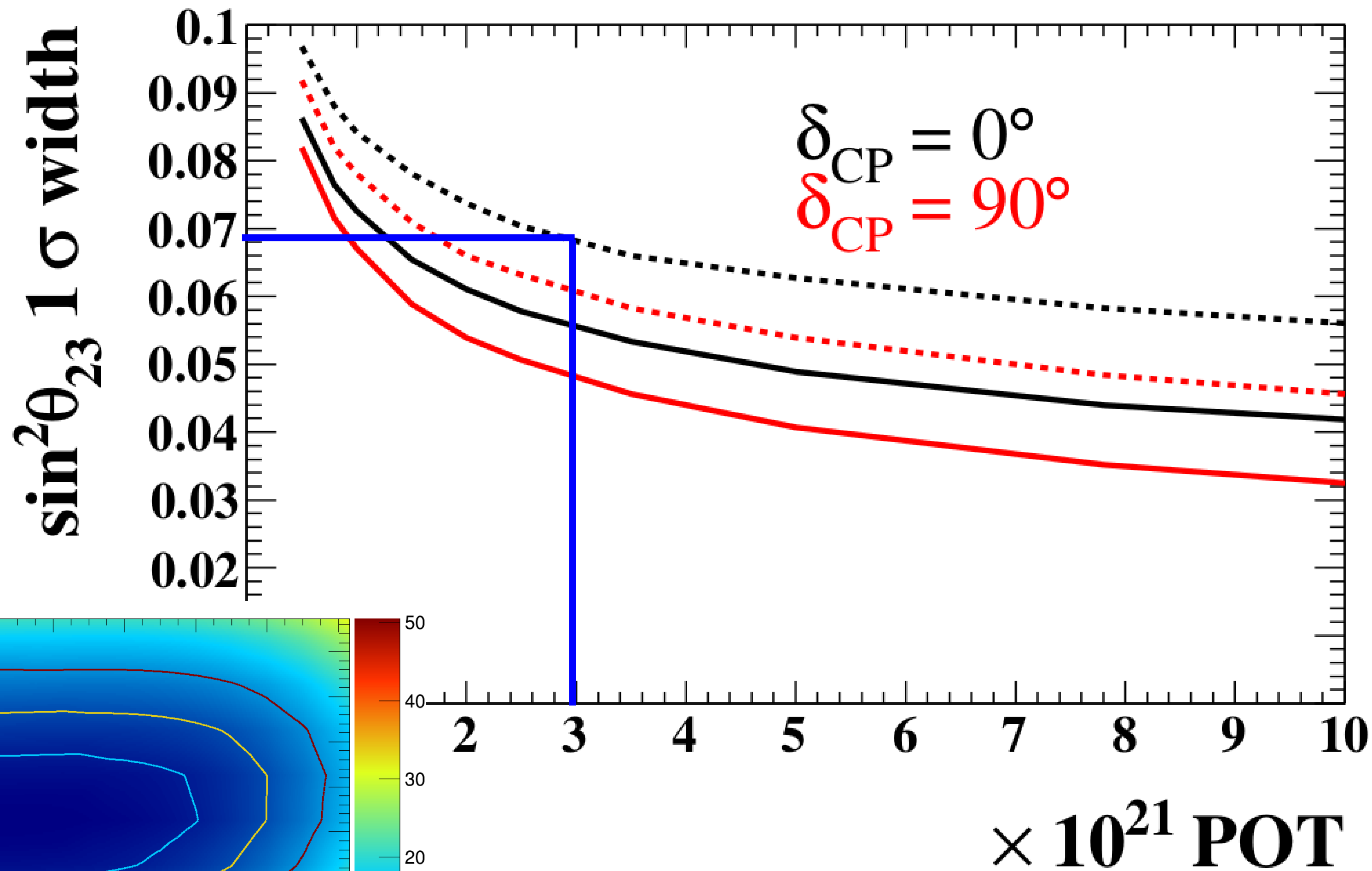
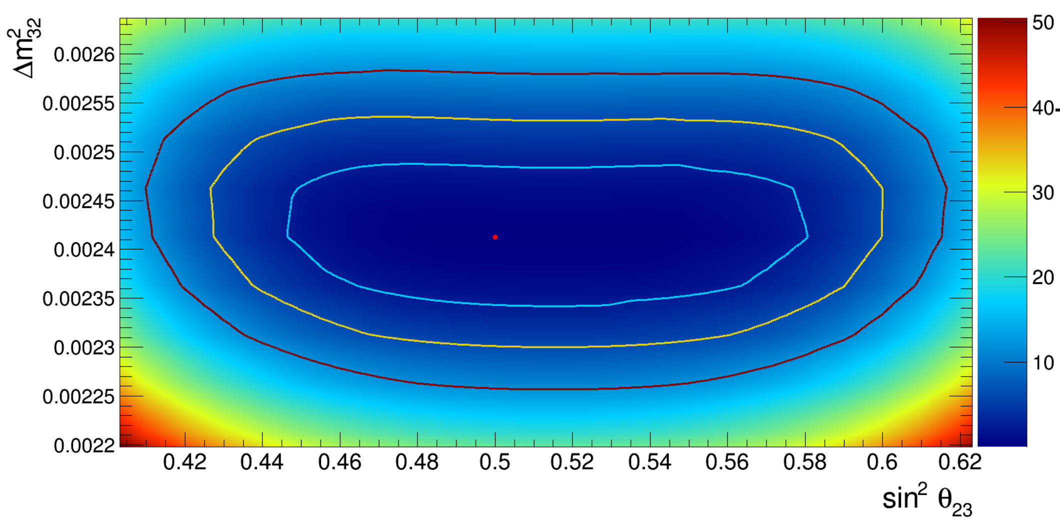
νPRISM:
Disappearance Analysis

Mark Scott for the νPRISM collaboration
νPRISM workshop
17th Mar 2015 - IPMU

$\sin^2\theta_{23}$ sensitivity studies

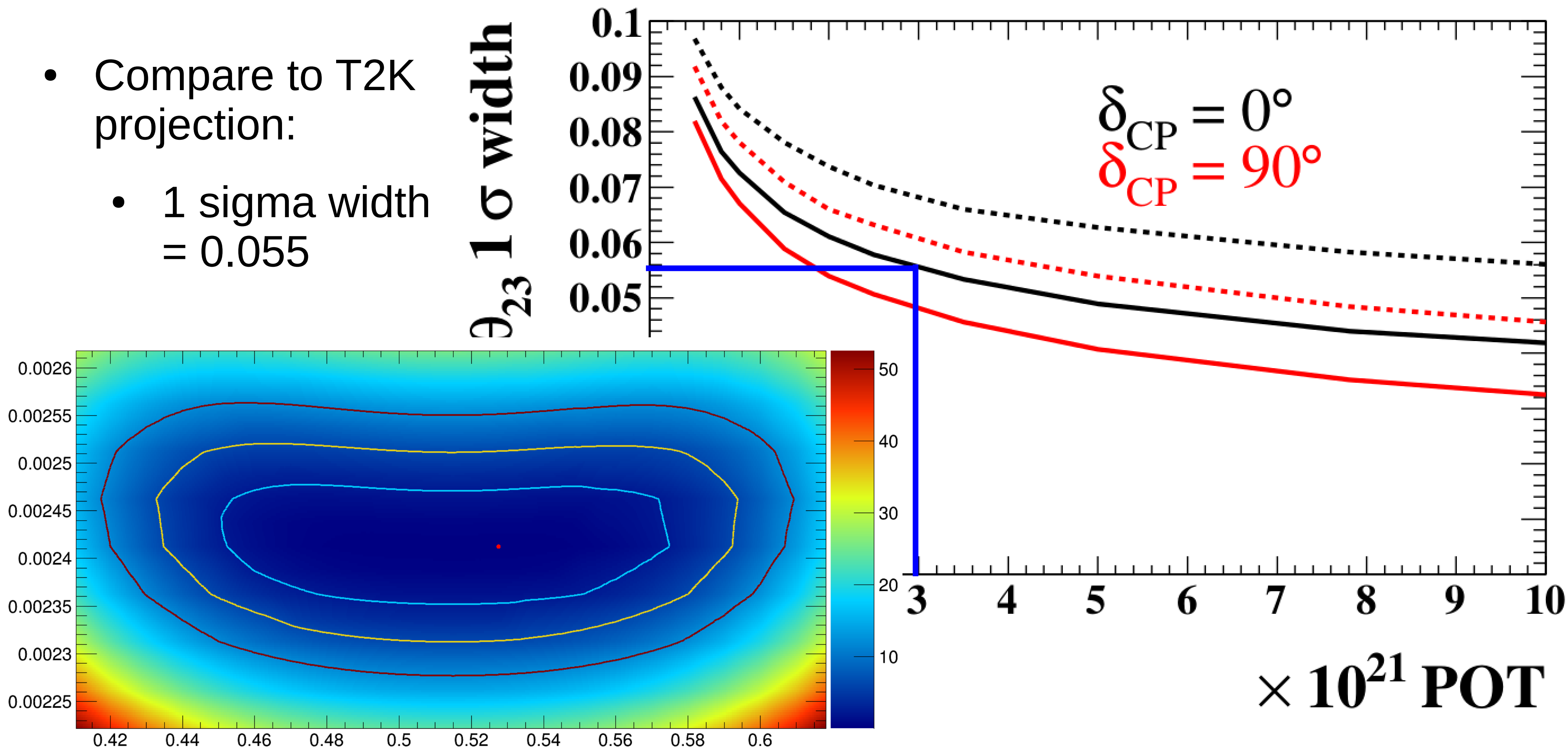
- At 6th HK meeting showed initial sensitivity plots for T2K statistics - 1 sigma width = 0.065, with current systematics
- Compare to T2K projection:
  - 1 sigma width = 0.068
  - nuPRISM slightly better than T2K





With no systematic error...

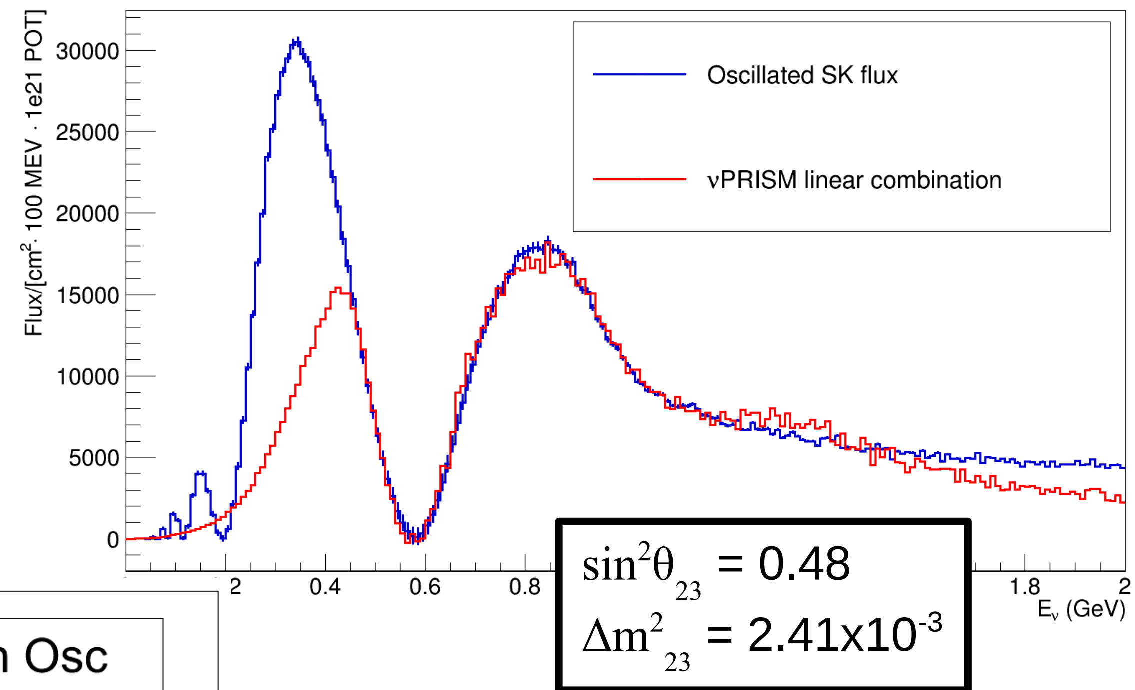
- nuPRISM naïve 1 sigma width = 0.062
- Compare to T2K projection:
  - 1 sigma width = 0.055

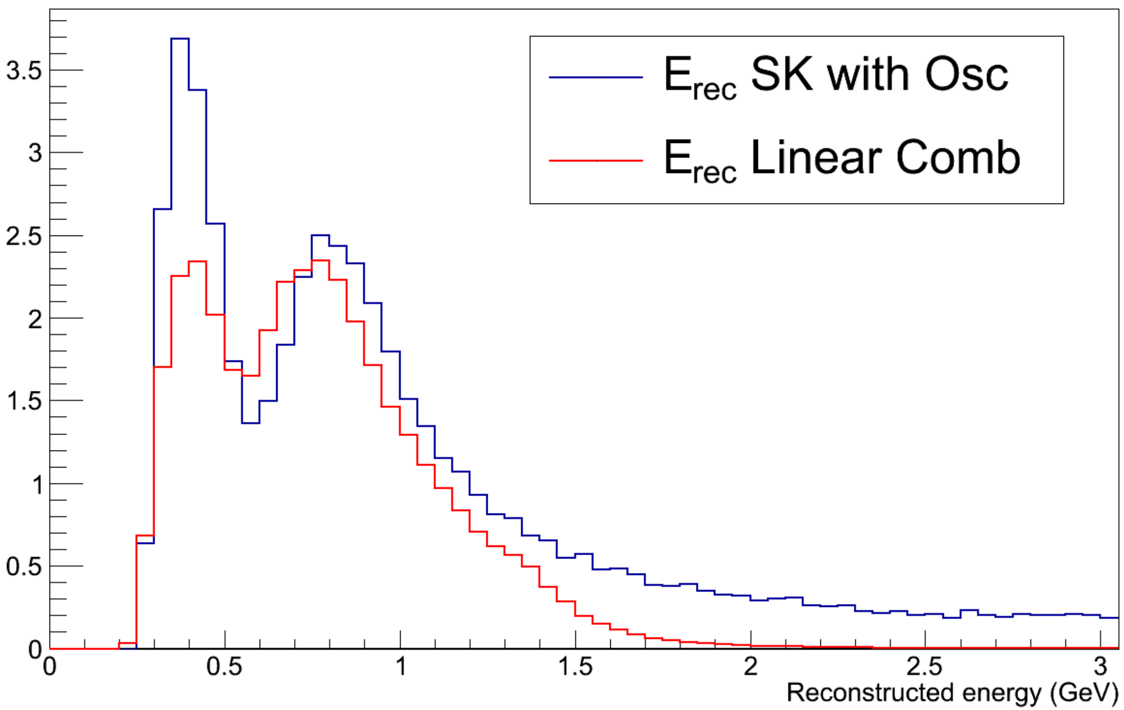


- Need to understand why the nuPRISM statistics only fit performs worse than the T2K statistics only fit

Why is νPRISM not better?

- Current flux fit matches SK flux very well around oscillation region
- Even so, there are differences in the reconstructed energy spectra

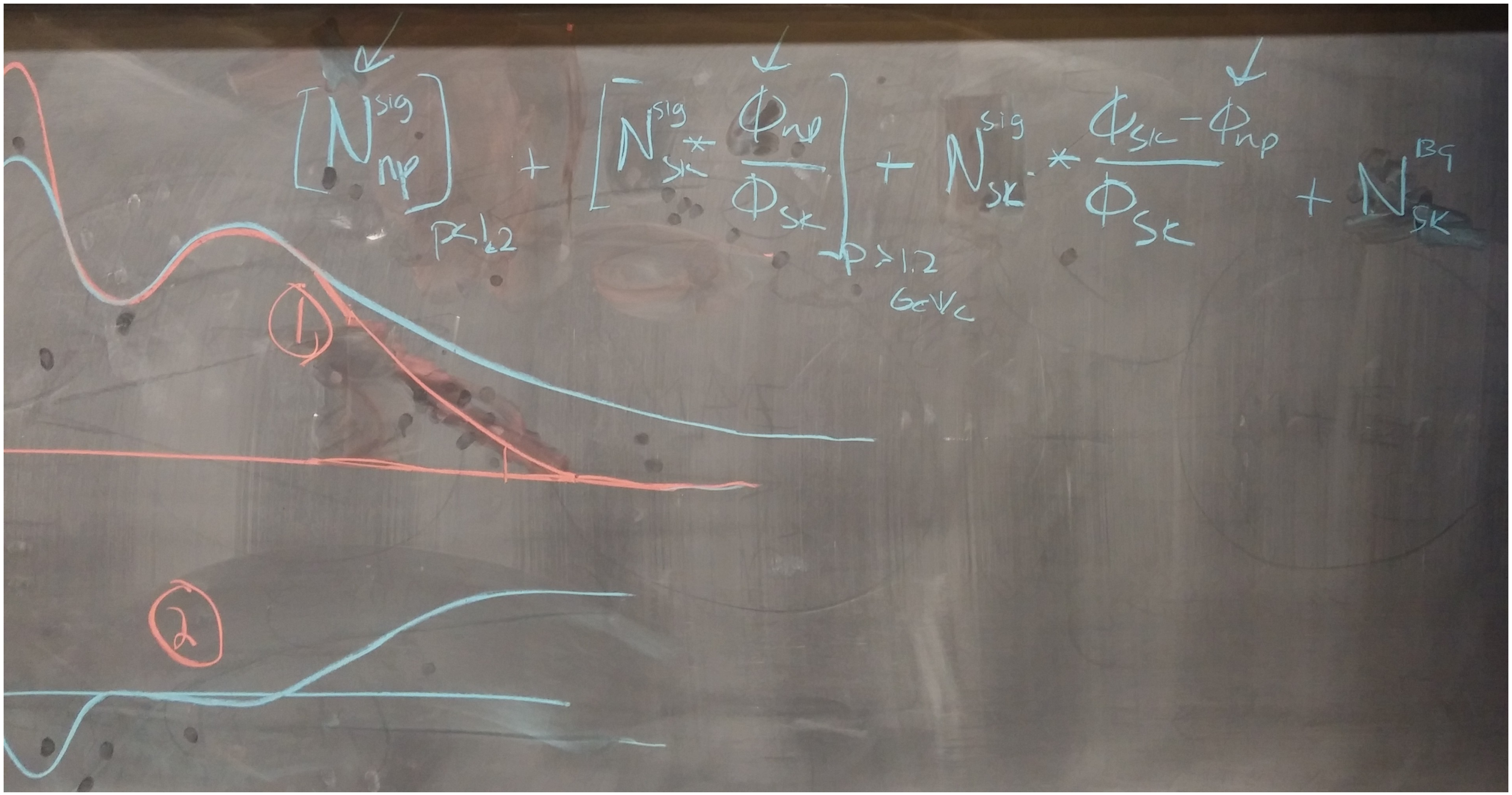




- Correct for these differences
  - Efficiency corrections
  - Add SK background
  - **Additive correction** – just brute force agreement

Planned work

- Following M.Hartz's suggestion, want to try performing analysis in a different way



Planned work

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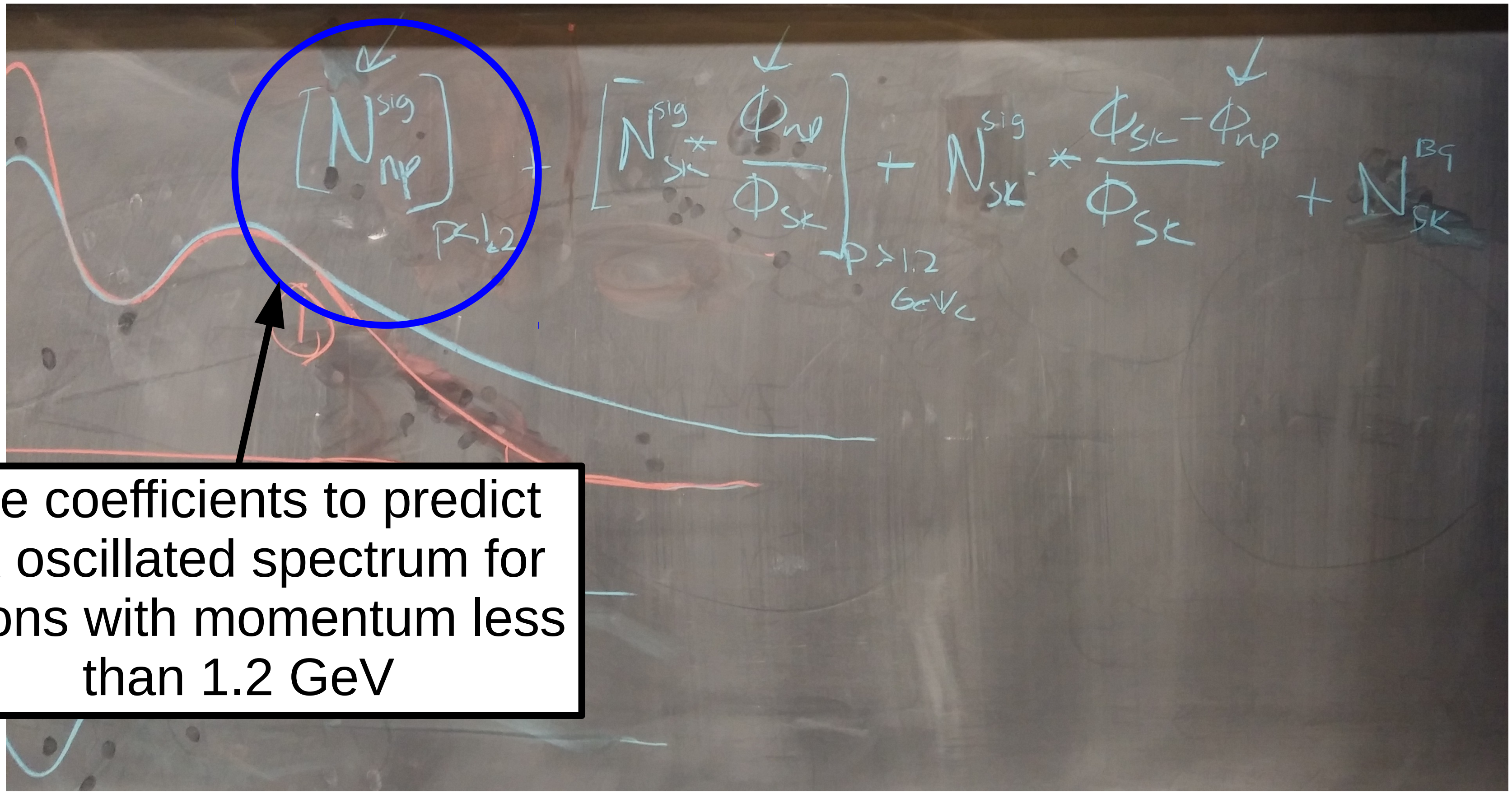

Use coefficients to predict SK oscillated spectrum for muons with momentum less than 1.2 GeV νPRISM TRIUMF

Planned work

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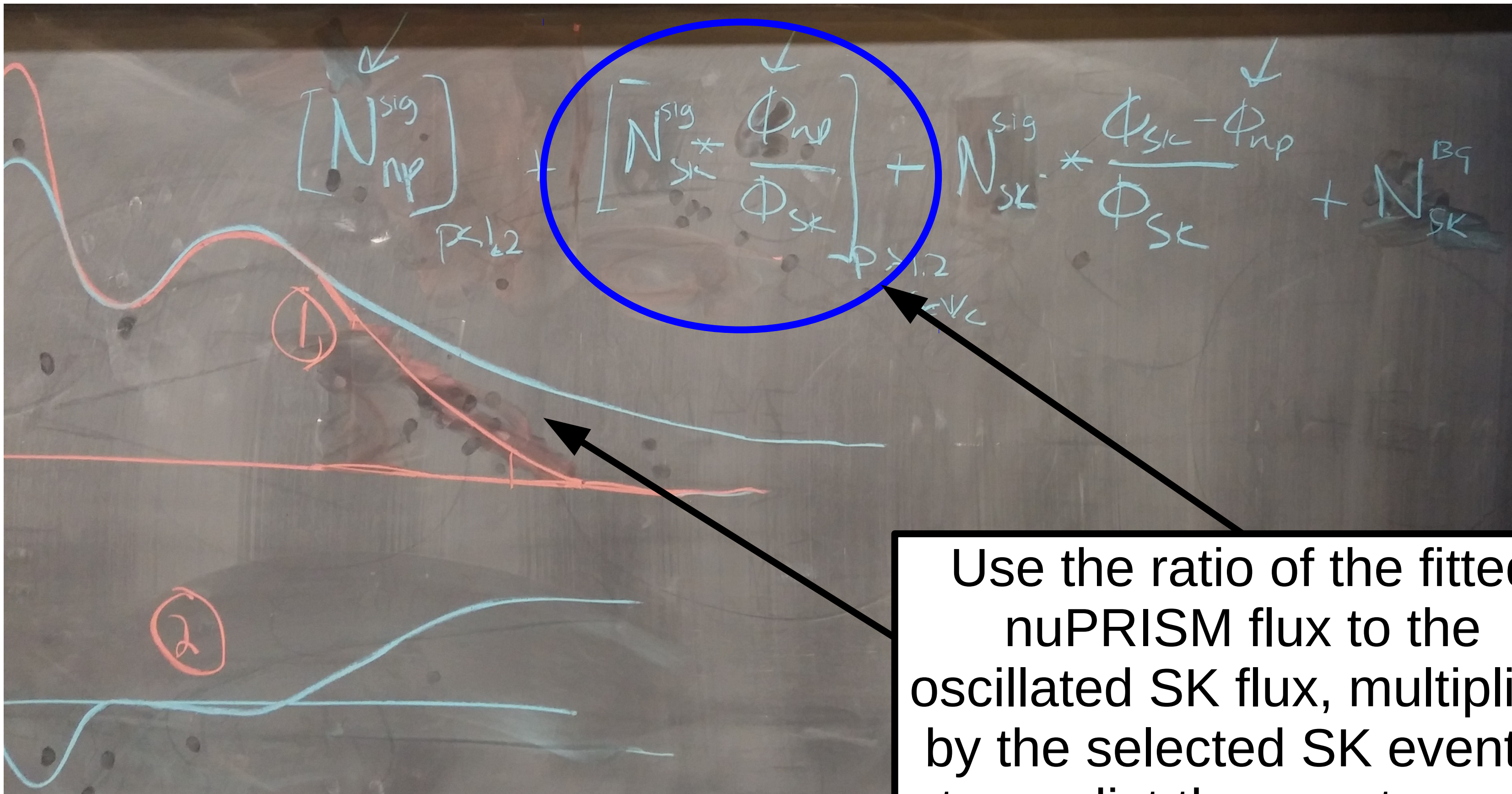

Use the ratio of the fitted nuPRISM flux to the oscillated SK flux, multiplied by the selected SK events, to predict the spectrum of muons above 1.2 GeV νPRISM

Planned work

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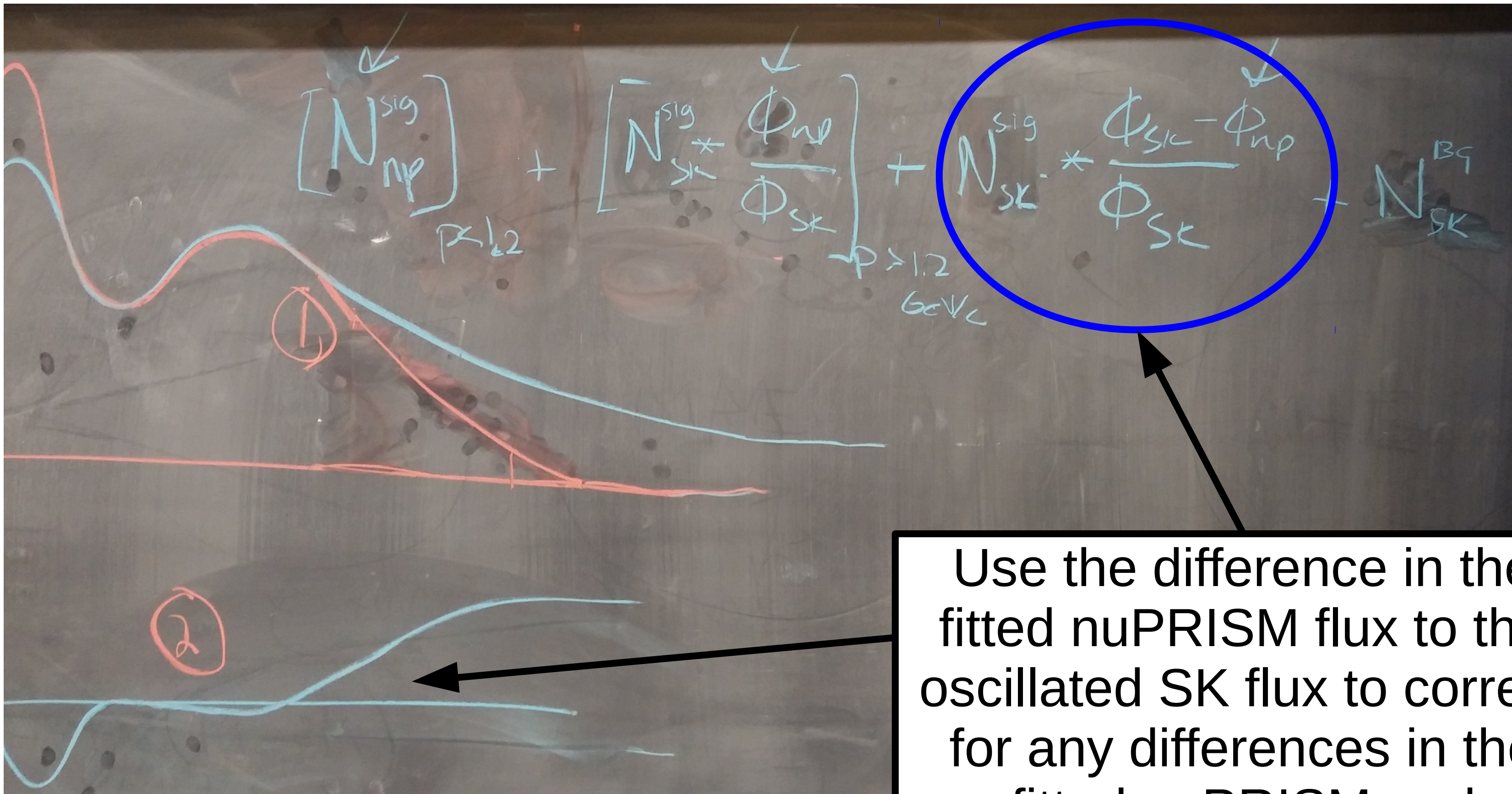
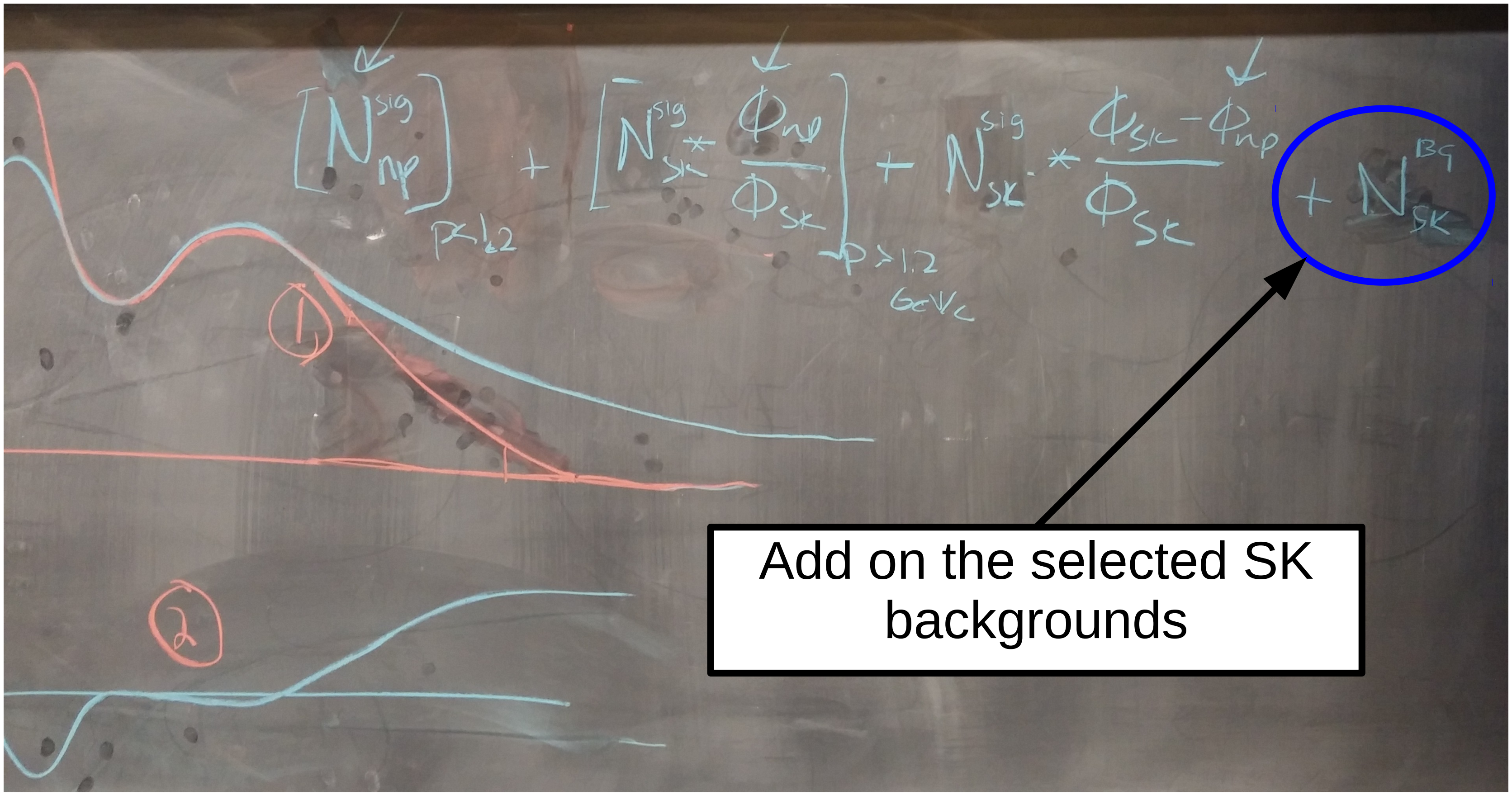


Use the difference in the fitted nuPRISM flux to the oscillated SK flux to correct for any differences in the fitted nuPRISM and oscillated SK fluxes

Planned work

- Following M.Hartz's suggestion, want to try performing analysis in a different way



- Only have efficiency corrections for muons below 1.2 GeV, where nuPRISM can contain and reconstruct them
- No 'additive' correction – everything comes from the SK MC or flux

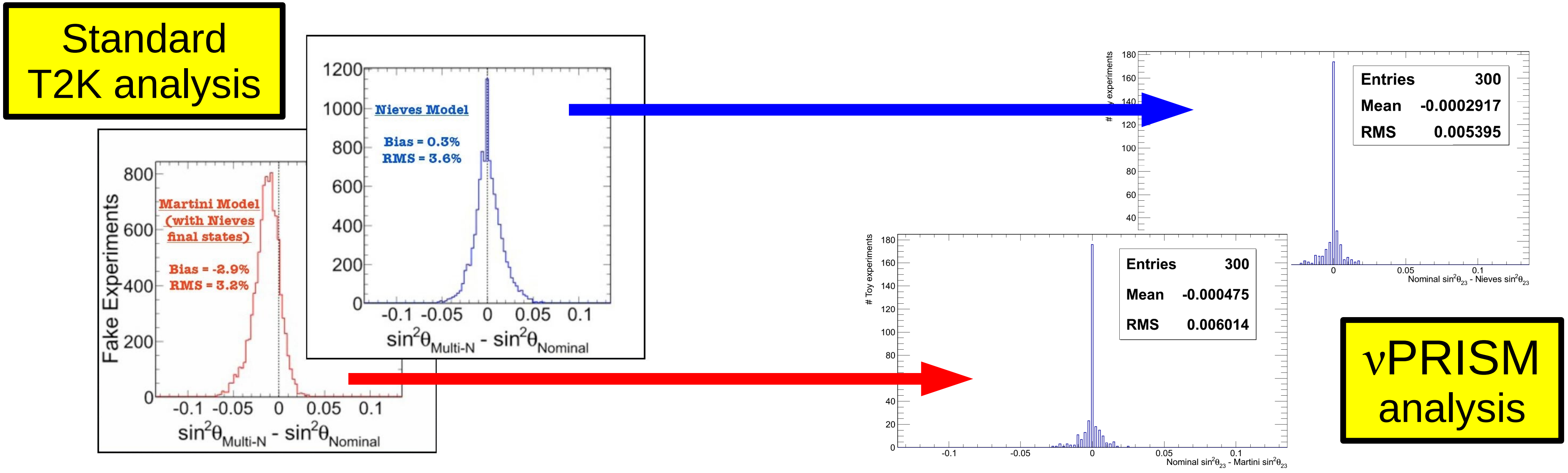
Summary

- nuPRISM is insensitive to mis-modelled nuclear effects in MC
- NuPRISM $\sin^2\theta_{23}$ sensitivity is as good as T2K, but should be better
  - Investigate analysis method
  - Examine each correction in detail
- Also want to produce T2K-like precision vs POT curves and sensitivity to non-maximal $\sin^2\theta_{23}$
- Quite a bit of work for 3 months!
- If anyone wants to get involved feel free to email/speak to me

Backup Slides

ν_μ disappearance analysis status

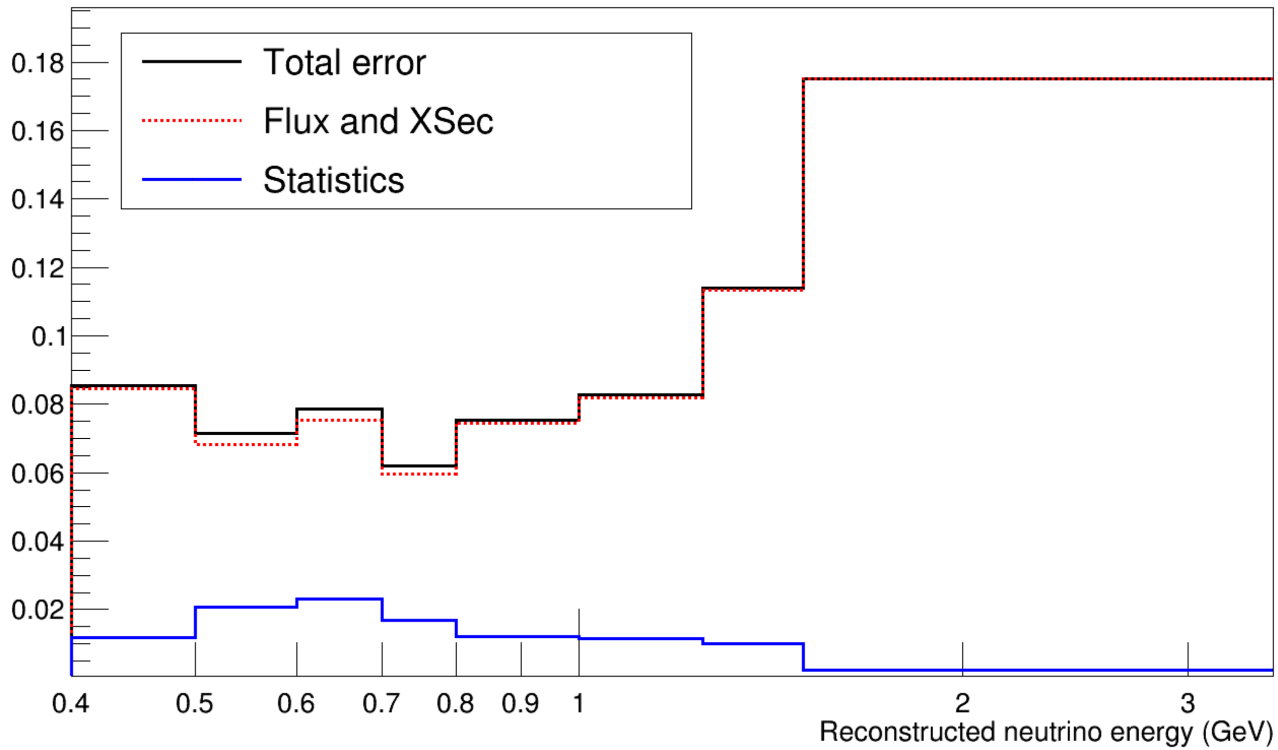
- At 5th HK meeting - νPRISM disappearance analysis unaffected by unknown nuclear model
- Incomplete MC model did not change the fitted oscillation parameters

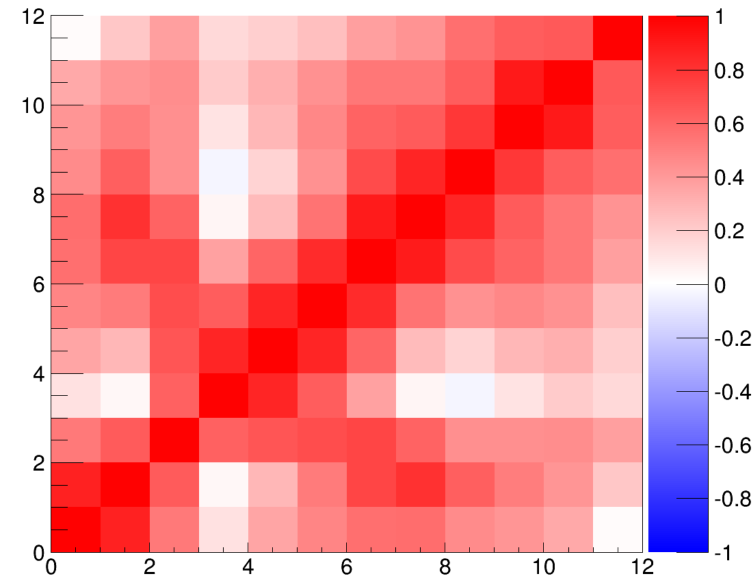


- Bug found in statistical uncertainty calculation:
  - Bug scaled down number of events at νPRISM by factor of 40

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

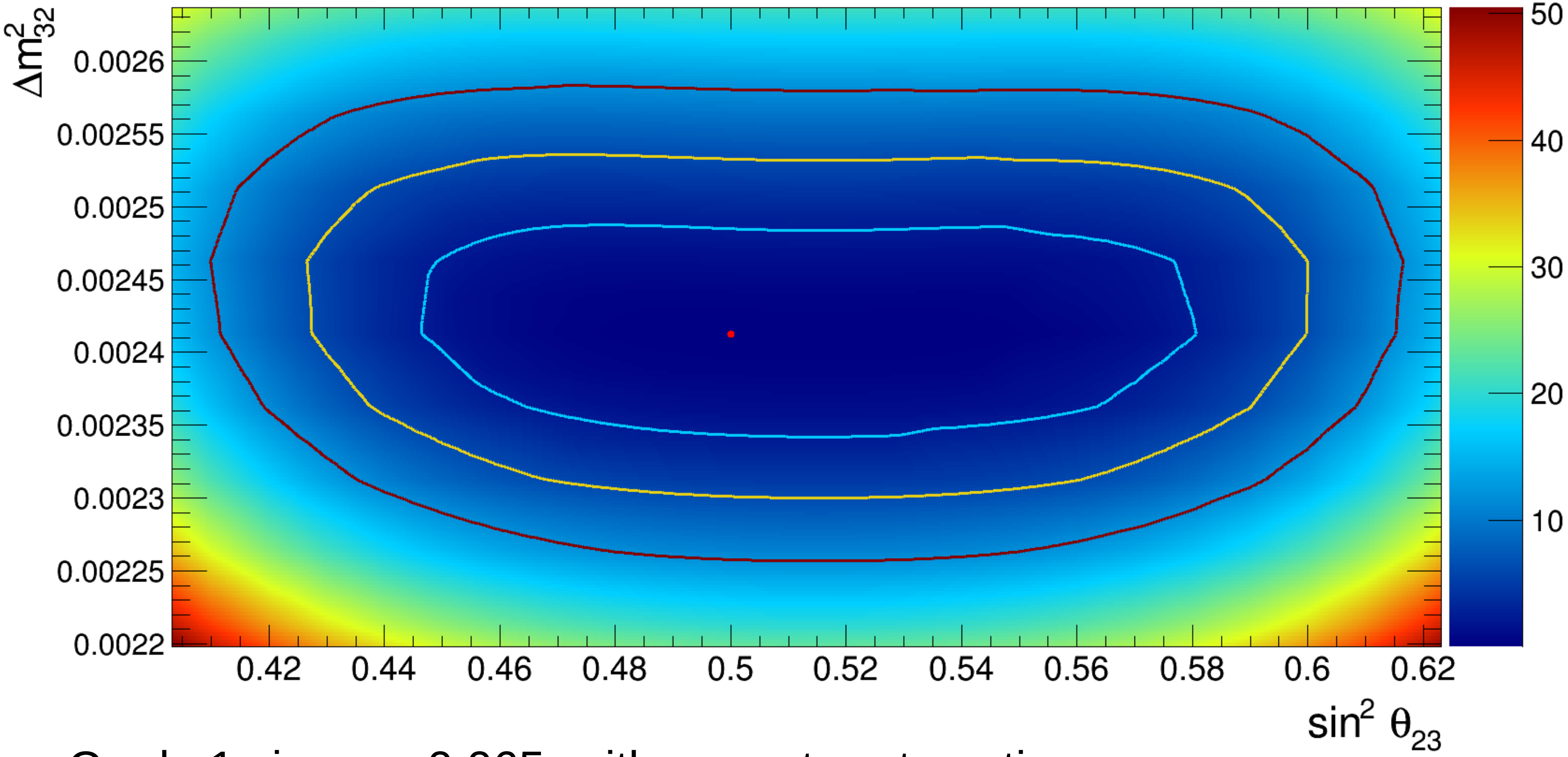
Sensitivity studies

- 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

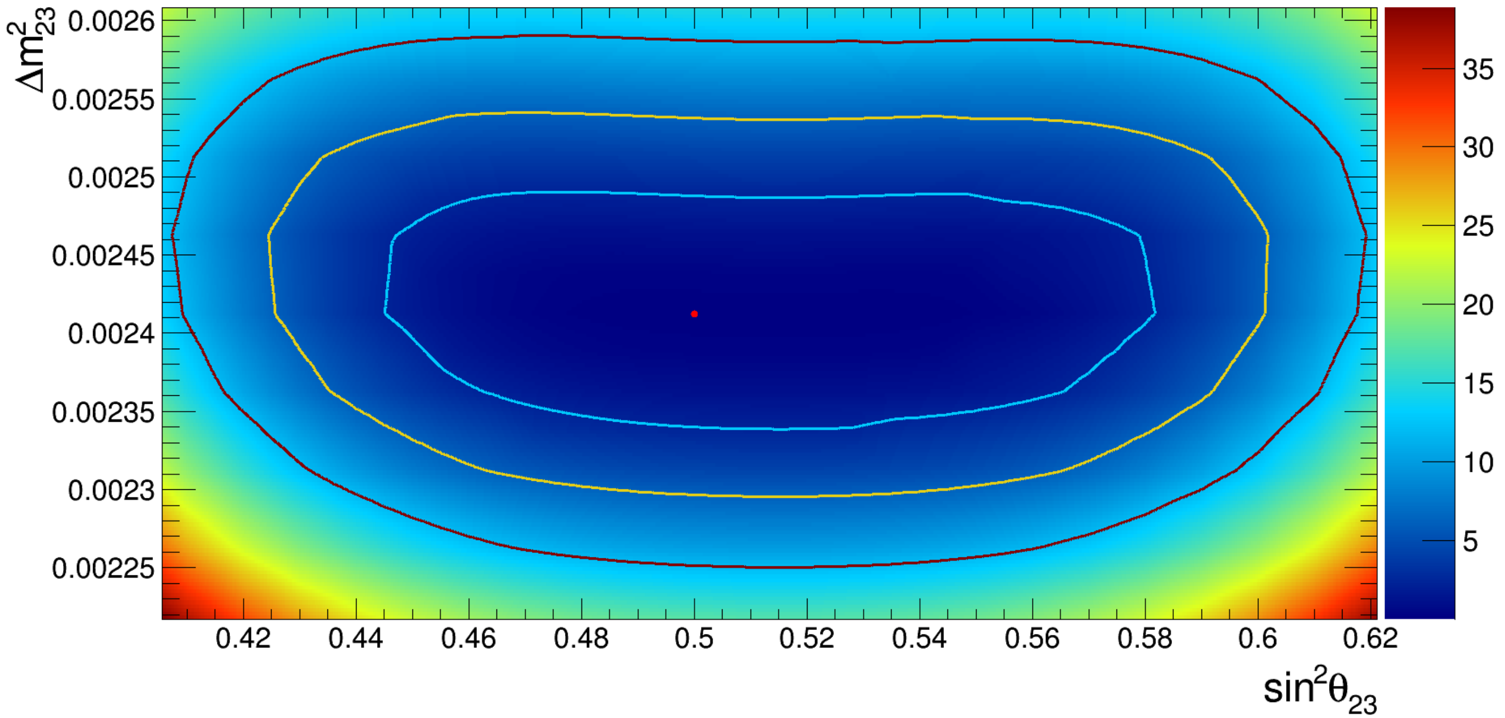


- Crude 1 sigma = 0.065, with current systematics

T2K sensitivity studies 2

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

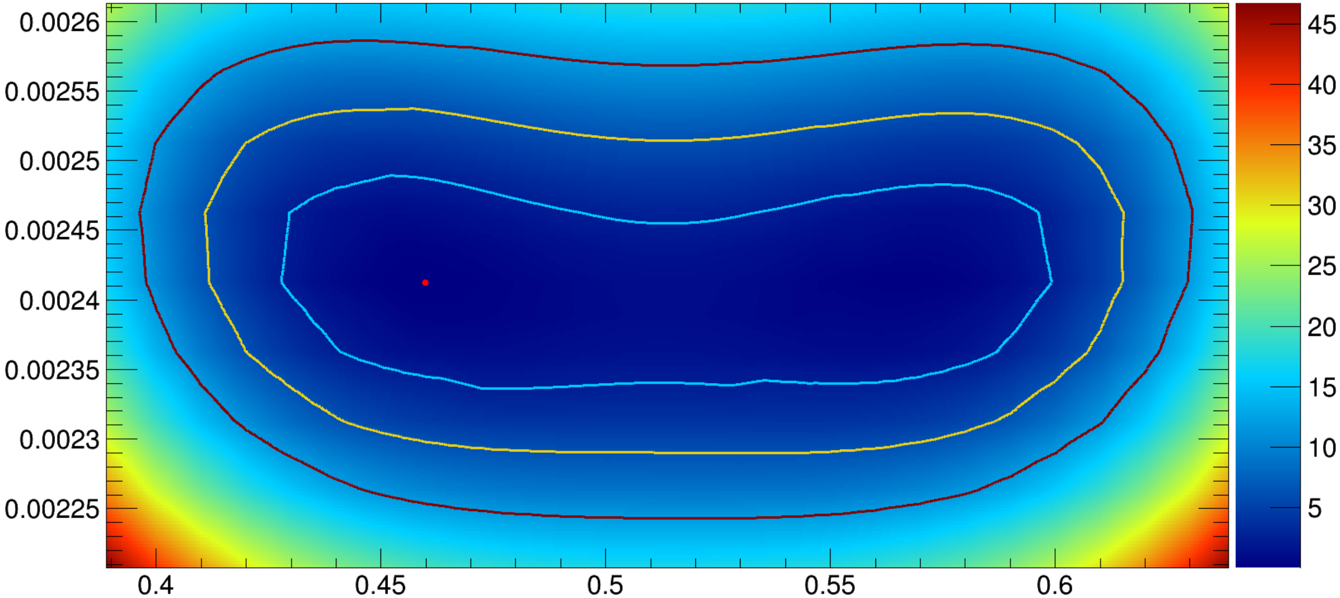
- NuPRISM 1 sigma width = 0.0675
- NuPRISM = T2K
- SK detector errors smaller than this?
- Correlations?



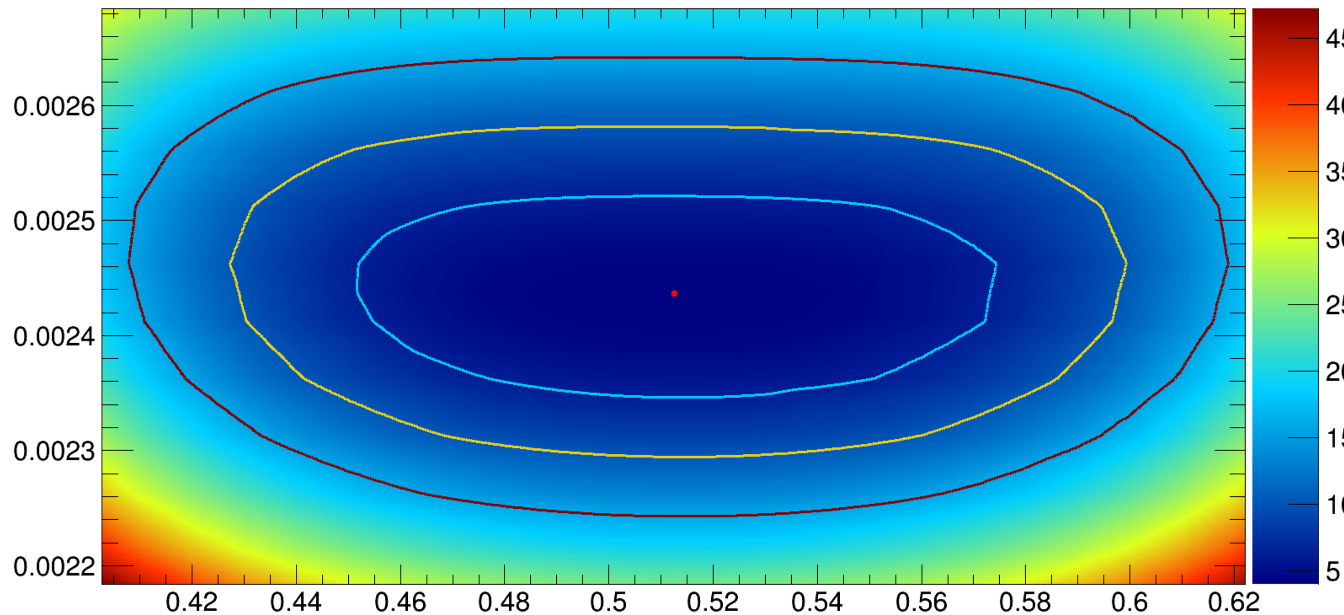
- Conservatively, NuPRISM analysis is equal to the current T2K projected sensitivities

T2K sensitivity studies 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



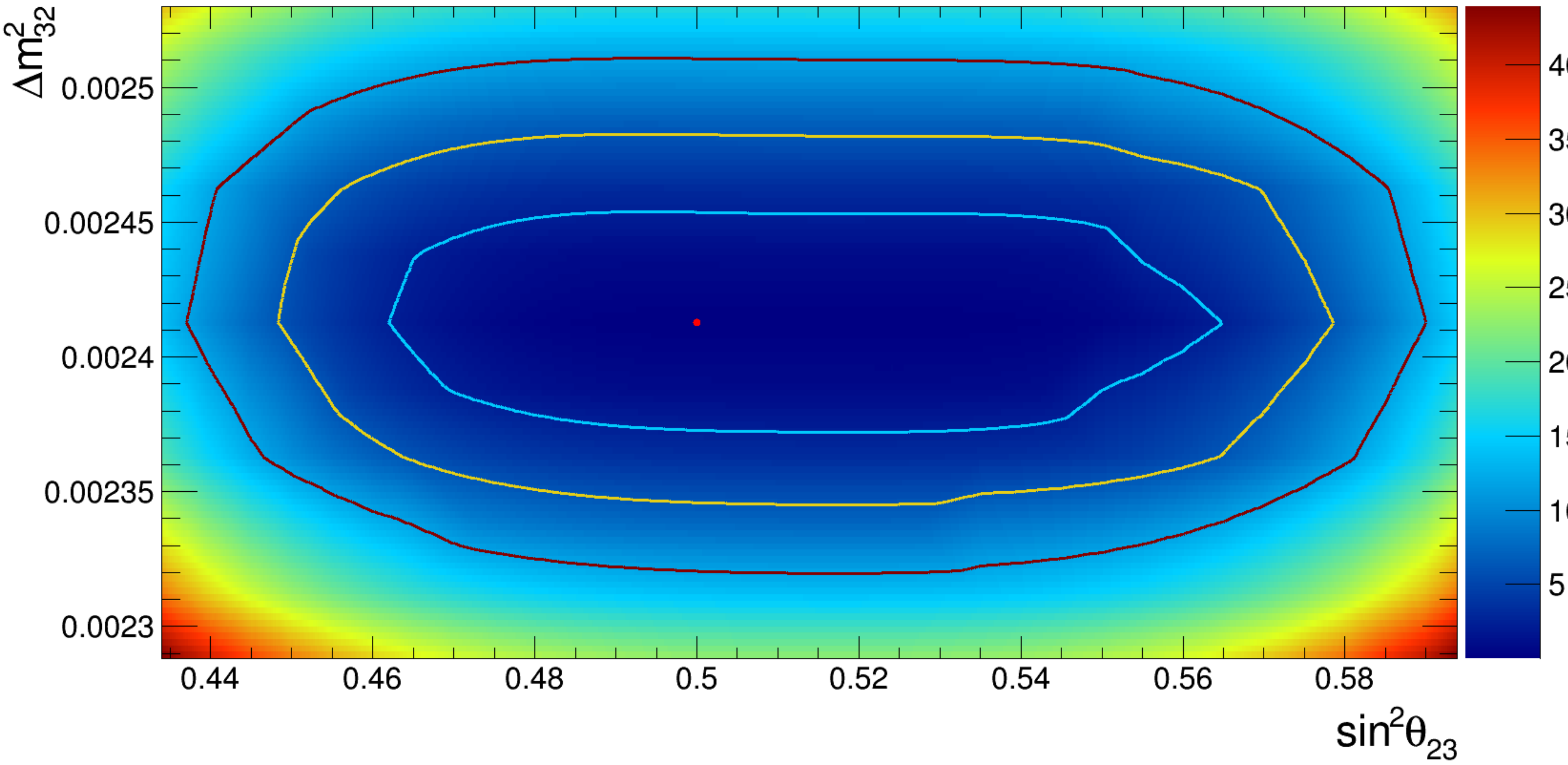
- See expected two-lobed structure when moving away from maximal mixing



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

T2HK sensitivity studies

- 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

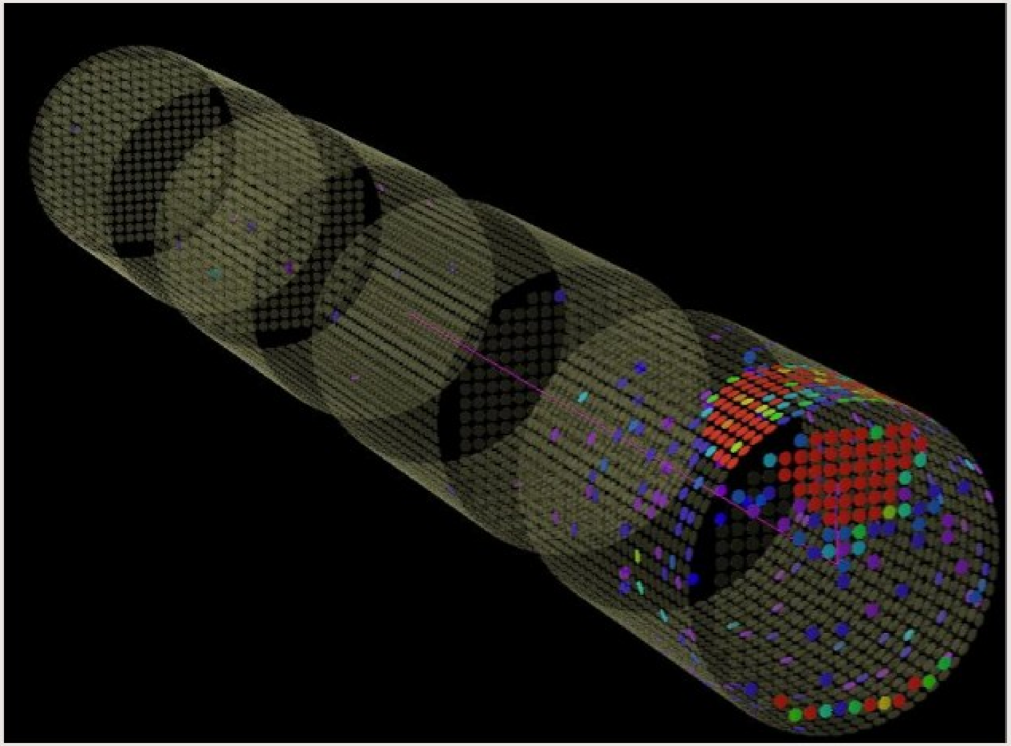
- Identify which flux systematics dominate – can these be reduced?
- Near detector constraint
  - Lets use them
  - Just take BANFF output – easy, but probably wrong
  - Joint fit? - Can't think how to combine with nuPRISM linear combinations
  - Use INGRID + ND280 to constrain flux
    - CC inclusive 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

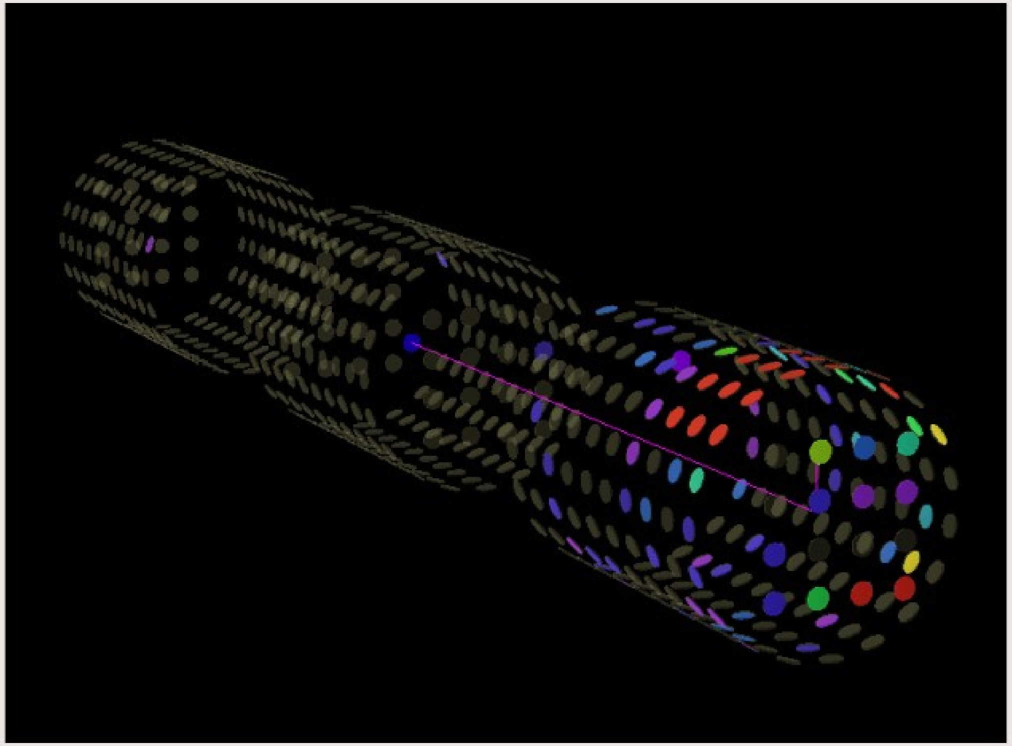
νPRISM simulation

- 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)
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 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

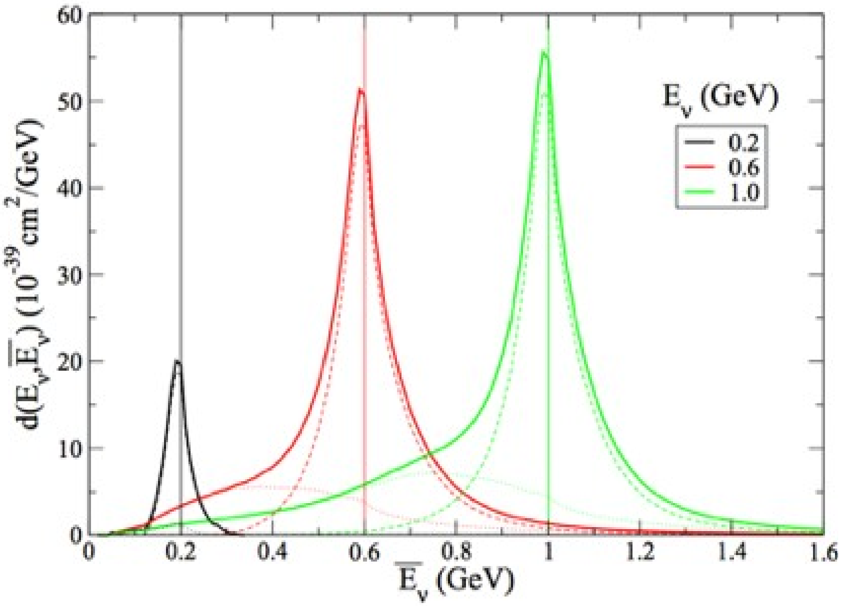
Summary

- 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

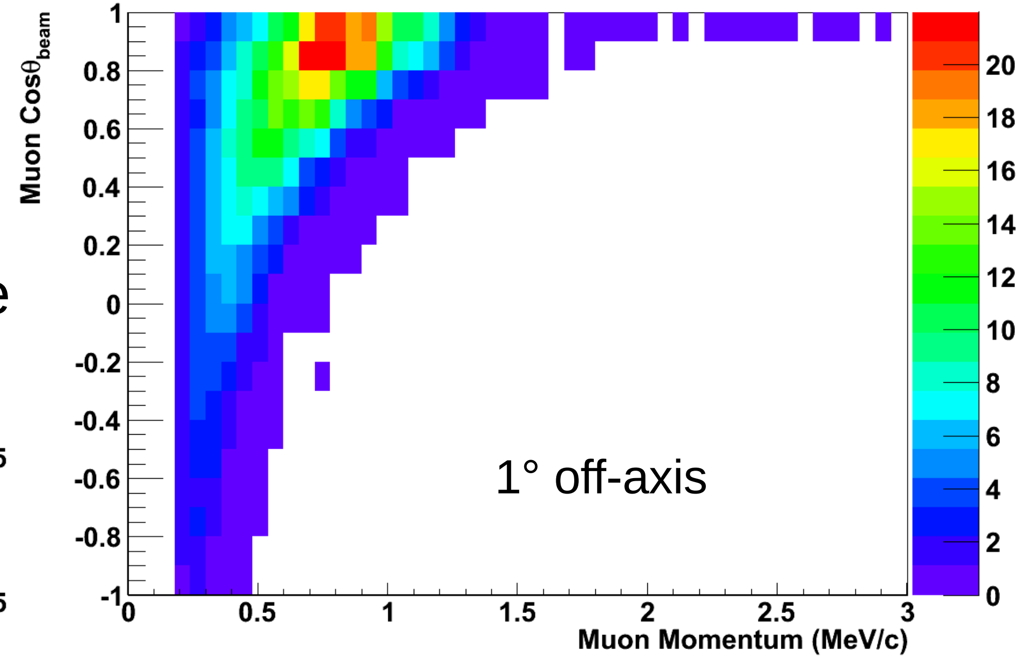
- Using the linear combination method, we can produce Gaussian beams with widths significantly less than an off-axis spectrum peaked at the same energy

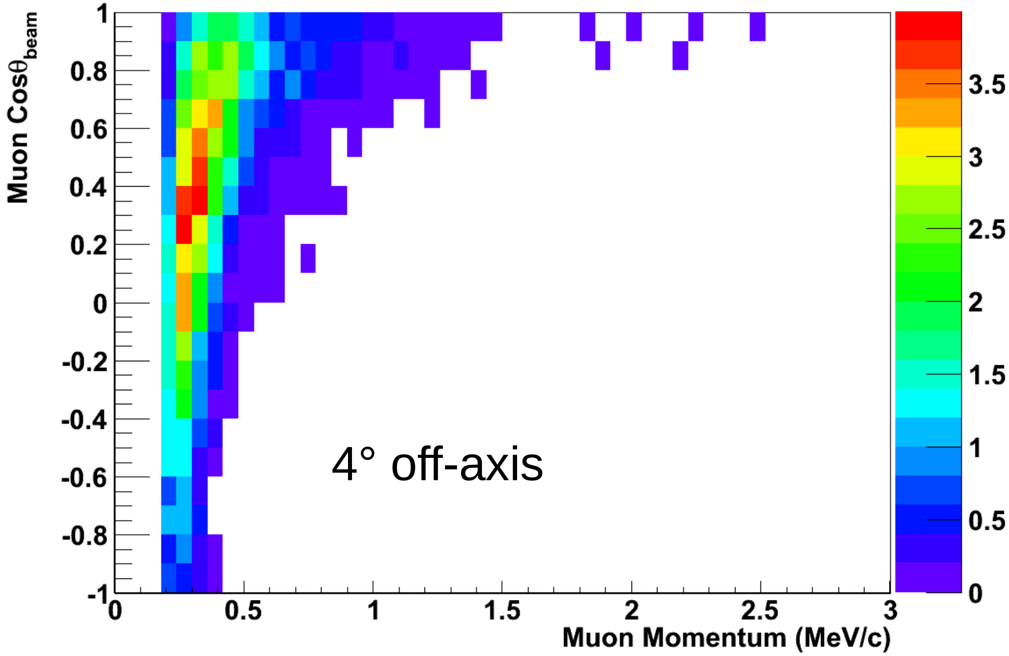
$$G(E_\nu;\mu,\sigma)=\sum_{i=1}^{\#\text{ of Off-axis bins}} c_i\varphi_i(E_\nu)$$

- 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

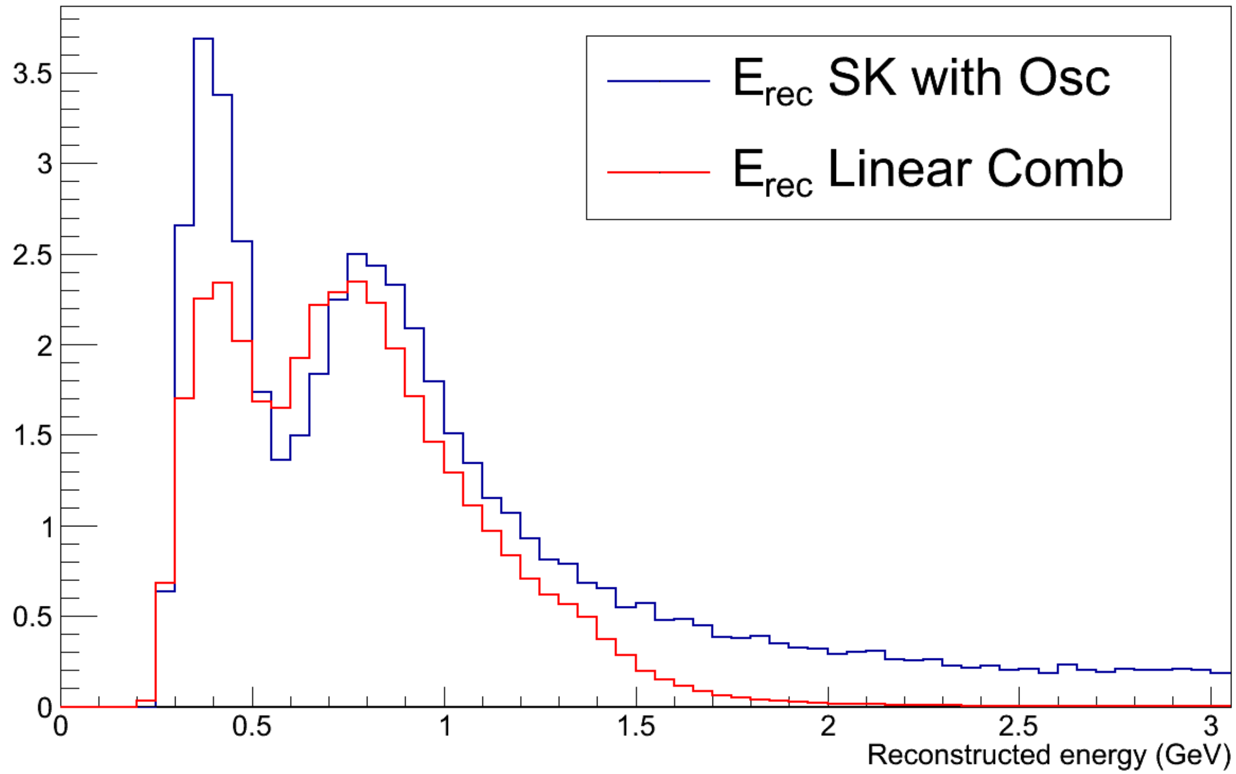




- Record the off-axis angle of the interaction, using the reconstructed vertex position

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



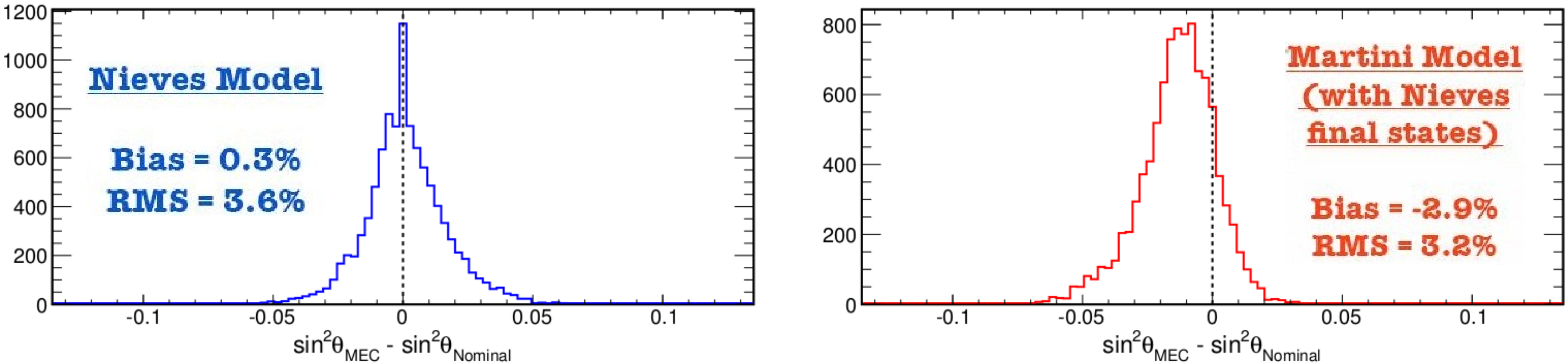
- To νPRISM data:
  - Background subtraction
  - Efficiency correction
  - Addition of selected SK background
- Introduce some model dependence

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

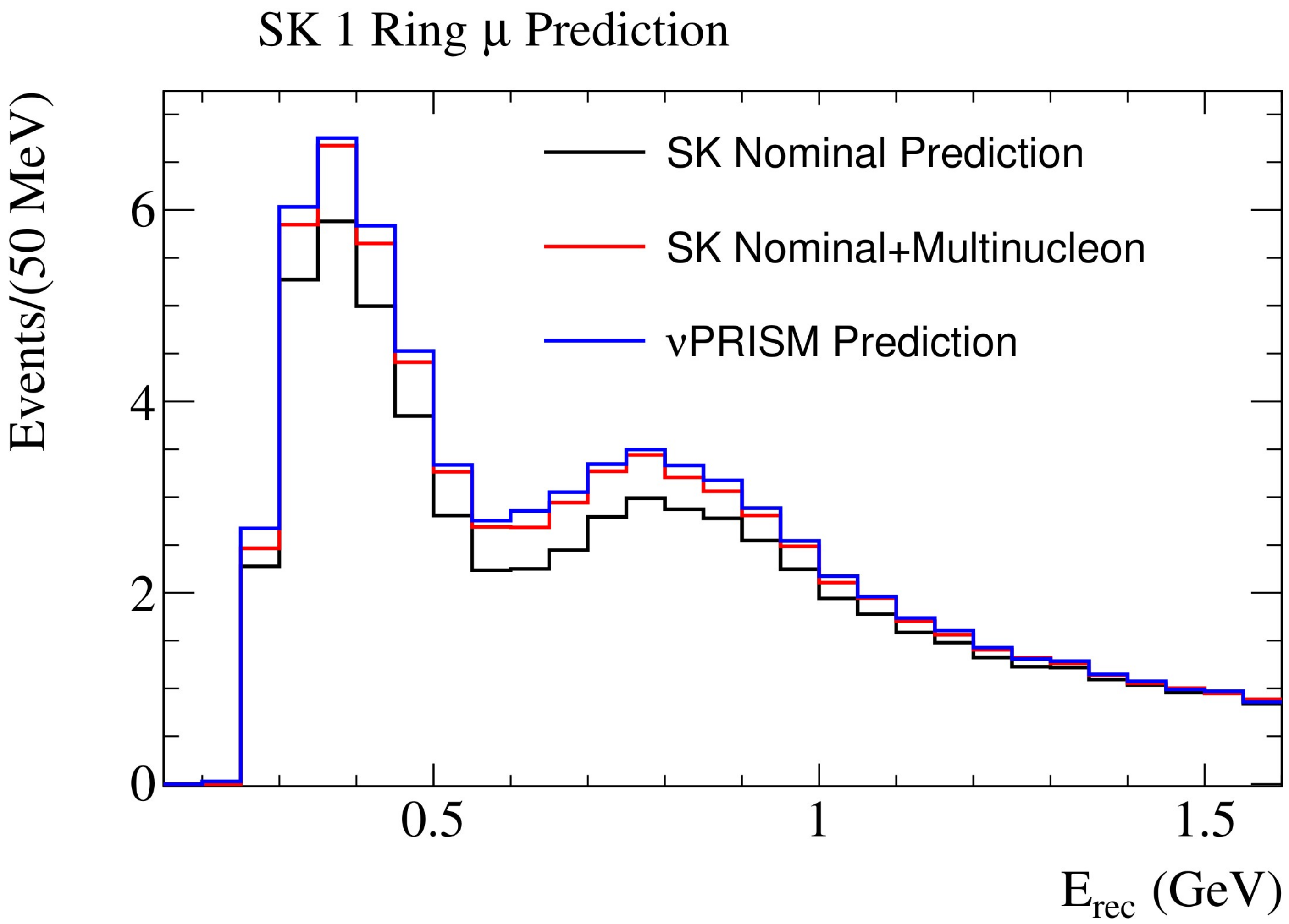
- MC-based analysis using full detector simulation, full systematics etc.
- Three fake datasets
  - Nominal NEUT MC
  - NEUT + meson exchange current (MEC) events from Nieves' model - Phys. Rev. C, 83:045501, Apr 2011
  - NEUT + MEC events based on Martini's model - Phys. Rev. C, 81:045502, Apr 2010
- 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



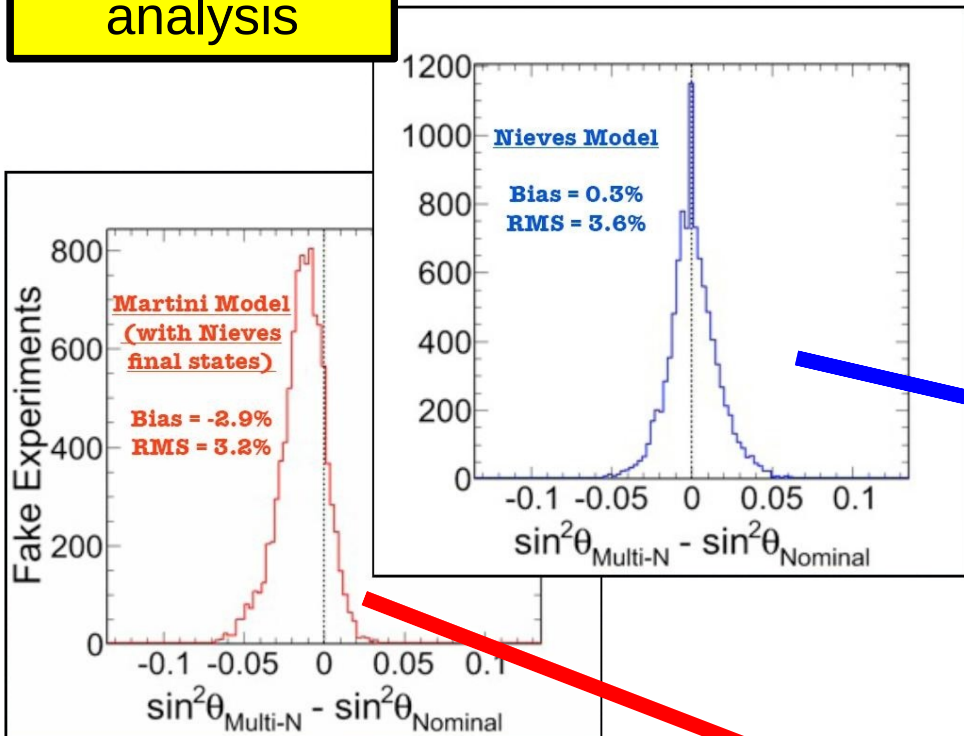
- See νPRISM prediction still reproduces oscillated SK spectrum when multi-nucleon events are present

Effect of multi-nucleon events at νPRISM

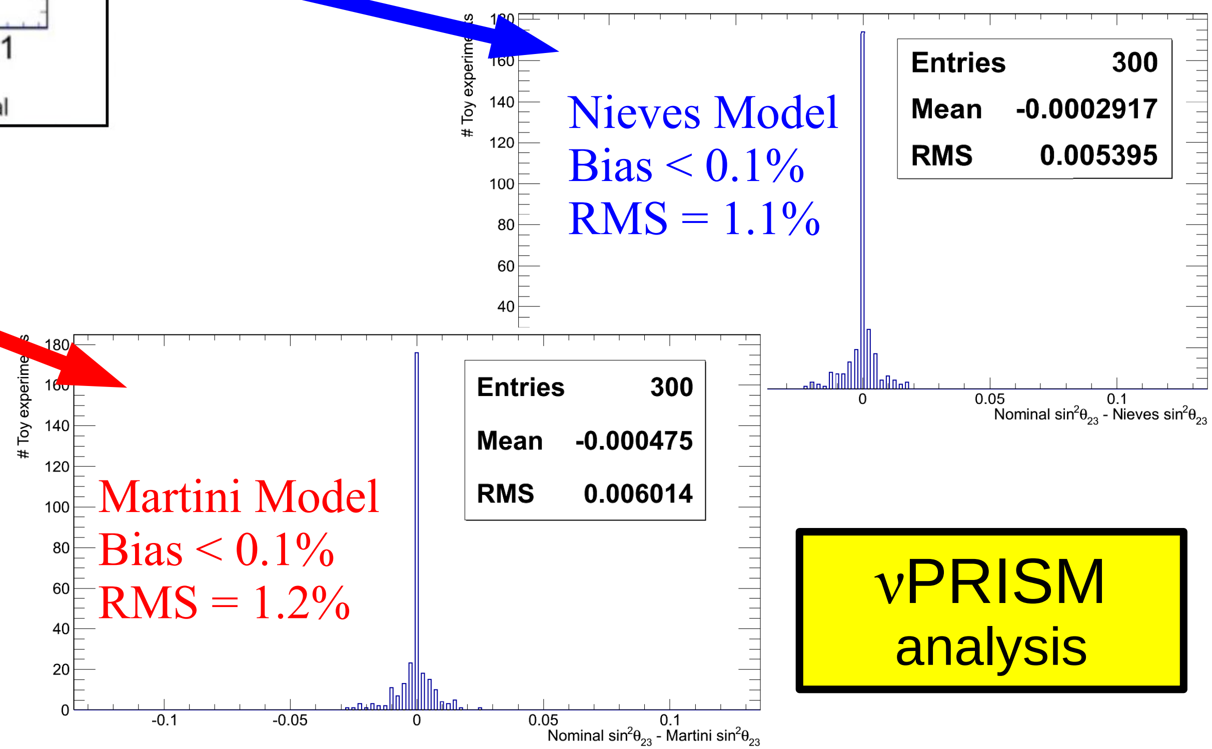
νPRISM

TRIUMF

Standard T2K analysis



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

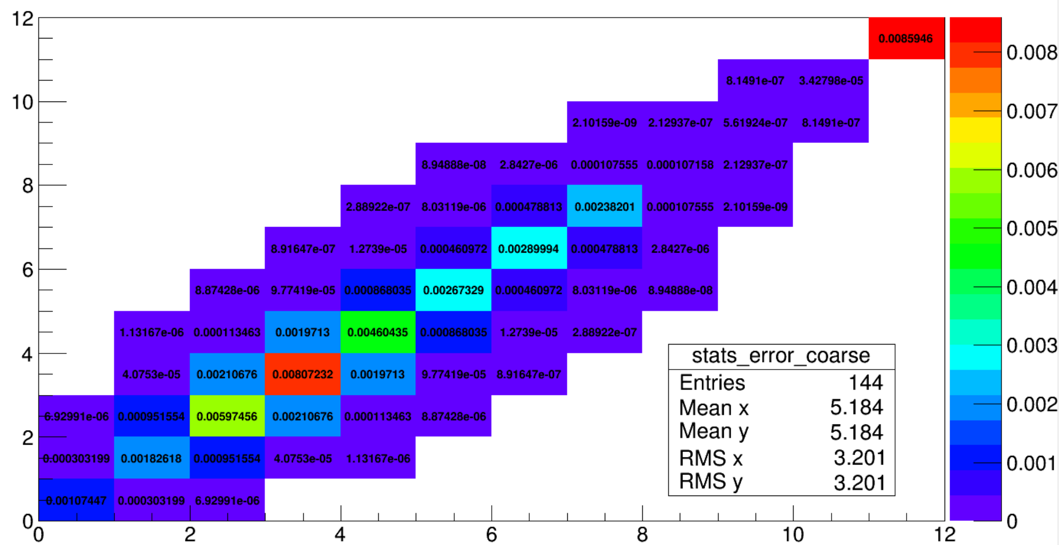


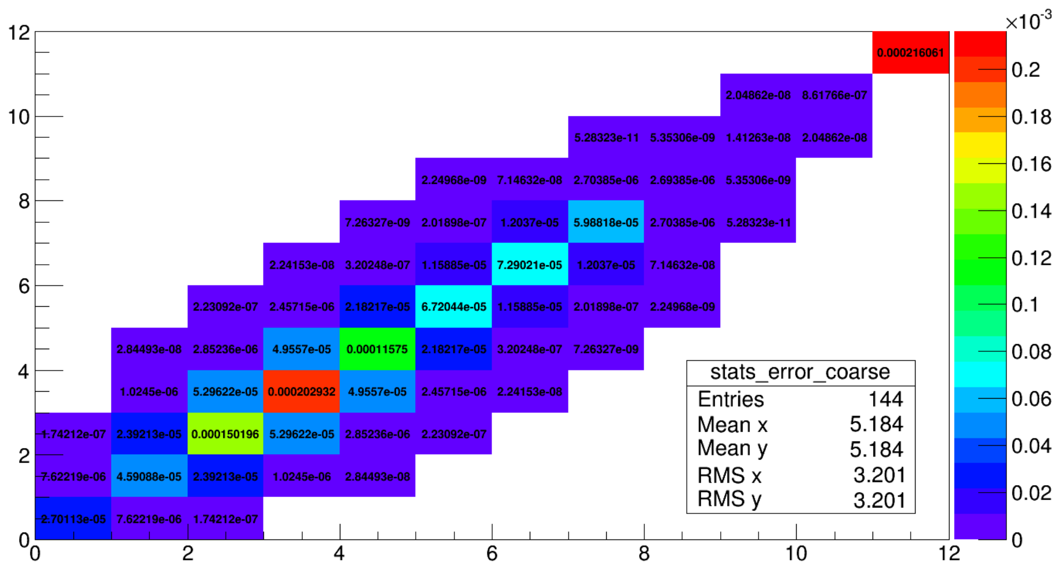
- νPRISM analysis largely independent of cross section model

νPRISM analysis

Validating the bug fix

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

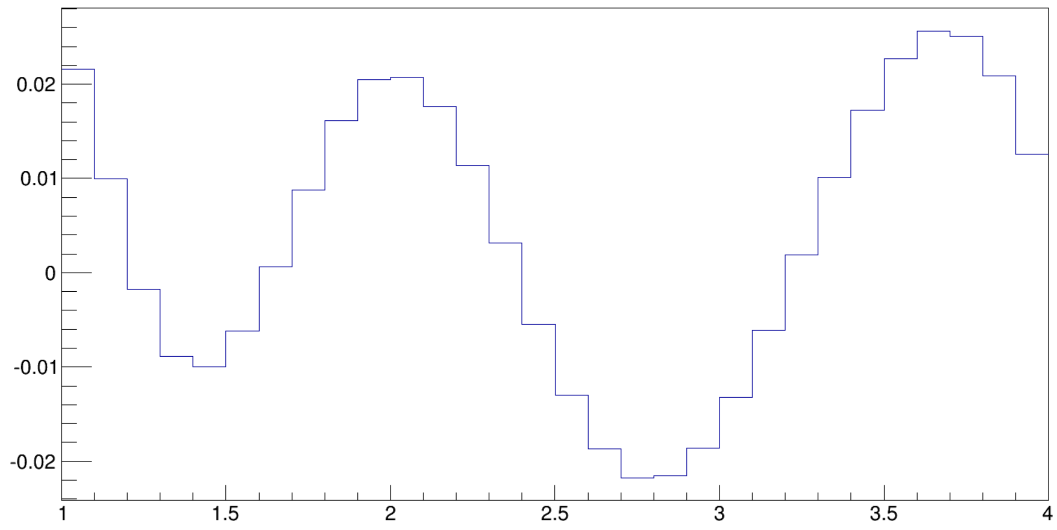


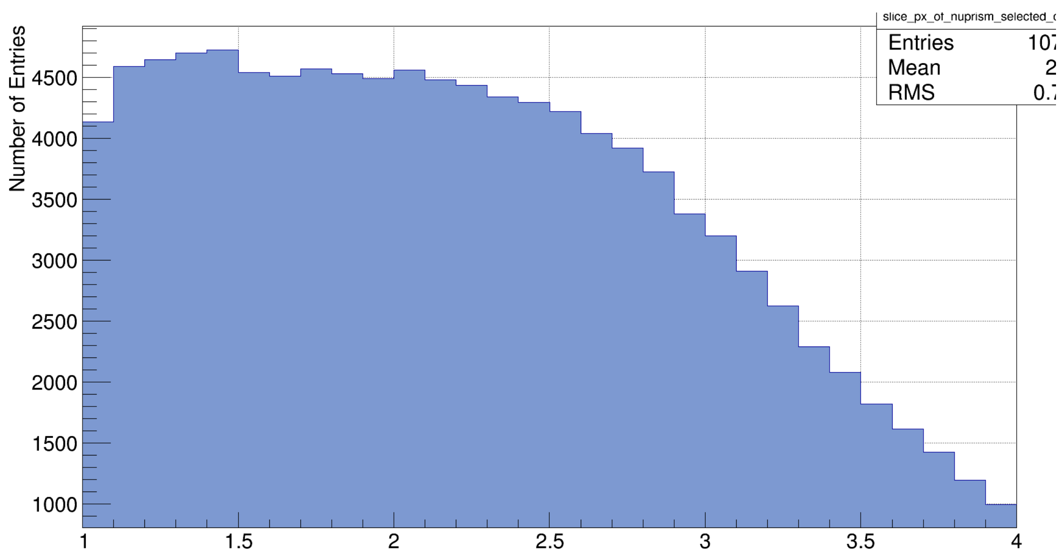


- Statistical uncertainty covariance matrix
- Buggy code on top, fixed code beneath
- In buggy code see statistical uncertainty of 8.8% in largest bin
  - Roughly same size as in analysis presented at last T2K meeting
  - Difference due to different oscillation parameters
- In fixed code, uncertainty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

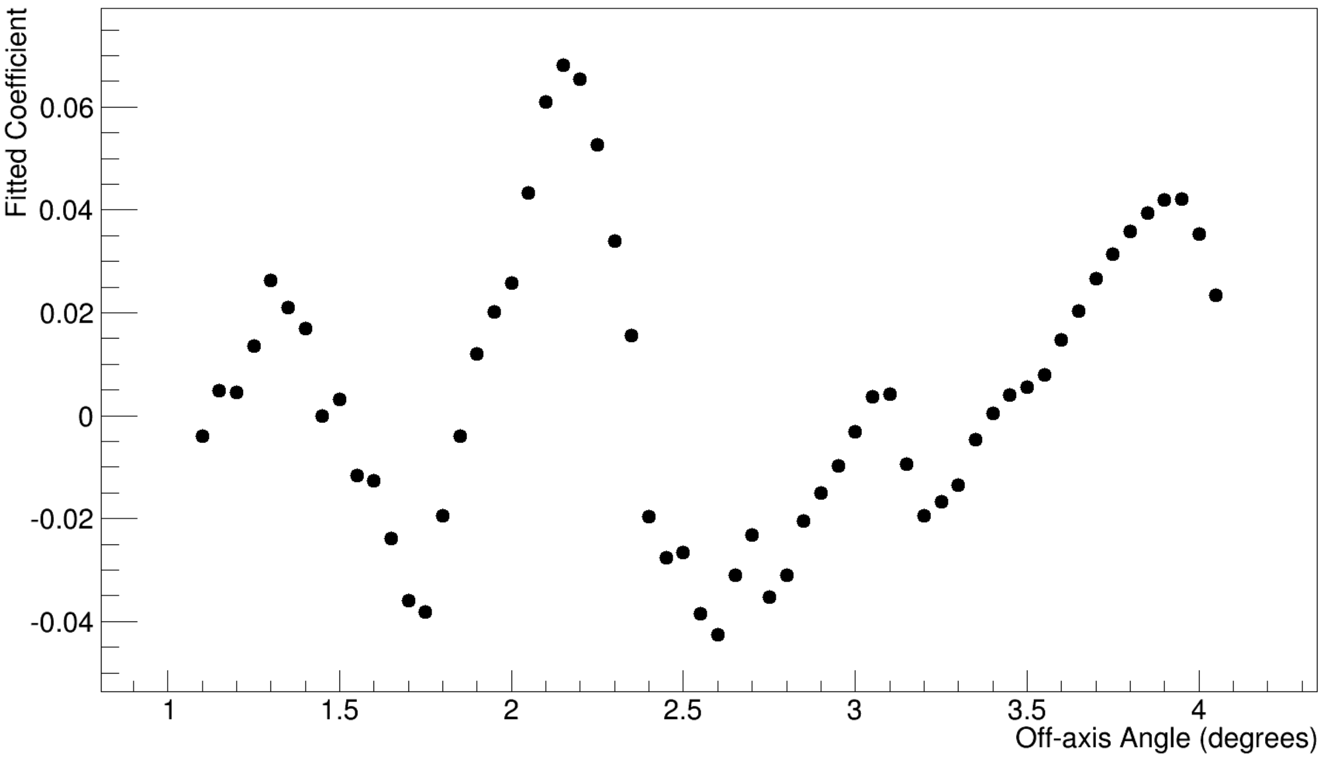
- N_Events = 220
- Error = 4.8
- Fractional error = 2.2%

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

New coefficients

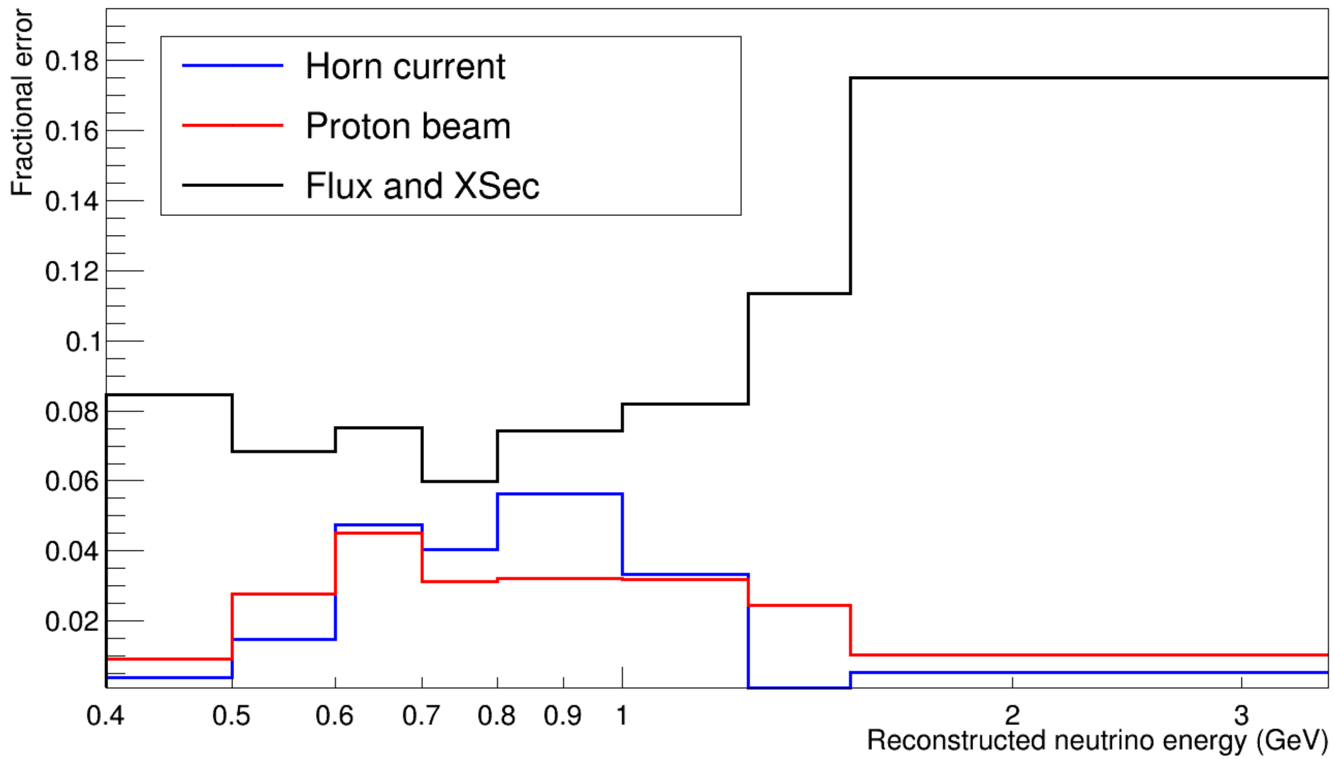
- Coefficients not as smooth as before
- Built on previous work to improve fit



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

Flux systematics

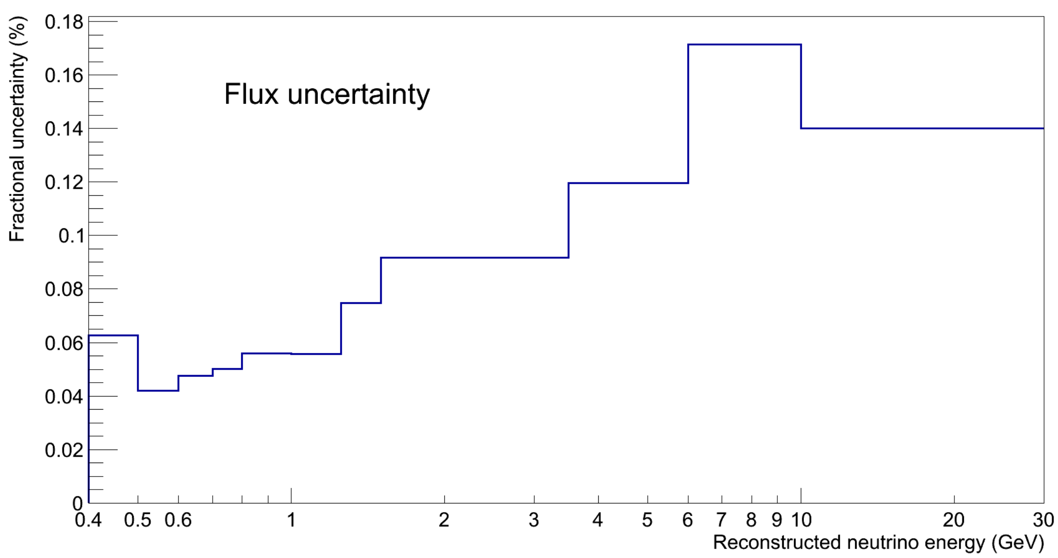
- Flux uncertainty increased from 5% to 7% at oscillation dip
- Largely driven by proton beam and horn current uncertainties

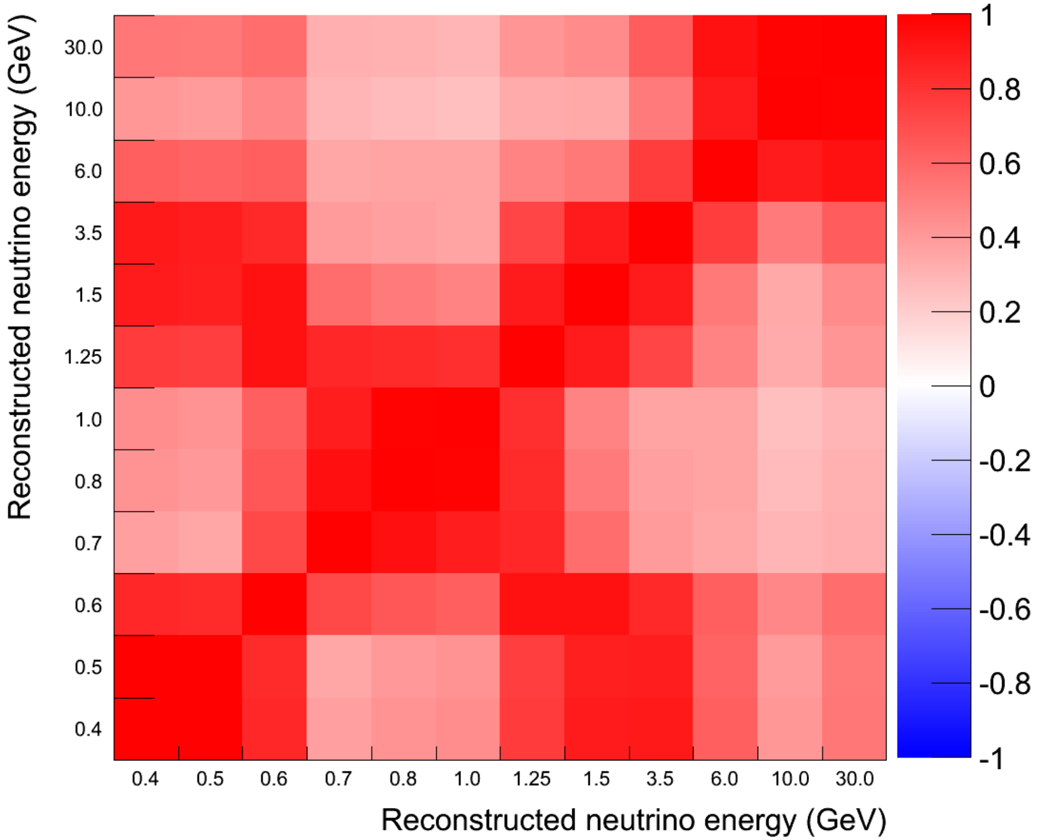


- Not unexpected:
  - More variation between neighbouring coefficients
  - Systematics that effect off-axis angle flux have bigger effect

Old flux uncertainty

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

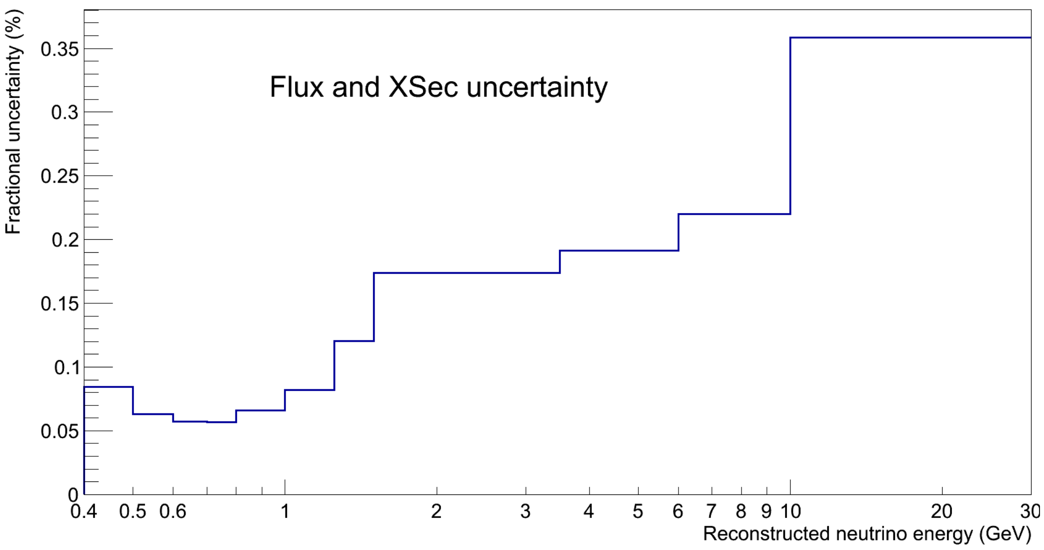


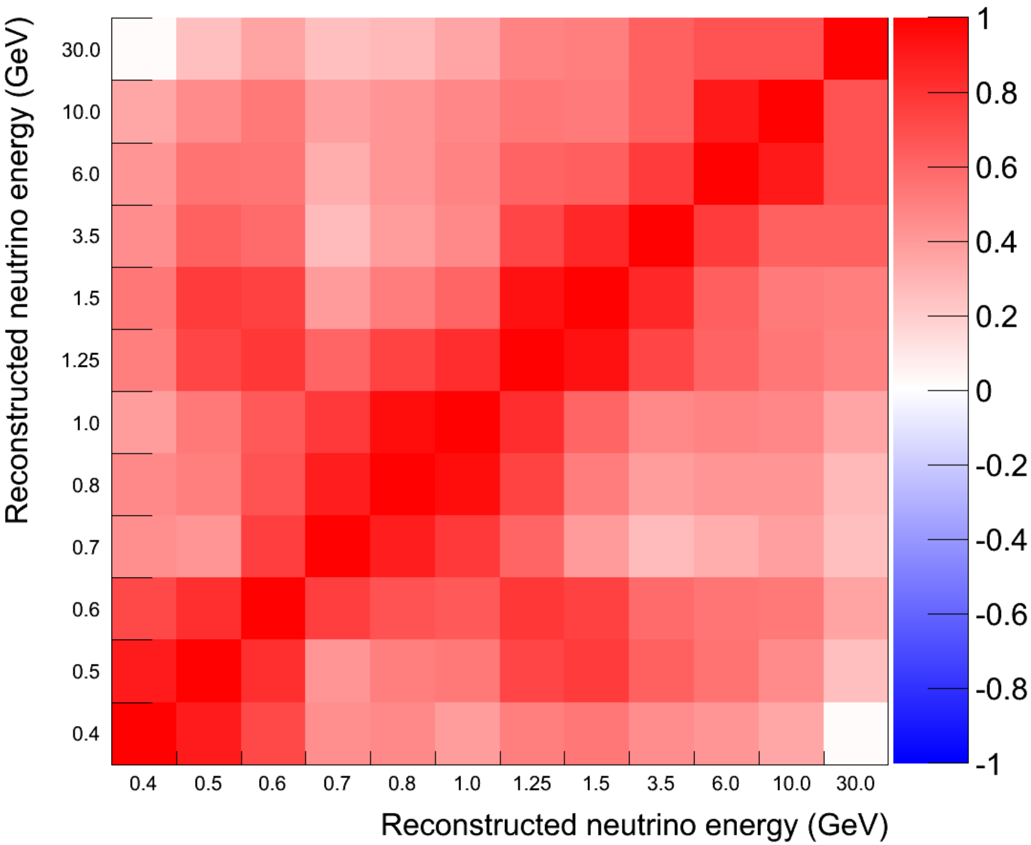


- Larger errors at high energy – no νPRISM events
- Error at oscillation dip around 4-5%

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

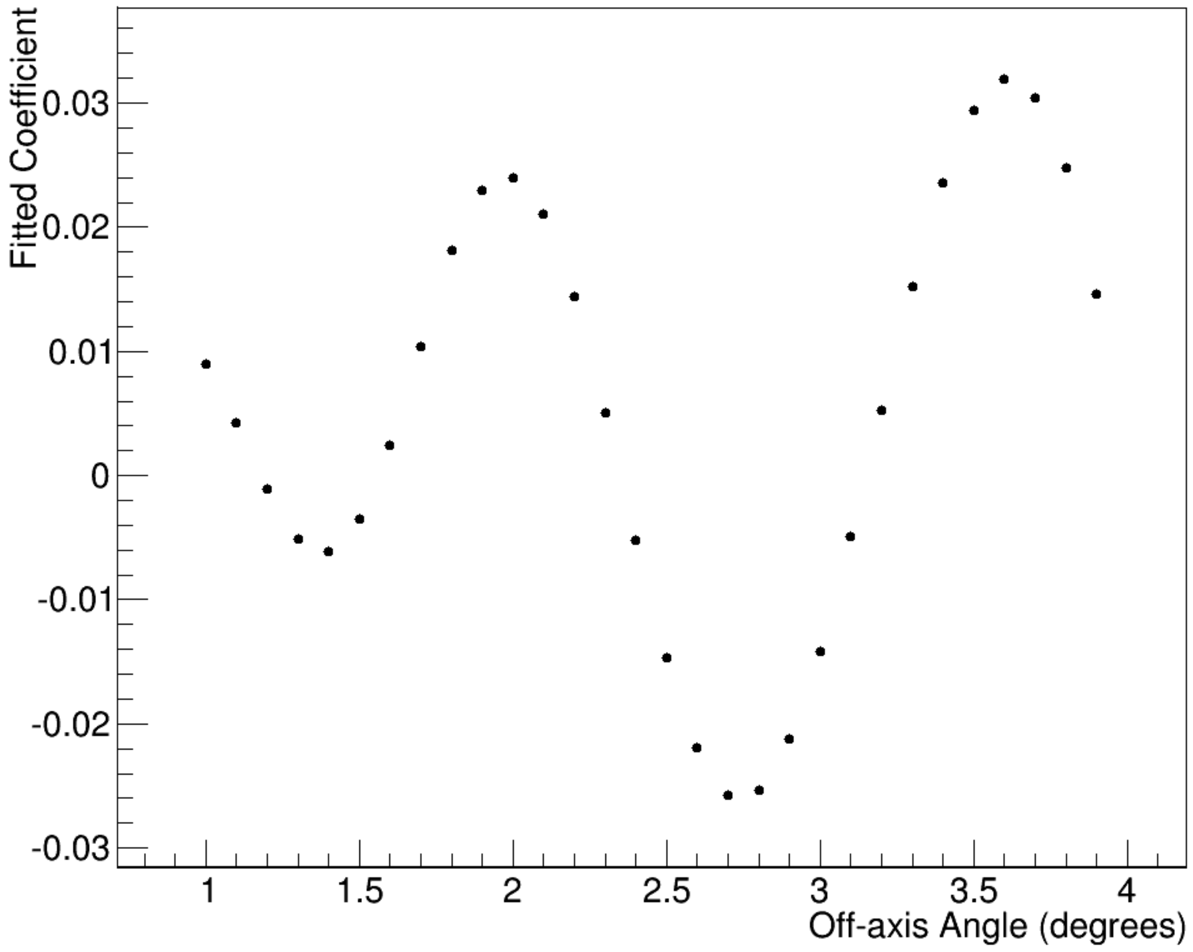




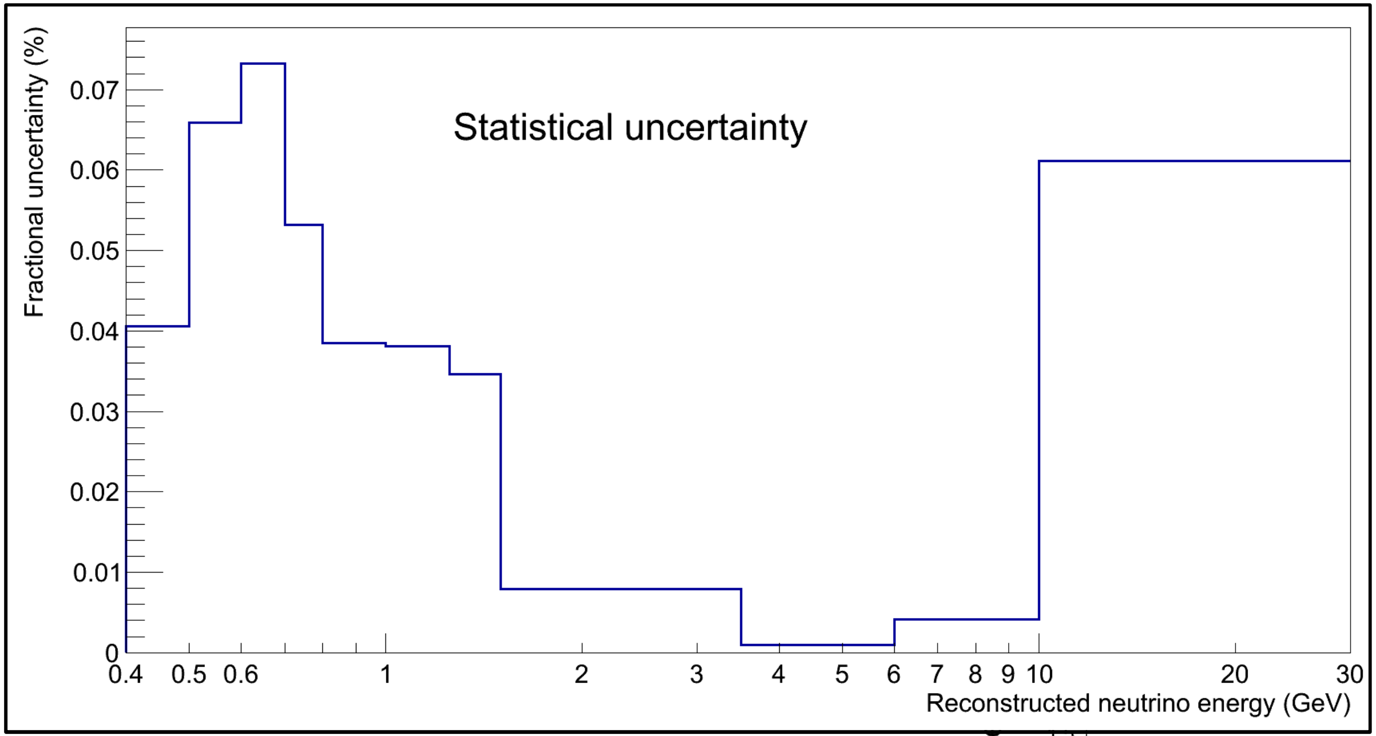
- Combined flux and cross section uncertainty around 5% at the oscillation dip

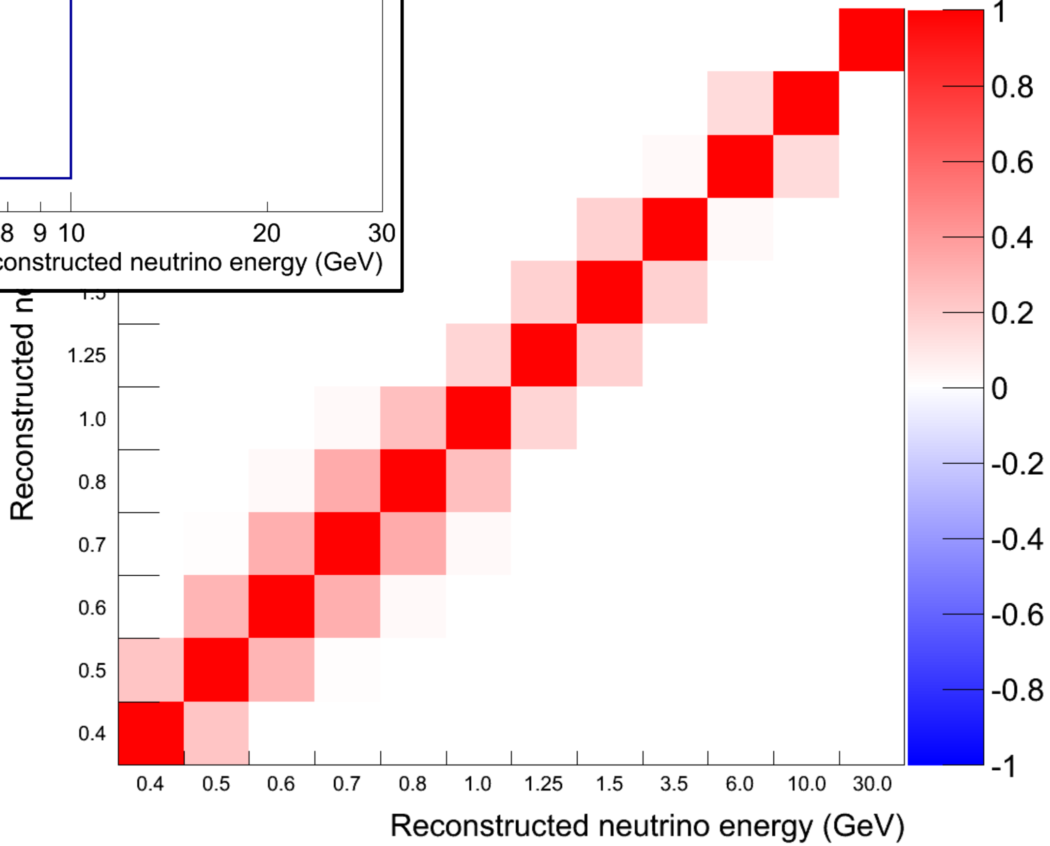
Old coefficients

- 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