νPRISM: A novel technique for uncertainty reduction in neutrino oscillation experiments

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Motivation

- Current neutrino oscillation experiments depend on neutrino interaction models
  - Current T2K ν_μ errors: 7.7% (5.0%)
  - Current T2K ν_e errors: 6.8% (4.7%)

T2K Collaboration, PRD 91, 072010 (2015)

- Future experiments that look to determine δ_{CP} need higher precision (<3% uncertainties)
- νPRISM is a technique to reduce uncertainties from neutrino interaction models
  - Data-driven way to determine the relationship between true and reconstructed neutrino energies
- I will focus on how νPRISM can be applied to future experiments that propose to measure CP violation in neutrinos

CP violating phase and oscillation asymmetry

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The probability for ν_μ to oscillate to ν_e is given as

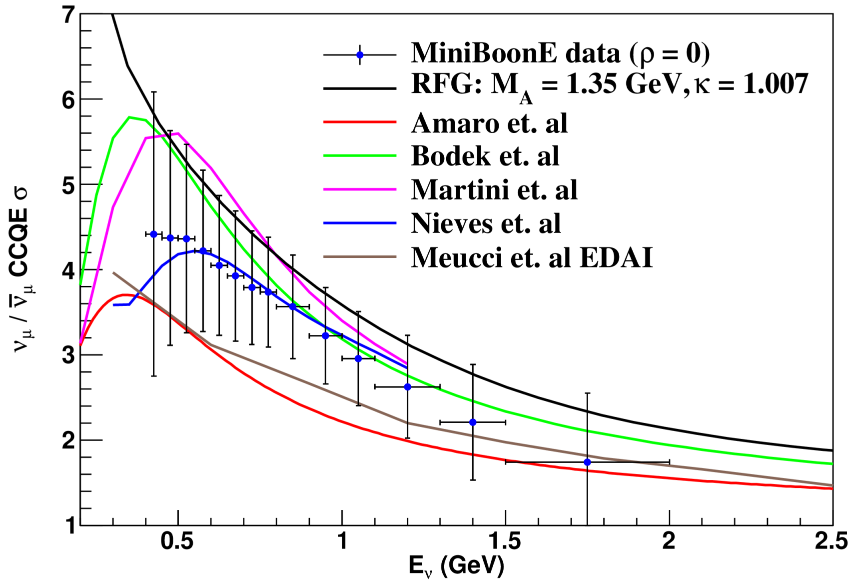
$$P_{\nu_\mu \to \nu_e} = \frac{1}{(A-1)^2} \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2[(A-1)\Delta]$$
$$-(+)\frac{\alpha}{A(1-A)} \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \times$$
$$\sin\delta_{CP} \sin\Delta \sin A\Delta \sin[(1-A)\Delta]$$
$$+\frac{\alpha}{A(1-A)} \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \times$$
$$\cos\delta_{CP} \cos\Delta \sin A\Delta \sin[(1-A)\Delta]$$
$$+\frac{\alpha^2}{A^2} \cos^2\theta_{23} \sin^2 2\theta_{12} \sin^2 A\Delta$$

Changes sign depending on neutrino (antineutrino)

- Future measurements compare neutrino and antineutrino probabilities to determine δ_{CP}, the CP violating phase

Neutrino vs antineutrino cross section

- Significant difference predicted between neutrino and antineutrino cross sections
  - Relevant for CP violation measurements



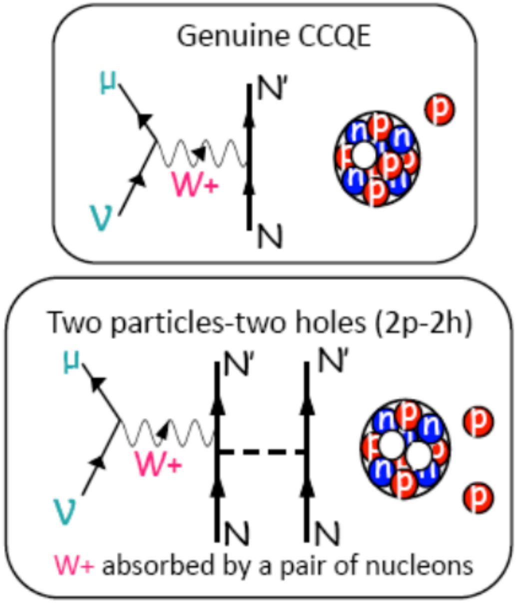
Joe Grange. NuInt2012

- Direct measurement of this difference independent of model is critical

Problem with energies

- Oscillation probability is dependent on true neutrino energy
- Data determined from final state particle kinematics
  - Outgoing 4-momentum measured by detector
  - Assuming single nucleon interaction (Genuine CCQE), then:

$$E_\nu^{QE} = \frac{2(M_n')E_\mu - ((M_n')^2 + m_\mu^2 - M_p^2)}{2 \cdot [(M_n') - E_\mu + \sqrt{E_\mu^2 - m_\mu^2} \cos\theta_\mu]}$$

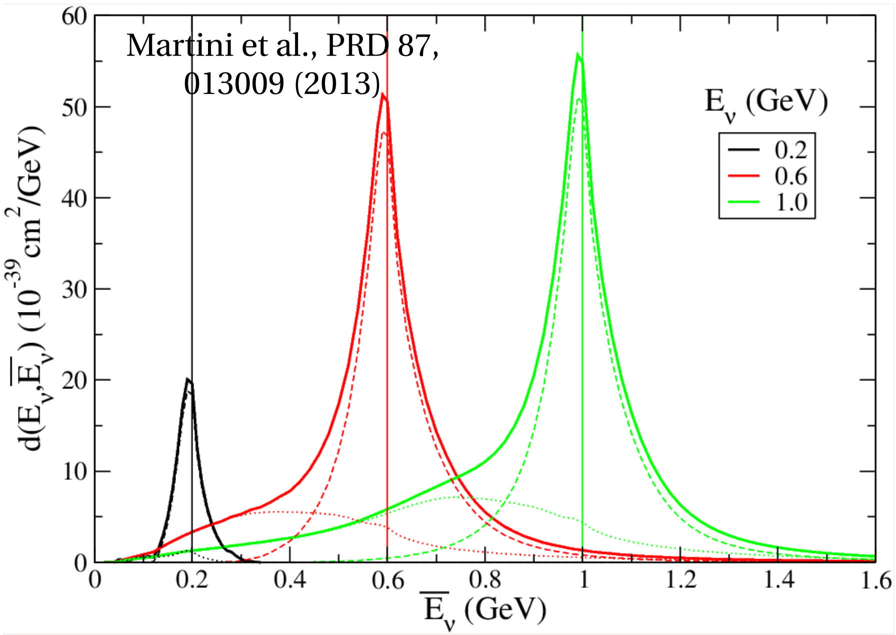


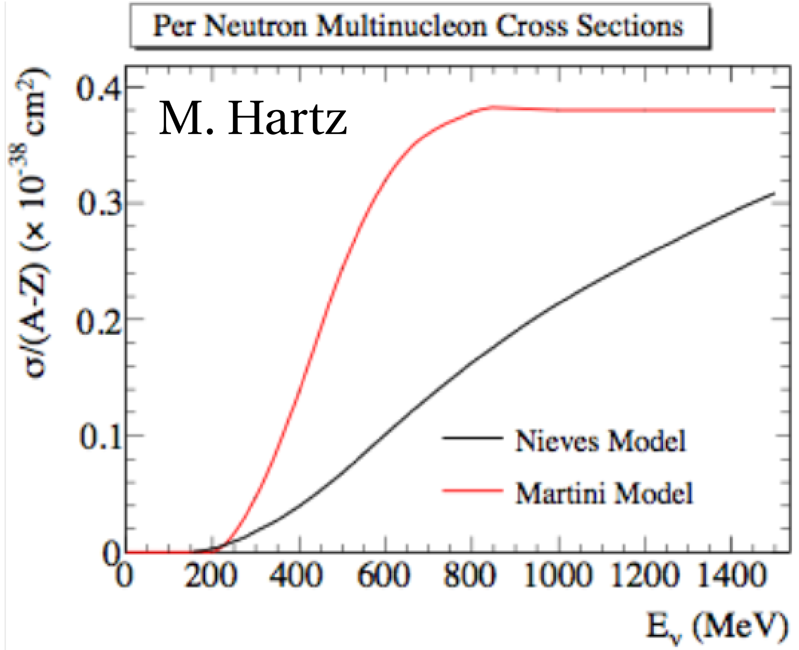
Picture by M. Martini

- We now know that neutrinos can interact with multiple nucleons (2p-2h, multinucleon)

Neutrino interaction models

- Multinucleon interactions cause a bias in the reconstructed neutrino energy

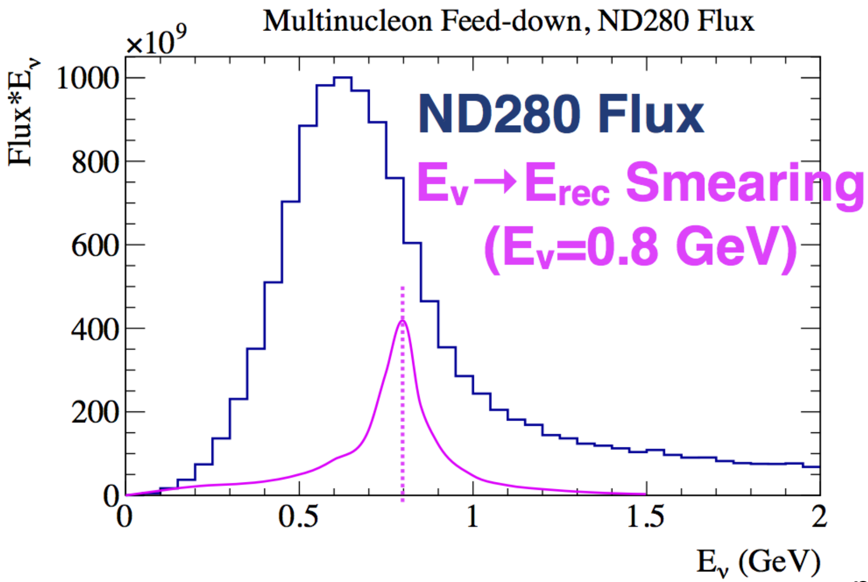


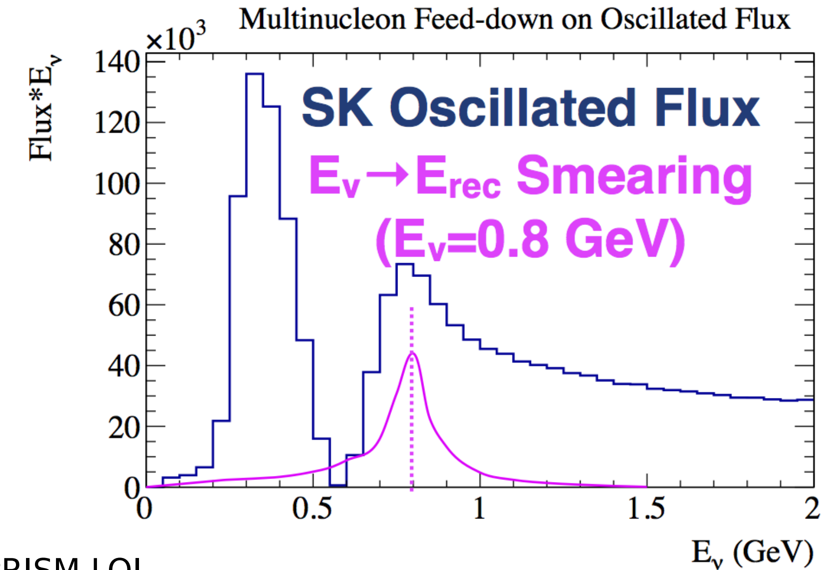


- Theoretical neutrino interaction models differ by a factor of 2-3
  - M. Martini, M. Ericson, G. Chanfray, and J. Marteau, PRC 80 065501 (2009)
  - J. Nieves, I. Ruiz Simo, and M. J. Vicente Vacas, PRC 83 045501 (2011)

Effect on measurements

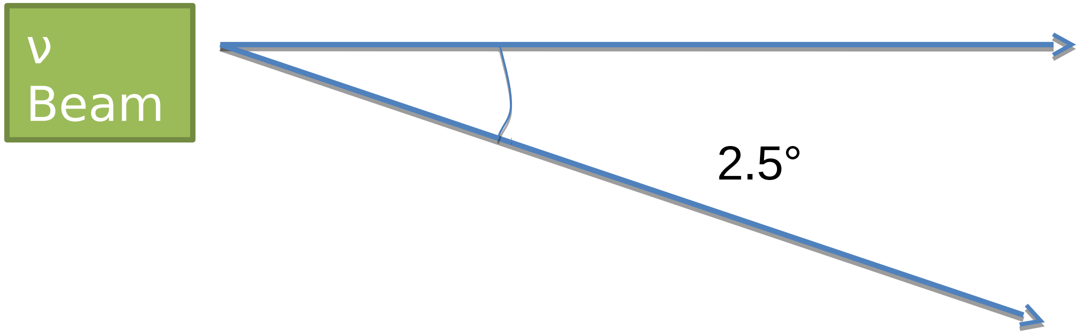
- Multinucleon processes cause a feed-down of events into the oscillation dip which affects the determination of oscillation parameters
  - All current experiments rely on the assumed neutrino-interaction model even with near detectors

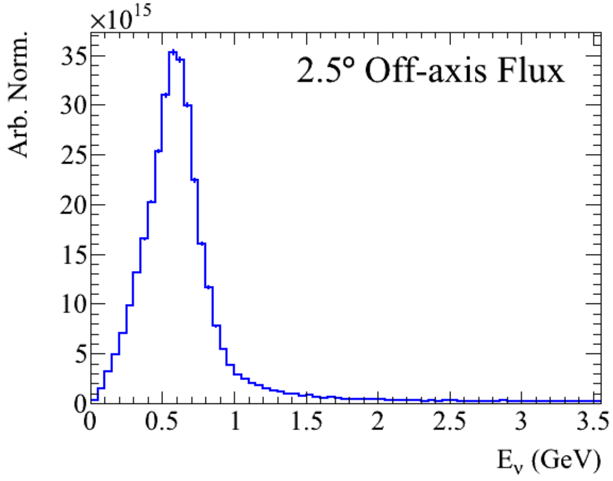




nuPRISM LOI. arXiv:1412.3086.

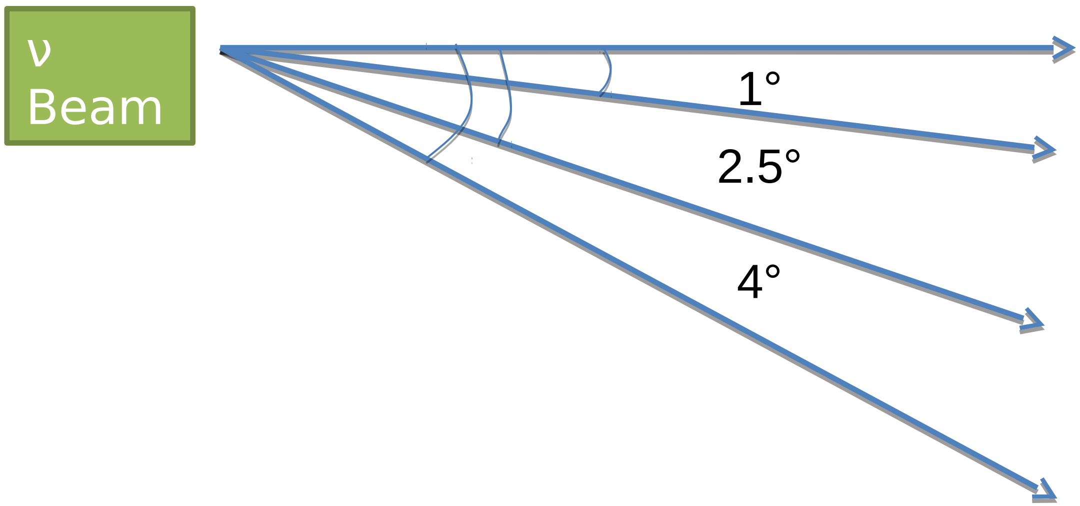
νPRISM concept

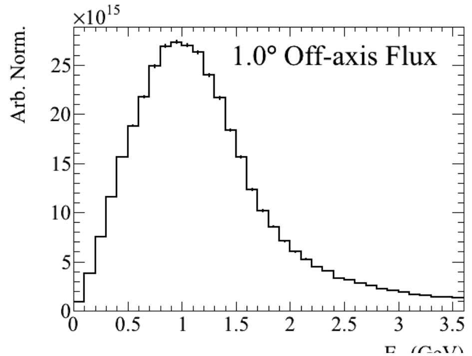


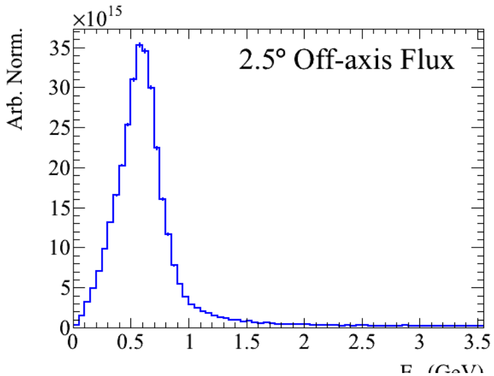


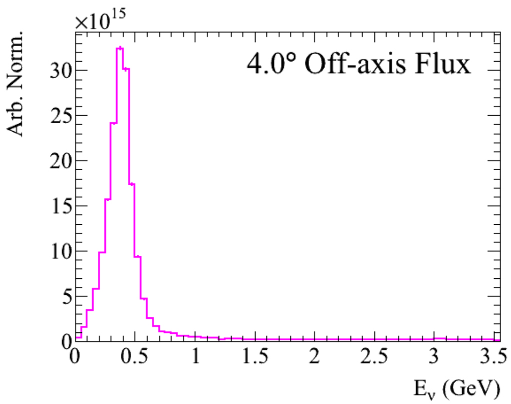
- Consider T2K beamline as an example
  - Can be either a neutrino or antineutrino beam

νPRISM concept





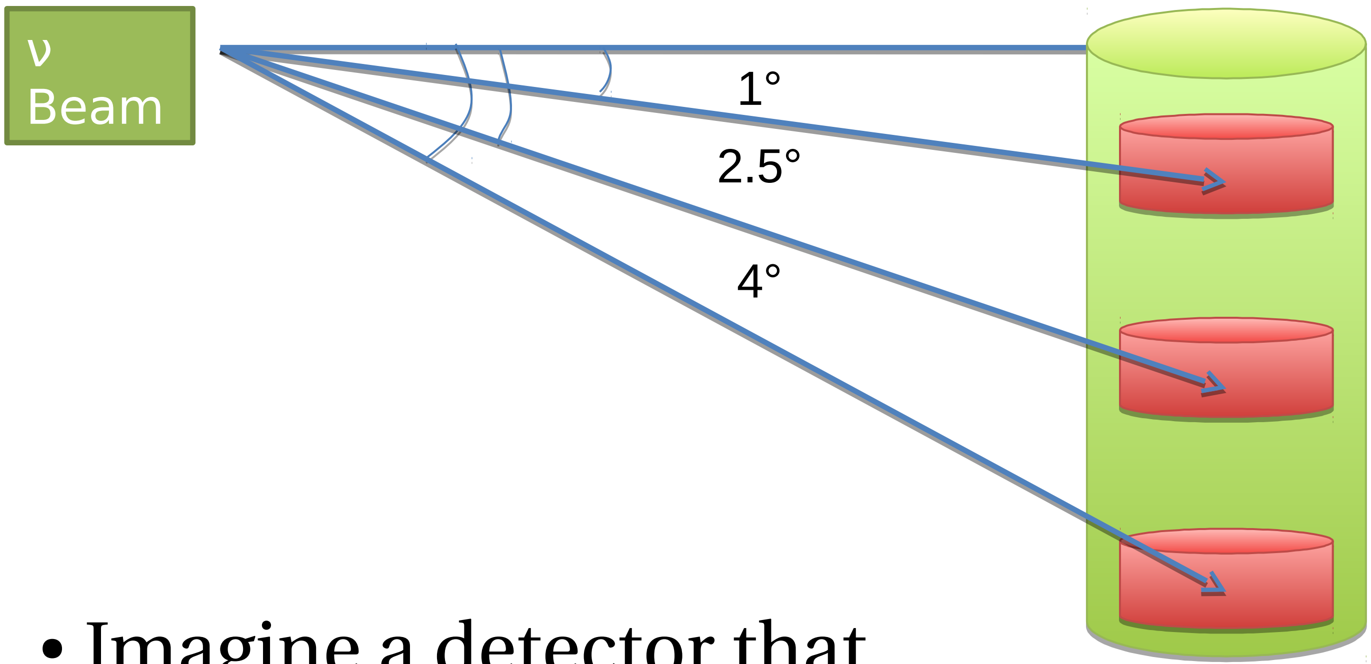


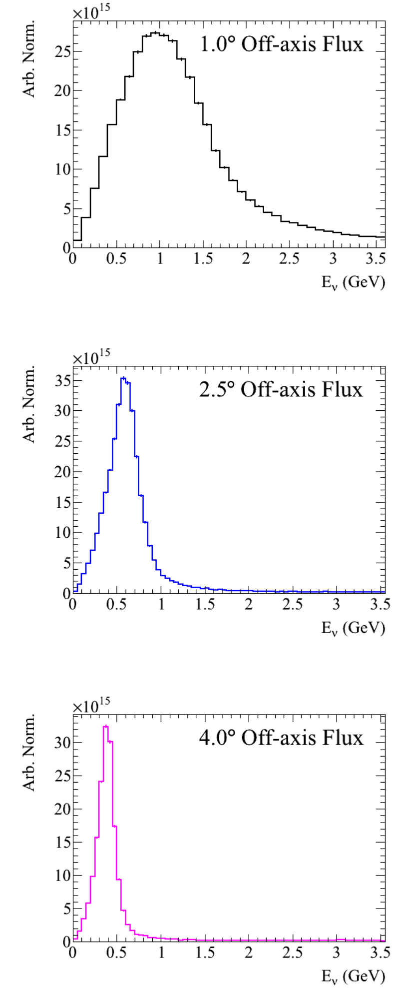


- Different off-axis angles change the neutrino flux width and peak position

nuPRISM LOI. arXiv:1412.3086.

νPRISM concept



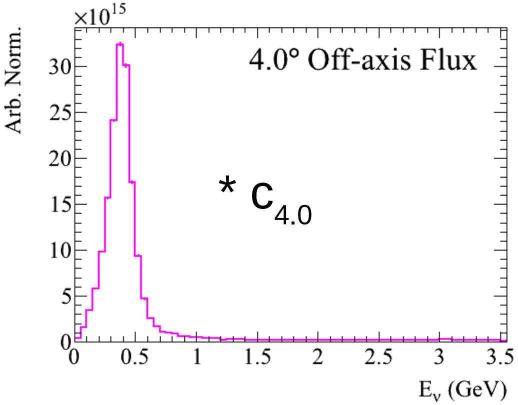


- Imagine a detector that spans a range of off-axis angles
  - Position in detector determines off-axis angle

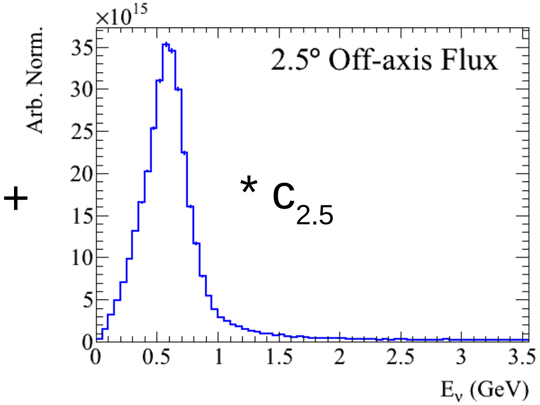
nuPRISM LOI. arXiv:1412.3086.

νPRISM: Monoenergetic flux

- Can make monoenergetic fluxes by taking linear combination of off-axis fluxes



$* c_{4.0}$ +



$* c_{2.5}$ =

$$\Phi(E_\nu) = \sum_{i=0^\circ}^{\theta_{max}} C_i \ \phi_i(E_\nu)$$

nuPRISM LOI. arXiv:1412.3086.

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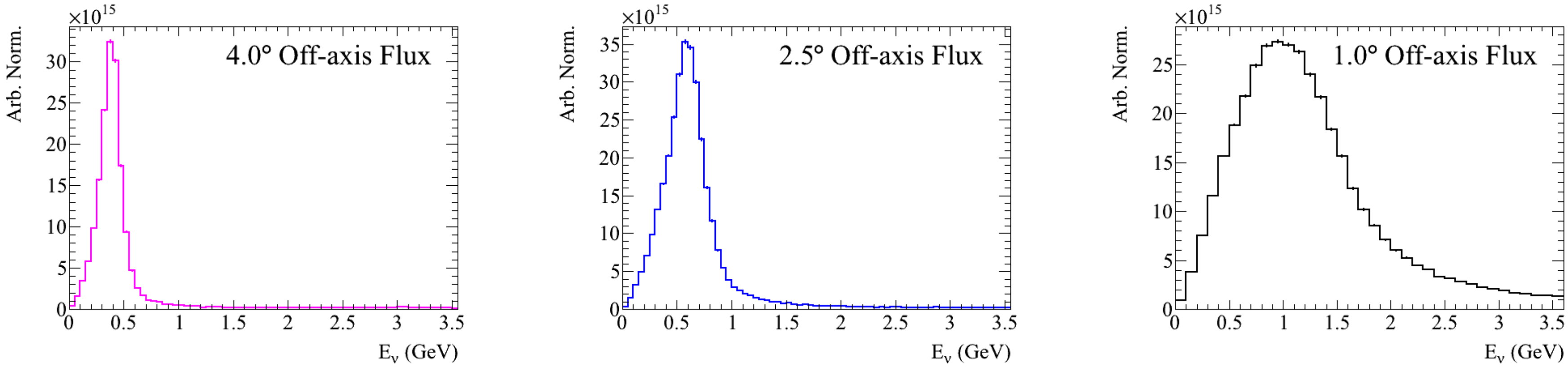
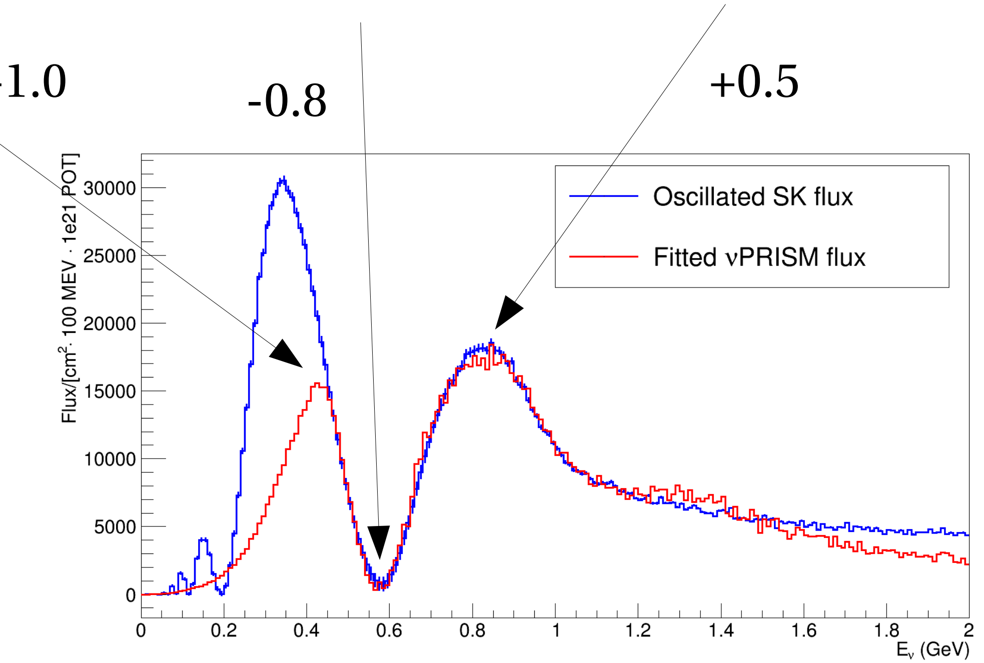


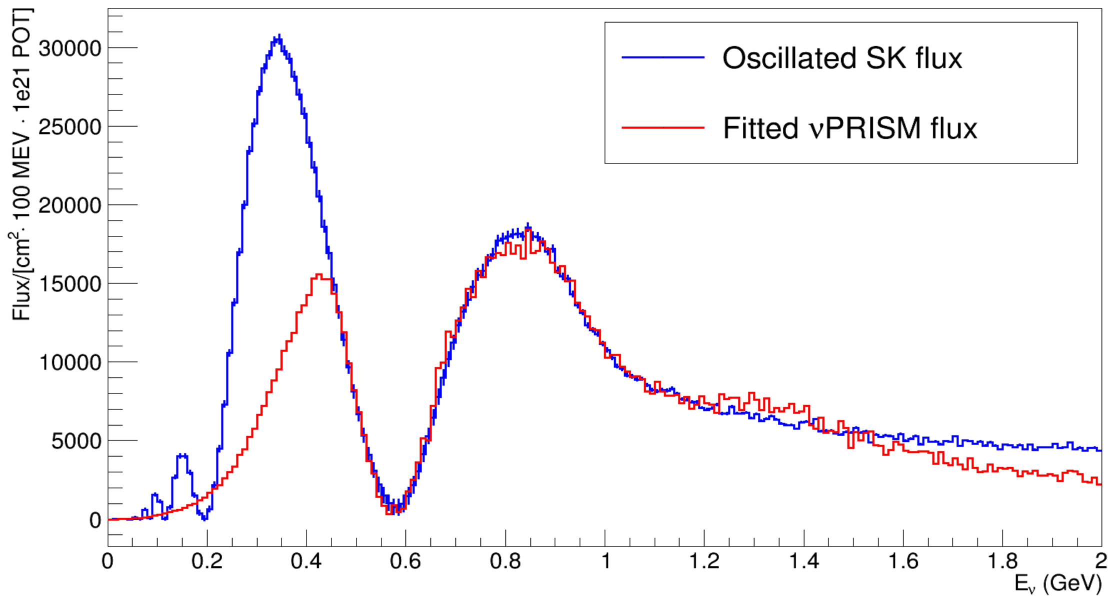


Similarly, a combination of fluxes can be used to recreate the far detector flux

nuPRISM LOI. arXiv:1412.3086.

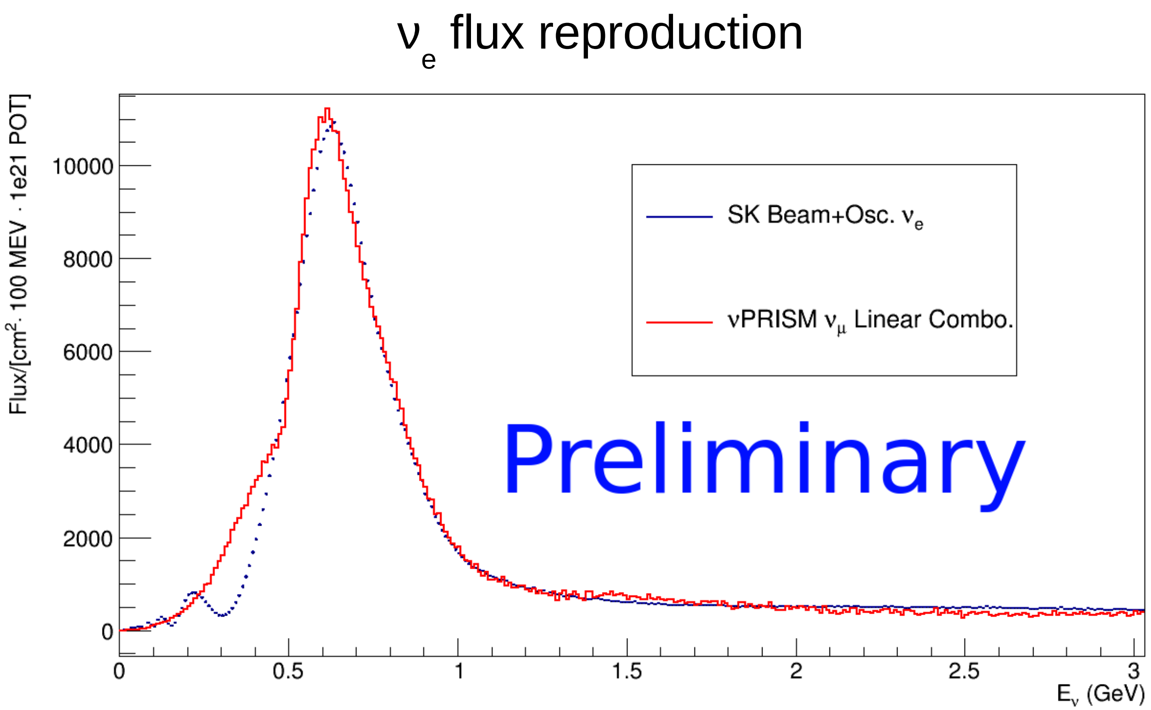
νPRISM: Advantages

- Can reproduce the oscillated far detector flux at near detector
- Allows for neutrino oscillation measurements without neutrino interaction models
  - Removing potential bias and systematic uncertainties



nuPRISM LOI. arXiv:1412.3086.

νPRISM: Additional fluxes



The same construction can be done for ν_e and antineutrino fluxes

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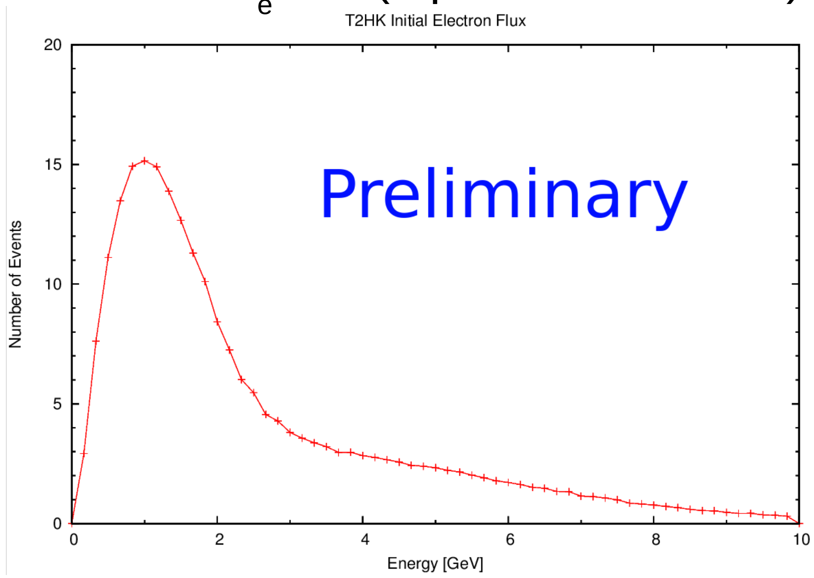
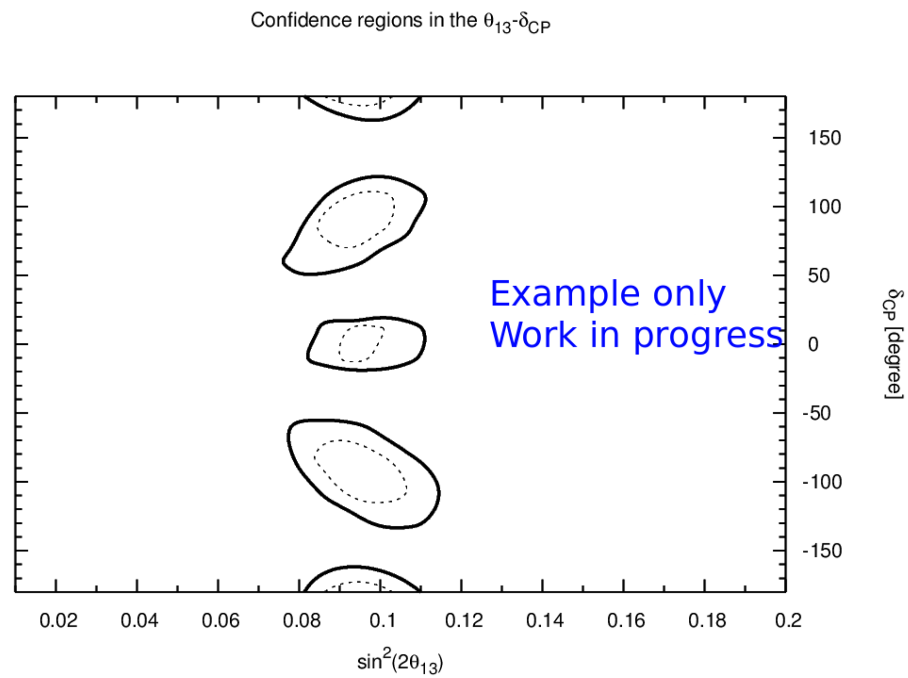
Evaluate the benefits of a νPRISM detector for the T2HK experiment, δ_{CP} measurement

- Uses T2K beamline
- Using GLoBES software package

(www.mpi-hd.mpg.de/lin/globes/)

νPRISM ν_e flux (Input into GLoBES)





Summary

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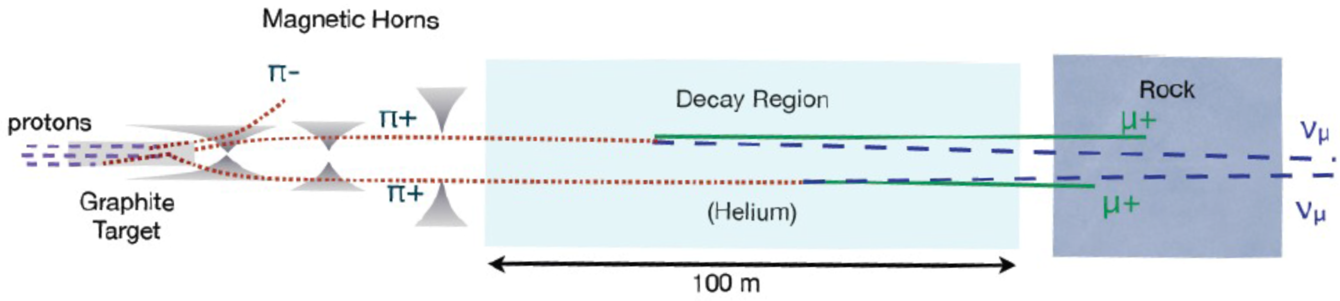
- Entering the era of precision measurements in neutrino oscillation experiments
- νPRISM is a data-driven way to remove uncertainties that arise from neutrino-nucleon interaction models
- Simulations continue to determine the effect on δ_{CP} measurements

Backup Slides

Case study: T2K

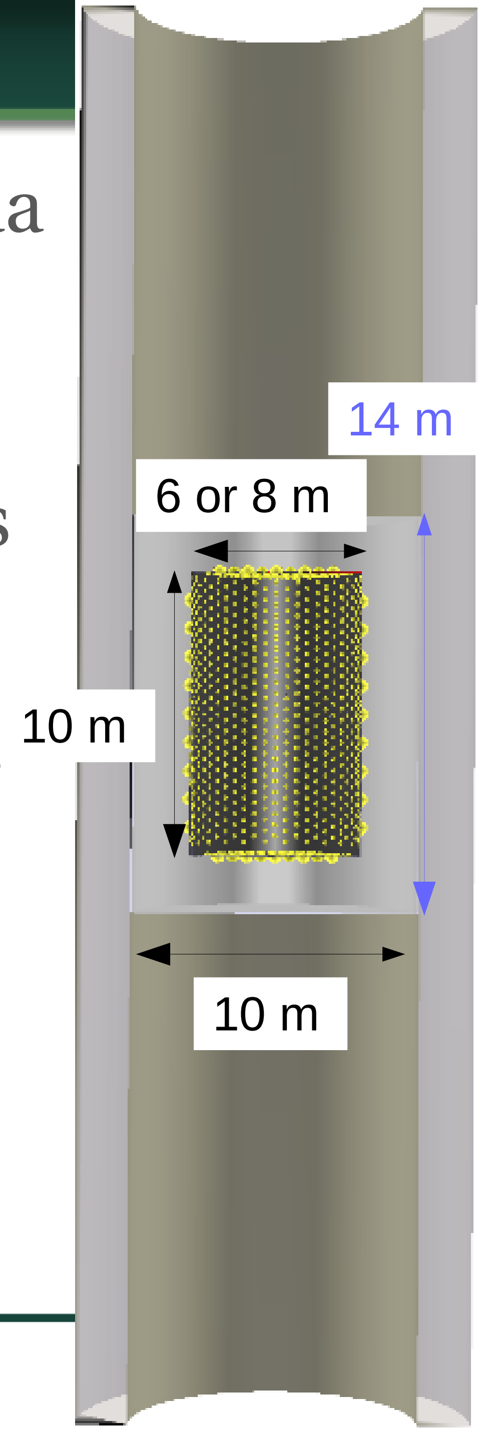
Neutrinos are produced from a proton beam at J-PARC, Tokai, Japan



1. Protons hit a target, producing pions and kaons, which decay into neutrinos
2. The beam is >99% ν_μ, small amount of ν_e
3. Switching the horn current produces predominant antineutrino beam (w/ ~10% neutrino)

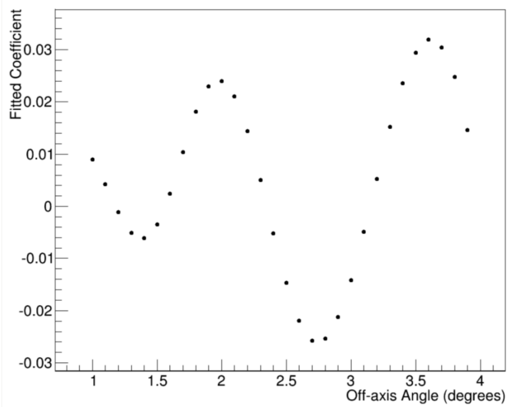
Proposed detector

- At 1km, need 50m tall tank to span oaa range
- Water Cherenkov detector
  - Directly measure NC backgrounds
- Baseline design:
  - Inner Detector (ID): 6 or 8m diam, 10m tall
  - Outer Detector (OD): 10m diam, 14m tall
- To improve incoming muons, OD surrounded by scintillator panels



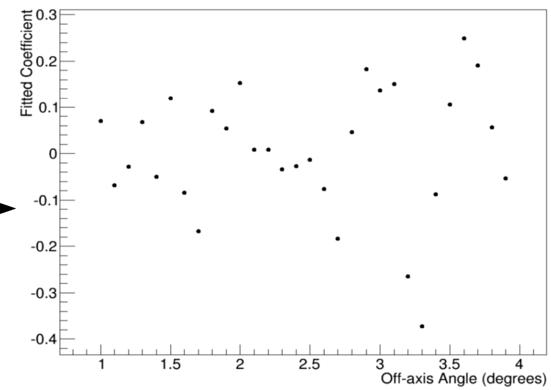
Coefficients

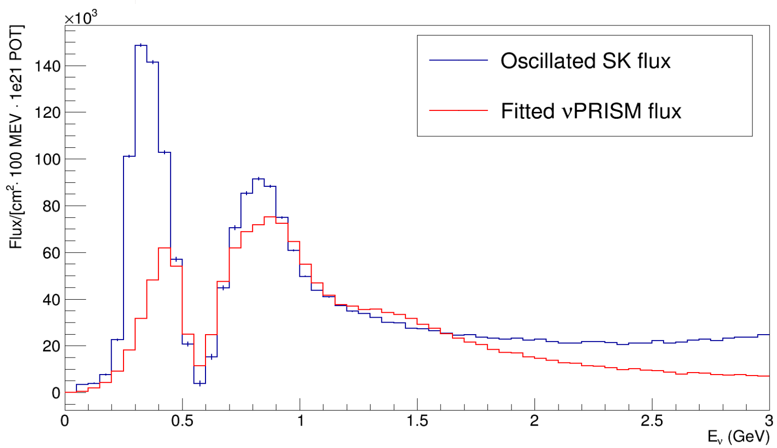
- Take each oaa flux and scale according to SK oscillated flux for best χ^2 fit
- Includes a smoothness penalty

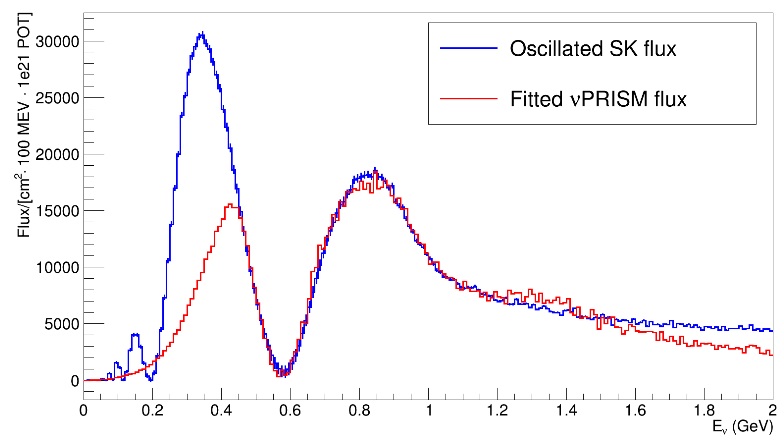


Forced smoothness

Free fit

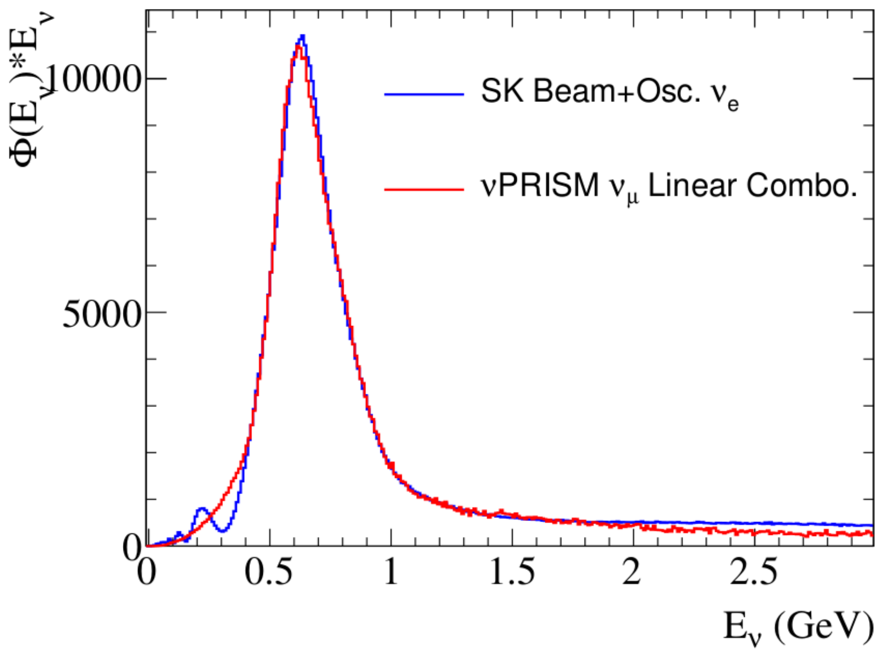


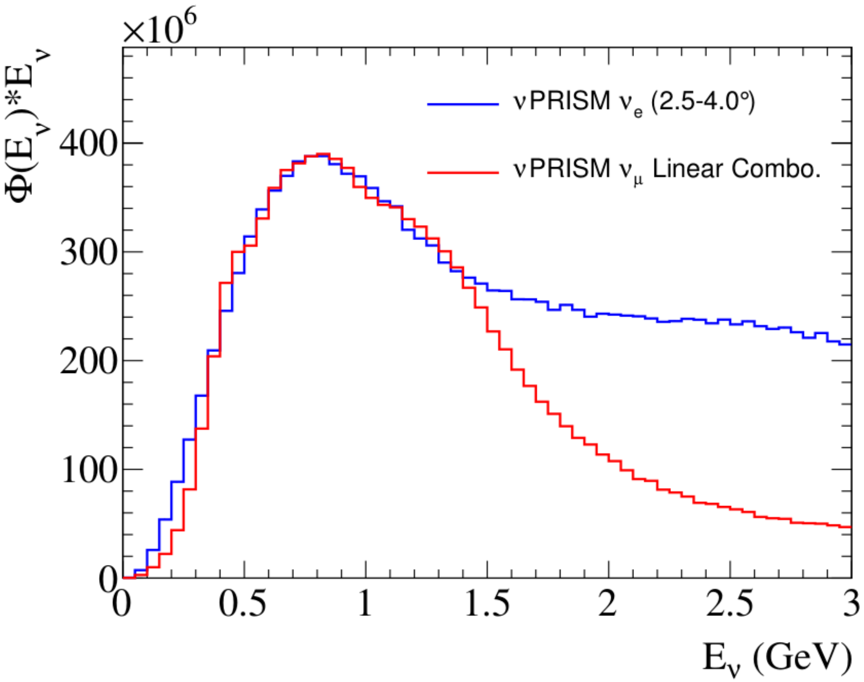




νPRISM ν_e appearance

1. Measure SK ν_e response with νPRISM ν_μ
2. Measure νPRISM ν_e response with νPRISM ν_μ
   - Need large mass ND to make a few percent measurement of $\sigma(\nu_\mu)/\sigma(\nu_e)$





νPRISM: Antineutrinos

- J-PARC can switch between ν-mode and anti-ν-mode by switching the beam focus
- Anti-ν-mode analysis same as for neutrinos
  - Need to consider much larger ν contamination
- Standard νPRISM oscillation analyses can be applied to anti-neutrinos