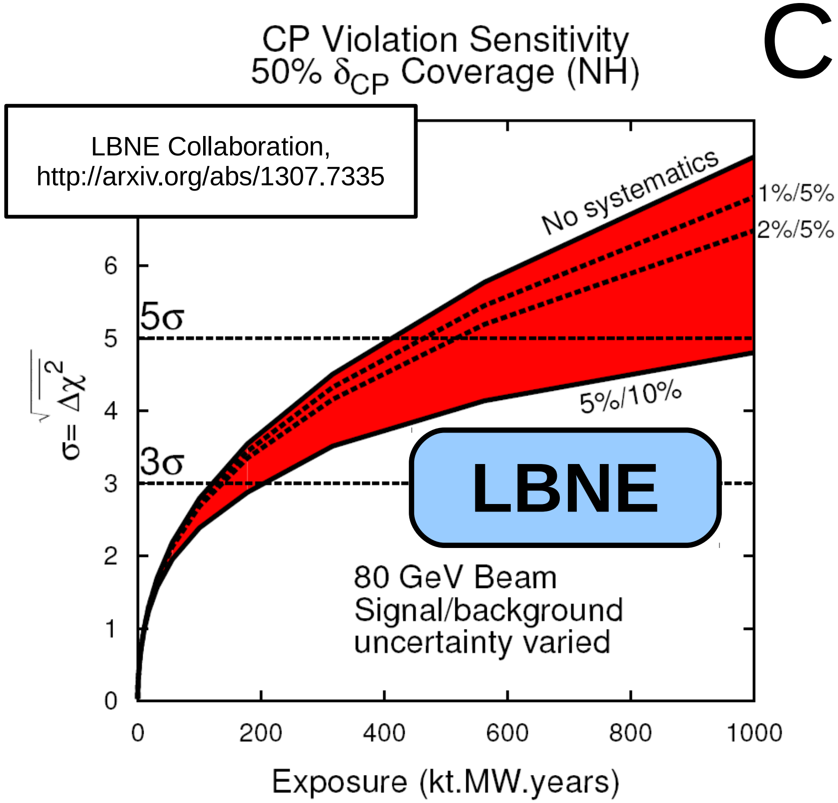
# $\nu$PRISM: A new way of probing neutrino interactions

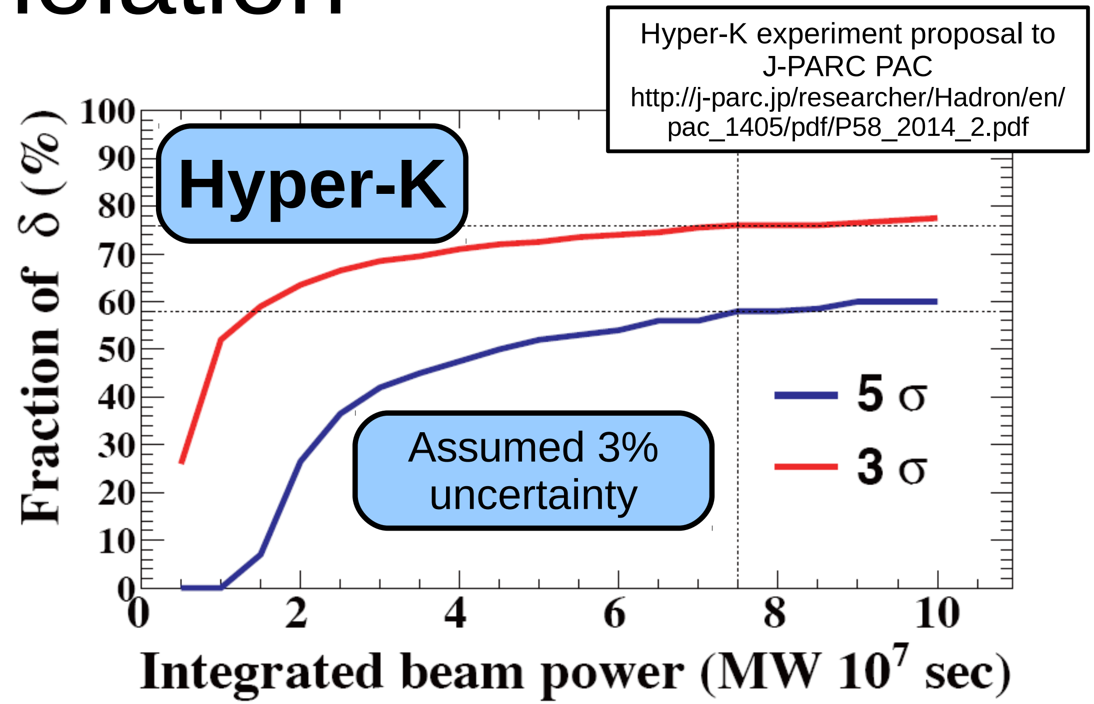
Mark Scott

NuFact 2014, Glasgow

TRIUMF

# Discovering leptonic CP violation




## T2K systematic uncertainty

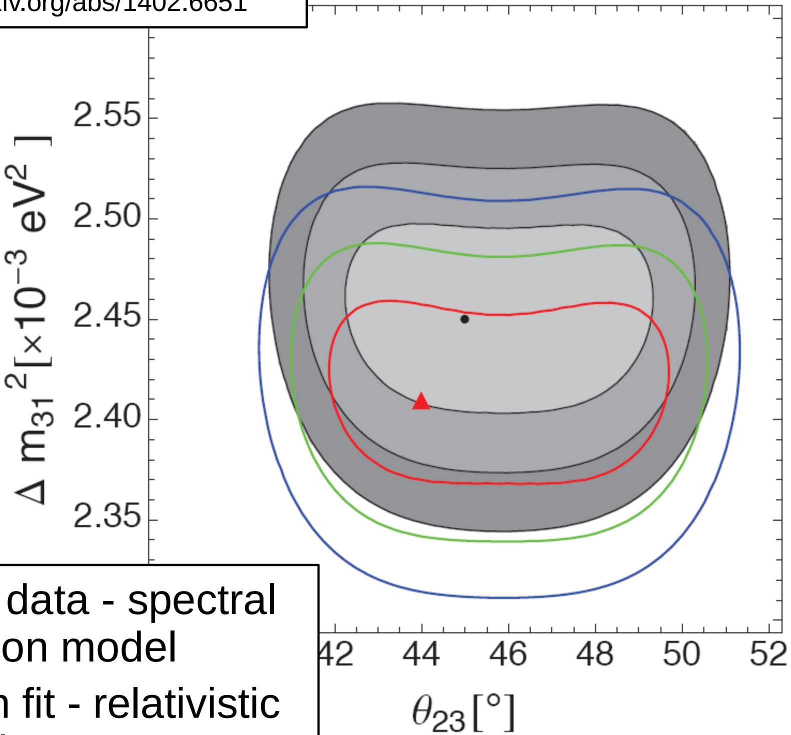
| | | $\nu_\mu$ sample | $\nu_e$ sample |
|---|---|---|---|
| ν flux and cross section | w/o ND measurement | 21.8% | 26.0% |
| | w/ ND measurement | 2.7% | 3.1% |
| ν cross section due to difference of nuclear target btw. near and far | | 5.0% | 4.7% |
| Final or Secondary Hadronic Interaction | | 3.0% | 2.4% |
| Super-K detector | | 4.0% | 2.7% |
| total | w/o ND measurement | 23.5% | 26.8% |
| | w/ ND measurement | 7.7% | 6.8% |

Fractional error on number-of-event prediction

- Future experiments will be systematics limited
- To meet P5 requirement (75% δCP coverage at 3σ):
  - Hyper-K = 3% **total** uncertainty
  - LBNF = 1% **total** uncertainty
- Neutrino interaction uncertainties dominate

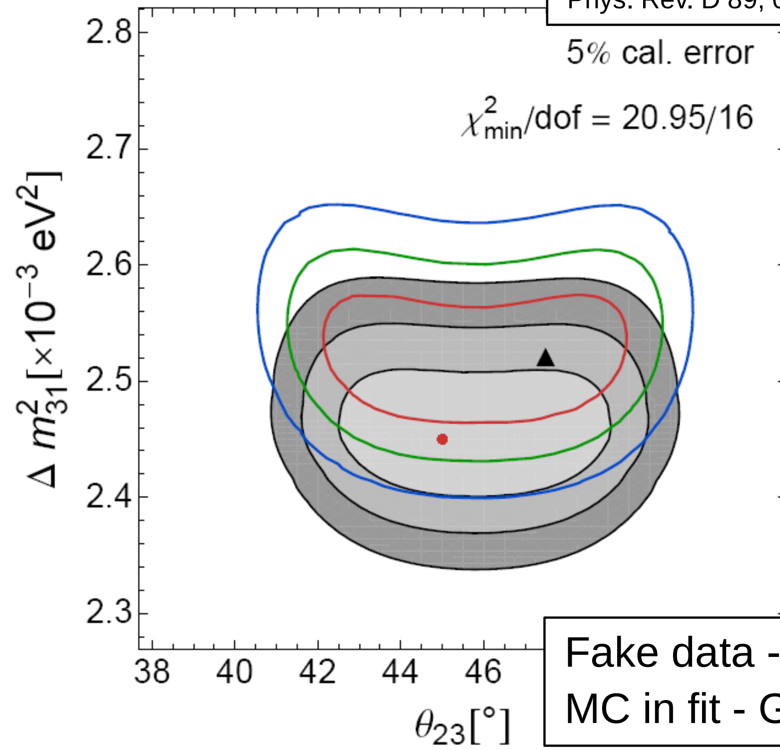
# What if our models are wrong?

C.-M. Jen *et al.*
http://arxiv.org/abs/1402.6651




Fake data - spectral function model
MC in fit - relativistic Fermi Gas

P. Coloma *et al.*
Phys. Rev. D 89, 073015 (2014)

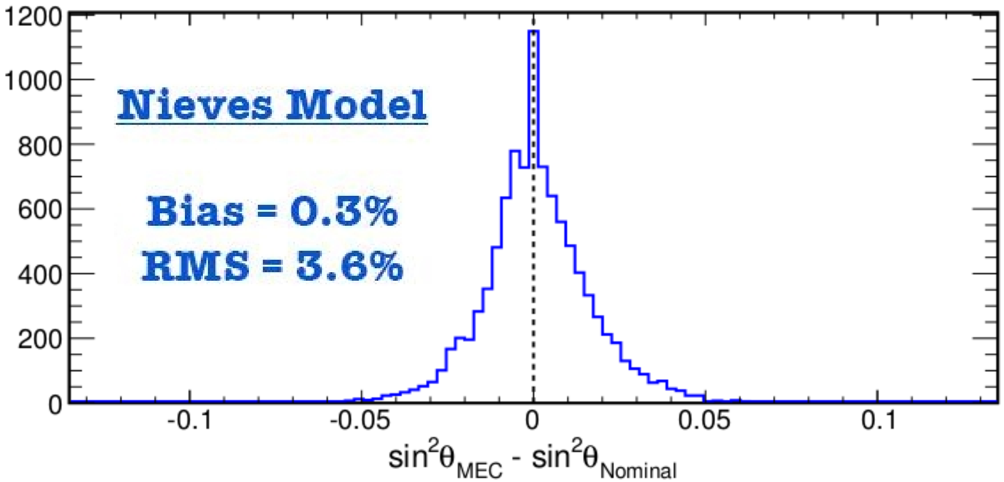


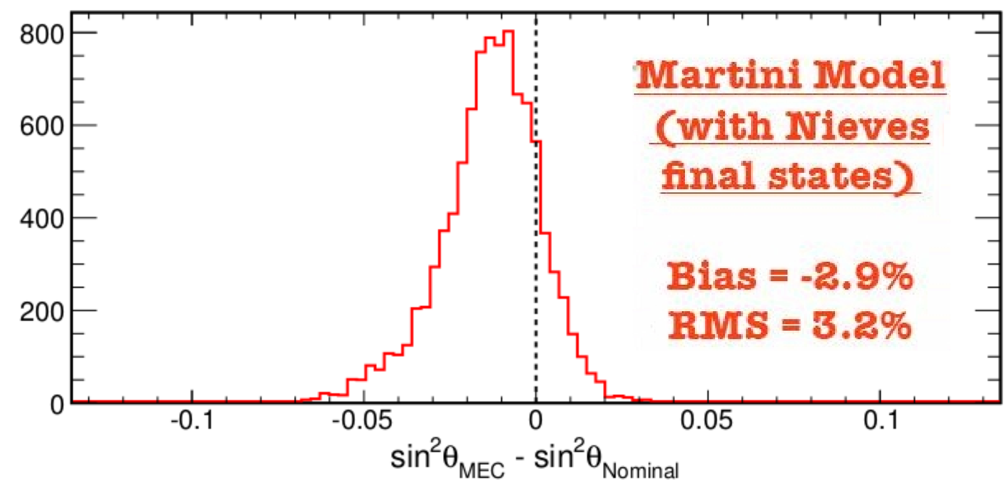

Fake data - GiBUU
MC in fit - GENIE

- Simulate a “T2K-like” experiment for muon neutrino disappearance analysis:
  - Shaded regions – perform fit using same model as fake data
  - Coloured lines – Fit results using a different nuclear model
  - Triangle/Dot – Best fit point

# 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 from Martini's model - Phys. Rev. C, 81:045502, Apr 2010
- Perform disappearance fit to extract $\theta_{23}$ in each case and compare



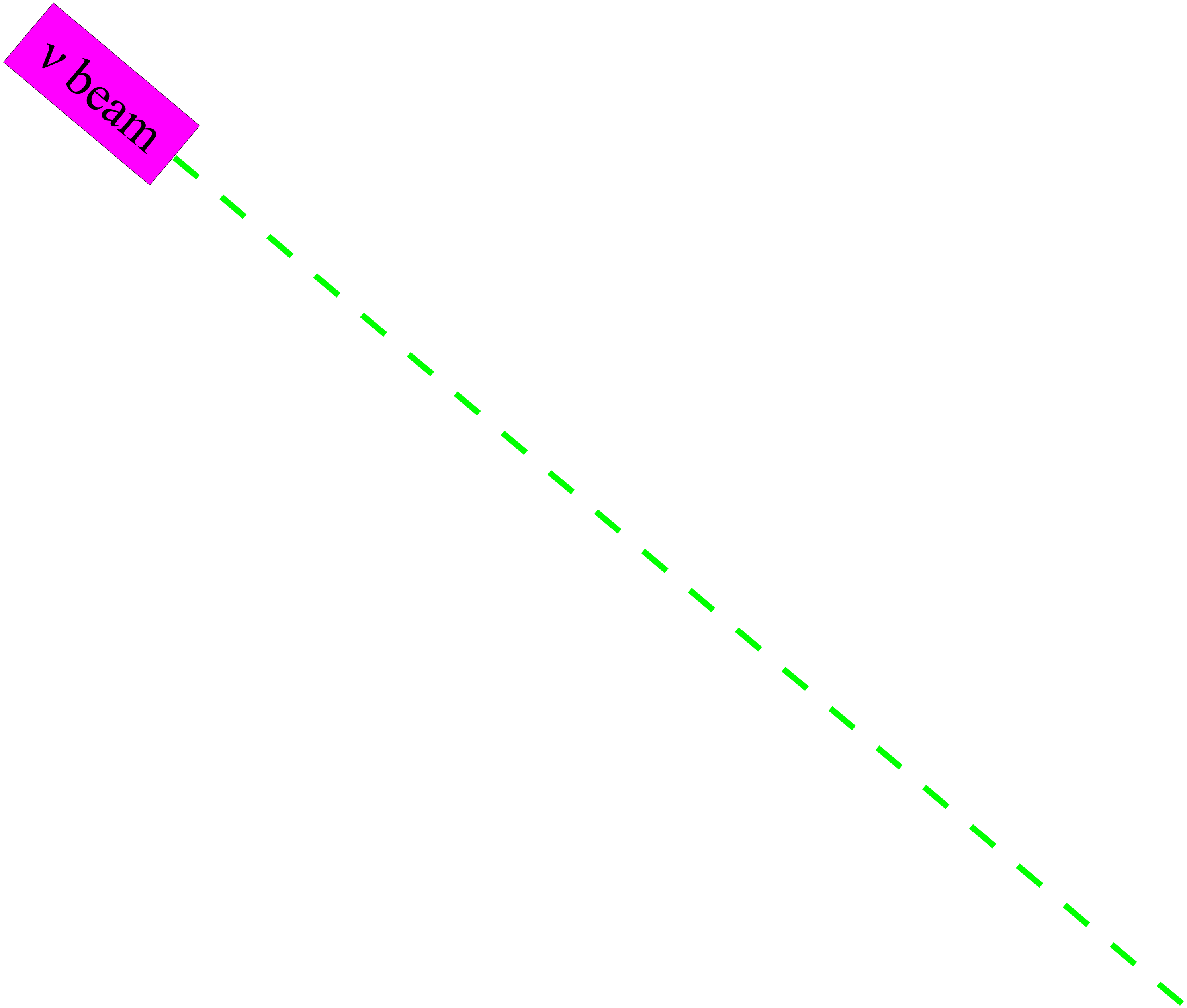




- Both models give ~3.5% RMS in $\sin^2\theta_{23}$, Martini model introduces ~3% bias
- Effects much smaller than current statistical uncertainty, but maybe large for future analyses

# The problem with neutrinos...

- Measuring neutrino interactions is hard
- Want to know cross section as function of interaction variables:
  - Neutrino energy
  - Momentum transfer ($Q^2$)
- Very hard (impossible) to measure these experimentally – usually rely on the models we are trying to tune!
- Is there a better way?

# νPRISM detector concept



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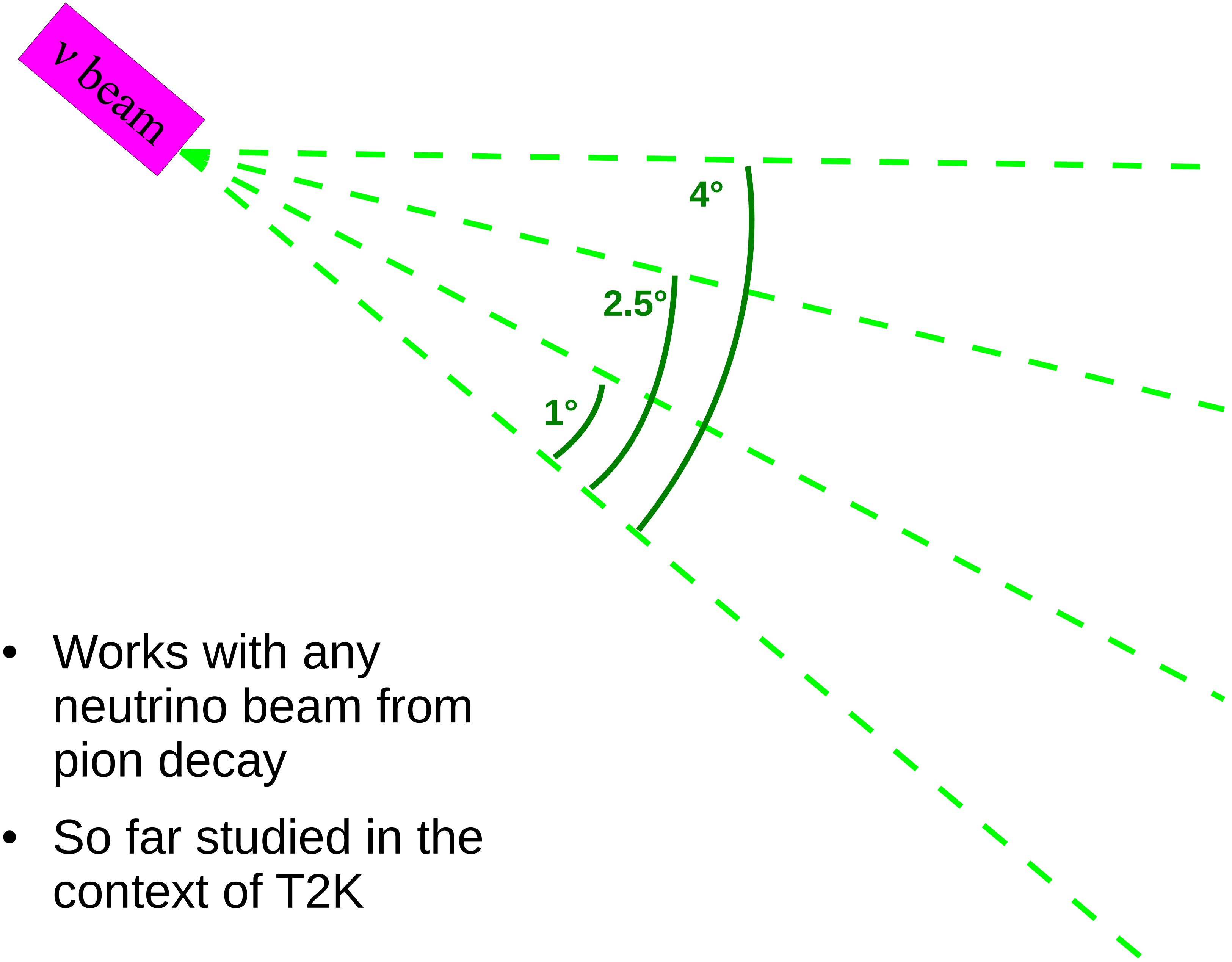


- Works with any neutrino beam from pion decay
- So far studied in the context of T2K

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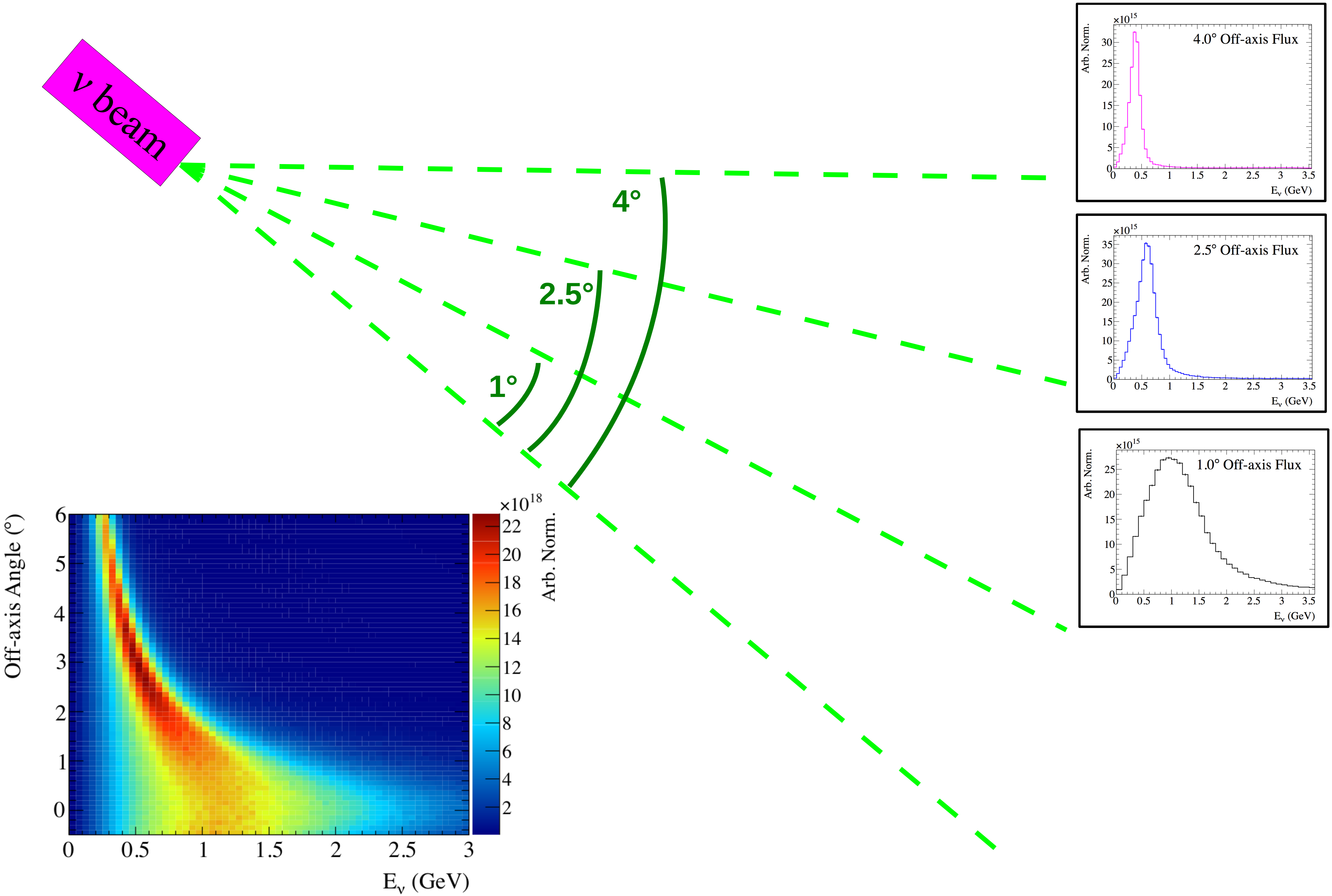

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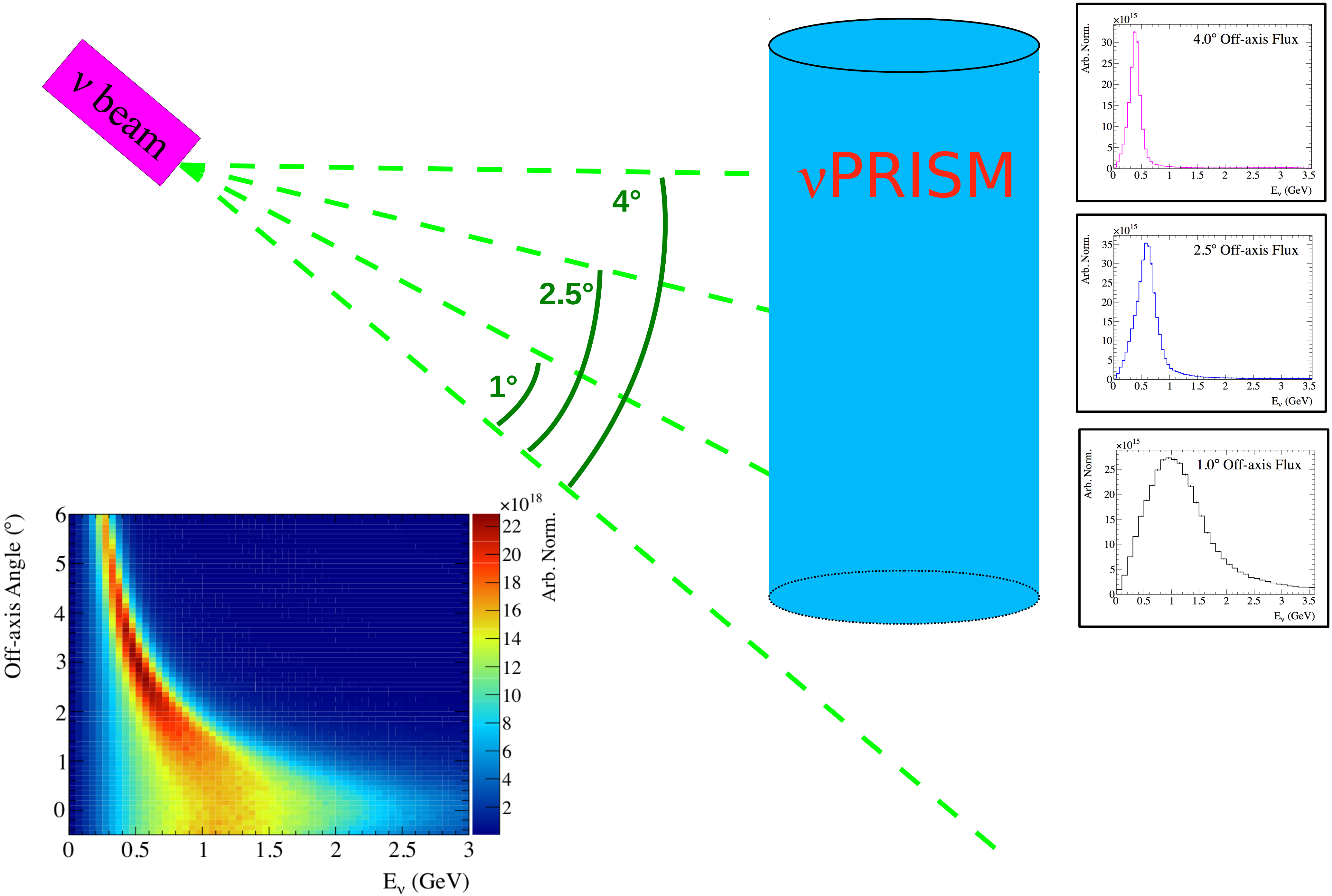

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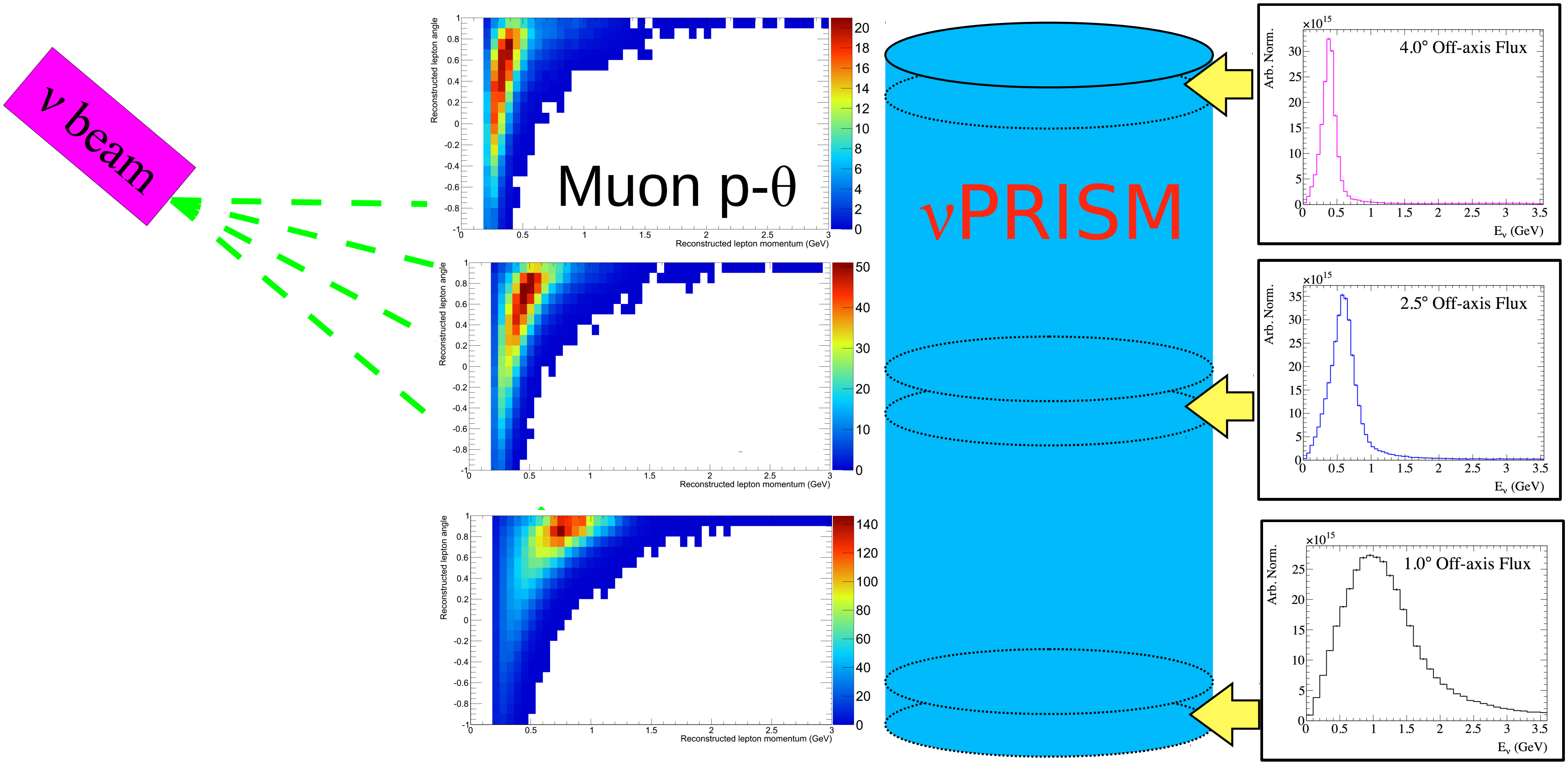

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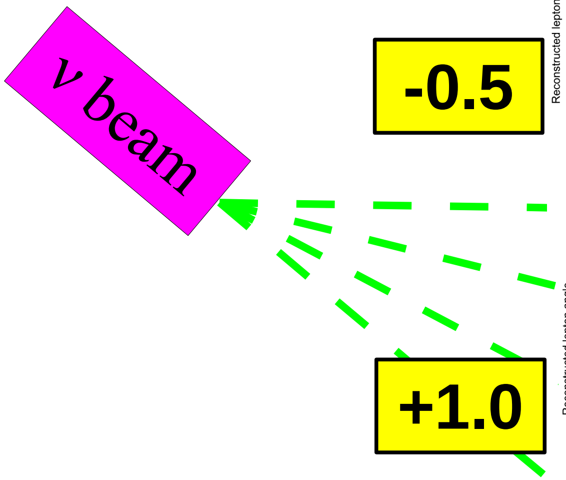
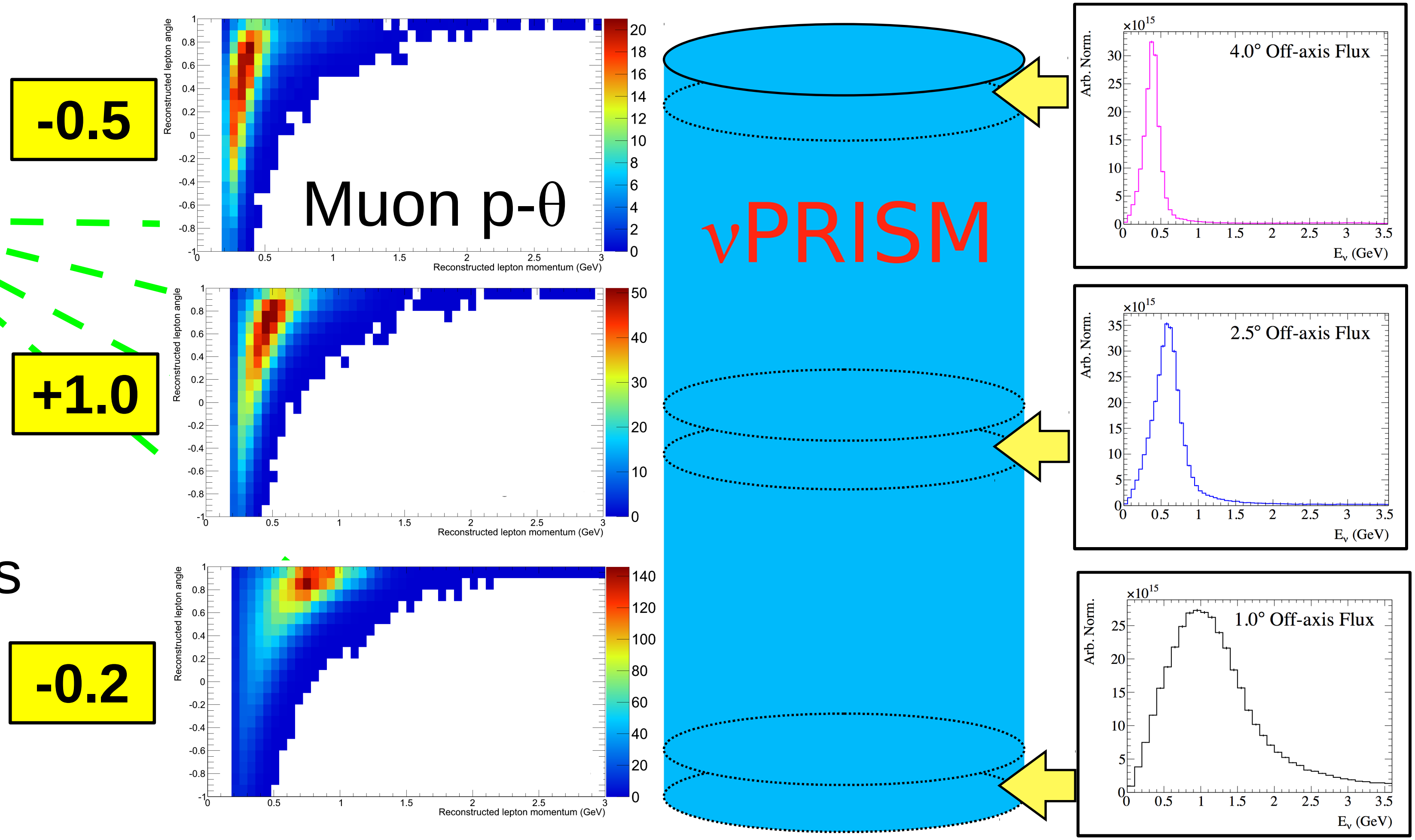
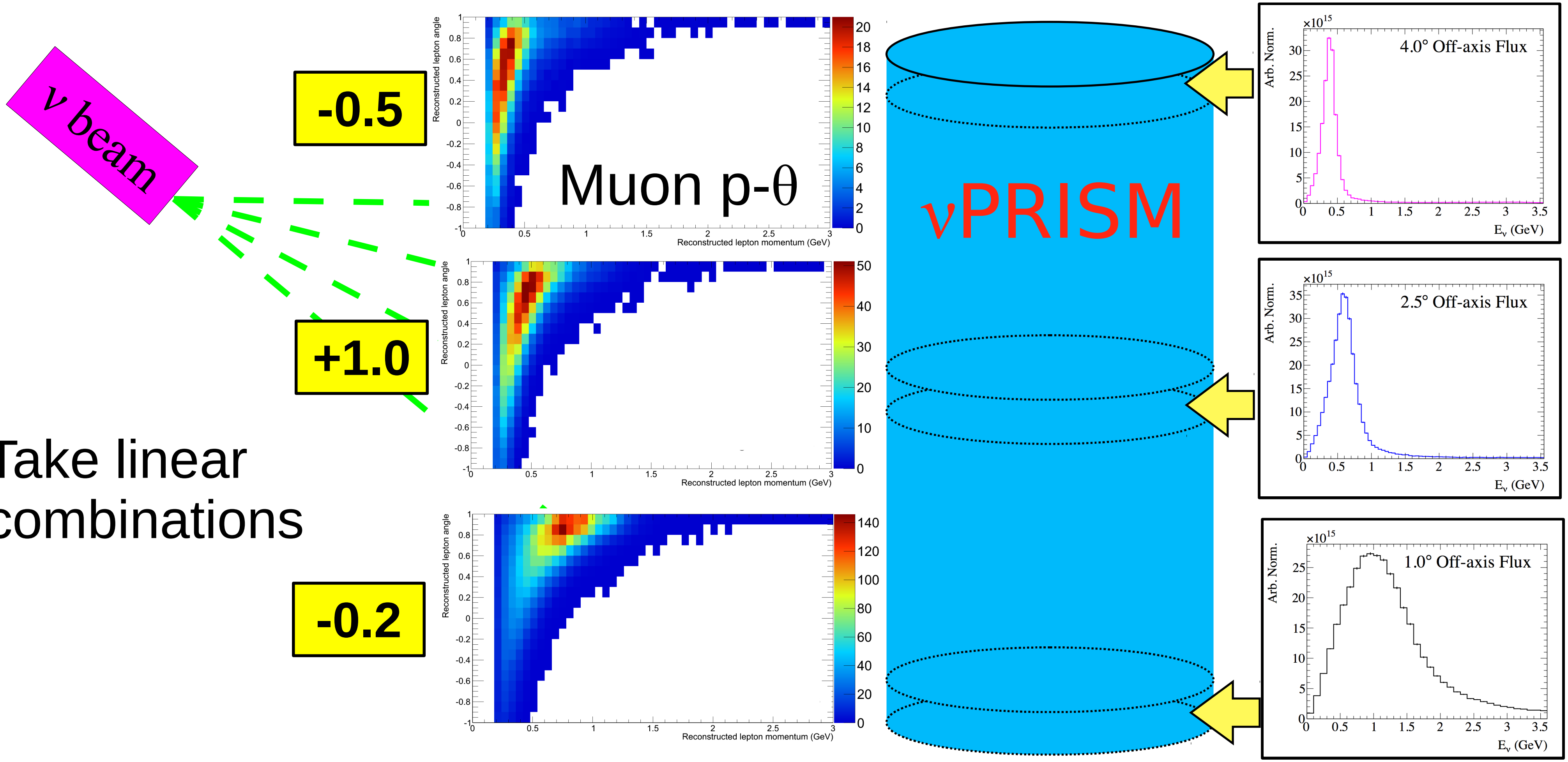



Take linear combinations

# νPRISM detector concept

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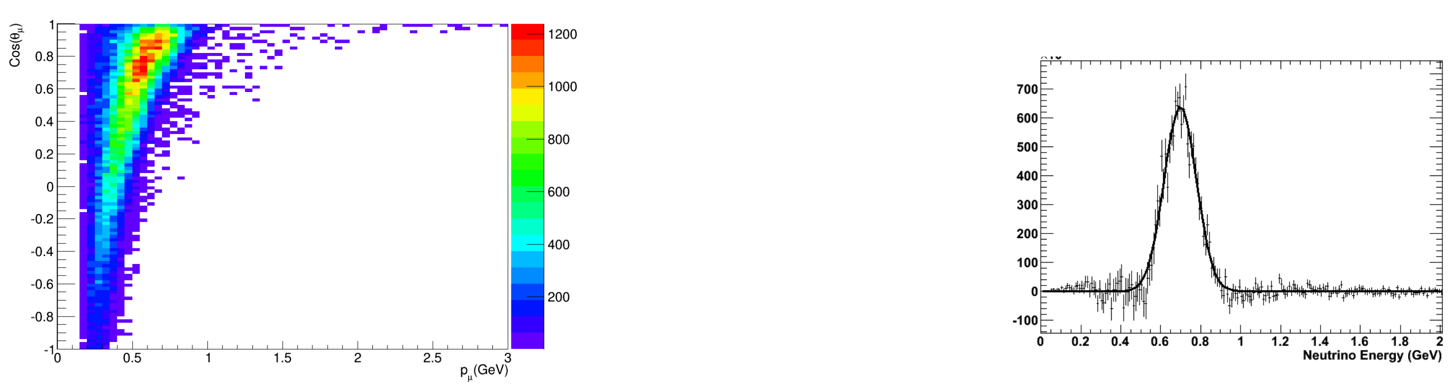
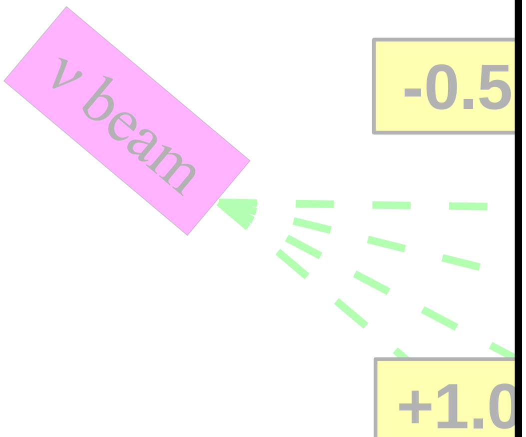
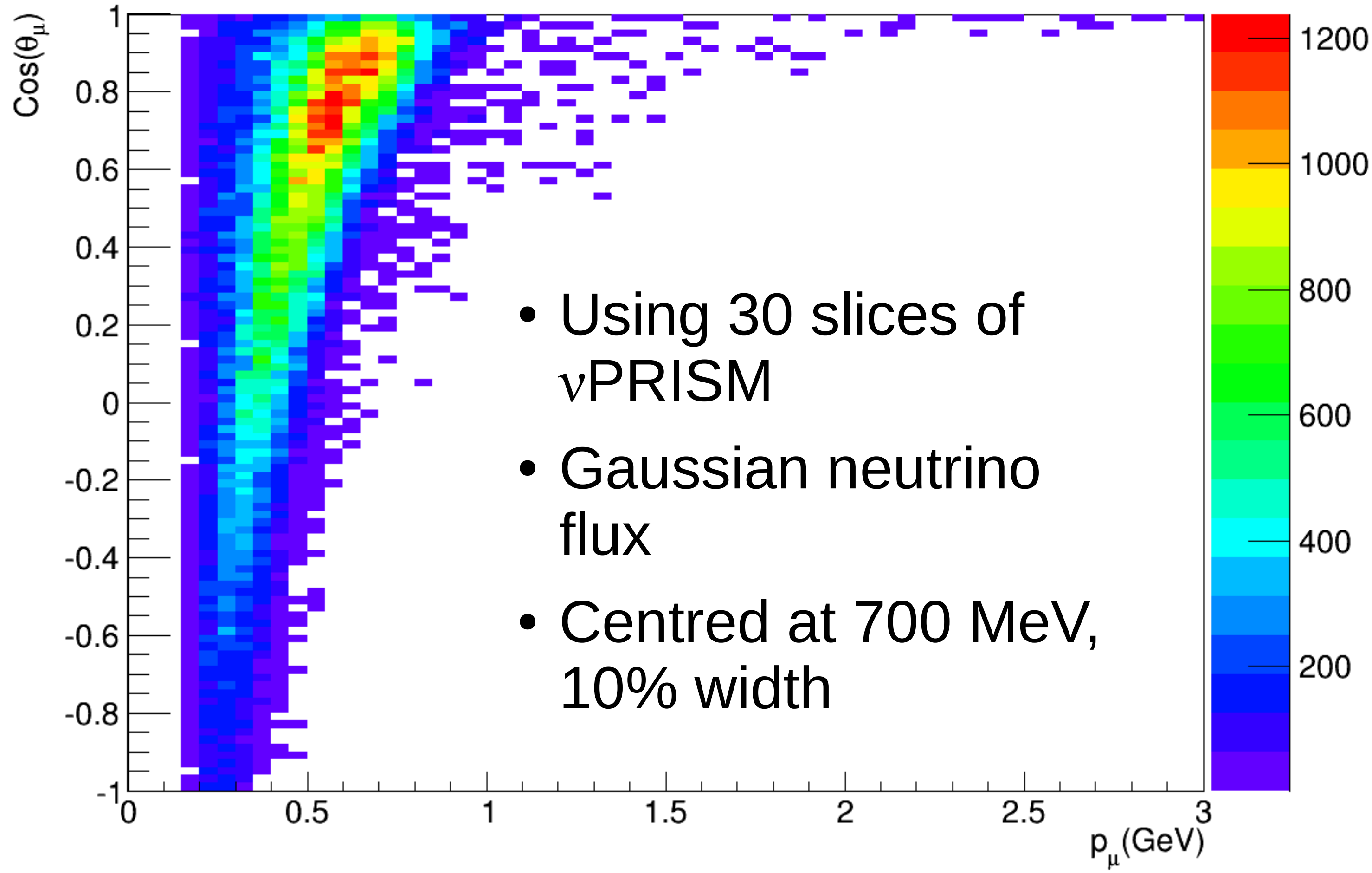
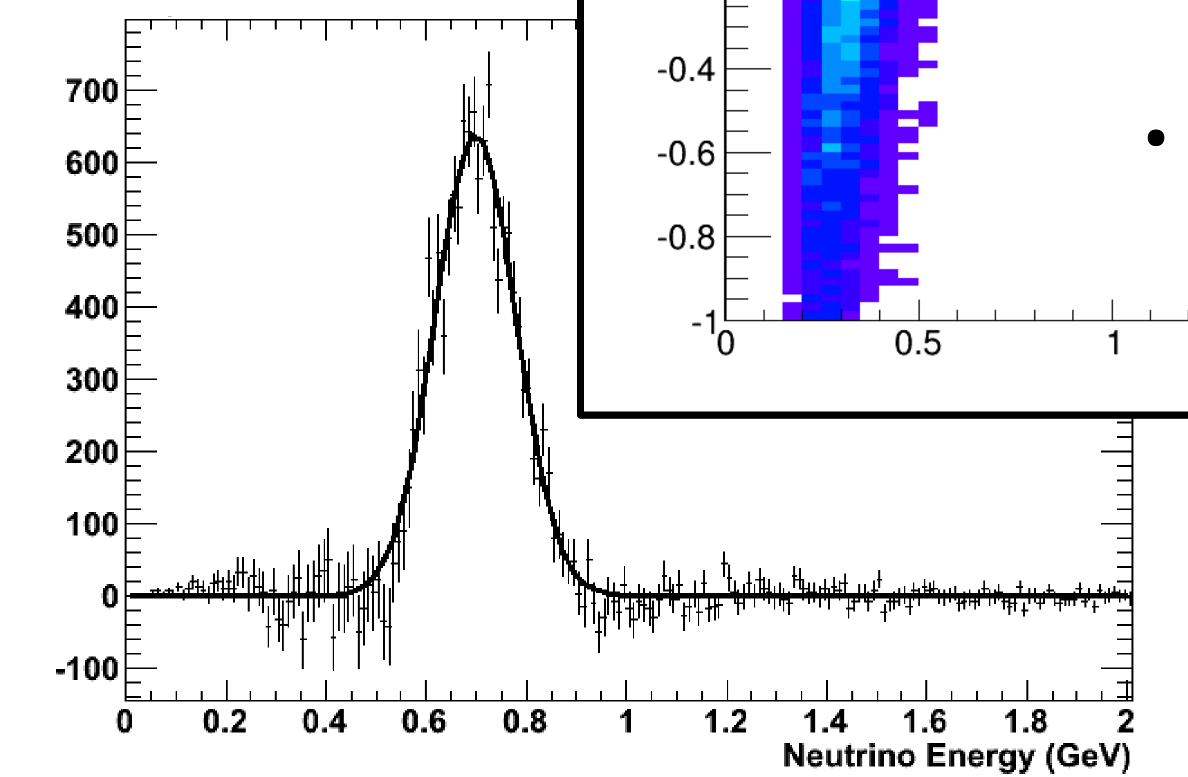


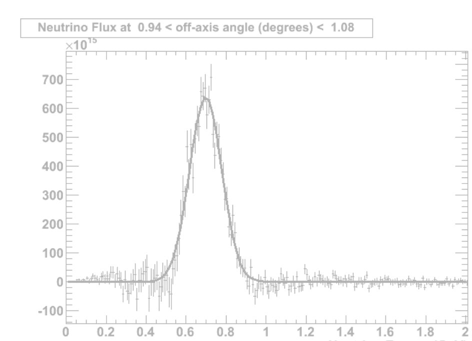
# νPRISM detector concept




- Using 30 slices of νPRISM
- Gaussian neutrino flux
- Centred at 700 MeV, 10% width



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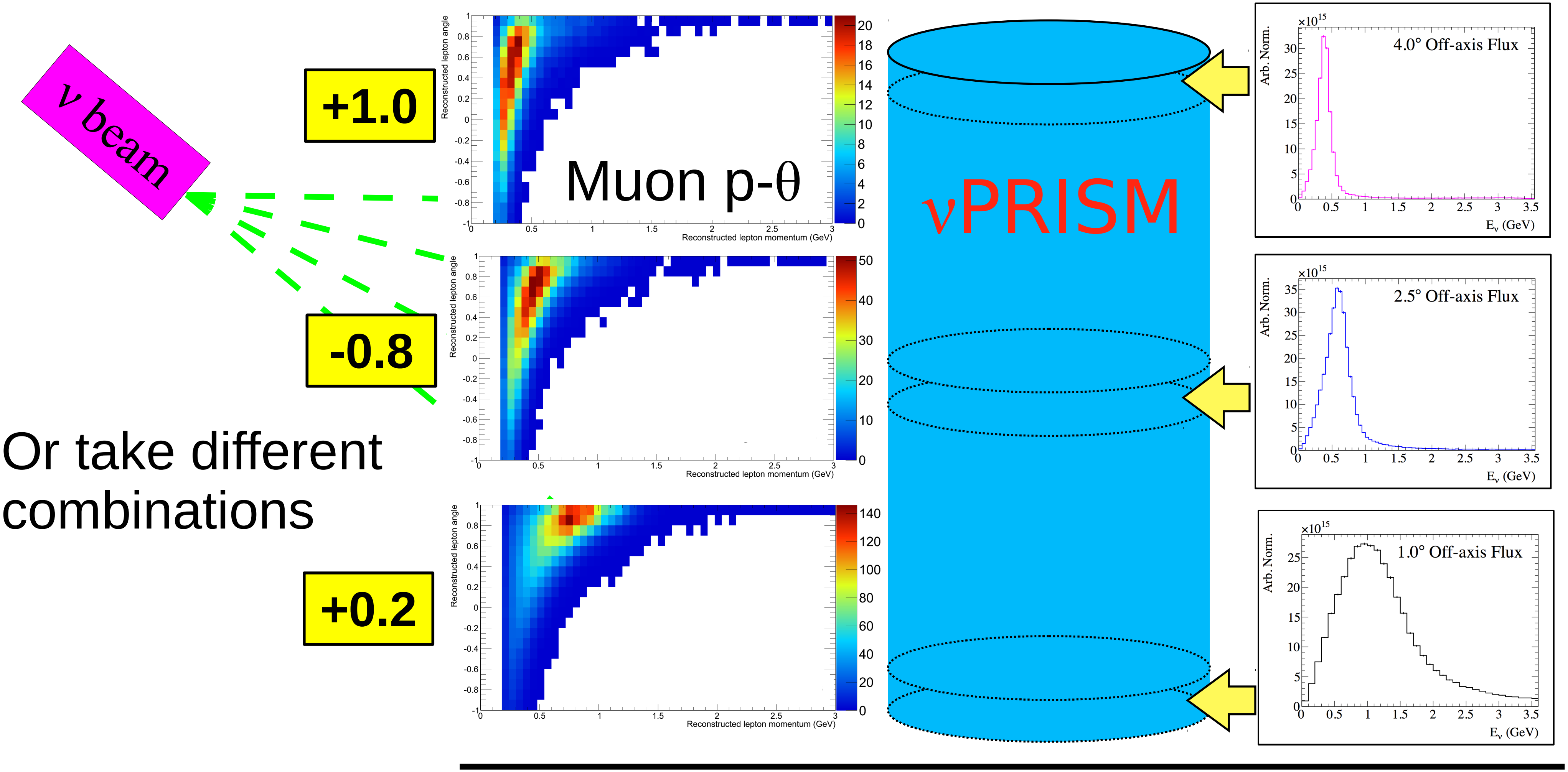
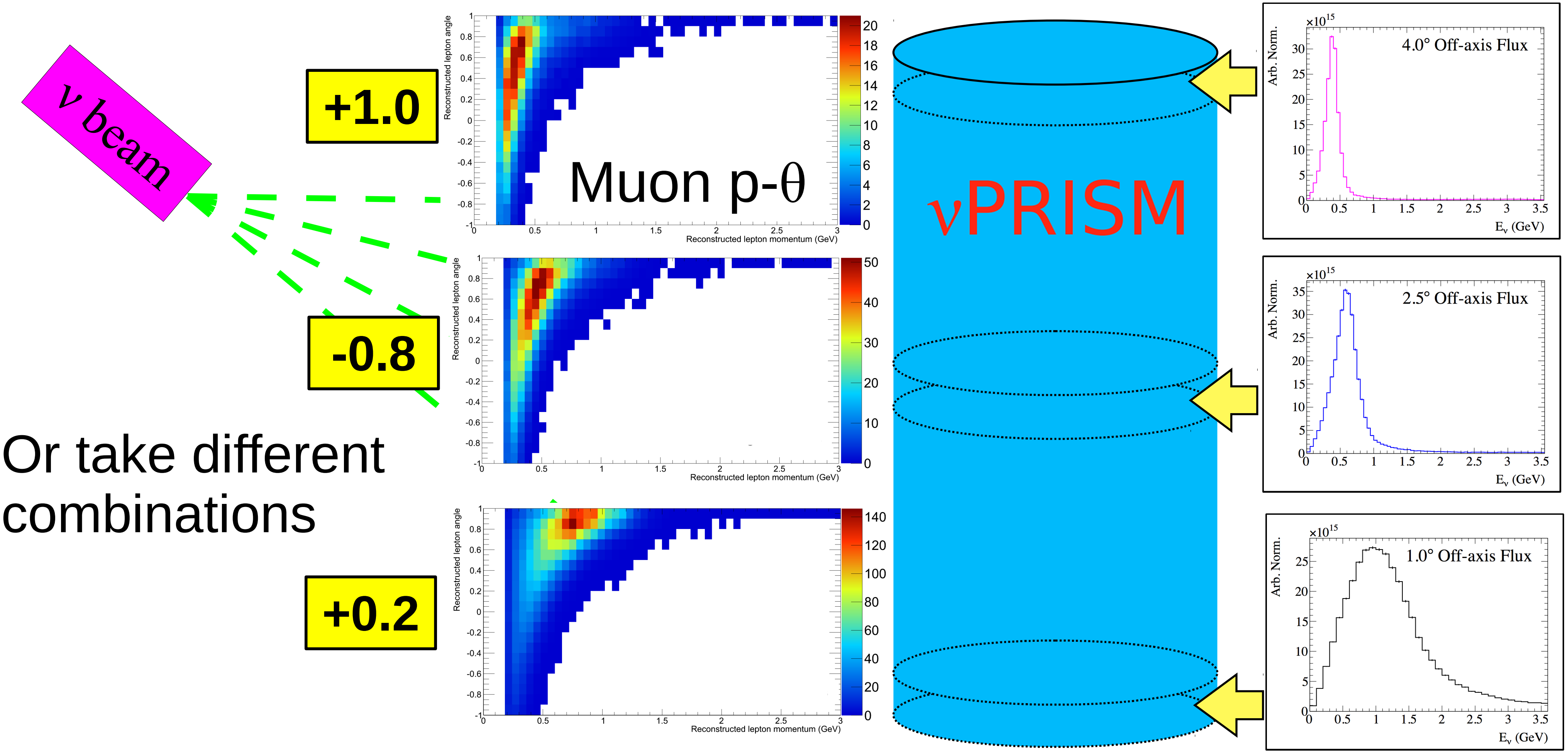



Or take different combinations

# νPRISM detector concept

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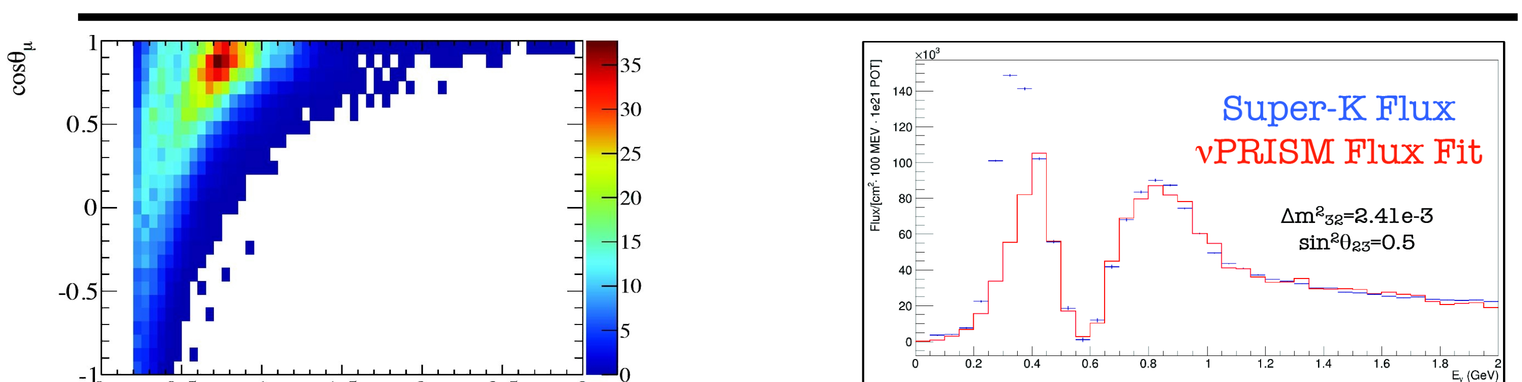

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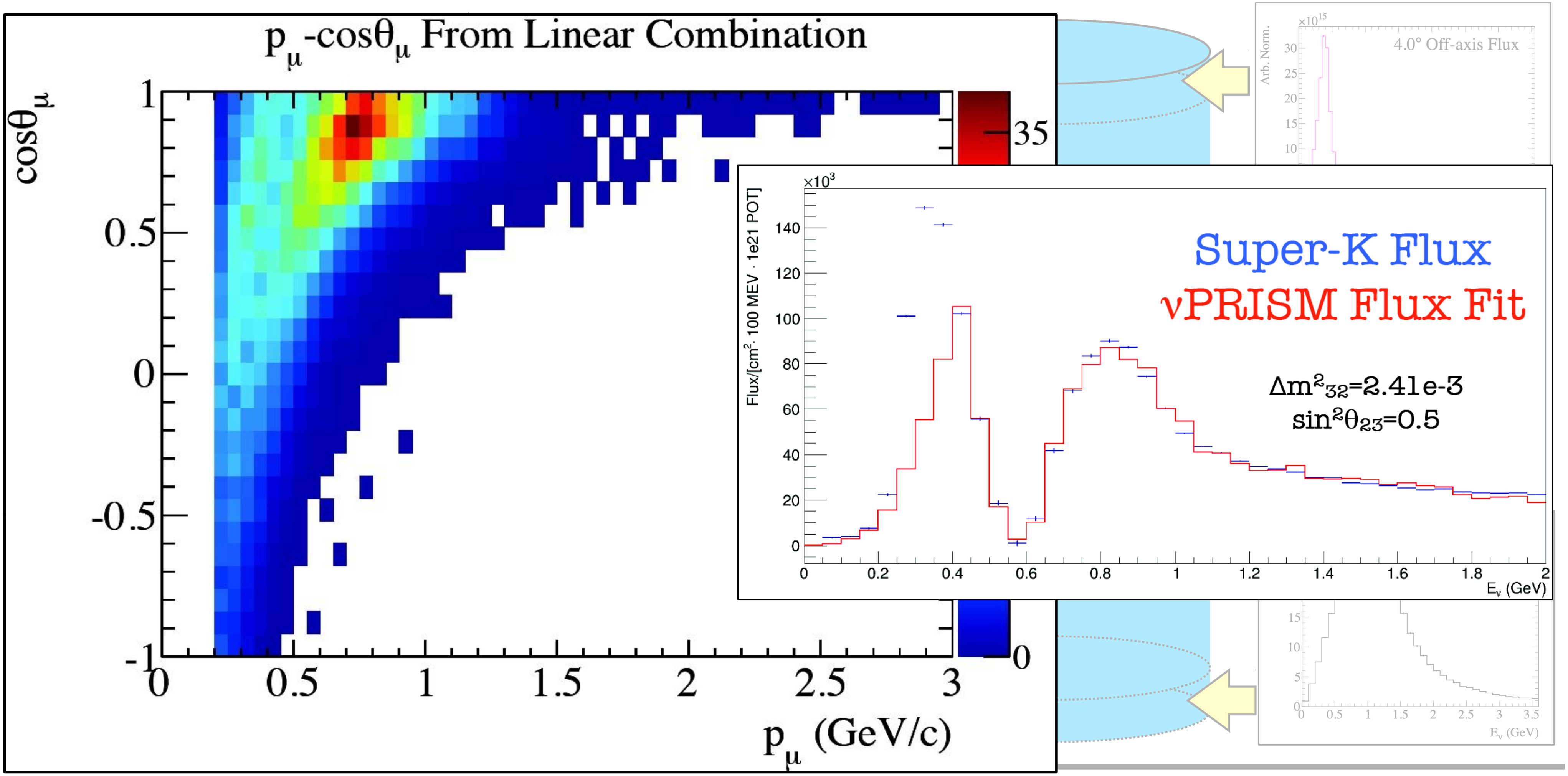
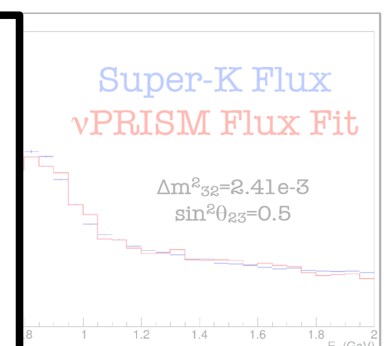
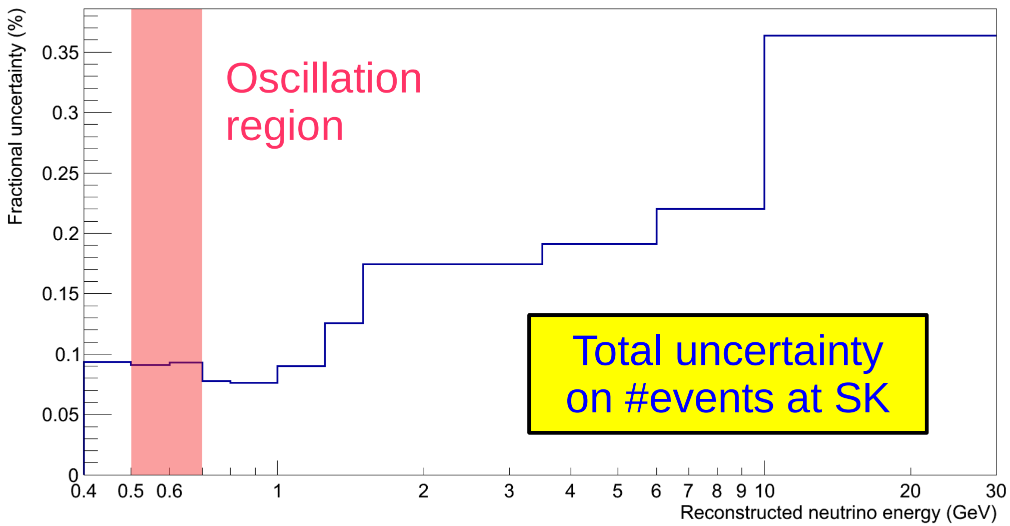


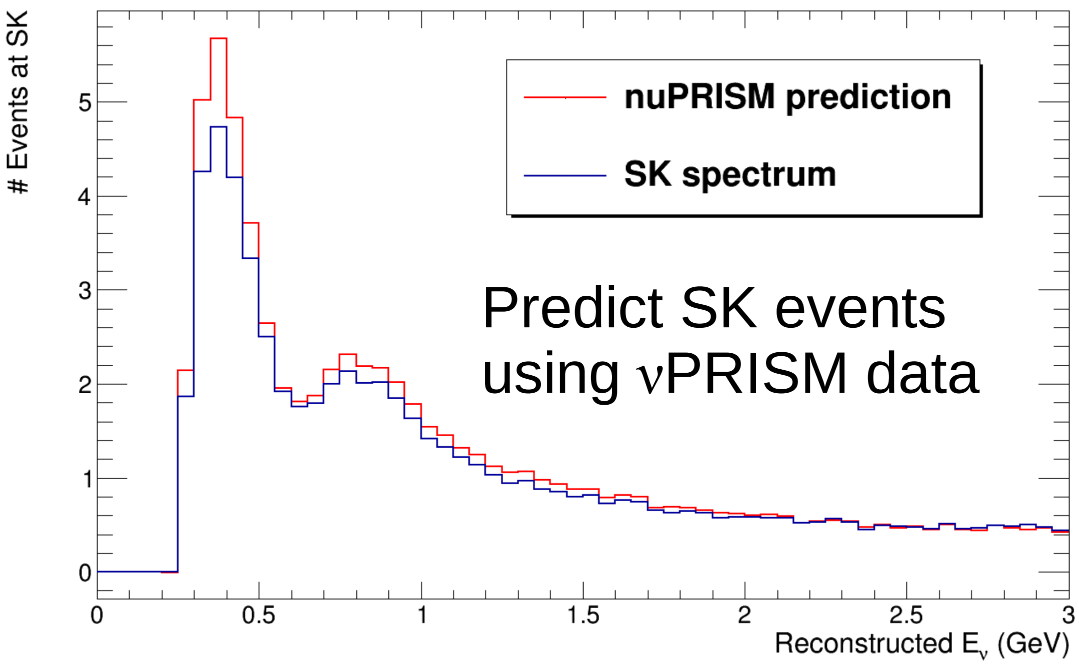

- Recreate oscillated neutrino flux at SK using near detector
- Directly measure muon p-θ for given value of oscillation parameters

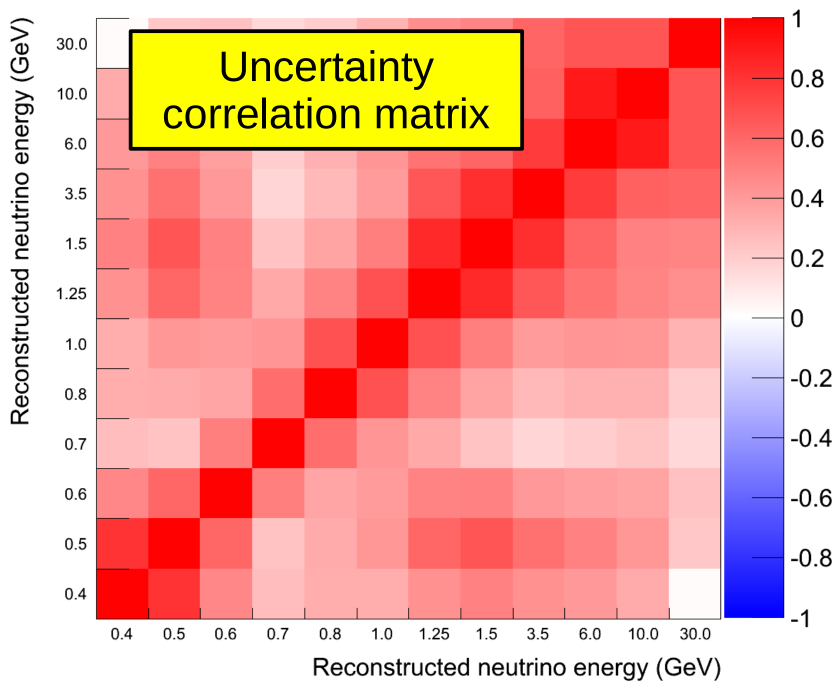


# νPRISM disappearance analysis

- Full analysis using νPRISM as near detector for T2K
- Take into account:
  - Statistical error from linear combinations
  - Neutrino beam uncertainties – direction, flux etc.
  - Interaction model uncertainties

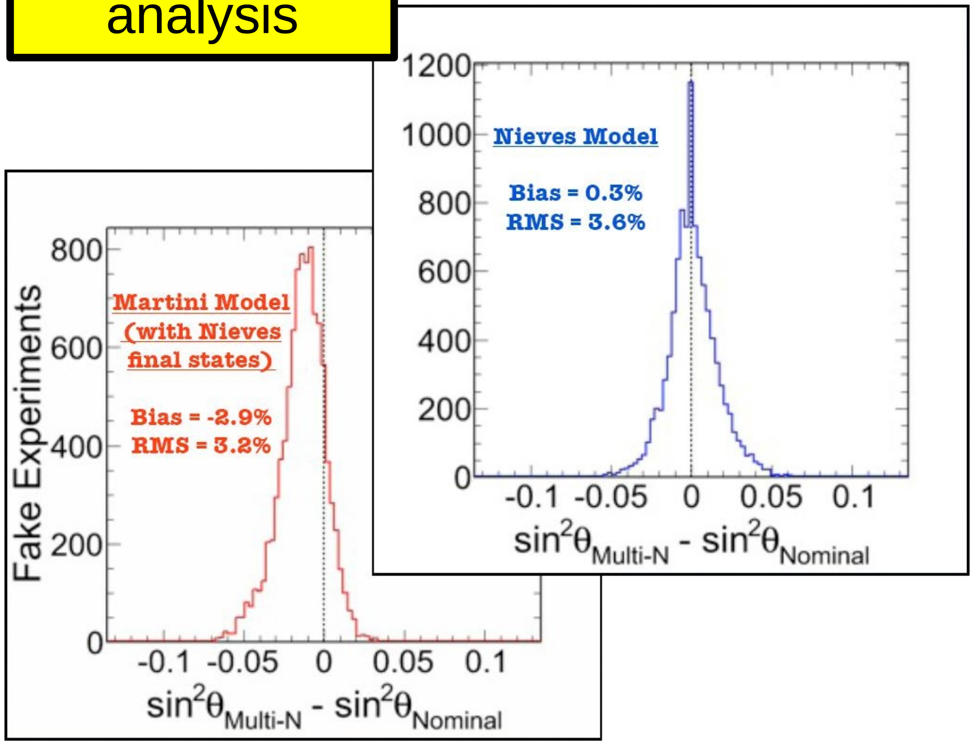


# Effect of multi-nucleon events at $\nu$PRISM

Standard T2K analysis




- Add np-nh events (Nieves and Martini models) to T2K fake data
- Perform disappearance fit to extract $\theta_{23}$
- Compare to result from fit to nominal fake data

# Effect of multi-nucleon events at νPRISM

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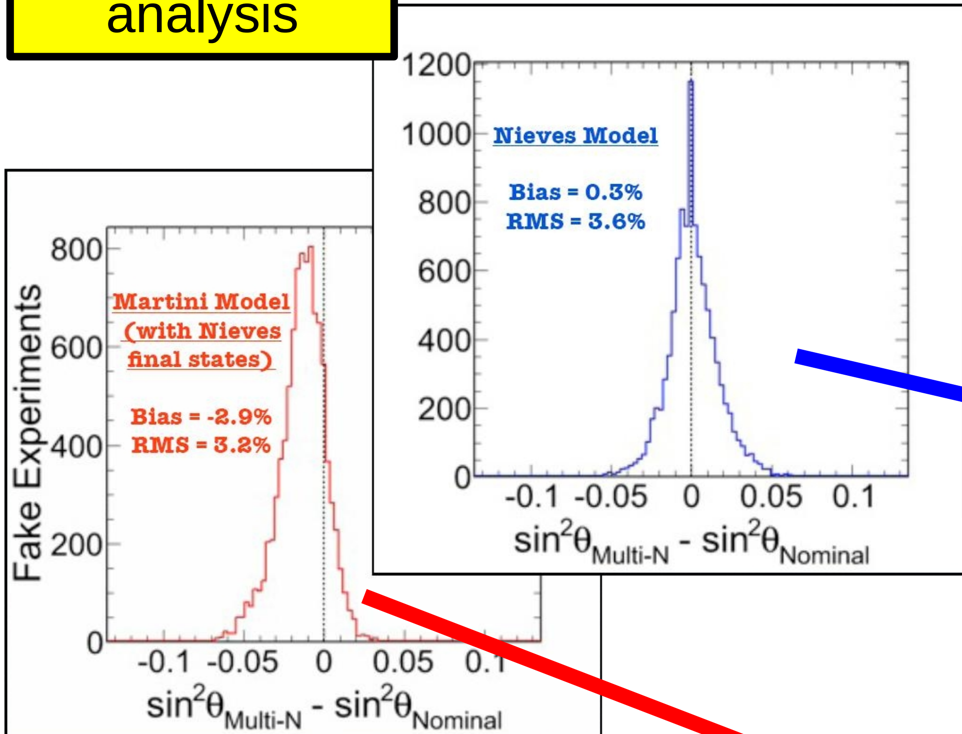


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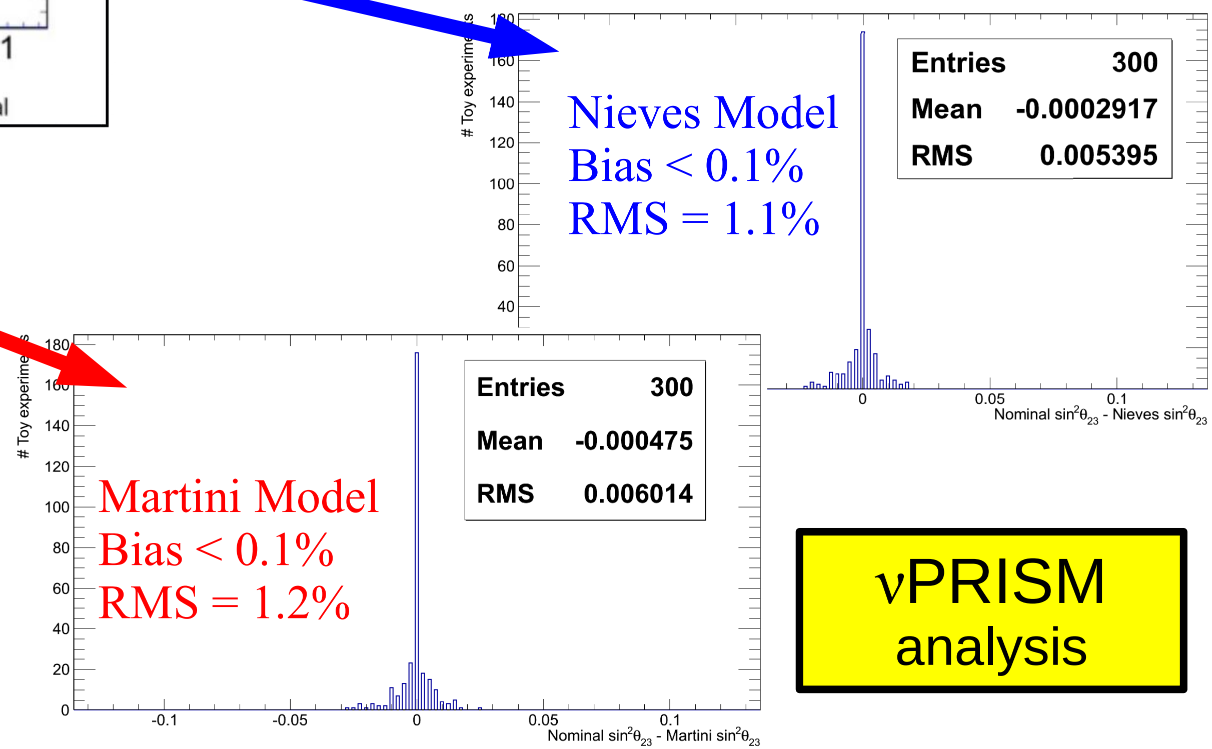
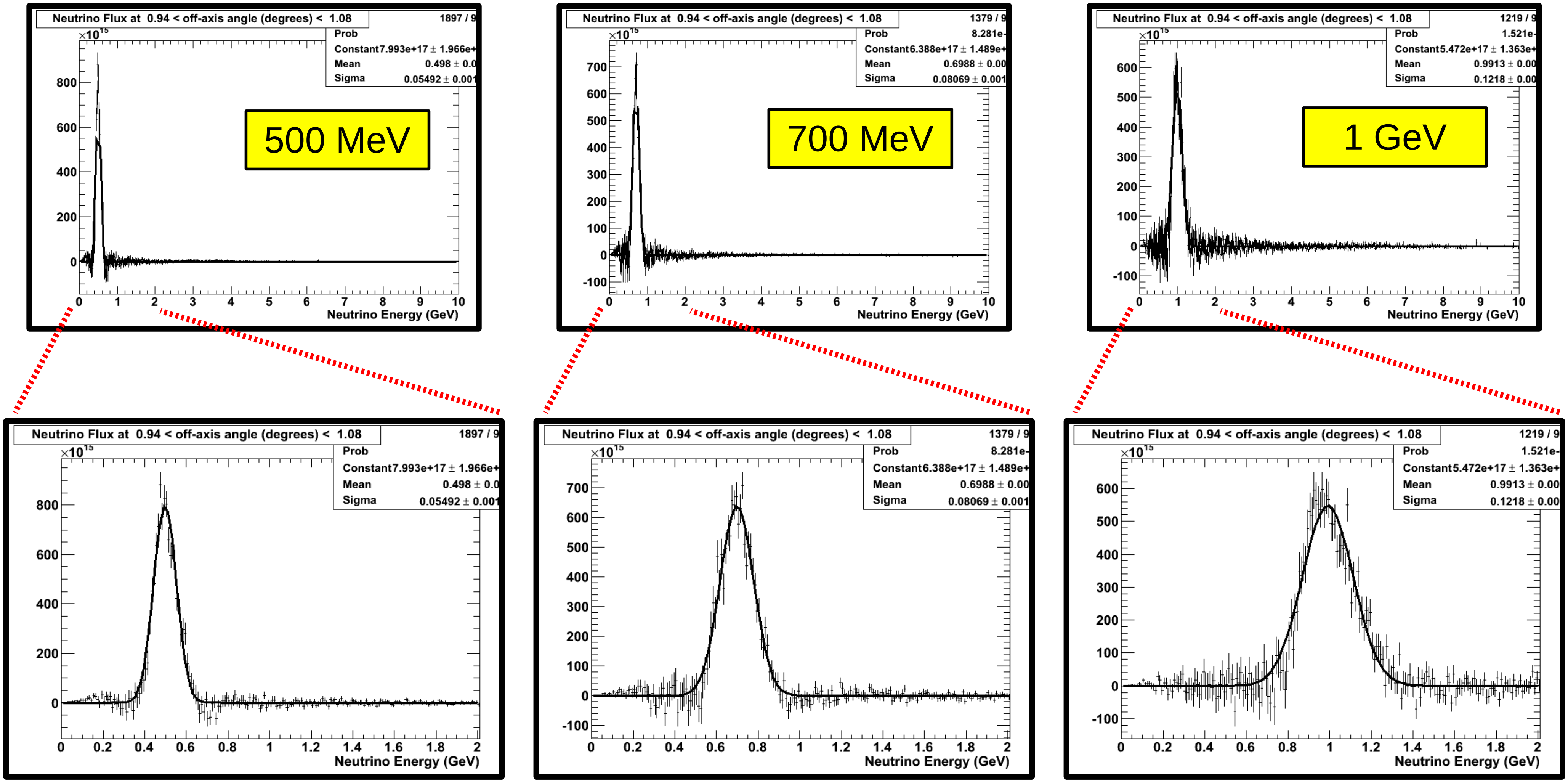



- Bias and RMS greatly reduced
- νPRISM analysis largely independent of cross section model

νPRISM analysis

# A neutrino spectrometer




- Gaussian spectra from ~0.4 GeV to ~1 GeV
  - Depends on off-axis span of νPRISM: 6° - 0.25 GeV, 0° - 1.2 GeV
- High energy tail cancelled in all cases

# The problem with neutrinos...

- Measuring neutrino interactions is hard
- Want to know cross section as function of interaction variables:
  - Neutrino energy
  - Momentum transfer ($Q^2$)
- Very hard (impossible) to measure these experimentally – usually rely on the models we are trying to tune!
- Is there a better way?

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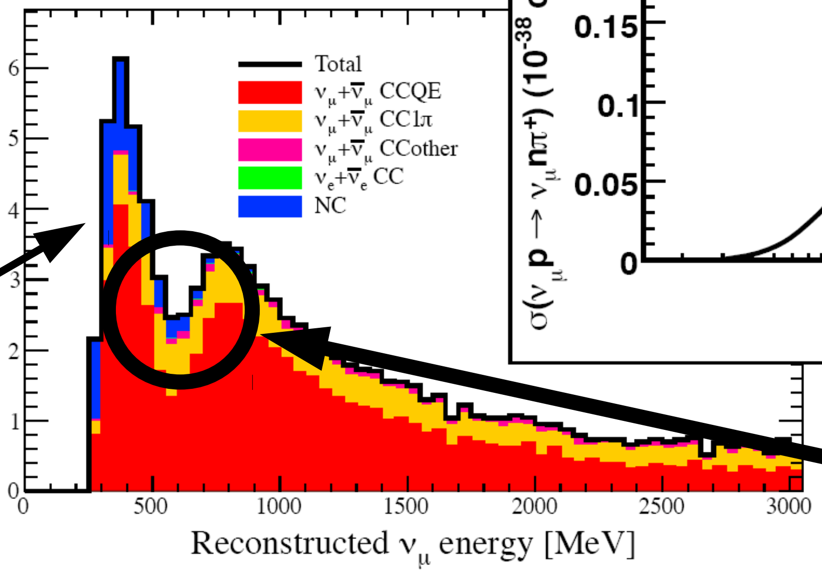
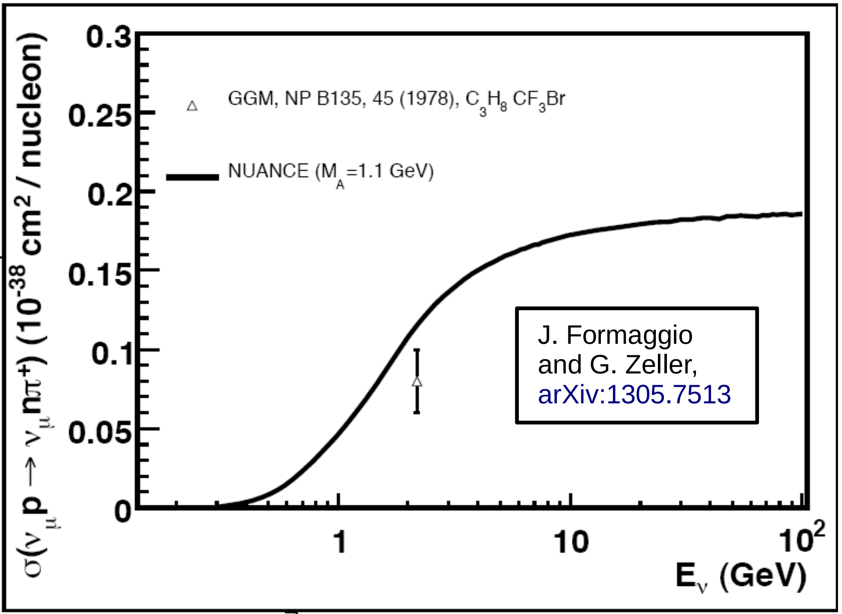
# Cross sections with a neutrino spectrometer

- We now know the neutrino energy!
  - Can calculate $Q^2$ directly – lepton information
- For charged current interactions:
  - Measure same cross section across a range of neutrino energies
  - Know correlations between energies
- For neutral current interactions:
  - First ever measurements as a function of $E_\nu$
- fiTQun reconstruction algorithm → measure pion kinematics
- Predicted oscillated spectrum at T2K far detector – broken down by interaction

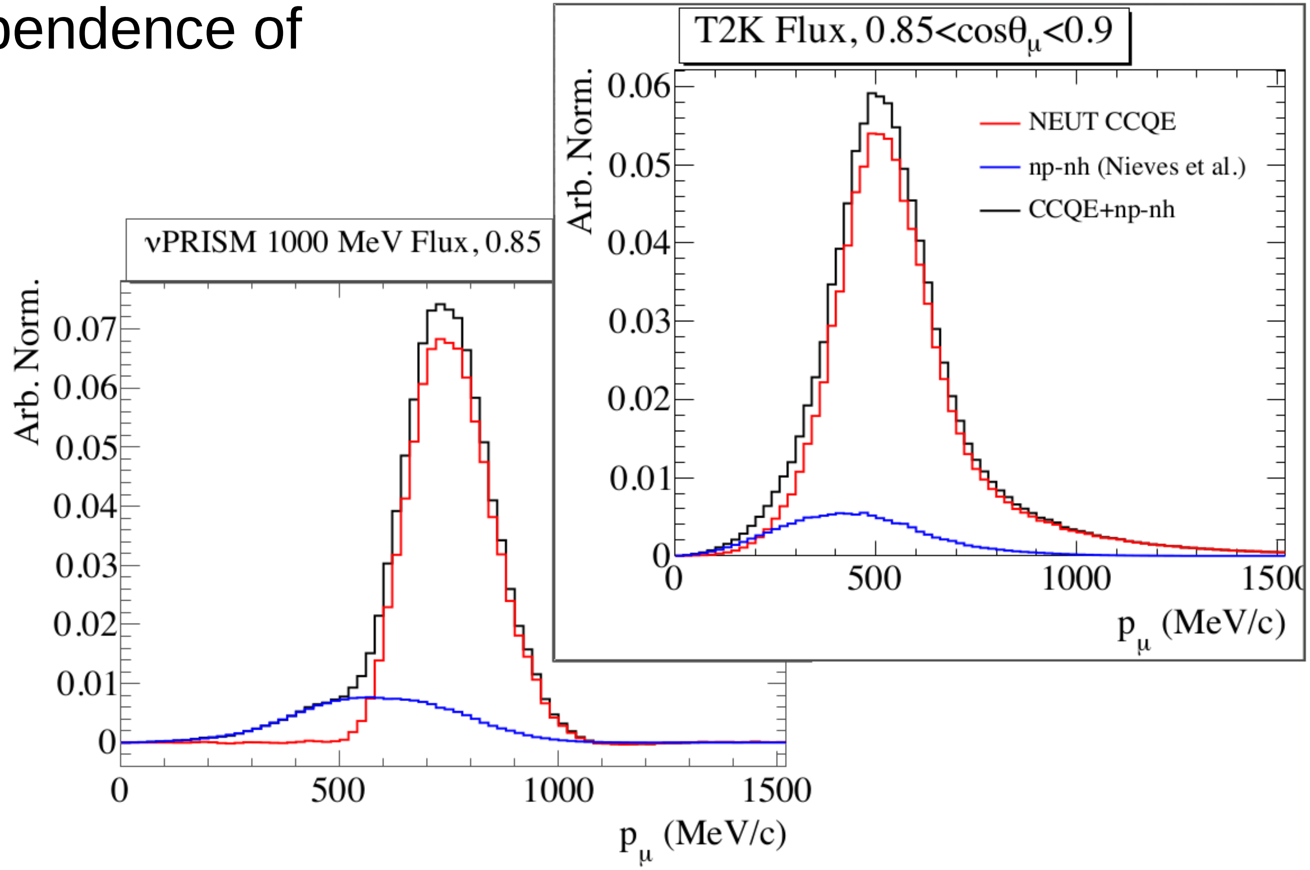



100% systematic uncertainty on $NC\pi^+$

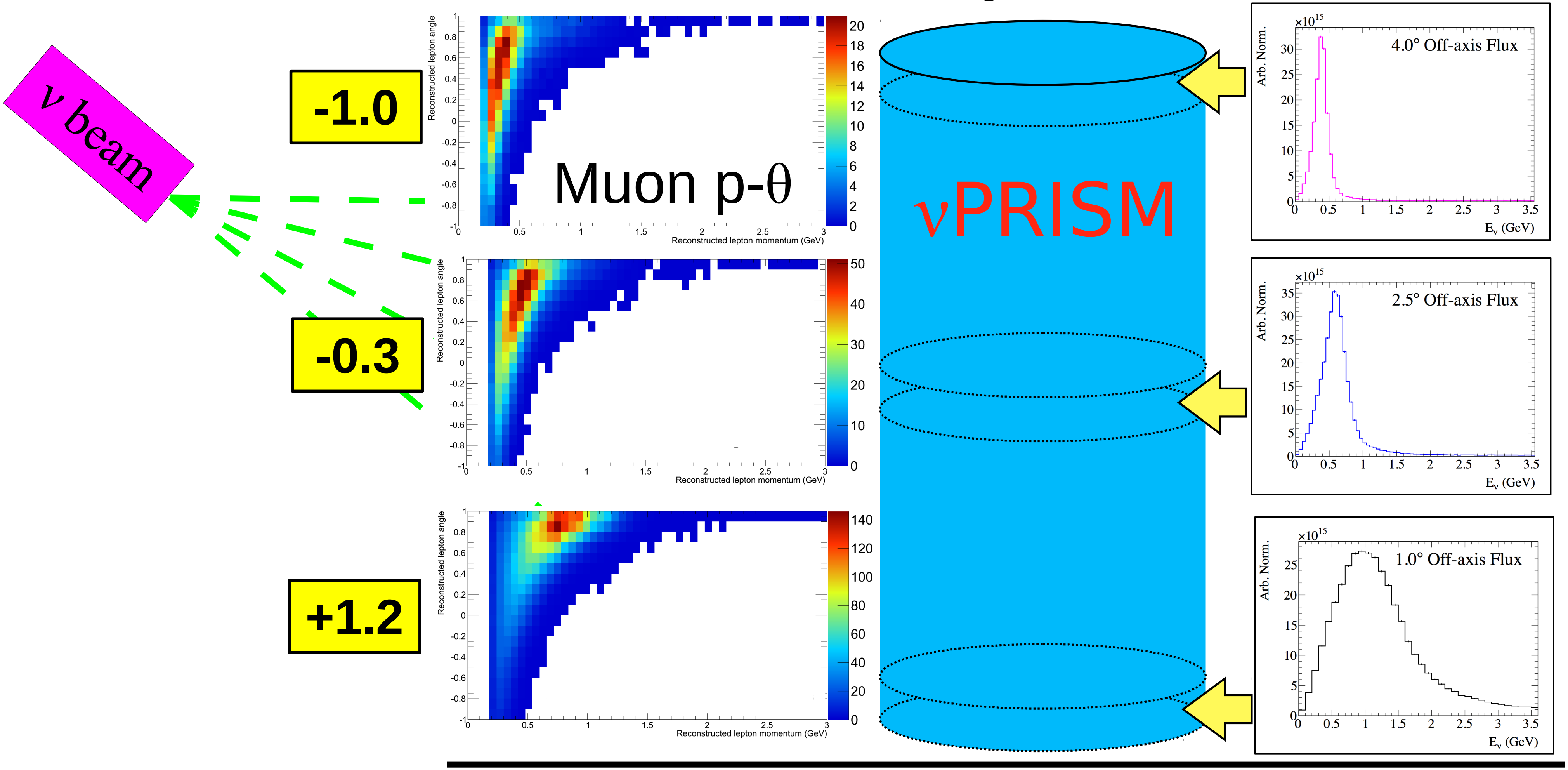
# Separating models

- Investigate energy dependence of interaction models
- Nieves *et al.* np-nh model (blue) with NEUT CCQE (red) model
- Top - T2K near detector flux
- Bottom – νPRISM 1 GeV monochromatic beam

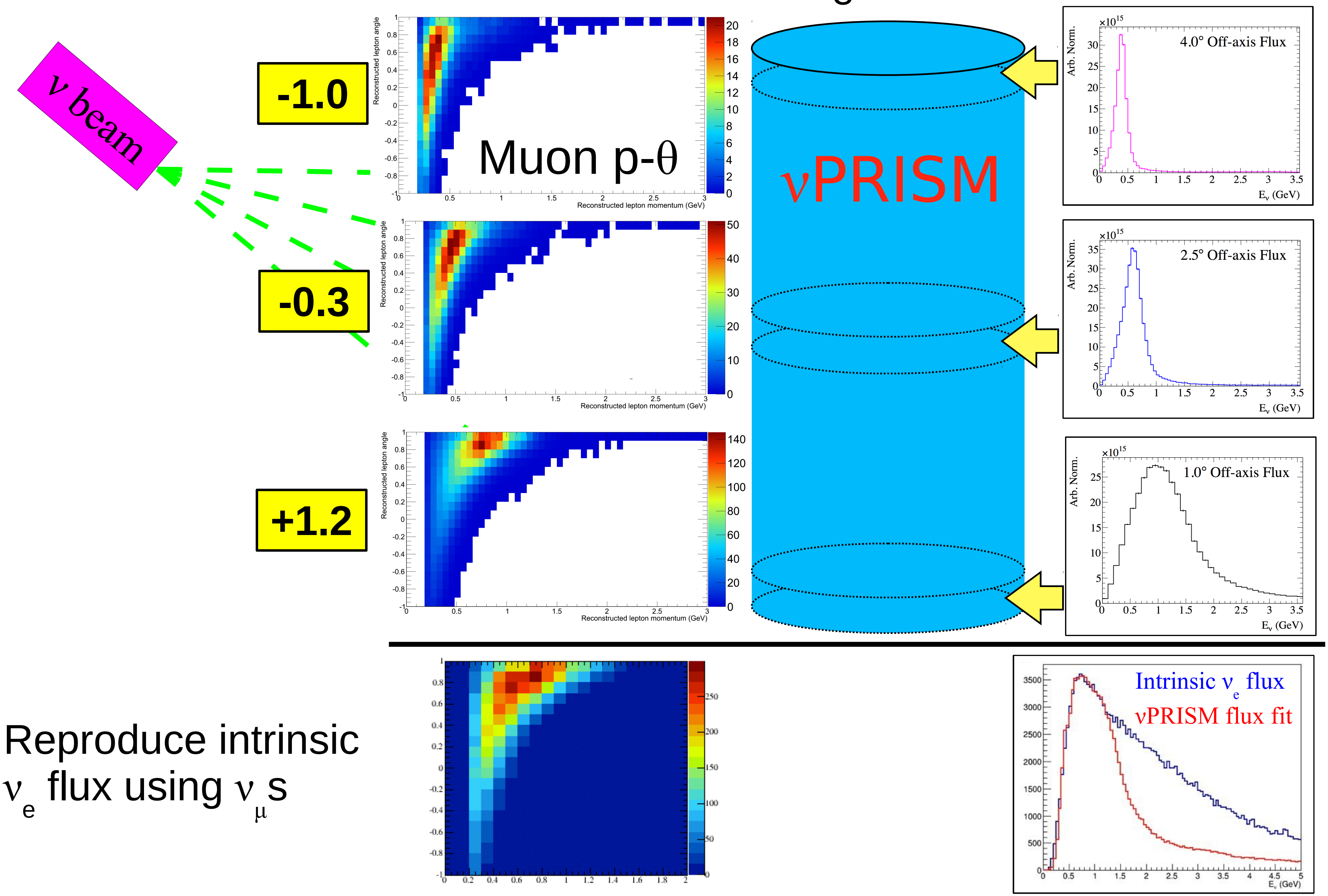



- np-nh model clearly different from CCQE model in νPRISM
- Measure across neutrino energy and lepton kinematic space – lots of power to separate models

# νPRISM with $\nu_e$'s

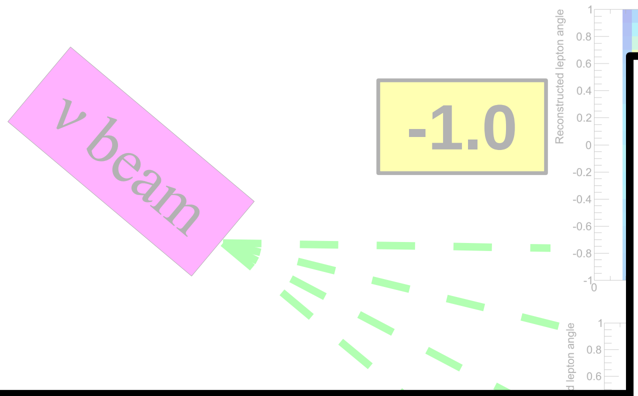


# νPRISM with $\nu_e$'s

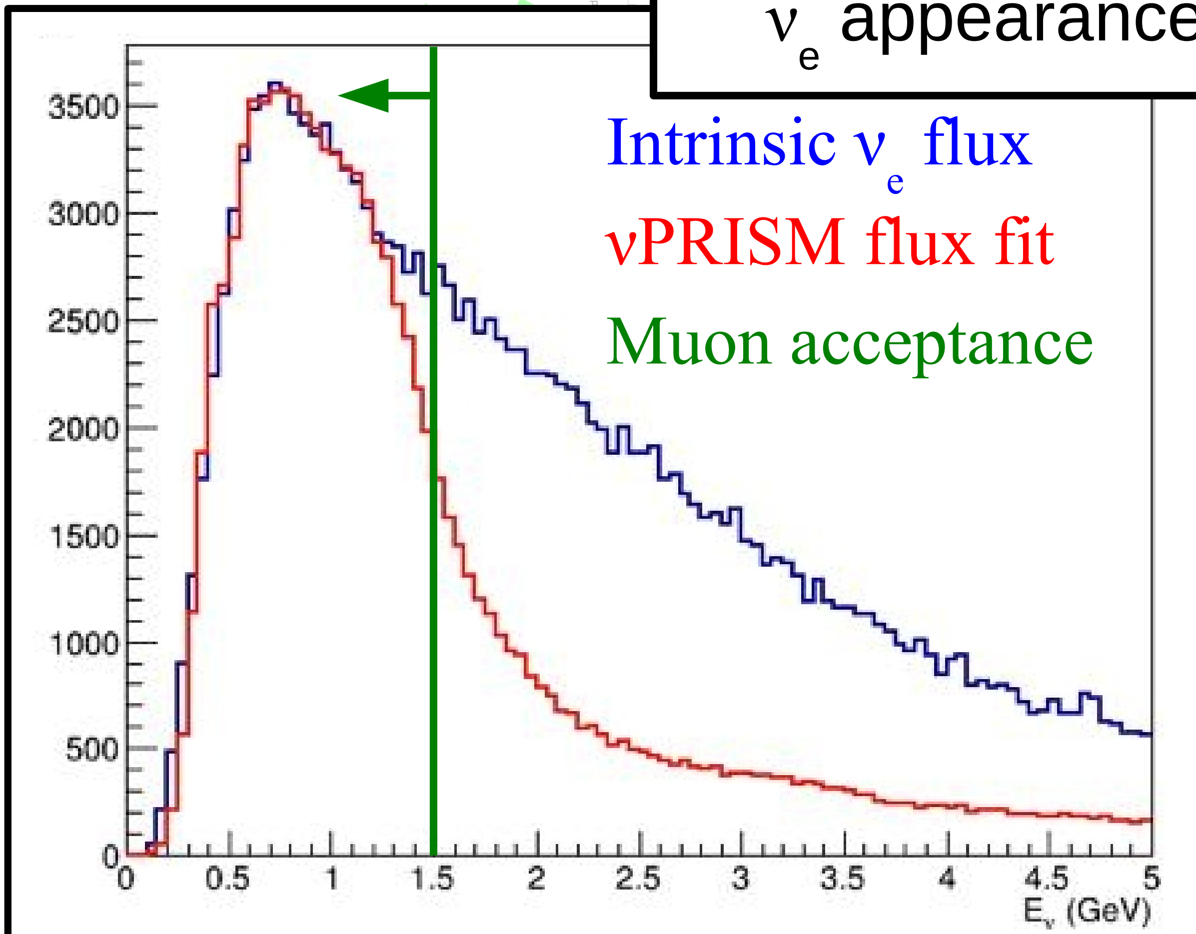


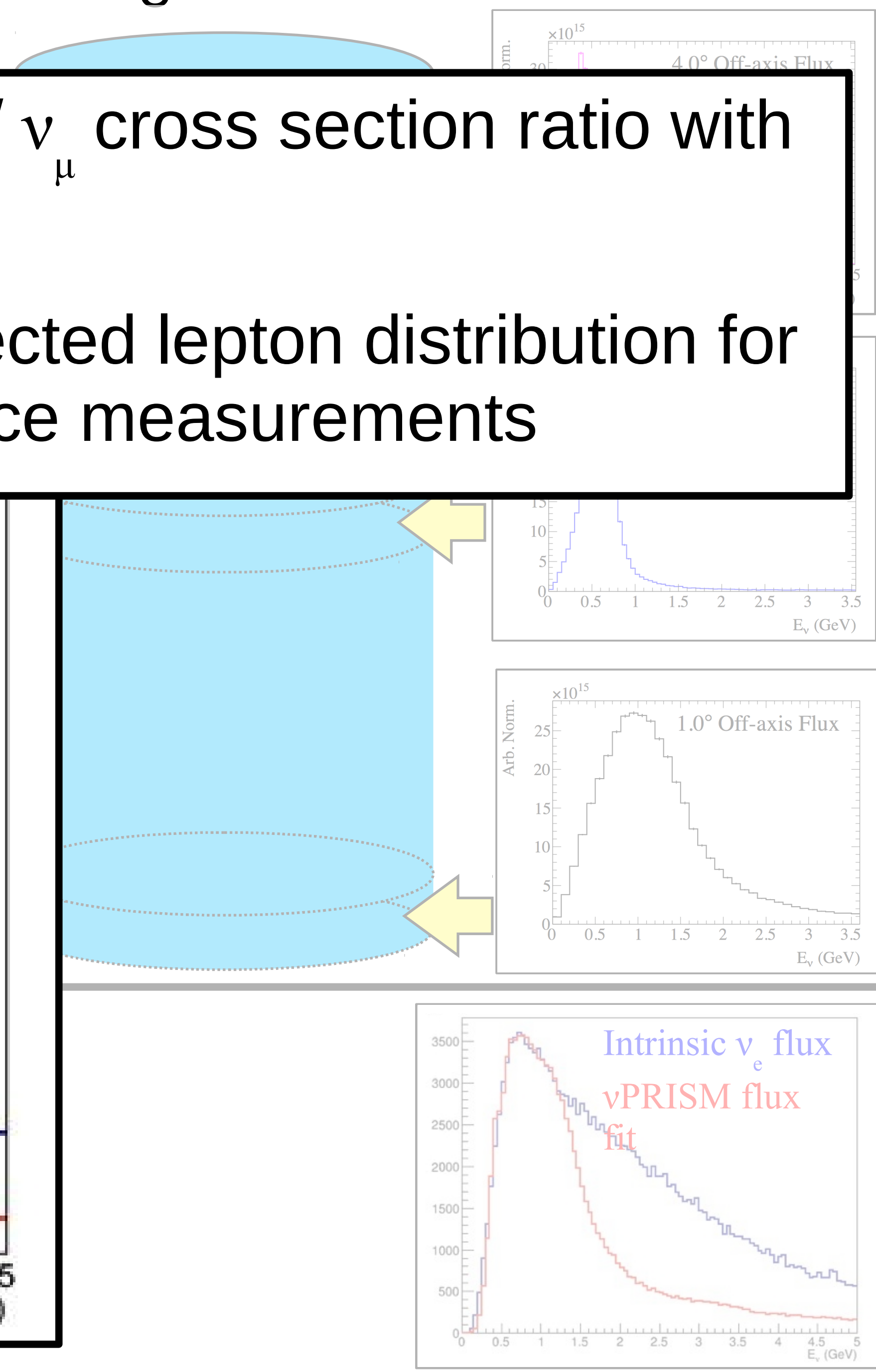

Reproduce intrinsic $\nu_e$ flux using $\nu_\mu$s

# νPRISM with $\nu_e$'s

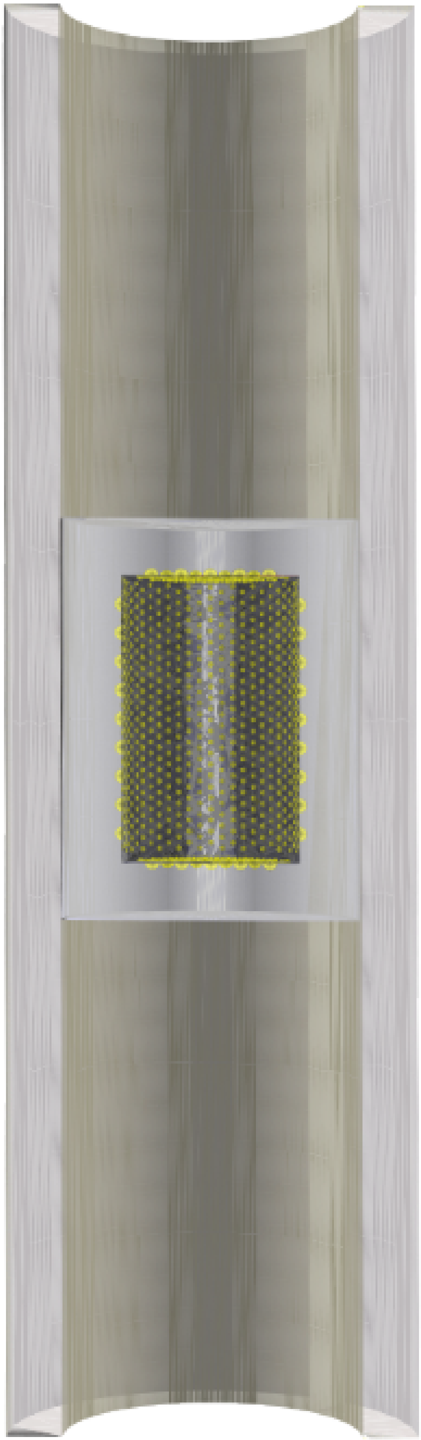



- Measure $\nu_e$ / $\nu_\mu$ cross section ratio with same flux
- Predict expected lepton distribution for $\nu_e$ appearance measurements

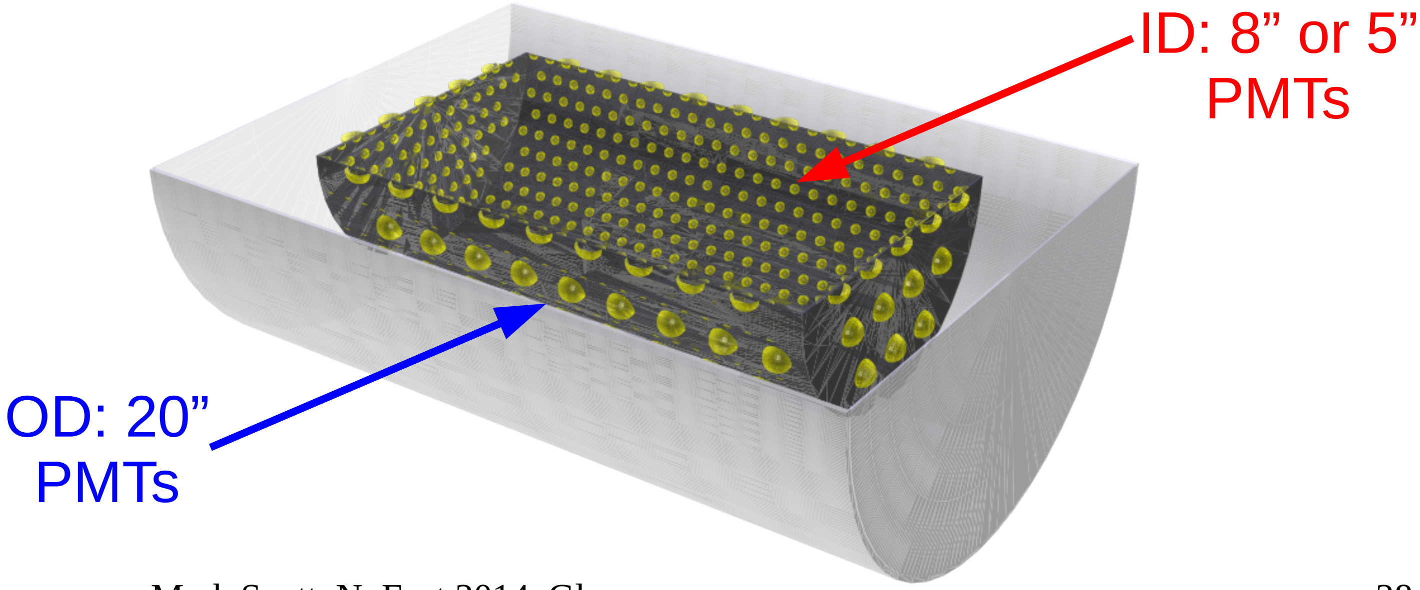


# νPRISM-lite

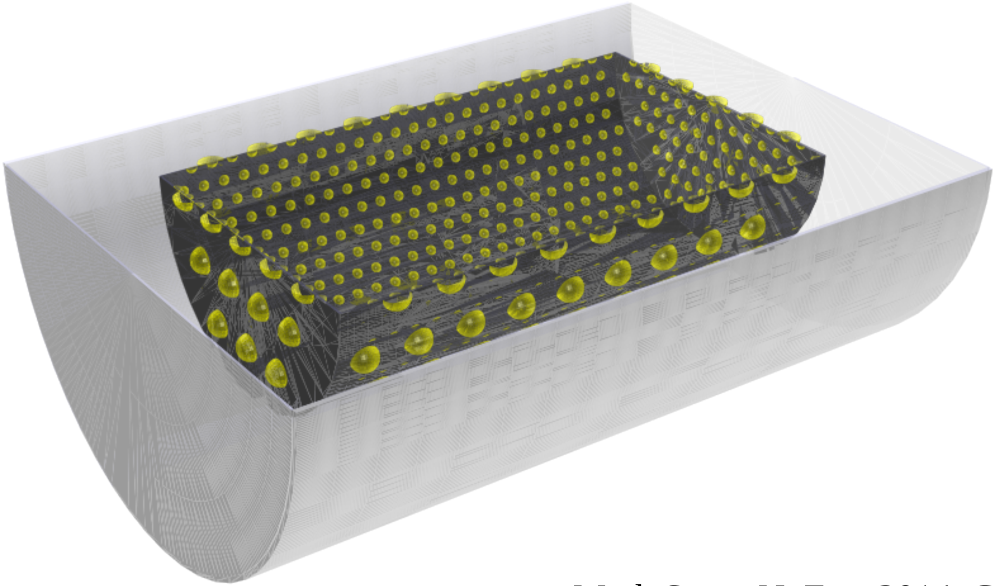


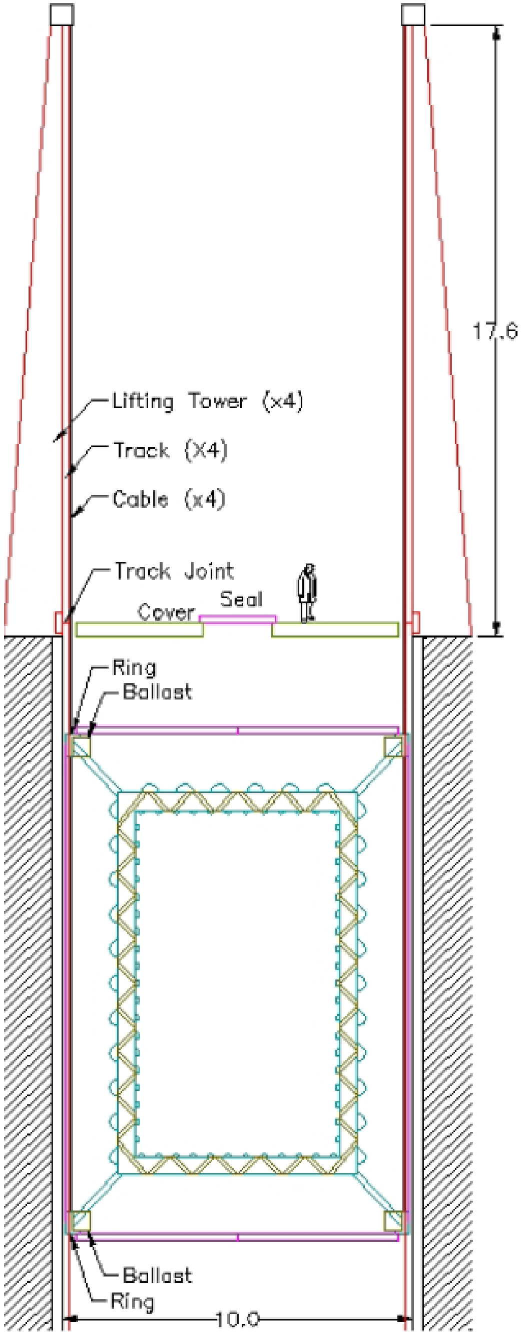
- Water Cherenkov detector spanning 1° – 4° off-axis
  - T2K beam points 3.6° downward, so get 4° off-axis for free
  - 52.5m tall if 1km from neutrino target
- Instrument movable cylinder:
  - Inner Detector (ID): 6 or 8m diameter, 10m tall
  - Outer Detector (OD): 10m diameter, 14m tall
- OD surrounded by scintillator panels – external veto



# Current status

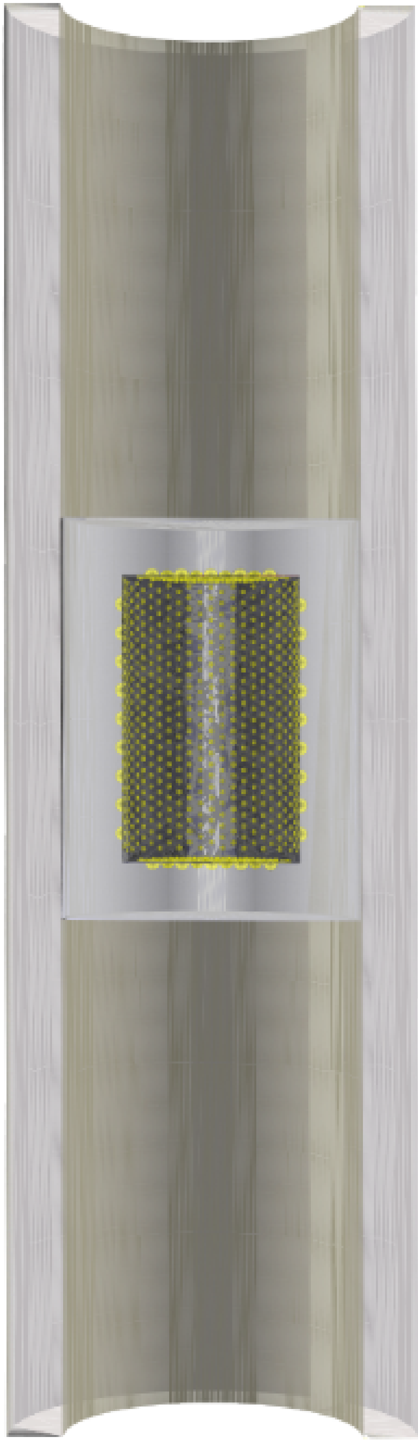
- Expression of Interest (EoI) document written:
  - Detailed $\nu_\mu$ disappearance results
  - Discussion of other physics applications
    - (CP violation, anti-ν, sterile neutrinos – See talk by J. Caravaca in oscillation session)
  - Preliminary detector design
- Currently preparing a full proposal





# Summary

- Precision neutrino physics requires a better understanding of neutrino interactions
- The νPRISM detector concept provides this:
  - Removes model bias in neutrino oscillation measurements
  - Measure NC cross section vs $E_\nu$
  - Separate models that are otherwise degenerate
  - Directly compare $\nu_e$ and $\nu_\mu$ cross section
- Hope to have a working example for T2K in 2019
  - Concept useful for any accelerator-based neutrino experiment



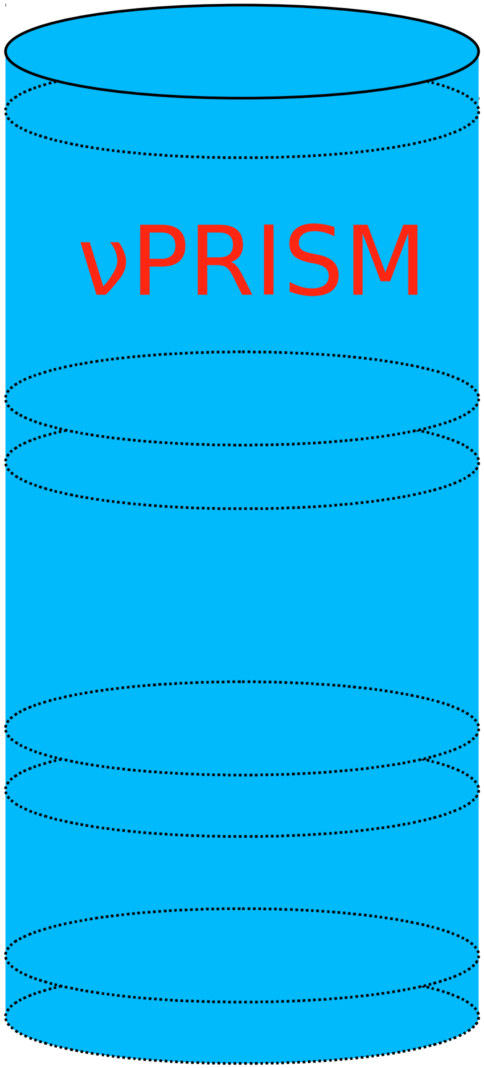
# Backup Slides

# $\nu_\mu$ Disappearance Analysis

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

# νPRISM Design

- Baseline design used in the oscillation studies

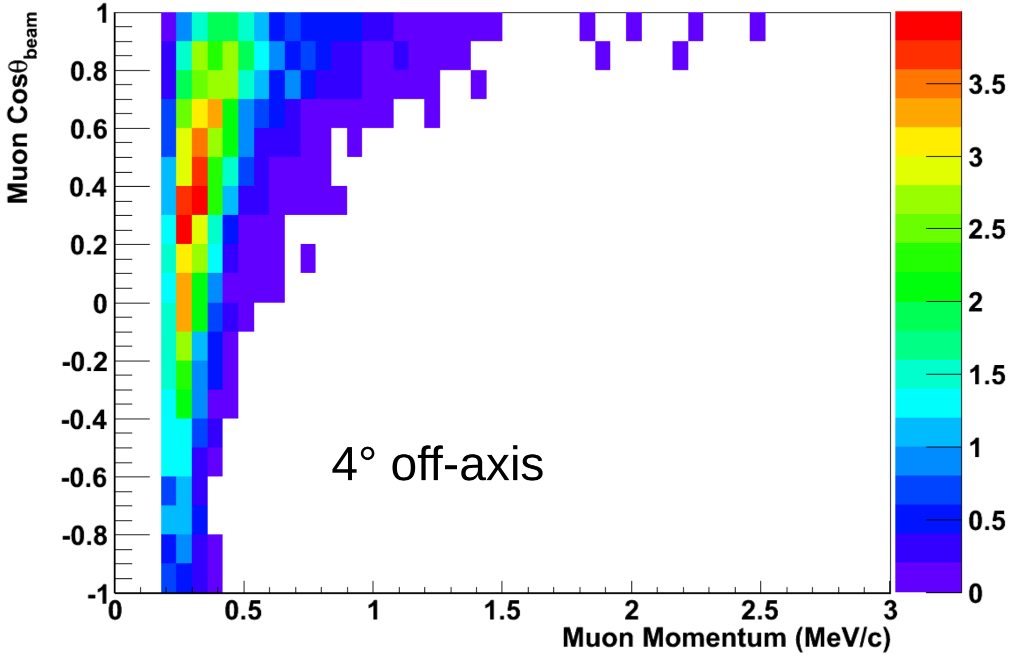


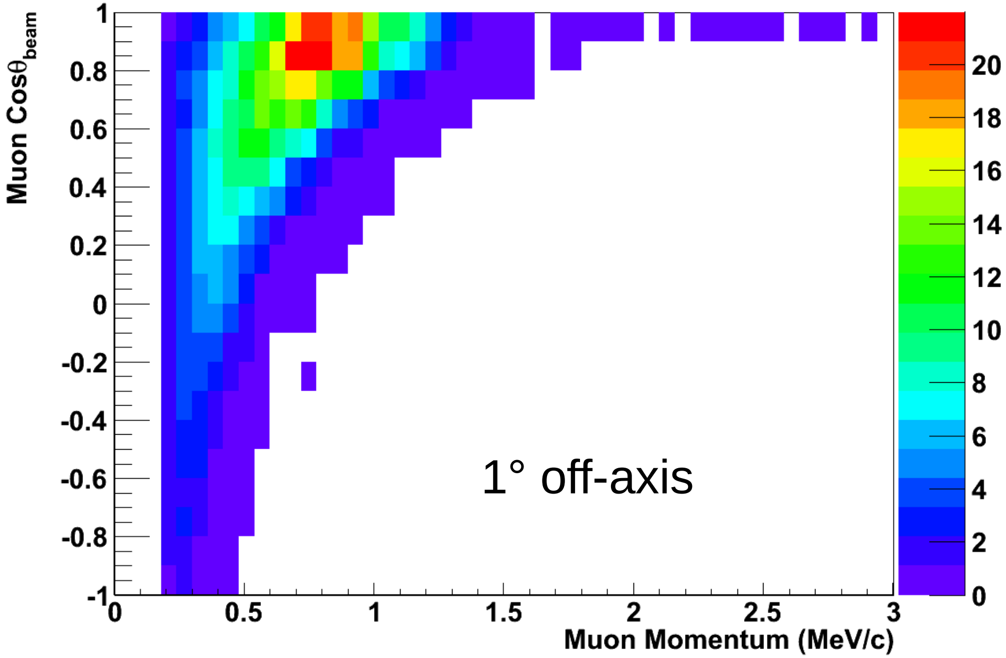

- 3m radius inner detector
- 52.5m tall – spanning 1-4 degrees off axis
- 1km from neutrino target

- 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

# Event Selection

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

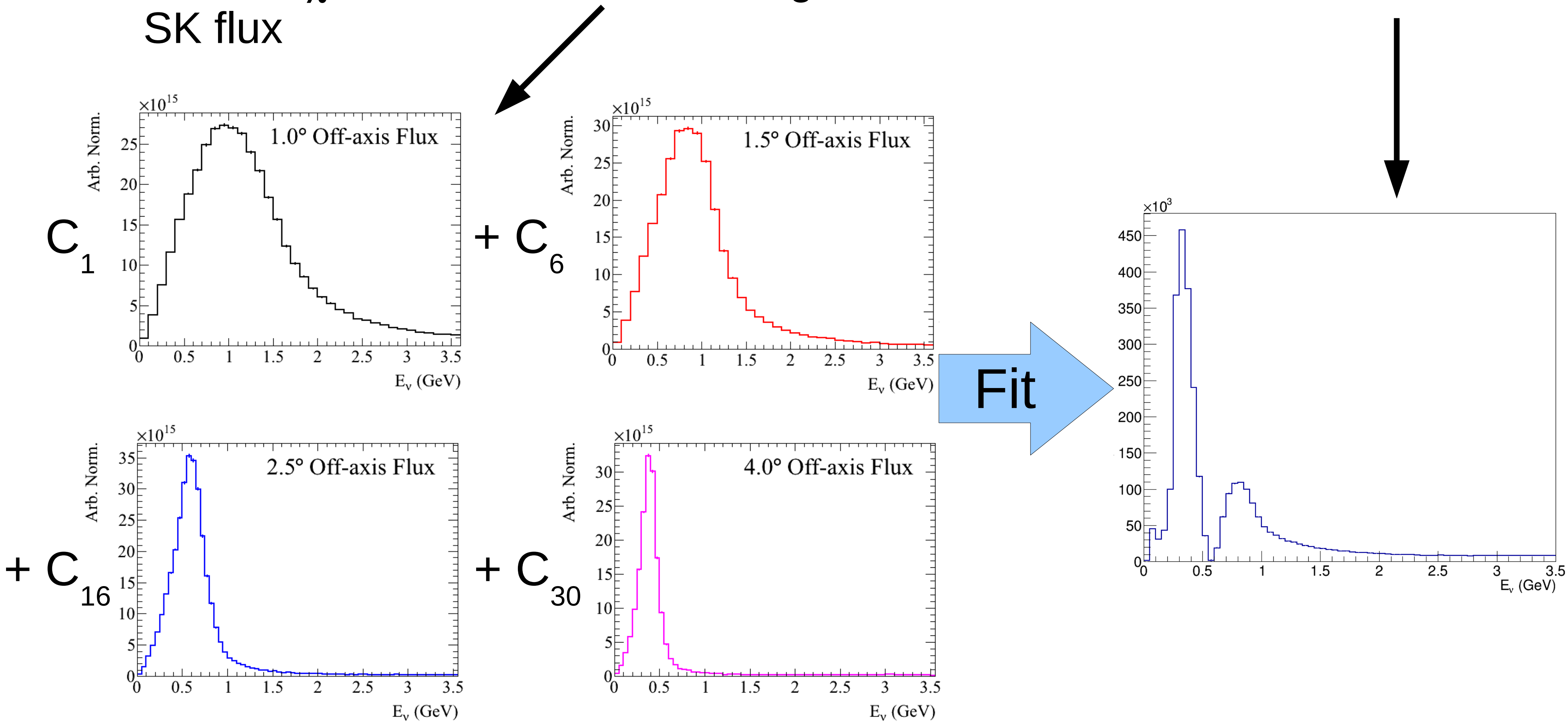



- Record the off-axis angle of the interaction, using the reconstructed vertex position

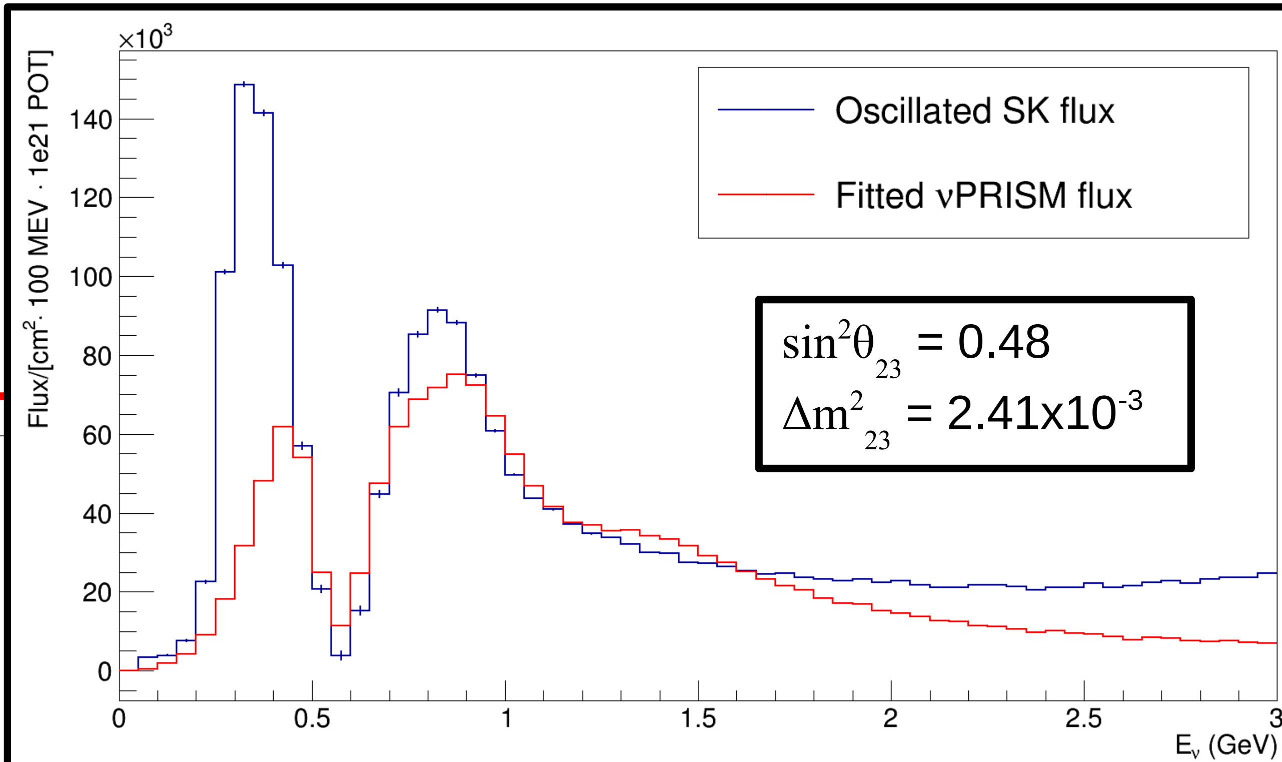
# Building the oscillated flux

- 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

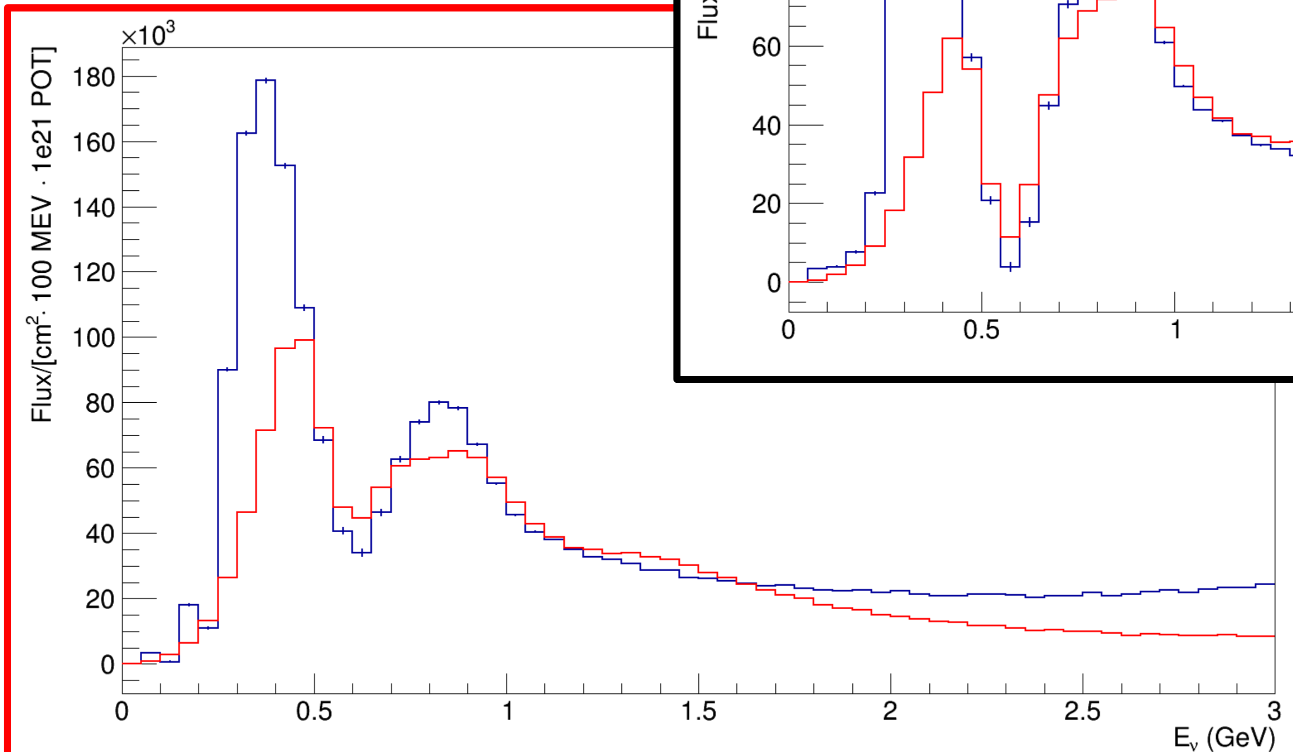


# Building the oscillated flux

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



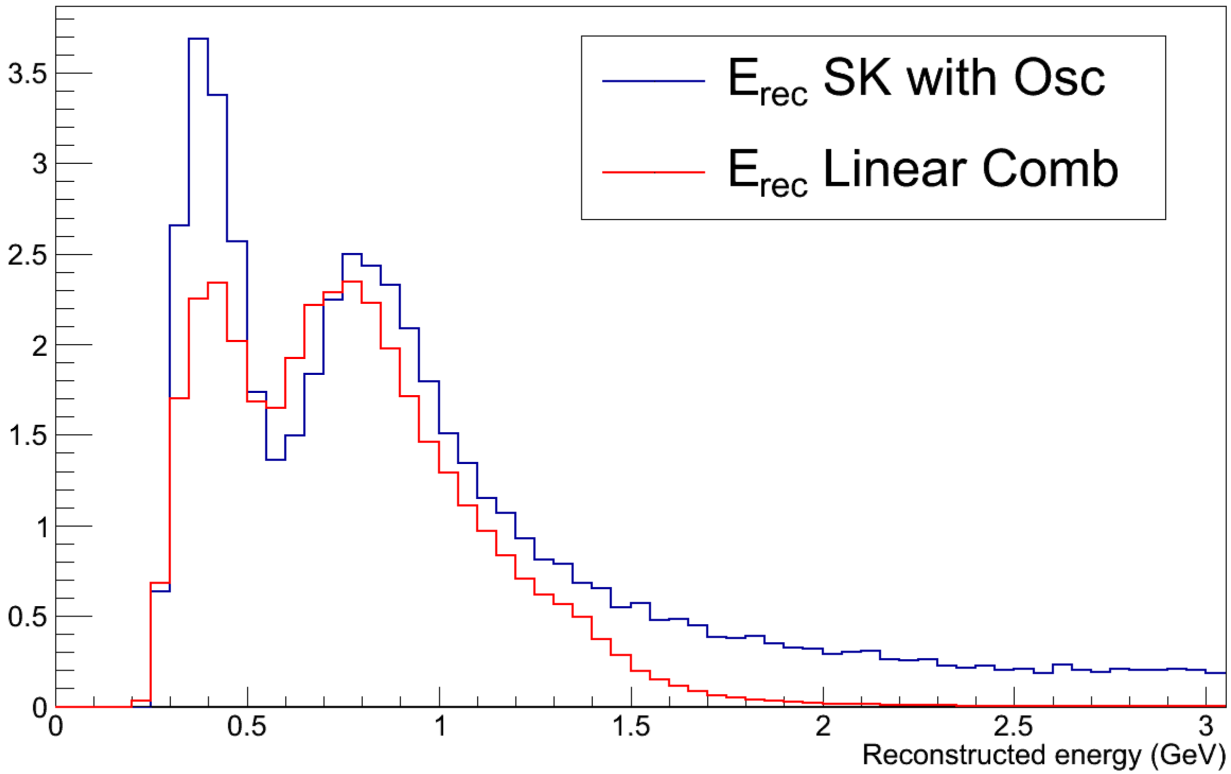

$\sin^2\theta_{23} = 0.61$
$\Delta m^2_{23} = 2.56\times10^{-3}$




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

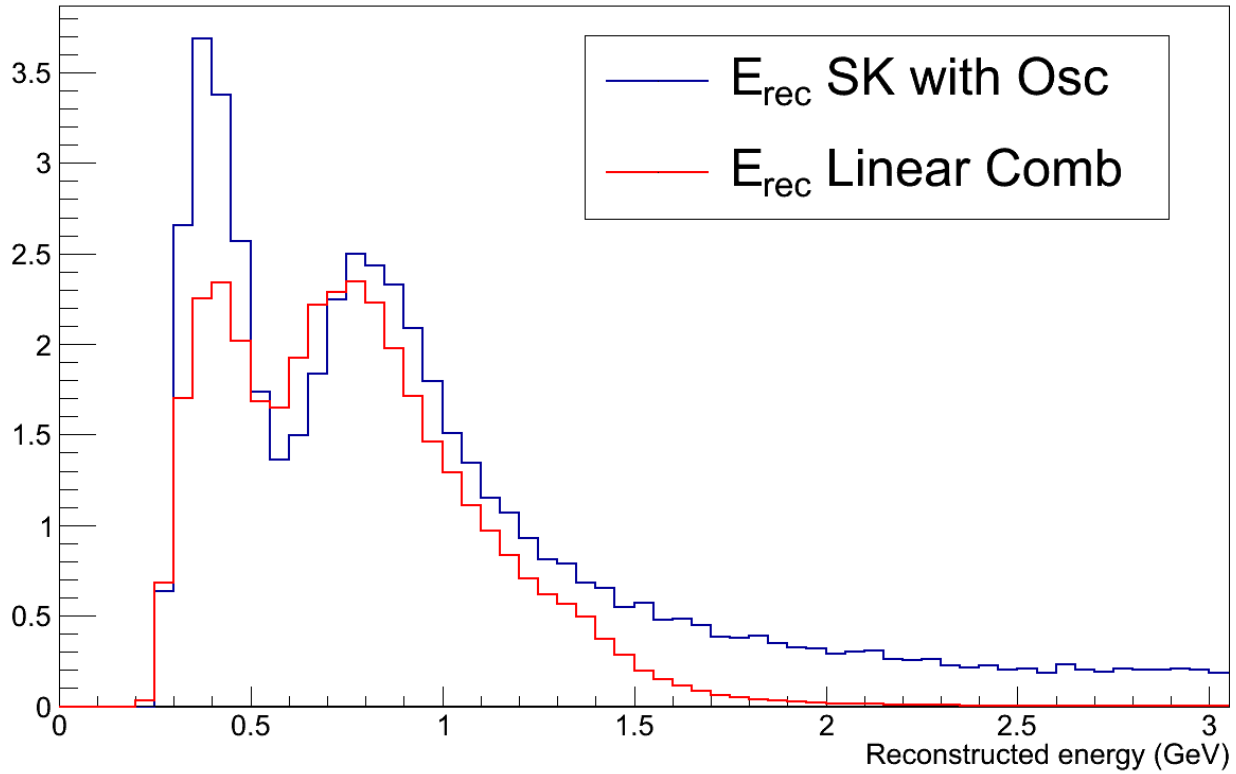
# SK prediction

- 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

# Additive correction



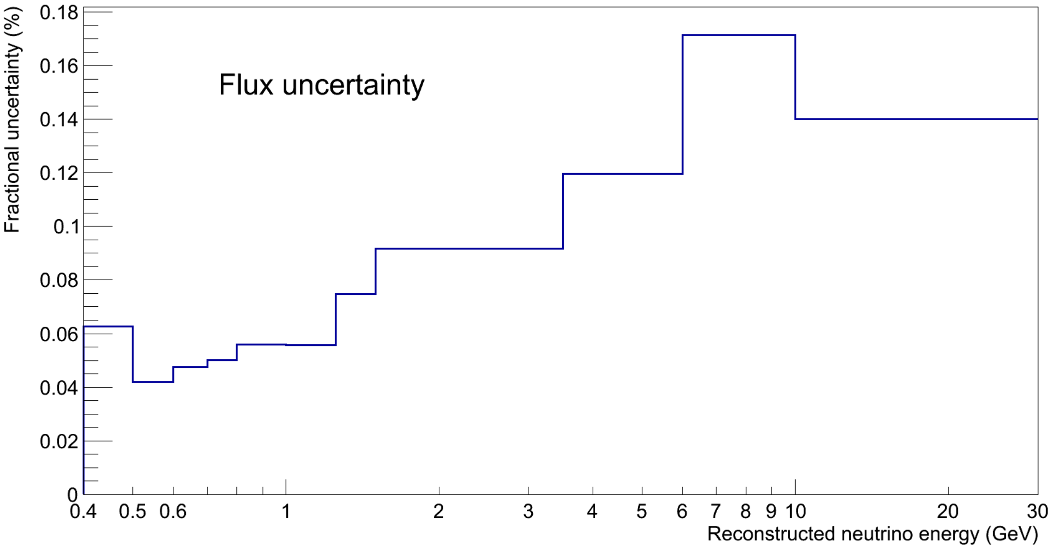

- Final step – additive correction
- Subtract selected SK spectrum from νPRISM prediction
- Add this difference to the νPRISM prediction
- If our MC exactly reproduces nature, νPRISM prediction will exactly match selected SK spectrum

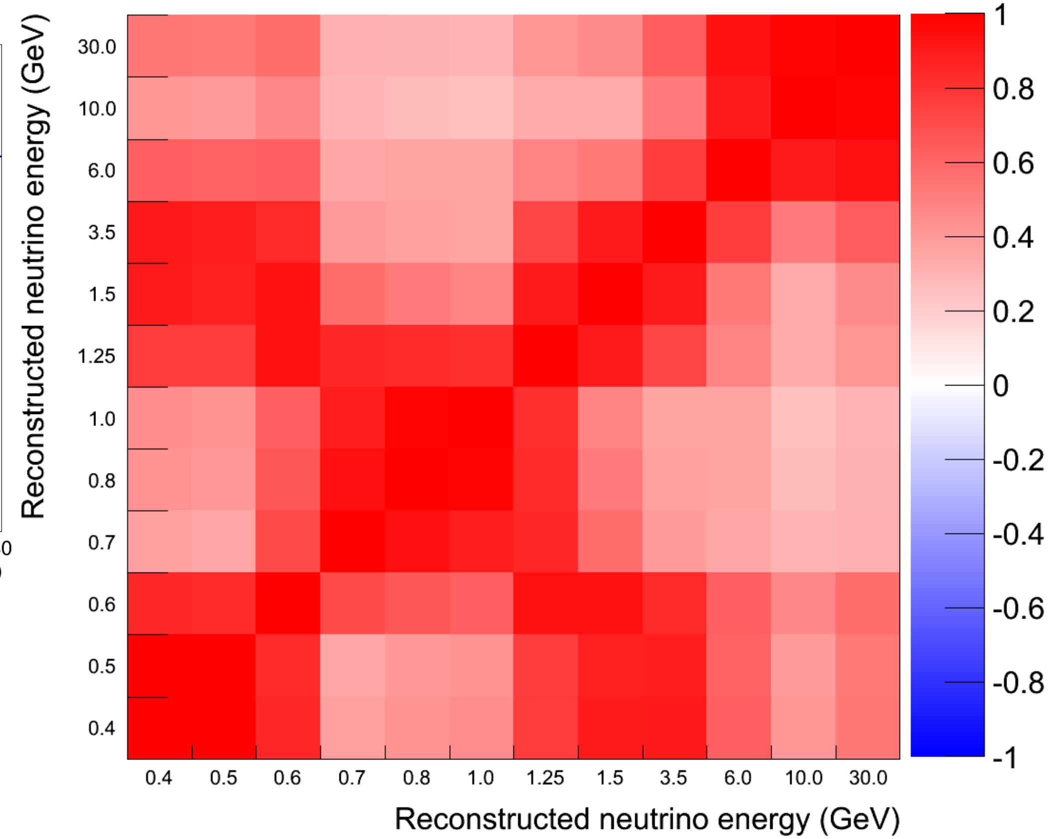
# Systematic uncertainties

- 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 uncertainty

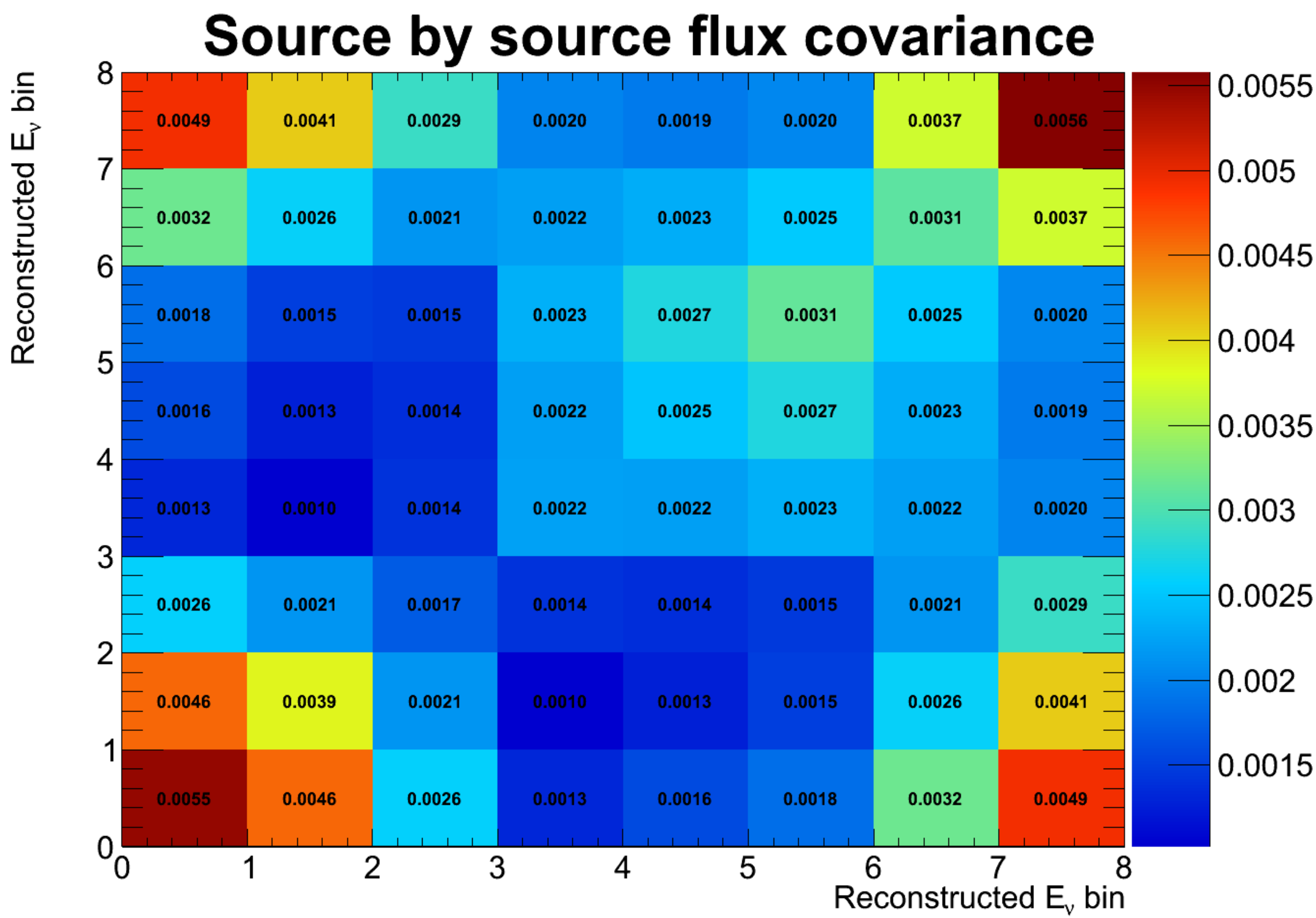
- Flux uncertainties come from 26 sources
  - Proton beam alignment
  - Hadron production
  - Etc.
  - Expect to be independent of one another

- 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

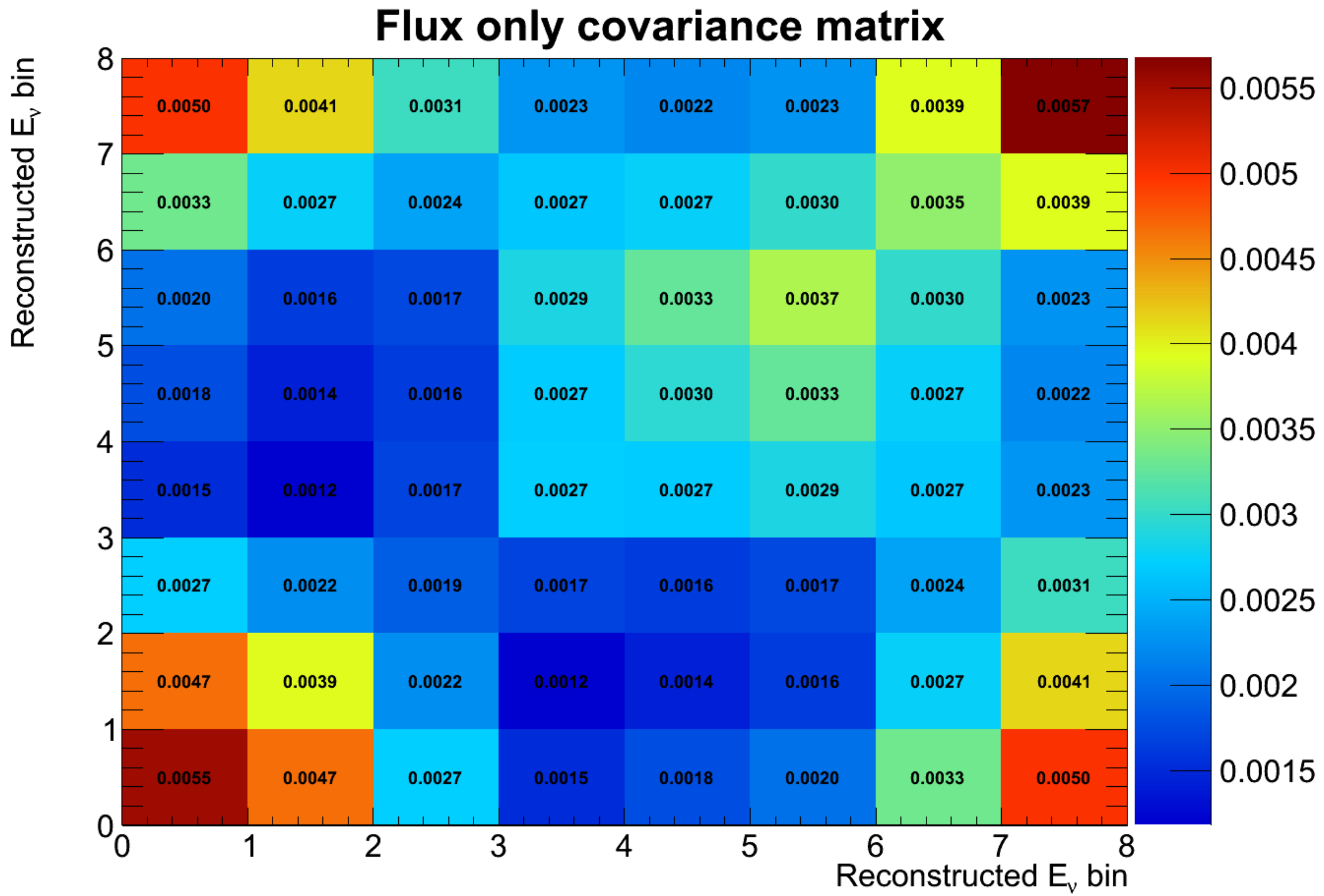
# Separate sources

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



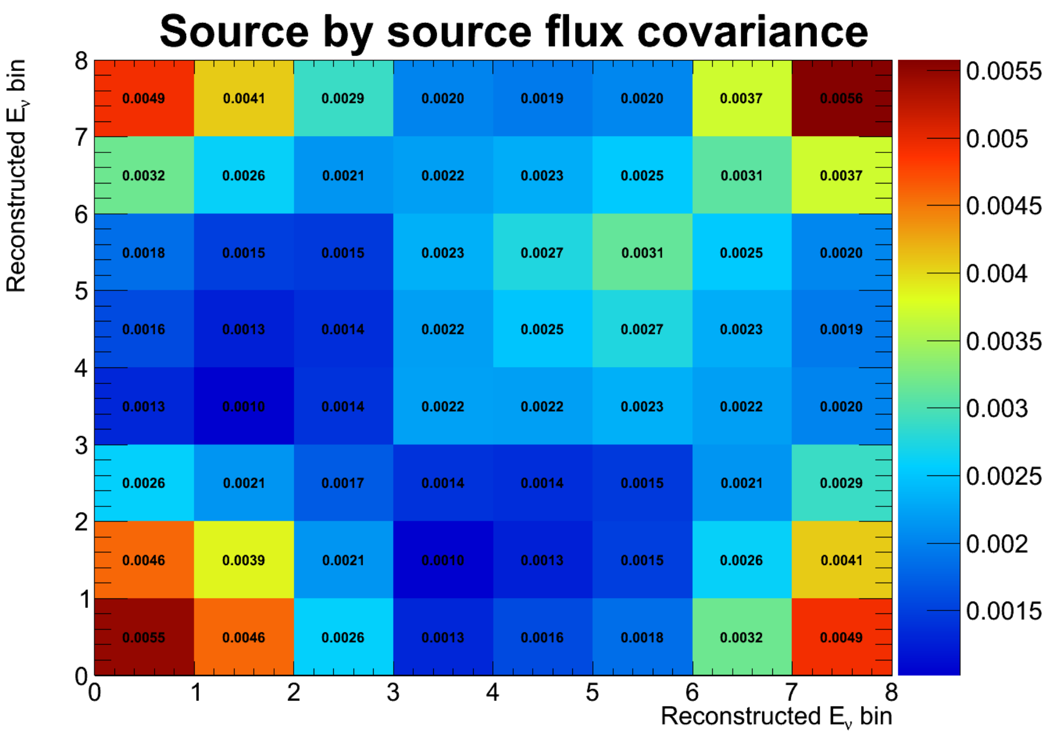
# Simultaneous variation

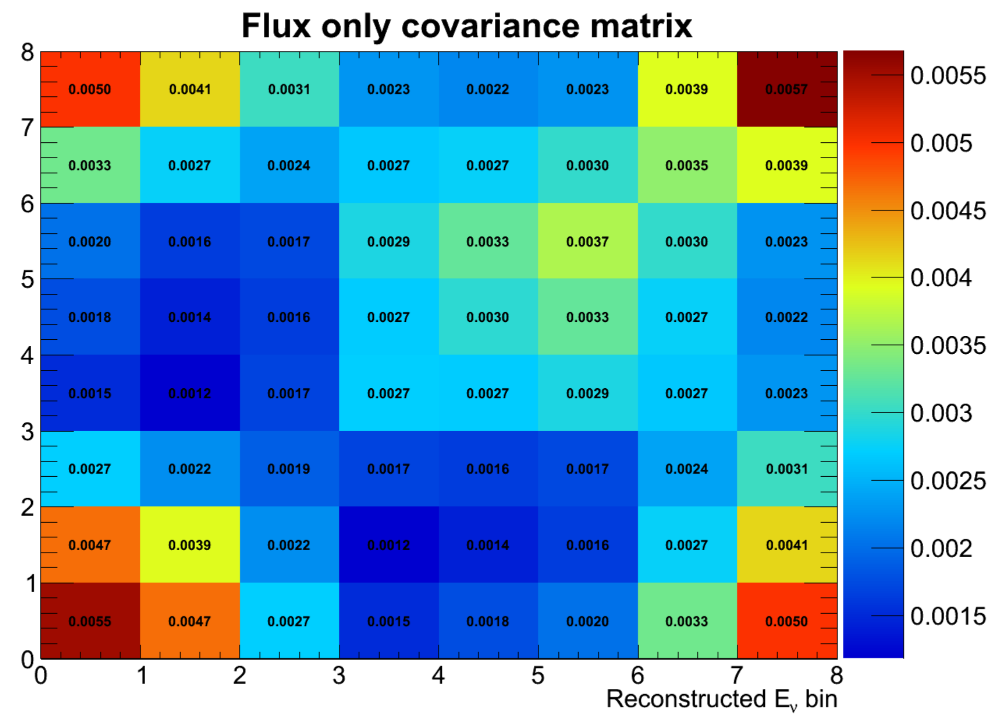
- Larger errors at high and low energy – no νPRISM events
- Error at oscillation dip (bin 3) around 5%



# Comparing flux uncertainty

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

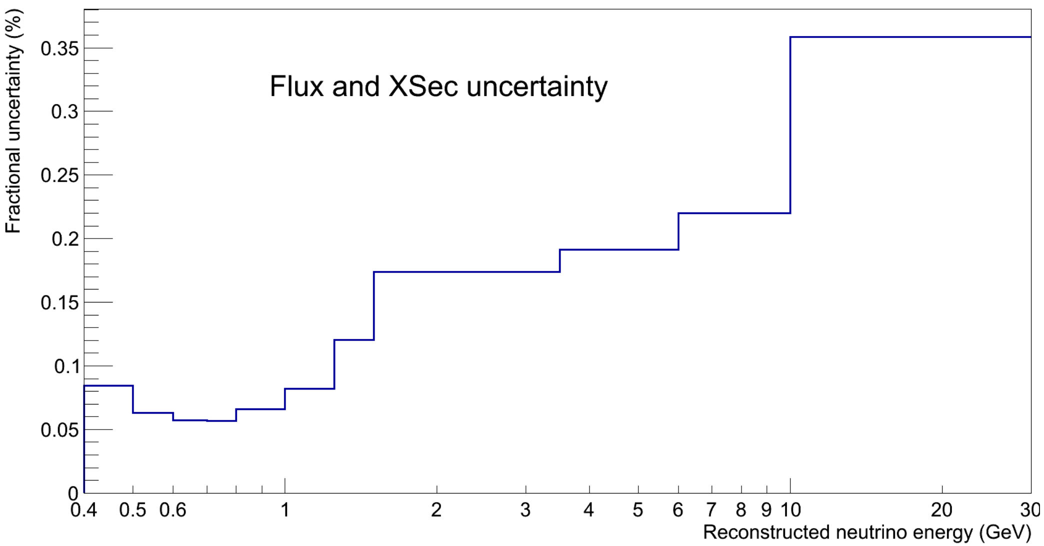


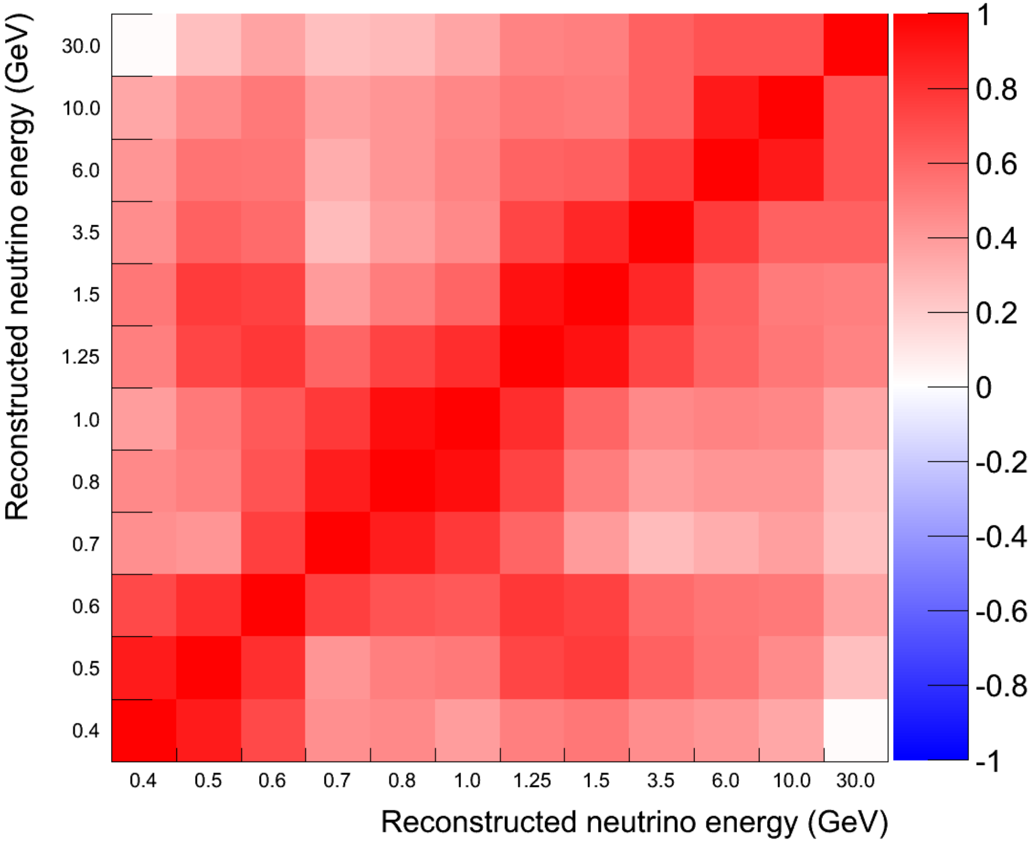




- Very good agreement between the two methods
- Confident flux uncertainties are being applied correctly

# Flux and 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

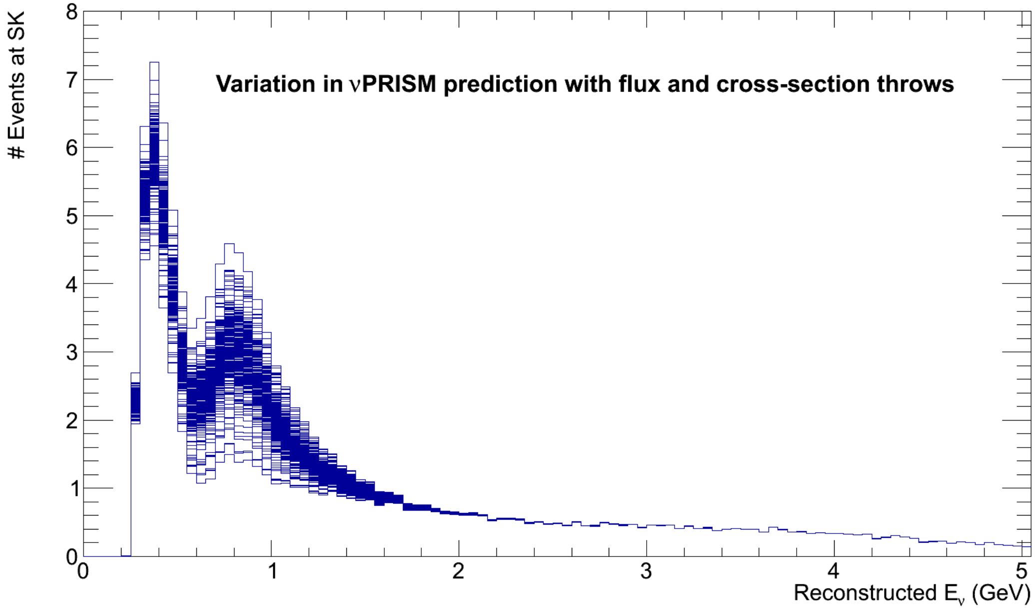


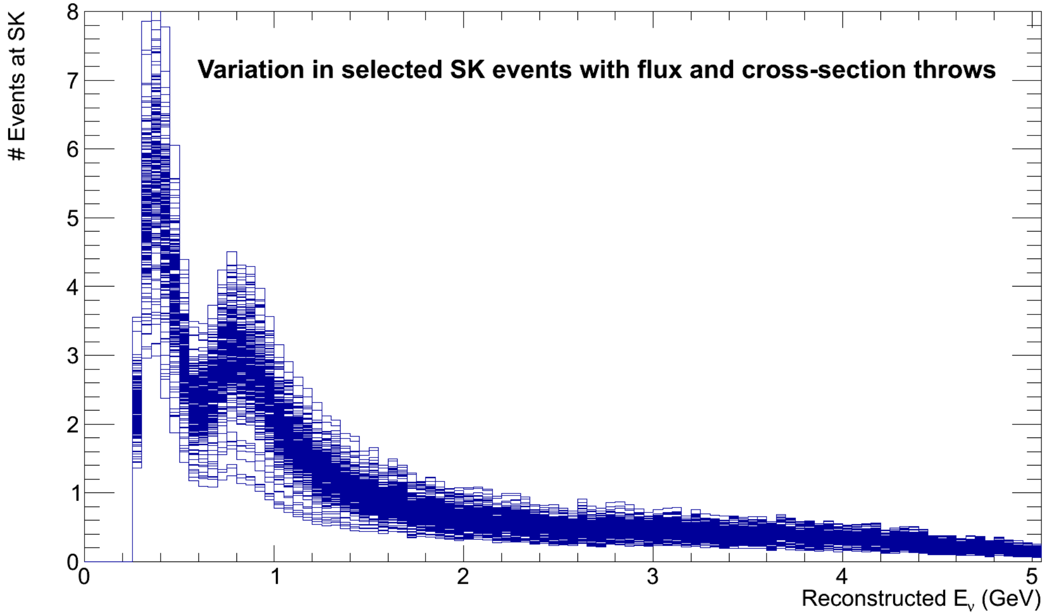




- Combined flux and cross section uncertainty around 5% at the oscillation dip

# Systematic throws

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



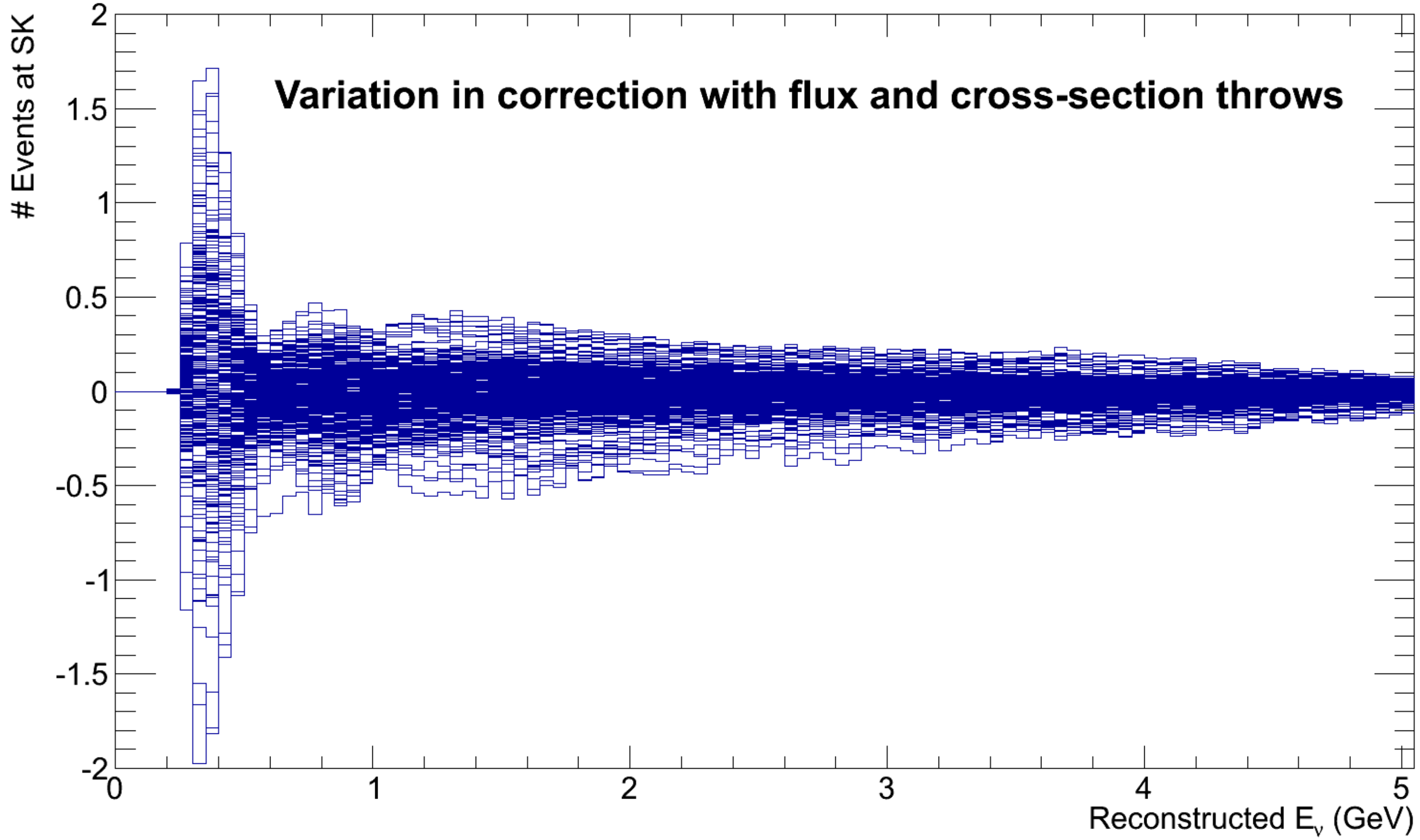




- Plots show all 300 throws of the νPRISM prediction (left) and selected SK events (right)

- 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

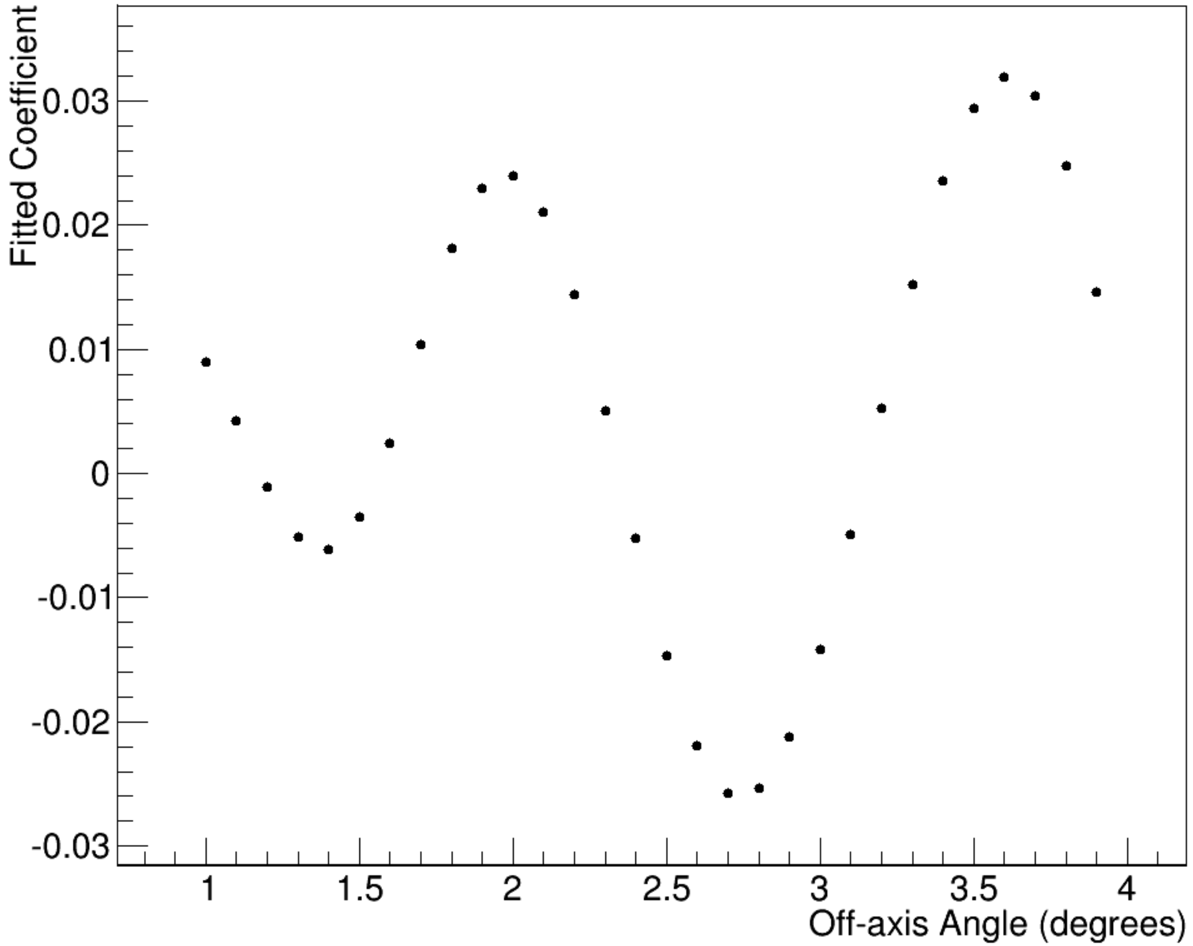
- Plot difference between selected SK events and νPRISM prediction for each throw



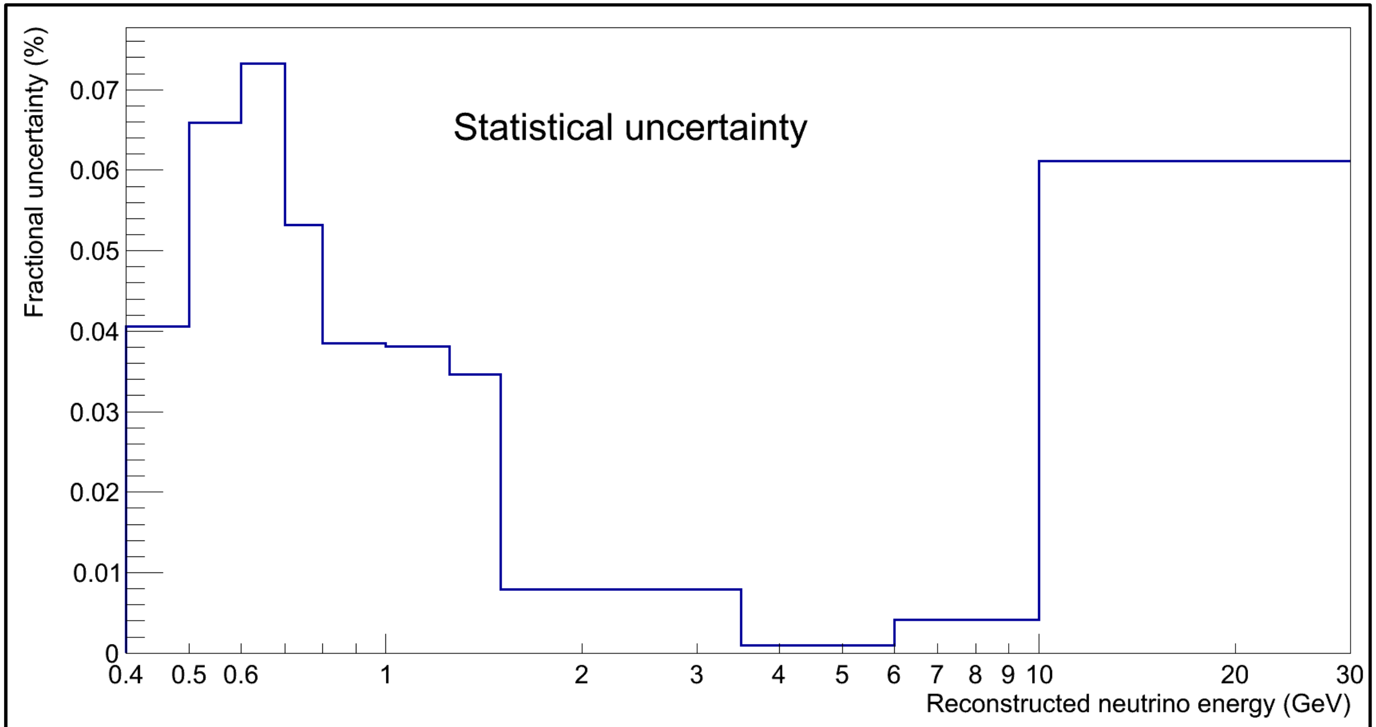

- Most of spectrum shows less than 0.5 event difference between SK and νPRISM prediction
- Systematic uncertainties are cancelling between the two detectors

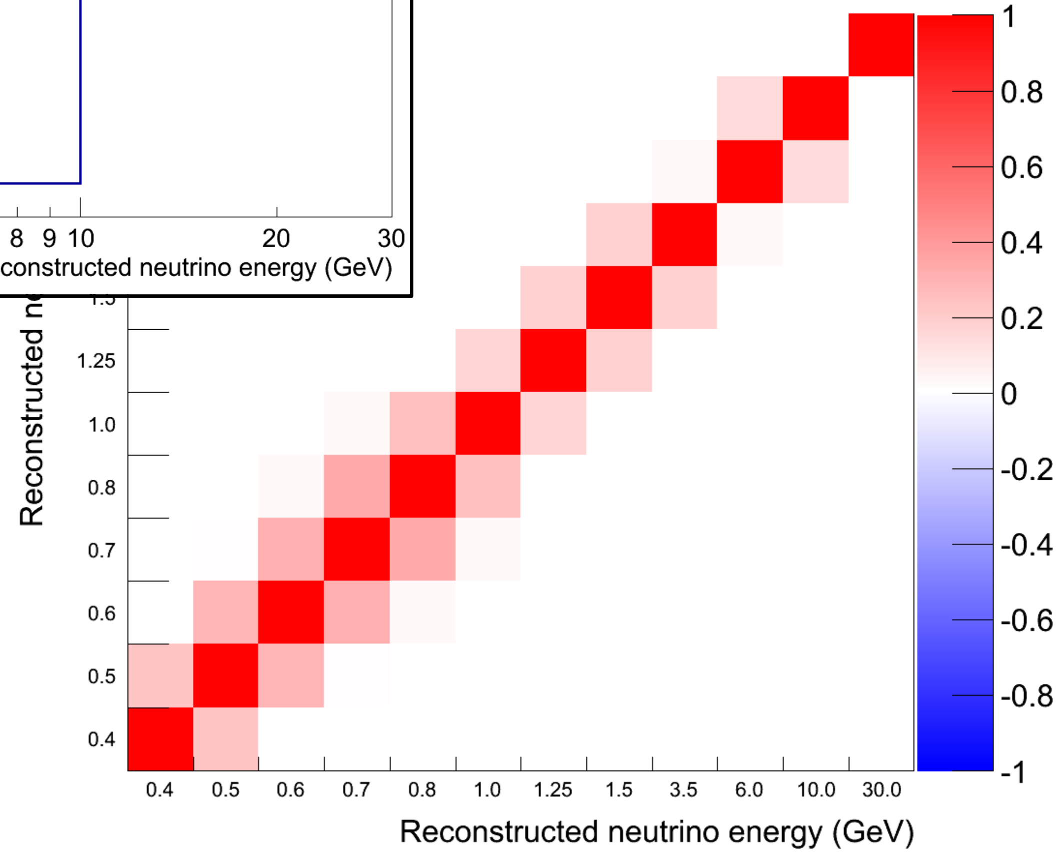
# Statistical uncertainties

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



# Statistical uncertainties

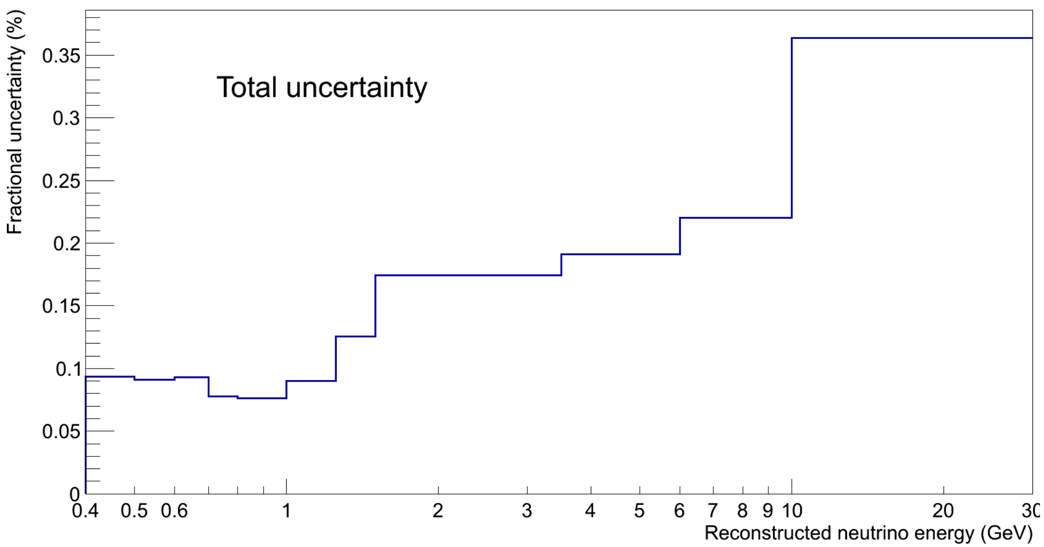


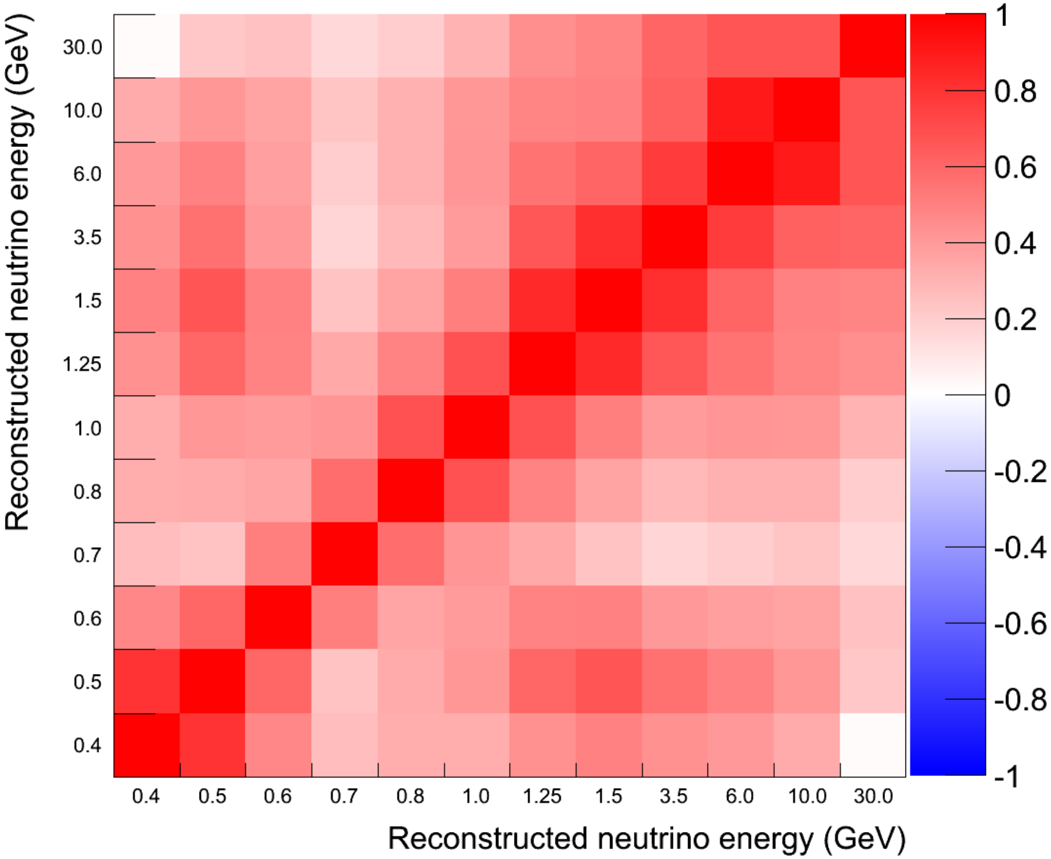




- Uncertainty maximal in oscillation dip – subtracting distributions to get zero events
- Statistical uncertainty ~7% in oscillation dip

# Total uncertainty

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



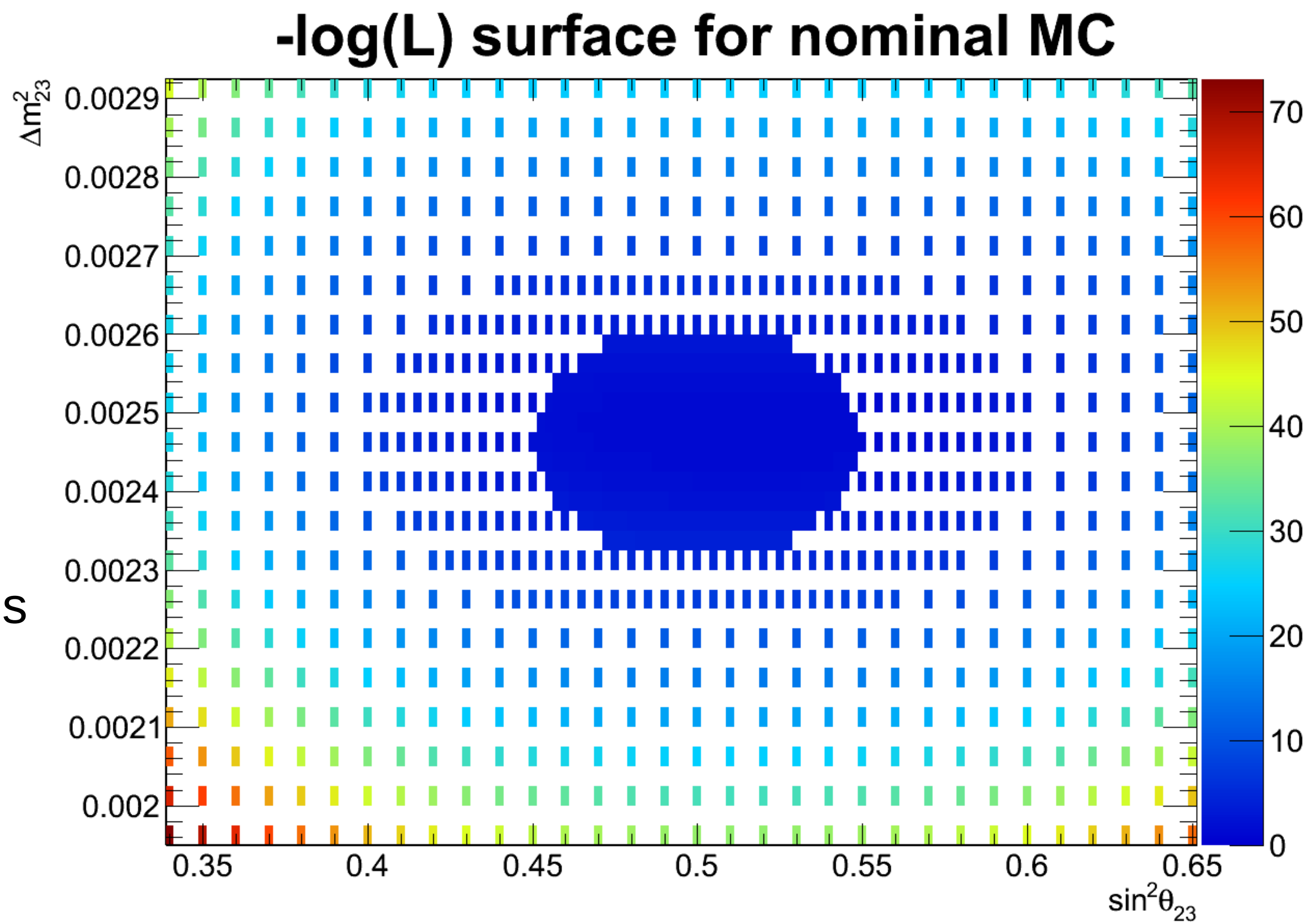




- Total uncertainty is <10% at oscillation peak
- ~7% statistical, 6% systematic

# Oscillation fit

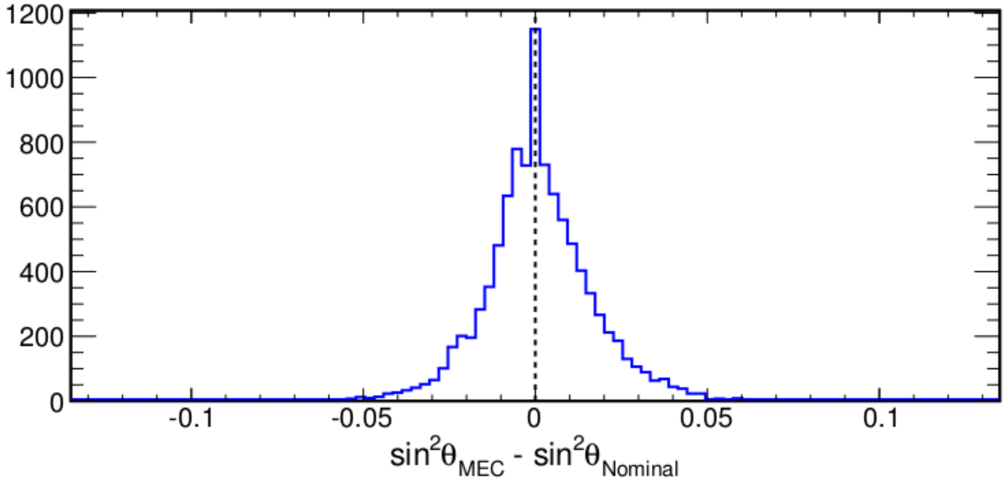
- Calculate covariance matrix and νPRISM prediction for various points in $\theta_{23}$ and $\Delta m^2$ phase space

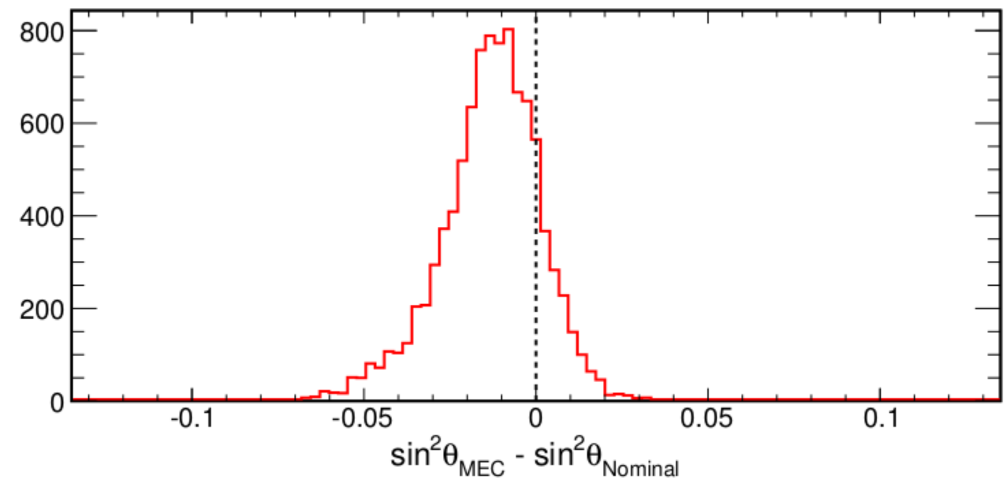
- Use Simple Fitter to calculate likelihood (L)
- Plot - ln(L) for all points in $\theta_{23}$ and $\Delta m^2$
- Minimum bin gives best fit oscillation parameters



# 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

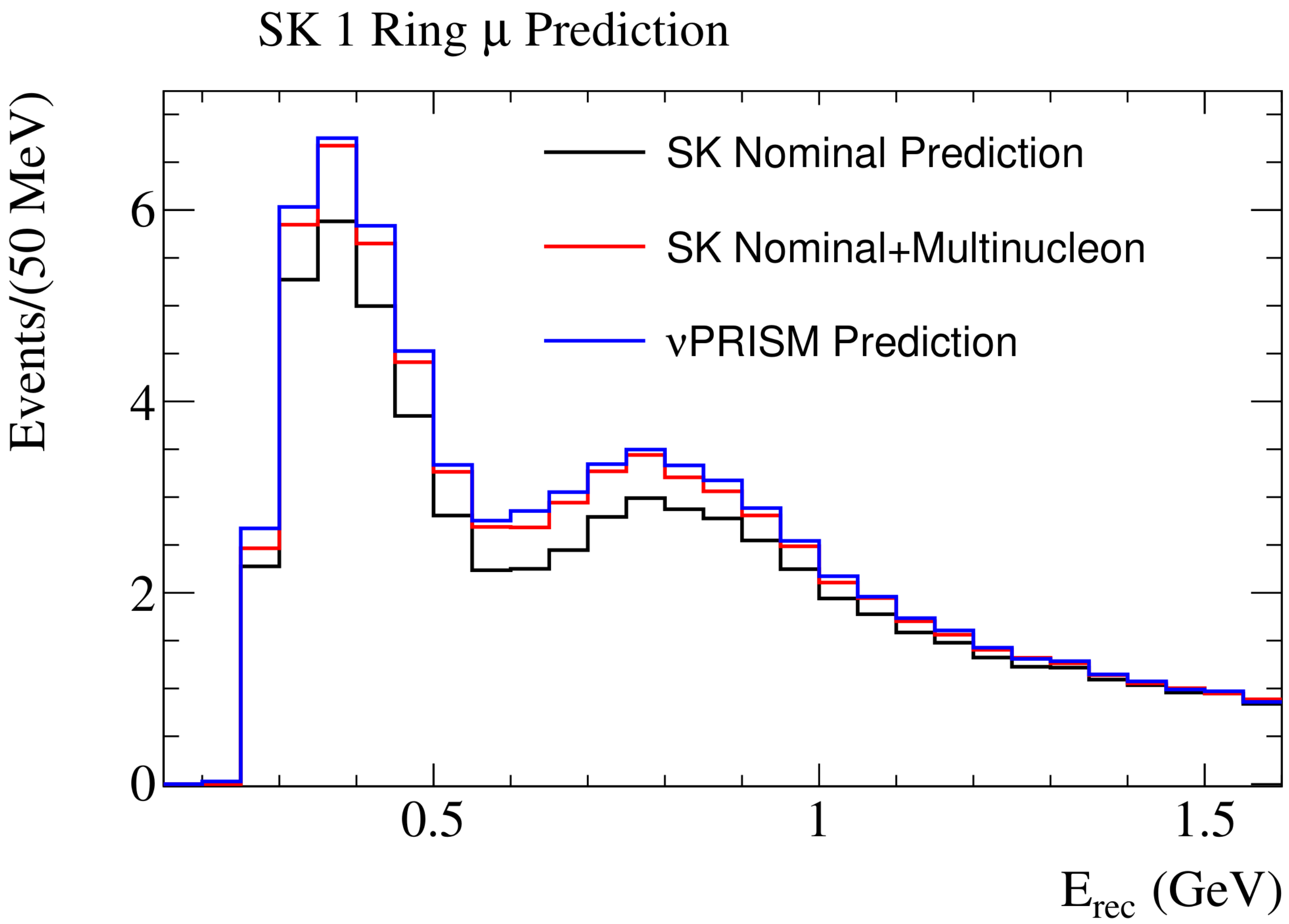



- Plots above show the result of the same analysis performed by T2K
- Using Nieves' MEC prediction on left, Martini mock up on right
- Both show ~3.5% spread, with a bias in the Martini case

# Multi-Nucleon example

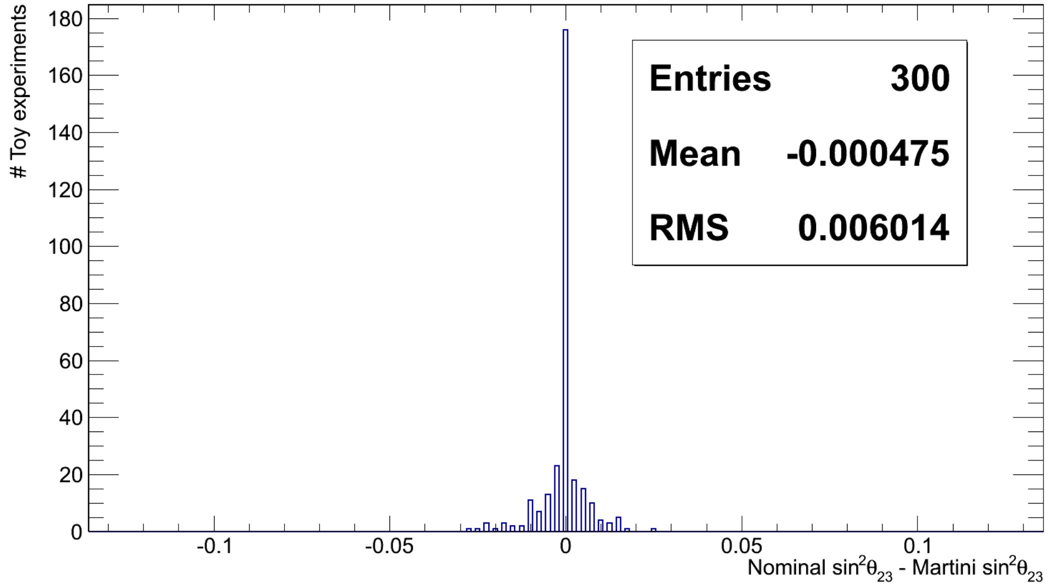
- Add multi-nucleon events to the nominal MC to make fake data

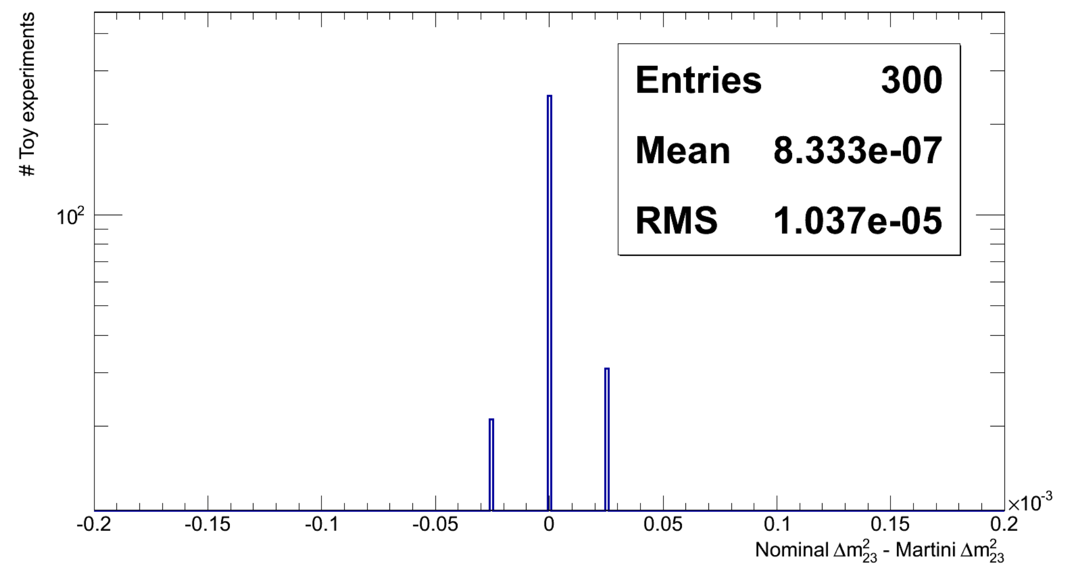



- See νPRISM prediction still reproduces oscillated SK spectrum when multi-nucleon events are present

# Martini MEC result

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

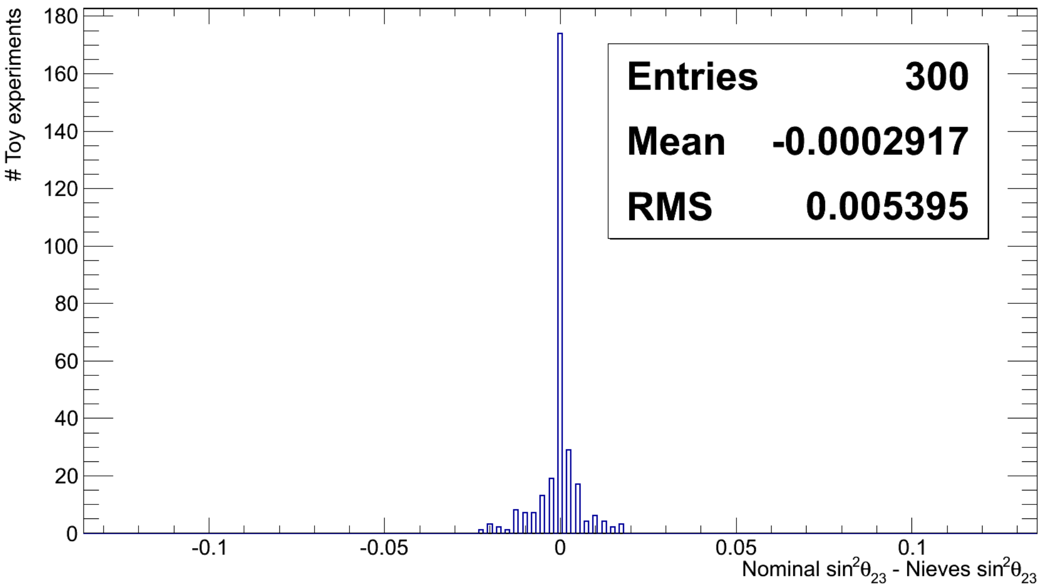


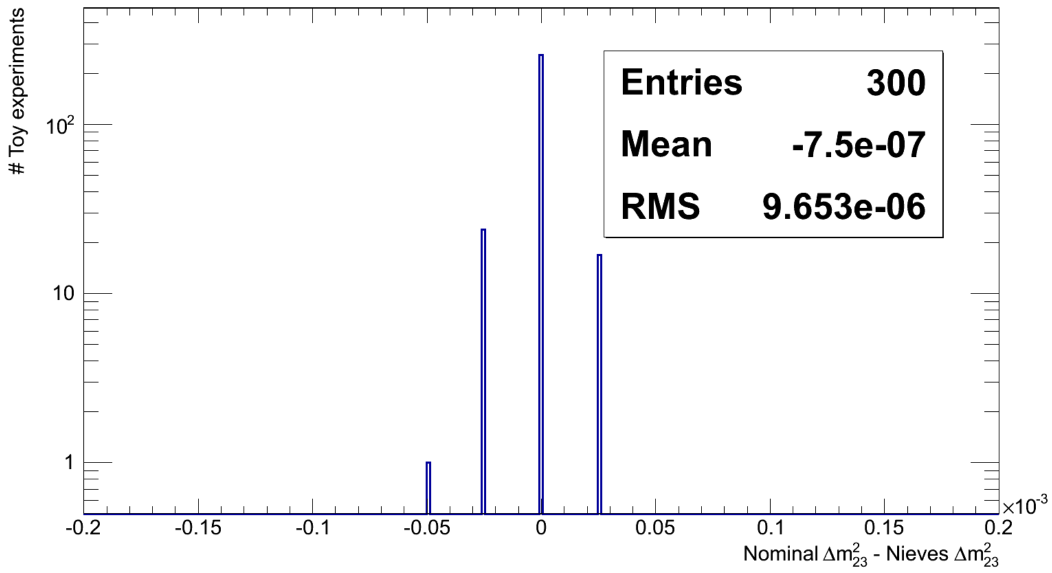




- Much smaller RMS in $\theta_{23}$ (left) and $\Delta m^2$ (right) than in T2K analysis
- No bias seen in $\theta_{23}$ plot
- $\nu$PRISM will provide the first data driven constraint on the effect of multi-nucleon events in oscillation measurements

# Nieves' result

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

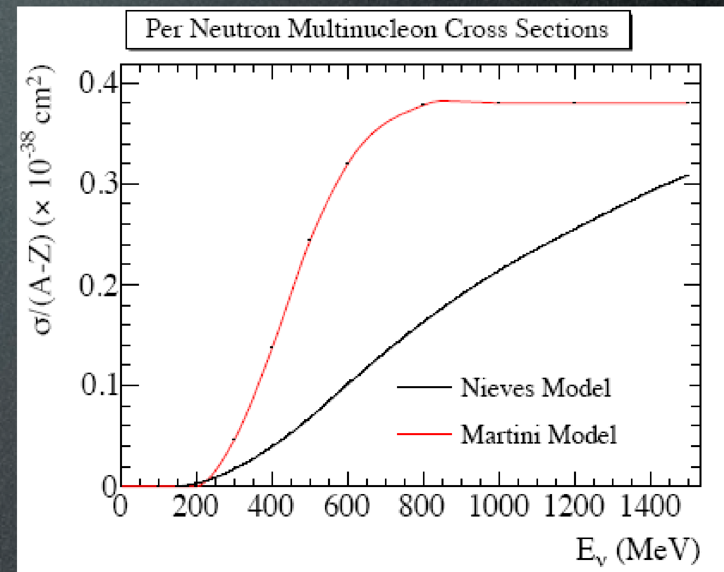


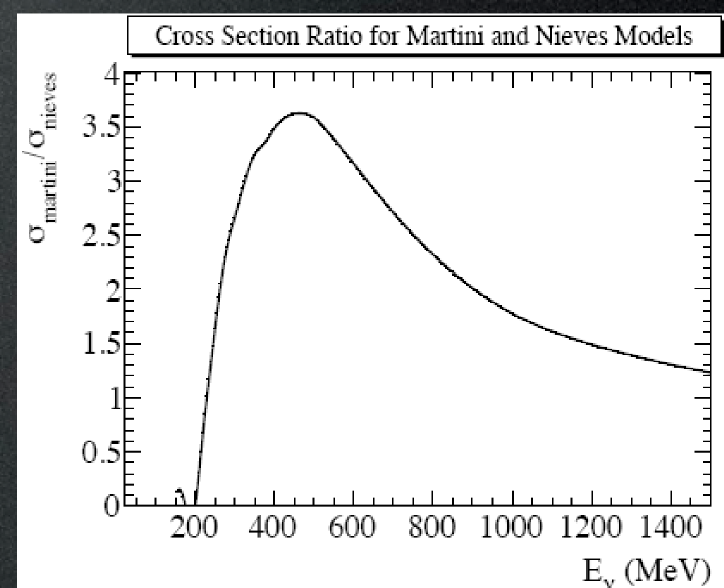




- Much smaller RMS in $\theta_{23}$ (left) and $\Delta m^2$ (right) than in T2K analysis
- Large spike at 0 difference in both plots

# How Well are the New Models Understood?

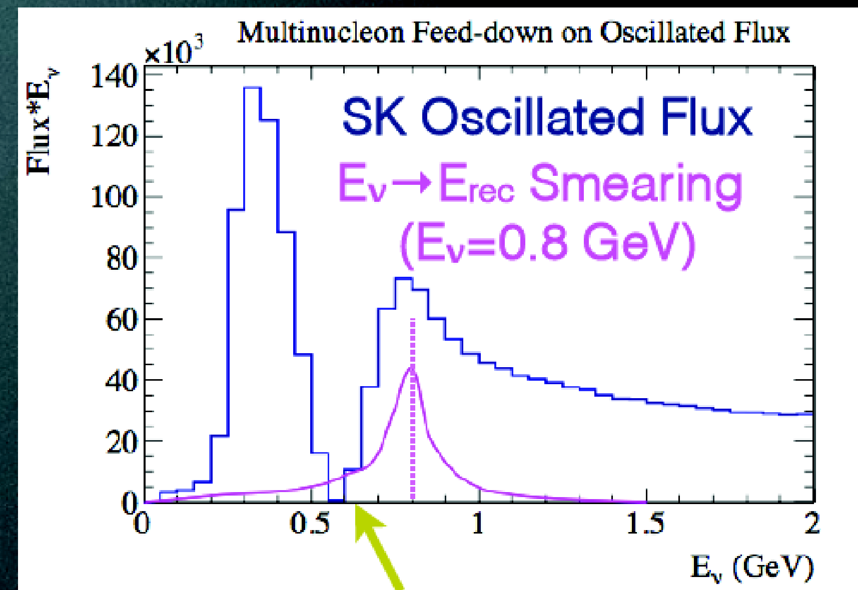
- It is very difficult to answer this question without a direct measurement
- However, the two most commonly used "new" models can be compared
  - J. Nieves, I. Ruiz Simo, and M. J. Vicente Vacas, PRC 83:045501 (2011)
  - M. Martini, M. Ericson, G. Chanfray, and J. Marteau, PRC 80:065501 (2009)
- Cross section differs by a factor of 2 to 3 over a large range of neutrino energies
- Which model is correct?
  - Is either model correct?
- Nuclear physics at 1 GeV is difficult



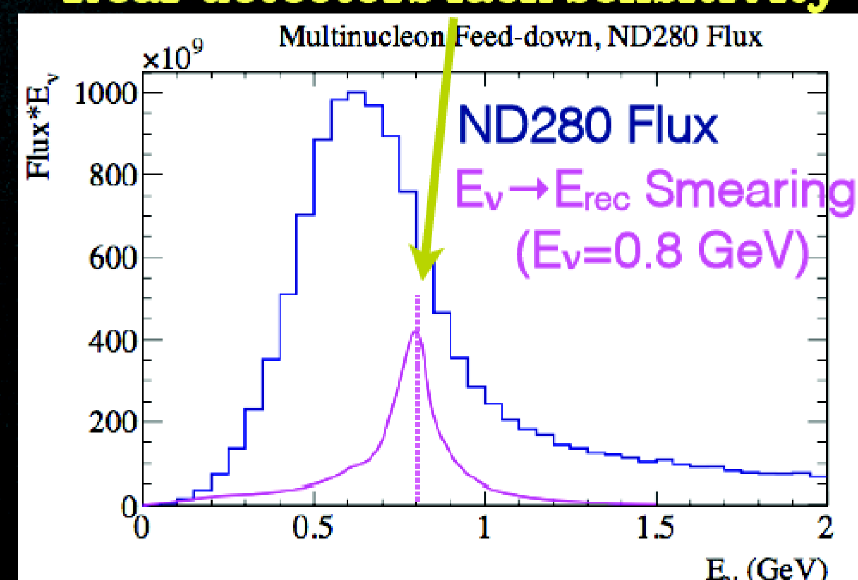
# Isn't This is Why Oscillation Experiments Build Near Detectors?

- Shouldn't cross section systematics cancel in a near/far fit?
  - Some errors, like total normalization, will cancel
- However, multi-nucleon effect causes feed-down of events into oscillation dip
  - Cannot disentangle with near detectors
    - Energy spectrum is not oscillated
- More multi-nucleon = smaller dip
  - **Multi-nucleon effects are largely degenerate with mixing angle effect!**



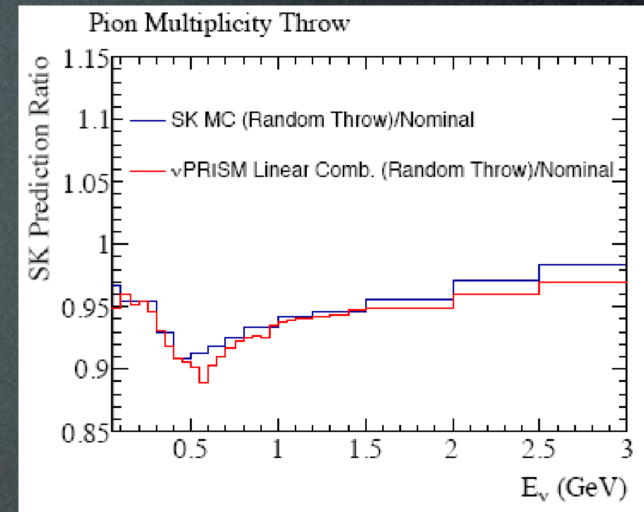

**Mixing Angle Bias!**

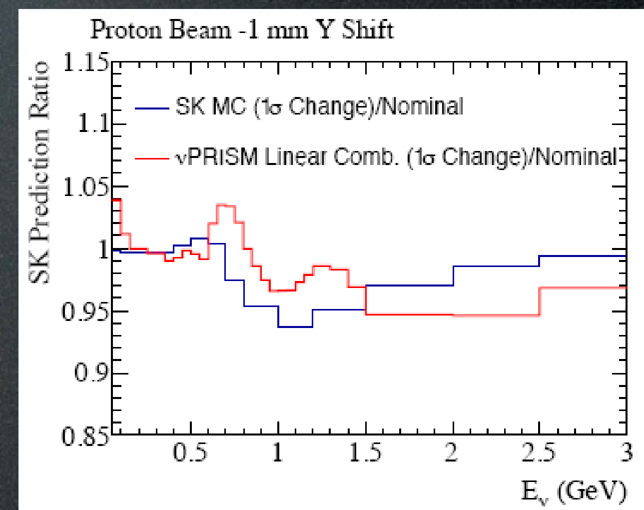
**Near detectors lack sensitivity**

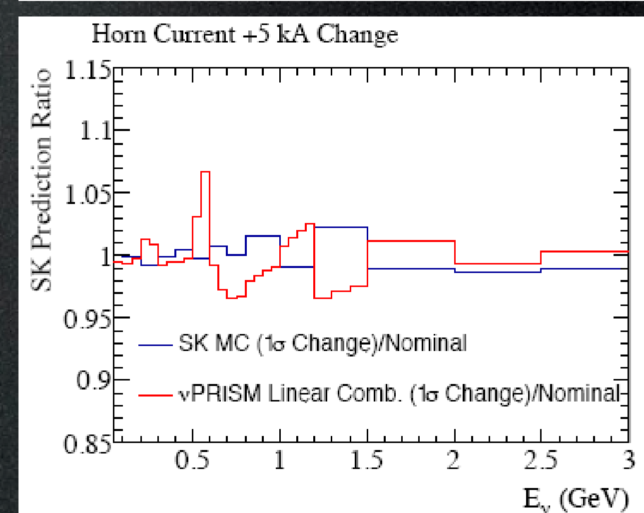


# Beam Errors

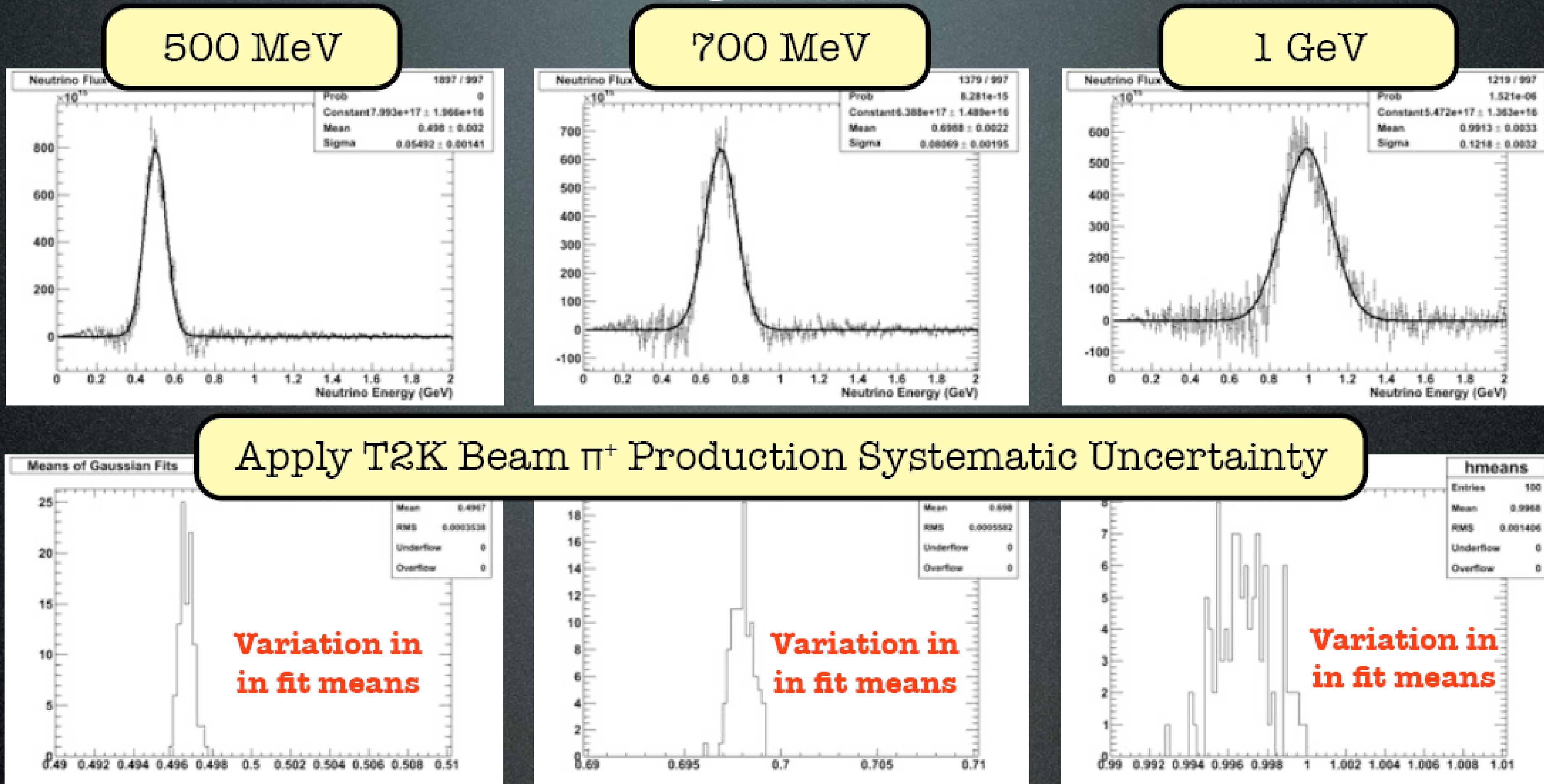
- Haven't we just replaced **unknown cross section errors** with **unknown flux errors**?
  - Yes! But only relative flux errors are important!
  - Cancelation exist between νPRISM and far detector variations
- **Normalization uncertainties will cancel** in the νPRISM analysis
  - Cancelations persist, even for the νPRISM linear combination
  - Shape errors are most important
- For scale, **10% variation** near the dip means **~1% variation** in $\sin^2 2\theta_{23}$
  - Although this region is dominated by feed down
- Full flux variations are reasonable
  - No constraint used (yet) from existing near detector!
    - Uncertainties set by NA61 and T2K beam data



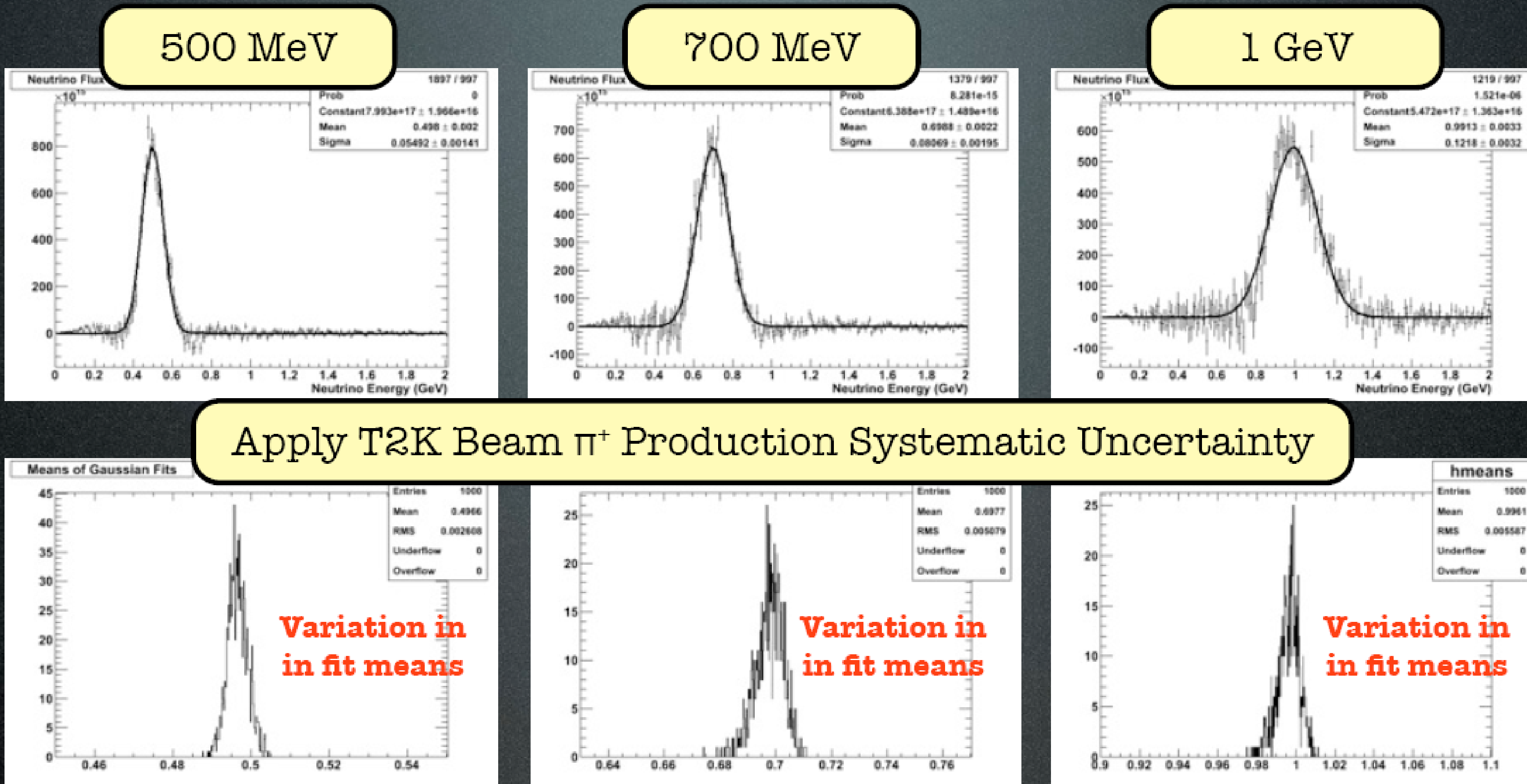



# Beam Systematics




- Apply **T2K $\pi^+$ production variations** to flux linear combinations
  - This is expected to be the dominant normalization uncertainty for T2HK
- Spread in neutrino energy due to $\pi^+$ production **uncertainty is $\mathcal{O}$(0.1%)**
  - More detailed study needed, but so far looks promising

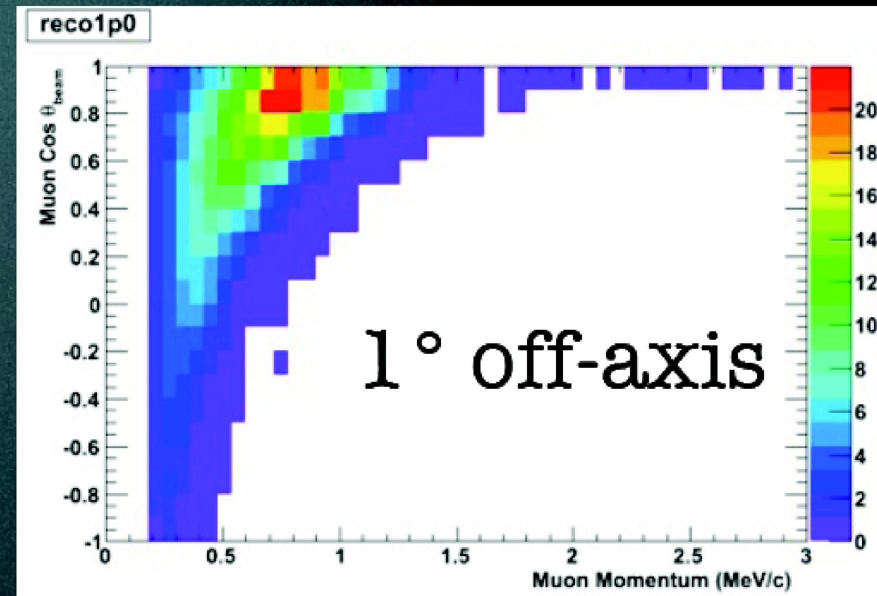
# Detector Systematics



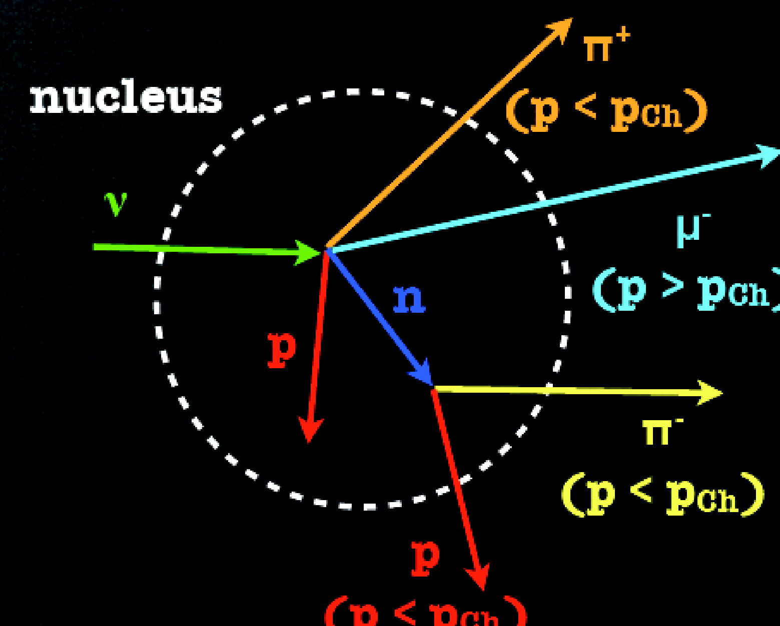

- Efficiency was randomly varied by 5% in each slice
  - The resulting variations in the fit means are still all below 1%
- Continuous variations across the detector can cause problems
  - Need homogeneous detector, and good monitoring & calibration

# Signal Selection/Definition

- **Same signal selection as used at Super-K**
  - Single, muon-like ring
- Signal events are defined as **all true single-ring, muon-like events**
  - A muon above Cherenkov threshold
  - All other particles below Cherenkov threshold
- νPRISM can measure **single muon response** for a given $E_\nu$ spectrum
  - Signal includes CCQE, multi-nucleon, $CC\pi^+$, etc.
  - No need to make individual measurements of each process and extrapolate to T2K flux

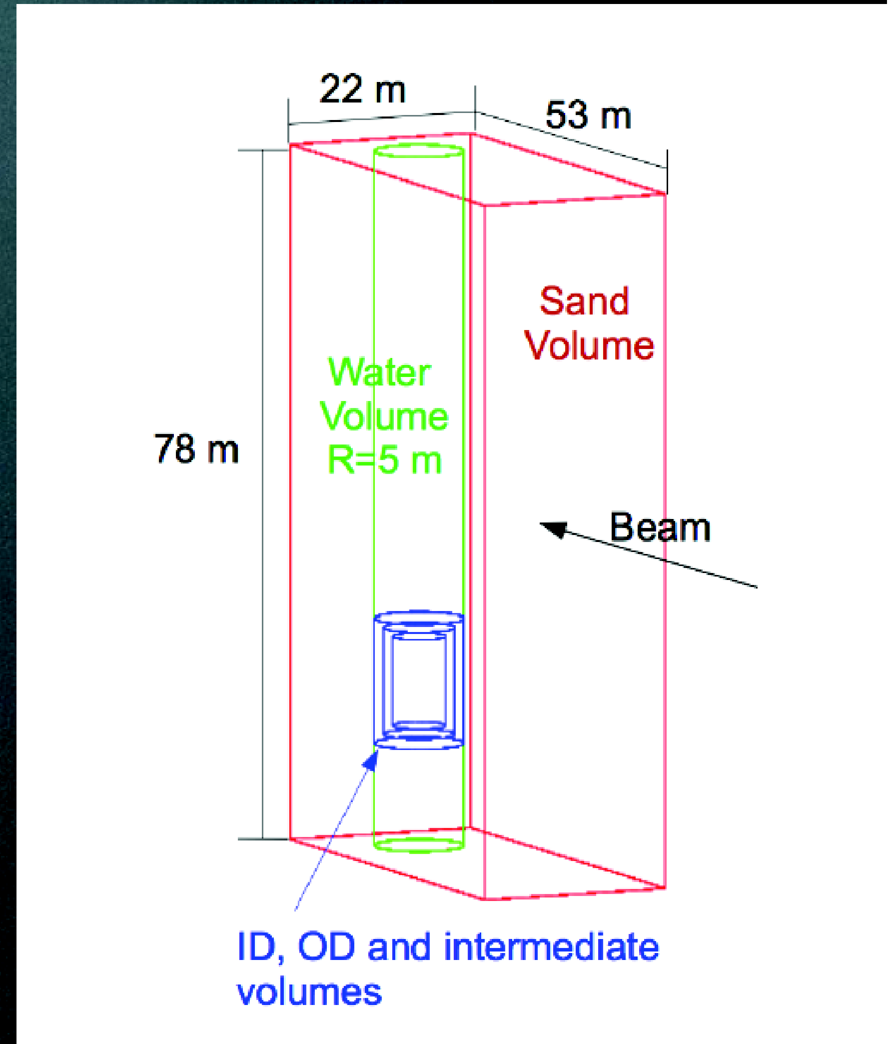



**Example Signal Event**



# Event Pileup at 1 km

- Full GEANT4 simulation of water and surrounding sand
    - Using T2K flux and neut cross section model
- 8 beam bunches per spill, separated by 670 ns with a width of 27 ns (FWHM)
- **41% chance of in-bunch OD activity during an ID-contained event**
    - Want to avoid vetoing only on OD light (i.e. using scintillator panels)
- **17% of bunches have ID activity from more than 1 interaction**
    - 10% of these have no OD activity
    - Need careful reconstruction studies
        - (but multi-ring reconstruction at Super-K works very well)




**Pileup Rates at 1 km Look Acceptable!**

# PMTs

- For the ID, both 8" and 5" PMTs are being considered
  - Perhaps with high-quantum-efficiency (HQE) coating
  - Also considering Hyper-K-style hybrid photodetectors (HPD)
- Initial Hamamatsu estimate for basic 8" R5912 PMT is much more expensive that assumed for 2km detector
  - **US $4.3M for 3,000 PMTs**
- UK/Texas company ETEL/ADIT has also been consulted
  - Basic 8" PMT is $1775
  - No HQE or HPD option available

## Hamamatsu Estimates

| Name | Type | QE% | Quantity | Price/PMT | Total Cost | Delivery Year |
|---|---|---|---|---|---|---|
| 5" PMT | R6594-WPassy | 25 | 8000 | 103,500 | 828M | |
| 5" PMT HQE | | 35 | 5714 | 123,700 | 707M | |
| 8" PMT | R5912-WPassy | 25 | 3215 | 143,000 | 460M | |
| 8" PMT HQE | | 35 | 2296 | 170,500 | 391M | |
| 8" HPD HQE | R12112-WPmodule | 35 | 2296 | 264,000 | 606M | 2014 |
| | | 35 | 2296 | 236,500 | 543M | 2015 |
| | | 35 | 2296 | 209,000 | 480M | 2016 |
| 20" PMT HQE | R12860-WPassy | 30 | 508 | 604,500 | 307M | 2014 |
| | | 30 | 508 | 572,000 | 291M | 2015 |
| | | 30 | 508 | 539,500 | 274M | 2016 |
| 20" HPD HQE | R12850-WPmodule | 30 | 508 | 715,000 | 363M | 2014 |
| | | 30 | 508 | 617,500 | 314M | 2015 |
| | | 30 | 508 | 520,000 | 264M | 2016 |
| 20" HPD HQE | R12850-WPmodule | 30 | 140 | 770,000 | 108M | 2014 |
| | | 30 | 140 | 665,000 | 93M | 2015 |
| | | 30 | 140 | 560,000 | 78M | 2016 |
| 20" PMT | R12860-WPassy | 30 | 140 | 651,000 | 91M | 2014 |
| | | 30 | 140 | 616,000 | 86M | 2015 |
| | | 30 | 140 | 581,000 | 81M | 2016 |