sacrificing statistical uncertainty
  - Maybe there are clever ways of combining slices
  - Fourier methods used in astronomy

- First studies of detector systematics show that sources of momentum bias must be controlled, though vertex resolution is less important

# Backup slides

# νPRISM Design

- Baseline design used in the oscillation studies

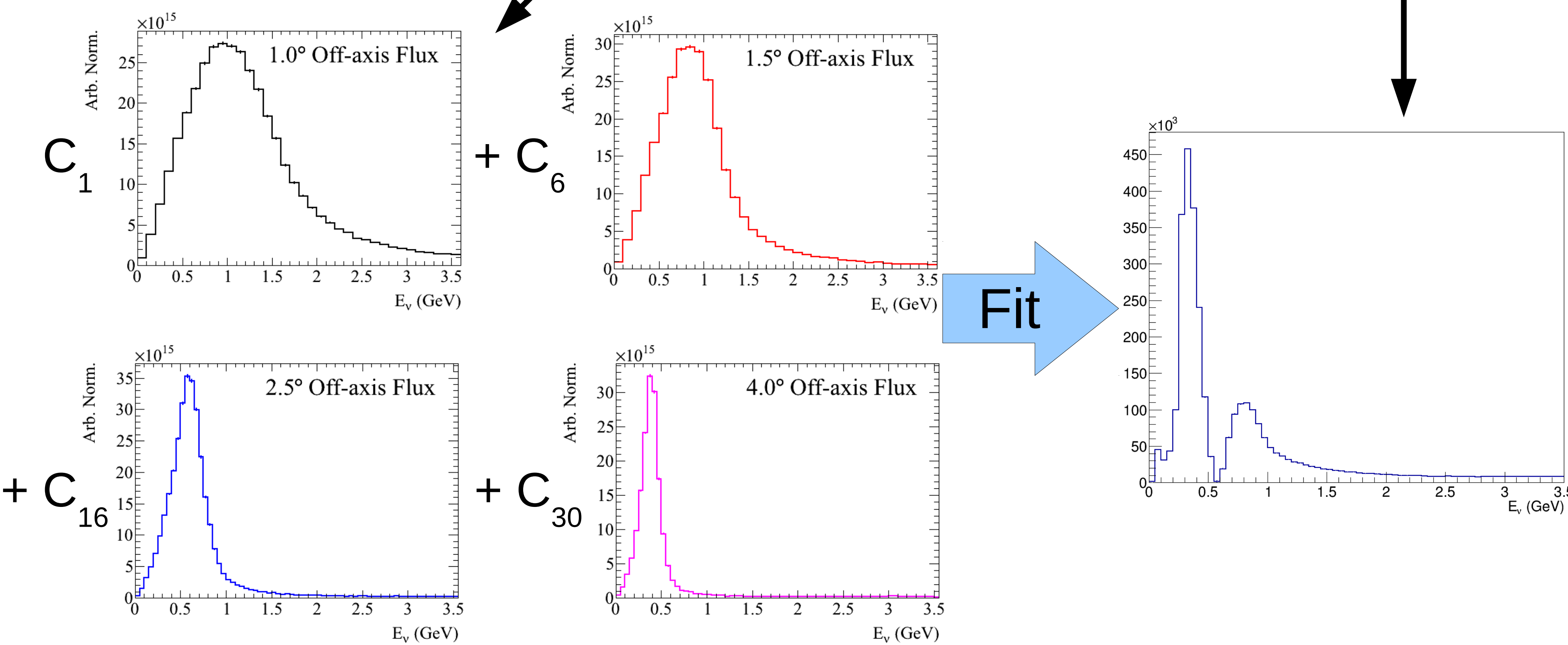



- 3m radius inner detector
- 52.5m tall – spanning 1-4 degrees off axis
- 1km from neutrino target

- 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

# Building the oscillated flux

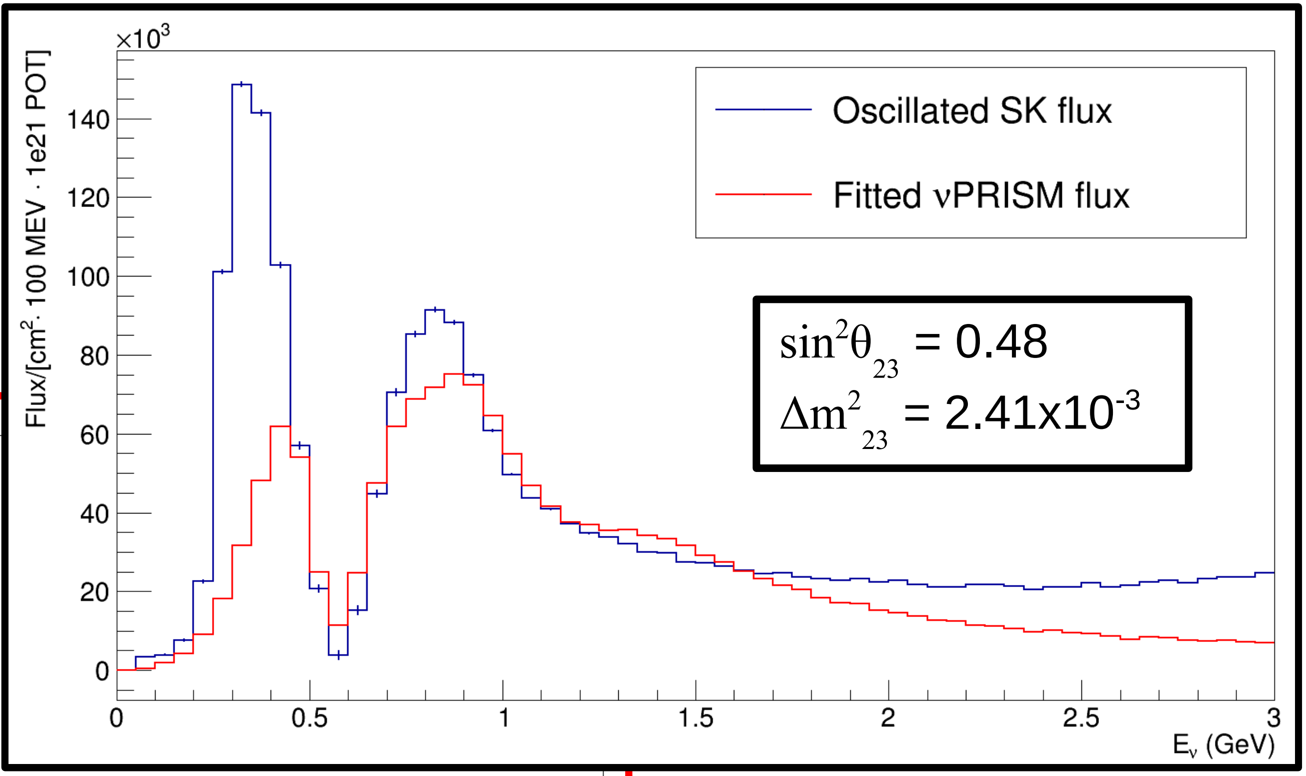
- All based on simulated neutrino flux at SK and νPRISM
- Slice νPRISM into 30 slices of 0.1 degree – assign each a weight
- MINUIT $\chi^2$ fit between sum of weighted νPRISM slices and oscillated SK flux

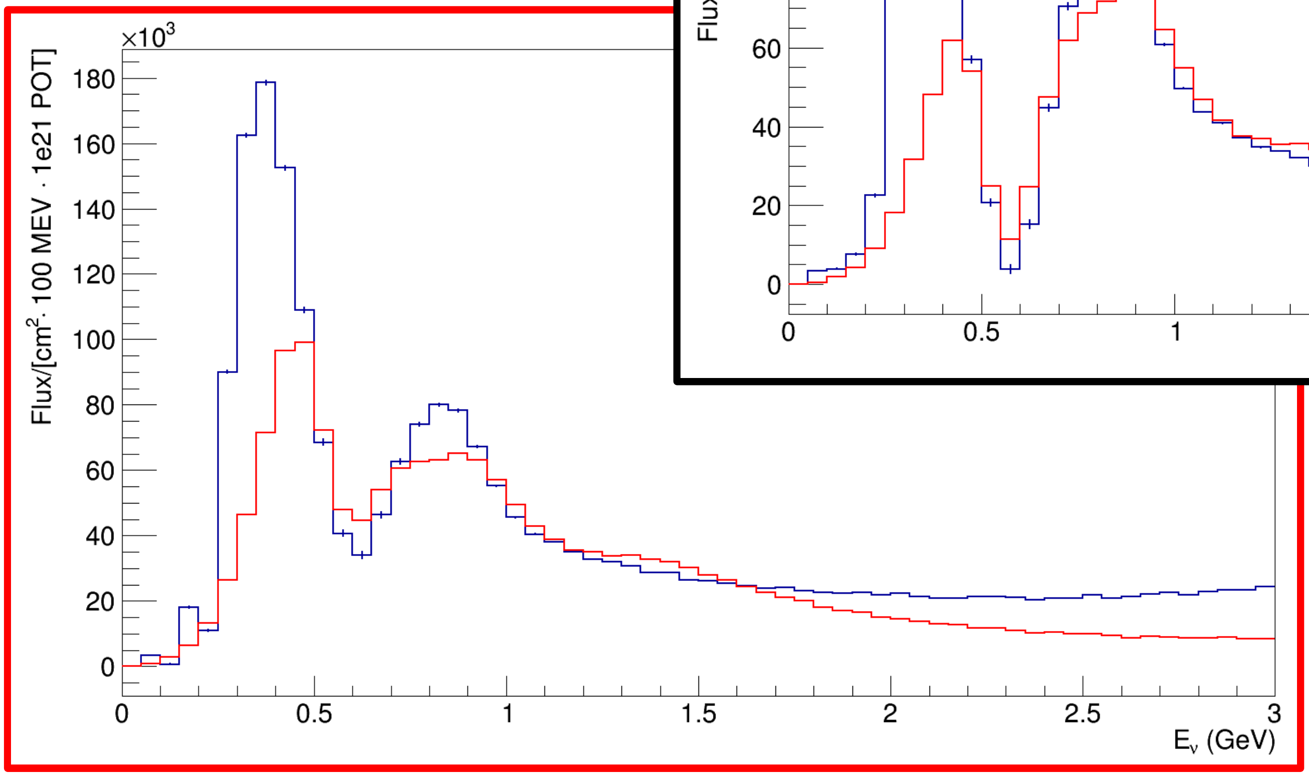


# Building the oscillated flux

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

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

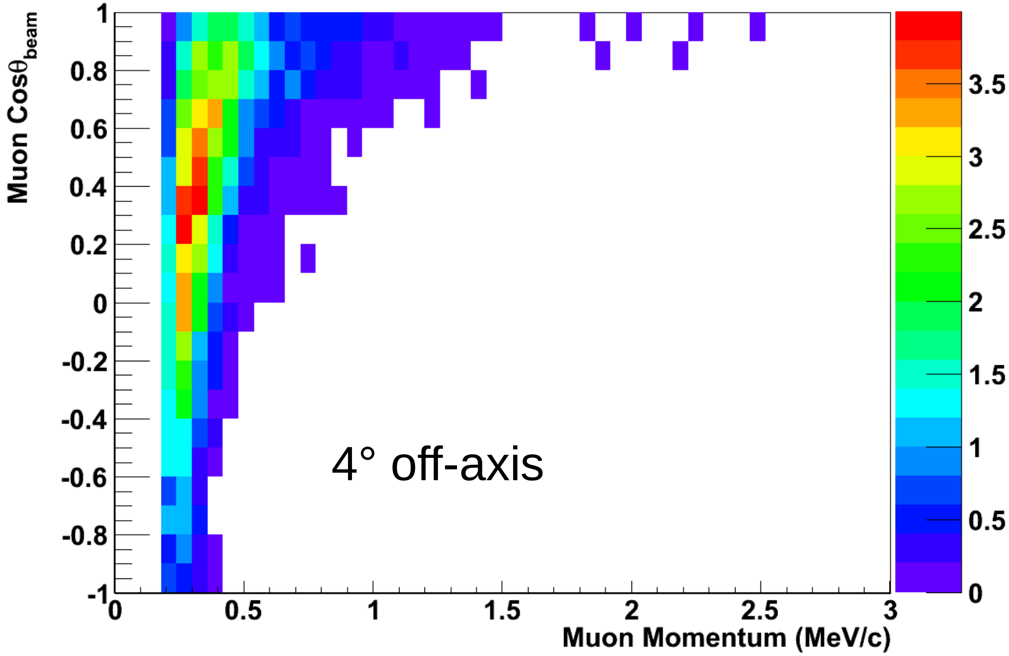


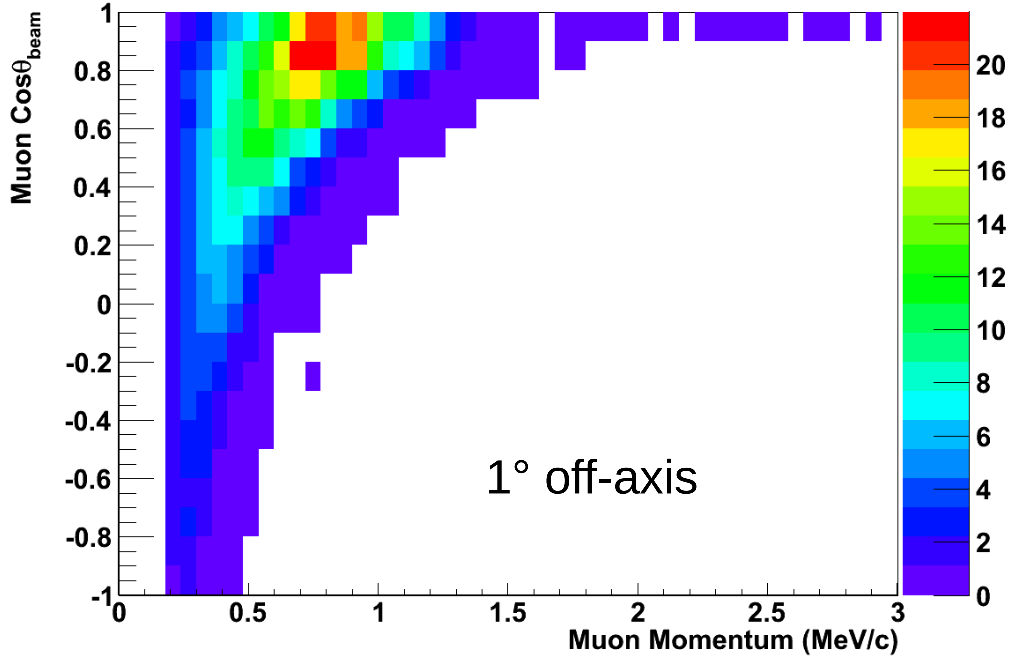




- Get a set of 30 $C_i$ coefficients for each pair of oscillation parameters

# Event Selection

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



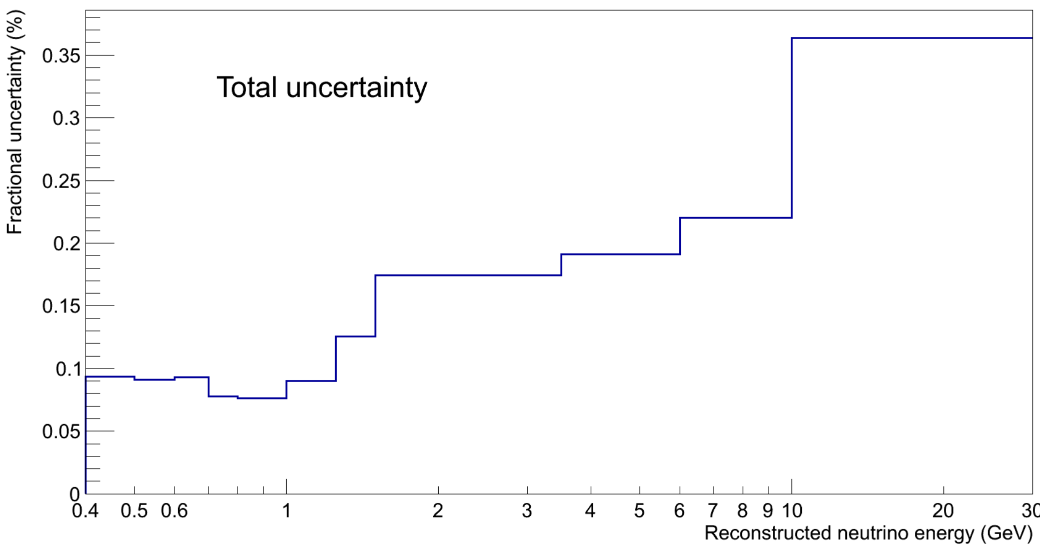

- Record the off-axis angle of the interaction, using the reconstructed vertex position

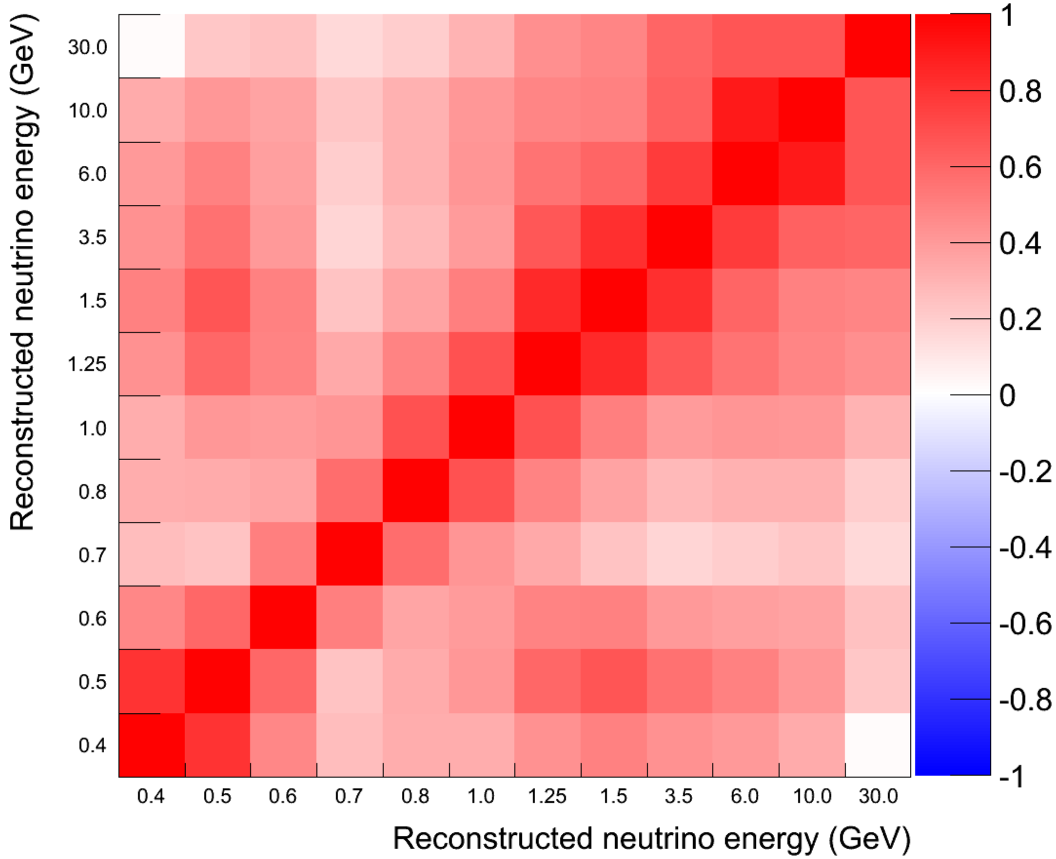
# Systematic uncertainties

- 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 – see later slides

# Total uncertainty

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



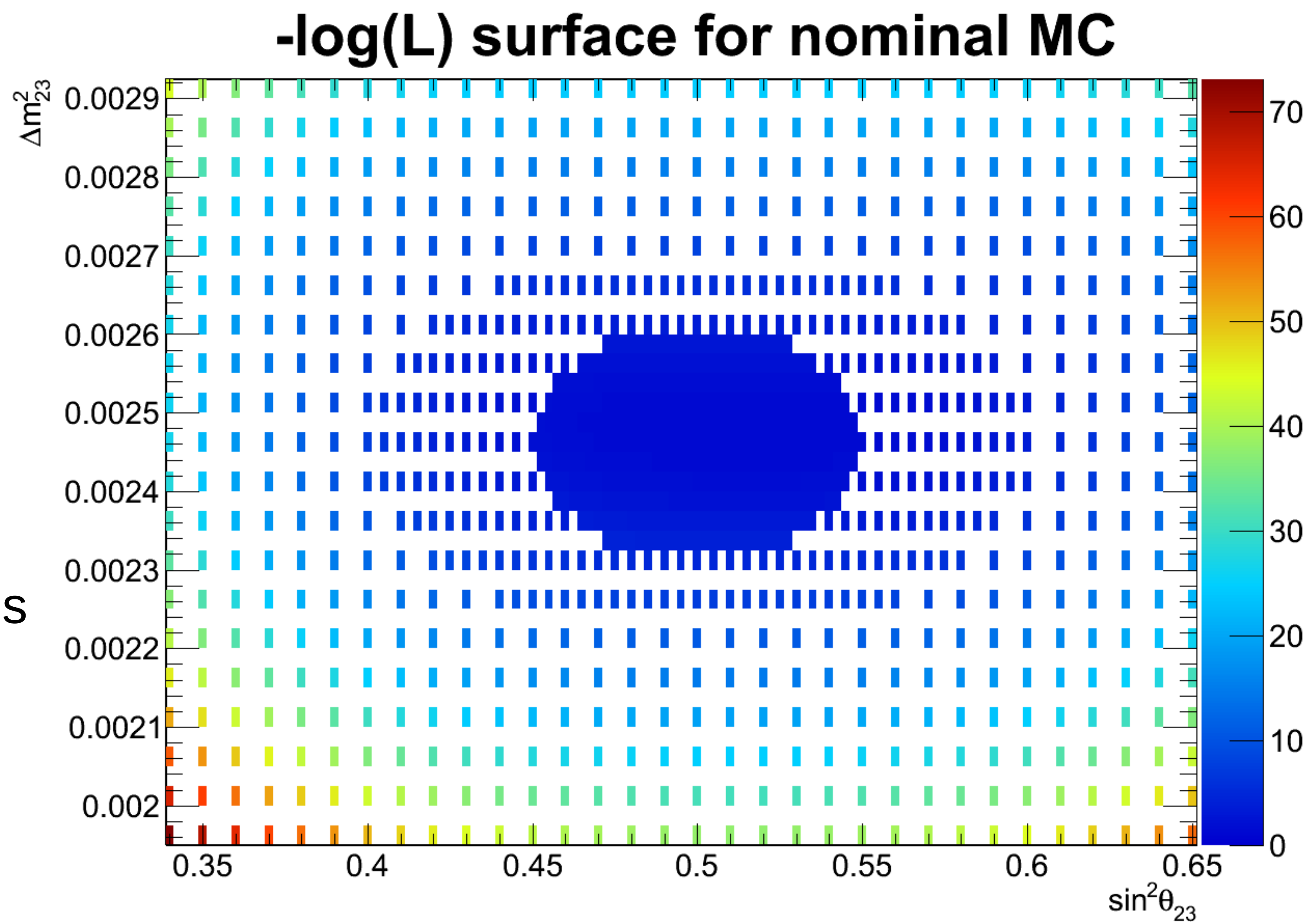




- Total uncertainty is <10% at oscillation peak
- ~7% statistical, 6% systematic

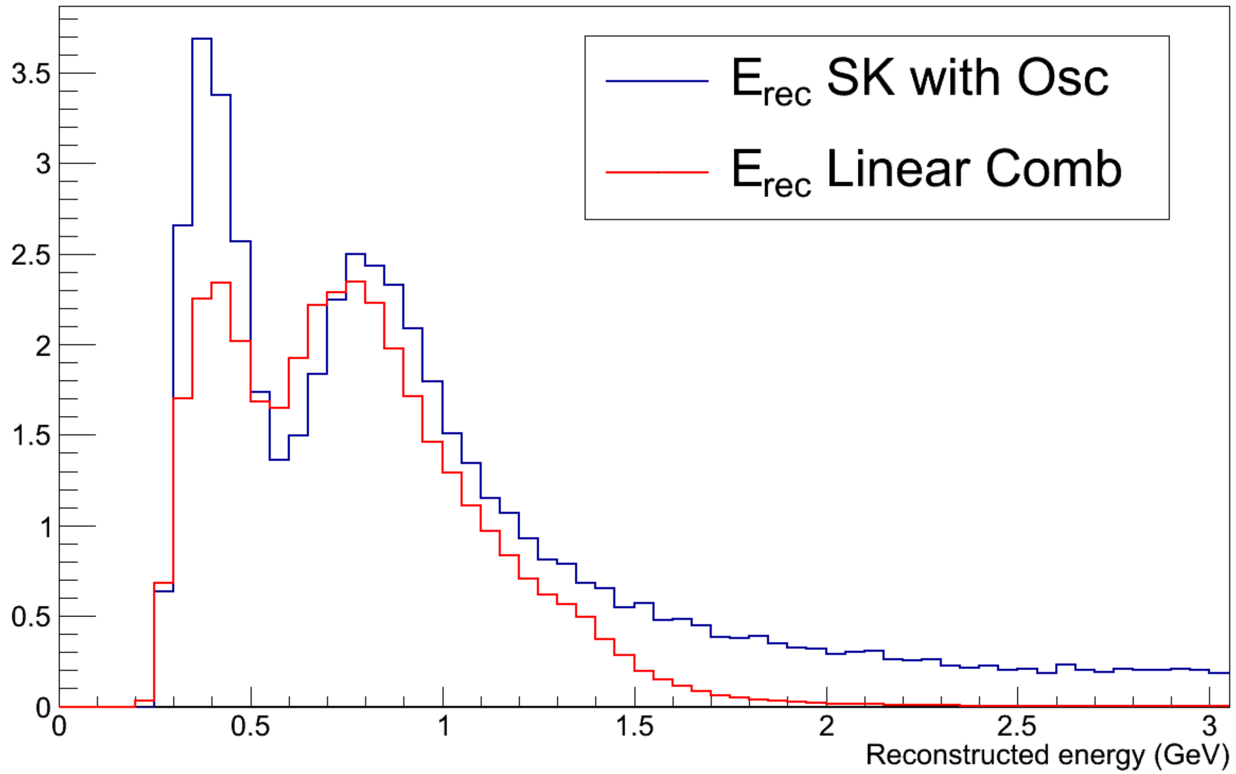
# Oscillation fit

- Calculate covariance matrix and $\nu$PRISM prediction for various points in $\theta_{23}$ and $\Delta m^2$ phase space

- Use Simple Fitter to calculate likelihood (L)
- Plot - ln(L) for all points in $\theta_{23}$ and $\Delta m^2$
- Minimum bin gives best fit 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

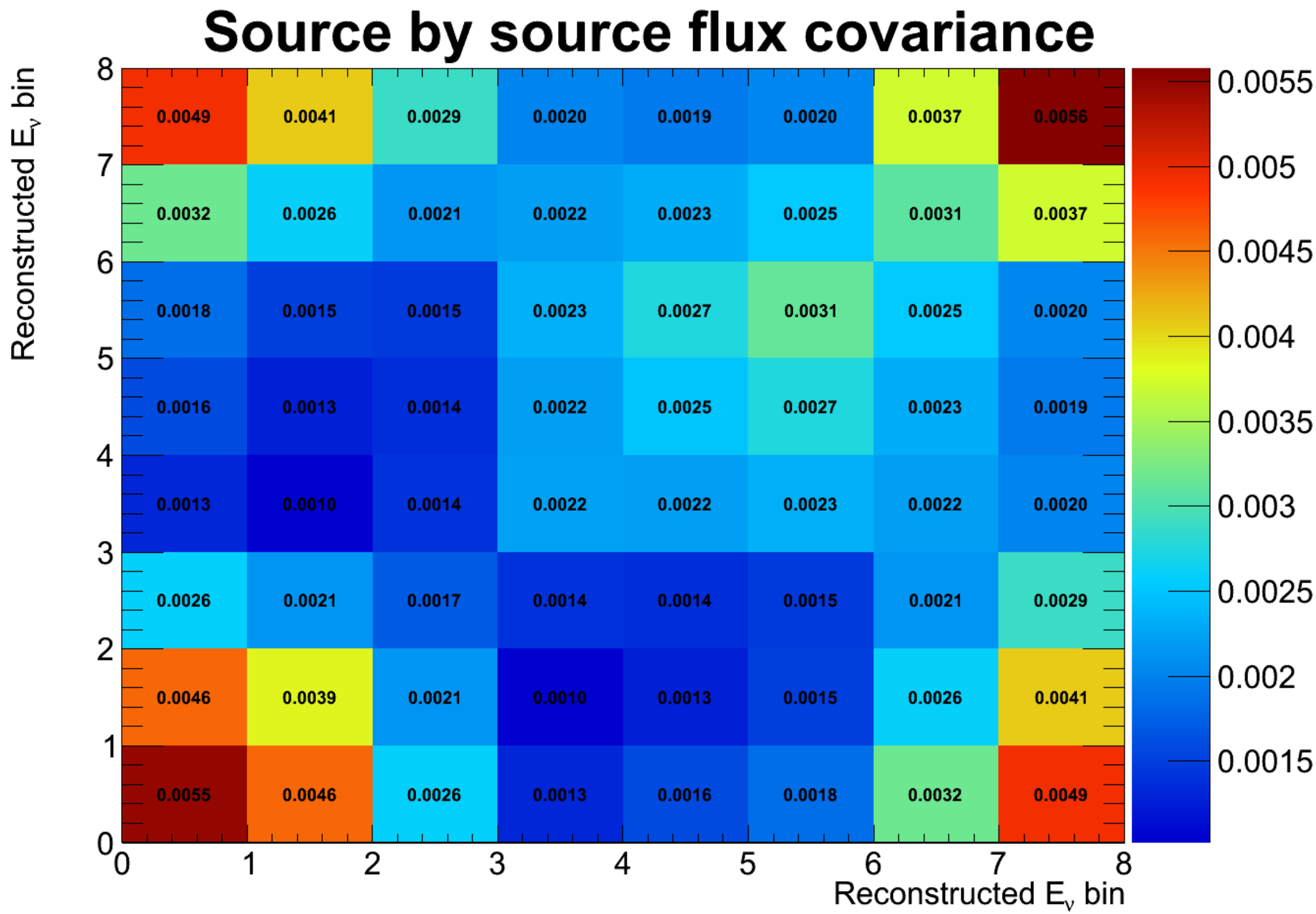
- Flux uncertainties come from 26 sources
  - Proton beam alignment
  - Hadron production
  - Etc.
  - Expect to be independent of one another

- 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

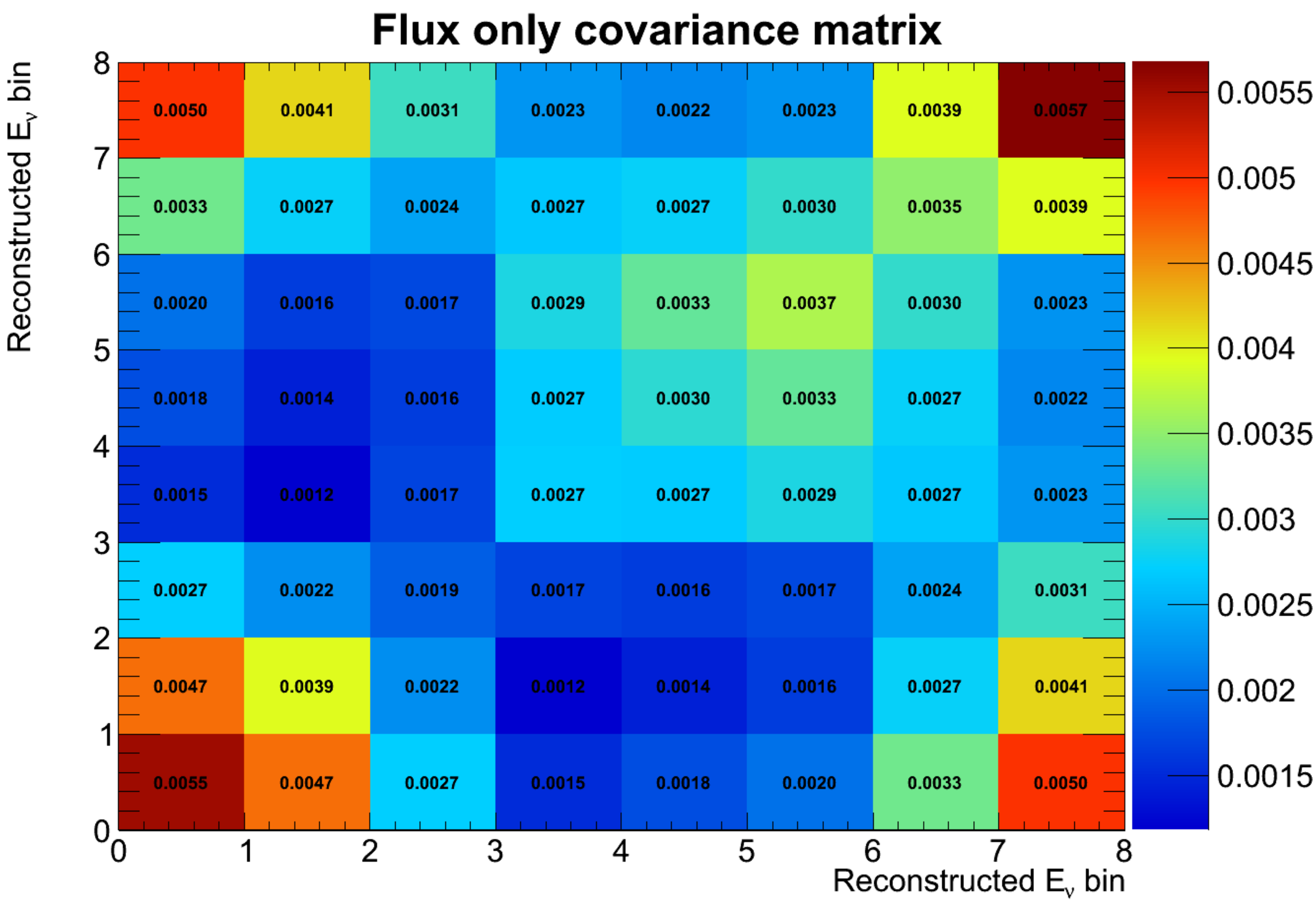
# Separate sources

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



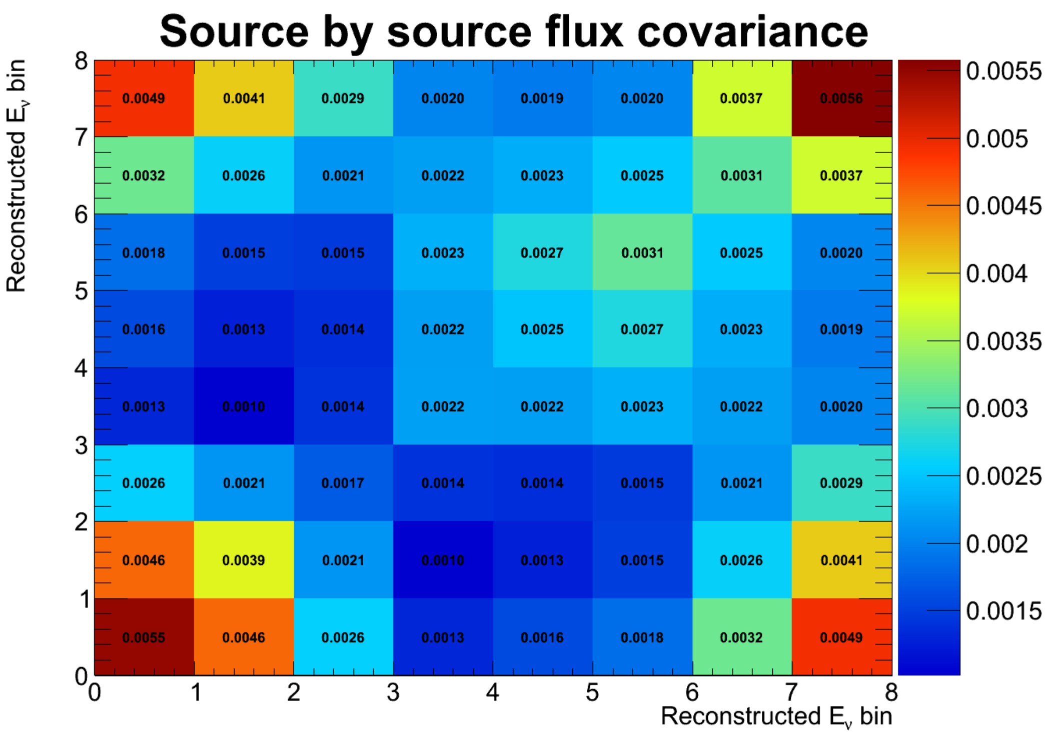
# Simultaneous variation

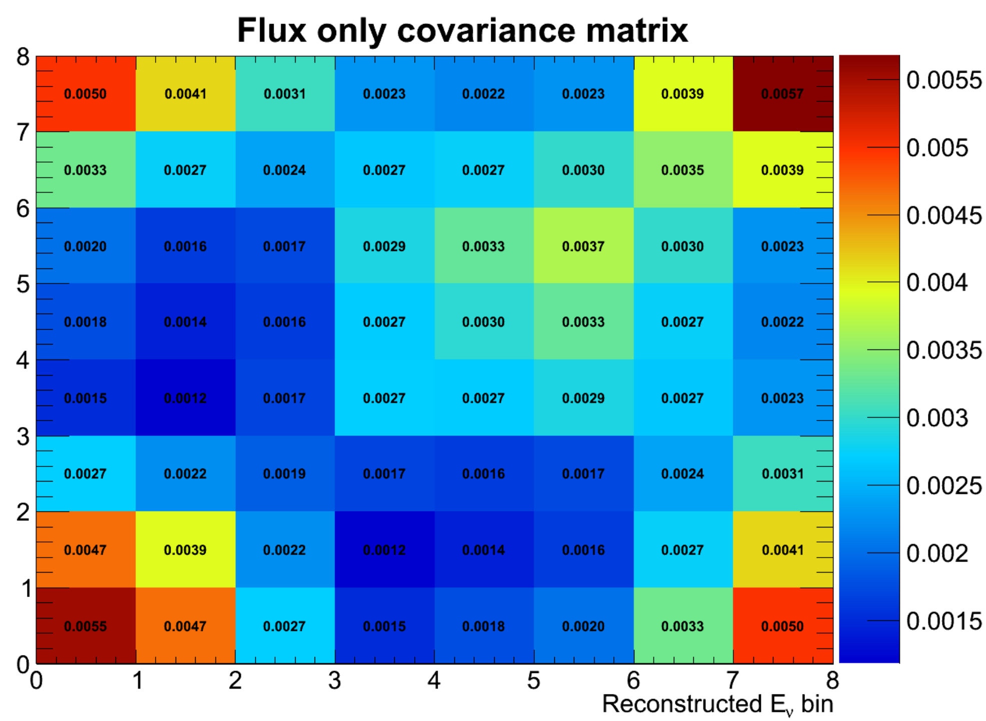
- Larger errors at high and low energy – no νPRISM events
- Error at oscillation dip (bin 3) around 5%



# Comparing flux uncertainty

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

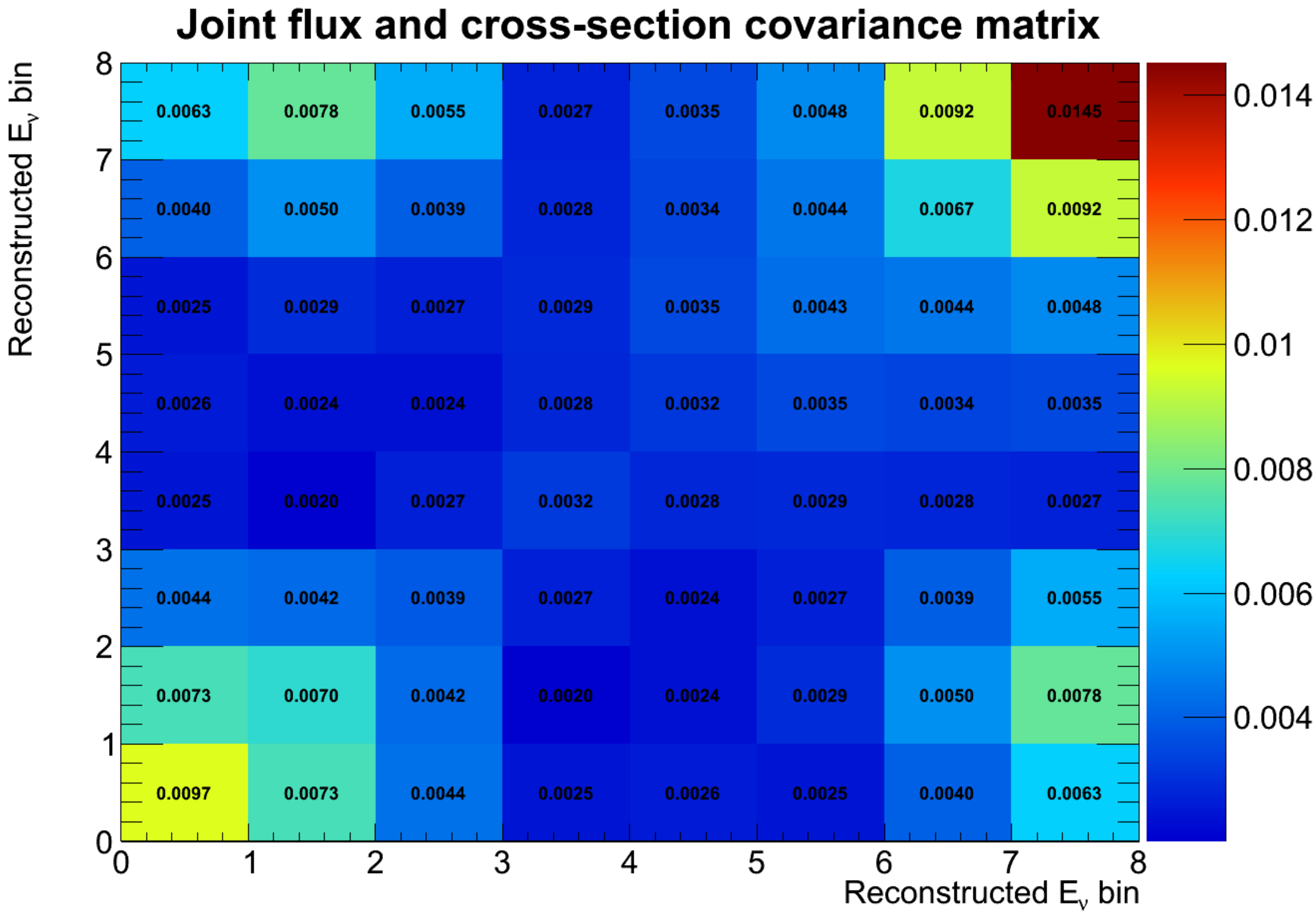



- Very good agreement between the two methods
- Confident flux uncertainties are being applied correctly

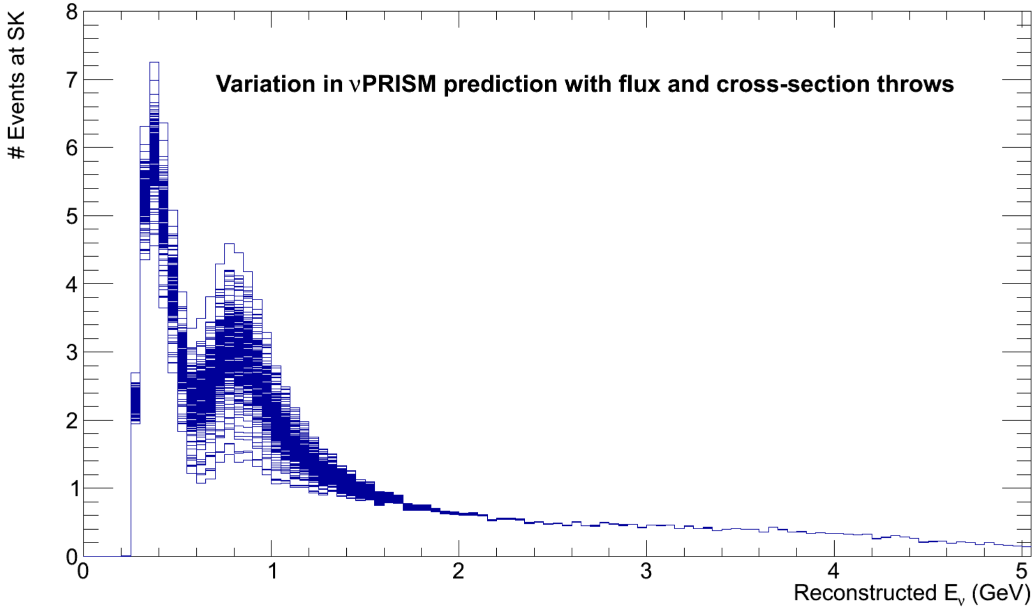
# Flux and cross section

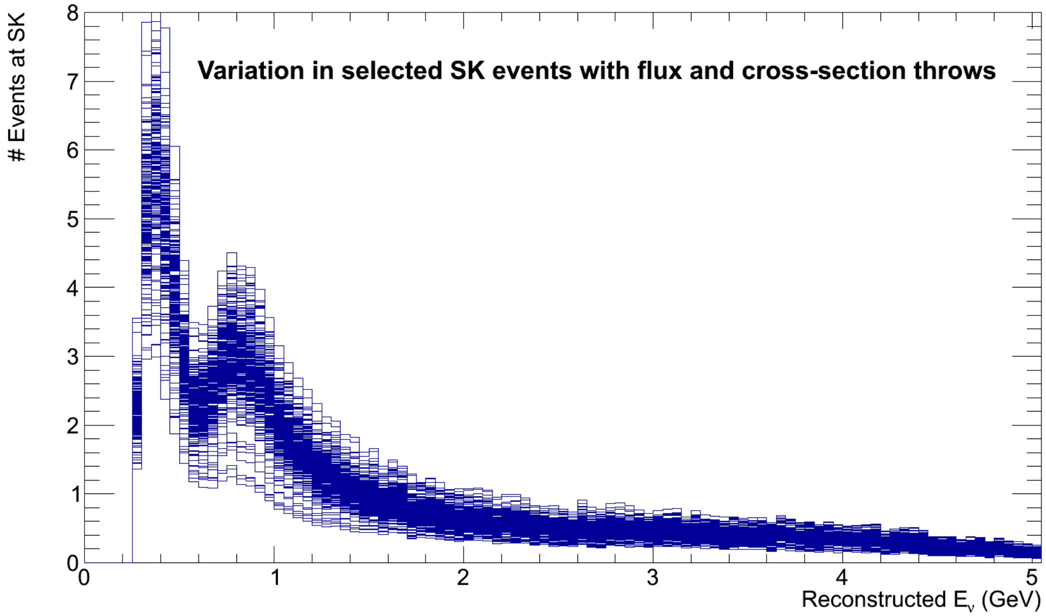
- When varying flux and cross section simultaneously the uncertainty in bin 3 (600 – 700 MeV) is 5.7%



# Systematic throws

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



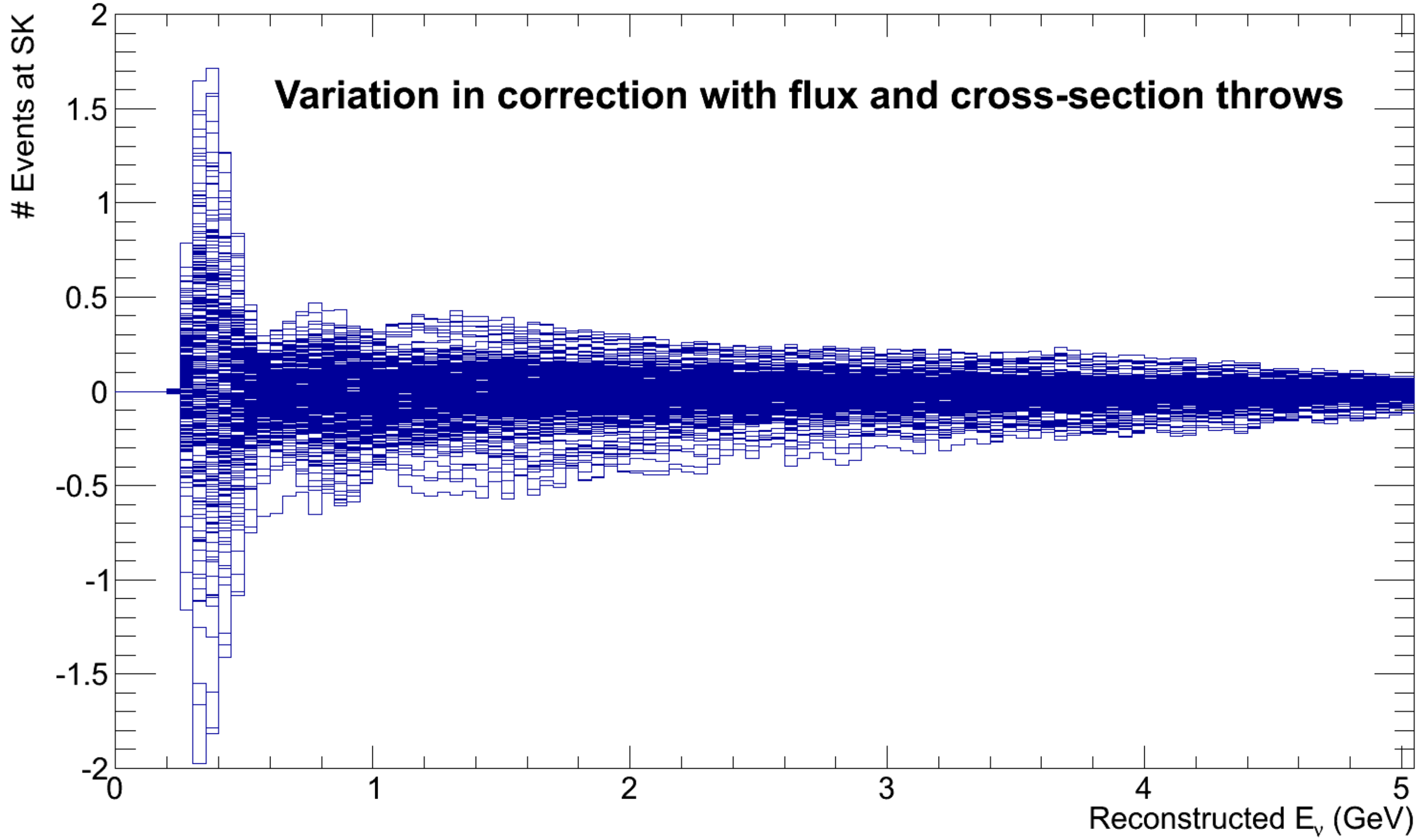




- Plots show all 300 throws of the νPRISM prediction (left) and selected SK events (right)

- 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

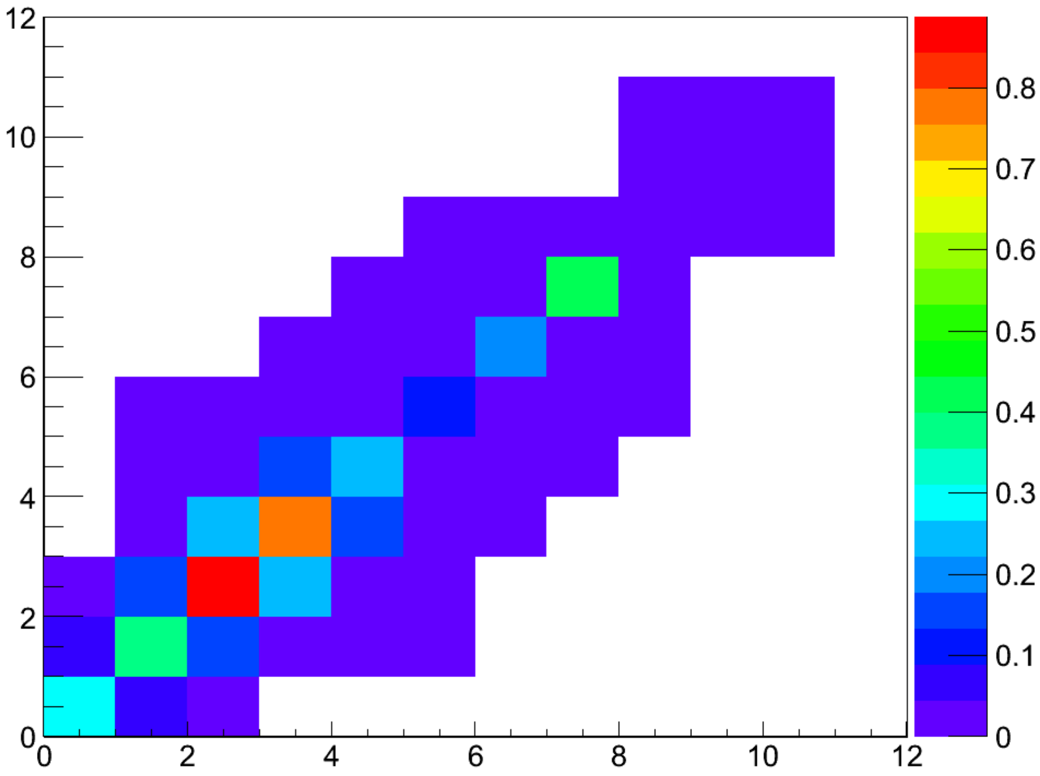
- Plot difference between selected SK events and νPRISM prediction for each throw




- 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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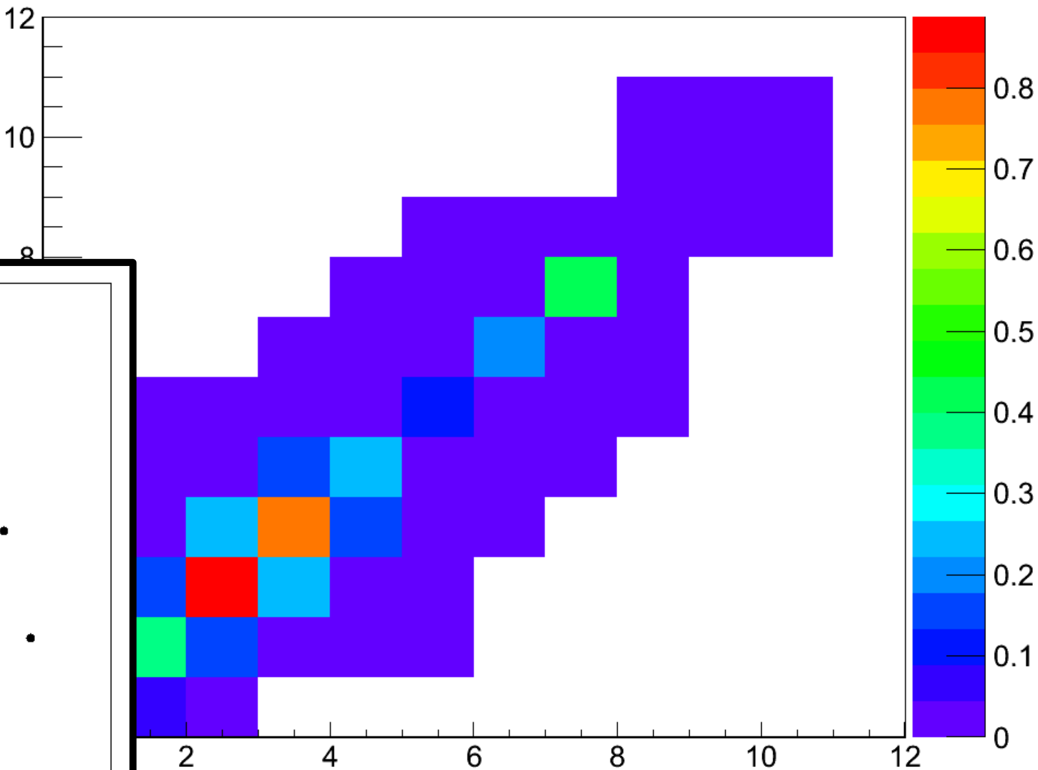
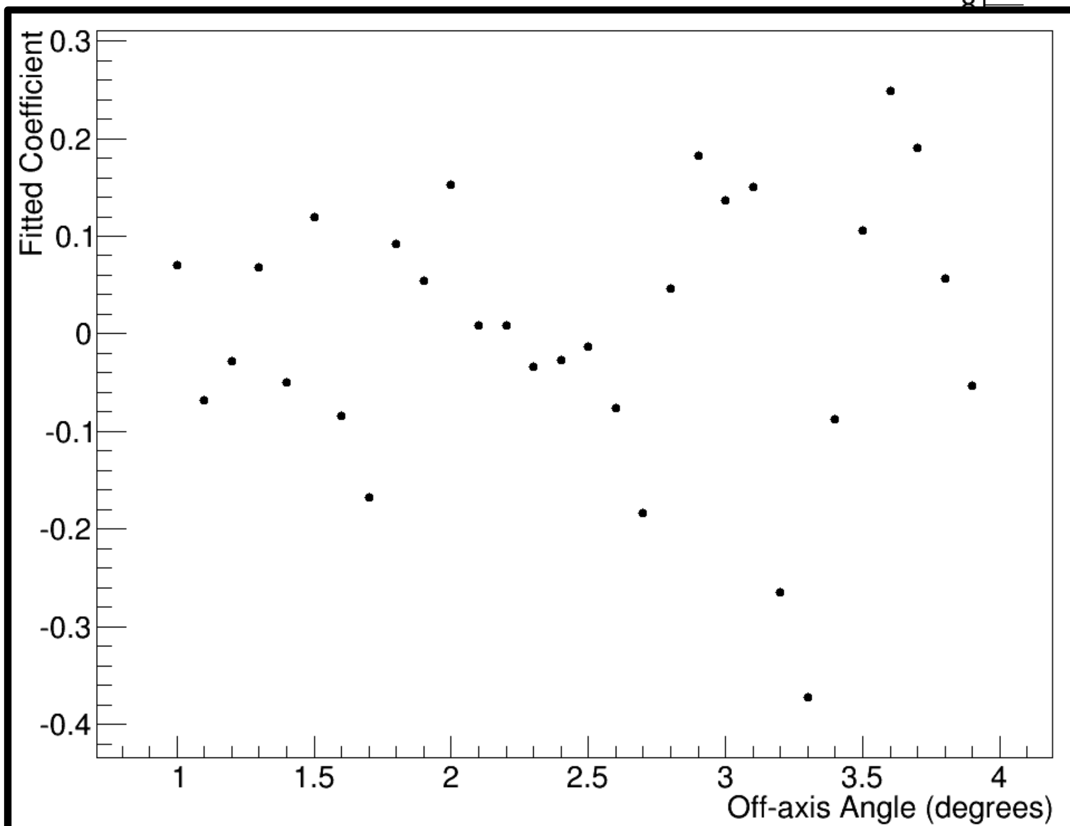
  - almost 100% uncertainty

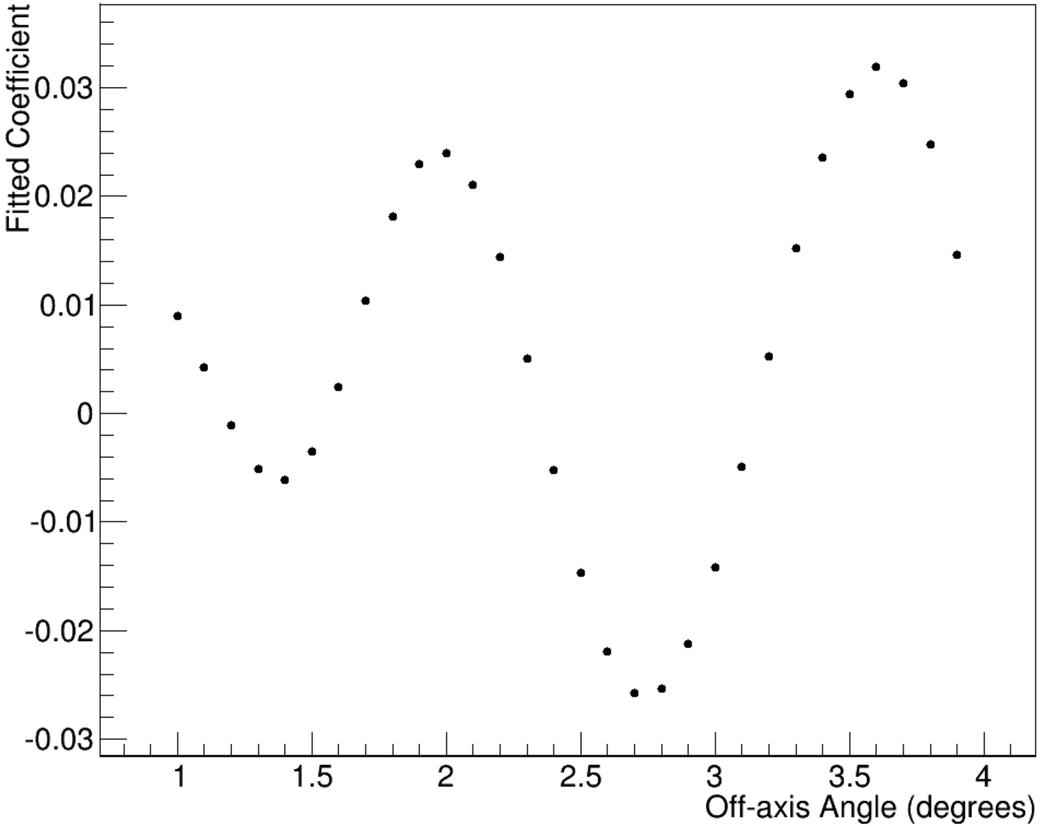



- Fit coefficients:
  - Rapidly varying
  - Relatively large

# Statistical uncertainties

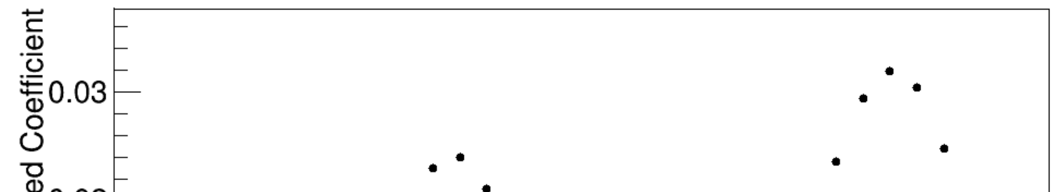
- Smooth linear combination – variations in neighbouring slices cancel out to large extent

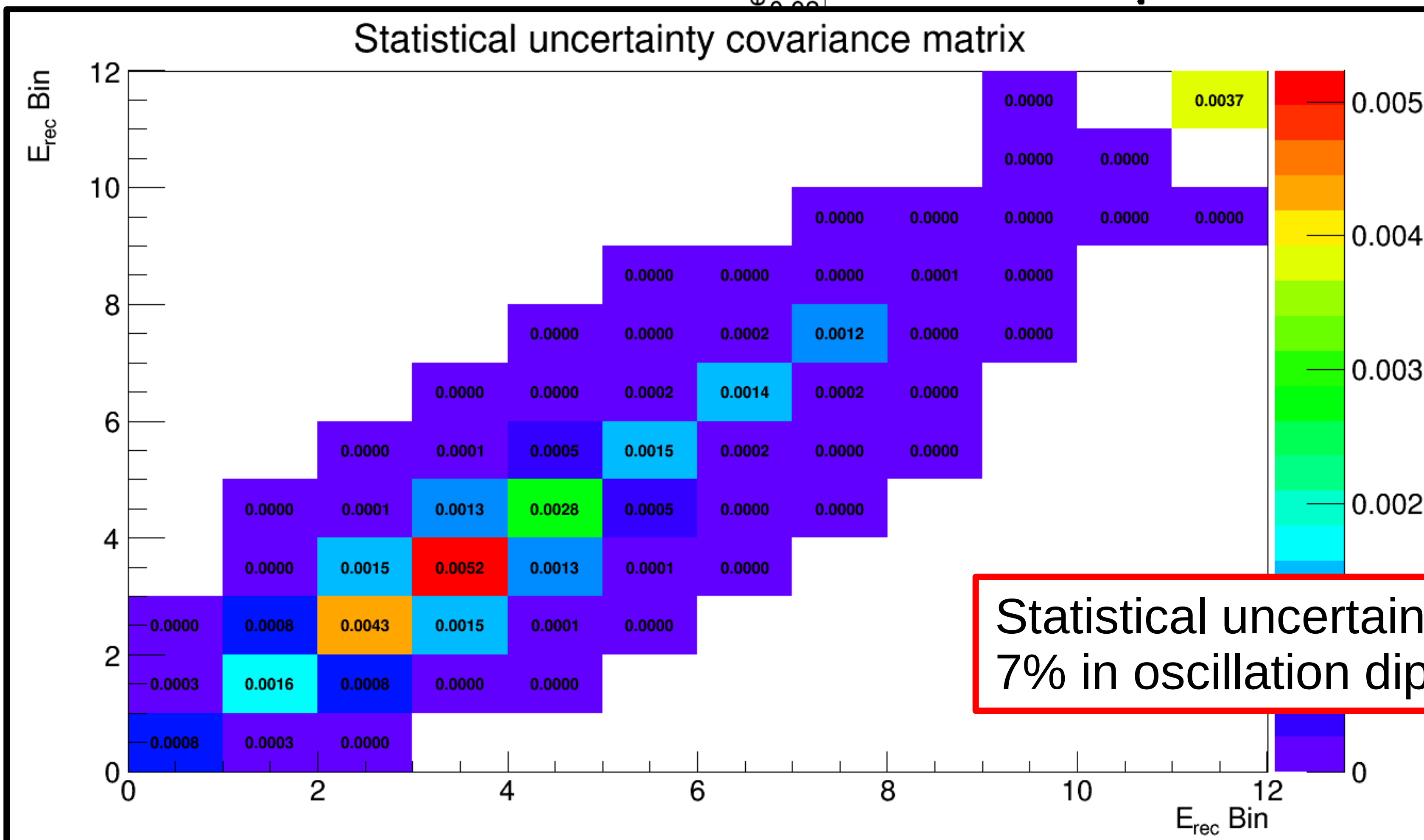


# Statistical uncertainties



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

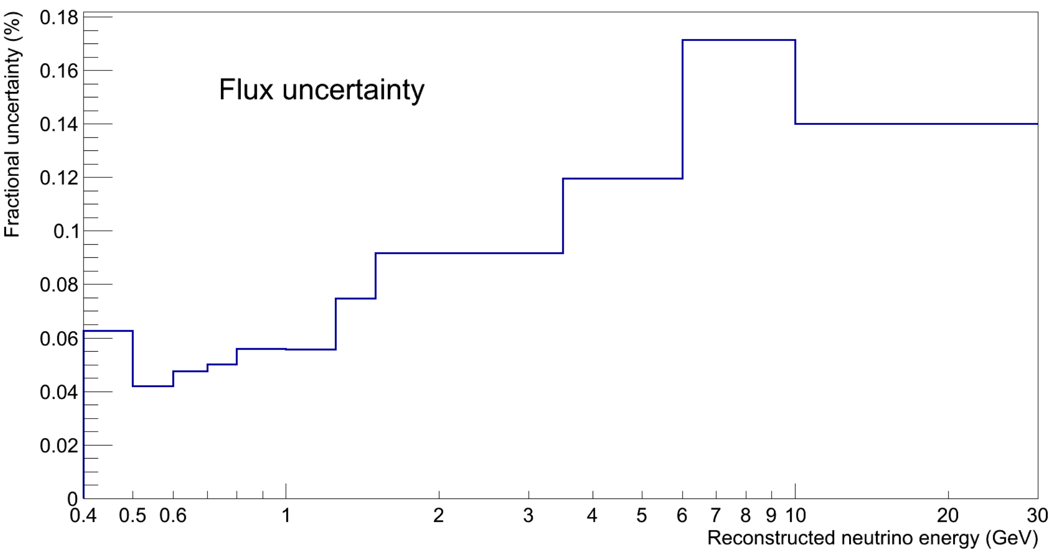


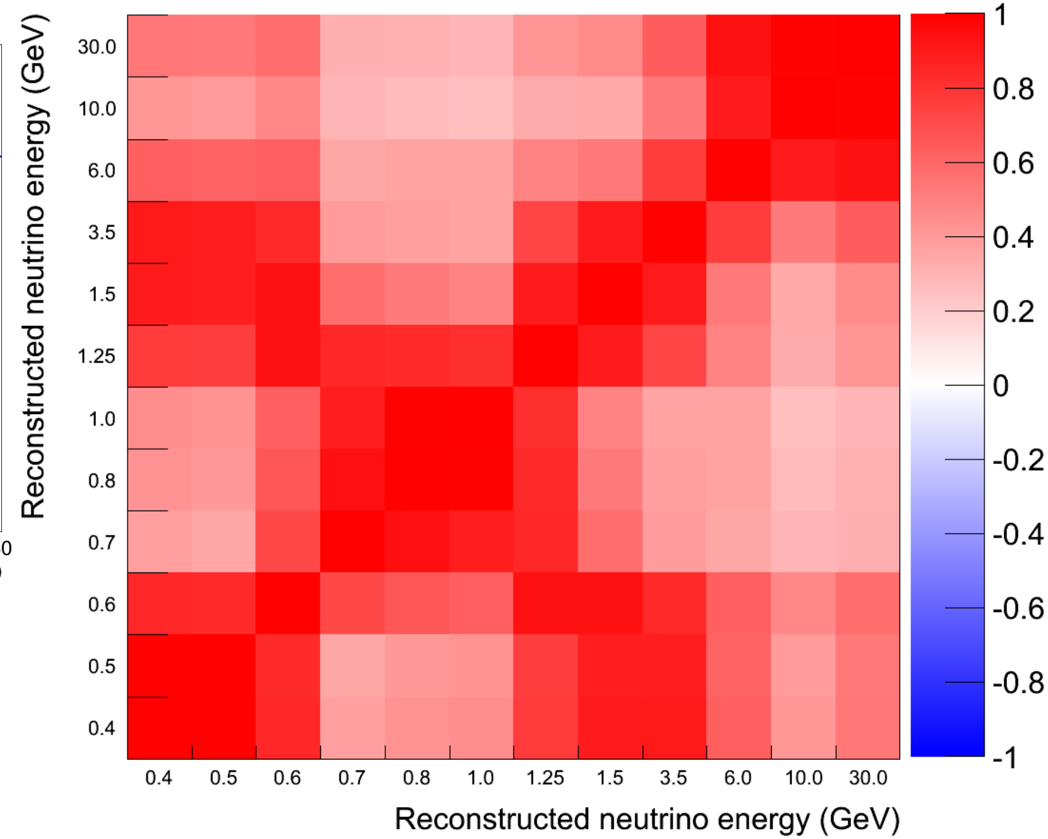




Statistical uncertainty around 7% in oscillation dip

# Flux uncertainty

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

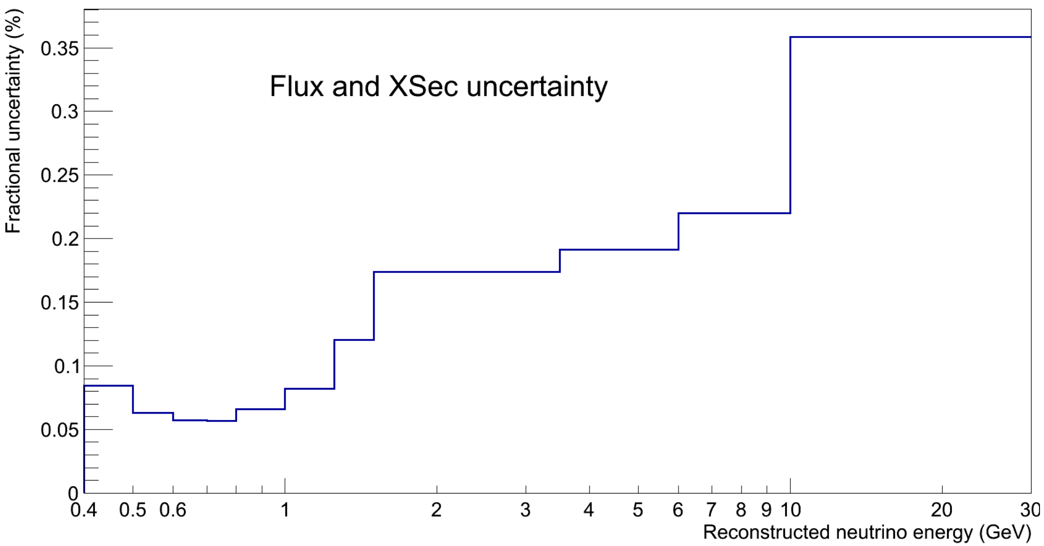


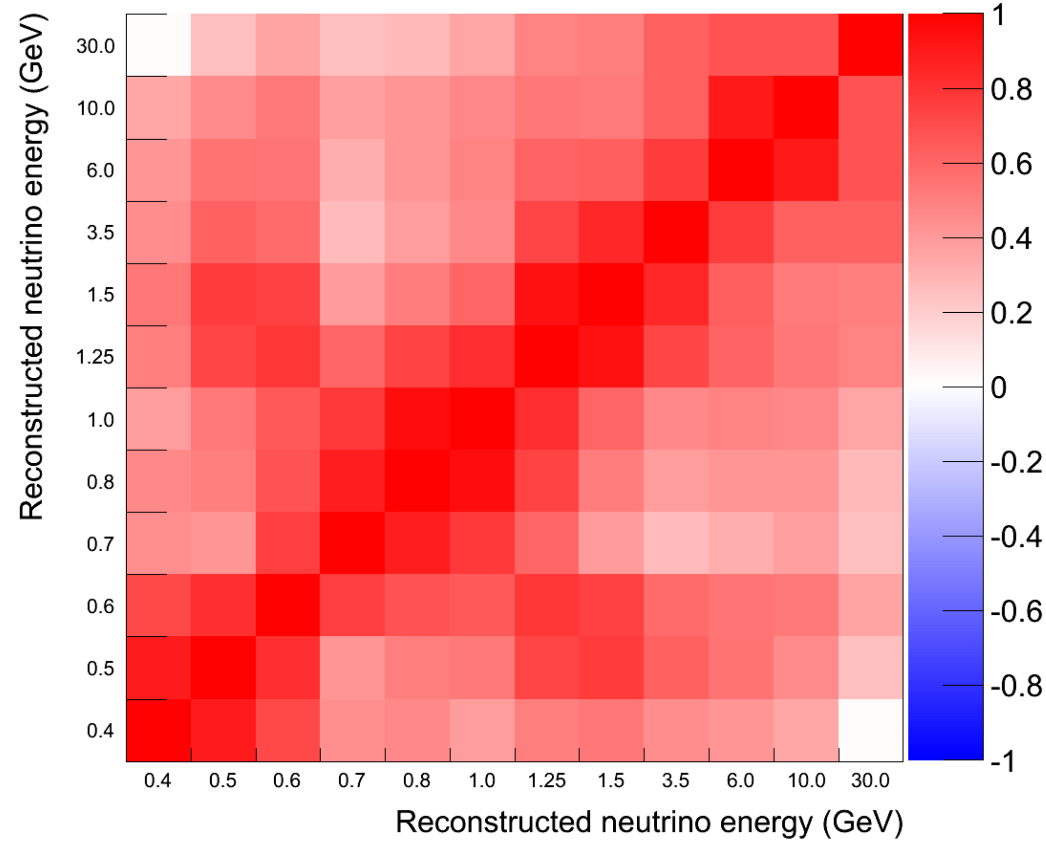




- Larger errors at high energy – no νPRISM events
- Error at oscillation dip around 4-5%

# 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

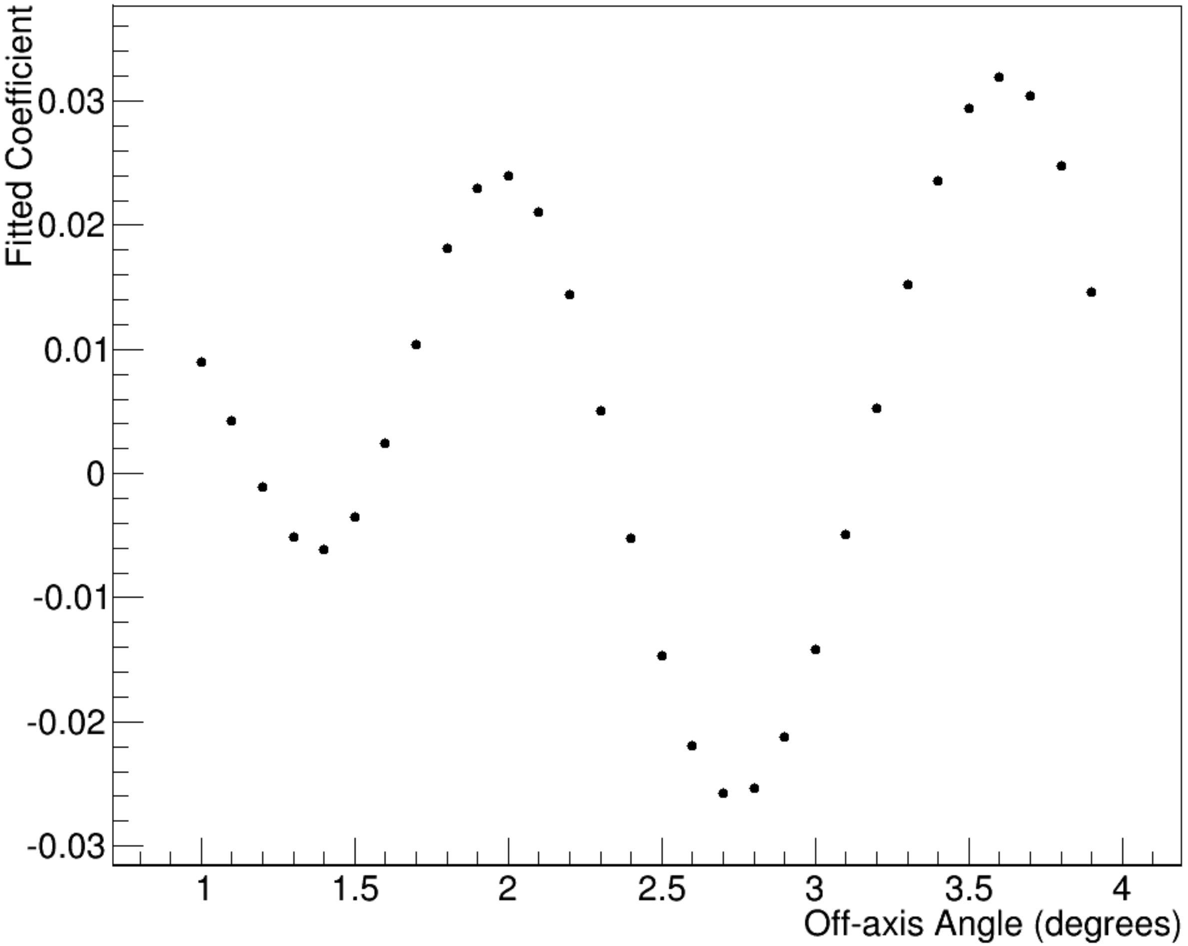


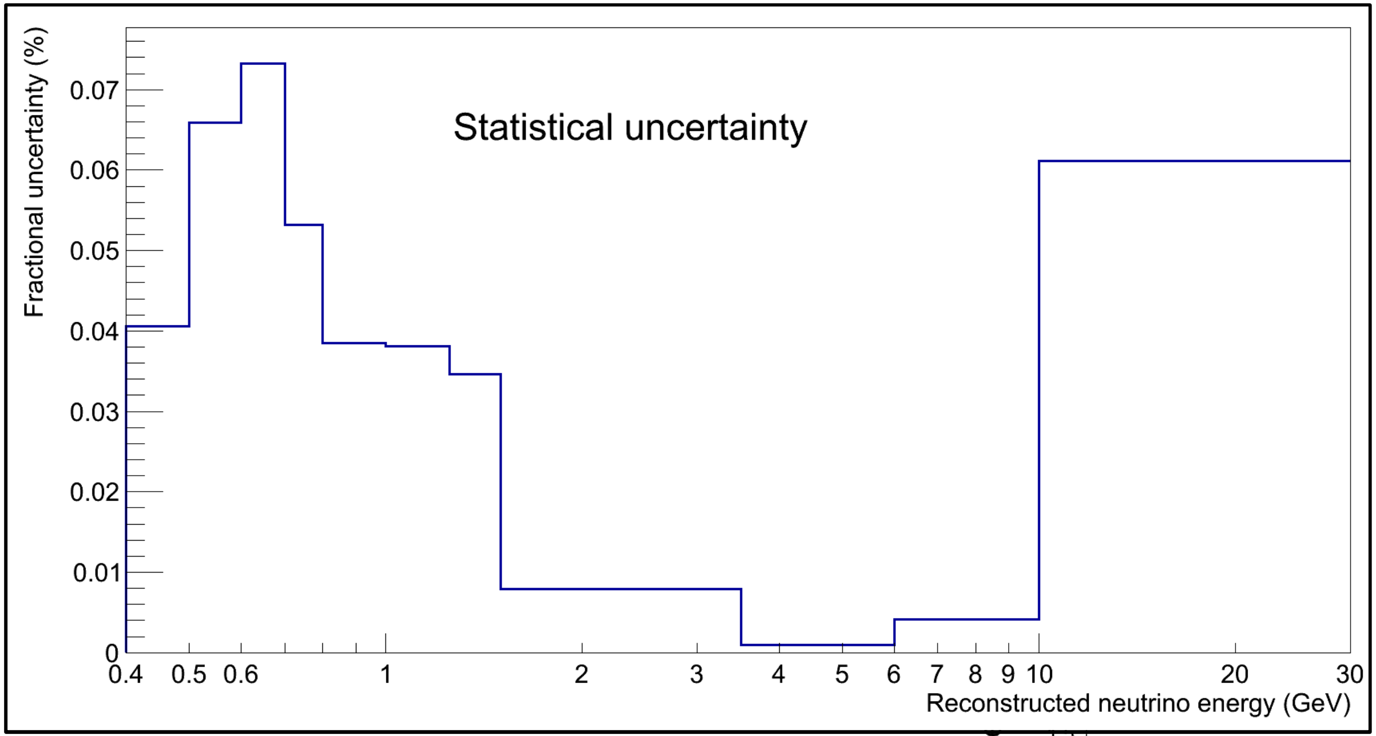

- Combined flux and cross section uncertainty around 5% at the oscillation dip

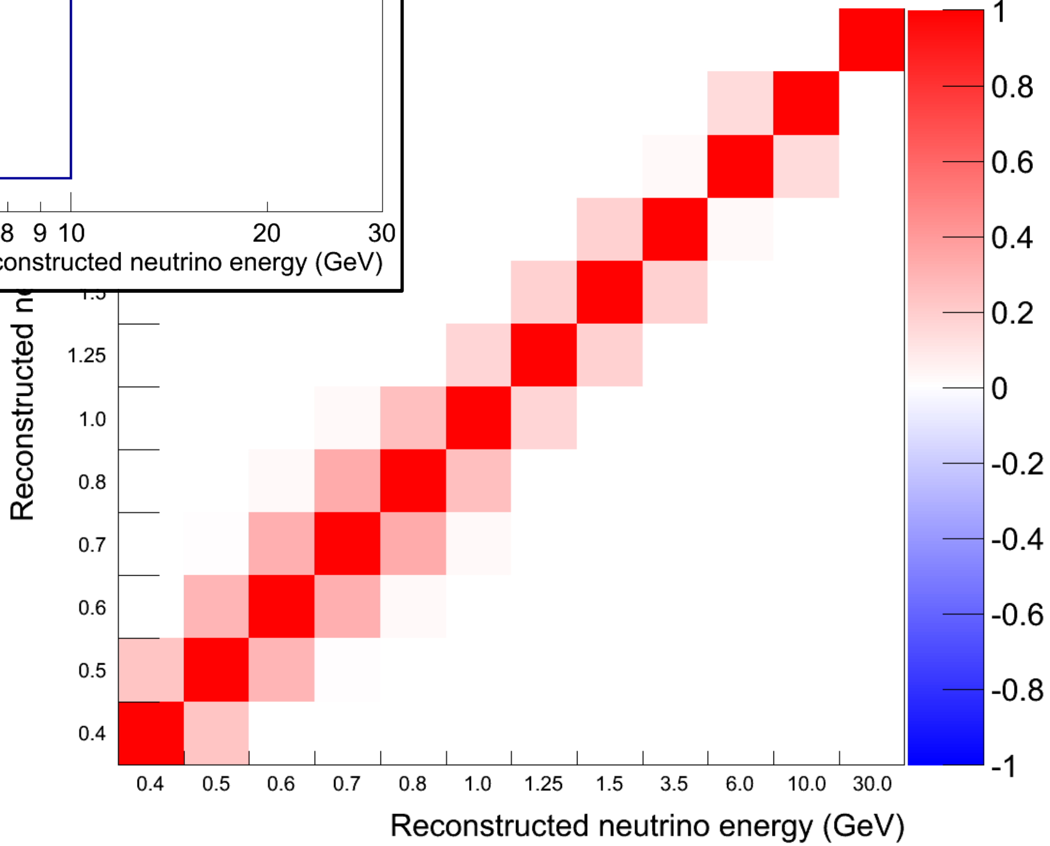
# Statistical uncertainties

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



# Statistical uncertainties

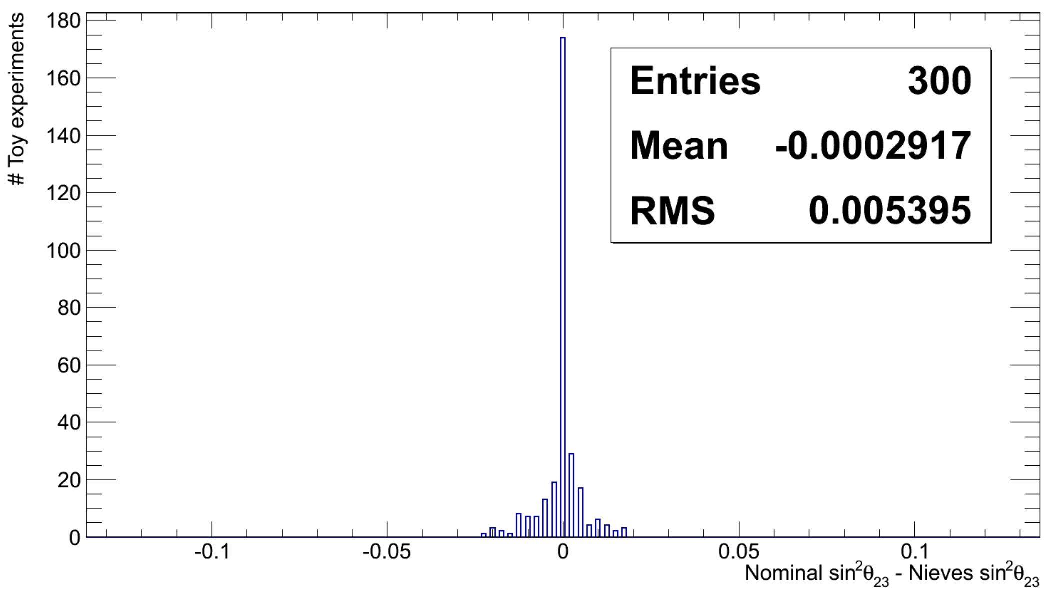


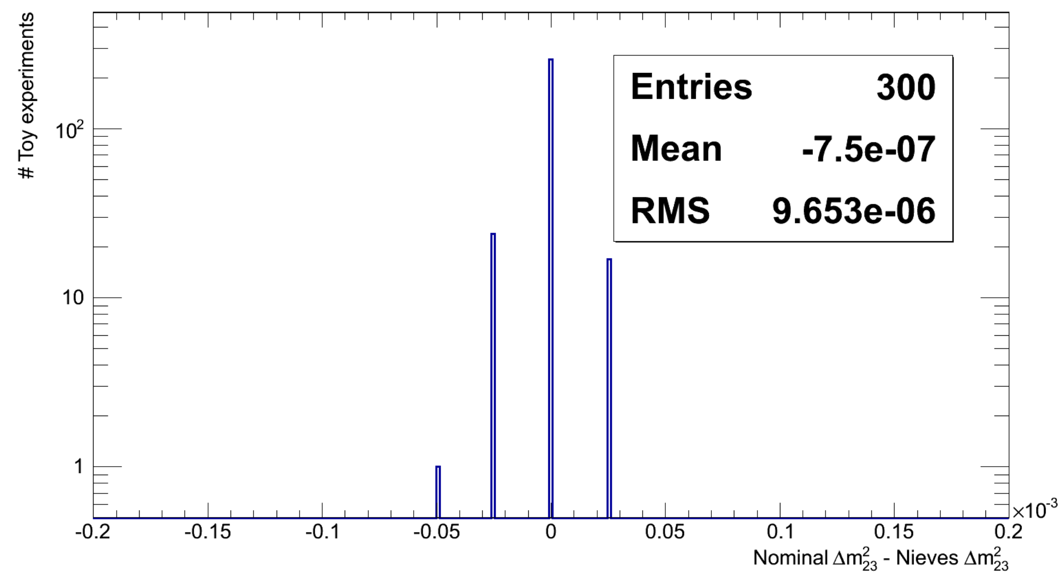




- Uncertainty maximal in oscillation dip – subtracting distributions to get zero events
- Statistical uncertainty ~7% in oscillation dip

# 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 $\theta_{23}$ (left) and $\Delta m^2$ (right) than in T2K analysis
- Large spike at 0 difference in both plots