# Flux Uncertainty and Sensitivity Studies for Near Detectors

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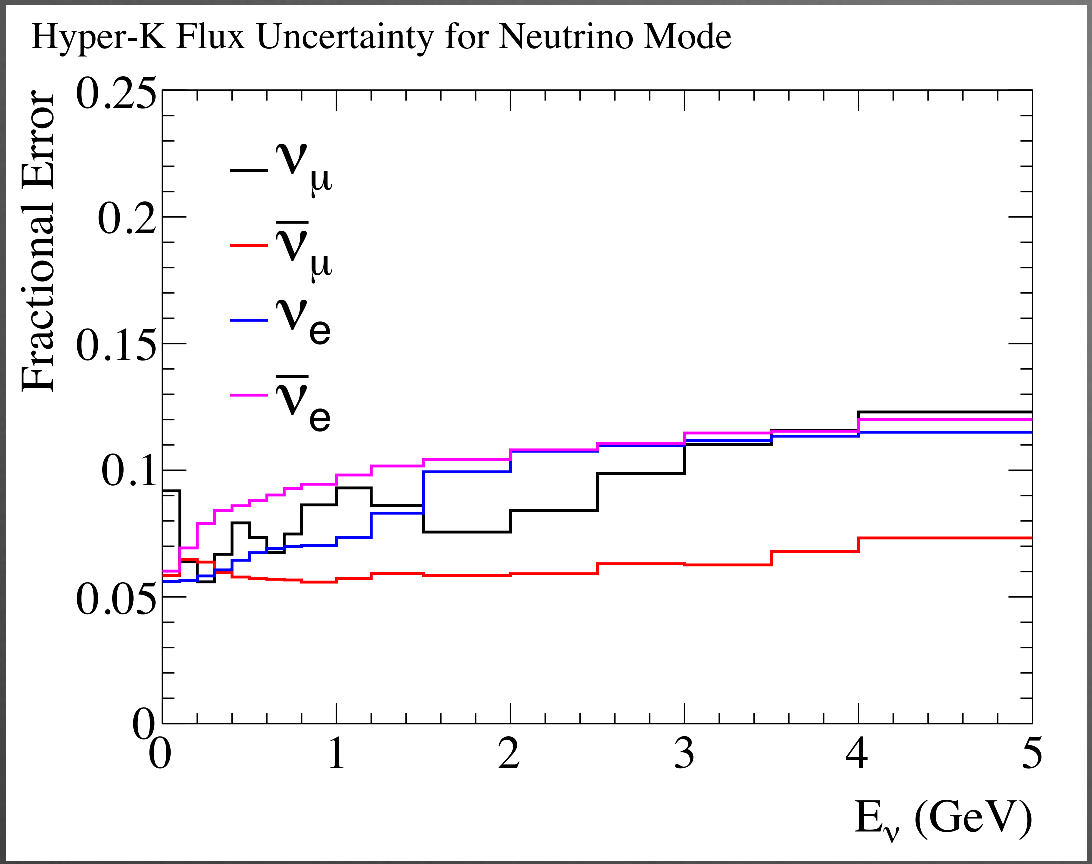
# Outline

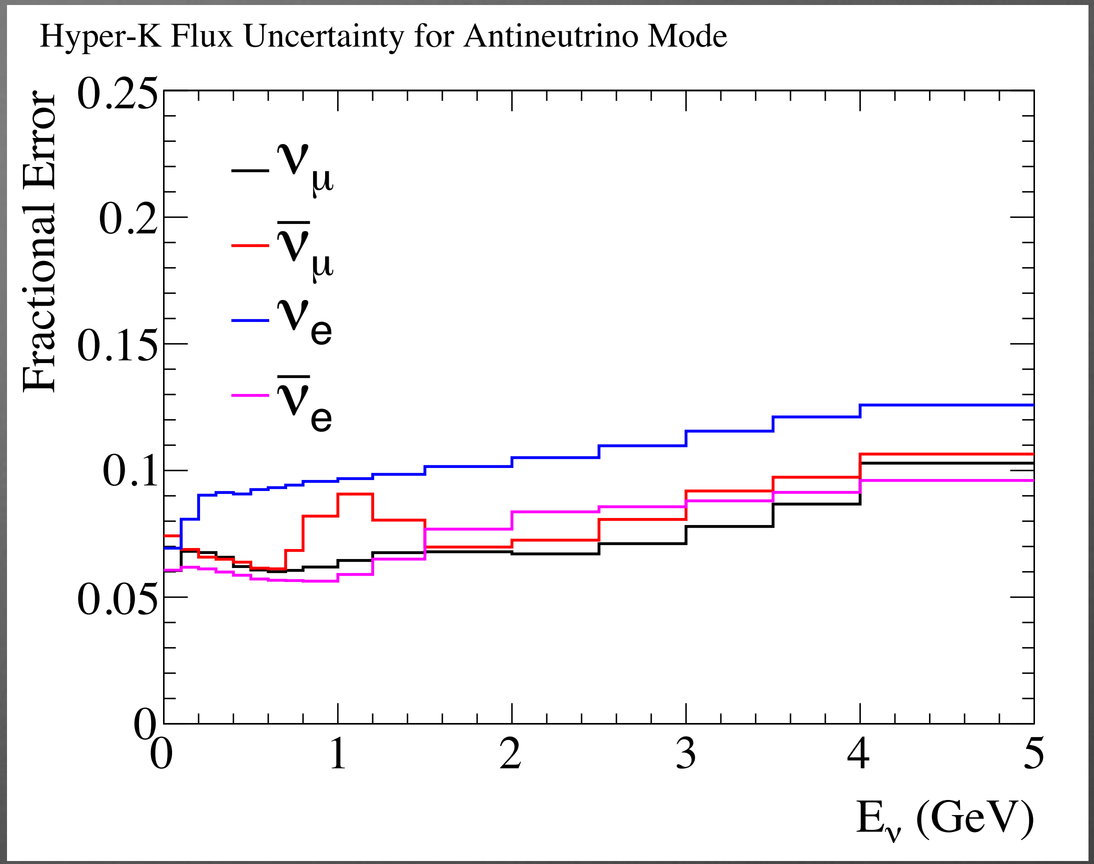
- Hyper-K flux and far-to-near ratio uncertainties
- Uncertainty dependence on baseline to near detectors
- Beam direction uncertainties and near detector position
- Updated treatment of systematic errors constrained by ND

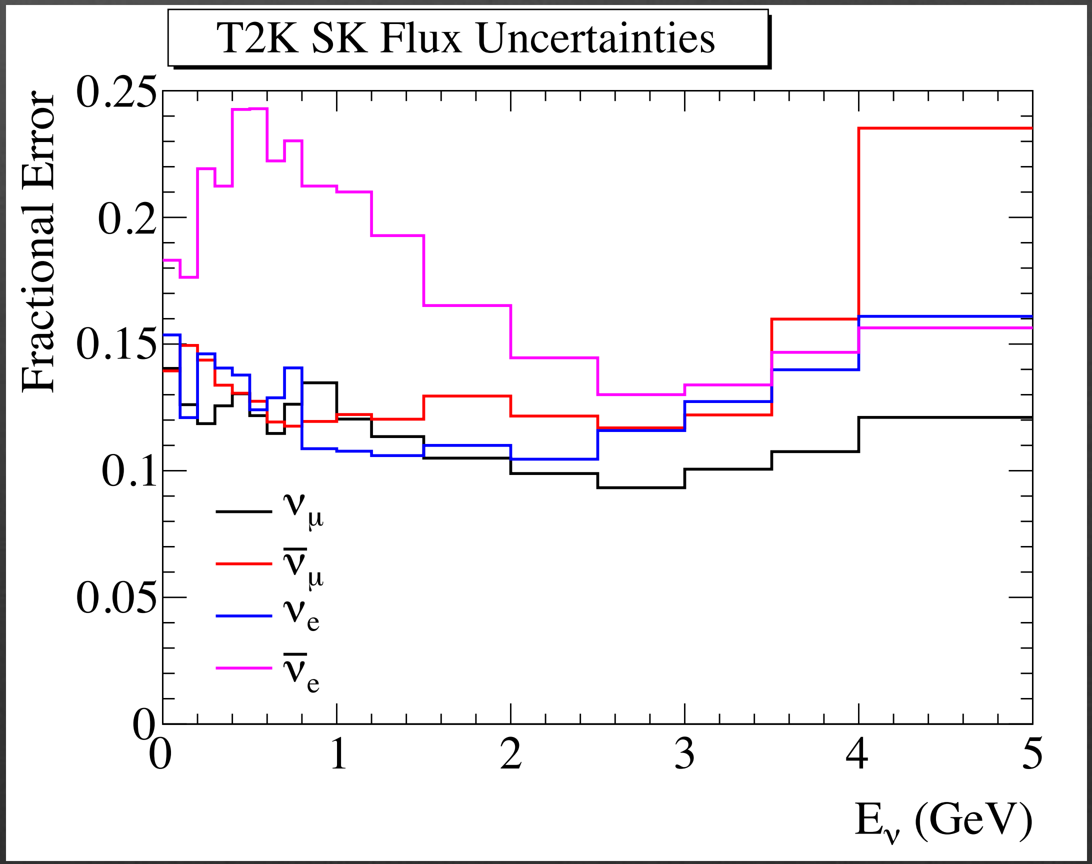
# Flux & Far-to-Near Ratio Uncertainties

- We have evaluated uncertainties on the flux and far-to-near ratios (F/N) based on the T2K flux model
    - Hadron production errors are updated assuming replica target data will be available
    - F/N errors give an estimate of the flux extrapolation uncertainty
- Can evaluate the error dependence on baseline to the near detector
- Errors on the F/N are split into two categories:
    - Errors that are evaluate with reweighting - hadron production, proton beam uncertainty, off-axis angle uncertainty
    - Errors that are evaluated with regeneration fo the flux - horn alignment, target alignment, horn currents

# Flux Uncertainties

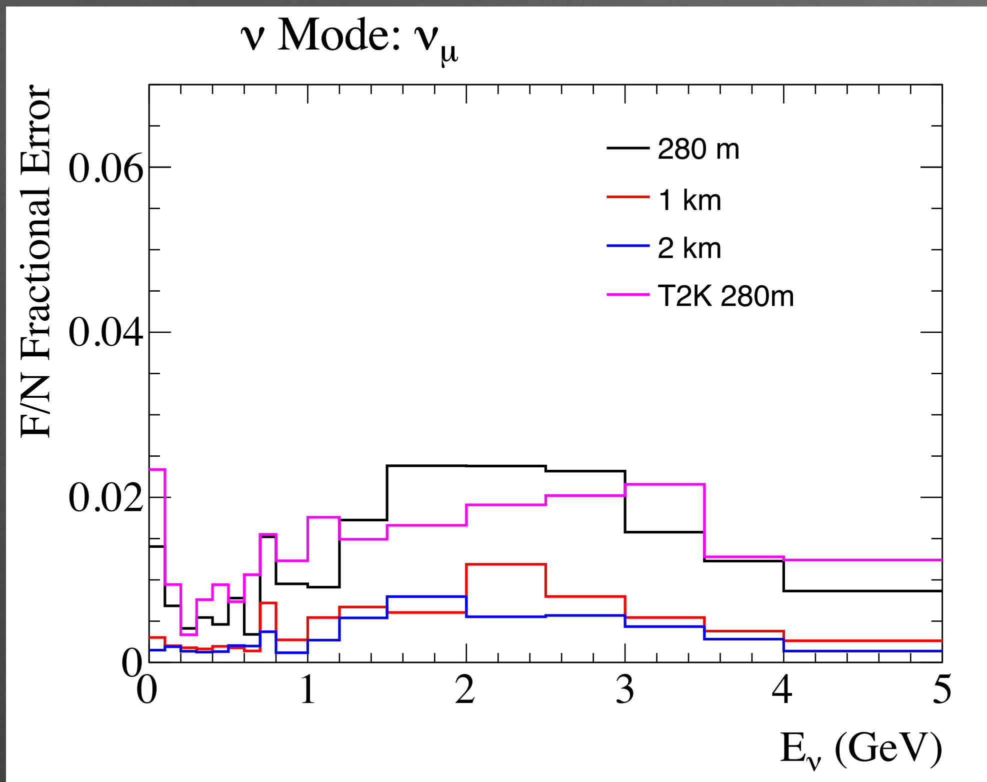


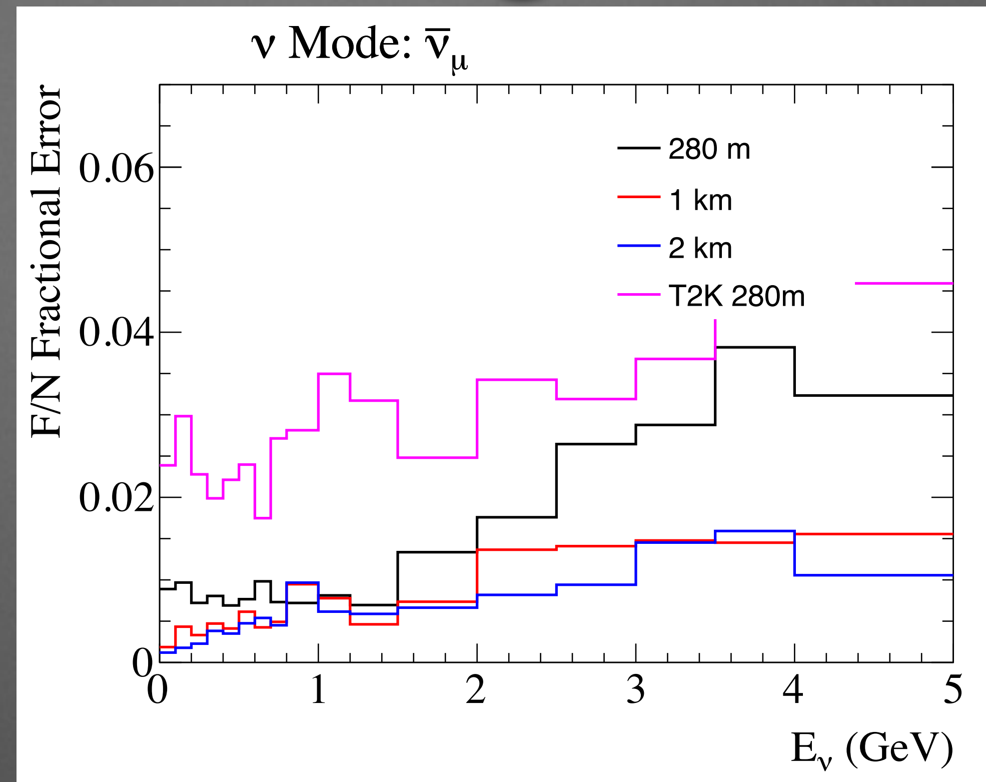



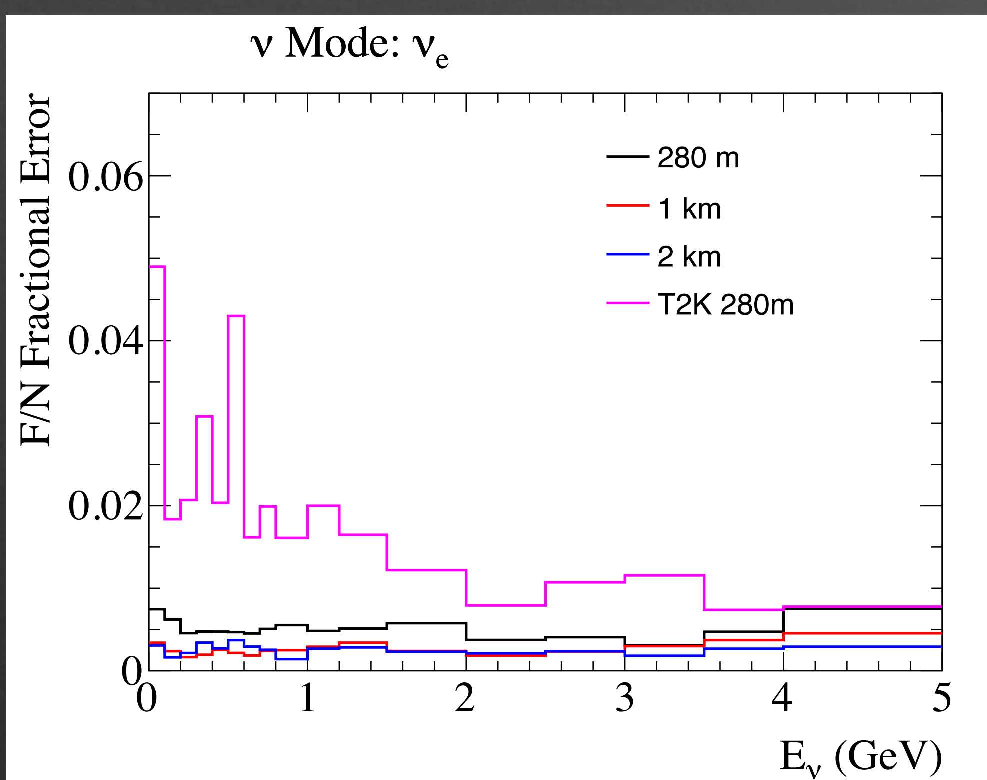



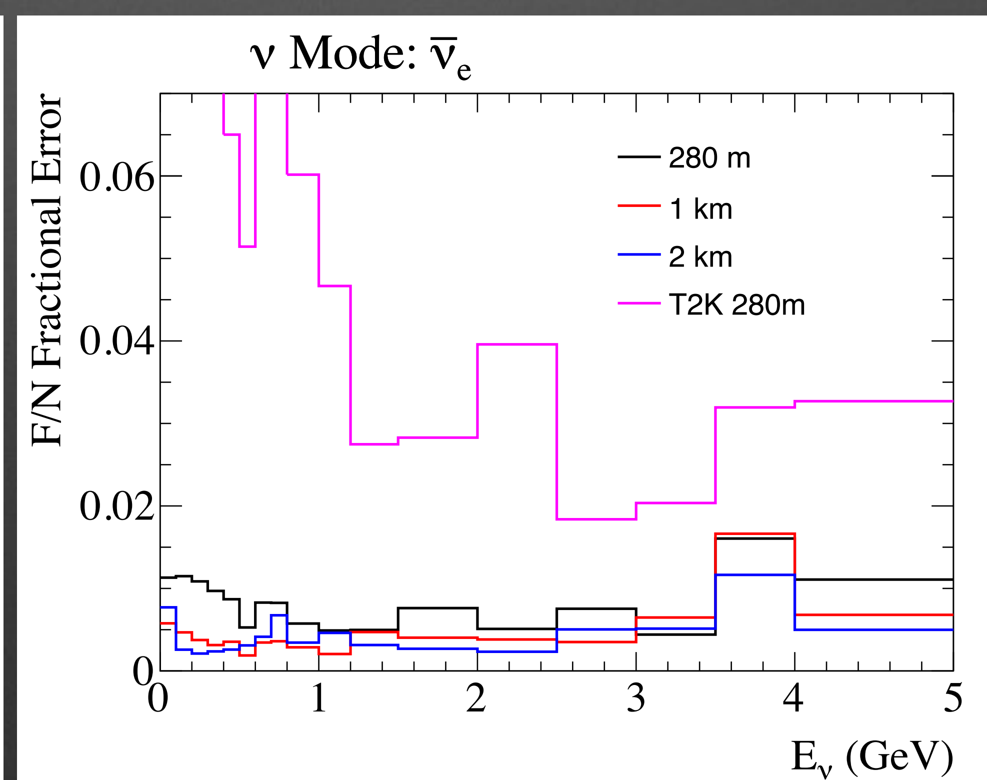

- Absolute flux errors for HK (top) are reduced by factor of ~2 compared to T2K errors (bottom)
  - From assumption of NA61 replica target hadron production data

# Neutrino Mode Reweighted F/N Errors



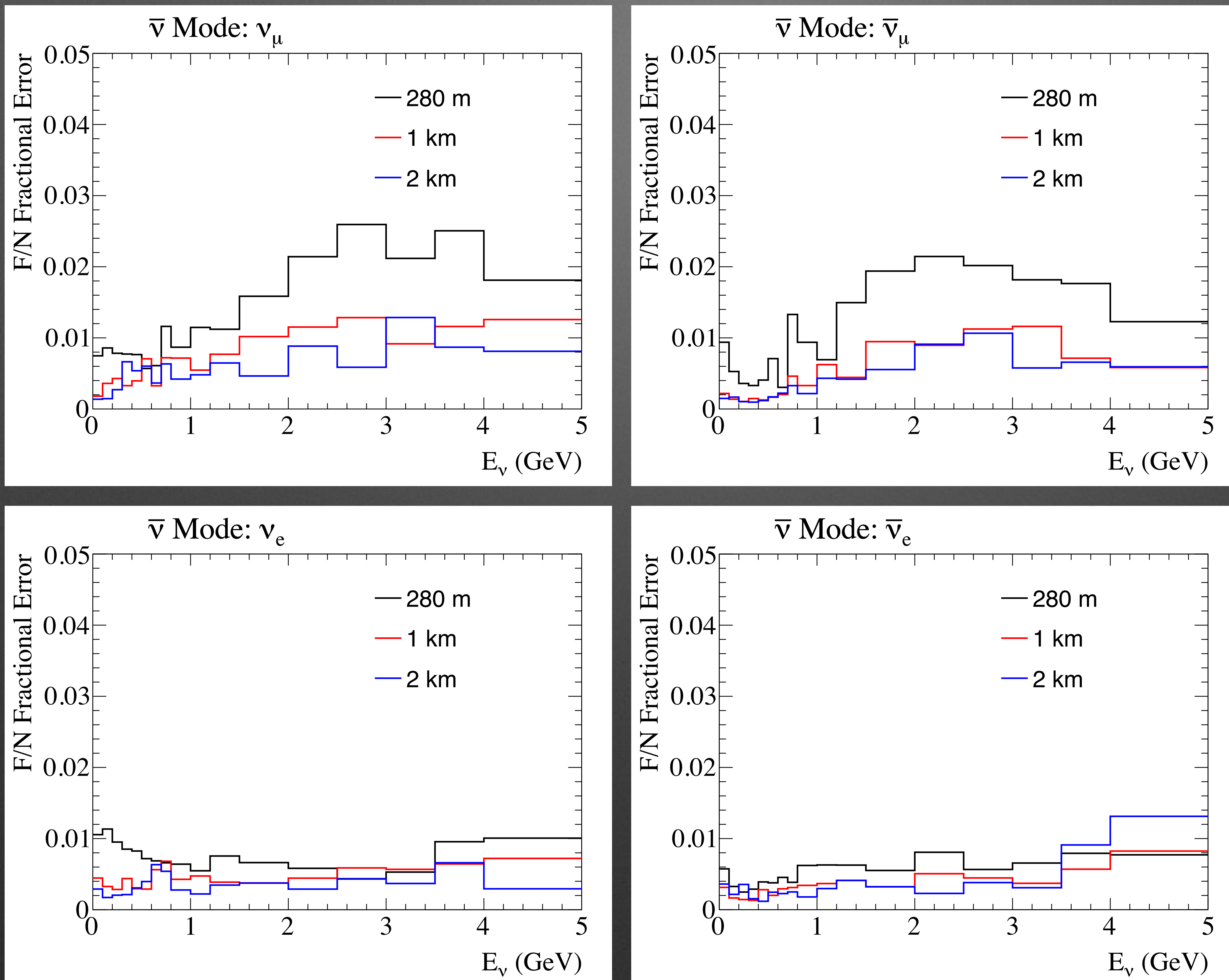




Write sign flux F/N errors are similar to T2K

Wrong sign and ve flux F/N errors are reduced compared to T2K

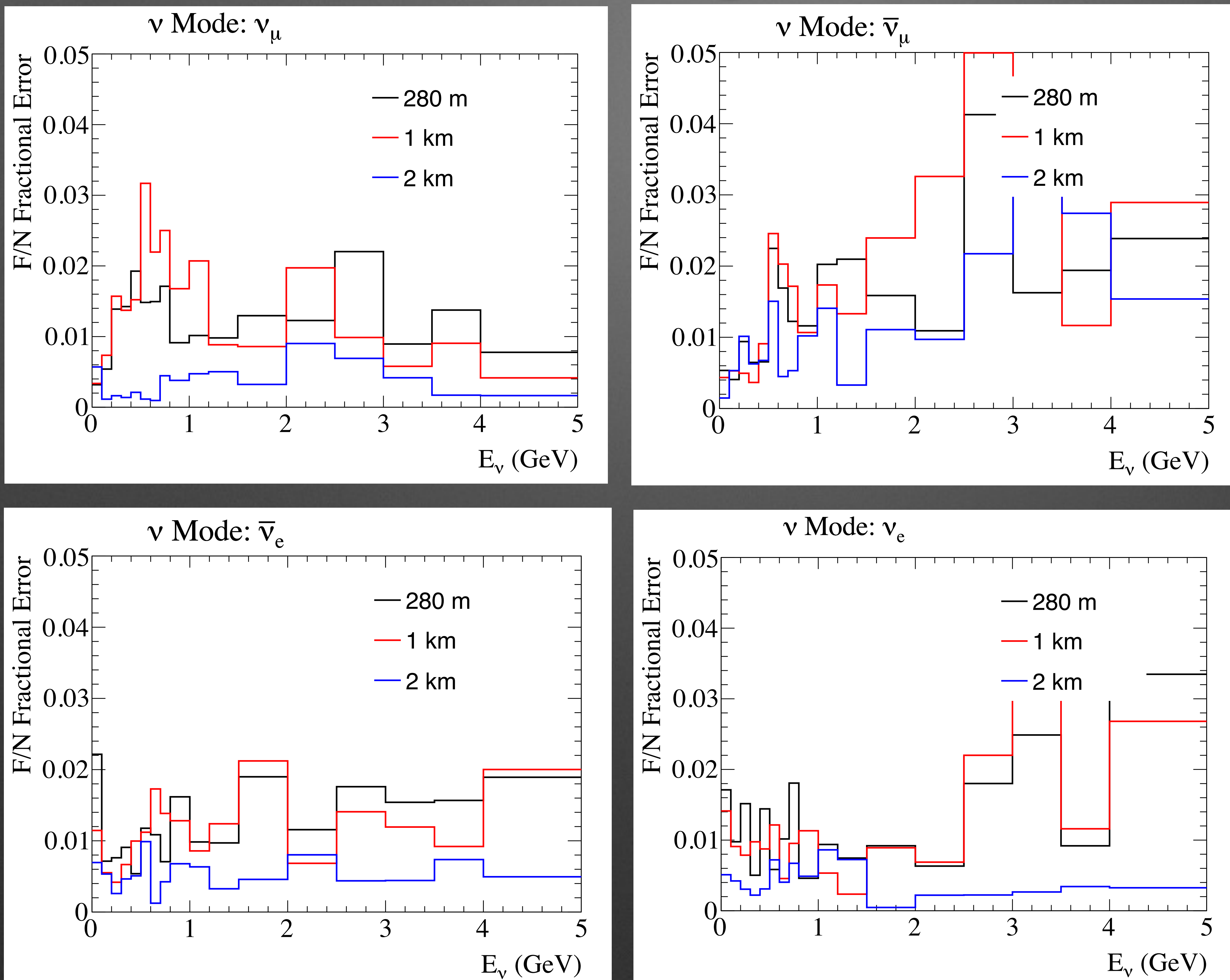
Some reduction of F/N error with longer baseline to near detector

# Antineutrino Mode Reweighted F/N Errors




Similar conclusions to neutrino mode

# Neutrino Mode Regenerated F/N Errors



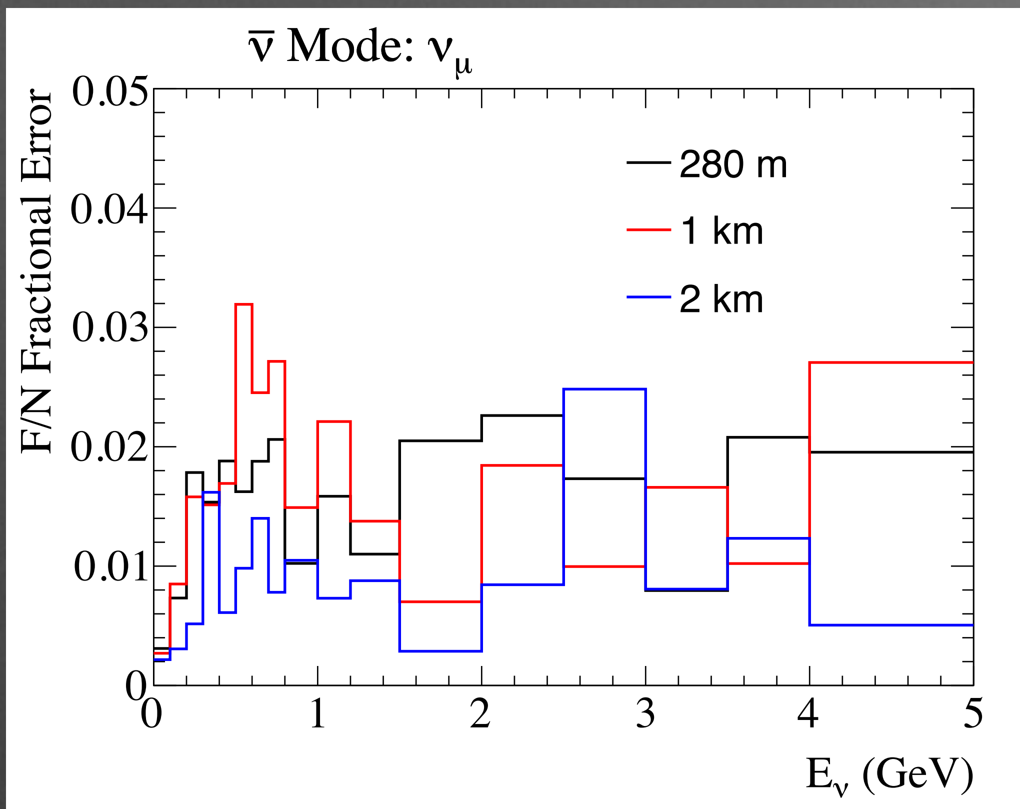

R. Terri

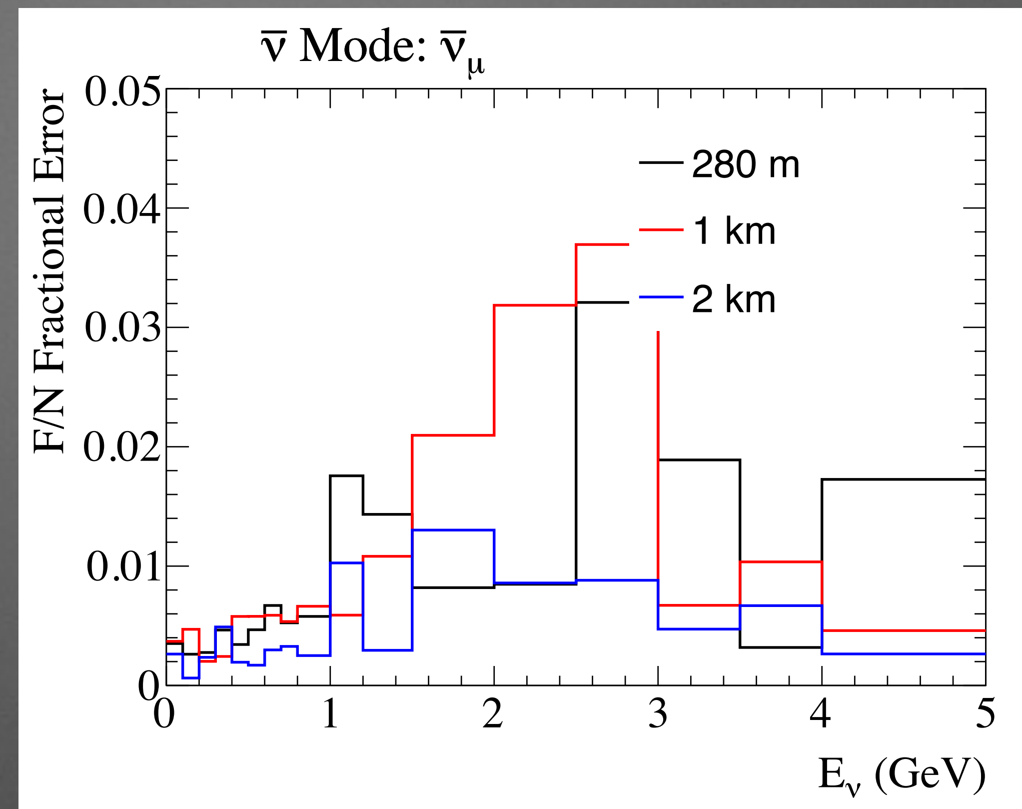
Statistical errors are significant.

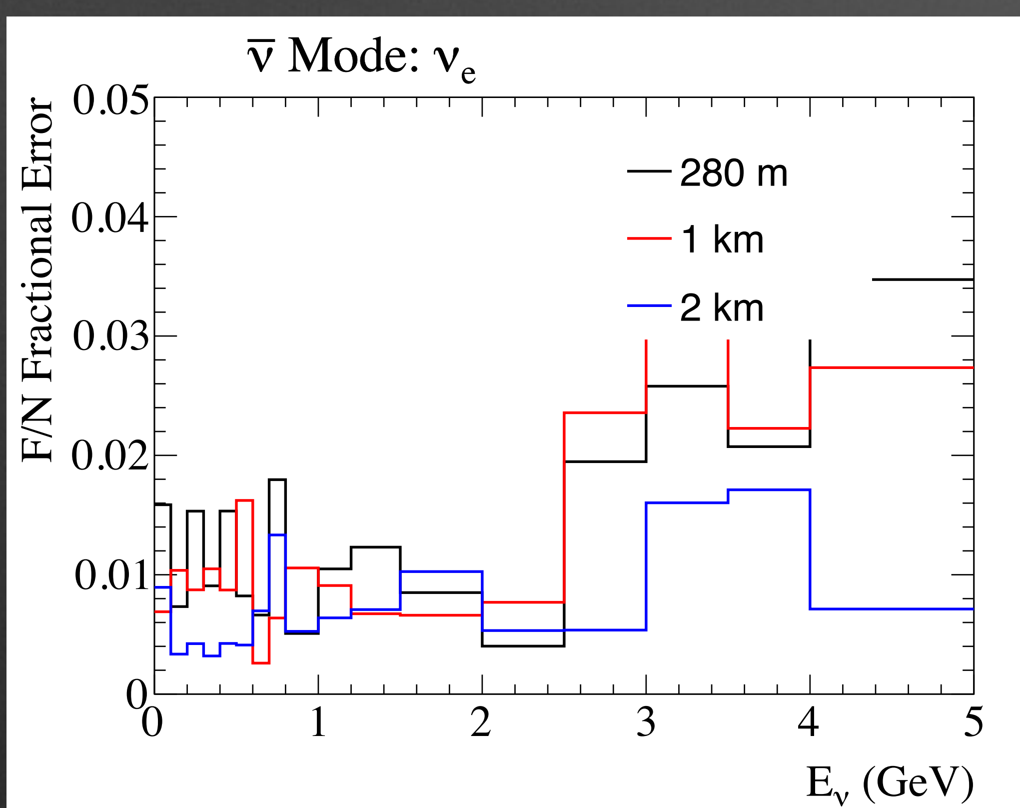
Higher statistics 2 km samples show alignment errors reduced to <1% for the right sign flux

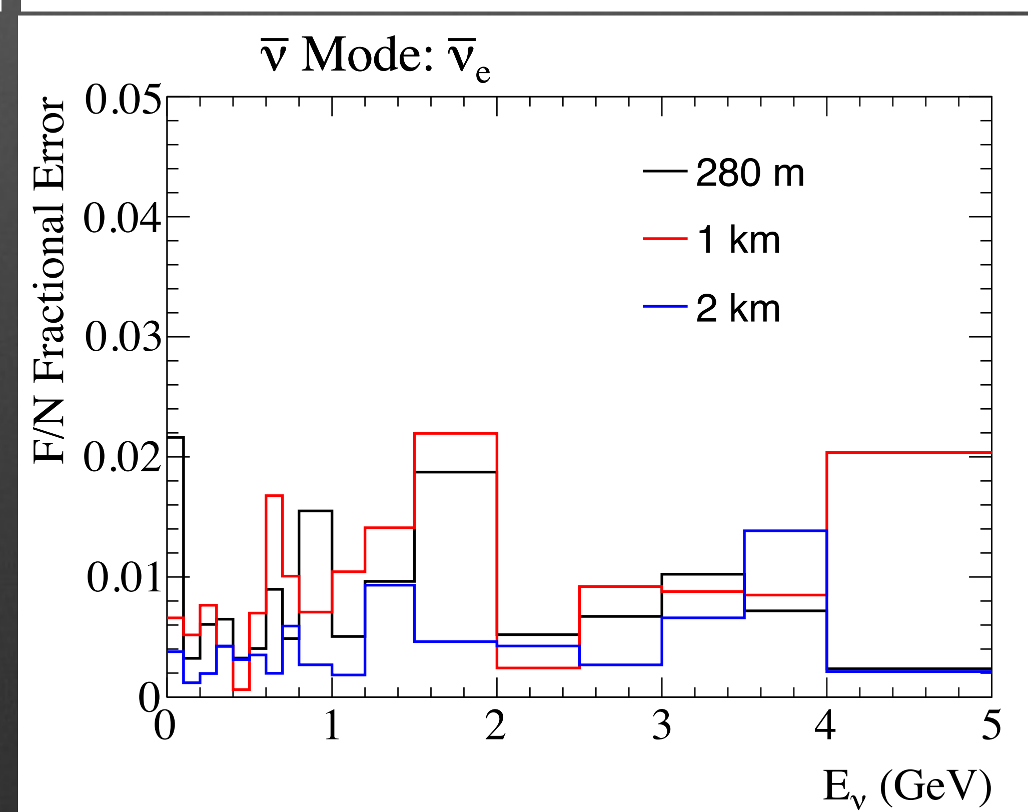
# Antineutrino Mode Regenerated F/N Errors

R. Terri



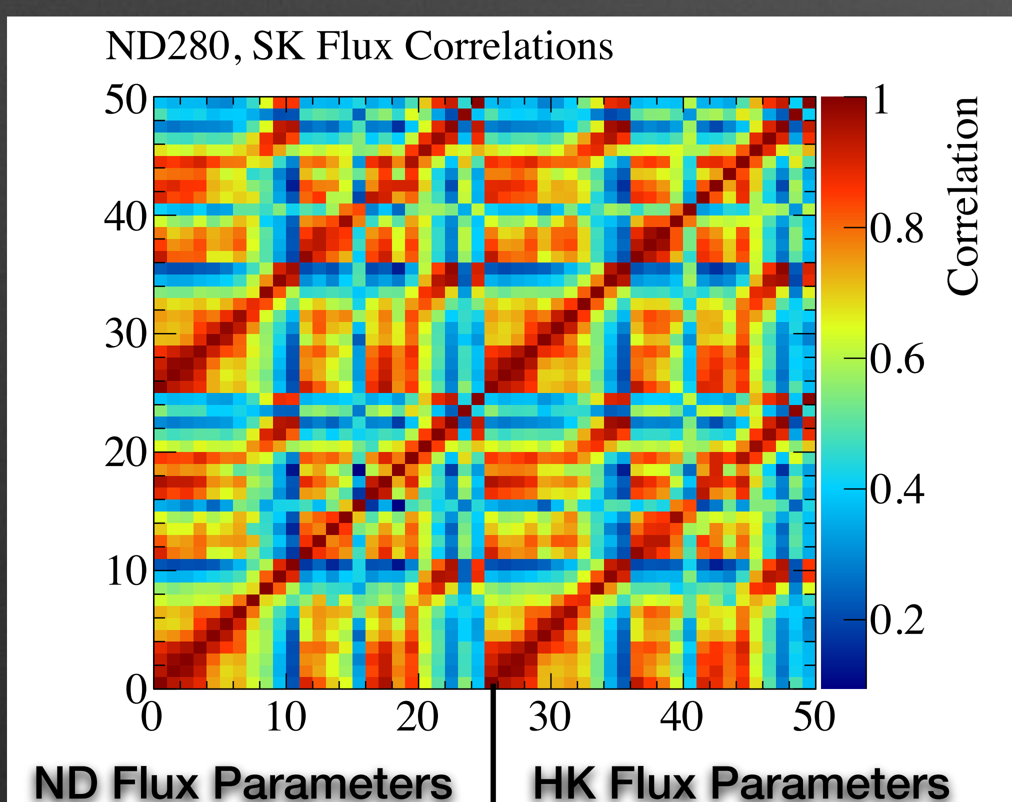

Similar conclusions to neutrino mode

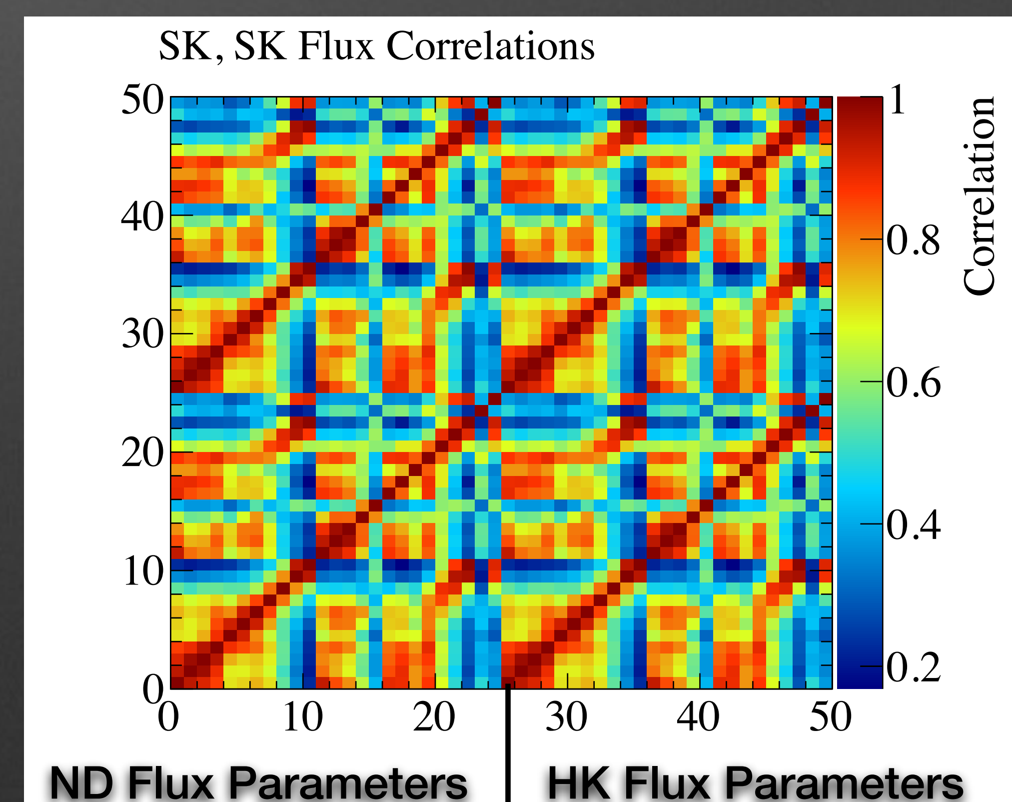
# Conclusion on F/N Ratio Uncertainties

- We see the F/N ratio error does depend on the baseline, but even 280 m flux has <1% errors near the flux peak for reweightable systematic variations
- Would need to generate many more statistics to evaluate all of the alignment errors to the <1% level
- We study an extreme case of F/N ratio errors to determine if baseline is important and this needs further study (next slide).

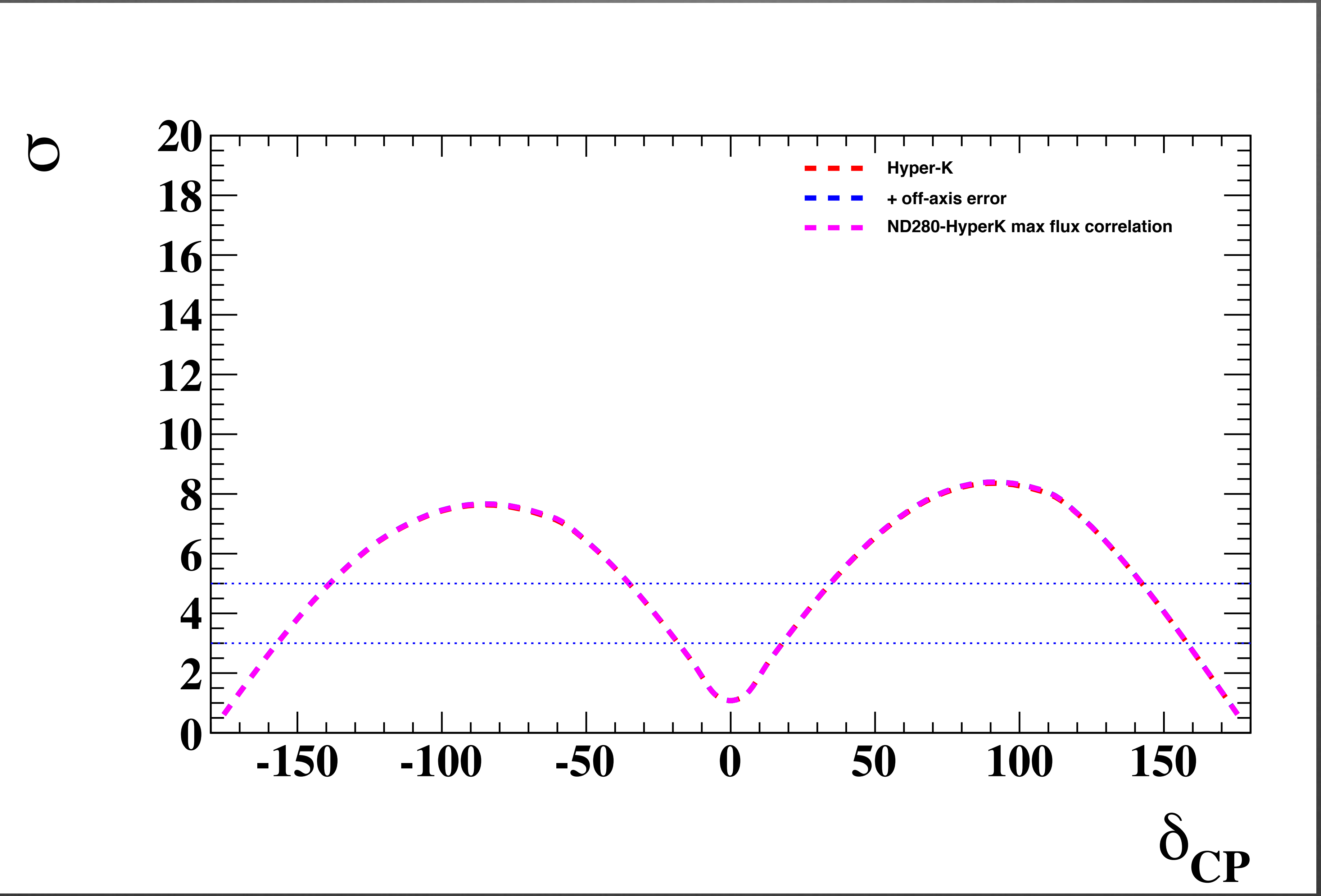
# Near Detector Baseline

- Is it important to have a near detector at a longer baseline so the flux is more similar to the far detector flux?
- We can check the extreme case: assume the flux uncertainties are identical at the near and far detector
  - Rerun the near detector fit and compare to the case where the 280 m flux uncertainties are used
  - Evaluate in the HK sensitivity framework



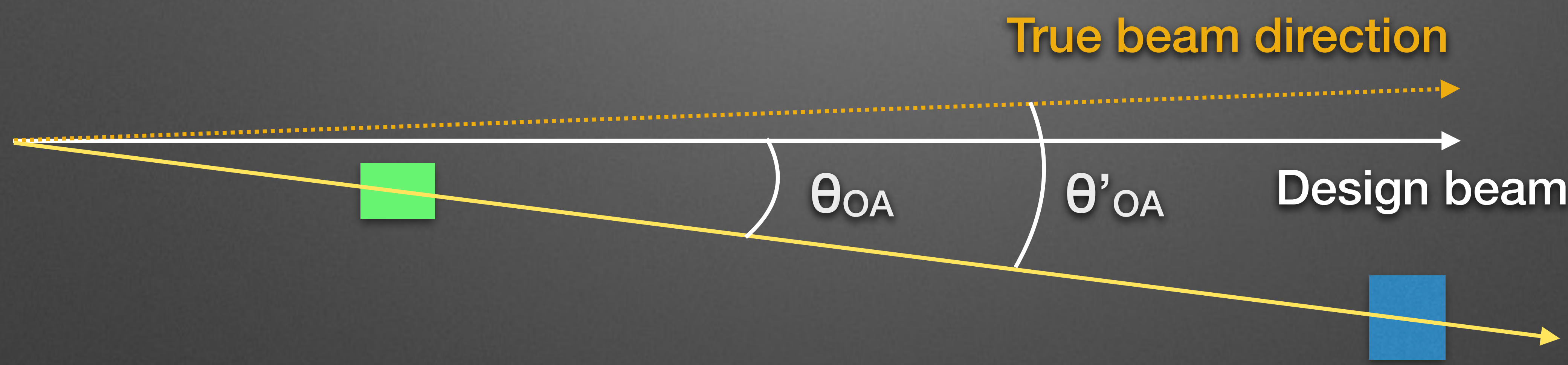
# Perfect Flux Correlation Sensitivity




- The CP violation sensitivity is not significantly improved by moving to perfect correlations for the near and far flux parameters
- In current sensitivity framework, ND baseline is not very important

# Beam Direction Uncertainty

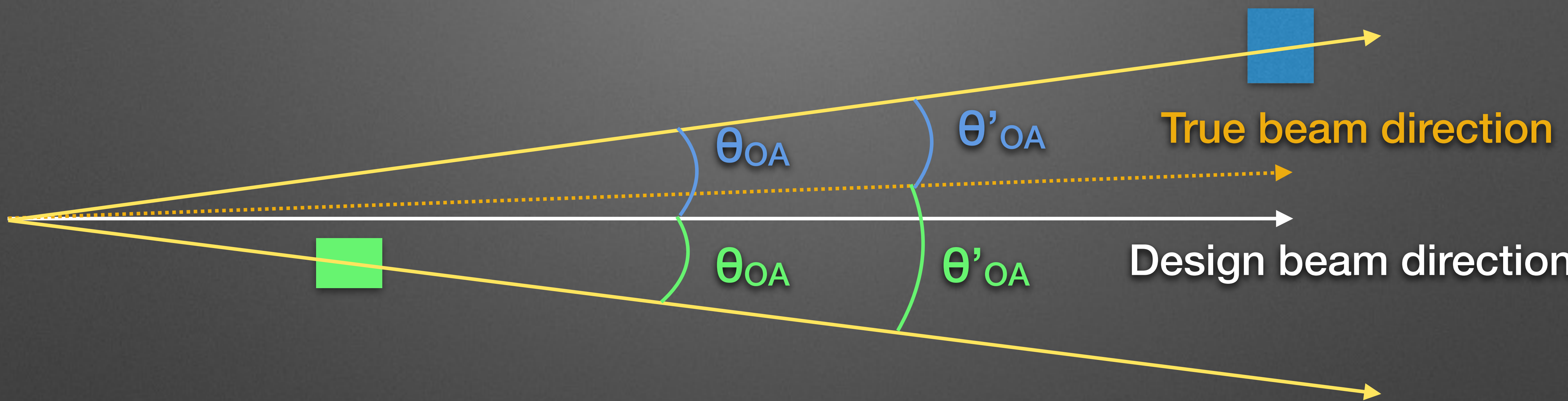
- If the near detector and far detector are in the same direction (ND280 and SK), then any change to the beam angle affects the near and far flux in the same way:




- The change in the flux is detected at the near detector and can be applied to the far detector prediction

# Near and Far Detectors, Different Direction

- However, near detector and far detector may have the same design off-axis angle but not be in the same direction (ND280 and Tochibora)

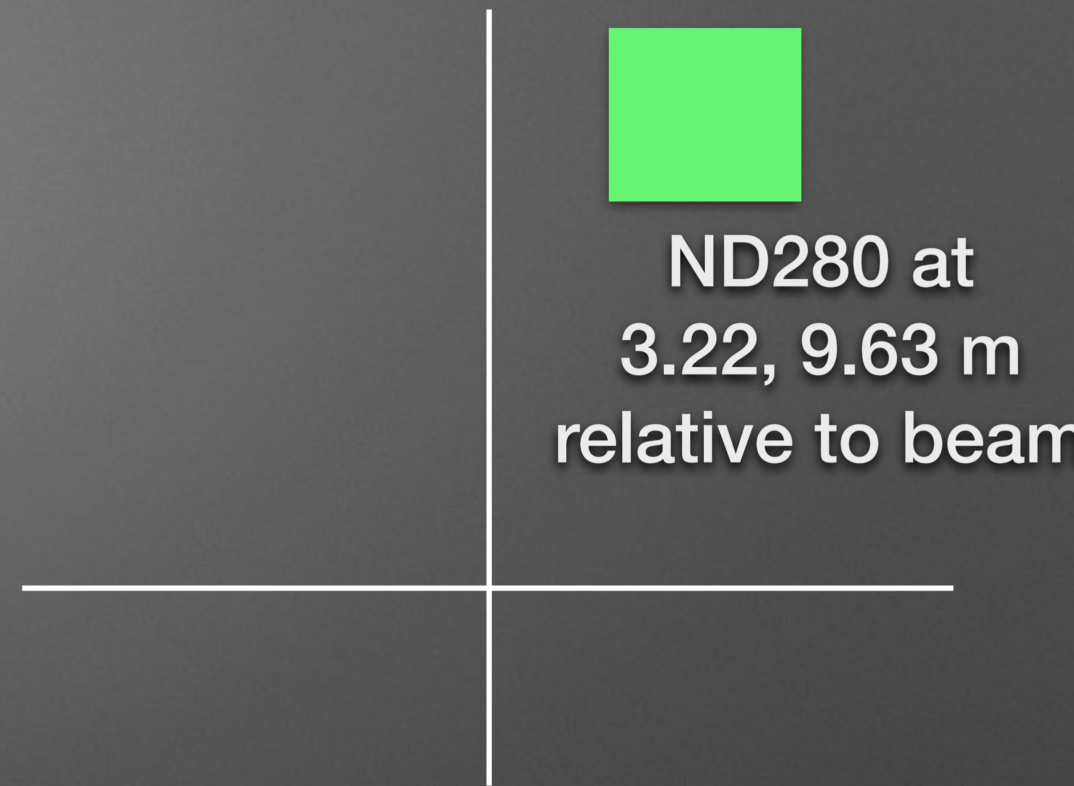


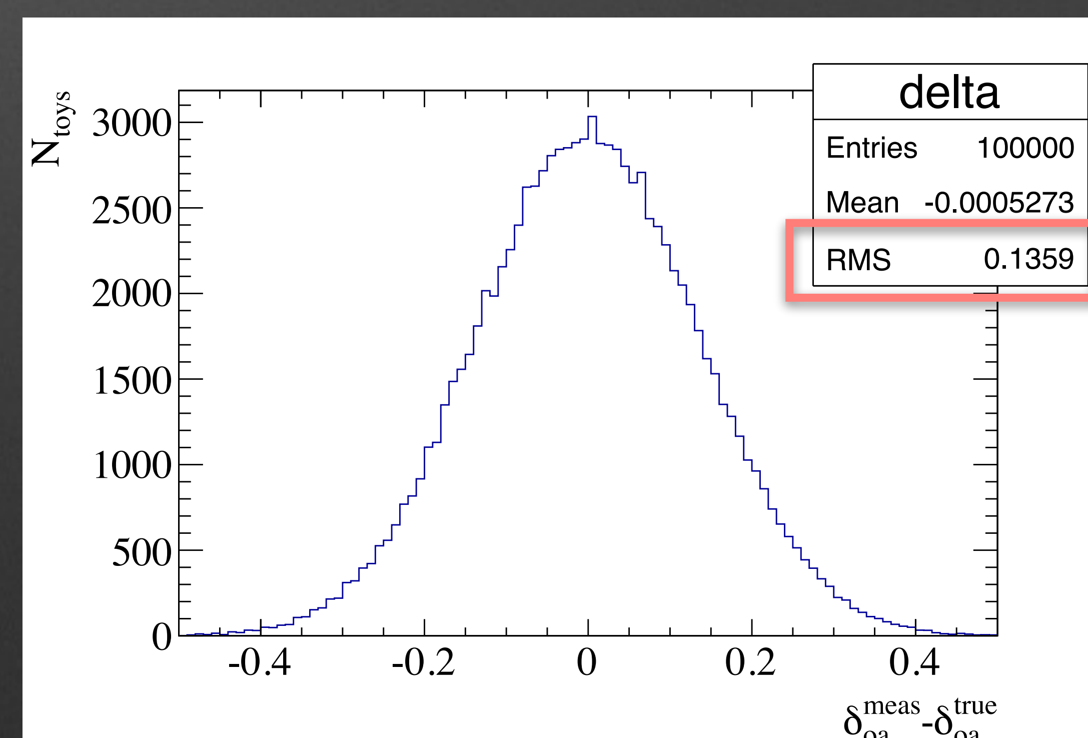

$$\theta'_{OA} \neq \theta'_{OA}$$

- Can't we say $\theta'_{OA} = 2\theta_{OA} - \theta'_{OA}$?
  - Doesn't work since an x shift of the beam affects the near and far detectors in the opposite direction while a y shift affects them in the same way - there is ambiguity

# Updated Beam Direction Uncertainty

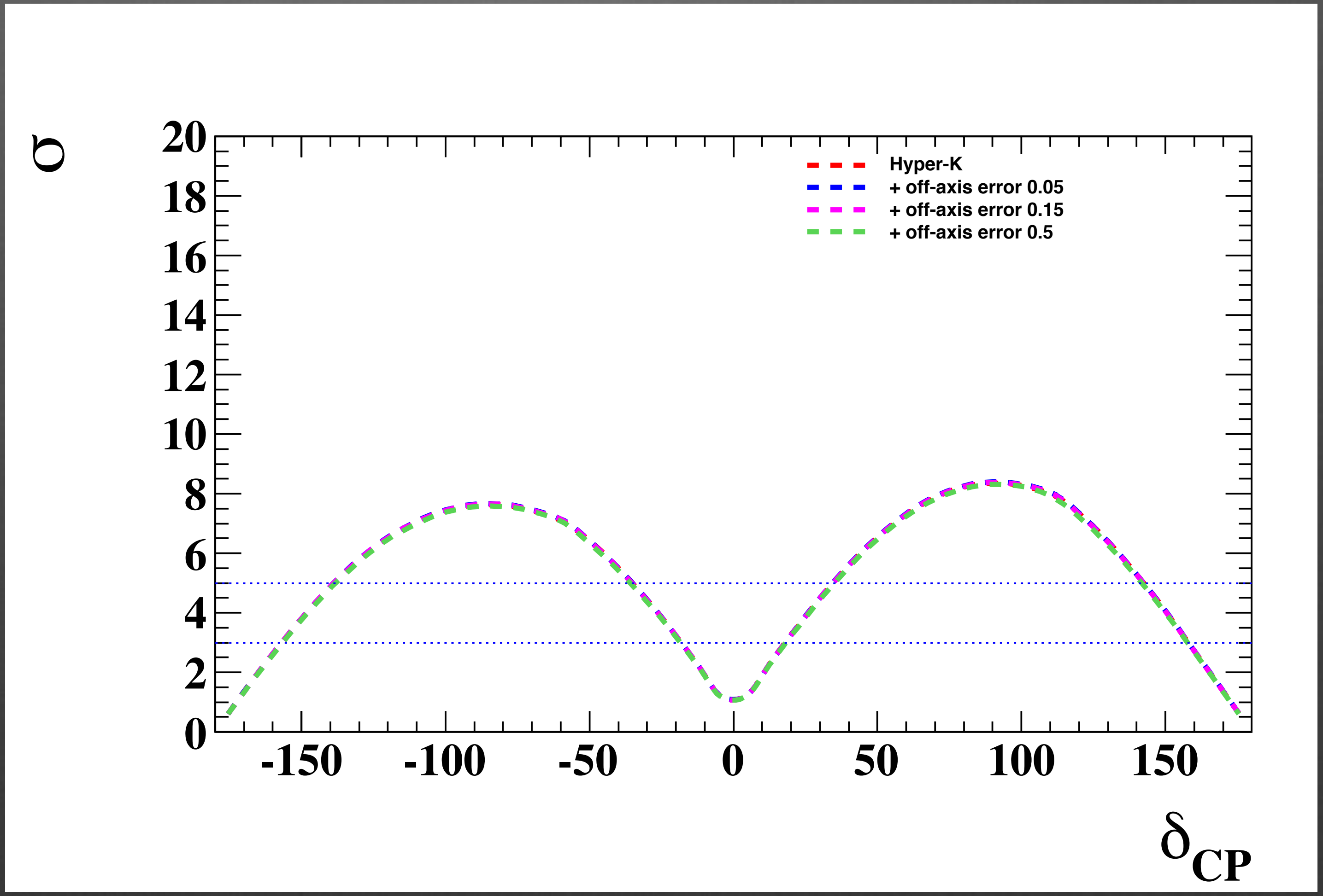
- Assume INGRID uncertainties on the beam center position are ~5 cm. Uncertainty from y has larger effect because most of off-axis effect comes from the vertical inclination
  - $\delta_y$ = 0.2 mrad
  - $\delta_x$ = 0.08 mrad
- If we assume any shift is completely in the y direction, then we introduce a systematic error of ~0.14 mrad in the far detector off-axis angle measurement



# Effect on Sensitivity Results on Sensitivities

- We evaluate off-axis angle uncertainties of 0.05, 0.14 and 0.7 mrad
  - This uncertainty is added after the near detector constraint
  - Uncorrelated for neutrinos and antineutrinos (assuming time dependence)




- Don't see a significant change to the sensitivity due to the off-axis angle error.

# Near Detector Constraint on Nuclear Model Parameters

- In the HK LOI sensitivity studies, there are parameters that are currently not constrained by T2K ND data because measurements are on carbon (mostly related to the nuclear effects for CC0π)
- We assume that these errors will either go to 0 or become significantly smaller when measurements are made on water
- Instead, we can assume that the current ND fit is on water and constrain these parameters

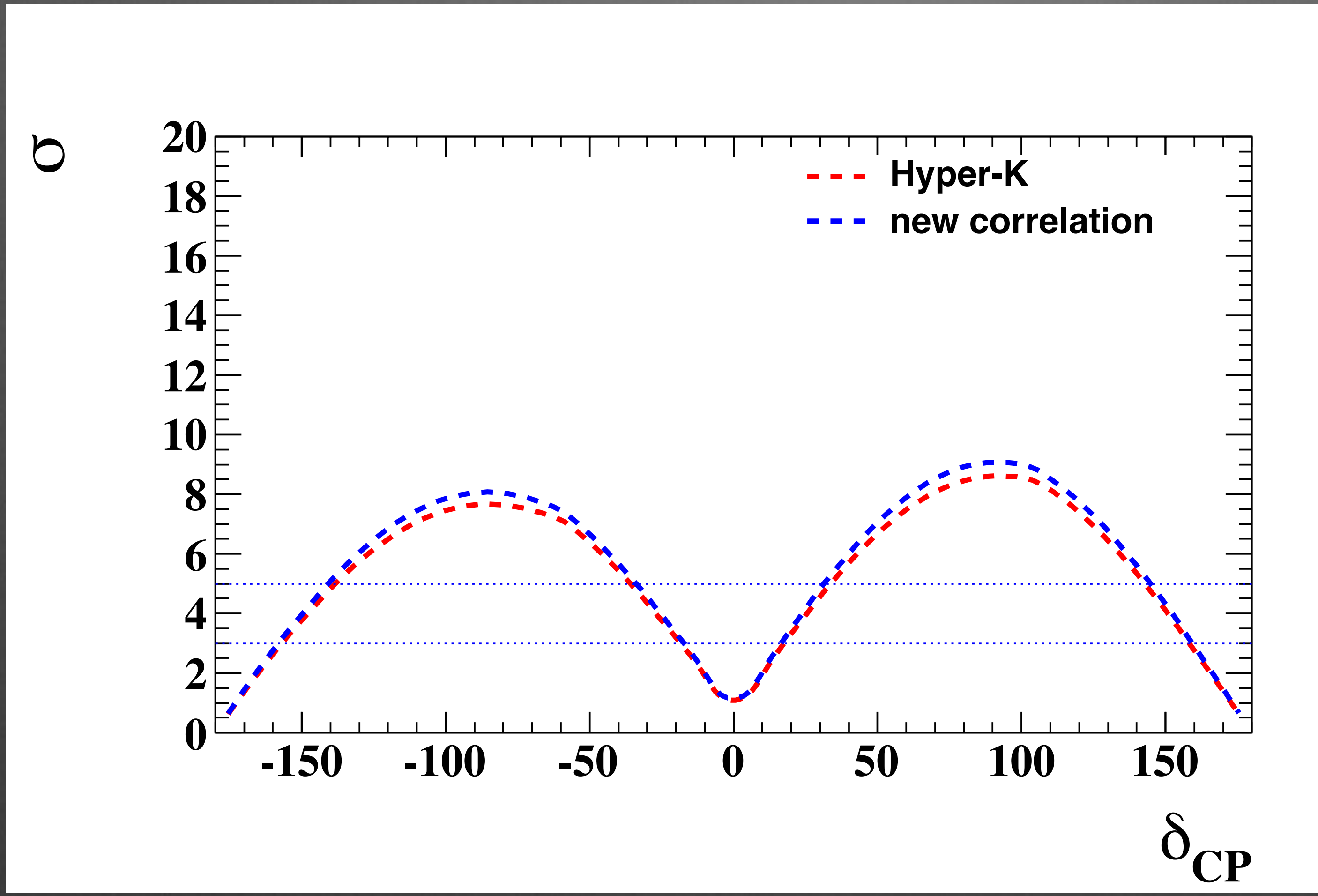
L. Cremonesi

| | Source | T2K | Hyper-K | With ND Constraint |
|---|---|---|---|---|
| I | Fit to Near detector[1] | T2K | T2K | |
| II | CC Other shape[2] | 0.4 | 0 | 0.29 |
| | Spectral function[2] | 1.0 | 0 | 0.13 |
| | Fermi momentum[2] | 0.138 | 0 | 0.049 |
| | Binding energy[2] | 0.36 | 0 | 0.21 |
| | CC Coherent[3] | 1 | 0.5 | |
| | NC Other[3] | 0.3 | 0.3 | |
| | NC Coherent[3] | 0.3 | 0.3 | |
| | Pion-less Δ decay[3] | 0.2 | 0.05 | 0.085 |
| | CC $\sigma_{\nu_e}/\sigma_{\nu_\mu}$ | not used | 0.03 | |
| | CC $\sigma_{\nu}/\sigma_{\bar{\nu}}$ | not used | 0.06 | |
| III | Final State Interactions | T2K | T2K | |
| | Far detector[4] | T2K | $T2K/\sqrt{20}$ | |

The fitted errors are used as well as the correlations to parameters previously constrained by the ND280 fit

# Results of ND Constraint on Nuclear Parameters

- The SimpleFitter sensitivity framework was modified to accept these additional systematic parameter correlations and rerun:




- The CP violation sensitivity is slightly improved by including the constraint on these parameters
- In the original framework, they are marginalized, reducing cancellations with flux parameters

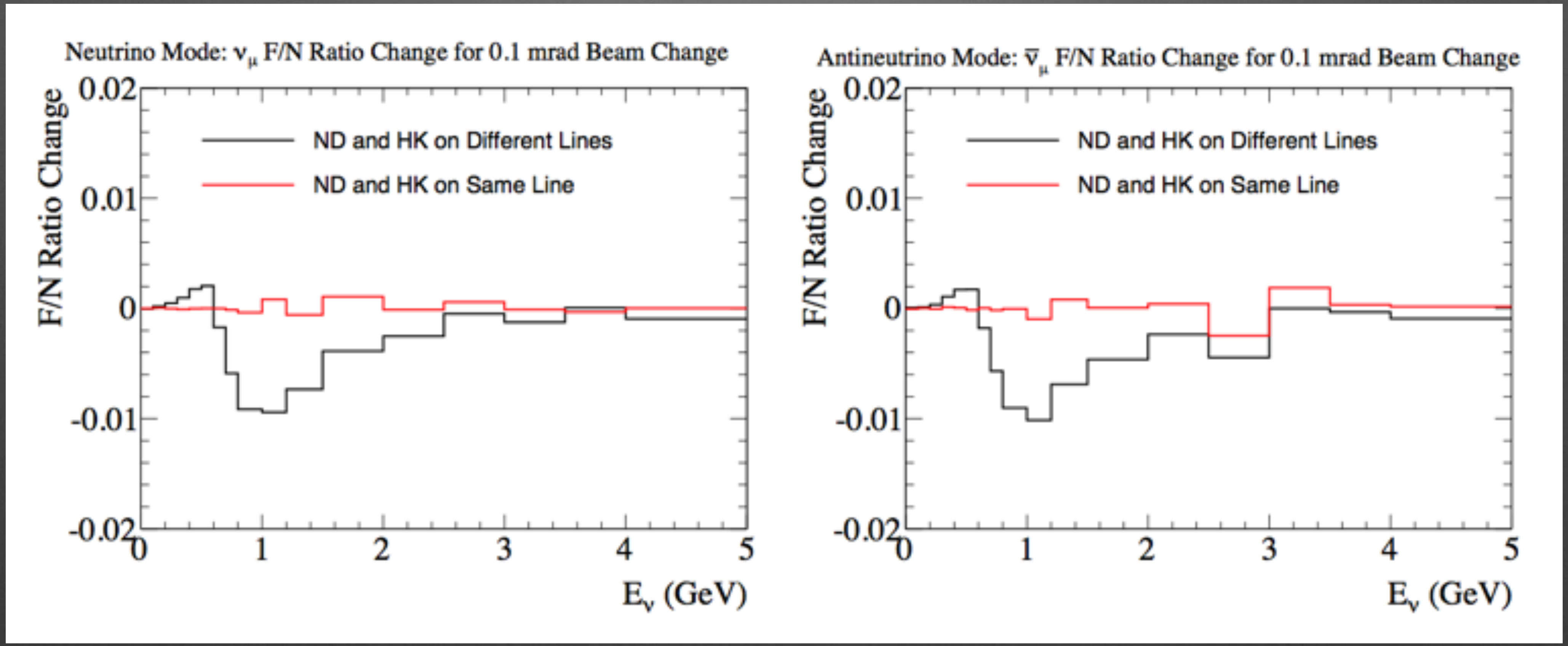
# Conclusion

- Flux unceraintties have been studied and there is a dependence of the extrapolation uncertainty on the baseline
  - Not a large effect for the CP violation sensitivity
- The beam direction uncertainty has been studied for the case where the near and far detector are not in the same direction
  - Once again, the effect on the CP violation sensitivity is small
- In the current near and far detector fitting framework, we studied the effect of constraining nuclear model parameters with the near detector, rather than setting the errors to 0
  - This tends to improve the CP violation sensitivity since there is better cancellation between flux and cross section parameters

# Extra Slides

# Off-axis Angle Error Treatment in LOI

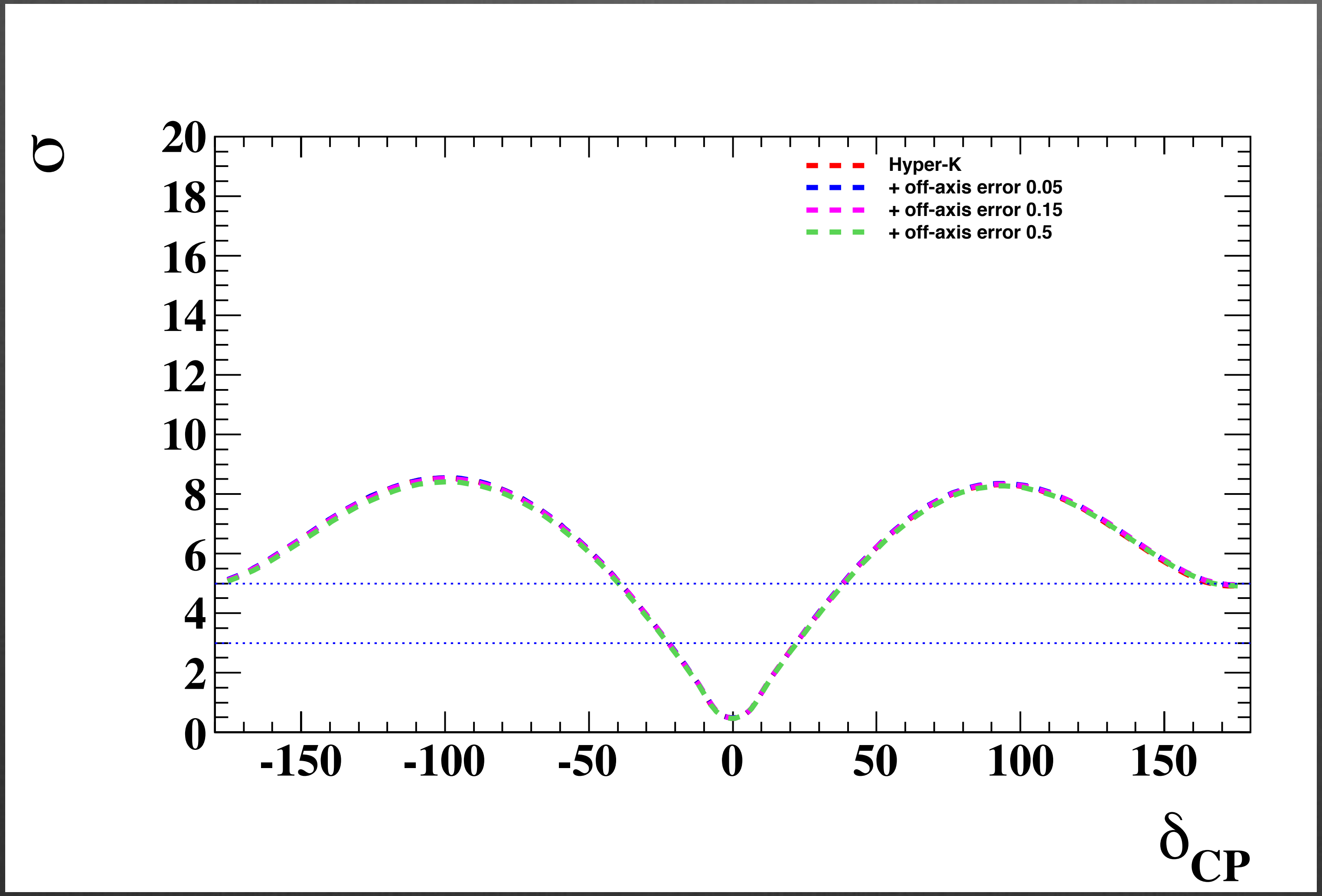
- In the LOI, we assigned and uncertainty equal to the difference between a +1 and -1 sigma shift of the beam x direction assuming a 1 sigma constraint of 0.1 mrad (2.5 cm) from INGRID:




- Introduces equivalent of a ~0.08 mrad uncertainty on the off-axis angle
- This may be underestimating the error because INGRID constraint is too tight
- Should better motivate assignment of 2x the x shift as uncertainty

# CP Conserving Degeneracy

- We check if the off-axis angle uncertainty affects the ability to separate δ=π and δ=0
- Look at sensitivity with Δχ2 calculate relative to δ=0




No significant change to the separation between the CP conserving solutions

# HK Prediction Uncertainty

- Neutrino mode appearance prediciton with fractional errors

- Solid are with the new near detector constraint on nuclear model parameters, dotted are the old errors.