Impact of Systematic Uncertainties for the Hyper-Kamiokande Experiment

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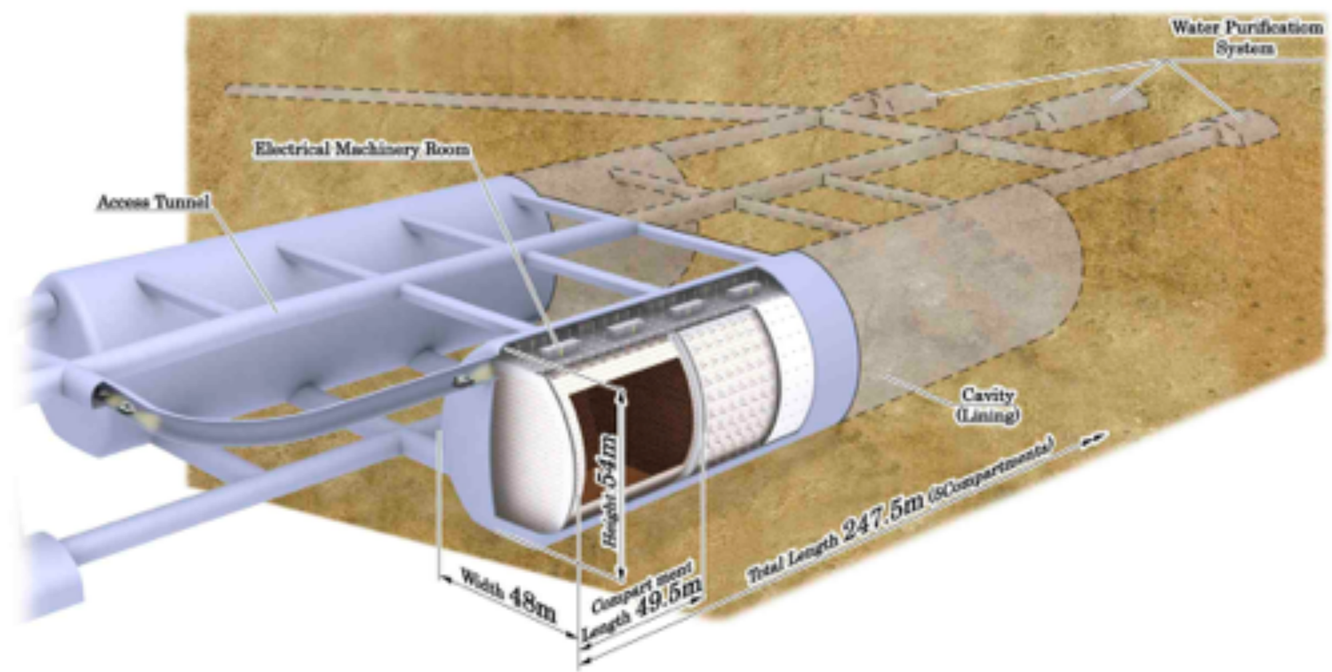
NuFact15, Rio de Janeiro
August 13, 2015

The Hyper-K Experiment

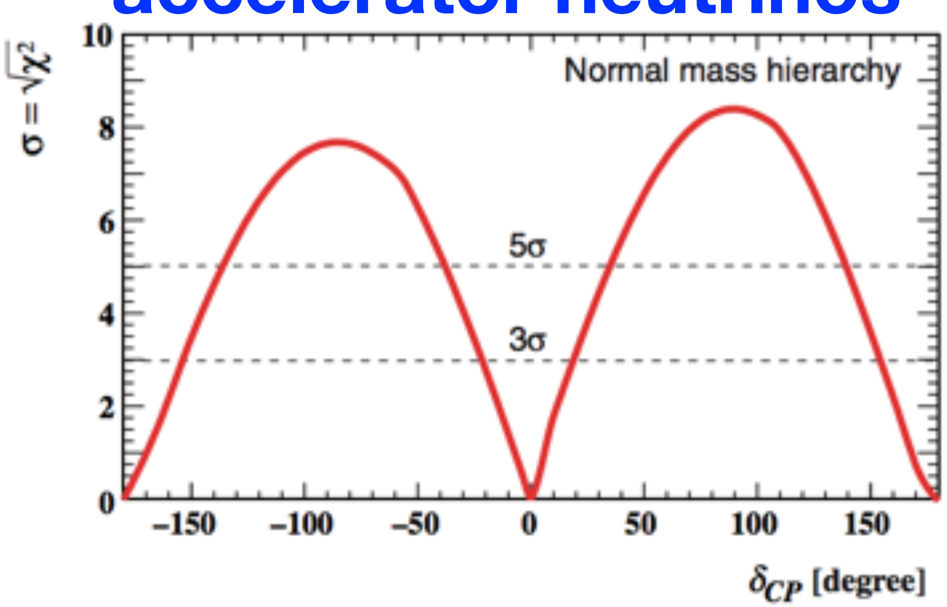
1 Mton water-Cherenkov detector
 (0.56 Mton fiducial mass)

295 km and 2.5° off-axis from the J-PARC neutrino beam

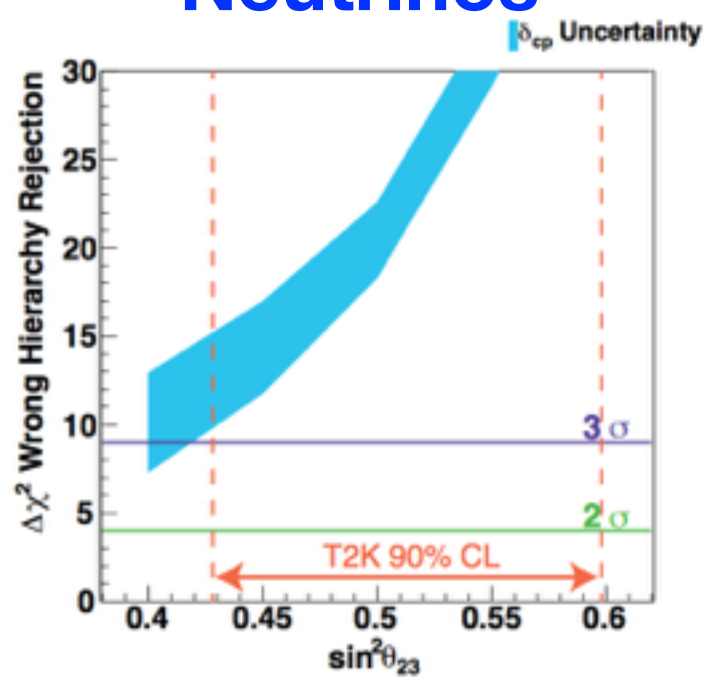
Broad physics program includes:



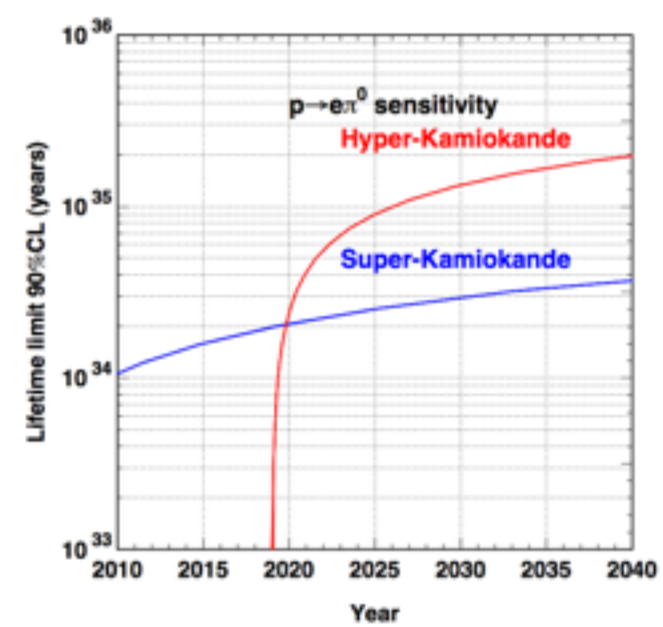
Long baseline accelerator neutrinos



Atmospheric Neutrinos



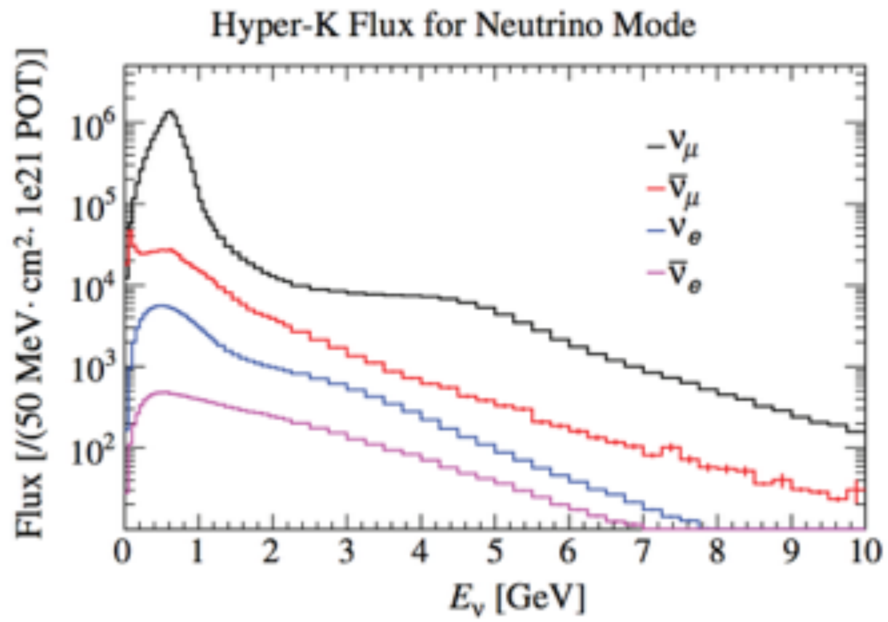
Nucleon Decay



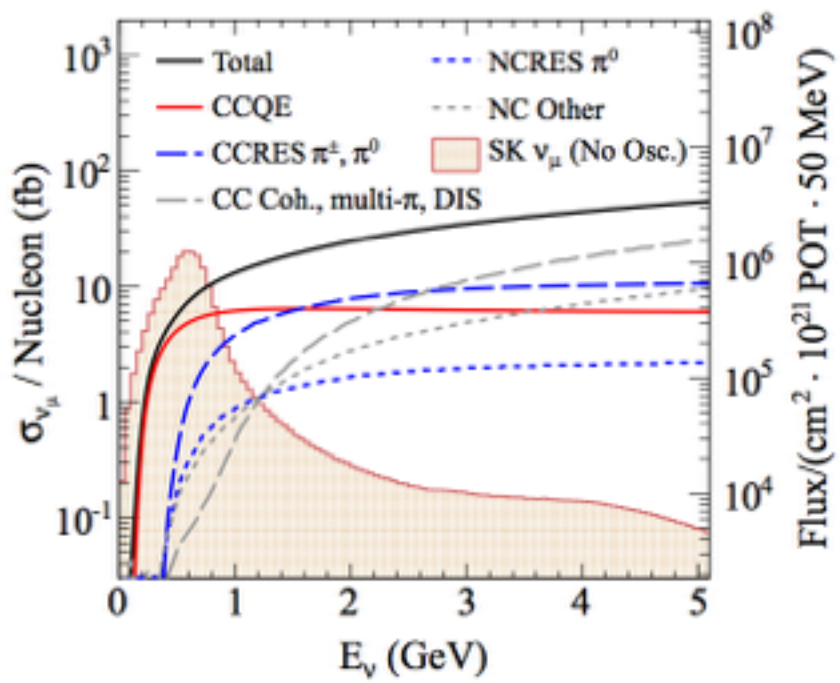
Sources of Systematic Uncertainty

Systematic errors arise in the modeling of:

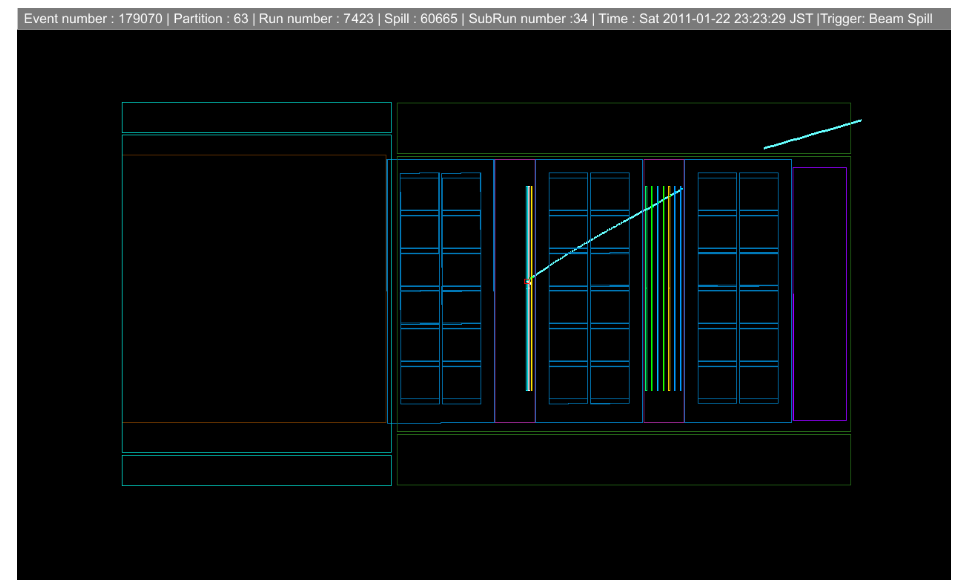
Neutrino Flux



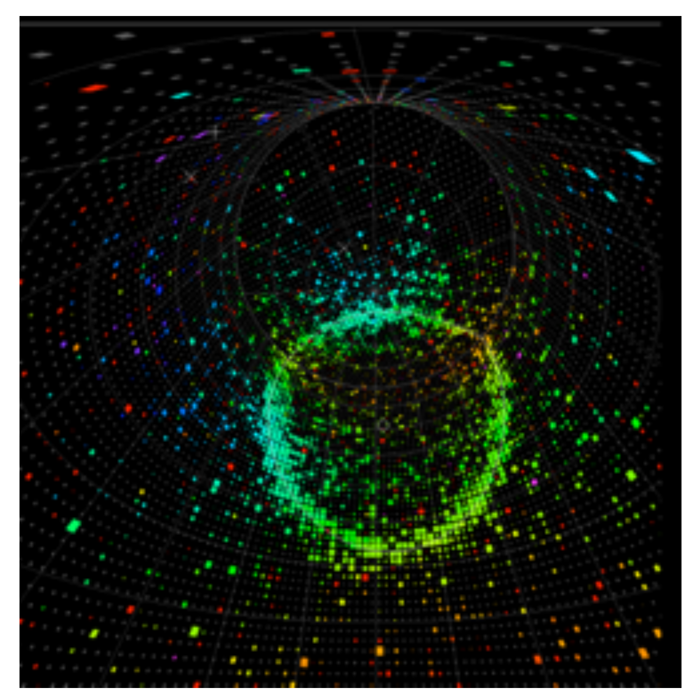
Neutrino Interactions



Near detector response

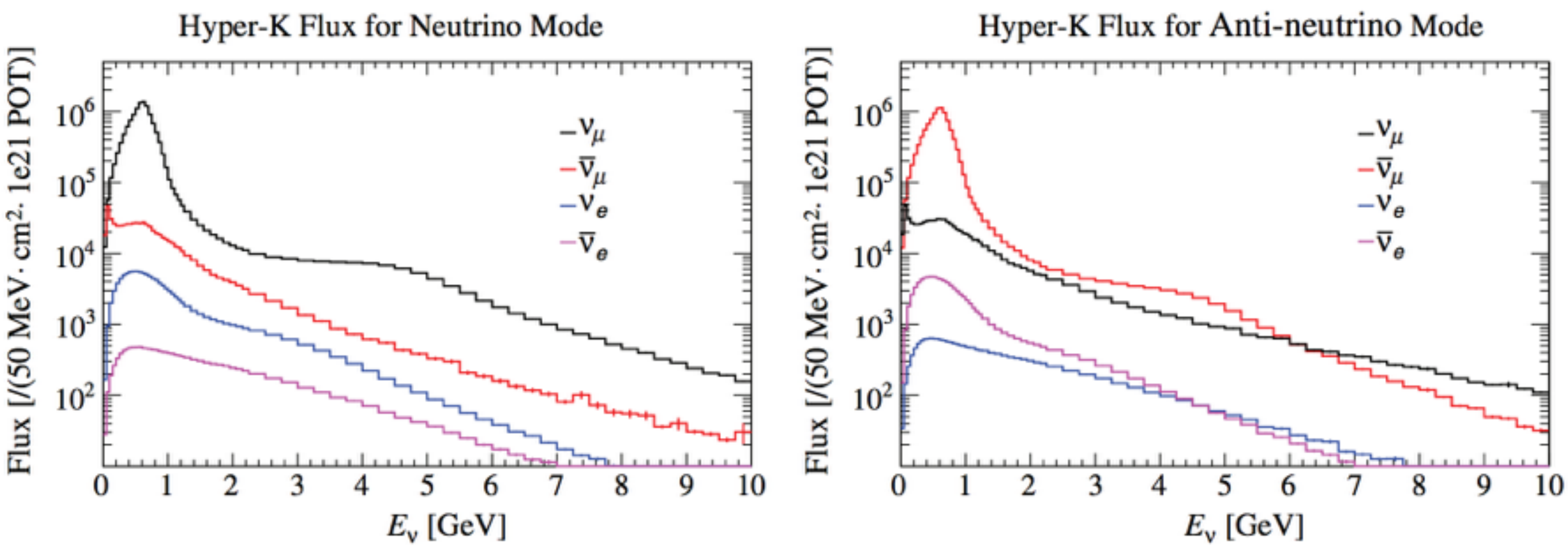


Far detector response



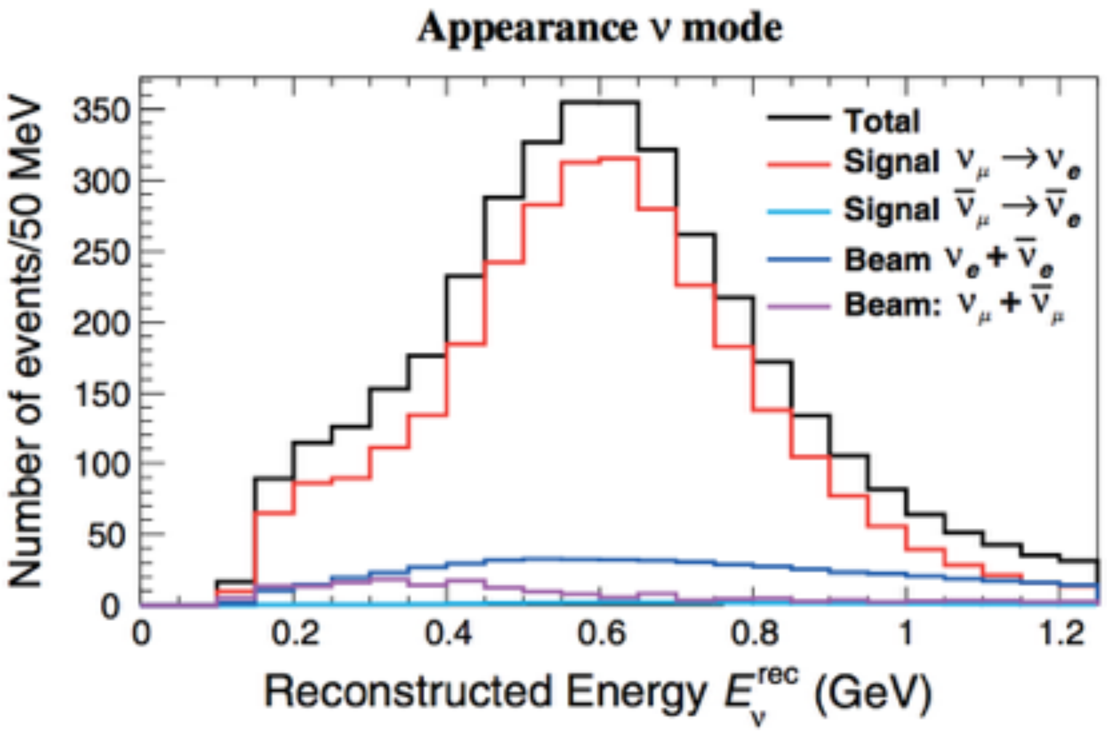
Focus of this talk

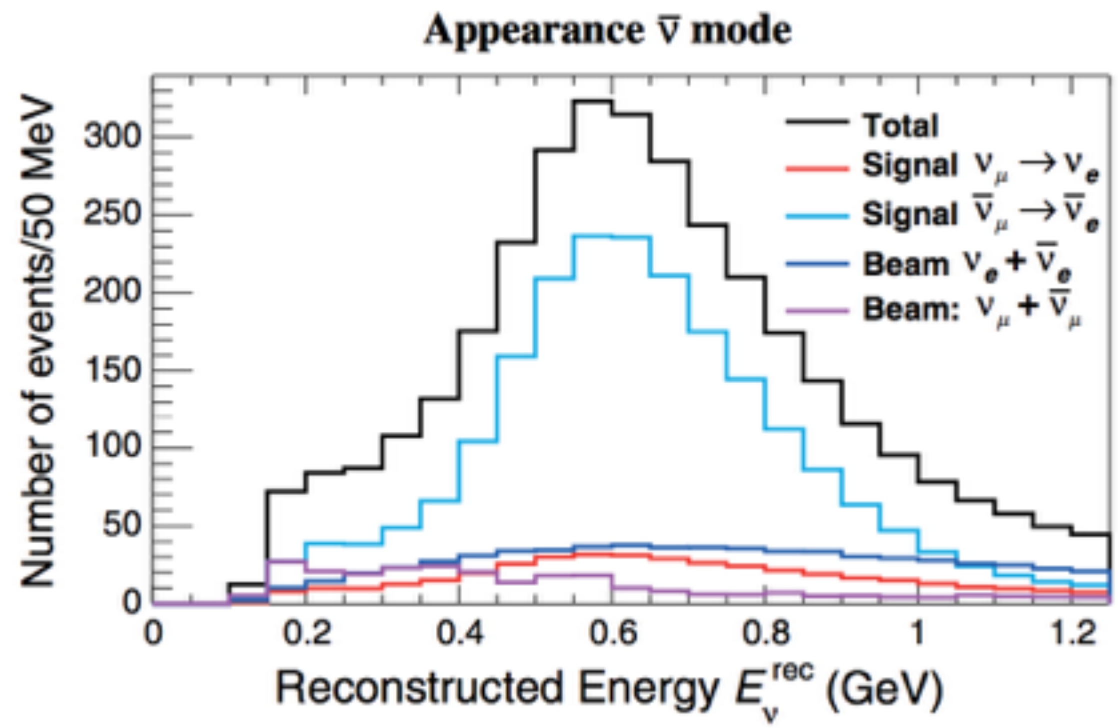
Neutrino Flux Prediction



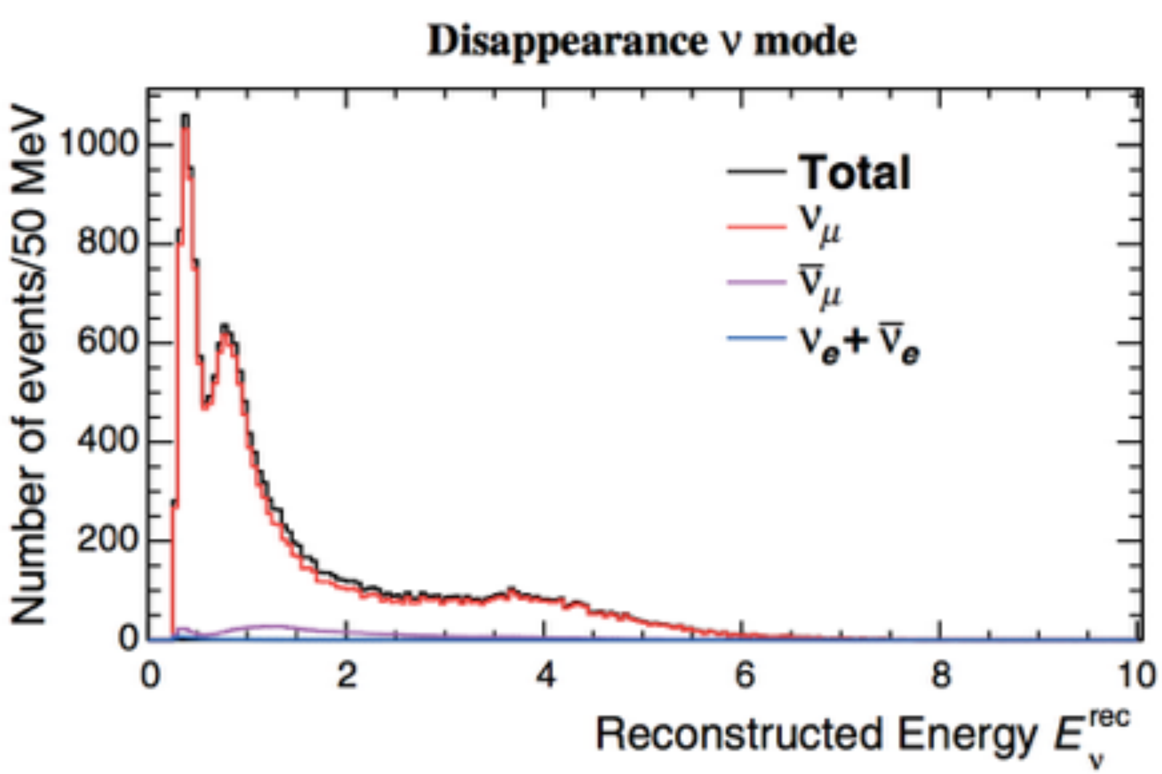
- Larger wrong sign flux is larger in antineutrino mode
- The electron neutrino background is ~0.5% near the peak

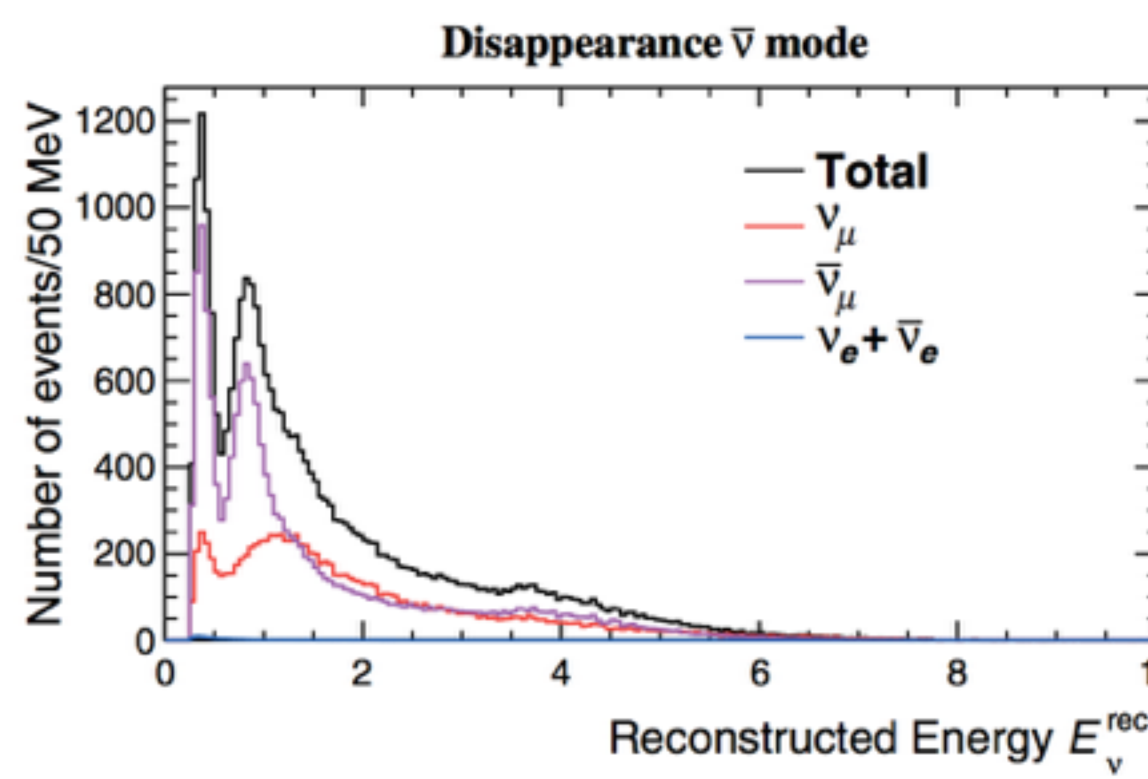
Event Rate Distributions





7.5 MW x 10^7 s

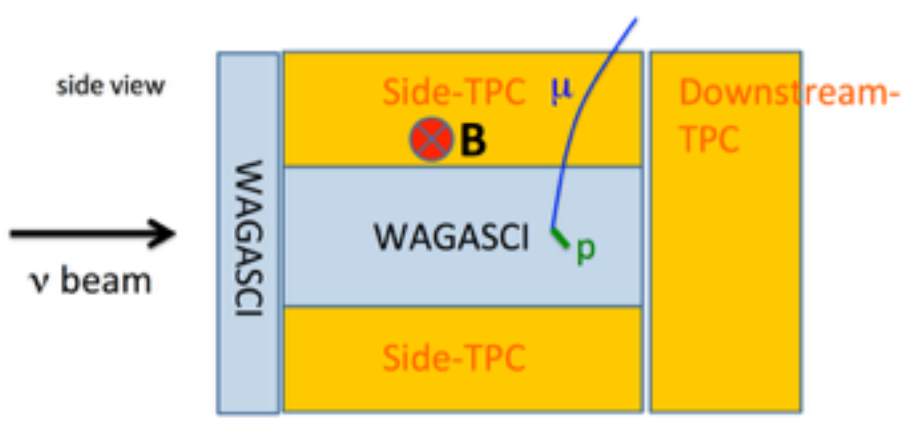




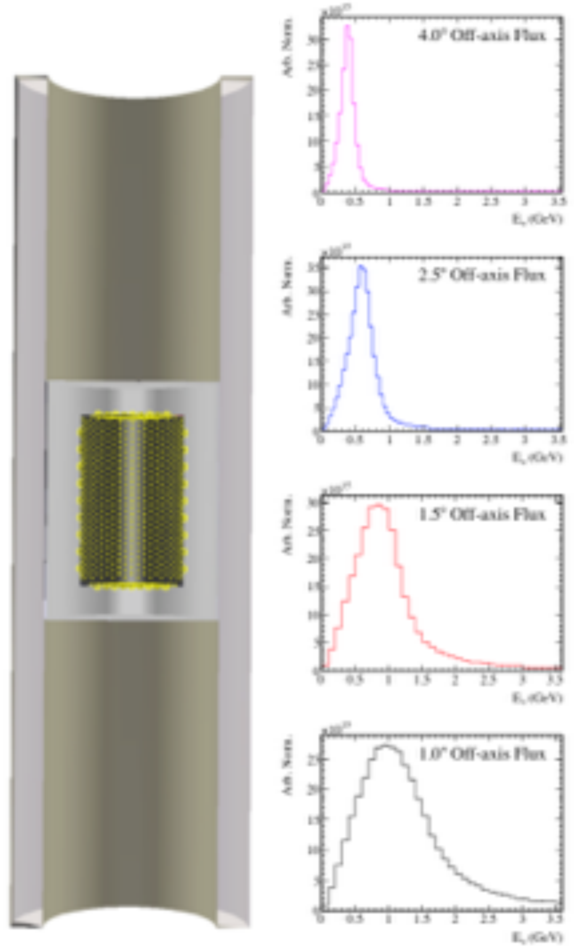
- Near detector data are used to constrain the predicted event rate in the far detector through the flux and cross section models
- HK is considering an upgrade to ND280 and a new intermediate water-Cherenkov detector (at 1-2 km baseline)

Tuesday 11:00 AM WG1-WG2 Session
K. Mahn, T2K Near Detectors
A. Minamino, T2K Upgraded and HK Near Detectors

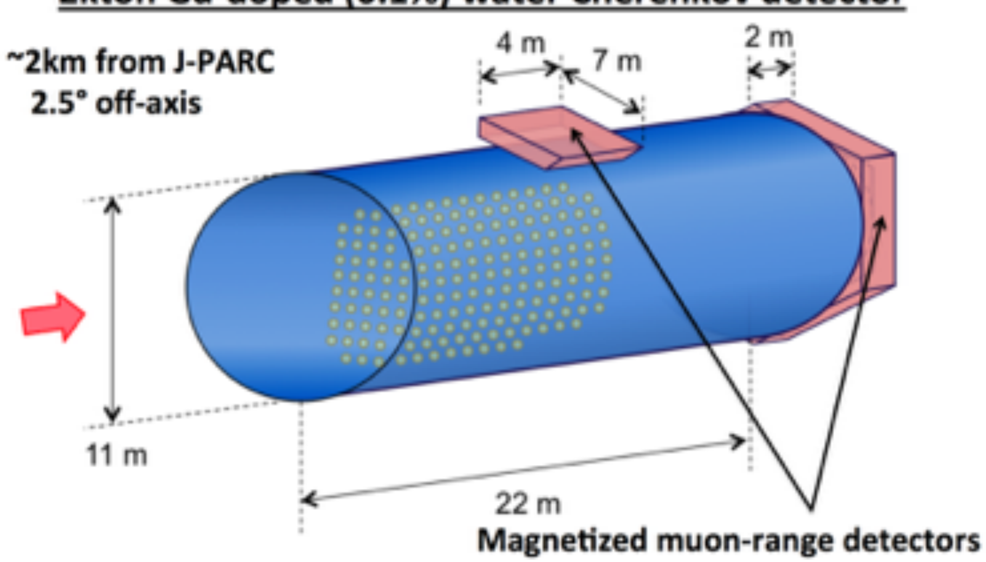
WAGASCI in ND280 magnet



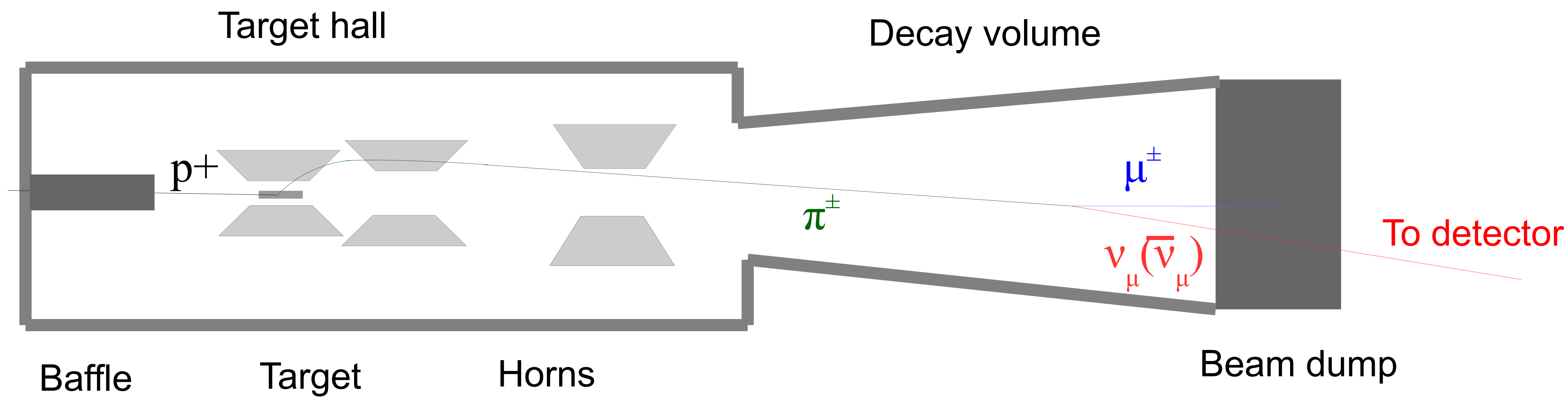
NuPRISM



TITUS



Neutrino Flux Model



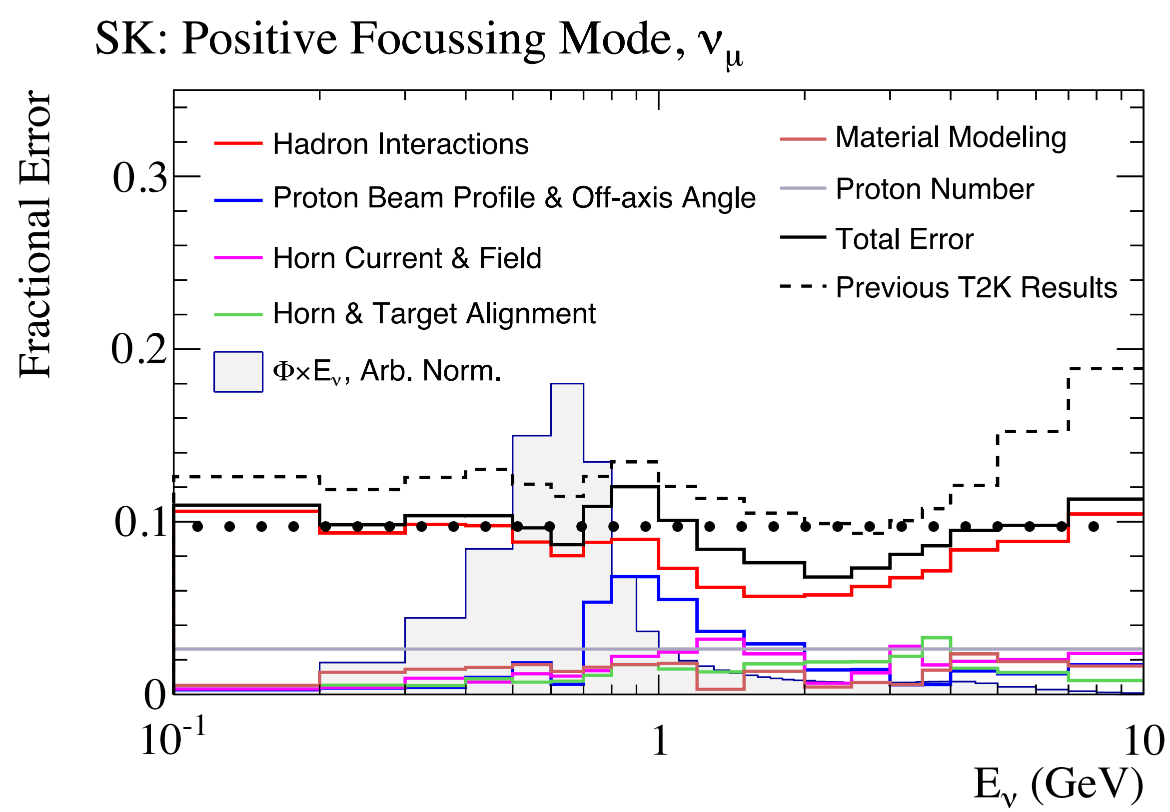
Flux prediction from data driven simulation:

- Proton beam monitor measurements
- Horn field measurements
- Beam-line component alignment measurements
- Hadron production measurements (NA61/SHINE)

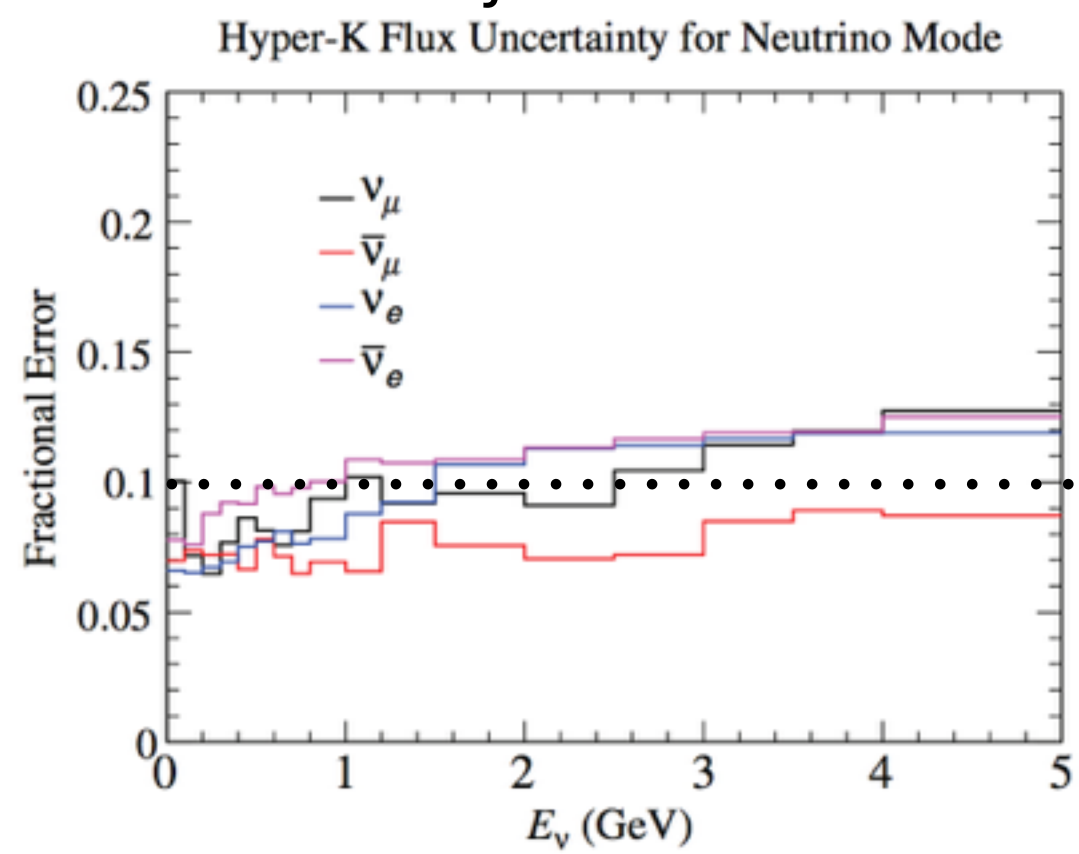
Dominant source of systematic error

Neutrino Flux Uncertainty

T2K

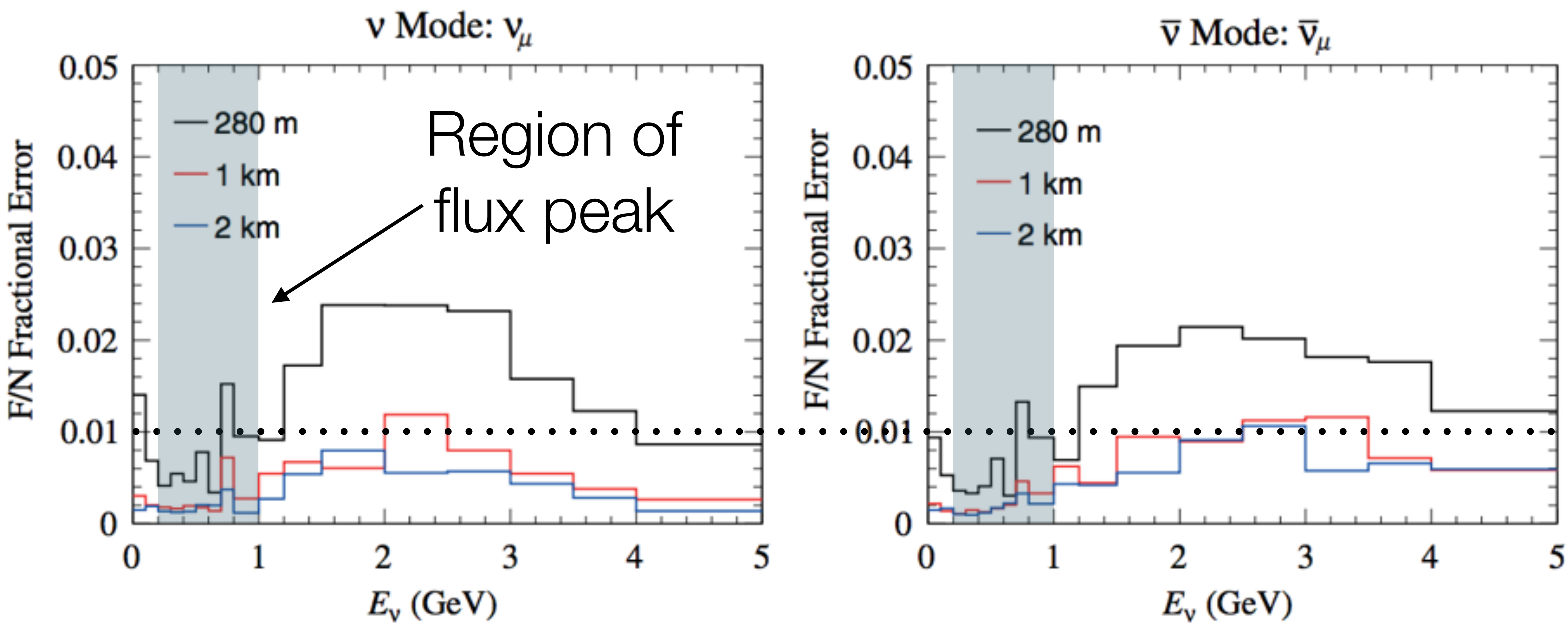


Projected HK



- Projected flux uncertainty for HK is based on the T2K uncertainty
- Error reduction due to assumption of hadron production data for replica target
    - Replica target data from NA61/SHINE is now being incorporated in the T2K flux prediction

Flux Near to Far Uncertainty



- Estimate the flux uncertainty in the near to far extrapolation: error on the far/near ratio
- In the flux peak region, error is <1% for near detector at 280 m (T2K ND280 detector)
- <0.5% uncertainty for intermediate detector sites at 1 km and 2 km
- We can achieve a sufficiently small flux uncertainty for the extrapolation
- Reducing the flux error is also important for testing the cross section model with near/ intermediate detector data

Interaction Model Uncertainties

- The current approach for interaction model errors is based on the T2K parameterization of the NEUT model and the near detector constraintes

Source of uncertainty	ν_μ CC	ν_e CC
Flux and common cross sections		
(w/o ND280 constraint)	21.7%	26.0%
(w ND280 constraint)	2.7%	3.2%
Independent cross sections	5.0%	4.7%
SK	4.0%	2.7%
FSI+SI(+PN)	3.0%	2.5%
Total		
(w/o ND280 constraint)	23.5%	26.8%
(w ND280 constraint)	7.7%	6.8%

Phys. Rev. D 91, 072010 (2015)

The fit to ND280 data constrains the flux and interaction models to the 3% level (excluding separate systemic parameters for the nuclear model/FSI)

Include uncertainties in the FSI and nuclear model assigned due to different target in the near and far detector (CH vs. H_2O)

Should be reduced with measurements on H_2O in near and intermediate detectors

For Hyper-K Sensitivities

For the published Hyper-K sensitivities, we have assumed improvements in the near/intermediate detector constraints

PTEP 2015, 053C02

Table 9. Uncertainties (in %) for the expected number of events at Hyper-K from the systematic uncertainties assumed in this study. ND: near detector.

		Flux & ND-constrained cross section	ND-independent cross section	Far detector	Total
ν mode	Appearance	3.0	1.2	0.7	3.3
	Disappearance	2.8	1.5	1.0	3.3
$\bar{\nu}$ mode	Appearance	5.6	2.0	1.7	6.2
	Disappearance	4.2	1.4	1.1	4.5

The uncertainty from the part of the models constrained by the near detector stays the same

Increased uncertainty in antineutrino mode due to modeling of the wrong sign component

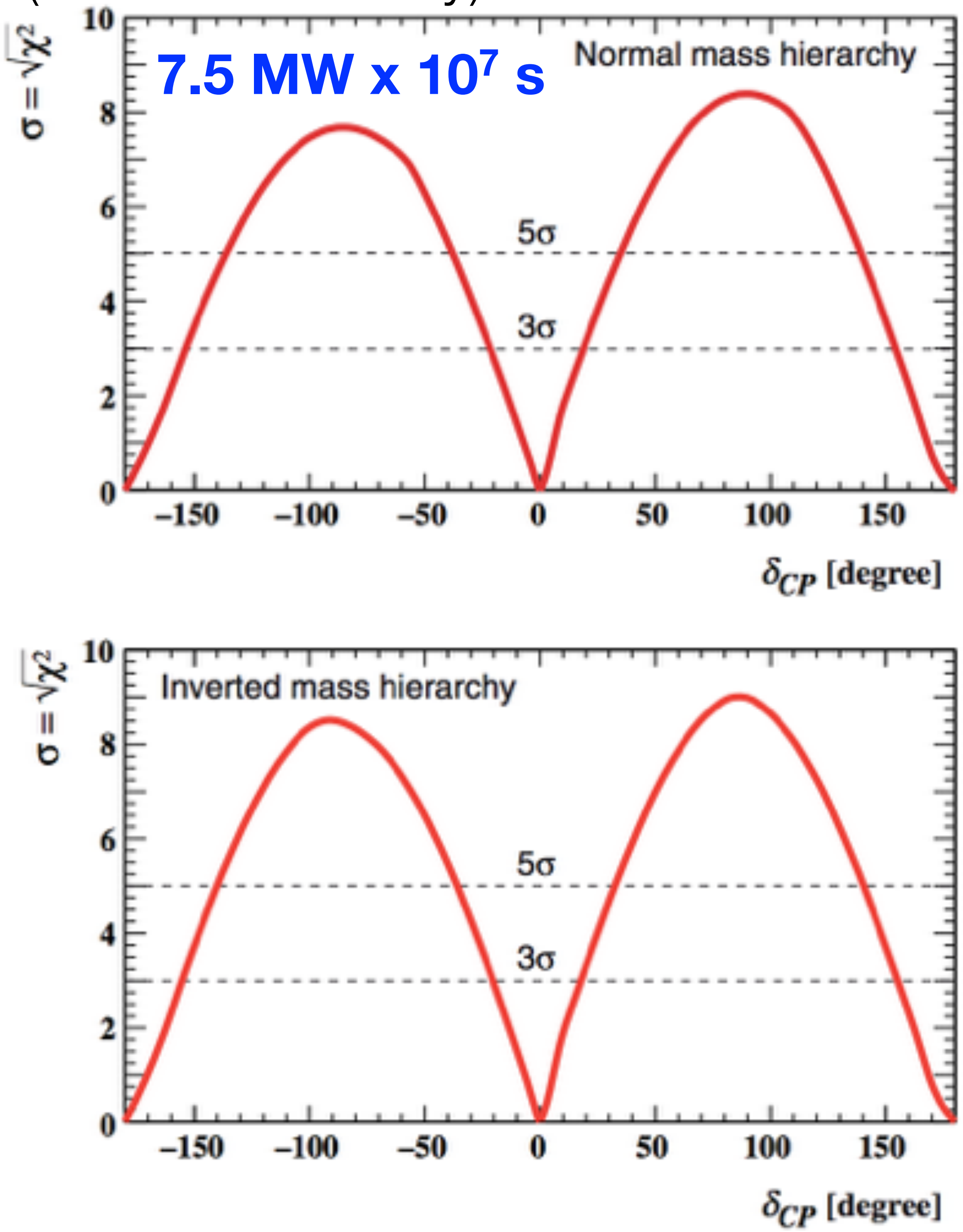
Assume no correlation between neutrino and antineutrino mode - conservative approach for CPV measurement

Uncertainties in the interaction model that cannot be constrained by the near detector are reduced

Improved H_2O measurements in upgraded ND280, measurements in intermediate water-Cherenkov detector

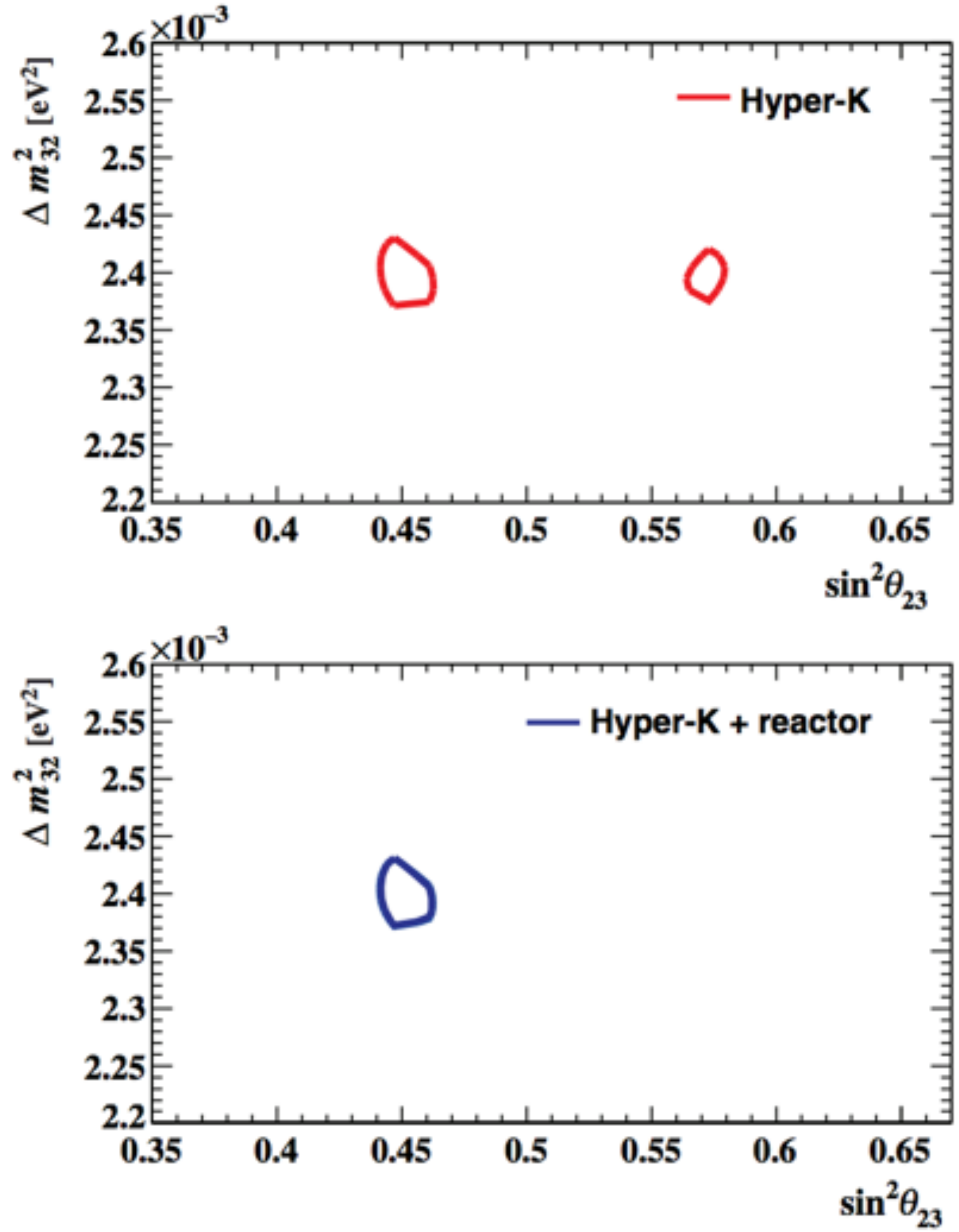
Hyper-K Sensitivities

CP violation discovery potential (known hierarchy)



3σ at 75% of δ_{cp} values

θ_{23}, Δm^2_{32} measurement



Individual Systematic Uncertainties

- We also carry out studies to evaluate the impact of individual systematic error sources
- Important input to the near/intermediate detector design
    - Identify the important systematic uncertainties
    - Choose near/intermediate detector designs that can make measurements to reduce the systematic uncertainties
- Will show some of the important systematic uncertainties in this talk

ν_e and $\bar{\nu}_e$ Cross Sections

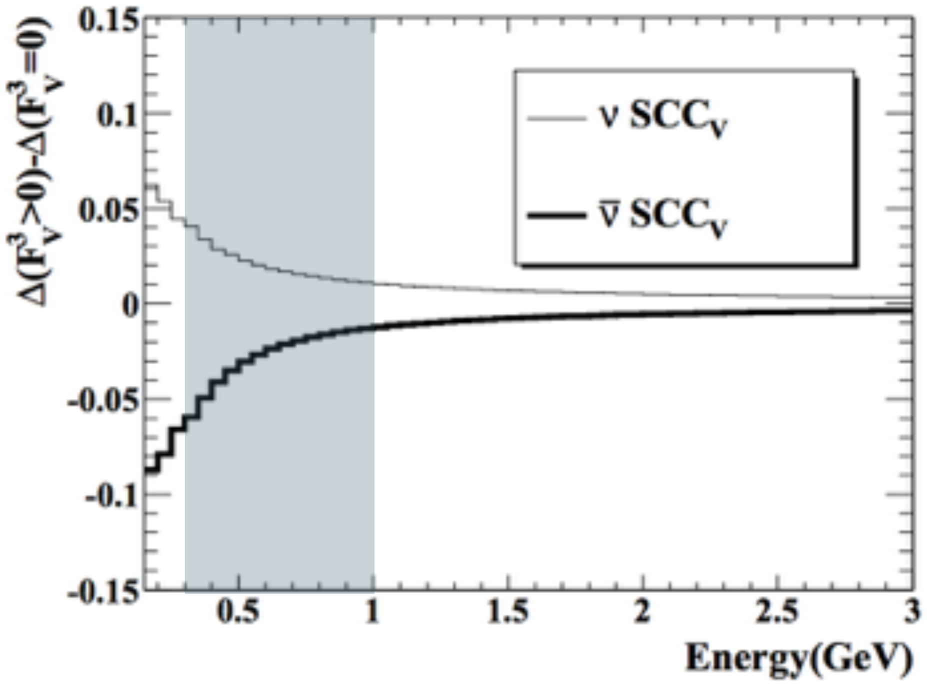
- We measure ν_μ and $\bar{\nu}_\mu$ rates in our near detectors
- To predict the ν_e and $\bar{\nu}_e$ rates at the far detector we need to correct for the cross-section difference
- No precision measurements of the ν_e, $\bar{\nu}_e$ cross sections at the energies of interest
- For CP violation measurement, the important quantity is $(\sigma_{\nu_e}/\sigma_{\nu_\mu})/(\sigma_{\bar{\nu}_e}/\sigma_{\bar{\nu}_\mu})$
- What are the theoretical uncertainties?

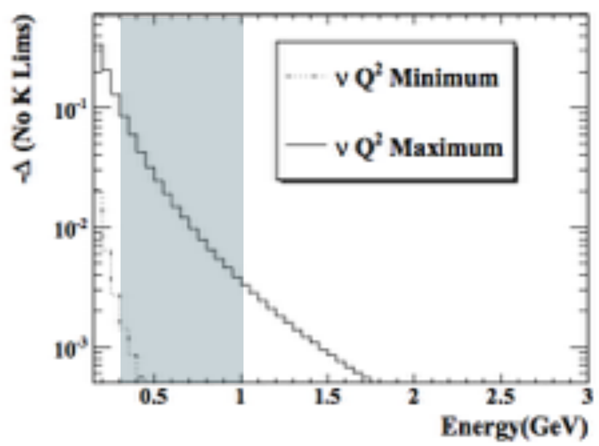
ν_e and $\bar{\nu}_e$ Cross Section Uncertainties

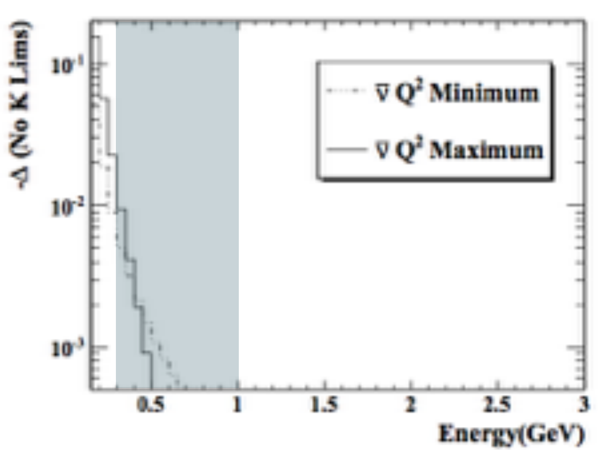
- Sources of theoretical uncertainty are consider by Day & McFarland (Phys.Rev. D86 (2012) 053003)
  - Inclusion of second class currents can change the cross section ratio by 2% at the flux peak
  - The kinematically allowed region is different

$$Q^2_{\substack{max \\ min}} = -m^2 + \frac{s - M^2}{\sqrt{s}} \left(E^*_\ell \pm |p^*_\ell|\right)$$

    - Effect is significant at the maximum Q^2 for neutrinos
  - Radiative corrections - should be calculated



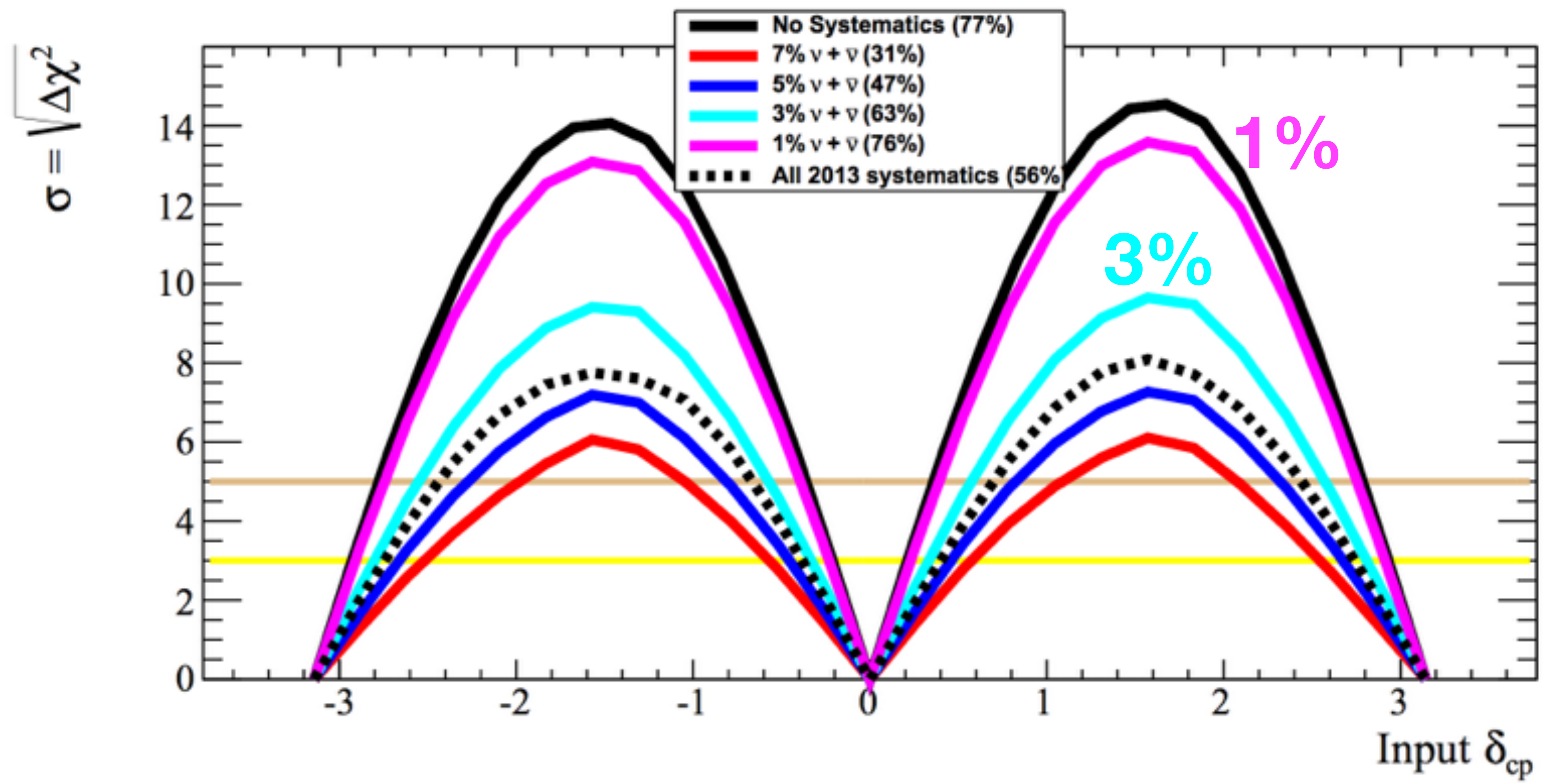




$\nu_e,\bar{\nu}_e$ Cross Section Sensitivity Impact

- Perform sensitivity study where the ν_e and $\bar{\nu}_e$ cross sections are assigned two uncorrelated normalization systematic parameters

- The uncertainties on the normalization parameters are varied and the impact on the CPV sensitivity is studied.



- The systematic uncertainty should be controlled to <1-2% to minimize the impact on the CPV discovery sensitivity

Direct measure of $\nu_e,\bar{\nu}_e$ Cross Sections

- Ideal place for measurement would be nuSTORM, but can we measure the cross sections in our conventional beam?
- The beam includes an intrinsic electron neutrino component (0.5% at the peak)

Can increase ν_e purity by going further off-axis

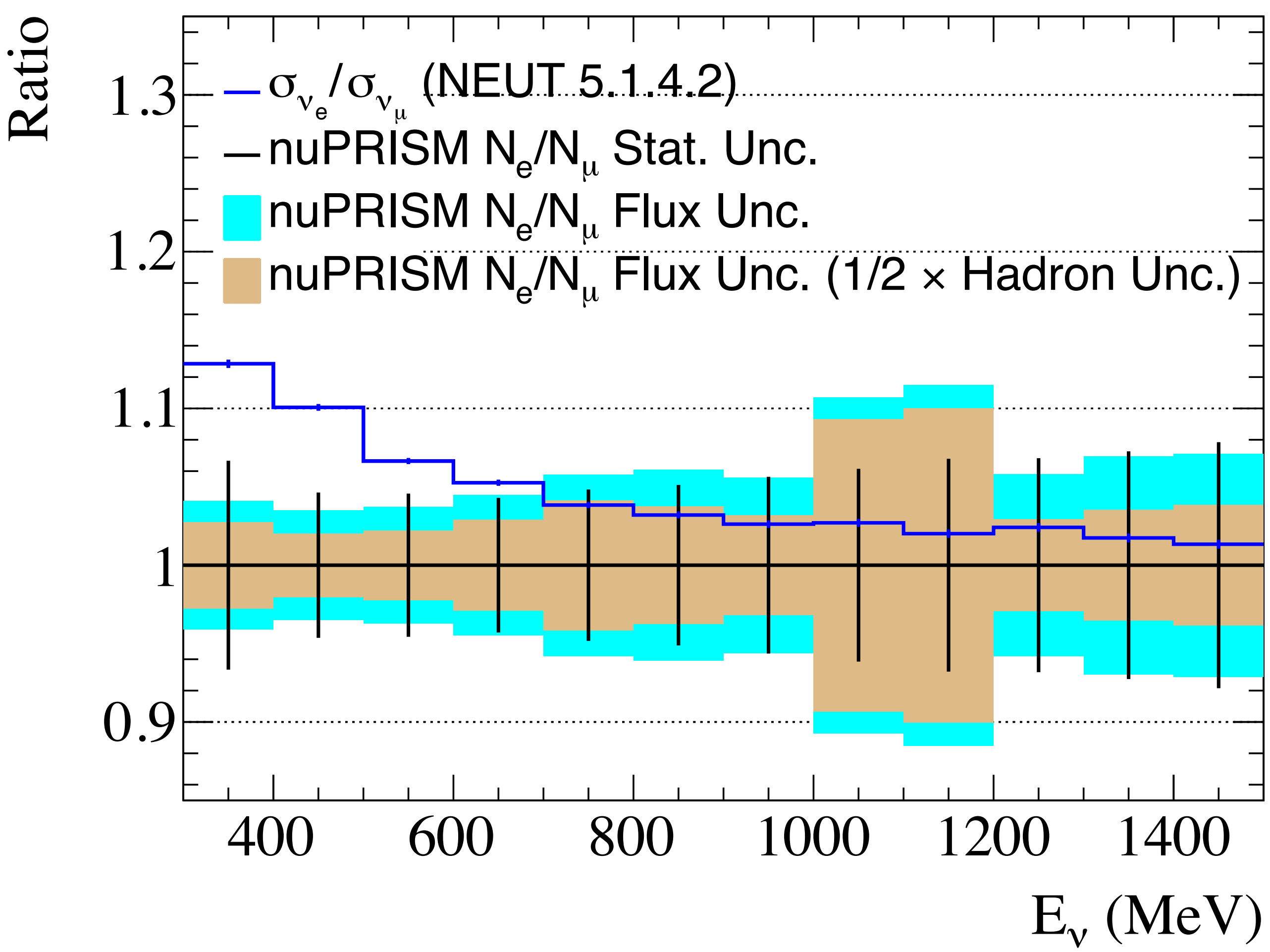
Off-axis angle (º)	ν_e Flux 0.3-0.9 GeV	ν_μ Flux 0.3-5.0 GeV	Ratio ν_e/ν_μ
2.5	1.24E+15	2.46E+17	0.507%
3.0	1.14E+15	1.90E+17	0.600%
3.5	1.00E+15	1.47E+17	0.679%
4.0	8.65E+14	1.14E+17	0.760%

At 2.5º, SK has 77% purity in the absence of oscillations

RUN1-4 6.570×10^{20}POT	MC Expectations w/ $\sin^2 2\theta_{13}=0$					Data
	$\nu_\mu+\bar{\nu}_\mu$ CC	$\nu_e+\bar{\nu}_e$ CC	NC	BG total	Signal	
fiTQun π^0	0.07	3.50	0.96	4.53	0.40	28

$\nu_e,\bar{\nu}_e$ Cross Sections Precision

- We estimated flux model and statistical errors for a $\sigma_{\nu_e}/\sigma_{\nu_\mu}$ measurement in NuPRISM



	Flux Error	Hadron x1/2	Stat. Error
300-600 MeV	3.2%	1.7%	2.9%
600-900 MeV	5.2%	3.4%	2.7%

- Preliminary study suggests that a 3% measurement or better is plausible.

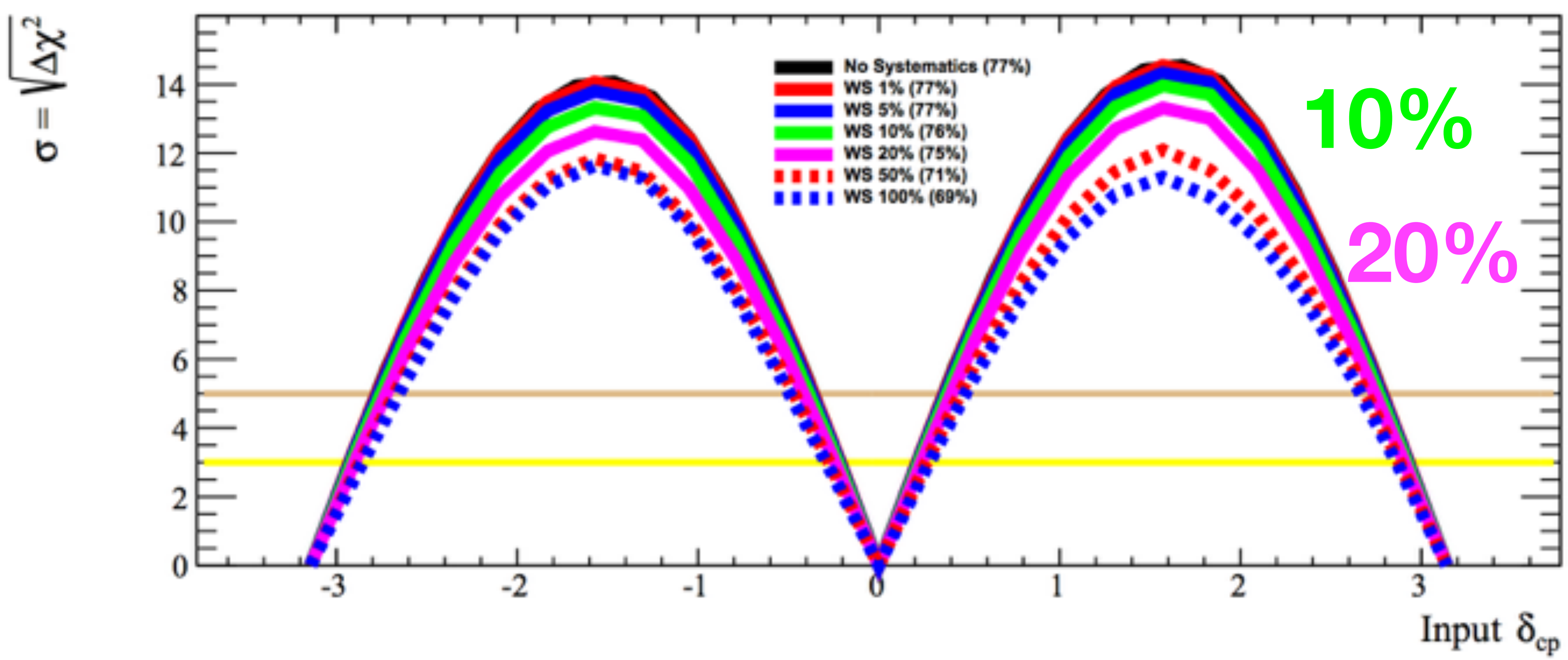
Wrong Sign Background

- In antineutrino mode, neutrinos contribute ~20% to the event rate:

Table 7. The expected number of ν_e candidate events. Normal mass hierarchy with $\sin^2 2\theta_{13} = 0.1$ and $\delta_{CP} = 0$ are assumed. Background (BG) is categorized by the flavor before oscillation.

	Signal		BG						
	$\nu_\mu \to \nu_e$	$\overline{\nu}_\mu \to \overline{\nu}_e$	ν_μ CC	$\overline{\nu}_\mu$ CC	ν_e CC	$\overline{\nu}_e$ CC	NC	BG total	Total
ν mode	3016	28	11	0	503	20	172	706	3750
$\bar{\nu}$ mode	$\boxed{396}$	2110	4	5	$\boxed{222}$	396	265	891	3397

- Study a normalization uncertainty on the wrong sign background:



- <10% uncertainty is necessary to have negligible impact on CPV sensitivity

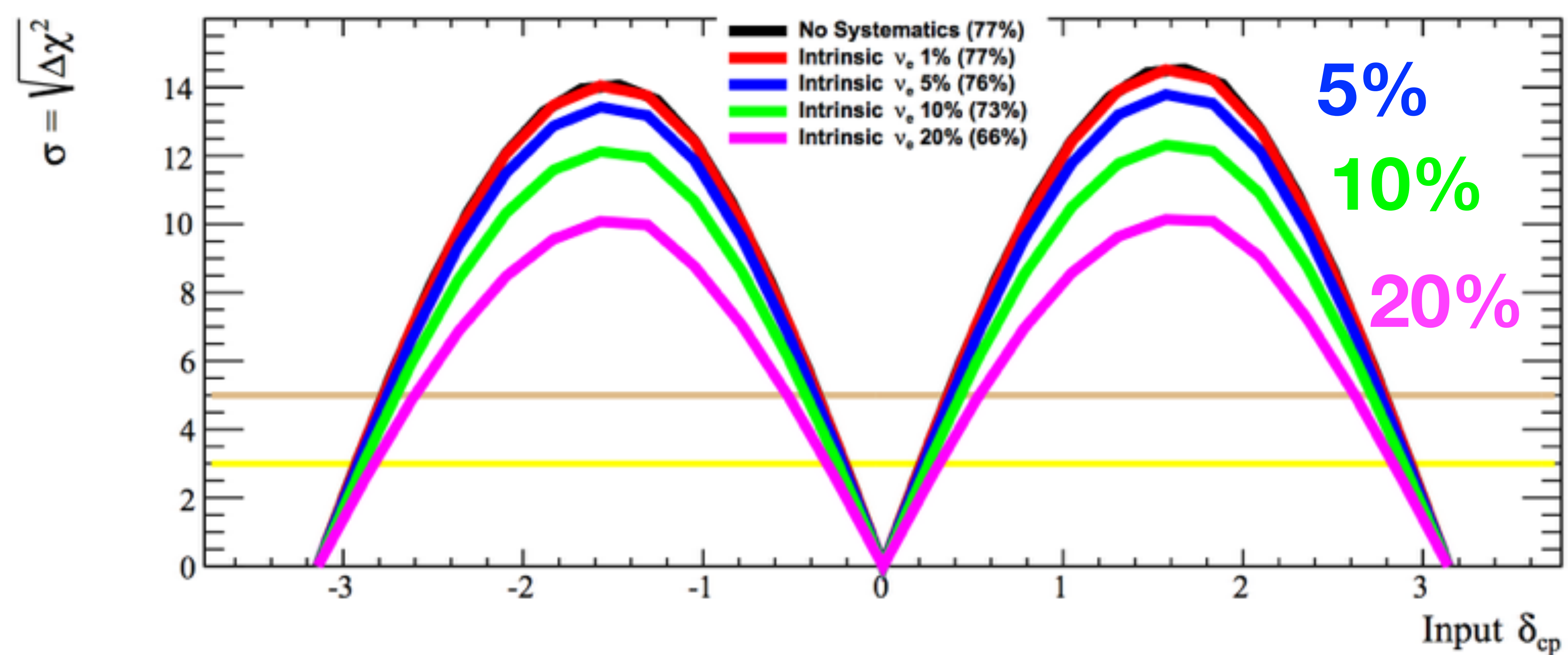
- Few % uncertainty can be achieved with a magnetized detector such as ND280

Intrinsic Electron Neutrino Background

- The intrinsic beam ν_e contribute ~15-20% to the event rate:

Table 7. The expected number of ν_e candidate events. Normal mass hierarchy with $\sin^2 2\theta_{13} = 0.1$ and $\delta_{CP} = 0$ are assumed. Background (BG) is categorized by the flavor before oscillation.

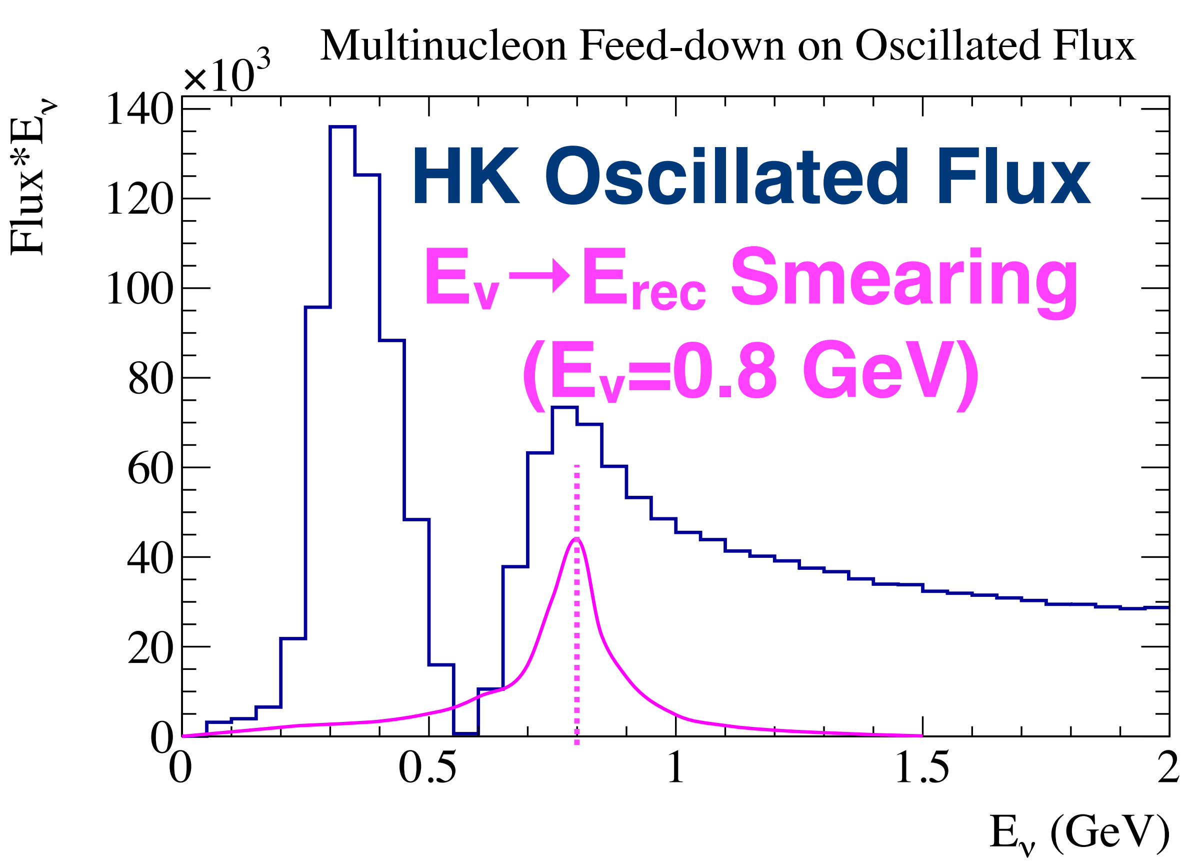
	Signal		BG						
	$\nu_\mu \to \nu_e$	$\overline{\nu}_\mu \to \overline{\nu}_e$	ν_μ CC	$\overline{\nu}_\mu$ CC	ν_e CC	$\overline{\nu}_e$ CC	NC	BG total	Total
ν mode	3016	28	11	0	503	20	172	706	3750
$\bar{\nu}$ mode	396	2110	4	5	222	396	265	891	3397

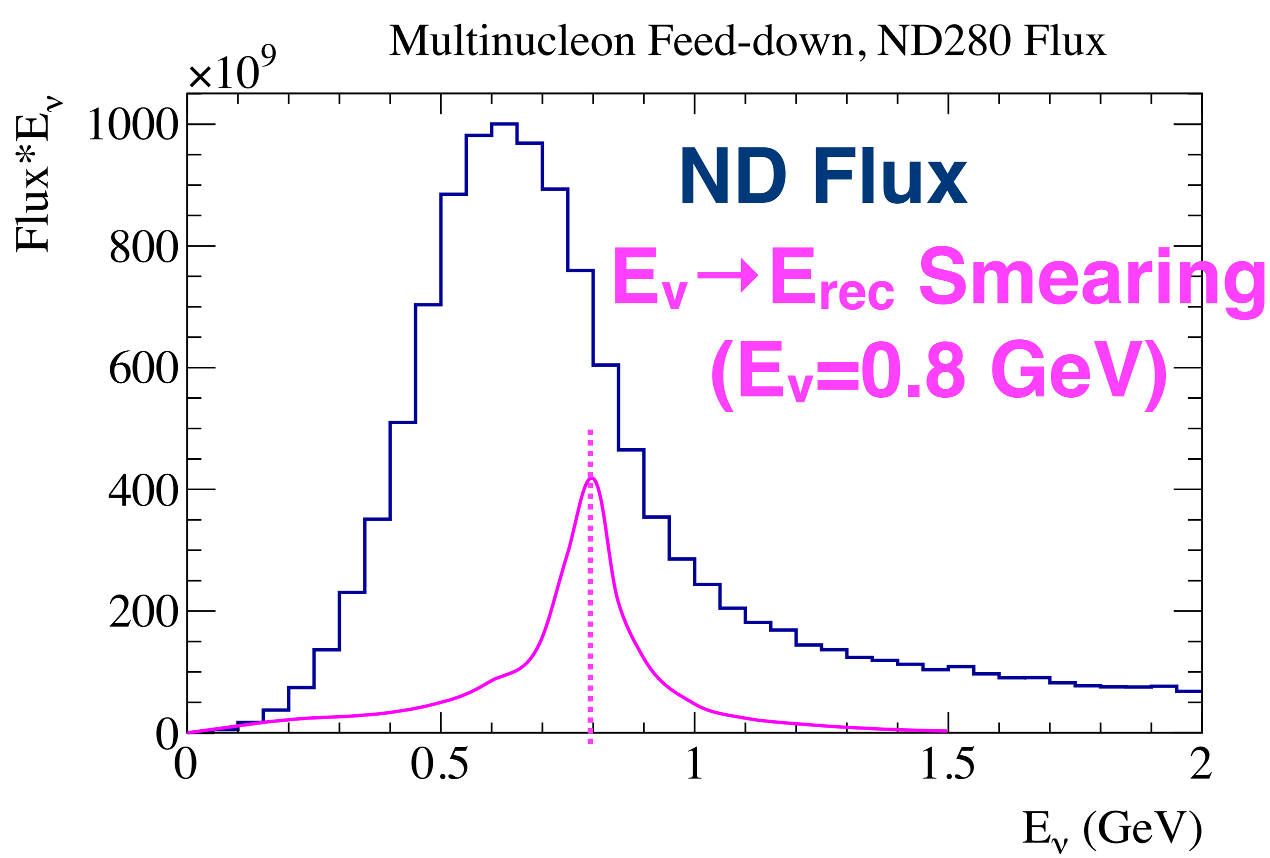


- <5% uncertainty is necessary to have negligible impact on CPV sensitivity
- <5% should be achievable with an intermediate WC detector (under study)

Energy Reconstruction Uncertainty

- The problem of energy reconstruction was covered in the neutrino-nucleus theory overview by M. Martini on Monday (12:30)
  - Non-QE interactions have a reconstructed energy that can deviate significantly from the true energy
  - Constraining this effect with near detector data is challenging since the near detector flux is broad and different from the far detector flux

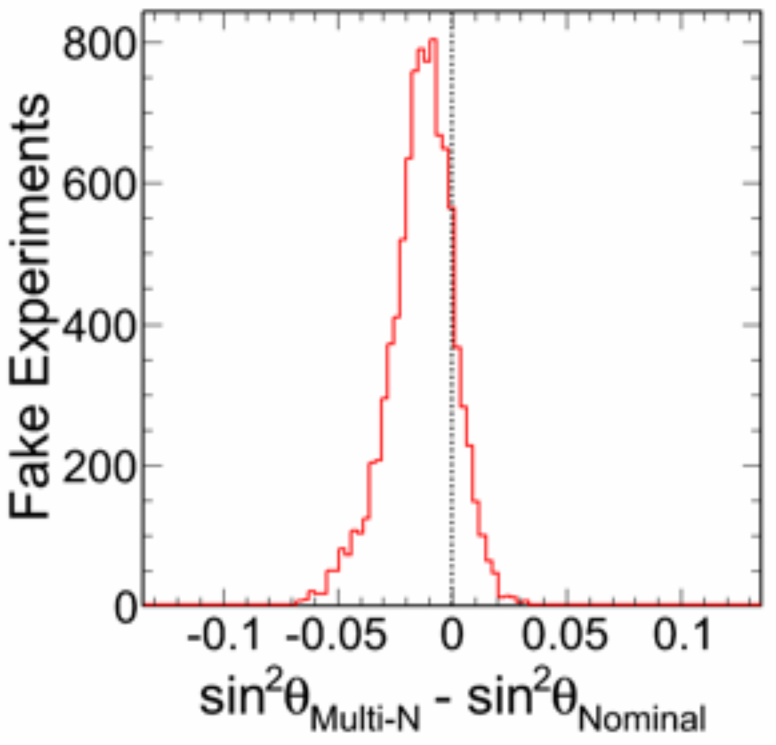




Impact on Disappearance Measurement

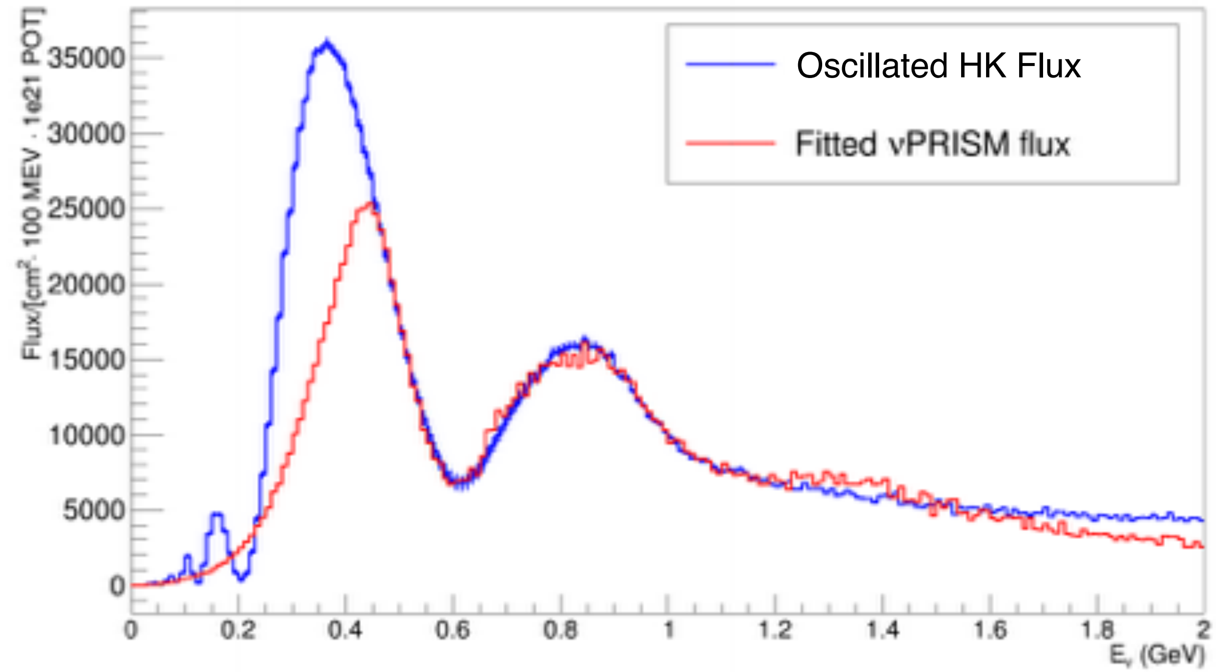
- The uncertainty on the energy smearing due to nuclear effects has a large impact on the ν_μ disappearance measurement since smeared events fill in the "dip" region
- HK aims for 1-3% precision on $\sin^2\theta_{23}$ (depends on the true value)
- T2K studied the impact of np-nh modeling uncertainty
  - Generate toy data with an ad-hoc np-nh model
  - Fit the toy data with the NEUT model (includes pion-less delta decay)
  - Evaluate the bias on the fitted oscillation parameters

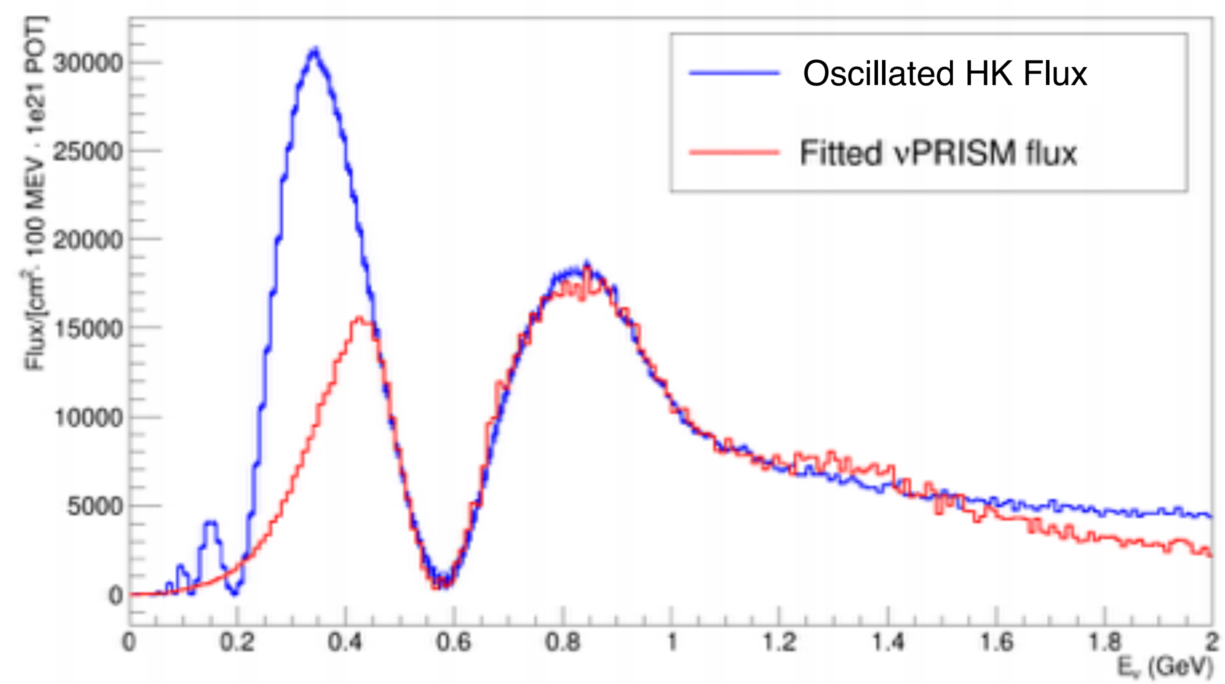
The average bias in the fitted $\sin^2\theta_{23}$ was 3%



Energy Reconstruction with NuPRISM

- NuPRISM: take advantage of the neutrino spectrum dependence with off-axis angle to make a near detector flux (through linear combinations) that matches the far detector flux
- In a study identical to the T2K study, the 3% bias on $\sin^2\theta_{23}$ is reduced to <0.1%



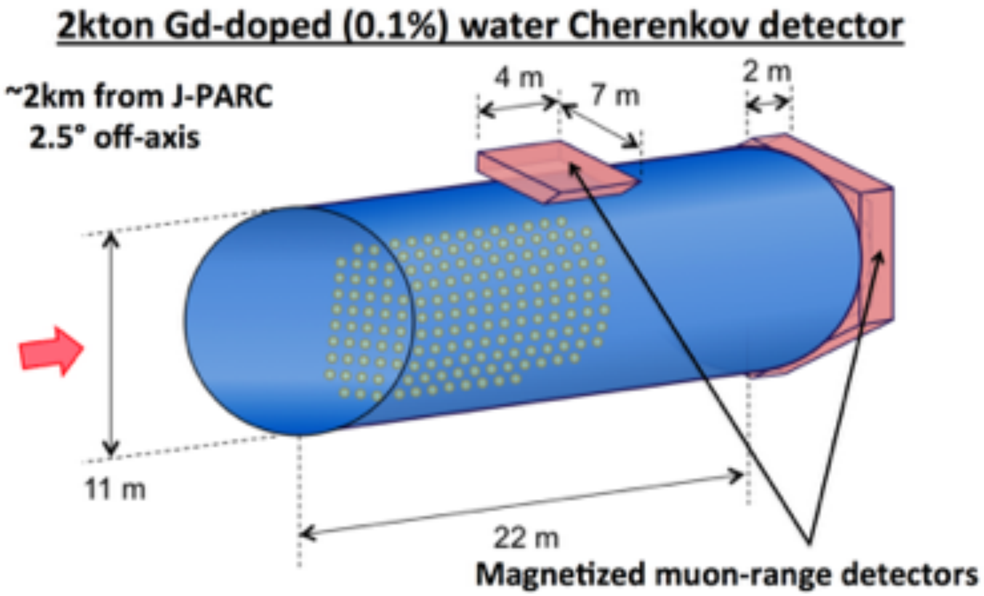


Proton Decay $p \to e\pi^0$

- The atmospheric neutrino background to the $p \to e\pi^0$ mode is:

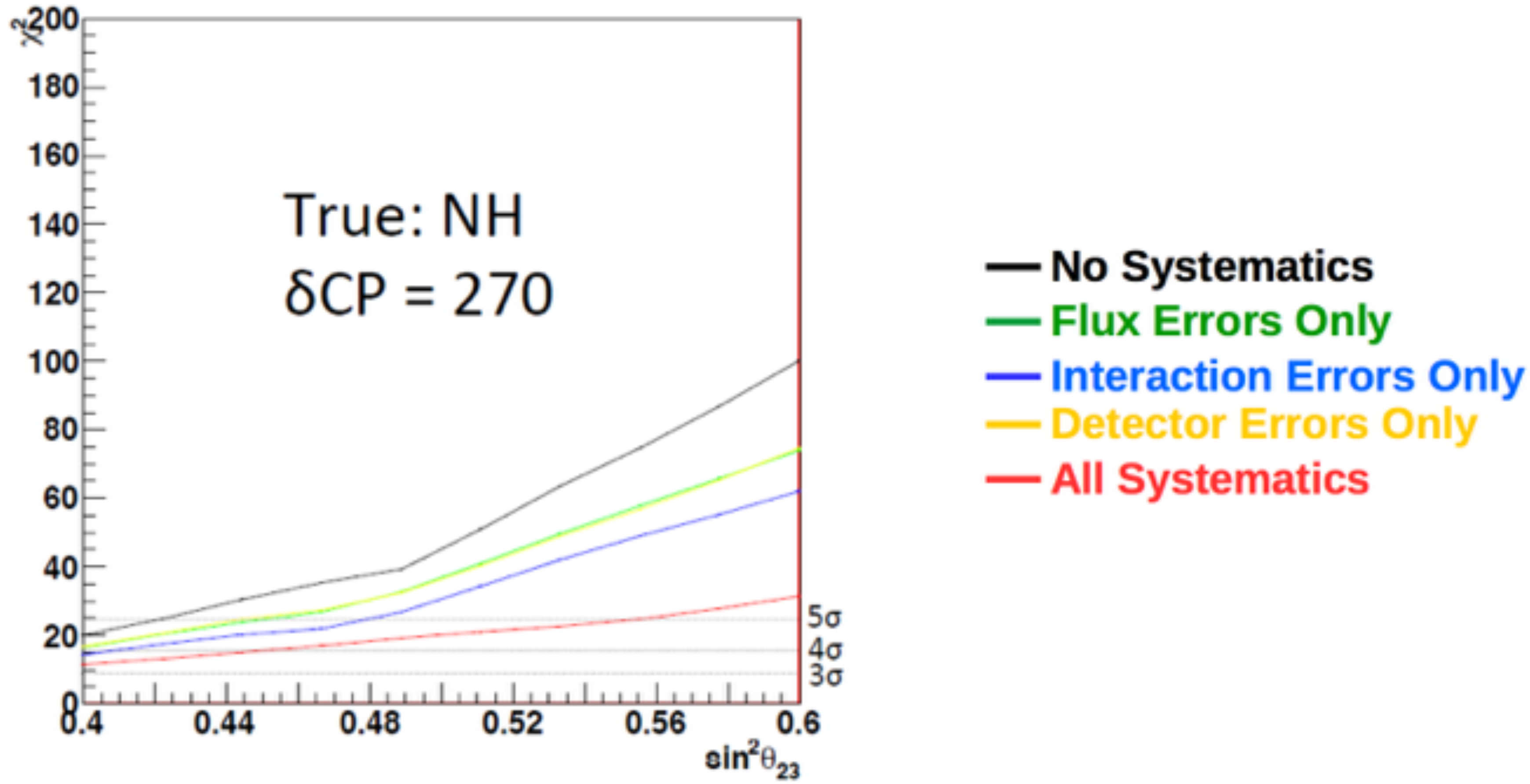
$$1.63^{+0.42}_{-0.33}(\text{stat})^{+0.45}_{-0.51}(\text{syst})\ \text{events/Megaton}\cdot\text{year}$$

- This background can be reduced with neutron tagging using captures on H or Gd
- This introduces a systematic uncertainty on the neutron multiplicity in atmospheric neutrino interactions
    - Should be controlled by measurements in neutrino beams:
    - ANNIE (see talk by M. Sanchez in Tuesday morning WG1+WG2 session)
    - TITUS: added benefit of a magnetized muon range detector to tag neutrino and antineutrino interactions



Atmospheric Neutrinos (Mass Hierarchy)

- The individual contributions of the systematic errors on the mass hierarchy sensitivity have been evaluated:



- Largest uncertainties are in the CC ν_τ and CC DIS cross section models
    - CC DIS may be constrained in our near detectors
- The flux uncertainties for the >1 GeV flux (7-12%) are also significant - May be reduced with new hadron production measurements

Conclusion

- Hyper-K is a precision neutrino oscillation experiment that requires control of systematic uncertainties at the few % level
- Studies to identify the dominant systematic effects on the Hyper-K sensitivities are being carried out
  - Feed into the near detector design and consideration of future hadron production measurements
  - The electron neutrino cross section is an important ongoing area of study
- Systematic uncertainties from neutrino interactions and atmospheric flux also enter the atmospheric neutrino and proton decay measurements
  - We are studying how to control these systematic errors to improve the sensitivity of Hyper-K

Thank you.