IMPERIAL

IMPACT OF FLUX SYSTEMATICS ON ND280 FITS

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Neutrino Oscillation

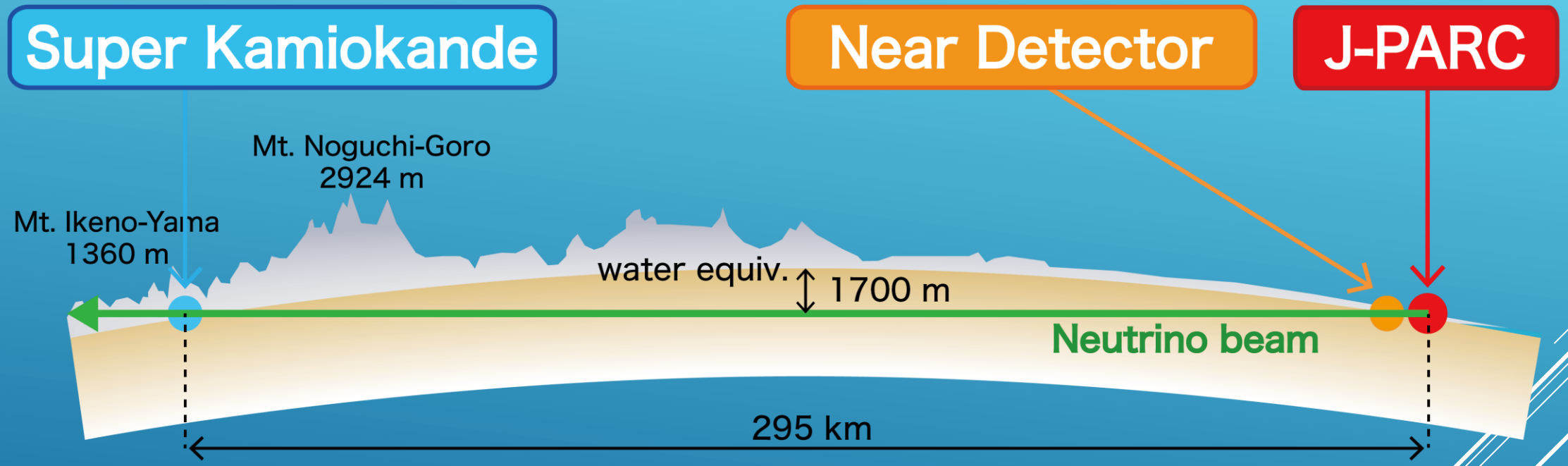
- Neutrinos interact as flavour eigenstates but propagate as mass eigenstates.
- The mixing between mass and flavour states is described by the PMNS matrix
- The probability of the oscillation from one flavour to another depends on the parameters described by this matrix.

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = U_{\text{PMNS}} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$$U_{\text{PMNS}} = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix}$$

T2K Experiment

https://doi.org/10.1016/j.nima.2011.06.067

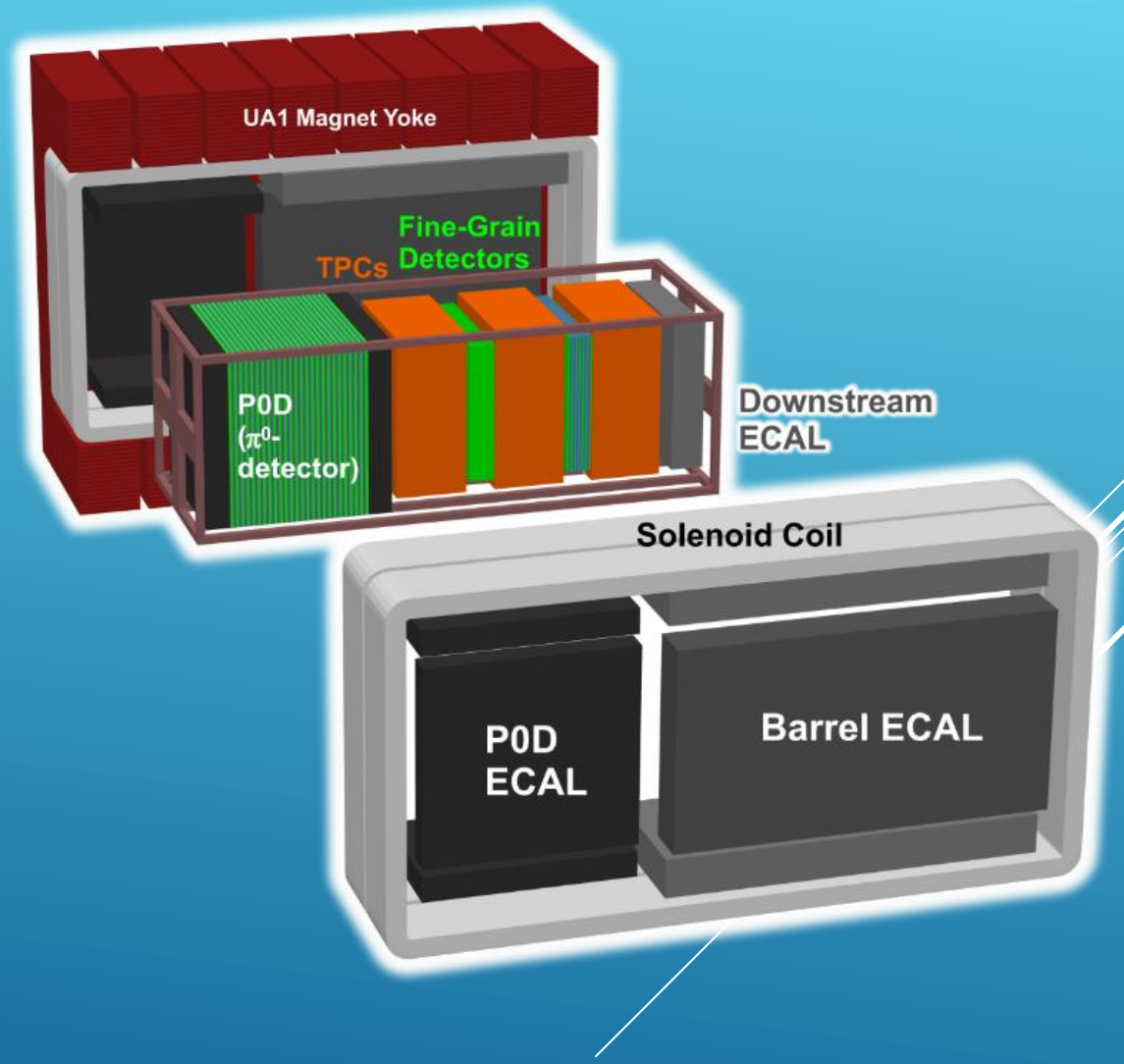


- The T2K (Tokai to Kamioka) experiment is a long baseline neutrino oscillation experiment, designed to measure parameters from the PMNS matrix.

T2K Experiment

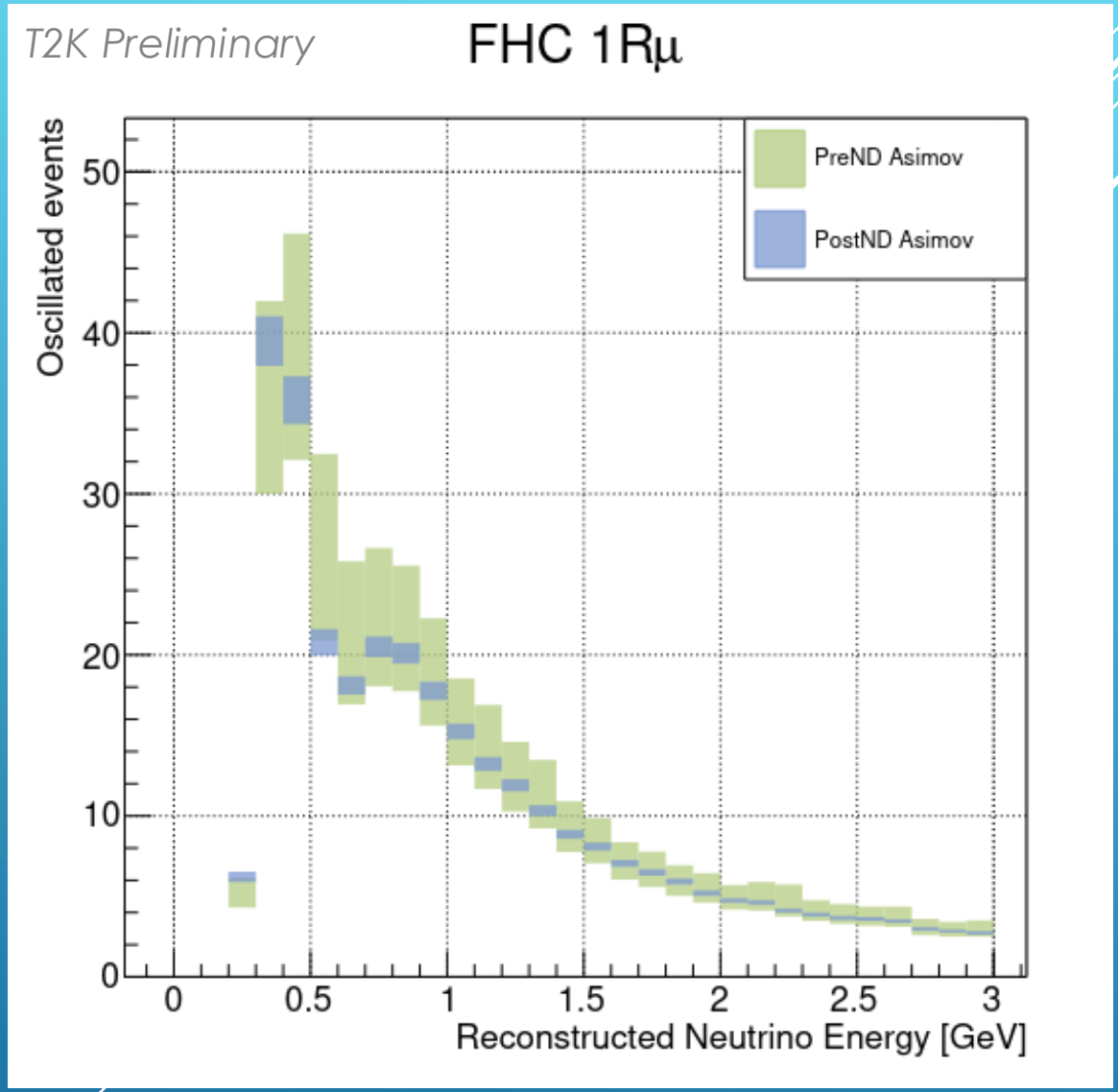
https://doi.org/10.1016/j.nima.2011.06.067

- Within the ND280 detector, fine grained detectors are composed of plastic scintillators that act as target mass for neutrino interaction.
- TPCs enclosed in the magnet track the particle trajectories which help identify the neutrino.
- The ND280 detector constrains the neutrino flux and interaction cross section to predict the event rate at SK.



T2K Oscillation Analysis

- The oscillation analysis uses a parameterised fit to ND280 data.
- The neutrino-nucleus interaction model has a significant uncertainty, ND fit greatly reduced that.



Flux Uncertainties

- The neutrino flux at ND280 and SK is modeled using a detailed Monte Carlo simulation of the beam line.
- Uncertainties in the simulation come from various components of the beamline

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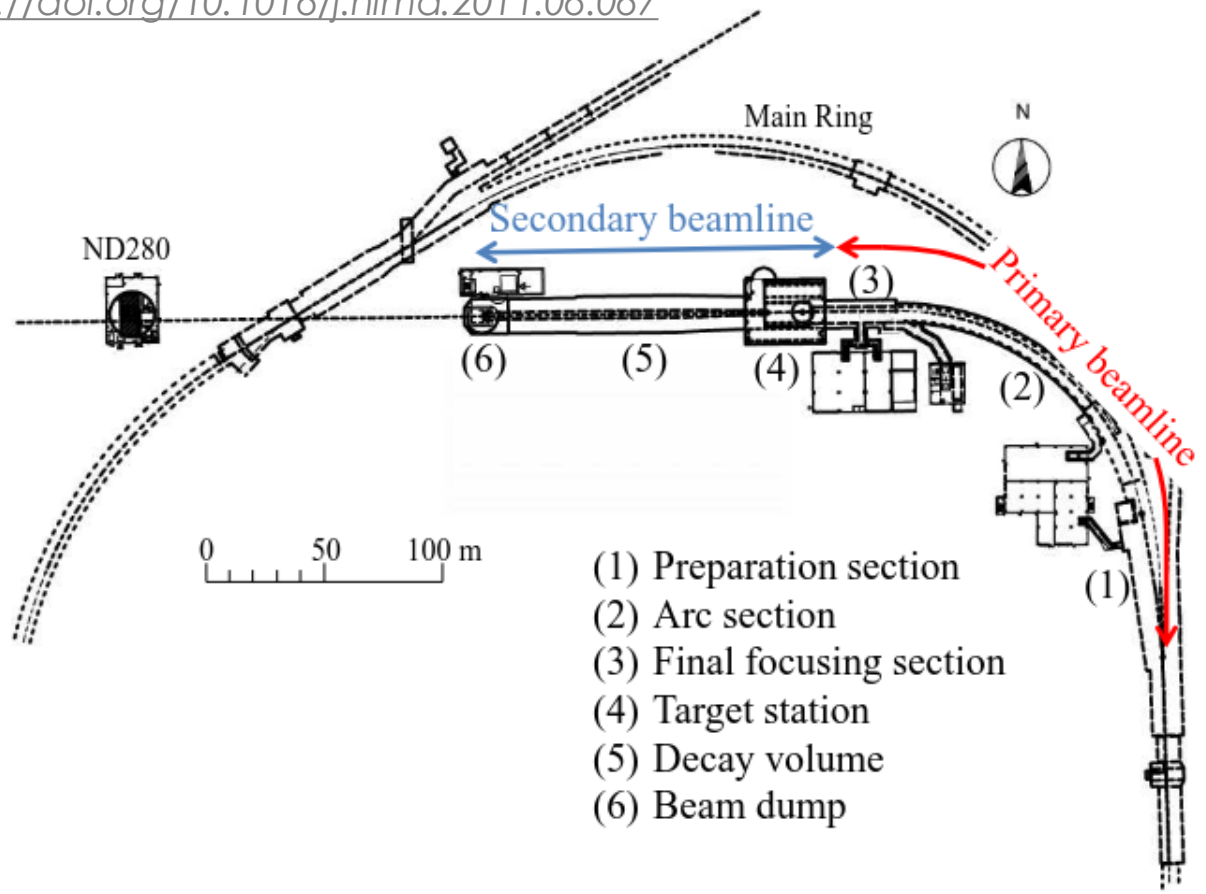
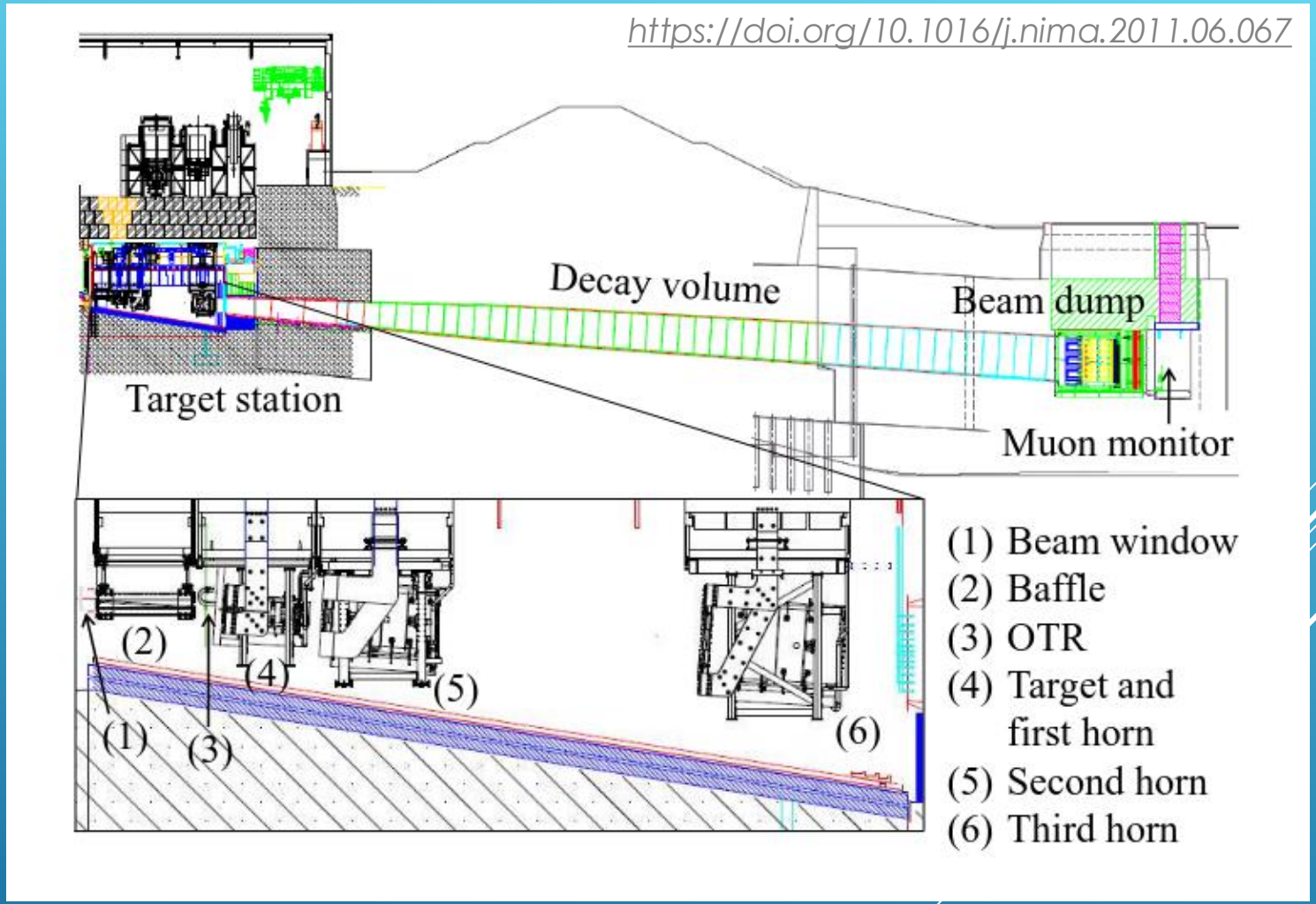


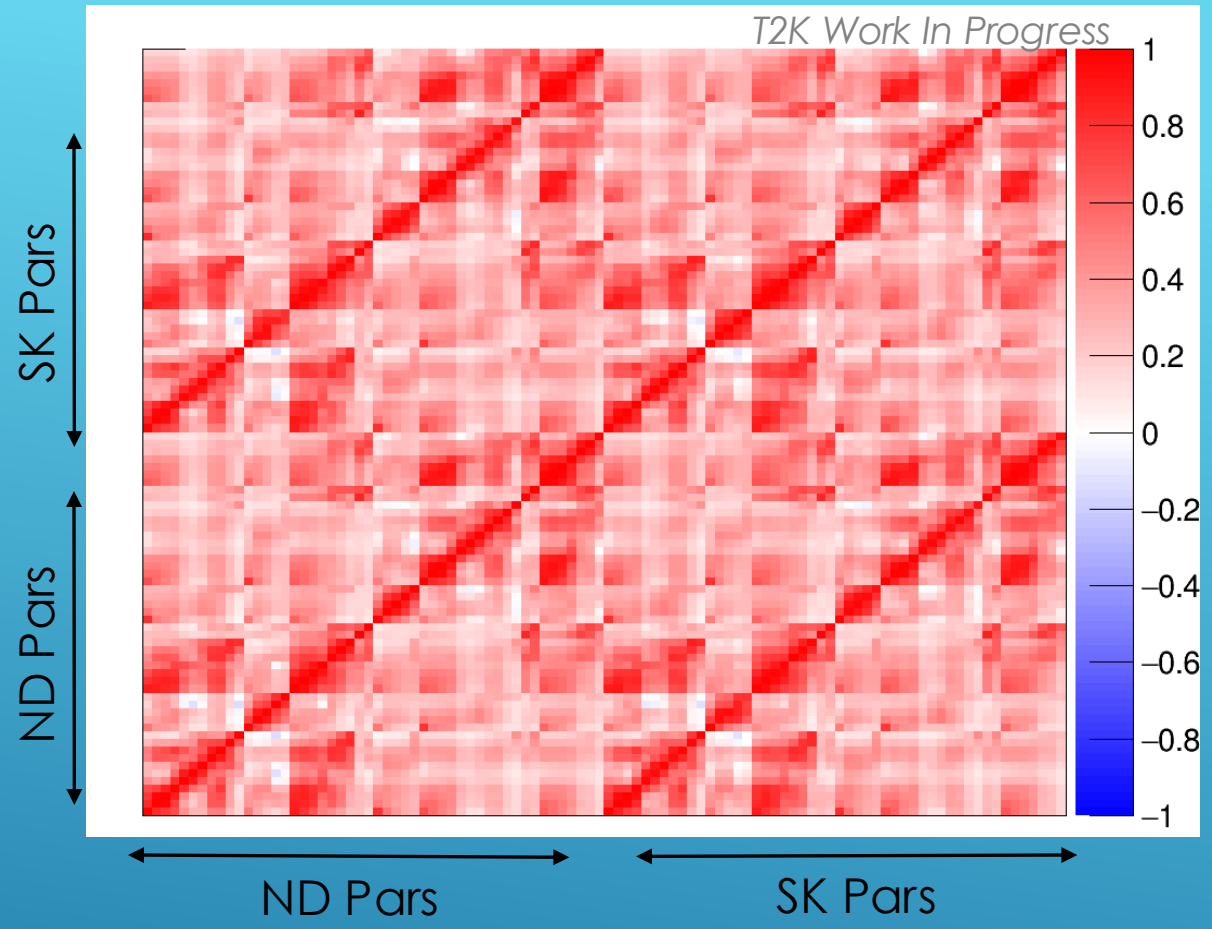
Flux Uncertainties

- The protons collide with the target to produce mesons.
- Magnetic horn focus the charged pions and kaons towards SK
- These decay in the decay volume to produce neutrinos



Flux Prior

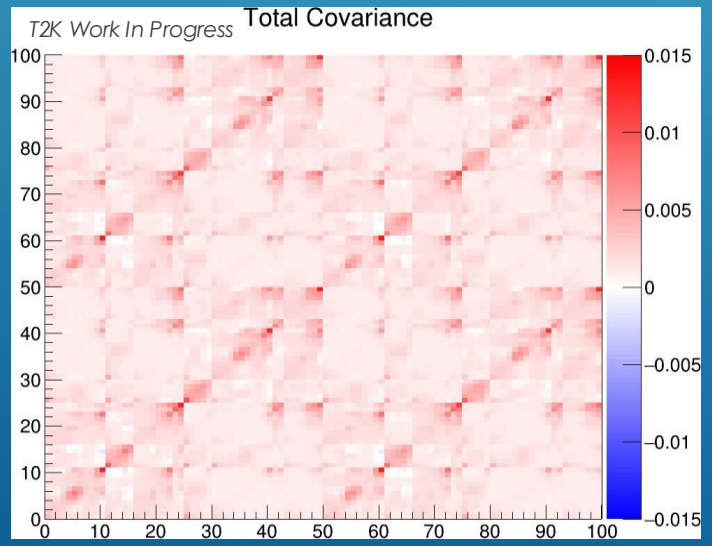
- The systematic uncertainties (each individual source) from the flux prediction and neutrino interaction model are described by a parameterization.



- The near detector and the far detector are both at the same off-axis angle from the beam (~2.5 deg) so they experience almost the same flux. ND data constrains the ND parameters and because of **strong correlations** flux parameters at SK are constrained.

Underlying Systematics

- The flux prior is a parameterisation of the flux systematics, which has contribution from,
  - Meson multiplicity
  - Meson rescatter
  - Secondary nucleon
  - Horn current
  - Horn field asymmetry
  - Horn misalignment
  - Proton beam profile
  - Proton number
  - MC stat
  - Simulation material
  - Interaction length
  - Target misalignment
  - Off axis angle
  - Replica target
- The sum of all these covariance matrices gives the prior covariance matrix.



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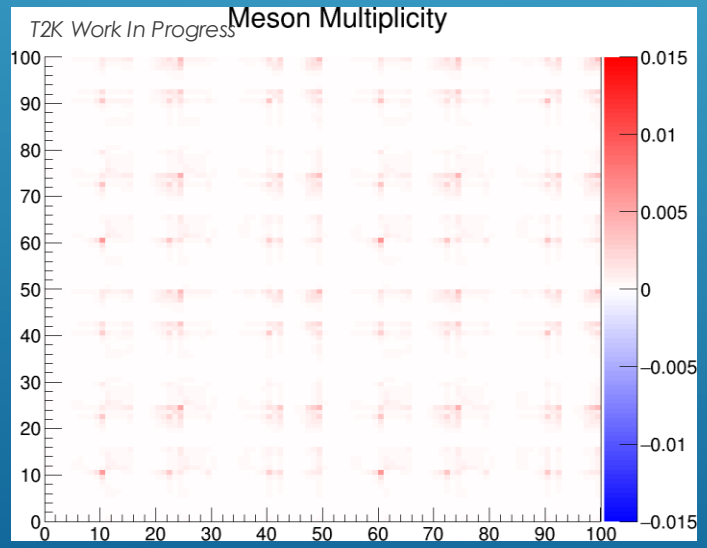

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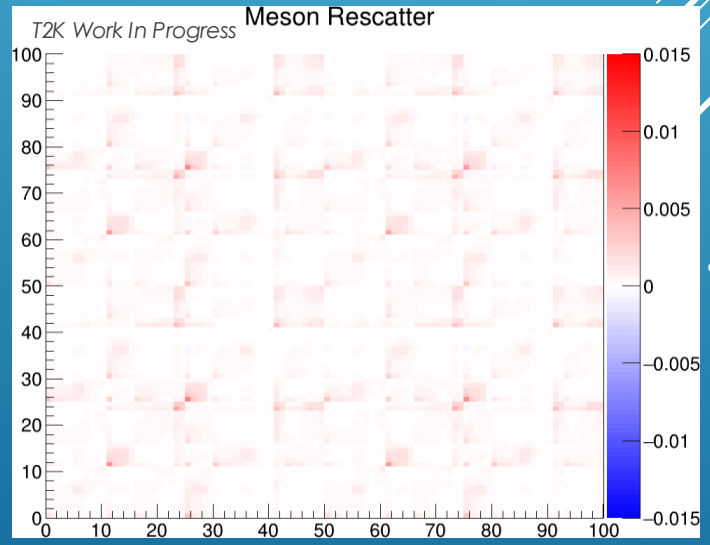

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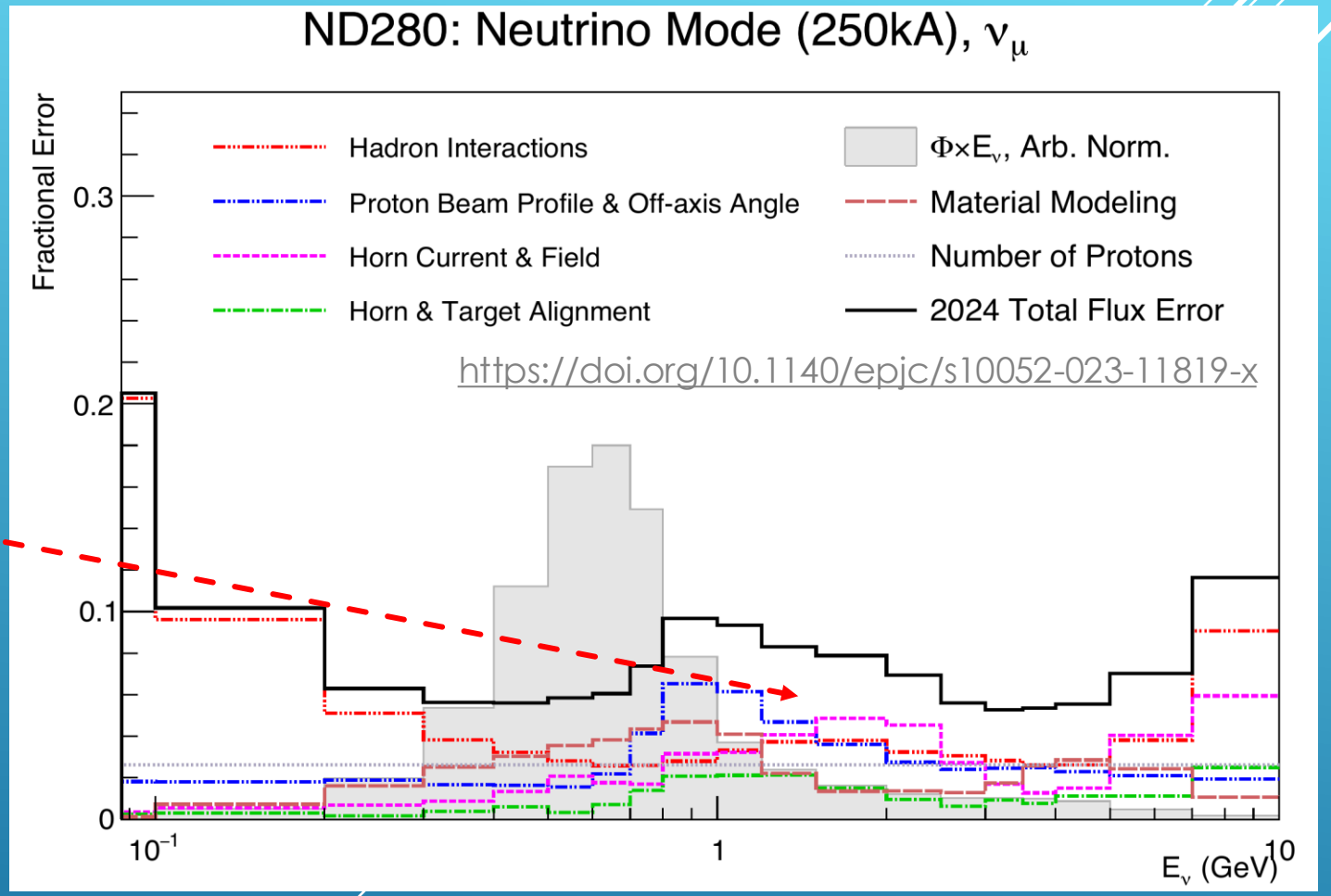
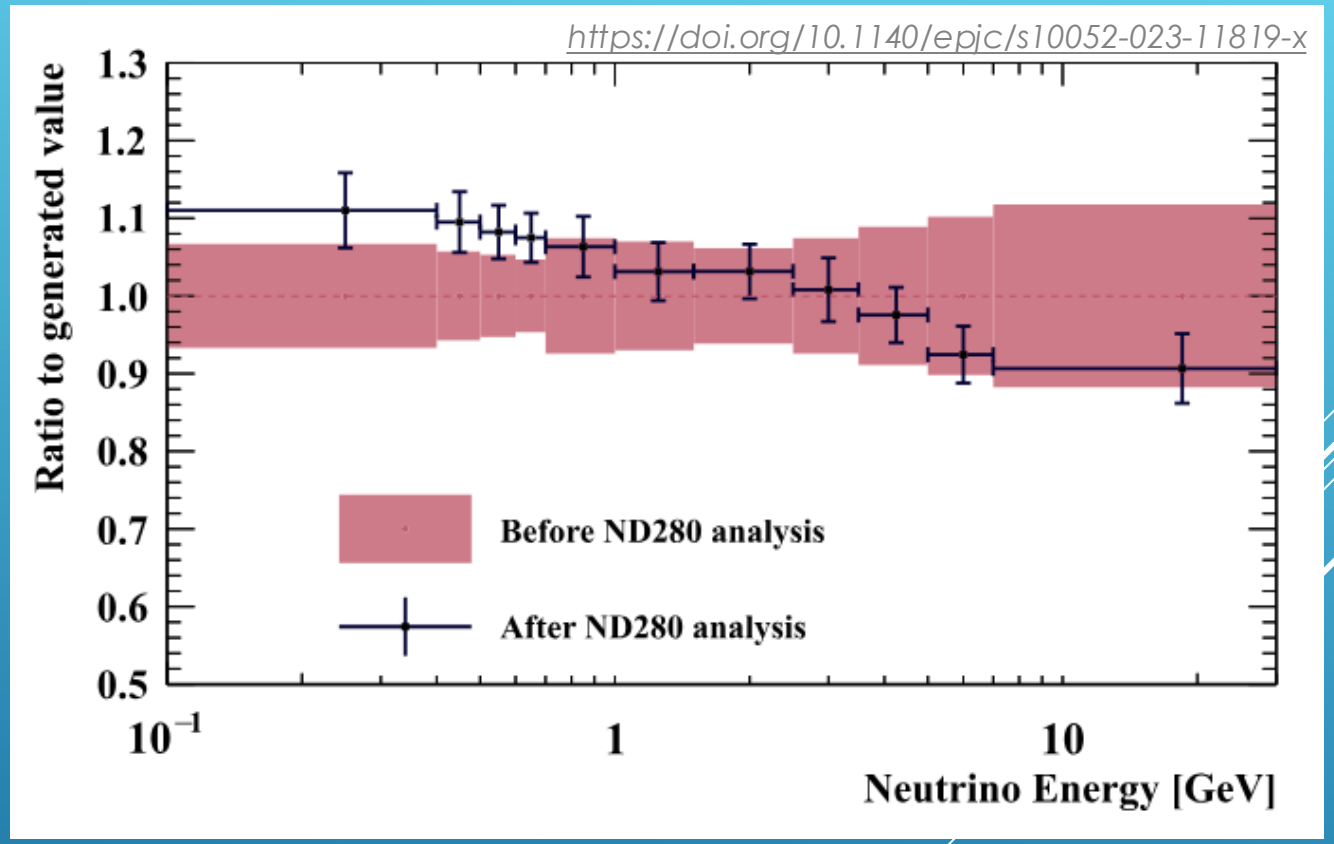
Uncertainty at ND280

- Uncertainty on flux at ND, only from the priors
- In this energy region most uncertainty is from horn current and Field



Motivation

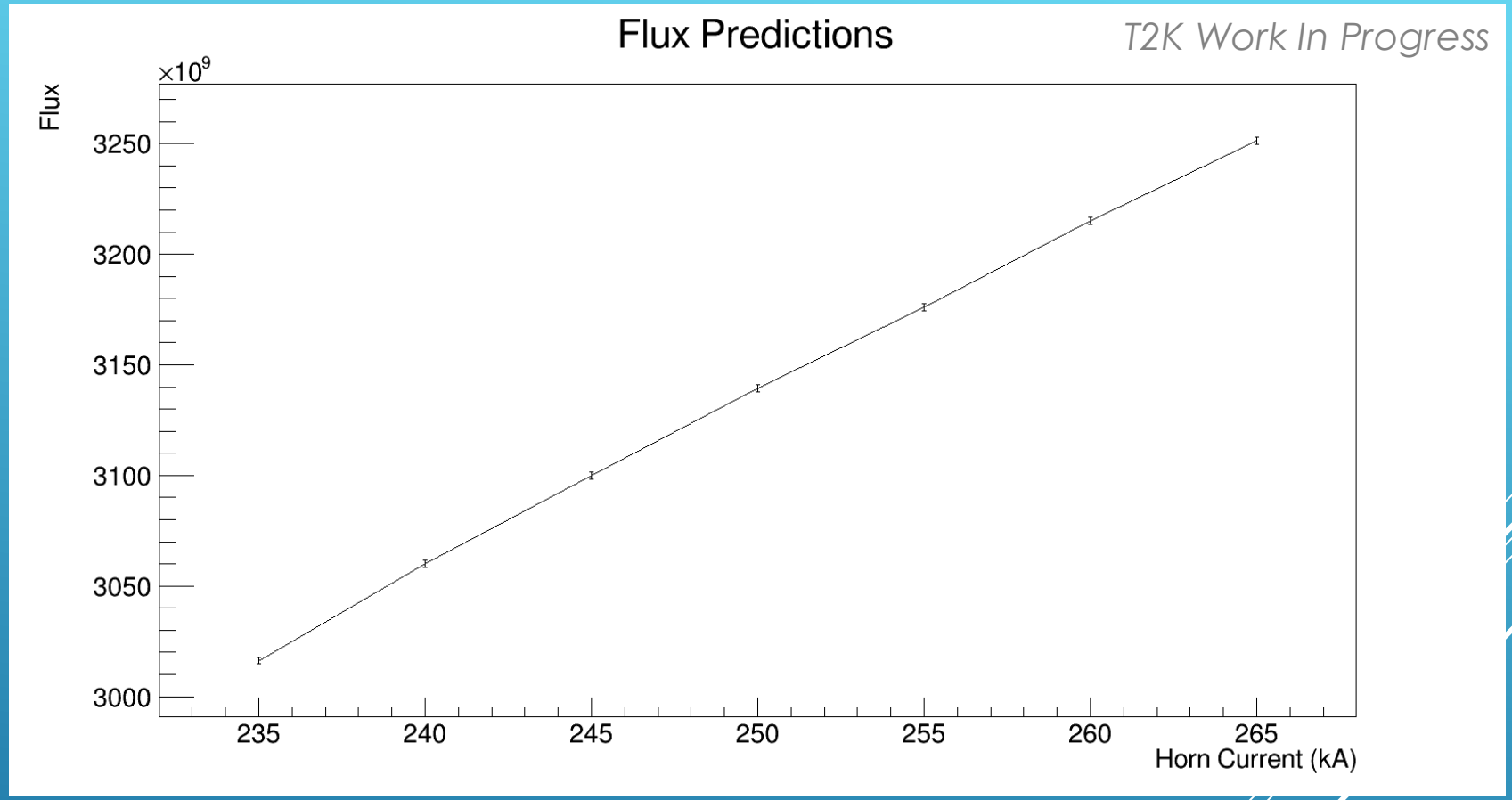
- ND fit does not directly constrain the underlying systematics that make up the flux matrix but instead constrains the parameters in the parameterization.
- Interpretation of these post fit parameters in the context of flux systematics is difficult.
- If a flux systematic is used as parameter directly in the fit instead of the covariance matrix, the post fit results could be more interpretive.



Pre vs Post fit values of parameters

Direct implementation of flux systematic

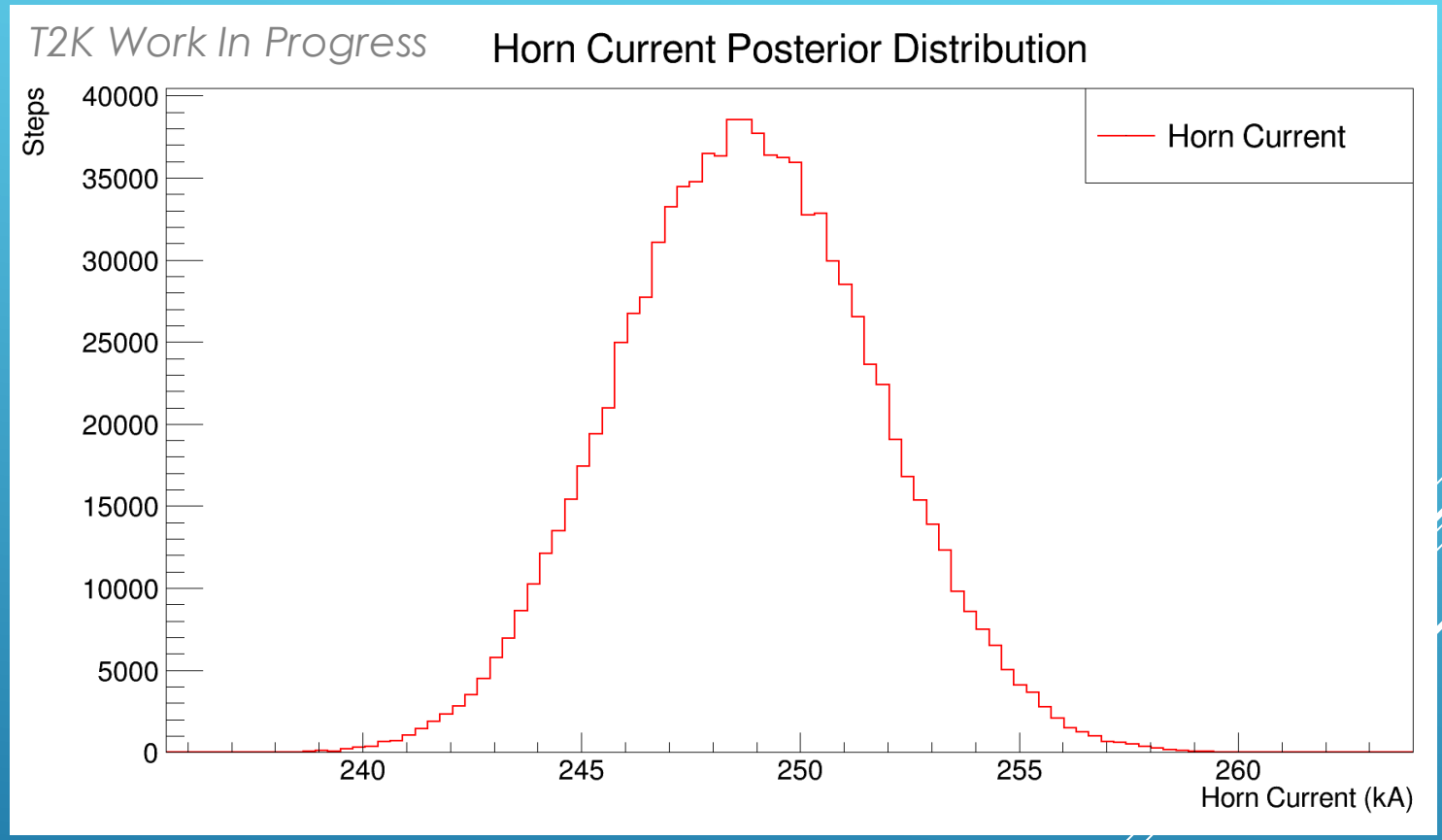
- It is possible to create a flux prediction for different horn current values.
- The response of the flux can be interpolated between these generated flux values.



- The fitter can then use these values to generated event rate prediction for any value of the parameter, horn current in this case.

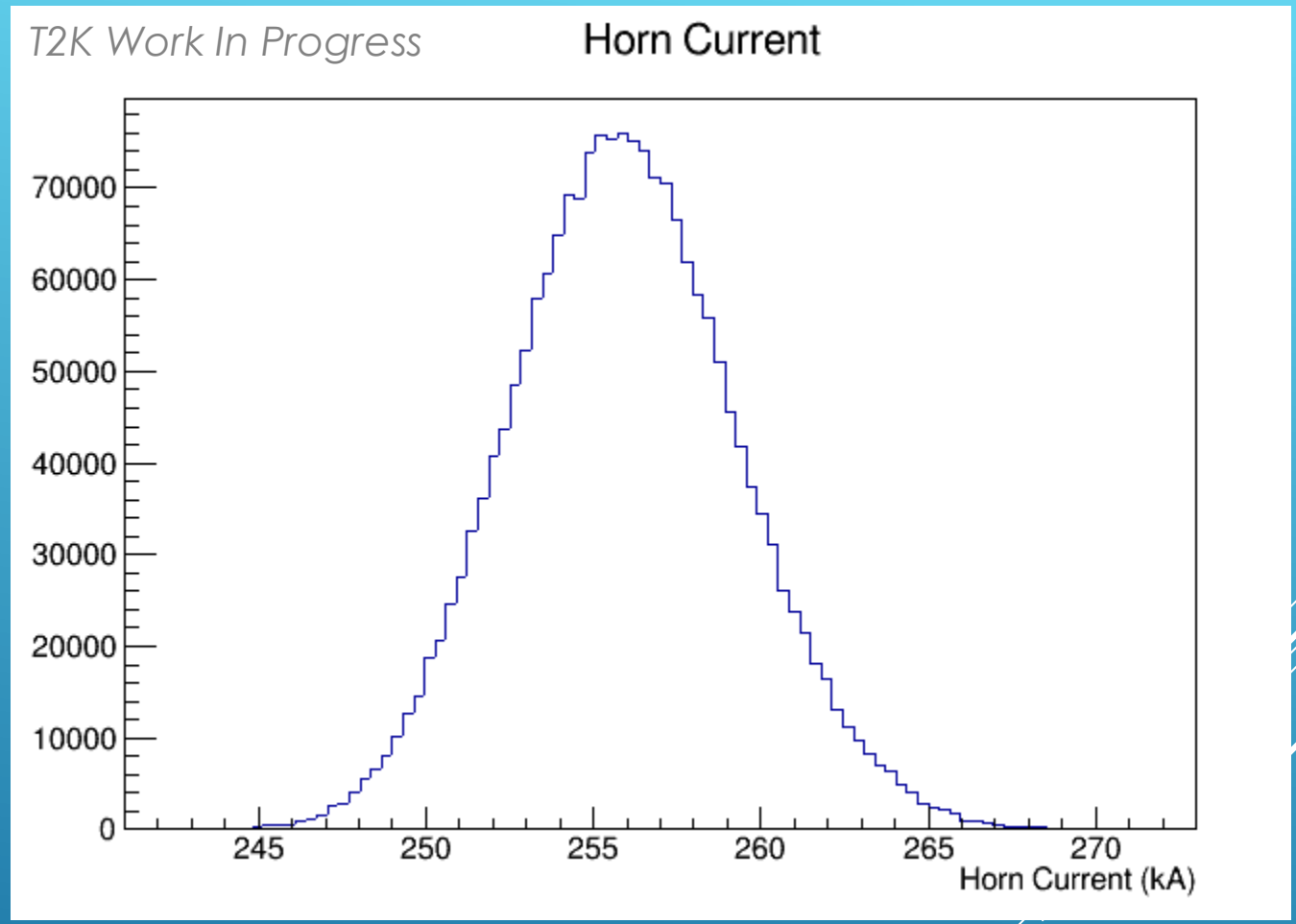
ND Sensitivity

- The ND fit with flux systematic (horn current) directly used in the fit.
- The pre fit uncertainty on the horn current is 5kA
- The post fit central value is 248.9kA with an uncertainty of 2.9kA.



Fake Data

- Sensitivity check with fake data where horn current is 255 kA.
- The ND fit does have the ability to measure the horn current if it is off nominal.
- The post fit central value is 255.9kA with an uncertainty of 3.4kA



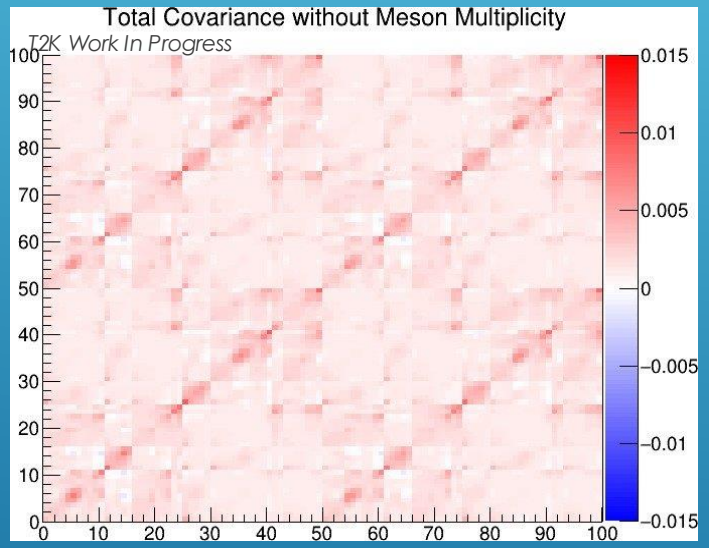
Summary and future work

- Directly implementing the flux systematics which are physical quantities, allows for a more interpretable result.
- It can allow ND fit to isolate individual impact of the systematics on the total event rate uncertainty at ND and SK.
- This study is applicable for Hyper-K which is going to need better understood flux uncertainties.
- This study can motivate additional external constrains on the flux prior to improve the flux model.

BACKUP

Method

- Remove one covariance matrix from the total and use the rest as a prior covariance matrix
- Essentially having complete understanding of the underlying systematic



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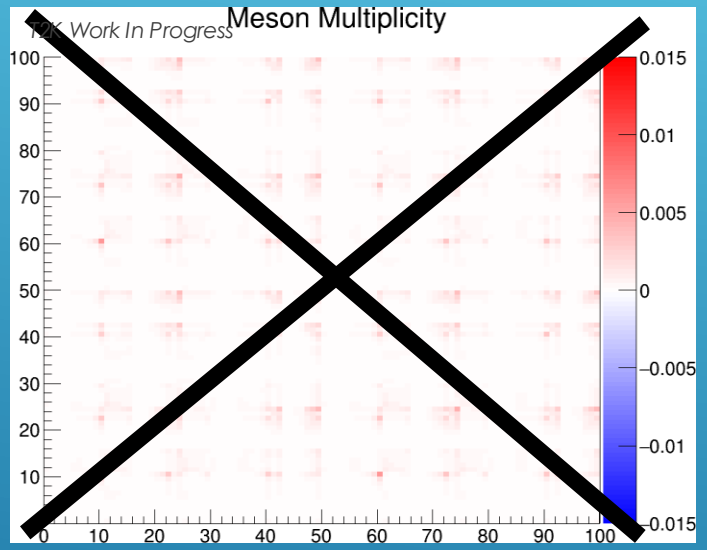

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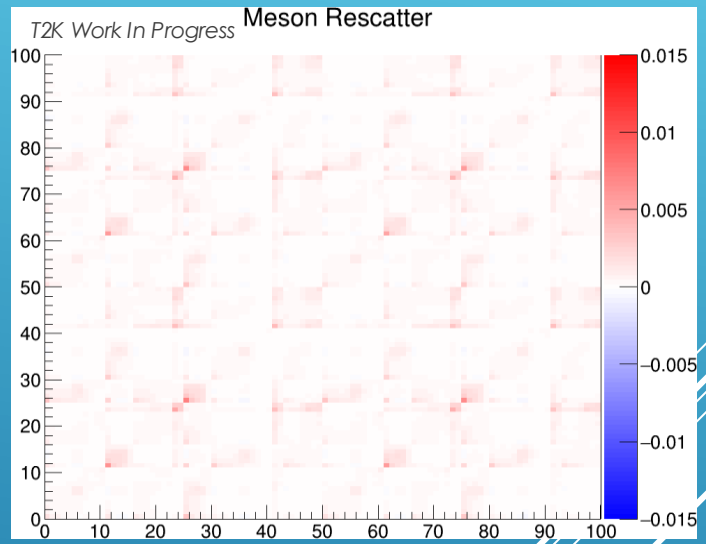

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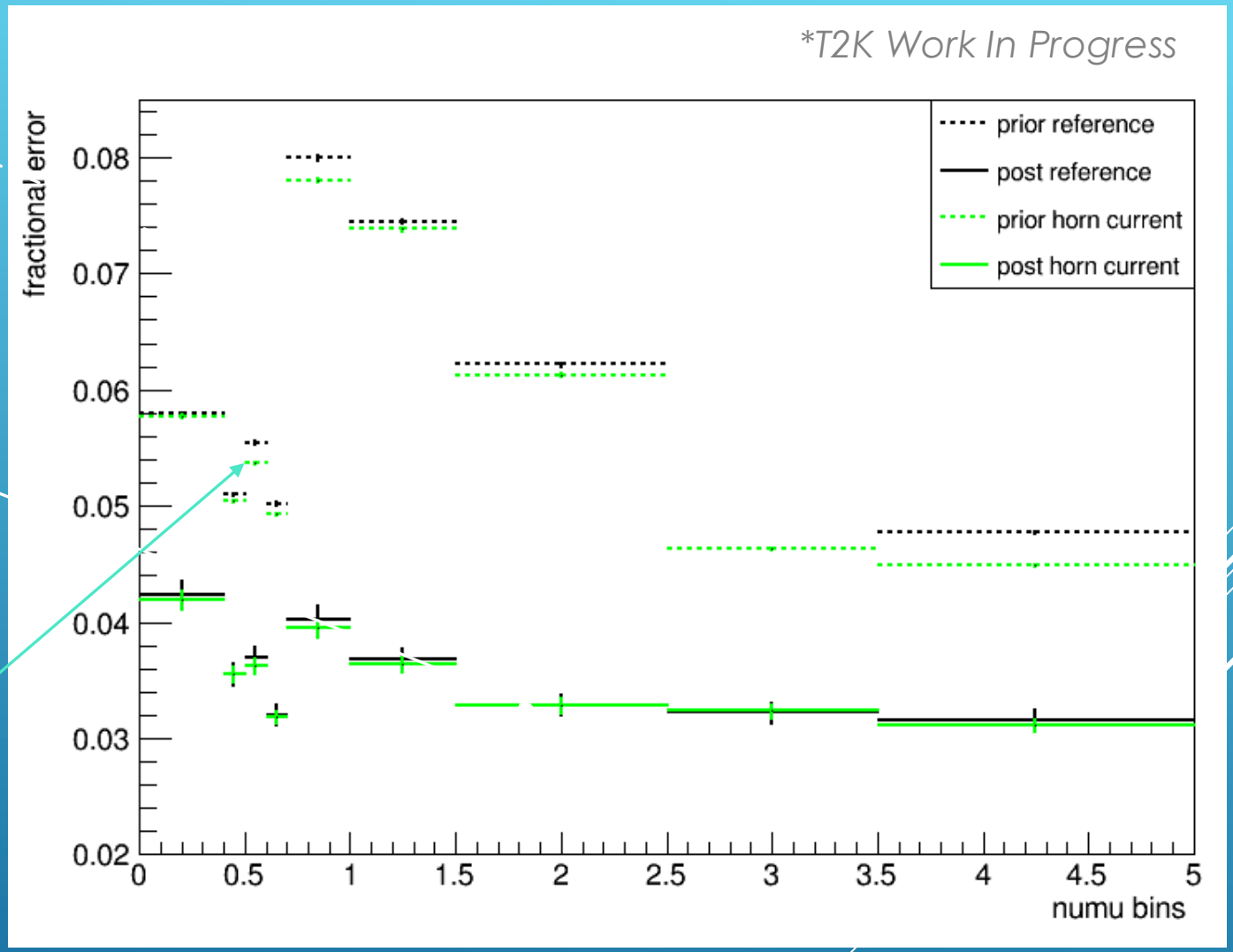
- Use this new covariance matrix as input to ND fit (asimov)

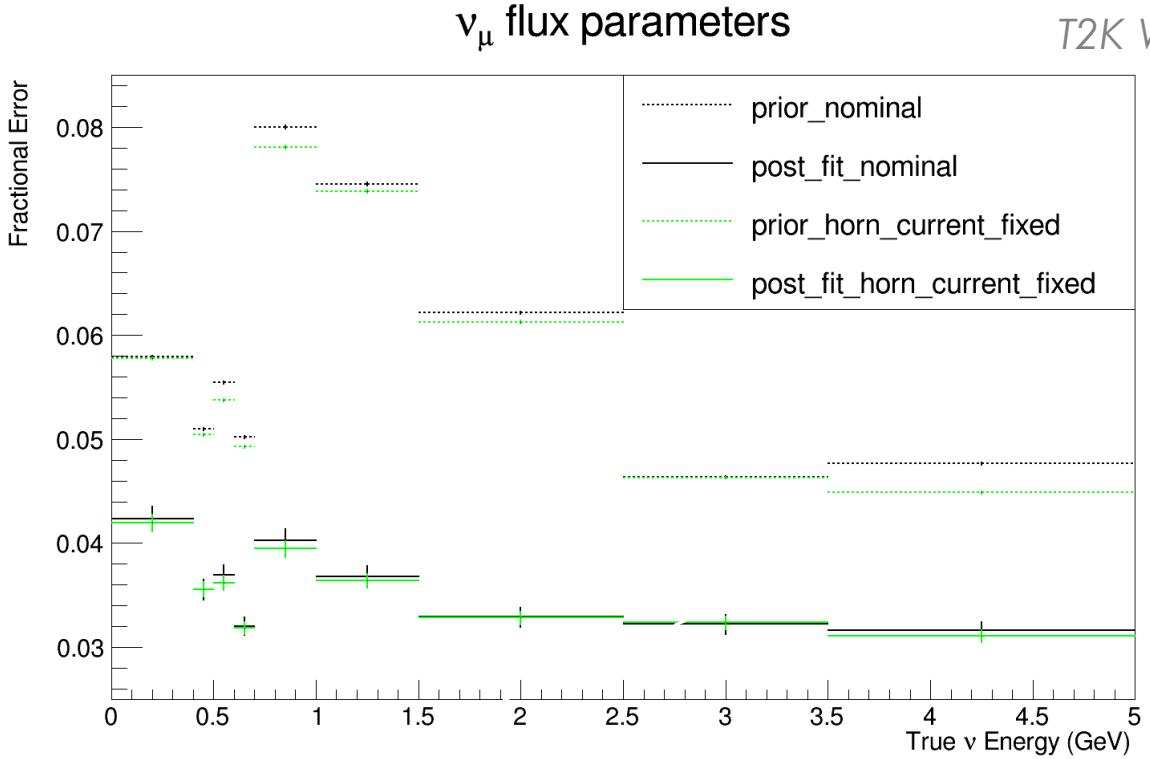
Note : This flux matrix is combined with xsec and then used in the fit.

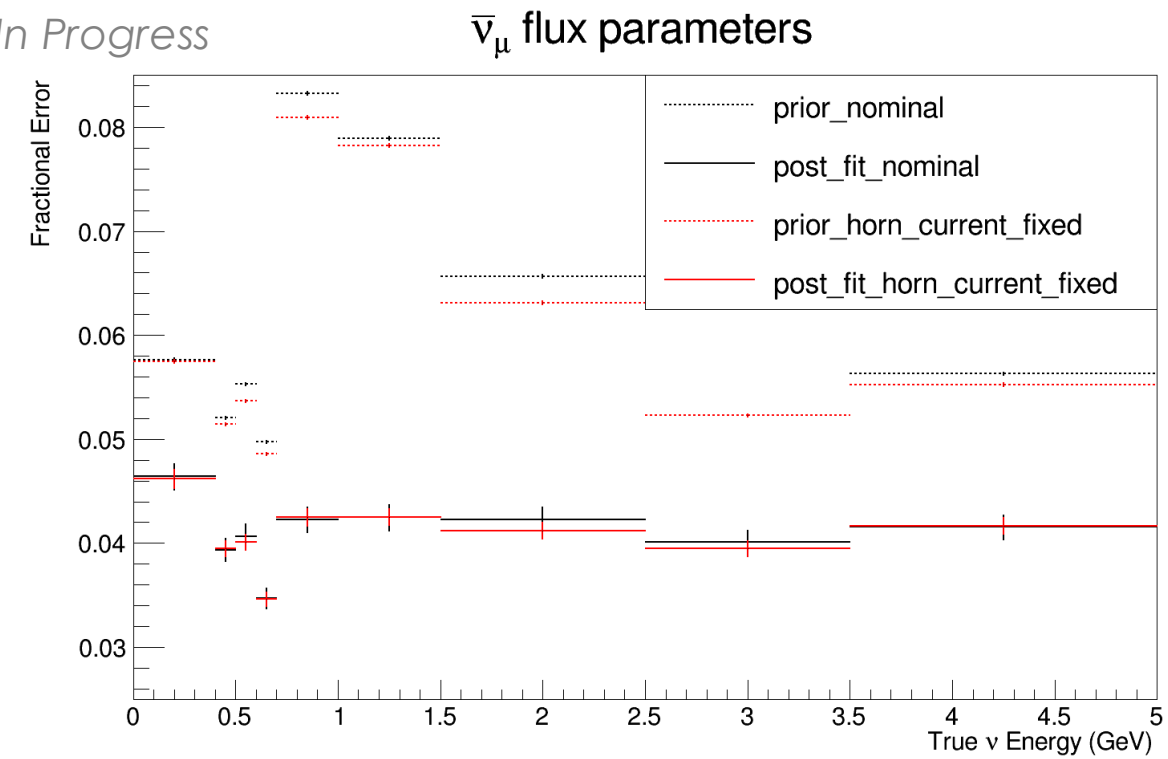
Interpretation

- 6.4% uncertainty prior to the nominal fit
- Removing the horn current uncertainty from the flux reduces the uncertainty to 6.2%
- 3.4% uncertainty after the nominal fit
- Just because uncertainty on prior is reduced does not mean post fit error will be reduced as the flux matrix is combined with xsec matrix and then used in the ND fit, so, ND can provide sufficient constrain that the prior freedom does not matter
- For this parameter, the uncertainty is reduced by further 0.2% compared to nominal ND fit by fixing horn current.



Horn Current



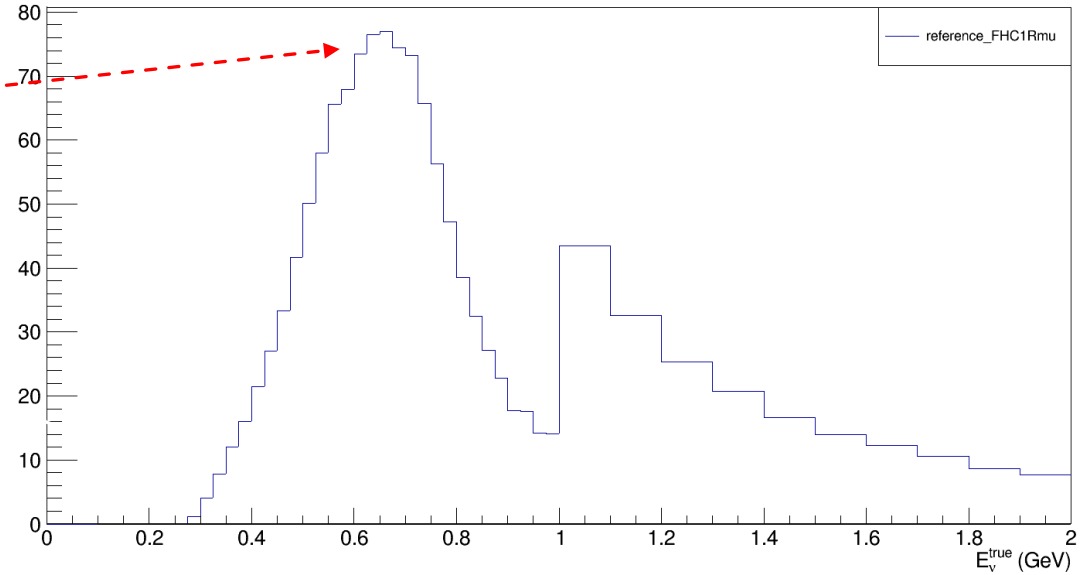


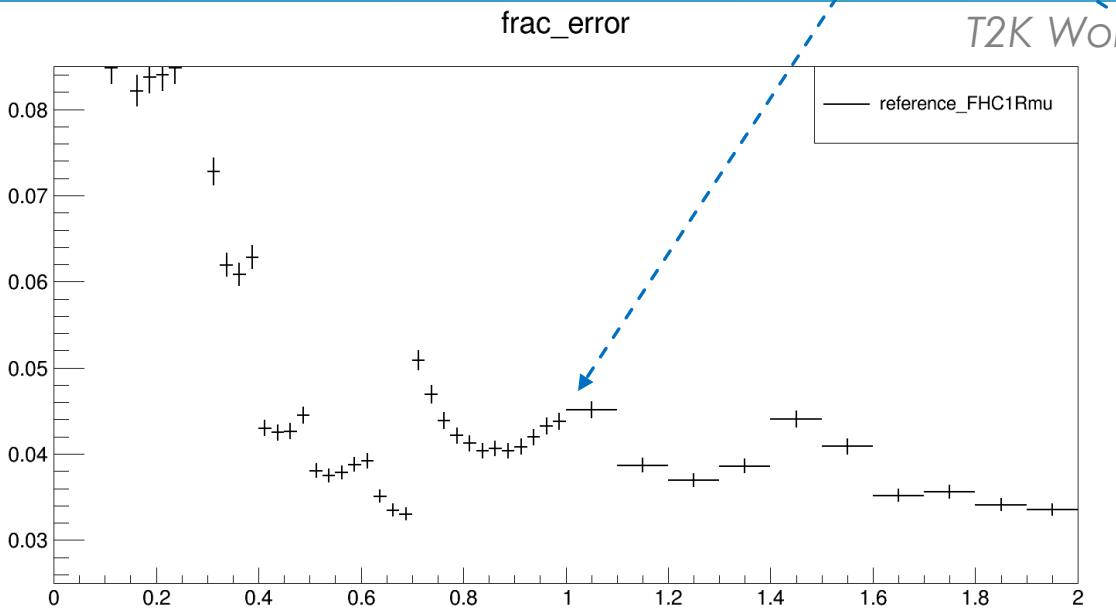
- Horn current has its highest impact on the prior in high energy region.
- The post fit errors are not significantly impacted by horn current uncertainty compared to the nominal fit of both nu and anti nu parameters, so ND potentially constrains the well enough already.

SK Posterior Predictive

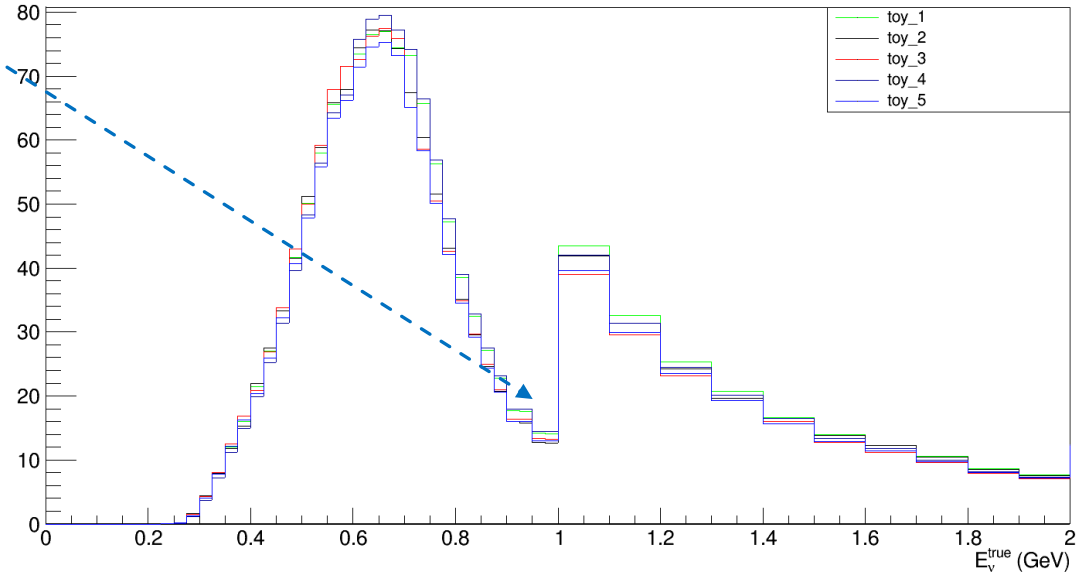
- Oscillations are off
- True neutrino energy binning

- The uncertainty is std dev from the distribution of event rates in each bin

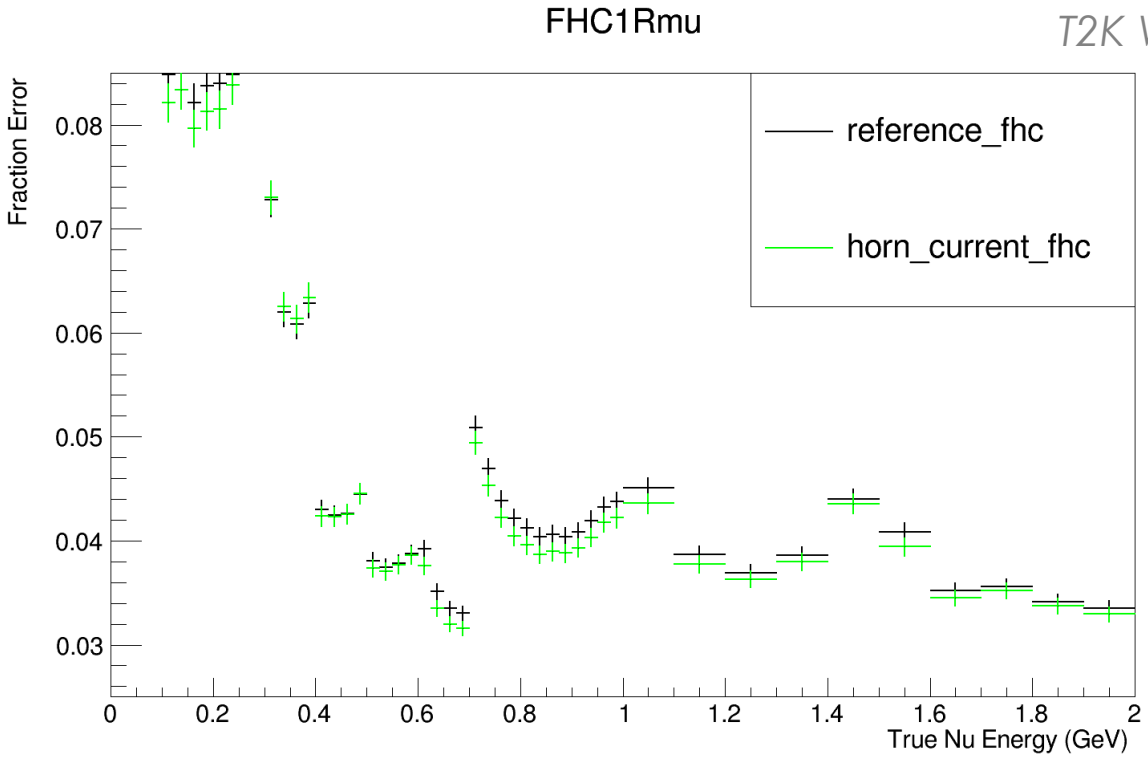


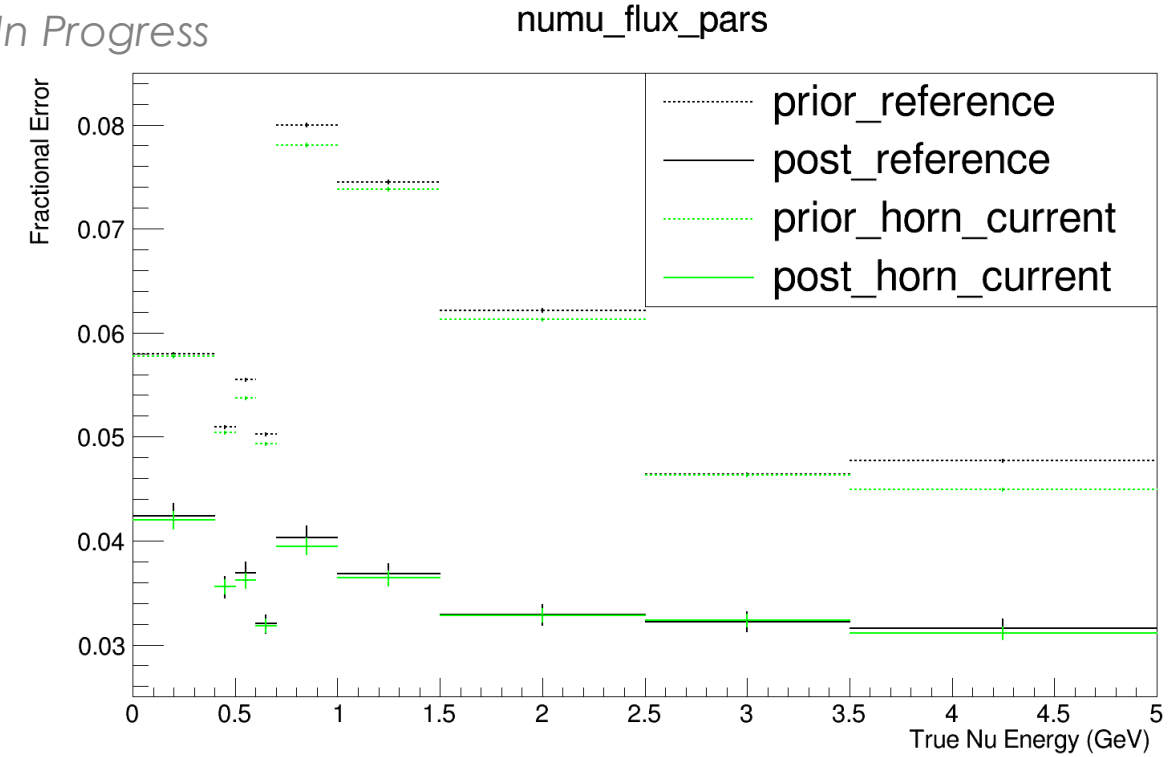


T2K Work In Progress



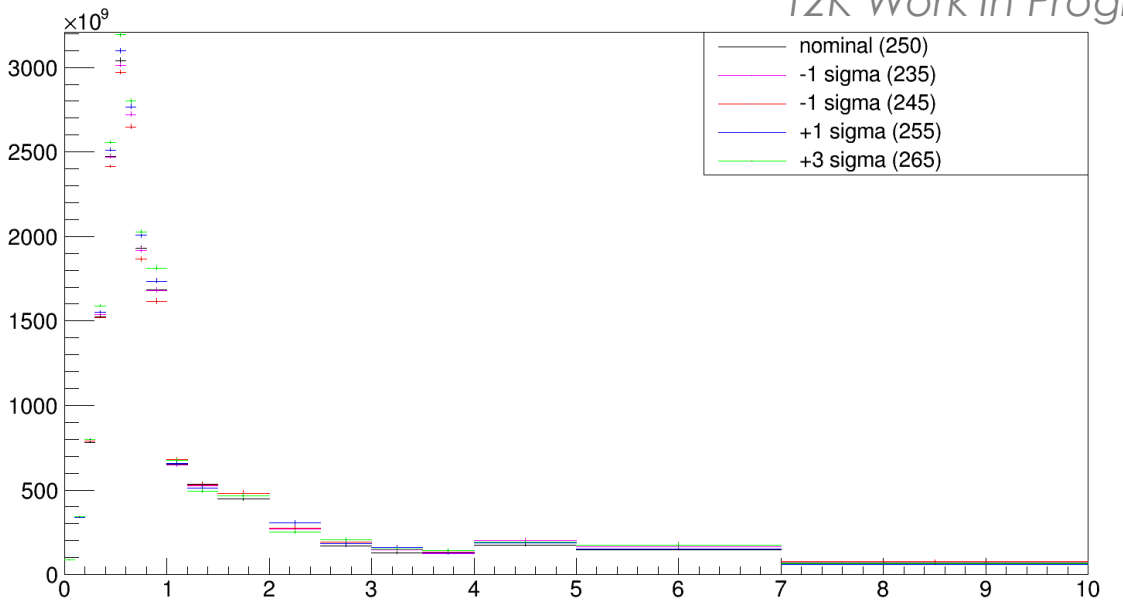
Horn Current





- ~0.2% drop in uncertainty in FHC1Rmu sample.

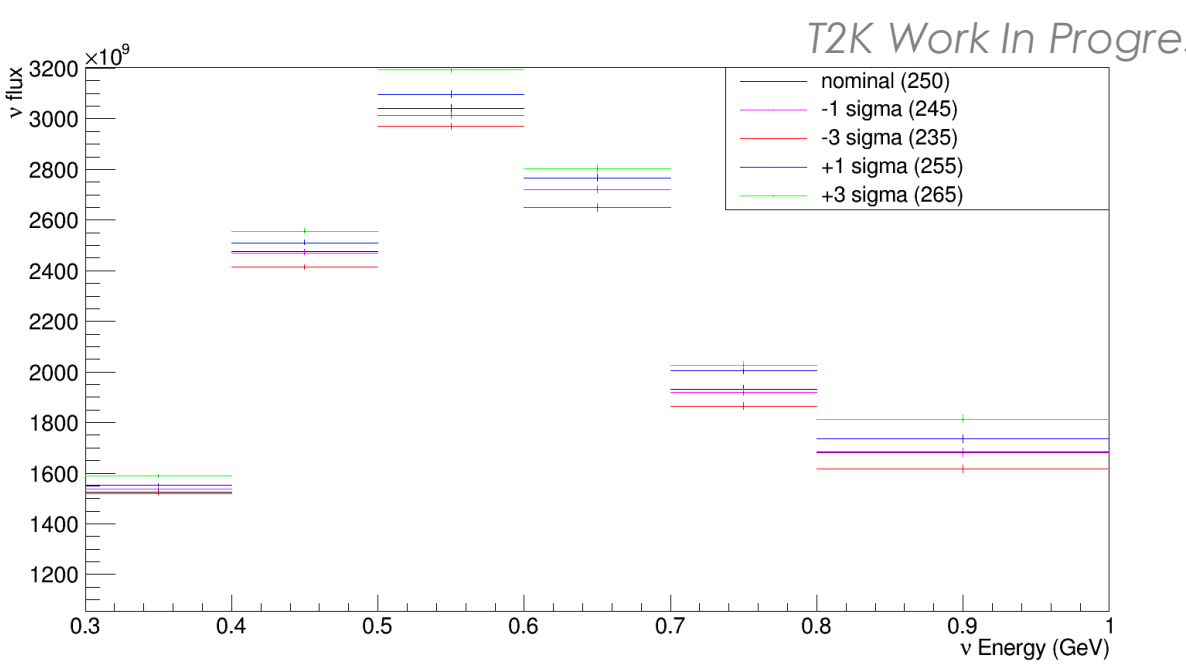
Flux Predictions -->



- Flux predictions for nu flux
- +/- 1 and 3 sigma uncertainty in horn current
- Nominal is 250 kA (FHC mode)
- Decent enough stat for now

Zoomed in

- Only Horn current in Jnubeam is changed
- Same Fluka files (since nothing related to proton beam or target is changed)
- About 100 fluka files are used out of ~1000

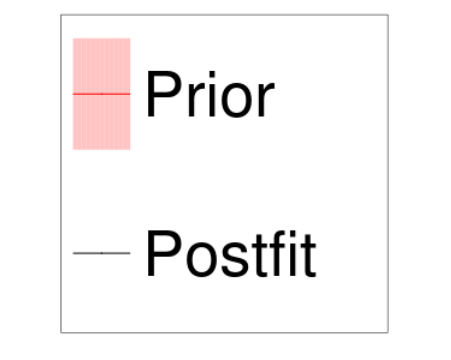


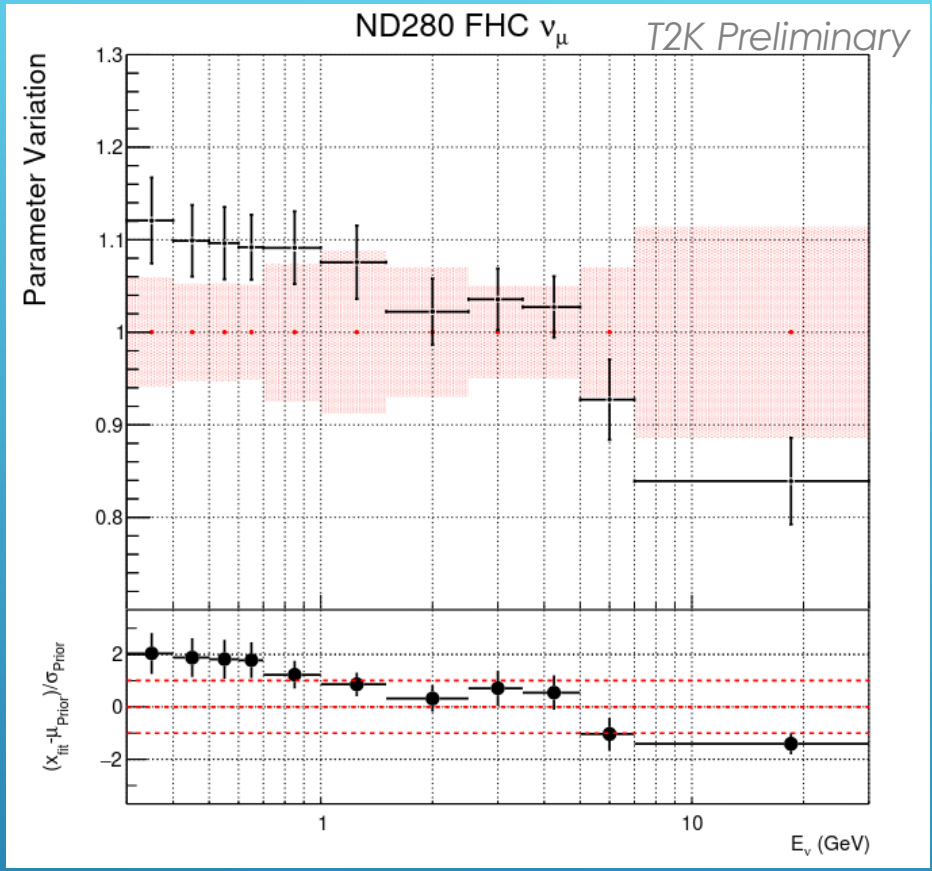
ND fit implementation

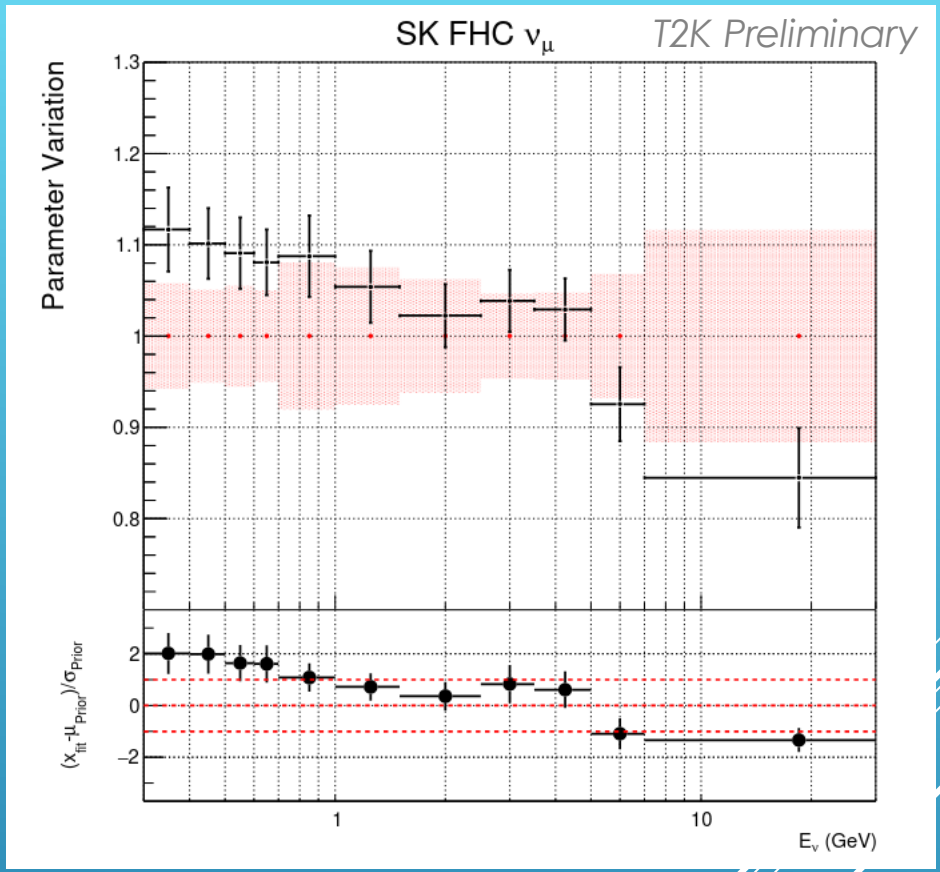
- In T2K, the MaCh3 fitter is used, it is a Markov Chain Monte Carlo based fitter. It varies the parameters to maximize the likelihood and explores the parameter space to give a posterior distribution for each parameter.

- In the T2K analysis, reweighting is used to adjust event weights in Monte Carlo (MC) simulations to account for systematic uncertainties and improve agreement with data. This is crucial for modeling flux uncertainties, neutrino interaction uncertainties, and detector effects.

ND pulls







- The plot shows the uncertainty on parameters, pre fit and post fit. It also shows how much the central value of the parameters changes from the nominal.