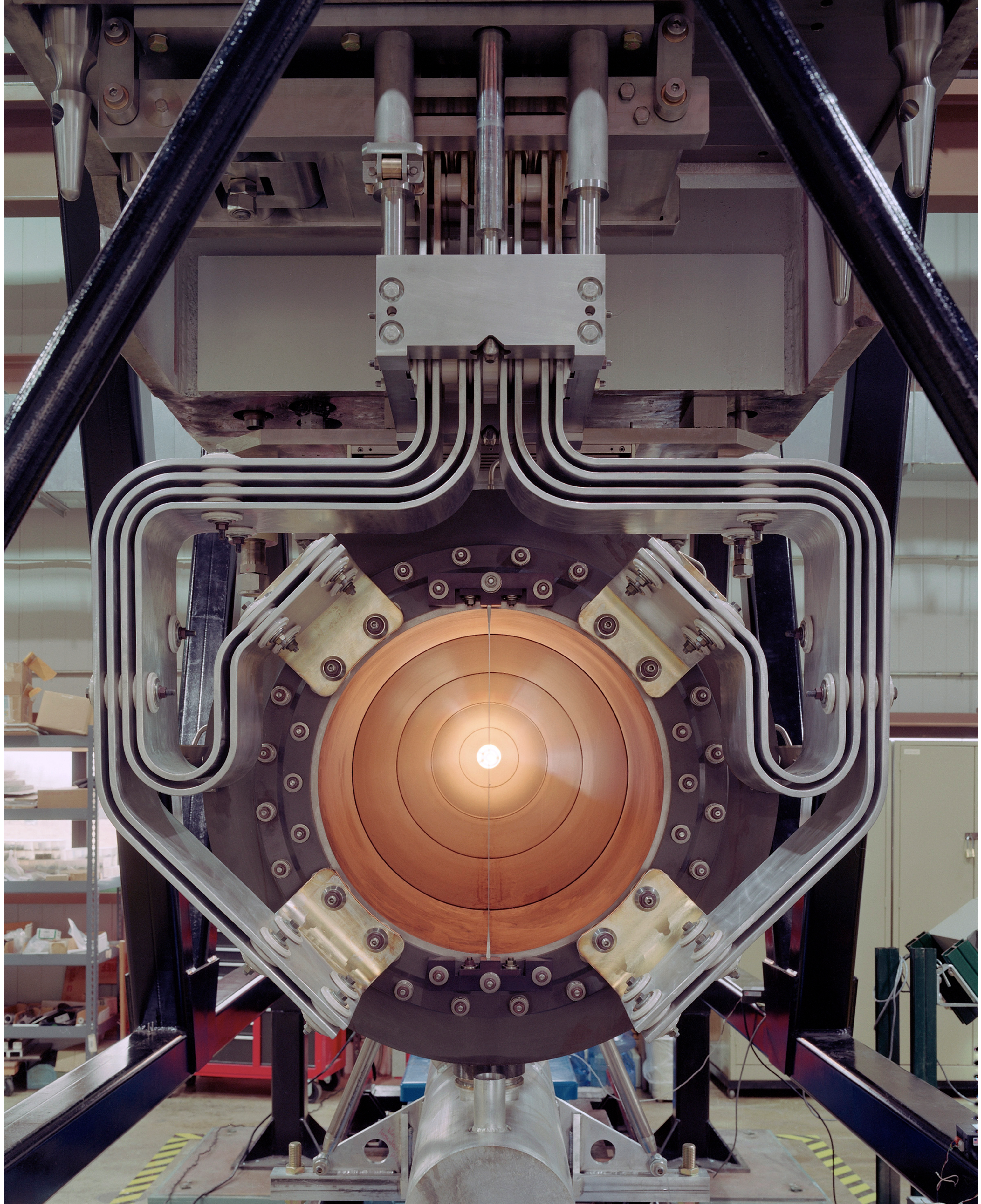
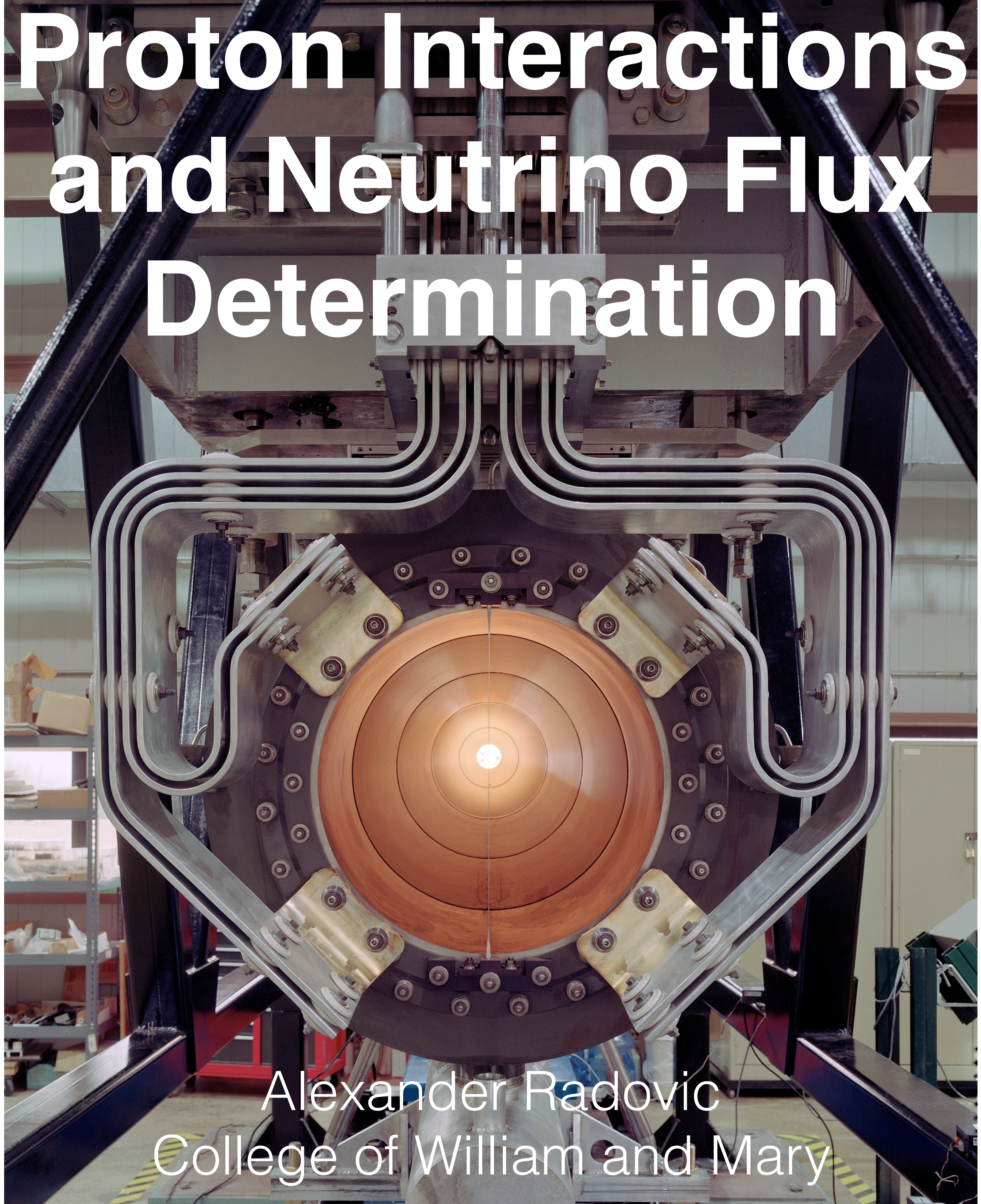


Proton Interactions and Neutrino Flux Determination



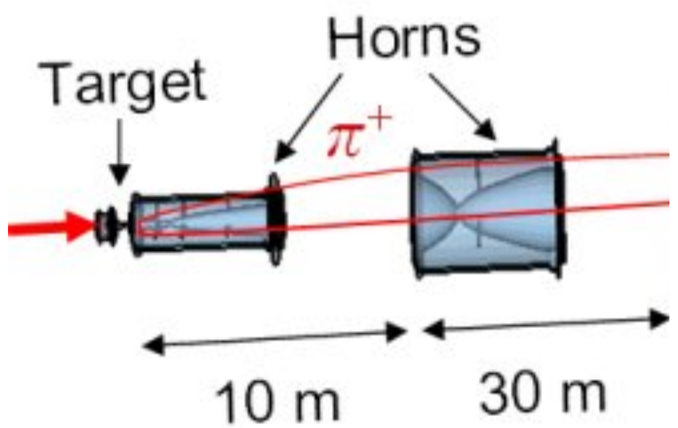
Alexander Radovic
College of William and Mary

Wideband Beams

QCD: Protons impinge on a target (carbon, beryllium etc.) to produce pions and kaons.

EM: Magnetic focusing “horns” produce magnetic fields that focus those pions and kaons into a decay pipe, where they decay to produce a neutrino beam.

Wideband Beams



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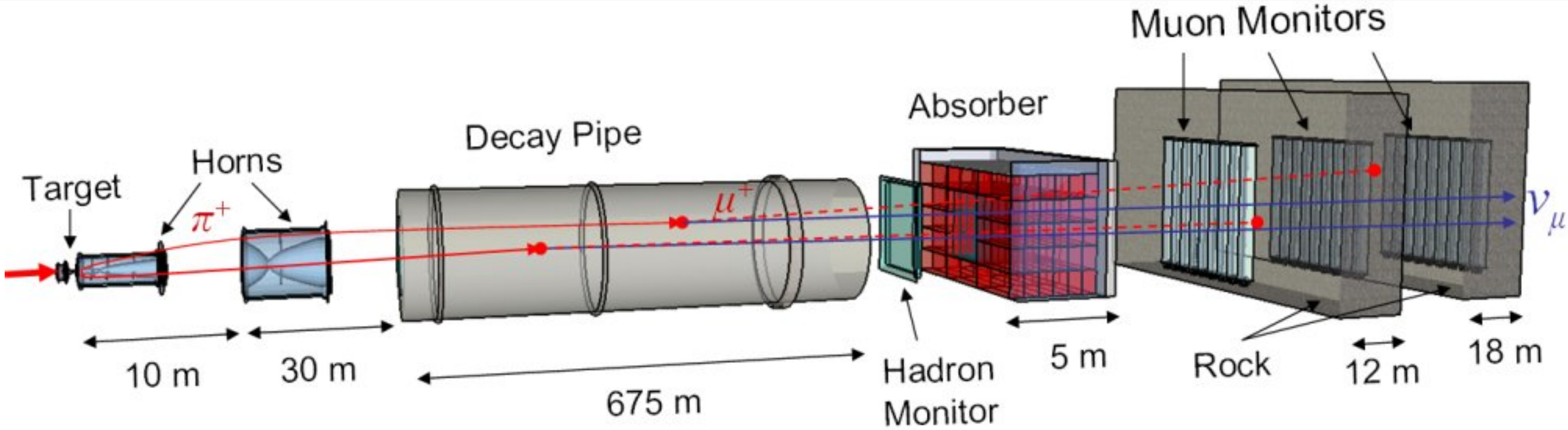

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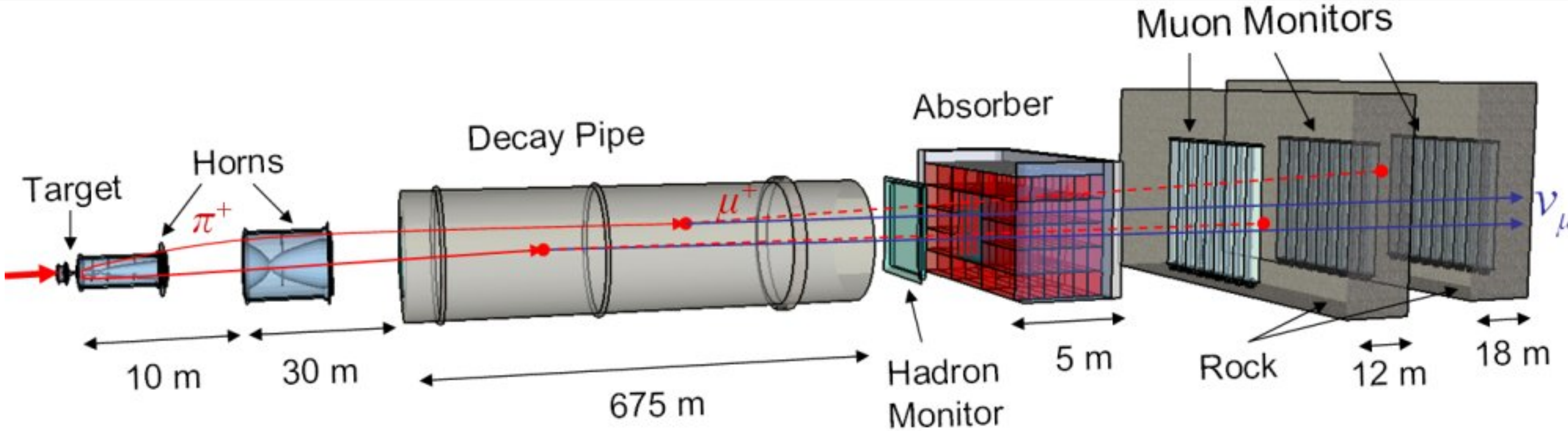
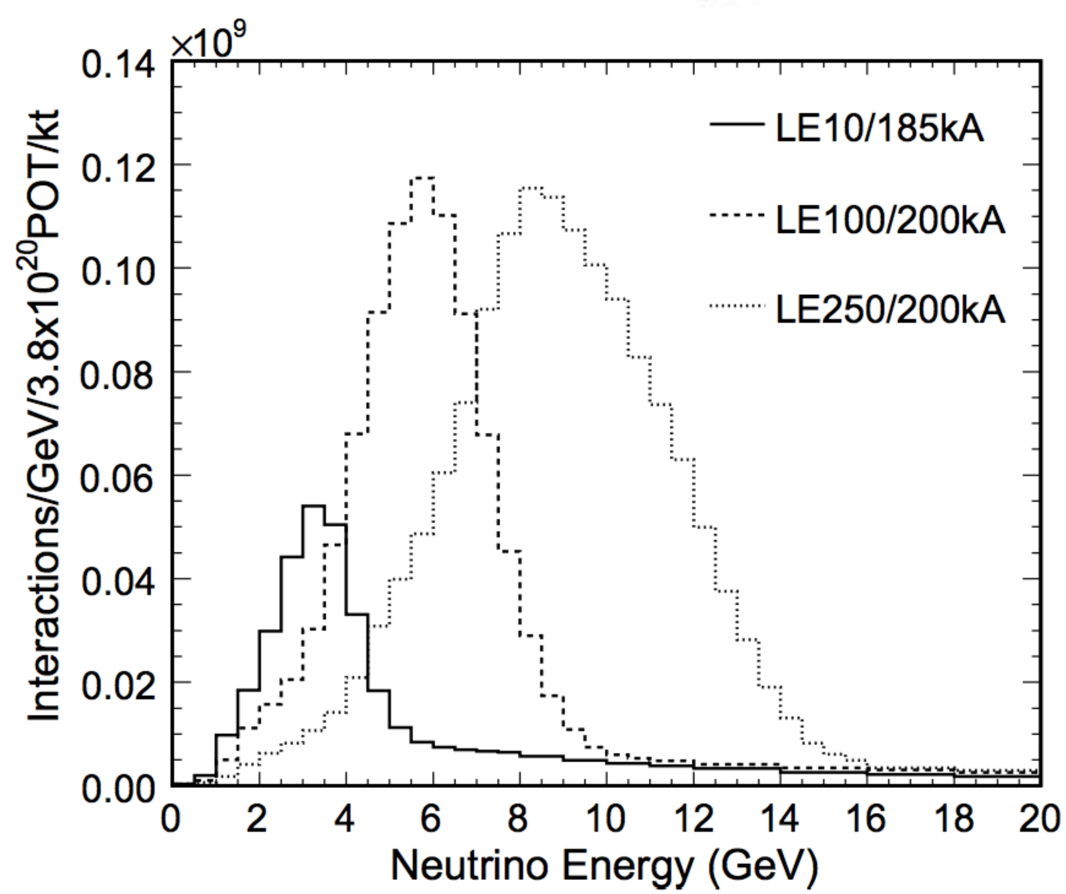
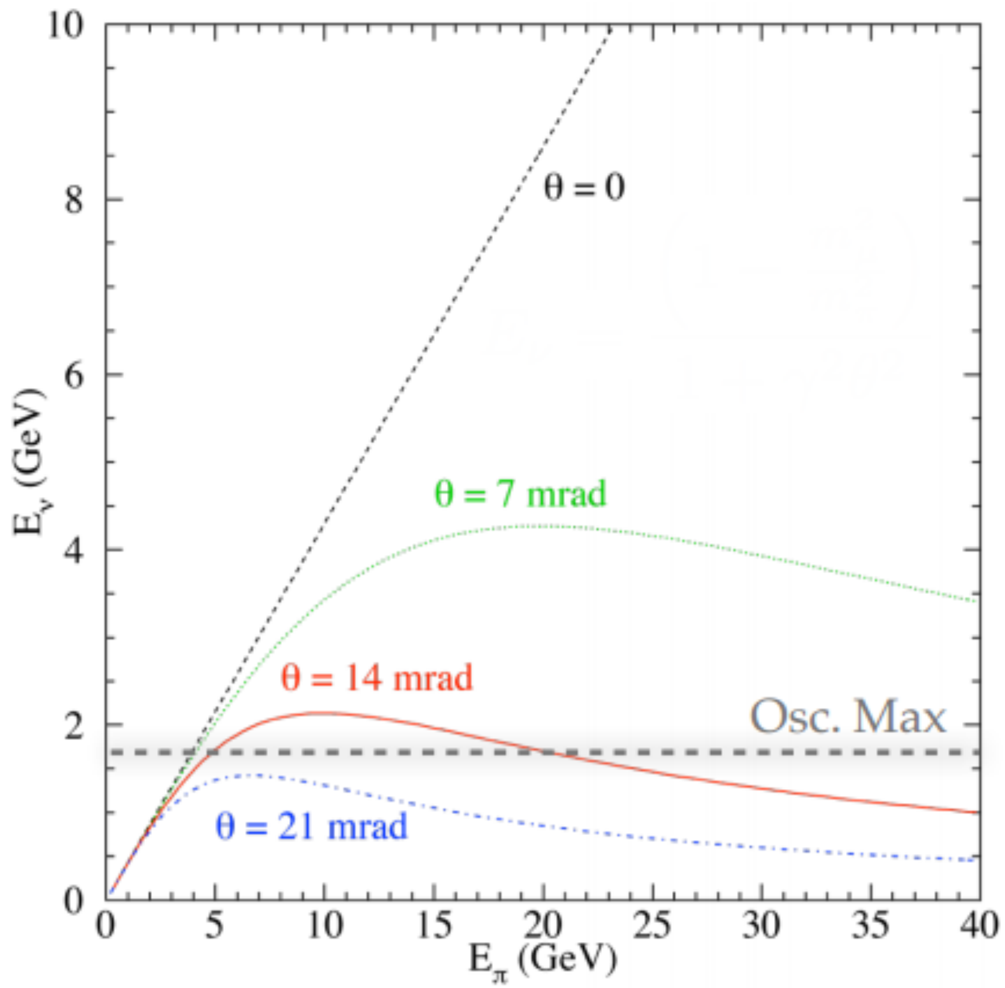
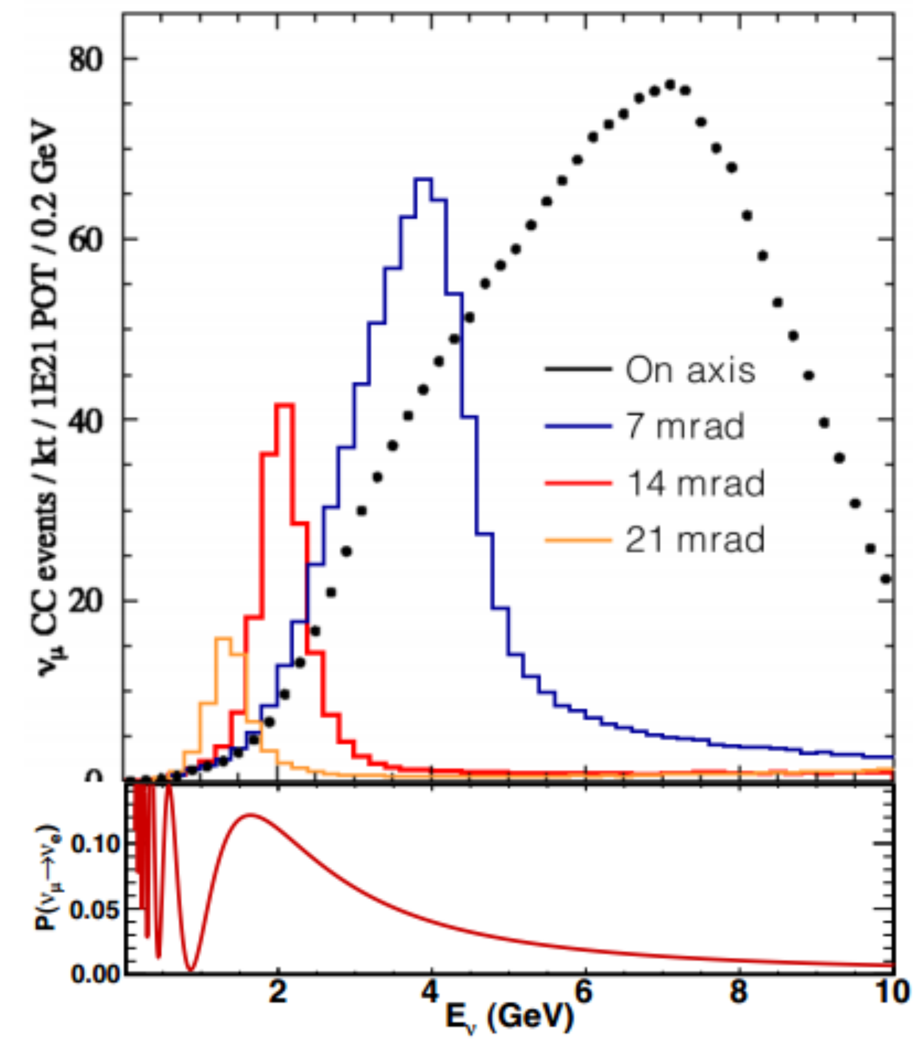




The Same Beam Seen at Multiple Experiments

Relative positioning of experiments in the same beam affects sampling of the focused beam, and thus the spectrum. From broad higher energy and intensity on axis flux, to narrow sharply peaked and lower energy flux off the main axis.





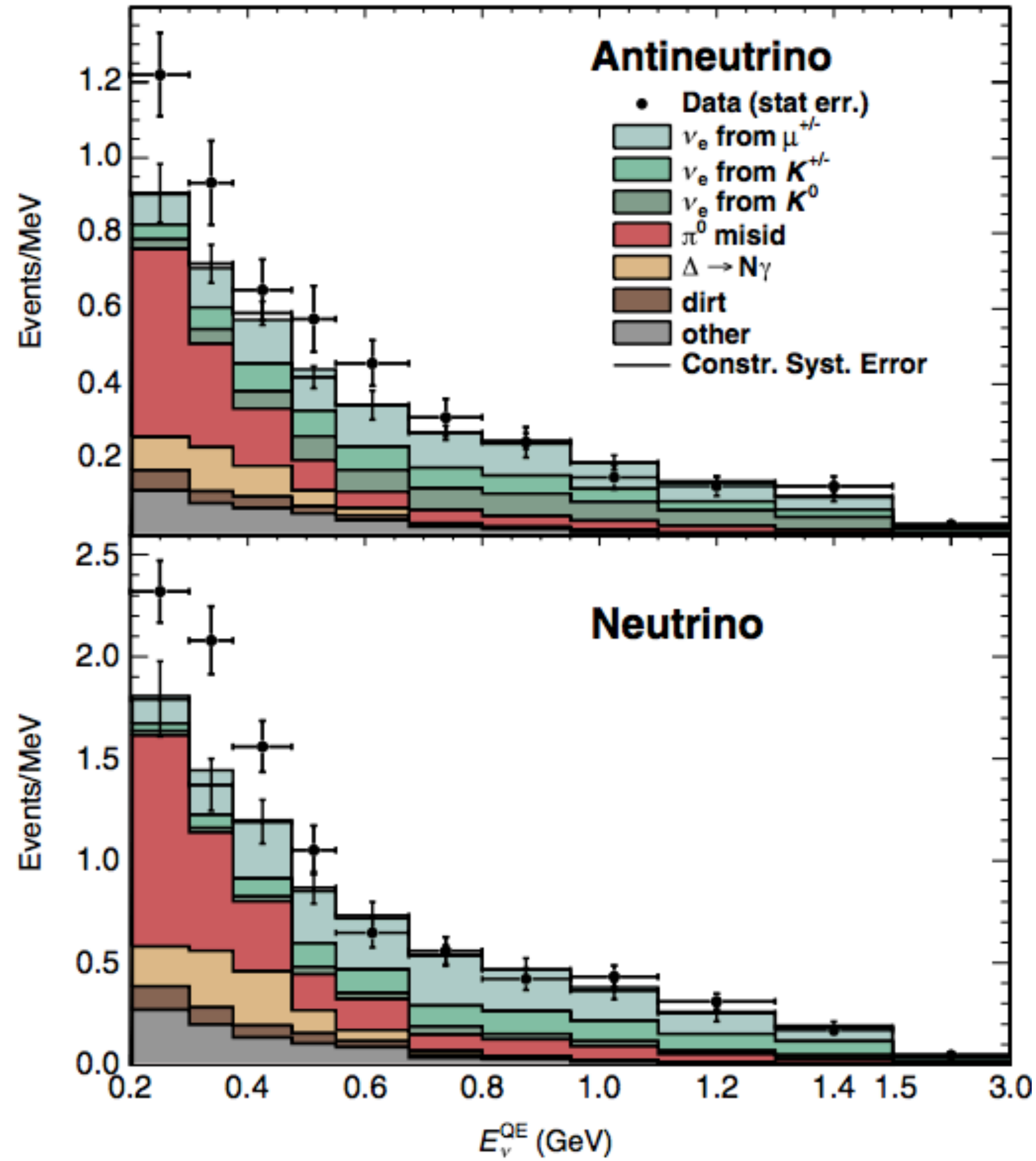
$$F = \left(\frac{2\gamma}{1+\gamma\theta^2}\right)^2 \frac{A}{4\pi z^2}$$

$$E_\nu = \frac{\left(1 - \frac{m_\mu^2}{m_{\pi,K}^2}\right) E_{\pi,K}}{1+\gamma^2\theta^2}$$

Why do we care about the flux?

Supporting two primary lines of effort:

Single Detector measurements, where precise knowledge of the incoming flux rate and shape is essential. See cross section measurements, short baseline oscillation searches, and dark matter production searches for example.

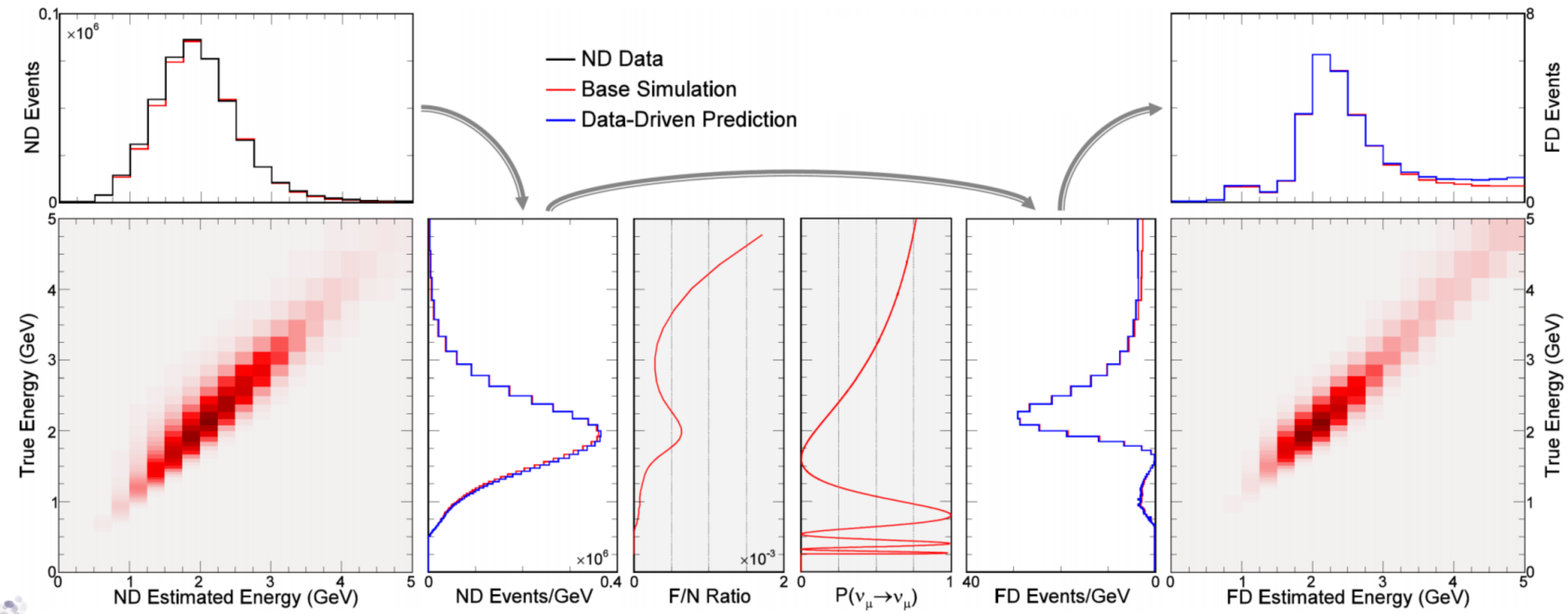


MiniBooNE, PRL 110, 161801 (2013)

Why do we care about the flux?

Supporting two primary lines of effort:

Multi detector measurements, where constraints on the flux rate and uncertainty allow us to correctly constrain our Far Detector(s) using our Near Detectors. Important even when detector technology is shared, as it's rarely truly identical. Detector modeling problems could hide behind large flux uncertainties.



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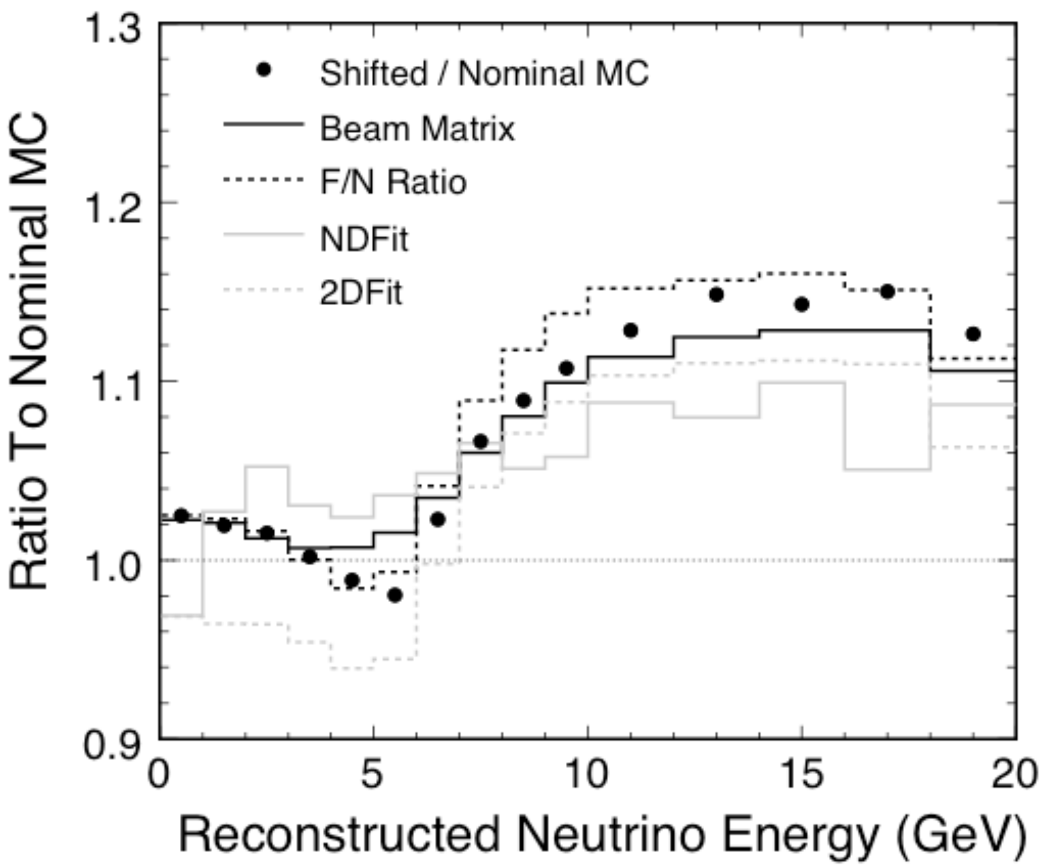
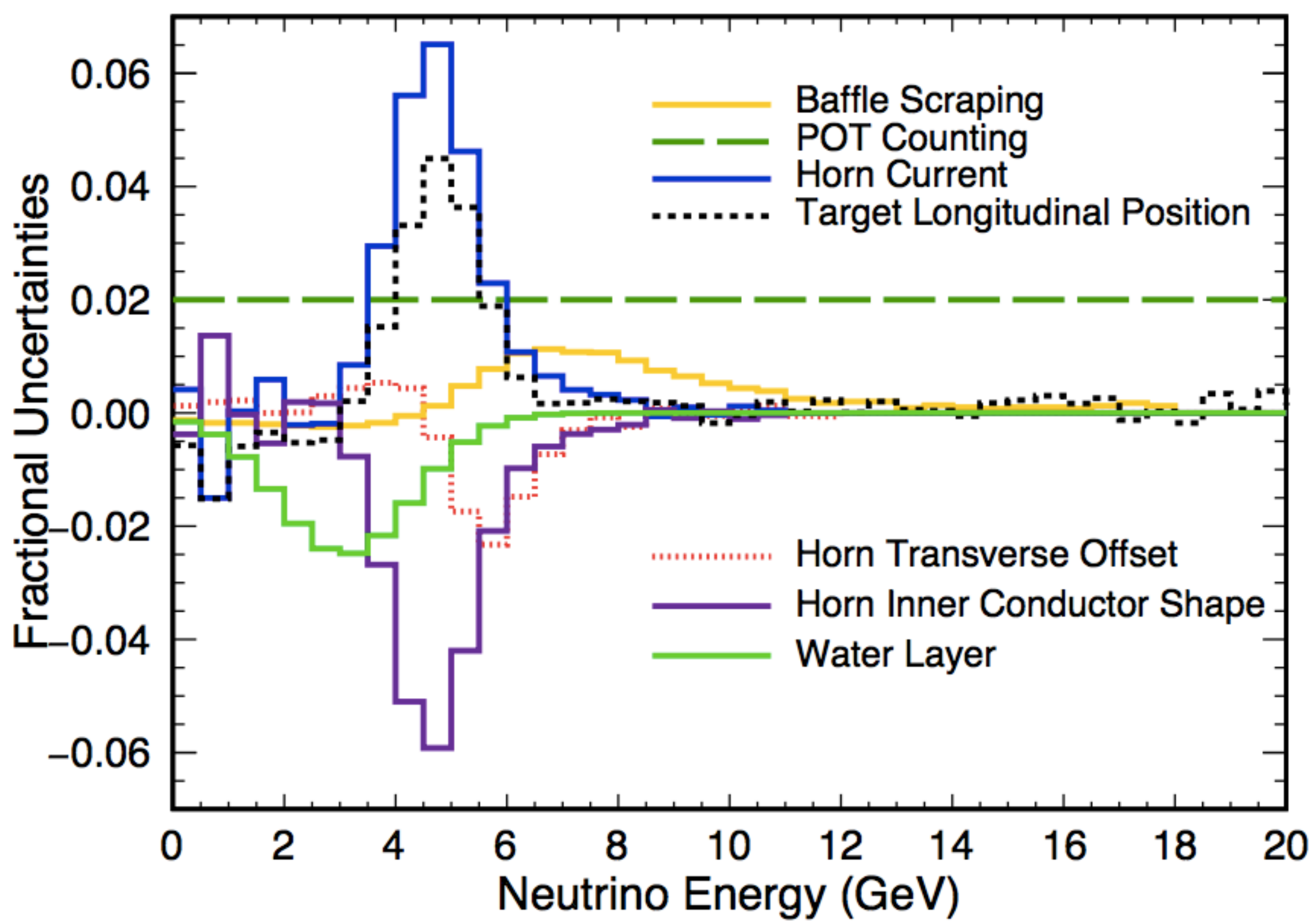


A Priori Predictions and Uncertainties

What do we know a priori?

Focusing, Geometry, Uncertainties

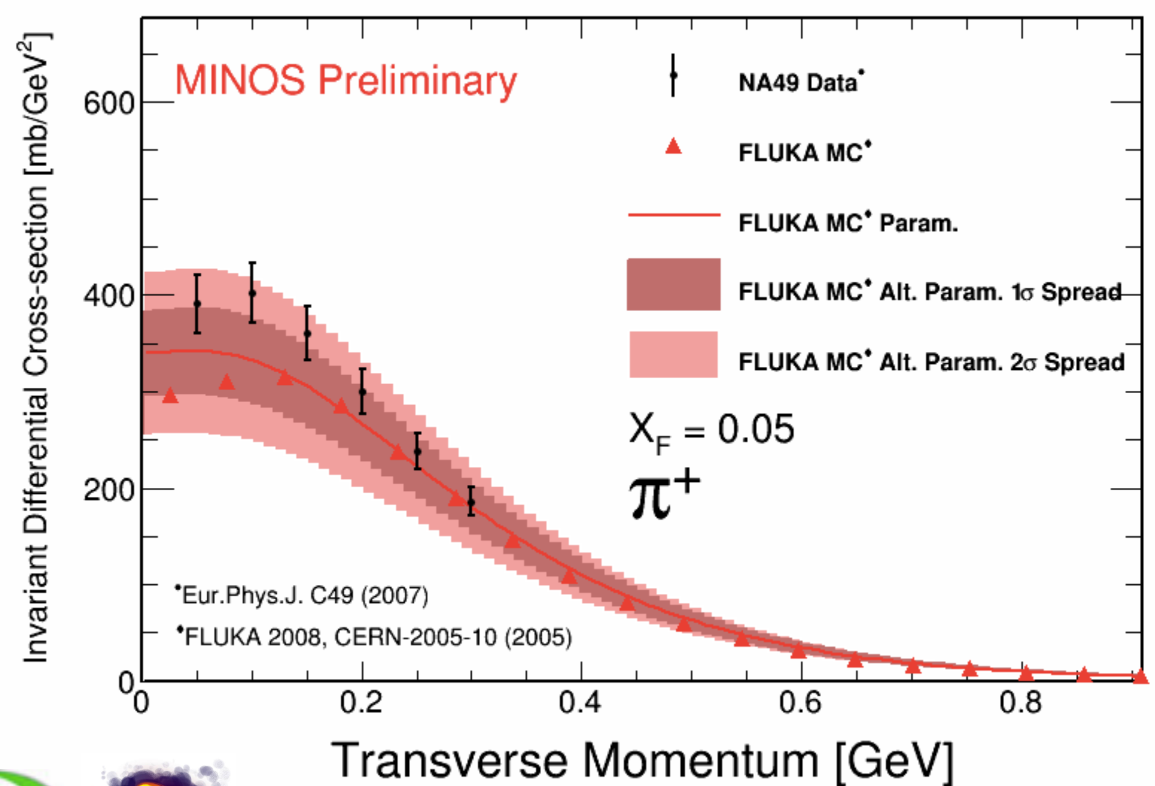
Estimates comes from uncertainty in measurement of the characteristics of the beam (target position, horn current etc.) or to represent potential deficiencies in how an aspect of the geometry is handled (horn shape etc.)

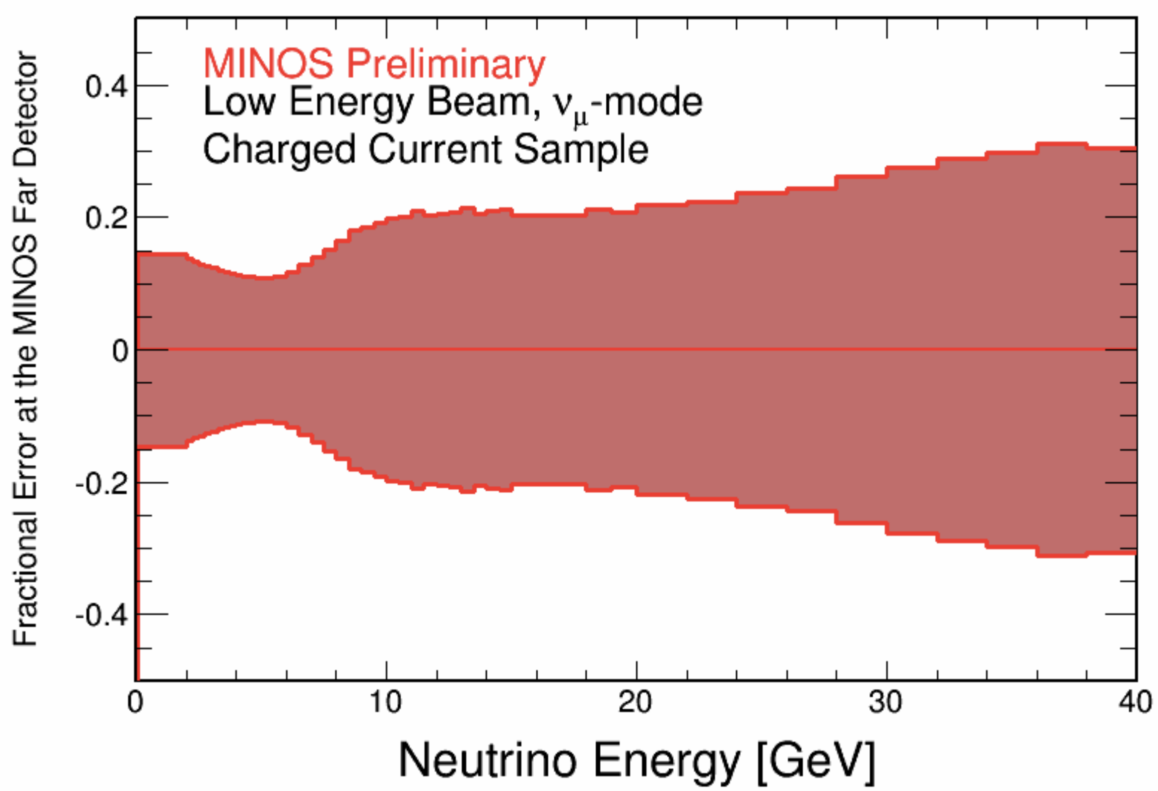


"Neutrino flux predictions for the NuMI beam", L. Aliaga et al (MINERvA Collaboration), Phys. Rev. D 94, 092005 (2016)

Hadron Production Uncertainties

Driven by the difficulty of modeling complex QCD. Attempts at a priori uncertainties often come from model spread and provide at best an error envelope. More complex methods motivated by fixed target yield data/mc disagreement produce an actual covariance matrix, but suggest a very large flux uncertainty. Usually our dominant flux uncertainty.

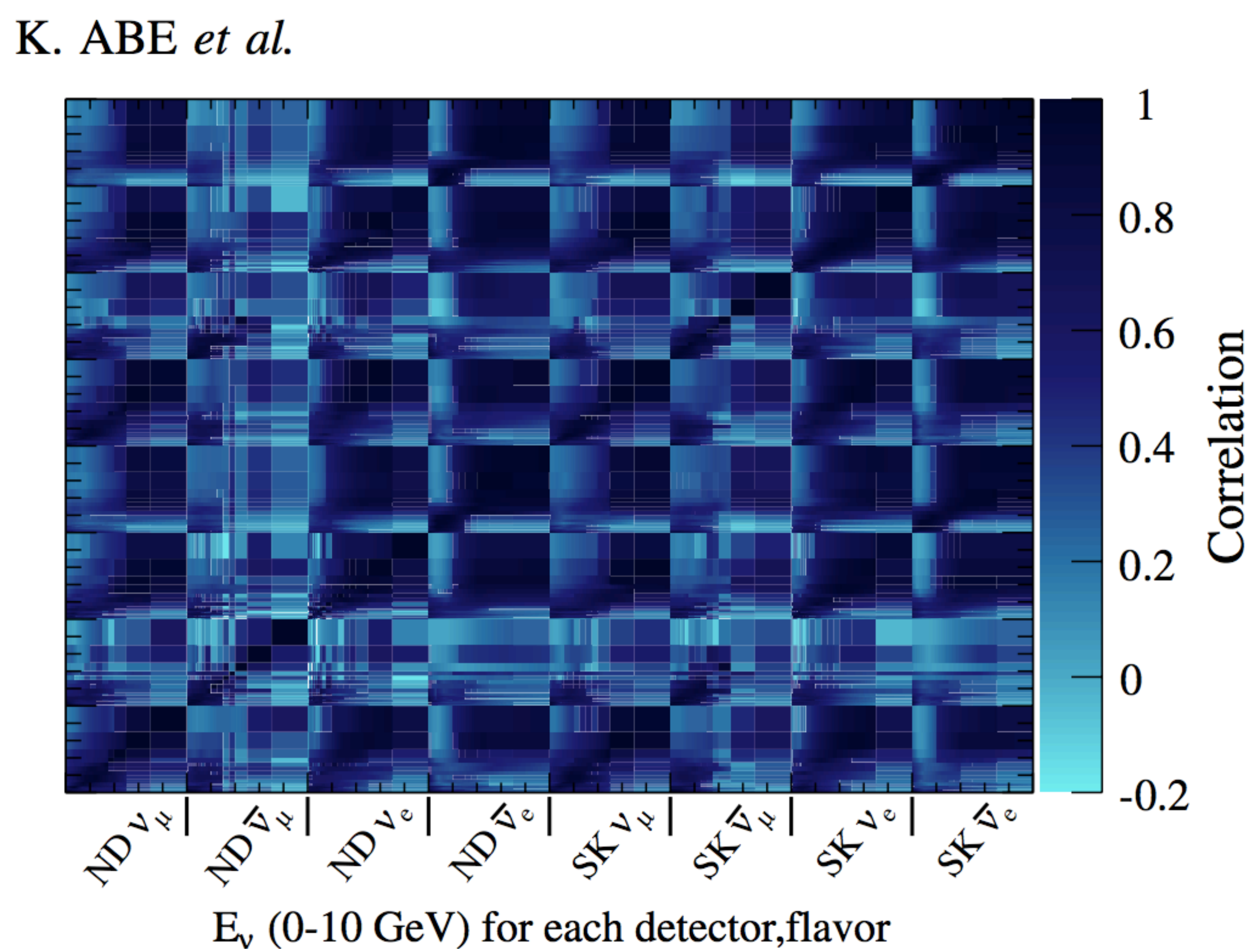




Aside: Reporting Uncertainty

We need more than just error envelopes. Propagating constituent errors forward to alternative flux allows us to build covariance and correlation matrices.

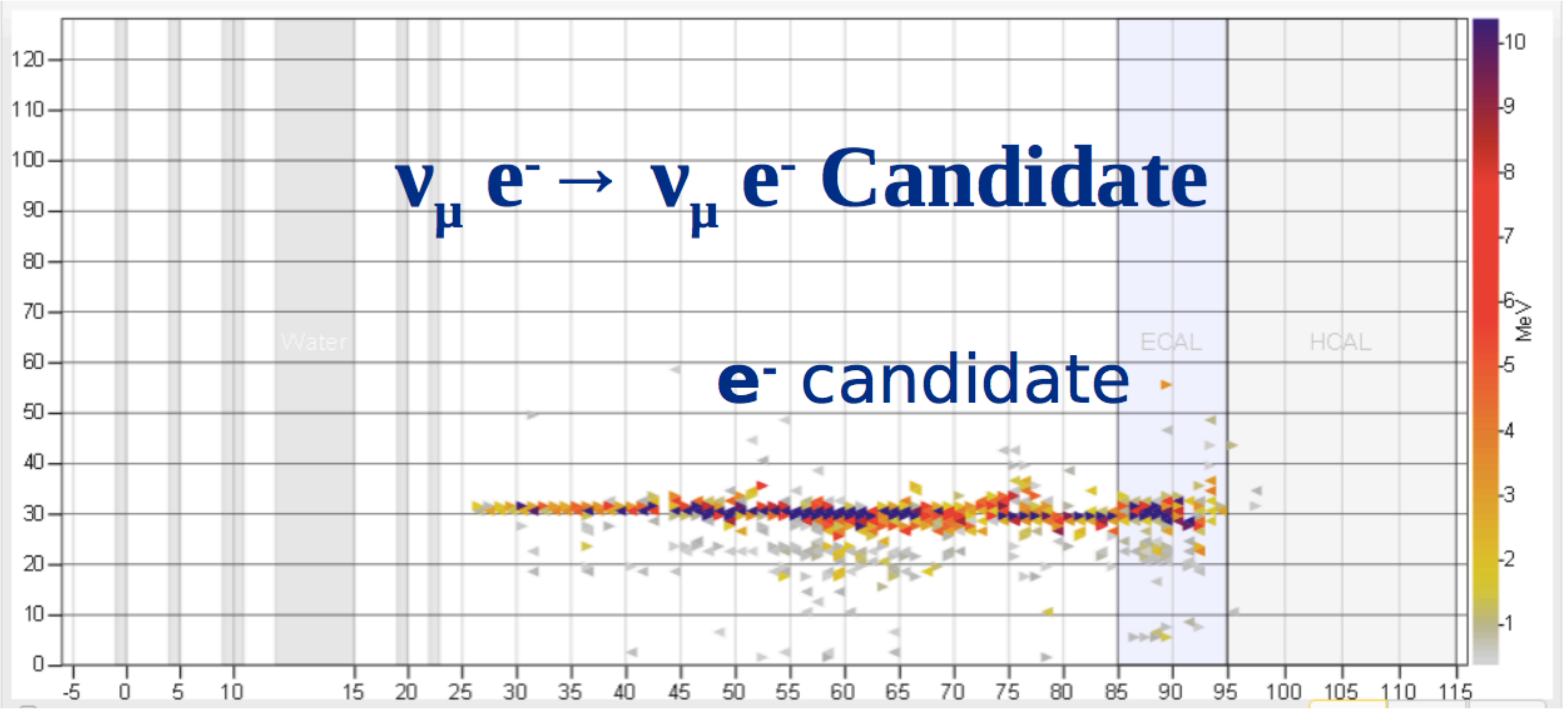
Analysis can then either take add to their error matrix or take principal components as terms in their fit.



"T2K neutrino flux prediction", K. Abe et al. (T2K Collaboration), Phys Rev. D 87, 012001 (2013)

Internal Beam Constraints

What can you learn about your beam from your own data?

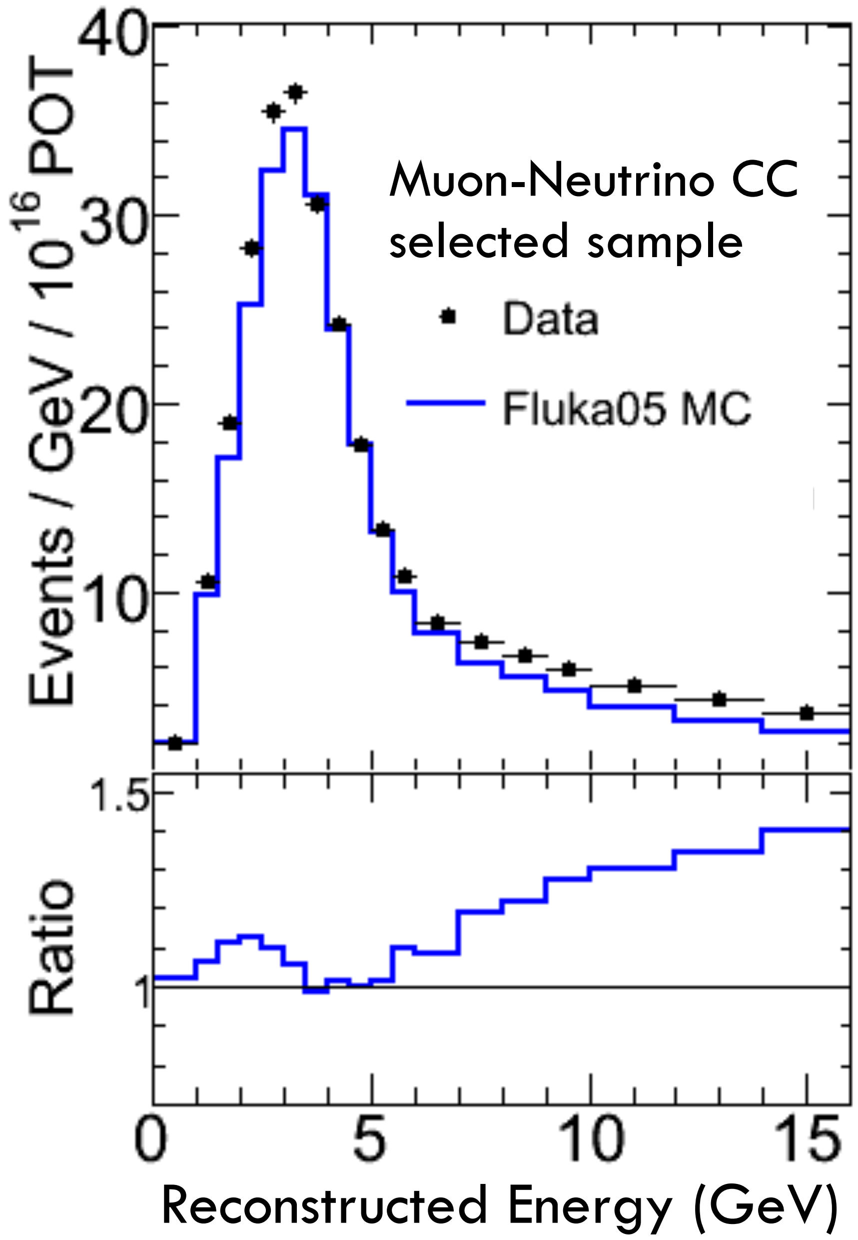


"Measurement of neutrino flux from neutrino-electron elastic scattering", J. Park et al. (MINERvA Collaboration), Phys. Rev. D 93, 112007 (2016)

Tuning to Measured Spectra

We have beautiful detectors designed to measure and characterize neutrino beams, why not use them to constrain our flux?

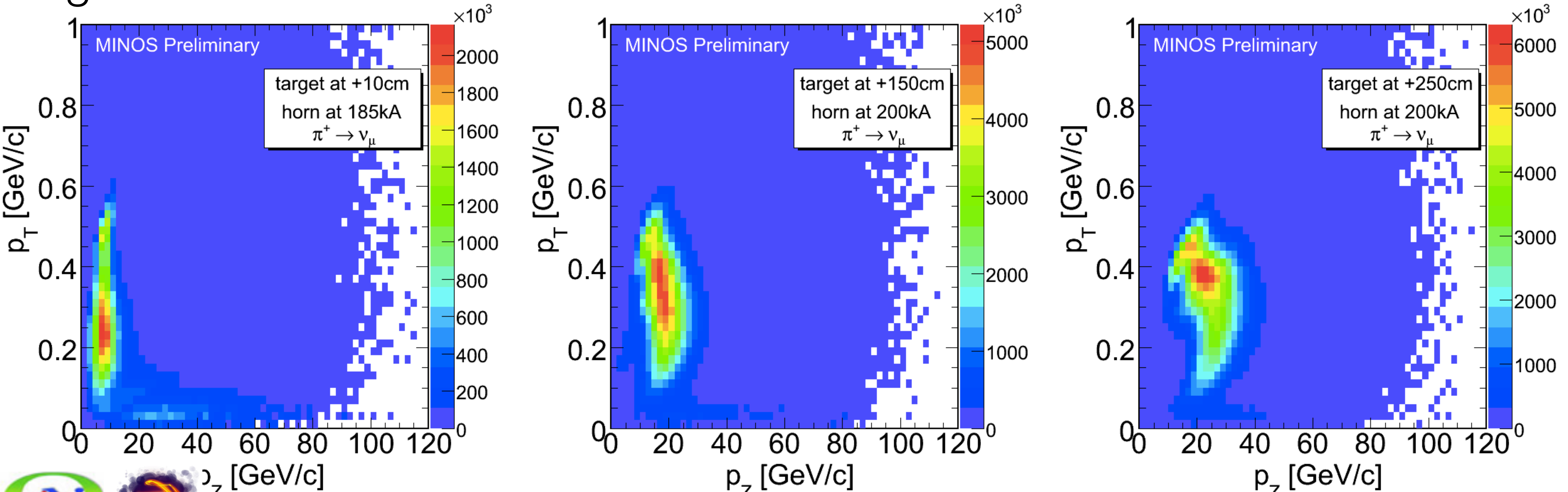
Perhaps the simplest approach is use your standard analysis sample and to take advantage of multiple beam modes and physically motivated parameterizations of hadron production to produce a fit constraining the observed flux.



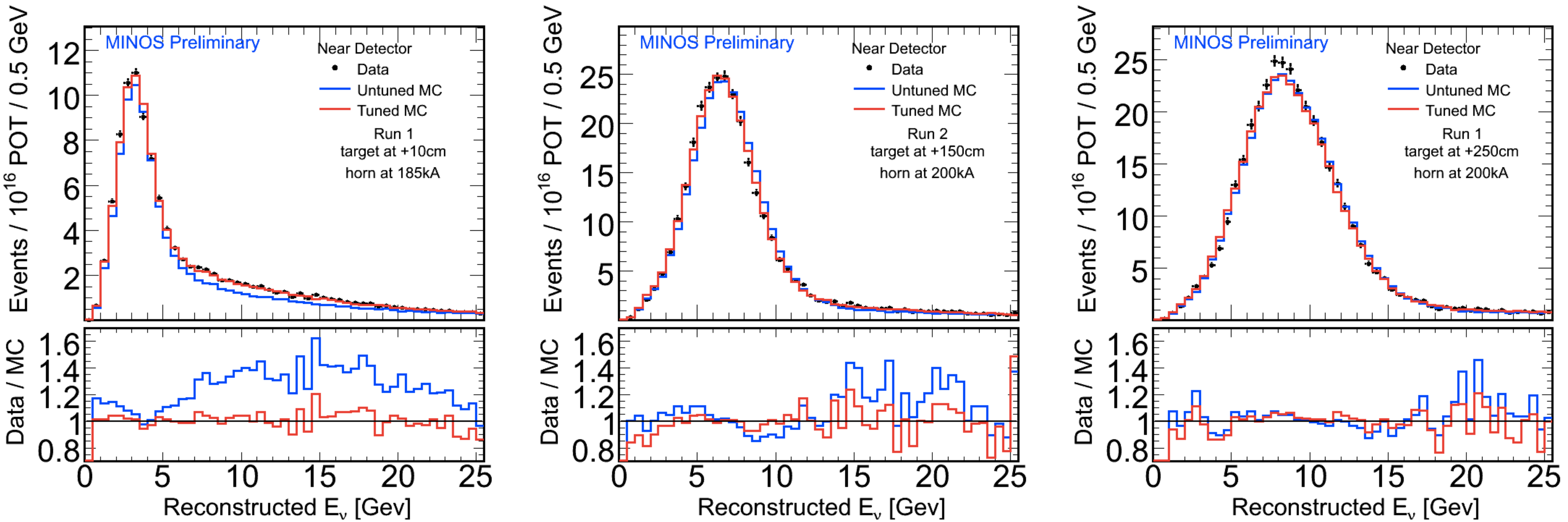
Different Beam Modes

Data/MC disagreement which varies as a function of energy in different beam modes, can be interpreted as flux uncertainties rather than detector or cross-section uncertainties.

Additionally, as each beam mode gives access to a different region of Pion and Kaon production phase space so that we can better constrain our parameterization of the raw yield of hadron production coming off of the target.



Fit Result: Final Tuned Flux



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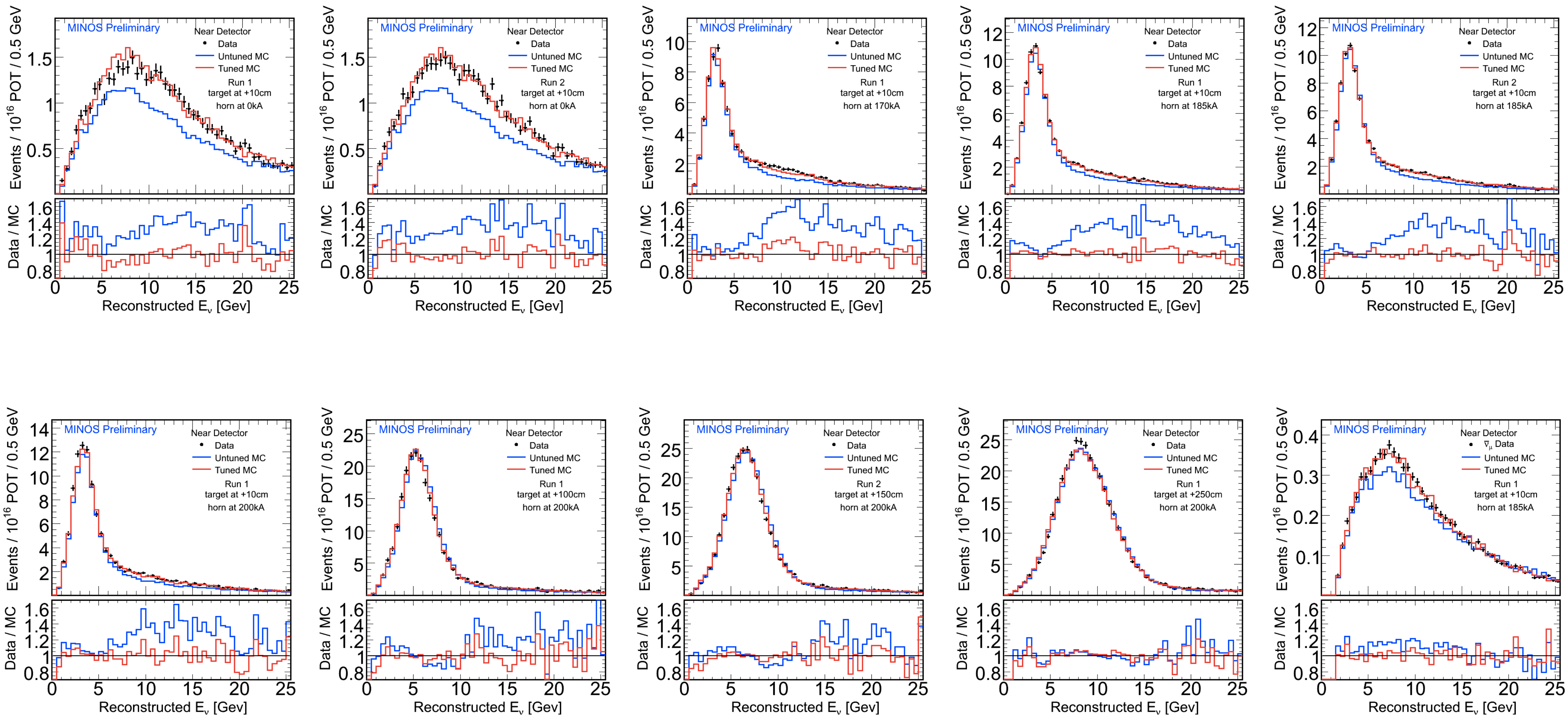
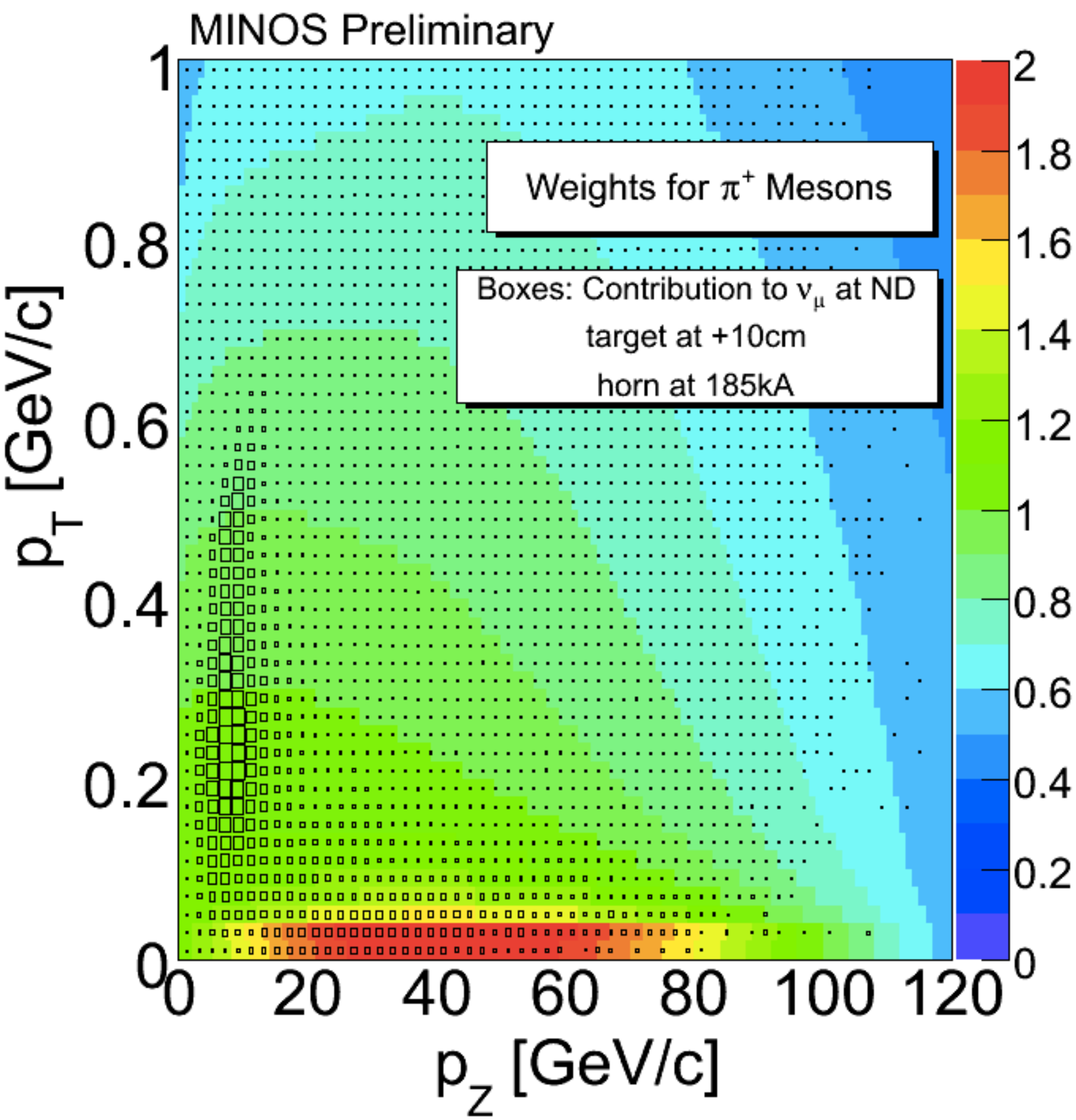
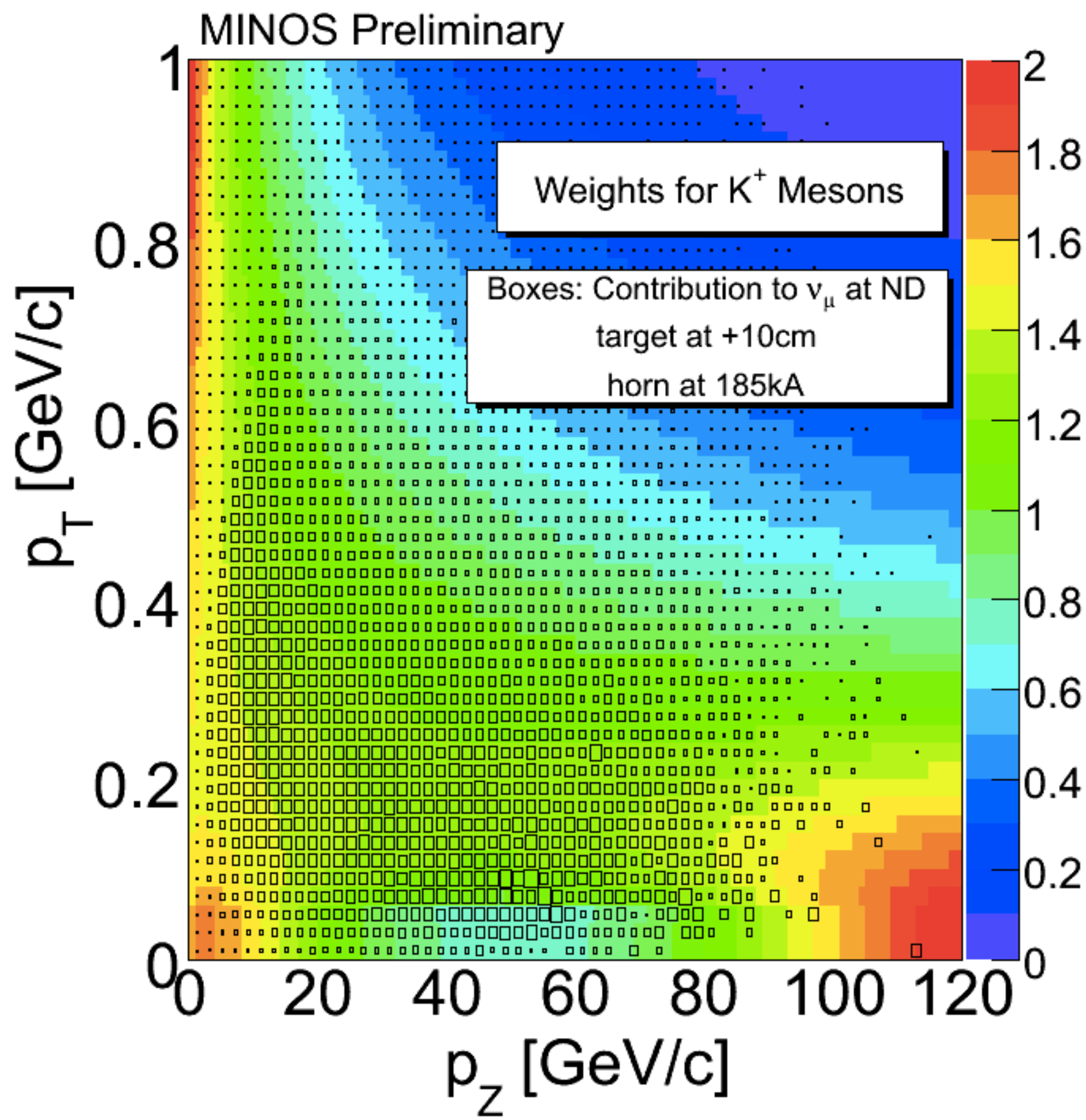


Fit Result: Hadron Production Weights

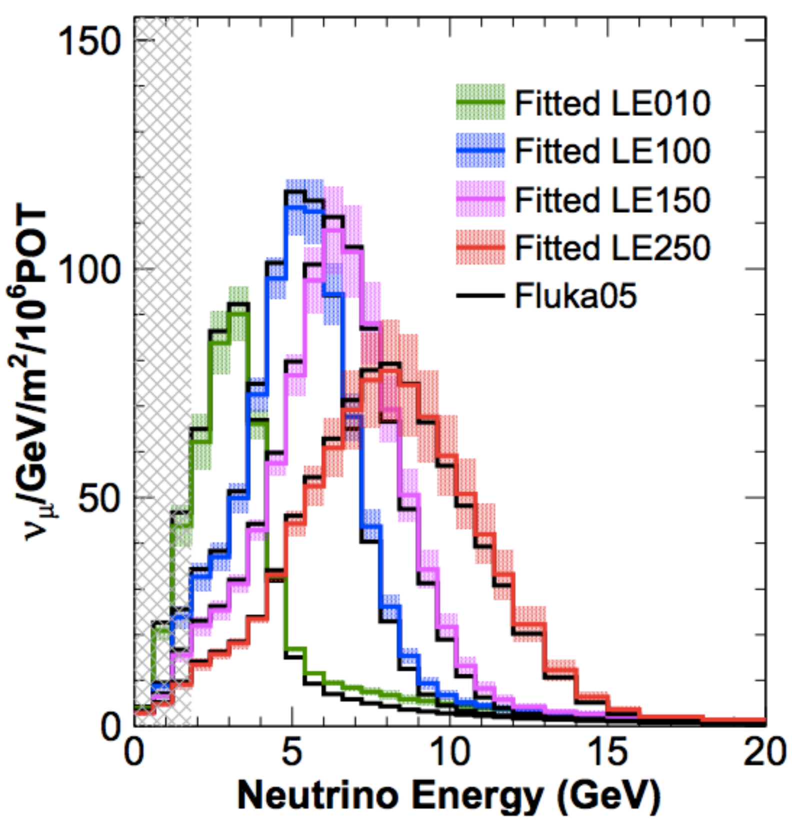


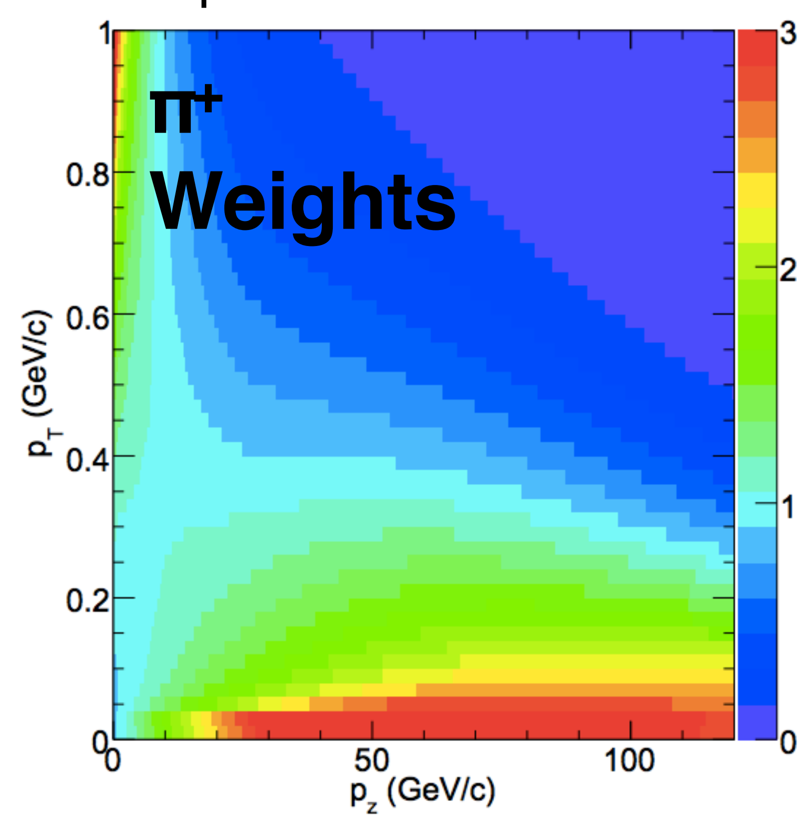


Beam Monitoring Tools

We can also attempt to measure the flux by taking advantage of beam monitoring tools, for example measuring the rate and energy of muons produced in pion and kaon decays in the decay pipe.

That approach was explored at NuMI* using the Muon Monitors just after the decay pipe. Whilst the fit has a large uncertainty the final result is largely consistent with that of the MINOS beam fitting. With work beam monitoring tools like muon monitors can be a powerful constraint on a beam.

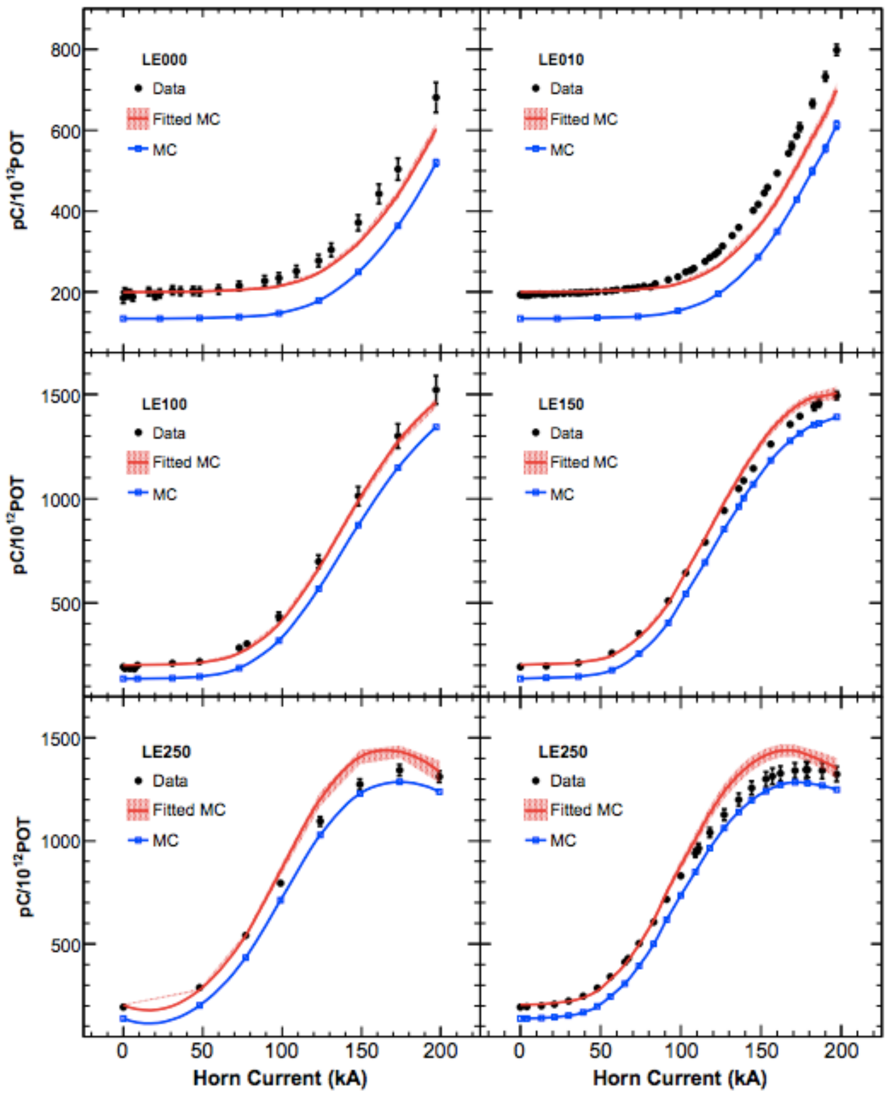




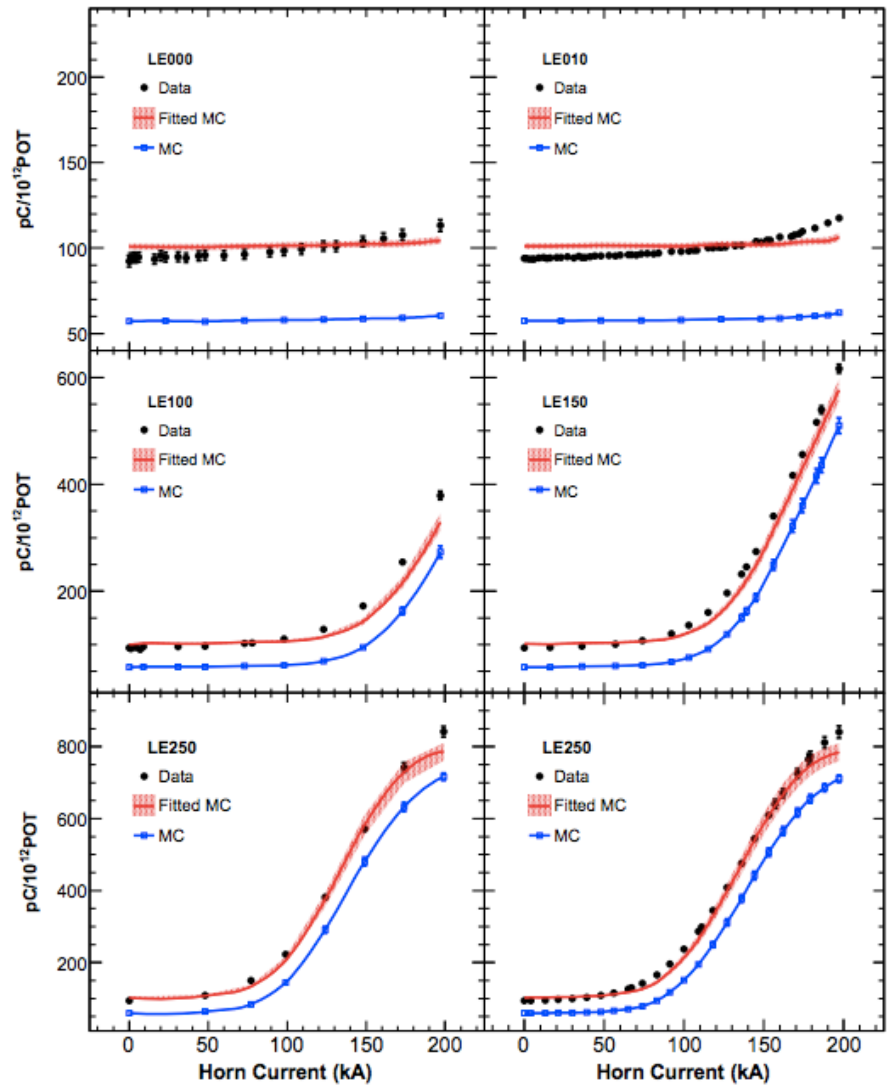
*Laura Jean Loiacono, University of Texas at Austin, May 2010
"Measurement of the muon neutrino inclusive charged current cross section on iron using the MINOS detector"
Fermilab-Thesis-2011-06

The Muon Monitors

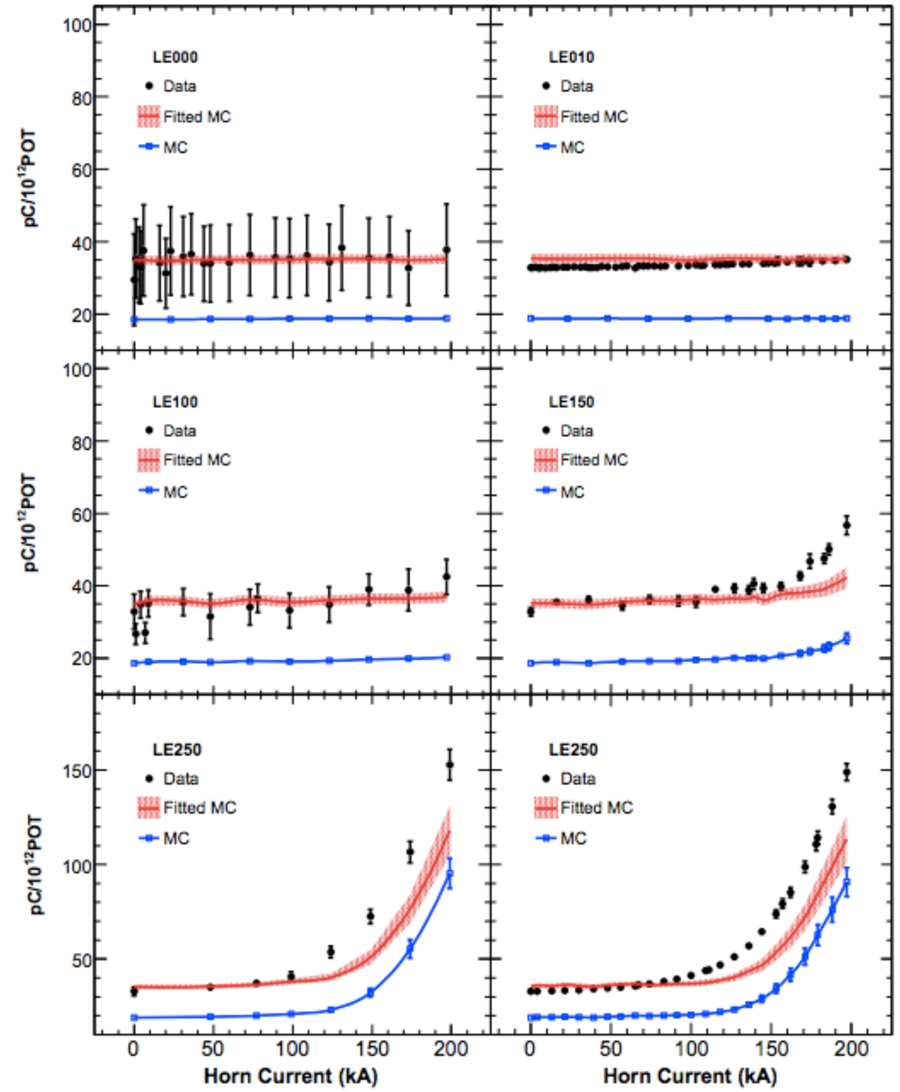
Monitor 1:



Monitor 2:



Monitor 3:

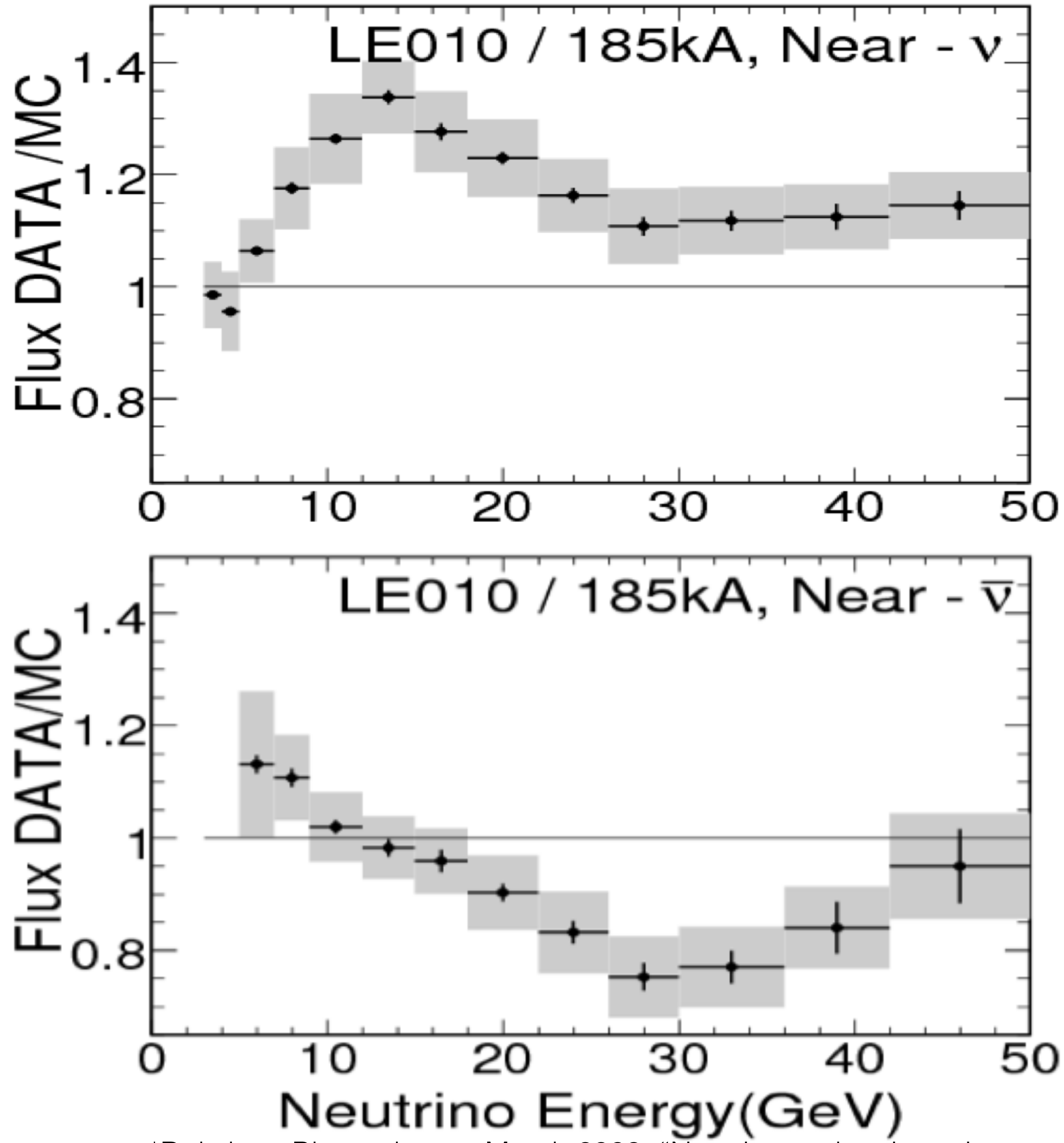


The Low ν Method

Another method is to attempt to measure the flux by selecting events with a well understood cross section.

One approach is to select for CC events with a low inelasticity*neutrino energy or "ν".

Used in a preliminary MINOS cross section analysis* this study showed that data/MC discrepancy at the MINOS ND was indeed largely driven by the difference between the measured and predicted flux.

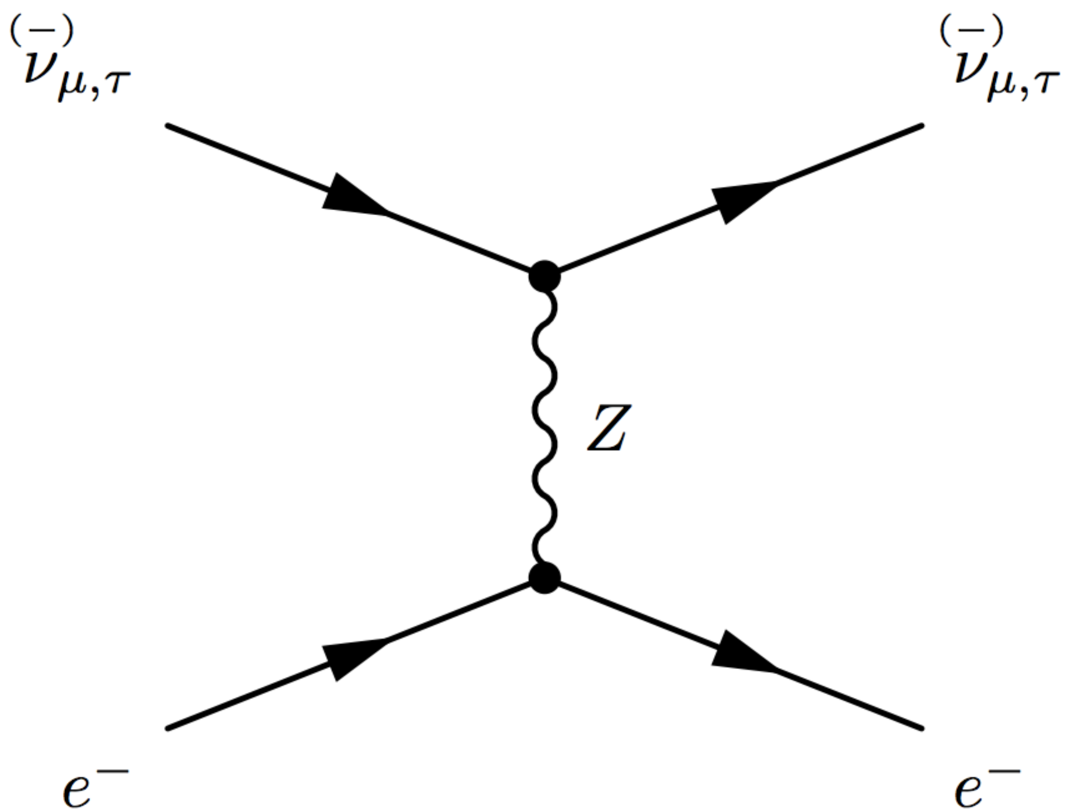


*Debdatta Bhattacharya, March 2009, "Neutrino and antineutrino inclusive charged-current cross section measurement with the MINOS near detector", Fermilab-Thesis-2009-11

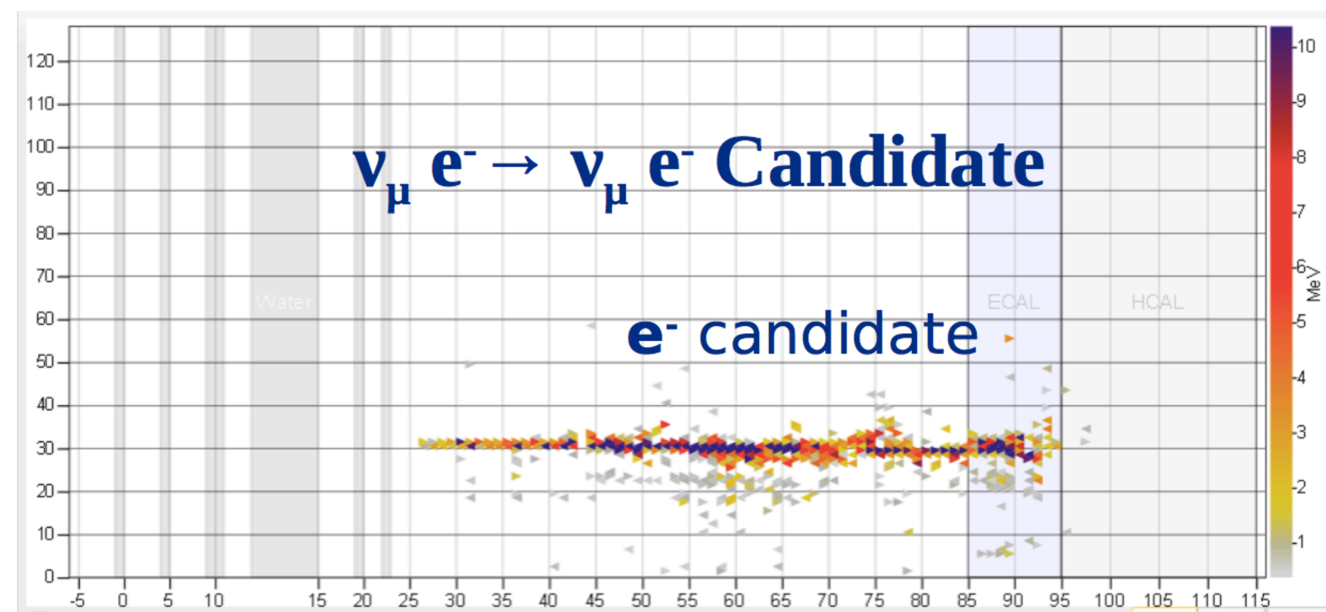
ν on E Scattering

Similarly we can select rare, but iconic and well modeled ν on E scattering interactions. As these have a large NC component, precise hadron production modeling constraints are difficult, but it can give excellent constraints on the overall flux rate.

Pioneered at MINERvA as part of their flux determination.



"Measurement of neutrino flux from neutrino-electron elastic scattering", J. Park et al. (MINERvA Collaboration), Phys. Rev. D 93, 112007 (2016)



$$\mathbf{E_e}\theta^2 < \mathbf{2m_e}$$

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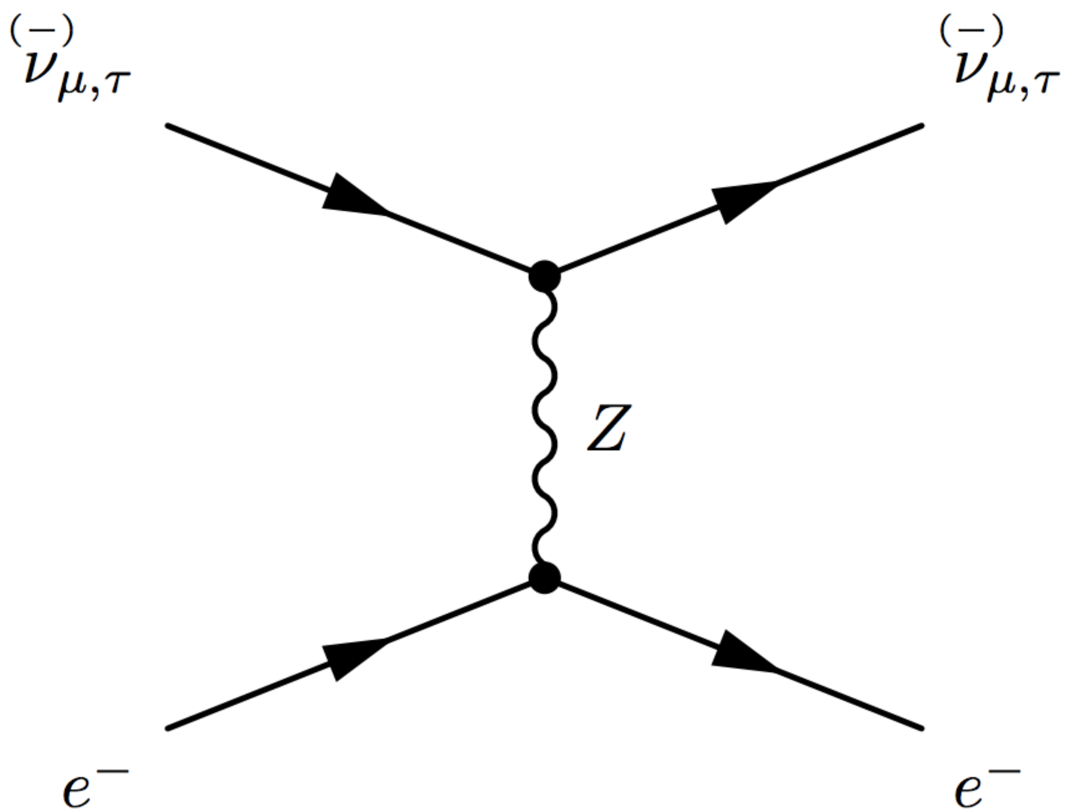

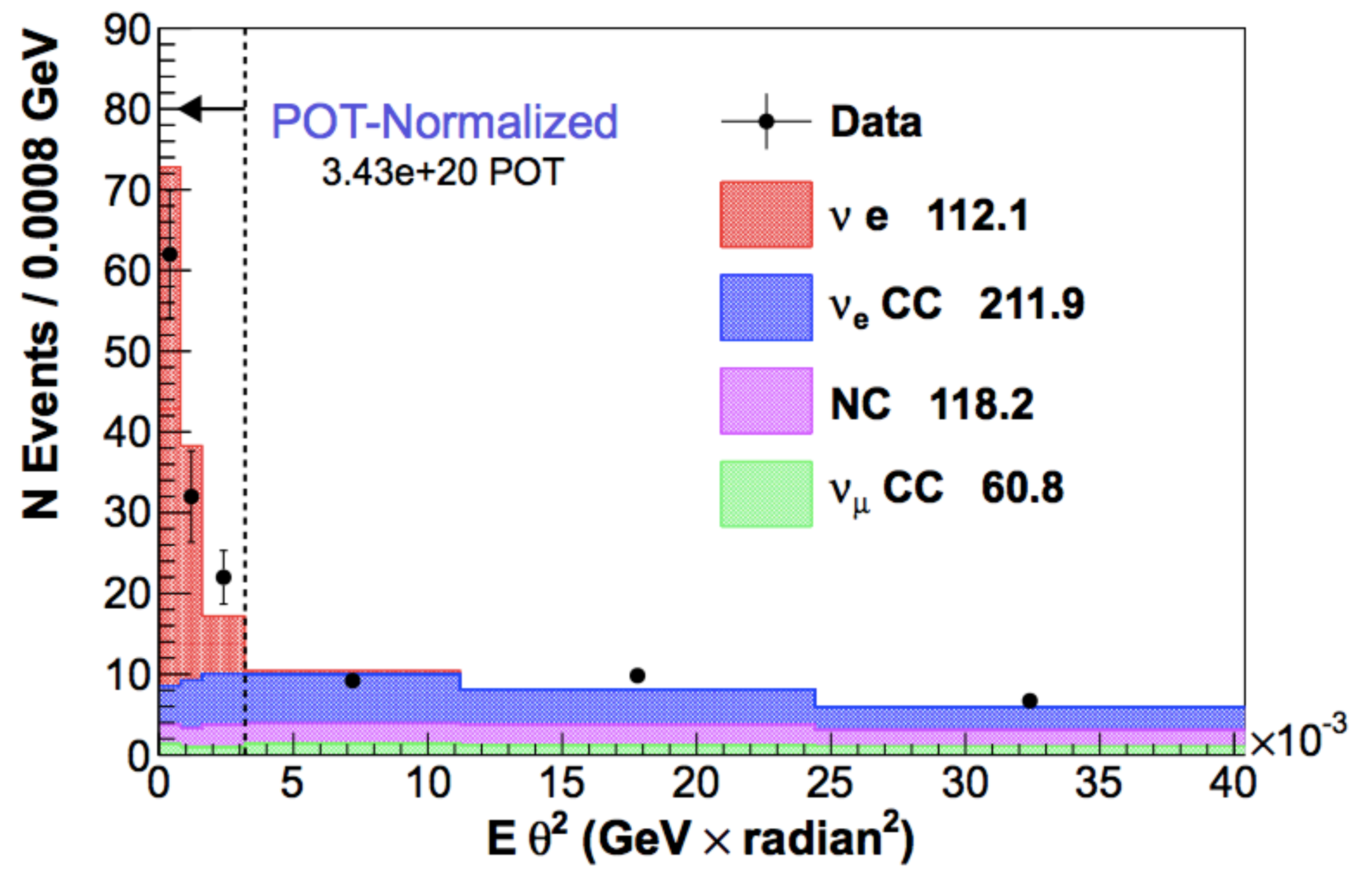

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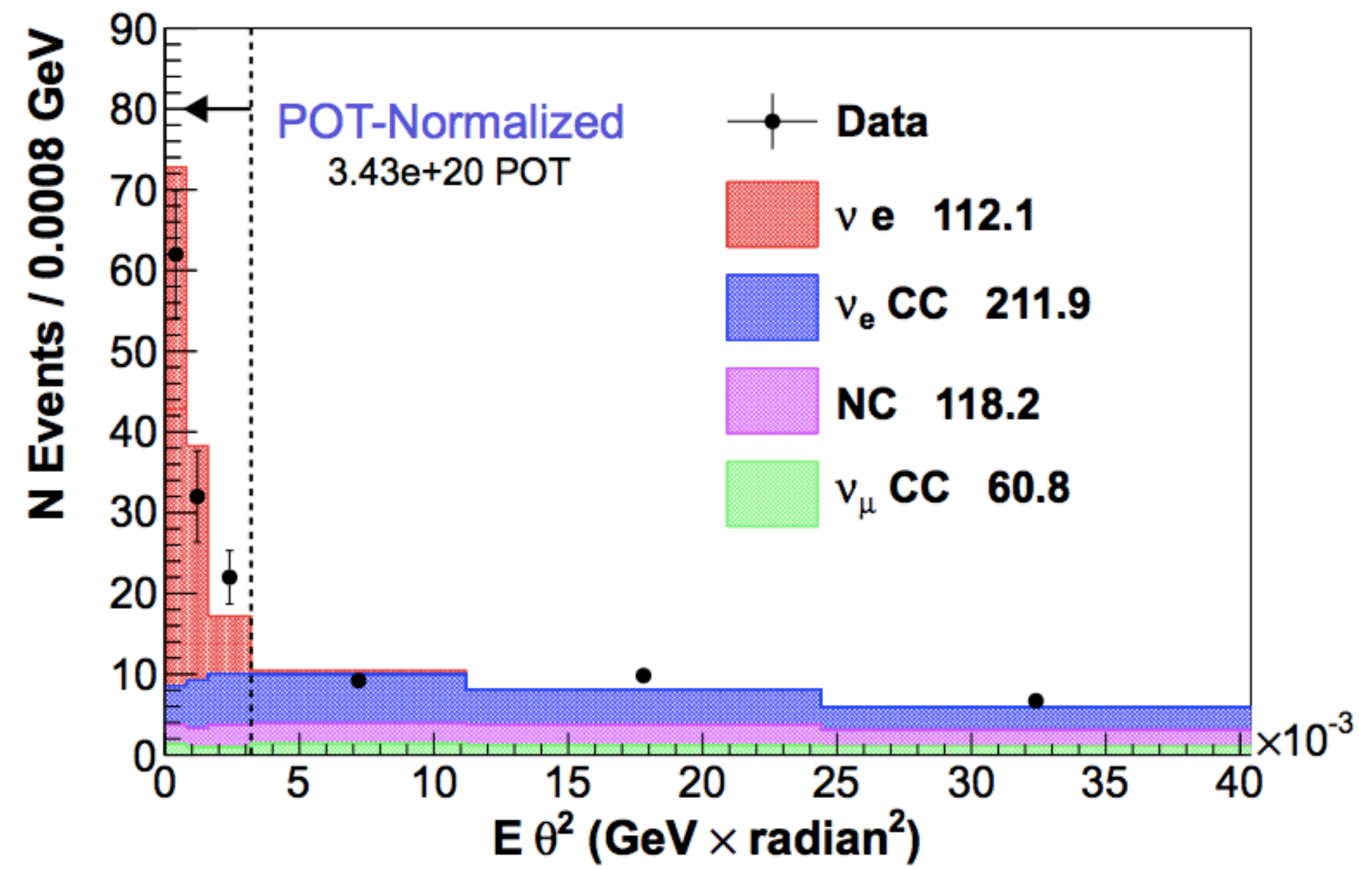
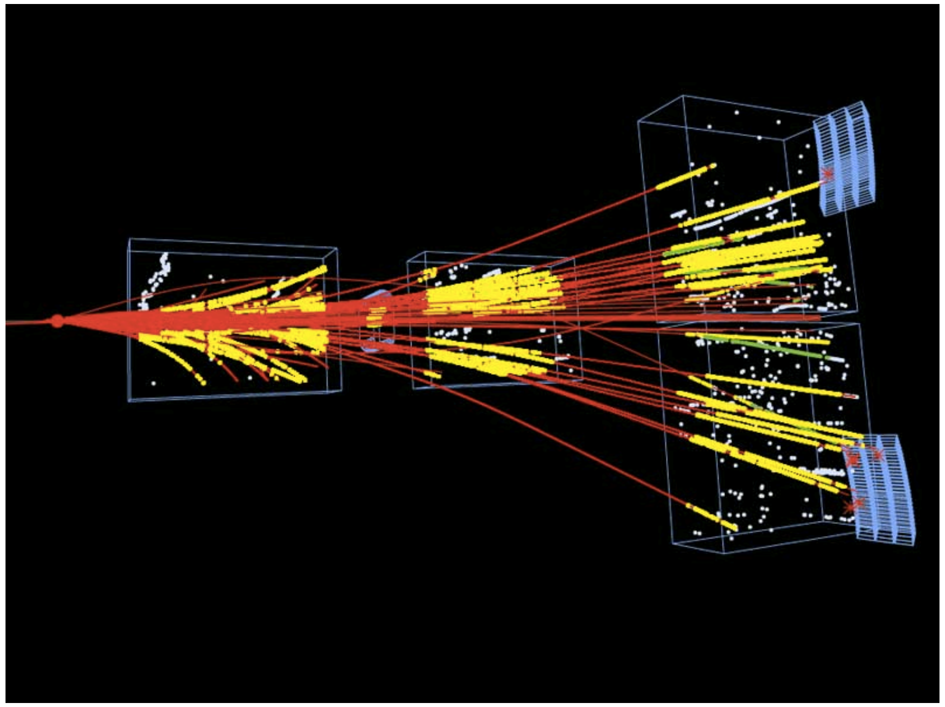
Excellent poster and talk from Edgar of the MINERvA collaboration at this meeting if you'd like to know more!



"Measurement of neutrino flux from neutrino-electron elastic scattering", J. Park et al. (MINERvA Collaboration), Phys. Rev. D 93, 112007 (2016)

External Beam Constraints

What can you learn about your neutrino beam using external fixed target data?

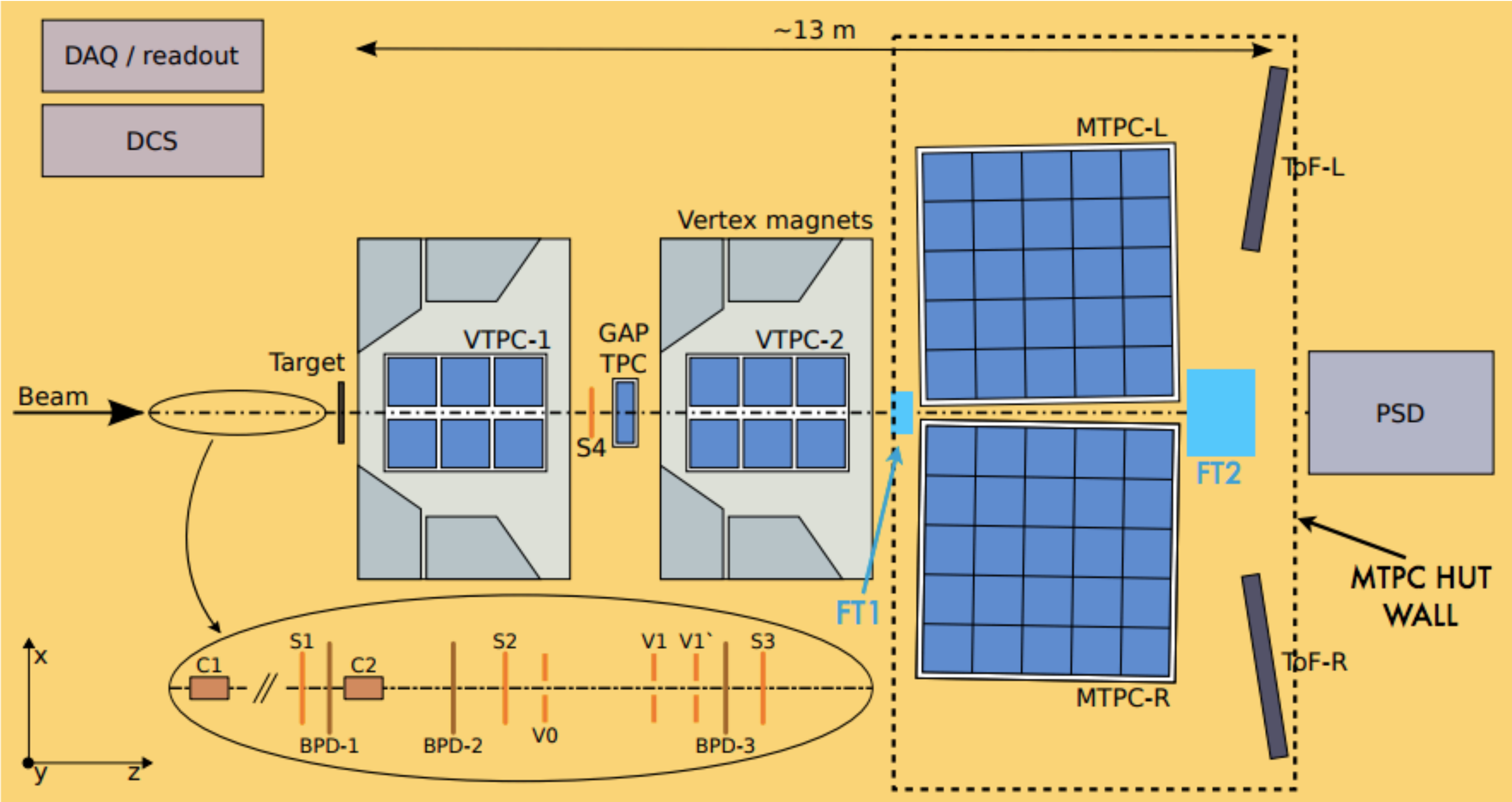


"Hadron Production Measurements for Fermilab Neutrino Beams", ADDENDUM TO THE NA61/SHINE PROPOSAL SPSC-P-330, The US-NA61 Collaboration and the NA61/SHINE Collaboration

Fixed Target Experiments

In fixed target experiments beam and trigger detectors allow precise identification of each beam hadron, and characterization of its kinematics. They then use a series of downstream TPCs to characterize the hadrons produced. In so called “thin target” studies where minimal target material is present that data can be used to produce cross section constraints.

Alternatively, where full thick “replica” targets are deployed we obtain measurements of the final yield expected on that specific target.



“Hadron Production Measurements for Fermilab Neutrino Beams”, ADDENDUM TO THE NA61/SHINE PROPOSAL SPSC-P-330, The US-NA61 Collaboration and the NA61/SHINE Collaboration

Using External Data

What if you're attempting to measure something that might modify your flux? How to focusing and hadron production effects? Detector and flux effects?

Fixed target experiments like NA49, NA61, MIPP, and HARP give us data to directly constrain the hadron production.

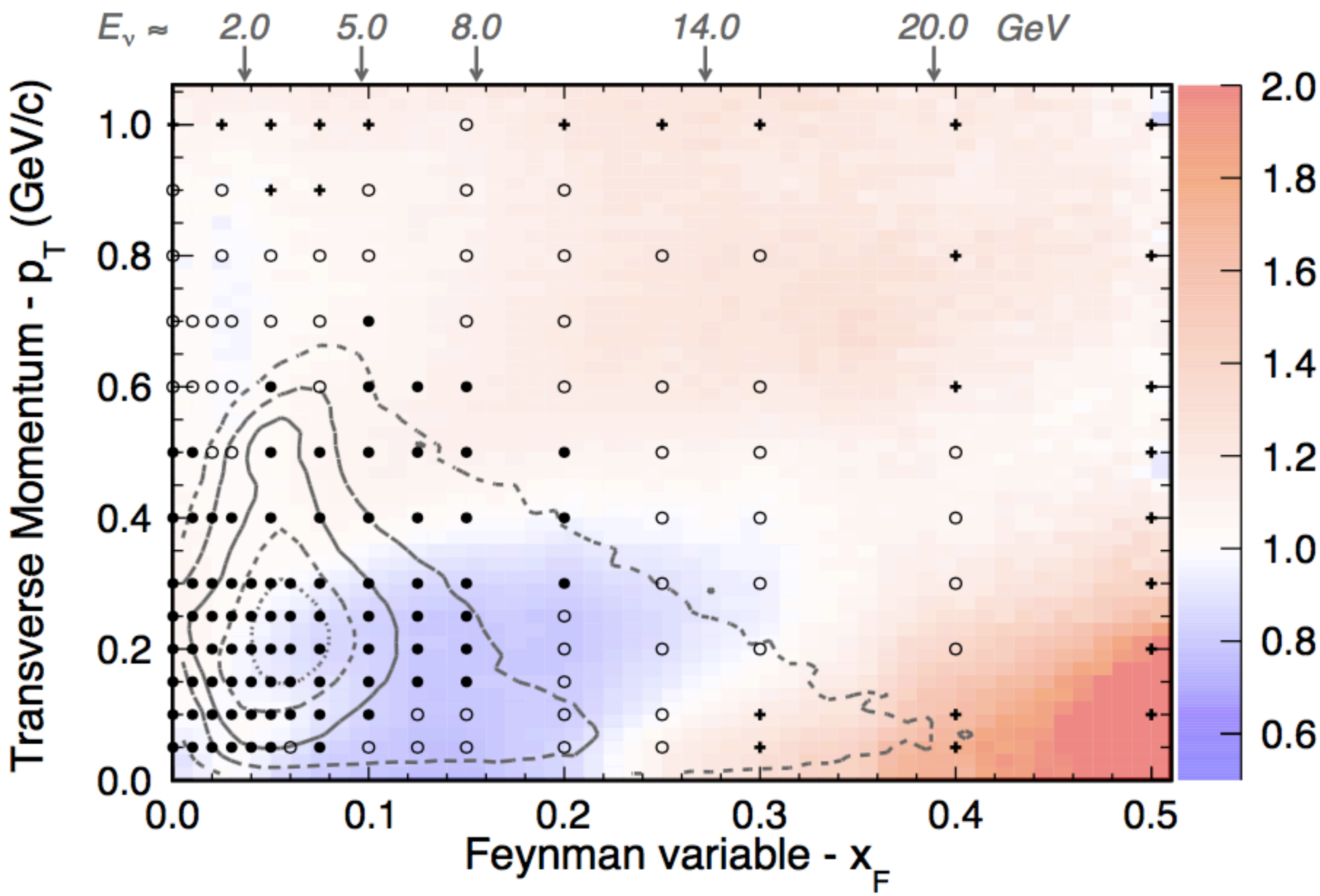
The general strategy is then:

- Tabulate interactions and materials for each ν's ancestor
- Find relevant data on those interactions (thick or thin target, often a combination)
- Reweight the simulations interactions to match the data
- Assign and propagate uncertainties

Thin Target Data

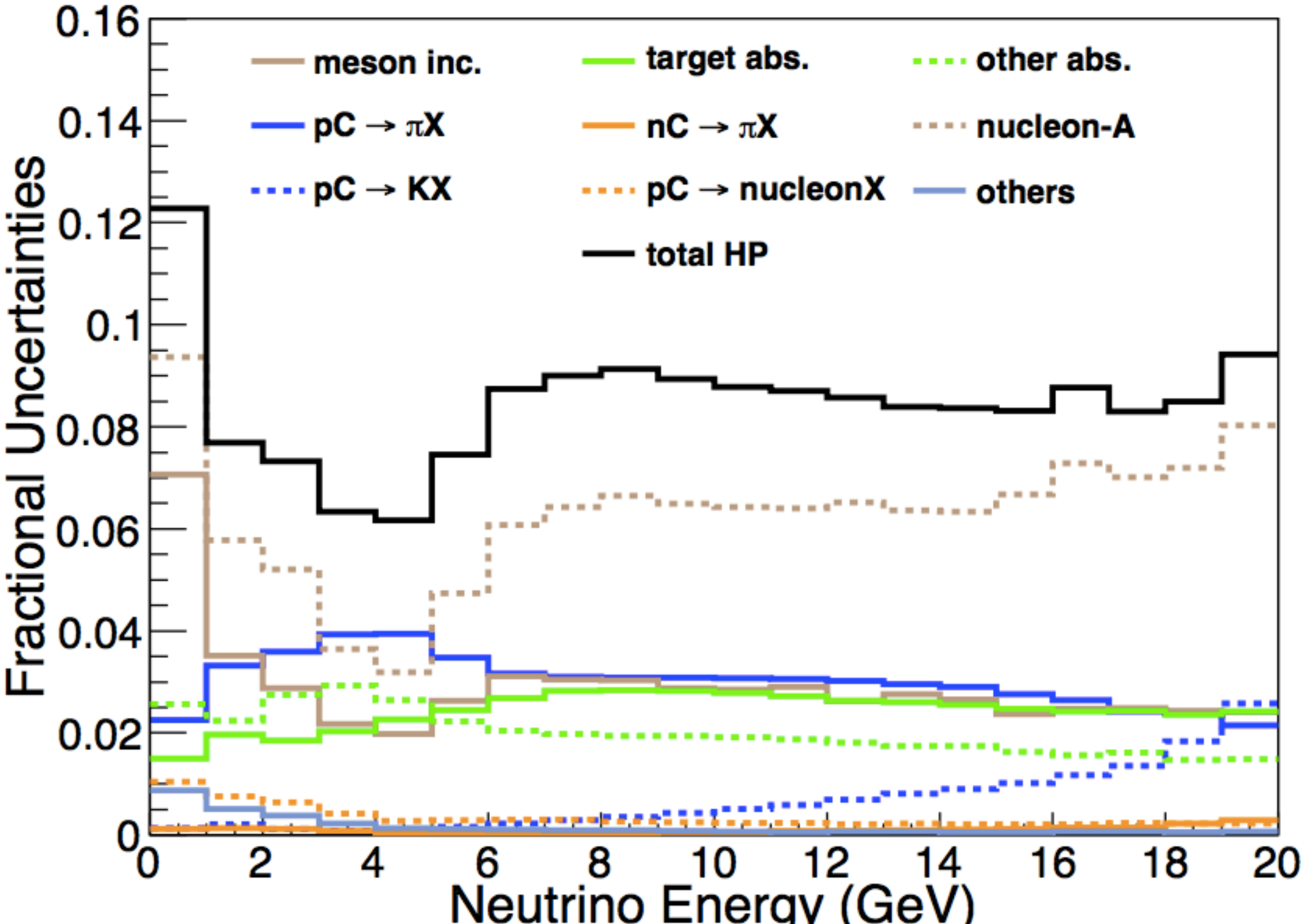
Working with thin target data, such as NA49 at MINERvA, there is excellent coverage for the initial pion/kaon production kinematics.

Thin target- no data on re-interaction. However detailed accounting allows them to assign uncertainties related to possible re-interaction in the target material.



"Neutrino flux predictions for the NuMI beam", L. Aliaga et al (MINERvA Collaboration), Phys. Rev. D 94, 092005 (2016)

Assigning Uncertainty, Thin Target

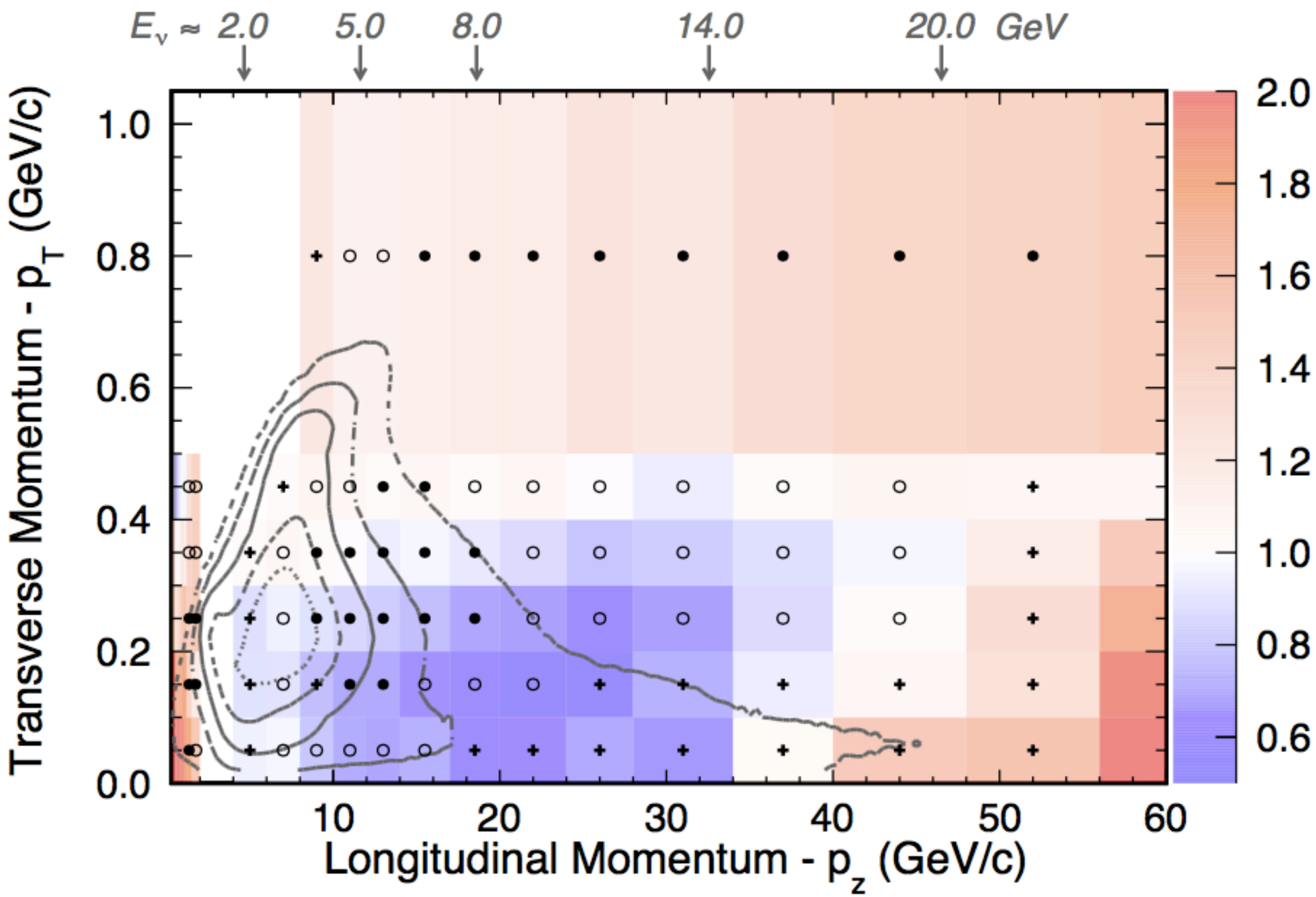


“Neutrino flux predictions for the NuMI beam”, L. Aliaga et al (MINERvA Collaboration), Phys. Rev. D 94, 092005 (2016)

Thick Target Data

Working with thick target data, such as MIPP at MINERvA, minimizes uncertainties related to possible re-interaction in the target material.

Can use the thin target data wherever coverage isn't optimal.



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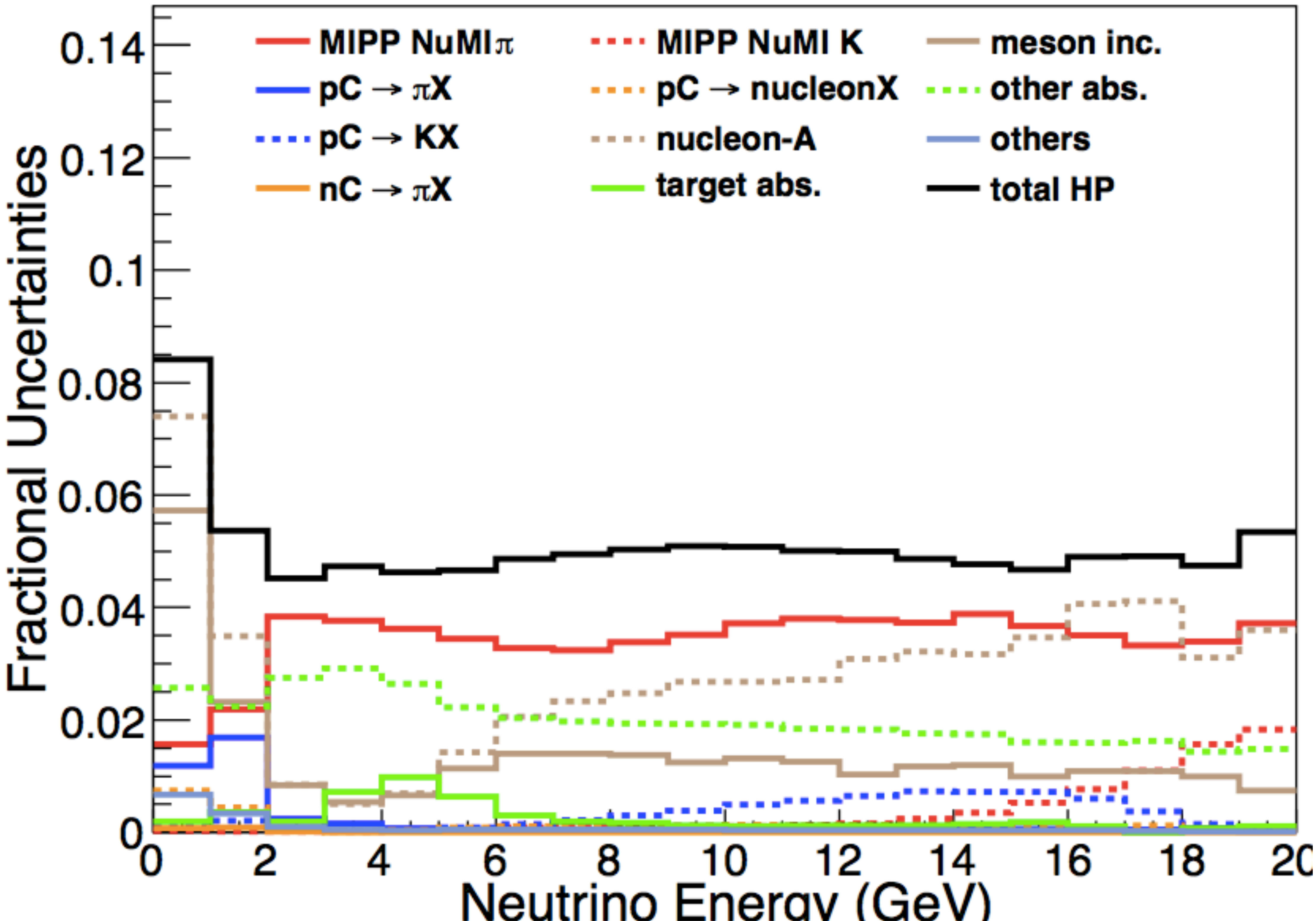
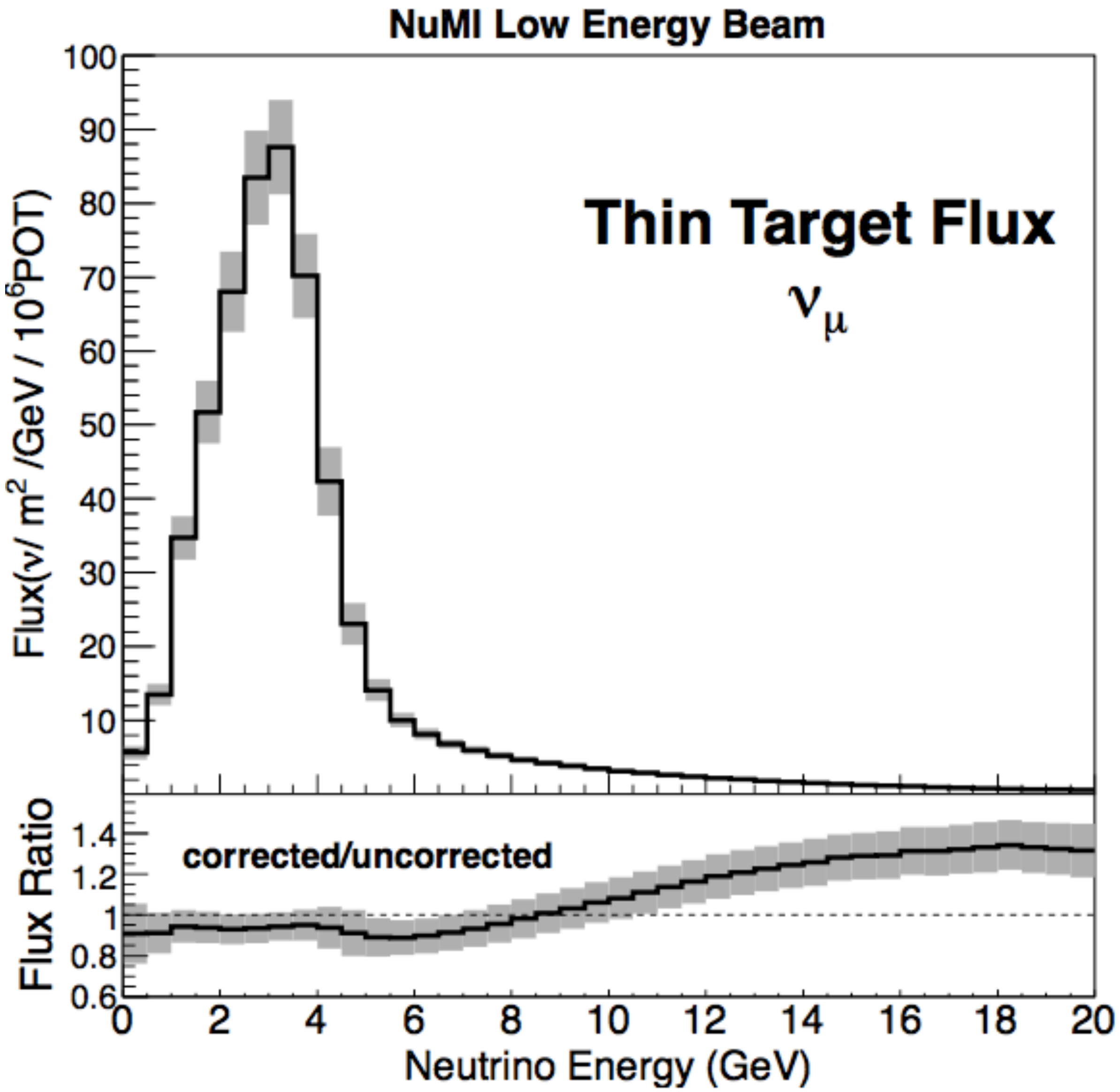
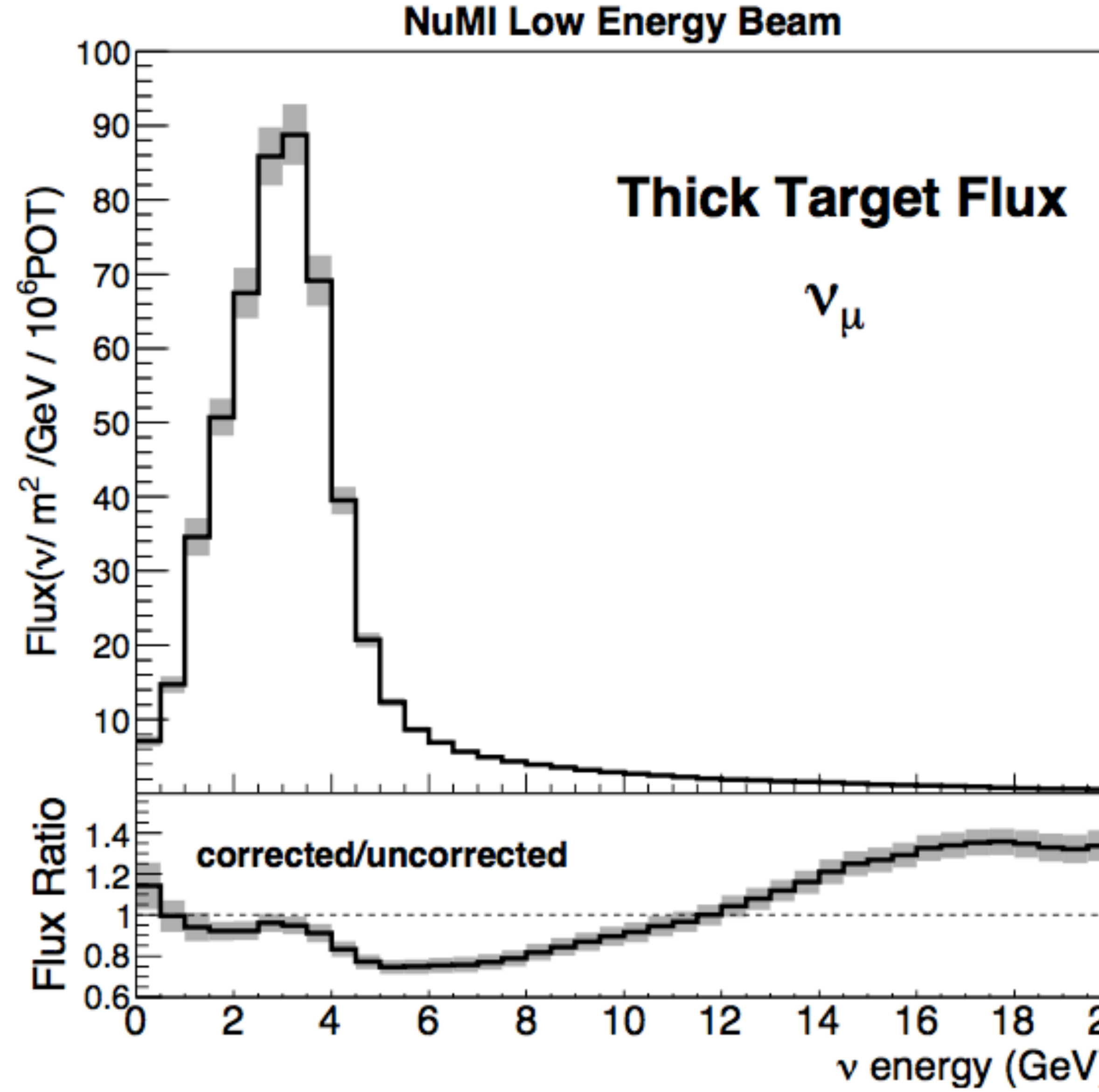


"Neutrino flux predictions for the NuMI beam", L. Aliaga et al (MINERvA Collaboration), Phys. Rev. D 94, 092005 (2016)

One flux from four data sources





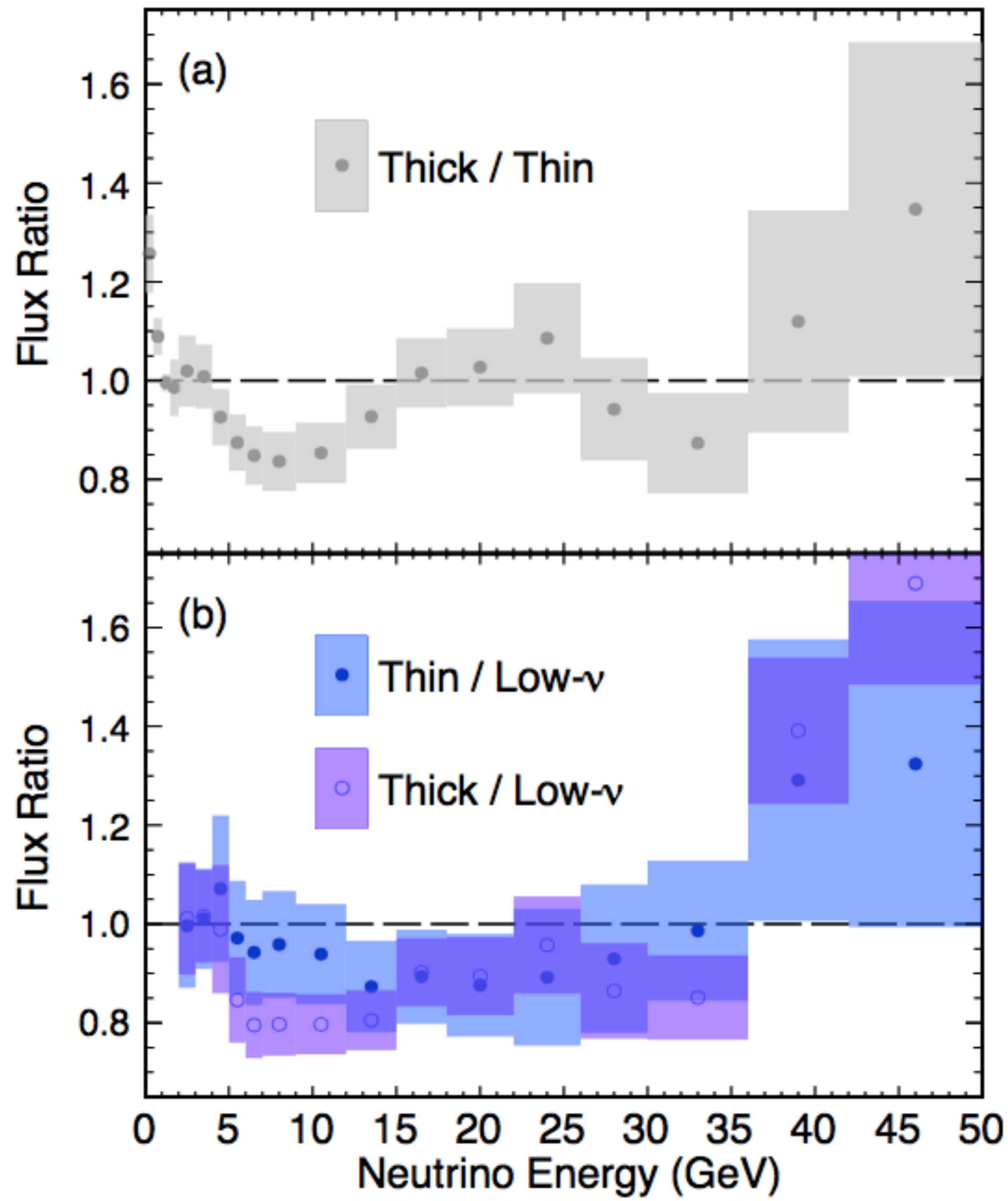
Two well motivated fluxes, how to choose?

"Neutrino flux predictions for the NuMI beam", L. Aliaga et al (MINERvA Collaboration), Phys. Rev. D 94, 092005 (2016)

One flux from four data sources

Well developed internal lever arms, like low-ν, can allow us to disentangle conflicting external data motivated flux.

We can't just blindly rely on external data, we need internal crosschecks to test and validate our flux.

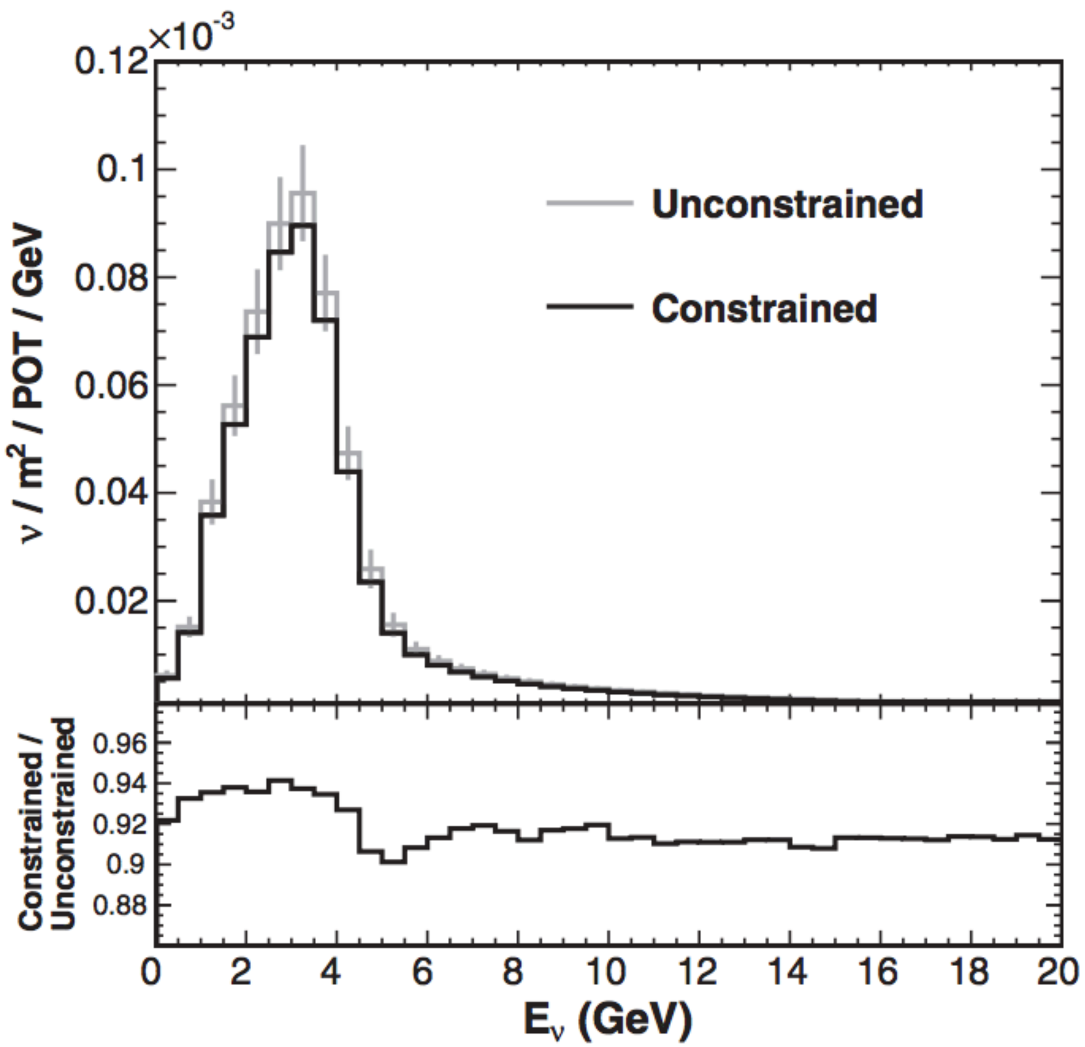


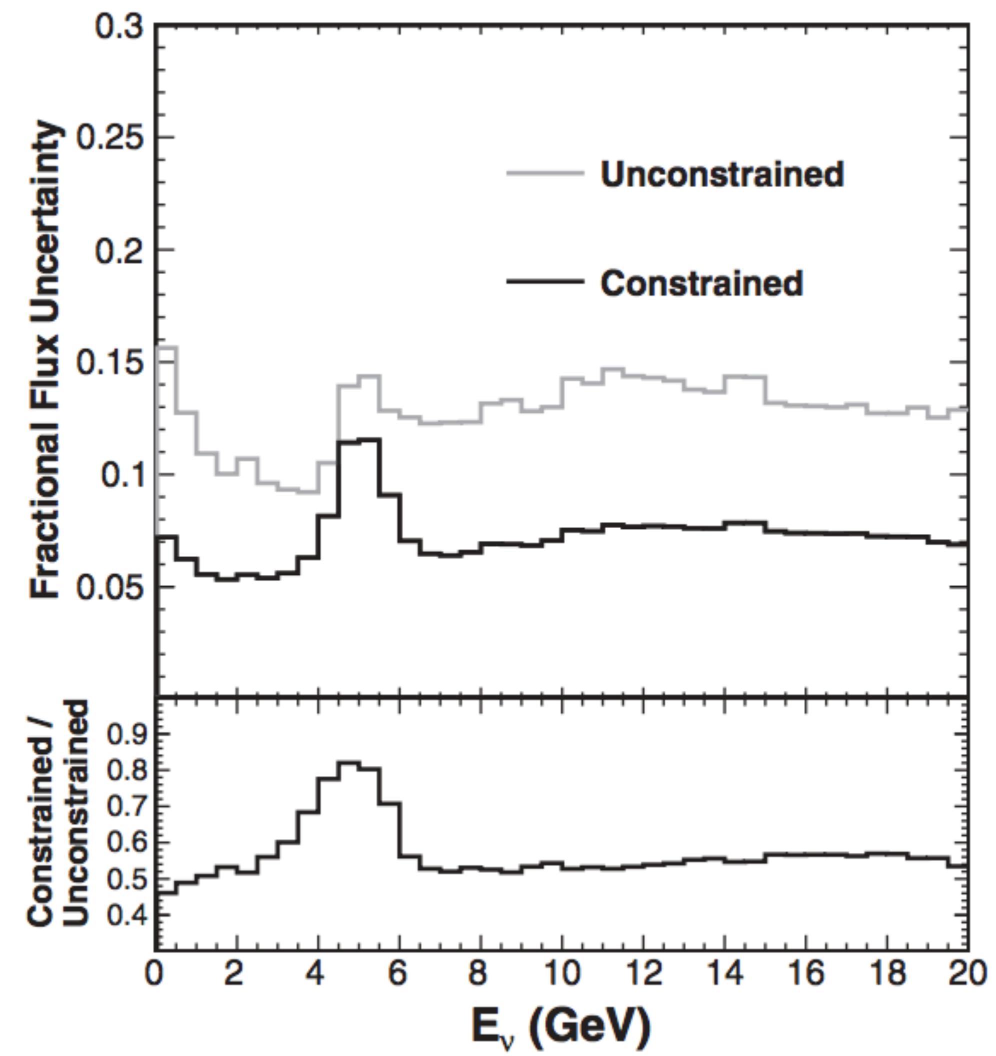
“Neutrino flux predictions for the NuMI beam”, L. Aliaga et al (MINERvA Collaboration), Phys. Rev. D 94, 092005 (2016)

“Measurements of the inclusive neutrino and antineutrino charged current cross sections in MINERvA using the low-ν flux method”, J. Devan et al. (The MINERvA Collaboration) Phys. Rev. D 94, 112007 (2016)

One flux from four data sources

Others, like ν on e scattering, can be combined with external constraints to produce a flux prediction with an even lower (normalization) uncertainty.





"Measurement of neutrino flux from neutrino-electron elastic scattering", J. Park et al. (MINERvA Collaboration), Phys. Rev. D 93, 112007 (2016)

Summary

Fixed target measurements, thin and thick, have proven to be the most powerful tool we have to constrain our flux. Cornerstone of excellent work at MiniBooNE*, T2K**, and MINERvA***.

Whilst thin and thick target experiments like HARP/NA49/MIPP/NA61 give us strong constraints on our hadron yield but we need other methods to check that their data is consistent with our own.

Future precision experiments, like DUNE, are pursuing using existing thin target data, supporting their own thick target experiment (USNA61), and developing analysis tools to test their flux with their own data (in particular ν on e scattering). It's vital that all these lines of effort continue to grow to reach the precision DUNE is targeting.

*"Neutrino flux prediction at MiniBooNE", A. A. Aguilar-Arevalo et al. (MiniBooNE Collaboration), Phys. Rev. D 79, 072002 (2009)
**"T2K neutrino flux prediction", K. Abe et al. (T2K Collaboration), Phys Rev. D 87, 012001 (2013)
***"Neutrino flux predictions for the NuMI beam", L. Aliaga et al (MINERvA Collaboration), Phys. Rev. D 94, 092005 (2016)