Neutrino Flux Prediction in NuMI and DUNE

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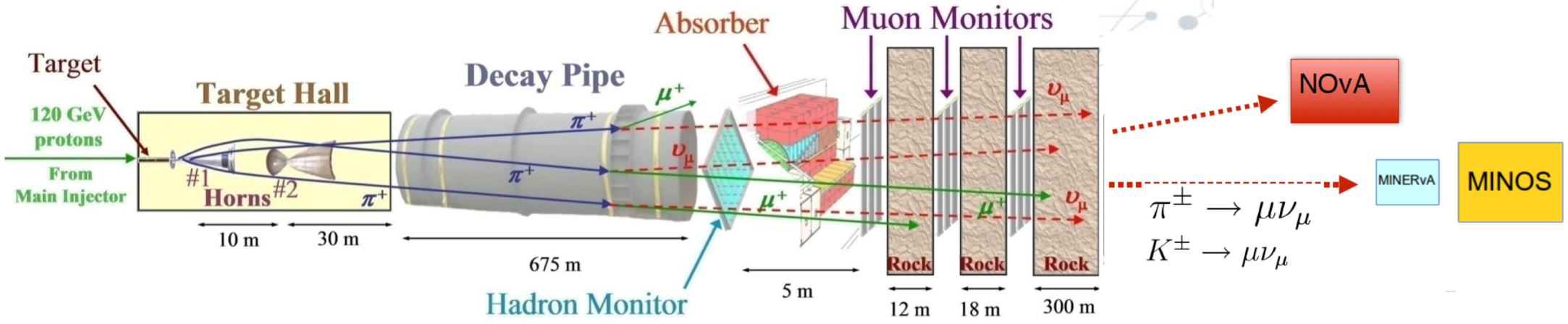
NuMI Beamline

More Detailed Overview



1. Proton Beam ➢ 120GeV, high intensity
2. Pion Production Target ➢ Thin Carbon Rod
3. Focusing System ➢ Focusing System
4. Decay Region ➢ Tunnel, filled with helium
5. Monitors, Absorbers, Shieldings ➢ Filter out the muons

Neutrino Flux Prediction

- Challenges in Neutrino Flux Prediction:
  - Predicting neutrino flux is a multi step process and we do not understand every process completely.
  - Main challenges in flux prediction can be divided into 2 categories.

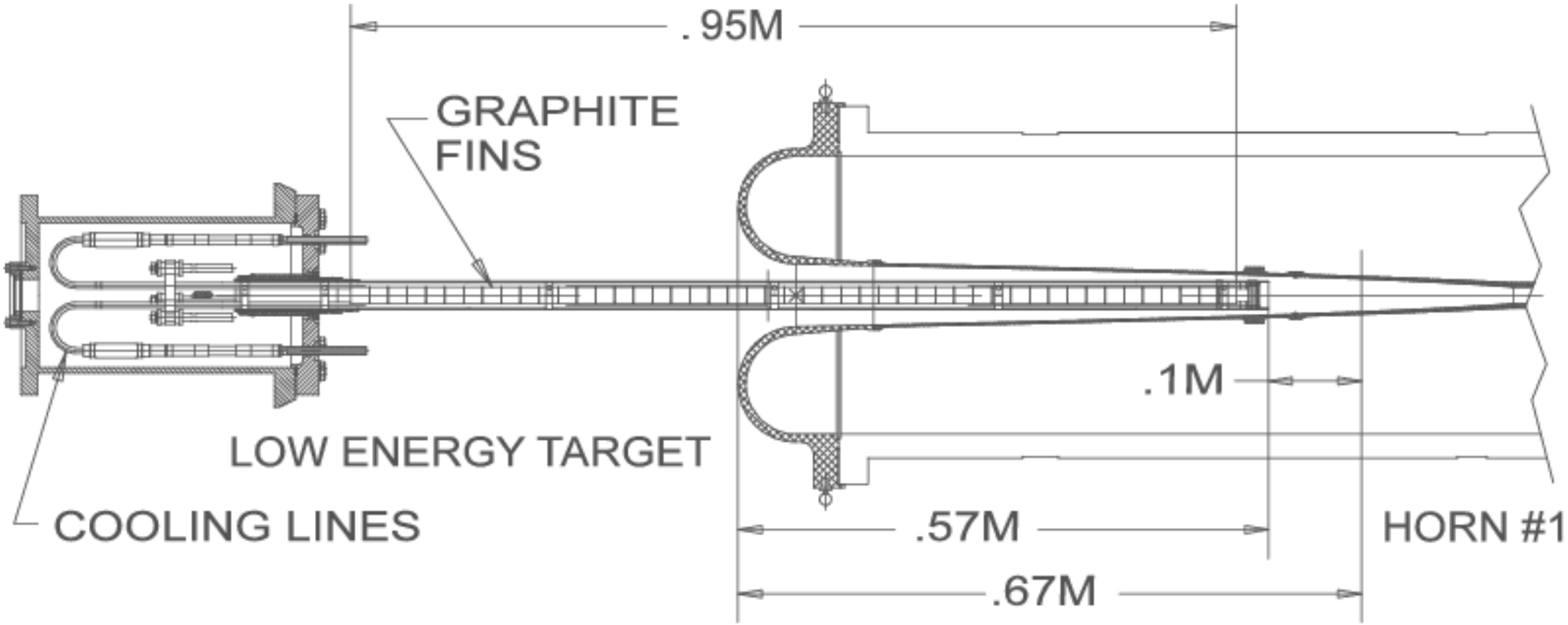
1. Beam Focusing Uncertainties

   →Target position, horn current, horn dimensions and etc.

   →Focusing parameters are optimized to get small uncertainties around the focusing peak of the neutrino flux

2. Later slides…

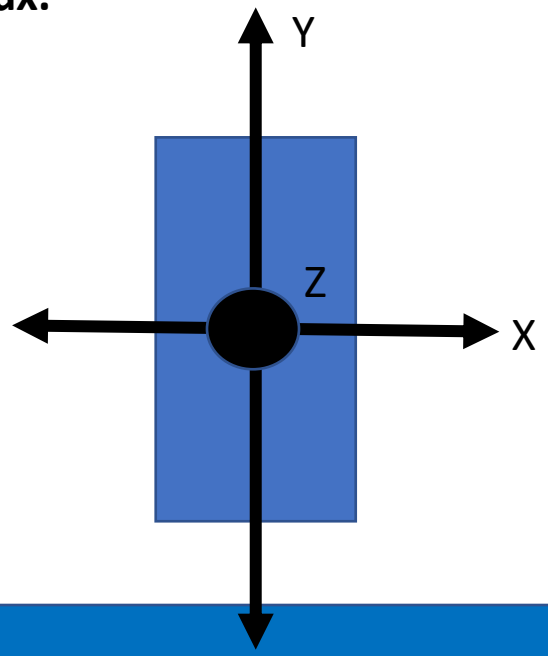
The NuMI LE Target and Horn



Beam component parameters for NuMI

Parameter	Nominal Value	Sigma Value
Beam Position (X)	0 mm	1 mm
Beam Position (Y)	0 mm	1 mm
Beam Spot Size	1.5 mm	0.3 mm
Horn Water Layer	1 mm	0.5 mm
Horncurrent	200 kA	1 kA
Horn1 Position (X)	0 mm	1 mm
Horn1 Position (Y)	0 mm	1 mm
Target Position (X)	0 mm	1 mm
Target Position (Y)	0 mm	1 mm
Target Position (Z)	-1433 mm	3 mm

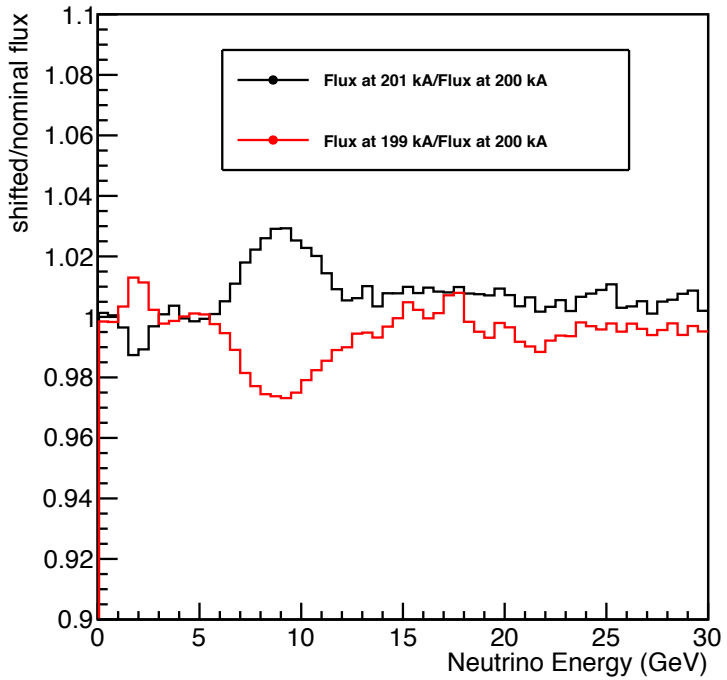
- **Beam Parameters have very small uncertainties/tolerances (every mm matters!)**
- **Parameters optimized to have small uncertainties around the focusing peak of the neutrino flux.**



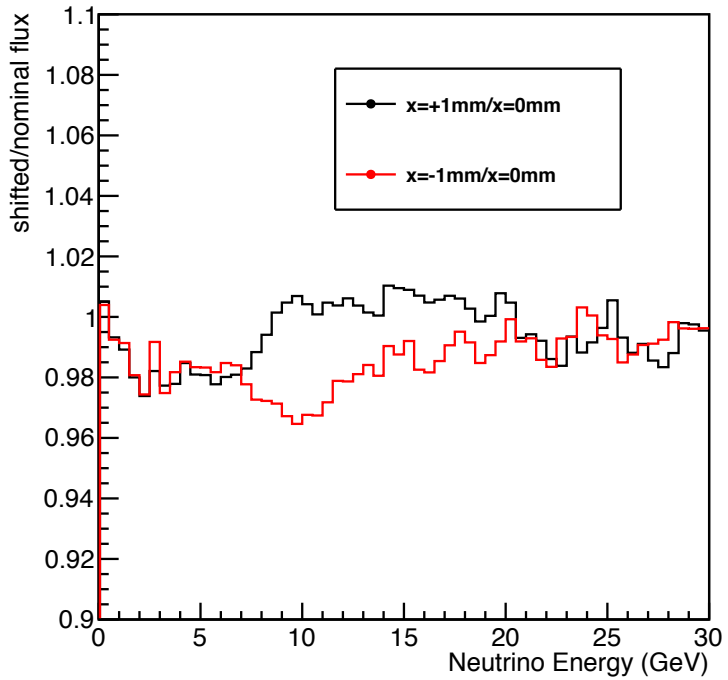
***Recently, NoVA (off-axis detector) has added uncertainty due to Earth's Magnetic field.**

Neutrino Beam is along Z

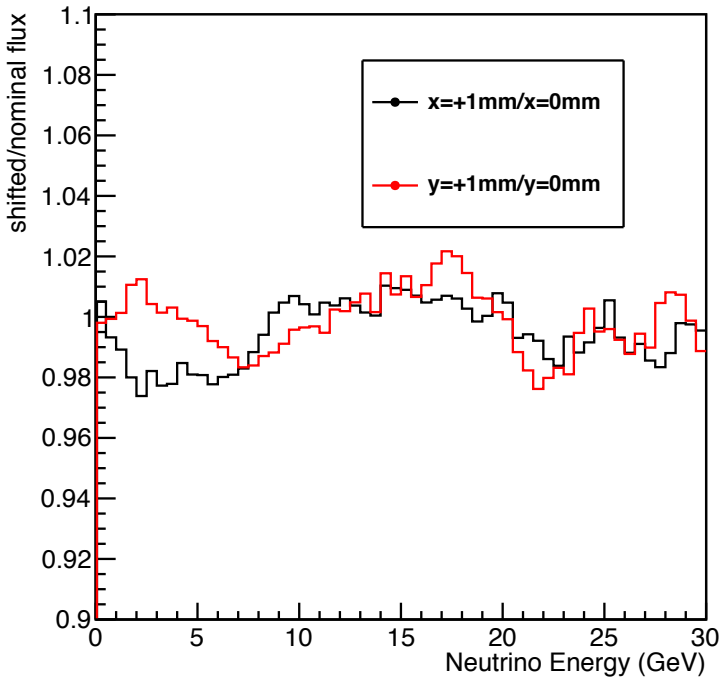
Beam Parameters and Neutrino Flux



Change in flux due to change in horn current within its tolerance.



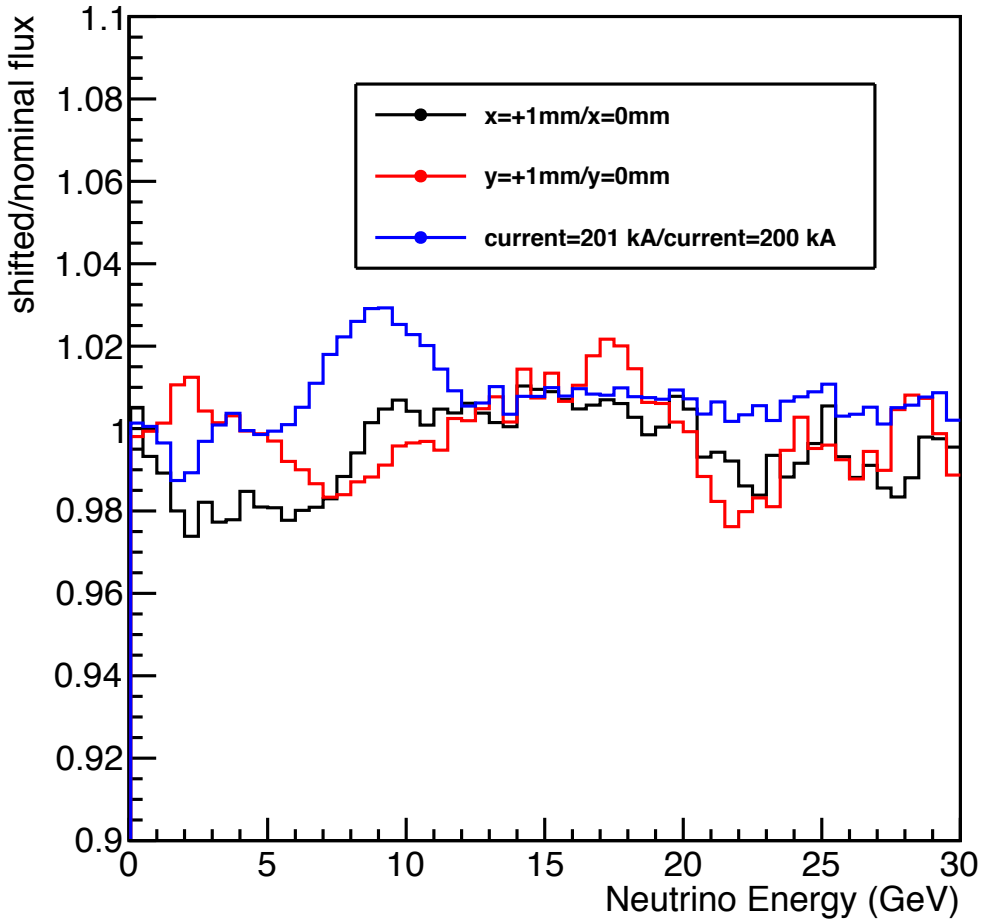
Moving target in positive or negative direction in horizontal (x) direction by 1 mm



Change in flux due to moving target along X or Y directions.

Medium Energy neutrino flux at MINERvA/on-axis detector

Beam Parameters and Neutrino Flux

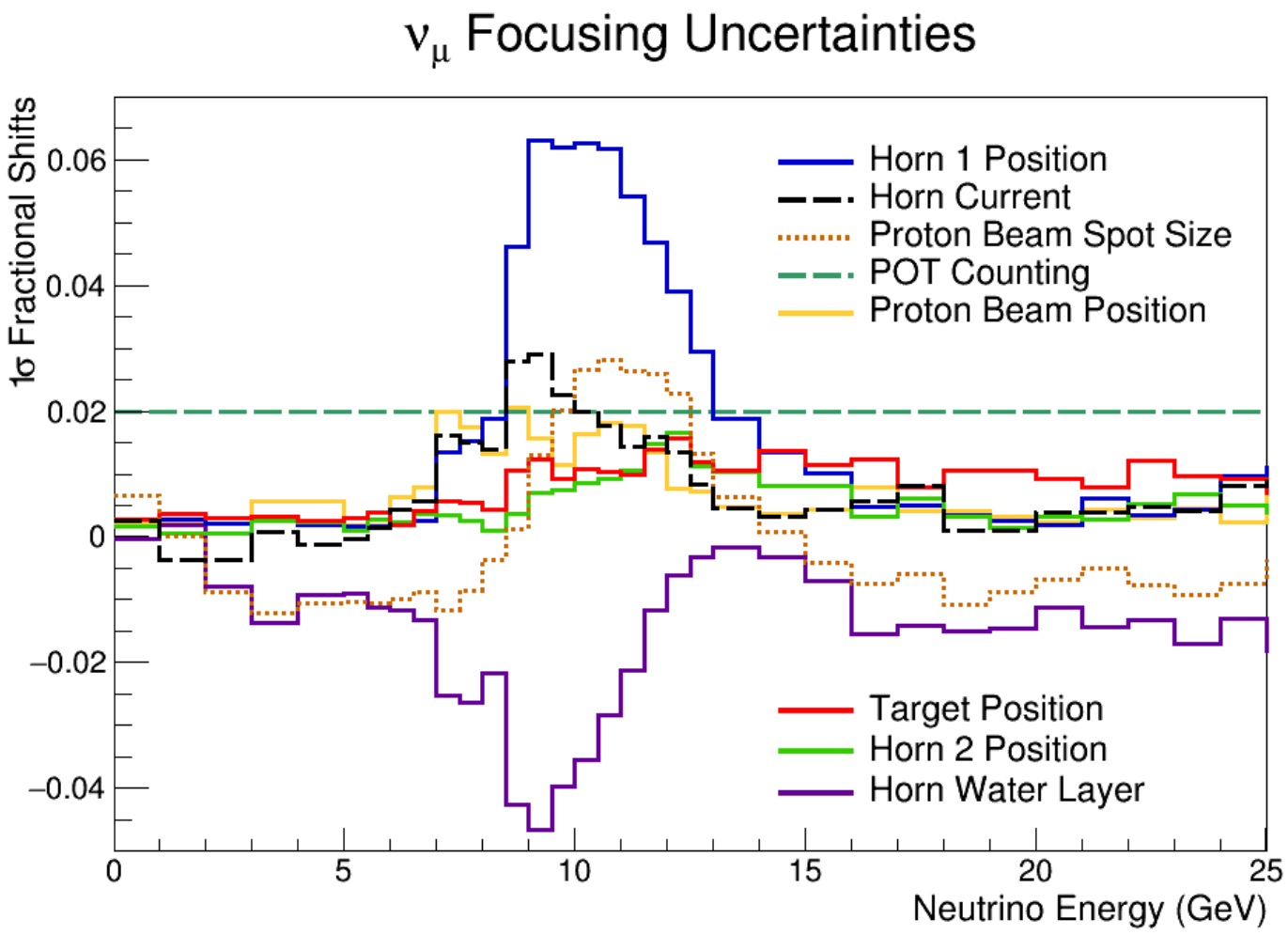


Medium Energy neutrino flux at MINERvA/on-axis detector

Different Beam parameters have different sensitivities in different neutrino energy regions.

Focusing uncertainties are calculated by taking into account these sensitivities when the parameters are moved within their 1 sigma limits.

Focusing Uncertainties



Medium Energy neutrino flux at MINERvA/on-axis detector

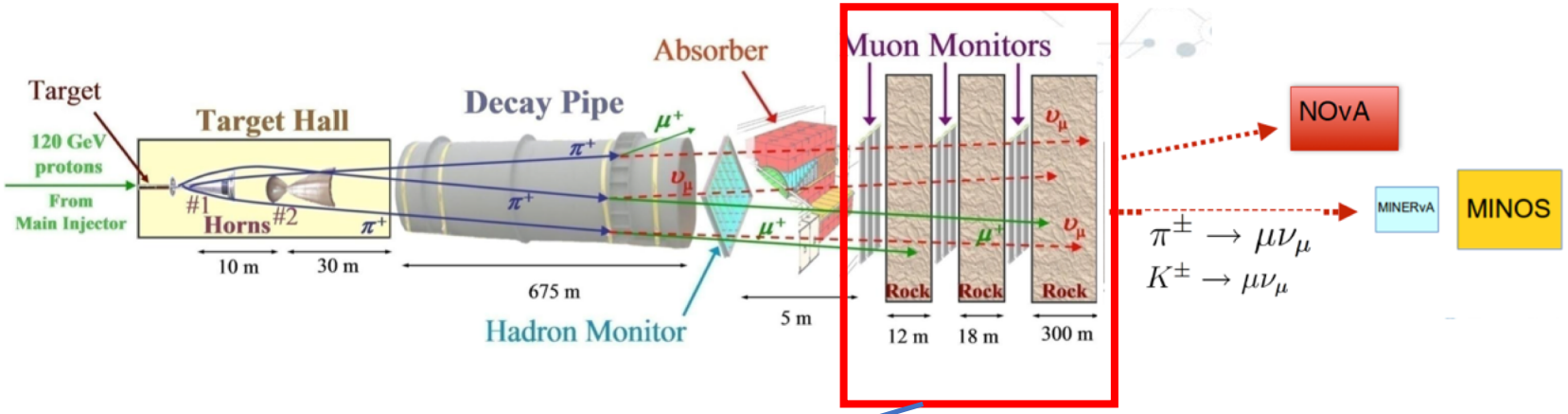
These are the NuMI focusing uncertainties evaluated for the MINERvA Medium Energy Run.

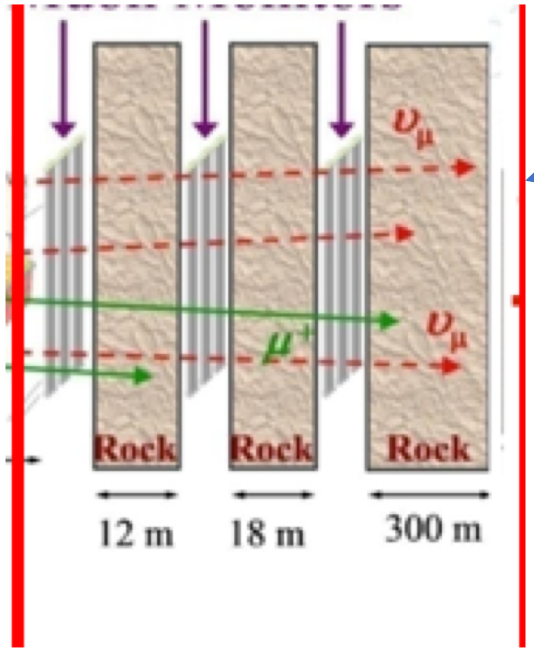
The total uncertainty is calculated by adding uncertainty from each of the parameters in quadrature.

Stability of Focusing parameters

- Uncertainties on focusing parameters are small and there are different effects at different regions of the neutrino energy spectrum.
- Beam monitoring is used to check the stability of the beam.
- We monitor Accidental or gradual shift in beam parameters.
- MINERvA + MINOS detectors acted as a beam monitor for NOvA experiment before they shut down.
- Current effort is to utilize the muon monitors to check the beam quality and possible status of beam parameters.

Muon Monitors and Neutrino Flux

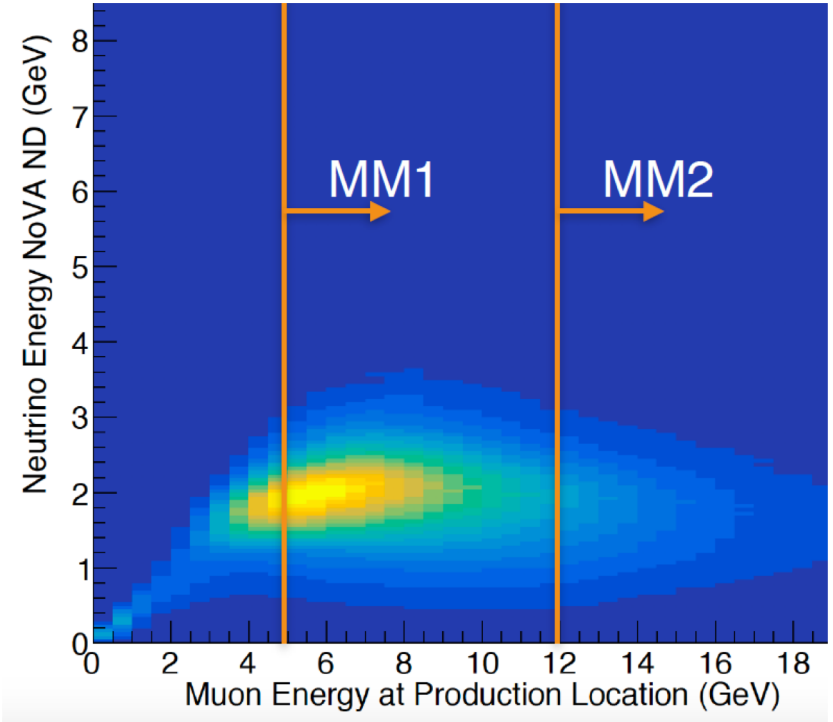




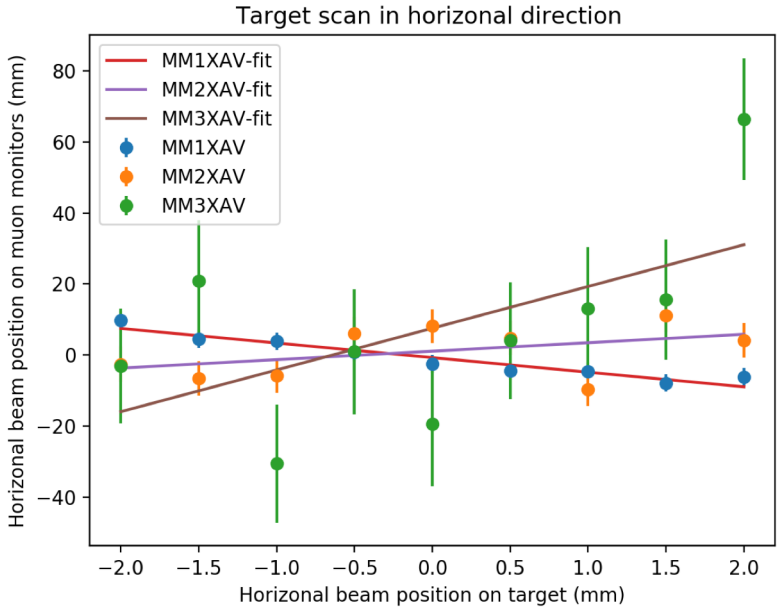
3 Muon Monitors (MM) after the absorber at different distances. Separated by layers of rock.

Muons from pion decay range out as they loose energy in the materials. Low energy muons range out in the rock letting downstream MM see only high energy muons.

Muon Monitors and Neutrino Flux

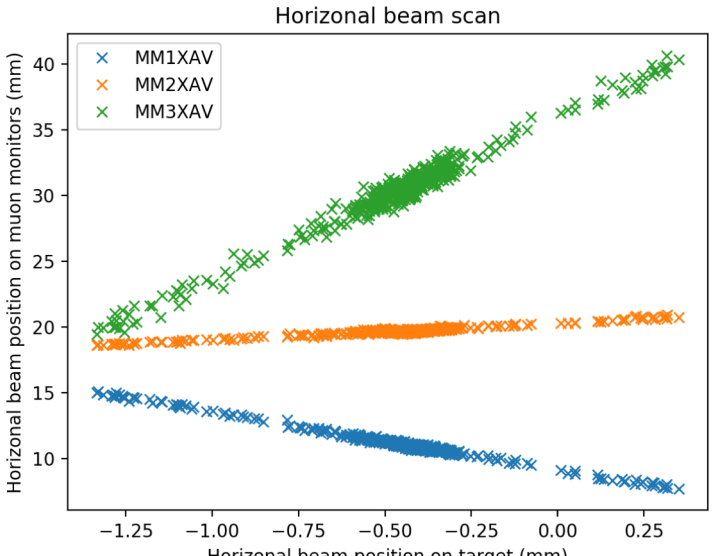


Plot shows the coverage of muons by muon monitors and corresponding neutrino flux spectra at NoVA (off axis) near detector



Target Scan and the response seen in muon monitors (Athula Wickremasinghe)

Simulation of target scan and MM response agrees within limit with the data (Yiding Yu)



Neutrino Flux Prediction

- Challenges in Neutrino Flux Prediction

~~1. Beam Focusing Uncertainties~~

~~→Target position, horn current, horn dimensions and etc.~~

~~→Focusing parameters are optimized to get small uncertainties around the focusing peak of the neutrino flux~~

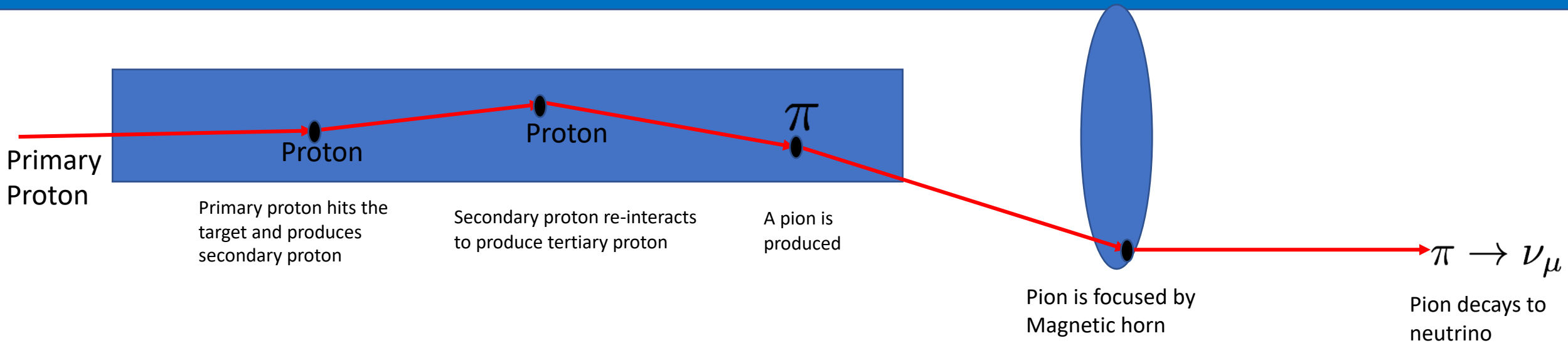
2. Hadron Production Uncertainties

→Our neutrino simulation tool (GEANT4) has uncertainties in the hadronic models that are intermediate interactions for neutrino production.

→There is newer data (NA49, MIPP, NA61) that can help give a more accurate prediction

→Use those data to constrain the hadron production models.

Hadron Production Uncertainties

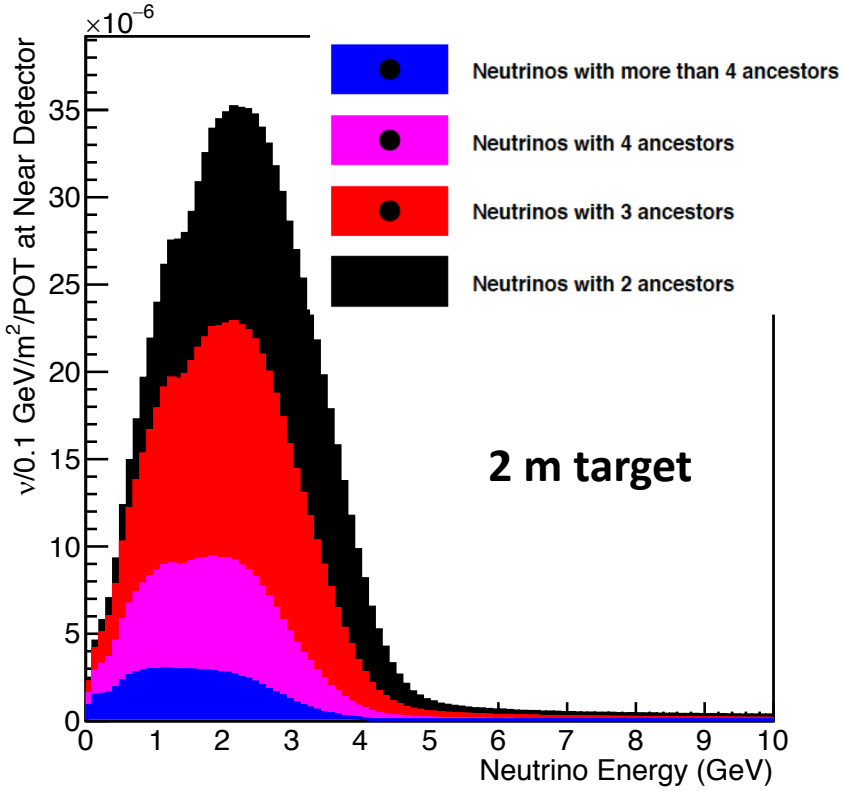


1. PROTONS HIT CARBON.
2. CHARGED PIONS ARE PRODUCED.
3. PIONS DECAY TO NEUTRINOS.

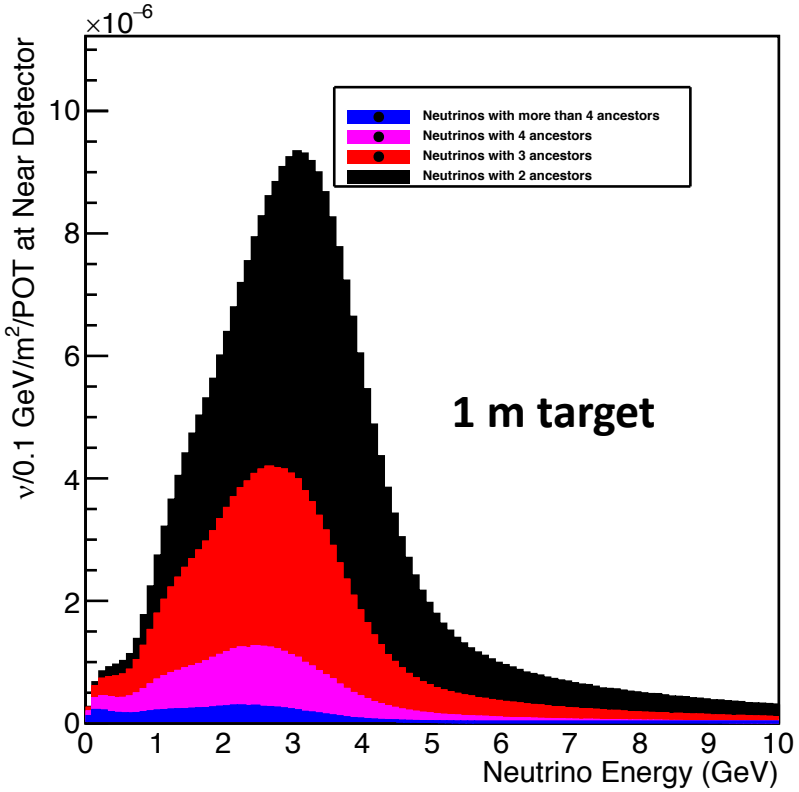
Neutrino Production in the NuMI beamline is basically a 3 step process
But….
Re-interactions in the target and absorption of hadrons in the beamline materials needs to be taken into account.
Our simulation tool needs to take these effects into account.

Hadron Production Effects on ν flux

Numu Flux at DUNE Near Detector



Numu LE Flux at the MINERvA Detector

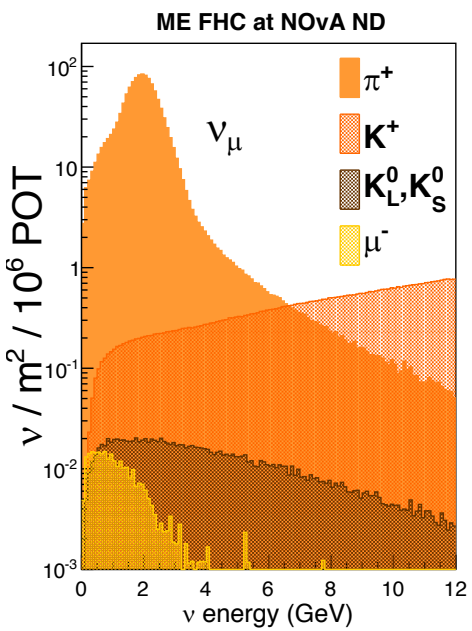


The LBNF target is recently "updated" to 1.5-1.8 meters.

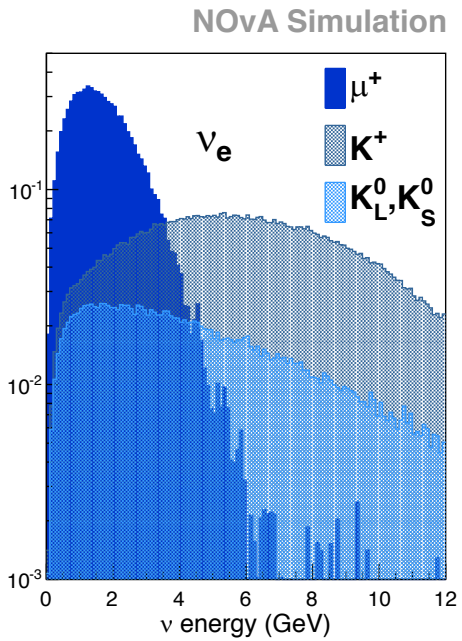
- Long NuMI target (1m) means a significant fraction of flux will come from multiple interactions of hadrons.
- In case of DUNE, it is more prominent (2m long target).

Hadron Production Uncertainties

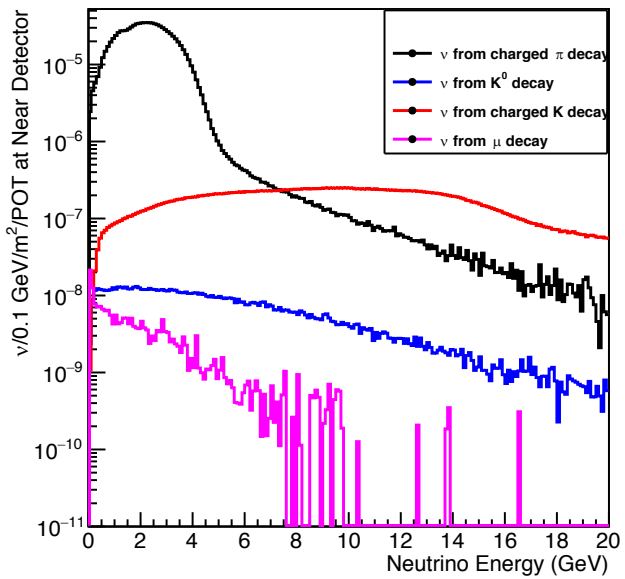
Off axis detector



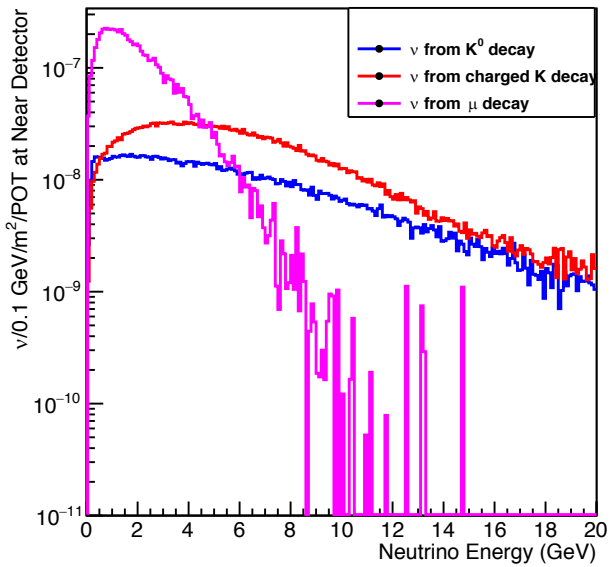
Off axis detector



Muon Neutrino Flux at DUNE Near Detector (on axis)



Electron Neutrino Flux at DUNE Near Detector (on axis)



In case of both NuMI and DUNE beamline, neutrinos at focusing peak come from pion decay.
High energy neutrinos mostly come from charged kaon decay.
There are small contributions from neutral kaons and muons as well.

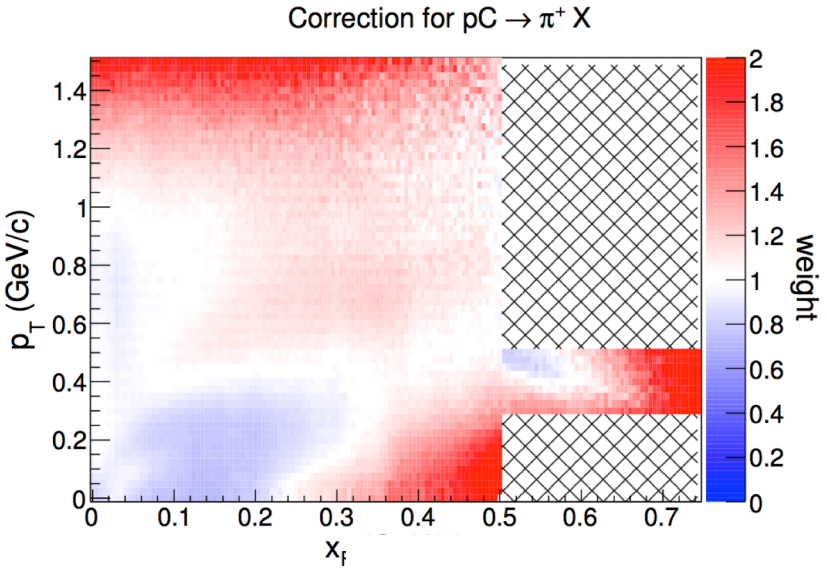
Hadron Production Uncertainies in NuMI and DUNE

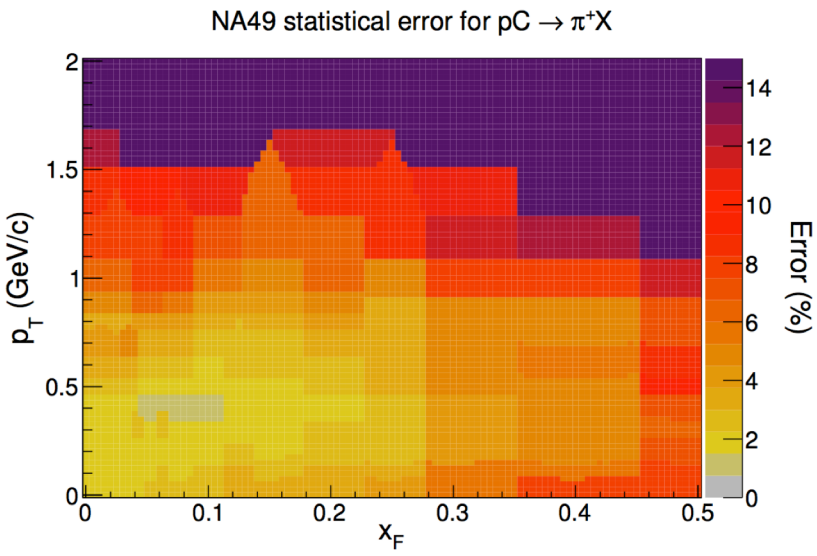
- MINERvA and NOvA use the neutrino flux determination package called Package to Predict Flux (PPFX)
- Correction for improved hadron production rates and uncertainties using existing thin target experiments
- Developed by Leo Aliaga (FNAL)

*L. Aliaga Soplin, *Neutrino Flux Prediction for the NuMI Beam,* URL: https://arxiv.org/pdf/1607.00704.pdf

Hadron Production Data Sets

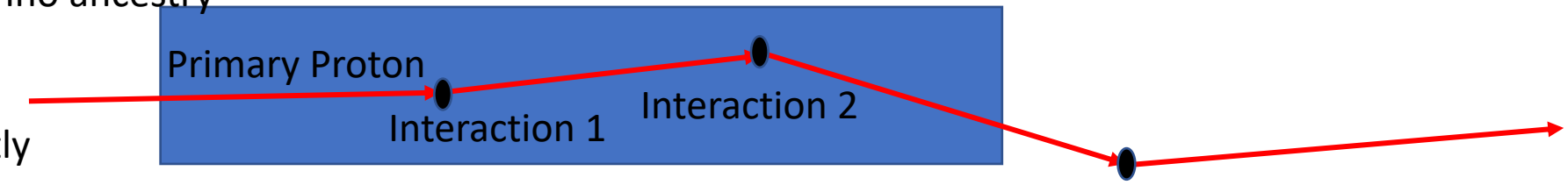
- Thin target data sets from *NA49*
- x_F →(-0.1,0.5) and p_T →(0,2 GeV/c)
  - Include *Barton* data to extend the coverage
  - x_F →(0.3,0.88) and p_T →(0.3,0.5 GeV/c)





Applying these data sets means:

- Looking back at neutrino ancestry
- For an interaction:
  - Covered directly
  - Covered indirectly
  - Or not at all



* NA49 Collaboration, Eur. Phys. J. C49, 897 (2007).
* NA49 Collaboration, Eur. Phys. J. C73, 2364 (2013).
* D. S. Barton et al., Phys. Rev. D 27, 2580 (1983)

Neutrino Flux Uncertainties from Hadron Production

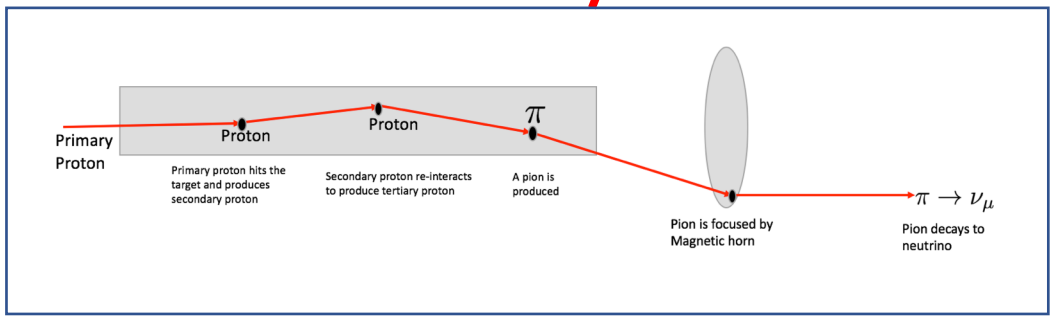
Simulation

Full Neutrino Ancestry

For
Each interaction in an ancestry

Coverage of interaction by Existing Data sets

- Direct Coverage
- Coverage By Extension
- No Coverage at all



Full ancestry of a neutrino event (from primary proton hitting target to neutrino production)

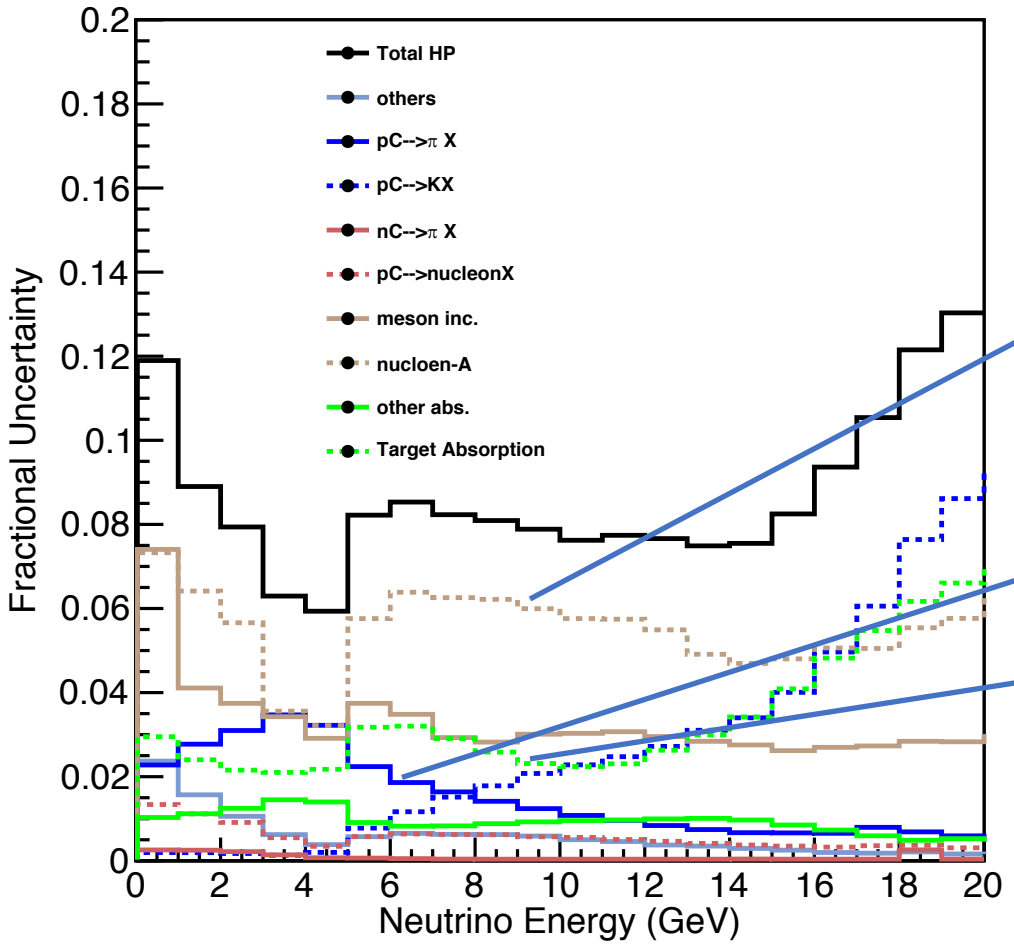
***Coverage by Extension of Data Sets**

Extend the coverage for interactions that are not covered directly wherever possible

***No Coverage at All**

Apply uncertainties based on best estimation from current physics models if an interaction is not covered directly or indirectly

Hadron Production Uncertainties –DUNE ND

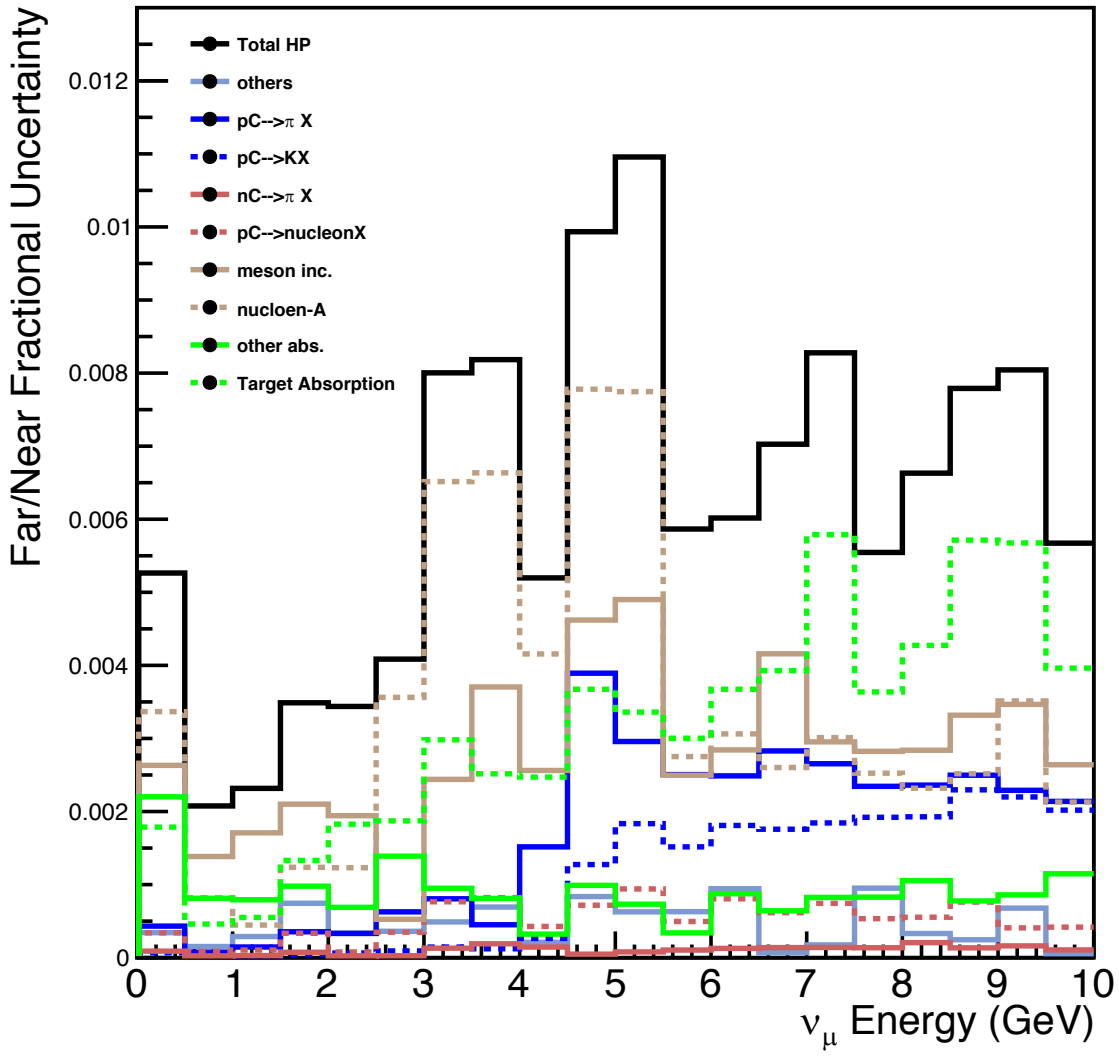


Quasi elastic interactions contribute large uncertainties in both the focusing and the tail of the neutrino flux peak.

Pions in carbon contribute large uncertainties at 4 GeV.

Target Absorption contributes 2 - 3% uncertainty in the region of interest.

Hadron Production Uncertainties on Far/Near ratio

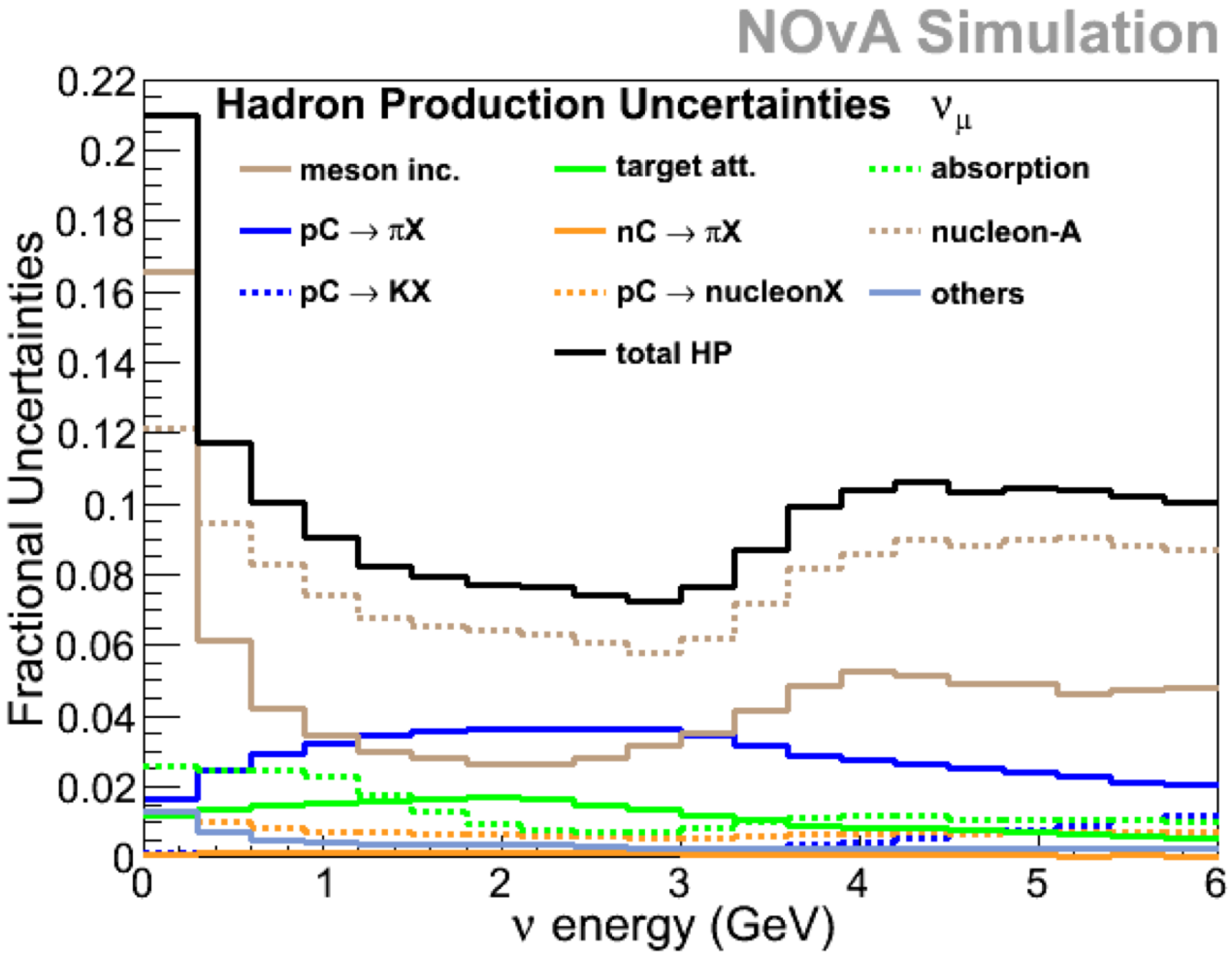


→Most of the hadron production uncertainties cancel out when in the flux ratio plot.

→Uncertainties on flux ratio themselves less than 1%.

GOTTA HAVE THAT NEAR DETECTOR!!!!

Hadron Production Uncertainties- NOvA ND

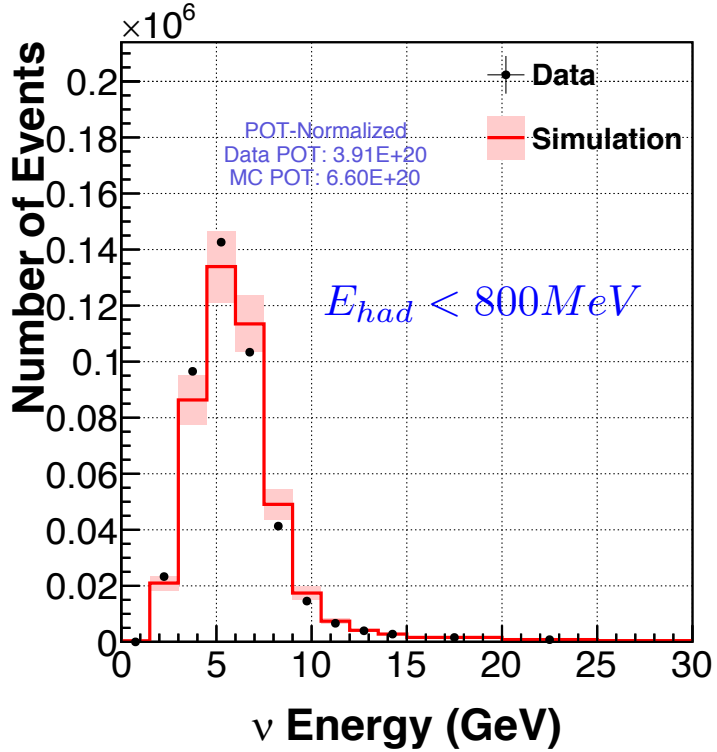


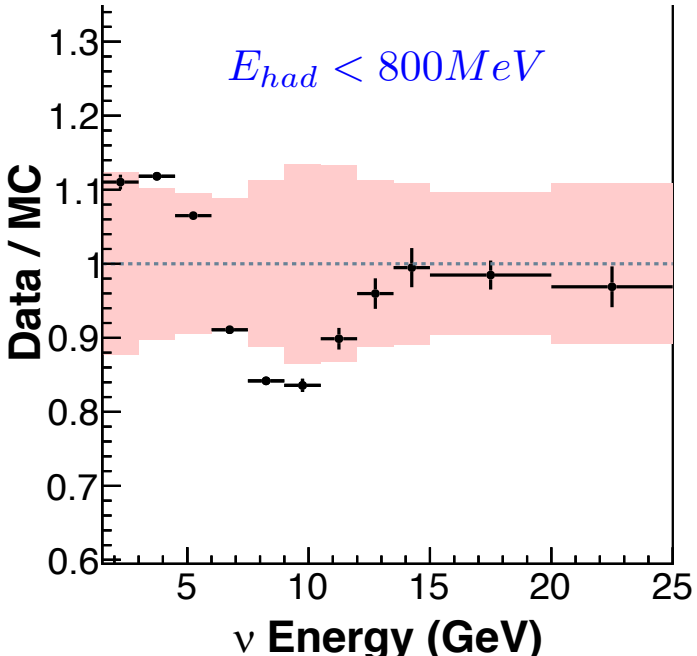
In case of NOvA also, the dominant uncertainties come from the QE interactions.

Pion productions in target and meson incidents are the remaining major contributors in the hadron production uncertainties.

MINERvA Flux “Issue” and our strategy

MINERvA's Flux discrepancy





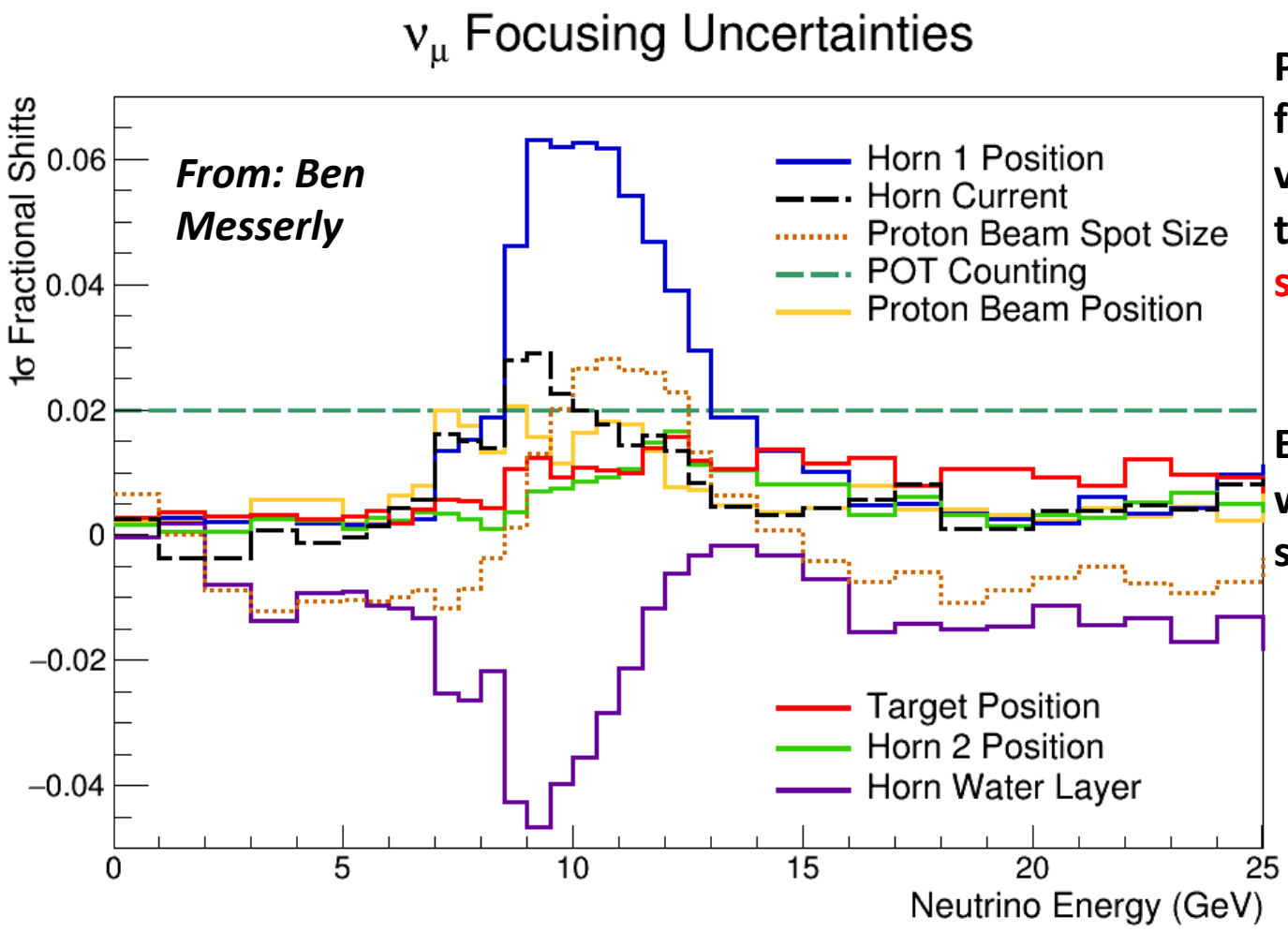
- **MINERvA sees a discrepancy in the DATA/MC Medium Energy predictions for cross sections.**
- **Since the Discrepancy is also seen in our low-nu measurements where the cross-section as a function of energy should be well understood ,we believe the discrepancy is coming from our flux prediction or is instrumental (and not cross section mis-modeling).**

MINERvA's Flux Problem

- Looked more like a flux problem and the "wiggle" (data/mc ratio) looked more like an effect due to a shift in focusing parameter.

- A multi-parameter data driven fit with focusing parameters as fit parameters was done to investigate the wiggle.

Flux Fits (Recipe)

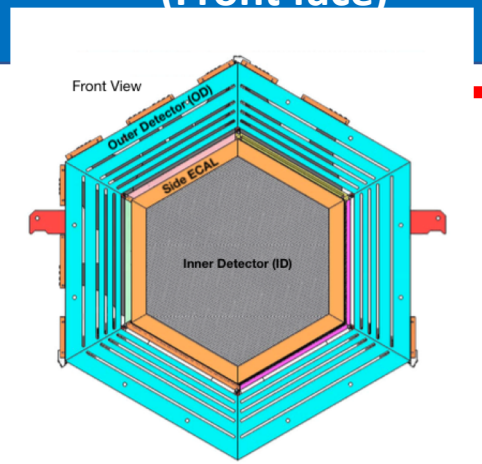


Plot the fractional variation in the flux as a function of neutrino energy as each parameter is varied by +/- 1 sigma, where the sigma values are taken from MINERvA ME Focusing uncertainties studies.

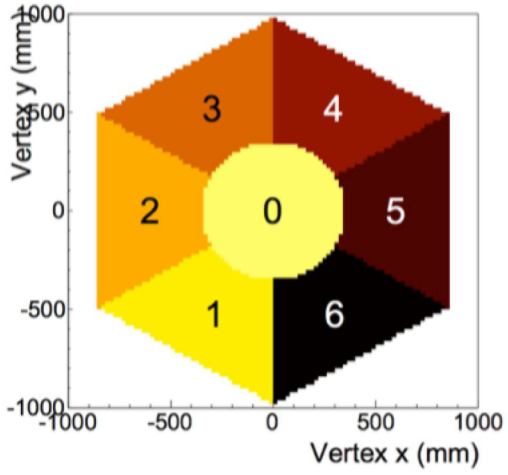
Each curve in this plot shows the change in the flux when we vary each focusing parameter by 1 sigma.

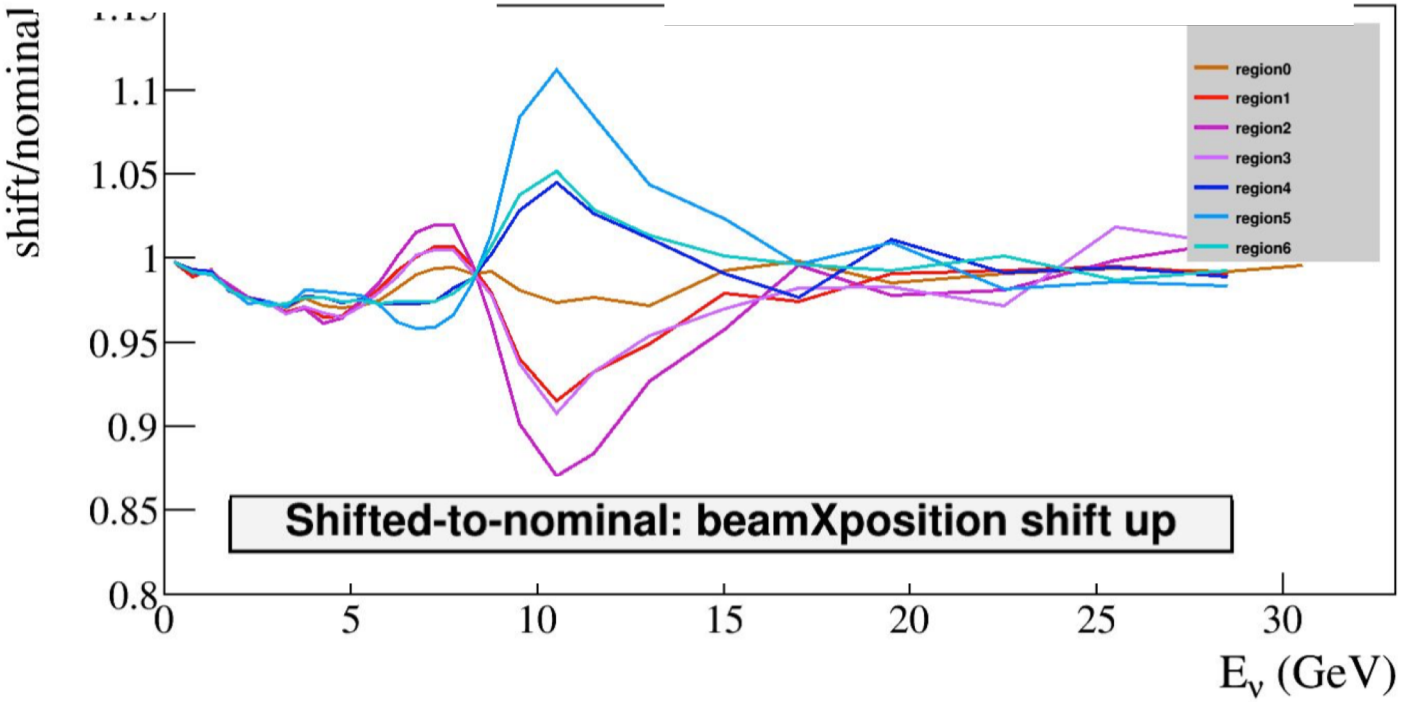
Flux Fits (Recipe)

MINERvA Detector (Front face)



Daisy bins of MINERvA Detector





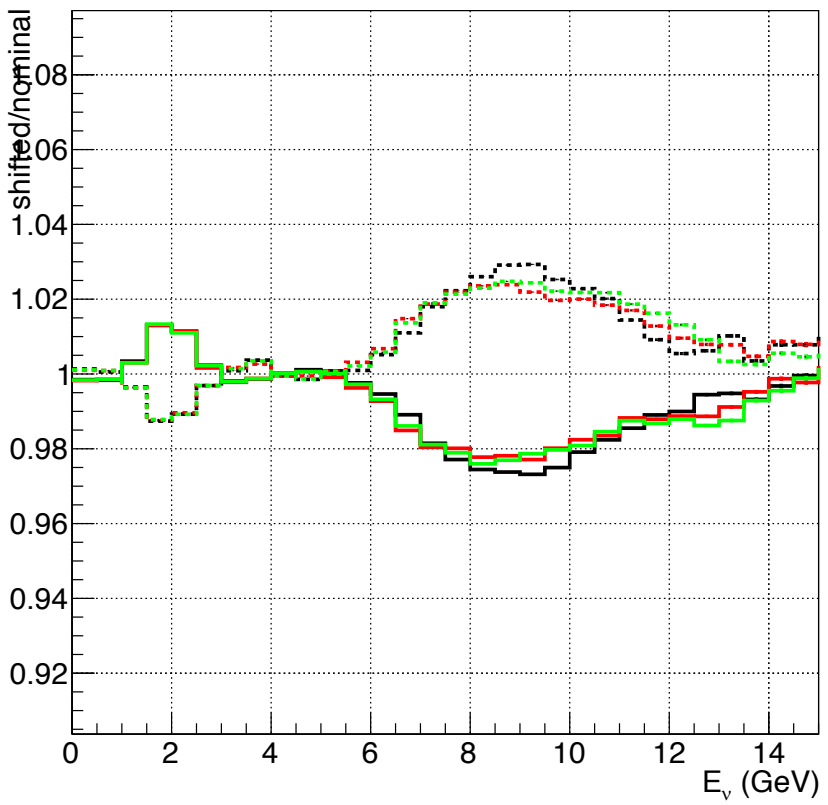
Shifting of a focusing parameter, by some amount do not produce uniform effects across the lateral face of the detector (facing towards the beam).

Hence, fitting of lownu MC to data as a function of focusing parameters is done over 7 different regions of the detector (also called daisy bins).

https://minerva-docdb.fnal.gov/cgi-bin/private/RetrieveFile?docid=14064&filename=20170518_Flux_Focusing_Ratios_Daisy_Binning.pdf&version=3

Input Fit Parameters

Parameter	Nominal Value	Sigma Value
Beam Position (X)	0 mm	1 mm
Beam Position (Y)	0 mm	1 mm
Beam Spot Size	1.5 mm	0.3 mm
Horn Water Layer	1 mm	0.5 mm
Horncurrent	200 kA	1 kA
Horn1 Position (X)	0 mm	1 mm
Horn1 Position (Y)	0 mm	1 mm
Target Position (X)	0 mm	1 mm
Target Position (Y)	0 mm	1 mm
Target Position (Z)	-1433 mm	3 mm



Horn Current (Next Slide)

Focusing Parameters and 1 Sigma shift values used for the fit

Fit Results

Parameter	Nominal Value	New Value	Sigma Value
Beam Position (X)	0 mm	-0.2±0.12 mm	1 mm
Beam Position (Y)	0 mm	-0.53±0.14 mm	1 mm
Beam Spot Size	1.5 mm	1.22±0.07 mm	0.3 mm
Horn Water Layer	1 mm	0.895±0.16 mm	0.5 mm
Horncurrent	200 kA	197.41±0.76 kA	1 kA
Horn1 Position (X)	0 mm	0±0.17 mm	1 mm
Horn1 Position (Y)	0 mm	-0.39±0.17 mm	1 mm
Target Position (X)	0 mm	-0.32±0.17 mm	1 mm
Target Position (Y)	0 mm	1.65±0.5 mm	1 mm
Target Position (Z)	-1433 mm	-1419.44±1.83 mm	3 mm

Fit prefers :

Large pull in horn current.

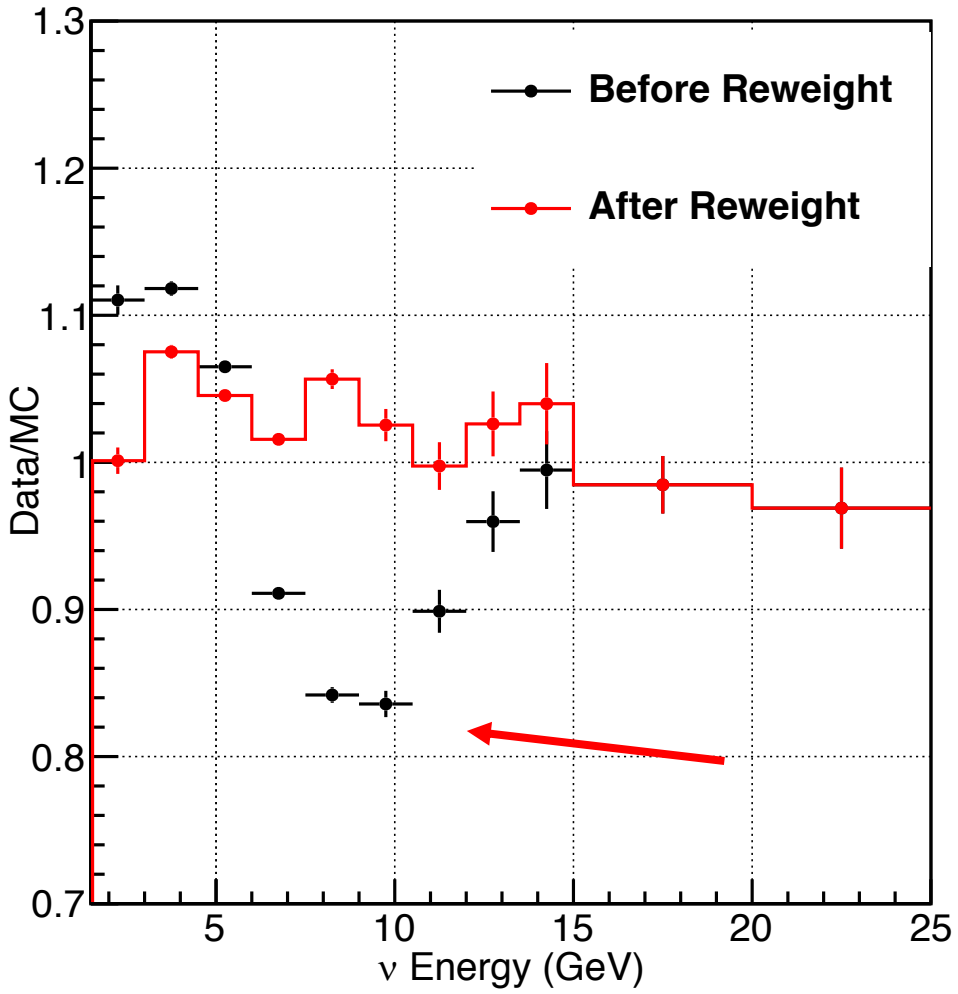
Large Pull longitudinal position of targetZ and

And they are correlated

units are mm unless specified

***X and Y are horizontal and vertical position**
Z is along the direction of beam

Observations/Result



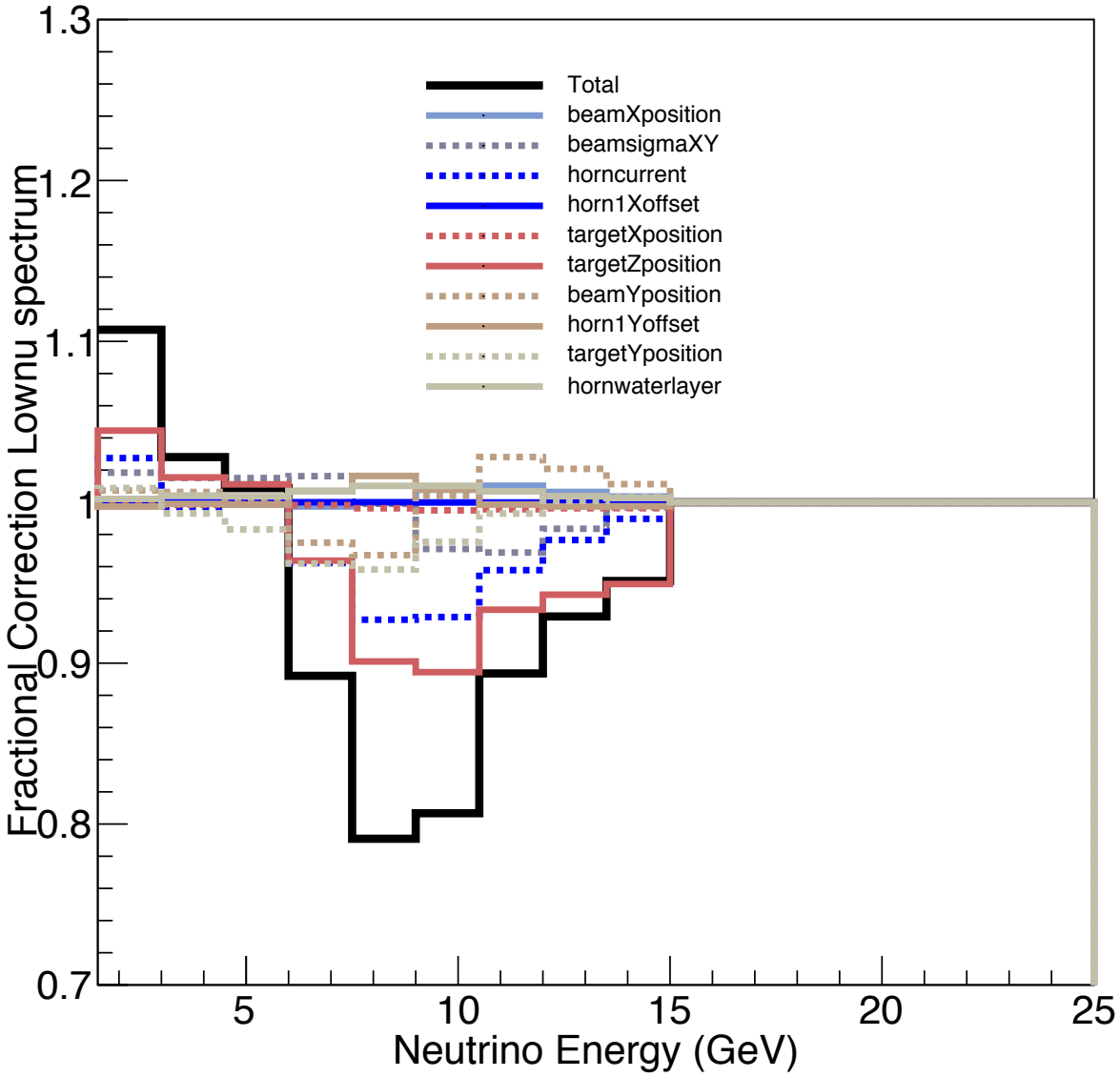
$E_{had} < 800 MeV$

Fit returns a weight function which is a function of shifted focusing parameters returned by the fit

And

Reweighing seems to fix the wiggle problem. However it comes with large baggage like a really large shift in target longitudinal position and or horn current (and correlations between different fit parameters).

Observations/Results

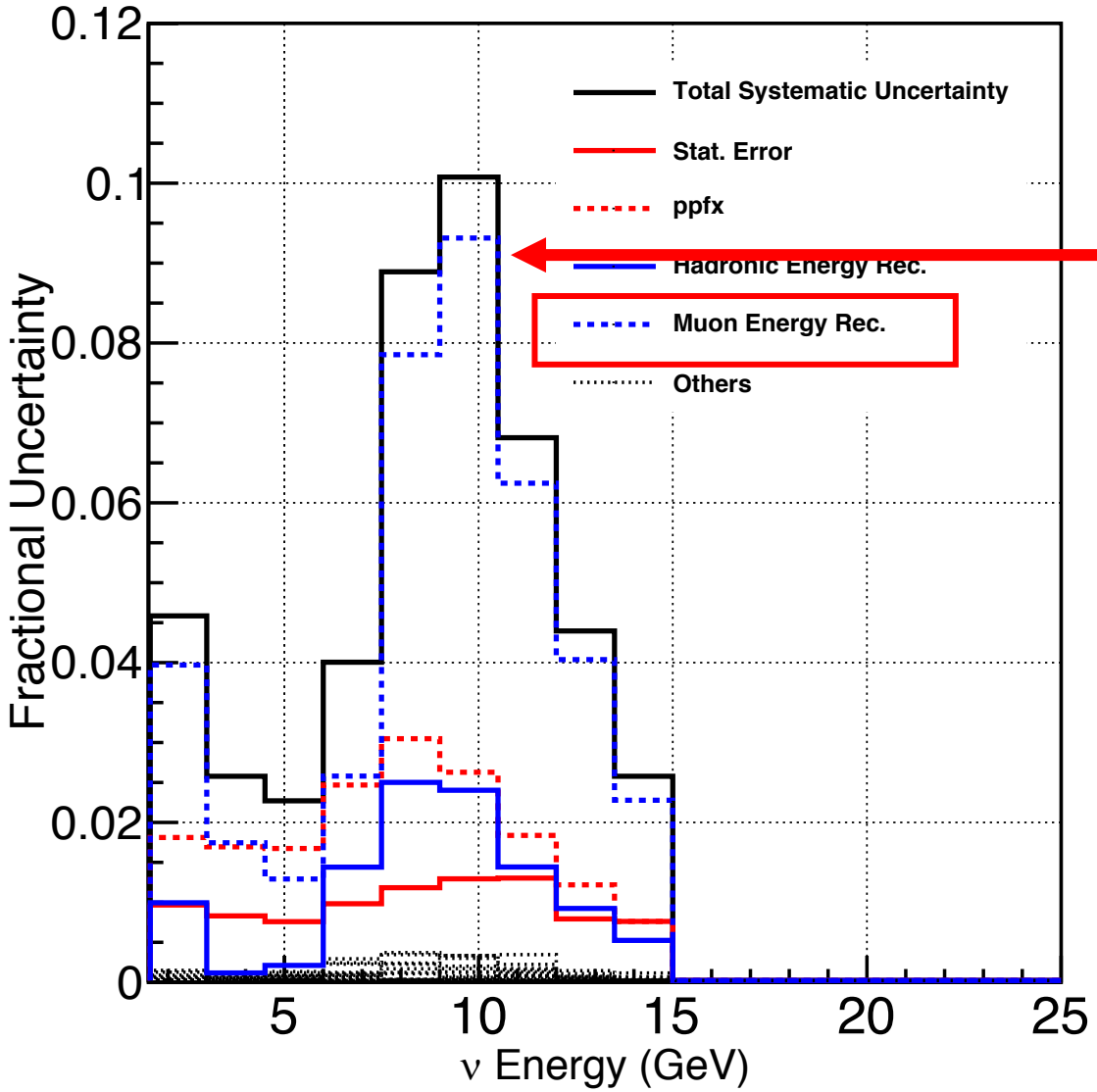


Fitting with focusing parameters

Decomposing the Correction returned by the fit into various components, we can see that shift in TargetZ and Horn Current are major contributors of overall corrections.

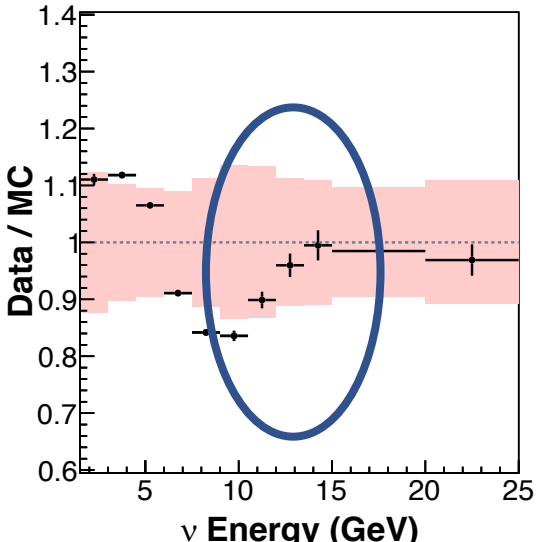
Not the End yet....

Could this be an experimental effect?

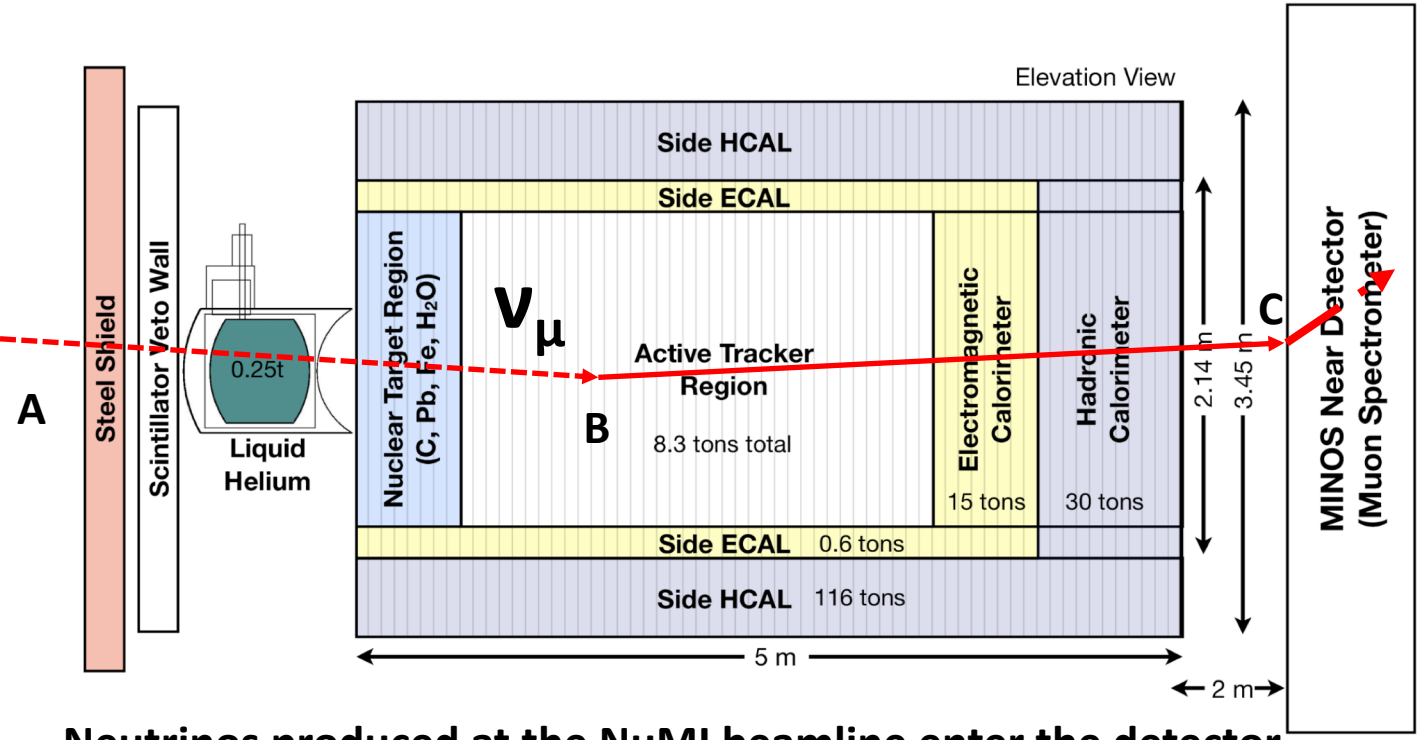


Uncertainty evaluation on the cross sections indicate a possible sensitivity to the energy scale.

- The uncertainty on Flux fit as we vary MINERvA Systematics comes mainly from **Muon Energy Reconstruction Systematics**.
- This systematics is due to the reconstruction of muons at MINOS detector.



MINERvA and MINOS



MINOS near detector is downstream of the MINERvA detector.

Muons exit the MINERvA detector and enter the MINOS detector.

Energy deposited on MINOS detector and bending of the Muon track due the B field in the detector is used to reconstruct energy and charge of the Muons.

Neutrinos produced at the NuMI beamline enter the detector from the left.

In the above schematic diagram:

A. A muon neutrino interacts with a nucleon.

B. Muon is produced in the detector which leaves a long track.

C. Enters the MINOS detector which is magnetized. Muon bends in the B field of the MINOS detector.

Fit with Muon Energy Scale as a new Fit Parameter

- Fit done by including muon energy reconstruction as a new fit parameter.
- Fit is done with and without adding priors.
  - Without adding the priors, parameters can explore their phase space without any constraints.
  - Test if priors prevent focusing parameter to explore large shift values.
- Both methods prefer a pull in muon energy scale.

Flux Fit Conclusions

- MINERvA has two hypotheses about what caused the flux problem.
- Hypothesis 1: Focusing parameters →Requires large pull in target Z position and or Horn current.
- Hypothesis 2: Muon Energy Reconstruction →Requires around 1.5 sigma pull on the MINOS energy scale.
- MINERvA has currently gone with hypothesis 2
  - No concrete evidence of large misalignment of any focusing parameters
  - Pull in muon energy scale not only mimics the flux wiggle but also shifting it doesn't require touching the focusing parameters.
  - Fit done with and without priors on parameters preferred a pull in muon energy scale.
  - Hypothesis 1 or alternate hypotheses in case new **concrete** future evidence show up.

Best Fit with/without Priors

Parameter	BestFit ±Stat Error ± Sys Error (Priors)	BestFit ±Stat Error ± Sys Error (No Priors)	1 Sigma Shift
Beam Position (X)	-0.26±0.22±0.12	-0.34±0.26±0.12	1 mm
Beam Position (Y)	0.70±0.22±0.17	0.77±0.26±0.25	1 mm
Target Position (X)	-0.8±0.28±0.14	-0.84±0.28±0.14	1 mm
Target Position (Y)	1.71±0.56±0.79	2.27±0.72±1.17	3 mm
Target Position (Z)	0.36±0.61±0.13	0.20±0.78±0.11	1 mm
Horn 1 Position (X)	-0.14±0.32±0.10	-0.29±0.44±0.47	1 mm
Horn 1 Position (Y)	0.02±0.33±0.25	-0.13±0.48±0.47	1 mm
Beam Spot Size	0.59±0.31±0.12	-0.34±0.26±0.12	0.3 mm
Horn Water Layer	0.63±0.46±0.24	0.43±0.60±0.14	1 mm
Horn Current	-0.98±0.69±0.49	-2.0±1.39±1.4	1 kA
Muon Energy Scale	1.75±0.17±0.33	1.58±0.24±0.43	2 % on pmu

→Focusing parameters shifts further away from their nominal position.
→Errors on fit parameters are larger (fit can explore parameter phase space without any constraint in all alternate universes).

Flux Problem and Implications

- Solutions aside, the flux problem and the solutions that MINERvA came up with shows that in case of future experiments like DUNE, a similar scenario could make it hard to untangle the focusing and energy reconstruction issue.
- Both solutions present additional challenges to incorporate the new systematics from the solutions given by the fit and correlation effects.
- MINERvA's possible solution could provide examples for similar issue in future experiments.

Backup

What is Low nu?

If we write neutrino cross section as a function of ν:

$$\frac{\nu}{E_\nu}$$

Energy Transferred to the recoil system

Energy of Incoming Neutrino

$$\frac{d\sigma}{d\nu} = \frac{G_F^2 M}{\pi}\int_0^1 \left(F_2 - \boxed{\frac{\nu}{E_\nu}}[F_2 \mp xF_3] + \boxed{\frac{\nu}{2E_\nu^2}}\left[\frac{Mx(1-R_L)}{1+R_L}F_2\right] + \boxed{\frac{\nu^2}{2E_\nu^2}}\left[\frac{F_2}{1+R_L} \mp xF_3\right]\right) dx,$$

$$For\ \nu << E_\nu$$

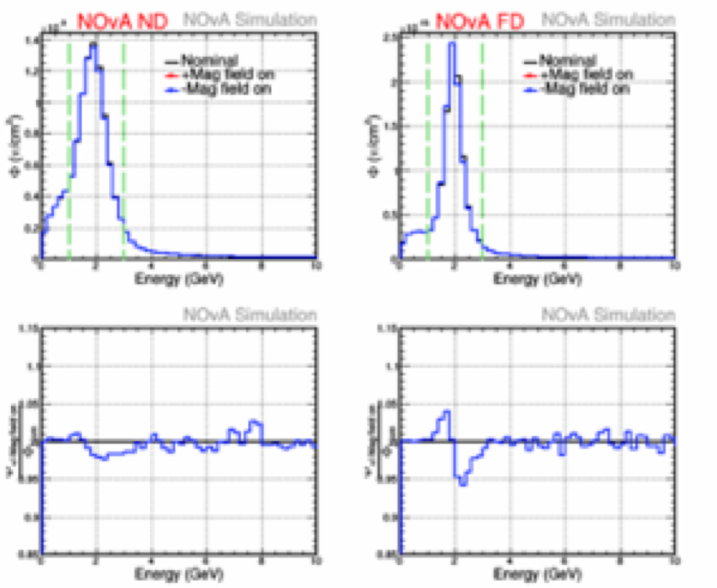
0 0 0

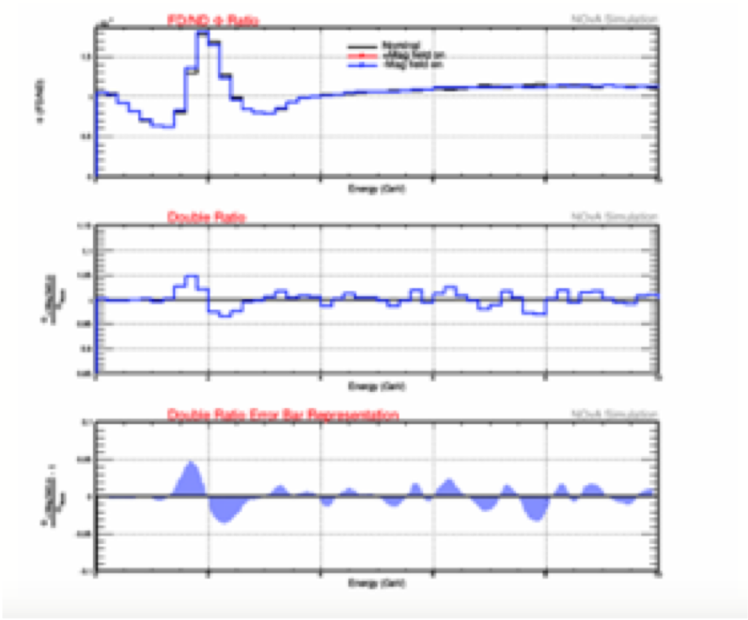
$$\frac{d\sigma}{d\nu} = \frac{G_F^2 M}{\pi}\int_0^1 \left(F_2 - \boxed{\frac{\nu}{E_\nu}}[F_2 \mp xF_3] + \boxed{\frac{\nu}{2E_\nu^2}}\left[\frac{Mx(1-R_L)}{1+R_L}F_2\right] + \boxed{\frac{\nu^2}{2E_\nu^2}}\left[\frac{F_2}{1+R_L} \mp xF_3\right]\right) dx,$$

$$\frac{d\sigma}{d\nu} \approx \frac{G_F^2 M}{\pi}\int_0^1 F_2 dx$$

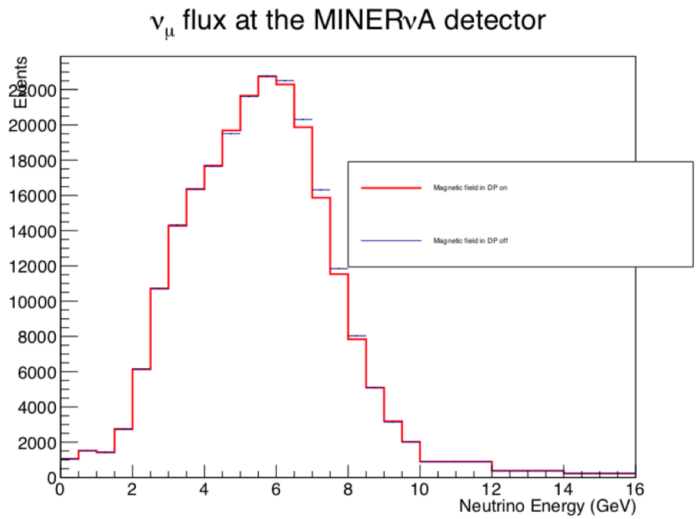
Low nu Cross section becomes constant as a a function of neutrino energy

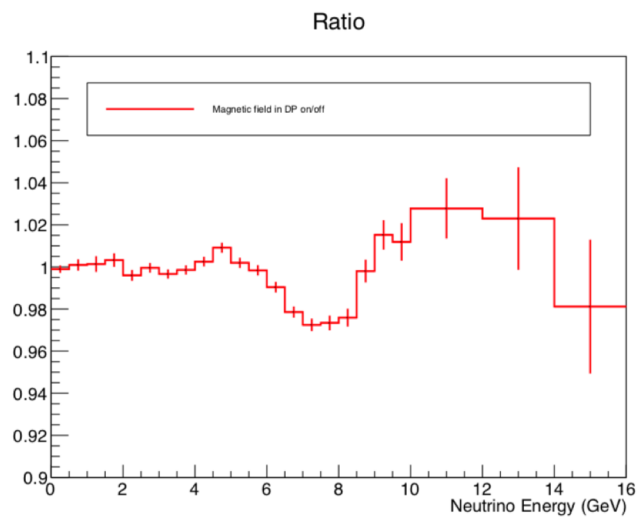
Decay Pipe Magnetic field and Neutrino Flux





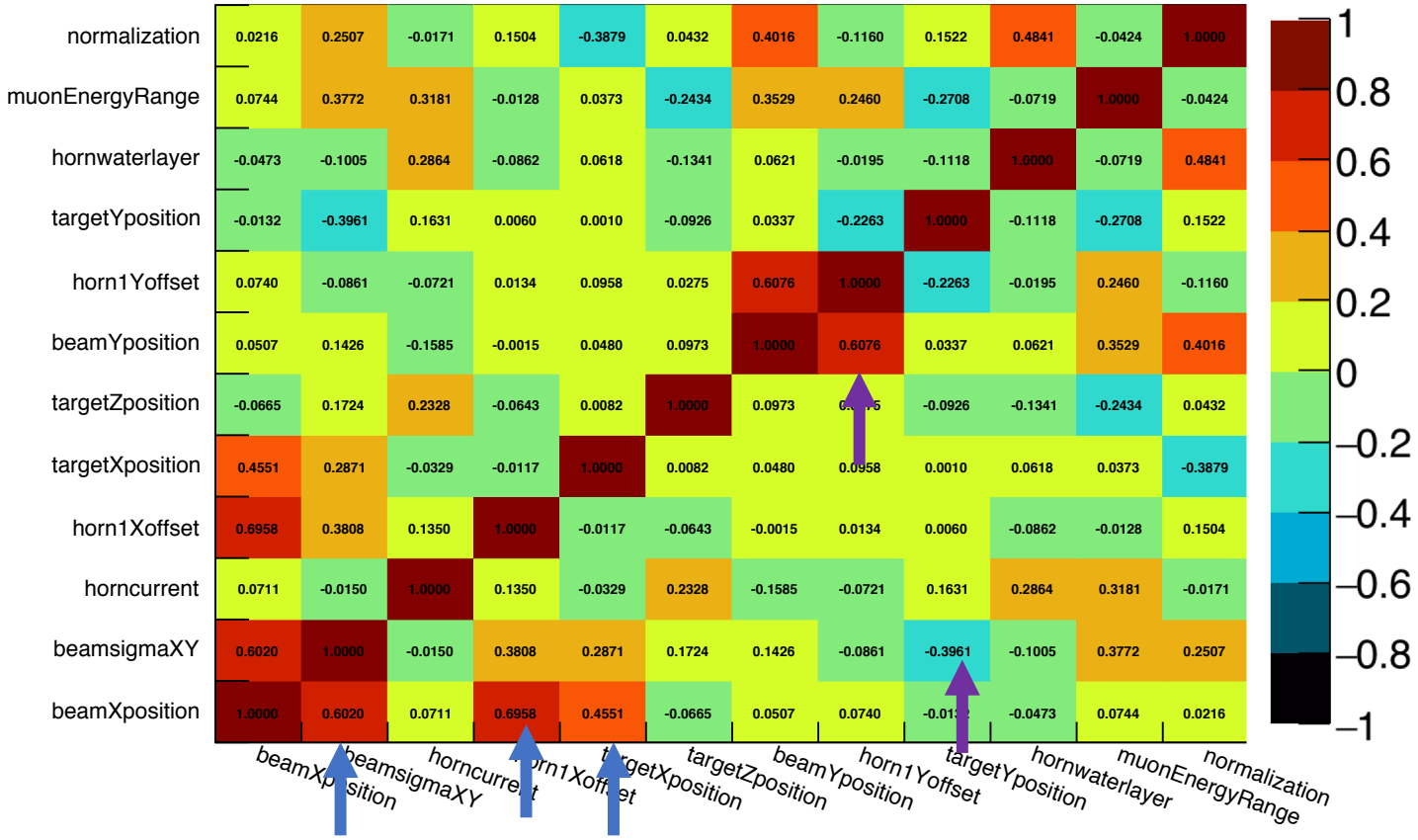
Effect of B field on neutrino flux at NoVA Detectors. Upto 5% effect on the NoVa near/far double ratio in focusing peak.
While the uncertainty on far detector flux is large.
Uncertainty doesn't cancel out.
(Linda Cremonesi, NoVA)





Effect of B field on the MINERvA flux (less than 2%)
(Miguel Hernandez, MINERvA)

Correlation Matrix



The fit also gives the correlation between the fitting parameters.

Things to Notice:

X position shifts are strongly correlated (horn1X vs target X, beam X vs target X, beamX vs horn1X)→Blue Arrows

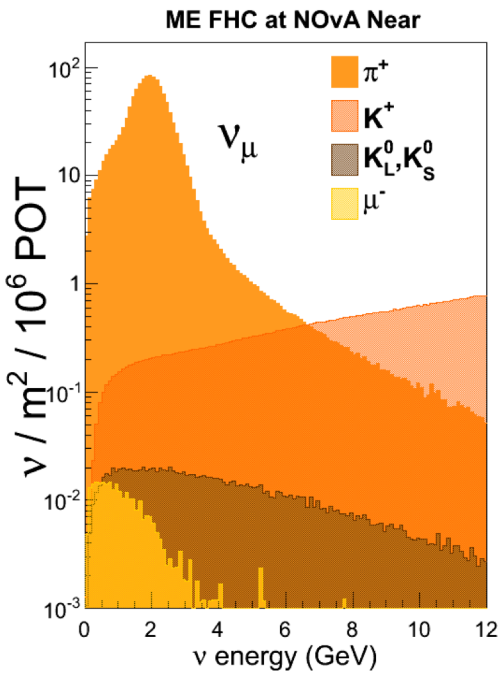
Y positions shifts have similar trend→Purple Arrows

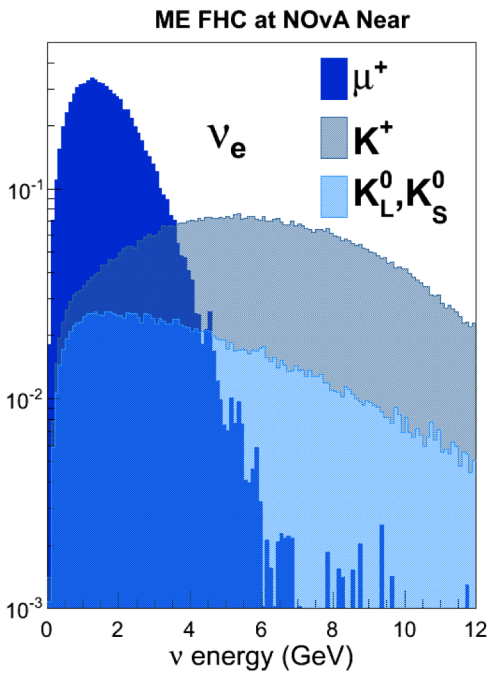
Correlations between beam parameters and muonEnergyRange

→Weak Correlation with X offsets of Focusing Parmaeters

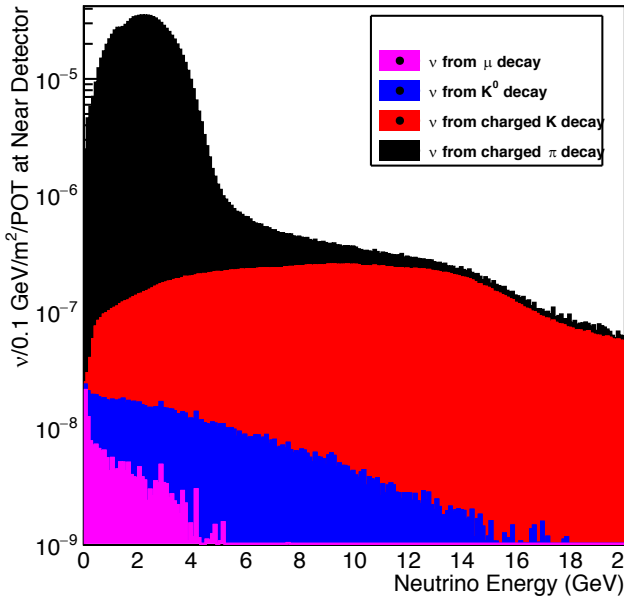
→Not Weak Correlation with Y offsets of Focusing parameters +Horn Current

Hadron Production Uncertainties

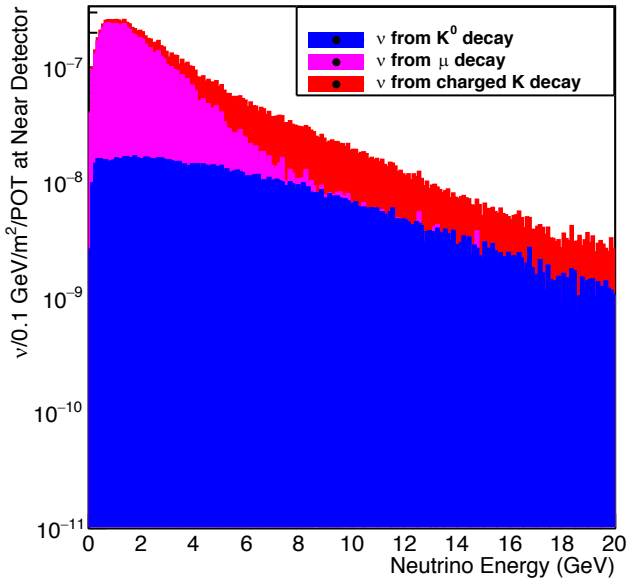




Muon Neutrino Flux at DUNE Near Detector

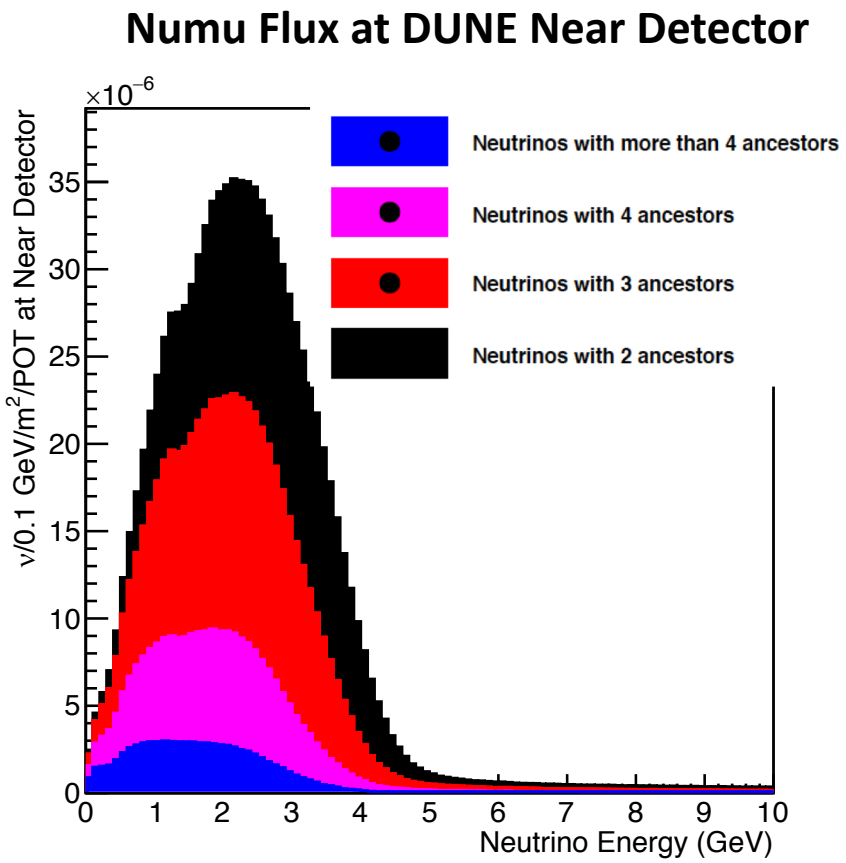


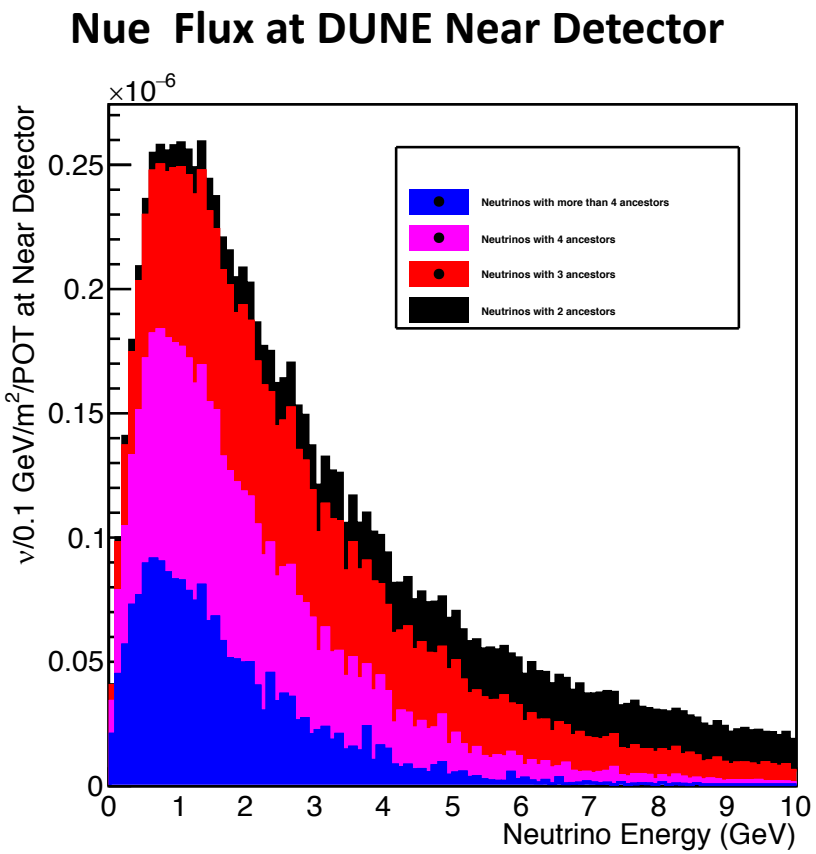
Electron Neutrino Flux at DUNE Near Detector



In case of both NuMI and DUNE beamline, neutrinos at focusing peak come from pion decay.
High energy neutrinos mostly come from chared kaon decay.
There are small contributions from neutral kaons and muons as well.

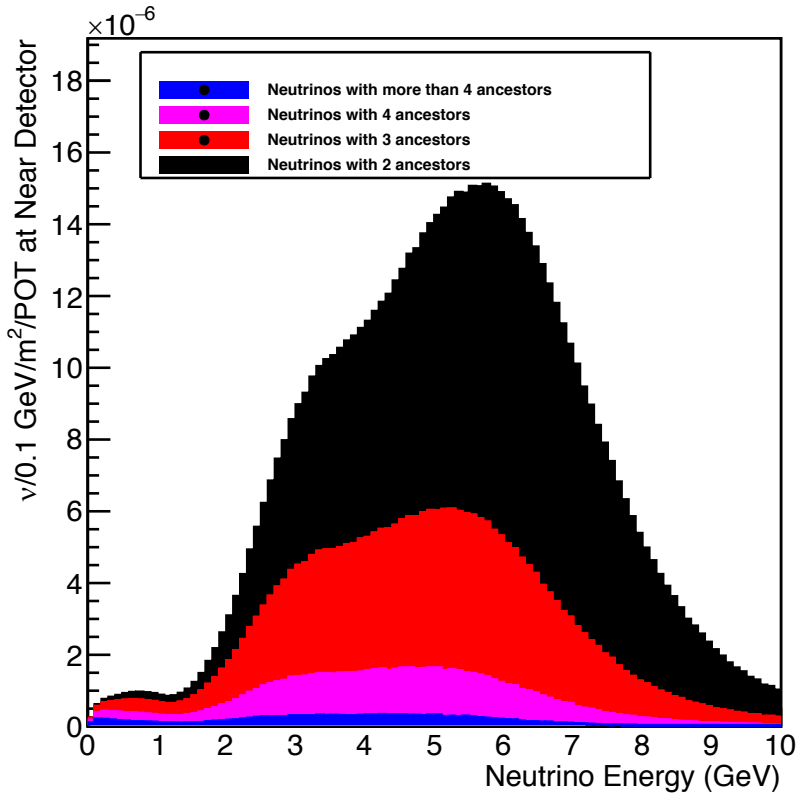
Hadron Production Uncertainties



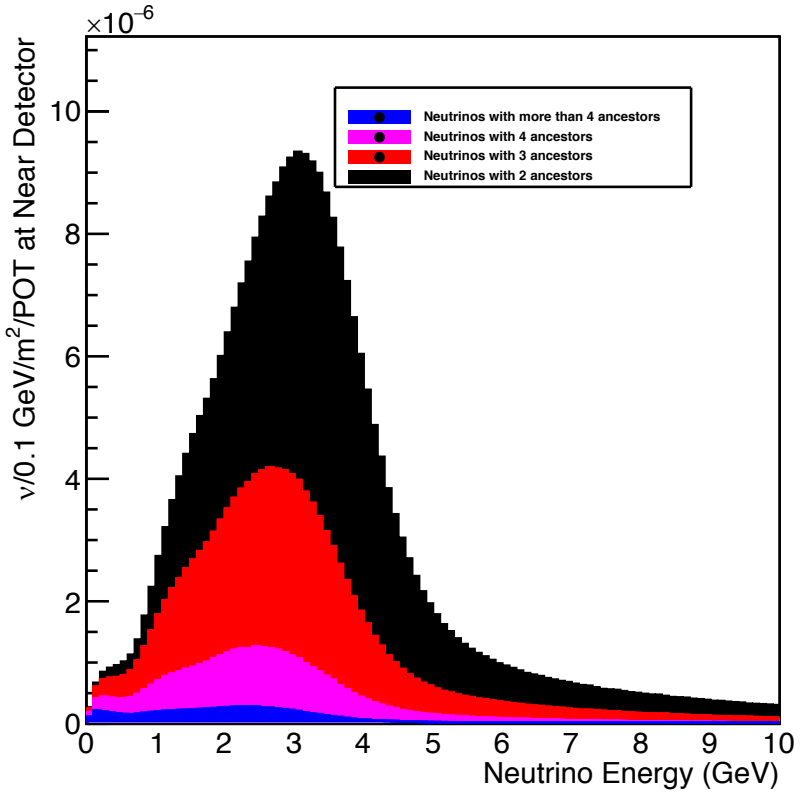


- Long NuMI target (1m) means a significant fraction of flux will come from multiple interactions of hadrons.
- In case of DUNE, it is more prominent (2m long target).

NuMI Low Energy and Medium Energy nu Flux



Medium Energy neutrino Flux



Low Energy neutrino Flux