νPRISM: An experimental solution to the problems of neutrino interactions in long baseline neutrino experiments

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Neutrino oscillation

- Neutrinos have two sets of eigenstates – flavour and mass
  - Interact through flavour states
  - Propagate in mass states

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$P_{\alpha\rightarrow\beta} = \left|\langle \nu_\beta | \nu_\alpha(t) \rangle\right|^2 = \left| \sum_i U^*_{\alpha i} U_{\beta i} e^{-i m_i^2 L/2E} \right|^2$$

- Long baseline experiments sample neutrino flavour states after oscillation
  - Oscillation probability is function of neutrino energy, *E*, and propagation distance *L*
  - *L* is fixed – measuring flavour composition of beam as function of energy probes PMNS mixing matrix *U* and mass splitting

T2K 2016 systematics

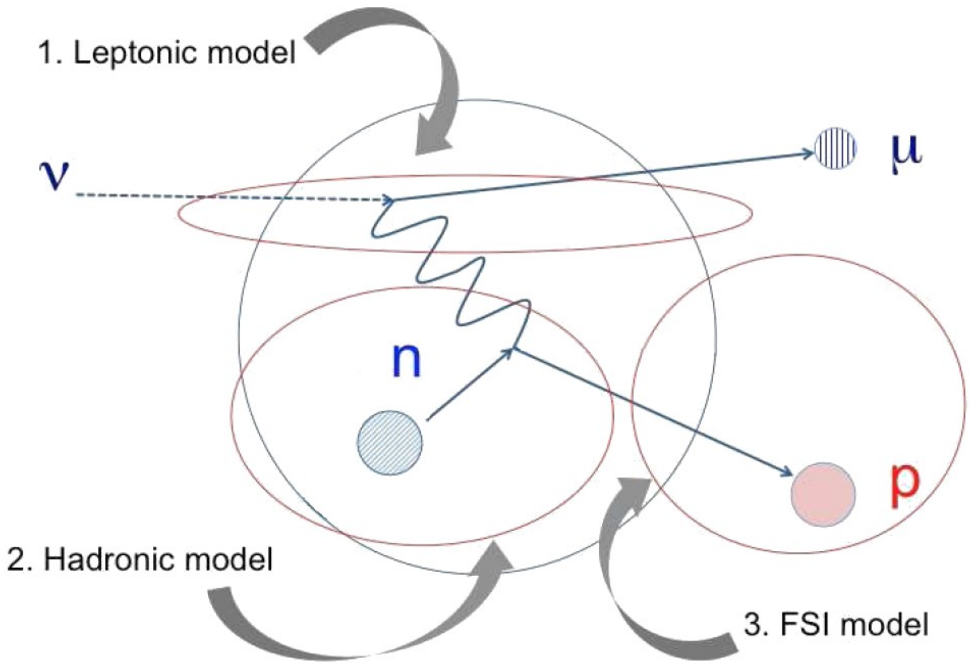
Source of uncertainty	μ-like $\delta\left(\frac{\#\nu\text{-mode}}{\#\bar{\nu}\text{-mode}}\right) / \left\langle\frac{\#\nu\text{-mode}}{\#\bar{\nu}\text{-mode}}\right\rangle$	e-like $\delta\left(\frac{\#\nu\text{-mode}}{\#\bar{\nu}\text{-mode}}\right) / \left\langle\frac{\#\nu\text{-mode}}{\#\bar{\nu}\text{-mode}}\right\rangle$
SKDet	0.07%	1.6%
FSI+SI	2.6%	3.6%
Flux	1.8%	1.8%
Flux+XSec (ND280 constrained)	1.9%	2.2%
XSec NC other (uncorr)	0.0%	0.2%
XSec NC 1γ (uncorr)	0.0%	1.5%
XSec ν_e / ν_μ (uncorr)	0.0%	3.1%
Flux+XSec	1.9%	4.1%
All	3.2%	5.8%

Preliminary

- CP measurement depends on uncertainty on ν_e/anti-ν_e ratio
- Dominant uncertainties:
  - Final state interactions (FSI), secondary interactions (SI)
  - Electron/Muon cross-section ratios
  - ND280 flux + cross-section constraint
- All depend on **nuclear** model

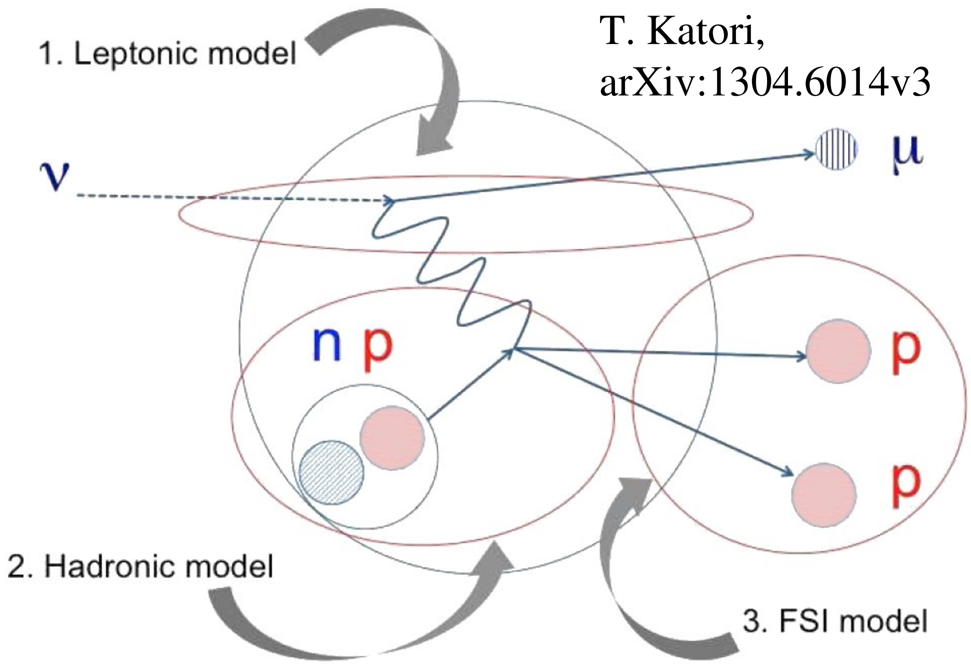
Nuclear models

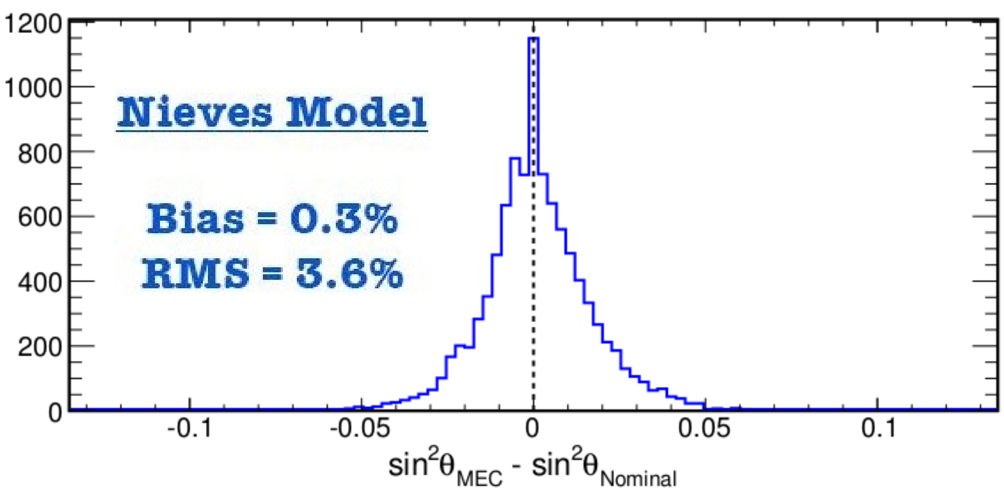
- CCQE process is main signal at far detector
  - 2-body interaction
  - Calculate neutrino energy from lepton kinematics

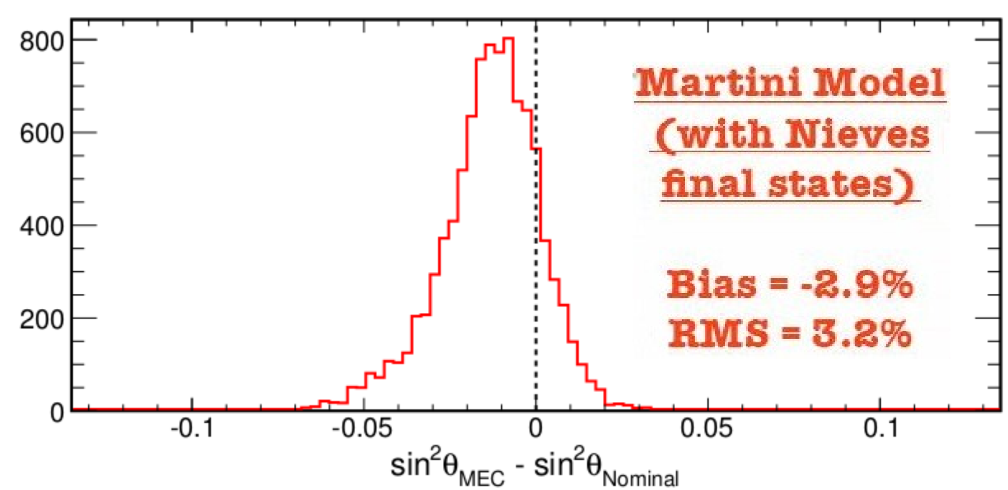


Nuclear models

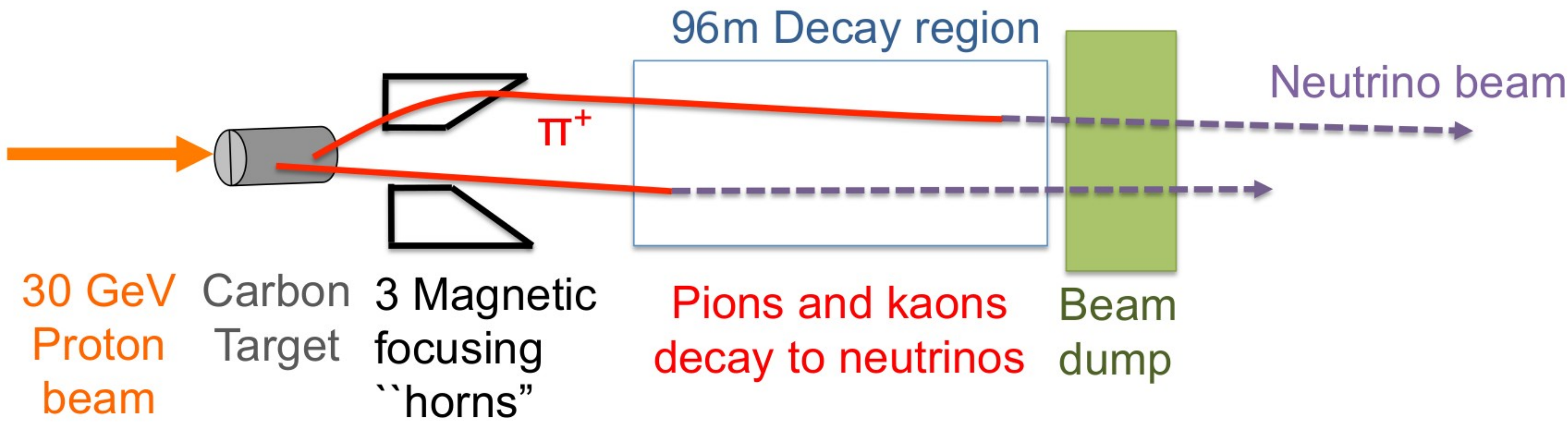
- CCQE process is main signal at far detector
  - 2-body interaction
  - Calculate neutrino energy from lepton kinematics
- Also have 2p-2h (and other) interactions
  - Mimic CCQE signal
  - Lepton kinematics under-predict neutrino energy
  - Cross-section depends on nuclear model



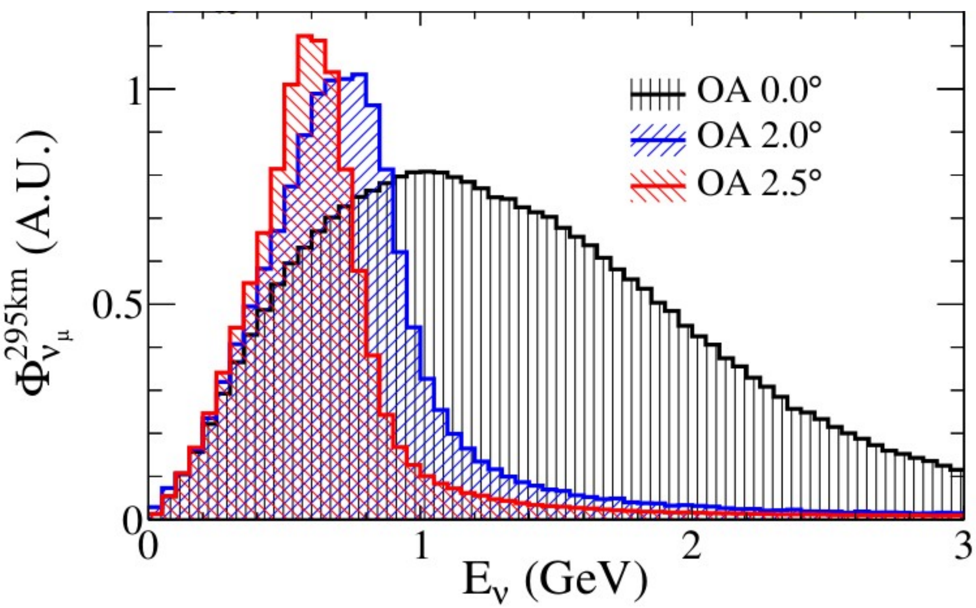




T2K neutrino beam

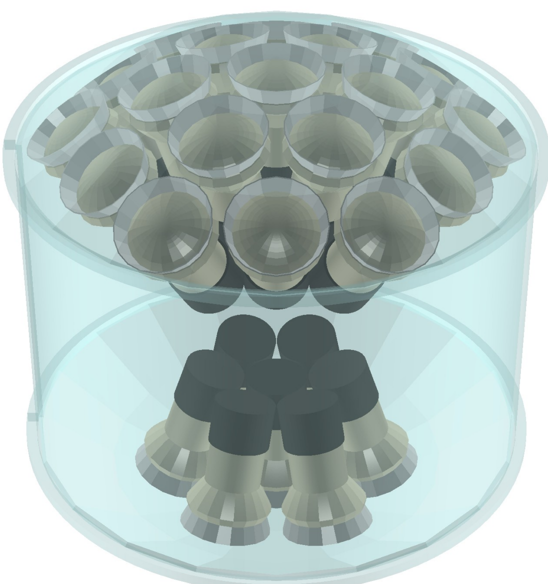


- Protons collide with target → pions
- Pions focussed by magnetic horns
- Pions decay in flight → neutrinos
- **“Off-axis”** effect – moving away from beam axis
  - Reduces peak energy of neutrino flux
  - Produces narrower energy distribution



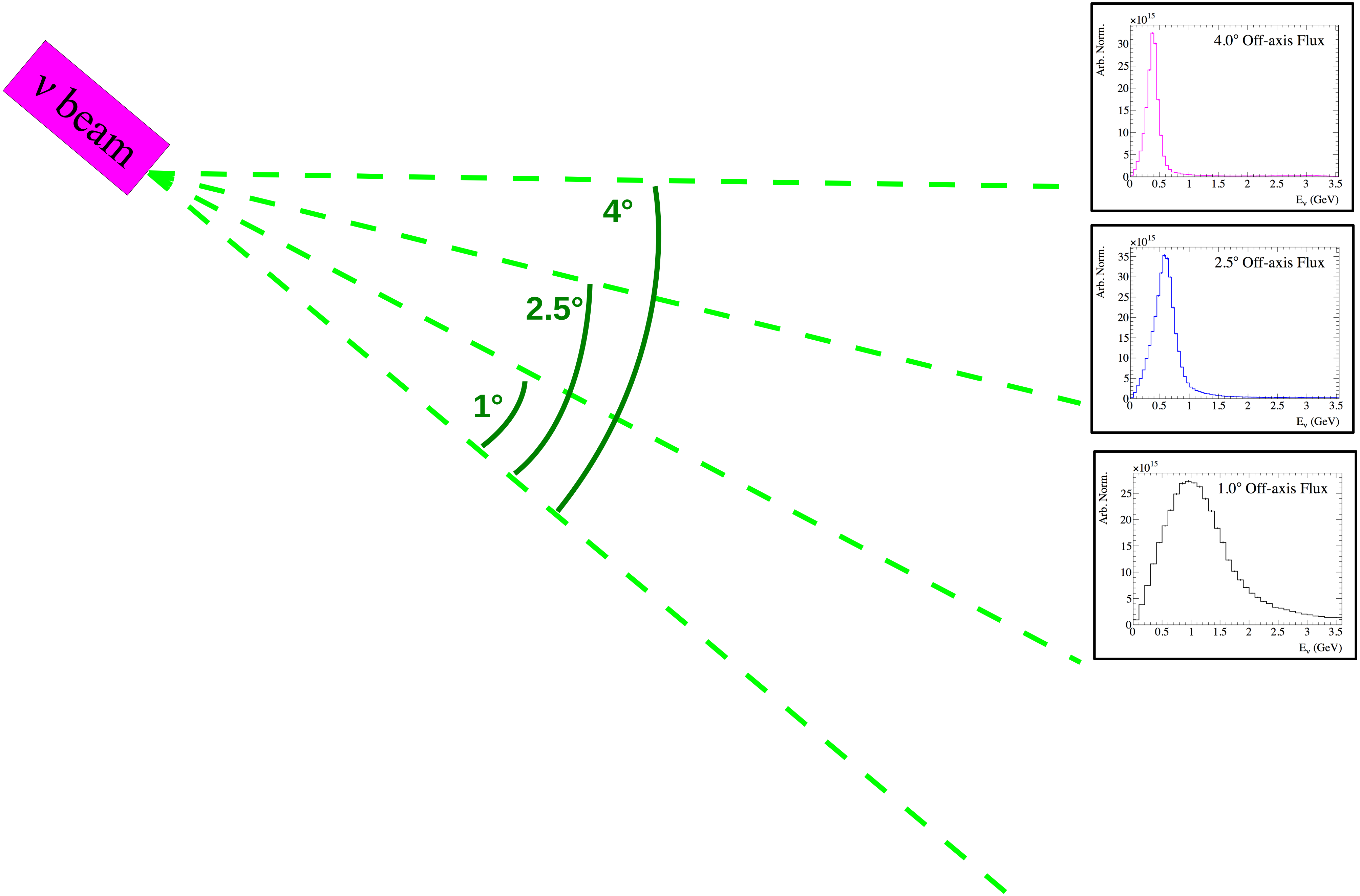
NuPRISM proposal

- Water Cherenkov detector spanning 1° – 4° from the neutrino beam axis
  - 52.5m tall, 1km from T2K neutrino production target
- Instrumented movable cylinder:
  - Inner Detector (ID): 8m diameter, 10m tall
  - Outer Detector (OD): 10m diameter, 14m tall

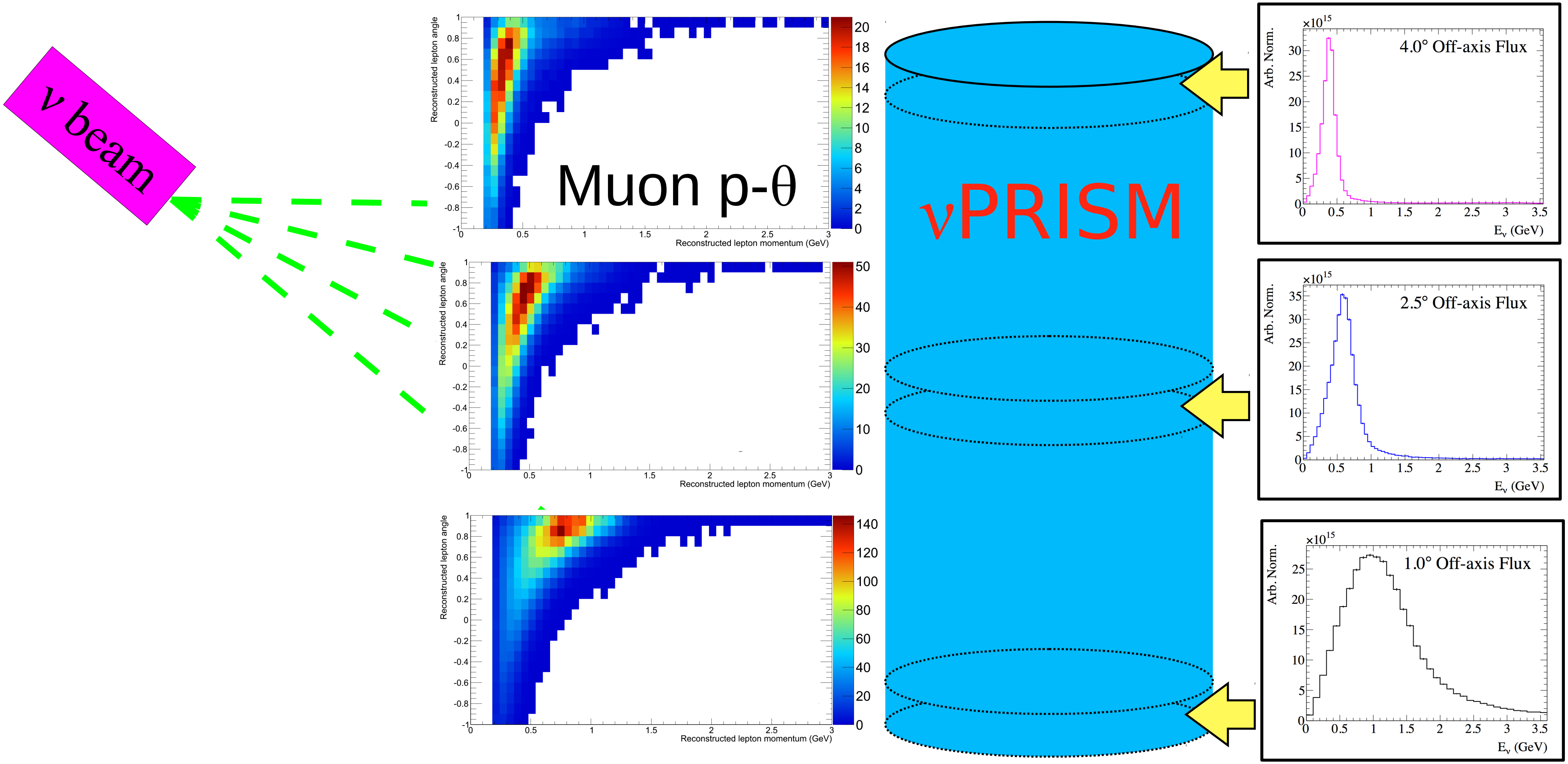


- Multi-PMT modules observe ID and OD
- Investigating scintillator veto planes around detector

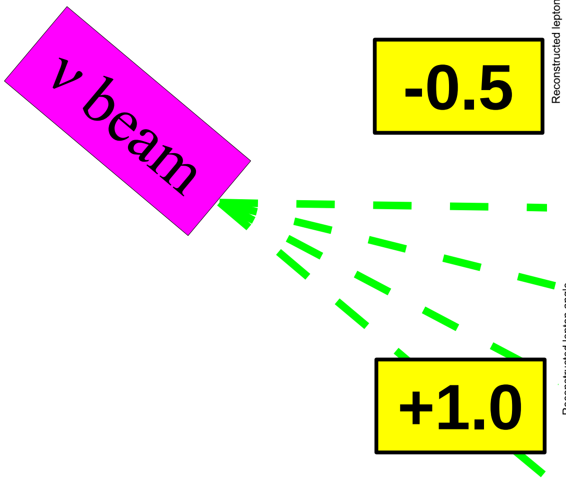
NuPRISM concept

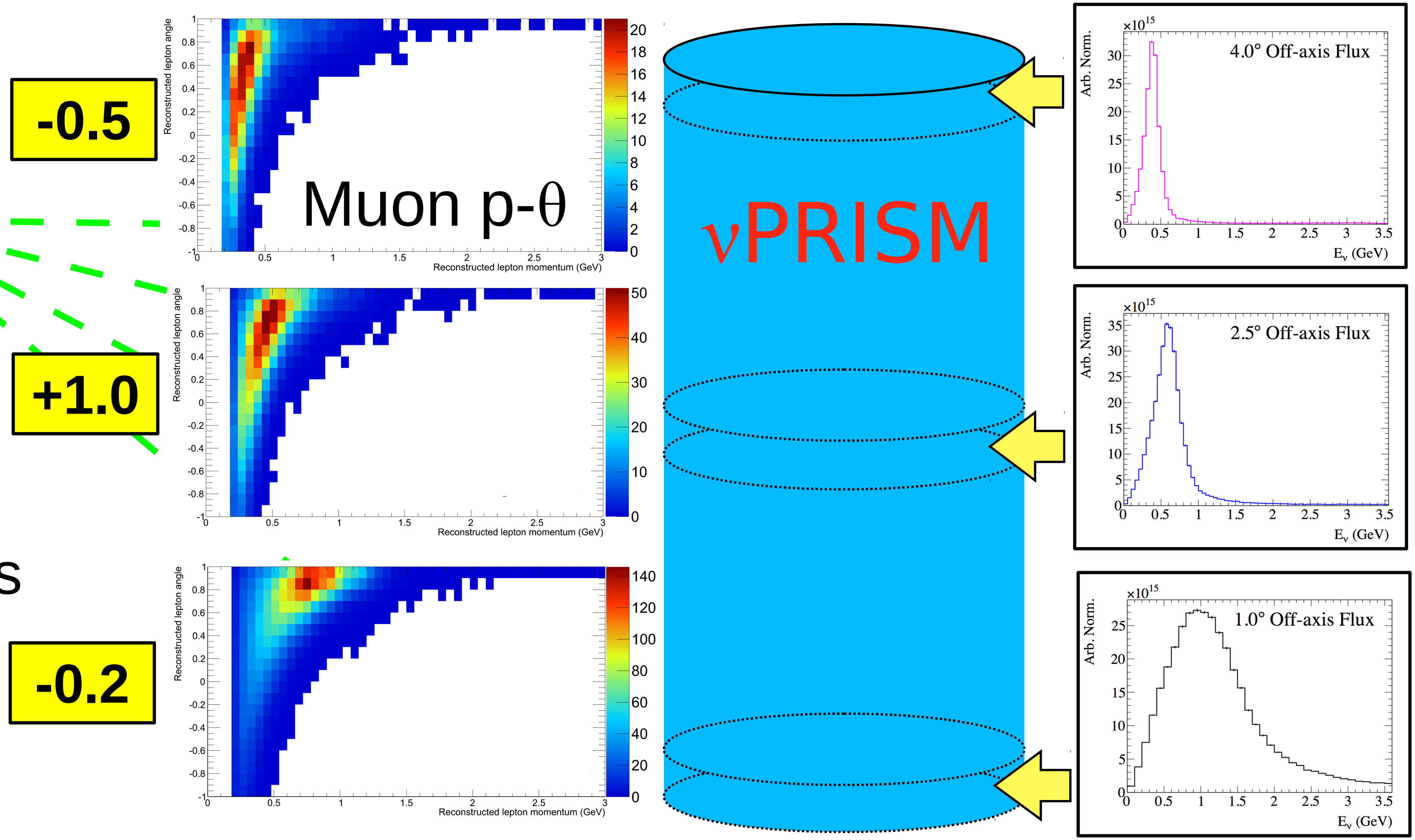


NuPRISM concept



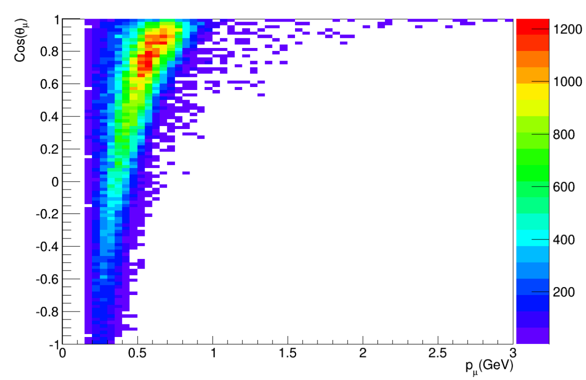
Mono-energetic beams

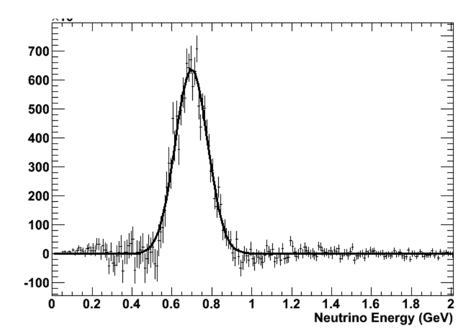




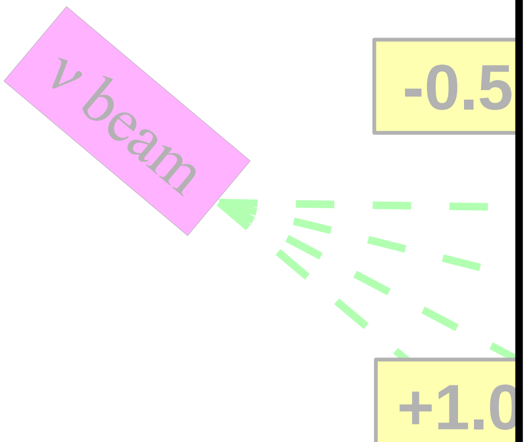
Take linear combinations

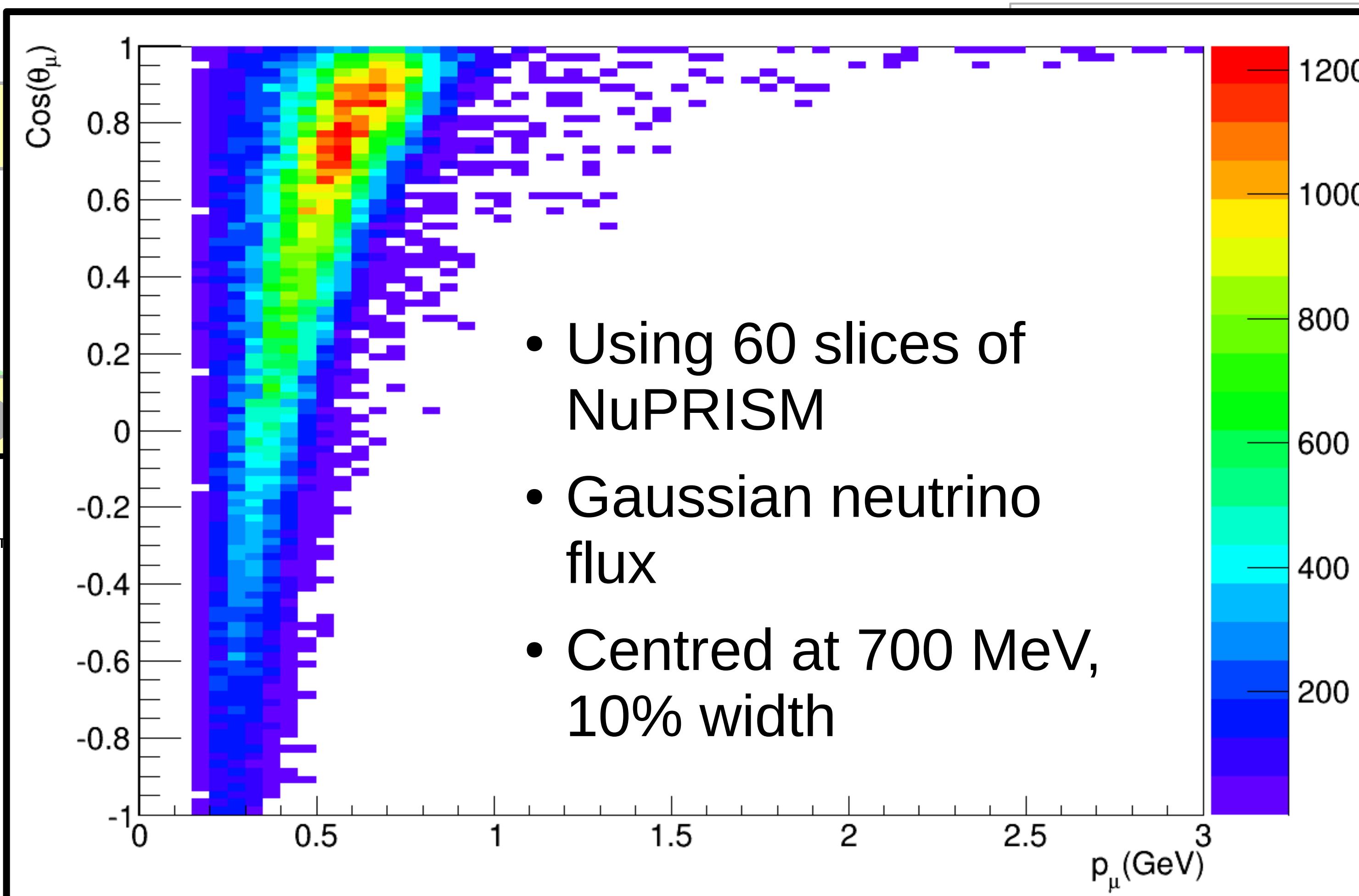
Subtract tails of distribution



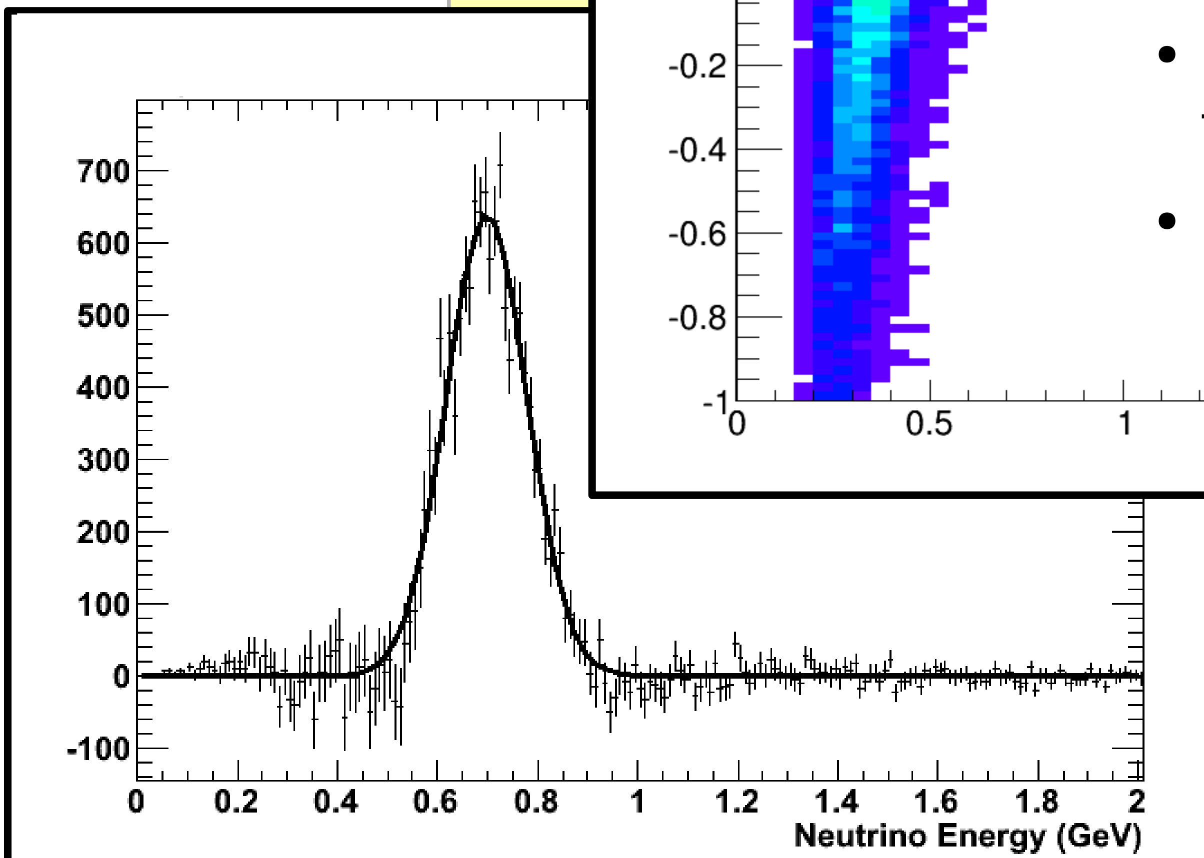


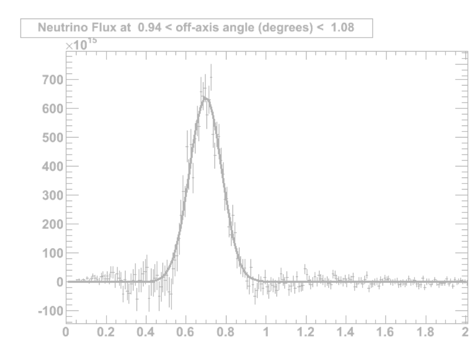
Mono-energetic beams



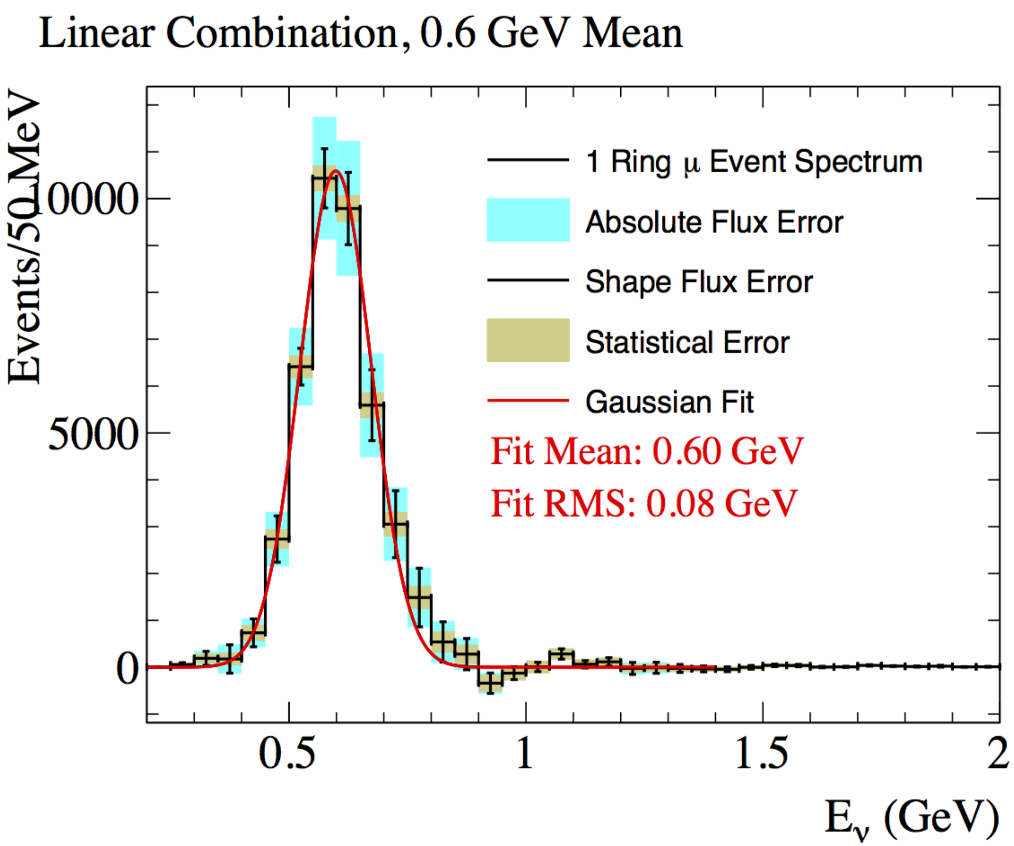


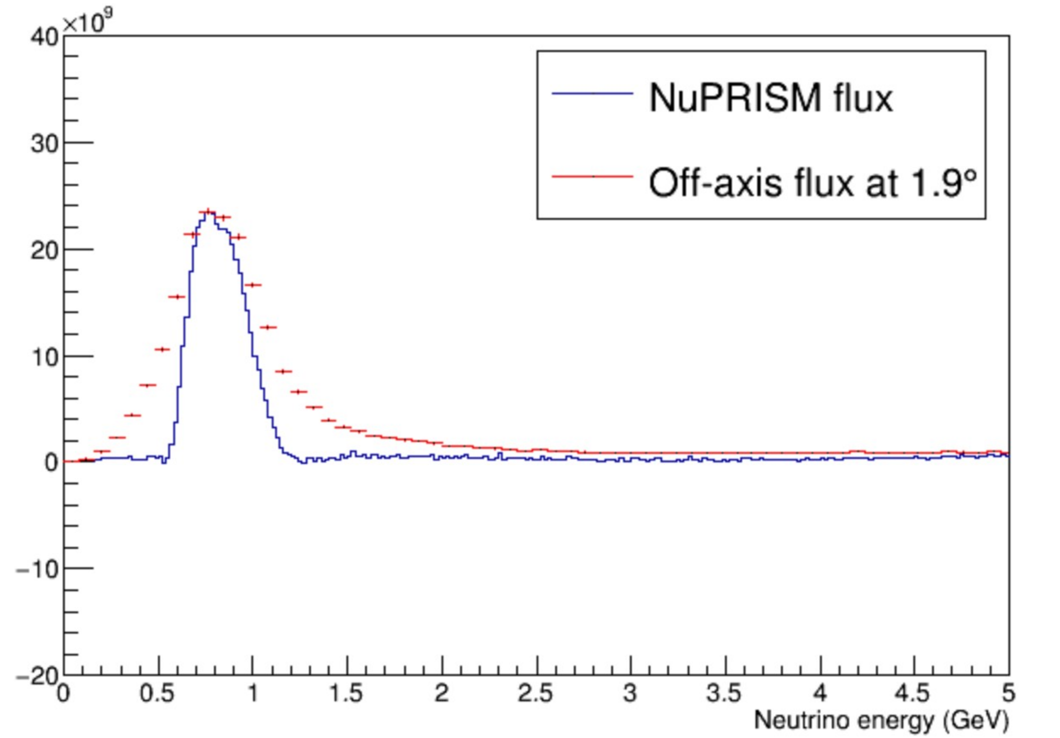
- Using 60 slices of NuPRISM
- Gaussian neutrino flux
- Centred at 700 MeV, 10% width





Mono-energetic beams in practice

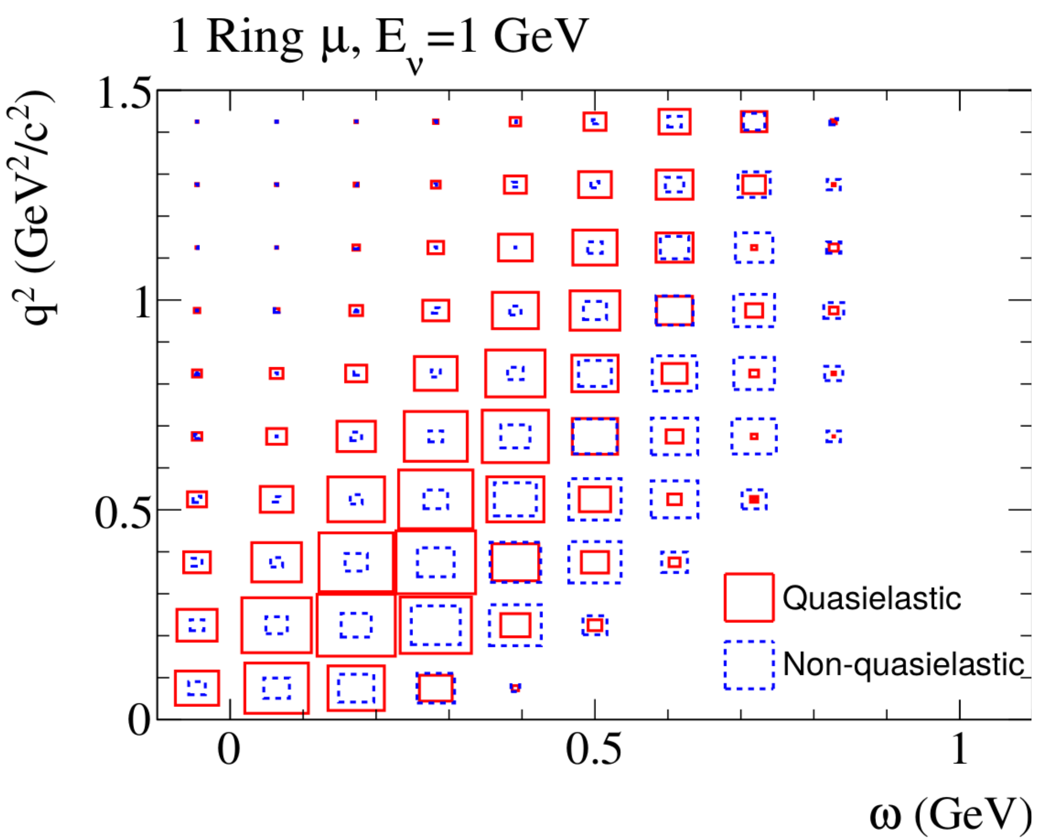


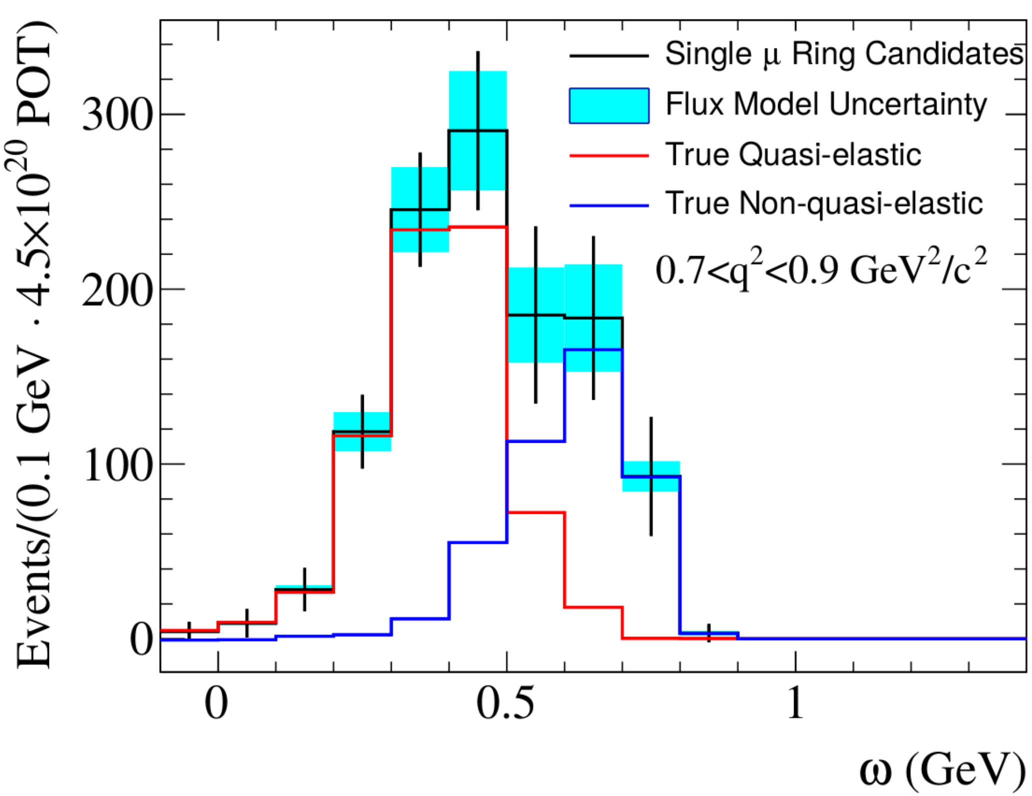


- Gaussian neutrino beams with neutrino energy from 400 MeV → 1200 MeV
    - Determined by off-axis angular span of detector
- Full T2K flux error shown
- High and low energy tails greatly reduced

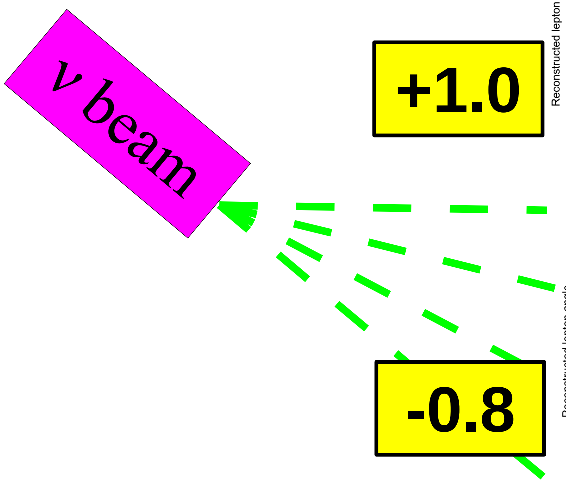
How can we use them?

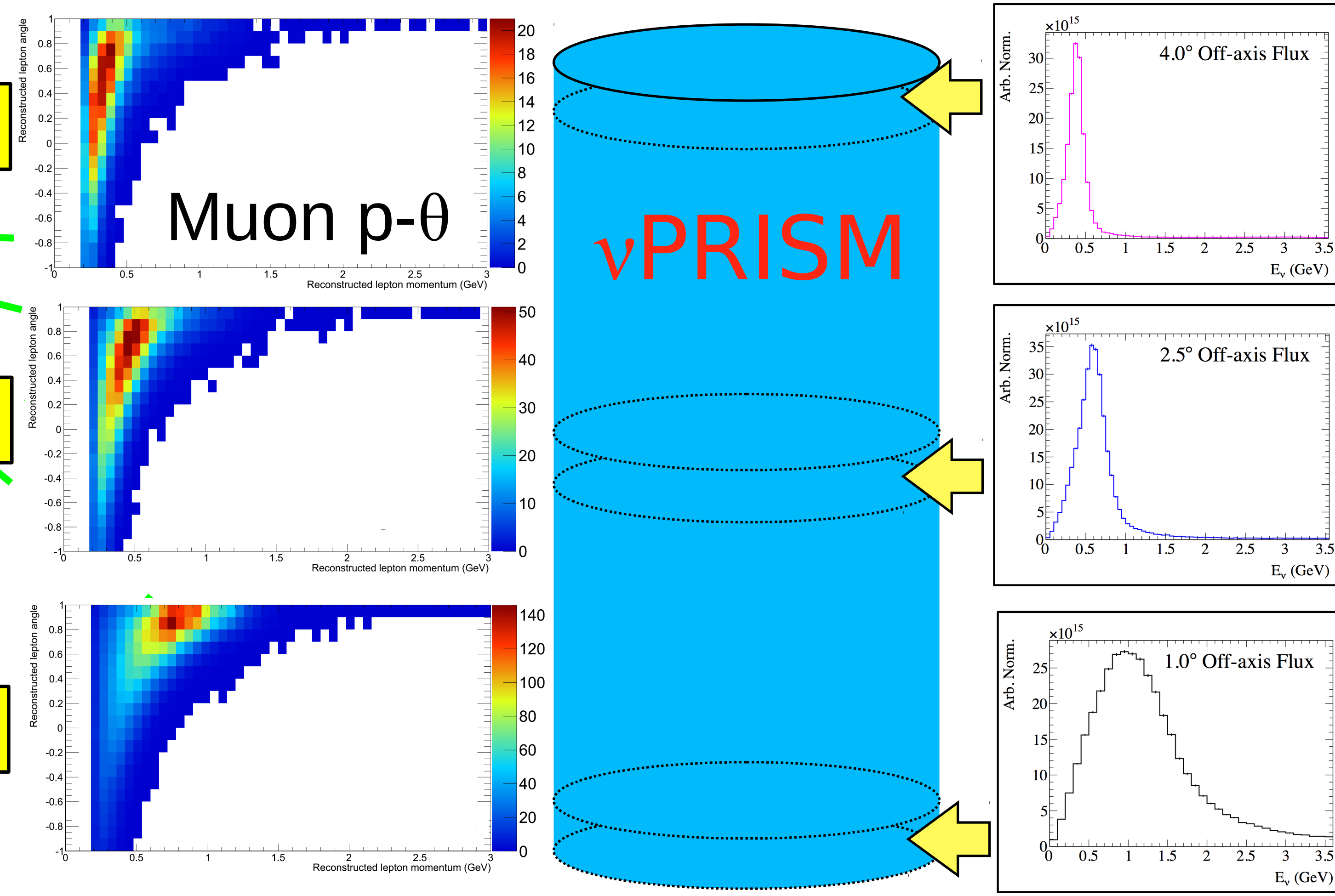
- Provides more information on neutrino interactions
- Measure in data:
  - As function of true neutrino energy
    - In same detector → highly correlated flux and detector systematics
  - Can also calculate true q^2 and ω
  - Clear separation between quasi-elastic (QE) and non-QE events





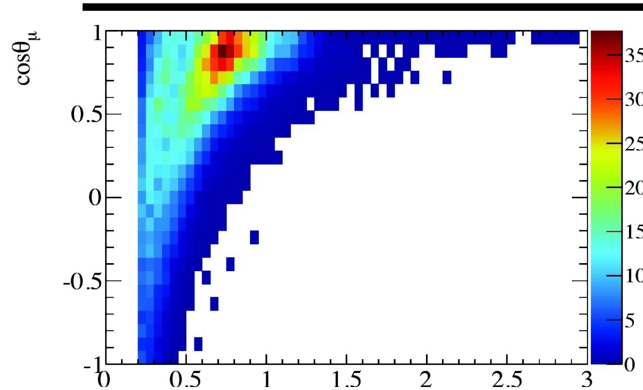
νPRISM NuPRISM detector concept

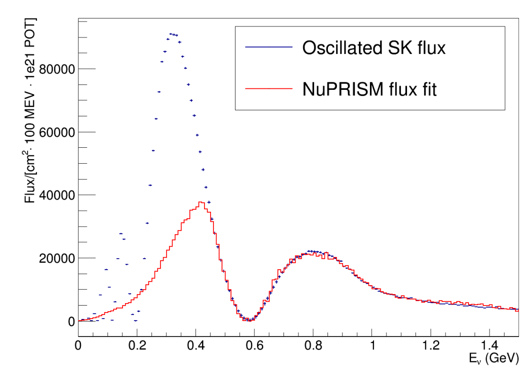




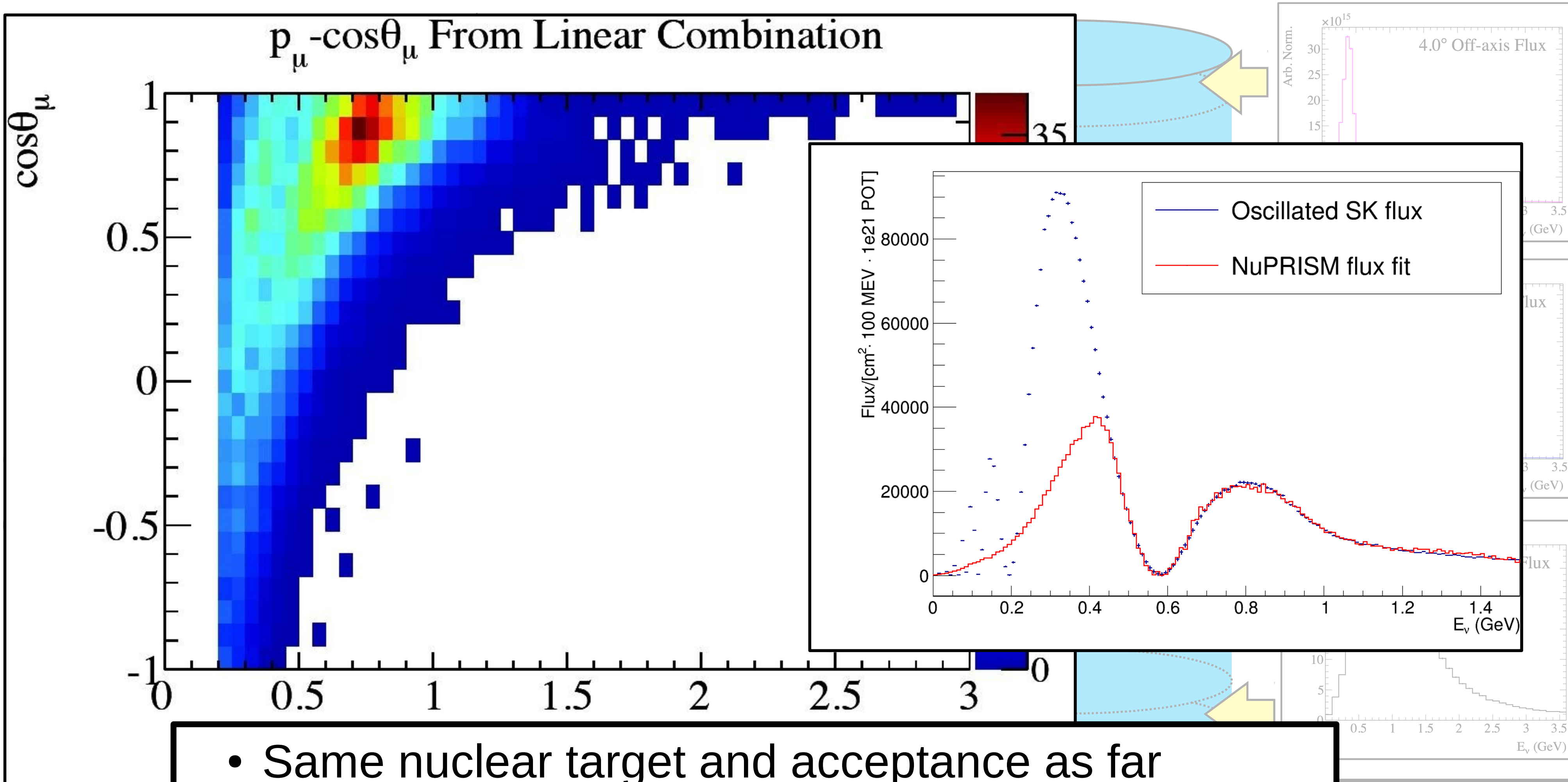
Or take different combinations

+0.2

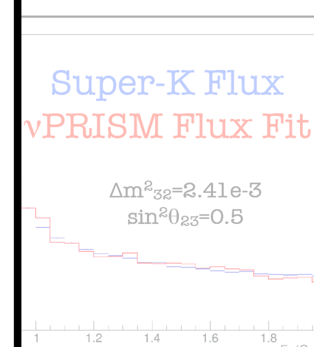




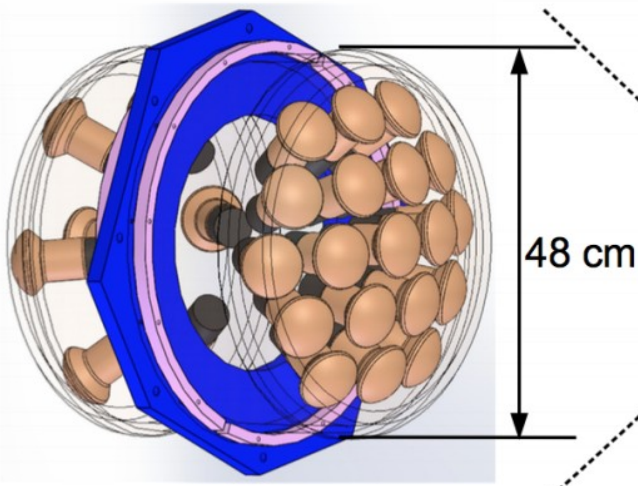
NuPRISM detector concept

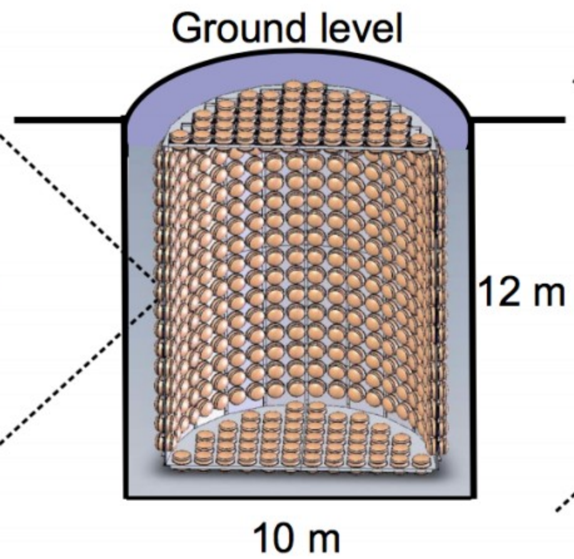


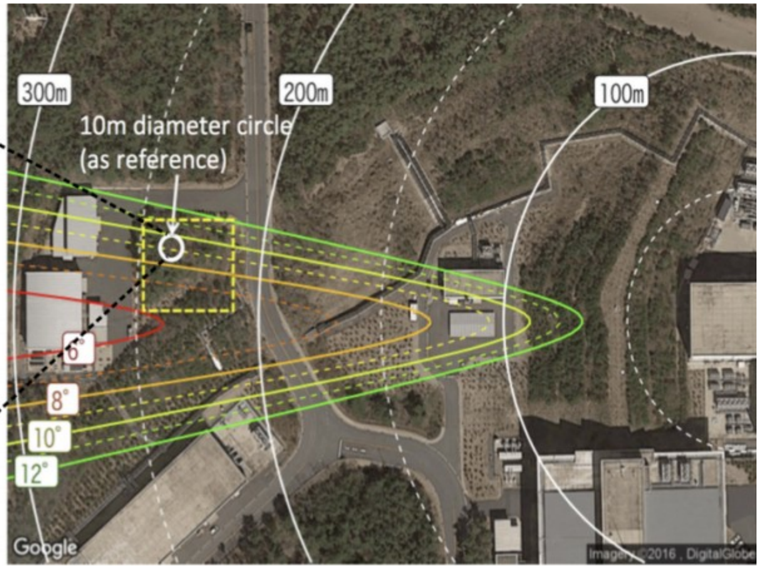
- Same nuclear target and acceptance as far detector
- Near and far fluxes match:
  - Directly compare NuPRISM and far detector data to obtain oscillation parameter
  - Independent of neutrino interaction model



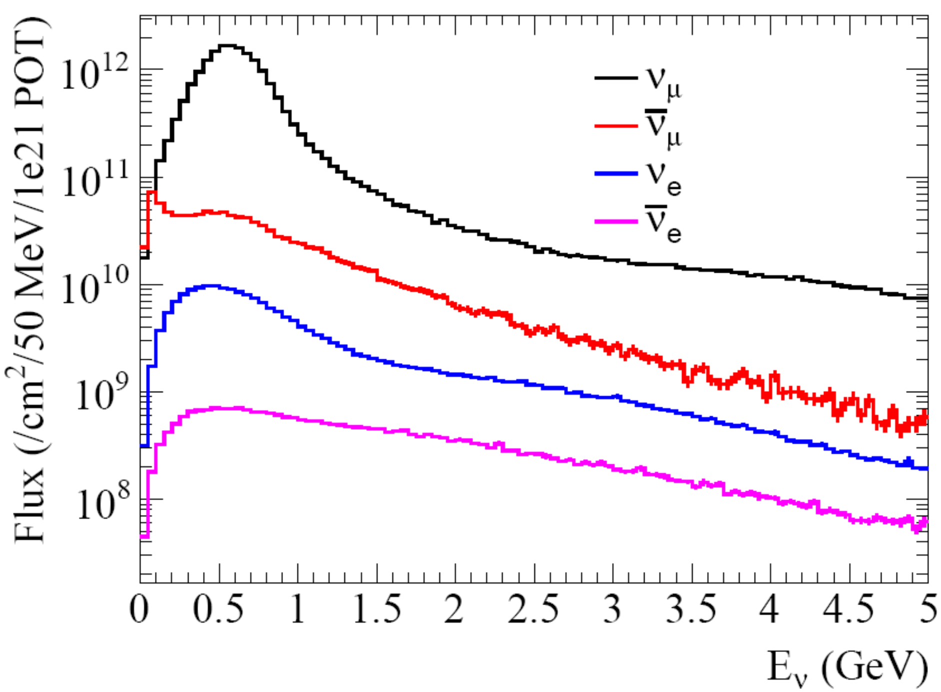
NuPRISM Phase-0



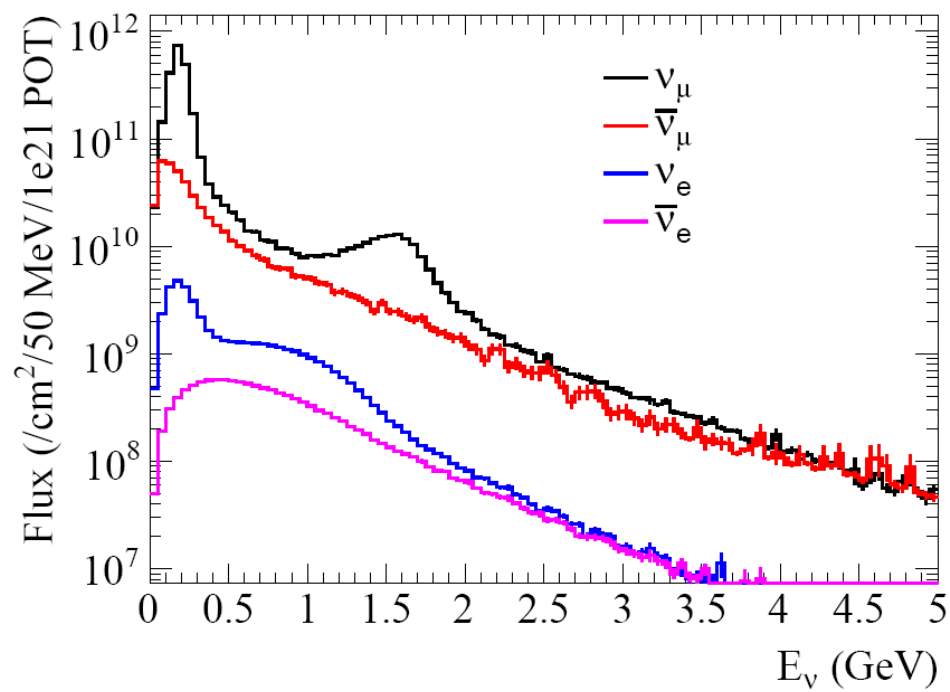




OAA = 2.5

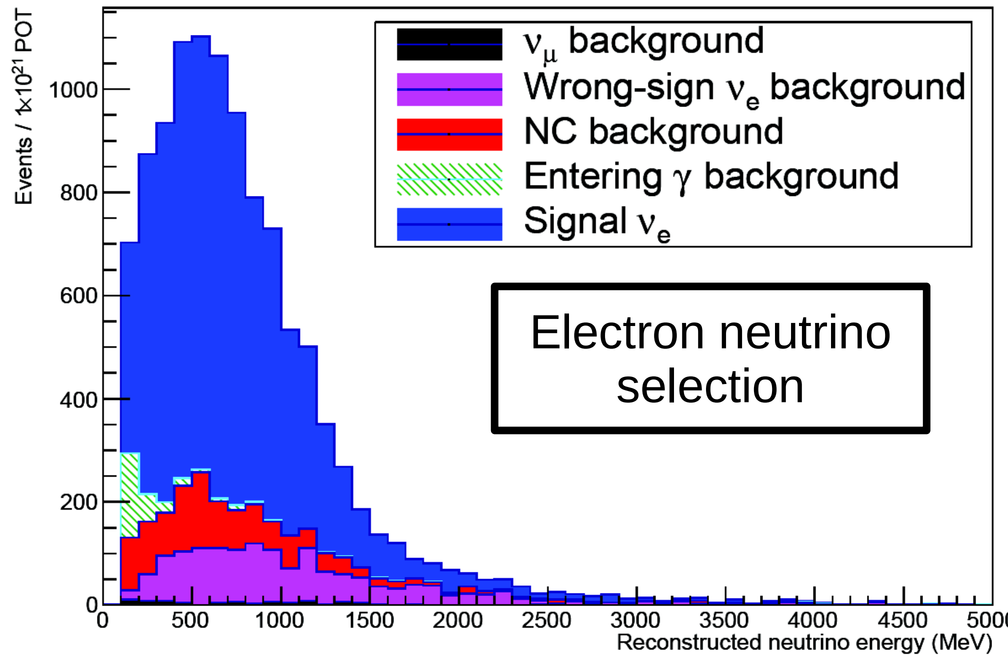


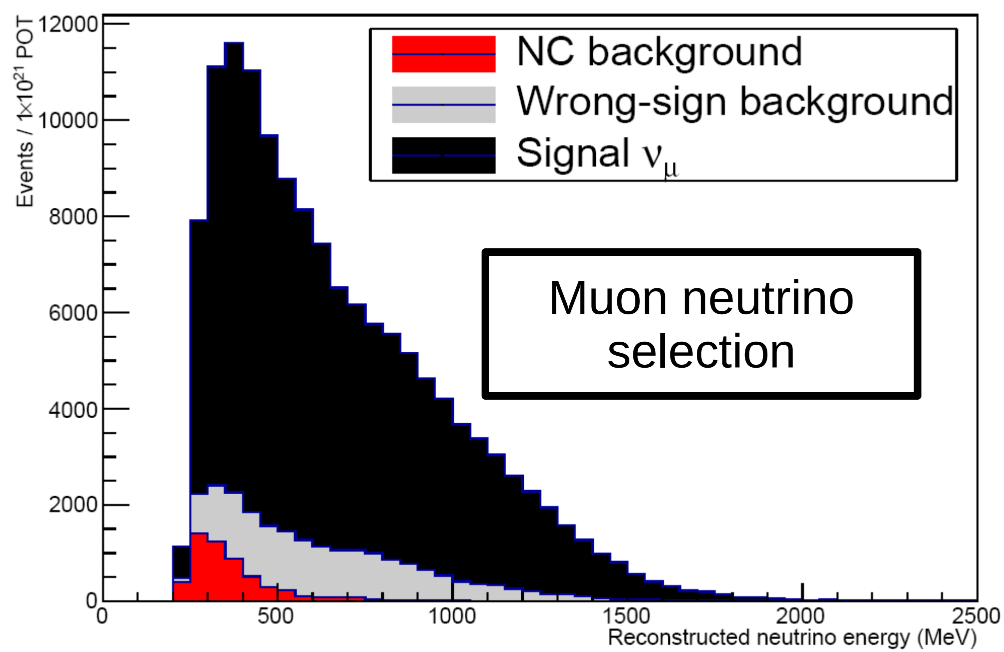
OAA = 9.0



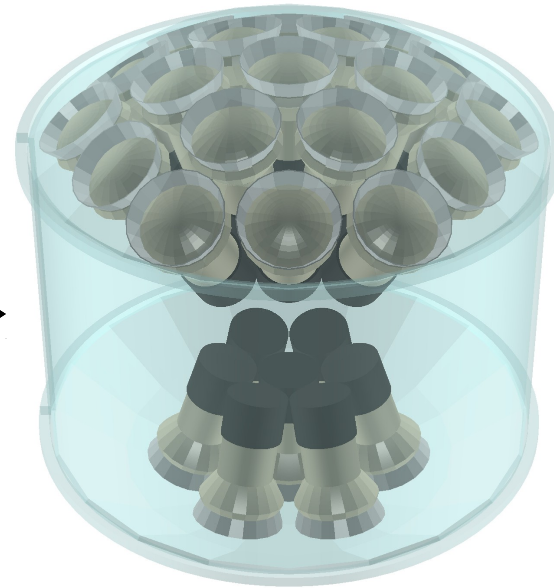
Phase-0 Physics

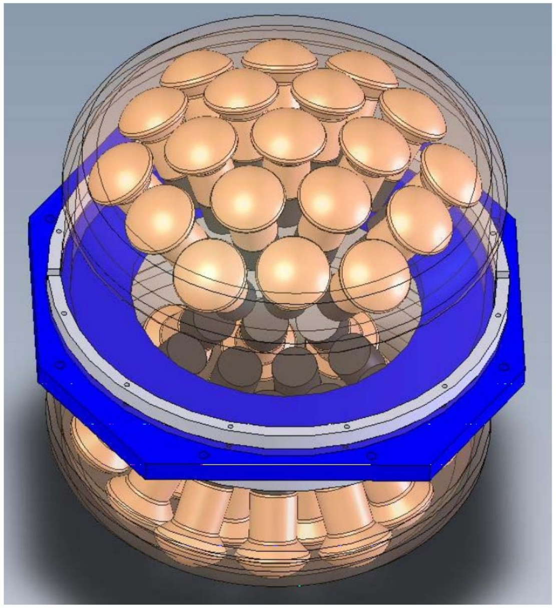
- Initial event selections for position 9 degrees off-axis
- 1e21 POT, ½ year of expected exposure
    - Large, pure electron neutrino sample
    - Electron neutrino energy ~700 MeV
- High statistics measurement of ν_e / ν_μ cross section
- Gadolinium doping possible
    - Measure neutron multiplicities from neutrino interactions

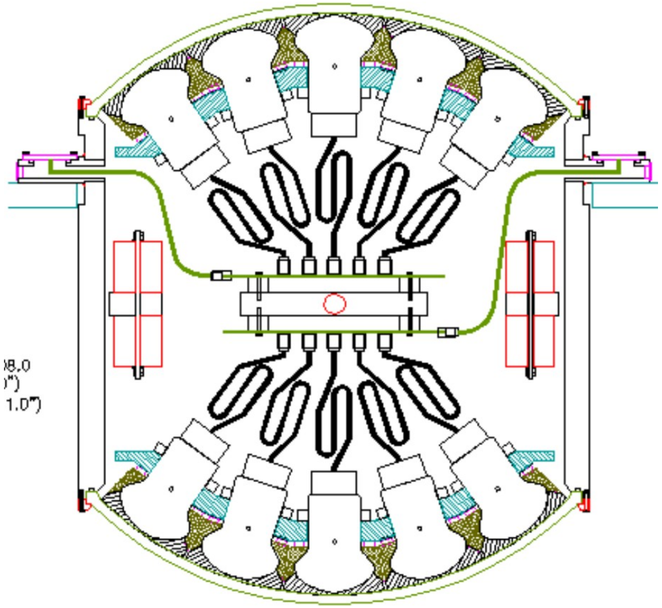




NuPRISM mPMT modules







- Ongoing development in Canada
- 3in PMTs in pressure vessel with electronics
- Evolution of design:
  - Asymmetric PMT distribution
  - Forward focussed
- Collaborating with Canadian IceCube group
- Expect first prototypes soon!

Summary

Oscillation experiments will be limited by systematics not statistics

- Dominant systematics hard to constrain with traditional near detectors

The NuPRISM detector provides a solution

- Same nuclear target and technology as far detector
- Match near and far fluxes
  - Oscillation analyses independent of interaction model

NuPRISM also enables:

- Unique probe of cross-sections
- Powerful sterile neutrino searches

NuPRISM Phase-0

- High statistics electron neutrino cross-section measurement
- Show control of detector systematics to required level

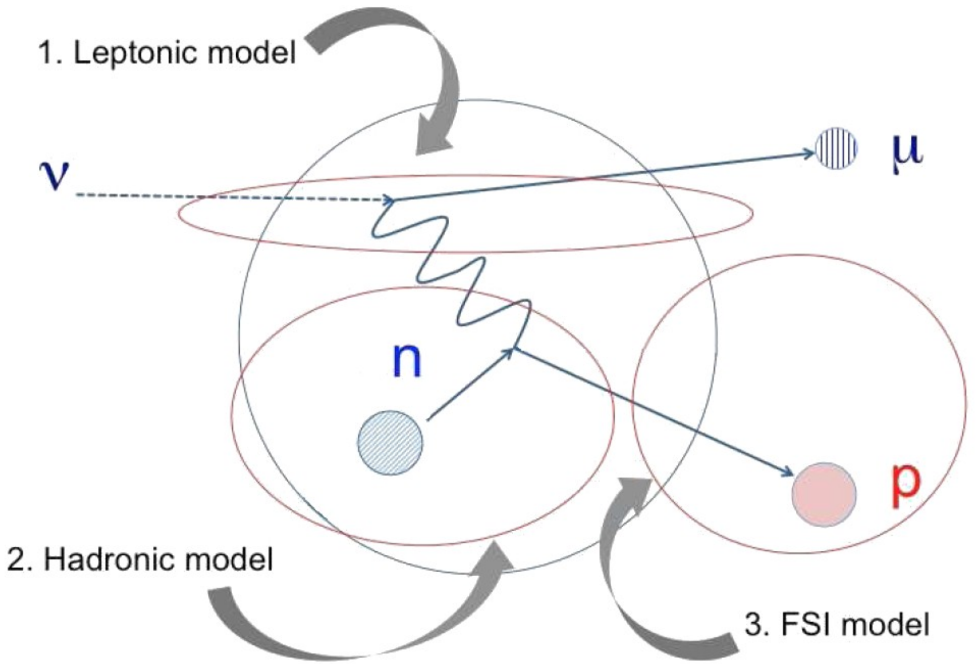
Backup Slides

NuPRISM status

- NuPRISM project granted stage-1 status by J-PARC PAC in summer 2016
  - “the scientific merit of the proposal is high and the experimental methods are sound”
  - “This status will help the proponents to negotiate with funding agencies"
- Receiving laboratory support to develop TDR for stage-2 approval
  - Stage-2 = “Green light for the experiment to proceed".
- Hope to have TDR approved at J-PARC PAC in early 2018
- Construction of NuPRISM-0 will be completed by 2021, plan to start data taking in early 2022.
- Hope that the construction of NuPRISM-1 will start in FY2021 and complete in FY2023
  - Feedback from the early result from NuPRISM-0
  - NuPRISM-1 would start data taking in late 2023 or early 2024

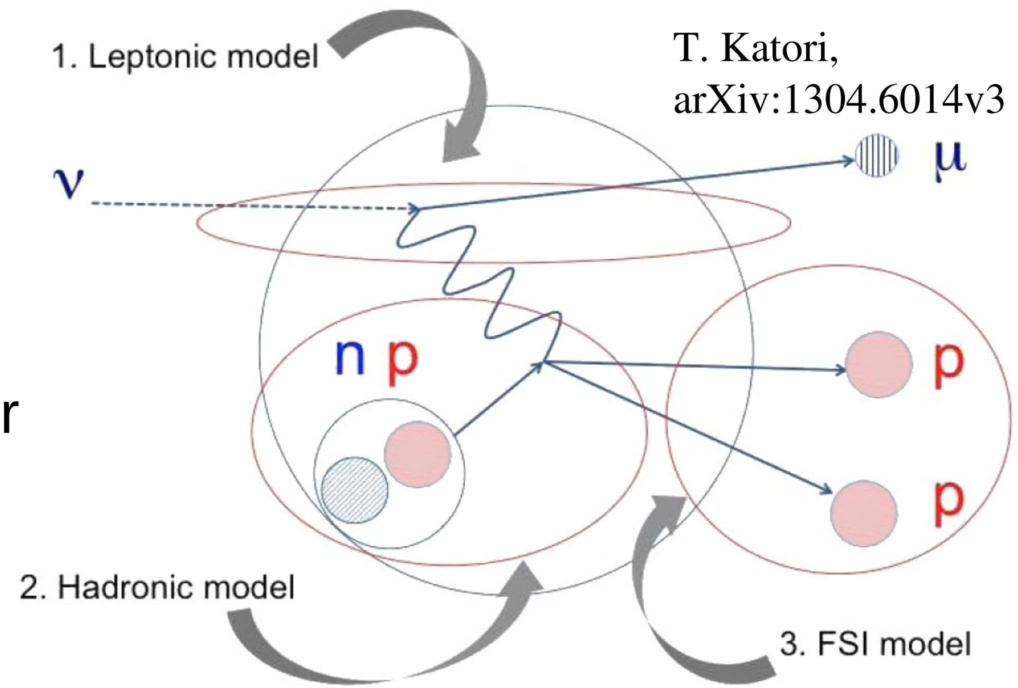
Nuclear models

- CCQE process is main signal at far detector
  - 2-body interaction
  - Lepton kinematics give neutrino energy

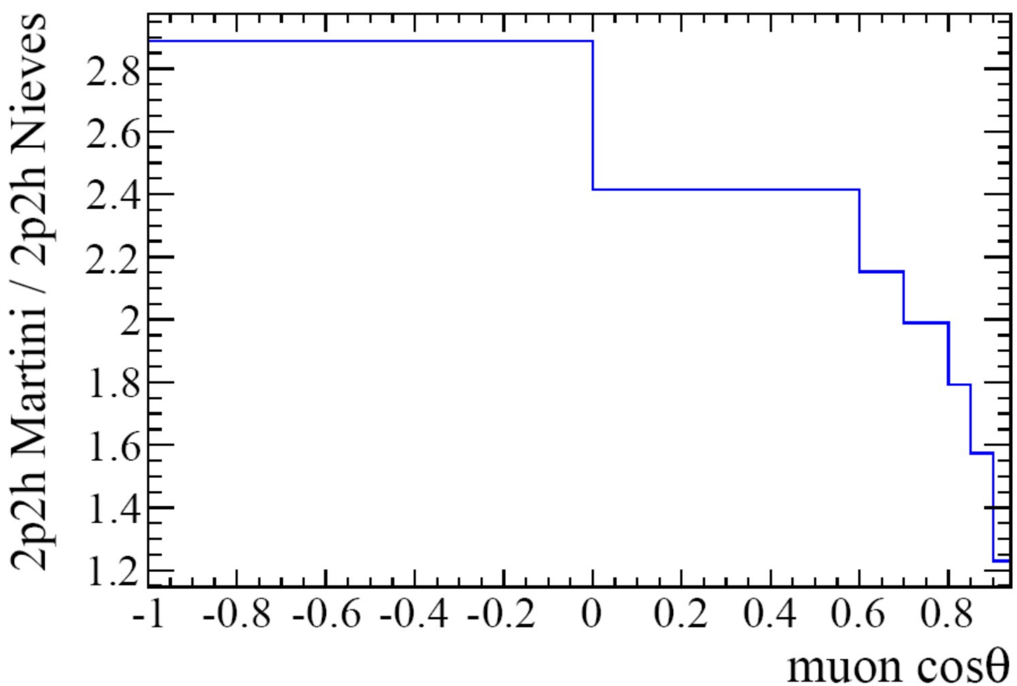


Nuclear models

- CCQE process is main signal at far detector
- Also have 2p-2h (and other) interactions
  - Mimic CCQE signal
  - Lepton kinematics **do not** give neutrino energy
  - Cross-section depends on nuclear model

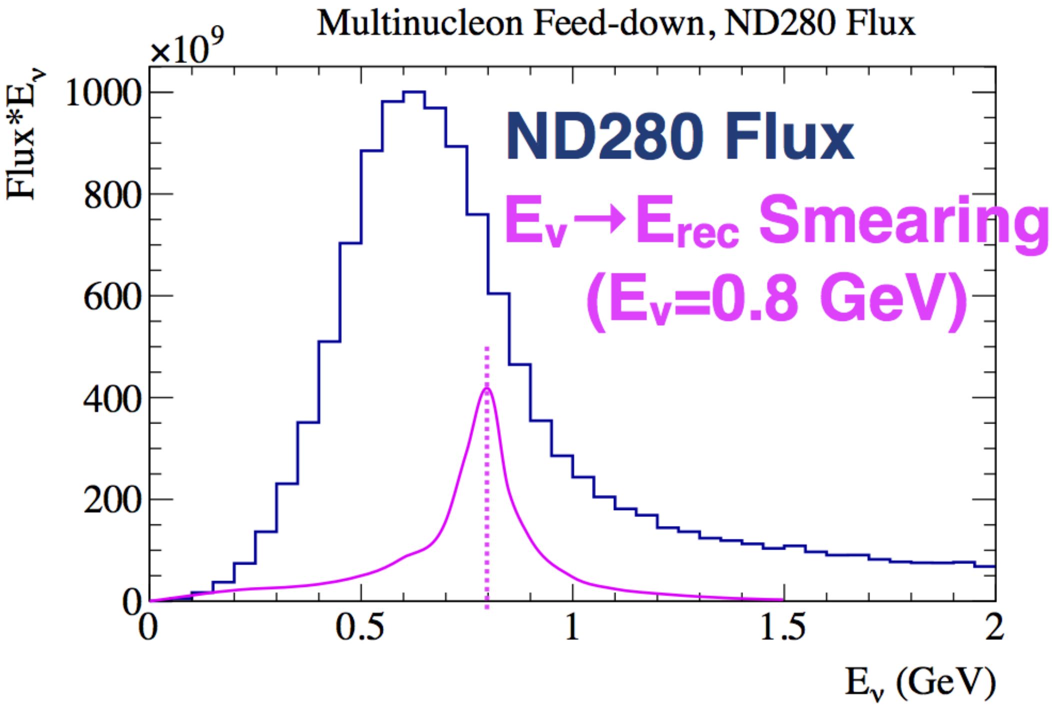


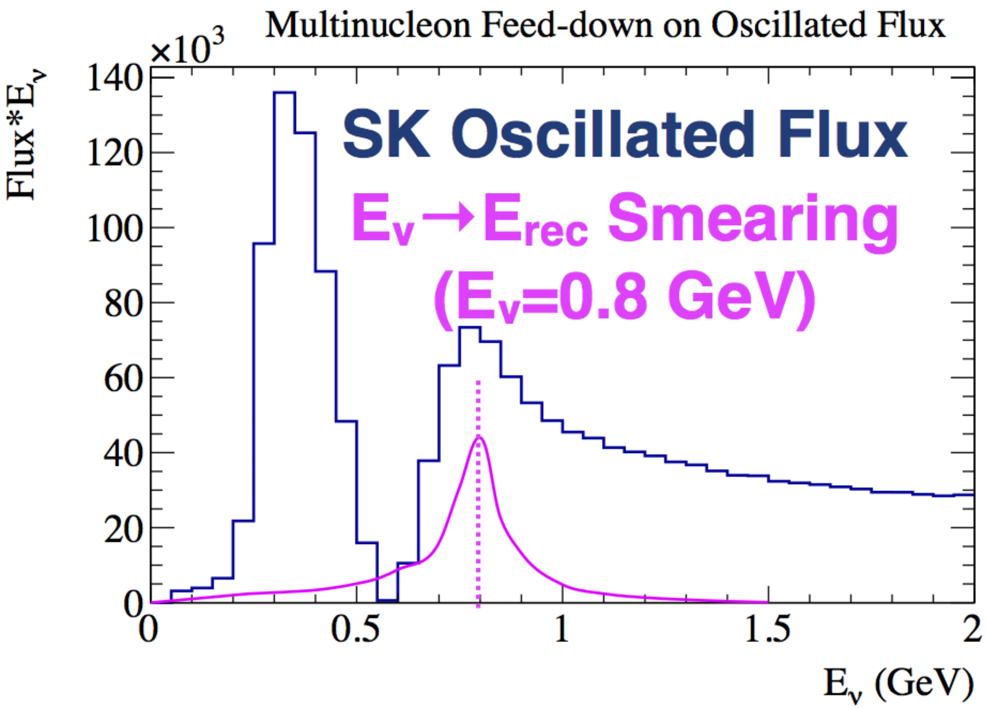
T. Katori, arXiv:1304.6014v3



- Martini and Nieves groups each calculated 2p-2h cross-section
  - Same underlying model, two implementations
  - What about different models?

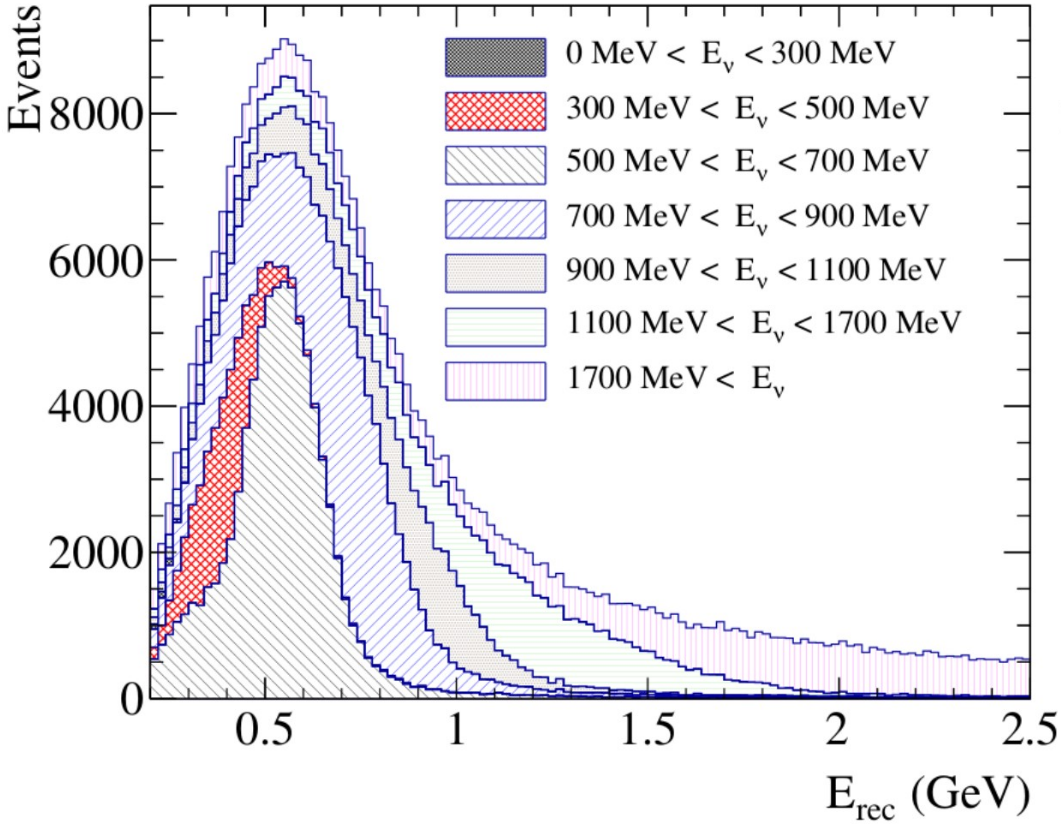
How does this affect oscillation analyses?

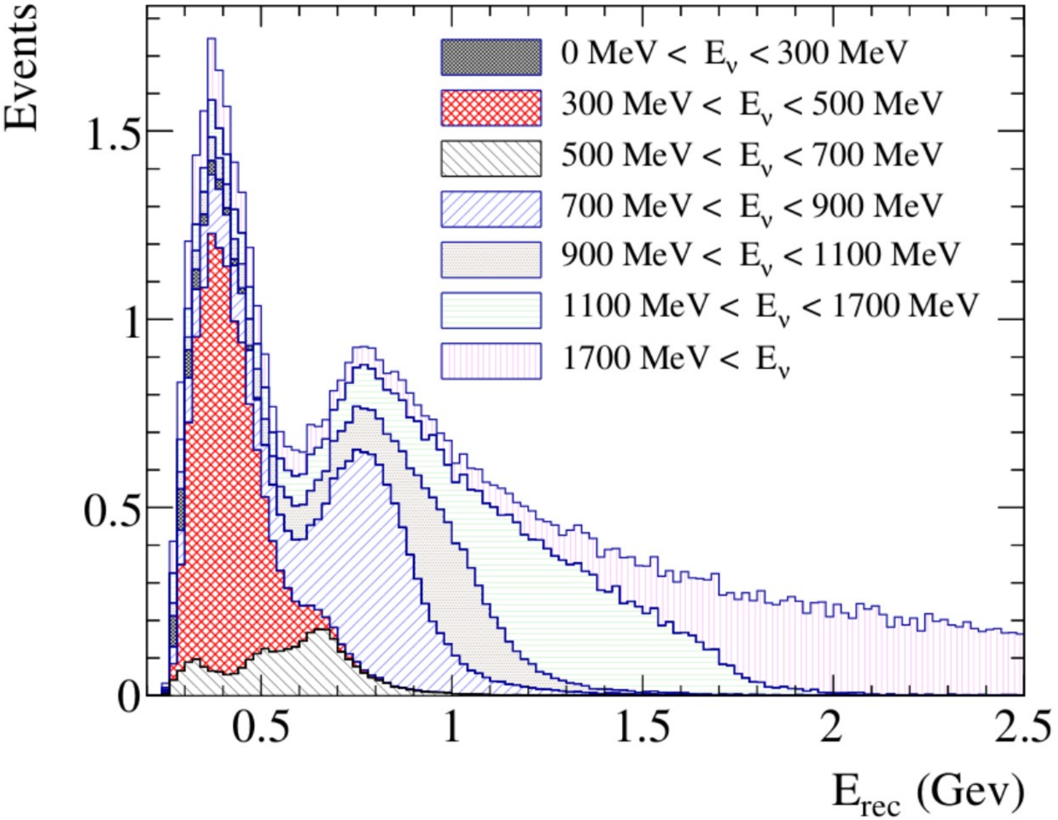




- At near detector, effect of 2p-2h events 'hidden' under neutrino flux – hard to constrain
- At maximum oscillation, neutrino flux goes to zero
- Biased energy reconstruction smears 2p-2h events into oscillation dip – 'feed-down'
  - Size of feed-down effect not well known

Effect of oscillation on near detector extrapolation

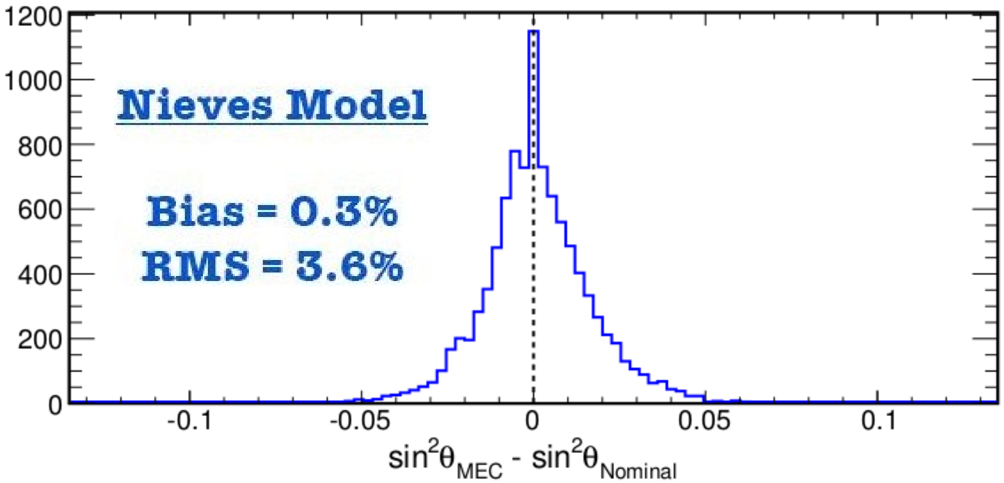


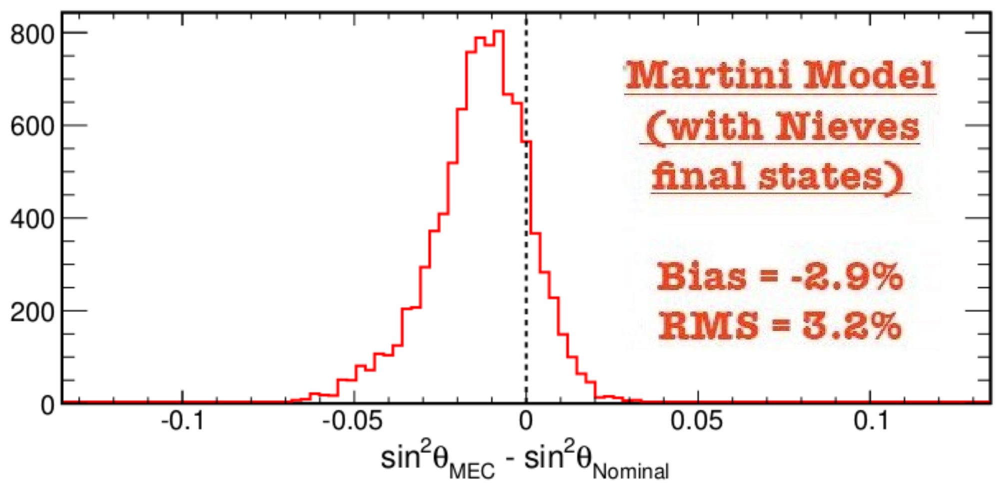


- Near detector event spectrum on left, oscillated far detector spectrum on right
- Near detector tunes to 500 – 700 MeV events, far detector sees higher energy events
  - Can lead to biased tuning

T2K 2p-2h study

- MC-based analysis using full detector simulation, full systematics etc.
- Three fake datasets
  - Nominal NEUT MC
  - NEUT + 2p-2h events from Nieves' model - Phys. Rev. C, 83:045501, Apr 2011
  - NEUT + 2p-2h 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

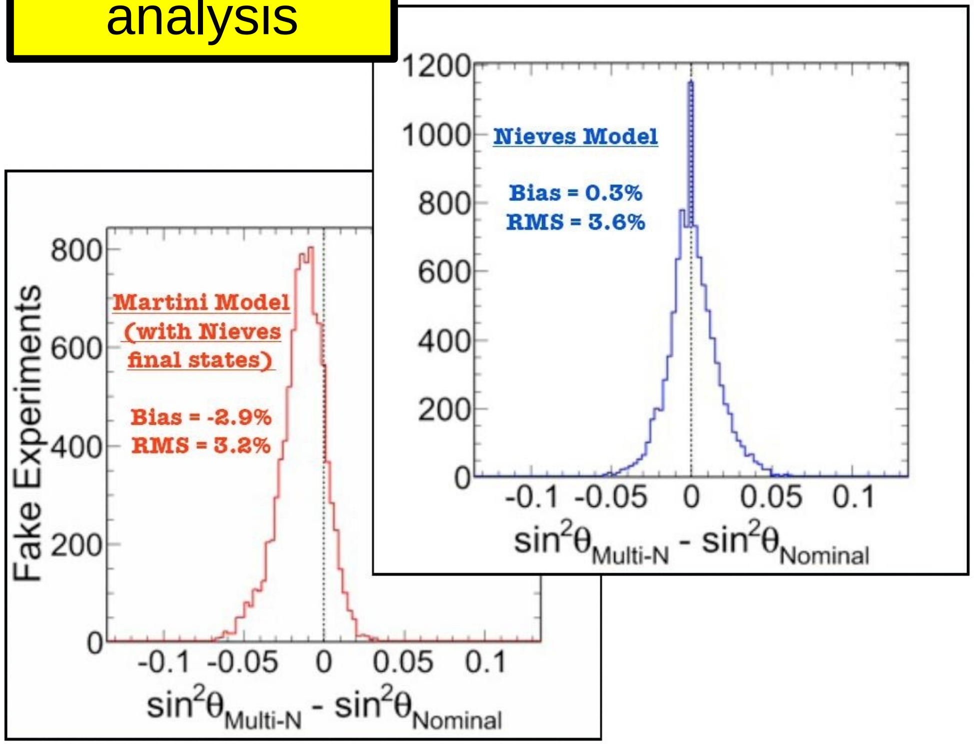




- Models give ~3.5% RMS in $\sin^2\theta_{23}$, Martini model introduces ~3% bias

Effect of 2p-2h events at νPRISM

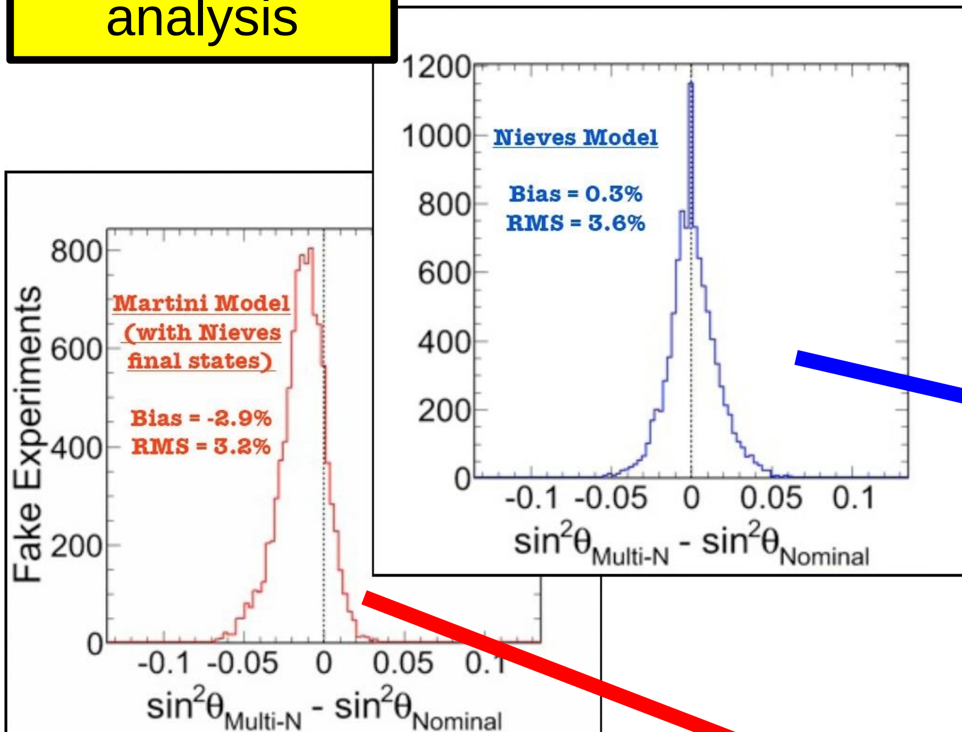
Standard T2K analysis



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

Effect of 2p-2h events at νPRISM

Standard T2K analysis



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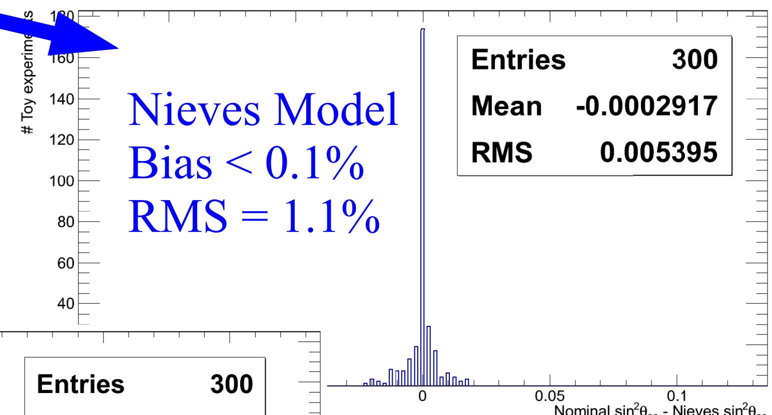
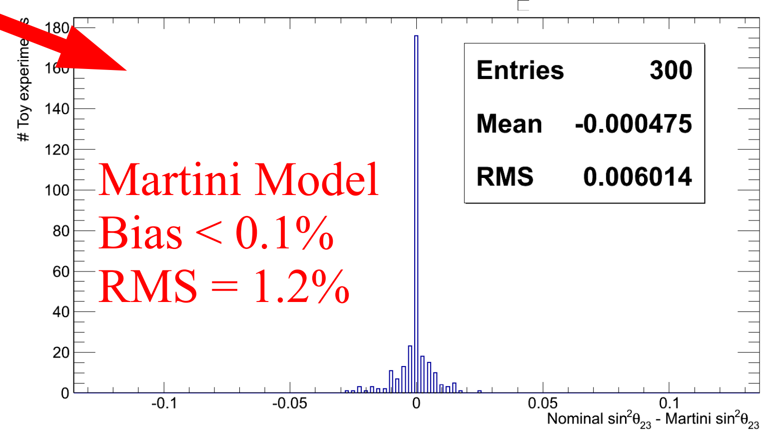


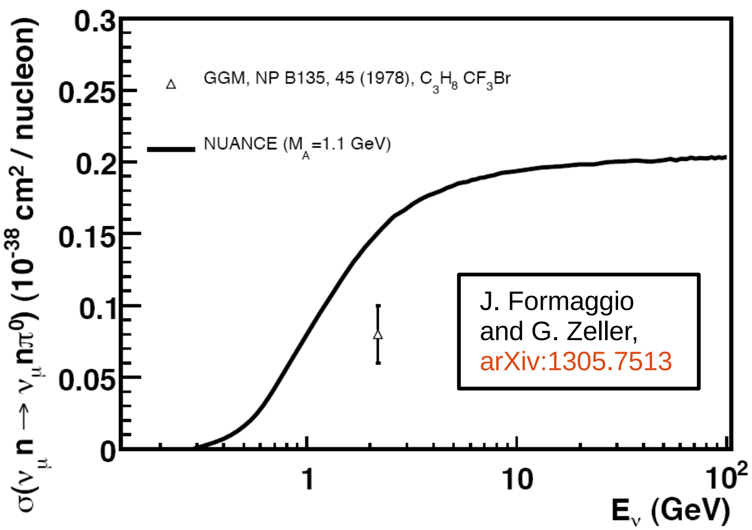


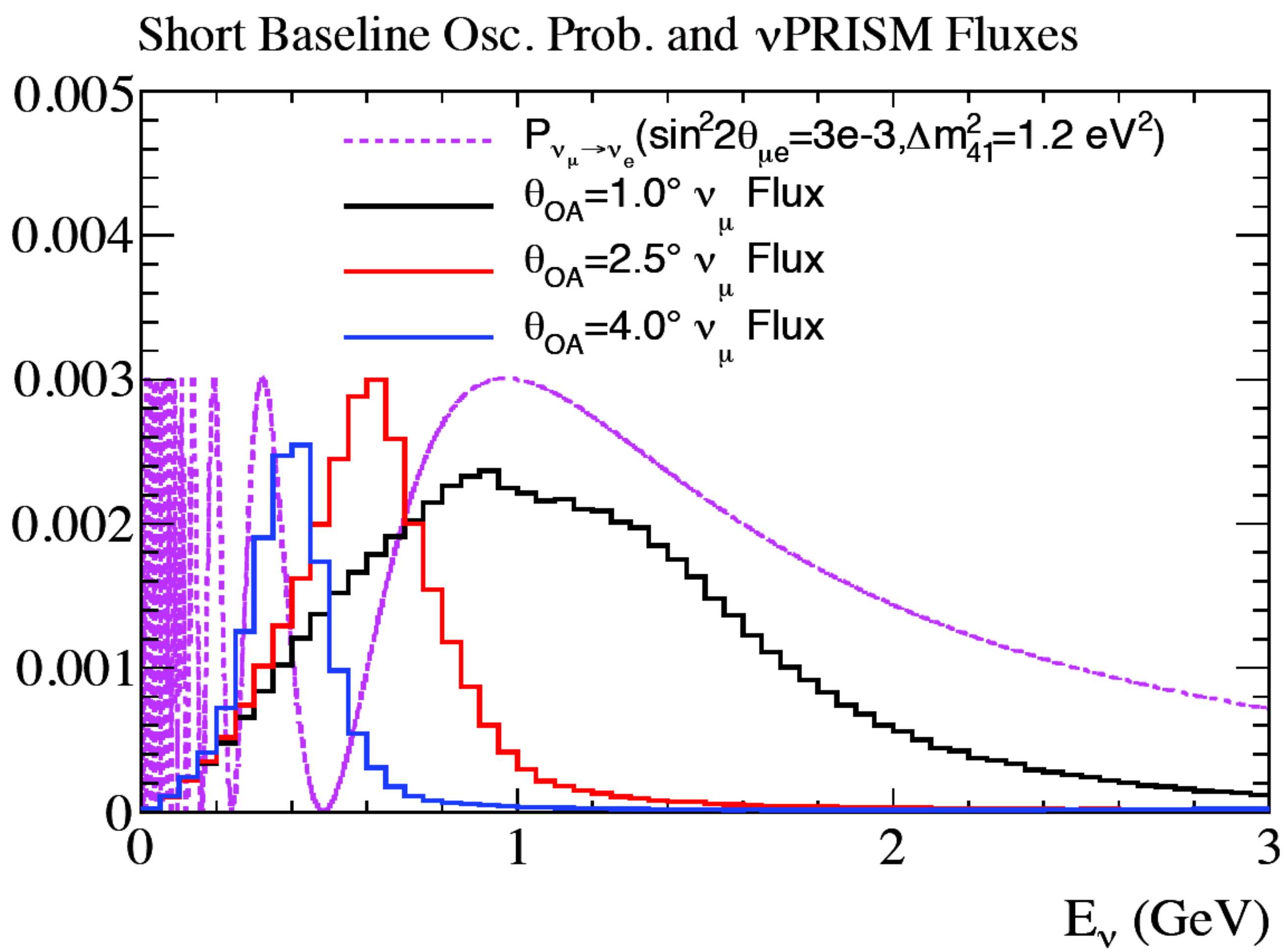
- Bias and RMS greatly reduced
- νPRISM analysis largely independent of cross section model

νPRISM analysis

Short baseline oscillations

- NuPRISM – same L/E range as LSND and MiniBooNE sterile results
- Neutrino flux variation across NuPRISM provides unique capabilities
  - Directly probe oscillation curve
  - Constrain backgrounds
    - Energy dependence
    - Direct measurements



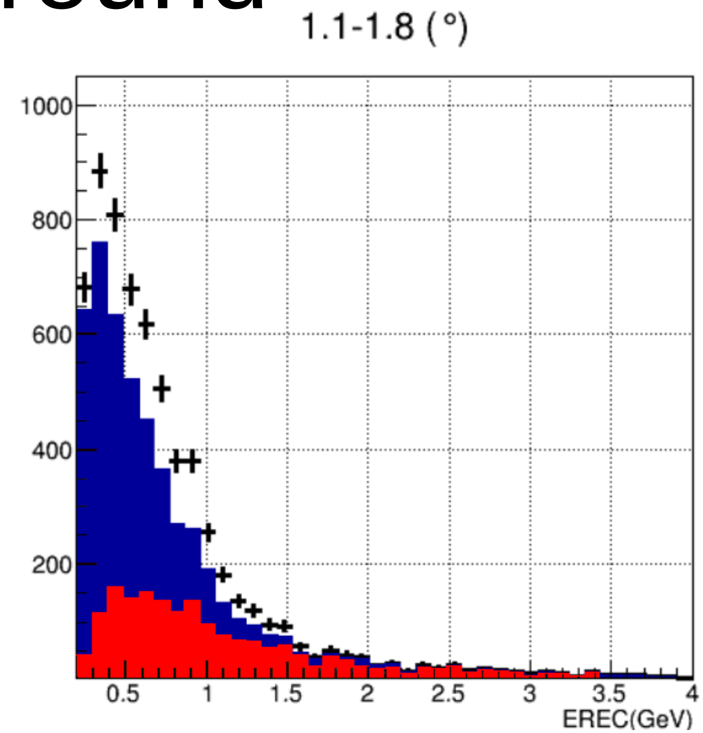


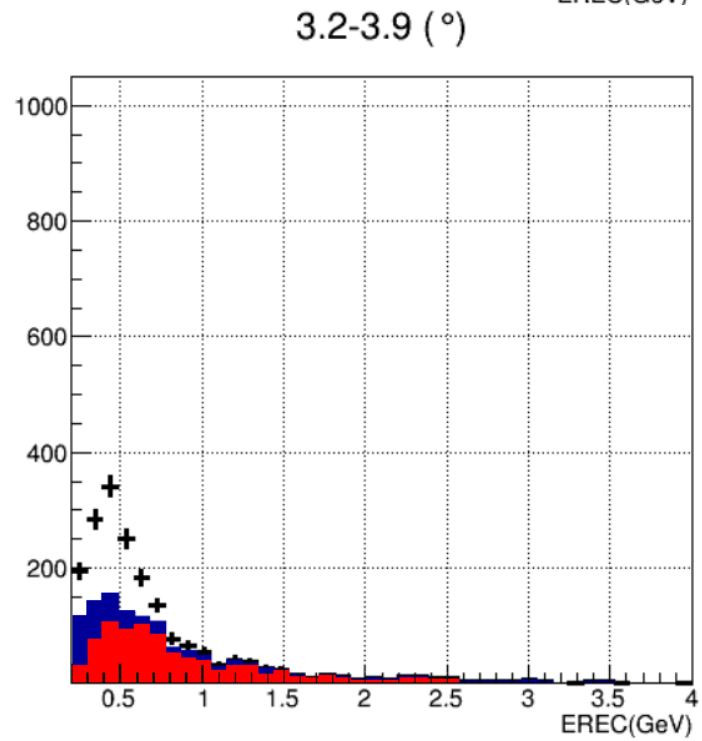
Signal and background

- Search for ν_e appearance using ν_μ events to constrain flux
- Full T2K flux and cross section uncertainties included

Points = Appearance signal
Red = Intrinsic ν_e bkgd
Blue = ν_μ bkgd

- On-axis (top)
  - High ν_μ contamination
  - Broad signal distribution
- Off-axis (bottom)
  - Very little ν_μ contamination
  - Signal peaked at low reconstructed energy

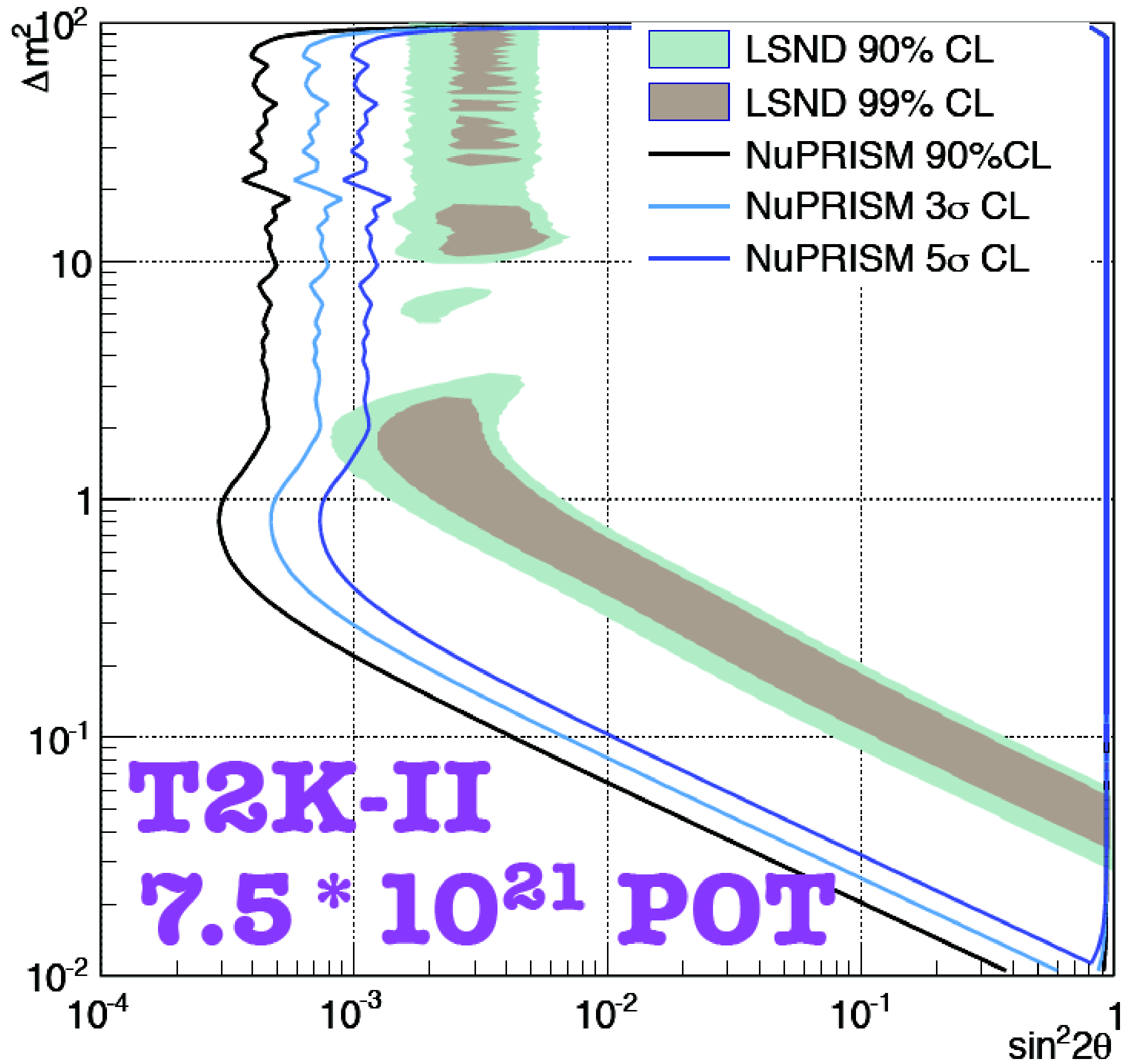




Sterile sensitivity

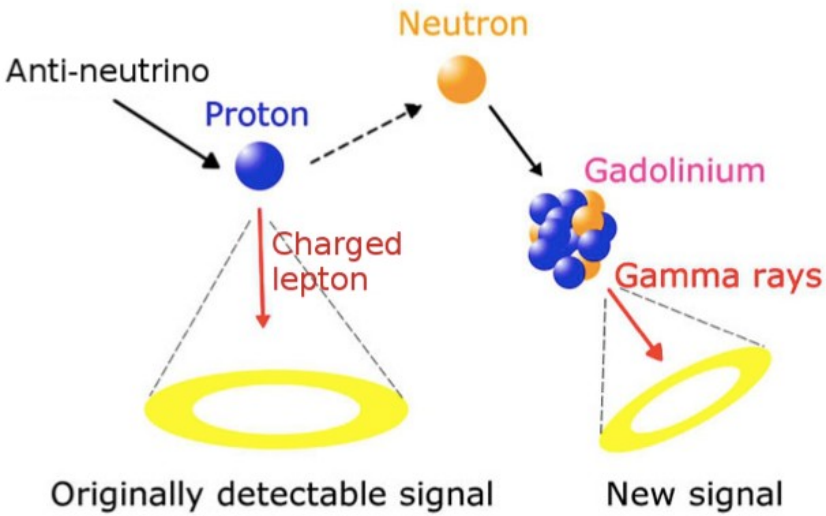
- NuPRISM neutrino fluxes peak at different energies for a given baseline
- Sterile oscillation has different energy dependency than background cross-sections → can separate them

- Excludes (almost) entire LSND allowed region at 5σ
  - Comparable to Fermilab SBN
- Statistics limited!
  - Expect results to improve:
    - Full reconstruction and selection
    - Direct constraint of backgrounds
    - Include T2K near detector



Gadolinium doping

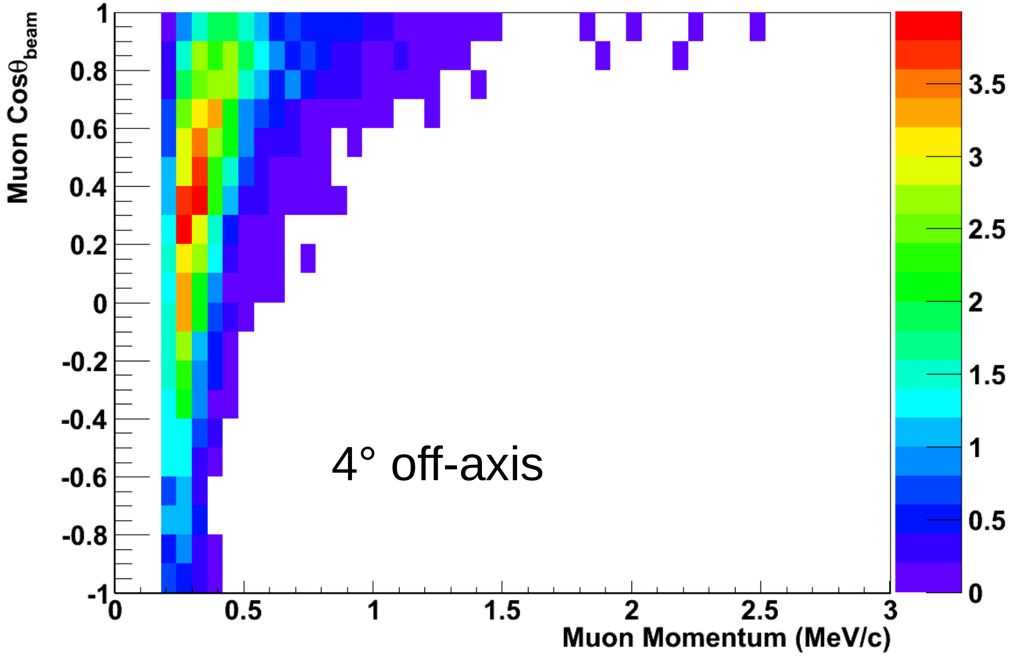
- Neutrons capture on Gd
  - 49,000b capture cross section
  - 8 MeV gamma cascade, 4-5 MeV visible
  - 0.1% doping → 90% neutrons capture on Gd

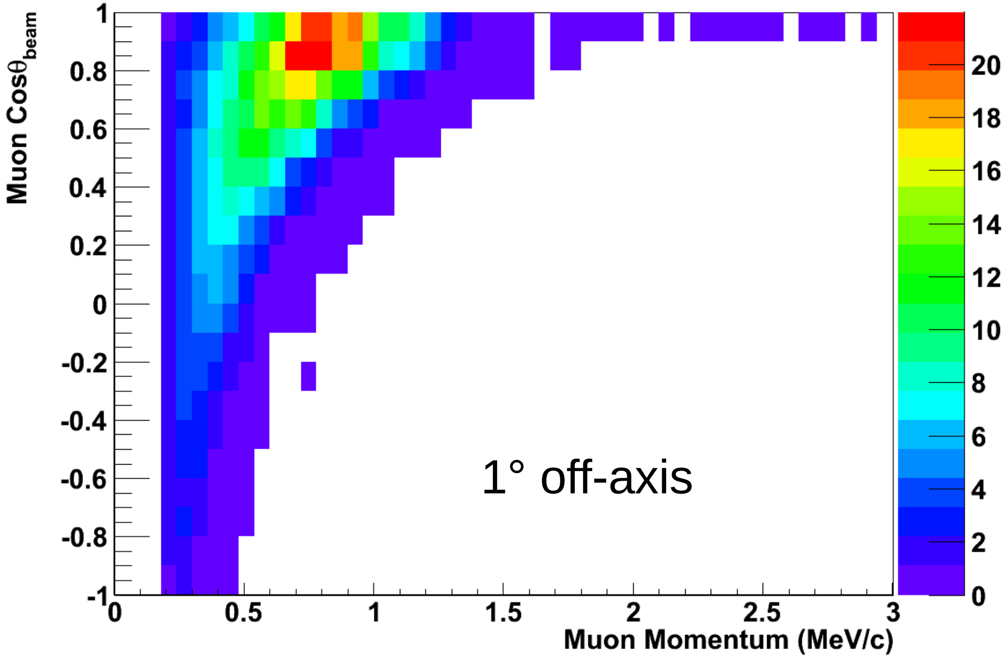


- SK planning to load Gd in future – increase sensitivity to supernovae
  - Statistically separate neutrino interactions from anti-neutrino
  - Tag proton decay backgrounds
- But, neutron emission from neutrino interactions largely unknown
- NuPRISM can measure this:
  - Mono-energetic neutrino source
  - Neutron capture rates as a function of lepton kinematics

Event Selection

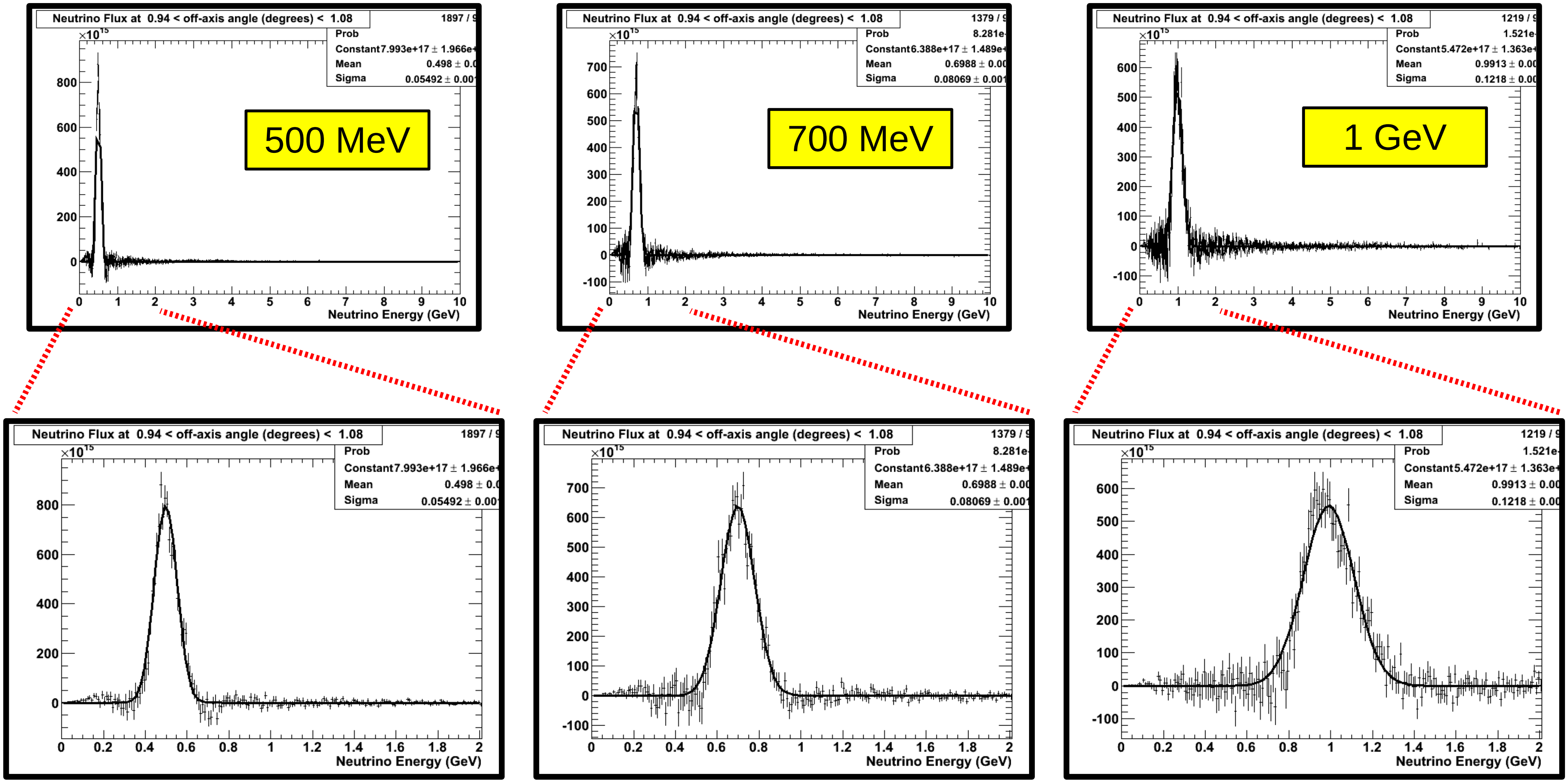
- Same event selection as at SK:
  - Single ring
  - Muon-like
  - Fully contained in fiducial volume





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

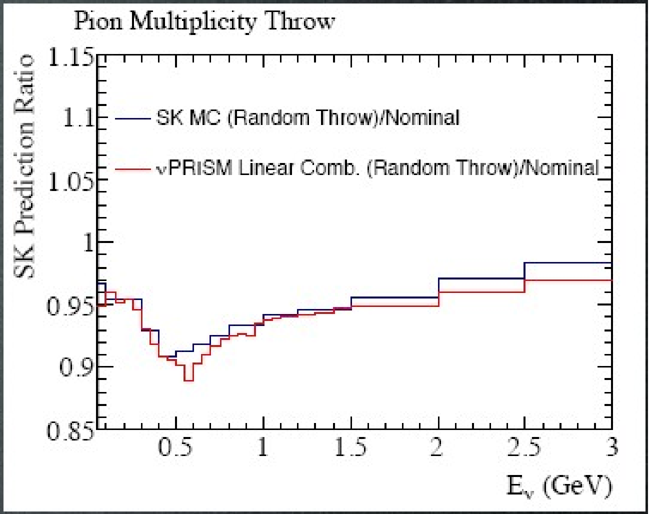
A neutrino spectrometer

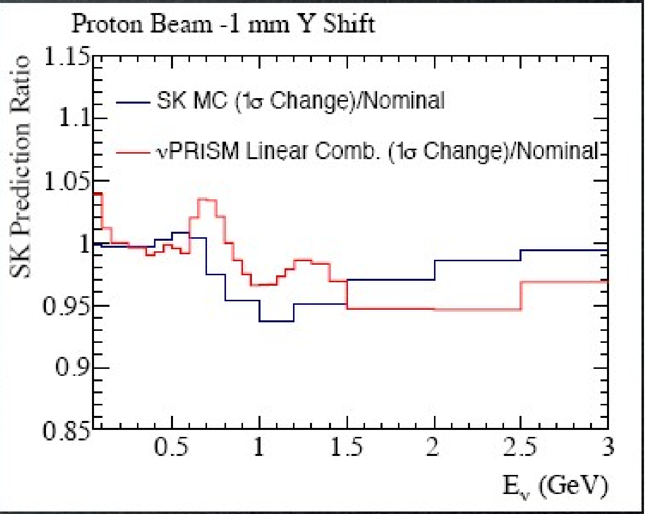


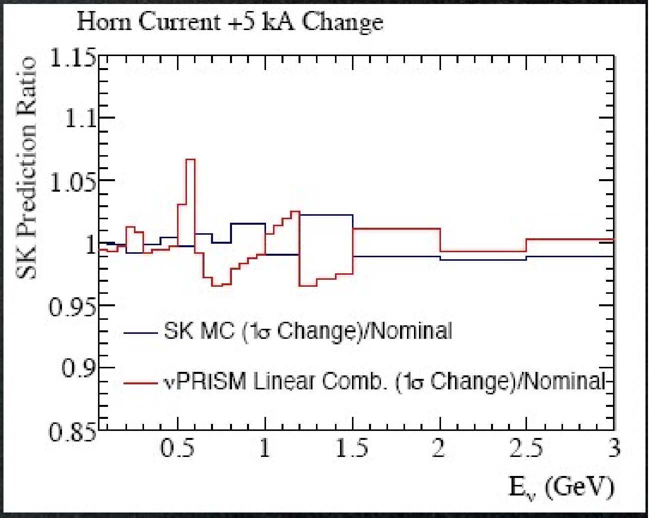
- Gaussian spectra from ~0.4 GeV to ~1 GeV
  - Depends on off-axis span of νPRISM: 6° - 0.25 GeV, 0° - 1.2 GeV
- High energy tail cancelled in all cases

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

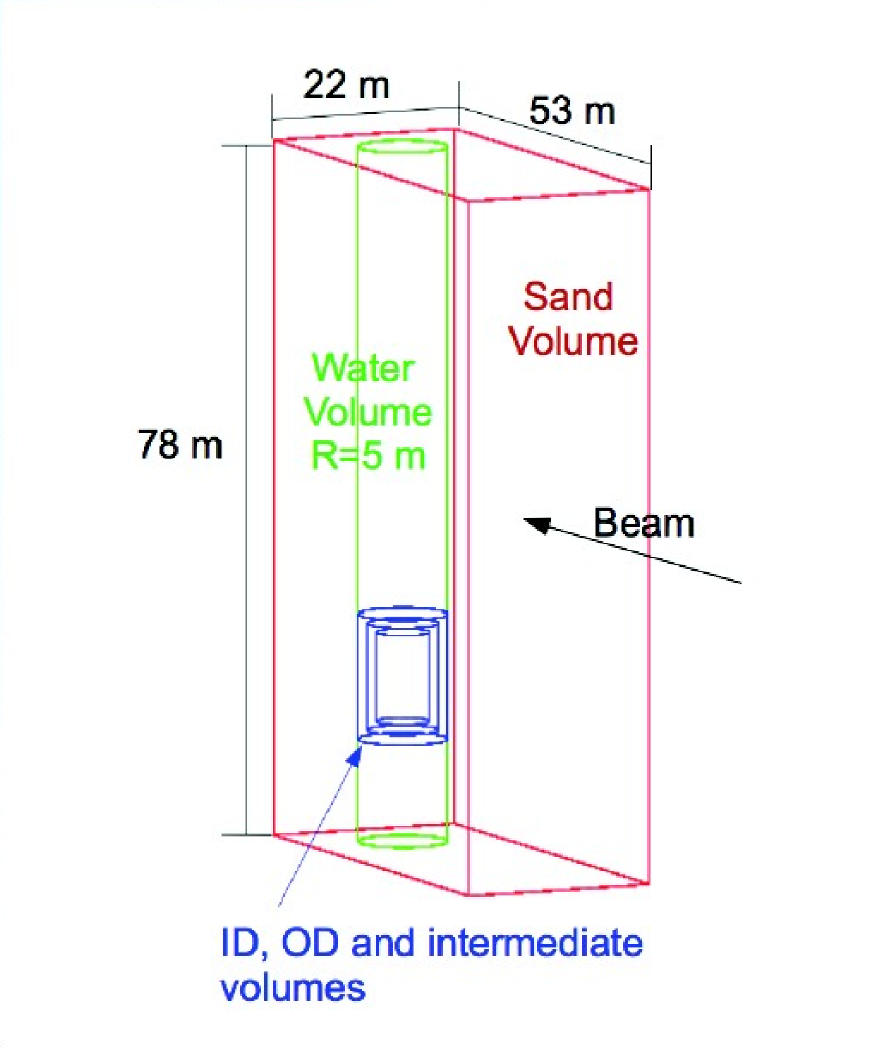






Event Pileup at 1 km

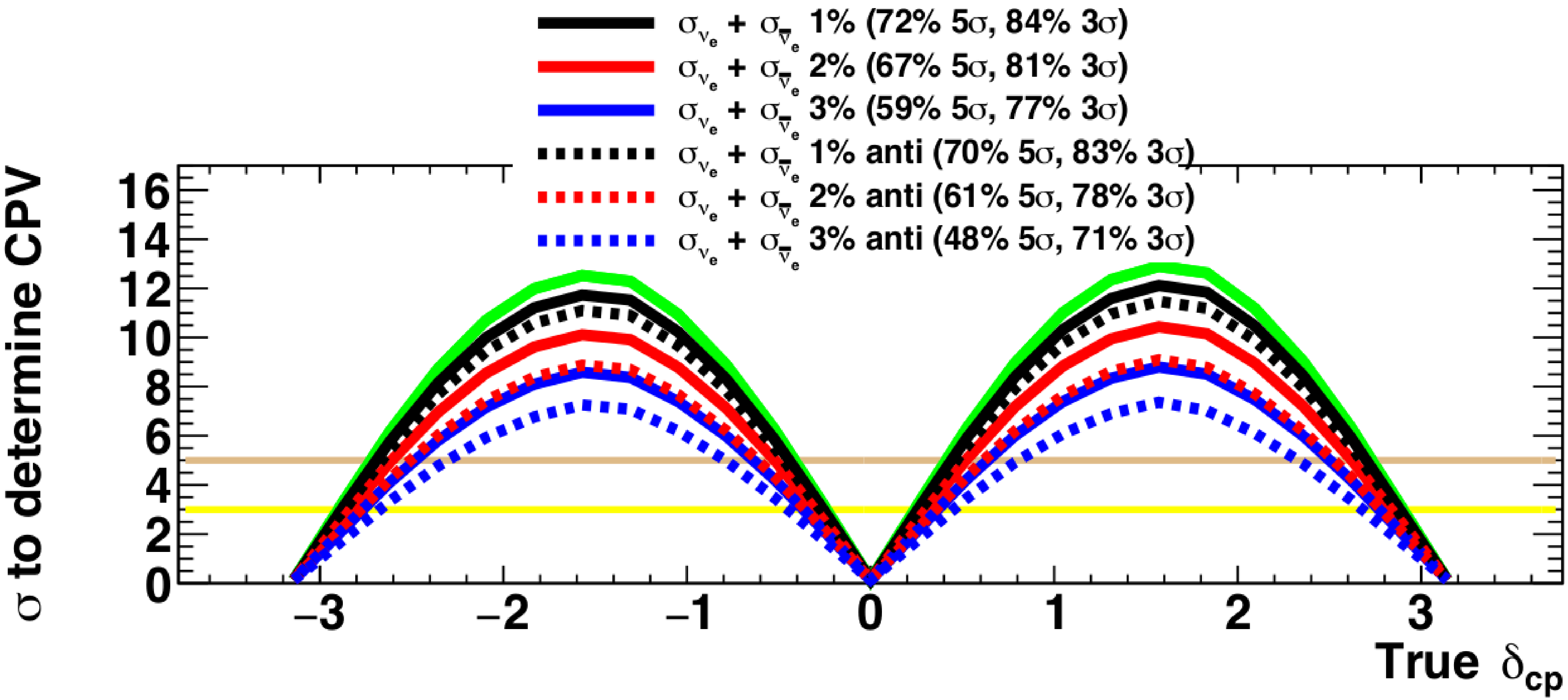
- Full GEANT4 simulation of water and surrounding sand
    - Using T2K flux and neut cross section model
- 8 beam bunches per spill, separated by 670 ns with a width of 27 ns (FWHM)
- **41% chance of in-bunch OD activity during an ID-contained event**
    - Want to avoid vetoing only on OD light (i.e. 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!

ν_e cross-section

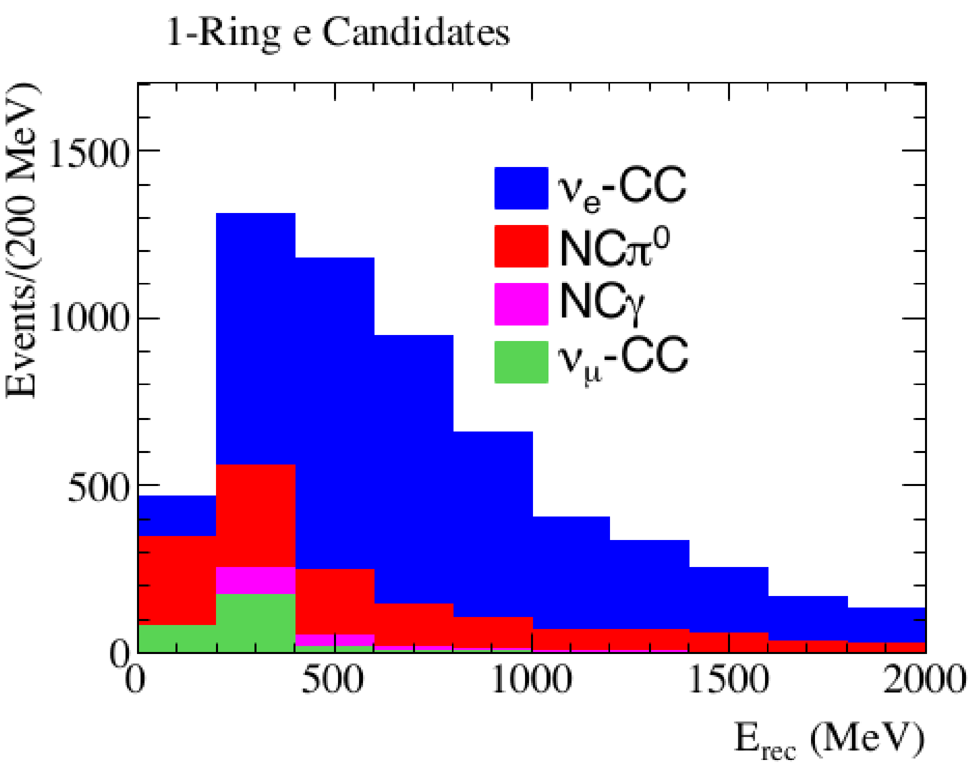
- Current uncertainty based on theory
  - ~3.5% uncertainty on T2K CP violation measurement

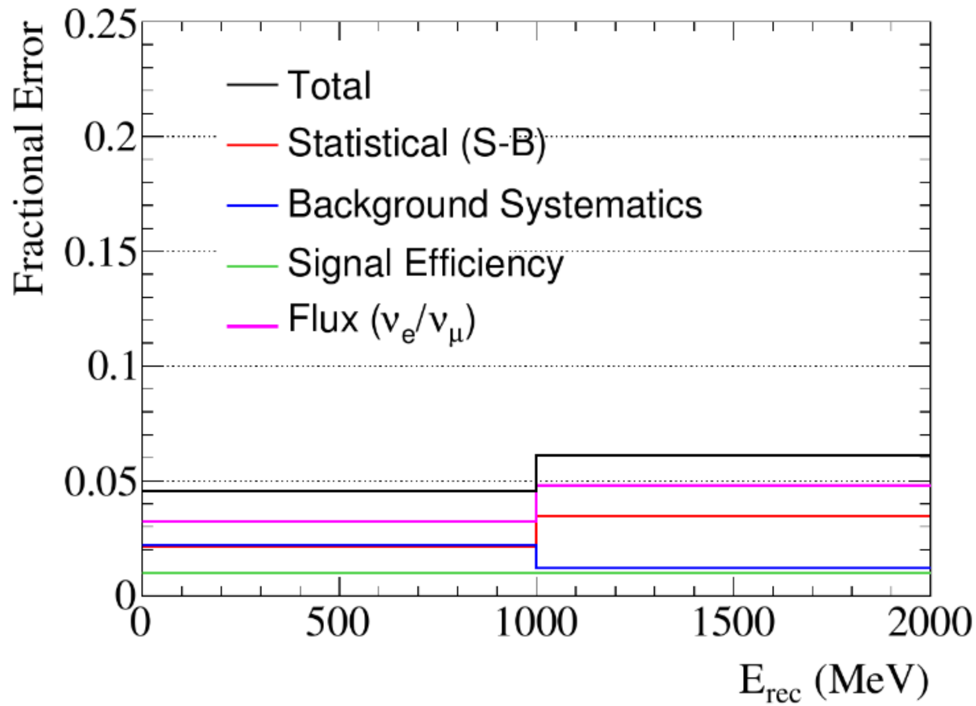


- Hyper-K sensitivity to observe CP violation for various uncertainties on ν_e cross-section
- Significantly degrade sensitivity

ν_e cross-section

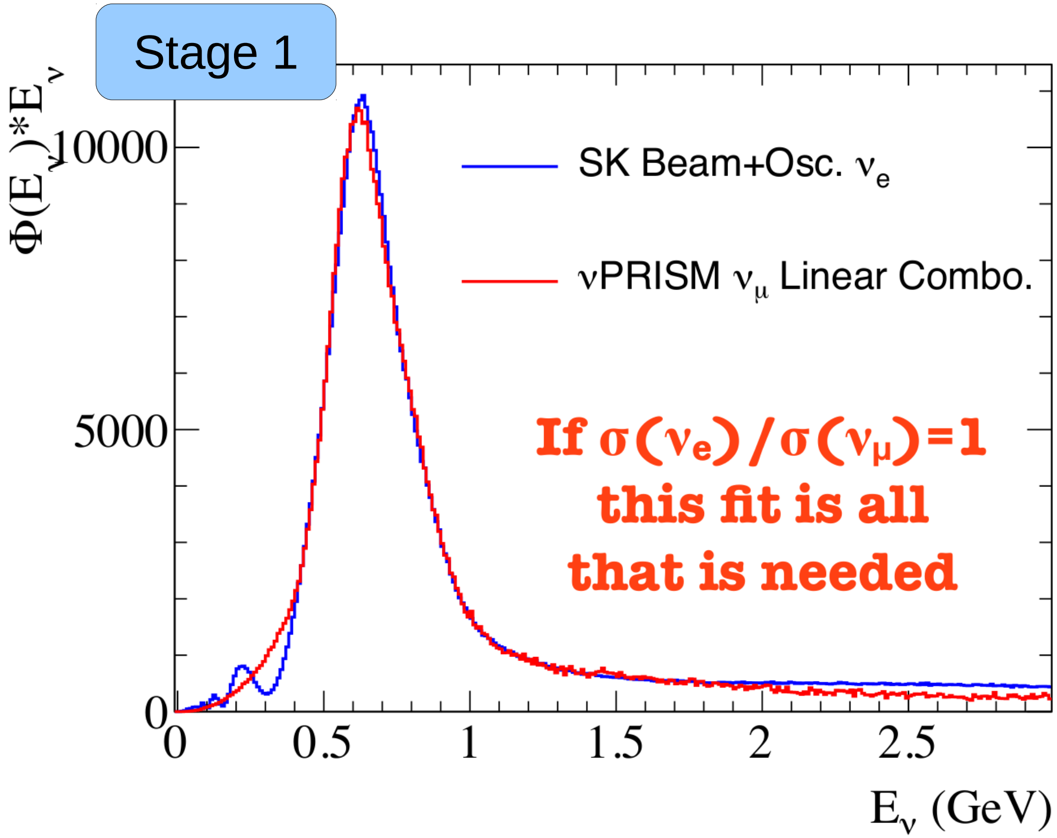
- Current uncertainty based on theory
  - ~3.5% uncertainty on T2K CP violation measurement
- We should measure this!

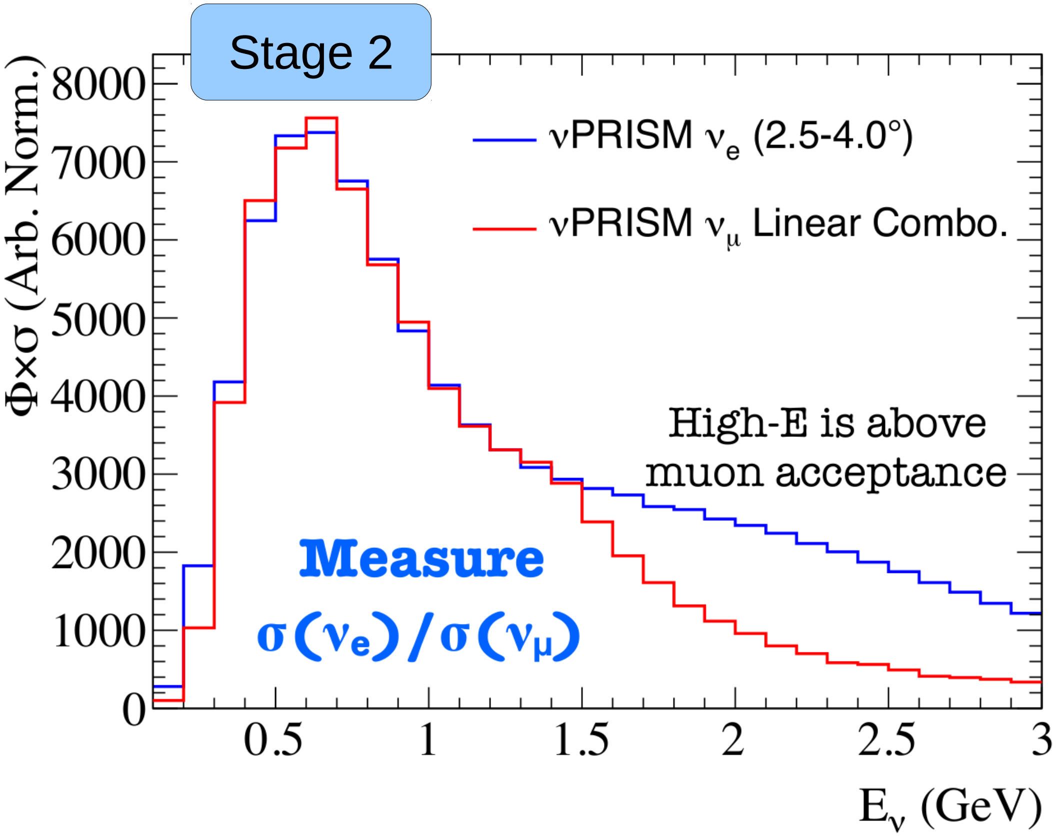




- Expect ~5000 events < 2 GeV per 1e^{21} POT at 73% purity
  - 2% statistical uncertainty in region of interest
- Conservative error estimate of <5%, dominated by flux ratio uncertainty
  - Replica target data will reduce flux ratio uncertainty

ν_e oscillation at NuPRISM



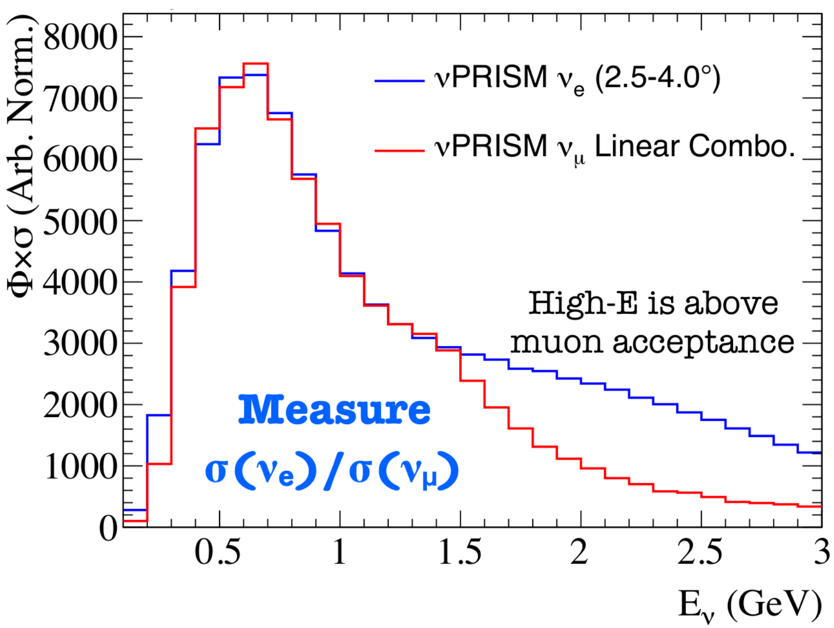


- 3 stage approach
  - Match SK ν_e appearance flux using NuPRISM ν_μ flux
  - Match NuPRISM instrinsic ν_e flux using NuPRISM ν_μ flux - measure cross-section ratio **with same flux**
  - Measure beam and NC backgrounds using 2.5° NuPRISM flux

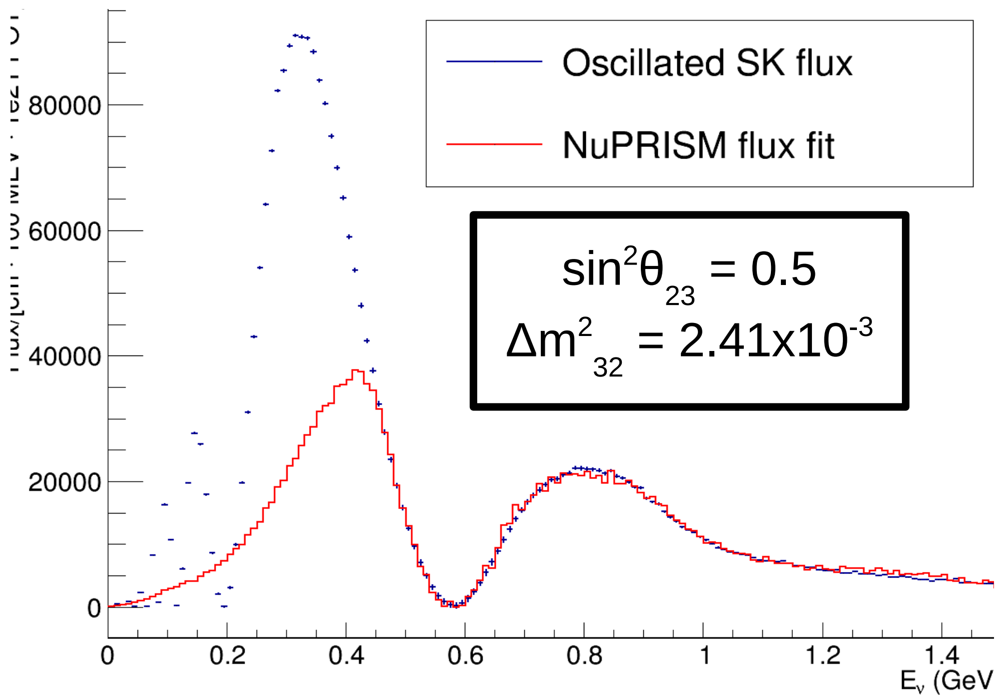
Benefits for ν_e at NuPRISM

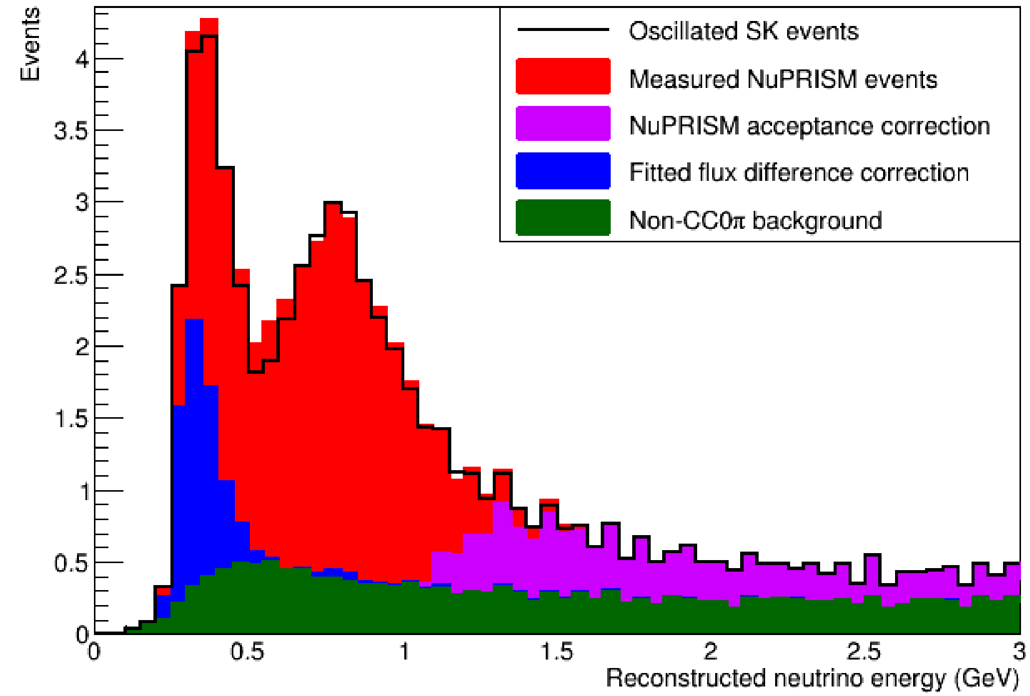
- Water Cherenkov detector, same as SK, so can make high purity electron-neutrino sample
- Going off-axis increases relative fraction of intrinsic electron neutrinos in beam
- Large statistics
- Matching fluxes
  - For appearance signal
    - Nuclear effects
    - FSI, SI
      - All cancel!
  - For cross-section
    - Same interaction modes
    - Same energy dependence
- Dominant, theory driven systematics cancelled out experimentally

Off-axis angle (°)	ve Flux 0.3-0.9 GeV	νμ Flux 0.3-5.0 GeV	Ratio ve/νμ
2.5	1.24E+15	2.46E+17	0.507%
3.0	1.14E+15	1.90E+17	0.600%
3.5	1.00E+15	1.47E+17	0.679%
4.0	8.65E+14	1.14E+17	0.760%



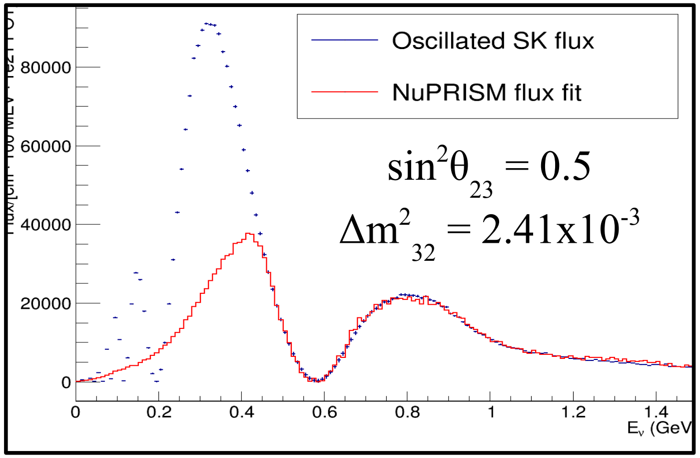
ν Oscillation with NuPRISM

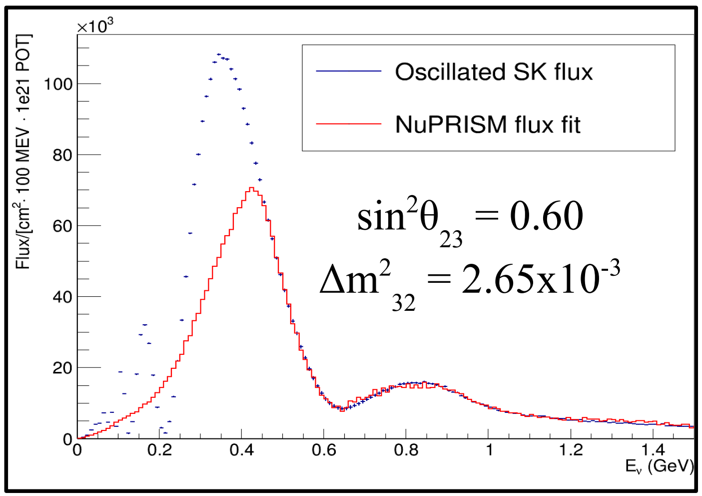


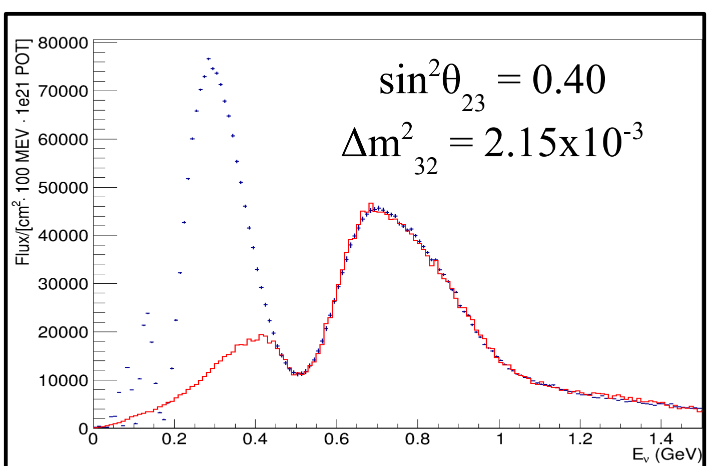


- Event rate = Flux(E_ν) * Cross-section(E_ν) * Efficiency
- NuPRISM and SK have water target – same interaction cross-section
- If fluxes (and efficiency) match:
  - NuPRISM linear combination event rate == **oscillated** SK event rate
  - No cross-section model, no effect from wrong model choice
  - Directly compare to SK data to get oscillation parameters

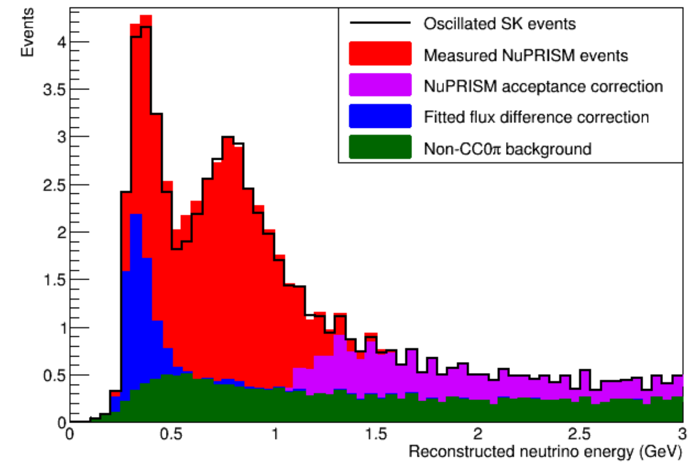
ν Oscillation with NuPRISM

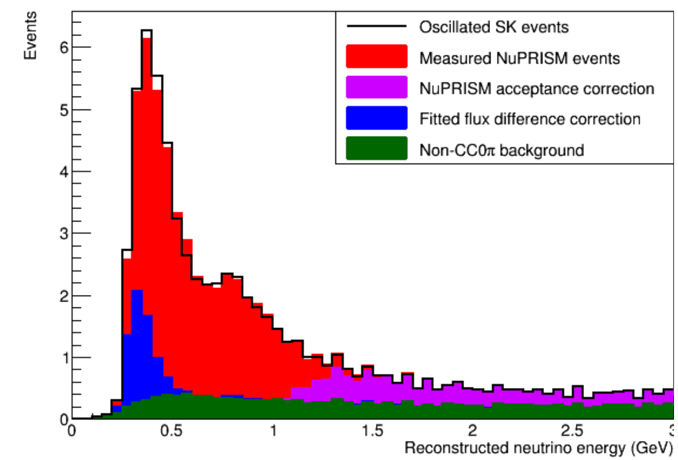


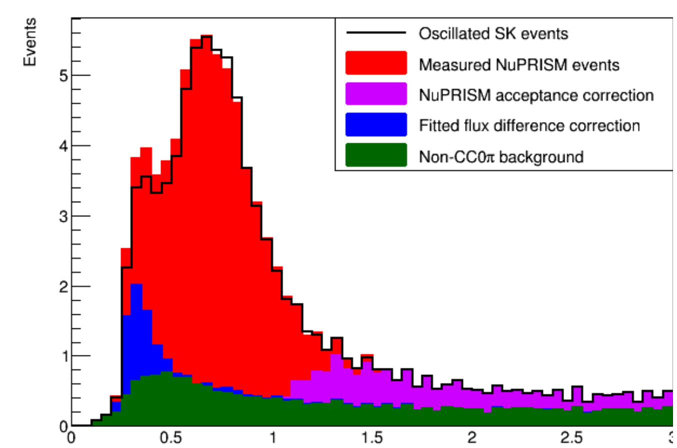




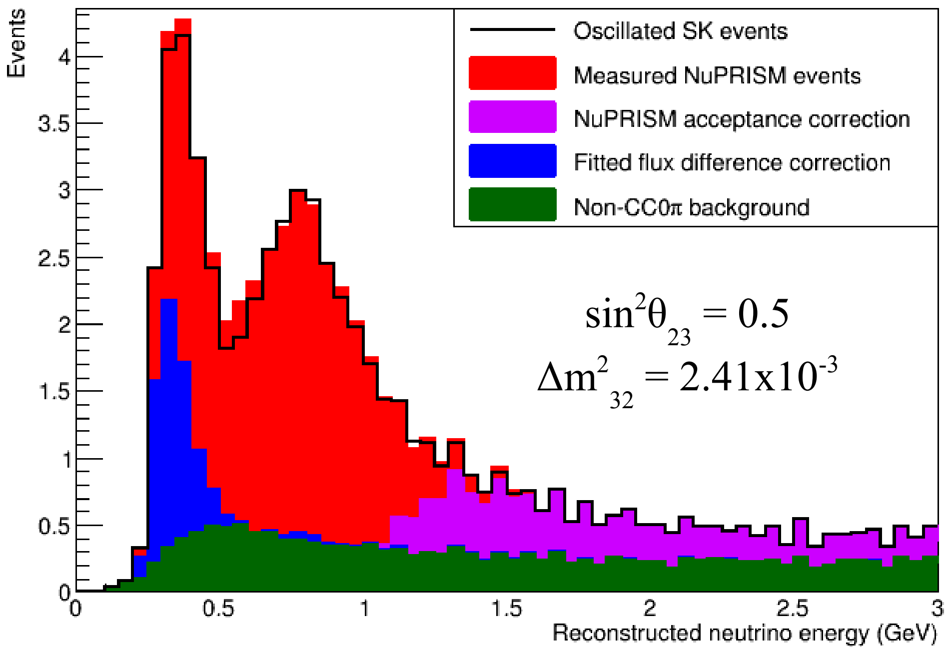
- Red – directly measured in NuPRISM data
- Blue – flux fit difference correction
- Magenta – Acceptance correction
  - NuPRISM only 8m wide
  - Can contain muons up to ~1.2GeV
- Green – SK background correction
  - Cancelation with bkg subtracted at NuPRISM
- **Majority of SK prediction directly measured**

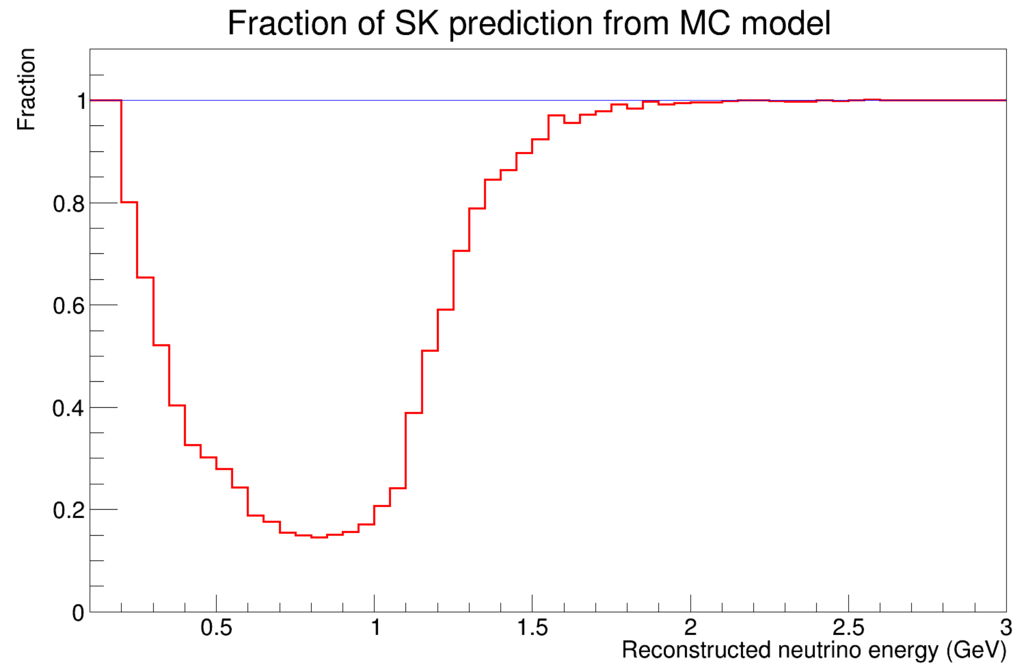






νPRISM ν Oscillation with NuPRISM TRIUMF





- Choice of model can bias oscillation measurements
  - Cannot rely on model to be correct
  - Cannot assume models available cover all possibilities
- NuPRISM measurement relies on model for ~20% of SK prediction in oscillation region
  - Compared to 100% for traditional near detector analysis
  - Greatly reduce effect of model choice

2p-2h events

- Add 2p-2h events to SK and NuPRISM MC to create fake dataset
  - Neutrino interaction model does not include these events
- Redo linear combinations using fake data
- NuPRISM correctly predicts SK event rate!