Neutrino Flux Uncertainties for Tokai to Hyper-Kamiokande (T2HK)

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Purpose of These Studies

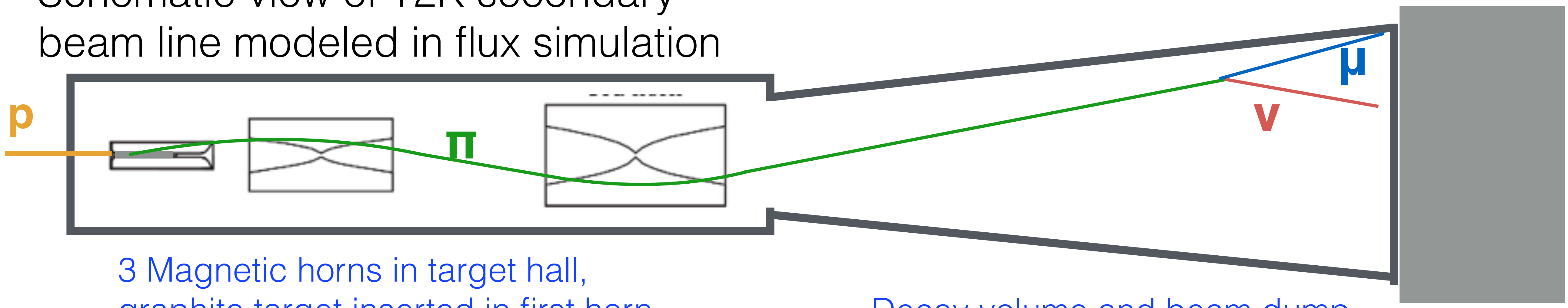
- Uncertainties on the neutrino flux are important systematic errors in neutrino oscillation measurements
- Experiments make measurements with near detectors to update and refine their models of the neutrino flux and interaction cross sections
  - Uncertainties on the flux should be evaluated in the context of near detector rate measurements and extrapolation methods
- We study the “extrapolation” uncertainties for different near detector sites
  - Simplest format is uncertainty on the far-to-near ratio

$$\Phi^{far}(E_\nu) = \boxed{\frac{\Phi^{far}_{pred.}(E_\nu)}{\Phi^{near}_{pred.}(E_\nu)}} * \Phi^{near}_{meas.}(E_\nu)$$

  - We also consider a covariance matrix between the flux predictions at the near and far detectors that can be used in a simultaneous fits to near and far detector data

T2K Flux Simulation

Schematic view of T2K secondary beam line modeled in flux simulation



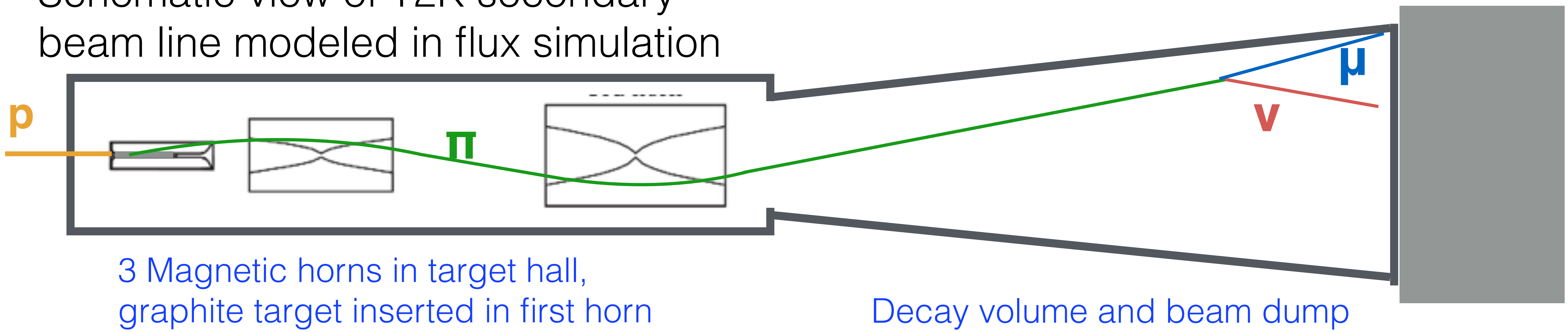
3 Magnetic horns in target hall, graphite target inserted in first horn

Decay volume and beam dump

Flux prediction from data driven simulation

- Input proton beam profile measured by beam monitors
- Simulate interactions in T2K target with combination of NA61/SHINE hadron production data and FLUKA
- Model beam line elements including horns, target hall, decay volume and beam dump in GEANT3
  - Interactions in material by GCALOR with tuning from hadron production data
  - Fields in horns based on current and field measurements
- Particles are decayed based on measured branching ratios and lifetimes

T2K Flux Uncertainties



Schematic view of T2K secondary beam line modeled in flux simulation

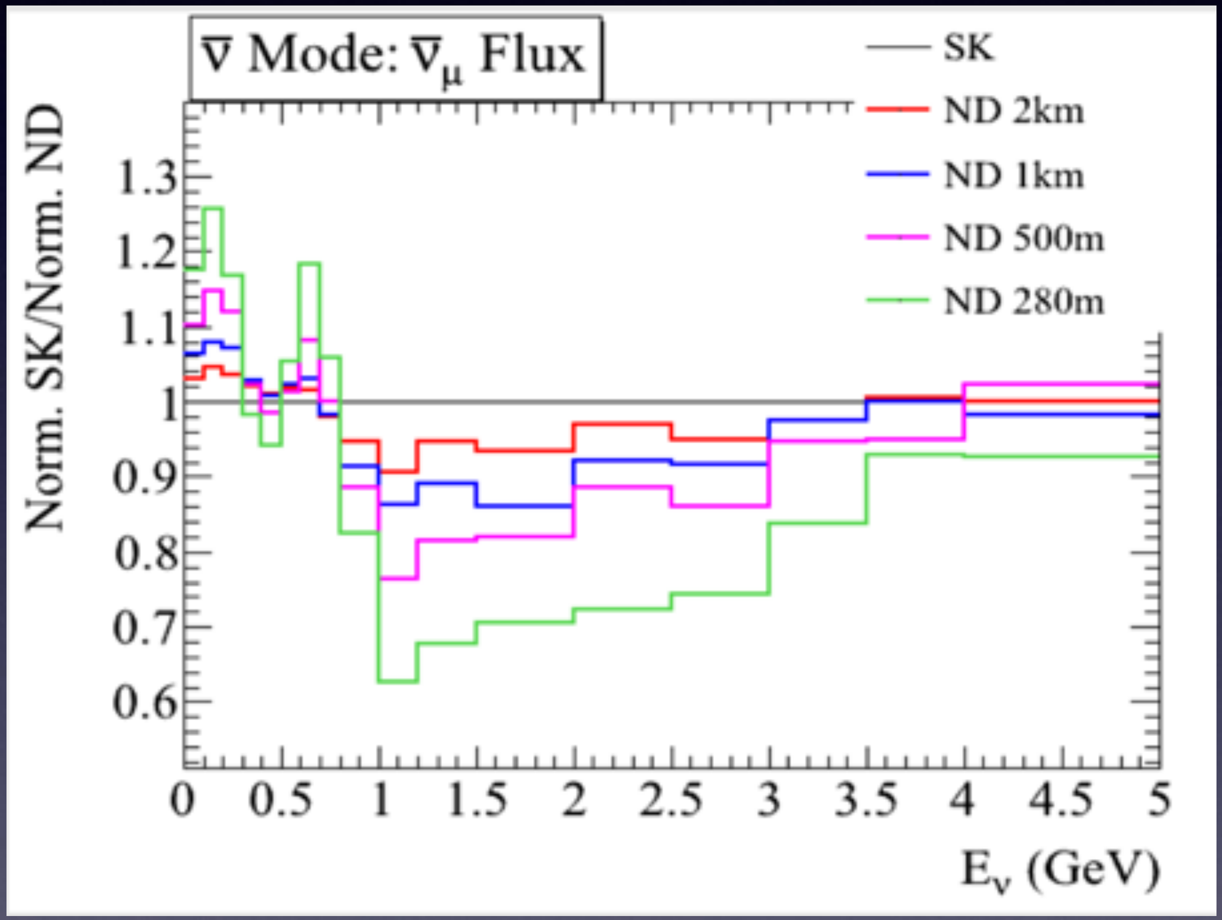
Sources of uncertainties in the data driven simulation

- Systematic uncertainties of the proton beam profile measurements
- Systematic uncertainties of hadron production data
  - NA61/SHINE data uncertainties
  - Extrapolation from thin target hadron production data to long T2K target (90 cm)
  - Interactions in horns (Al), decay volume walls (Fe) or beam dump (C)
- Systematic uncertainties of horn current and field measurements
- Alignment uncertainties of the target and horns

Flux Dependence on Distance from Target

The T2K off-axis near detector (ND280) is 280 m from the production target

It sees a line source of pion decays while SK sees a point source -> the far near ratio is not flat

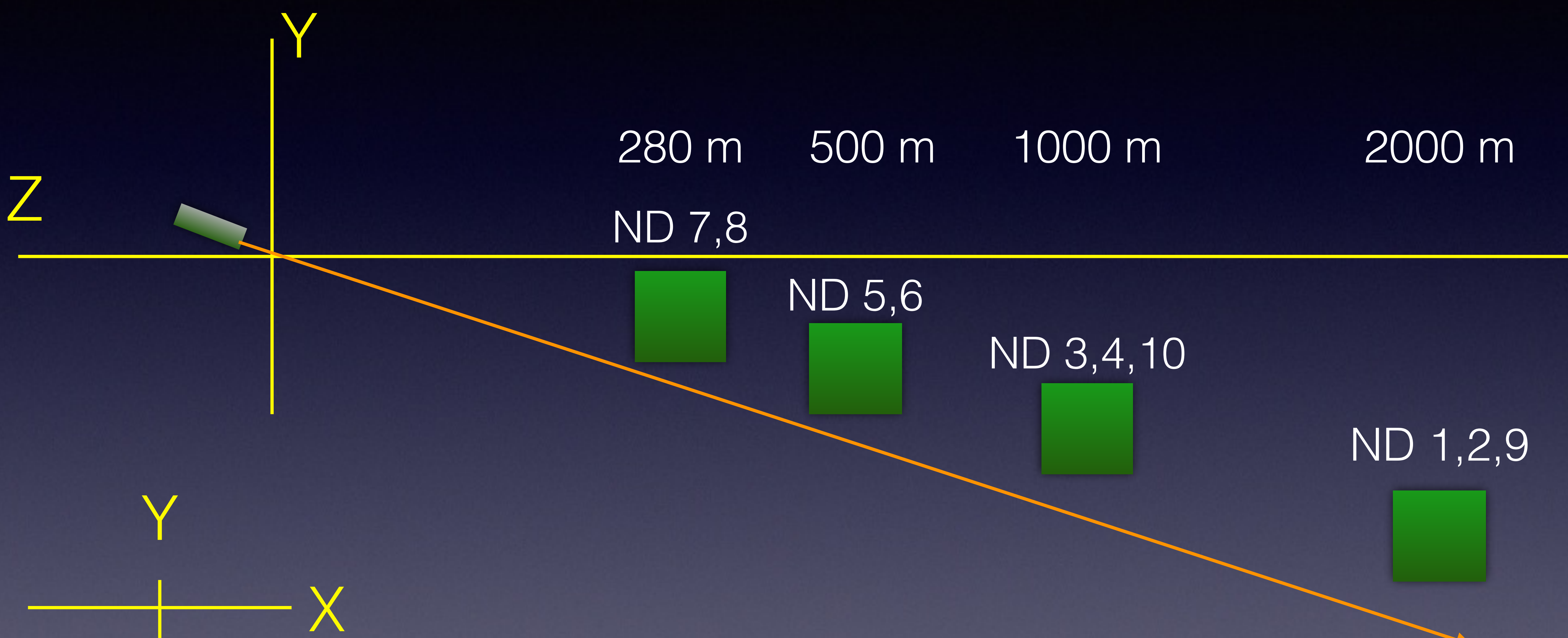


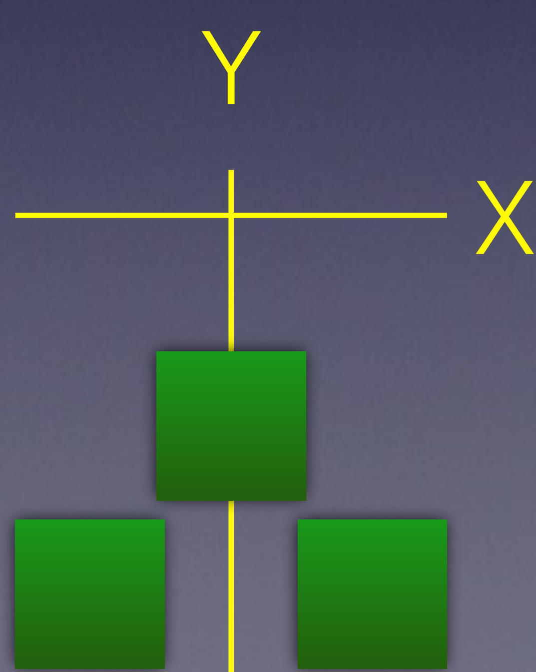
The flux becomes more similar to the SK flux further from the target and the F/N ratio become flatter

Expect the uncertainties on the flux extrapolation to decrease as well -> We want to study the dependence

Flux Samples For Studies

- We generated fluxes for 10 near detector (ND) positions and one far detector (SK) with 200e6 protons on target at each
- 320 kA horn currents

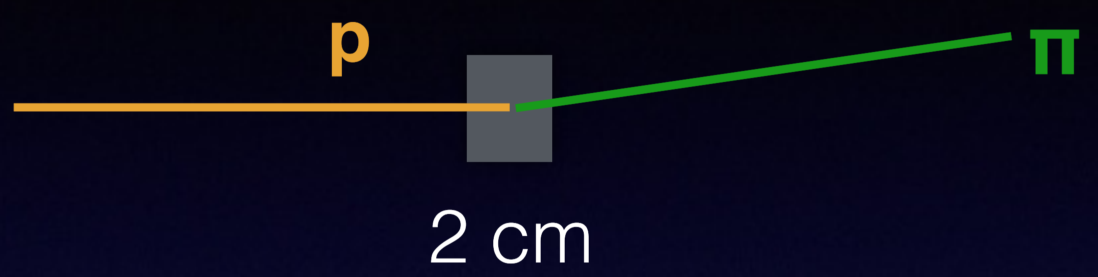




For each Z position we generate fluxes in both Mozumi and Tochibora directions. For 1 and 2 km we also generate fluxes at 2.5 degree off-axis with X=0

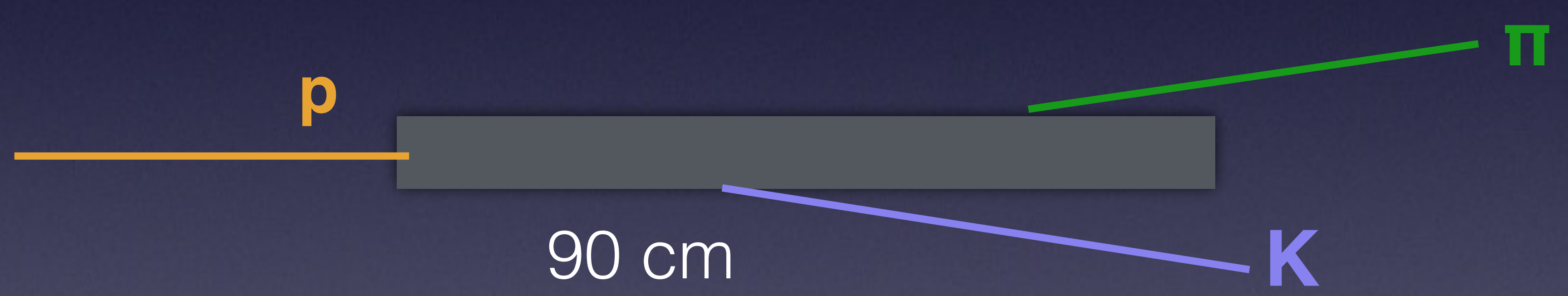
Treatment of Uncertainties for Hadron Production in the Target

Currently T2K uses thin target particle multiplicity data from NA61/SHINE:



T2K must model particle reinteractions in the target and apply uncertainties

NA61/SHINE will eventually supply particle multiplicities from a T2K replica target

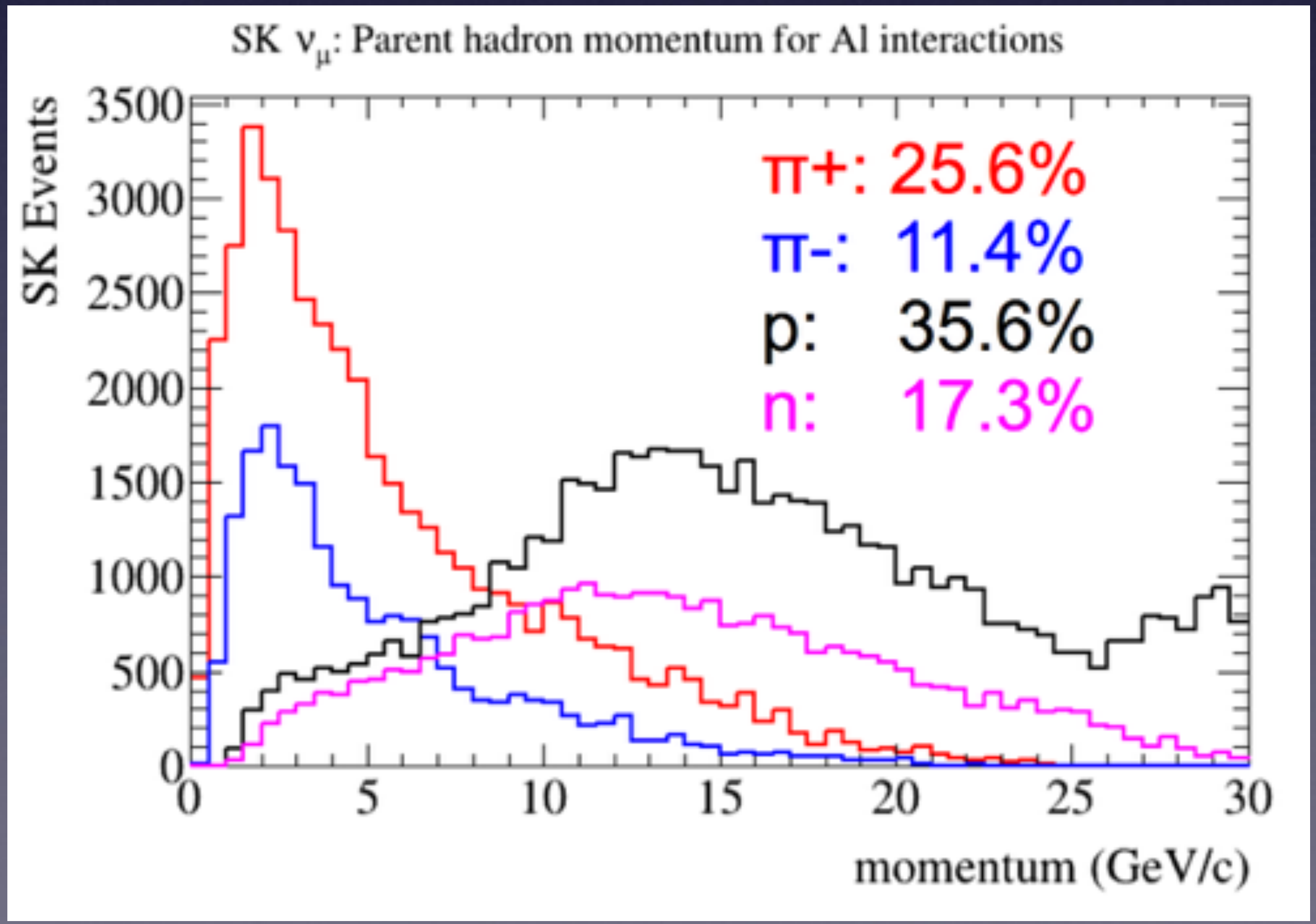


We assume that T2HK would have replica target data with uncertainties similar to the current NA61/SHINE thin target multiplicity uncertainties for pions

We assume an additional 10% normalization uncertainty for kaon multiplicities since the particle ID uncertainties from NA61/SHINE are larger

Importance of Out-of-Target Interactions

- ~50% of the wrong sign flux is from interactions chains that include hadronic interactions outside of the target. Only ~12% for the right sign flux.
- True for both neutrino and antineutrino beams, but wrong sign rates are enhanced in the antineutrino beam by the interaction cross section
- Can't be modeled with replica target data -> have to rely on thin target data
- Interactions are mostly in the horns (Al) or decay volume walls (Fe)



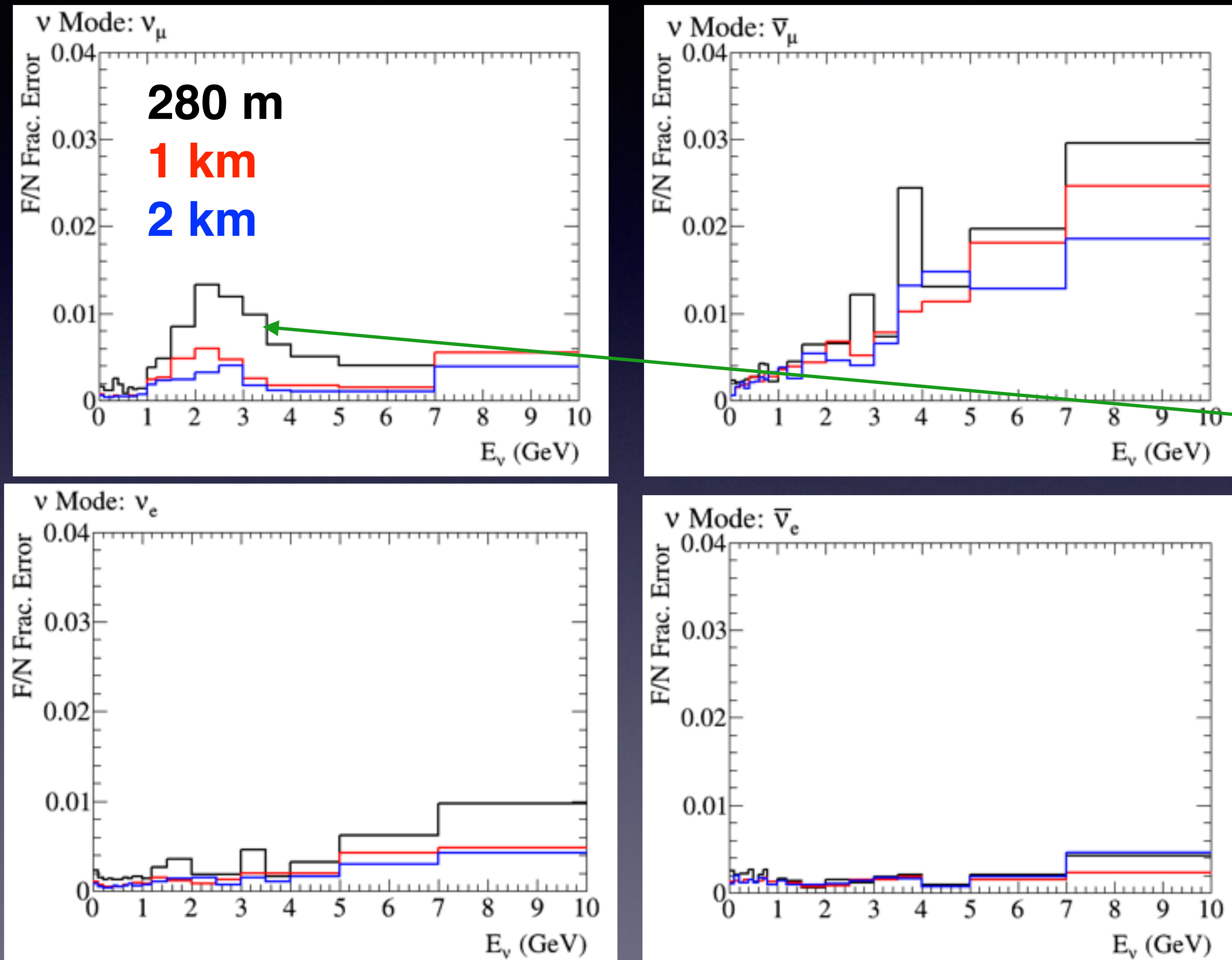
The interacting hadrons can be pions (kaons) or nucleons

Here the momentum and particle type are shown for the νμ flux in antineutrino mode for interactions in the horns

Uncertainties for Out-of-Target Interactions

- For pion production from out-of-target nucleon interactions
  - Use NA61/SHINE multiplicity uncertainties
  - Apply 5%(10%) normalization and shape uncertainties for interactions in Al(Fe) to model uncertainties in scaling to different nuclear targets (based in T2K studies)
  - Should also apply uncertainty for scaling multiplicities to different interaction energies, but not yet implemented
- Currently have not applied uncertainties for pion rescattering (~1/3 of the out of target interactions)

Hadron Production F/N Ratio Errors: Neutrino Mode



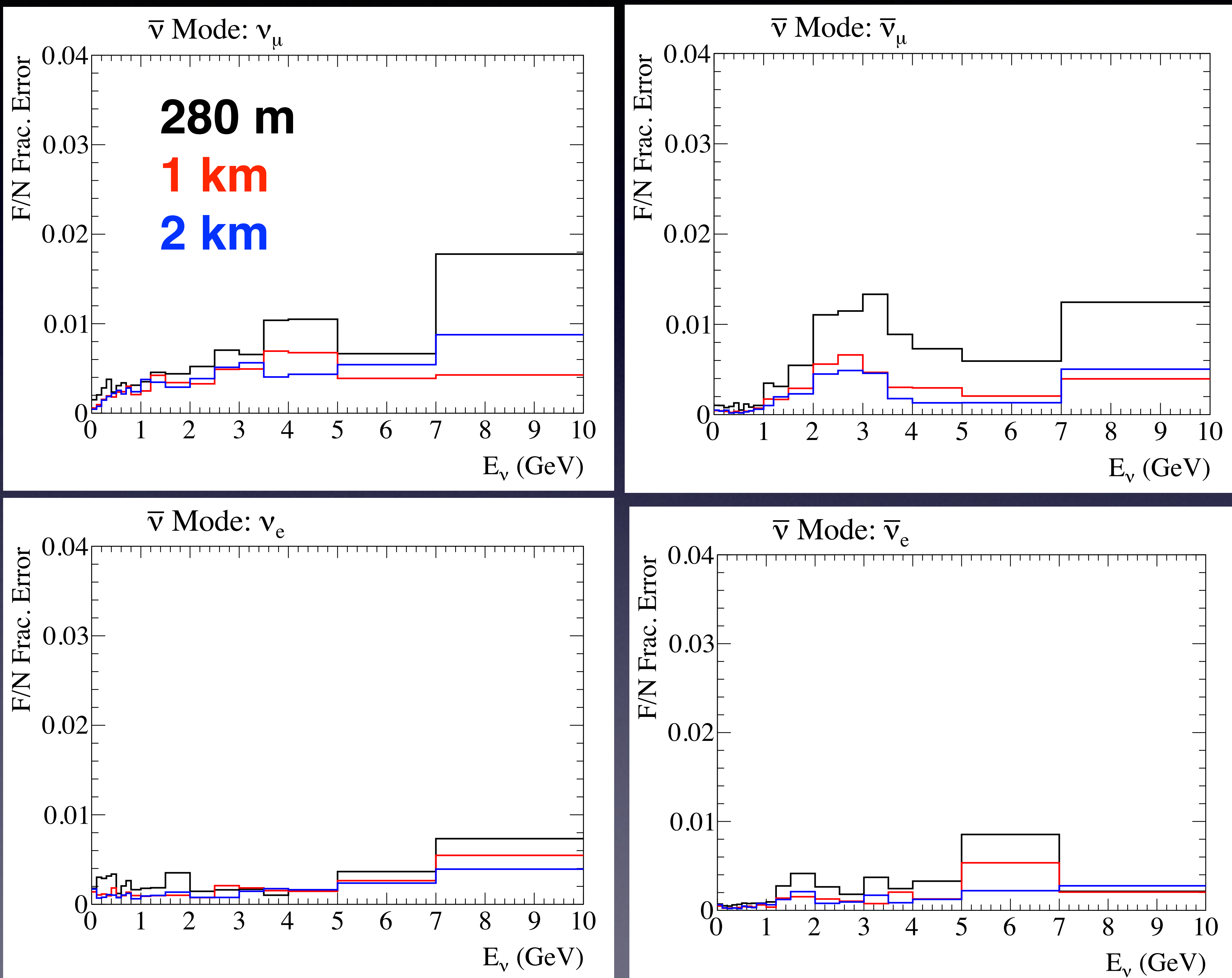
Uncertainties are <0.5% near the flux peak (600 MeV)

Larger error from 1-4 GeV. Significant contribution to flux from high energy pions (longer decay length)

Error is reduced by moving from 280 m -> 1km -> 2km

Reduction from 1km to 2km is small

Hadron Production F/N Ratio Errors: Antineutrino Mode



Conclusions are similar to neutrino mode

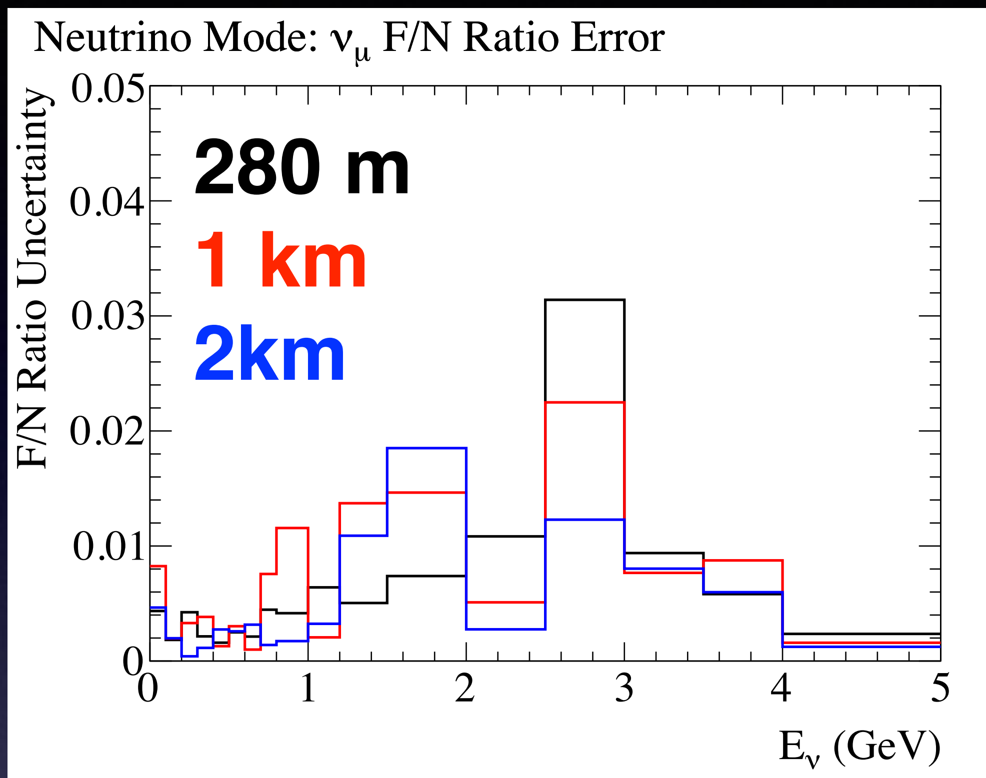
Still need to study for out-of-target interactions:

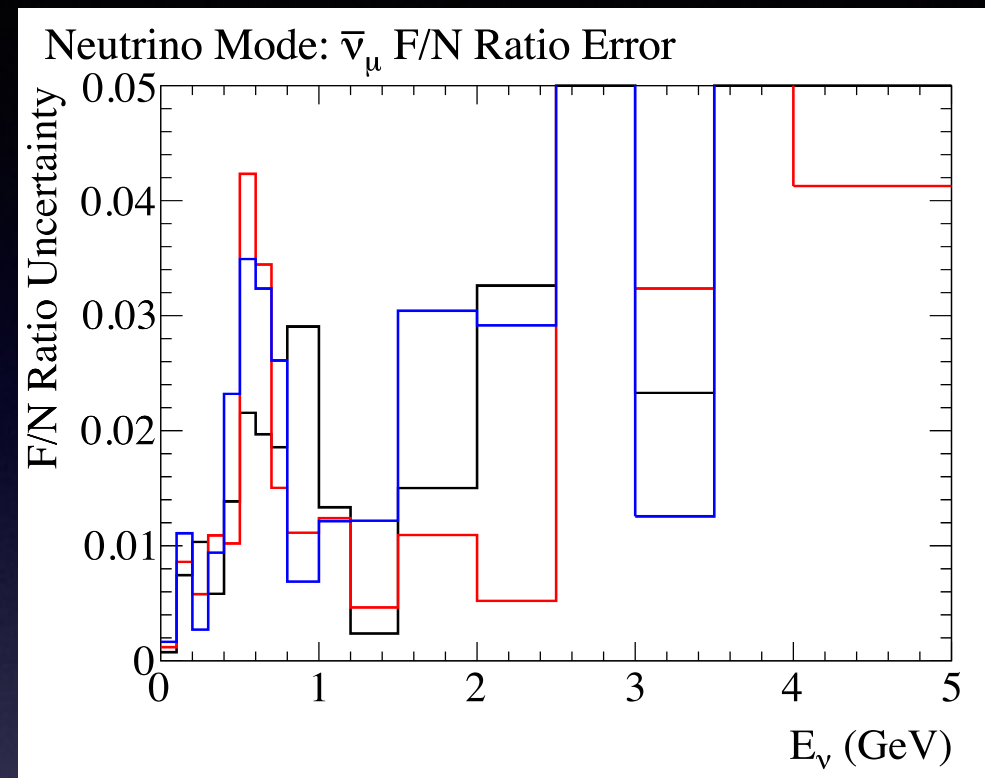
1. Pion rescattering
2. x_F scaling of multiplicity data
3. Interaction rate uncertainties

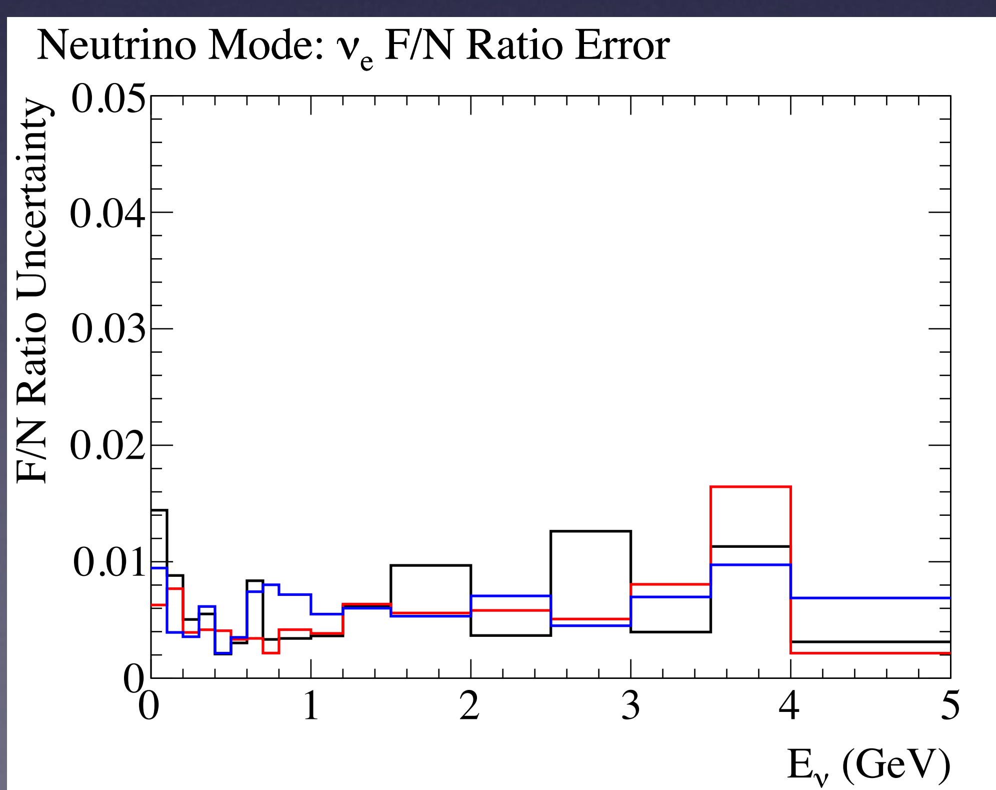
Alignment & Horn Current/Field Uncertainties

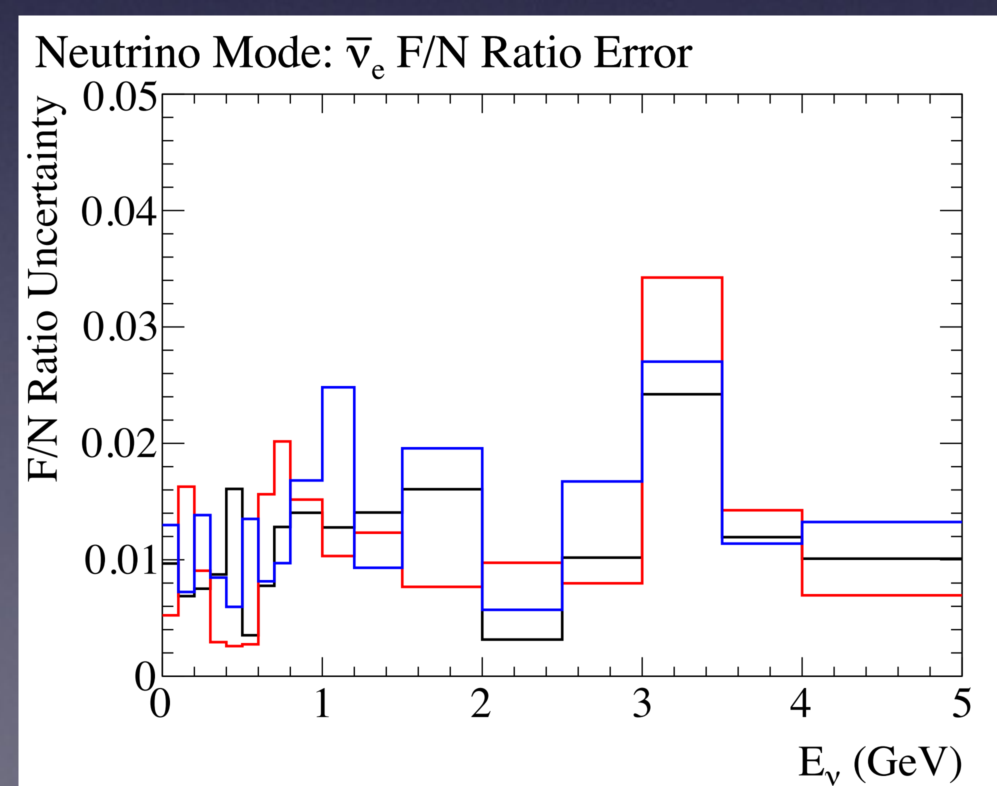
- Some uncertainties cannot be done by reweighting - need to regenerate the flux simulation
  - Horn current: 5 kA change to the horn current setting from uncertainty and stability of horn current monitor
  - Horn alignment: 1 mm shifts of horns 2 & 3 from alignment uncertainties. 1 mrad angular rotation of horn 1
  - Target alignment: 0.1-1.3 mrad rotations based on deviations from horn axis measured by T2K -> work in progress, but results not ready for this meeting
  - Horn field uncertainties: Adding azimuthal asymmetries in the horn fields and an anomalous field inside the horn 1 inner conductor -> not yet implemented

Alignment & Horn Current F/N Errors: Neutrino Mode









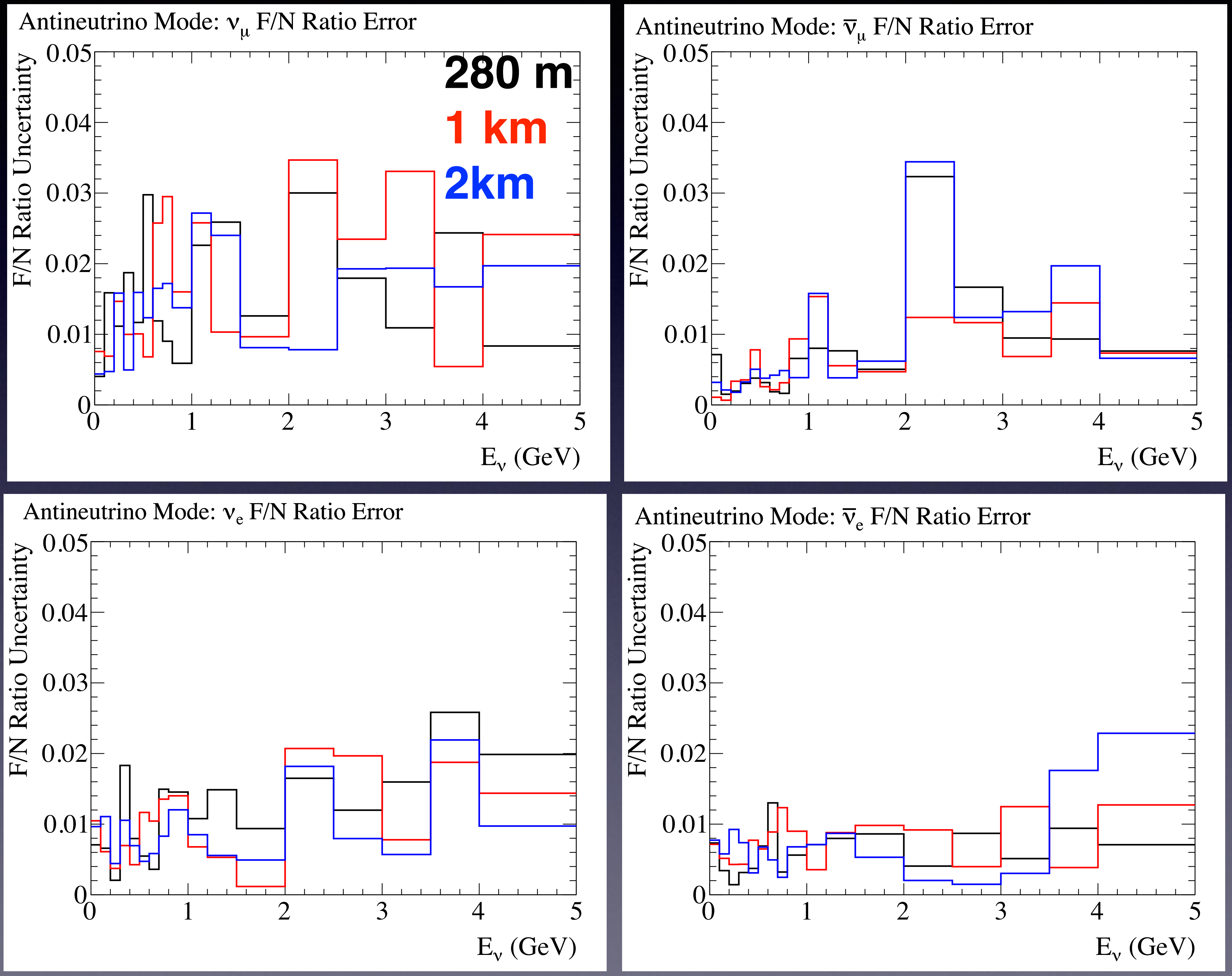
No clear reduction of error with distance from the target is seen

Still dominated by statistical errors on the toy samples

Statistics will be decreased

For now, take these errors as upper limits on the uncertainties

Alignment & Horn Current F/N Errors: Antineutrino Mode

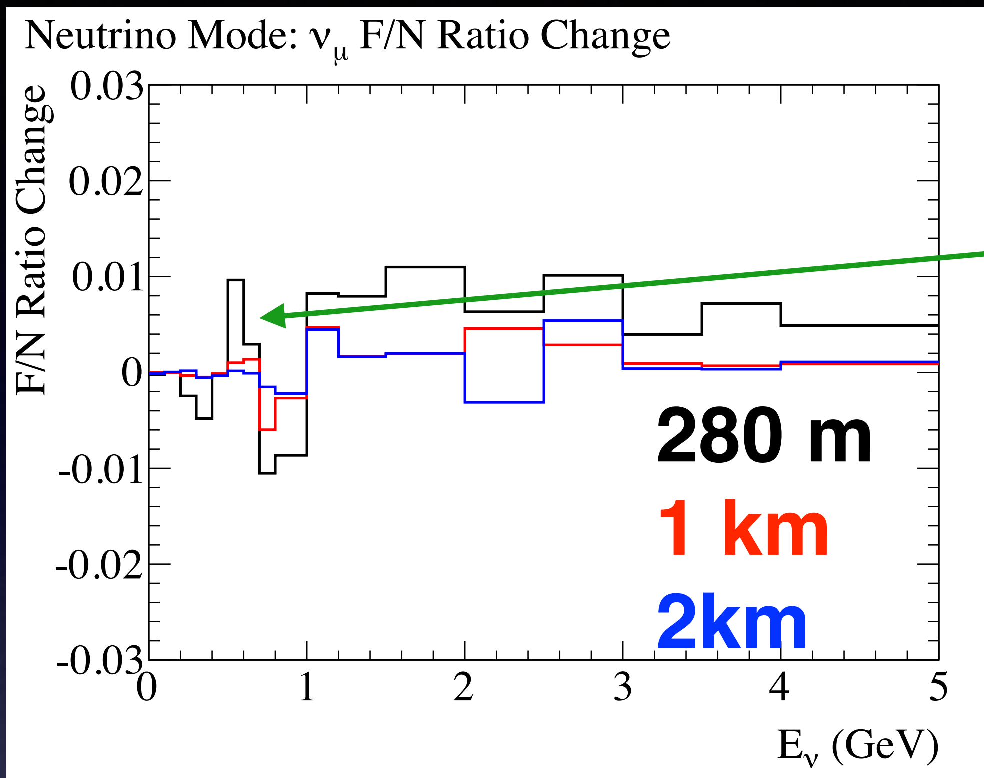


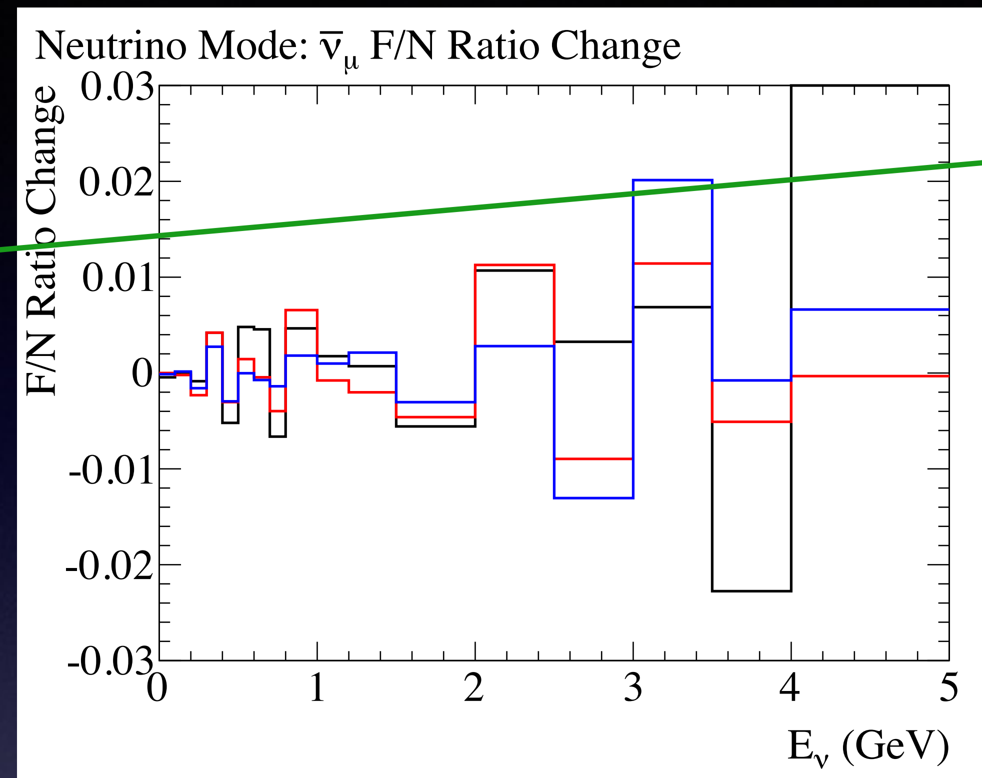
Conclusions are the same as previous slide

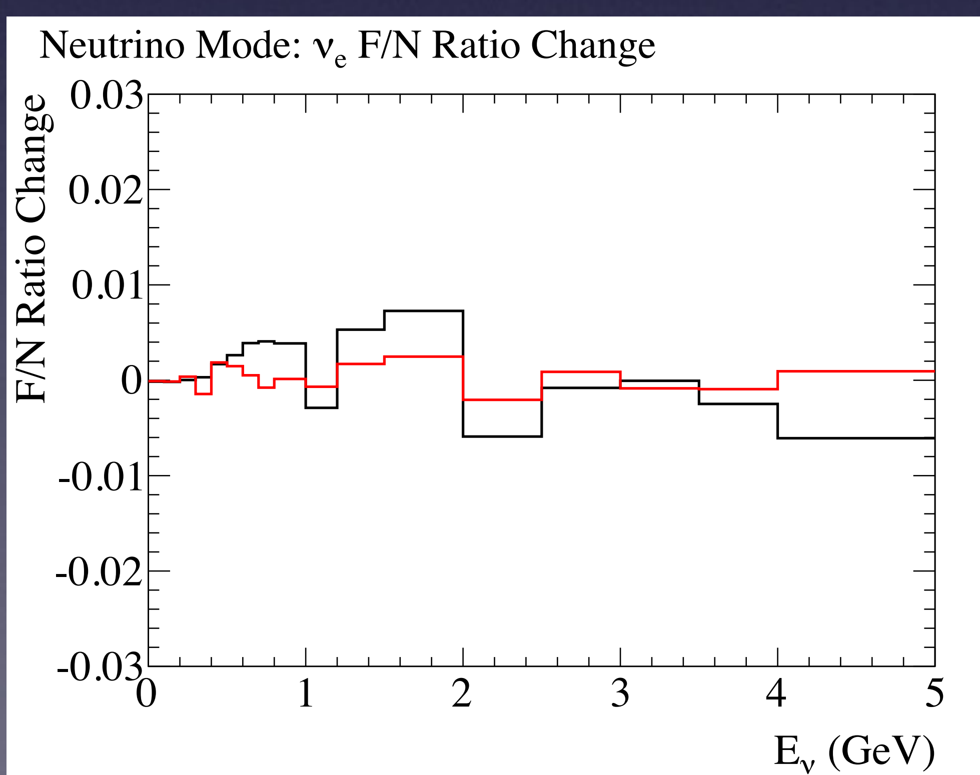
Off-axis Angle (Proton Beam) Uncertainty

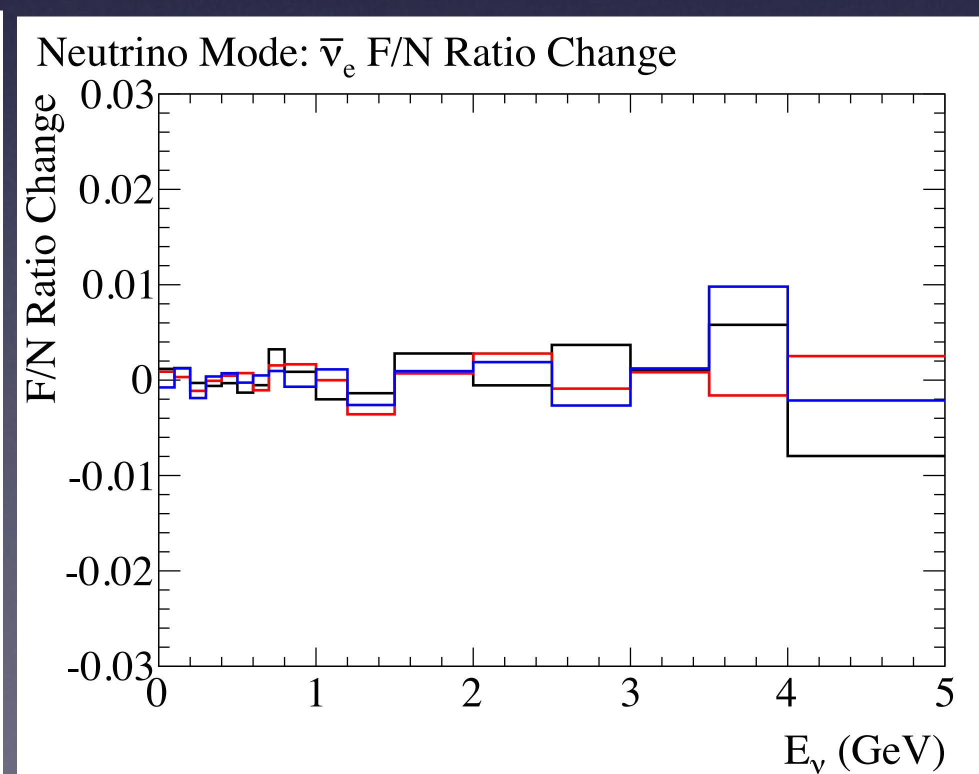
- Expect a 2-3% normalization uncertainty from uncertainty in the measurement of the proton current, but this cancels in the flux extrapolation
- Changing the proton beam position on the target corresponds to a change in the off-axis angle
  - The current T2K proton beam position uncertainty is equivalent to a 0.4 mrad shift of the off-axis angle by changing the beam Y direction
- For the following slide, it is assumed that the near detector is in the same direction as the far detector

Off-axis Angle F/N Ratio Uncertainty: Neutrino Mode









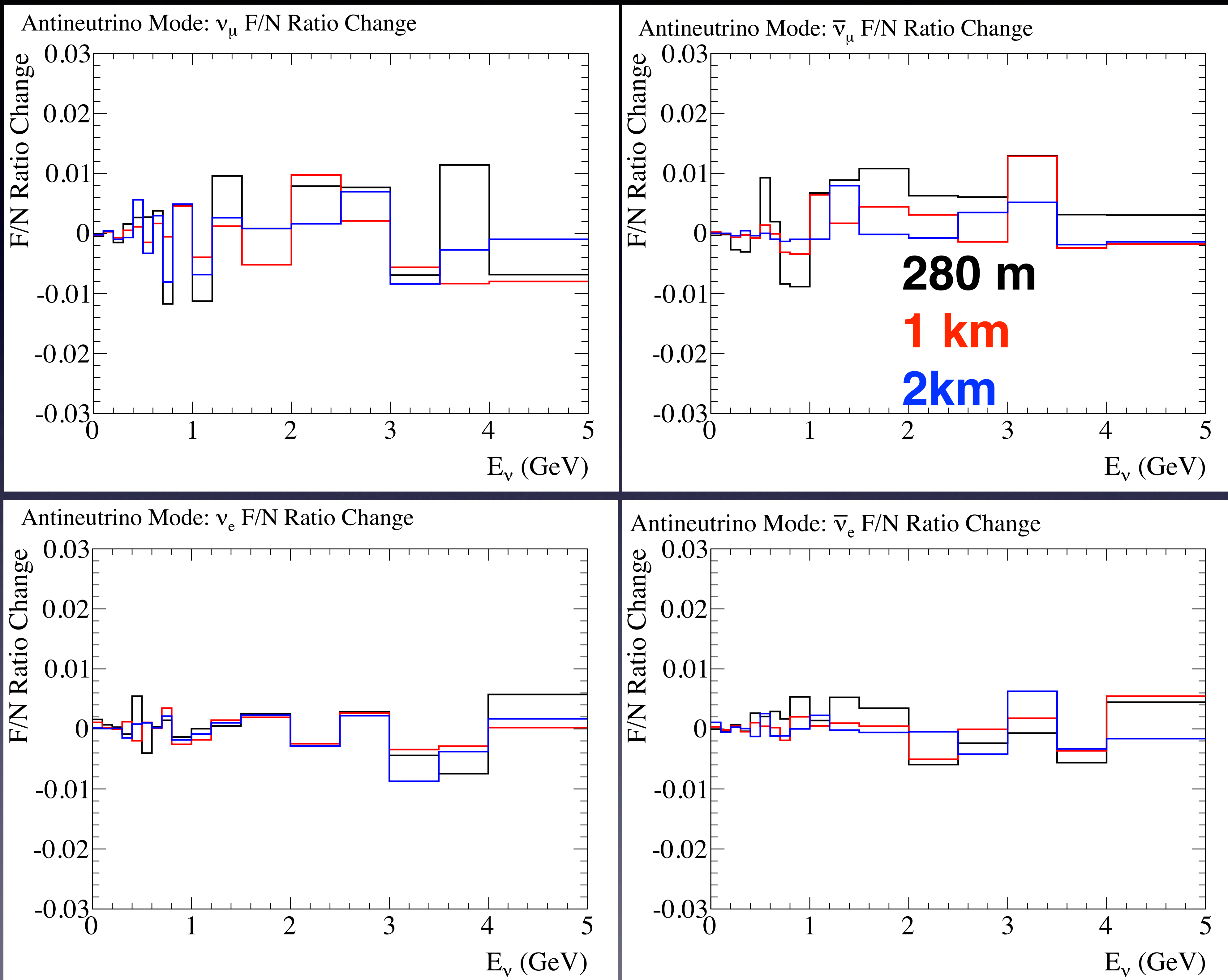
The F/N ratio change is reduced from 280 m to 1 km

Little reduction from 1 km to 2 km

Need to increase statistics for the wrong sign flux

For all three baselines, uncertainties are <1% near the flux peak

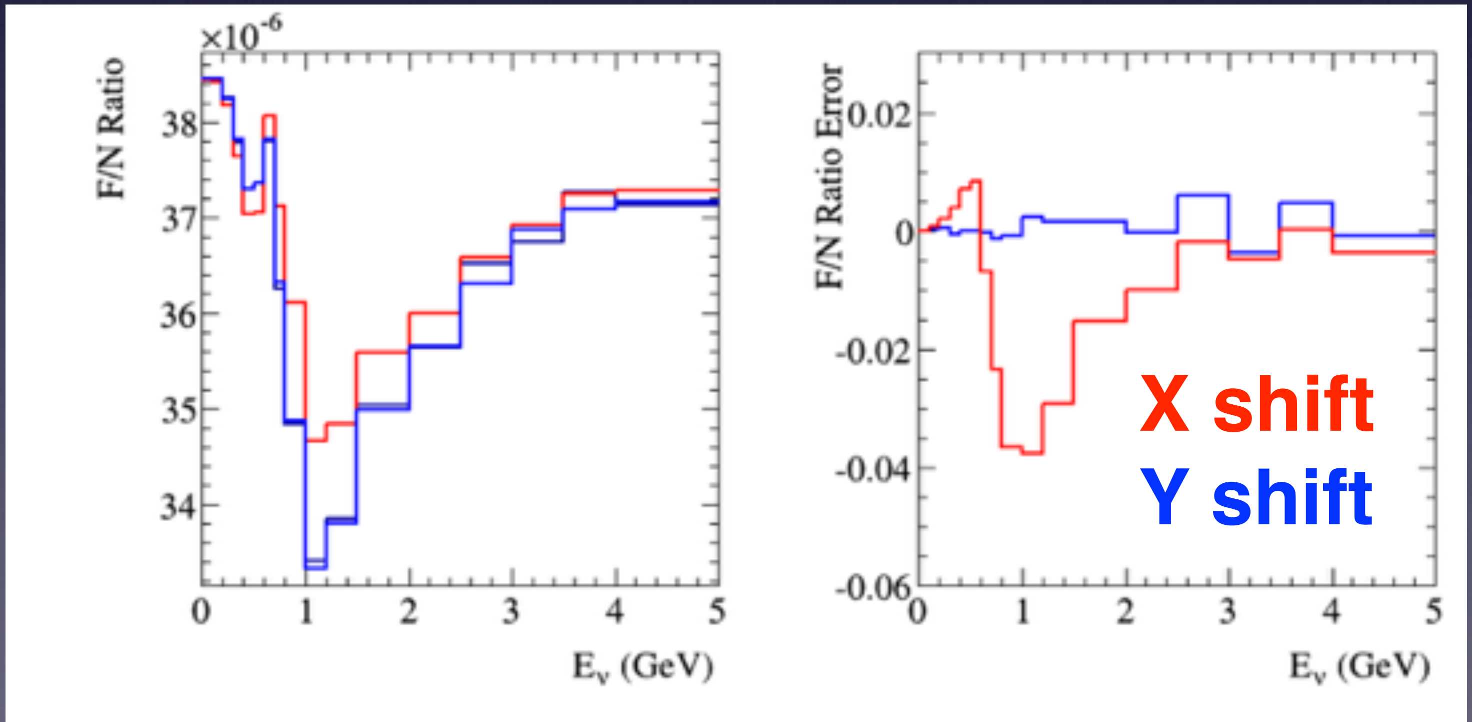
Off-axis Angle F/N Ratio Uncertainty: Antineutrino Mode



F/N ratio uncertainties are similar for antineutrino mode

Direction to Near Detector

- The T2K ND280 detector and SK are in the same direction
- The 2km detector that was proposed for T2K was in the direction of Tochibora
- Is it important to have the near detector in the same direction at the far detector?
- Considered an the uncertainty on the F/N ratio due to a shift of the beam direction in **0.4 mrad** in X and Y

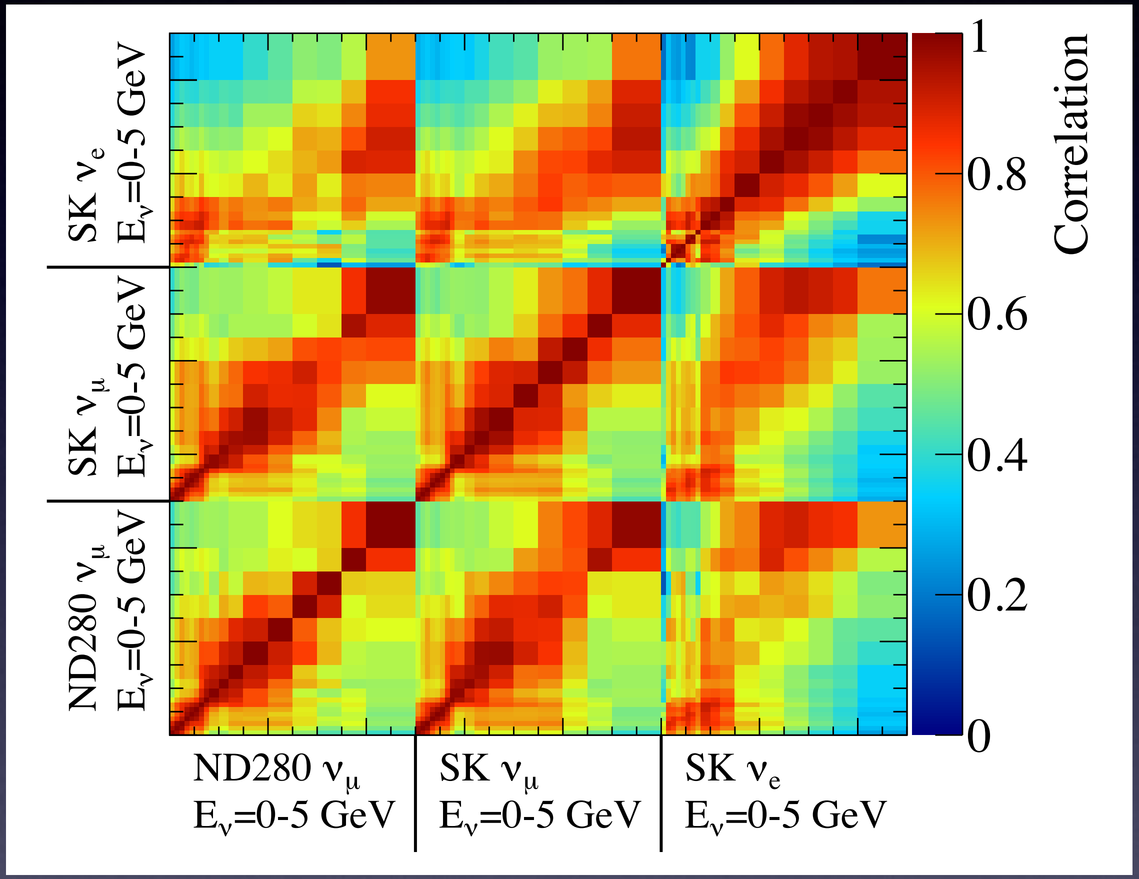


- The F/N ratio method doesn't work for X shift if near detector and far detector are at opposite X

- Would need a detector that can monitor the beam direction in X (maybe INGRID is good enough)

Flux Covariance matrix

- T2K fits the ND280 data using a covariance matrix that describes the uncertainties and correlations of the flux model as a function of energy and detector
- The SK flux is constrained through its correlations with the ND280 flux



- We will provide a similar covariance matrix for T2HK studies

Covariance Matrix Format

- We produce a covariance matrix for each pair of ND and SK fluxes
- For each detector, flavor and operation mode (neutrino or antineutrino) there are 20 bins in neutrino energy (GeV):

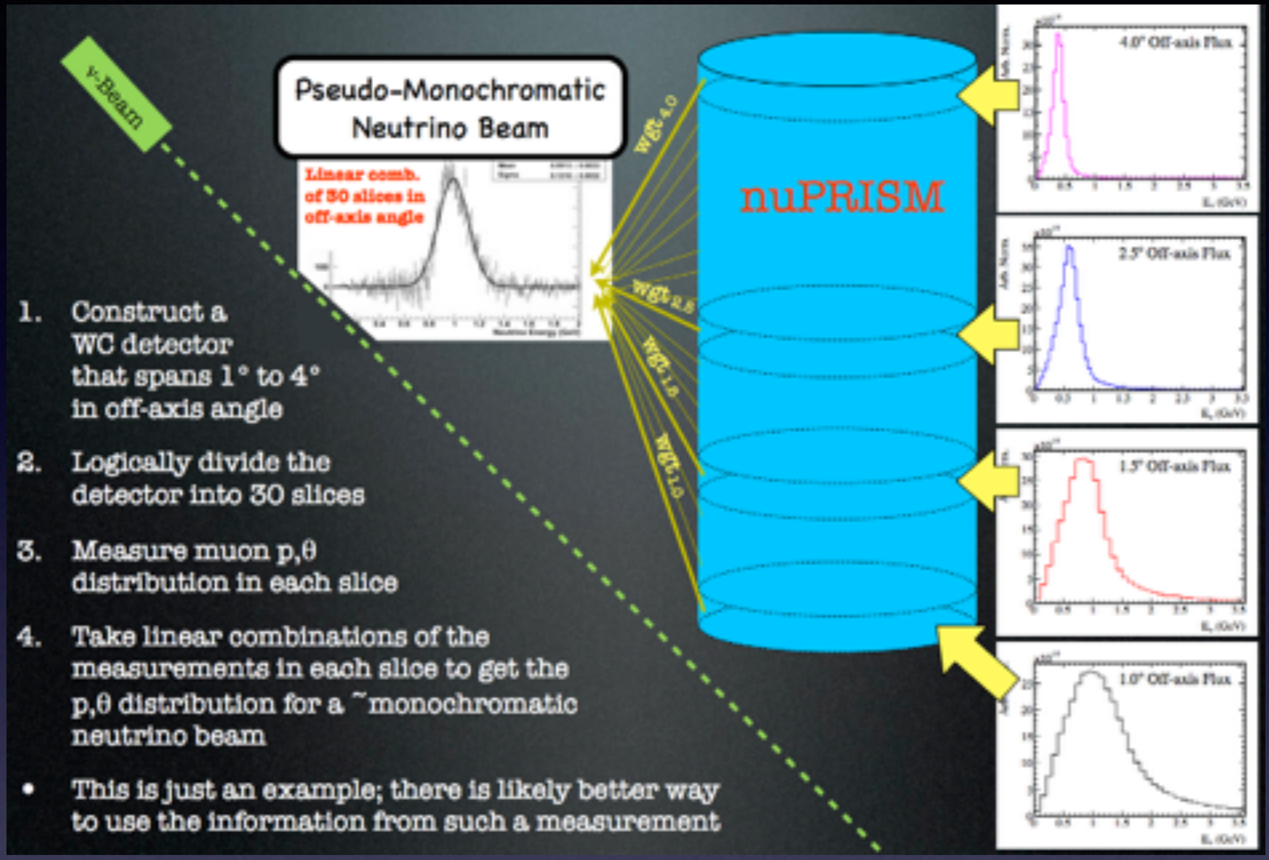
  0.0-0.1, 0.1-0.2, 0.2-0.3, 0.3-0.4, 0.4-0.5, 0.5-0.6, 0.6-0.7, 0.7-0.8, 0.8-1.0, 1.0-1.2, 1.2-1.5, 1.5-2.0, 2.0-2.5, 2.5-3.0, 3.0-3.5, 3.5-4.0, 4-5, 5-7, 7-10, 10-30

- The order of bins in the matrix is:
  - ND first, SK second (160 bins each)
  - For each detector, neutrino mode first, antineutrino mode second (80 bins each)
  - For each mode: ν_μ, $\overline{\nu}_\mu$, ν_e, $\overline{\nu}_e$, (20 bins each)

Uncertainties for νPRISM

See talk by M. Wilking

- νPRISM uses flux dependence on off-axis angle to produce pseudo-mono-energetic neutrino beams
- Measure relationship between neutrino energy and muon kinematics
- Need to know how flux uncertainties vary with off-axis angle
- Not practical produce a covariance matrix binned in energy and off-axis angle. It becomes too large



- νPRISM neutrino vectors are being generated with flux information stored (hadronic interaction chain, original proton properties)
- Will adapt flux reweighting code so that uncertainties can be directly applied to generated νPRISM MC files
- Will generate 1 sigma changes at νPRISM for uncertainties that can’t be treated with reweighting

Plans & Summary

- We have studied F/N ratio flux uncertainties for a number of error sources
  - Errors are reduced for ND fluxes at 1 or 2 km compared to 280 m
  - 280 m F/N ratio errors are still typically <1% near the flux peak
  - Still a few sources of uncertainties are missing from the studies
- We will release preliminary flux covariance matrices within the week, so they can be used for ND studies in the J-PARC PAC LOI
  - Can take special requests for covariance matrices that include any combination of ND fluxes
- Will adapt reweighting code to handle νPRISM events
- Will prepare a description of flux uncertainties for the J-PARC PAC LOI

Extra Slides