HADRON PRODUCTION NEEDS FOR THE E61 EXPERIMENT

Mark Hartz
Kavli IPMU, the University of Tokyo & TRIUMF
for the E61 Collaboration

LONG BASELINE NEUTRINOS IN JAPAN

Phys.Rev.Lett. 112 (2014) 061802

Muon (anti)neutrino survival:

$$P_{\mu\to\mu}=1-\left(\sin^2 2\theta_{23}-\sin^2\theta_{23}\cos 2\theta_{23}\sin^2 2\theta_{13}\right)\sin^2\left(\frac{\Delta m^2_{32}L}{4E_\nu}\right)+\ldots$$

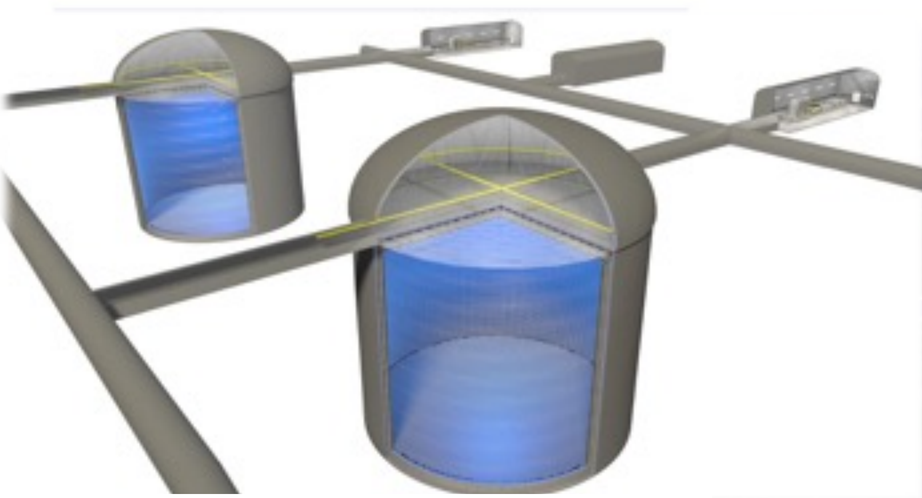
Generate beam of 99% muon (anti)neutrinos

Electron (anti)neutrino appearance:

$$P_{\mu\to e}=\sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)\mp\frac{\sin 2\theta_{12}\sin 2\theta_{23}}{2\sin\theta_{13}}\sin^2 2\theta_{13}\sin\left(\frac{\Delta m^2_{21}L}{4E_\nu}\right)\sin^2\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)\sin\delta_{CP}+\ldots$$

sign flips for antineutrinos = potential CP violation

LONG BASELINE NEUTRINOS IN JAPAN



Hyper-Kamiokande

Phys.Rev.Lett. 112 (2014) 061802

Muon (anti)neutrino survival:

$$P_{\mu\to\mu} = 1 - \left(\boxed{\sin^2 2\theta_{23}} - \sin^2\theta_{23}\cos 2\theta_{23}\sin^2 2\theta_{13}\right)\sin^2\left(\frac{\boxed{\Delta m^2_{32}}L}{4E_\nu}\right) + \ldots$$

Generate beam of 99% muon (anti)neutrinos

Electron (anti)neutrino appearance:

$$P_{\mu\to e} = \boxed{\sin^2\theta_{23}\sin^2 2\theta_{13}}\sin^2\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right) \boxed{\mp} \frac{\sin 2\theta_{12}\sin 2\theta_{23}}{2\sin\theta_{13}}\sin^2 2\theta_{13}\sin\left(\frac{\Delta m^2_{21}L}{4E_\nu}\right)\sin^2\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)\boxed{\sin\delta_{CP}} + \ldots$$

sign flips for antineutrinos = potential CP violation

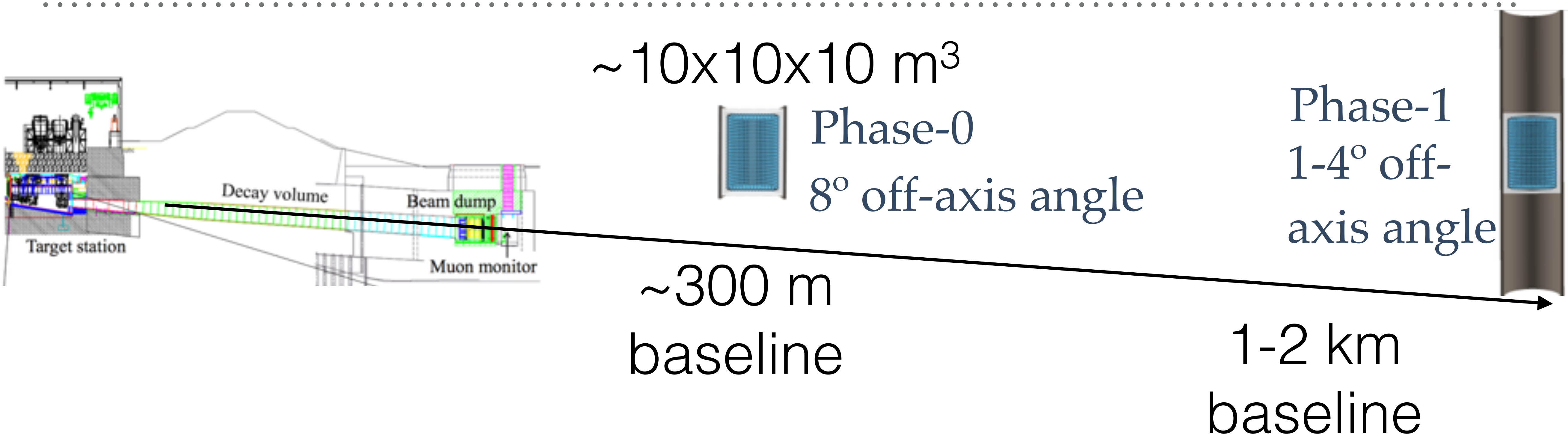
SYSTEMATIC ERRORS FOR T2K-II AND HYPER-K

Current T2K systematic errors

Systematic Error Type	1Re Neutrino Mode	1Re Antineutrino Mode
Far Detector Model	2.39%	3.09%
Final State/Secondary Interactions	2.50%	2.46%
Extrapolation from Near Detector	2.88%	3.22%
ν_e(bar)/ν_μ(bar)	2.65%	1.50%
NC1γ	1.44%	2.95%
Other	0.16%	0.33%
Total	5.42%	6.09%

- *Current T2K systematic errors are at the ~6% level*
- *Need reduction to <5% for T2K-II and <3% for Hyper-K*
- *Need to avoid "unknown unknowns" particularly in cross section modeling*
  - ***Modeling neutrino-nucleus scattering at ~1 GeV is a challenging nuclear physics problem!***

THE E61 EXPERIMENT

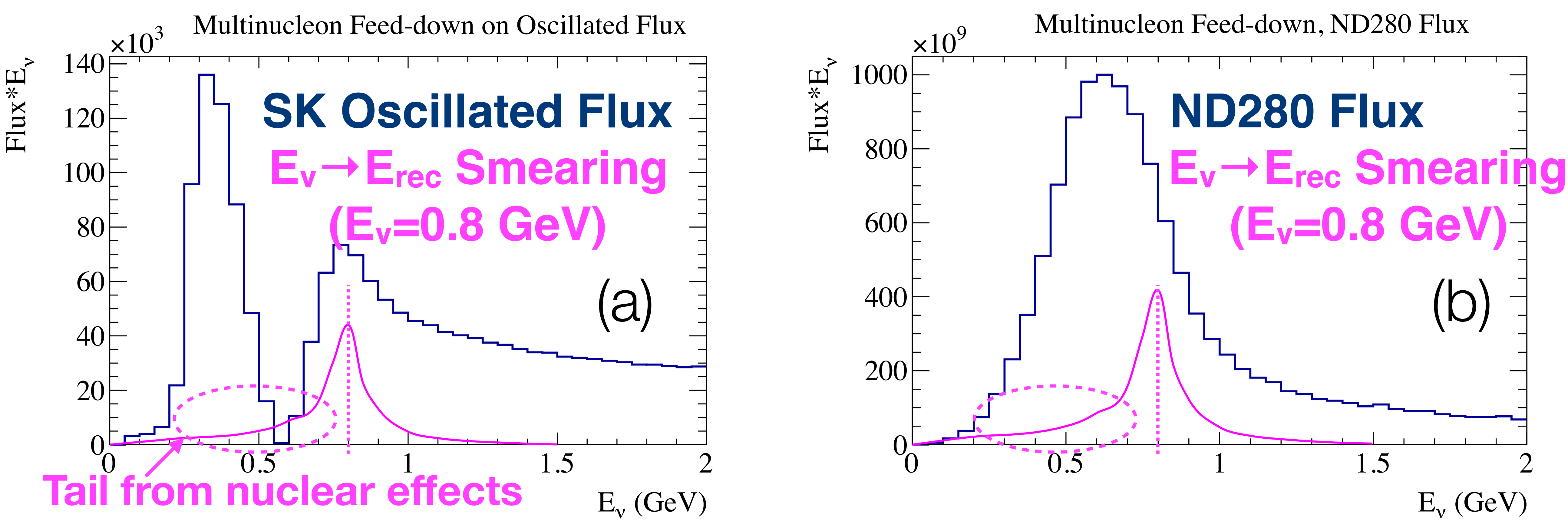


- ***E61*** *- proposed kiloton scale water Cherenkov detector where position can be moved to make measurements at different off-axis angles*
  - *Address critical neutrino-nucleus scattering uncertainties for T2K & Hyper-K*
- *Staged approach*
  - *Phase-0: stationary detector near existing T2K near detectors*
  - *Phase-1: detector at ~1 km from neutrino source, movable to 1-4° off-axis*
- *Have received stage 1 approval from the J-PARC PAC*
- *Recent merger of NuPRISM and TITUS collaboration to form single E61 collab.*

E61 PHYSICS

- *E61 will make measurements of critical neutrino-nucleus interaction processes for T2K and Hyper-K*
- *Measurements on water with sample angular acceptance as far detector*
- *4 key items for the future program:*
  - *Probing energy dependence of neutrino interactions through measurements at different off-axis angles*
  - *Measuring the* $\sigma(\nu_e)/\sigma(\nu_\mu)$ *and* $\sigma(\overline{\nu_e})/\sigma(\overline{\nu_\mu})$ *cross section ratios*
  - *Loading with Gd to study neutron production in neutrino nucleus scattering*
  - *Measurement of intrinsic neutral current and electron (anti)neutrino backgrounds for the long baseline program*

MOTIVATION: ENERGY RECONSTRUCTION

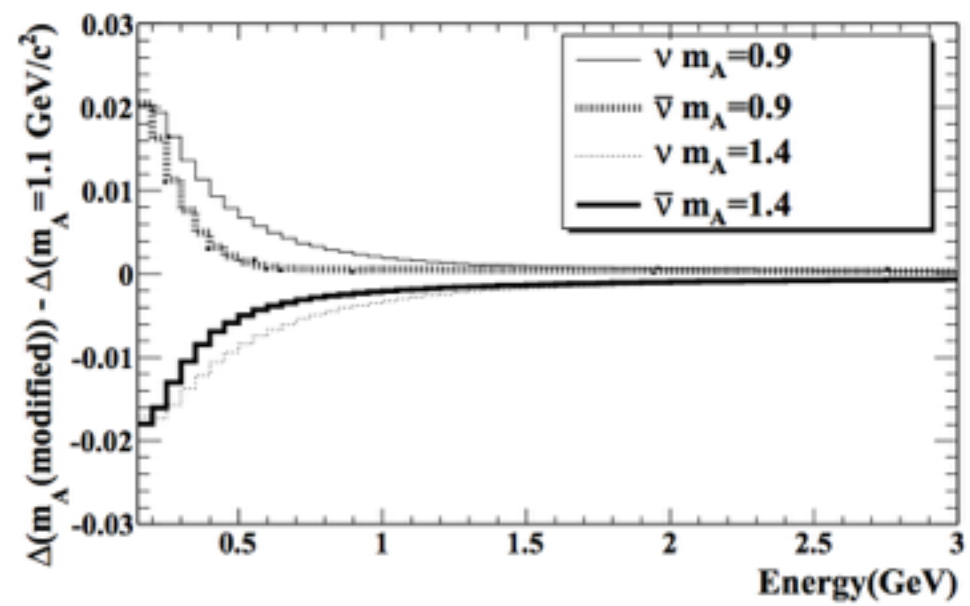


- *Observed spectra are smeared by nuclear effects - populate tails in particular*
- *Different fluxes in near and far detector*
  - *Impact of nuclear effects on the far detector observed spectrum cannot be directly measured in the near detector*

MOTIVATION: ELECTRON NEUTRINO CROSS SECTION

- *Observe mostly muon (anti)neutrino interactions in near detector*
- *CP violation is observed on electron (anti)neutrino interactions in far detector*
- *Sensitive to systematic errors on* $\sigma_{\nu_e}/\sigma_{\nu_\mu}, \sigma_{\bar{\nu}_e}/\sigma_{\bar{\nu}_\mu}$
- *Uncertainties can arise from:*
  - *Form factor uncertainties in cross section terms that depend on lepton mass*
  - *Phase nuclear effects combined with phase space differences due to mass*
  - *Radiative corrections (should be calculable)*

Phys.Rev. D86 (2012) 053003

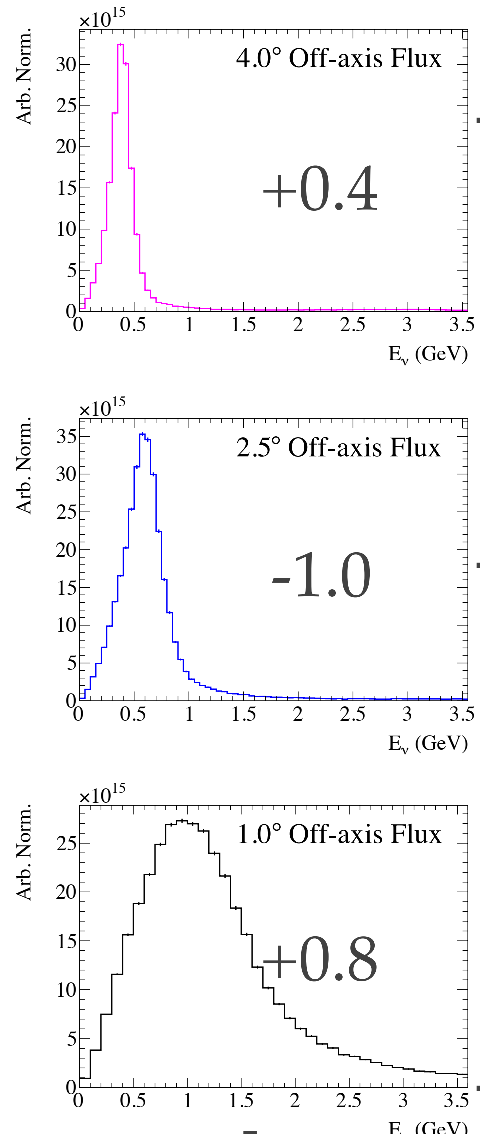


Uncertainty on relative cross section due to axial form factor uncertainty.

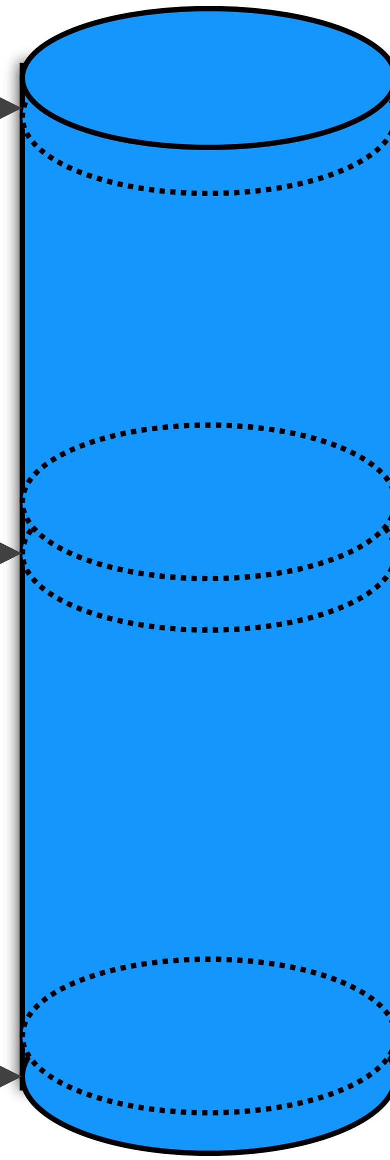
FLUX UNCERTAINTIES IN E61

- *As with all experiments probing neutrino interactions, E61 wants flux uncertainties that are as small as possible*
- *Here I will discussion flux uncertainties in two types of analyses:*
  - *Using off-axis dependence of flux to produce mono-energetic neutrino spectra*
  - *Measuring the $\sigma(\nu_e)/\sigma(\nu_\mu)$ in Phase-0 of the E61 experiment*
- *Caveat - all studies here use the T2K flux model based on tuning of hadronic interactions using NA61/SHINE **thin** target data*
  - *Expect reduction of errors with tuning based on replica target data*

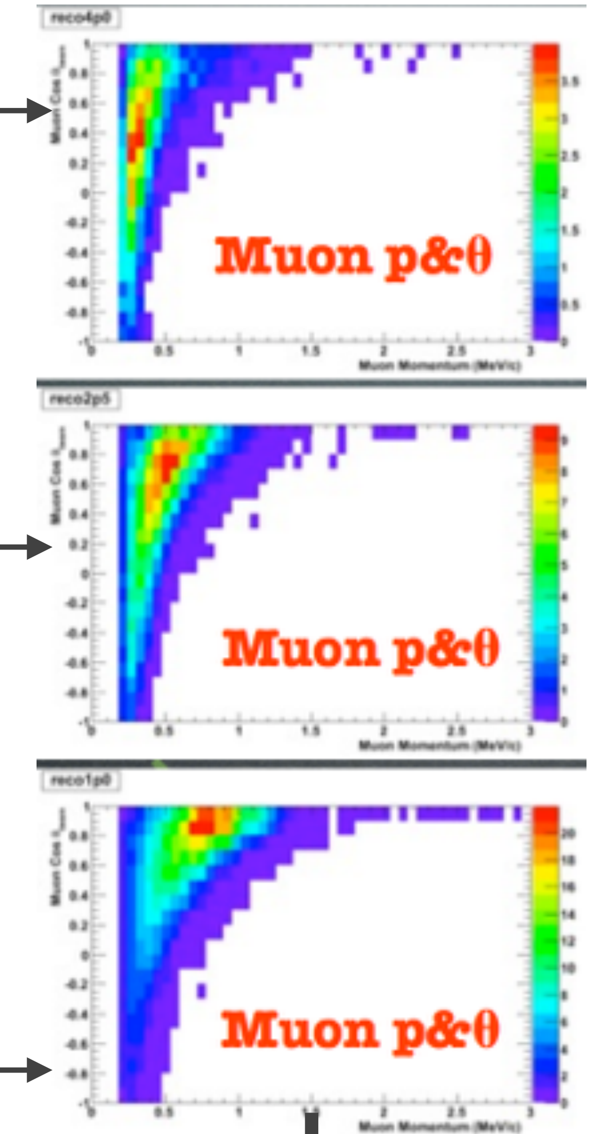
ADVANTAGE OF MULTIPLE OFF-AXIS ANGLE MEASUREMENTS

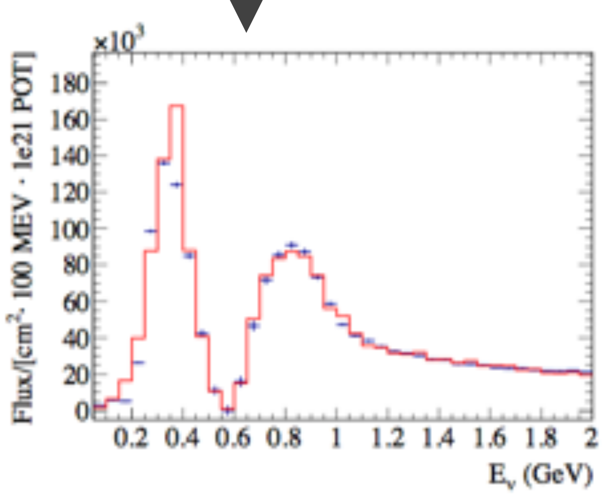


Spectra at at each off-axis bin

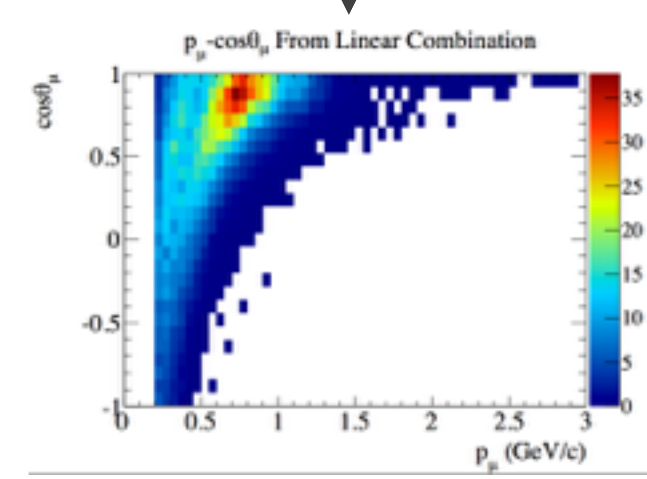


Observed muon kinematic distributions

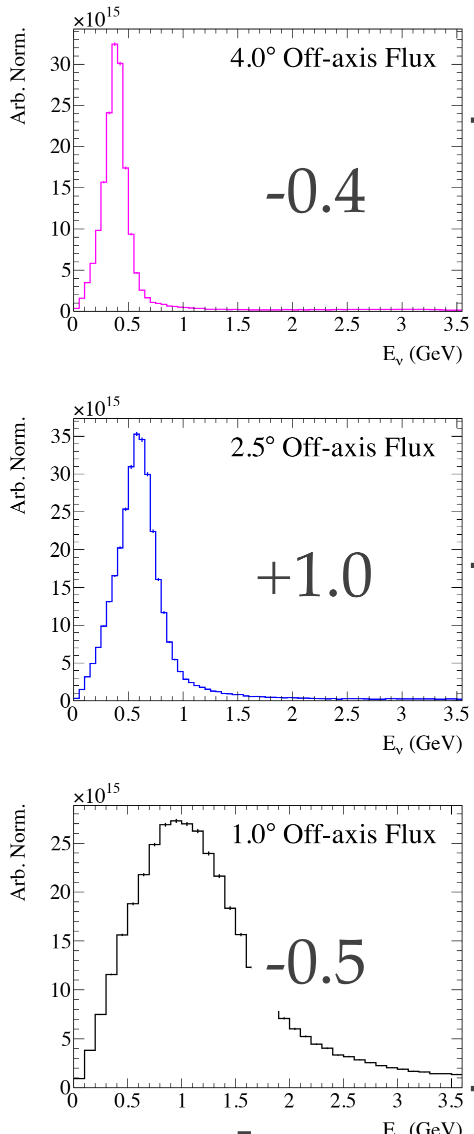




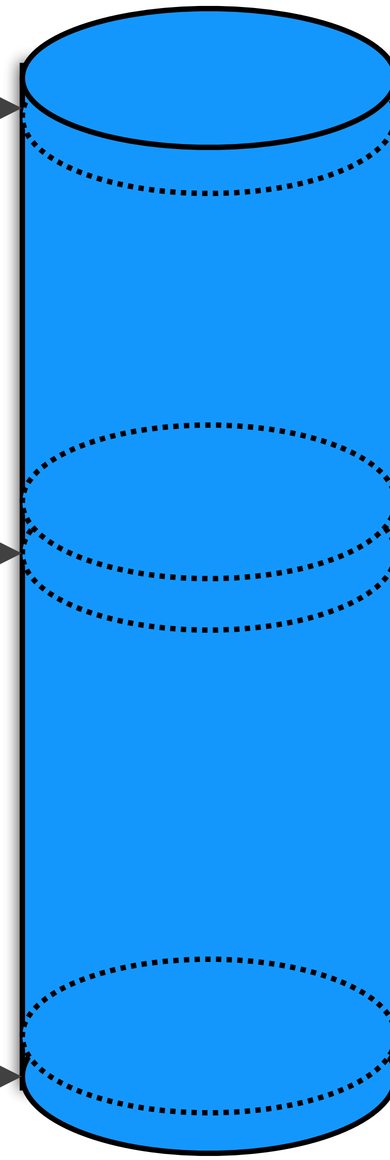
Linear combinations reproduce the oscillated flux, and predict muon kinematic distributions for the oscillated flux



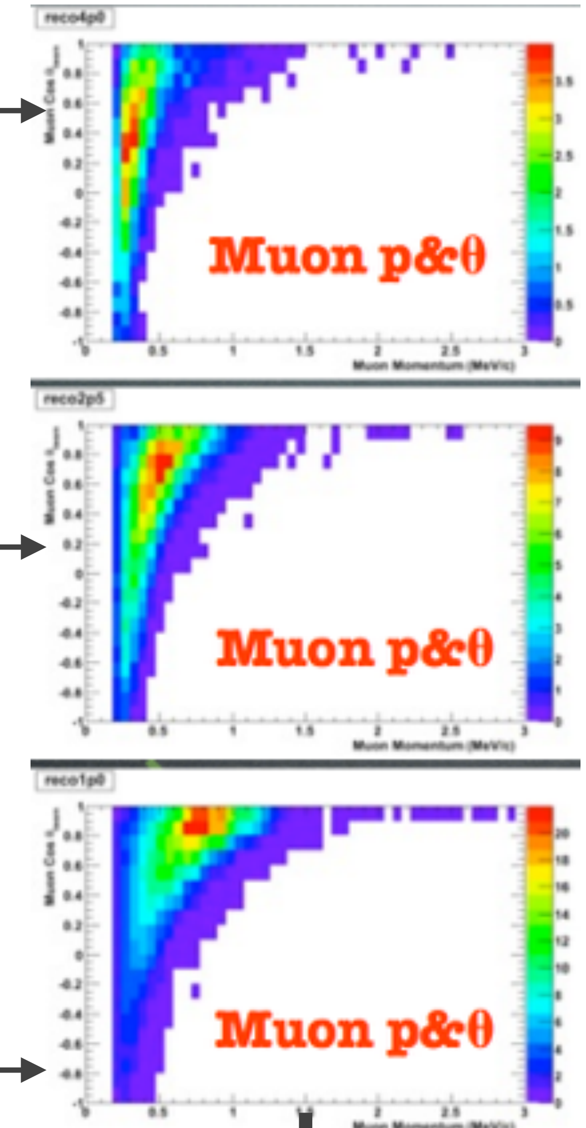
ADVANTAGE OF MULTIPLE OFF-AXIS ANGLE MEASUREMENTS

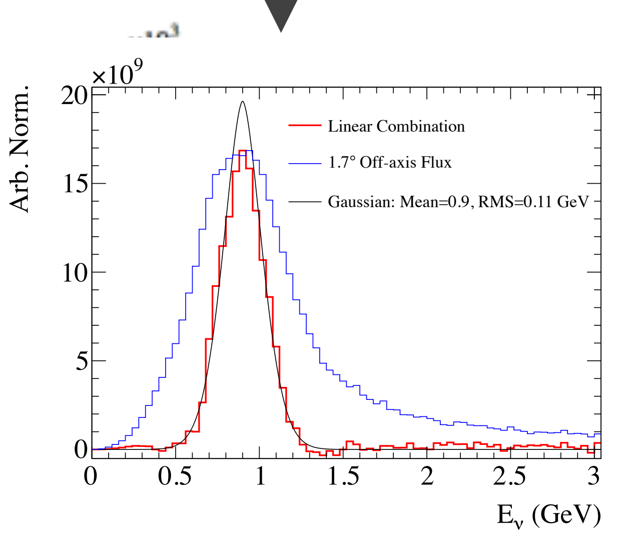


Spectra at at each off-axis bin

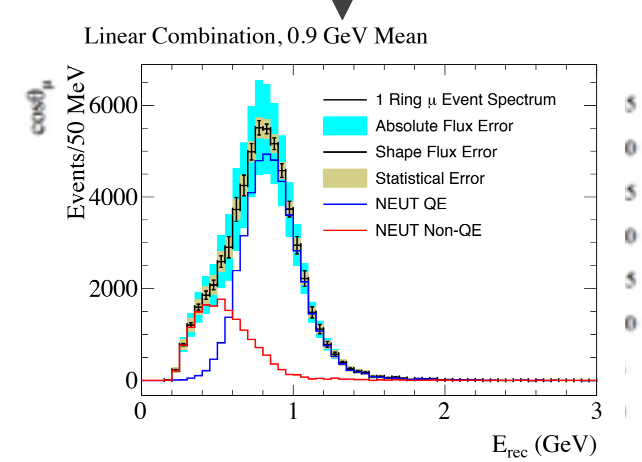


Observed muon kinematic distributions

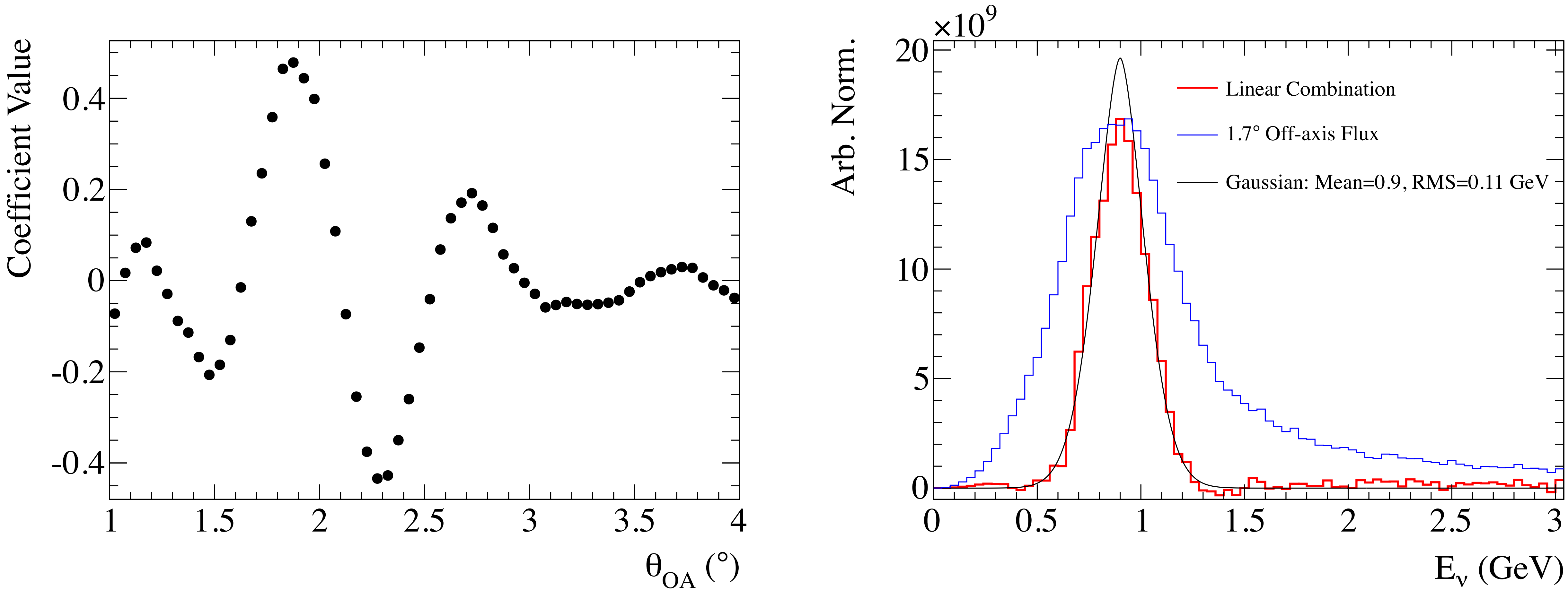




Linear combinations reproduce the oscillated flux, and predict muon kinematic distributions for the oscillated flux

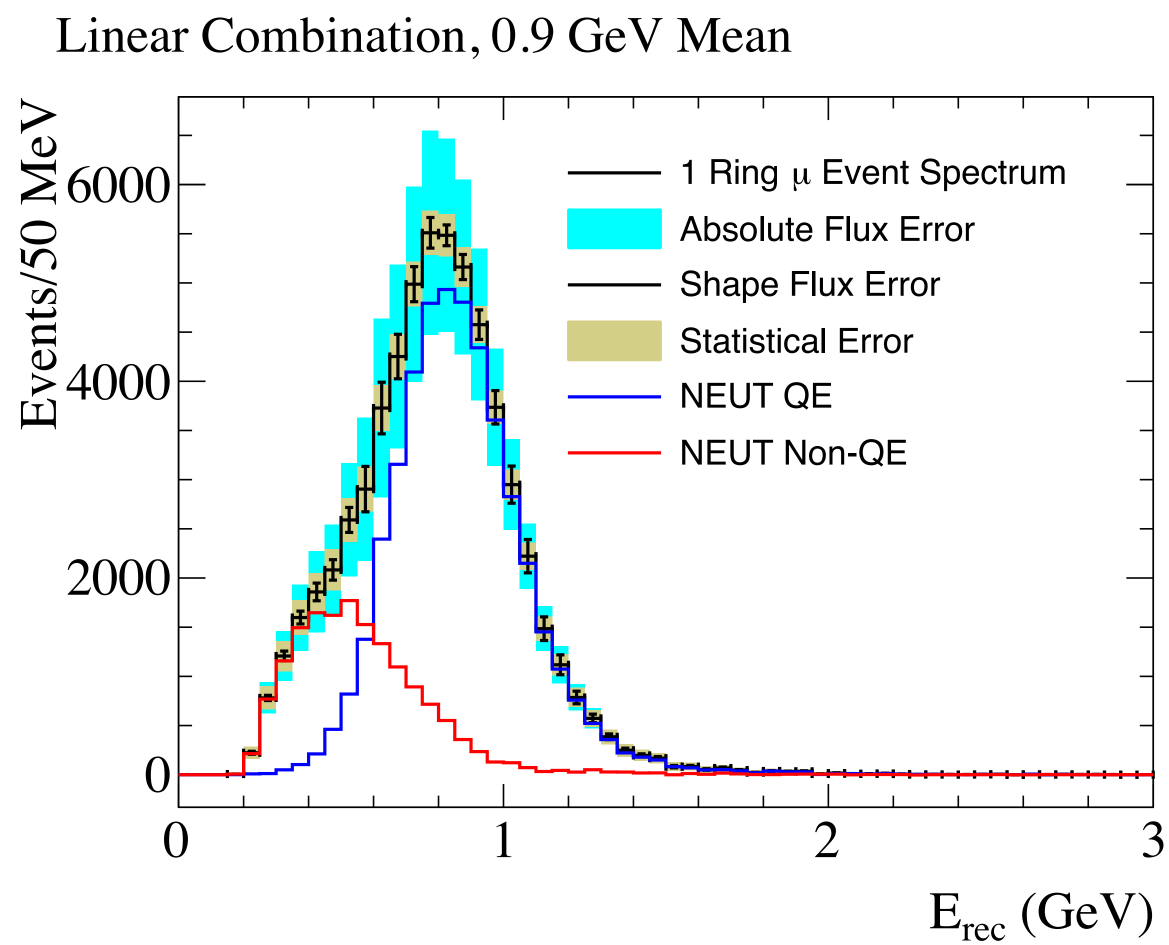


LINEAR COMBINATION FOR MONO-ENERGETIC BEAM



- *Using prior knowledge of flux model from hadron production data, find coefficients (left) as function of off-axis angle*
- *Adding off-axis fluxes with coefficients gives narrow spectrum (red on the right)*
- *To extract the correct coefficients, we need a precise prior flux model*

UNCERTAINTY FOR MONO-ENERGETIC ANALYSIS

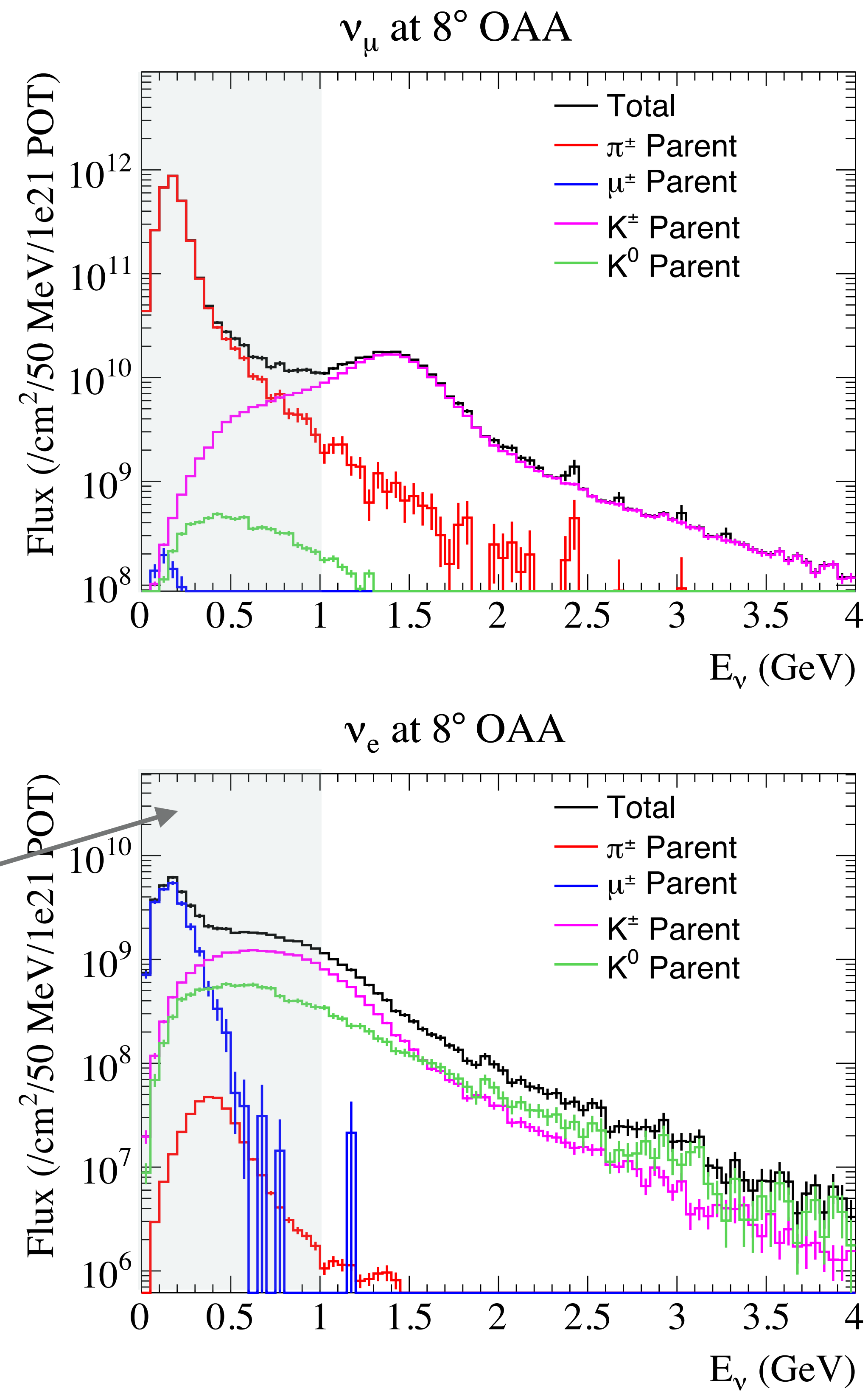


- *Simulate the reconstructed spectrum produced with linear coefficients from previous slide*
- *Propagate current T2K flux uncertainties*
- *Normalization error is ~20% (inflated from ~10% by linear combination analysis)*
  - *Shape error is small (black error bars)*
- *Main goal of this analysis is to measure shape effects, but we can also benefit from reduced flux errors to constrain the normalization uncertainty*

ELECTRON NEUTRINO CROSS SECTION IN PHASE-0

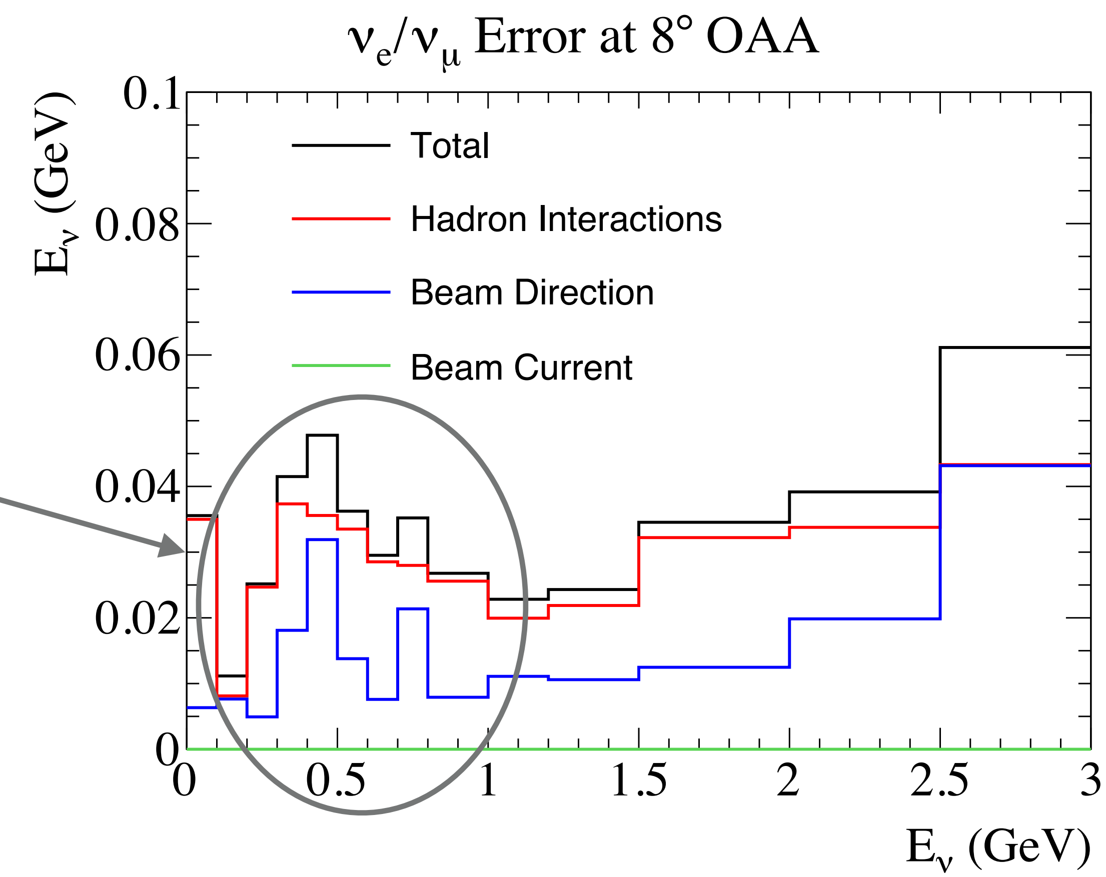
- *In phase-0, the baseline detector location is at 8° off-axis*
- *Being further off-axis increases the fraction of ν_e in the beam (produced in 3 body decay vs. 2 body decay for ν_μ)*
- *Here we will measure the ratio $\sigma(\nu_e)/\sigma(\nu_\mu)$*
- *Depends on how well we know the flux ratio $\Phi(\nu_e)/\Phi(\nu_\mu)$*

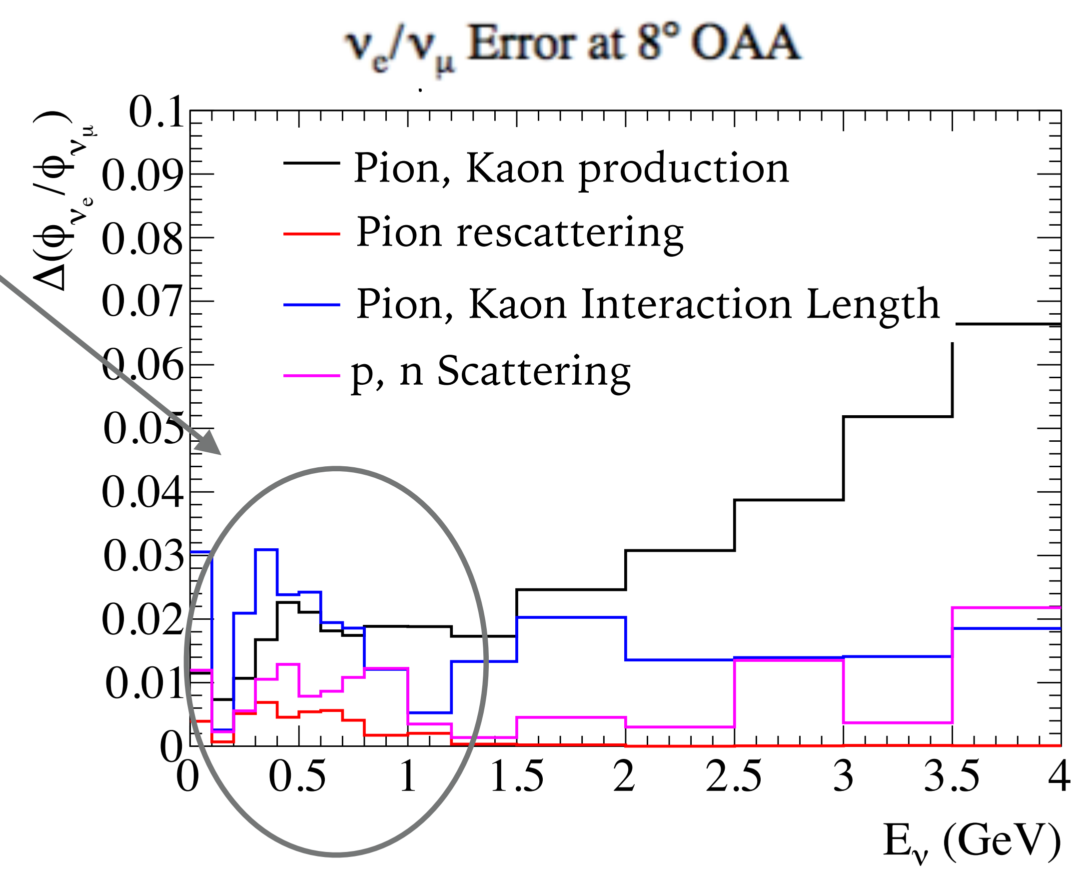
Sub-GeV energy range is of particular interest.



FLUX RATIO UNCERTAINTY

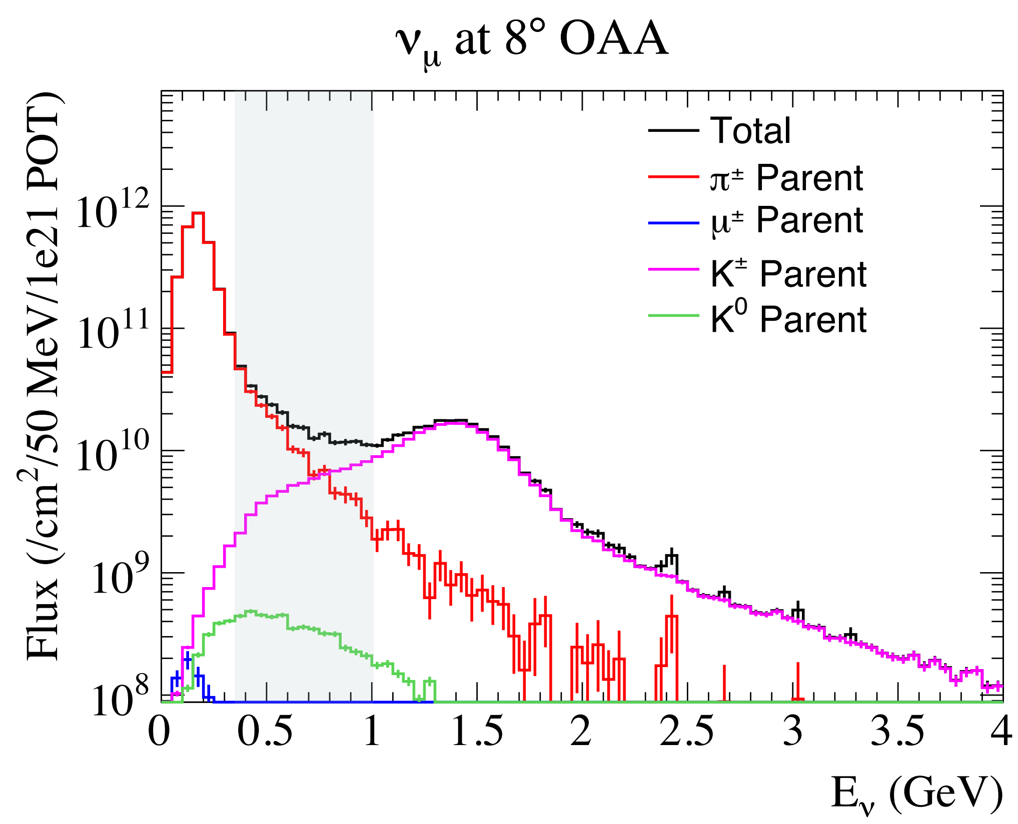
- *Hadron interaction uncertainties are dominant in the 0.2-1.0 GeV range for the flux ratio*
- *Largest error sources:*
  - *Pion and kaon interaction lengths*
  - *Pion and kaon production*

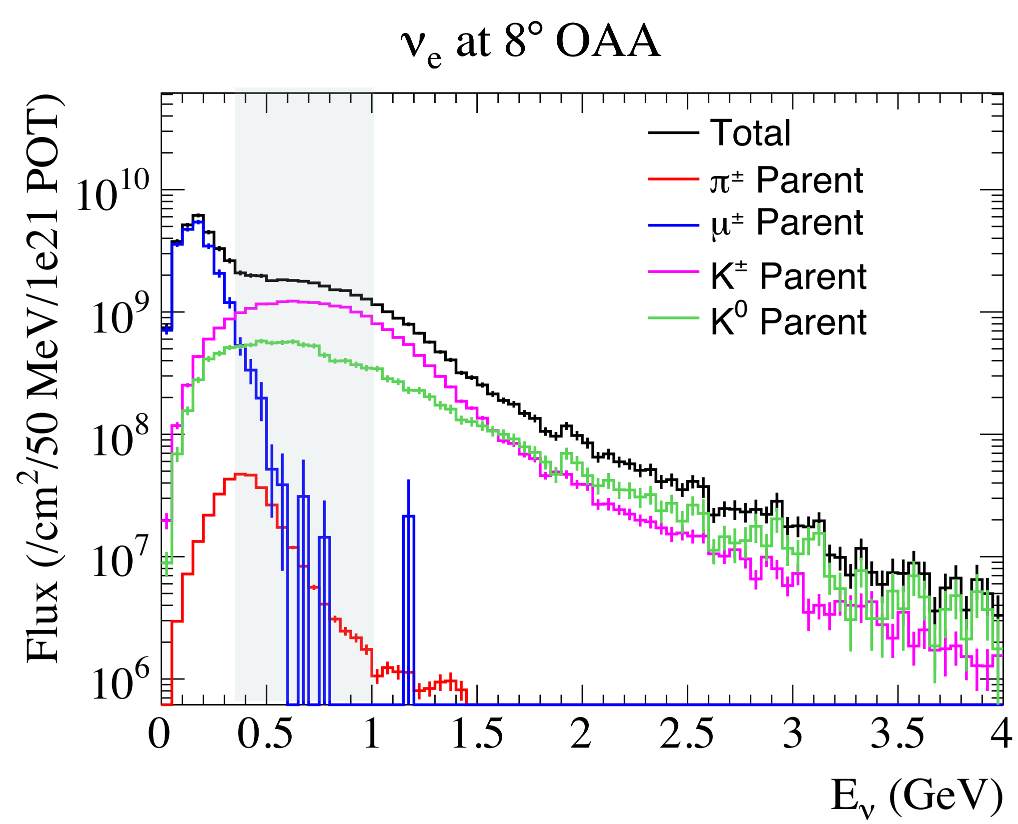




WHAT IS DRIVING THIS FLUX ERROR?

- *For electron neutrinos >0.35 GeV, the production through kaon decays becomes largest*
- *For muon neutrinos <0.7 GeV, production from pion decays is still dominant*
- *In this region, we are sensitive to uncertainties on the relative production and absorption rates of pions and kaons*
  - *Could benefit from reduced uncertainties on the relative rates*

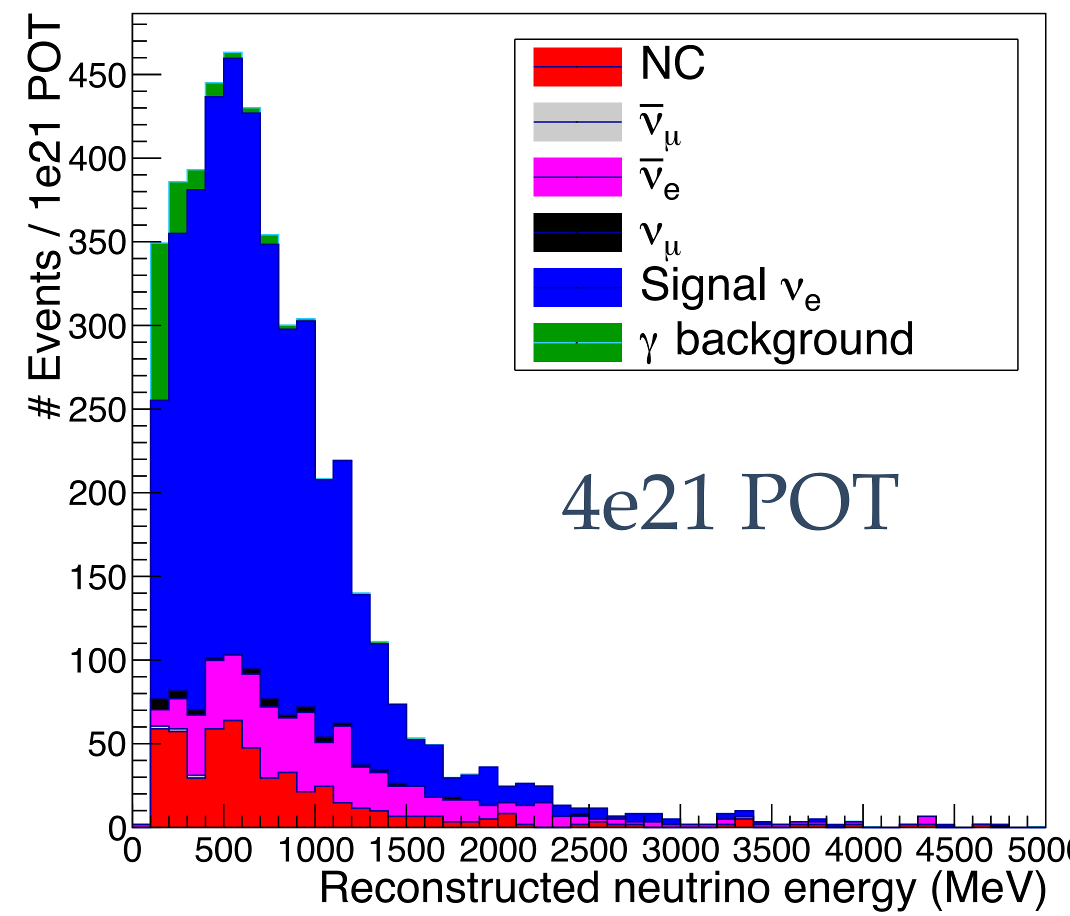




CROSS SECTION ANALYSIS RESULTS

- *We have studied the $\sigma(\nu_e)/\sigma(\nu_\mu)$ measurement using a full simulation and event reconstruction for Phase-0*
- *Includes backgrounds from interactions in the surrounding sand and detector*
- *A pure, high statistics sample of electron neutrino candidates can be selected*

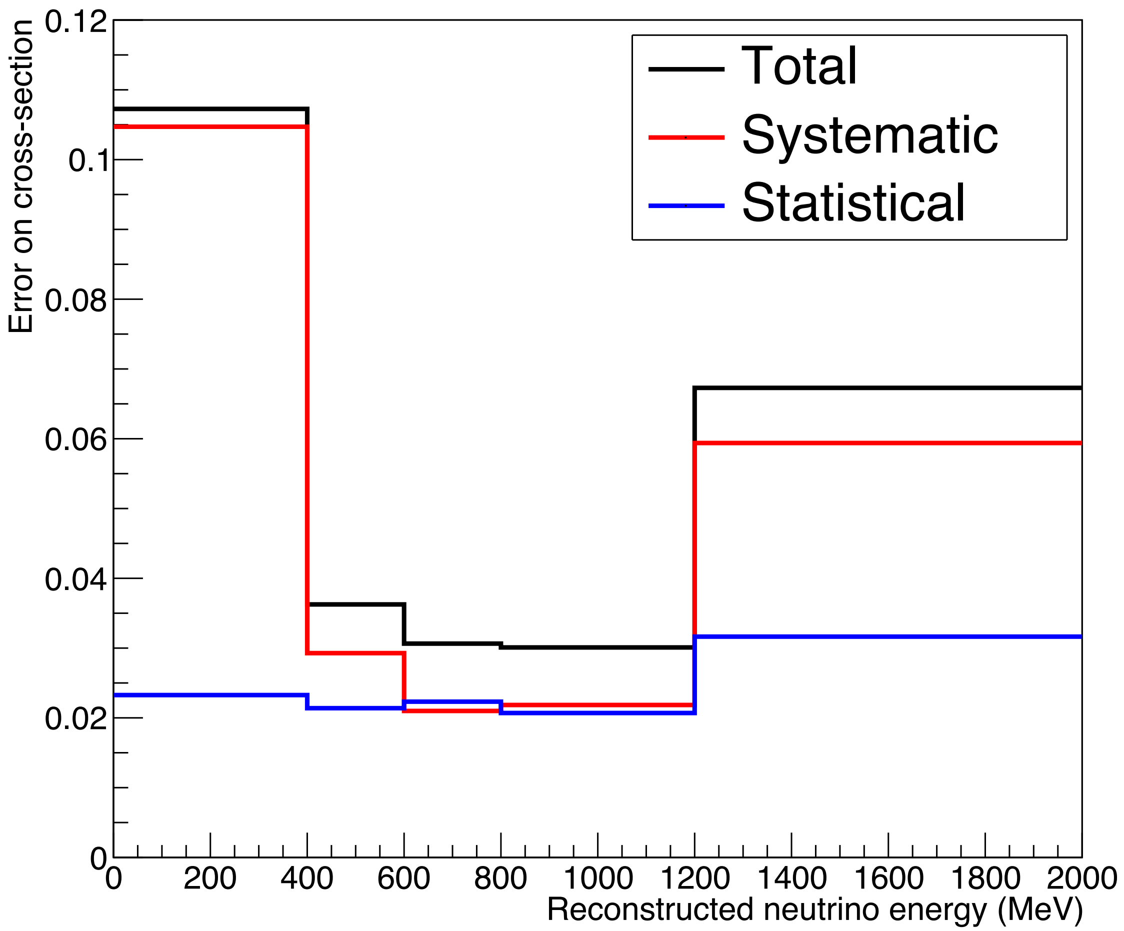
8 degrees off-axis



	Signal	$NC\pi^0$	$NC\gamma$	ν_μ-CC	Wrong Sign	Entering γ	Total	Purity
8° OAA	9656	1384	172	124	1216	648	13204	73.1%
6° OAA	13068	2672	356	236	972	648	17956	73.8%

SYSTEMATIC ERRORS IN CROSS-SECTION MEASUREMENT

- *In this analysis, we have considered systematic errors from the flux and cross section modeling*
- *The errors are propagated in bins of reconstructed energy*
- *In the 400-1200 MeV range, the systematic error is 2-3%*
- *Dominant contribution coming from flux uncertainties*
  - *Can benefit from further reduction*

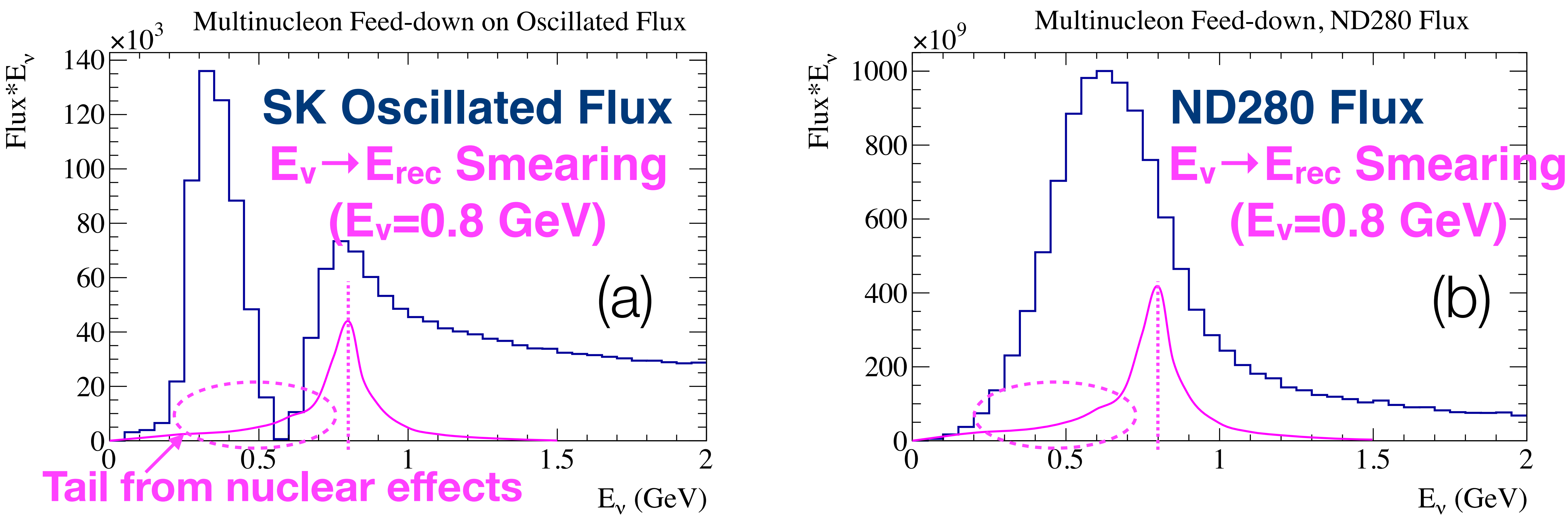


SUMMARY

- *E61 will make critical neutrino-nucleus scattering measurements for the T2K and Hyper-K physics programs*
- *Controlling flux modeling systematic errors is important for extracting the most precise neutrino scattering measurements*
- *I described two analyses where flux uncertainties are important, but they are important for all E61 analyses*
    - *Can benefit from an overall reduction in the flux uncertainties*
    - *Can benefit from the reduction of the relative uncertainties of pion and kaon production rates and interaction lengths*
- *All studies here were done hadron interaction tuning using NA61/SHINE thin target data*
    - *We should implement the replica target tuned flux and evaluate the key areas that need reduction*

EXTRA SLIDES

ENERGY RECONSTRUCTION



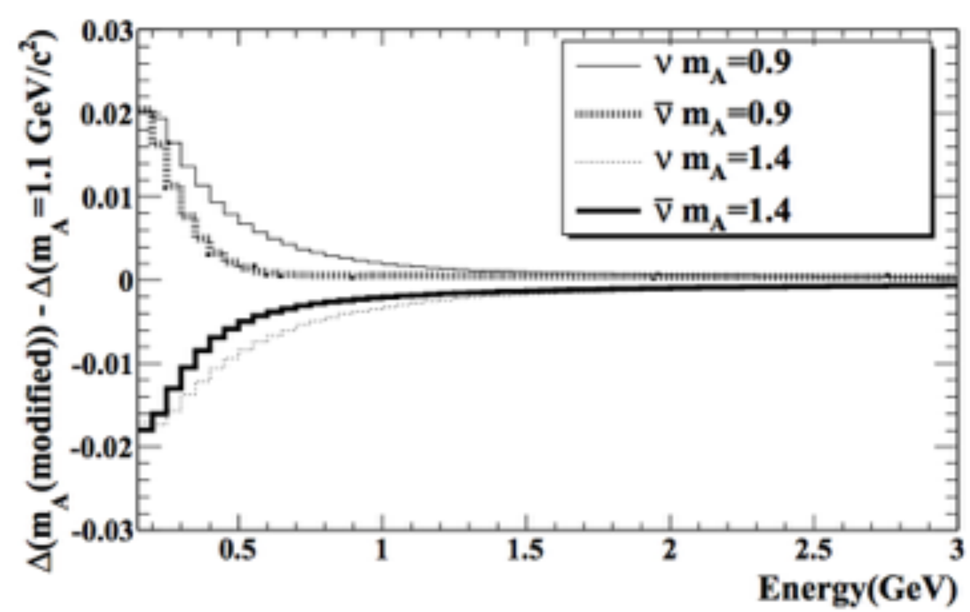
- ➤ *Observed spectra are smeared by nuclear effects - populate tails in particular*
- ➤ *Different fluxes in near and far detector*
  - ➤ *Impact of nuclear effects on the far detector observed spectrum cannot be directly measured in the near detector*

ELECTRON NEUTRINO CROSS SECTION

- *Observe mostly muon (anti)neutrino interactions in near detector*
- *CP violation is observed on electron (anti)neutrino interactions in far detector*
- *Sensitive to systematic errors on* $\sigma_{\nu_e}/\sigma_{\nu_\mu}, \sigma_{\overline{\nu}_e}/\sigma_{\overline{\nu}_\mu}$

- *Uncertainties can arise from:*
  - *Form factor uncertainties in cross section terms that depend on lepton mass*
  - *Phase nuclear effects combined with phase space differences due to mass*
  - *Radiative corrections (should be calculable)*

Phys.Rev. D86 (2012) 053003

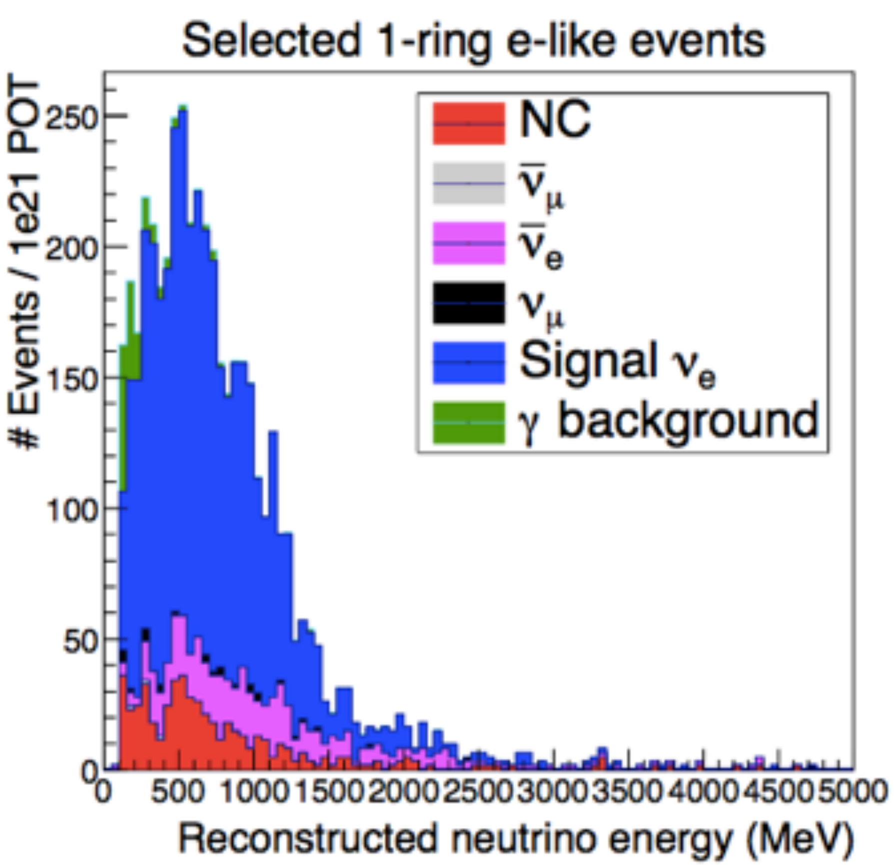


Uncertainty on relative cross section due to axial form factor uncertainty.

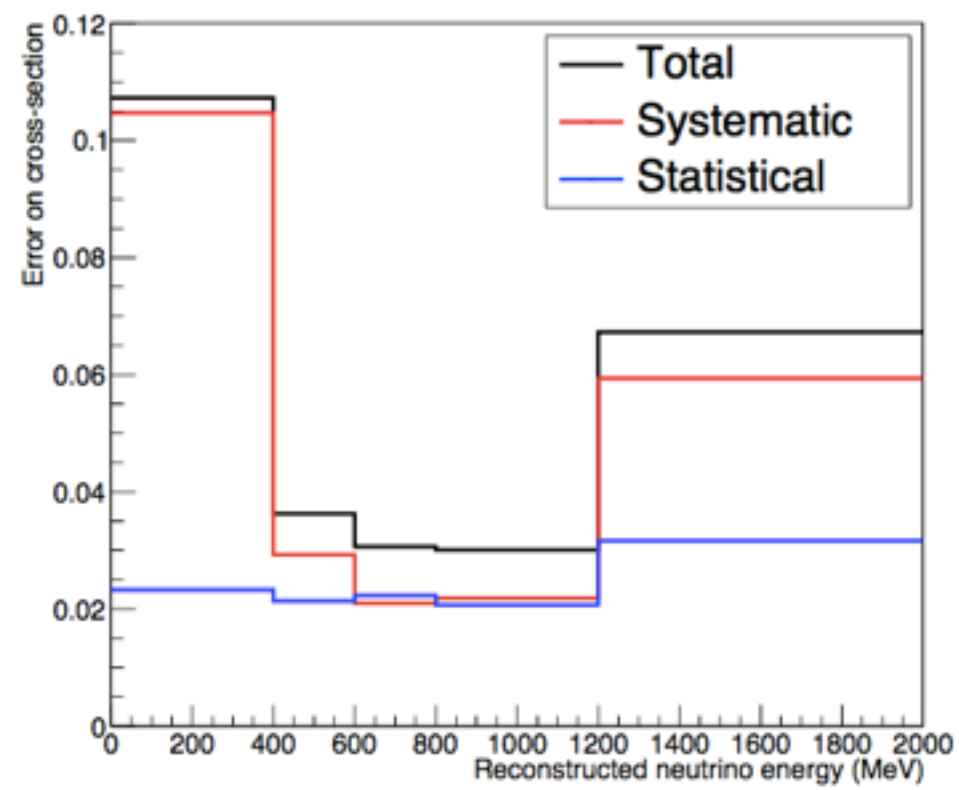
ELECTRON NEUTRINO CROSS SECTION MEASUREMENT

- *Beam contains contamination of electron (anti)neutrinos from muon and three-body kaon decays*
- *Fraction of ν_e increases further off-axis*
- *Phase-0: measurement of* $\sigma_{\nu_e}/\sigma_{\nu_\mu}$
- *Phase-1: measurement of* $\sigma_{\nu_e}/\sigma_{\nu_\mu}, \sigma_{\bar{\nu}_e}/\sigma_{\bar{\nu}_\mu}$

High purity ν_e in Phase-0

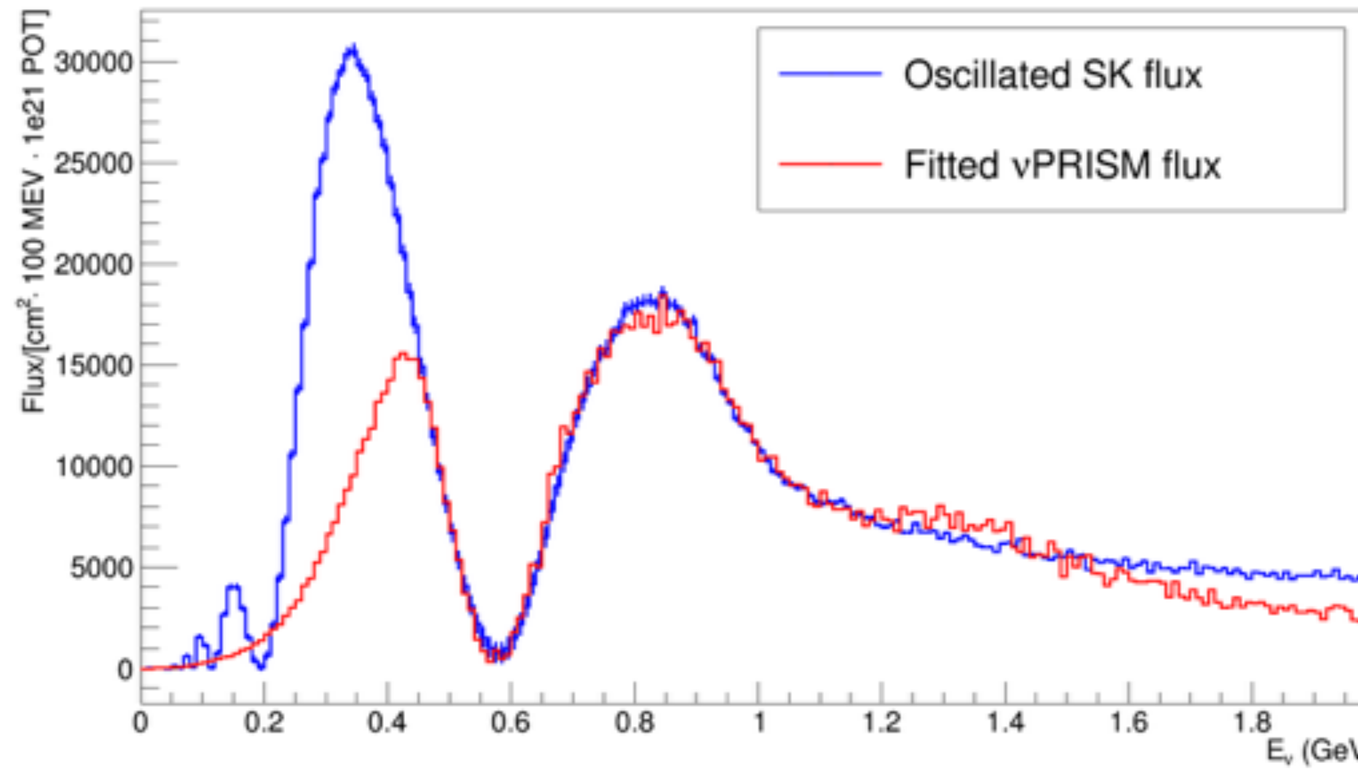


<3% systematic error on cross section ratio measurement between 400 MeV and 1200 MeV (region of interest)

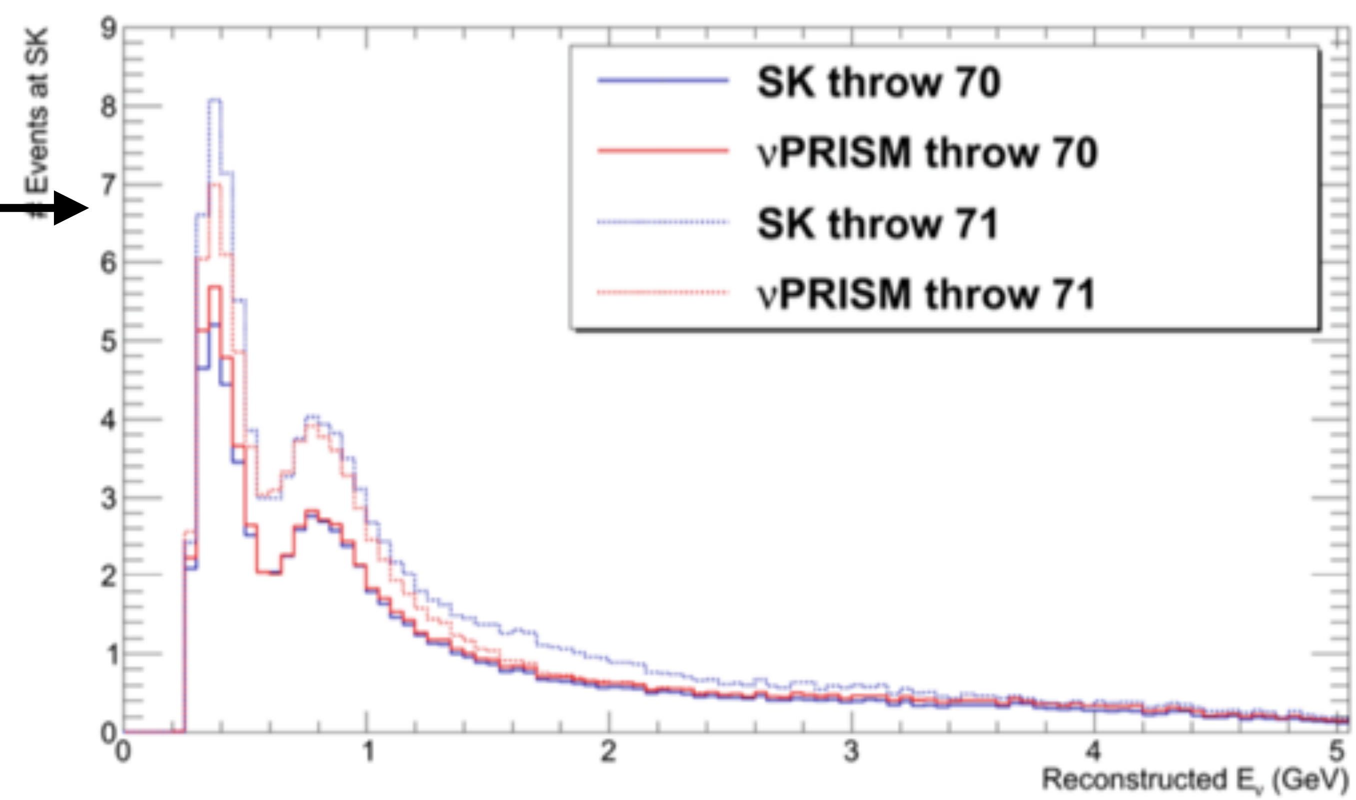


NUPRISM DISAPPEARANCE SPECTRUM

- Linear combination of off-axis fluxes reproduces the far detector spectrum with oscillation hypothesis applied

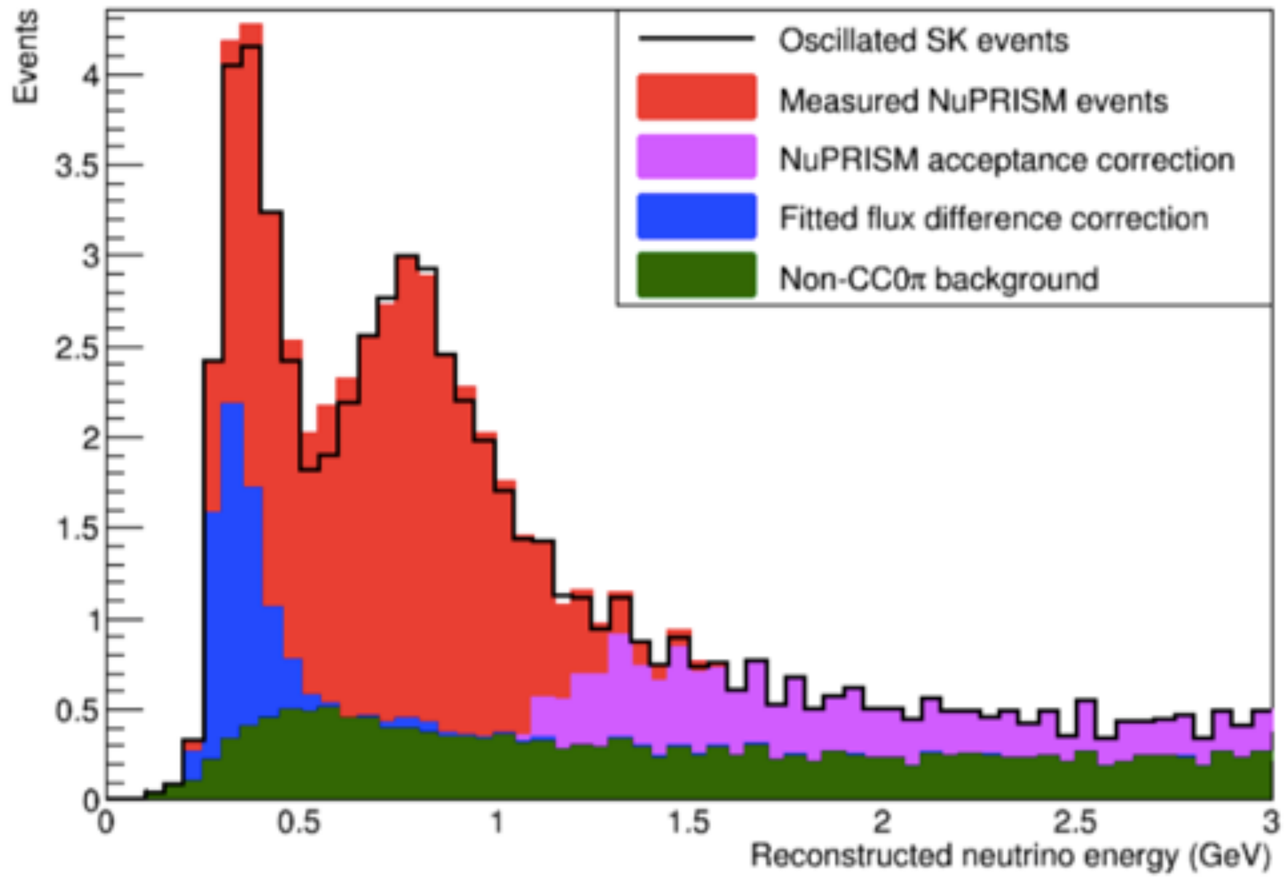


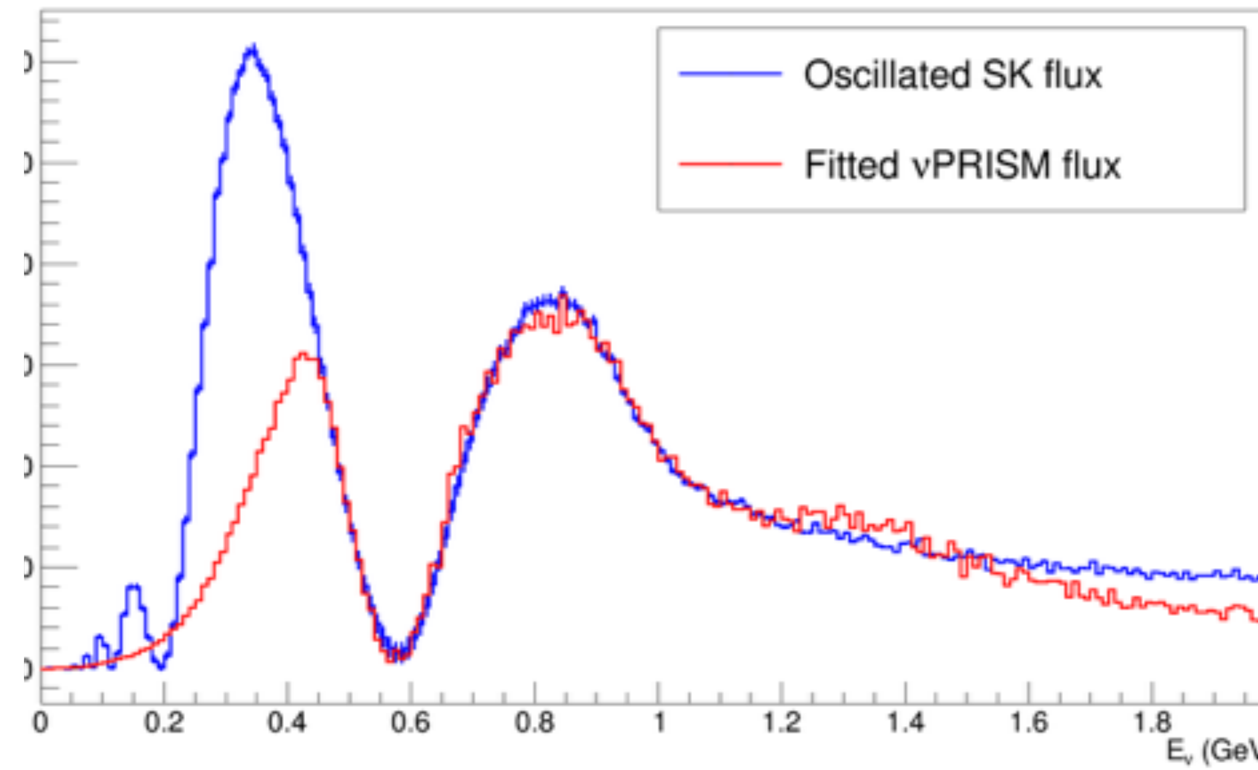
- The linear combination of off-axis measurements are used to predict the reconstructed energy distribution at the far detector

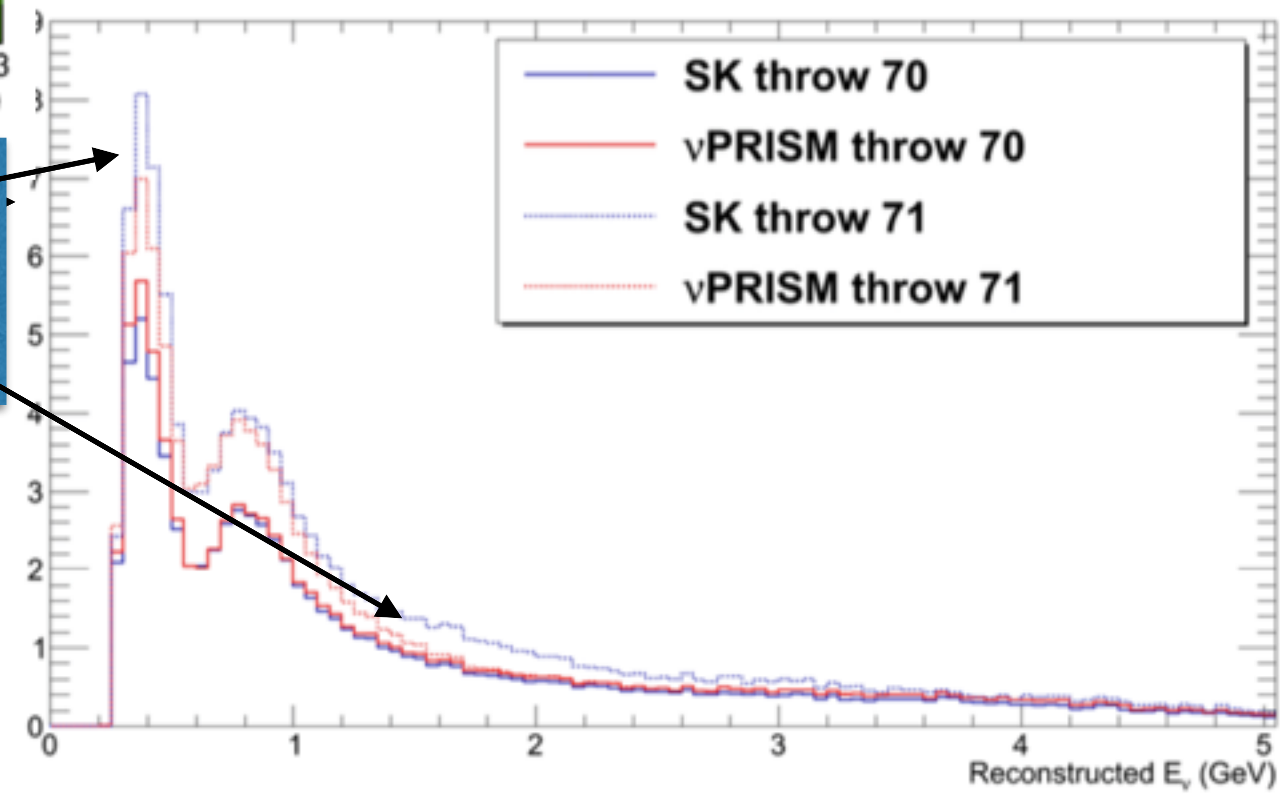


- The **4%** systematic error estimated using the T2K ND280 detector is **reduced to 1% with NuPRISM**

NUPRISM DISAPPEARANCE SPECTRUM





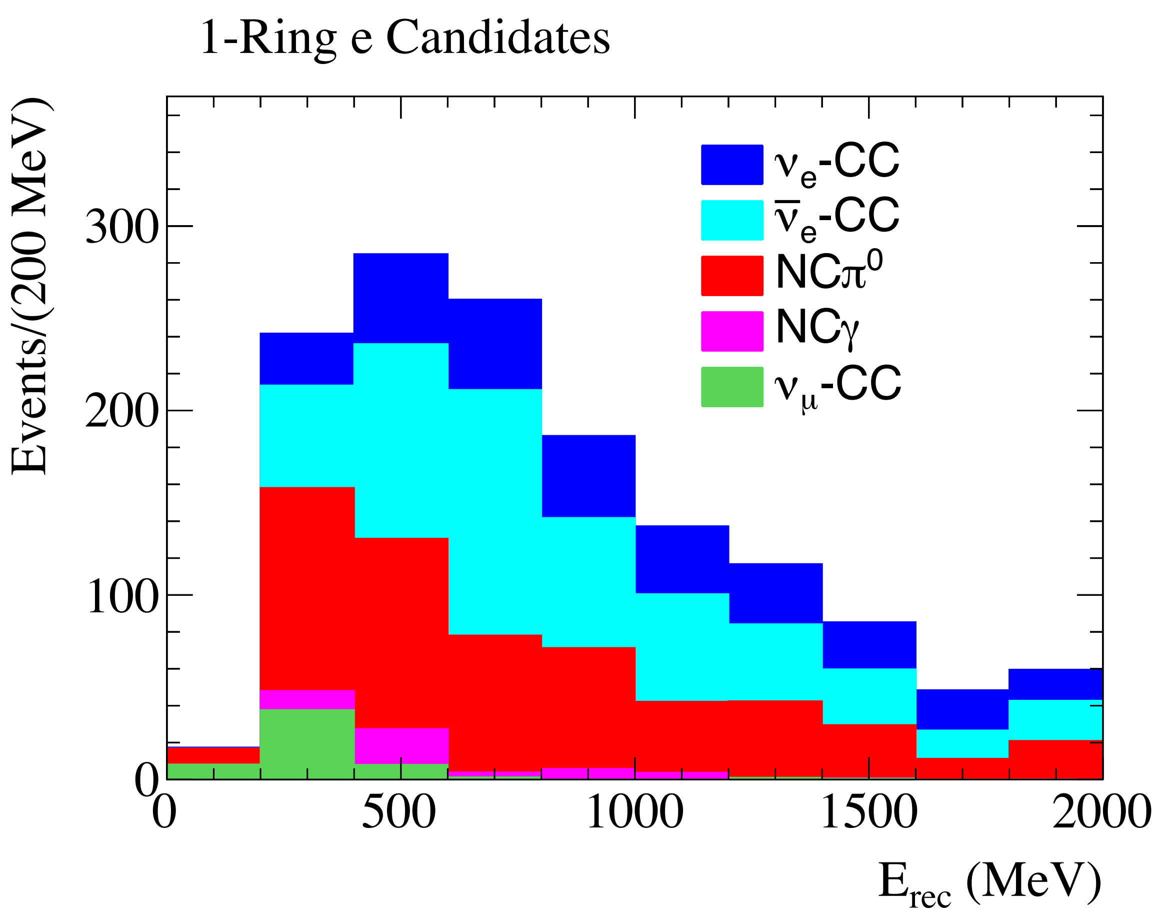


Variations at away from oscillation minimum due to flux and acceptance corrections

at t

- The 4% systematic error estimated using the T2K ND280 detector is **reduced to 1% with NuPRISM**

ELECTRON ANTINEUTRINOS IN PHASE-1

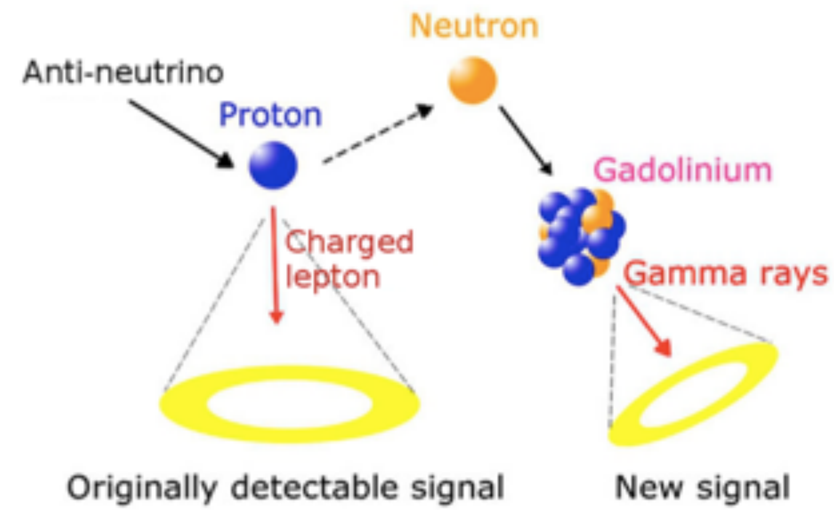


- At 2.5 degrees off-axis, the electron antineutrino rate is twice the electron neutrino rate
- NC background reduction can significantly improve the sample purity

	Events	Signal %	Wrong-Sign %	Bgnd. %
2.5	1128	37.5	18.4	44.1

NEUTRON MEASUREMENTS

- Super-K will be loaded with $Gd_2(SO_4)_3$ to increase neutron detection efficiency to ~90%



- Potential benefits to high energy physics program:
  - Rejection of atmospheric backgrounds to proton decay
  - Statistical separation of neutrinos and antineutrinos in atmospheric and accelerator samples
  - Another probe of the hadronic final states in neutrino-nucleus interactions

To use the additional information from the neutron detection, measurements of the neutron production in a intermediate/near detector are important