νPRISM
ν_μ disappearance analysis

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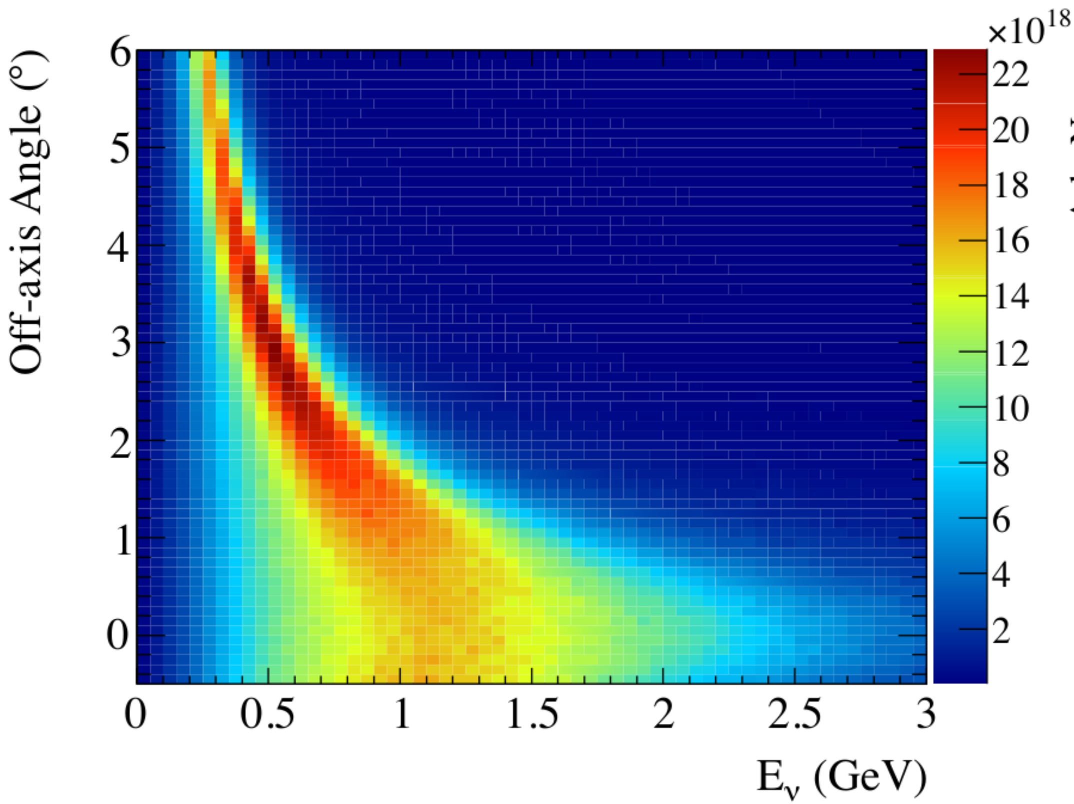
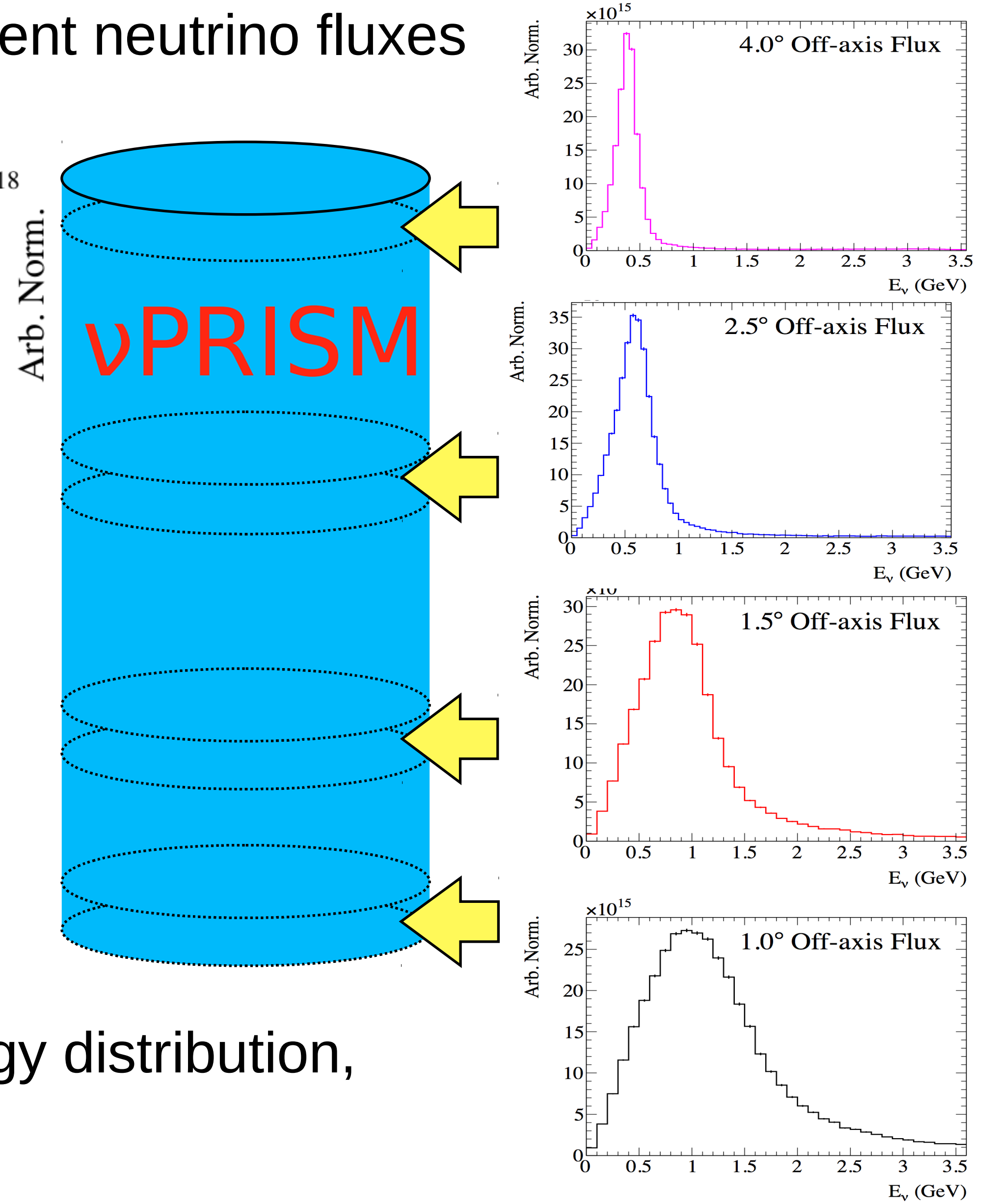
Hyper-K Near Detector Pre-meeting
July 19th 2014

νPRISM Concept

- Different off-axis angles see different neutrino fluxes

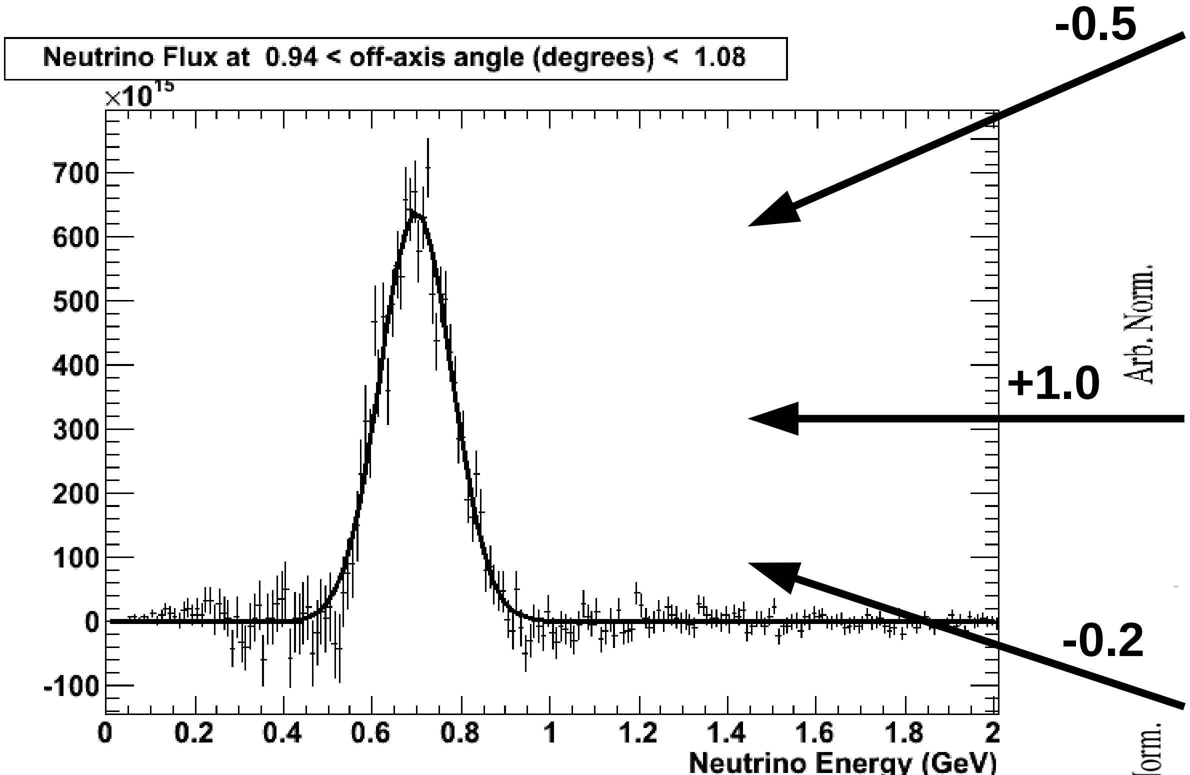


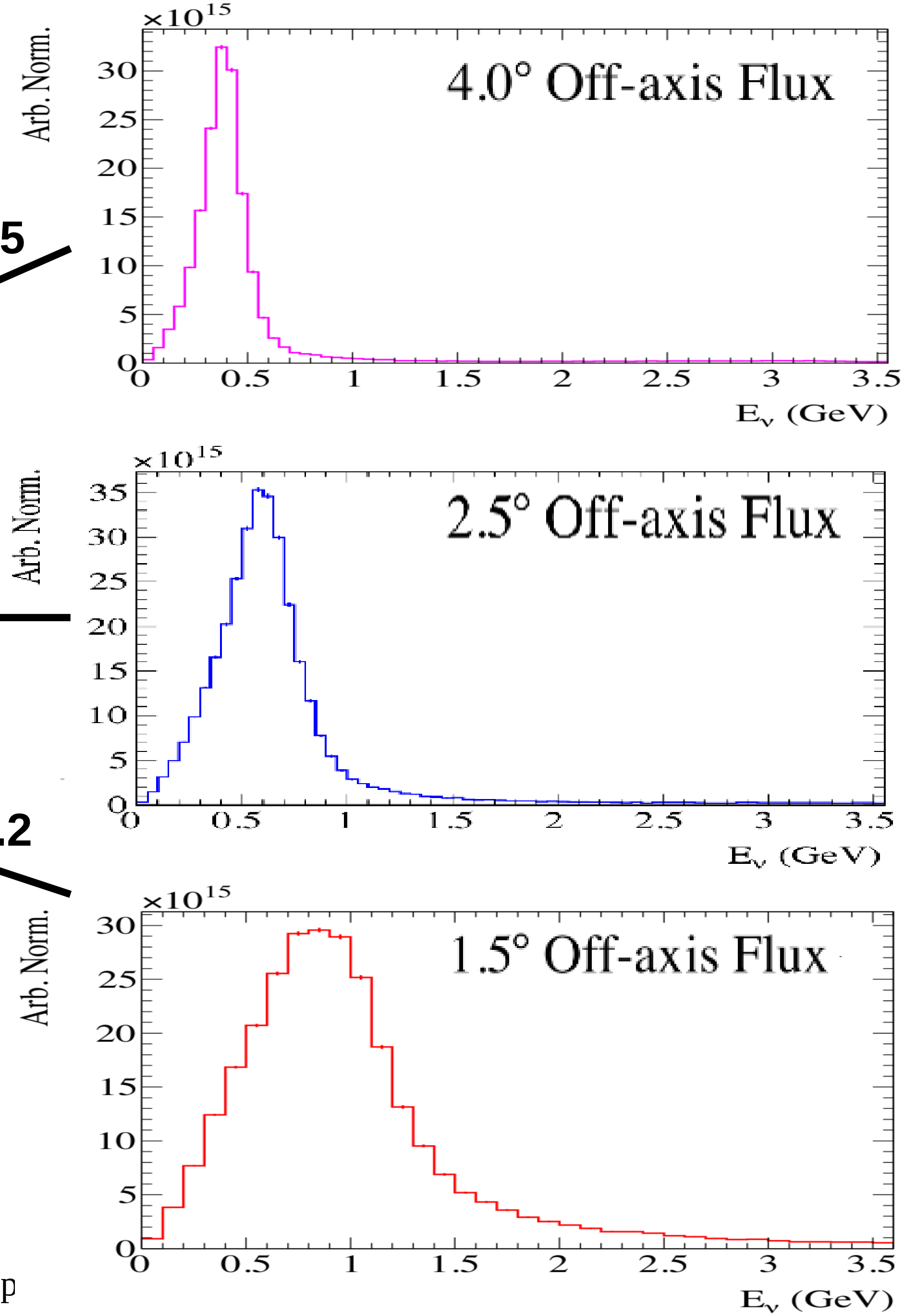


- Further off-axis → Narrower energy distribution, lower peak energy

Gaussian beams

- Can combine angular slices to create desired neutrino flux

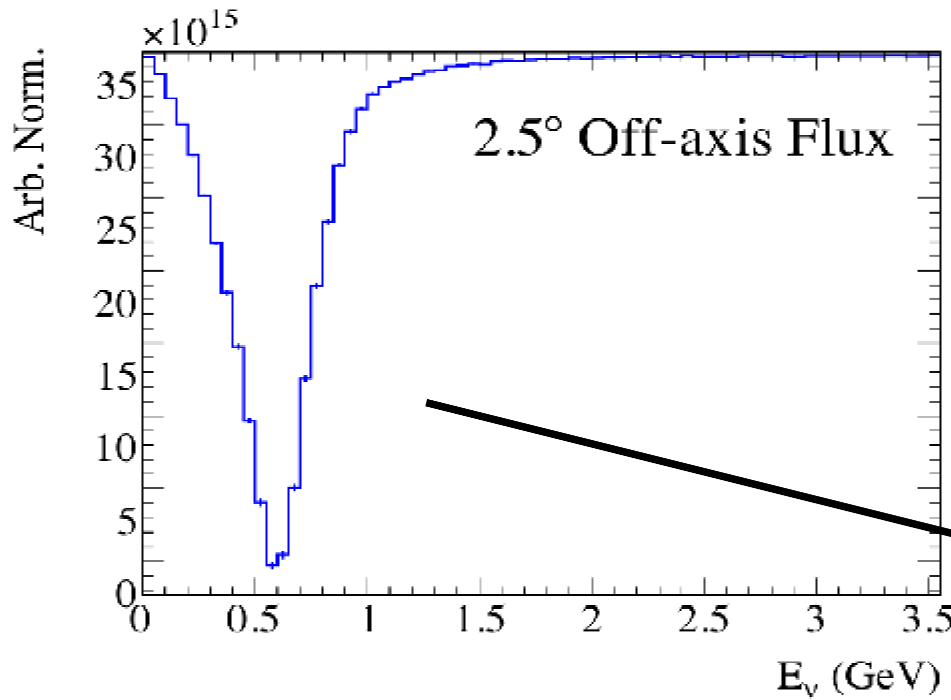




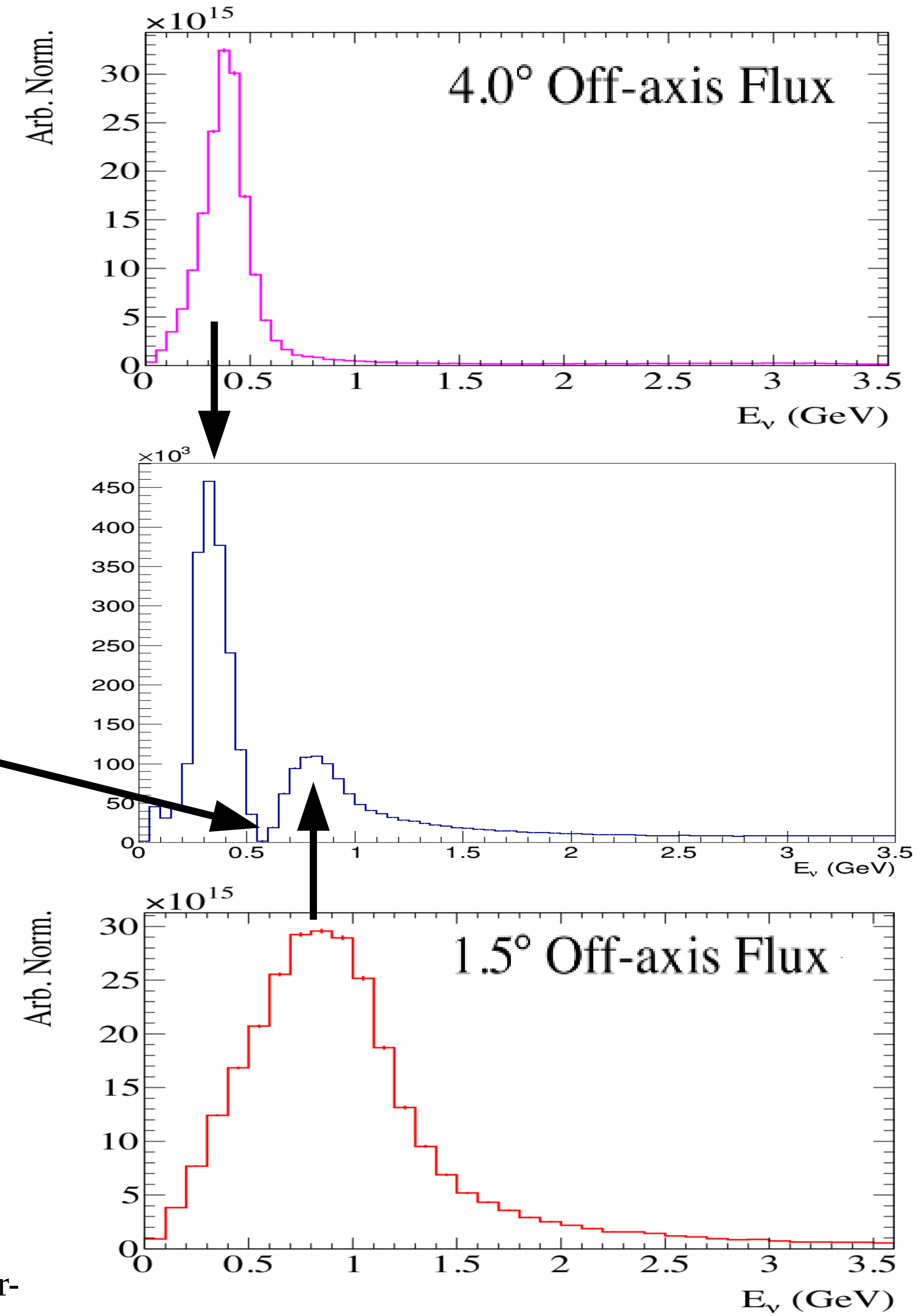
- Build a Gaussian neutrino flux!

Oscillated beam

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

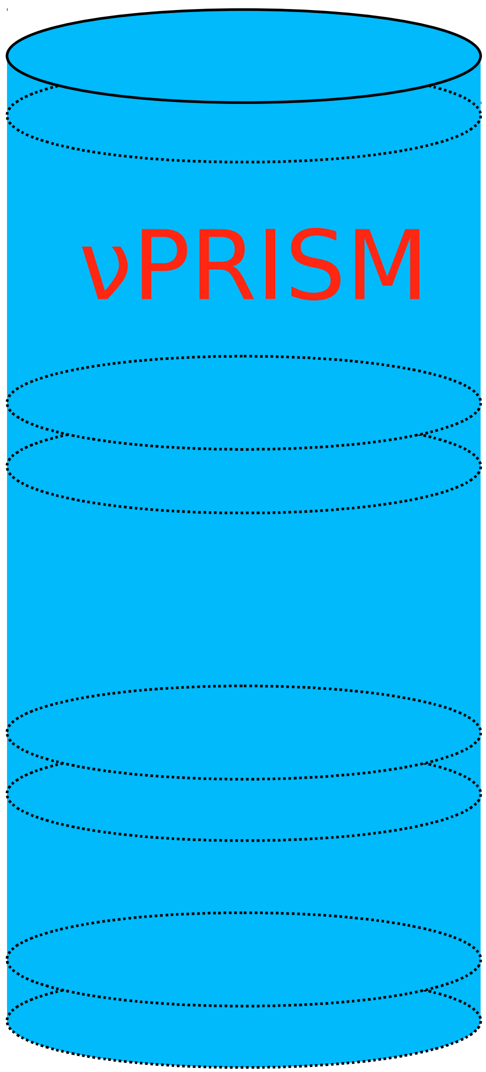


- 4° and 1.5° flux give the low and high energy peaks at SK
- Subtract the 2.5° flux to create the oscillation dip



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

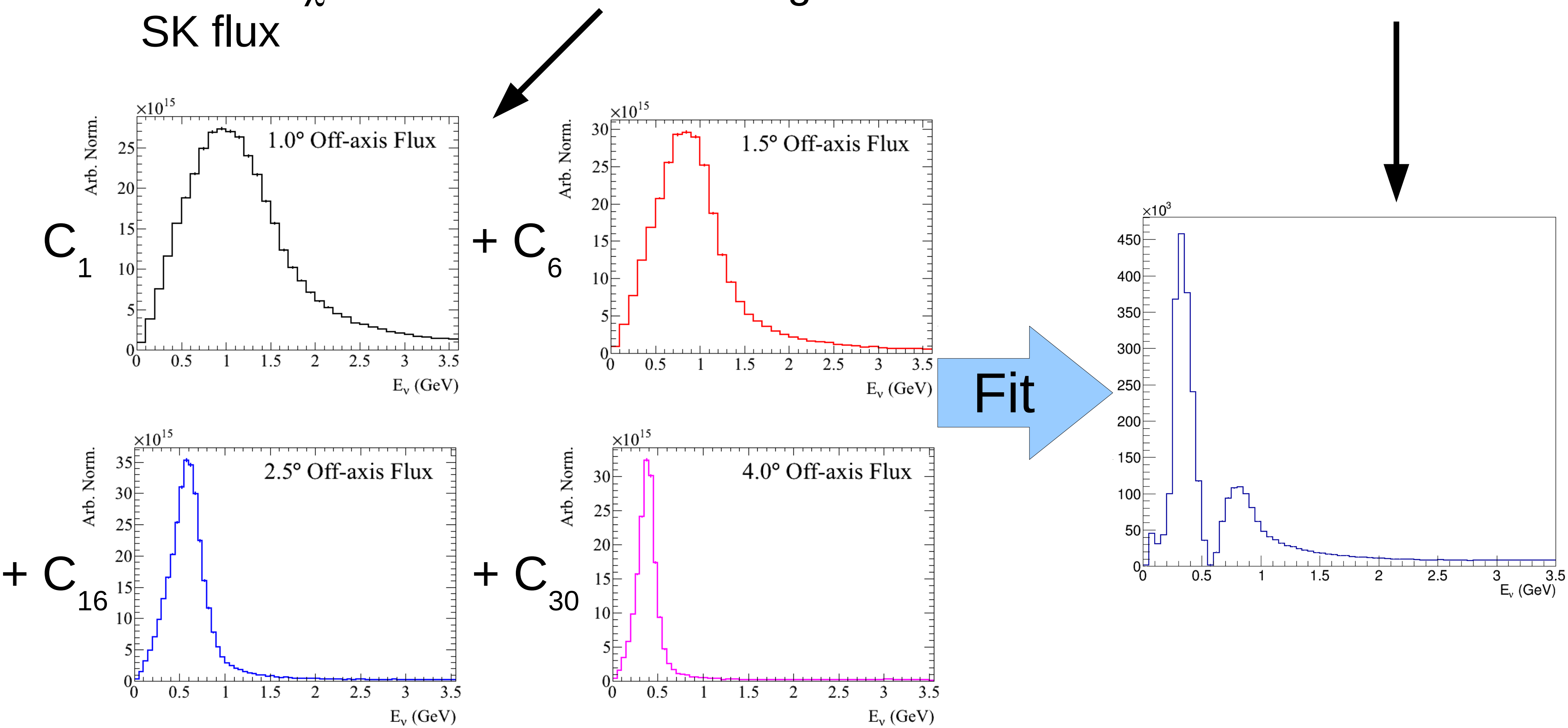
- νPRISM-lite:
  - Instrument 14m movable cylinder
  - Take data at different off-axis angles over run
  - Studies assumes 4.5 x 10^{20} POT in each off-axis slice of νPRISM

ν_μ Disappearance Analysis

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

Building the oscillated flux

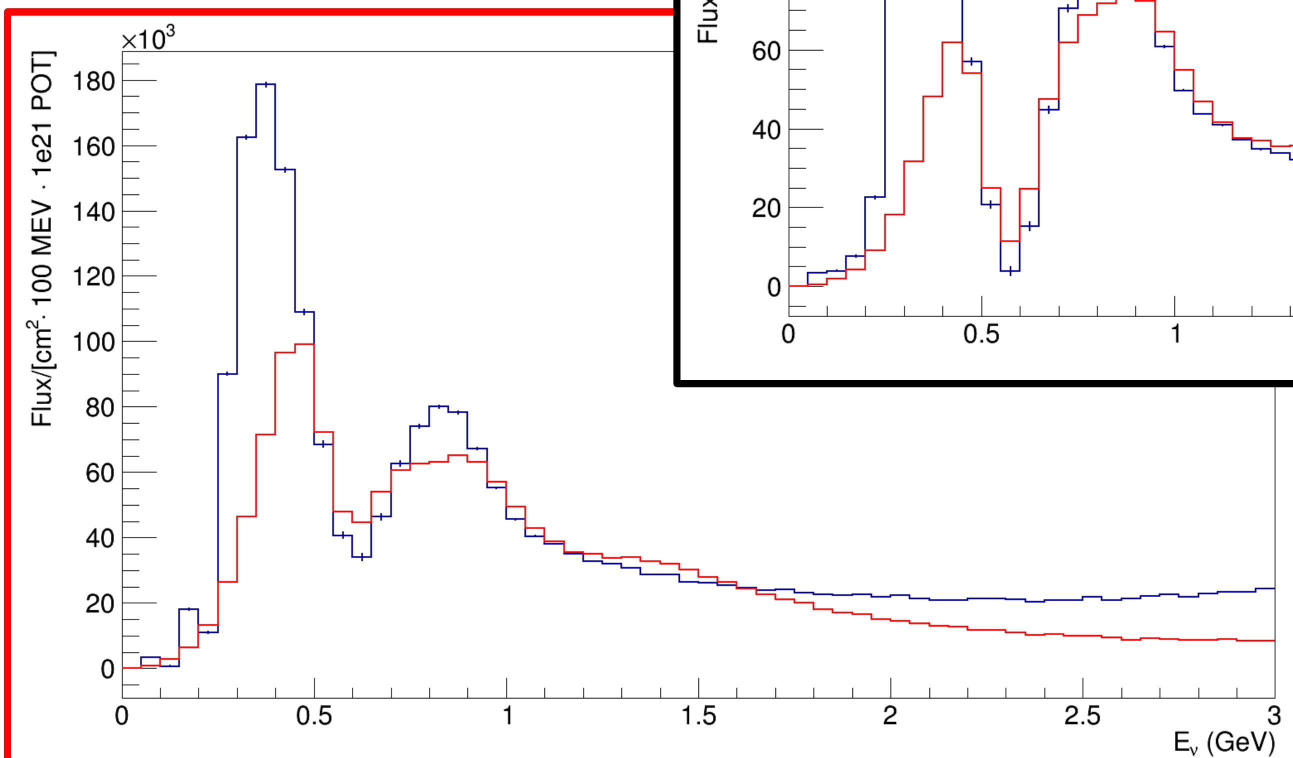
- All based on simulated neutrino flux at SK and νPRISM
- Slice νPRISM into 30 slices of 0.1 degree – assign each a weight
- MINUIT χ^2 fit between sum of weighted νPRISM slices and oscillated SK flux

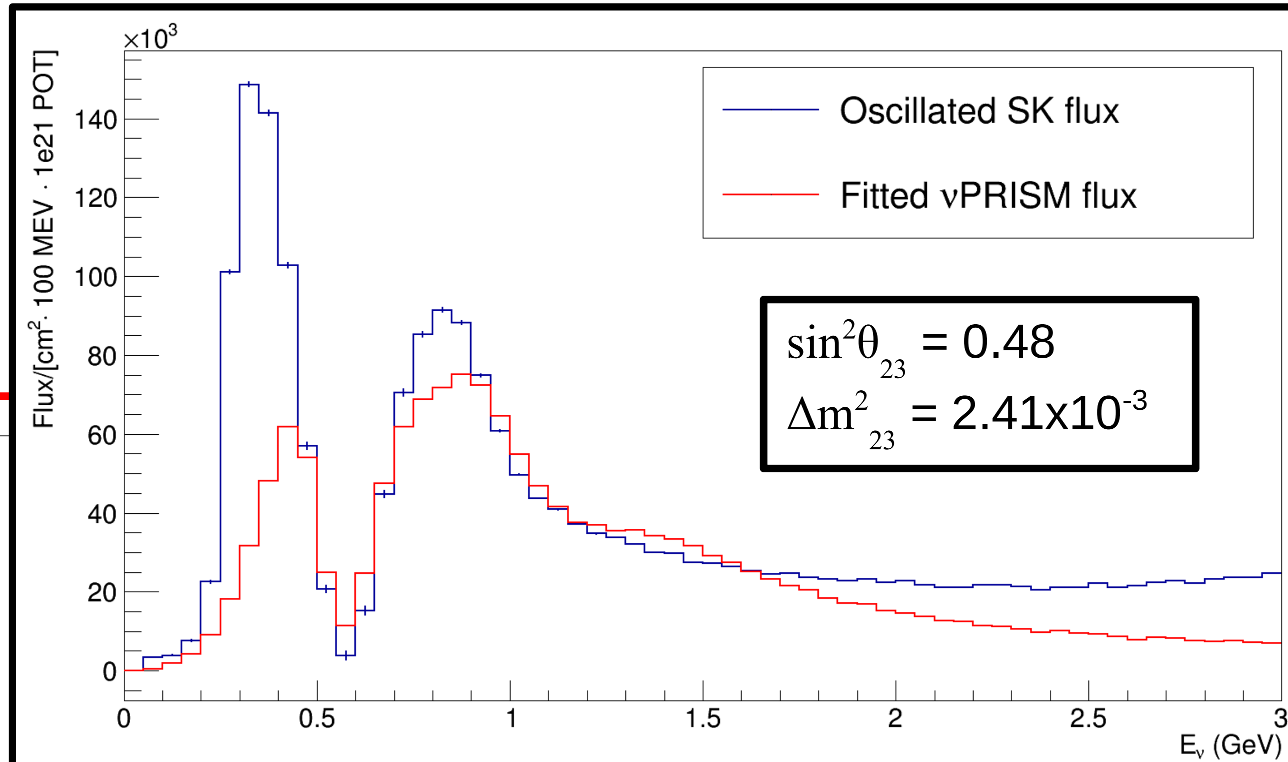


Building the oscillated flux

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

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

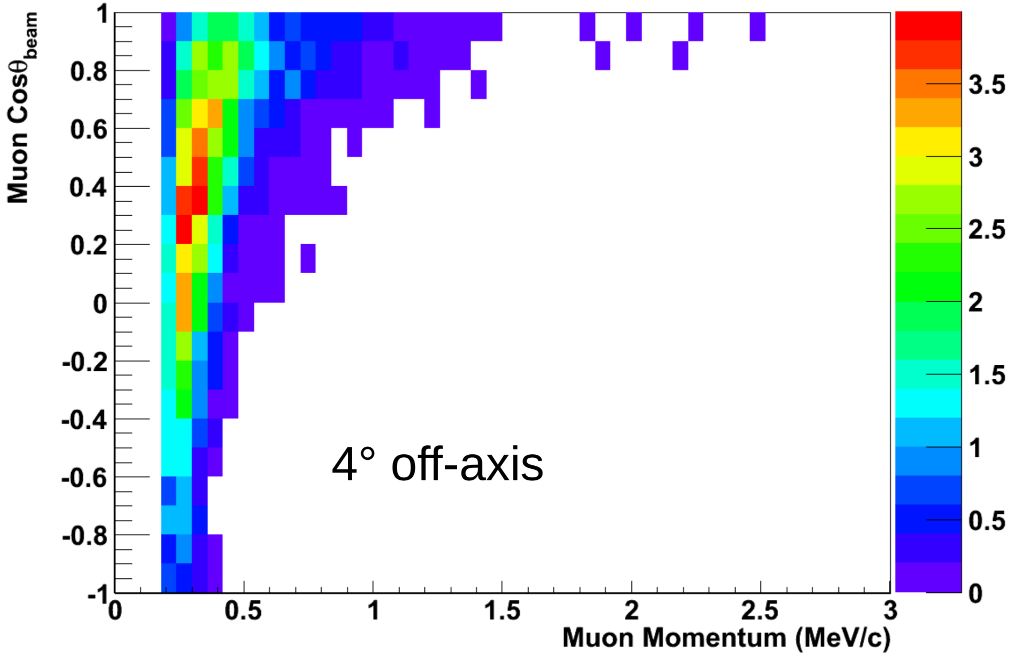


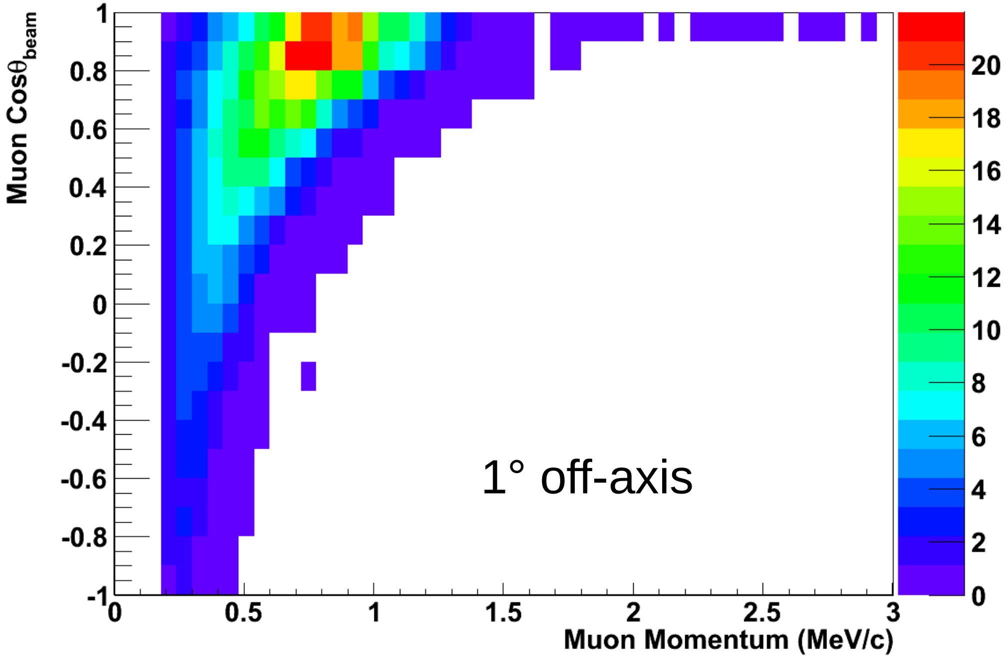


- Get a set of 30 C_i coefficients for each pair of oscillation parameters

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

Calculating SK prediction

- Calculate predicted spectrum at SK:

$$N^{pred}(E_{rec}) = \sum_i C_i \left(N_i^{Obs} - B_i^{MC} \right) \times \left(\frac{\epsilon_{E_{rec}}^{SK}}{\epsilon_{E_{rec}}^{nuPRISM}} \right) + B_{SK}^{MC}$$

where subscript *i* runs over the slices in off-axis angle, C_i are the flux fit coefficients, N_i is the selected event distribution, B_i is selected νPRISM background and B_{SK} is selected background at SK

- Select events at νPRISM in each off-axis slice
- Subtract background using MC prediction
- Multiply by flux fit coefficients and integrate over off-axis angles
- Correct for efficiency differences at νPRISM and SK
- Add selected background events at SK, again using MC prediction

Calculating SK prediction

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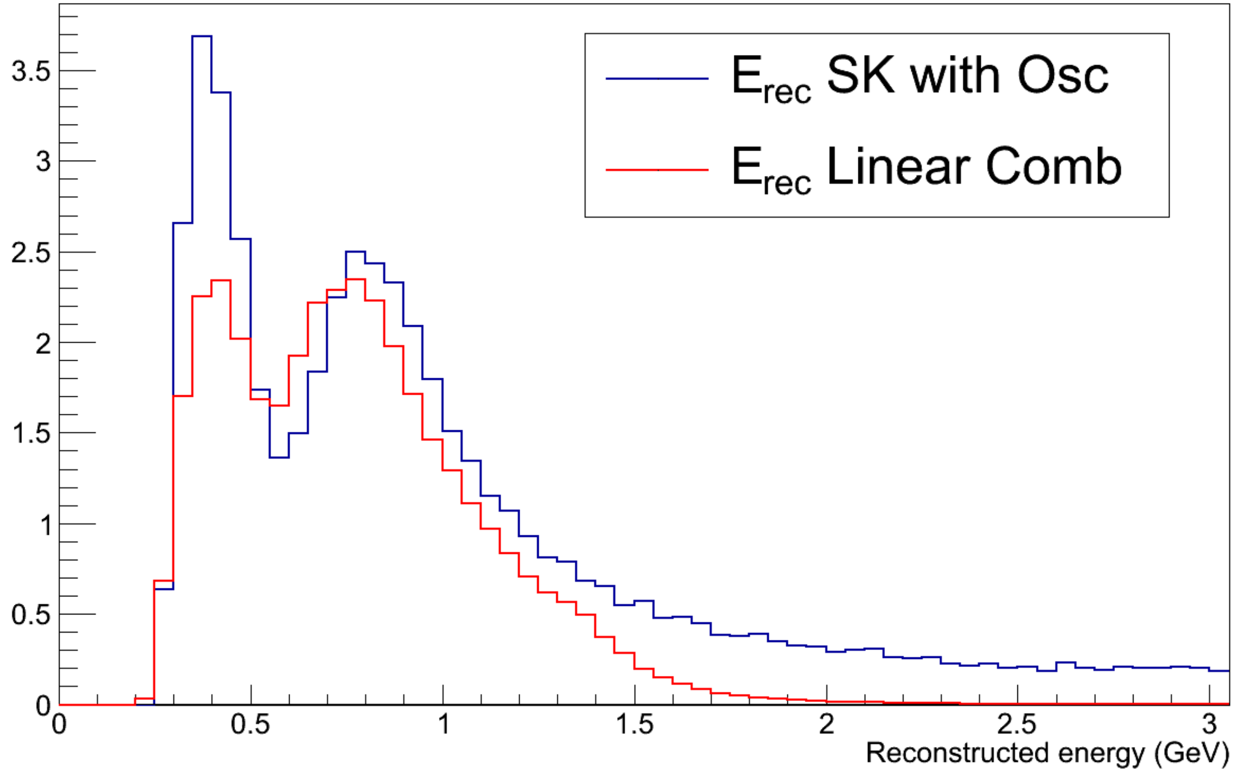
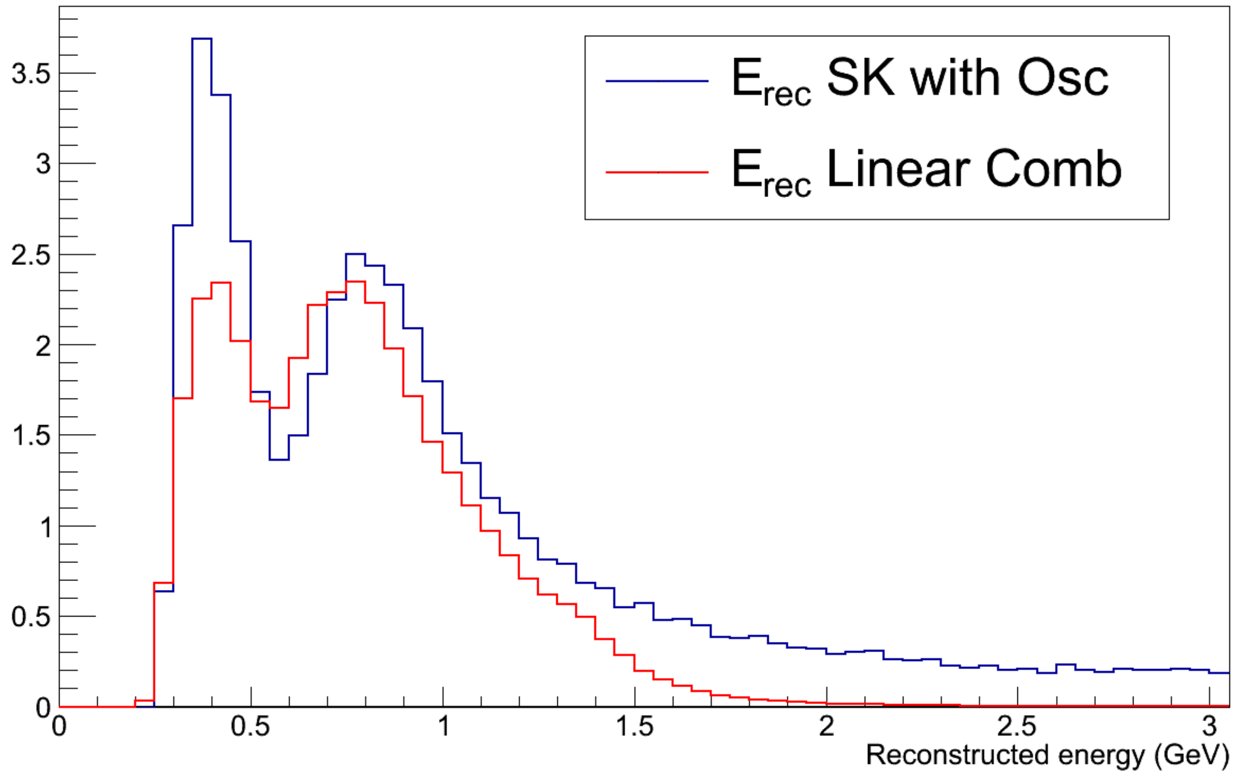


Final step



- 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

Systematic uncertainties

- This analysis takes flux and cross section uncertainties into account
  - Conservative detector systematics coming soon!
- Flux uncertainties calculated in same ways as for T2K oscillation analyses, but evaluated at νPRISM
- Cross section uncertainties should cancel between νPRISM and SK
  - Level of cancellation depends on how well we re-produce the oscillated SK neutrino flux
  - Flux uncertainties therefore affect the cross section uncertainties
  - 2nd order effects must be accounted for
- Perform Gaussian throws of both flux and cross section uncertainties and apply both at the same time

Flux uncertainty

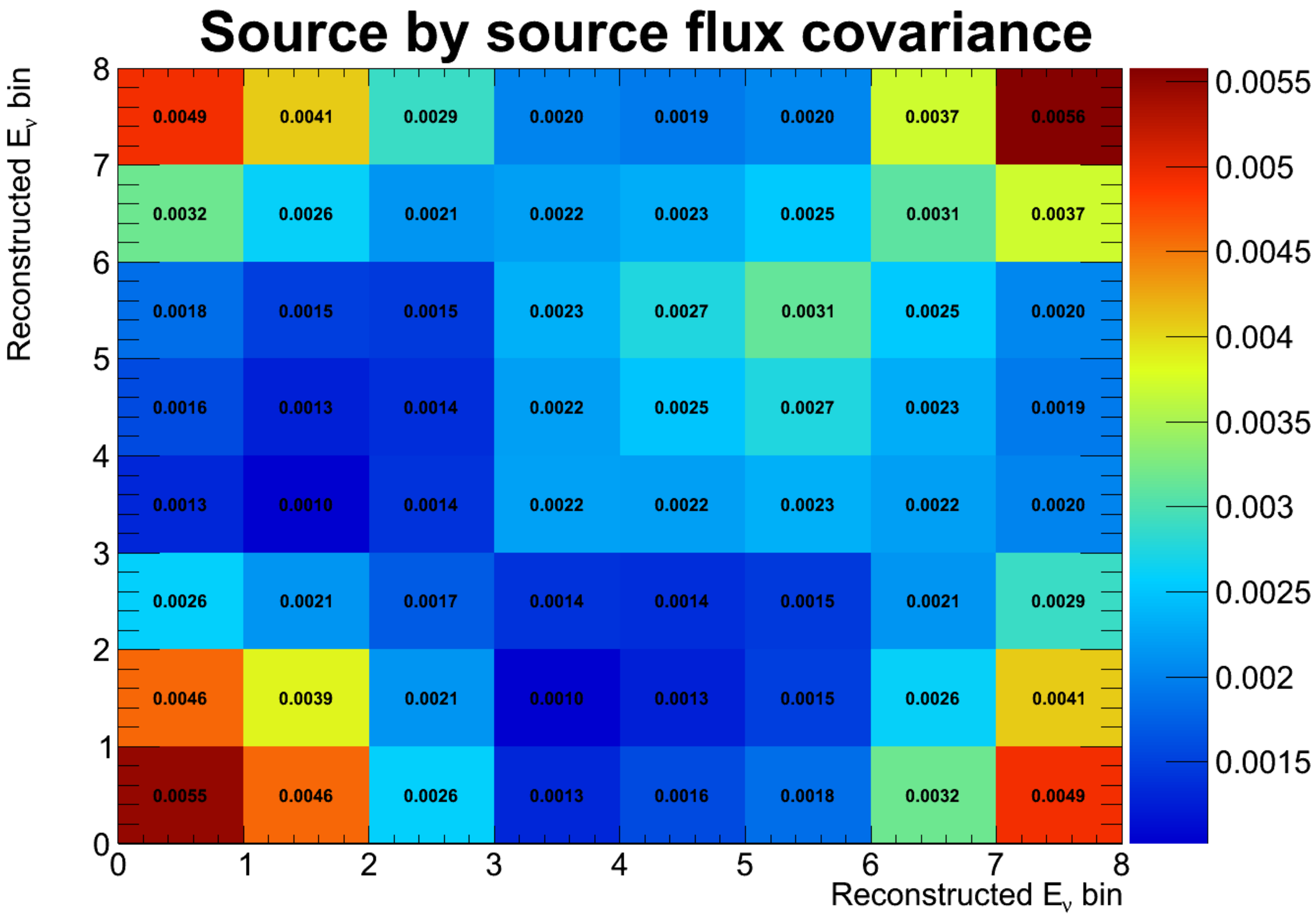
- Flux uncertainties come from 26 sources
  - Proton beam alignment
  - Hadron production
  - Etc.
  - Expect to be independent of one another

- 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

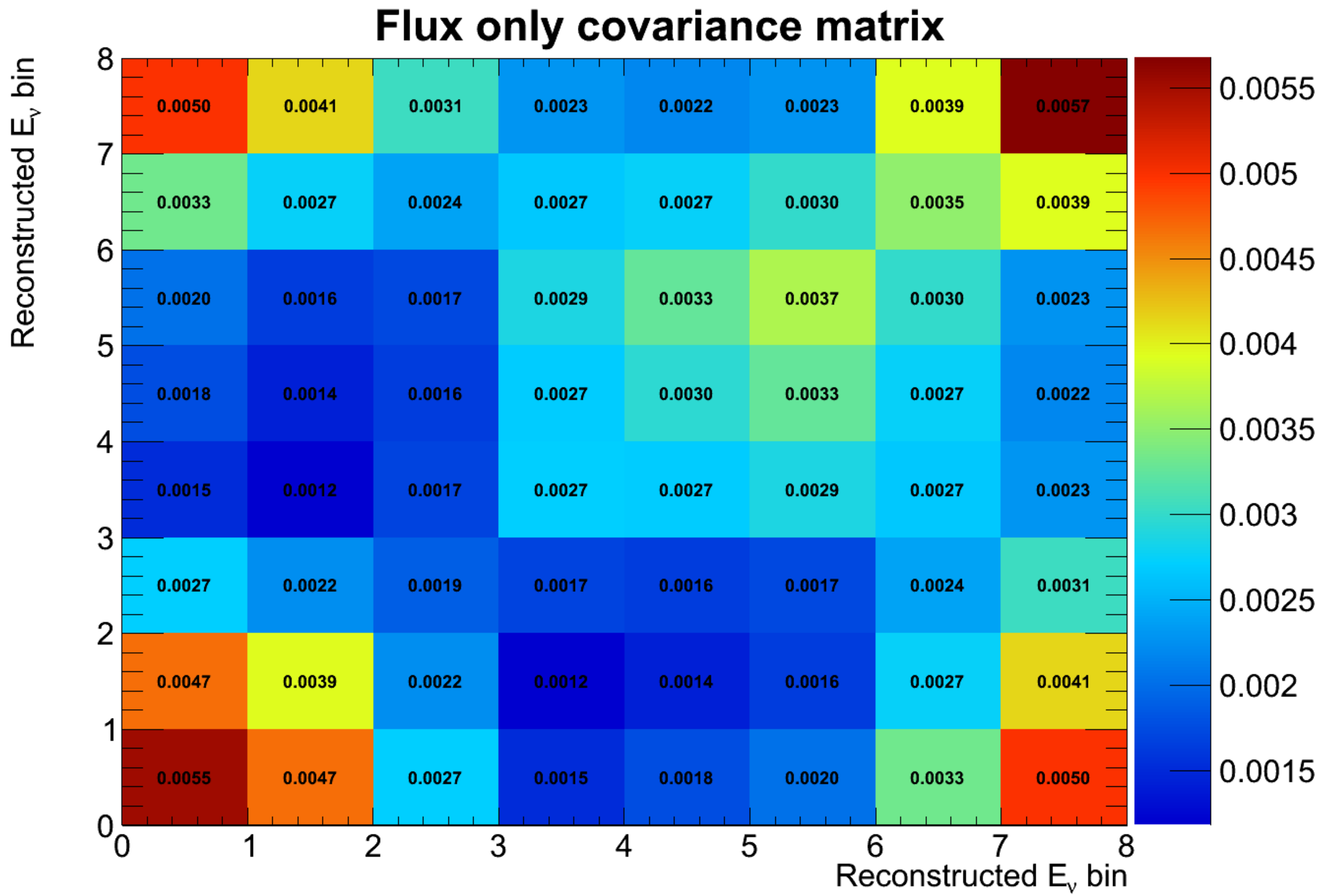
Separate sources

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



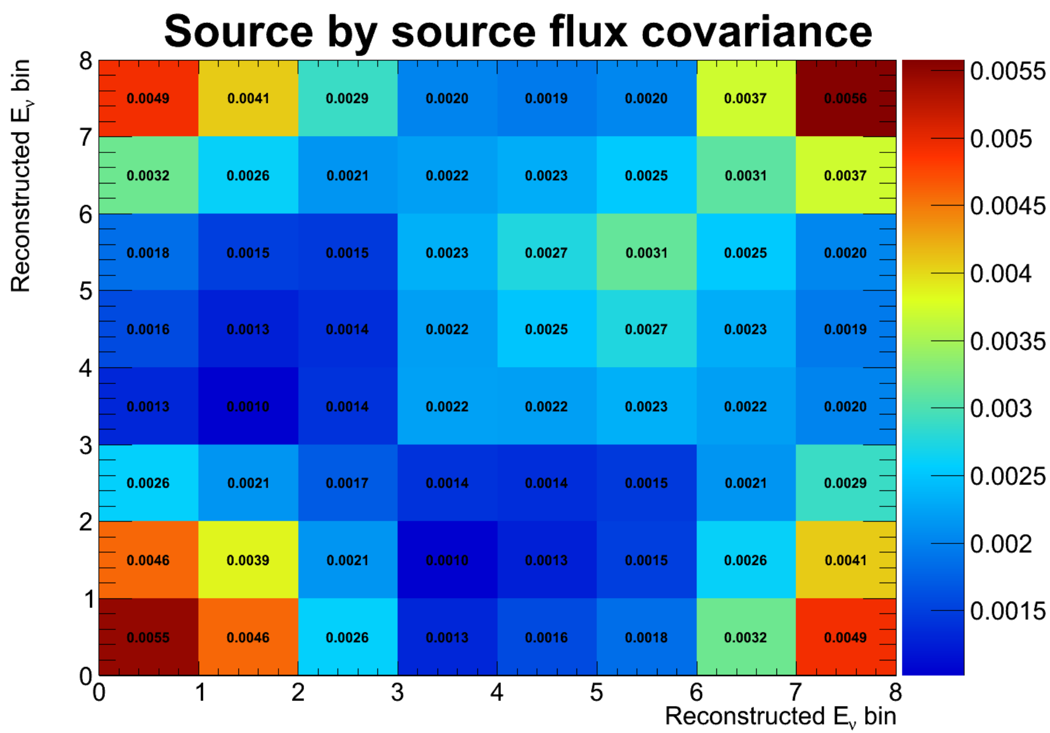
Simultaneous variation

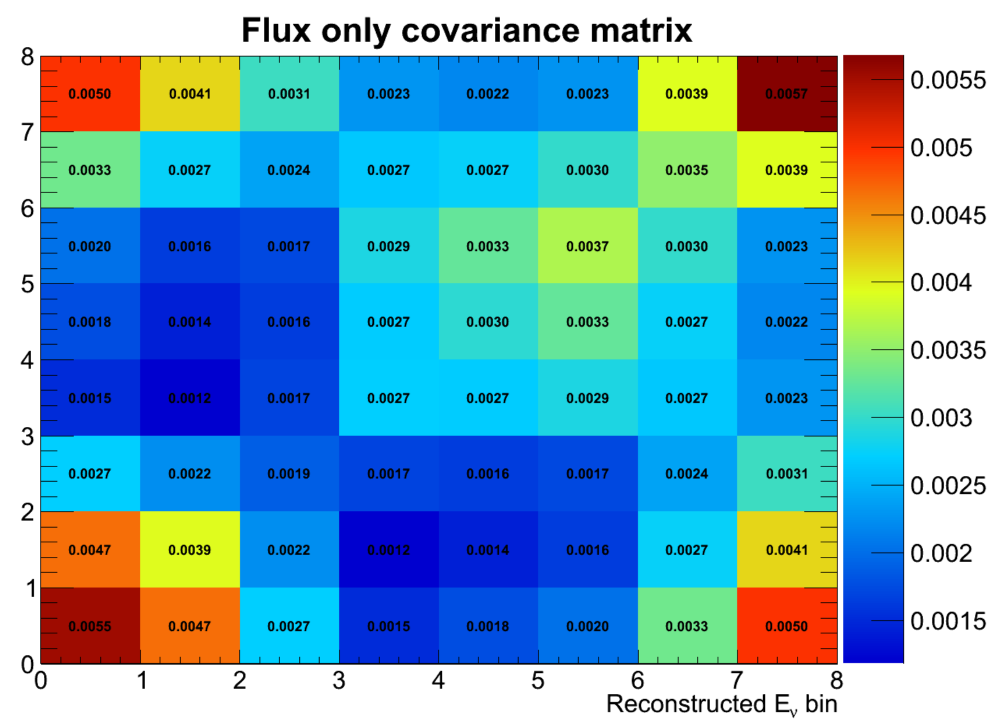
- Larger errors at high and low energy – no νPRISM events
- Error at oscillation dip (bin 3) around 5%



Comparing flux uncertainty

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

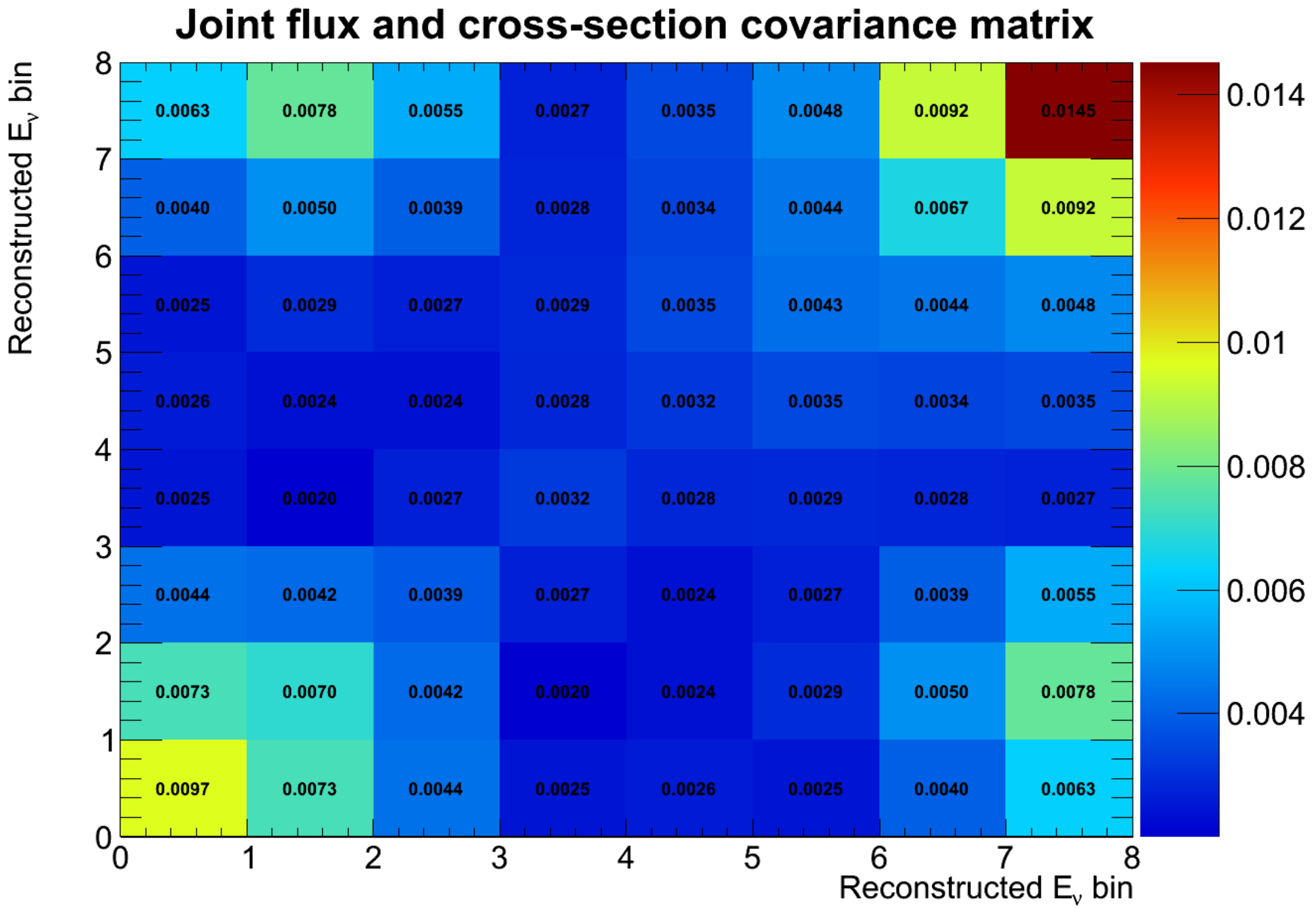




- Very good agreement between the two methods
- Confident flux uncertainties are being applied correctly

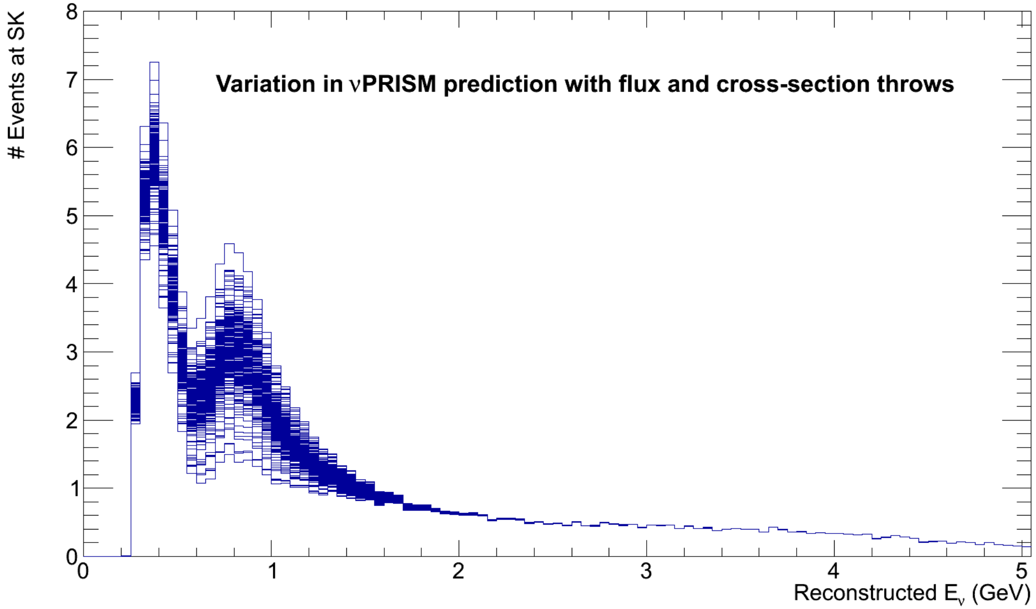
Flux and cross section

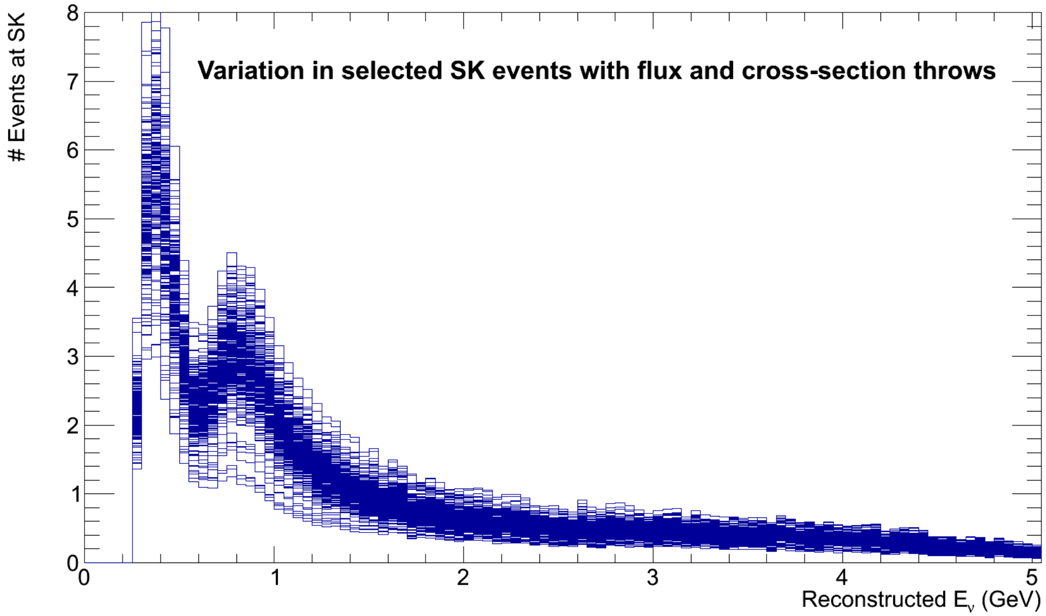
- When varying flux and cross section simultaneously the uncertainty in bin 3 (600 – 700 MeV) is 5.7%



Systematic throws

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



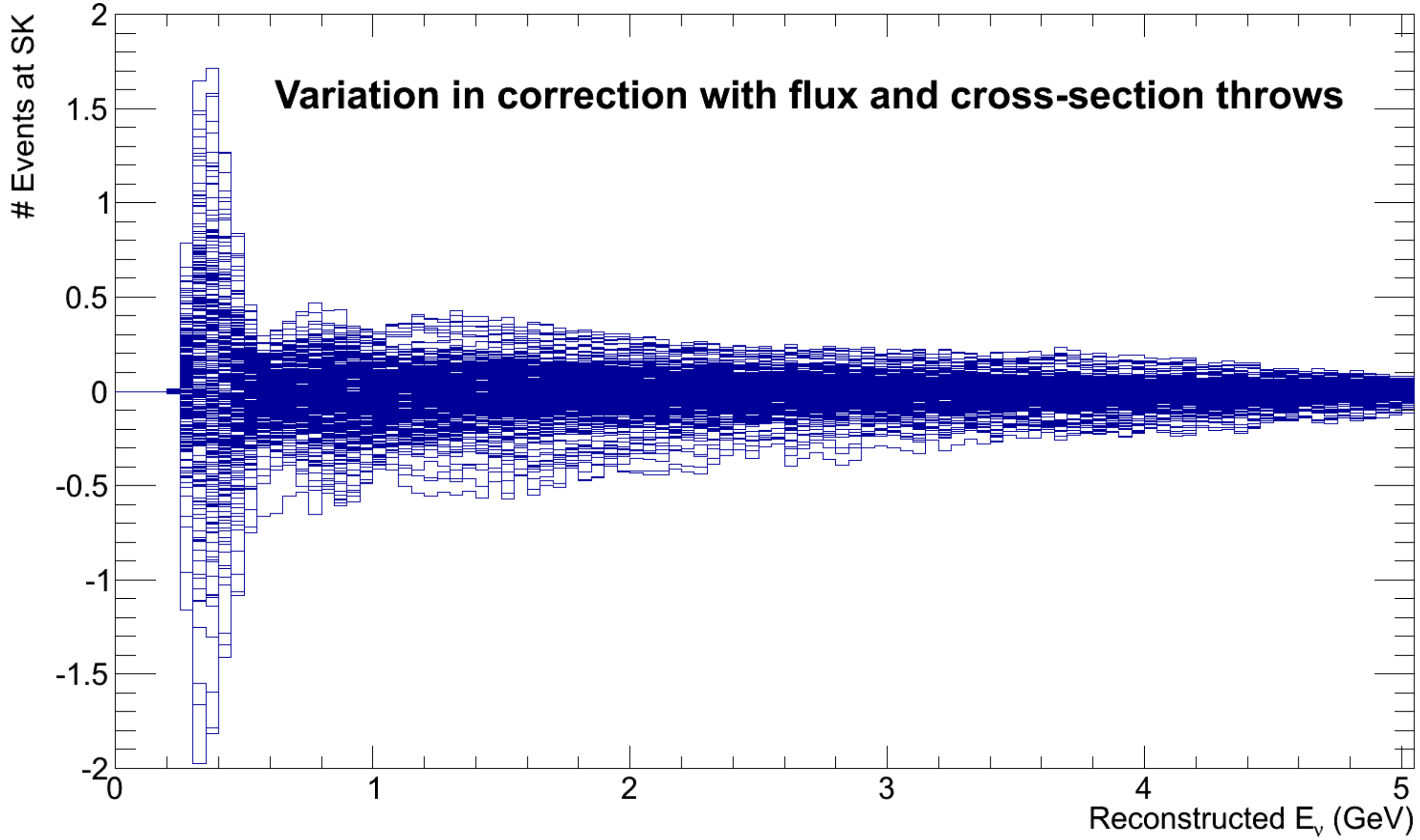


- Plots show all 300 throws of the νPRISM prediction (left) and selected SK events (right)

- 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

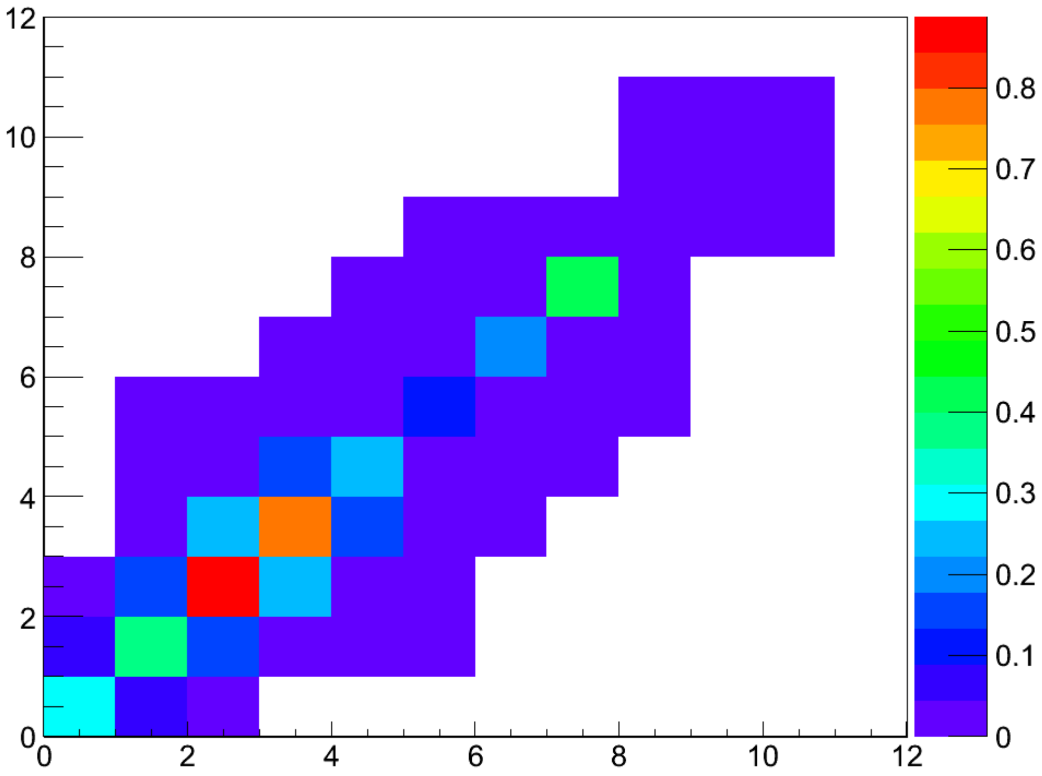


- Most of spectrum shows less than 0.5 event difference between SK and νPRISM prediction
- Systematic uncertainties are cancelling between the two detectors

Statistical uncertainties

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

  \- almost 100% uncertainty



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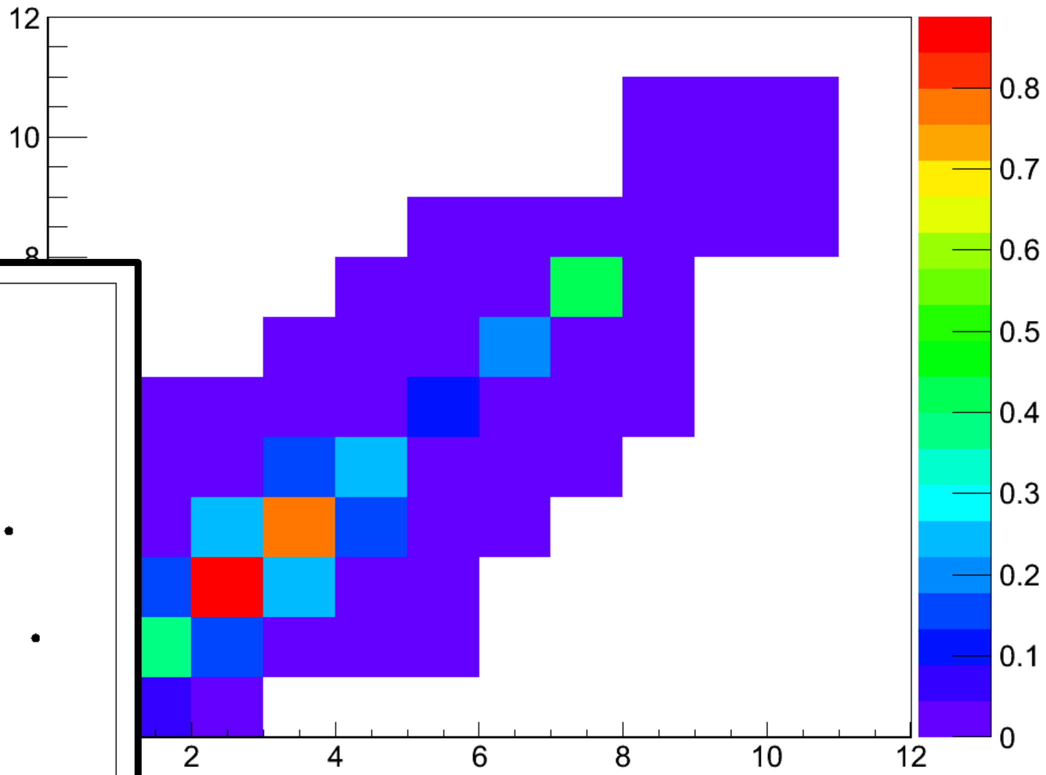
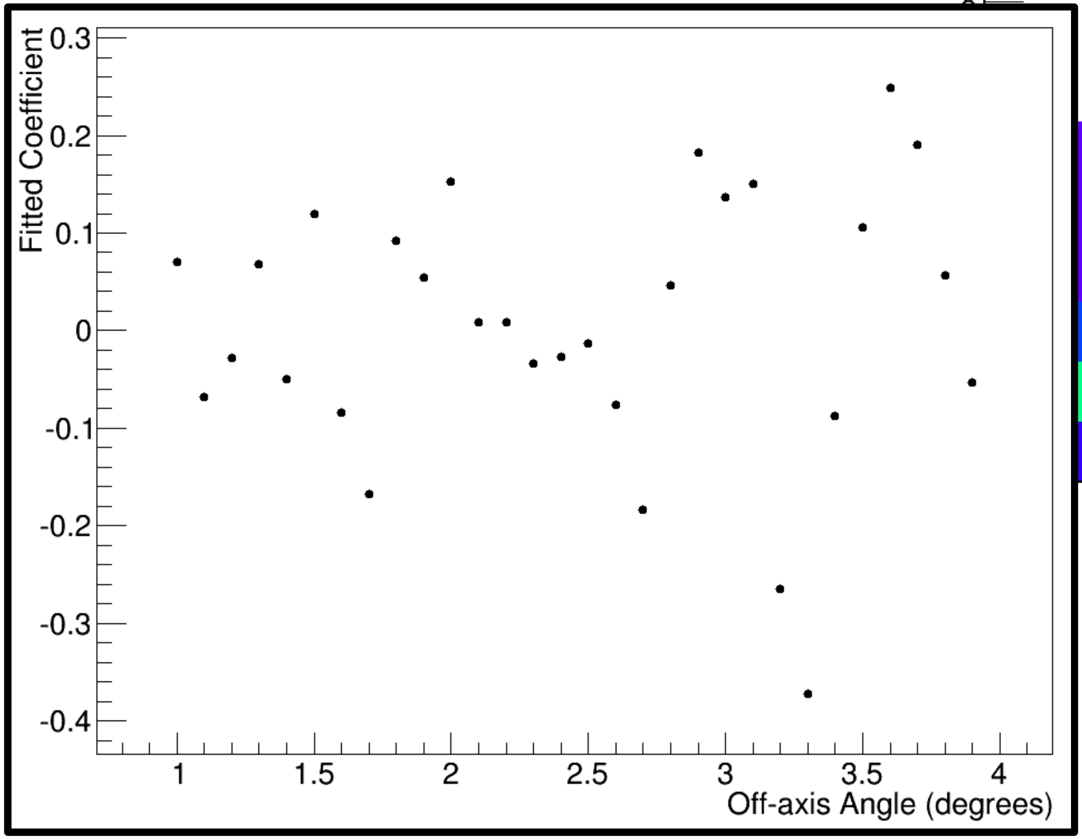
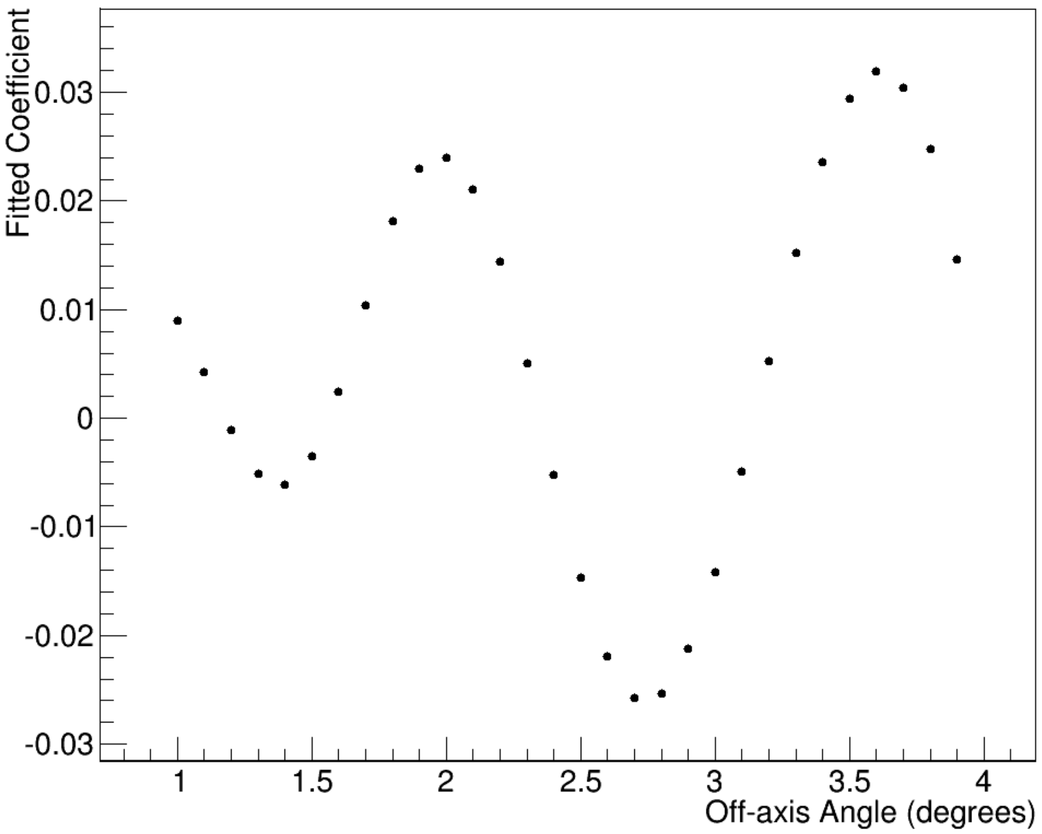




- Fit coefficients:
  - Rapidly varying
  - Relatively large

Statistical uncertainties

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



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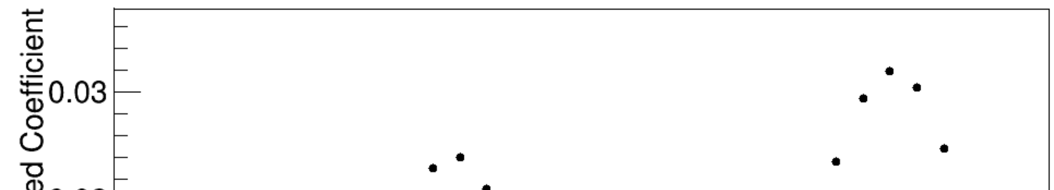
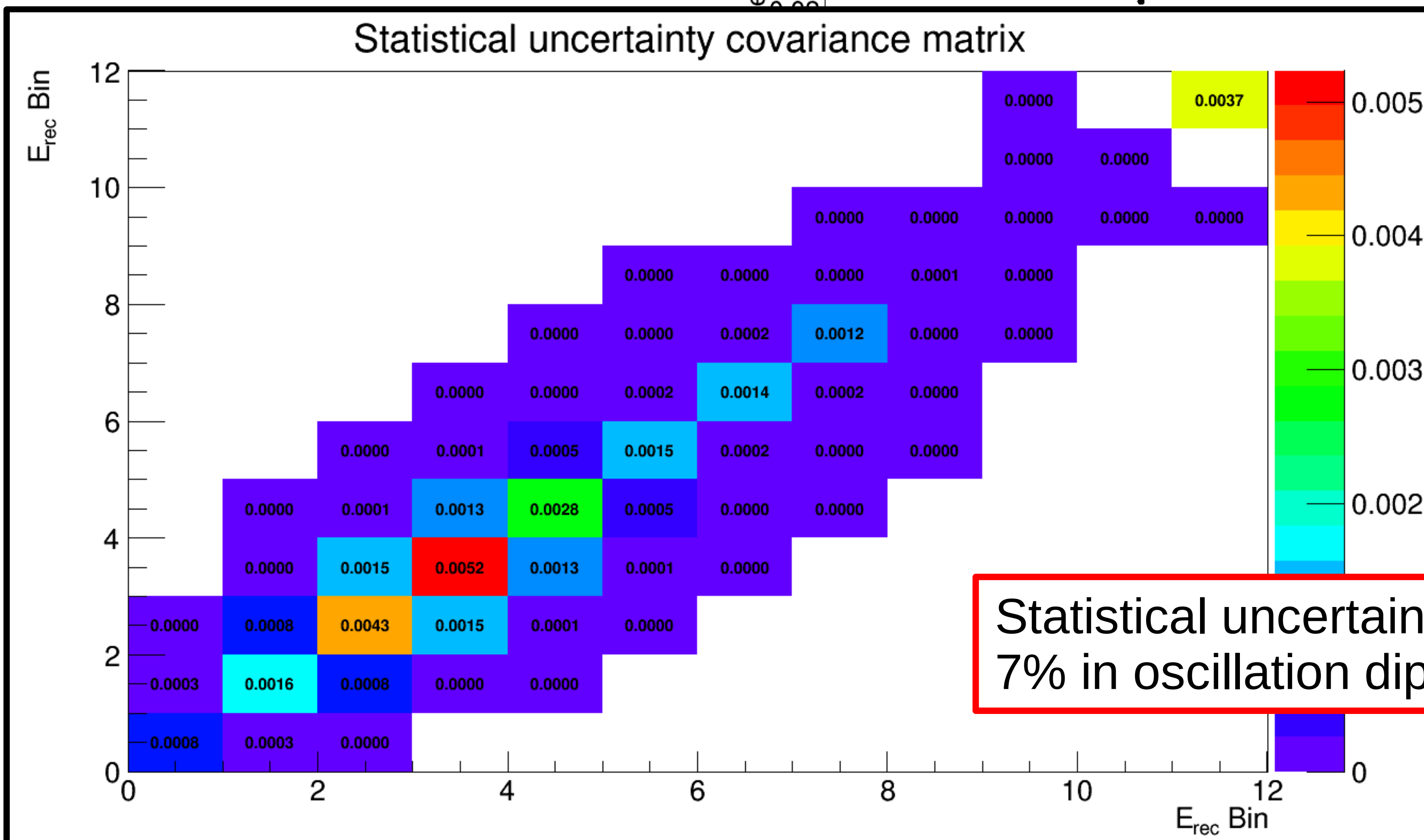


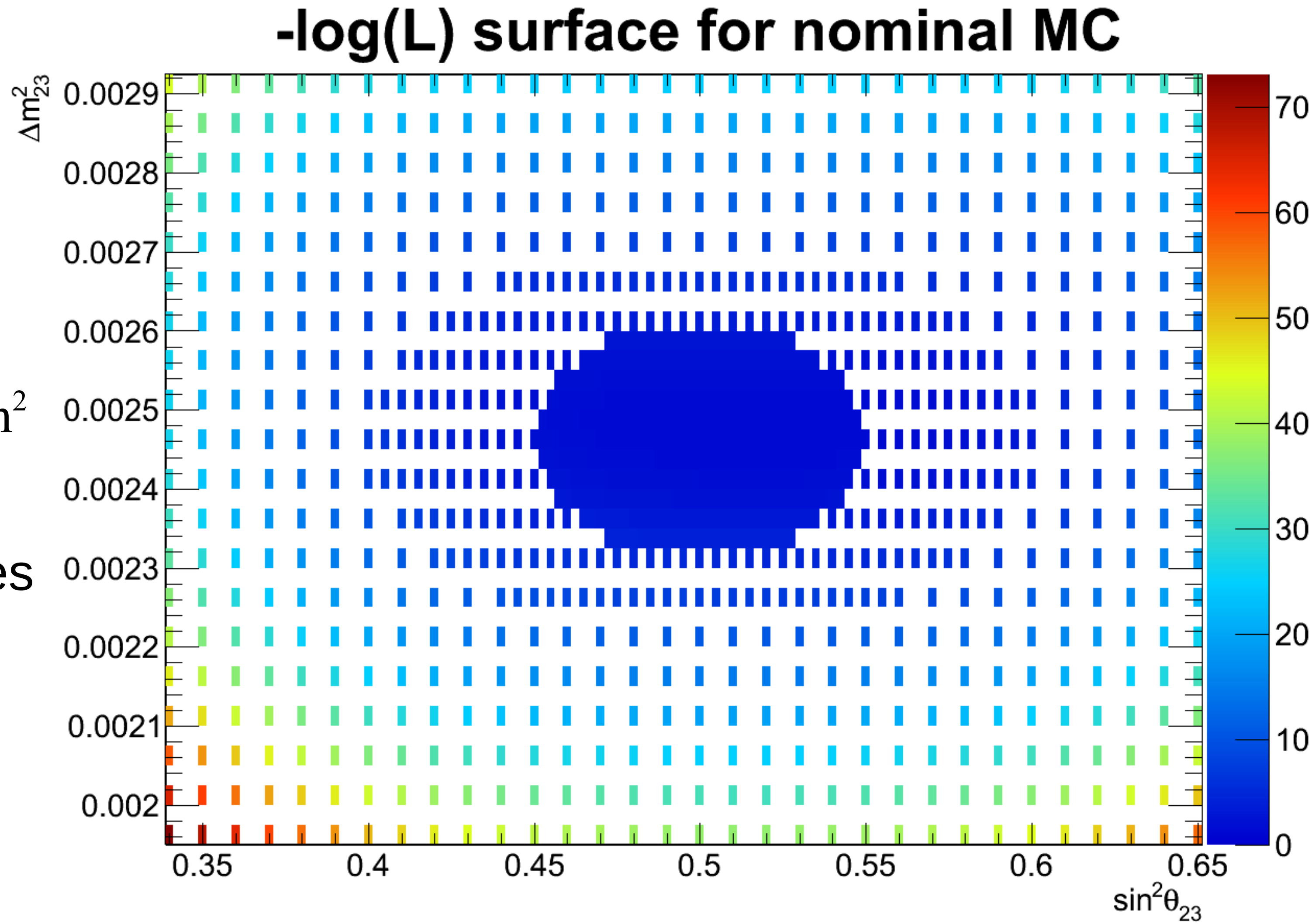


Statistical uncertainty around 7% in oscillation dip

Oscillation fit

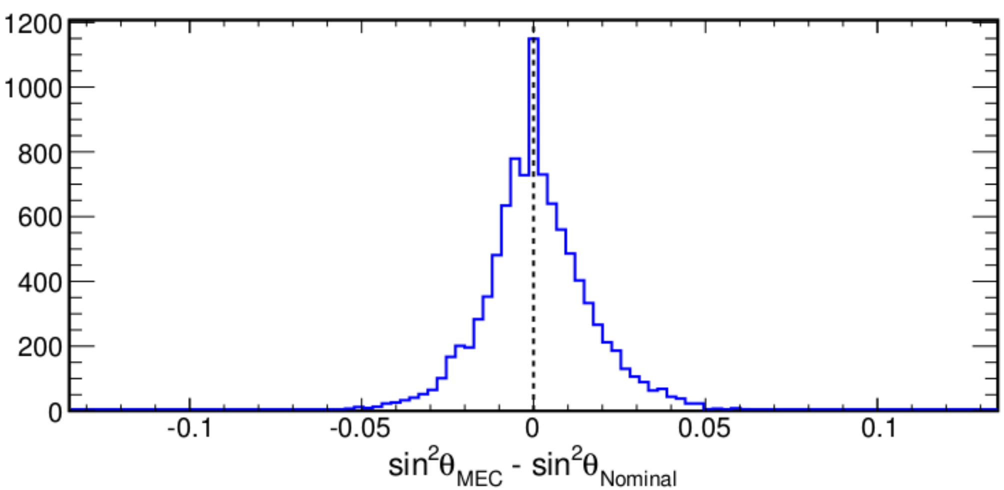
- Throw 300 SK and νPRISM fake data sets – flux + cross section
- Calculate covariance matrix and νPRISM prediction for points in θ_{23} and Δm^2 phase space

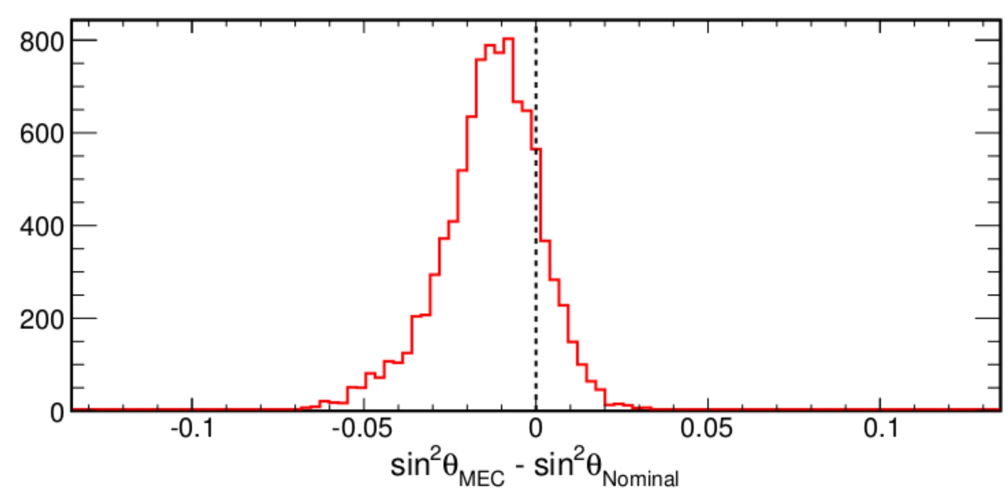
- Use the Simple Fitter framework to calculate likelihood -ln(L)
- Plot -ln(L) for all points in θ_{23} and Δm^2 phase space
- Minimum point gives best fit oscillation parameters



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

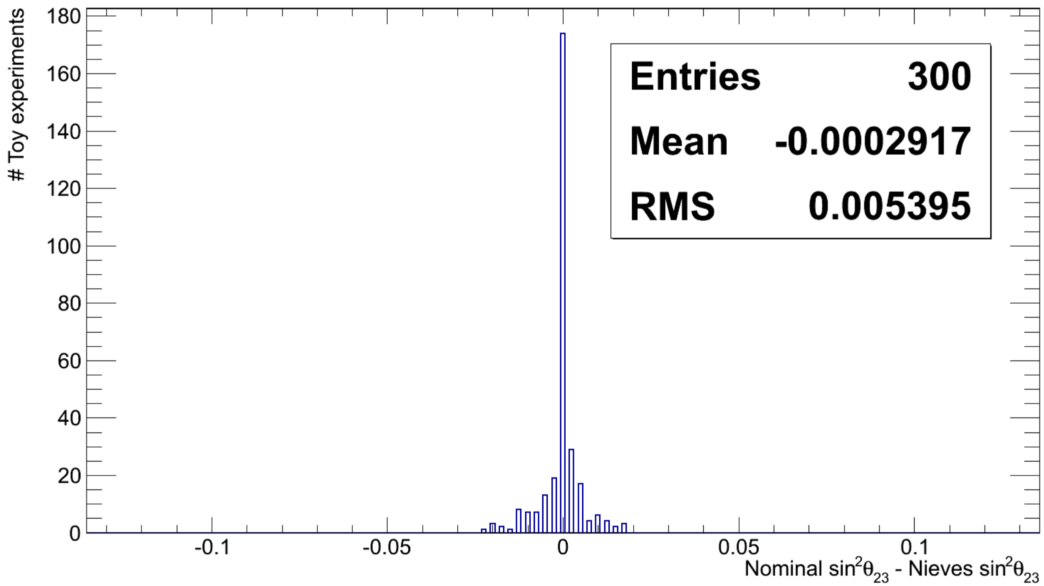


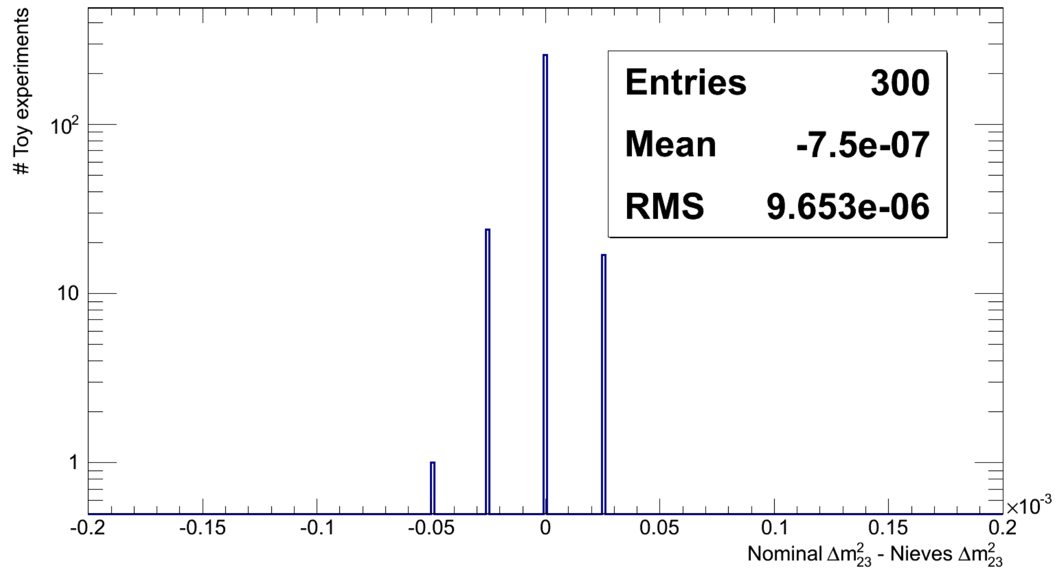


- Plots above show the result of the same analysis performed by T2K
- Using Nieves' MEC prediction on left, Martini on right
- Both show ~3.5% spread, with a bias in the Martini case

νPRISM Nieves' result

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

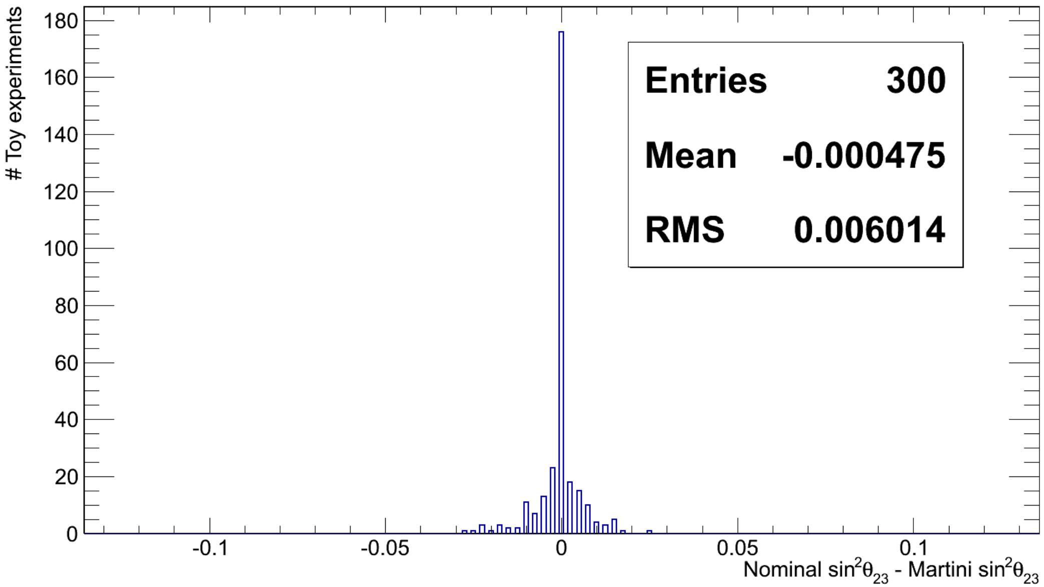


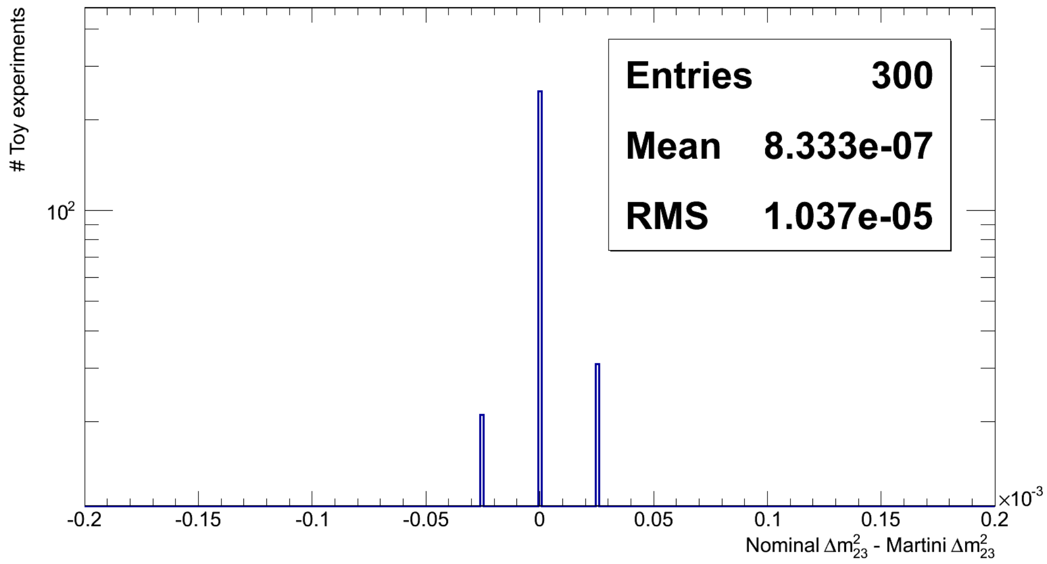


- Much smaller RMS in θ_{23} (left) and Δm^2 (right) than in T2K analysis
- Large spike at 0 difference in both plots

νPRISM Martini result

- Now look at adding Martini MEC events





- Again, much smaller RMS in θ_{23} (left) and Δm^2 (right) than in T2K analysis
- No bias seen in θ_{23} plot

Summary

- Unknown nuclear effects can create biases when measuring oscillation parameters
- νPRISM will provide the first data driven constraint on the effect these unknowns will have on oscillation parameter measurements
- νPRISM should also reduce the effect of all cross section uncertainties on neutrino oscillation results