



Use of Neutrino Scattering Events with Low Hadronic Recoil to Understand Flux and Detector Energy Scale

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1. Introduction

The MINERvA Experiment is a neutrino cross-section measurement experiment based at Fermilab that aims to study the neutrino cross-sections in different nuclei for neutrino energy ranging from 1 to 50 GeV to understand the nuclear effects on neutrino nucleus scattering and help the current and future oscillation experiments.

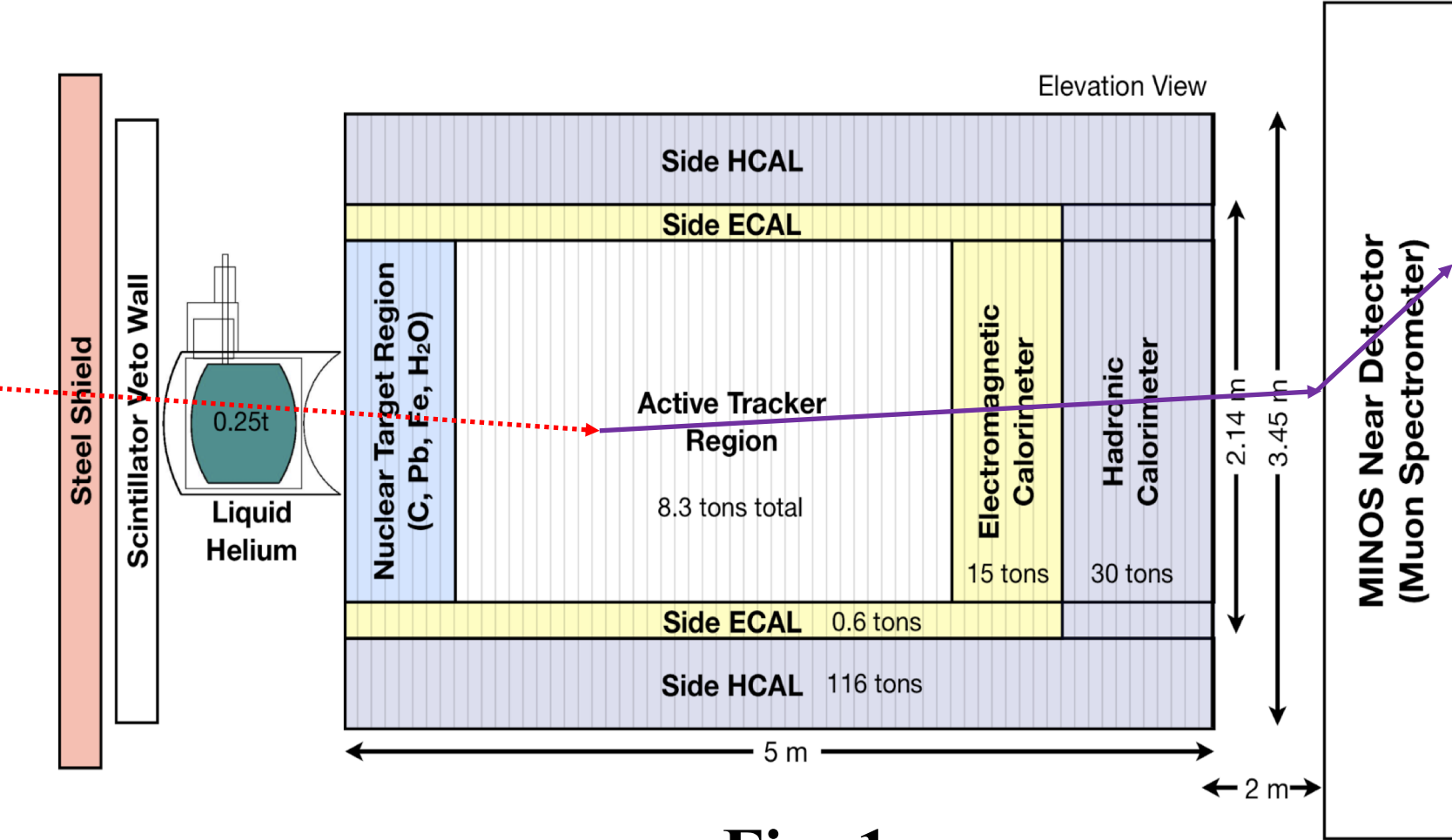


Fig: 1

Schematic diagram of MINERvA detector with MINOS near detector on the downstream end of the MINERvA detector

2. Motivation

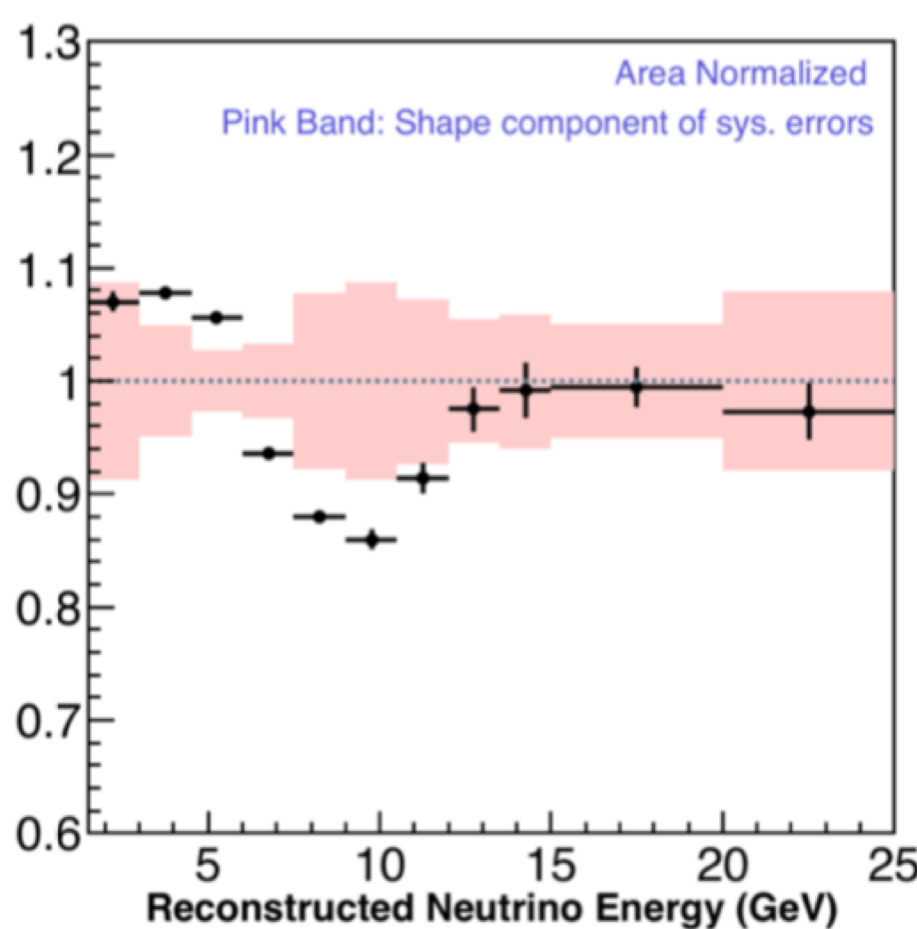


Fig: 2

- Discrepancy between MINERvA data and simulation as a function of neutrino energy.
- Shape of discrepancy between data and simulation larger than the shape of the systematics.
- Discrepancy observed in the low-recoil events (low-nu or low- ν) which are independent of cross-section.
- ν (nu): Non-muon recoil energy

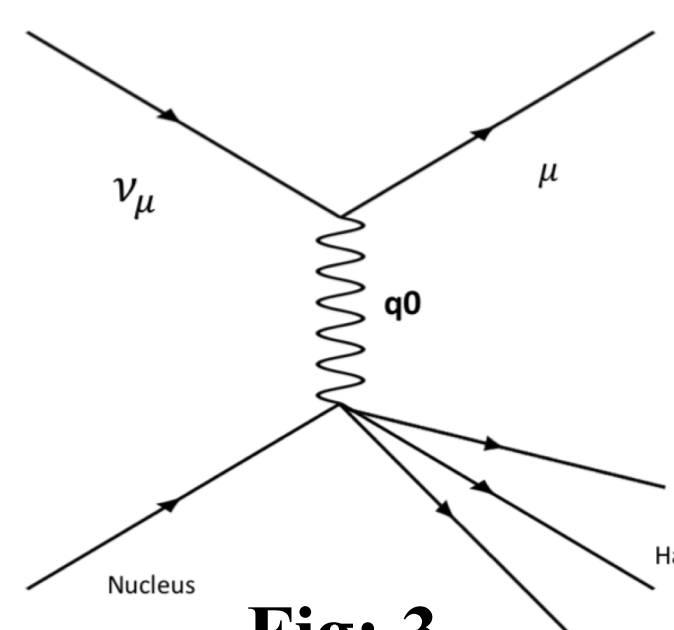


Fig: 3

- Feynman diagram of showing a charged current inclusive event (Figure 3)
- $E_\nu = E_\mu + q_0$
- $q_0 \rightarrow (\nu)$ is the energy transferred to the hadronic system.

3. Neutrino Nucleus interaction as a function of ν

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

- All the terms inside the integration are constant except for ν and E_ν .
- For $\nu \ll E_\nu$:
- $\frac{d\sigma}{d\nu} \approx \frac{G_F^2 M}{\pi} \int_0^1 F_2 dx$ (Cross-section has no energy dependence)
- Low-nu events can be used to measure the shape of the neutrino flux.

4. Reconstruction of Low-nu Sample in MINERvA

- Muon tracks that are matched in both MINERvA and MINOS.
- Energy of the recoil system basically energy reconstructed from all activities that are not part of the muon tracks.
- Low-nu Events : $\nu < 800 \text{ MeV}$

5. Source Of Uncertainties in Low-nu Distribution

- Focusing uncertainties
- Hadron production in the target and beamline
- Neutrino interaction models from GENIE
- Uncertainty on tunes applied by MINERvA for GENIE models
- Uncertainty related to muon reconstruction in MINERvA

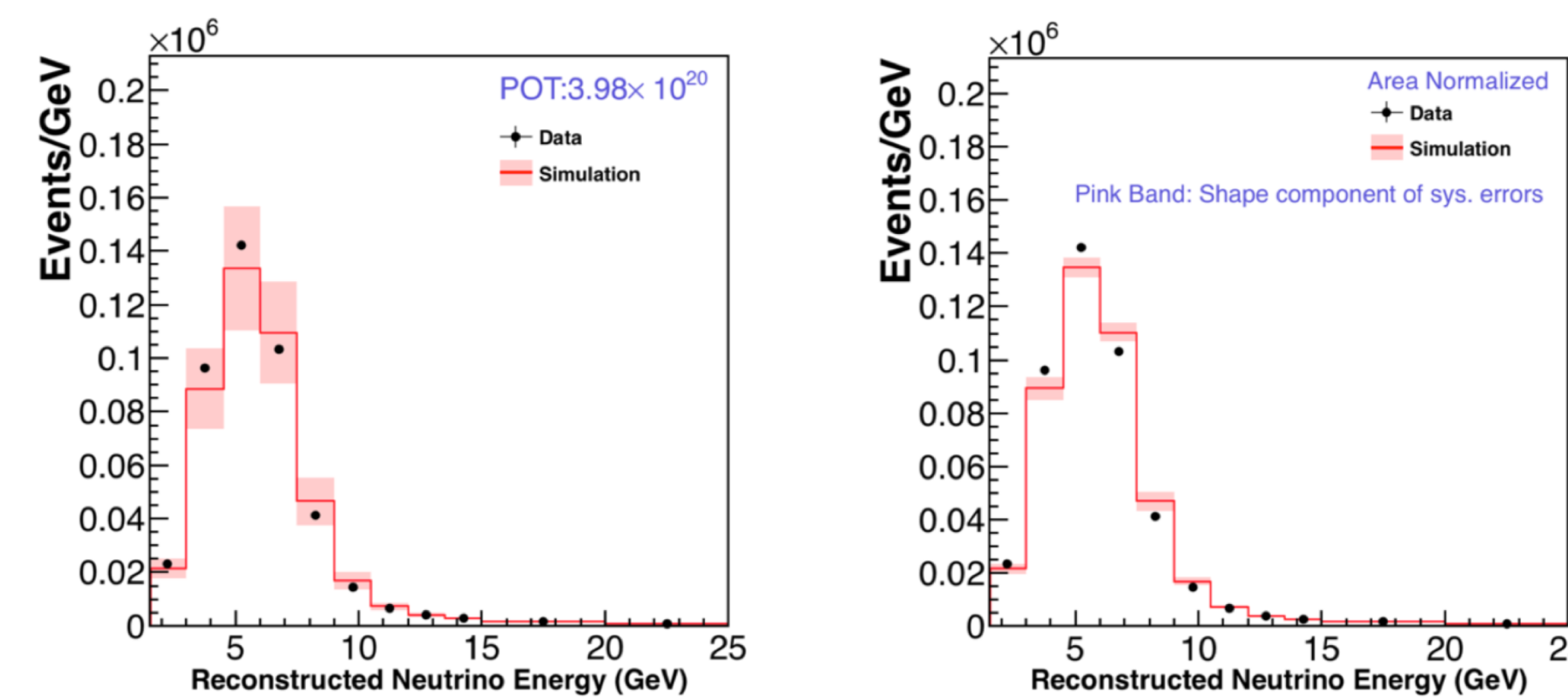


Fig: 4

- Figure 2 and 4 shows that the discrepancy itself is covered by the systematics but not the shape of discrepancy.

Two sources of uncertainty which can reproduce the above shape discrepancy:

- Beam Focusing Parameters
- Muon Energy Scale

6. Beam Focusing Uncertainties

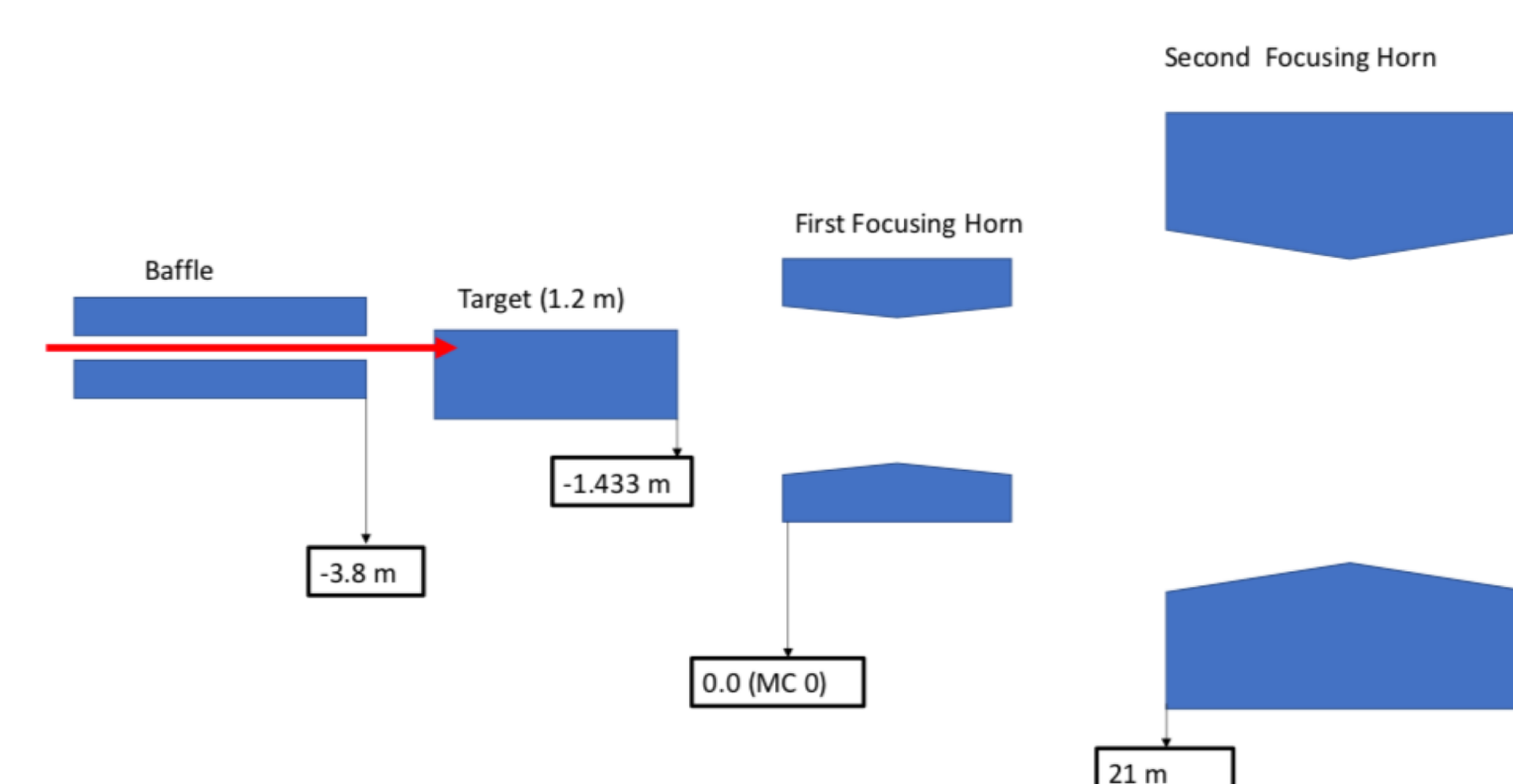


Fig: 5

- Neutrino Flux distribution seen by MINERvA is due to the fine tuning of various beam-line parameters in the NuMI beamline.

Parameter	Nominal Value	1 σ shift from Nominal 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	1.0 mm	0.5 mm
Horn Current	200 kA	1 kA
Horn 1 Position (X)	0 mm	1 mm
Horn 1 Position (Y)	0 mm	1 mm
Horn 1 Position (Z)	30 mm	2 mm
Horn 2 Position (X)	0 mm	1 mm
Horn 2 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	1 mm
POT Counting	0	0.02% of Total POT
Baffle Scraping	0	0.25% of POT

- Table 1 : Beam Parameters used in the MINERvA ME configuration

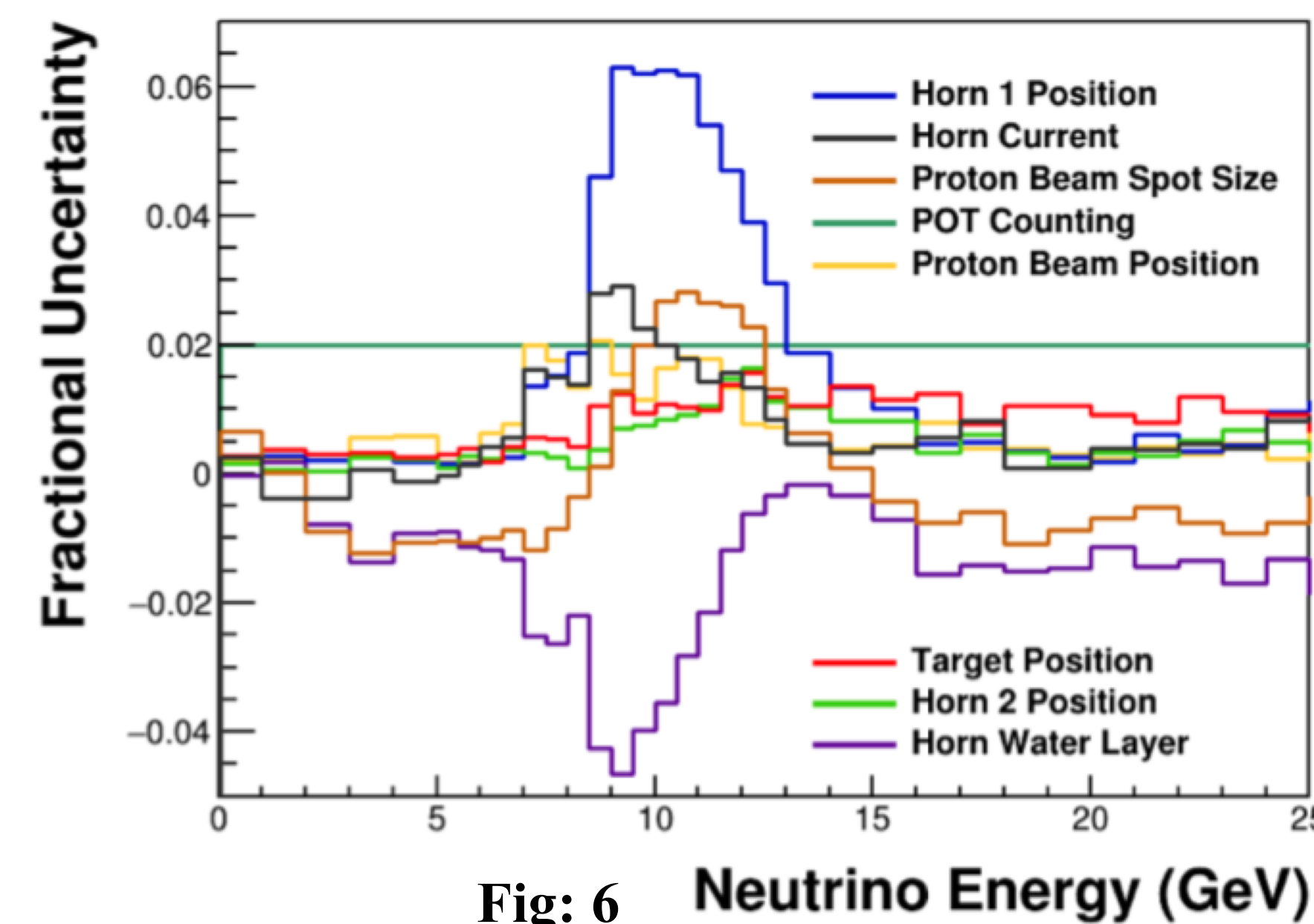


Fig: 6

- Figure 8: Fractional Uncertainty on the flux when beam parameters are shifted by 1 σ from their nominal values (See Table 1)

7. Muon Energy Scale

- Total Muon energy scale has the correction for muons reconstructed in both MINERvA and MINOS detector.
- Studies showed that only MINOS component is large enough to reproduce the discrepancy.
- 2% uncertainty on the momentum of muon due to the scale.

8. Fit to investigate the source of discrepancy

- Multi-parameter fit with beam parameters and MINOS muon energy scale as fit parameters.
- MINERvA being near to the NuMI beamline, changes of certain beam parameters will produce non-uniform effects across the face of the MINERvA detector.
- Fit to be done in different vertex regions of the MINERvA detector to take care of the non-uniform effect on flux due to beam parameters.
- Data reweighted by flux prediction based on muon energy scale shift.
- MC reweighted by flux prediction based on beam parameters shifts.

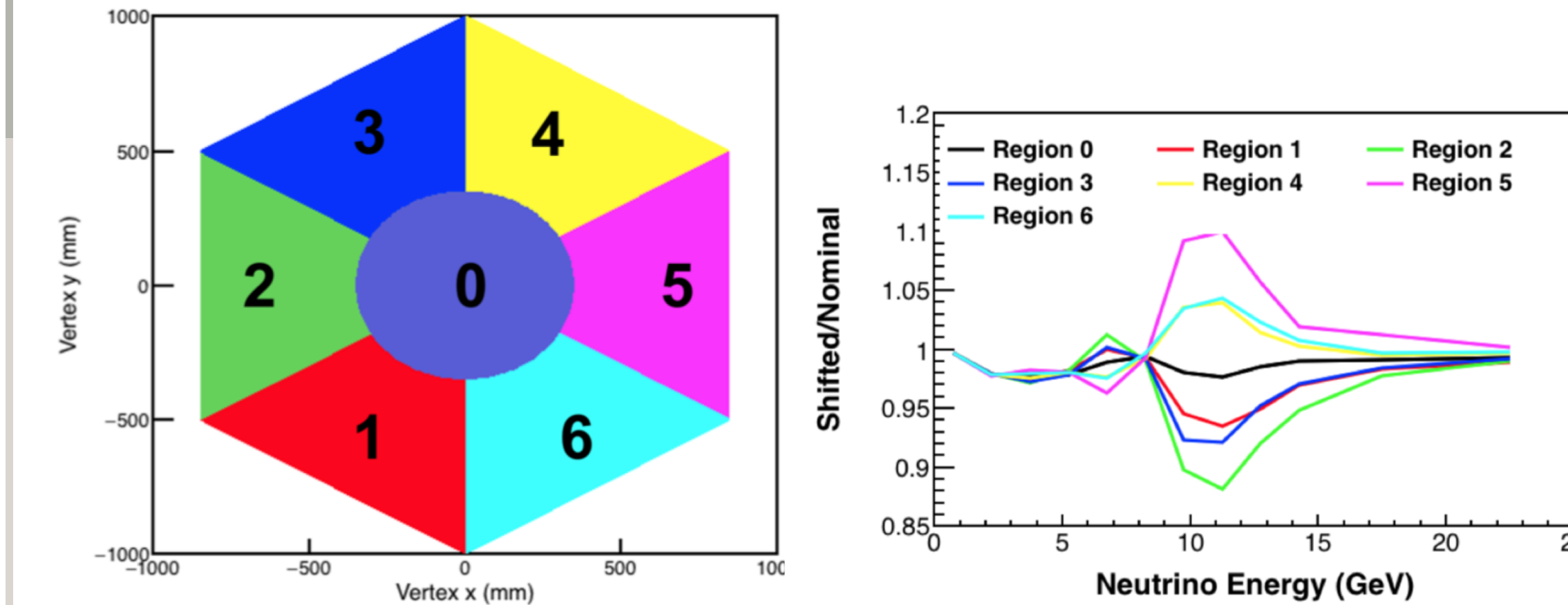


Fig: 7

- Different vertex regions where the fit is done (left) and the shift in flux in different vertex regions when target is shifted by +1 cm horizontally.

9. Fit Function

$$\chi^2_{prior} = \sum_{ij} \frac{(Data'_{ij} - MC'_{ij})^2}{\sigma_{ij}^2} + \sum_k (\alpha_k)^2$$

- $i \rightarrow$ Neutrino Energy Bin
- $j \rightarrow$ MINERvA vertex Region
- $\sigma^2 \rightarrow$ Combined stat. uncertainty of Data and MC
- $\alpha_k \rightarrow$ (Penalty term or prior) number of S.D that parameter k has been shifted from its nominal value (table 1). Target longitudinal position uncertainty is increased to 3 mm.

10. Results and Conclusion

Parameter	Nominal	Best Fit (No Prior)	Best Fit (Prior)
Beam Position (X)	0.0 mm	$-0.3 \pm 0.3 \pm 0.1 \text{ mm}$	$-0.3 \pm 0.2 \pm 0.1 \text{ mm}$
Beam Position (Y)	0.0 mm	$0.8 \pm 0.3 \pm 0.3 \text{ mm}$	$0.7 \pm 0.2 \pm 0.2 \text{ mm}$
Target Position (X)	0.0 mm	$-0.8 \pm 0.3 \pm 0.1 \text{ mm}$	$-0.8 \pm 0.3 \pm 0.1 \text{ mm}$
Target Position (Y)	0.0 mm	$2.3 \pm 0.7 \pm 1.2 \text{ mm}$	$1.7 \pm 0.6 \pm 0.8 \text{ mm}$
Target Position (Z)	-1433 mm	$-1432.4 \pm 2.4 \pm 0.3 \text{ mm}$	$-1431 \pm 1.8 \pm 0.3 \text{ mm}$
Horn 1 Position (X)	0.0 mm	$-0.3 \pm 0.4 \pm 0.5 \text{ mm}$	$-0.1 \pm 0.3 \pm 0.1 \text{ mm}$
Horn 1 Position (Y)	0.0 mm	$0.1 \pm 0.5 \pm 0.5 \text{ mm}$	$0.0 \pm 0.3 \pm 0.3 \text{ mm}$
Beam Spot Size	1.5 mm	$1.41 \pm 0.09 \pm 0.03 \text{ mm}$	$1.32 \pm 0.09 \pm 0.03 \text{ mm}$
Horn Water Layer	1.0 mm	$1.2 \pm 0.3 \pm 0.05 \text{ mm}$	$1.3 \pm 0.25 \pm 0.1 \text{ mm}$
Horn Current	200 kA	$198.0 \pm 1.4 \pm 1.4 \text{ kA}$	$199.1 \pm 0.7 \pm 0.5 \text{ kA}$
Muon Energy Scale	1.0	$1.032 \pm 0.004 \pm 0.008$	$1.036 \pm 0.004 \pm 0.006$

Table 2. Shift of beam parameters from the fits with and without priors.

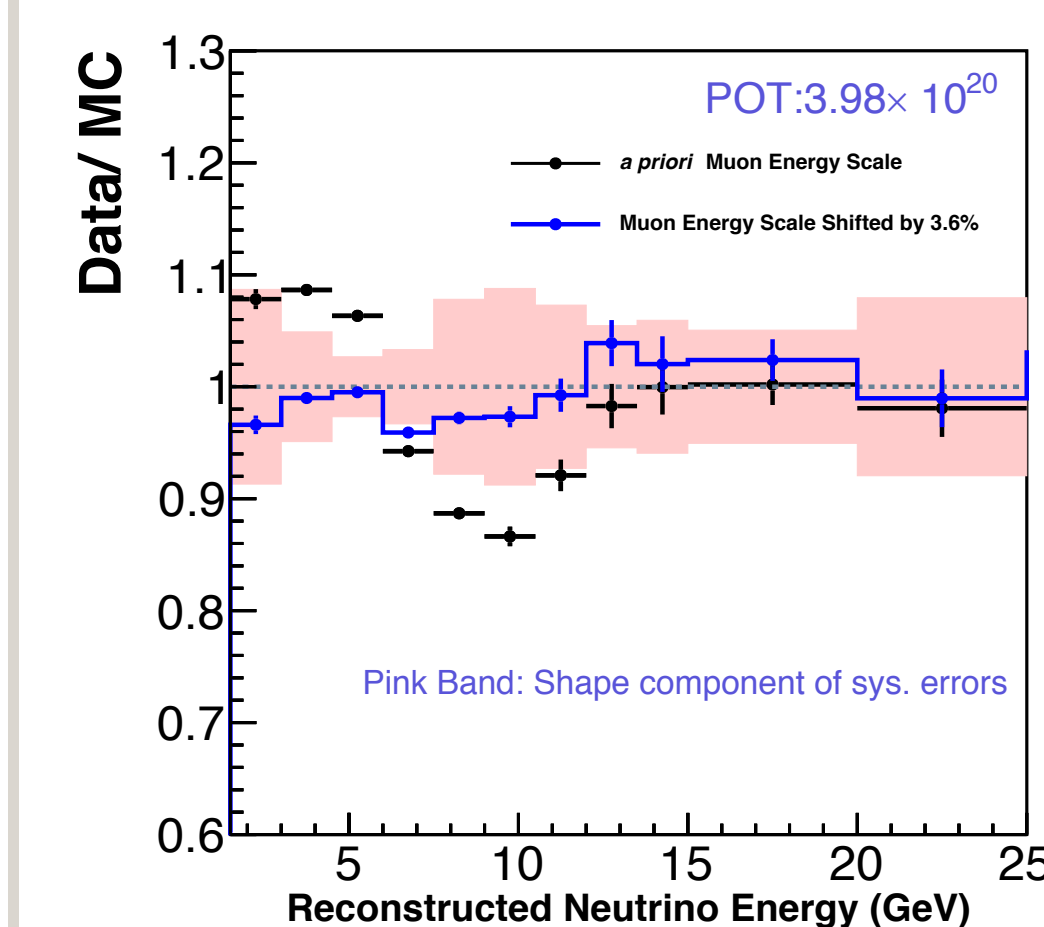


Fig: 8

- Fit prefers significant pull on Muon Energy Scale.
- Beam Parameters are mostly within their 1 σ values.
- Almost all the discrepancy is reproduced by the shift of Muon Energy Scale as seen in figure 10.
- Based on this study, MINERvA shifted the muon energy scale by 1.8% from its nominal value.
- Stay Tuned for upcoming JINST paper for more information!
arxiv.org/abs/2104.05769

11. Acknowledgement

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