Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

LBNF Neutrino Beam Monitoring

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Joint ND/BIWG Meeting

26 June 2019

Outline

- Why We Are Here
- LBNF Beamline Overview
- Beam Changes experienced at NuMI
- Impact of LBNF Misalignments on DUNE fluxes
- Primary and Secondary Monitoring Plans for LBNF
- What is needed from the Near Detector
  - (Or as much as we understand now)

Why Are We Here?

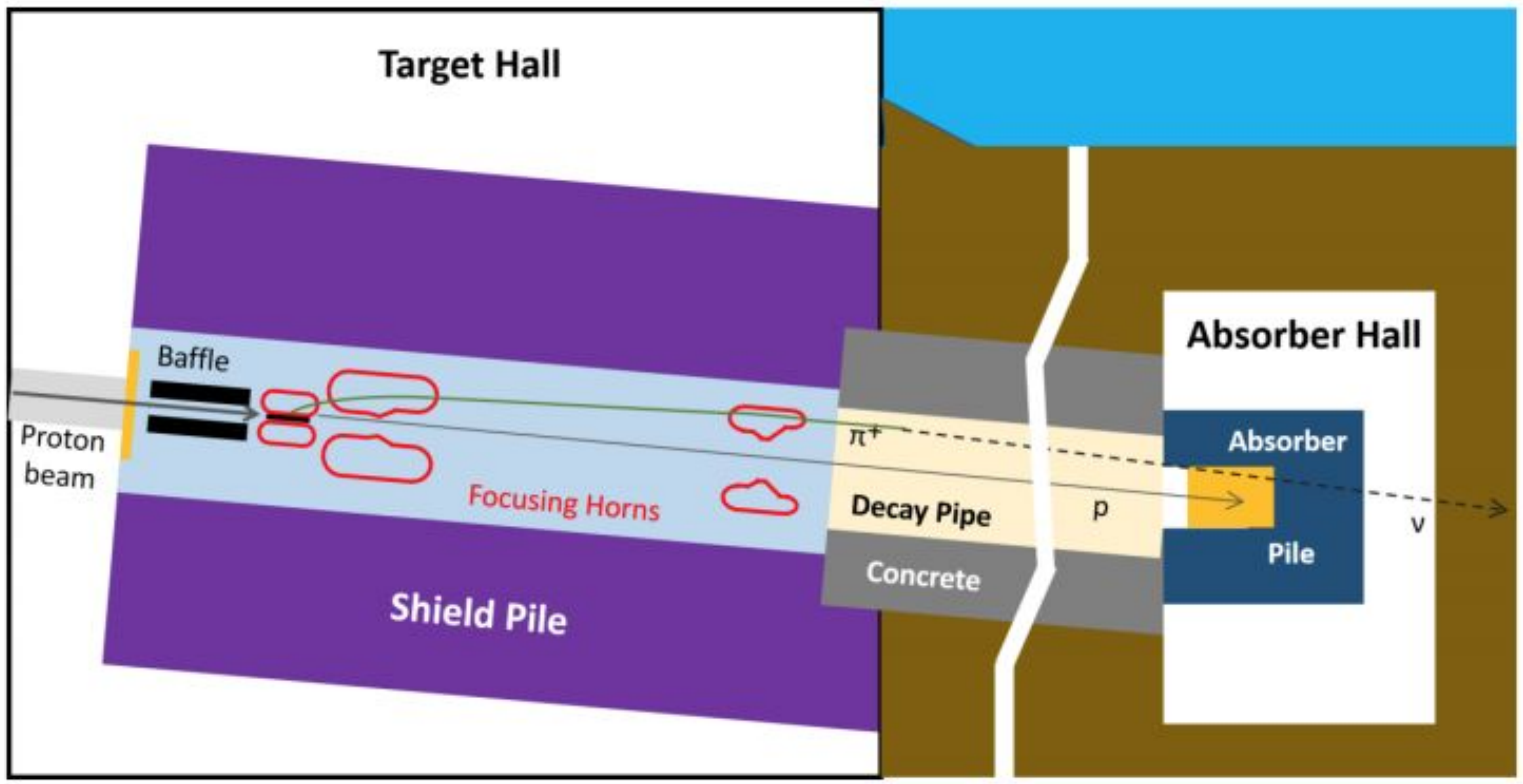
- NuMI experience indicates that having an on-axis measurement of the neutrino spectrum is extremely useful for monitoring the neutrino beam
- With DUNEPrism, most of the near detectors will be off-axis for significant fractions of the run; only the 3DST will be on-axis with the current plan
- At the recent LBNC review, the committee was not convinced of the importance of a dedicated on-axis detector capable of spectrum measurements
- The ND and BIWG groups must work together to make sure the LBNC understands the benefits of on-axis beam monitoring
    - And to understand what ND capabilities are required for beam monitoring

Disclaimer

- It is not possible to completely describe beam monitoring in a single talk
- And if it were, there would be better people to do it than me
- Today there is a conflict with practice talks that will keep a lot of LBNF beamline experts from joining us
- Today's talk is meant to give a basic overview of this situation
- We will want to involve beamline experts in the discussion going forward

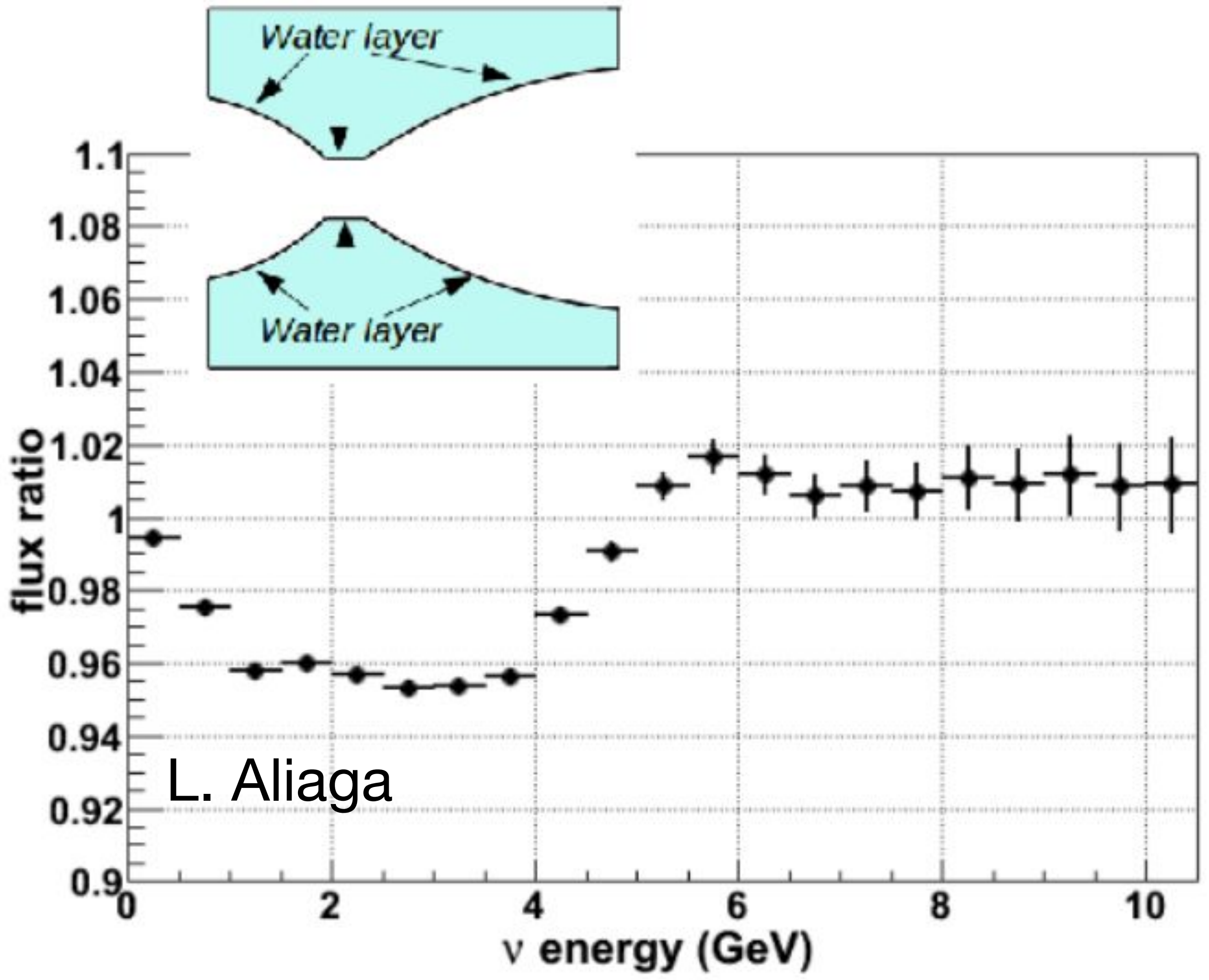
LBNF Beamline

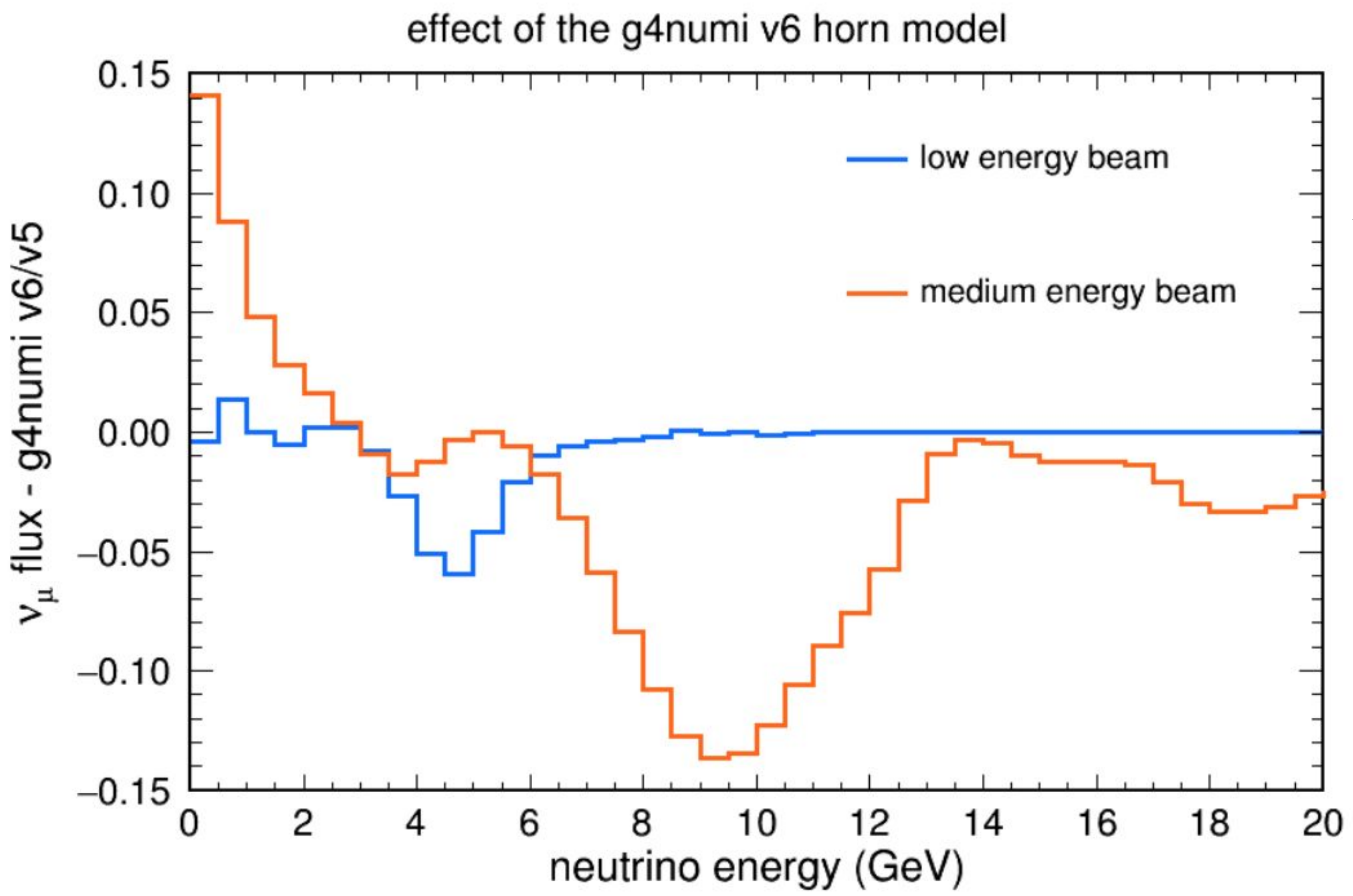
The beamline we are talking about monitoring is the "neutrino beam" portion of LBNF -- the part of the beam where protons are converted into neutrinos:



What are We Trying to Monitor?

There are various kinds of flux “problems” that can happen. There can be differences between the as-built beamline and our simulation that are semi-permanent:





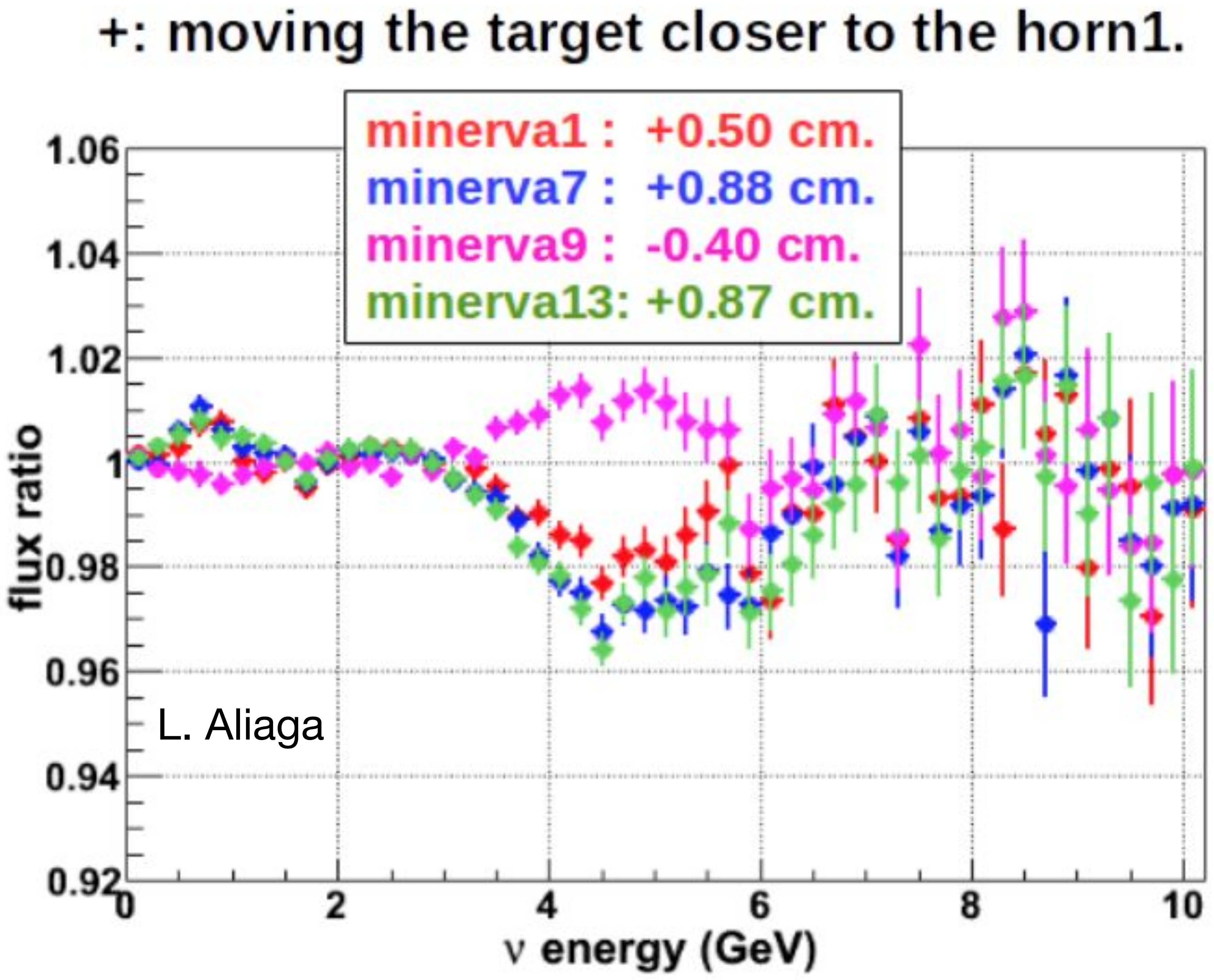
Two examples from NuMI

These can be big problems, but are not what we are talking about today, because they do not create changes with time.

These two examples were essentially deficiencies in the simulation.

What are We Trying to Monitor?`

Other problems happen because there are changes to the beamline during the run:



- These can also be big problems and *are* what we are talking about today
- Some of the changes we will simply record and simulate
- Other changes will be major problems that have to be corrected immediately
- Next few slides describe a few problems that happened in NuMI that are the sort of thing we are looking for in LBNF
- We can also be sure that LBNF will have new problems that haven't happened at NuMI

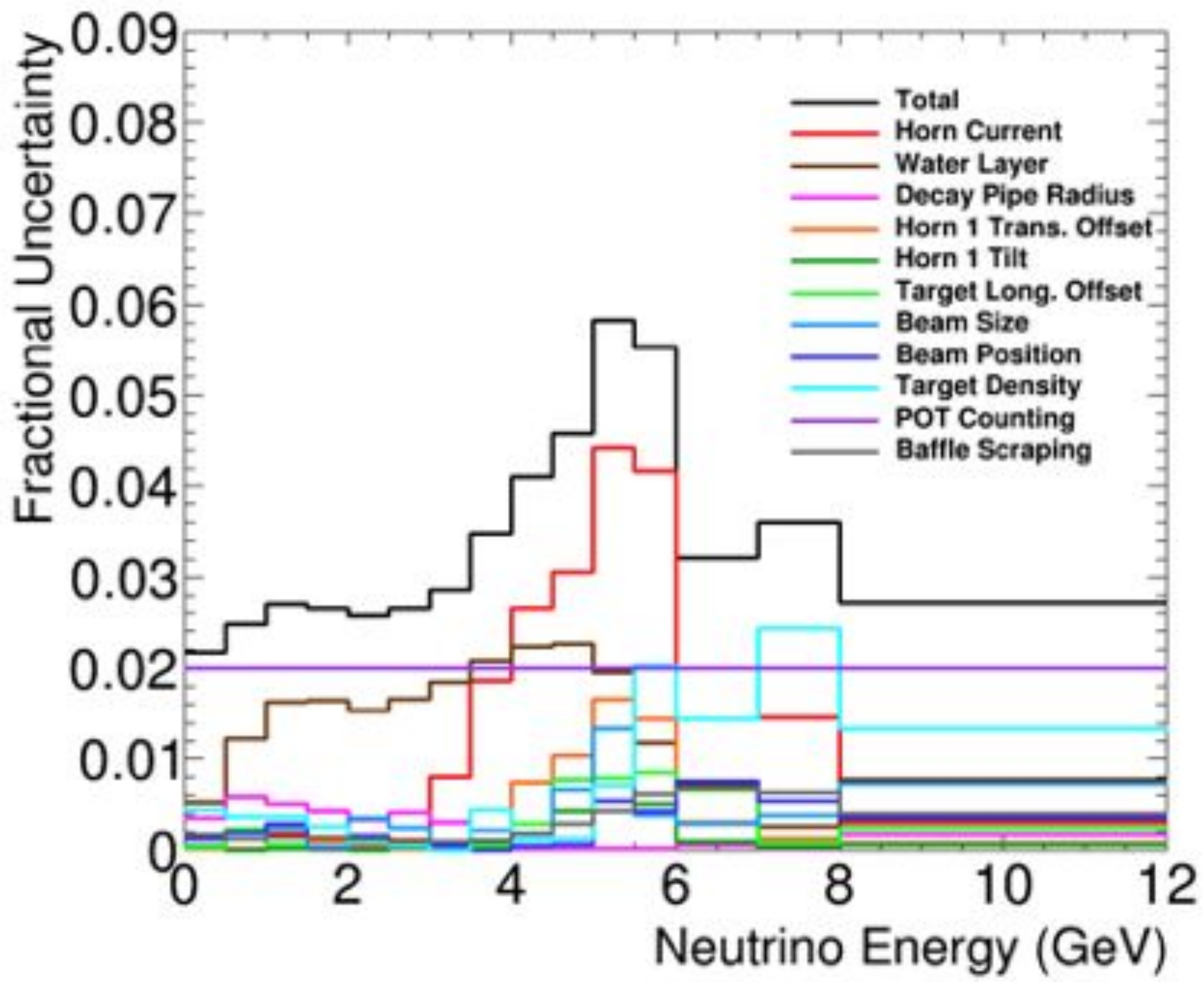
Impact of Alignment Parameters on DUNE Flux

We are particularly concerned about any of the parameters we include in our assessment of DUNE focusing uncertainties going out of tolerance:

LBNE DocDB 8410

Target position (each end)	0.5 mm
Horn 1 position (each end)	0.5 mm
Horn 2 position (each end)	0.5 mm
Far detector position	21 m
Decay pipe position	20 mm
Decay pipe radius	0.1 m
Horn current	2 kA
Horn water layer thickness	0.5 mm
Beam size at target	0.1 mm
Misalignment of shielding blocks	1 cm
Baffle scraping	0.25%
Beam position at target	0.45 mm
Beam angle at target	70 μrad
Near detector position	255 mm
Horn conductor skin depth	6 mm
Target density	2%

Table 1: Sources of beam misalignment and their expected tolerances, which were obtained from the LBNE CDR [1] where applicable and from conversations with beam experts otherwise.



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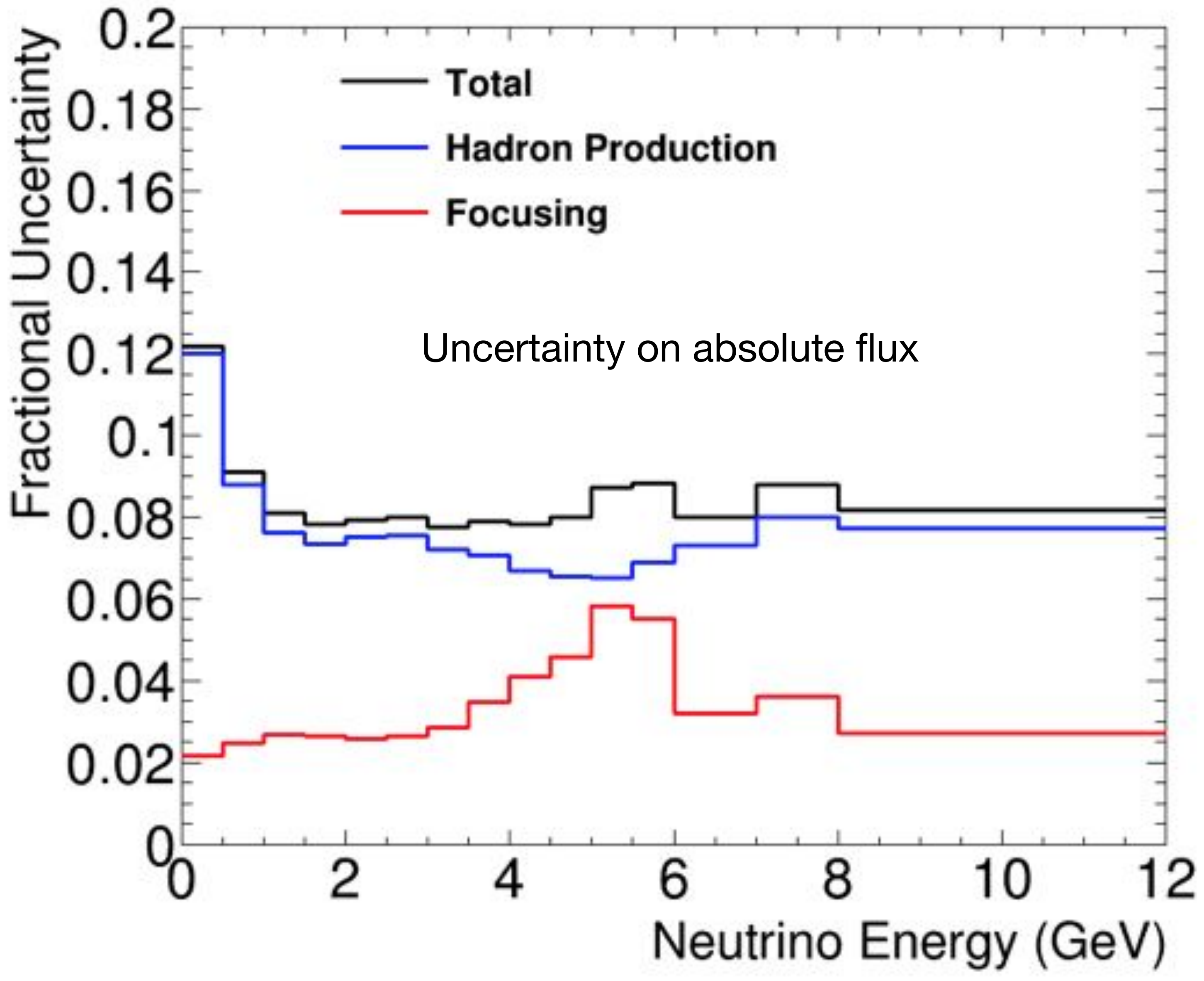
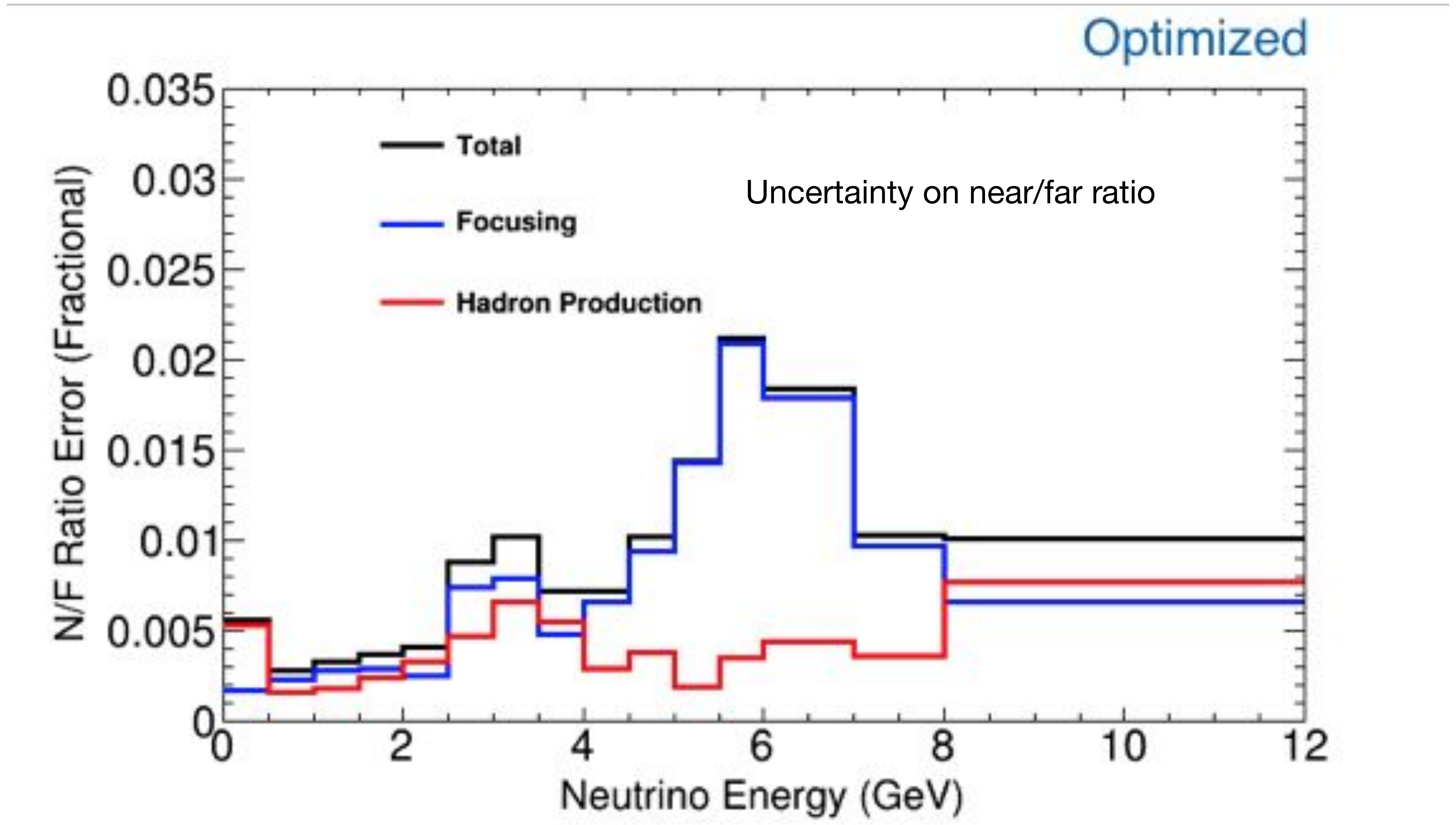
Impact of Alignment Parameters on DUNE Flux

Focusing uncertainties are currently sub-dominant compared to hadron production flux uncertainties, but they are the largest sources of uncertainty on the near/far flux ratio:





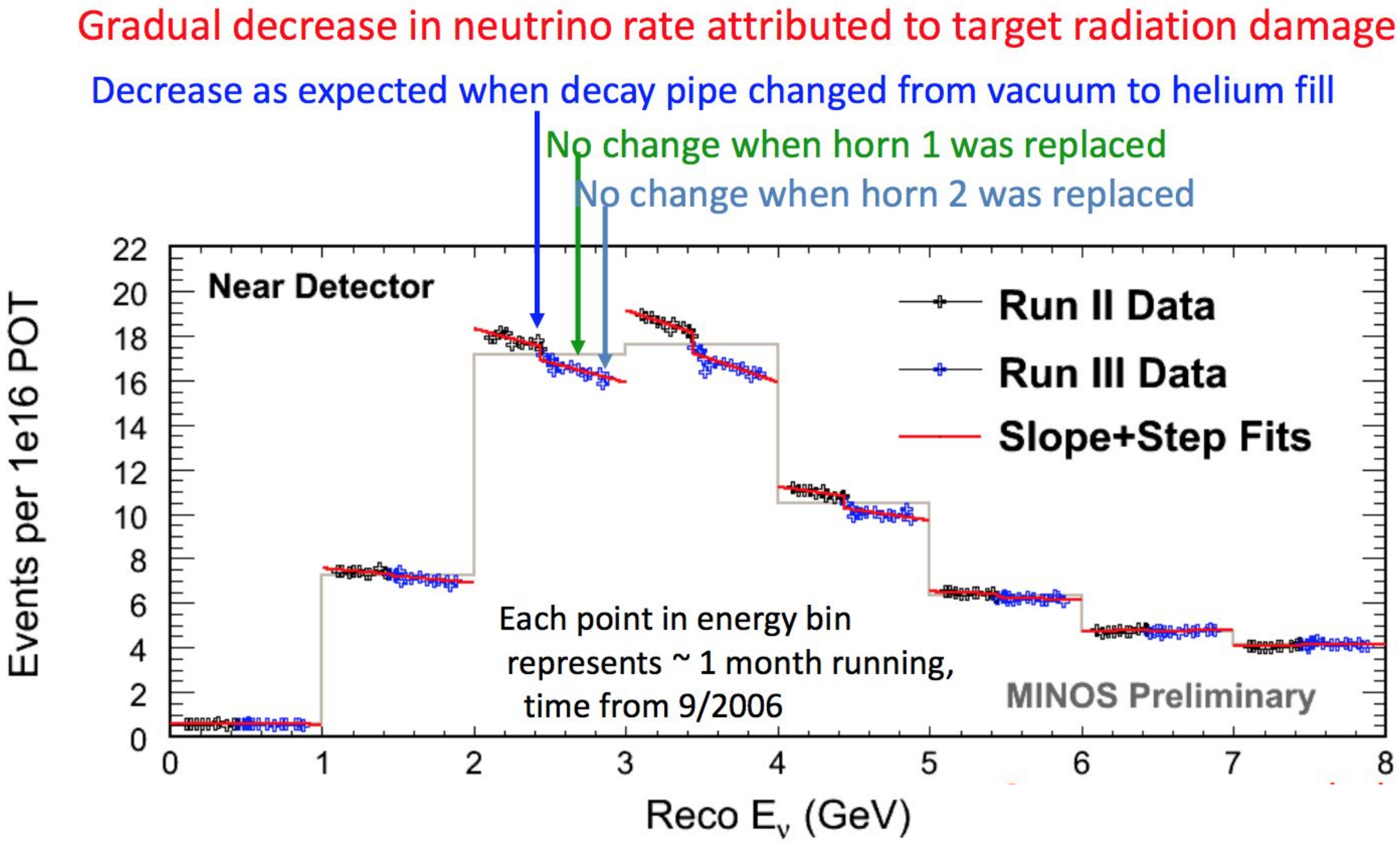
Impact of Alignment Parameters on DUNE Flux

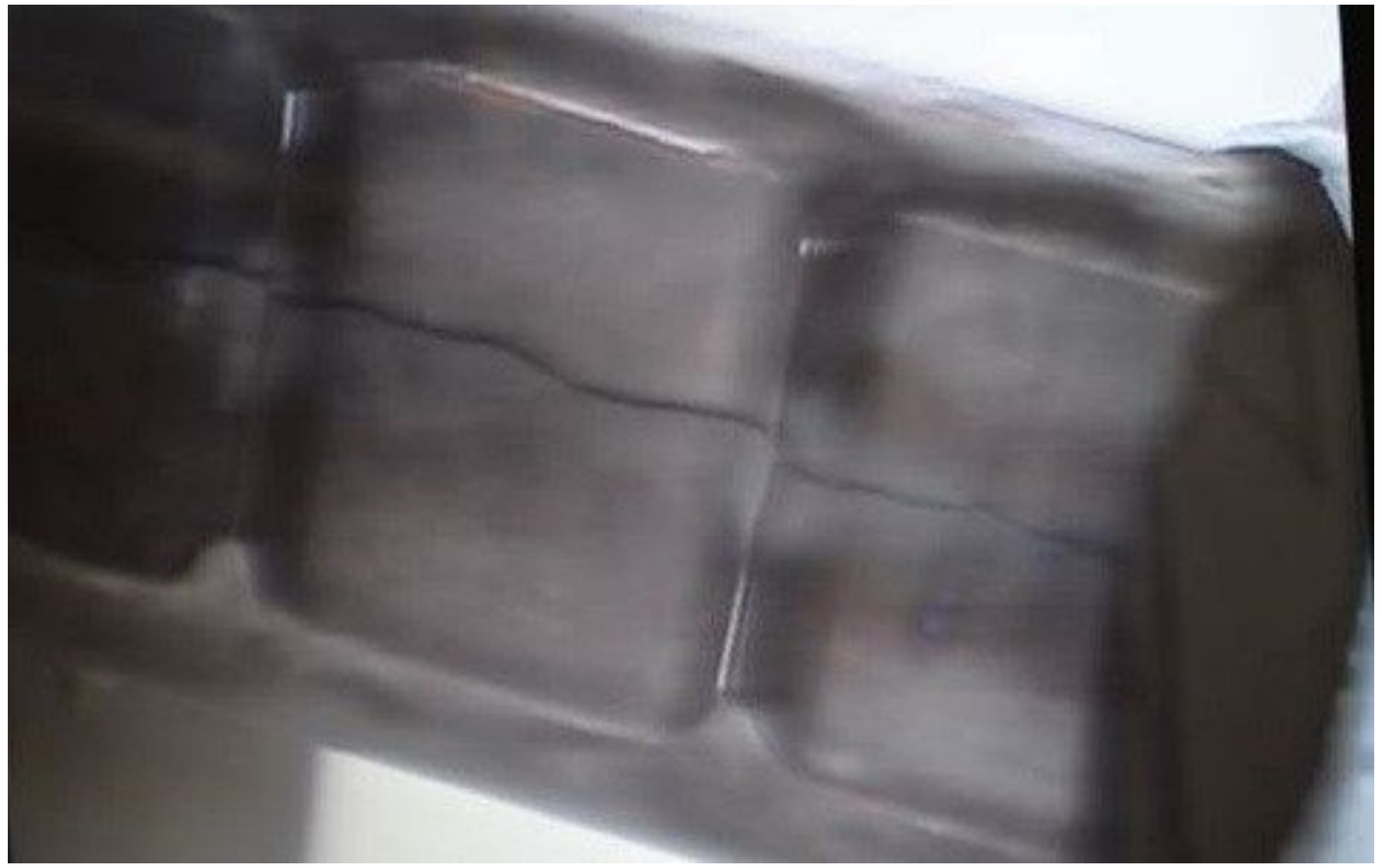
Effects on the flux are different, and often weaker, off-axis:

Plots from L. Pickering

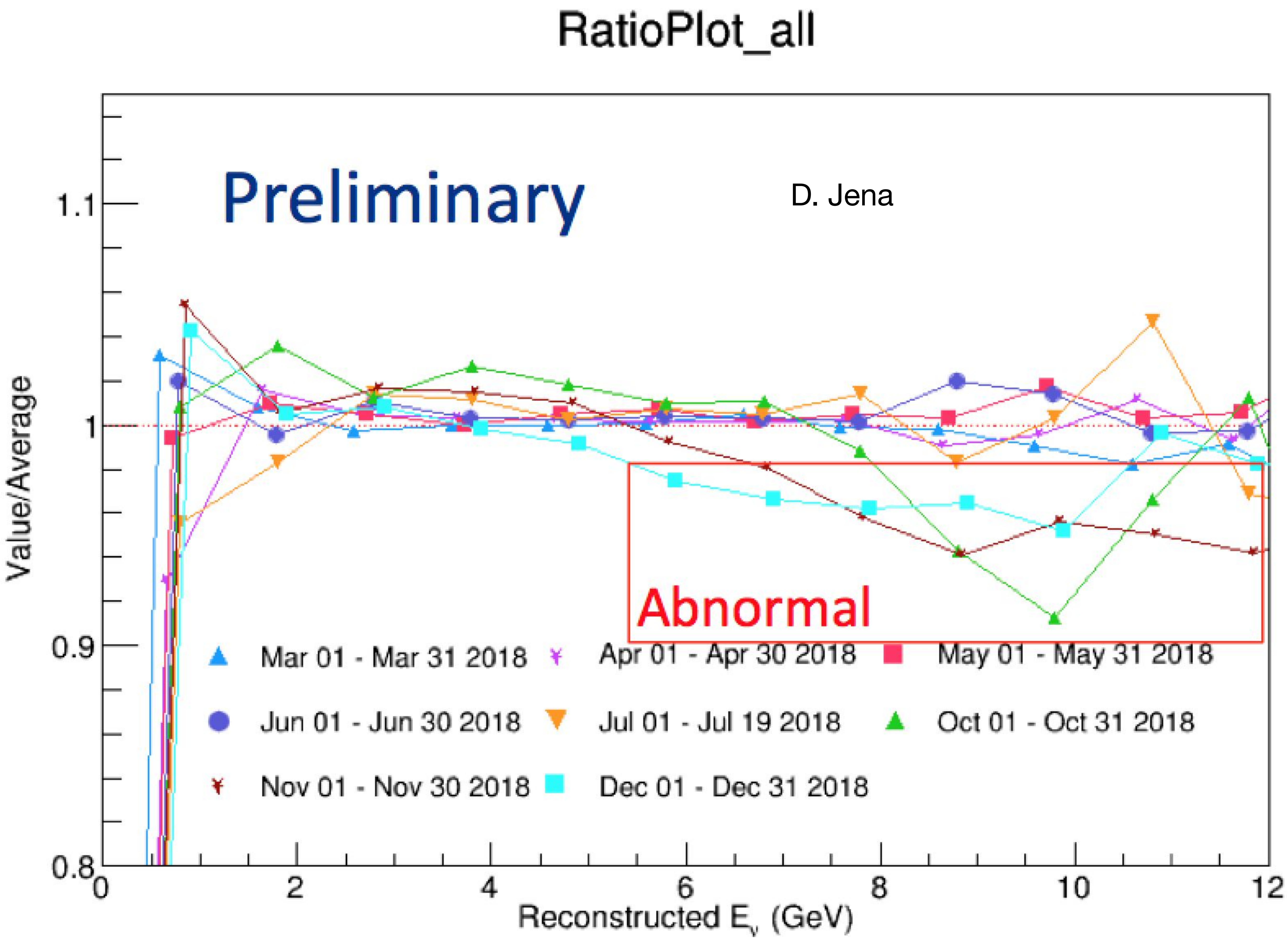
NuMI Experience: Target Degradation

An example from NuMI: degradation of target (NT02):



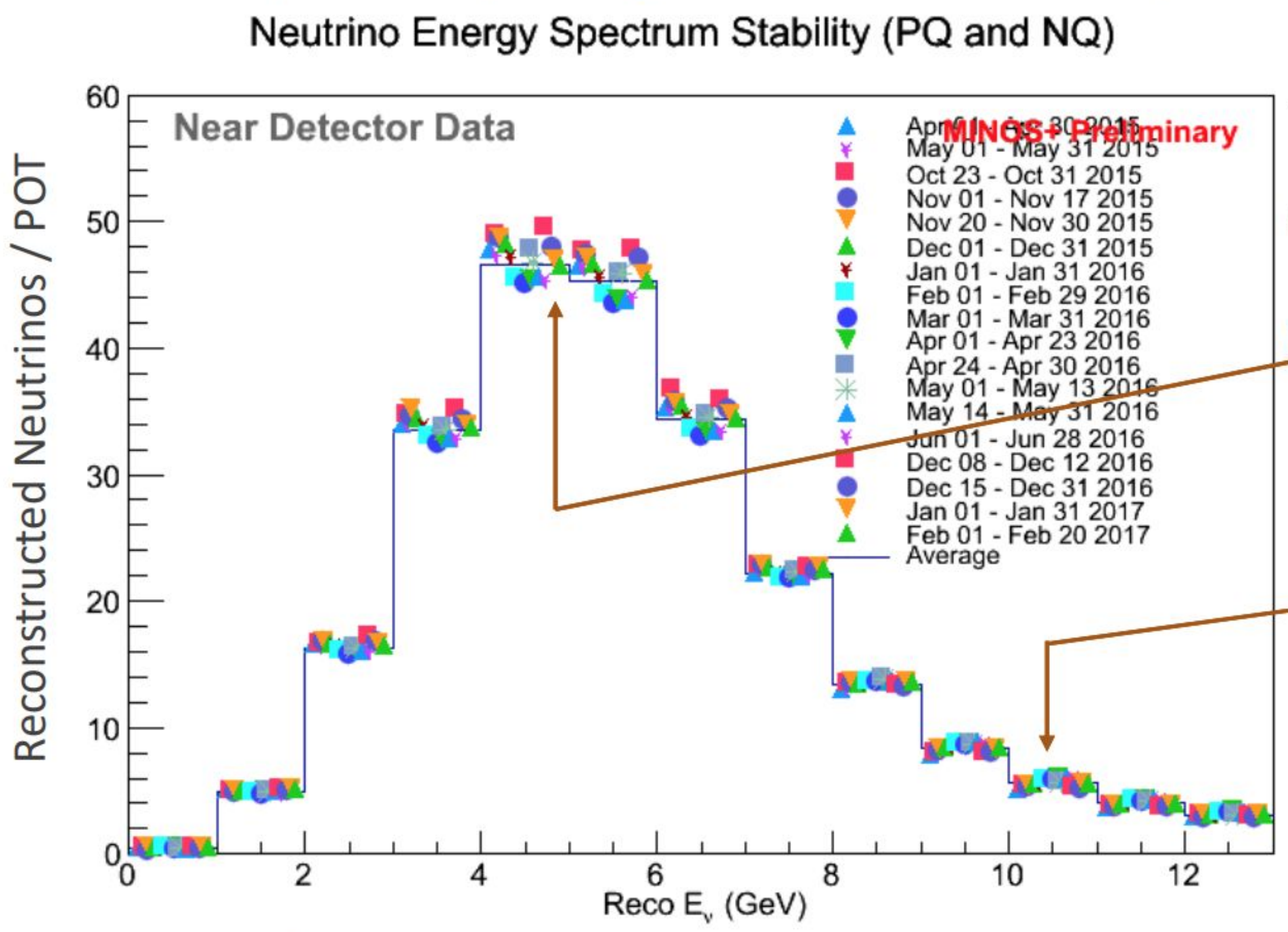


NuMI Experience: Beam Position on Target



- Change in neutrino energy spectrum in MINOS was seen in late 2018/early 2019
- Motivated beamline investigations that indicated that proton beam was shifted by 0.3-0.4 mm from center of target (close to NuMI/LBNF tolerance of 0.45)
- Whether this was the cause of the change is unknown because MINOS detector was turned off in spring of 2019

NuMI Experience: Horn Tilt



Time history in each 1 GeV neutrino energy bin
Apr. 2015 through Feb. 2017

Reconstructed Neutrinos/POT in ND going down again as beam power ramps up early '17.

But there had been unexplained bump in high energy tail in '16

J. Hylen

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NuMI Experience: Horn Tilt

A horn scan was performed that found a few mm tilt of the horn:

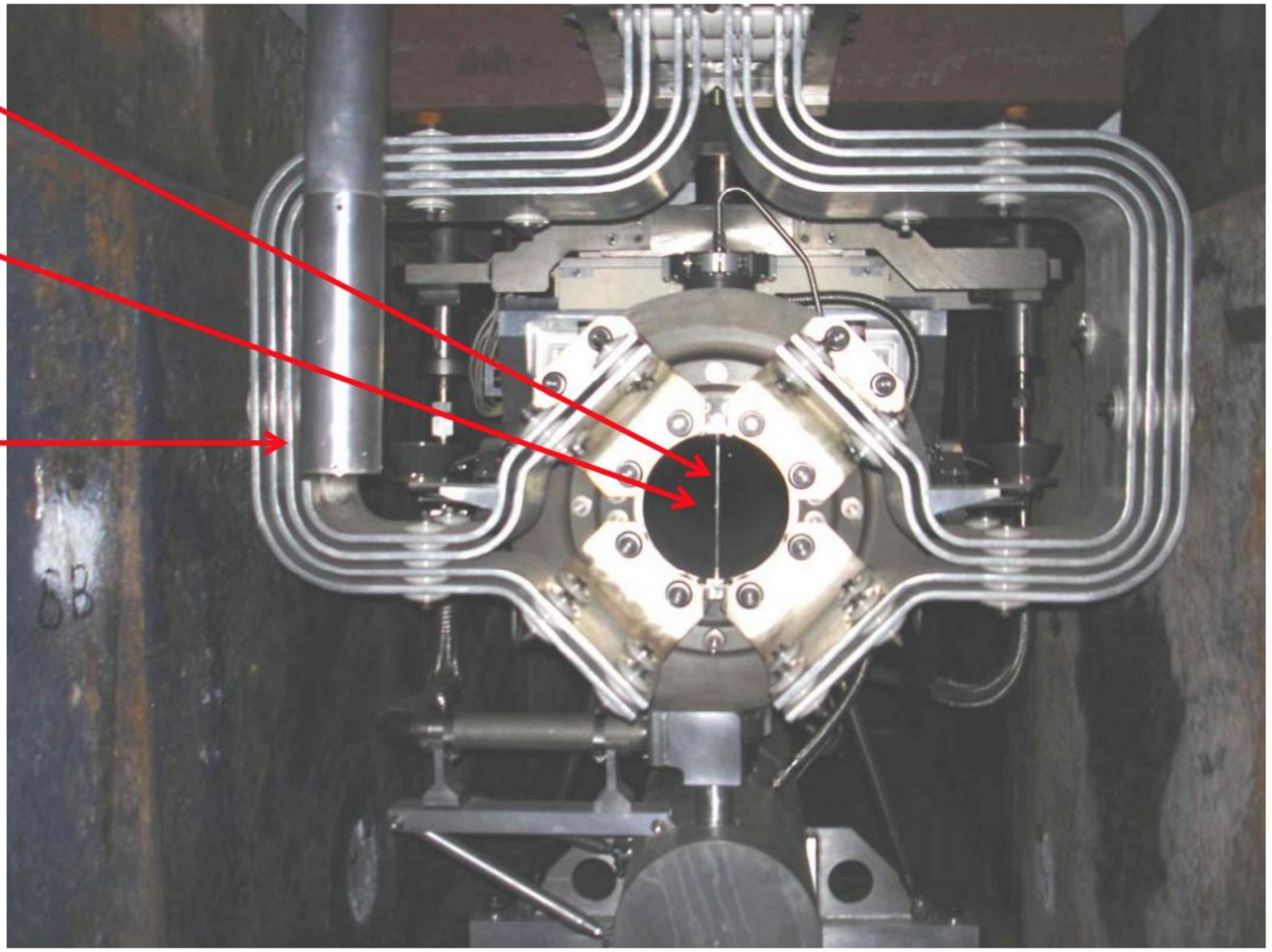
J. Hylen

Fin for beam horz. alignment

Nub for beam vert. align

Beam loss mon. to detect beam scatter from fin ("cross-hair"), also from beam to horn neck

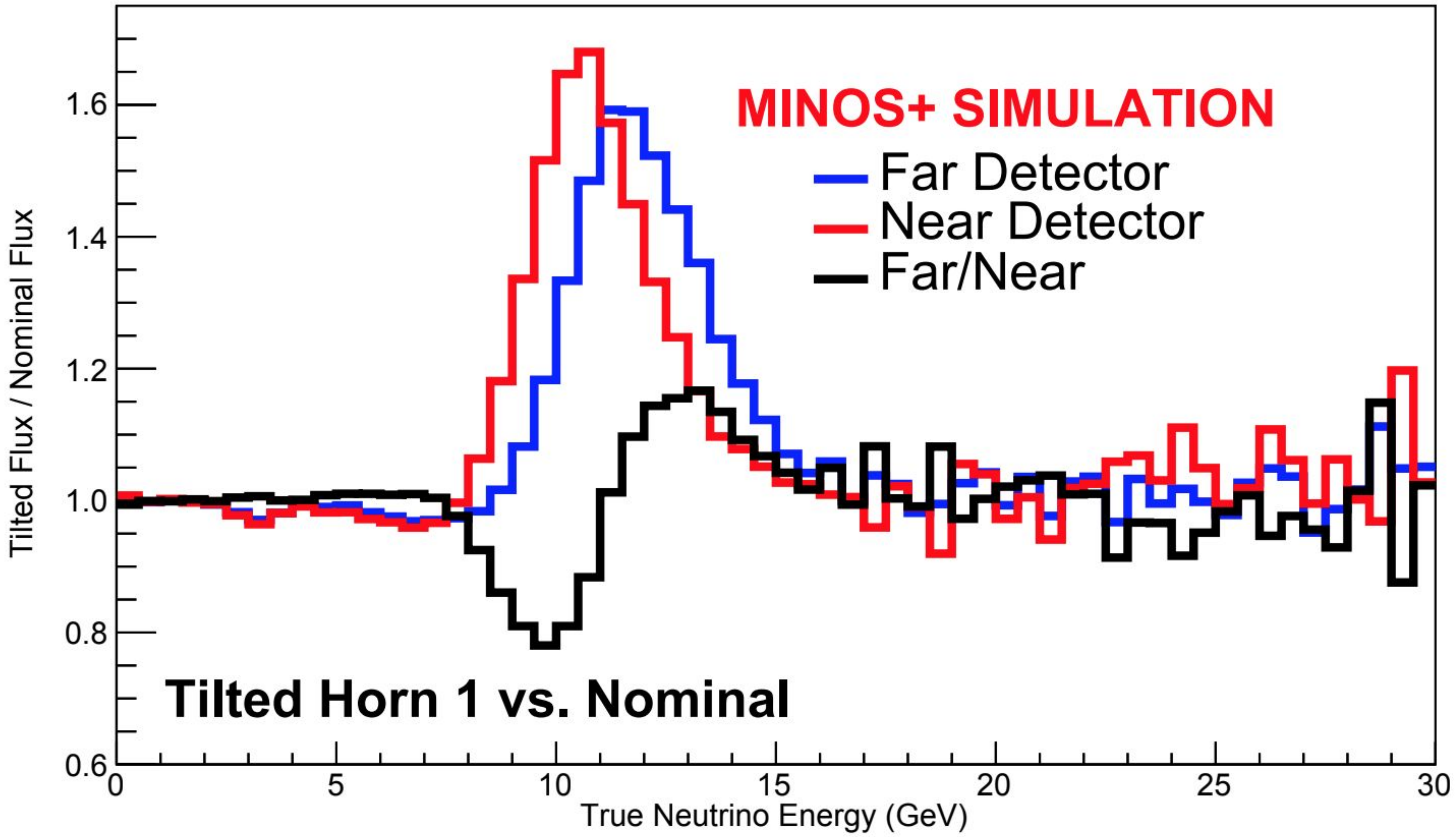
(Need target removed to allow beam scan of horn)

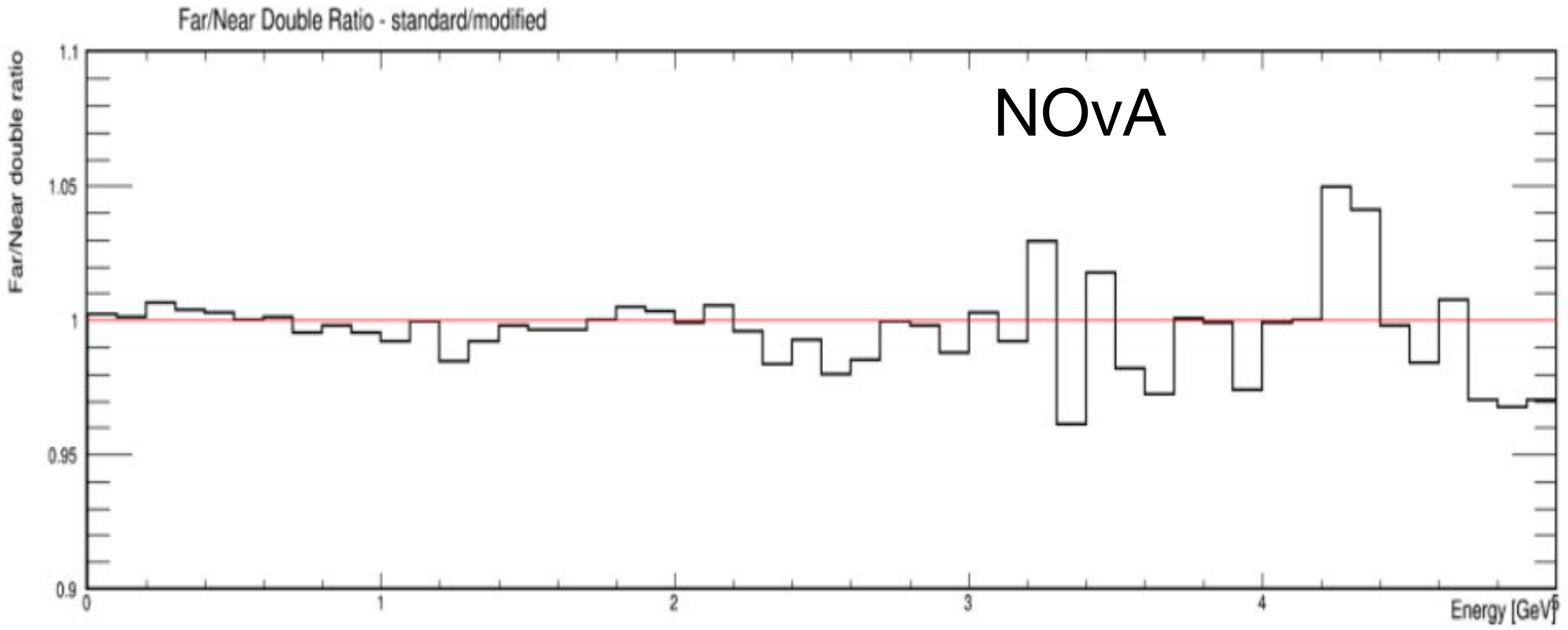


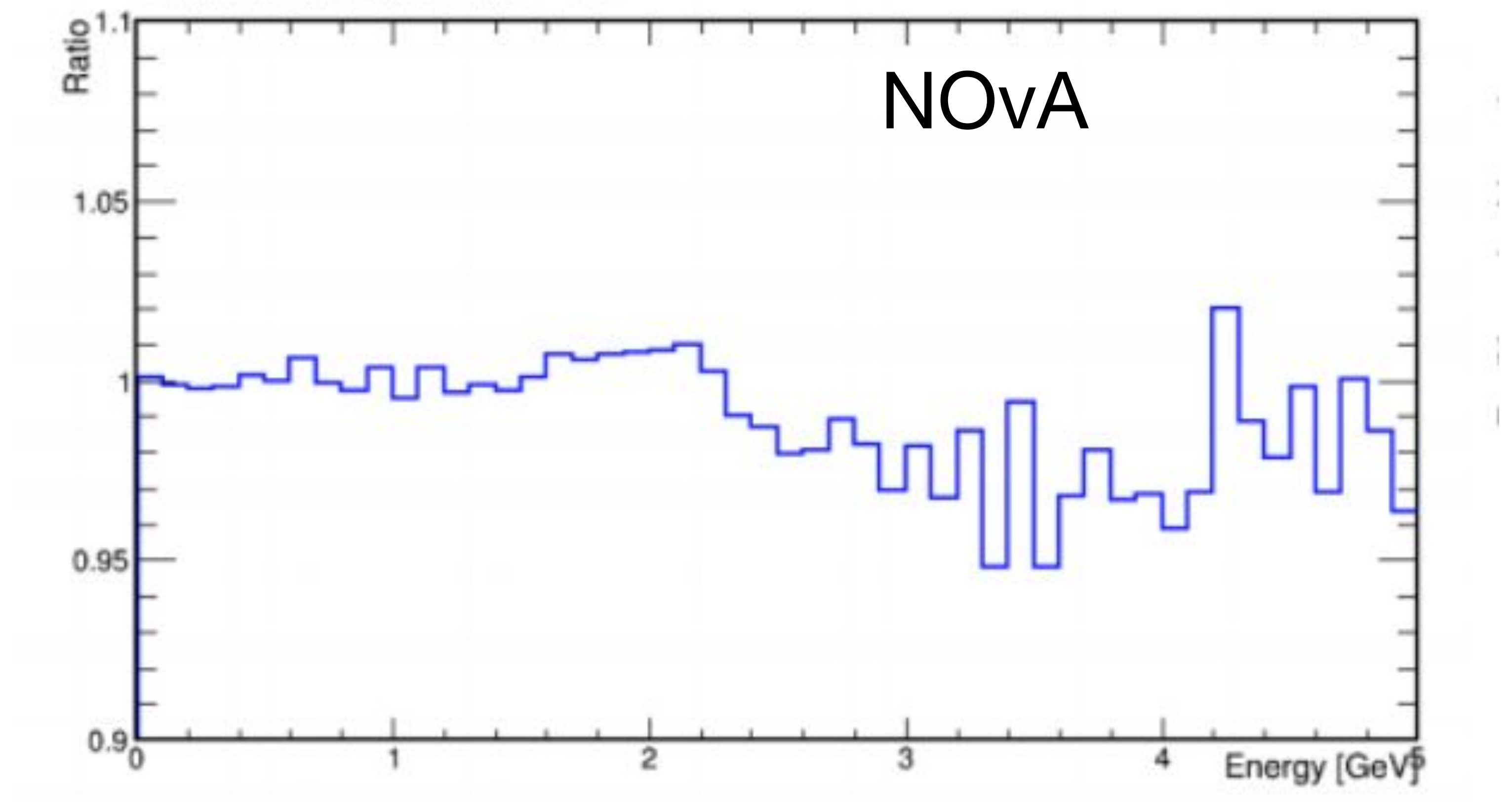
NuMI Experience: Horn Tilt

Effect of horn tilt on the flux, from the simulation:

Tom Carroll







Giulia Brunetti

Primary + Secondary Beam Monitoring at LBNF

After changes to the beamline (e.g. horn and target swaps), the horn, target, and baffle positions will first be measured by surveyors

Optimized Beam CDR

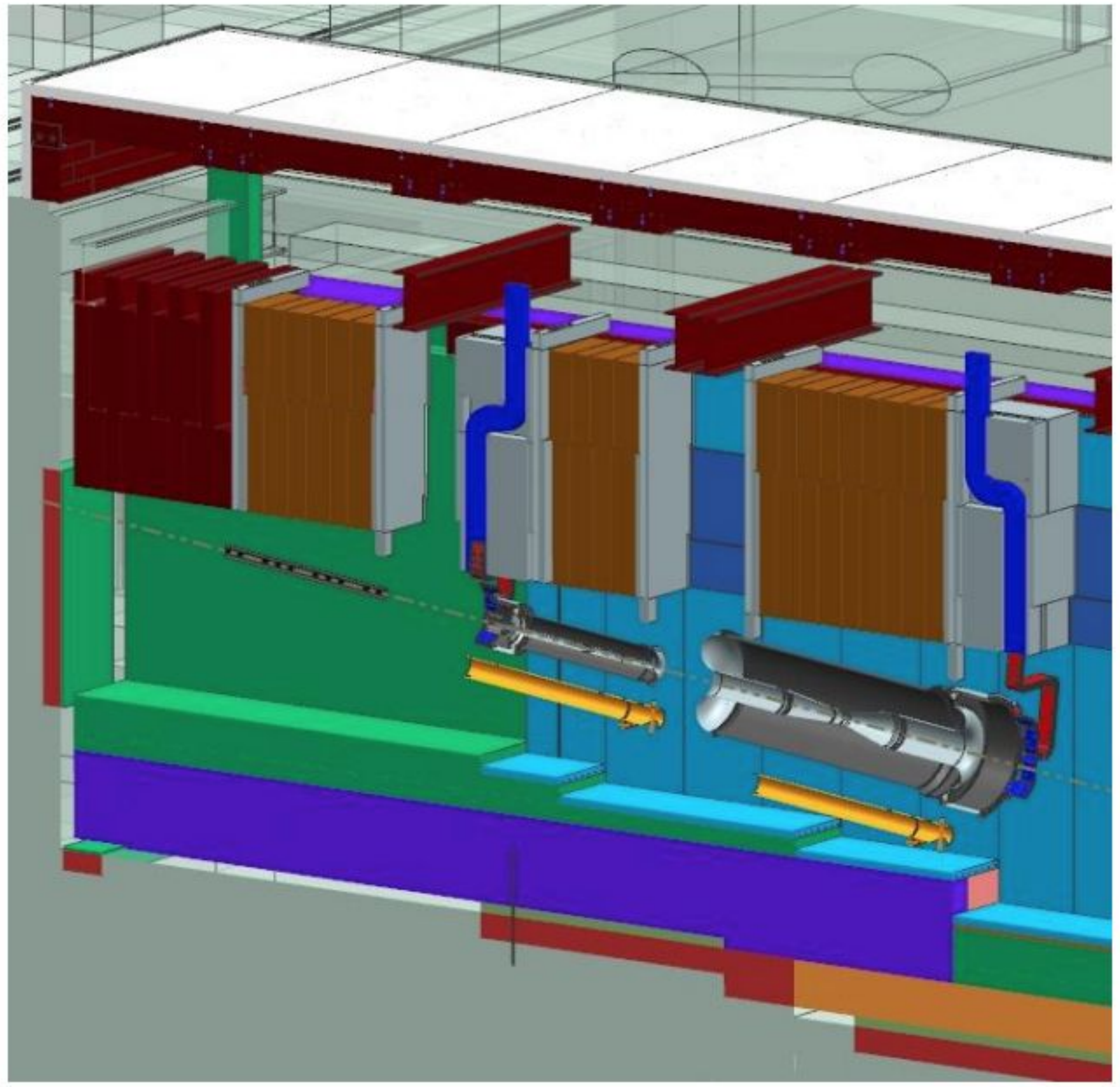


Figure 2-28: Baffle (left most beamline component) in the target chase under its shielding module. The baffle mounts to a carrier (space frame – not pictured).

- Survey measures position/angles of baffle, targets and horns to better than tolerances assumed in DUNE flux uncertainties (discussed later in this talk)
- But has to be performed prior to complete installation of shielding
- In NuMI, positions can shift after installation of shielding by ~ 0.75 mm (more than DUNE assumed tolerances)
- Post-survey position shift is expected to be significantly larger due to increased shielding weight

Primary + Secondary Beam Monitoring at LBNF

Positions after installation of shielding will be measured using “beam-based alignment”, wherein a low intensity beam is scanned across components:

Nucl.Instrum.Meth.A 568:548-560,2006

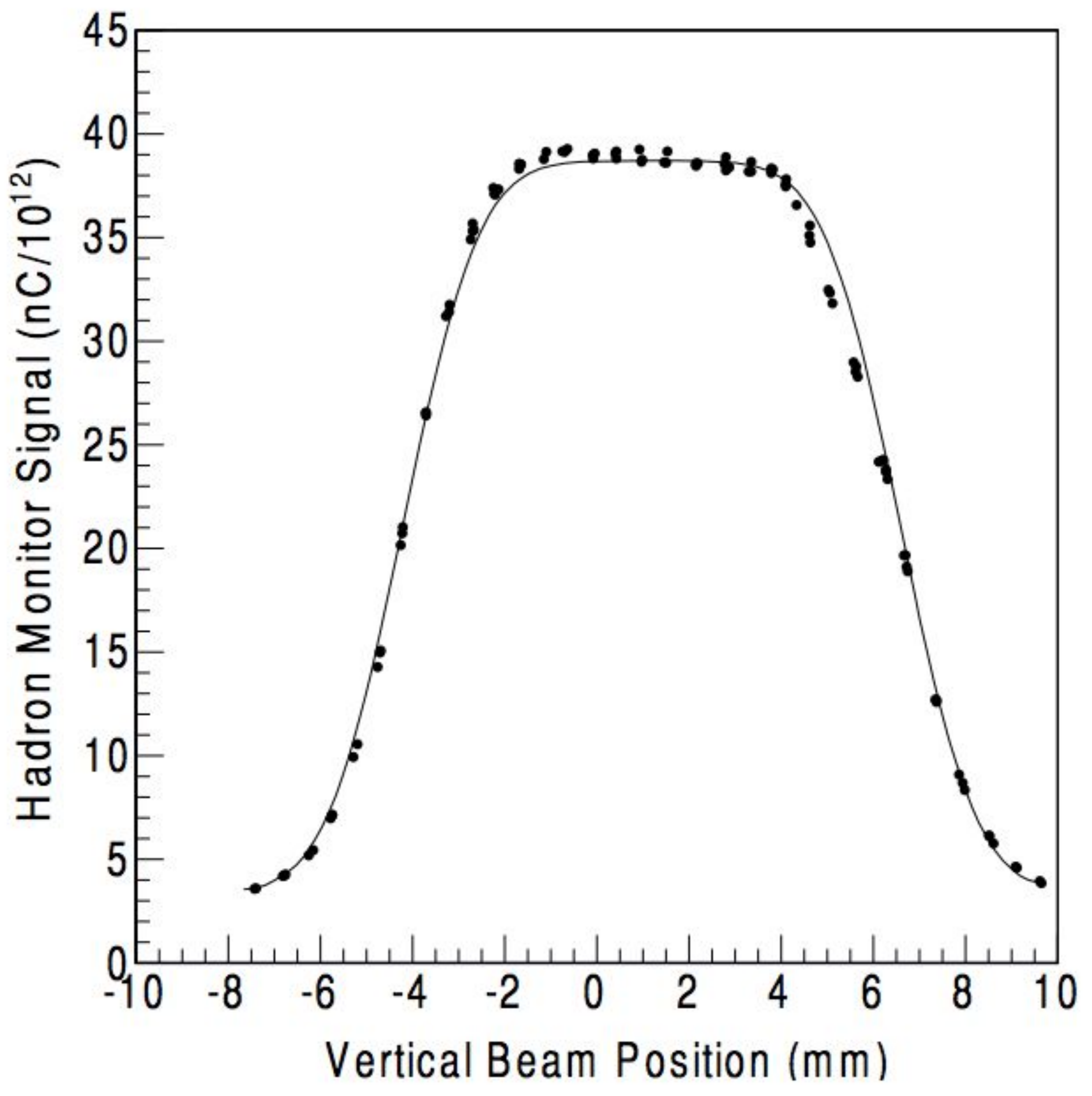


Figure 27: Vertical Scan of the Proton Beam Across the Target and Baffle. Plotted is the total amount of charge collected in the Hadron Monitor on March 5, 2005, normalized by proton beam intensity, as a function of proton beam position at the target. The edges on each side correspond to the edges of the baffle passage.

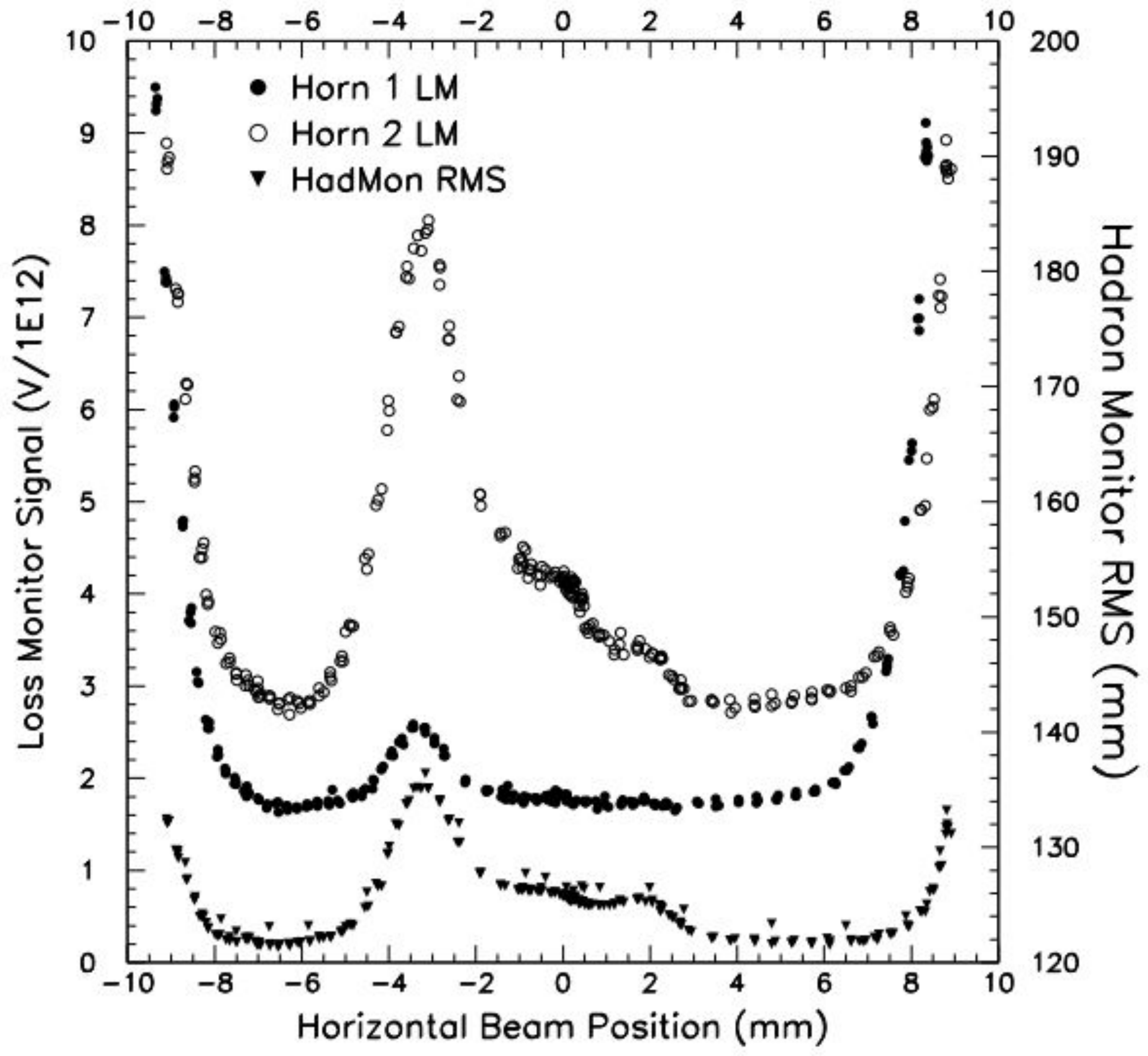


Fig. 14. Summary of measurements made to establish the horizontal positions and angles of the horns. Shown are the signals in the two loss monitors, one downstream of each horn, and the vertical RMS of the distribution in the Hadron Monitor about the centroid during a horizontal scan of the proton beam across the system.

Examples from NuMI

Beam based alignment will make use of horn crosshair loss monitors, hadron monitor and muon monitors

Horn loss monitors are used for cross-hair alignment scan and useless once target is installed; so not useful for monitoring during run

Primary + Secondary Beam Monitoring at LBNF

More on Hadron Monitor:

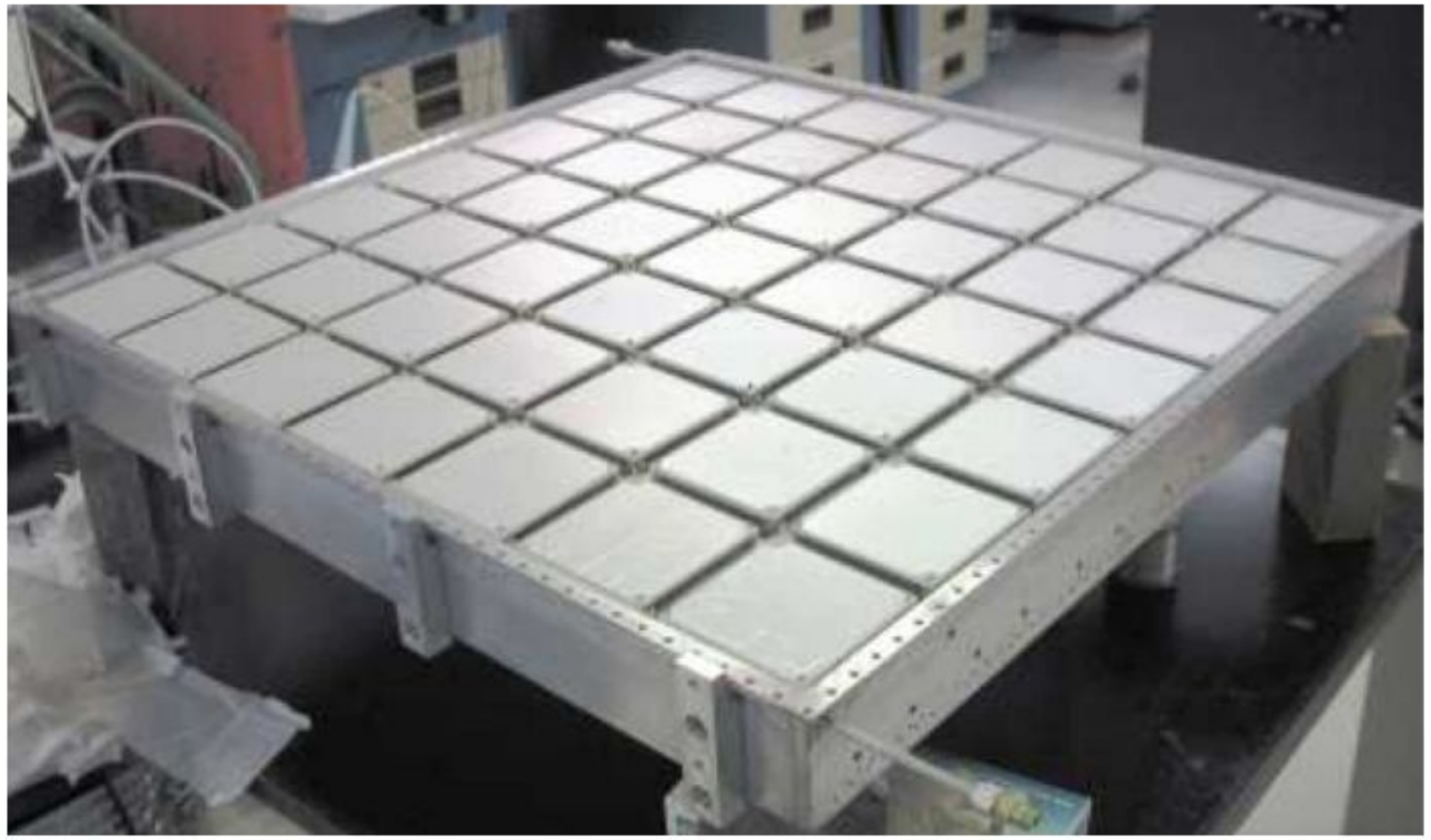


Figure 23: Photograph of the Hadron Monitor Ionization Chamber Array during Assembly. The array has 49 chambers and has a total area of approximately 1 m × 1 m. The hadron monitor chamber array uses helium as the ionization medium.

- NuMI hadron monitor is a 7x7 array of inization chambers, just upstream of the hadron absorber
- Nominal design for LBNF is similar to NuMI, but due to higher radiation environment, could use low pressure Argon instead of Helium and be removed from the beam during high intensity running
- Alternate SEM (Secondary Emission Monitor) design could potentially stay in the beam during high intensity running, but progress towards full design has been slow

Primary + Secondary Beam Monitoring at LBNF

More on Muon monitors:

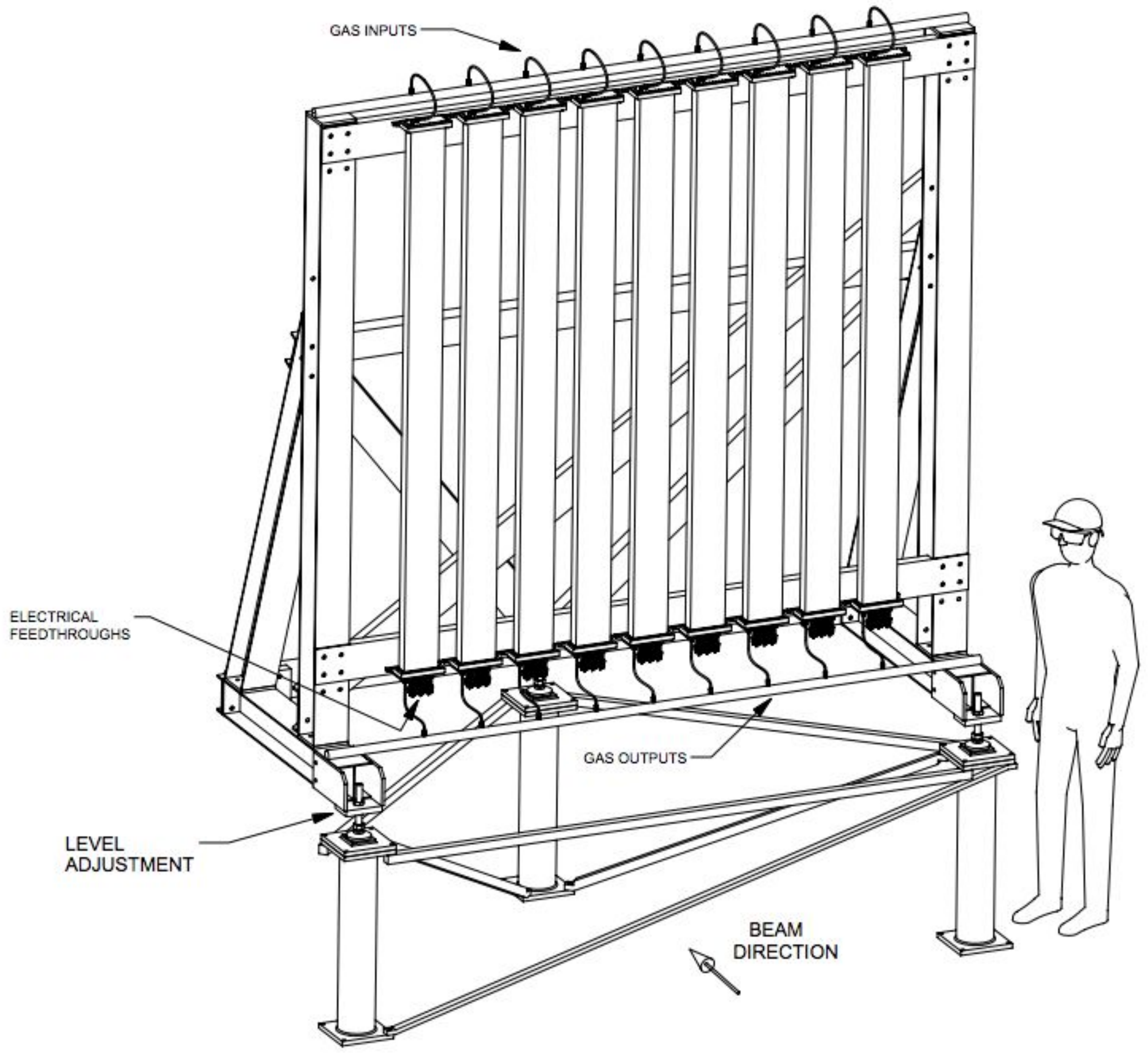
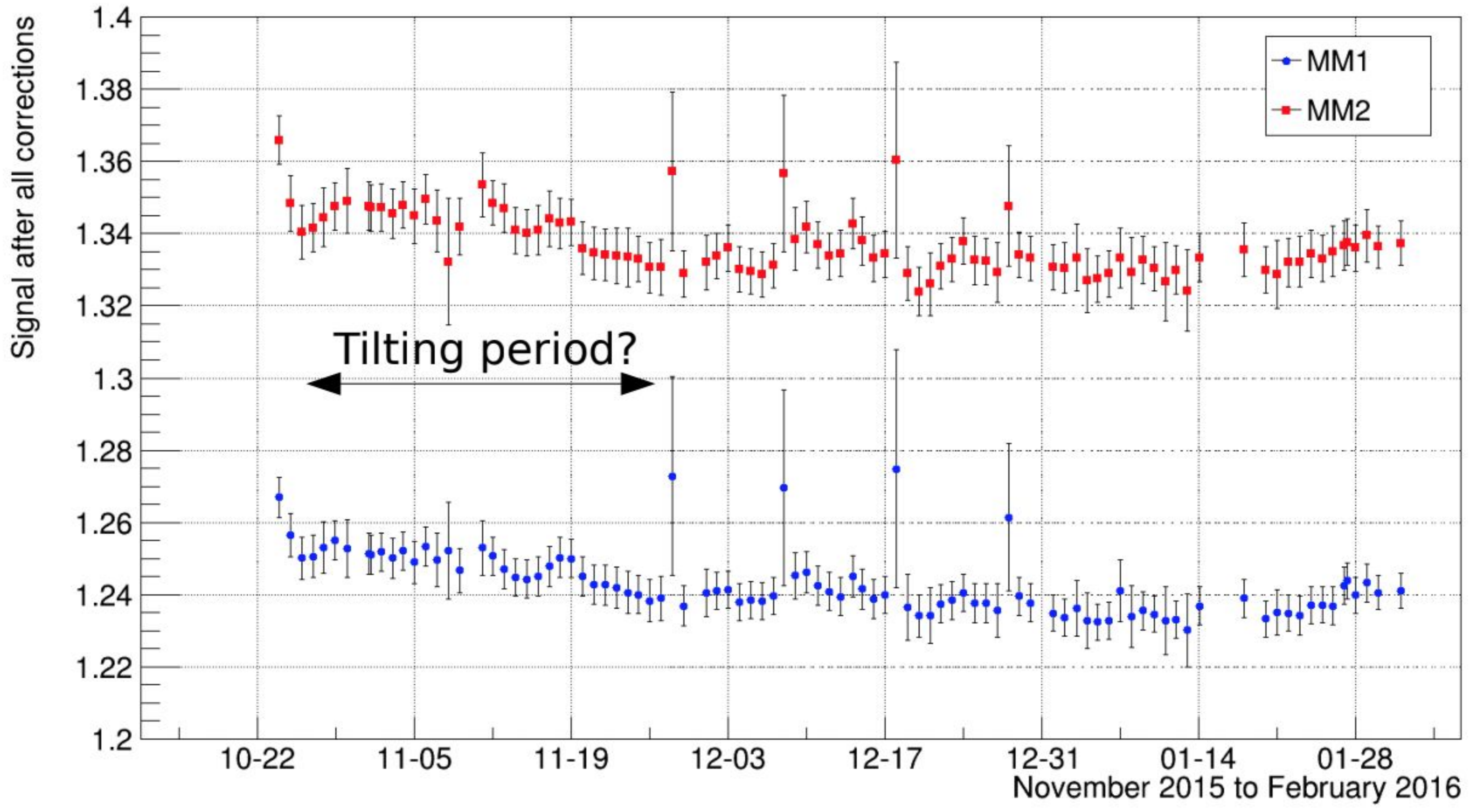


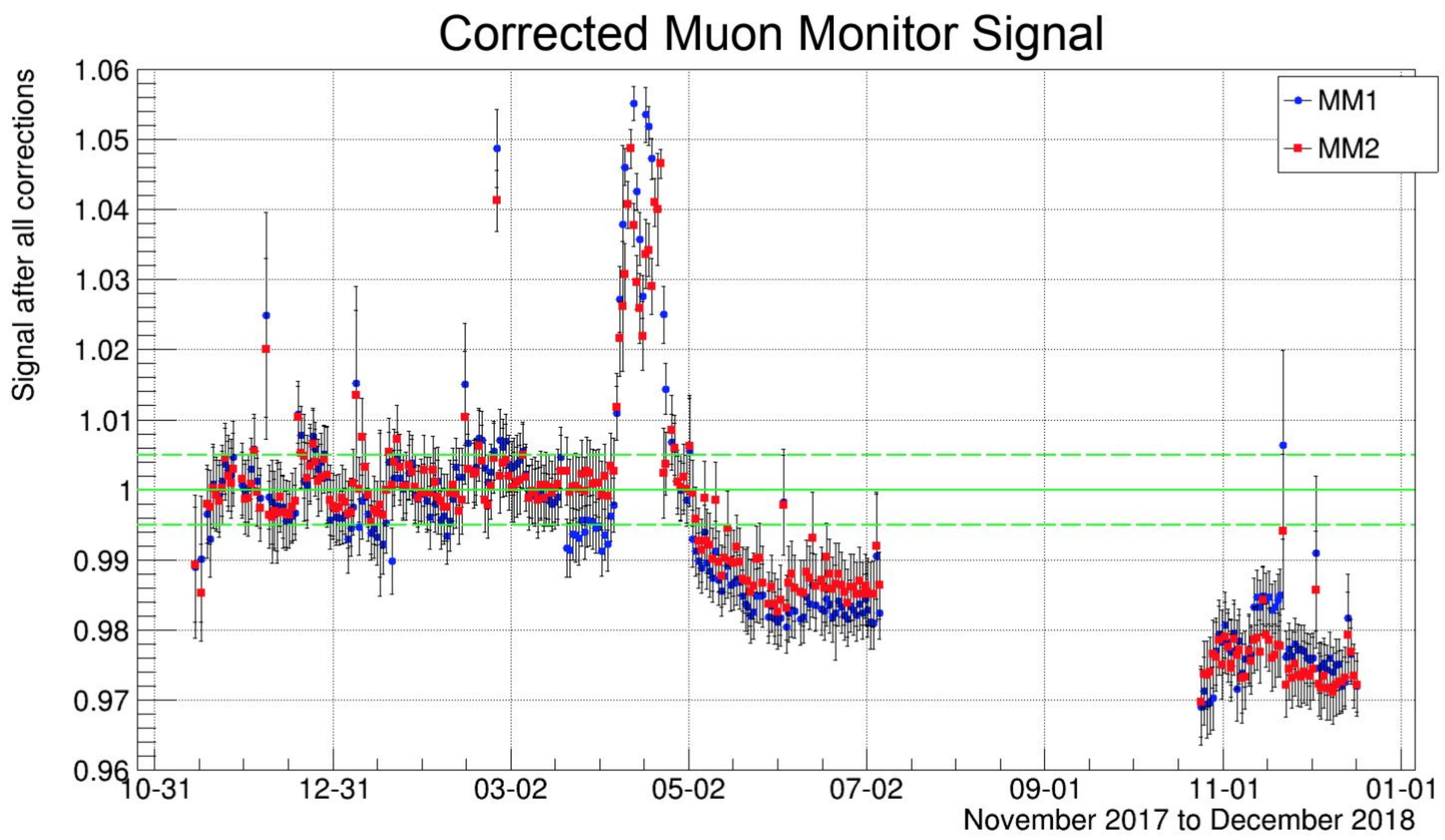
Figure 24: Schematic Drawing of a NuMI Beam Muon Monitor. The mounting of the nine tubes which contain the nine ionization chambers is shown to illustrate the construction and size of the muon monitors.

- NuMI muon monitors are three arrays of ionization chambers separated by rock, and suffer from a number of deficiencies (e.g. instabilities in gas system)
- LBNF muon monitoring system will likely be different than NuMI, but design is not yet fixed.
- Goal is 1% stability in detector response
- Low energy muons are lost in the absorber -> alignment effects that change the neutrino energy spectrum below ~2.5 GeV will not be seen in muon monitors.
- Muon monitor effort (and beam monitoring in general) has a strong need for new collaborators to work on both hardware and simulations

Primary + Secondary Beam Monitoring at LBNF

Muon monitors can also monitor stability of the beam, although this has proven challenging with the NuMI muon monitors:





Plots from T. Rehak

Primary + Secondary Beam Monitoring at LBNF

More notes on beam-based alignment at LBNF

- Alignment at LBNF will in general be more difficult than at NuMI
  - Three horns instead of two
  - At NuMI, the first horn is aligned without the target installed. At LBNF, Horn A cannot be directly beam aligned, but will only pick up alignment from being attached to the target, which will be beam aligned
  - Horn A will have to be removed to align horns B and C (and will therefore be done rarely)
  - The target scan will have to go out to larger radii than in NuMI
  - NuMI was built on very stable bedrock, but LBNF is not -- it will be on an artificial hill made of topsoil w/ concrete pillars to bedrock

Primary + Secondary Beam Monitoring at LBNF

Primary beam monitors

- Toroids will measure the number of protons on target
  - Assumption for flux uncertainty is that this measurement will be accurate to 2%
  - My understanding is that 2% is pretty conservative
- Beam position monitors will measure primary beam trajectory
- Profile monitors will measure beam spot size
- A TVPT/THPT (“Hylen Device”) will measure the position of the beam on the target
- All of these will monitor the beam during high intensity operation

Primary + Secondary Beam Monitoring at LBNF

Additional Instrumentation

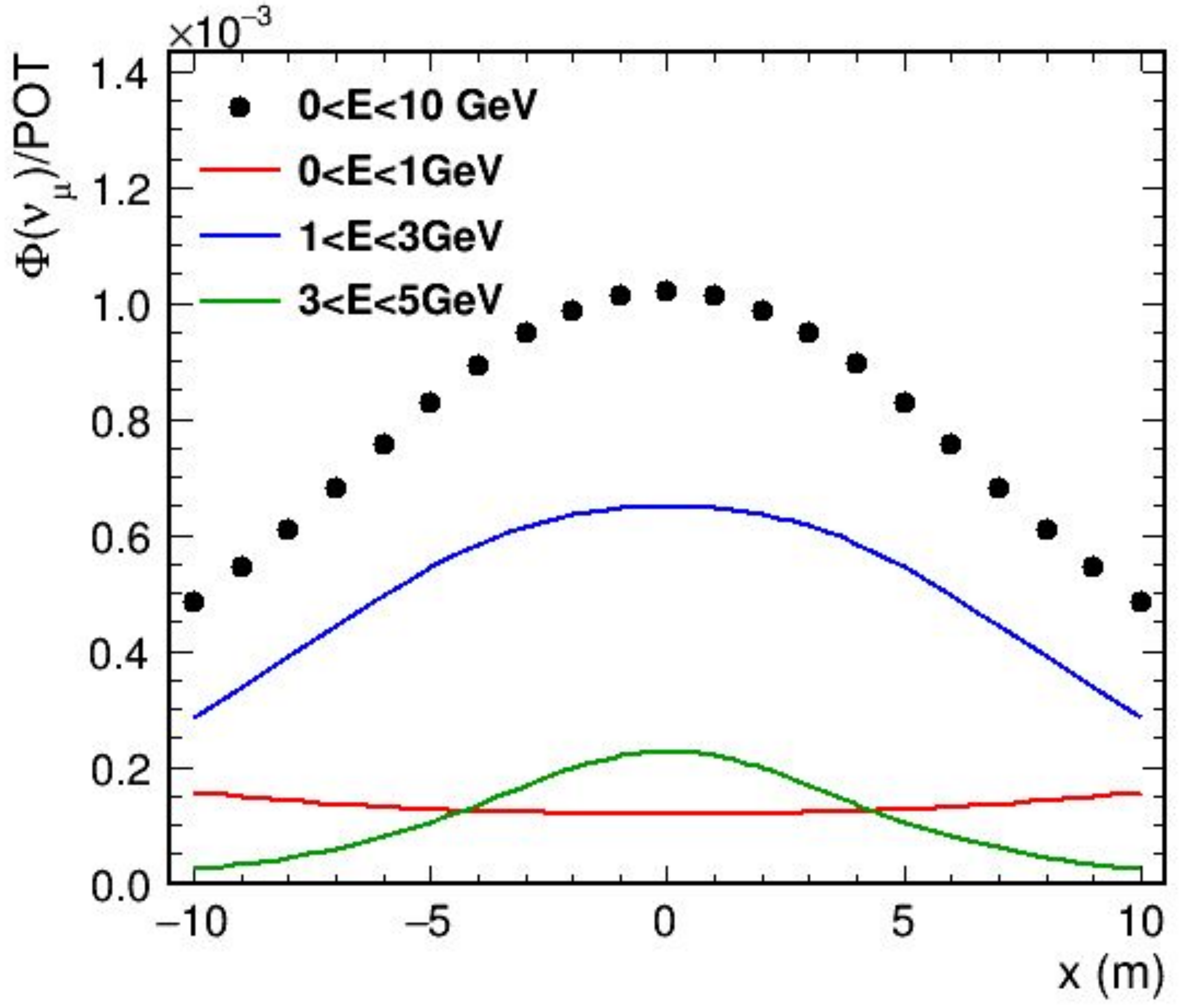
- A current monitor at the horn power supply
- Thermocouples for hardware protection
- Jim Hylen is also considering adding LDVT's and water monitors to watch for sags of horn supports, but these are not yet part of the project

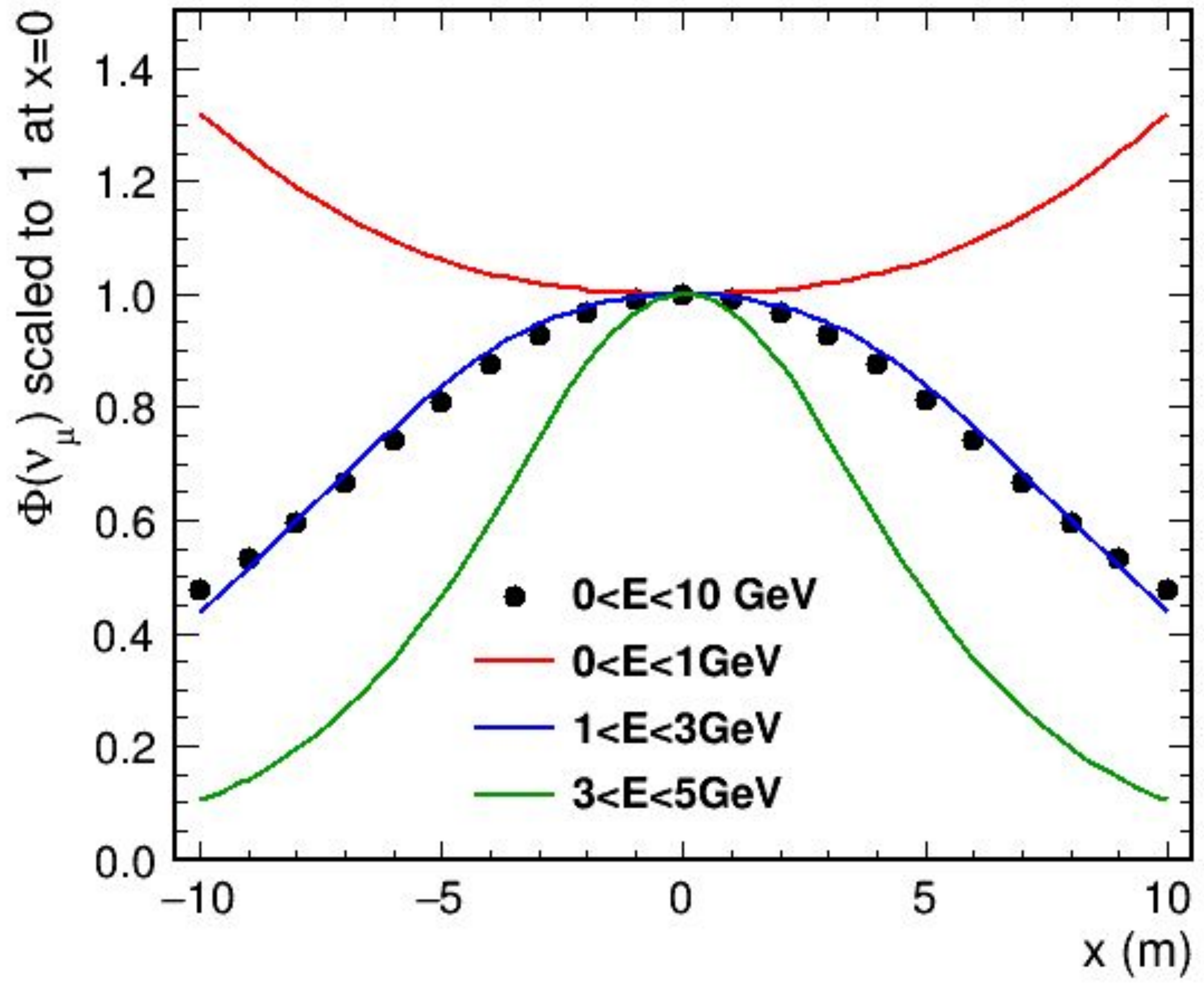
Needs from the Near Detector

- Distortions in the neutrino beam spectrum are likely be the only way we'll be able to see certain catastrophic changes to the beamline
  - Target degradation
  - Shifts of horn/target positions after beam-based alignment
- Measurements of the on-axis spectrum are also a valuable cross check of other alignment problems that will be monitored during the run
  - E.g. Proton beam direction/size/position and horn currents
- Muon monitors may be able to see some of these, but their capabilities are still unclear
- We (the BIWG leaders) consider it essential that we have an on-axis near detector that will be able to observe alignment parameters out of tolerance on ~a week scale
  - This could be by moving DUNEPrism on-axis regularly, but a dedicated on-axis measurement is clearly preferable
- Regular measurements of the neutrino beam size and centroid are also valuable
  - Some requirements were quoted in the CDR
  - We are not sure where these came from; modern studies are needed

Beam Profile

Plots from Zarko showing the size of the beam at the near detector:





Next Steps

- Studies showing what the 3DST can (and can't) detect on ~a week timescale need to be finished and clearly documented
- Need to understand frequency that DUNEPrism would need to return to on-axis position in order to effectively monitor the beam and ask whether that is actually realistic
- LBL group has asked for a shifted flux to understand impact of out-of-tolerance but realistic alignment problems on DUNEPrism analysis
  - The main thing preventing this is an agreement on what the shift should be
  - I suggest a few sigma horn current + a Horn A transverse position shift