νPRISM: Disappearance Analysis

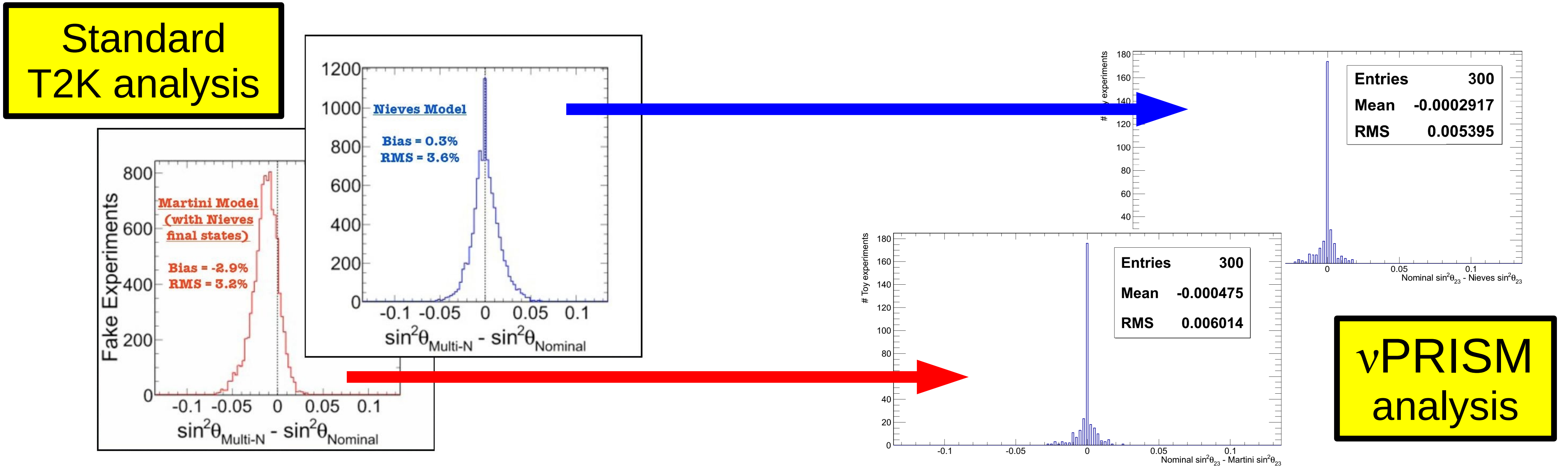
Mark Scott for the νPRISM collaboration

6th open Hyper-K meeting

1st Feb 2015 - IPMU

ν_μ disappearance analysis status

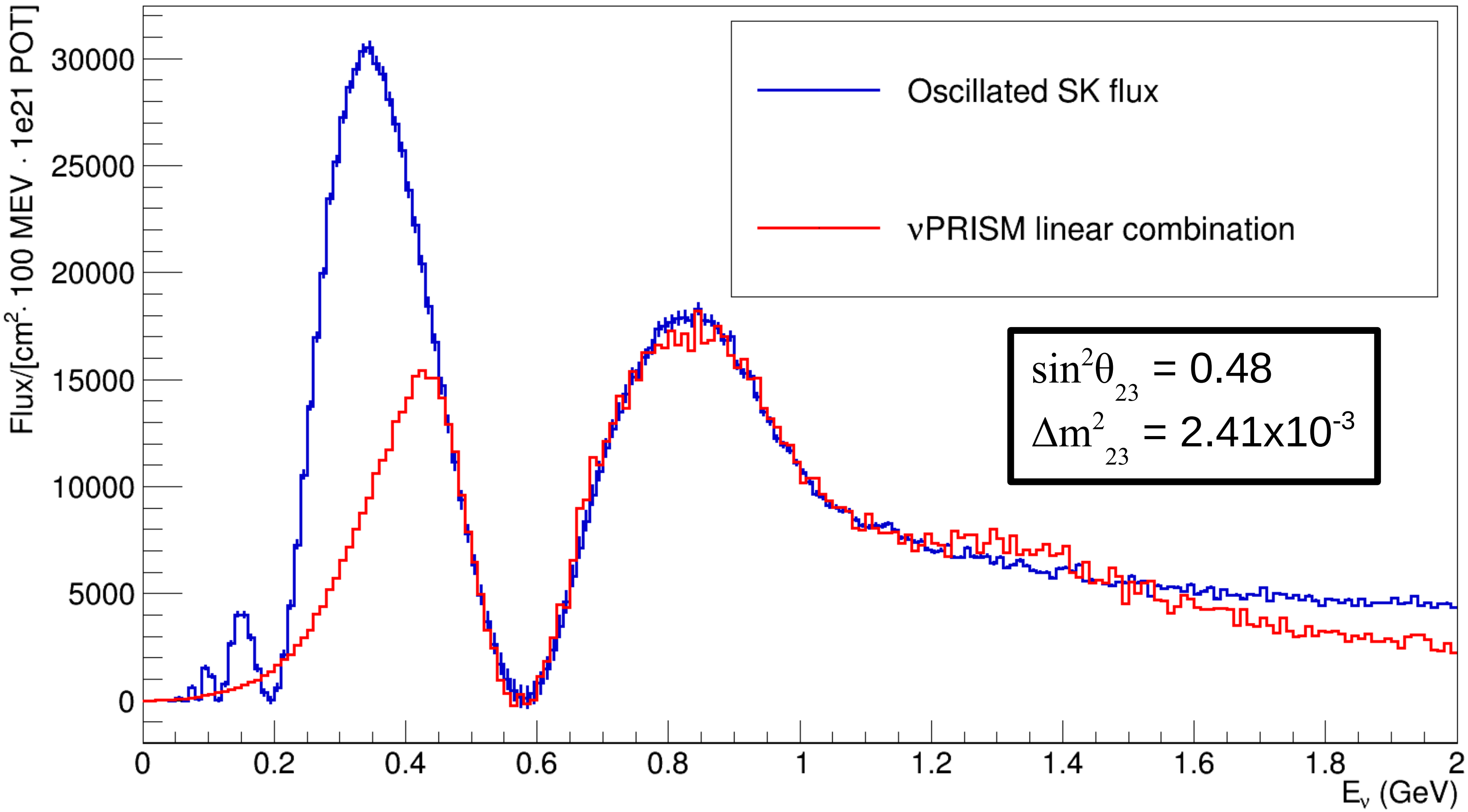
- At 5th HK meeting - νPRISM disappearance analysis unaffected by unknown nuclear model
- Incomplete MC model did not change the fitted oscillation parameters



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

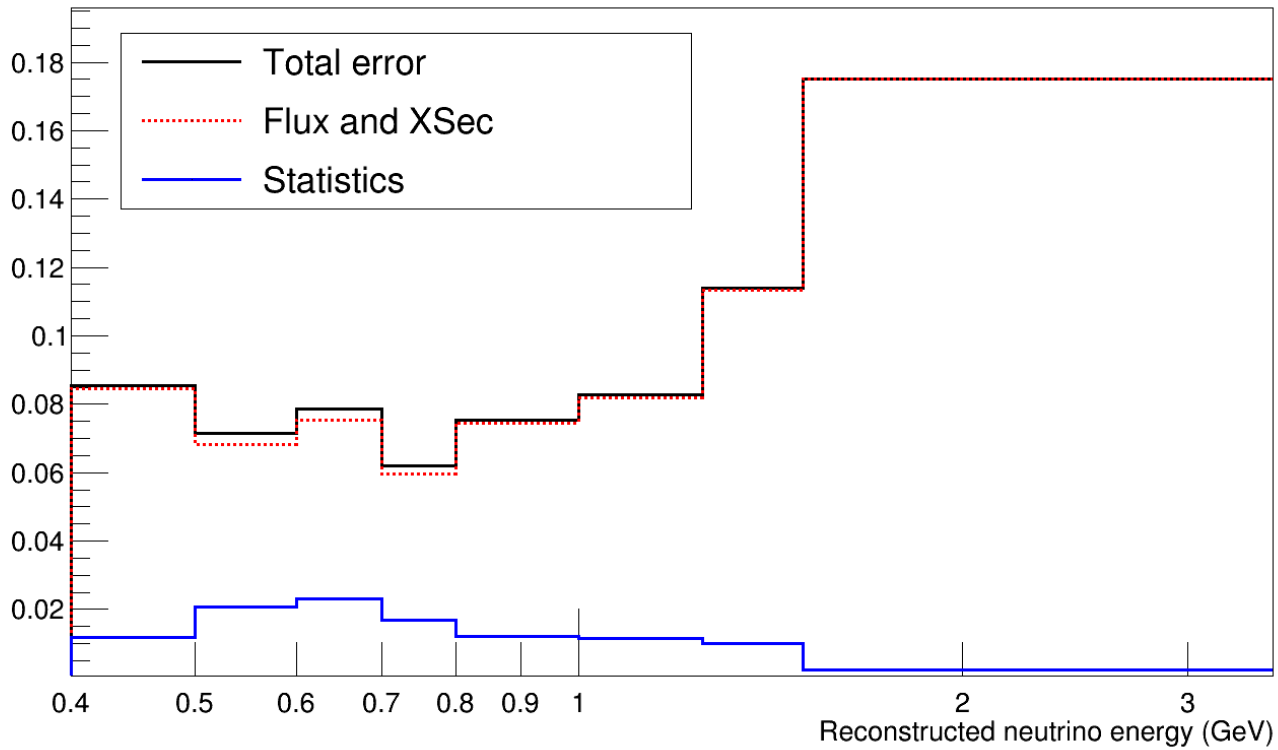
What can we do with this?

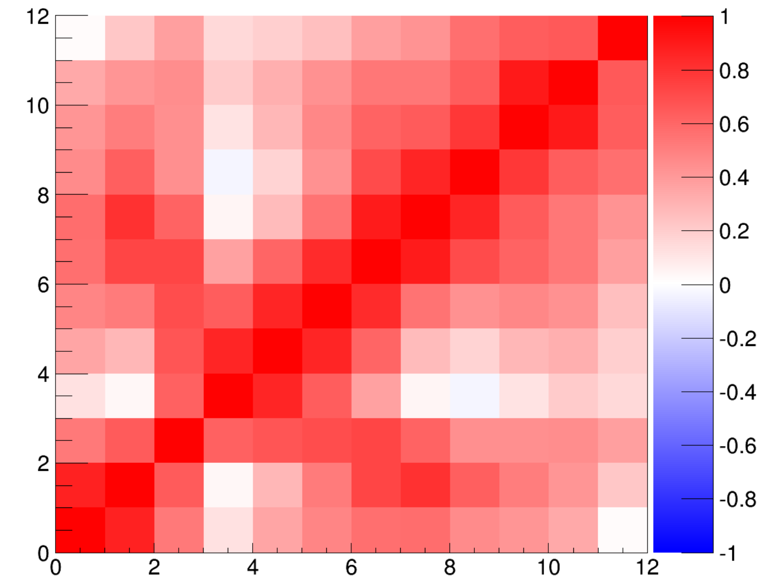
- Make better flux fits!
- Previously, large statistical uncertainty limited how well we could fit the oscillated SK flux
- Now we can do much better while keeping statistical uncertainty small



New uncertainties

- With new flux fit - total uncertainty in oscillation dip < 8%





- Correlation matrix very similar shape to previous analysis
- Statistical uncertainty dropped, but flux uncertainty increased – this was expected (see backup slides)
- Now systematics (which are reducible) dominate

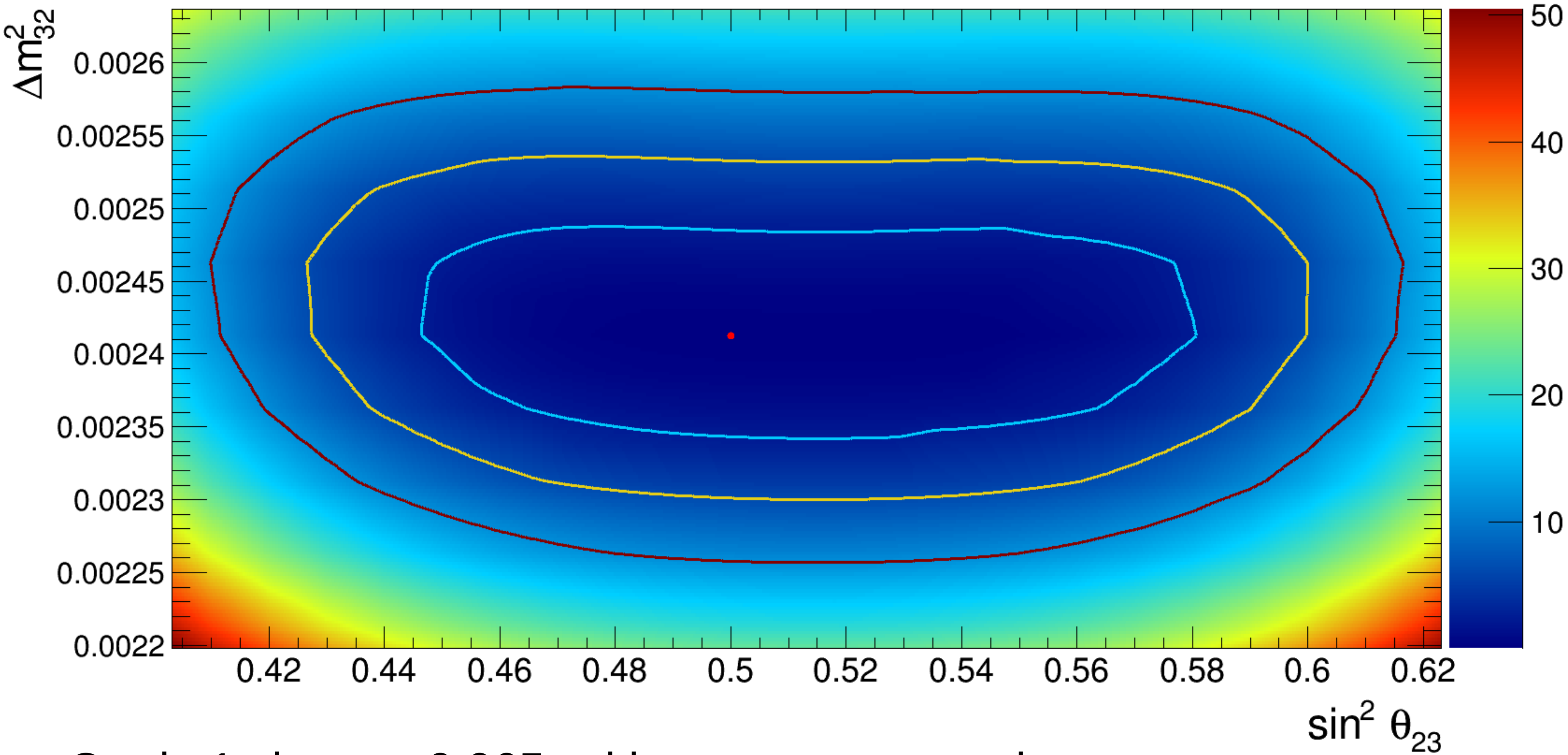
Sensitivity studies

- With new flux fit examine sensitivity to disappearance parameters
- Use same methodology as Future Sensitivities Task Force (FSTF)
- For the Asimov data set (nominal MC) choose dM^2 = 2.41e-3 and sin^2 theta_23 = 0.5 as the 'fake data'
- Perform grid scan over dM^2 and sin^2 theta_23 space, calculating the nuPRISM prediction and covariance matrix at each point
- Calculate the chi-squared value between prediction and the fake data at each point
- Use Delauney interpolation to smooth the delta chi-squared map this creates
- Create 1, 2 and 3 sigma contours

- In all plots there is 2.25e21 POT of nuPRISM neutrino MC
- There are currently no SK uncertainties

Sensitivity studies

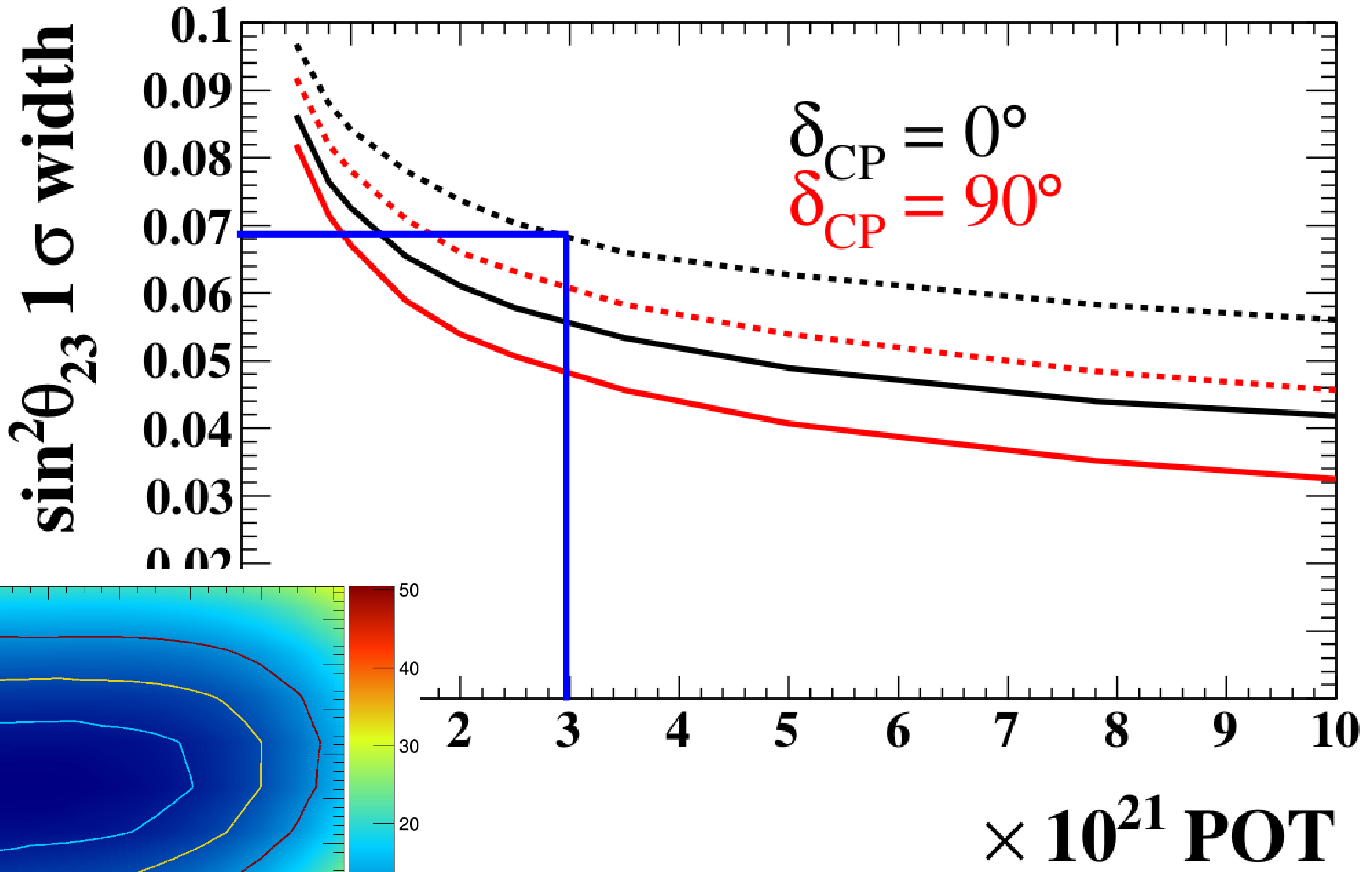
- For 3e21 POT at SK – roughly the expected T2K POT
- Sin^2 Theta_{23} = 0.5, dM^2 = 2.41e-3

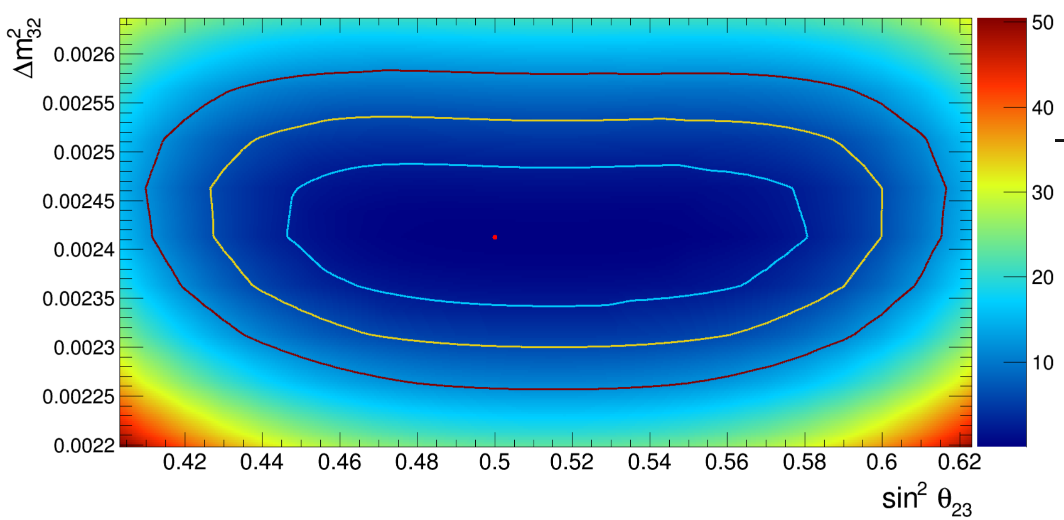


- Crude 1 sigma = 0.065, with current systematics

T2K sensitivity studies

- For 3e21 POT at SK – roughly the expected T2K POT
- Sin^2 Theta_{23} = 0.5, dM^2 = 2.41e-3
- Compare to T2K projection:
  - 1 sigma width = 0.068
  - NuPRISM < T2K

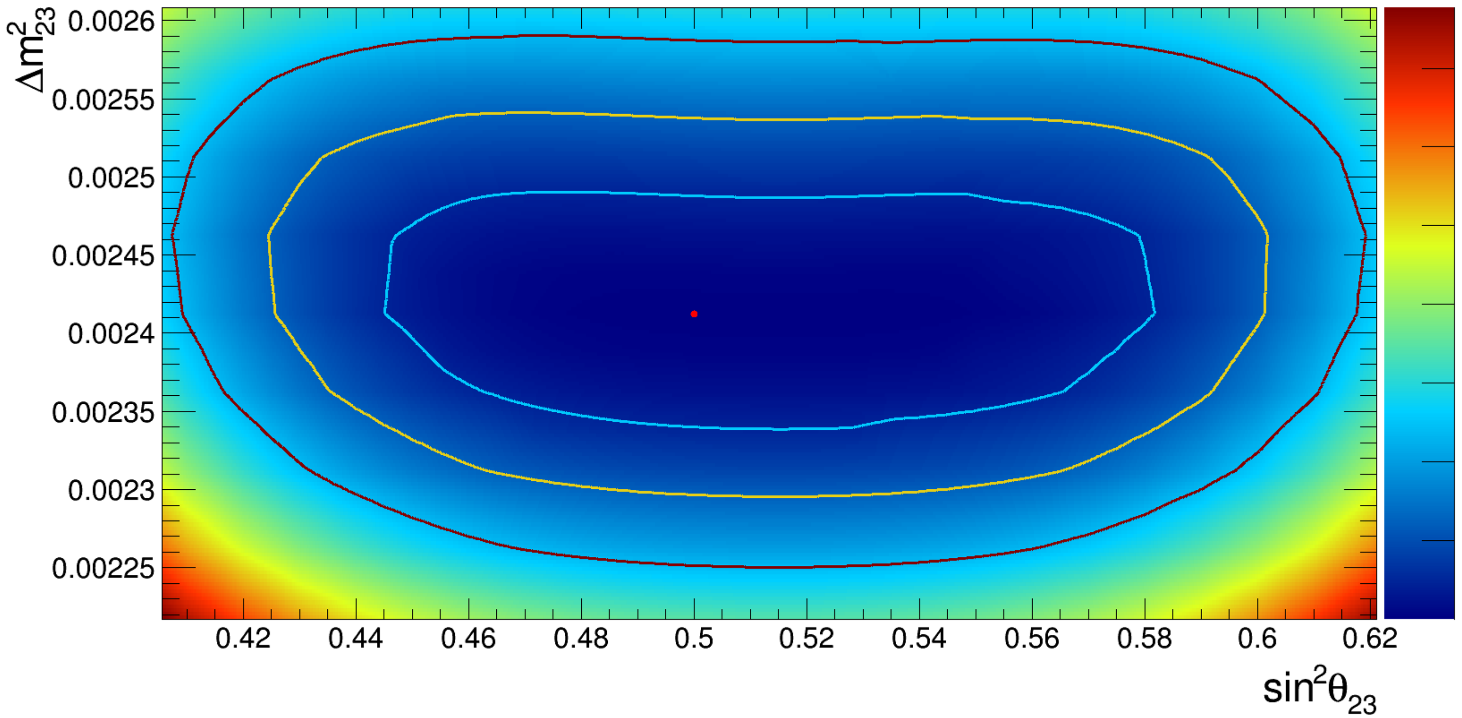




T2K sensitivity studies 2

- Add in a 5% uncorrelated error to mock-up SK detector uncertainty
- Sin^2 Theta_{23} = 0.5, dM^2 = 2.41e-3

- NuPRISM 1 sigma width = 0.0675
- NuPRISM = T2K
- SK detector errors smaller than this?
- Correlations?

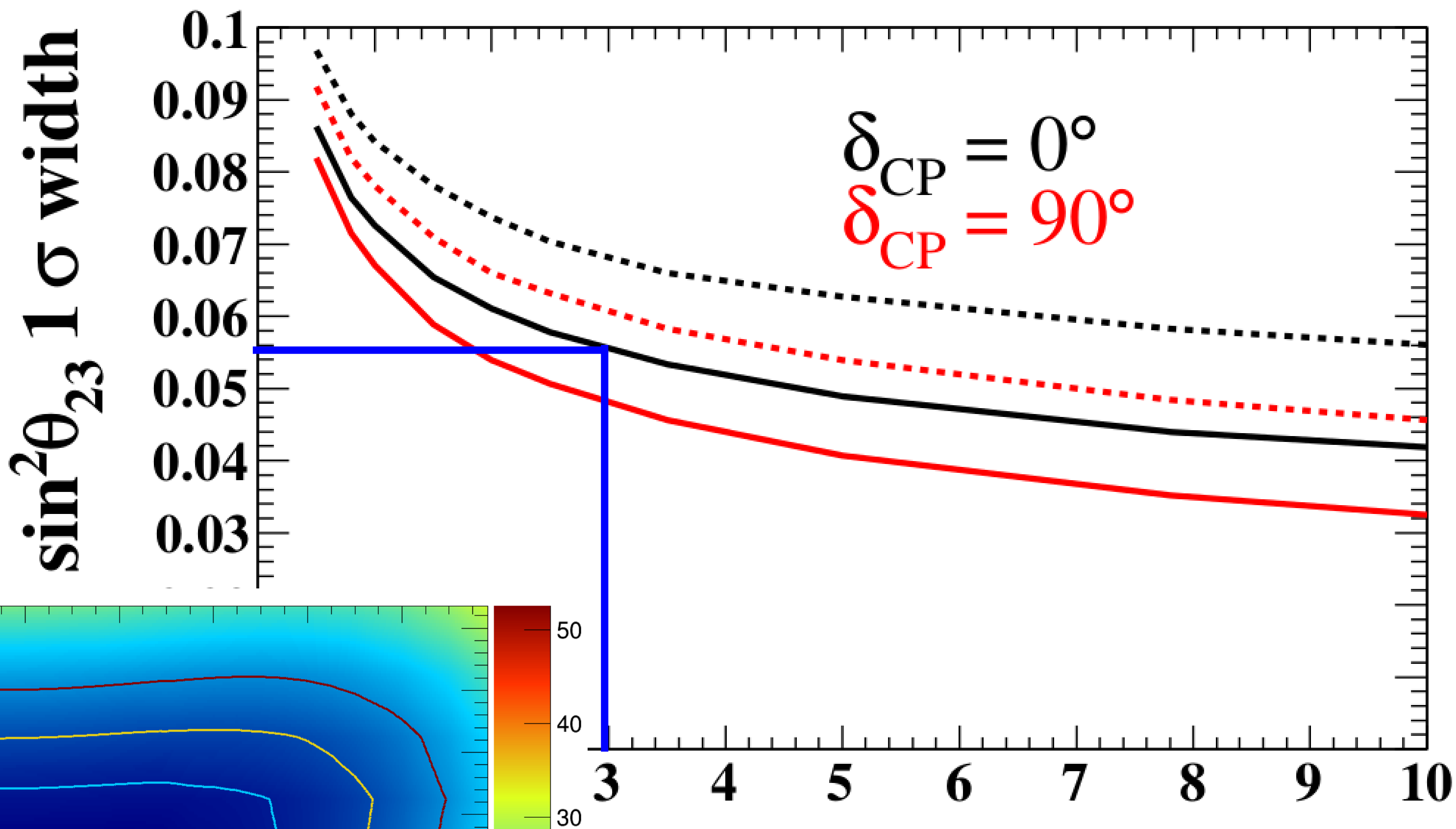


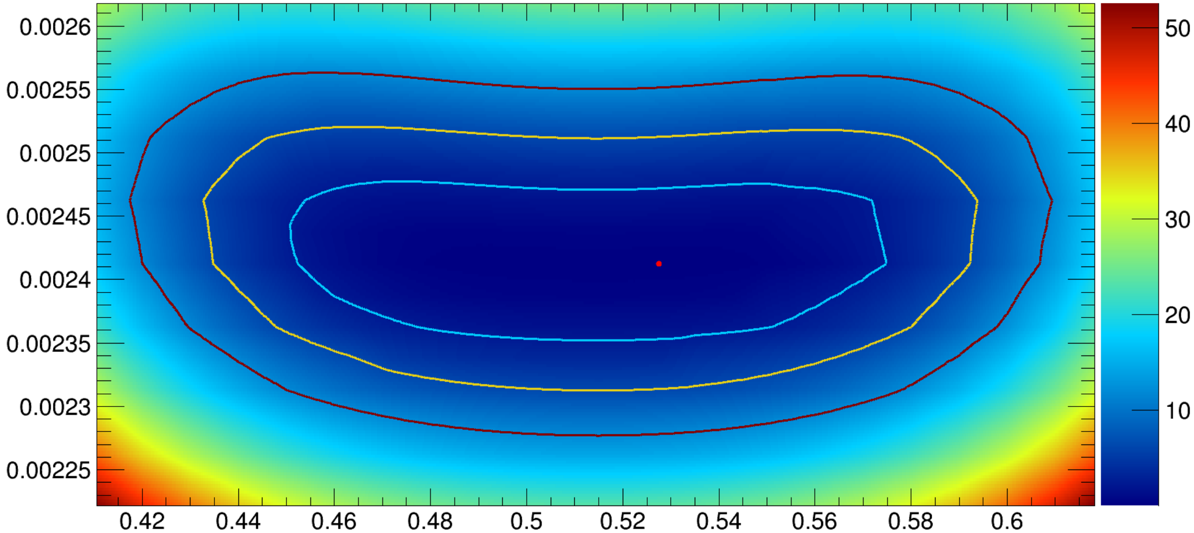
- Conservatively, NuPRISM analysis is equal to the current T2K projected sensitivities

T2K sensitivity studies 3

- With no systematic uncertainties
- NuPRISM naïve 1 sigma width = 0.062
- Compare to T2K projection:
  - 1 sigma width = 0.055
- 0.062 > 0.055

????????????

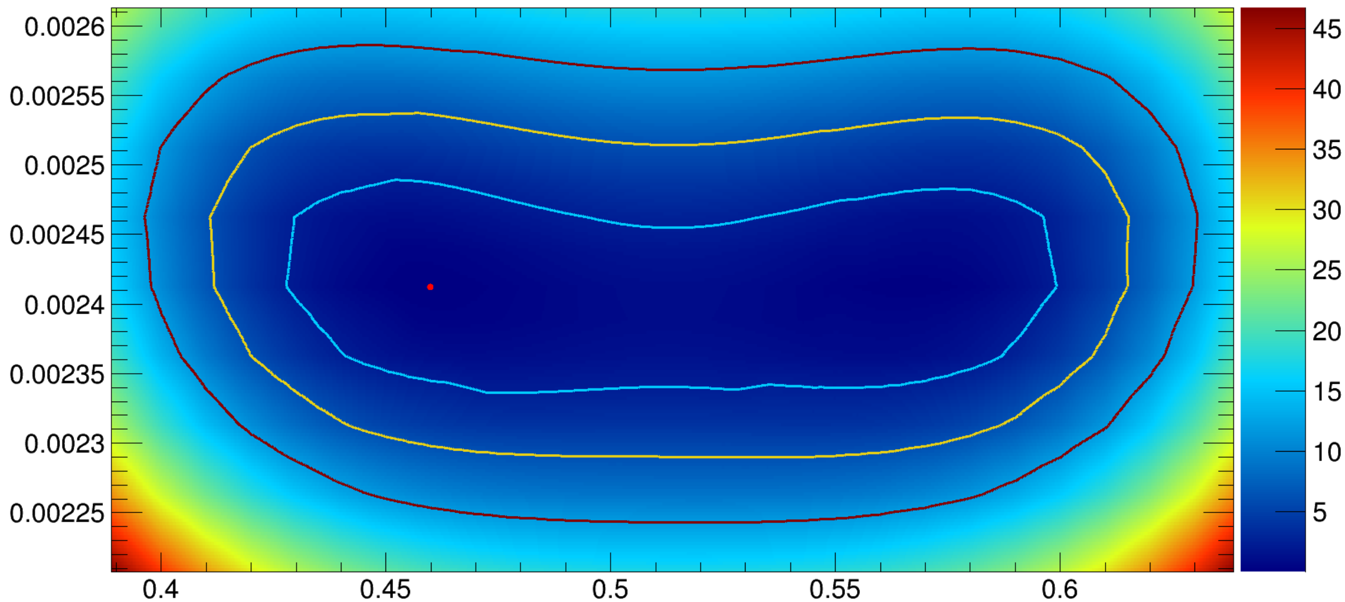




- Need to talk to FSTF people understand difference

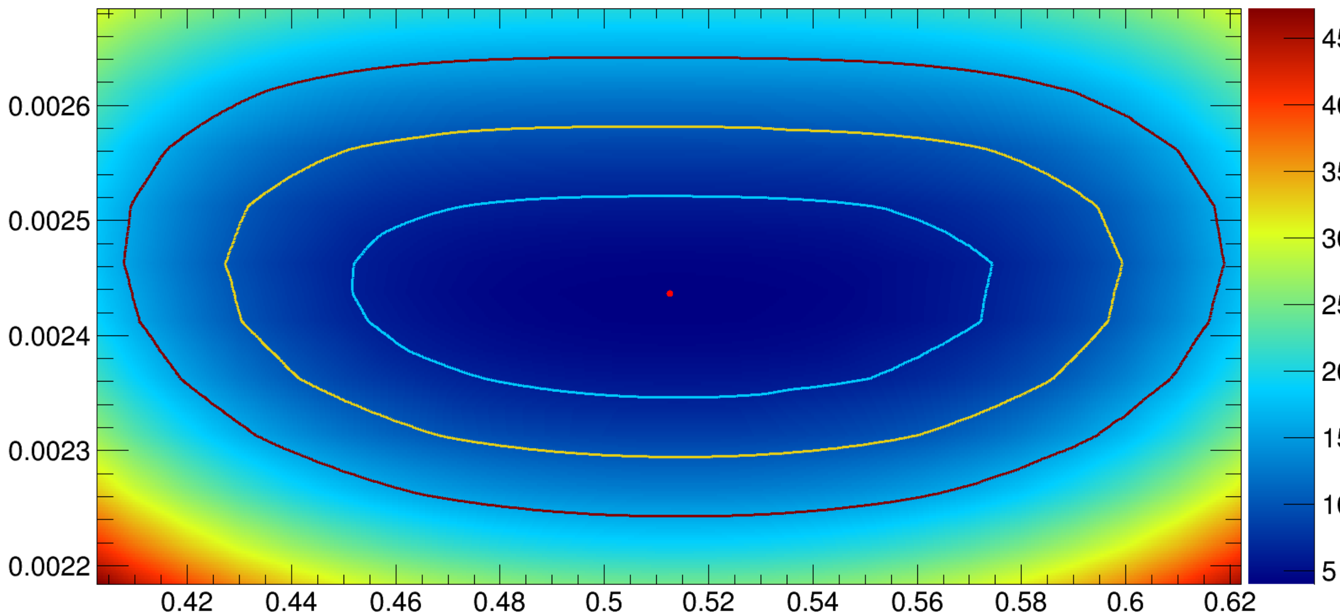
T2K sensitivity studies 4

- Sin^2 theta_{23} = 0.5, now check at Sin^2 theta_{23} = 0.46 (top)
- Using Asimov data set before, want to check what thrown data looks like



- See expected two-lobed structure when moving away from maximal mixing

- For a single throw, contours are compatible with Asimov data set

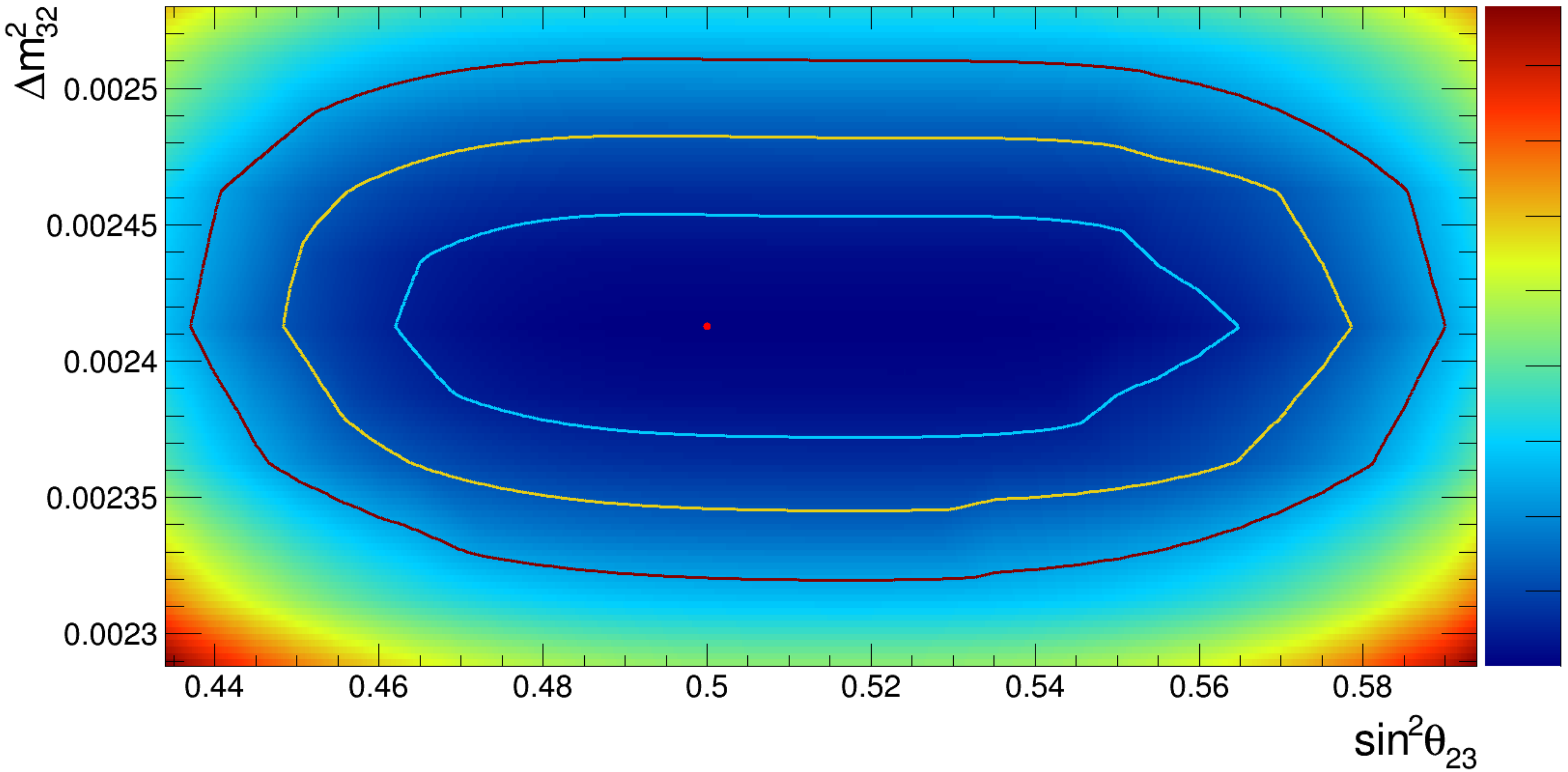


νPRISM

T2HK sensitivity studies

TRIUMF

- Sin^2 theta_{23} = 0.5, but at 1.56e22 POT at SK
- Maybe ~ HK statistics?



- 1 sigma width < 0.050, compared to ~0.056 at T2K

νPRISM sensitivity summary and future work

- NuPRISM, with rough SK errors is as good as the T2K projected sensitivity
- Asimov sensitivities are compatible with thrown sensitivities, and different values of sin^2 theta_23
- Increasing statistics leads to reduction in 1 sigma width, at ~same rate as FSTF showed

- Still to do:
  - Convert 2D contours into 1D widths
  - Work out why stats only width is wider than FSTF stats only width
  - Do full SK systematics + HK statistics sensitivities
  - Octant sensitivity

Future ideas

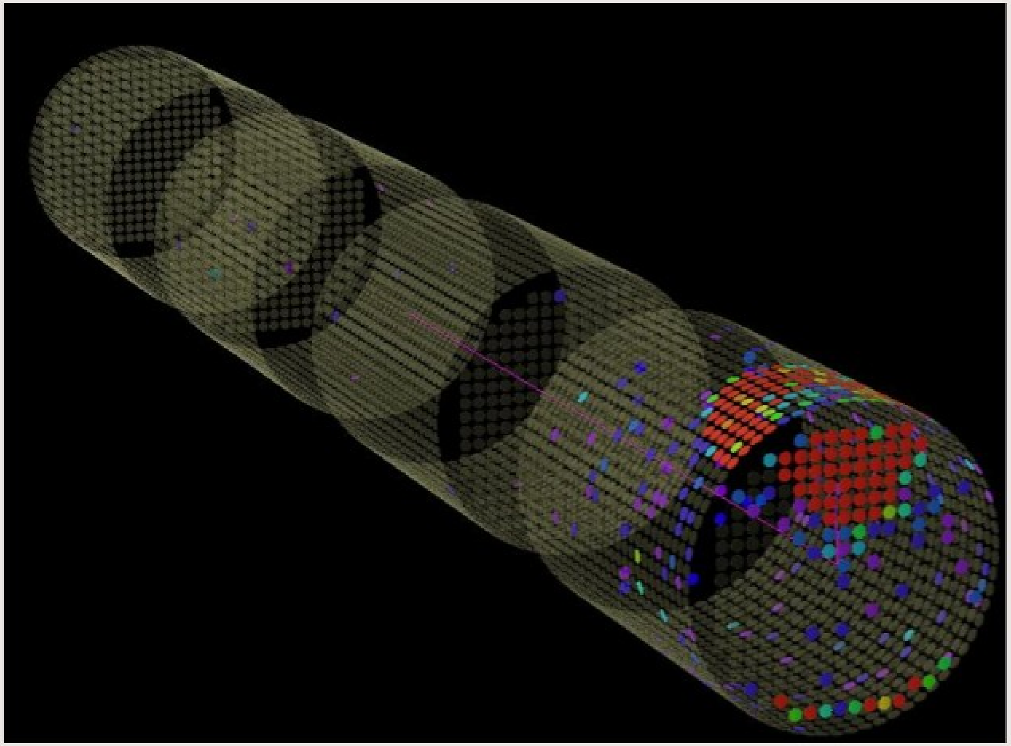
- Identify which flux systematics dominate – can these be reduced?
- Near detector constraint
  - Lets use them
  - Just take BANFF output – easy, but probably wrong
  - Joint fit? - Can't think how to combine with nuPRISM linear combinations
  - Use INGRID + ND280 to constrain flux
    - CC inclusive samples in both
    - INGRID = 0 – 0.8 degrees off axis
    - ND280 = 2 – 3 degrees off axis if we use ECal events
    - Good for T2K, cross section analyses

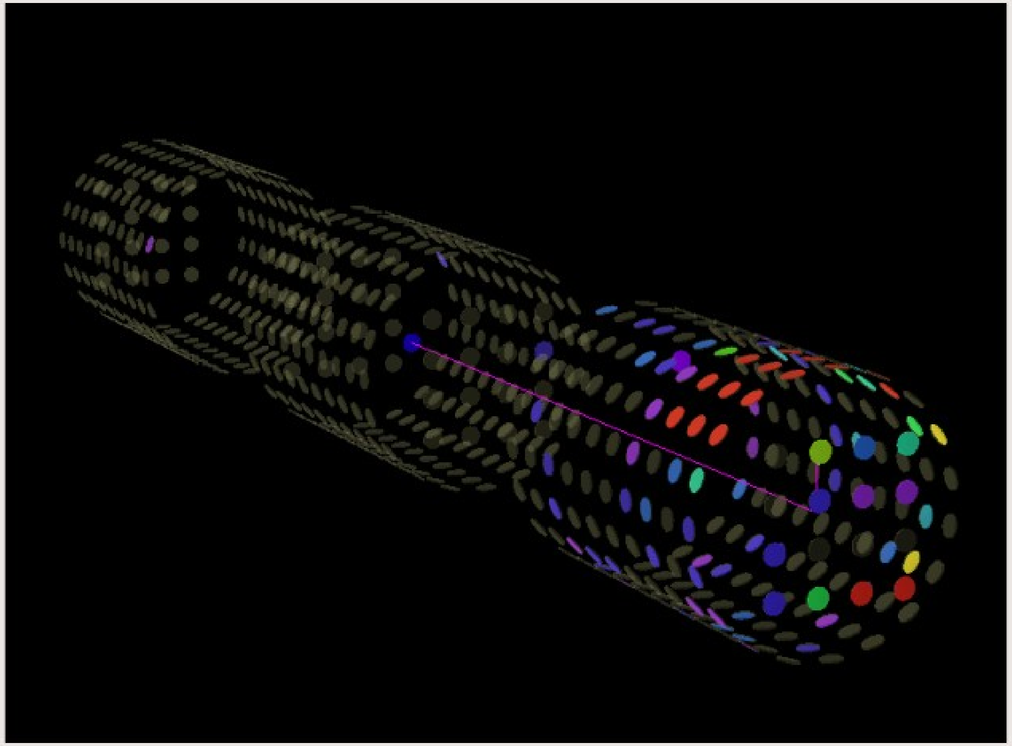
νPRISM simulation

- Working to create full detector simulation using WCSim and fiTQun
- Majority of work performed by two Co-op students at TRIUMF – Alex Lam and Carl Rethmeier
- Current status:
  - Variable νPRISM detector geometry present in older version of WCSim
    - Can vary detector size, PMT coverage, PMT type, number of compartments
  - Can generate fiTQun scattering table with any 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
- Have full software chain set up to create files for analysis

WCSim

- Example of two extreme νPRISM configurations in WCSim





Radius = 0.127m (10inch diameter)	Radius = 0.254m (20inch diameter)
Percent Coverage = 60%	Percent Coverage = 20%
nSections = 4	nSections = 3
SectionHeight = 8.0m	SectionHeight = 10.0m
SectionGap = 4.0m	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 PMTs are changed, retuning is necessary
- Need to solve reconstruction for real detector uncertainties!
- Mike studying the QE and angular acceptance of these PMTs to determine how different they are from the Super-K 20” PMTs
- Work ongoing, hopefully will get some manpower focussed on nuPRISM reconstruction:
  - Need to migrate WCSim changes to latest version
  - NuPRISM specific version of fiTQun?
  - Upload everything to GitHub
  - Scripts to run full chain and process

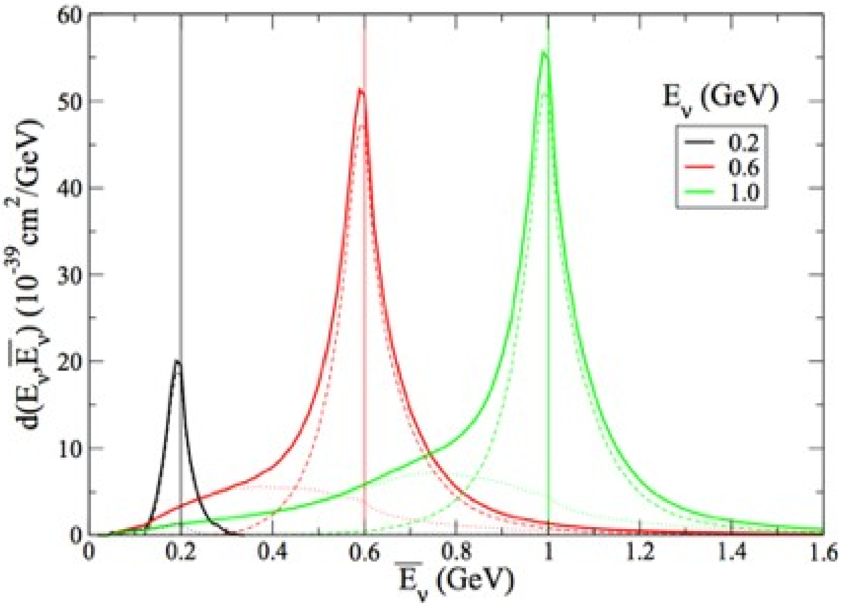
Summary

- Disappearance sensitivity studies are encouraging
  - Soon will have much more stringent analysis
  - Appear to be more capable than ND280 fit
- Full simulation and reconstruction needed to estimate detector systematics and reconstruction ability
  - More work to start soon
  - Want to see how reconstruction is affected, hopefully improved

Backup slides

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

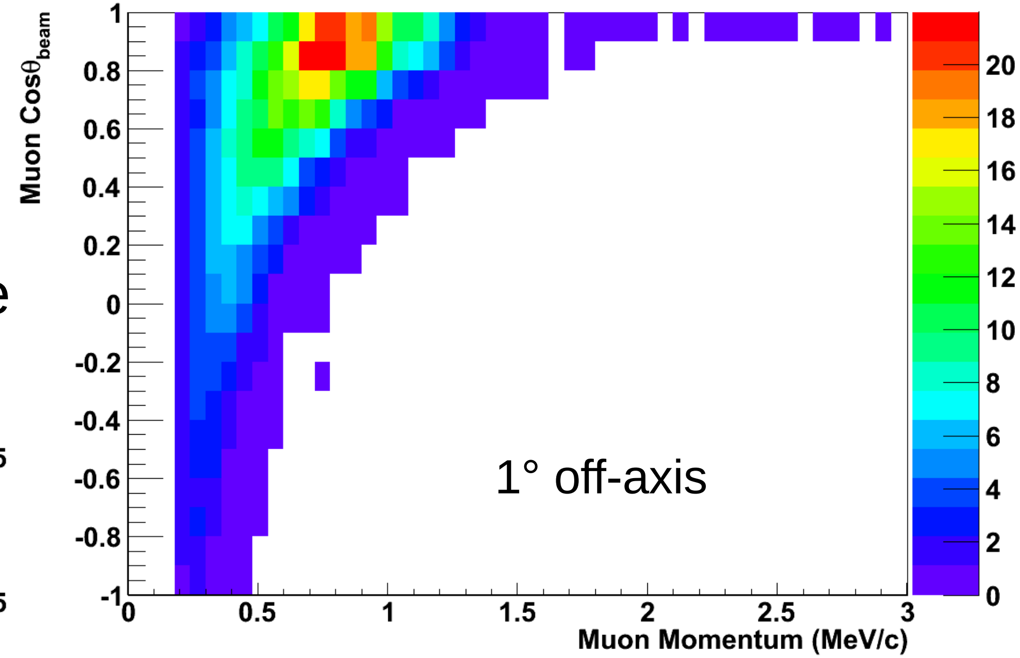
- Using the linear combination method, we can produce Gaussian beams with widths significantly less than an off-axis spectrum peaked at the same energy

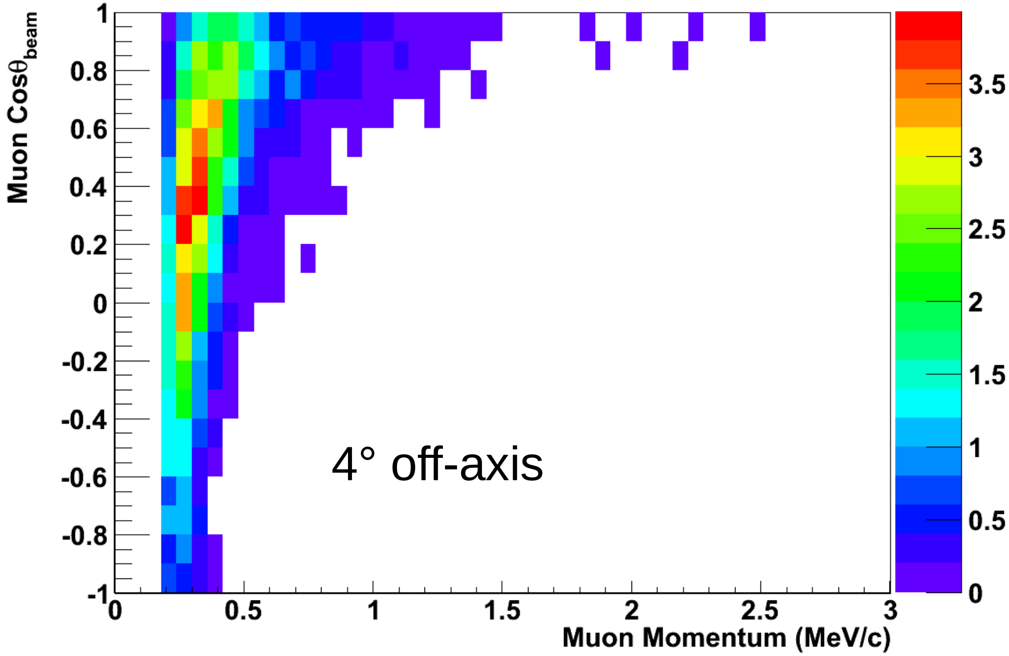
$$G(E_\nu;\mu,\sigma)=\sum_{i=1}^{\#\text{ of Off-axis bins}} c_i \varphi_i(E_\nu)$$

- 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

Event Selection

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

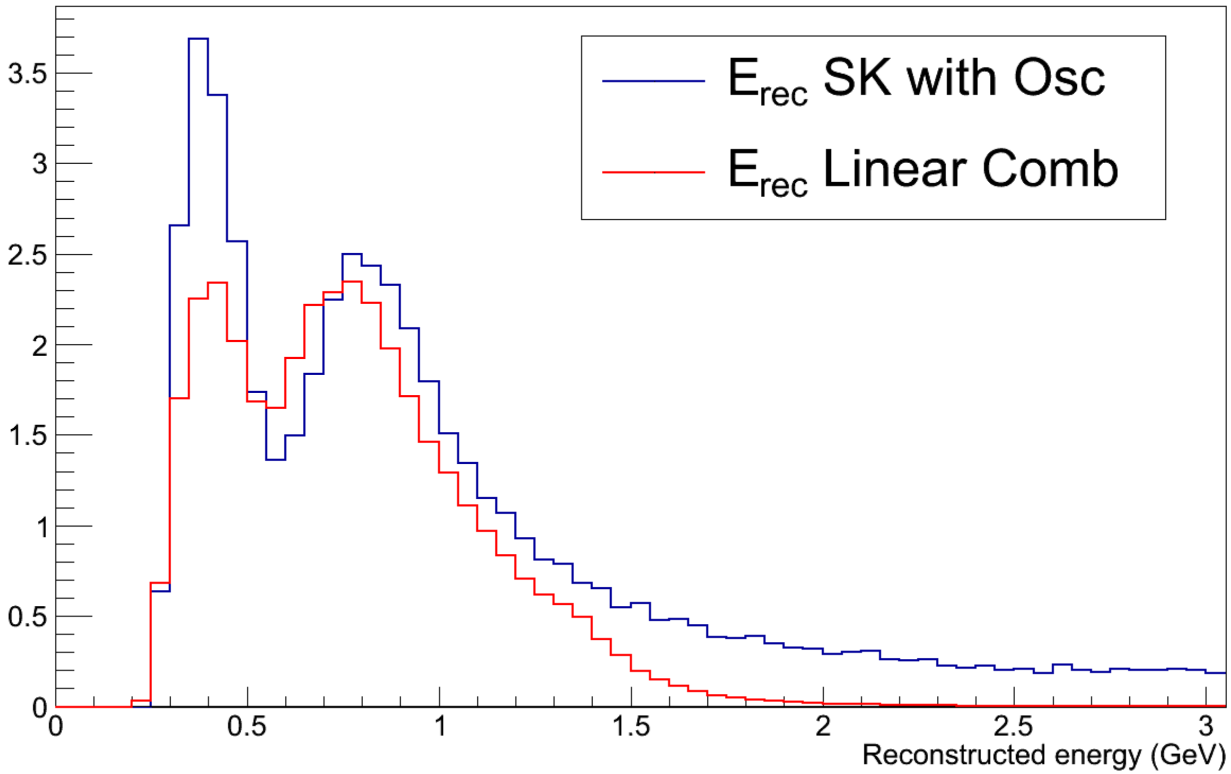




- Record the off-axis angle of the interaction, using the reconstructed vertex position

SK event 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



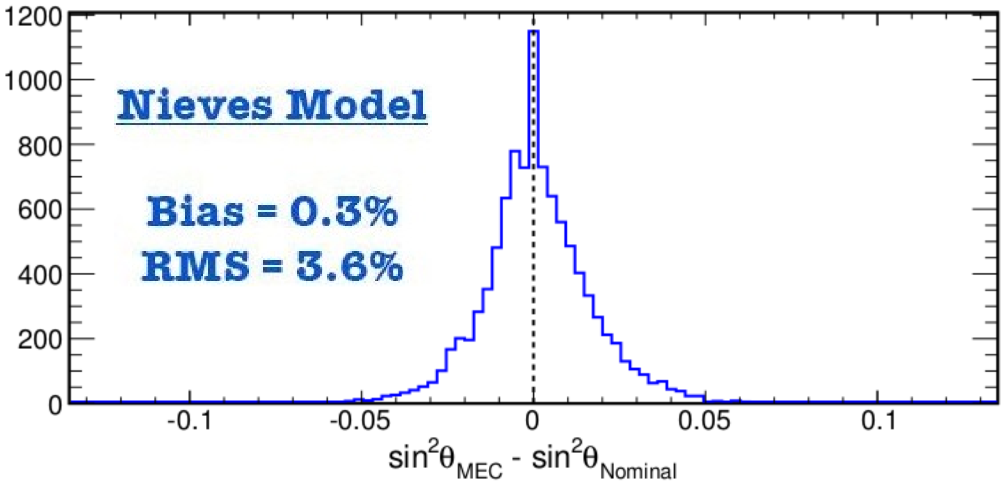
- To νPRISM data:
  - Background subtraction
  - Efficiency correction
  - Addition of selected SK background
- Introduce some model dependence

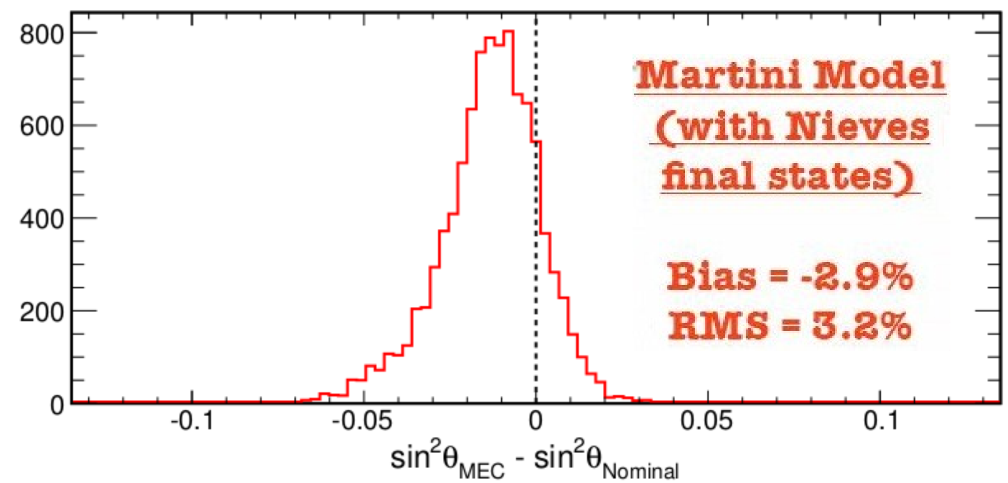
Systematic uncertainties

- 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 difference between the νPRISM prediction and the varied SK MC
  - Use this to calculate fractional covariance matrix for νPRISM prediction
- This analysis takes flux and cross section uncertainties into account
  - Initial detector systematics being studied

T2K multi-nucleon study

- MC-based analysis using full detector simulation, full systematics etc.
- Three fake datasets
  - Nominal NEUT MC
  - NEUT + meson exchange current (MEC) events from Nieves' model - Phys. Rev. C, 83:045501, Apr 2011
  - NEUT + MEC events based on Martini's model - Phys. Rev. C, 81:045502, Apr 2010
- Perform disappearance fit to extract θ_{23} in each case and compare

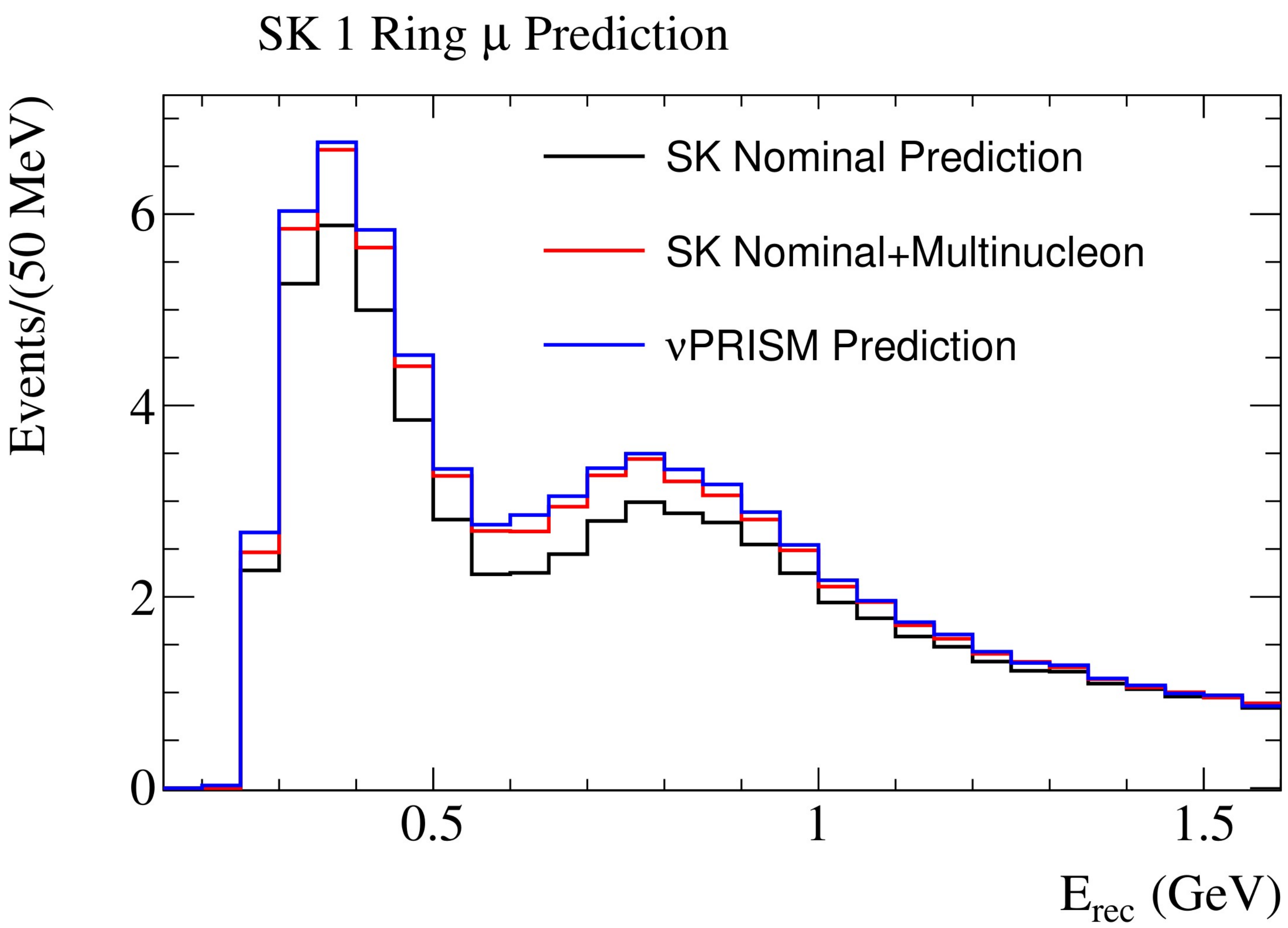




- Both models give ~3.5% RMS in $\sin^2\theta_{23}$, Martini model introduces ~3% bias
- Effects much smaller than current statistical uncertainty, but maybe large for future analyses

Multi-Nucleon example

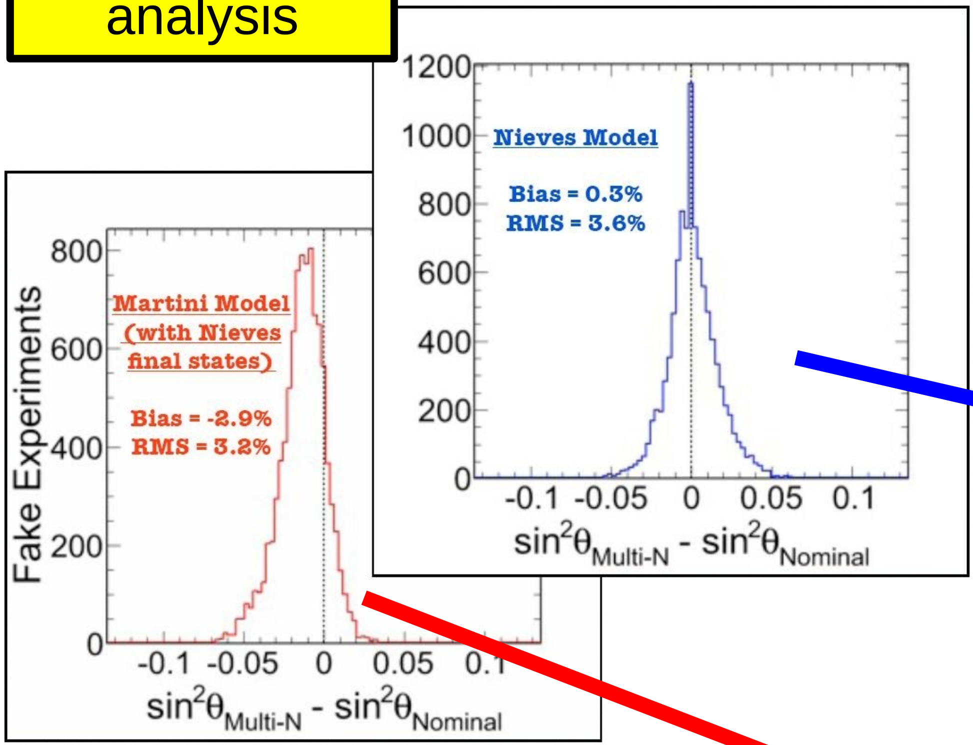
- Add multi-nucleon events to the nominal MC to make fake data



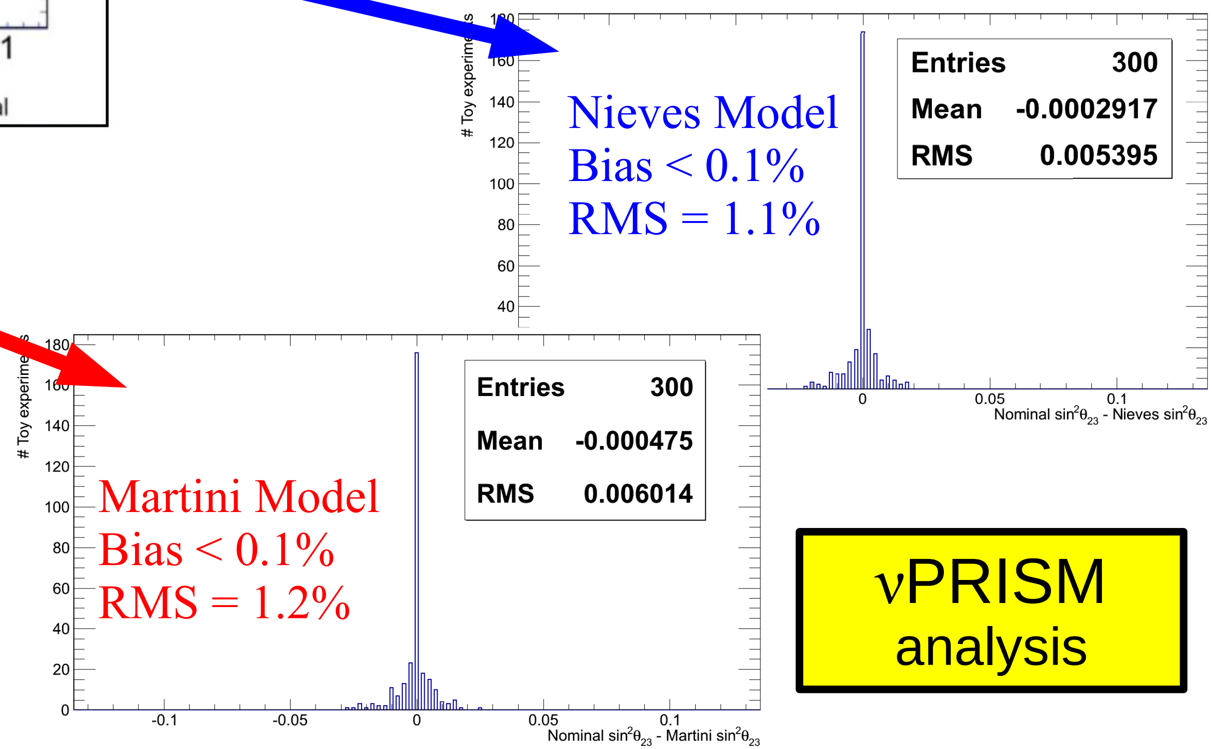
- See νPRISM prediction still reproduces oscillated SK spectrum when multi-nucleon events are present

Effect of multi-nucleon events at νPRISM

Standard T2K analysis



- Performed same MEC study as T2K
- Bias and RMS greatly reduced

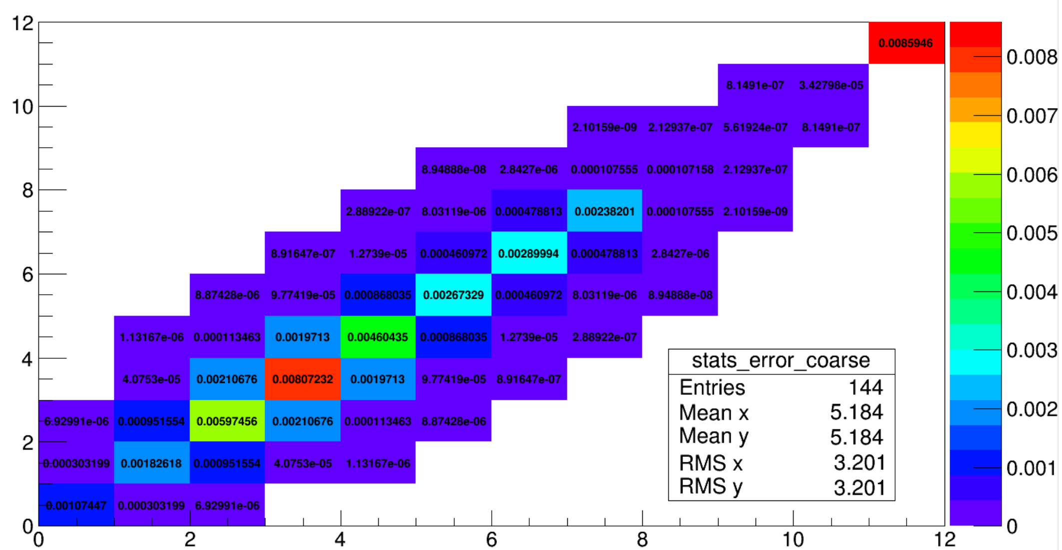


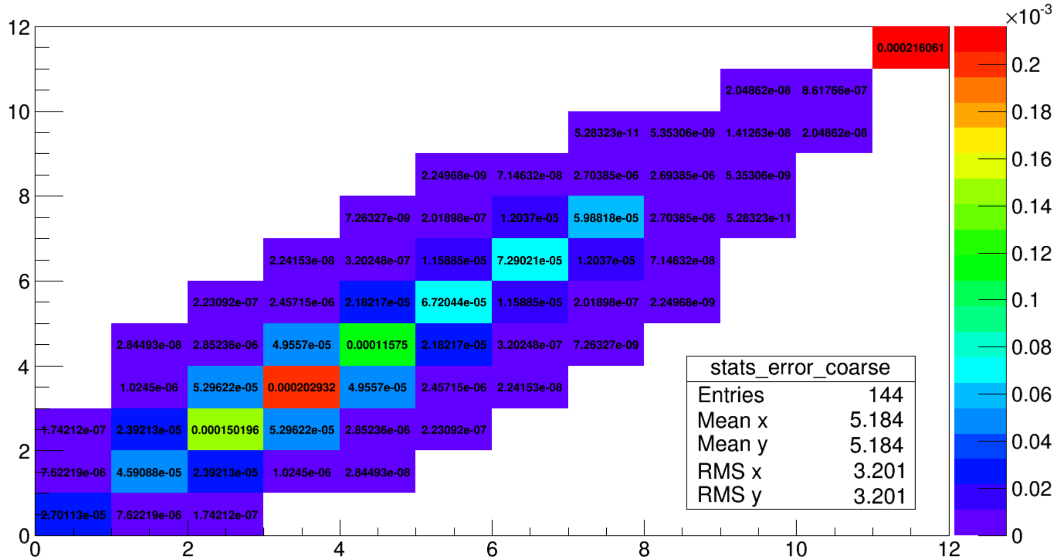
- νPRISM analysis largely independent of cross section model

νPRISM analysis

Validating the bug fix

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

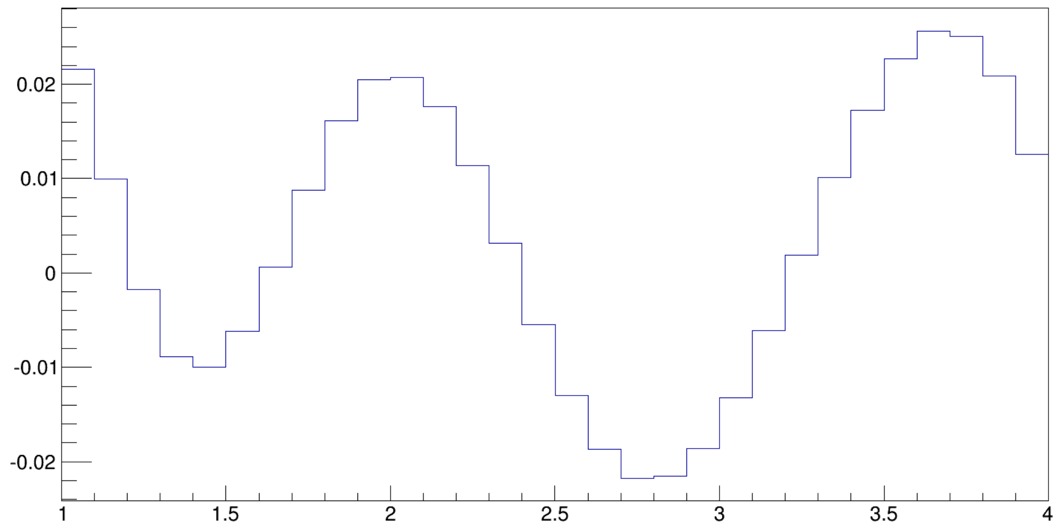


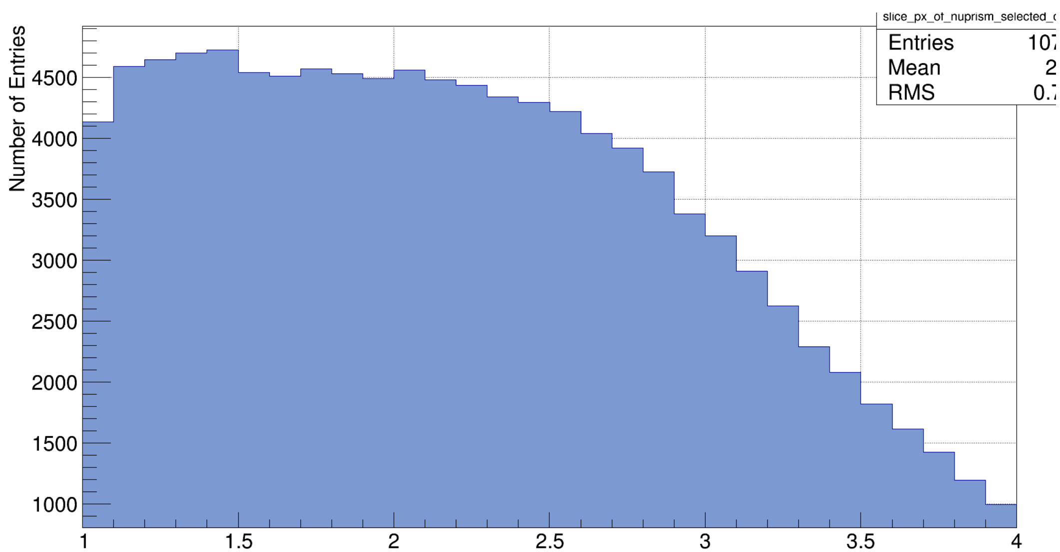


- Statistical uncertainty covariance matrix
- Buggy code on top, fixed code beneath
- In buggy code see statistical uncertainty of 8.8% in largest bin
    - Roughly same size as in analysis presented at last T2K meeting
    - Difference due to different oscillation parameters
- In fixed code, uncertainty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

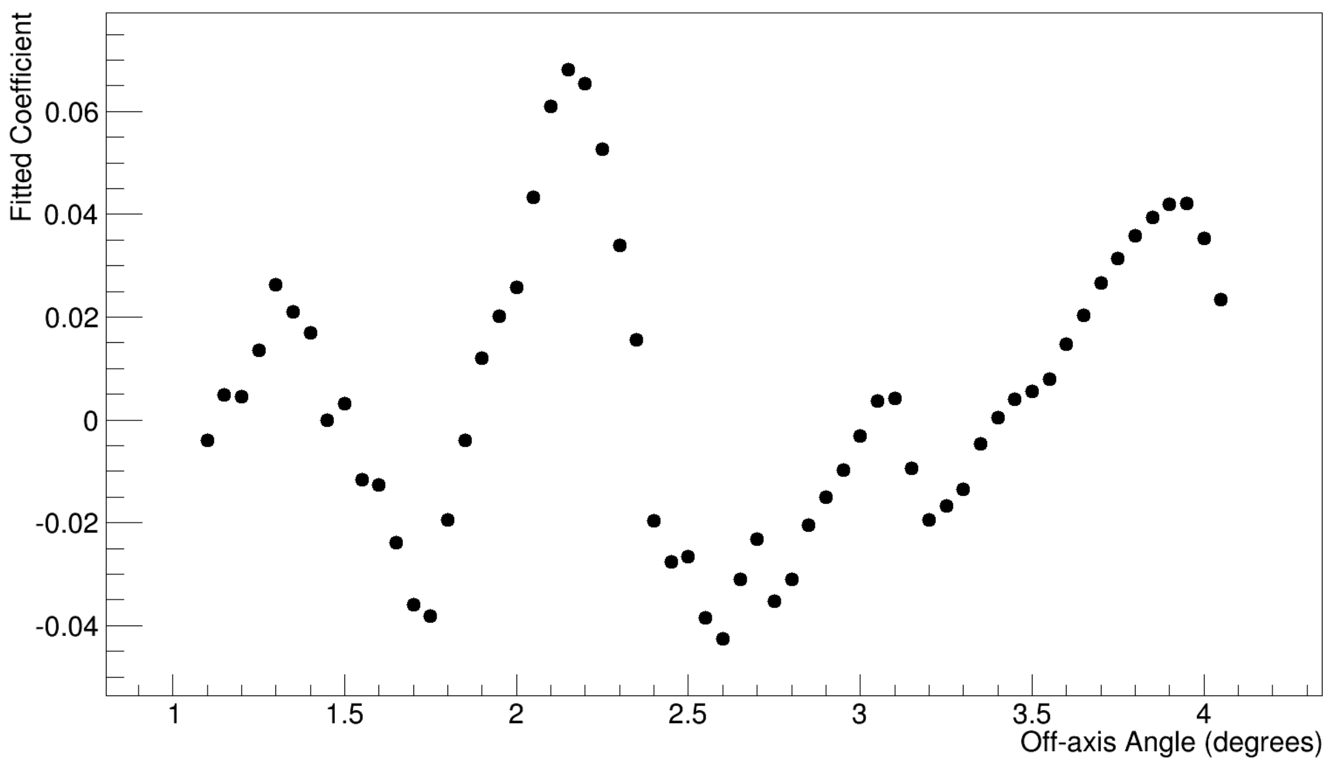
Validating the bug fix 3

- 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

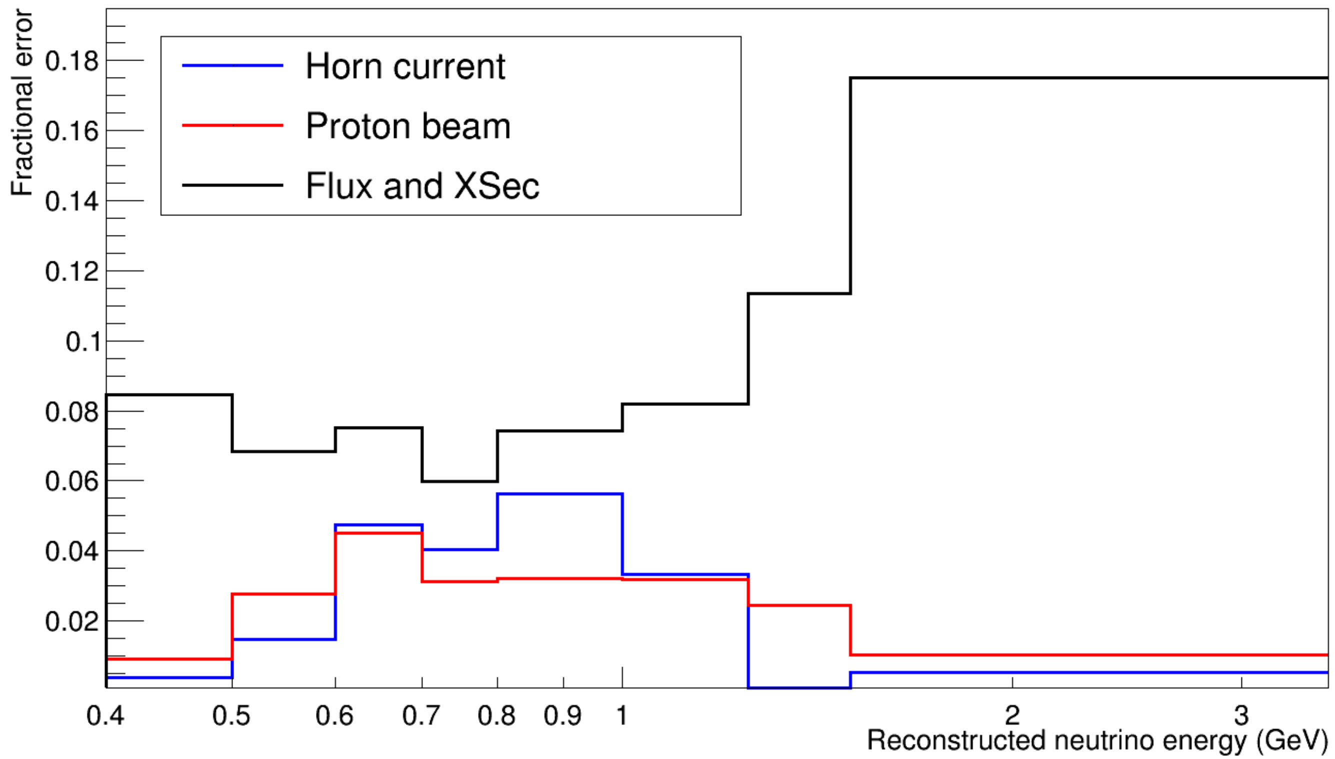
- Coefficients not as smooth as before
- Built on previous work to improve fit



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

Flux systematics

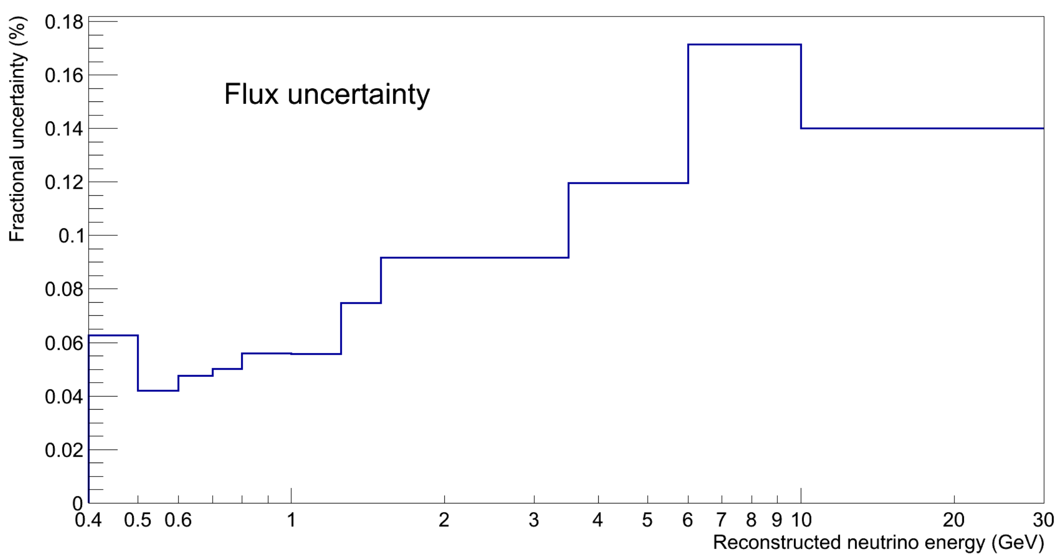
- Flux uncertainty increased from 5% to 7% at oscillation dip
- Largely driven by proton beam and horn current uncertainties

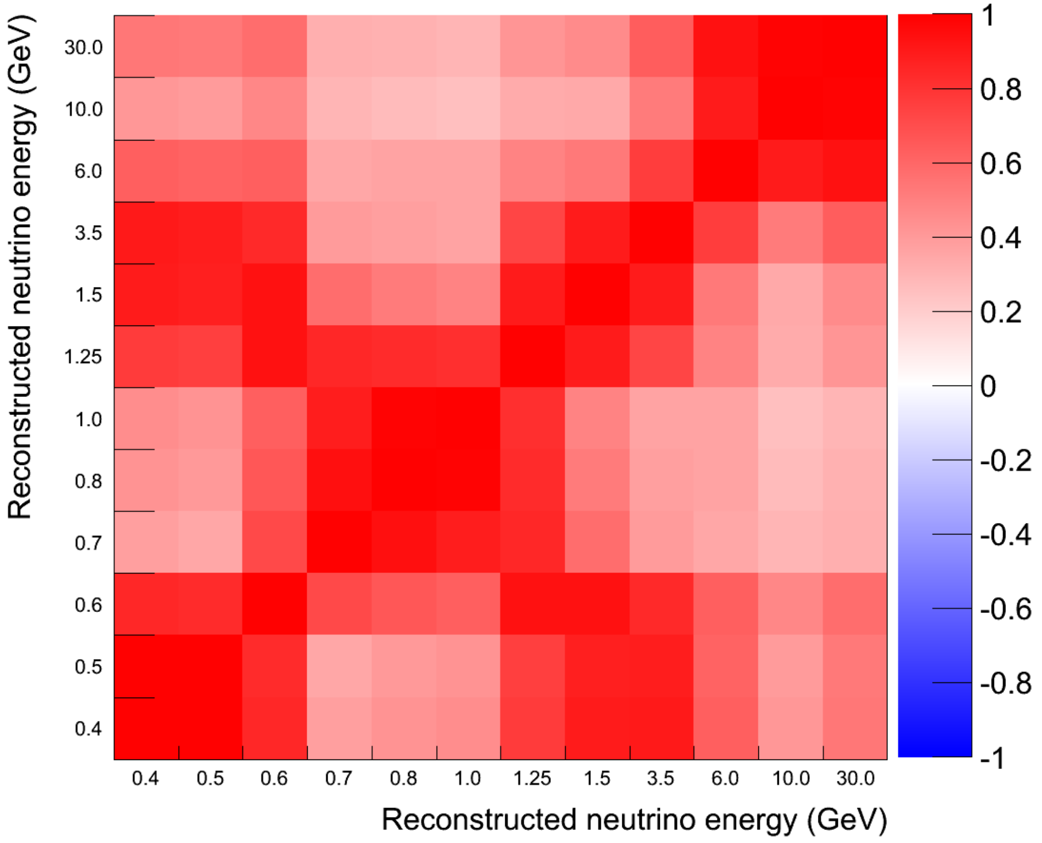


- Not unexpected:
  - More variation between neighbouring coefficients
  - Systematics that effect off-axis angle flux have bigger effect

Old flux uncertainty

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

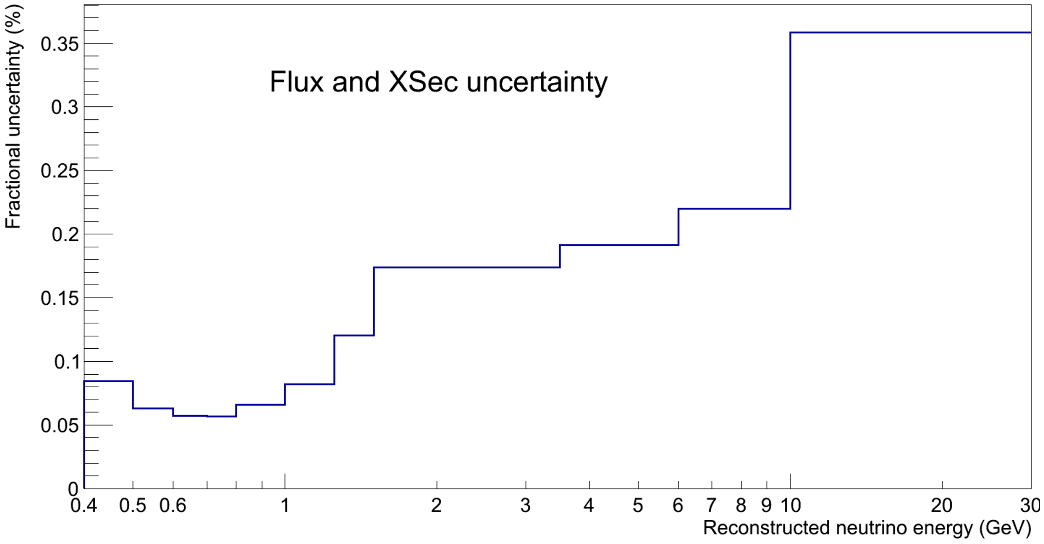


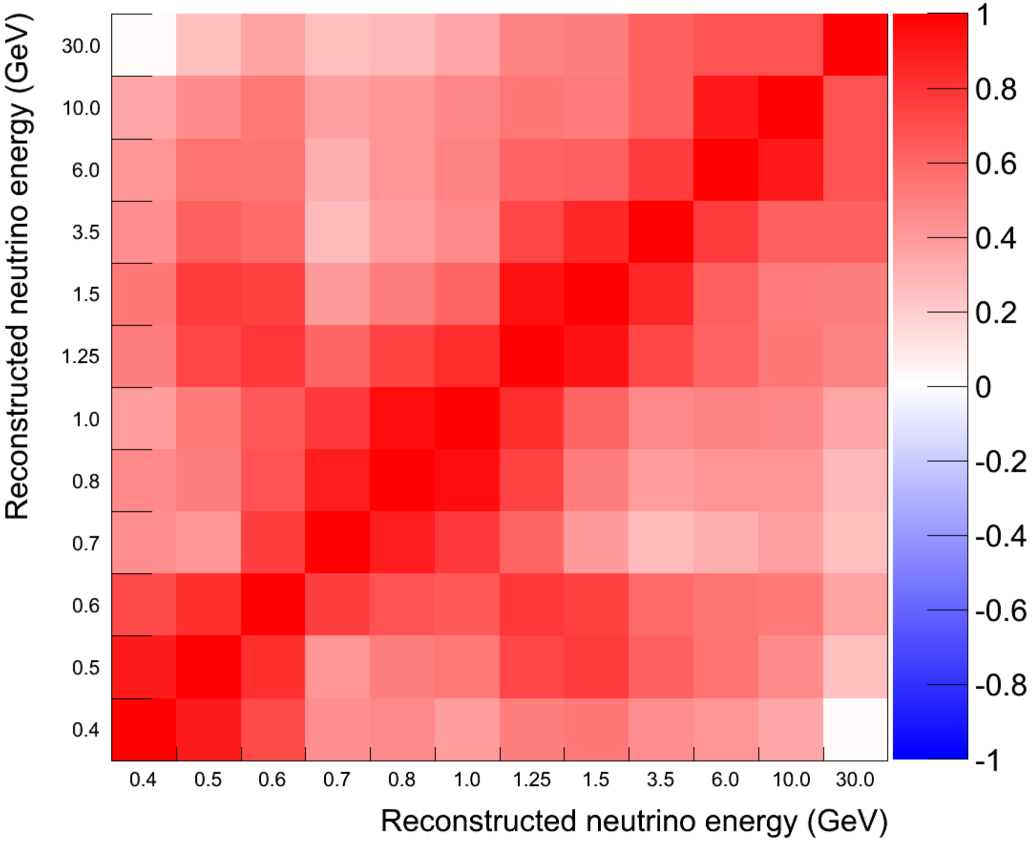


- Larger errors at high energy – no νPRISM events
- Error at oscillation dip around 4-5%

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

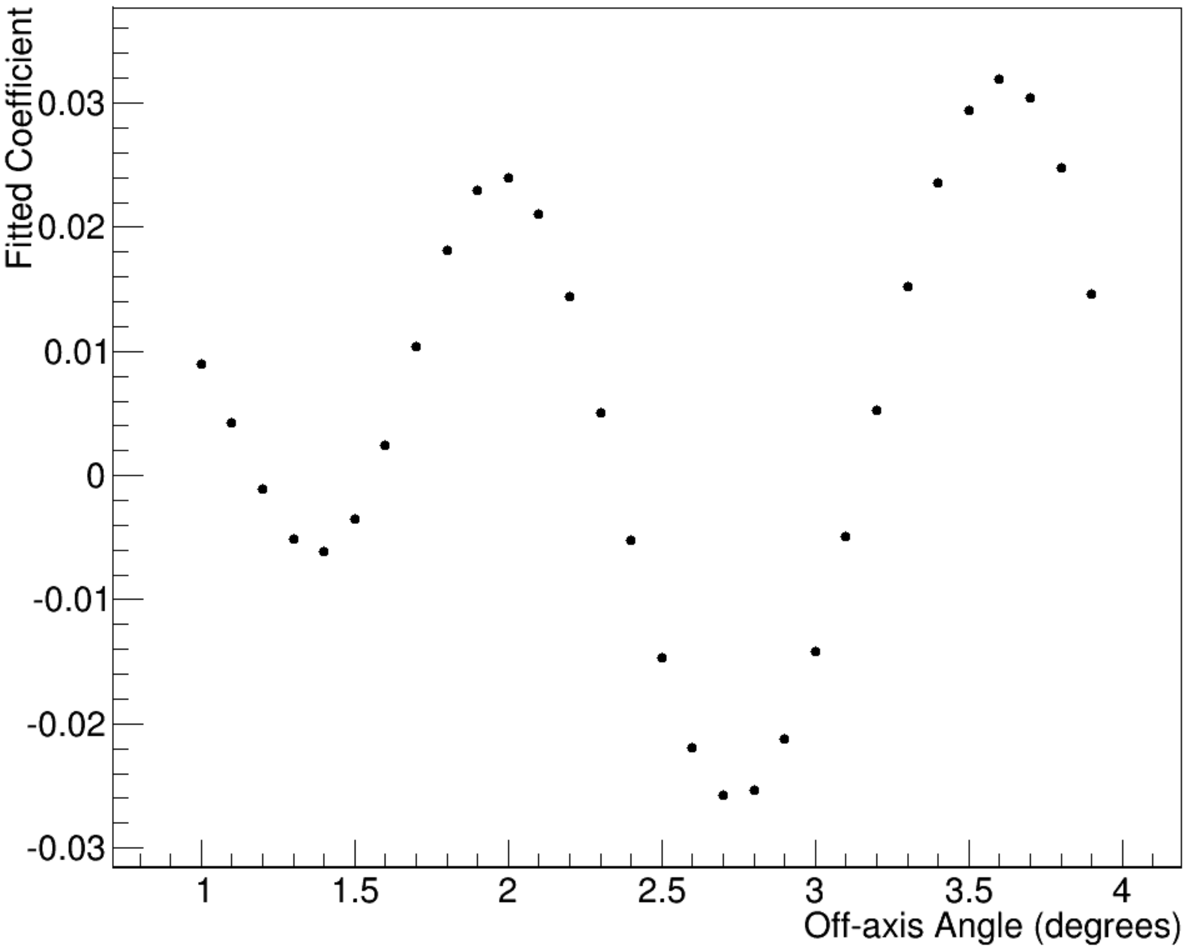




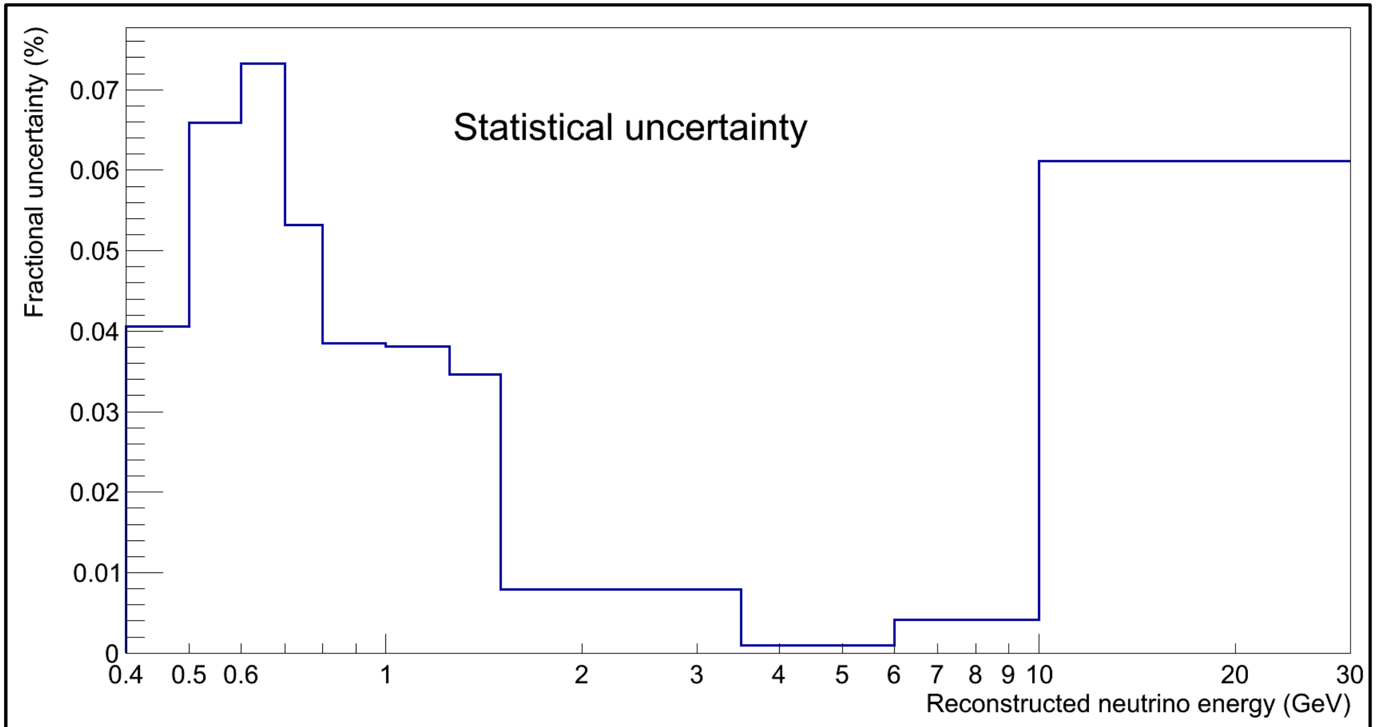
- Combined flux and cross section uncertainty around 5% at the oscillation dip

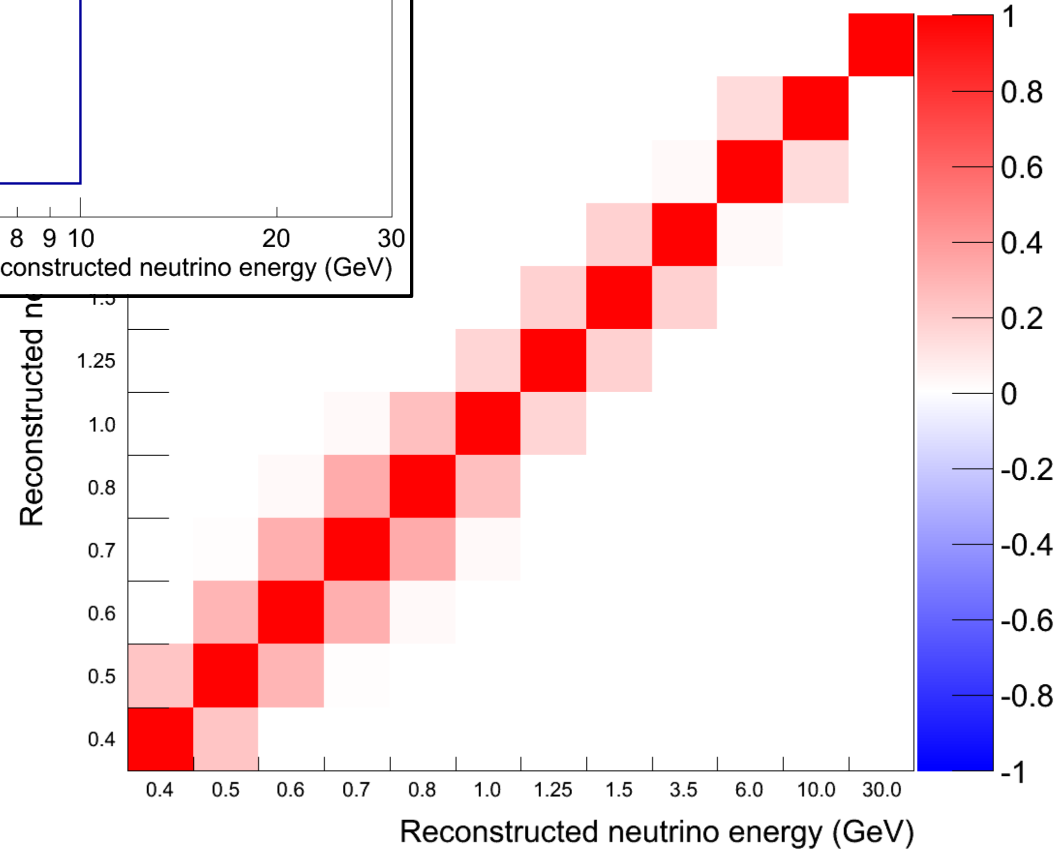
Old coefficients

- 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