Investigating the NuMI beam focusing uncertainties for MINERνA flux

Bruce Howard, Jr.

SOME VOCABULARY

Vocabulary

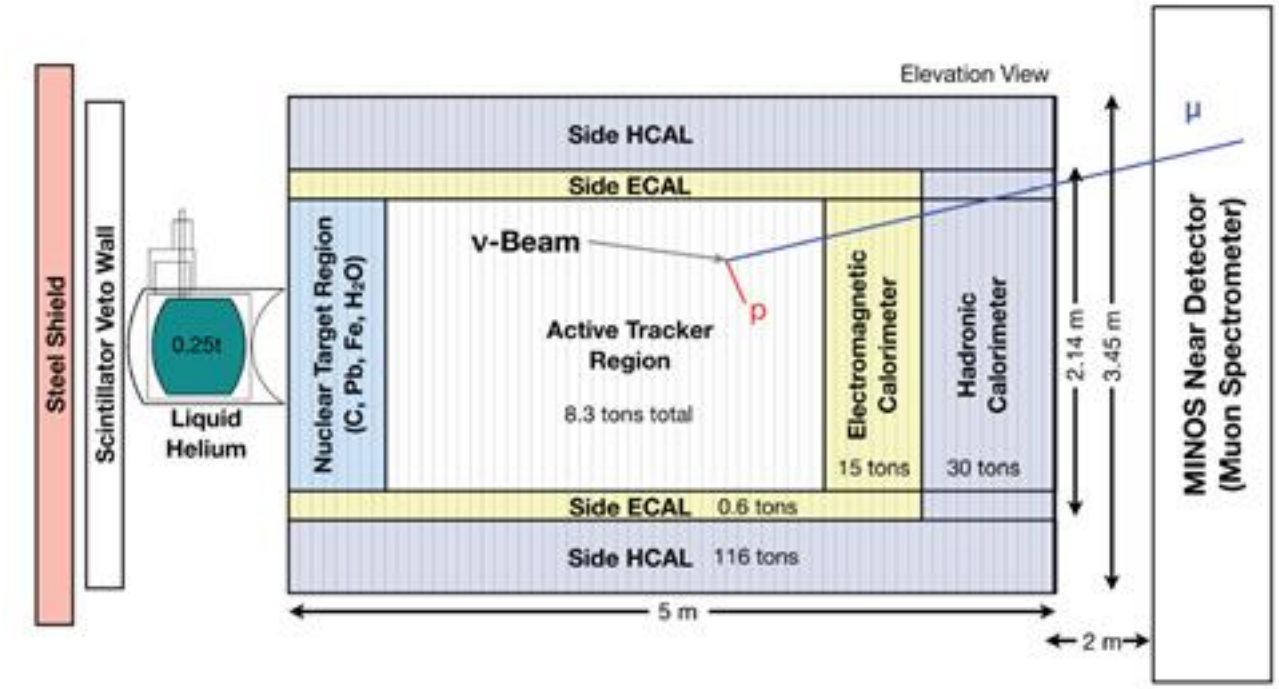
- POT: Protons on Target
- Hadron: Particle made up of quarks
  - Meson = hadron composed of one quark and one antiquark (π, K, J/ψ, etc.)
  - Baryon = hadron composed of three quarks (p, n, Δ, etc.)
- Flux: a way of describing how many events occur (Events/m^2/GeV/reference # POT)
  - Similar in a way to the astronomical definition

SOME MORE VOCABULARY

- MC: stands for Monte Carlo simulation
  - Creates simulated data given the laws of physics and other inputs. More on this later.
- Ntuple: list of data

MINERvA and me

MINERνA



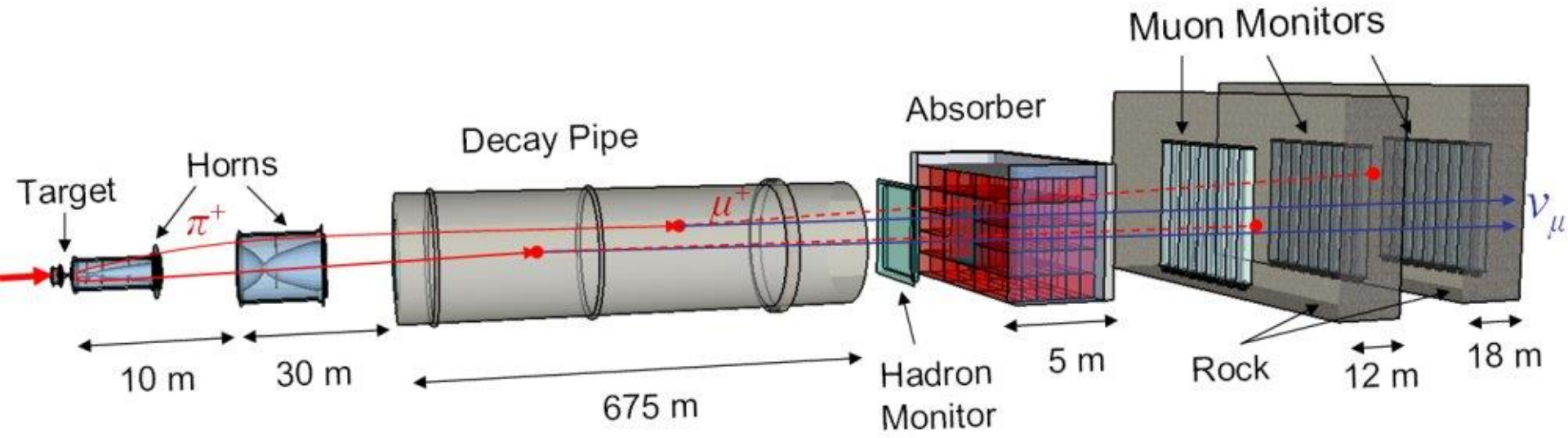
Schematic depiction of the MINERνA detector[1]

- Some of the many goals[1]:
  - Learn more about energy-dependence of neutrino interactions
  - Examine differences between interactions involving neutrinos and those involving anti-neutrinos
  - Learn more about backgrounds to oscillation experiments
- For cross-section analyses, knowing the flux is really important
  - Need to know flux to know the probability of an interaction
  - Further investigation of the parameters involved could reduce the flux uncertainties

HOW DO WE GET OUR NEUTRINOS?

NuMI

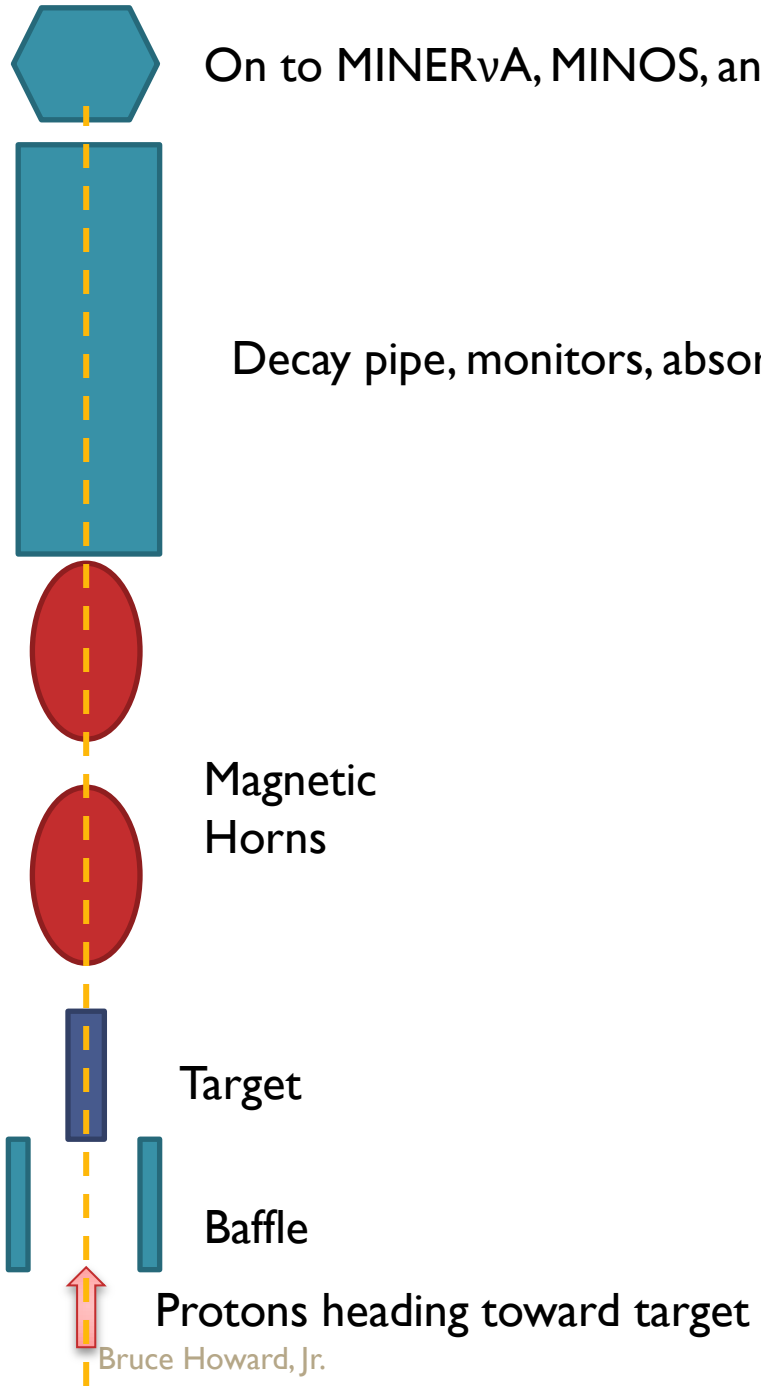
- Neutrinos at the Main Injector
- MINERvA, MINOS, soon NOvA
  - Low energy run completed
    - Analysis ongoing
  - Medium energy run starting!!
- There are a multitude of uncertainties in the beam focusing parameters
  - Leads to flux uncertainties – next few slides will explain further
  - Want to study this further to pare down the neutrino flux uncertainties



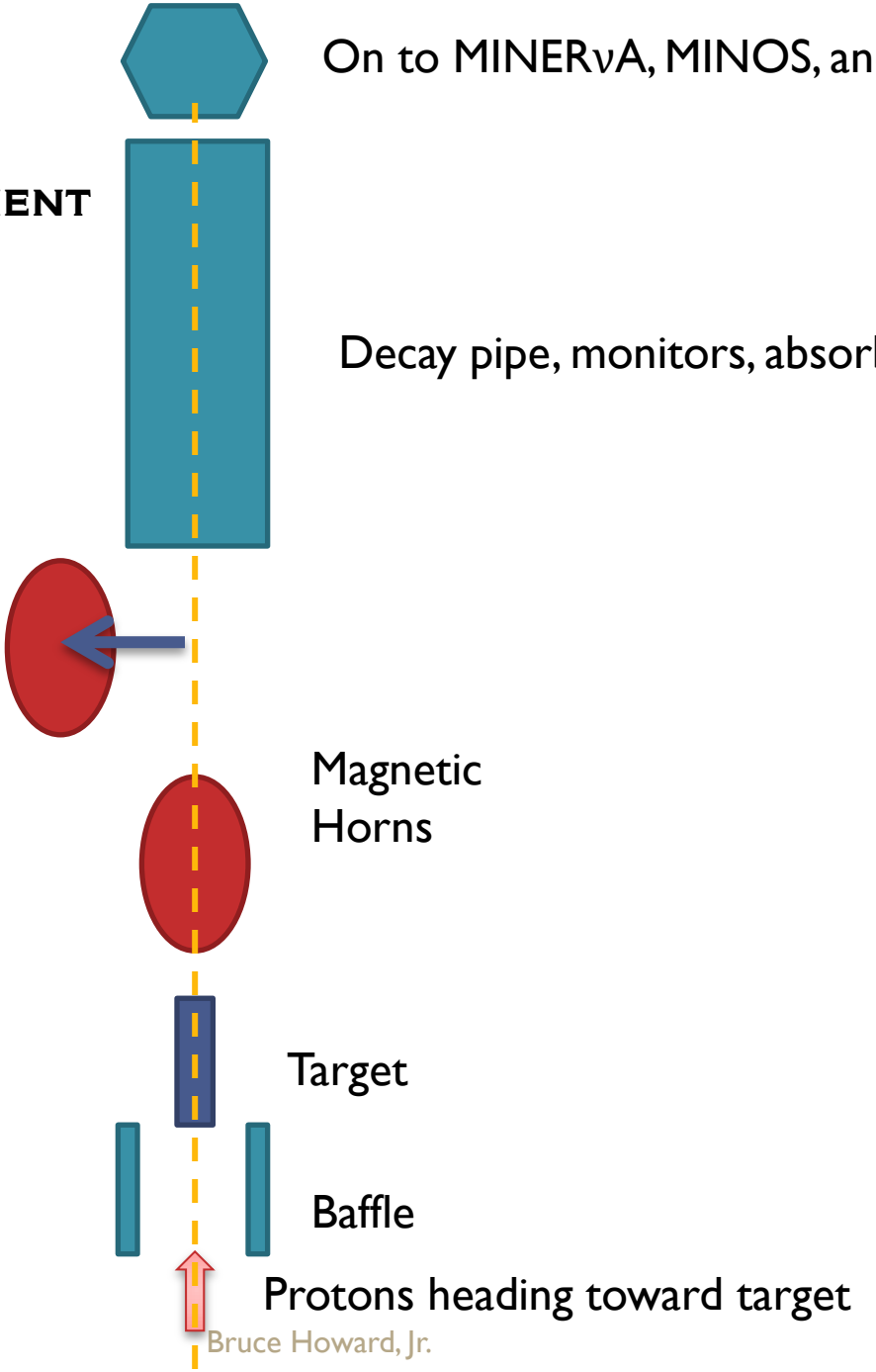
Figures courtesy Žarko Pavlović: from website above [2] and from thesis below[3]

Source	Uncertainty
Number of protons on target	2.0 %
Horn transverse misalignment	1.0 mm
Horn tilt	0.2 mrad
Horn current miscalibration	1.0 %
Horn current distribution	$\delta = 6$ mm/$\delta = \infty$
Baffle scraping	0.25 %
Misalignment of shielding blocks	1.0 cm
Target density	2 %

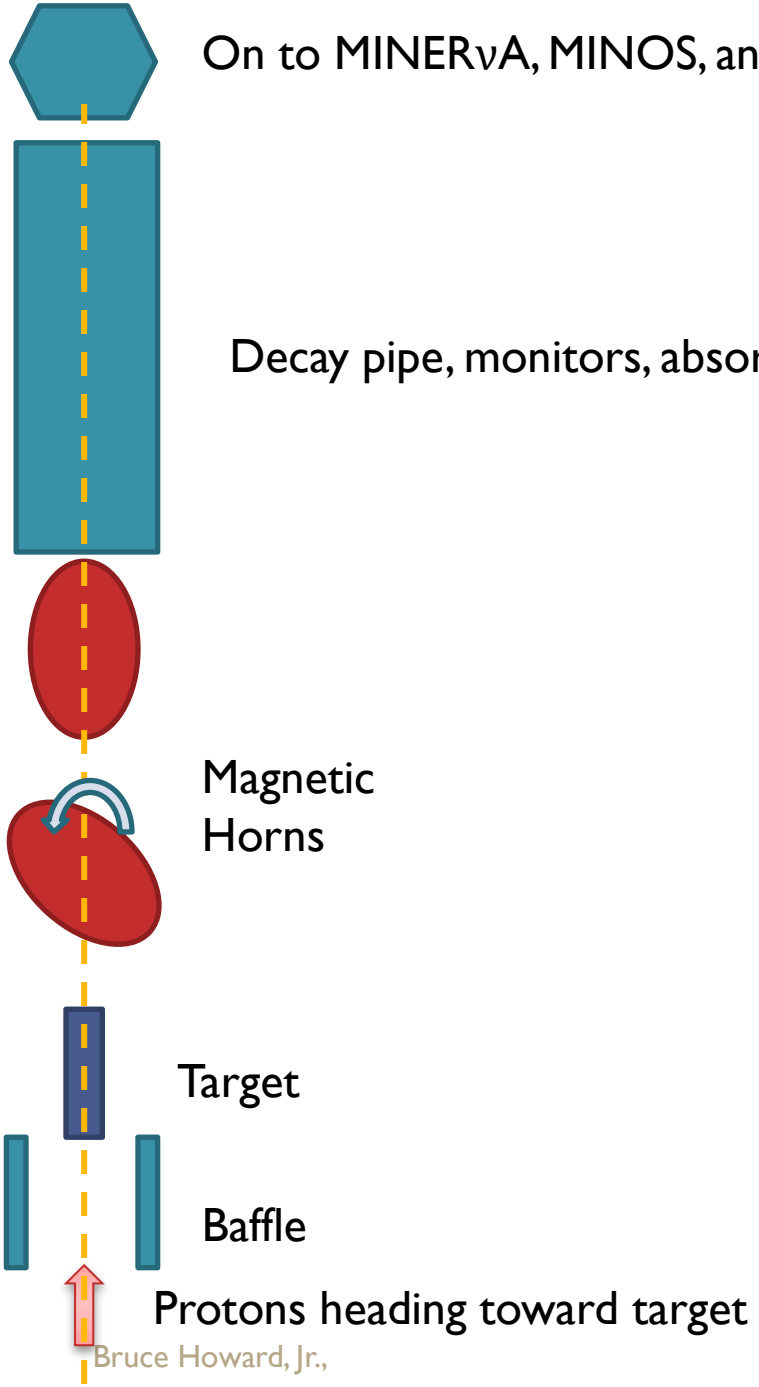
NuMI sketch


On to MINERνA, MINOS, and NOνA
Decay pipe, monitors, absorbers
Magnetic
Horns
Target
Baffle
Protons heading toward target

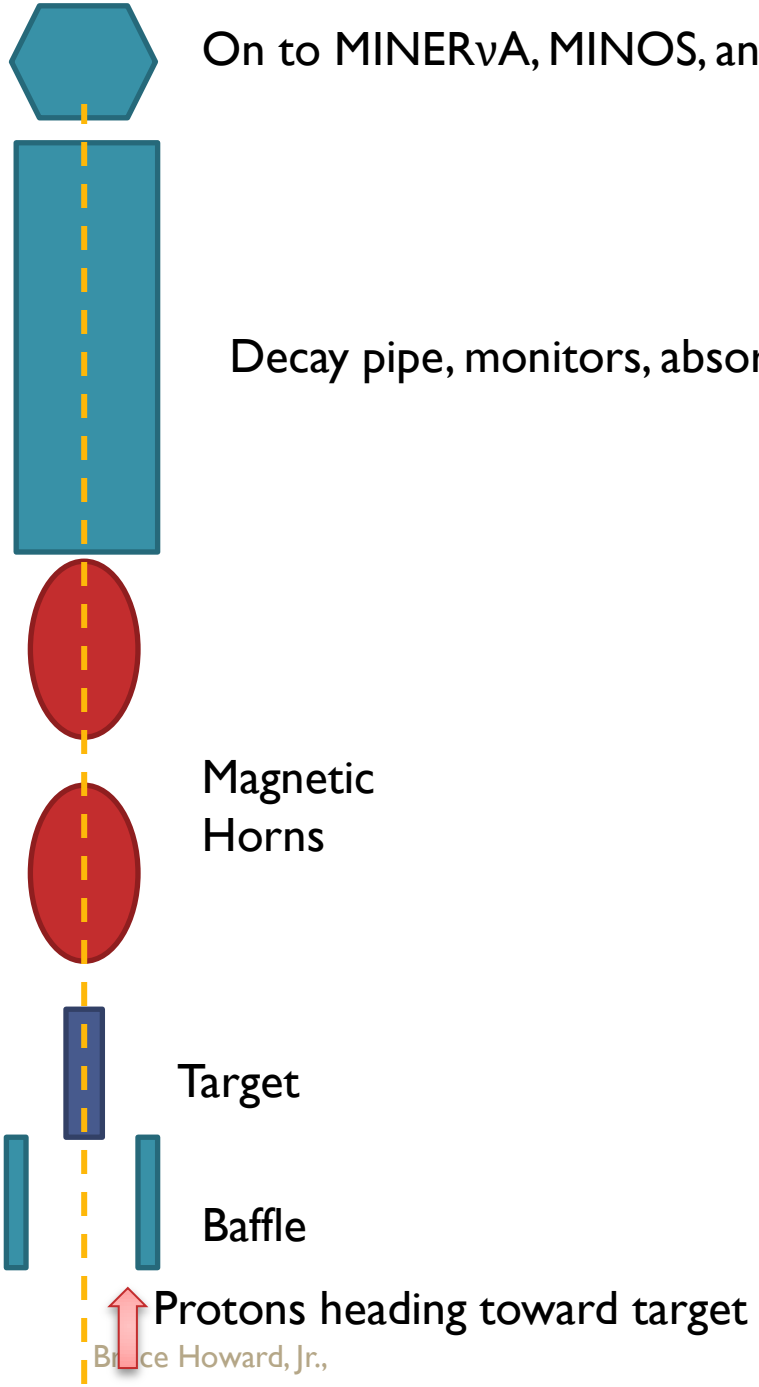
Example: horn 2 transverse misalignment



Example: horn 1 angular misalignment



Example: baffle scraping



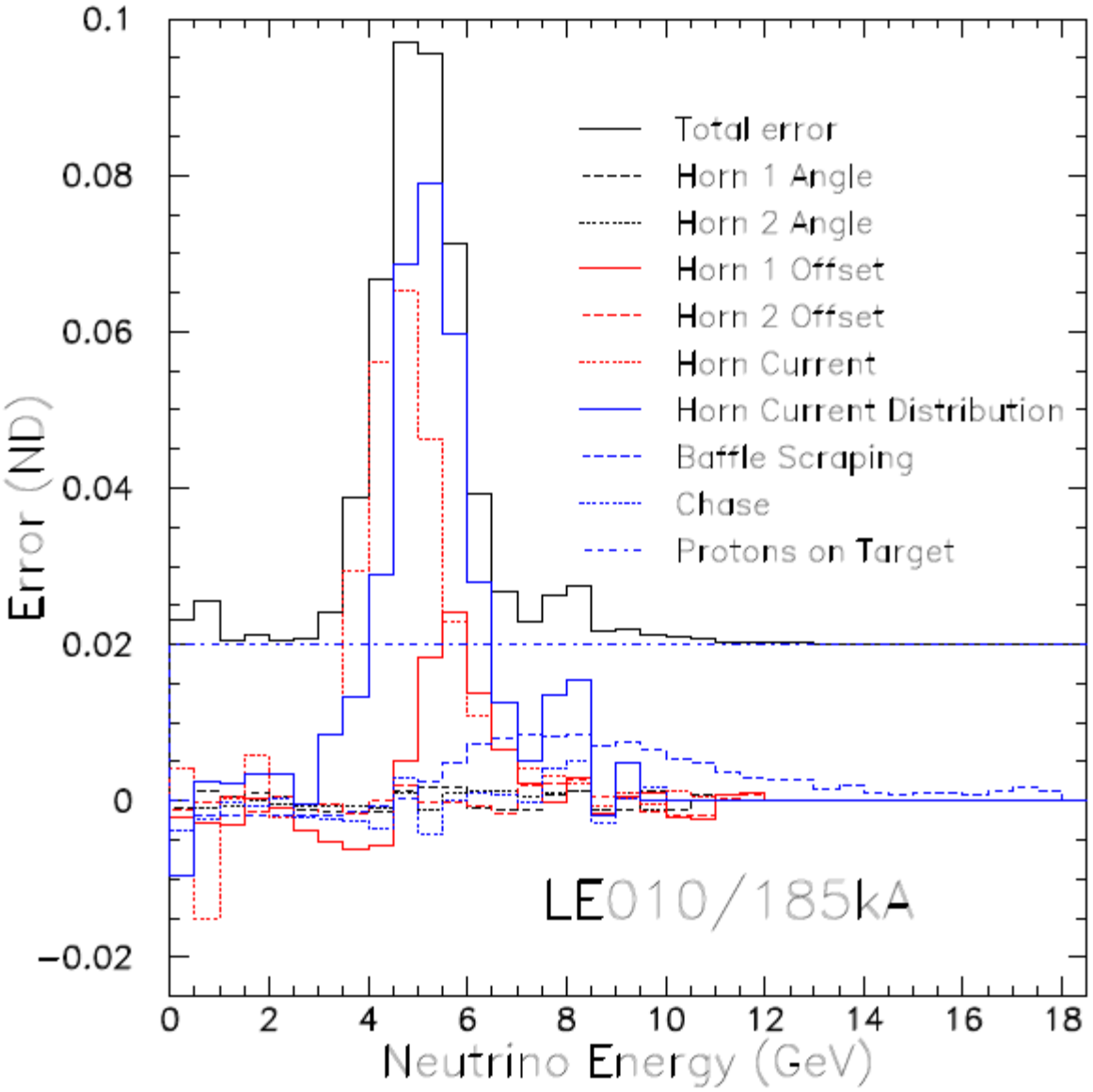


Figure courtesy Žarko Pavlović [3]

Procedure

- Basic idea of determining these uncertainties is similar to that shown by Žarko, in his thesis[3]
  - He used PBEAM (fast MC); I am using G4NuMI (full MC taking into account geometry)

Enter GEANT4/G4NuMI

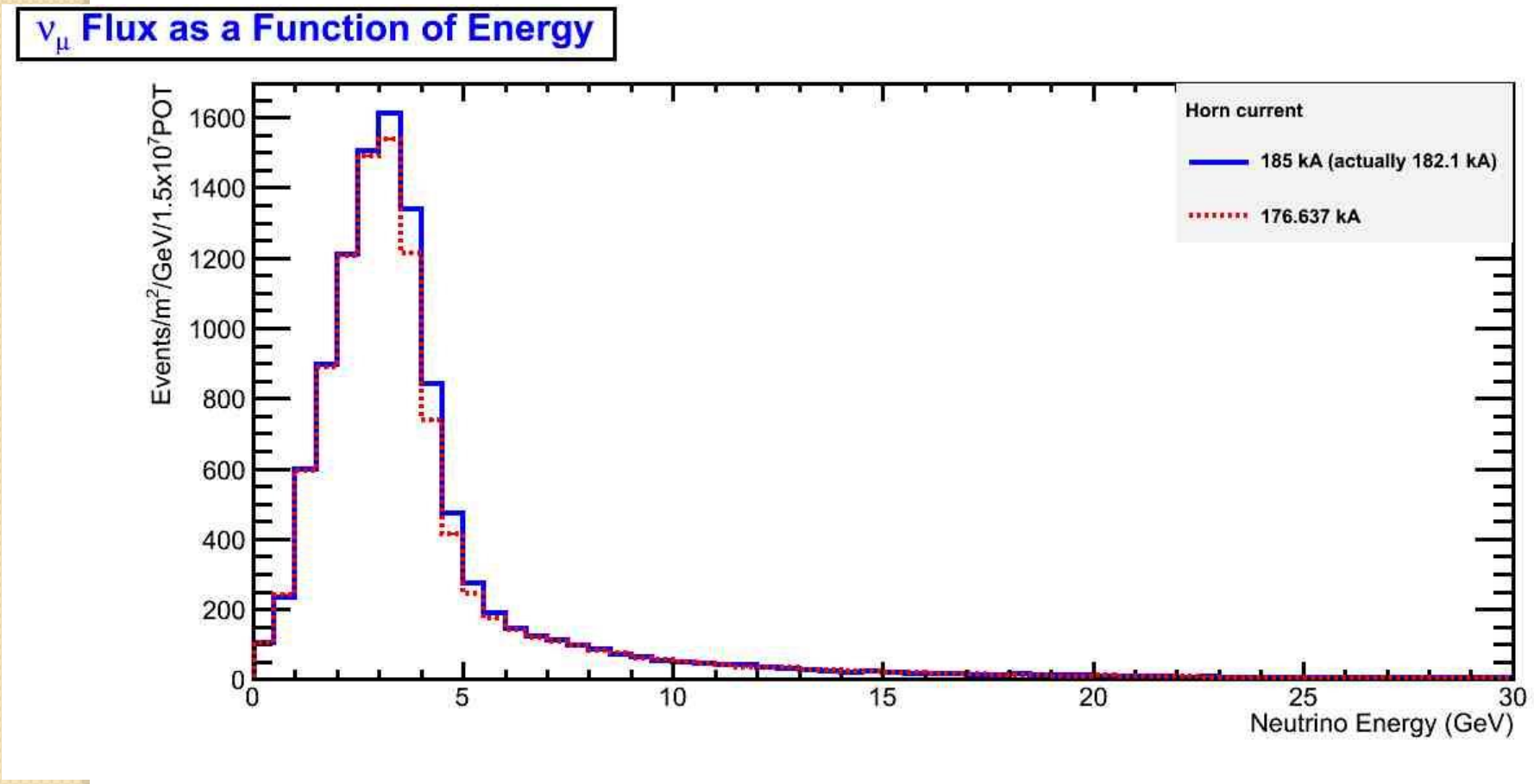
- G4NuMI is a GEANT4 full Monte Carlo simulation that constructs the geometry of the NuMI beamline
  - Takes a long time to run, hence why PBEAM has been chosen the past
  - Stores output data in ntuples
    - Example of a piece of G4NuMI output on next slide

```
protonX          = -1.59694
protonY          = 0.620618
protonZ          = -4100
protonPx         = 0
protonPy         = 0
protonPz         = 120000
nuTarZ           = -450
hornCurrent      = 182.1
Ndxdz            = 0.00610391
Ndydz            = -0.0465298
Npz              = 0.575557
Nenergy          = 0.576191
NdxdzNear[11]    = 0.000192682 , 0.000204263 , 0.0153025 , 0.0248308 , 0.0328637 ,
                   0.0428495 , 0.0615526 , 0.000237585 , 0.110696 , 0.00465562 ,
                   -0.00441251

NdydzNear[11]    = -0.000311746 , -0.00634126 , -0.0111289 , -0.011552 , -0.014367 ,
                   -0.00961686 , -0.000719961 , 0.165077 , 0.333918 , 0.00322858 ,
                   -0.00396492

NenergyN[11]     = 1.74019 , 3.07338 , 1.87173 , 0.897251 , 0.552057 ,
                   0.326057 , 0.154178 , 0.0189507 , 0.00495134 , 1.25971 ,
                   2.17511

NWtNear[11]      = 0.00304688 , 0.0106802 , 0.00457982 , 0.00113352 , 0.000465618 ,
                   0.00027595 , 0.000127081 , 5.34807e-07 , 1.11886e-07 , 0.00154764 ,
                   0.00491298

NdxdzFar[2]      = 1.38802e-07 , 3.56578e-05

NdydzFar[2]      = -2.24572e-07 , 0.000100171

NenergyF[2]      = 1.6907 , 1.67619

NWtFar[2]        = 1.49247e-09 , 1.20357e-09
```

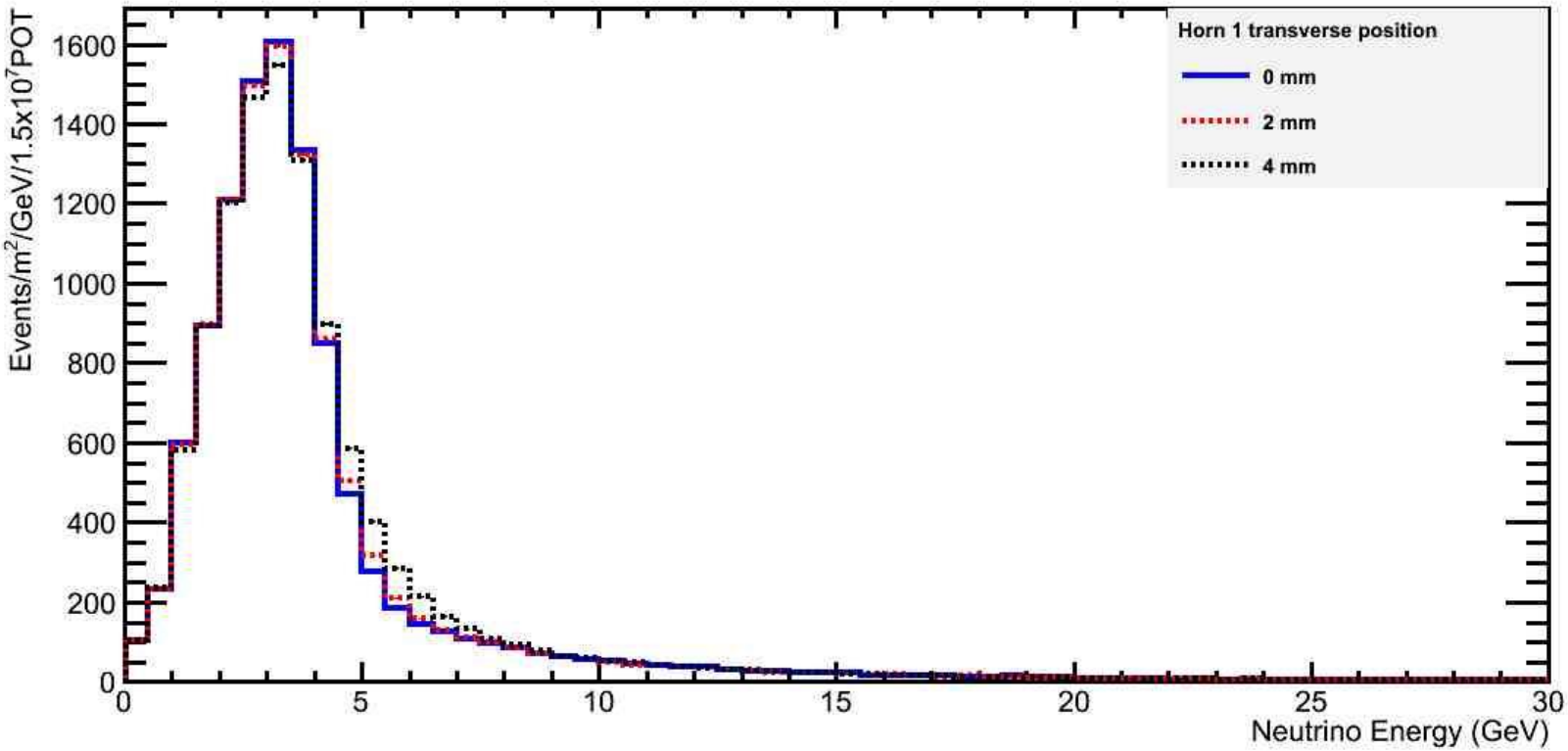
Sequence of Steps (Details to follow)

- Edit G4NuMI source code as needed
- Generate ntuples by running MC
- Plot flux spectra for these ntuples for the various parameters (Flux vs. $E_{neutrino}$)
- From these flux spectra, take ratios to see how these fluxes change with changes to parameters.
  - Make sensitivity plots
  - From fit to sensitivity plots, extract the fractional uncertainty in neutrino flux

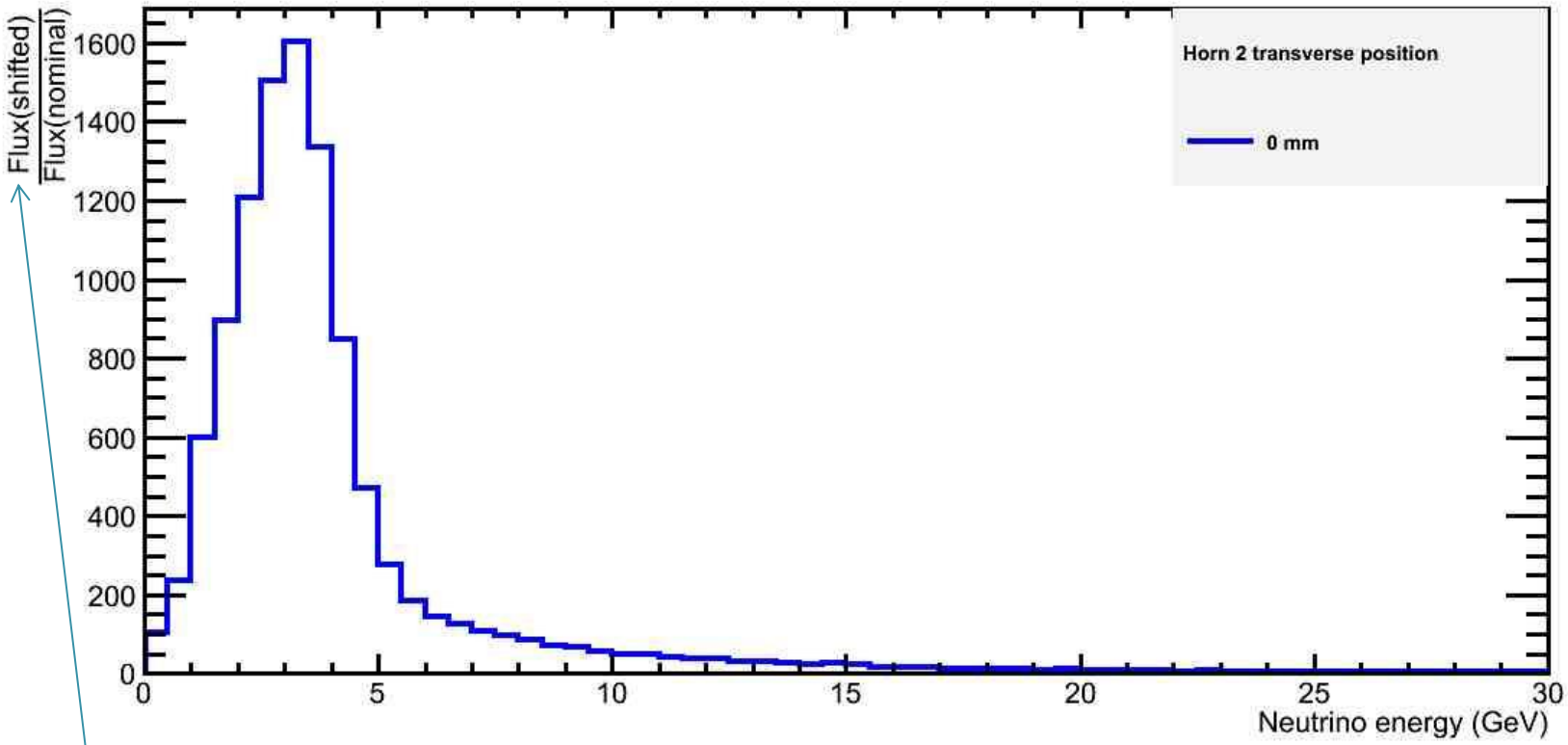
Simulated data for order 10^7 POT per parameter value



ν_μ Flux as a Function of Energy

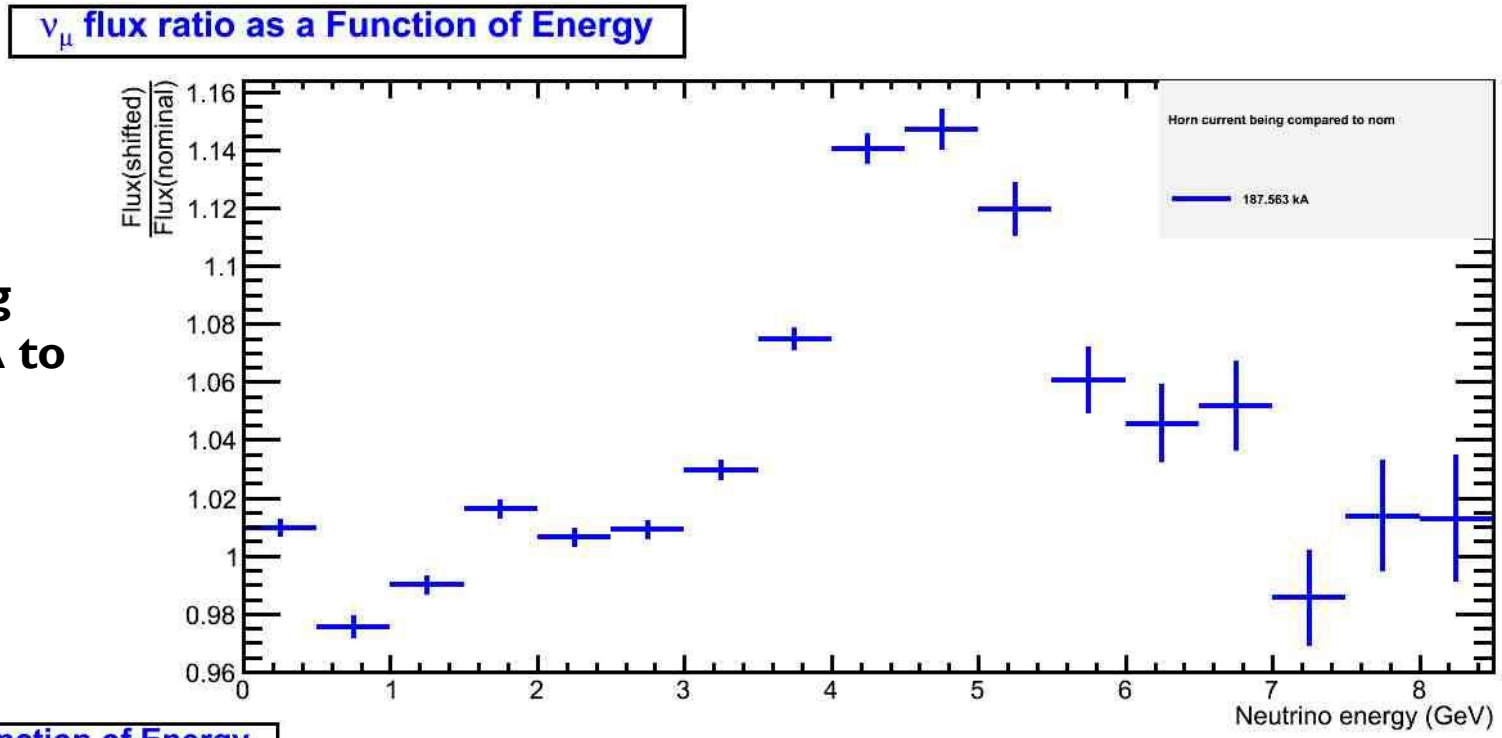


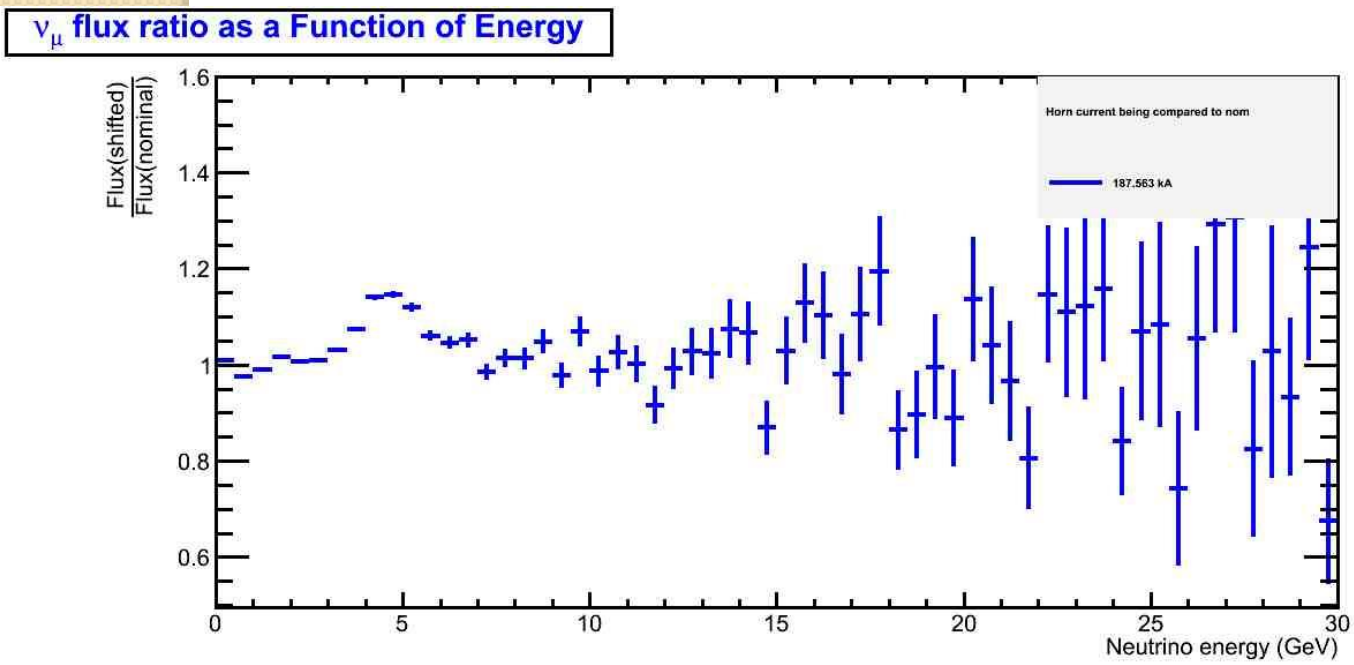
ν_μ flux as a Function of Energy



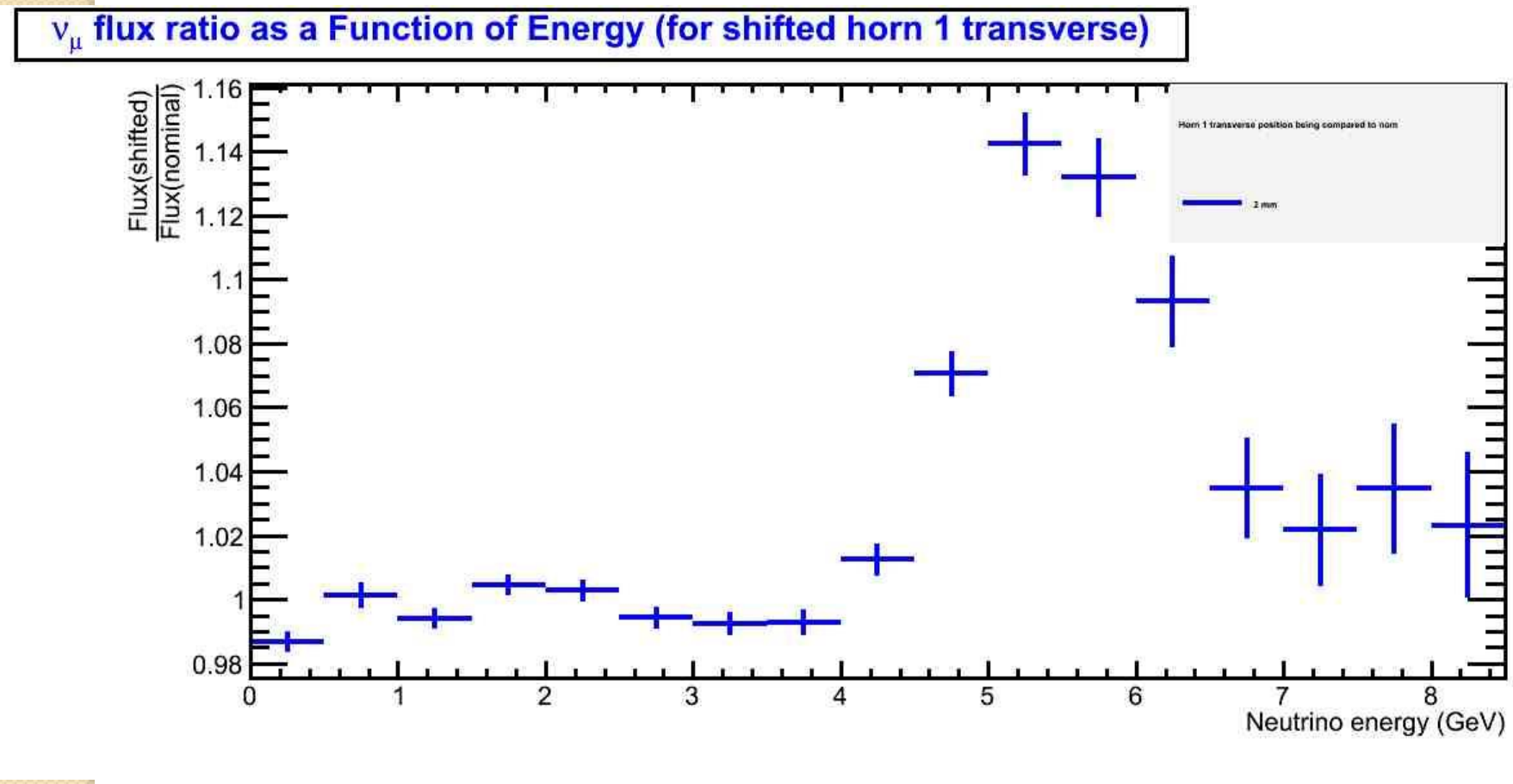
Actually, it's Events/m^2/GeV/1.5e7 POT

Comparing 187.563 kA to 182.1 kA





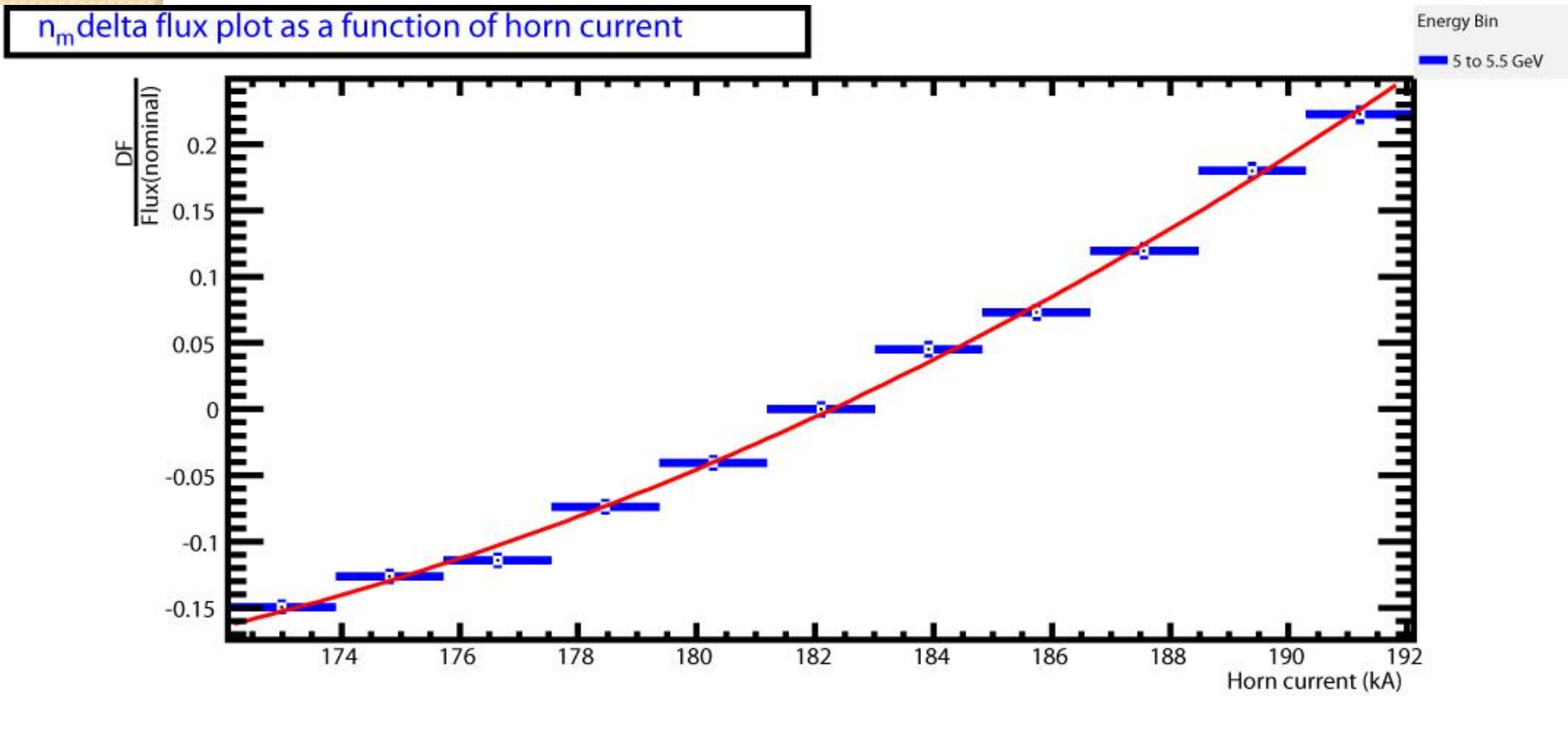
Comparing 2 mm to 0 mm

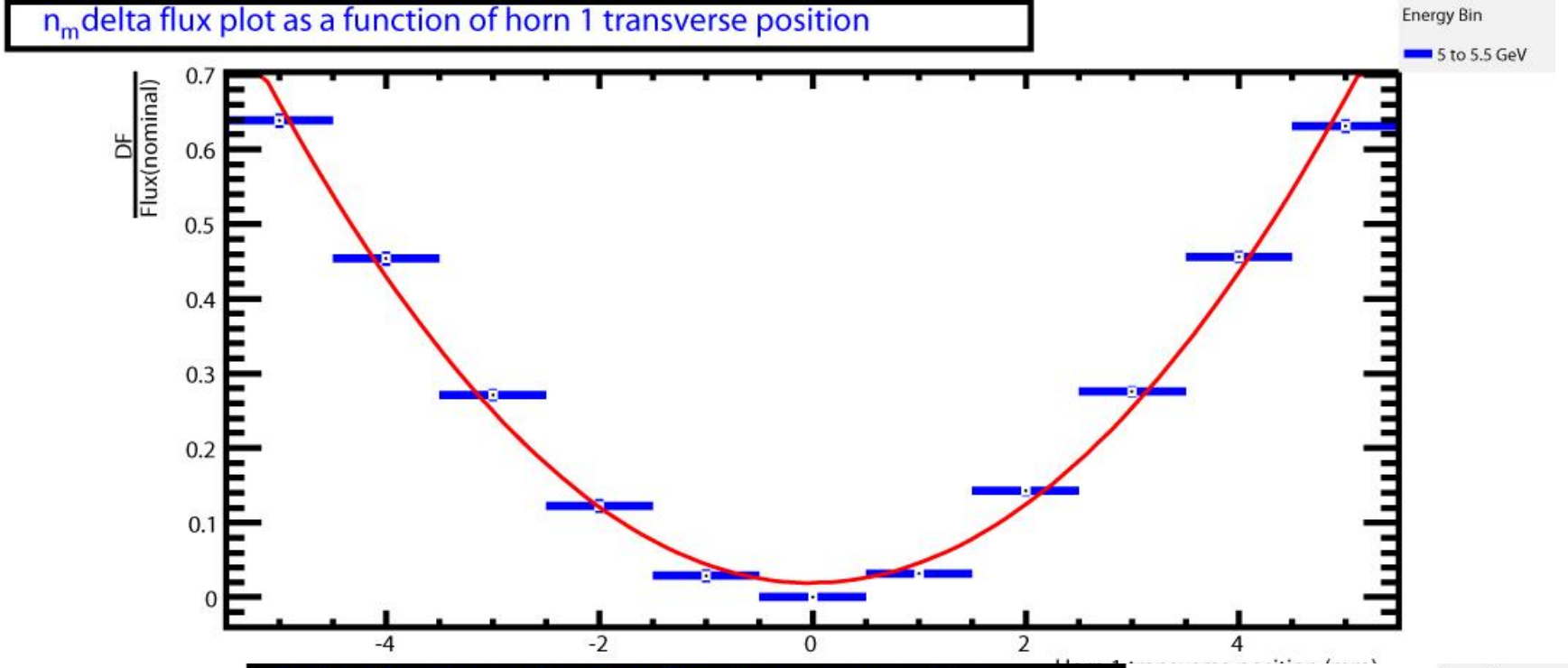


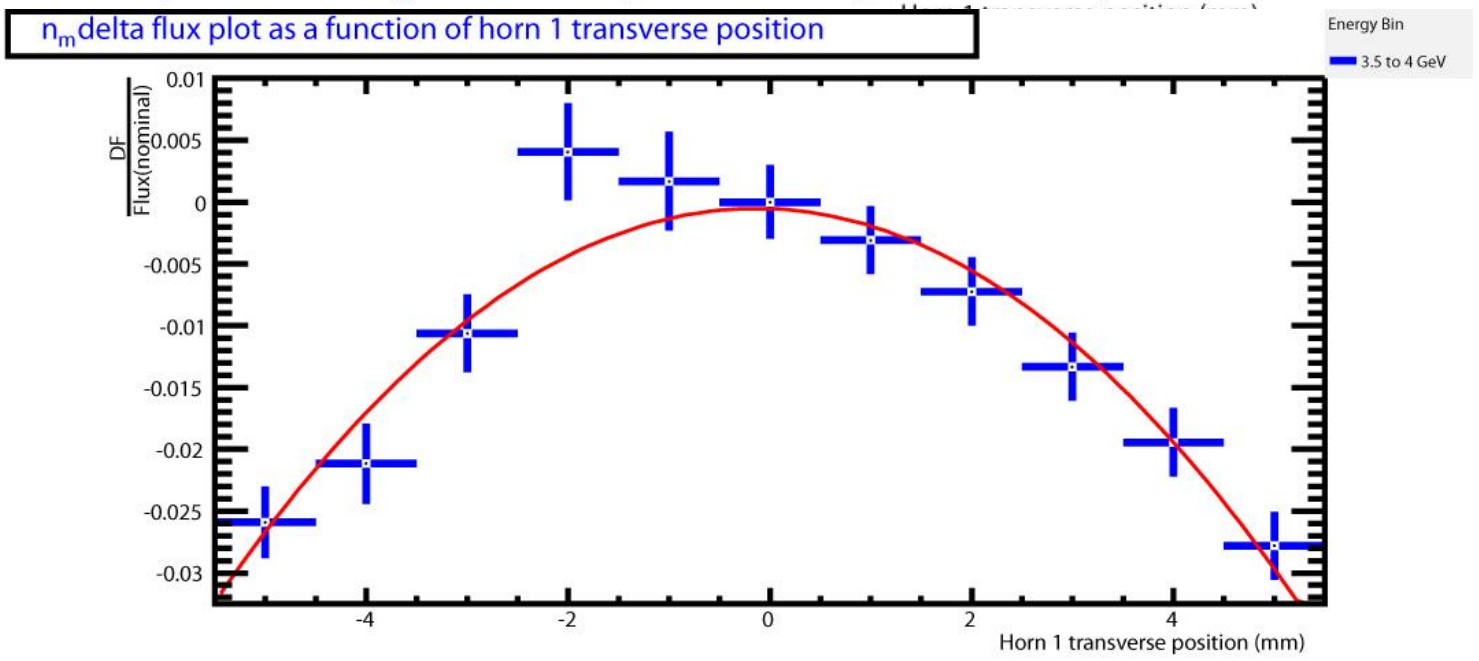
$n_m = \nu_\mu$

$$\mathrm{DF} = \frac{F(s) - F(n)}{F(n)}$$

To fix a bug in the visual representation of the following sensitivity plots, I had to rasterize the .EPS files at larger sizes. The originals are posted in backups.

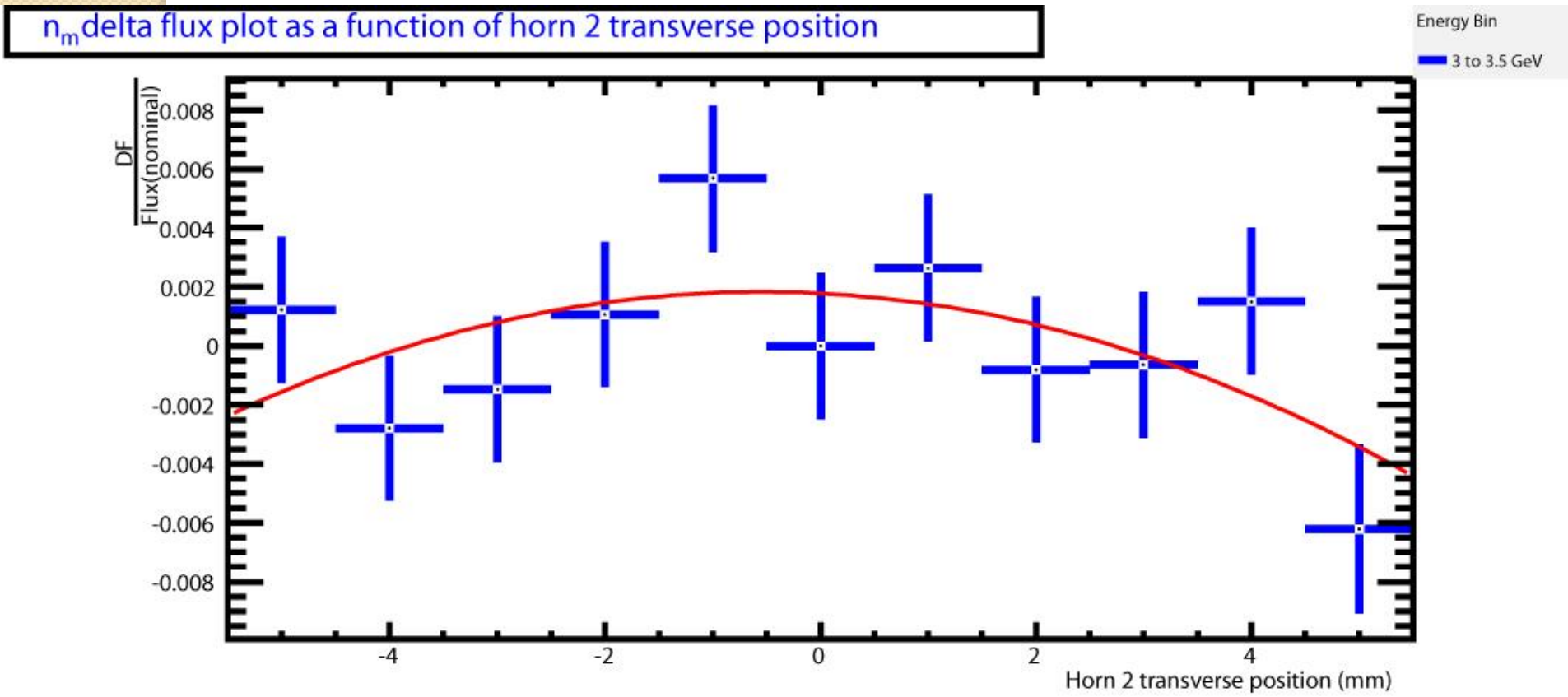






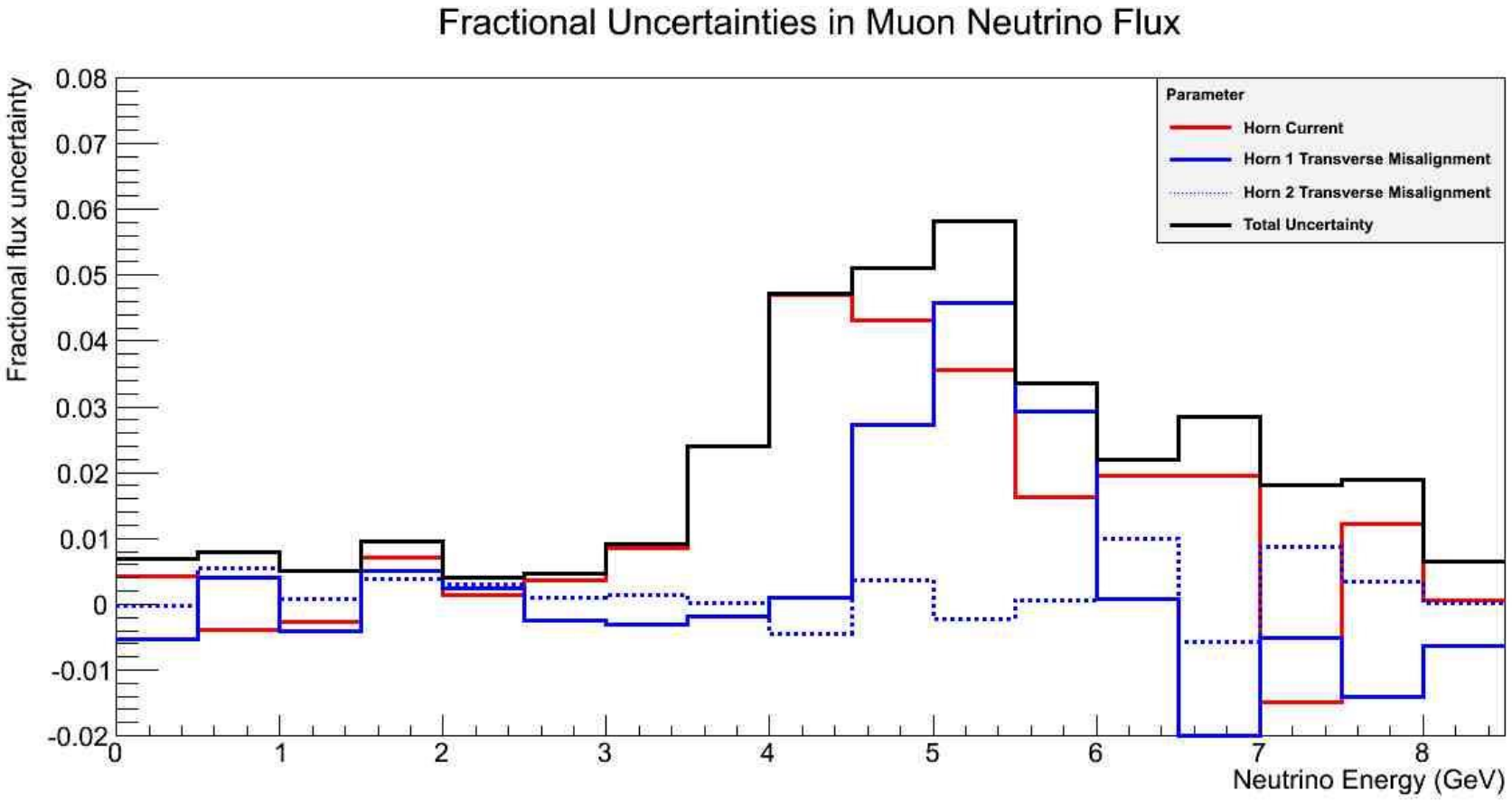
$n_m = \nu_\mu$

$$DF = \frac{F(s) - F(n)}{F(n)}$$



$n_m = \nu_\mu$

$$DF = \frac{F(s) - F(n)}{F(n)}$$



Shapes are VERY close to those found in [3] and give me hope of finding better flux uncertainties!!!

Conclusions

- Currently have investigated some of the important NuMI parameters
  - Machinery working
  - Higher statistics should make things even better: working on it
- File repository: my analysis scripts and changes I made to the G4NuMI source will appear in a directory for others in my collaboration to use if they wish/need to use them

Into the future…

- BUT I'M NOT DONE YET!!
  - Will be continuing to work on this project when I return to Pittsburgh [on Saturday…]
- In the future:
  - Other parameters not included at present
  - ν_e flux uncertainty study
    - Will help current electron neutrino studies, such as Jeremy and perhaps Jaewon
  - Medium energy runs!
    - Need to understand the flux uncertainties in the NOνA era
- NA61 – will work on reducing flux uncertainties arising from hadron production

Acknowledgements

This work was supported in part by the U.S. Department of Energy, Office of Science, Office of Workforce Development for Teachers and Scientists (WDTS) under the Science Undergraduate Laboratory Internship (SULI) program.

I would like to express gratitude toward several people for this research. First, I would like to acknowledge Jyotsna Osta for being a great mentor. I would also like to thank Deborah Harris for her role as a co-mentor. Additionally, Leonidas Aliaga is someone who provided helpful words on many occasions and had some scripts that I could adapt to aid my studies. The whole MINERνA collaboration deserves acknowledgement for their kindness and for simply being an awesome group of people. Furthermore, I would like to thank Žarko Pavlović, whose research for MINOS helped to guide me and who was willing to answer a few questions I had about his research. Additionally, I give thanks to Erik Ramberg, Roger Dixon, Carol Angarola, and the DOE Office of Science, for without their coordinated efforts this opportunity would not have been possible. Finally, I want to acknowledge the professors of the University of Pittsburgh Department of Physics and Astronomy, who taught me well and provided me with invaluable experiences, some of which were helpful to me during this research. One specific member of the department I'd like to thank is Vittorio Paolone, with whom I will continue this line of research upon returning to Pittsburgh.

References

[1] The MINERvA Collaboration, "MINERvA Summary," MINERvA Document 6444-v12, 2013.
[2] Žarko Pavlović, "Talks/Posters," *Zarko Pavlovic*, <http://www.hep.utexas.edu/~zarko/talks.htm> (10 July 2013).
[3] Žarko Pavlović, Ph.D. thesis, The University of Texas at Austin, 2008. Retrieved from MINOS Document 5694-v1.

Figures included in the backup slides have their sources (and web addresses) listed beside them, if applicable.

BACKUP

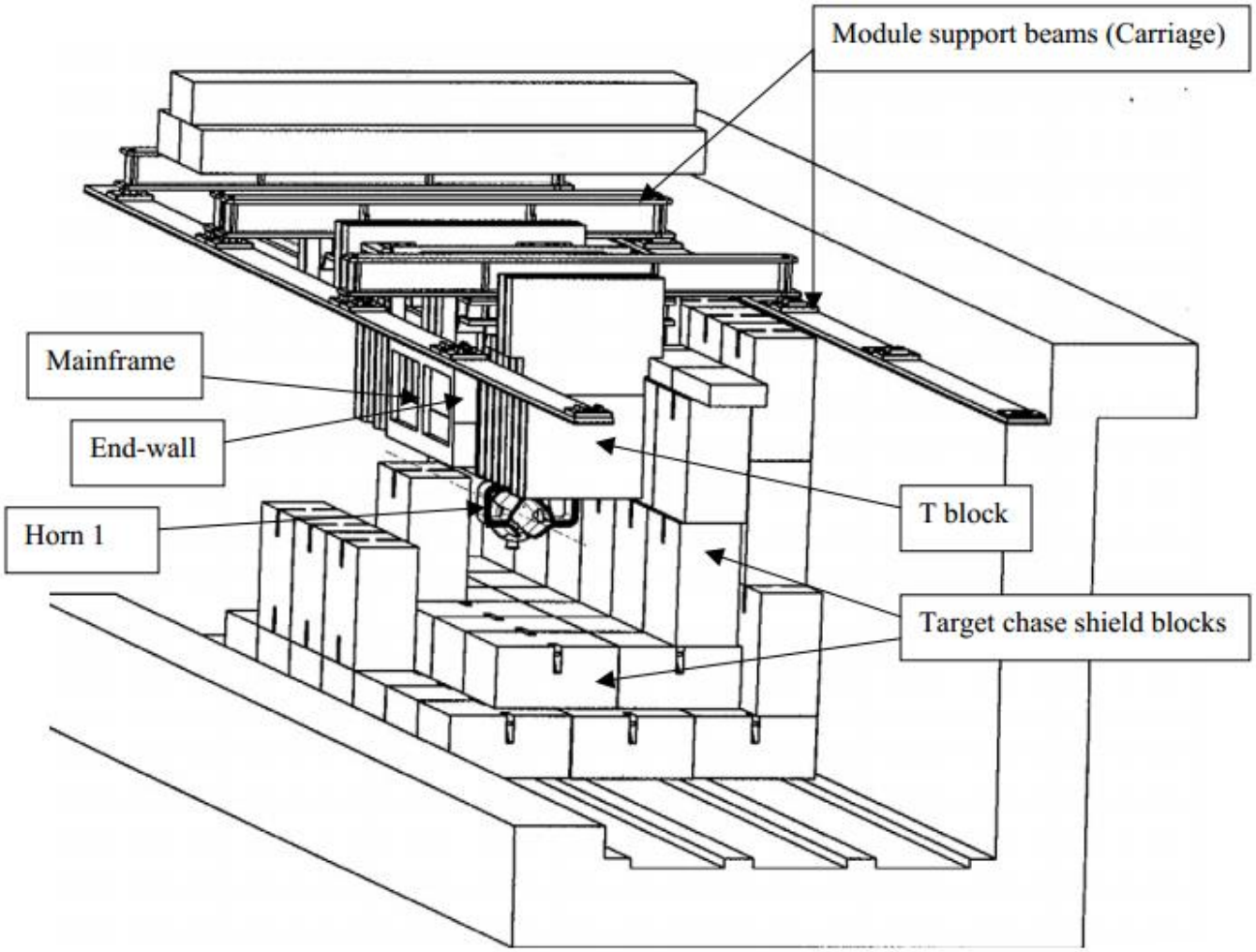
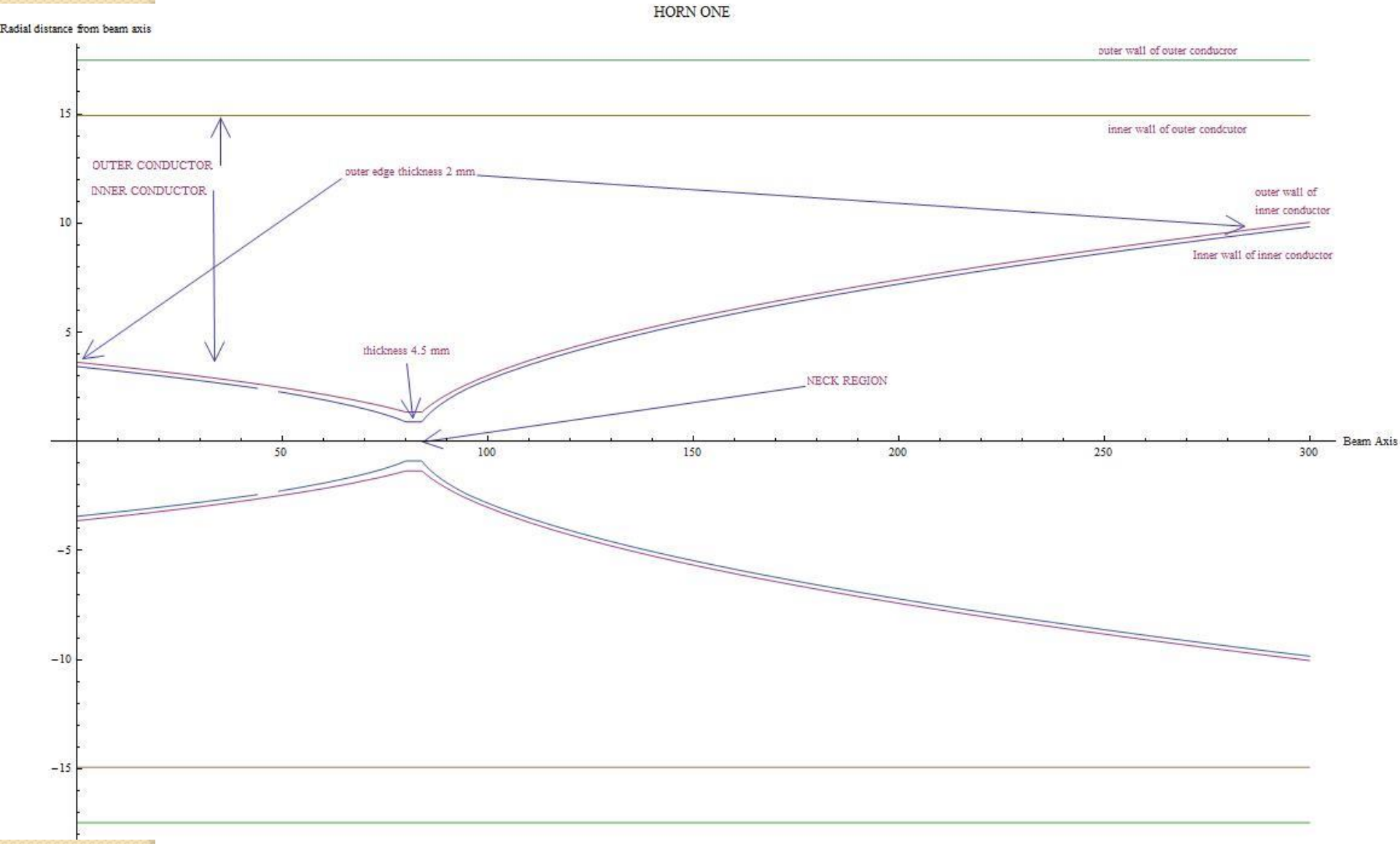


Figure 4.2-25. Schematic representation of the NuMI target chase showing the Horn 1 module and its T-blocks.

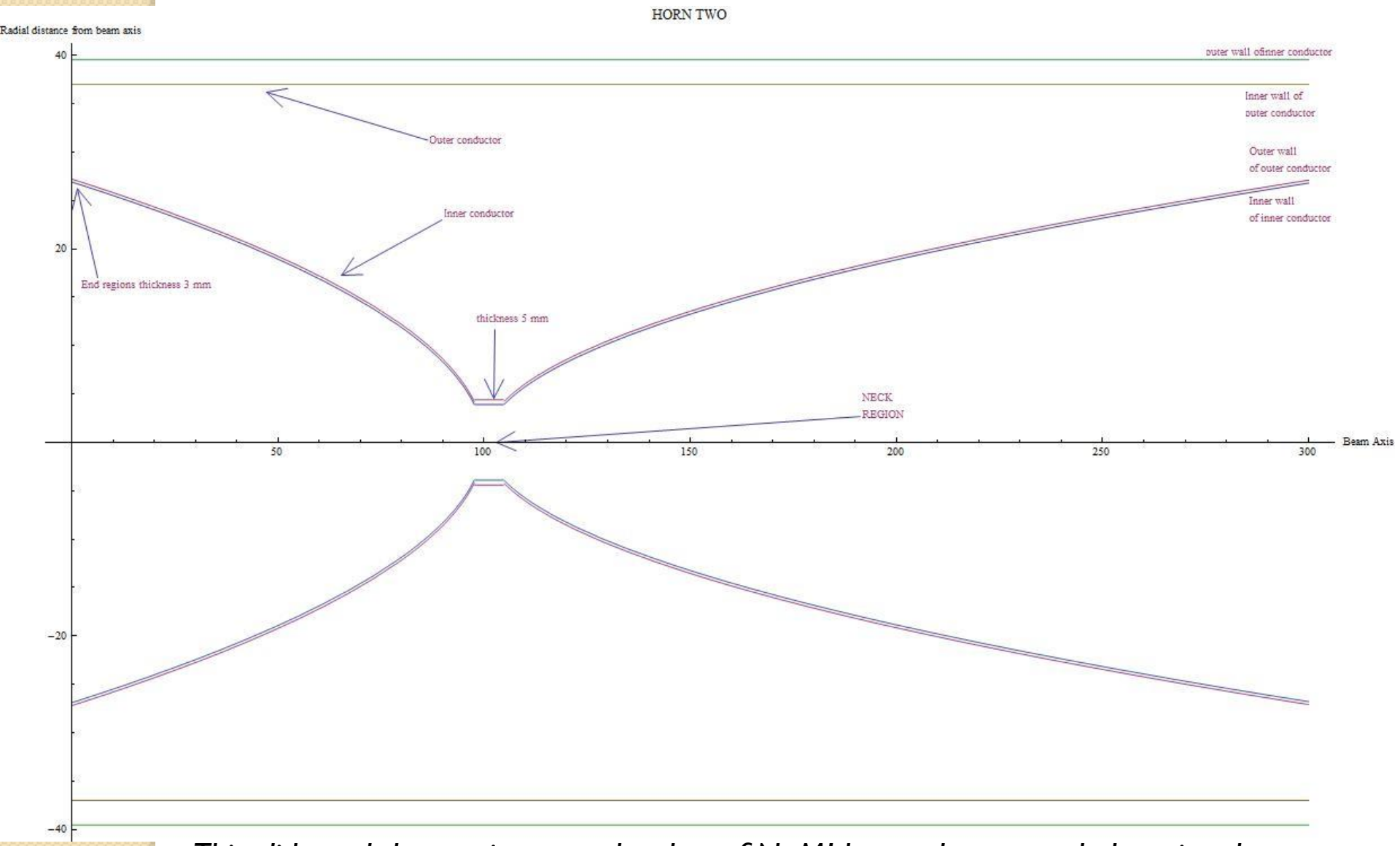
NuMI TDH available online: http://www-numi.fnal.gov/numwork/tdh/tdh_index.html

NuMI TDH, Section 4.2.9

http://www-numi.fnal.gov/numwork/tdh/tdh_index.html

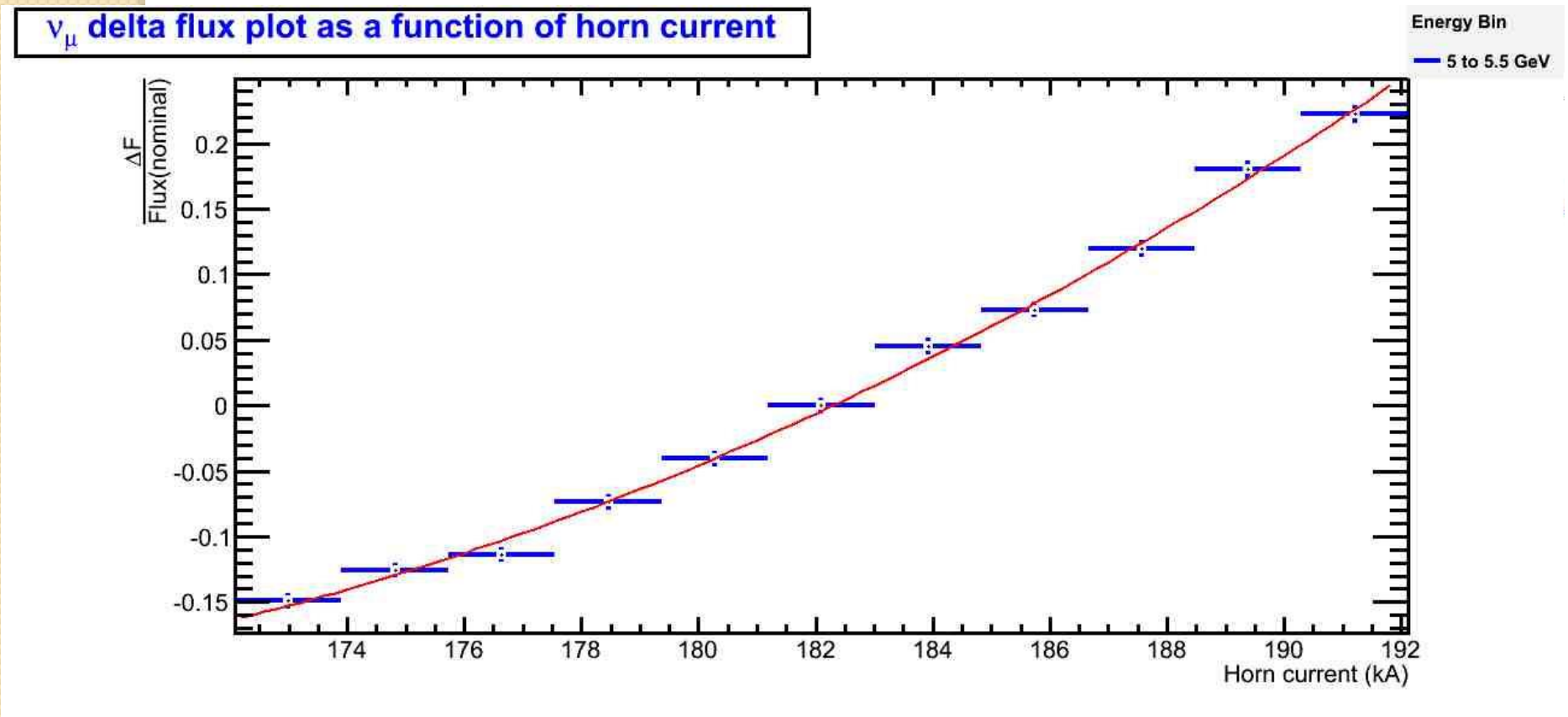


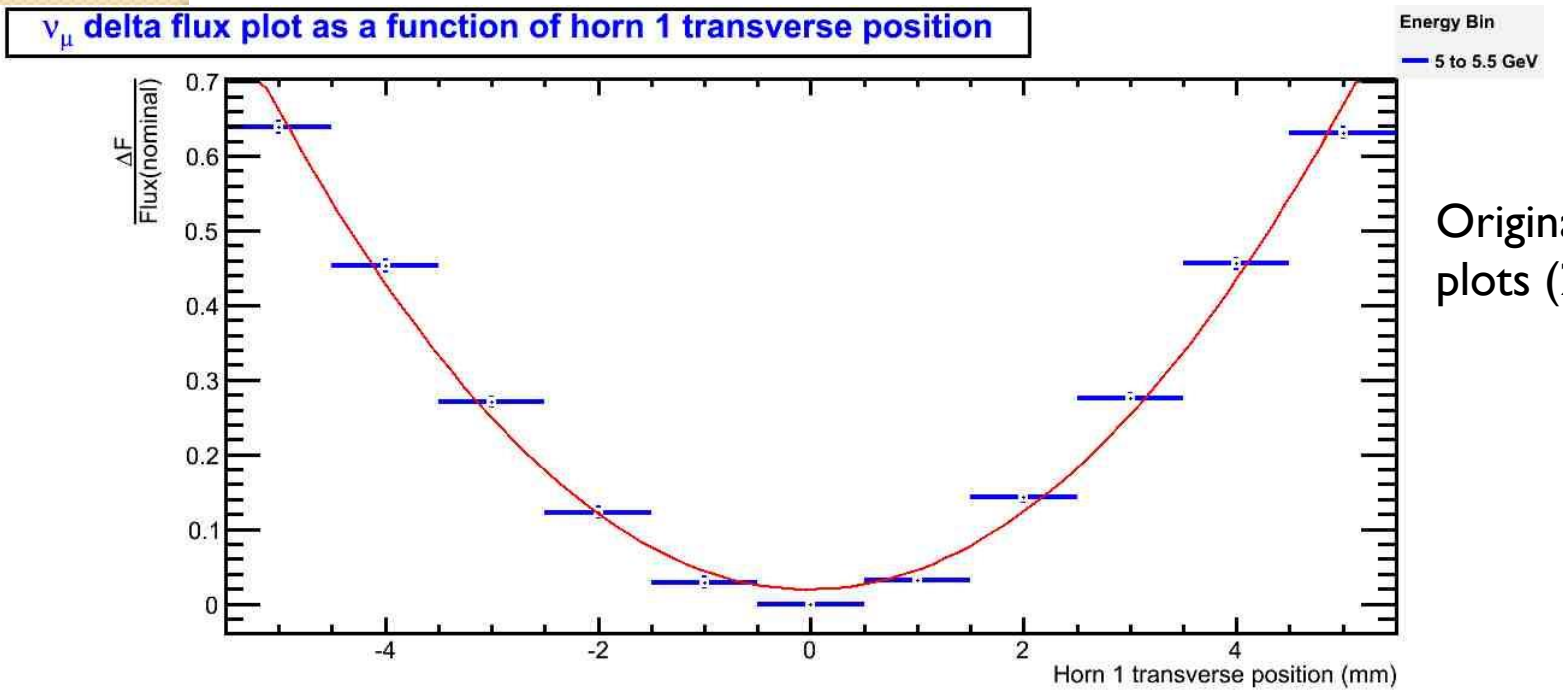
This slide and next are sketches of NuMI horns shapes made by using the equations listed in NuMI TDH, Section 4.2.4: http://www-numi.fnal.gov/numwork/tdh/TDH_V2_4.2.4-horns.pdf



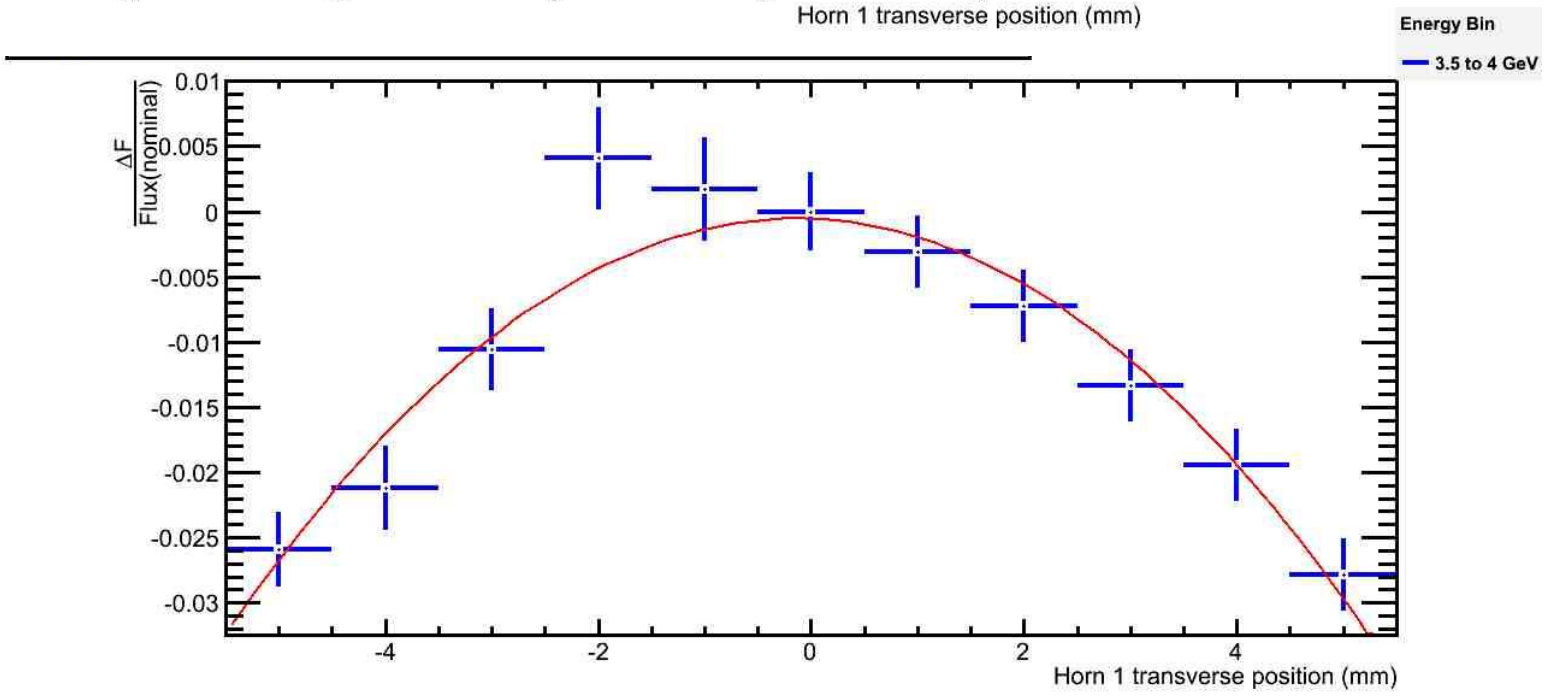
This slide and the previous are sketches of NuMI horns shapes made by using the equations listed in NuMI TDH, Section 4.2.4: http://www-numi.fnal.gov/numwork/tdh/TDH_V2_4.2.4-horns.pdf

Original sensitivity plots (1/3)

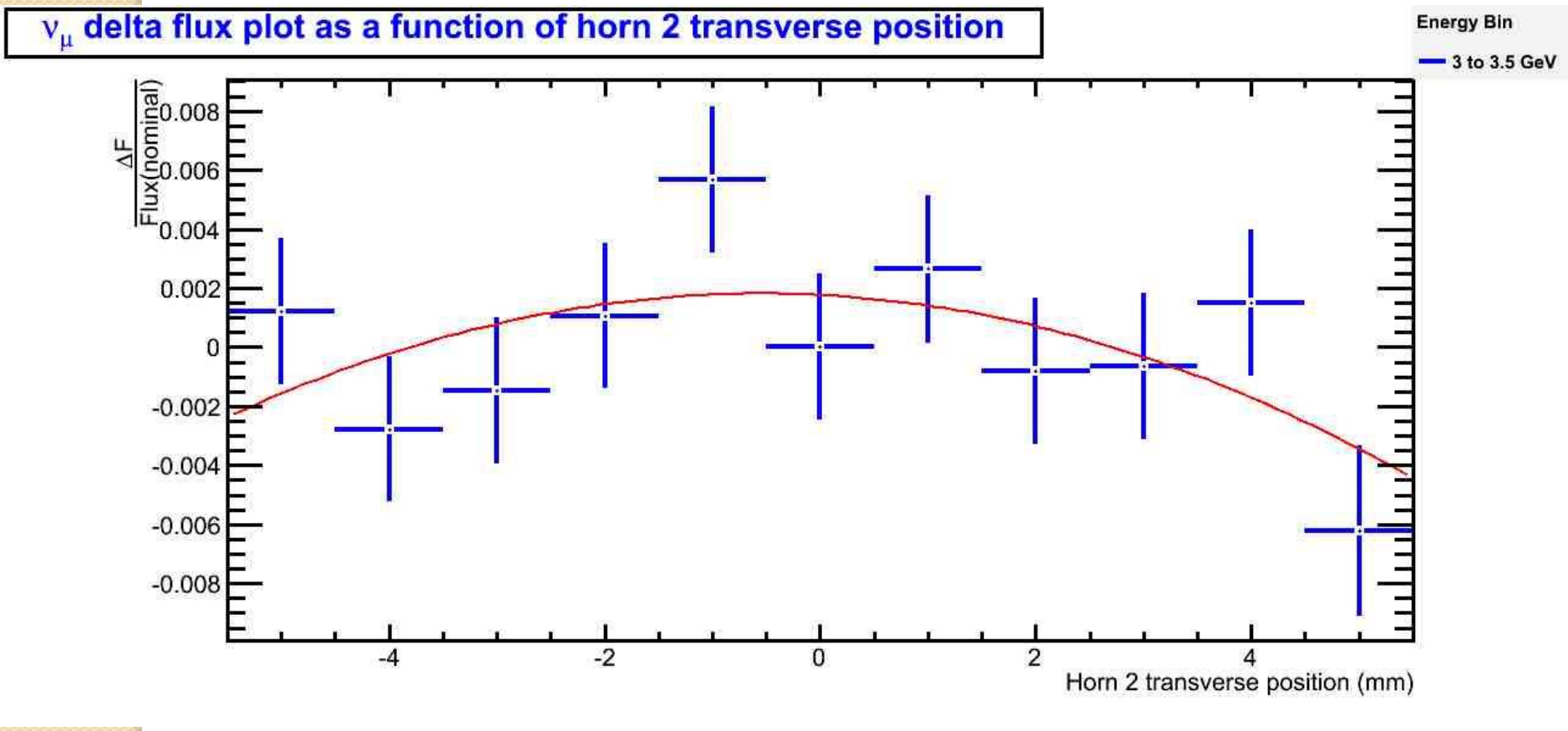


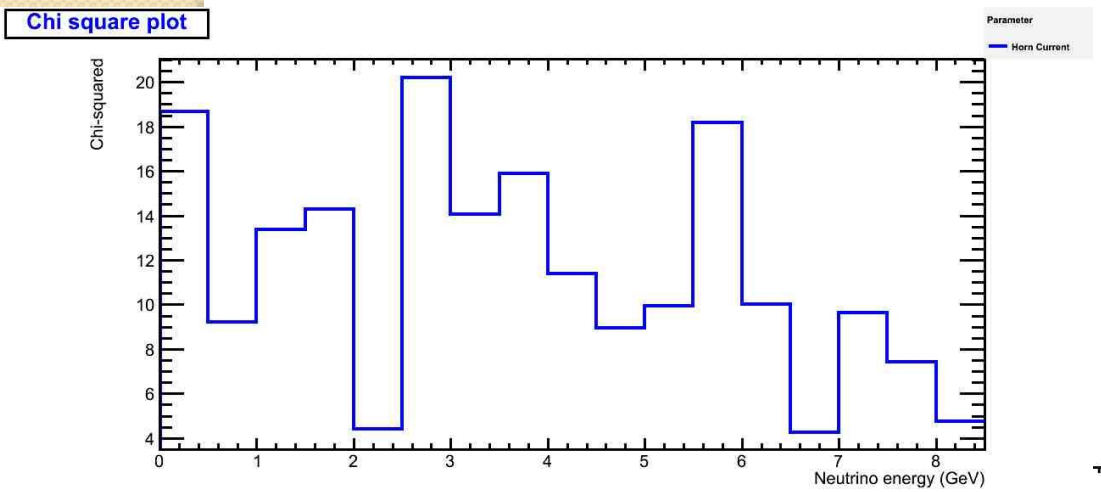


Original sensitivity plots (2/3)

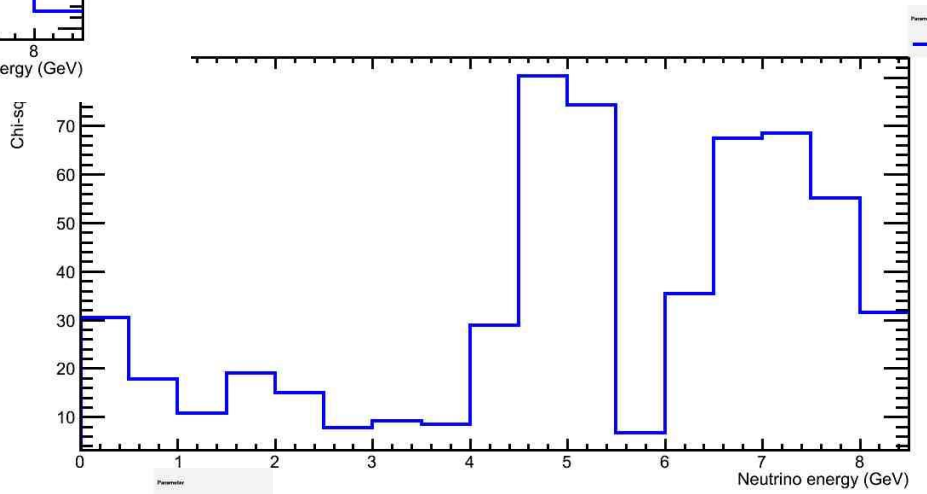


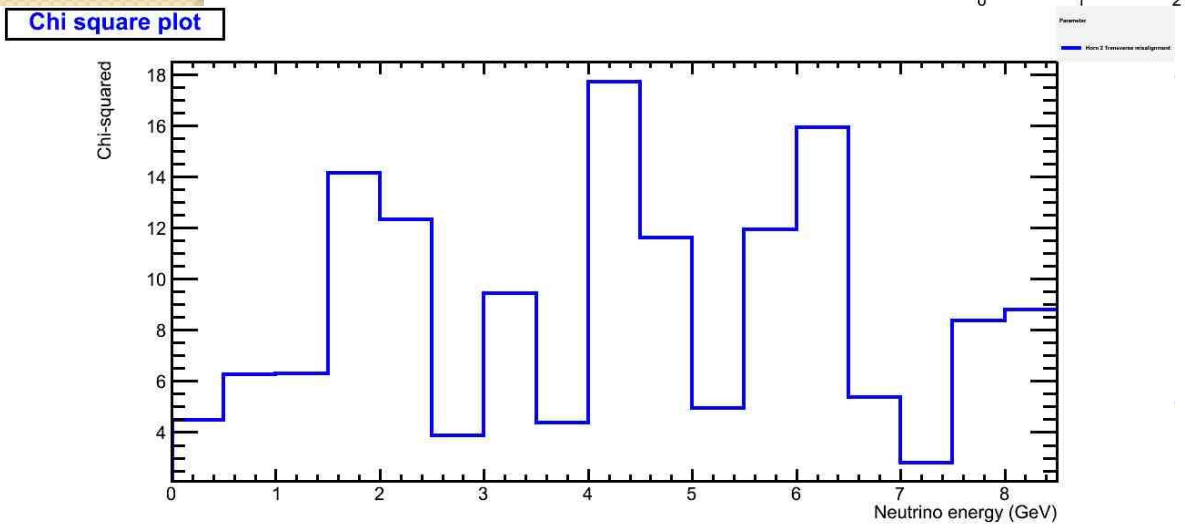
Original sensitivity plots (3/3)





Chi-squared plots:
Top: horn current
Middle: horn1 misalignment
Bottom: horn 2 misalignment





Some other parameters I can investigate

- Those considered by Zarko:
  - Horn current distribution
  - Horn tilt
  - Baffle scraping
  - Misalignment of shielding blocks
  - Target density
- Those not considered by Zarko but are potentially important for us to consider:
  - Target z position (i.e. along the beamline)
  - Target tilt
  - Dipole effects