Future Neutrino-Nucleus Deep Inelastic Scattering in the MINERvA Detector

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On behalf of the MINERvA collaboration
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DIS 2015

Nuclear Structure Functions

The nuclear environment is not a simple place. There are nuclear effects that take *nucleon* structure functions and change them into *nuclear* structure functions.

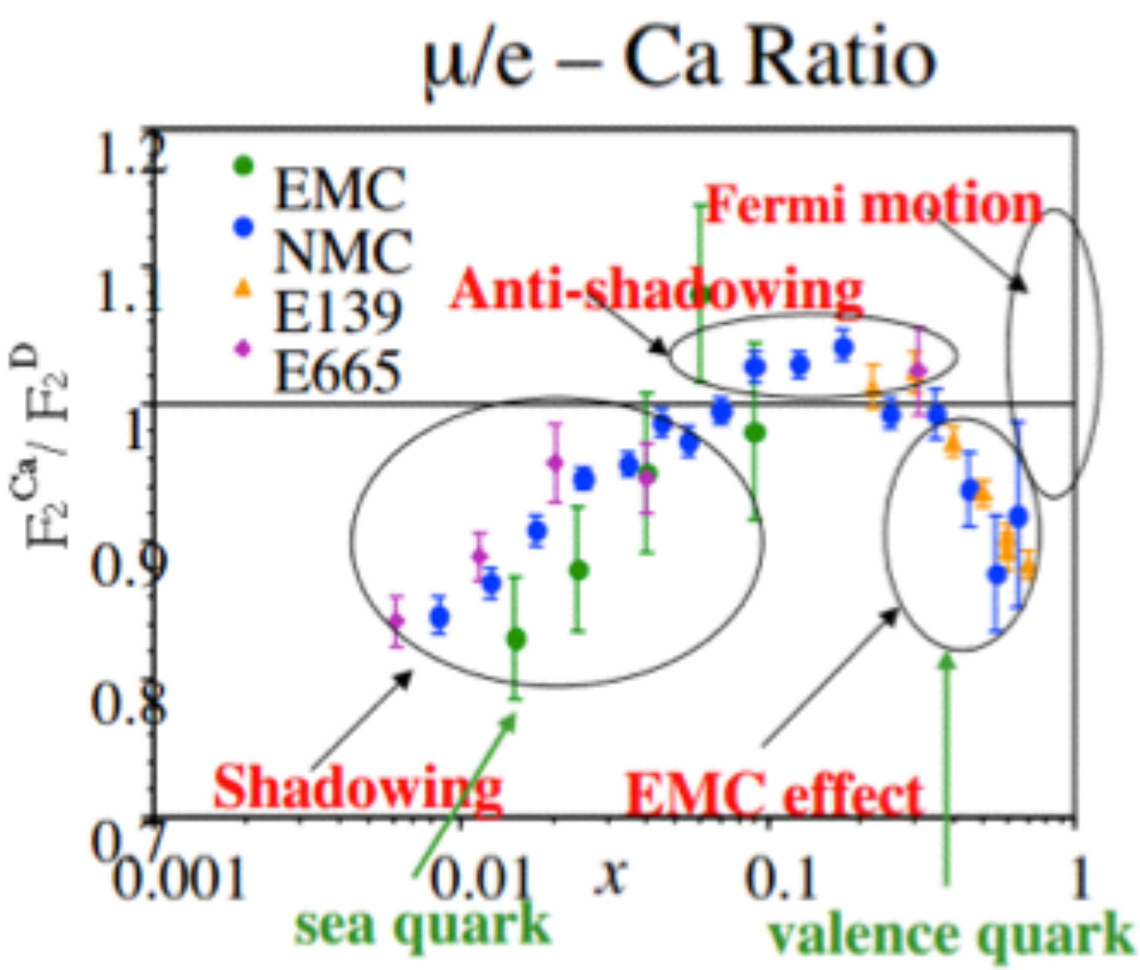
The neutrino cross section can be broken down and described in three functions.

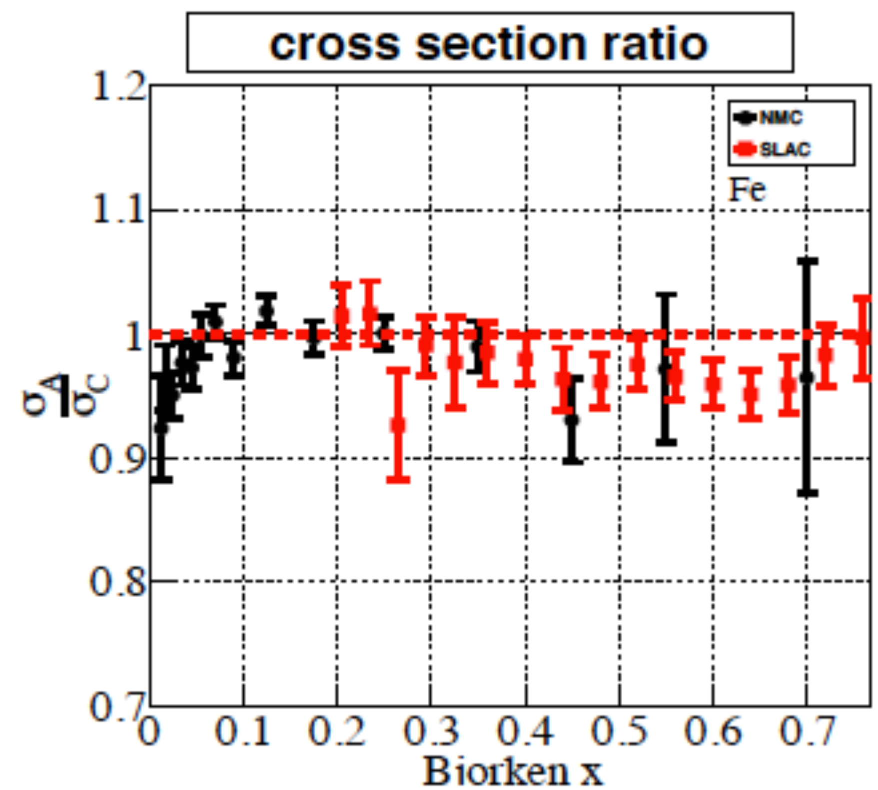
$$\frac{d^2\sigma^{\nu(\bar{\nu})A}}{dxdy} = \frac{G_F^2 M E_\nu}{\pi(1+Q^2/M_W^2)}\left[\frac{y^2}{2}2x\boxed{F_1^{\nu(\bar{\nu})A}} + \left(1-y-\frac{Mxy}{2E_\nu}\right)\boxed{F_2^{\nu(\bar{\nu})A}} \pm y\left(1-\frac{y}{2}\right)\boxed{xF_3^{\nu(\bar{\nu})A}}\right]$$

F_1 can be expressed in terms of F_2 and a ratio R, leaving only F_2 and F_3. By adding and subtracting the cross sections of neutrinos and anti-neutrinos, we can extract the structure functions and help describe the structure of nuclei.

$$2F_2 \propto \sigma_\nu + \sigma_{\bar{\nu}} \qquad\qquad 2xF_3 \propto \sigma_\nu - \sigma_{\bar{\nu}}$$

Why Lepton DIS?





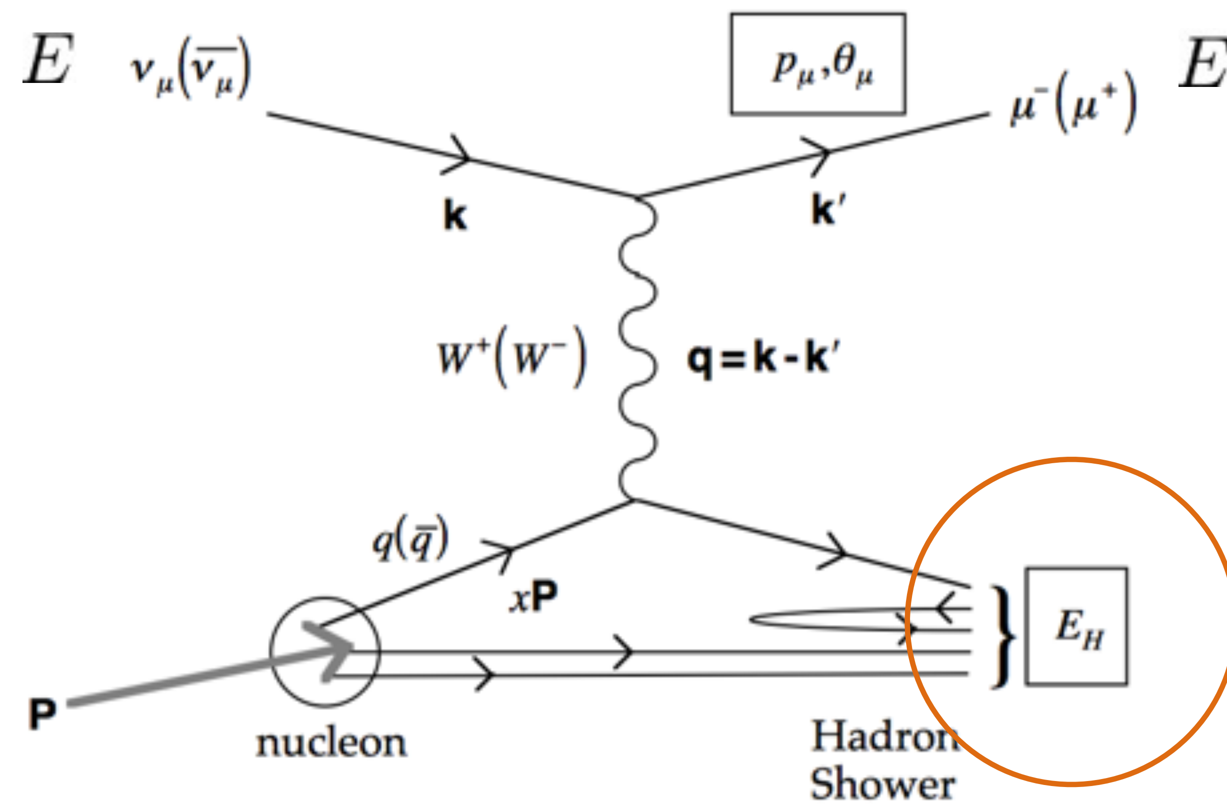
Data from the two charged lepton scattering experiments on Iron

- Lepton-hadron scattering tests the quark-parton model.
- The quark-parton model was created to provide a simple physical picture that explained Bjorken Scaling.
- Must be built up into looking at real hadronic systems, rather than free quarks.
- It was initially investigated with charged-lepton interactions leading to intriguing measurements of ratios of A/D as a function of x.

$$x = \frac{Q^2}{2m\nu}$$

Neutrino Induced DIS

- Charged Current neutrino inelastic scattering exchanges a W boson, as opposed to a photon.
- The V-A structure of the scattering current projects left handed particles and right handed anti-particles.
- This leads to a non-zero F_3, as parity is violated in the weak interaction.

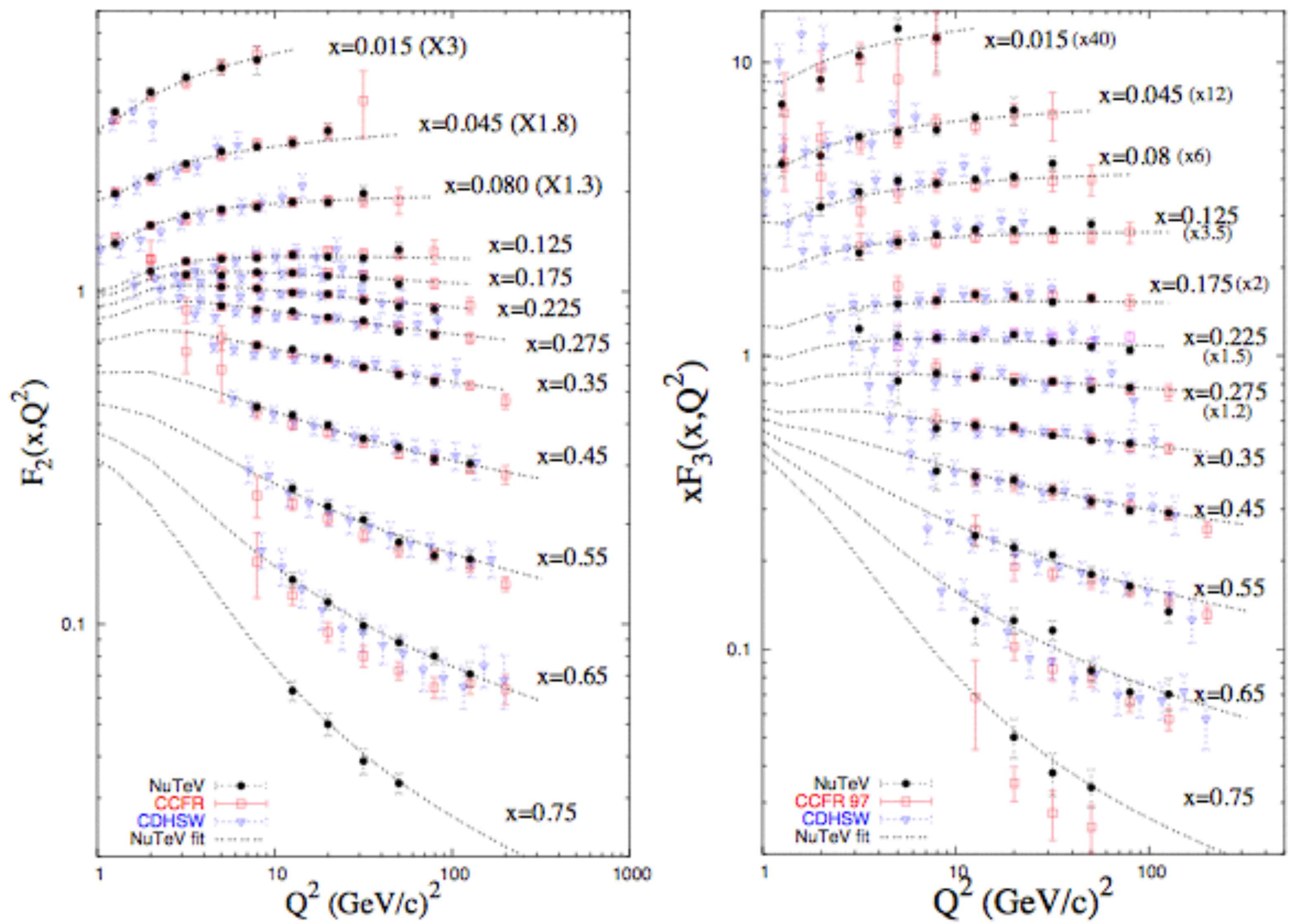


$$xF_3^{\nu,\bar{\nu}}(x,y) = 2\sum_i (q_i(x) - \bar{q}_i(x))$$

$$F_2^{\nu,\bar{\nu}}(x,y) = 2\sum_i (q_i(x) + \bar{q}_i(x))$$

Nuclear Structure Function Analysis

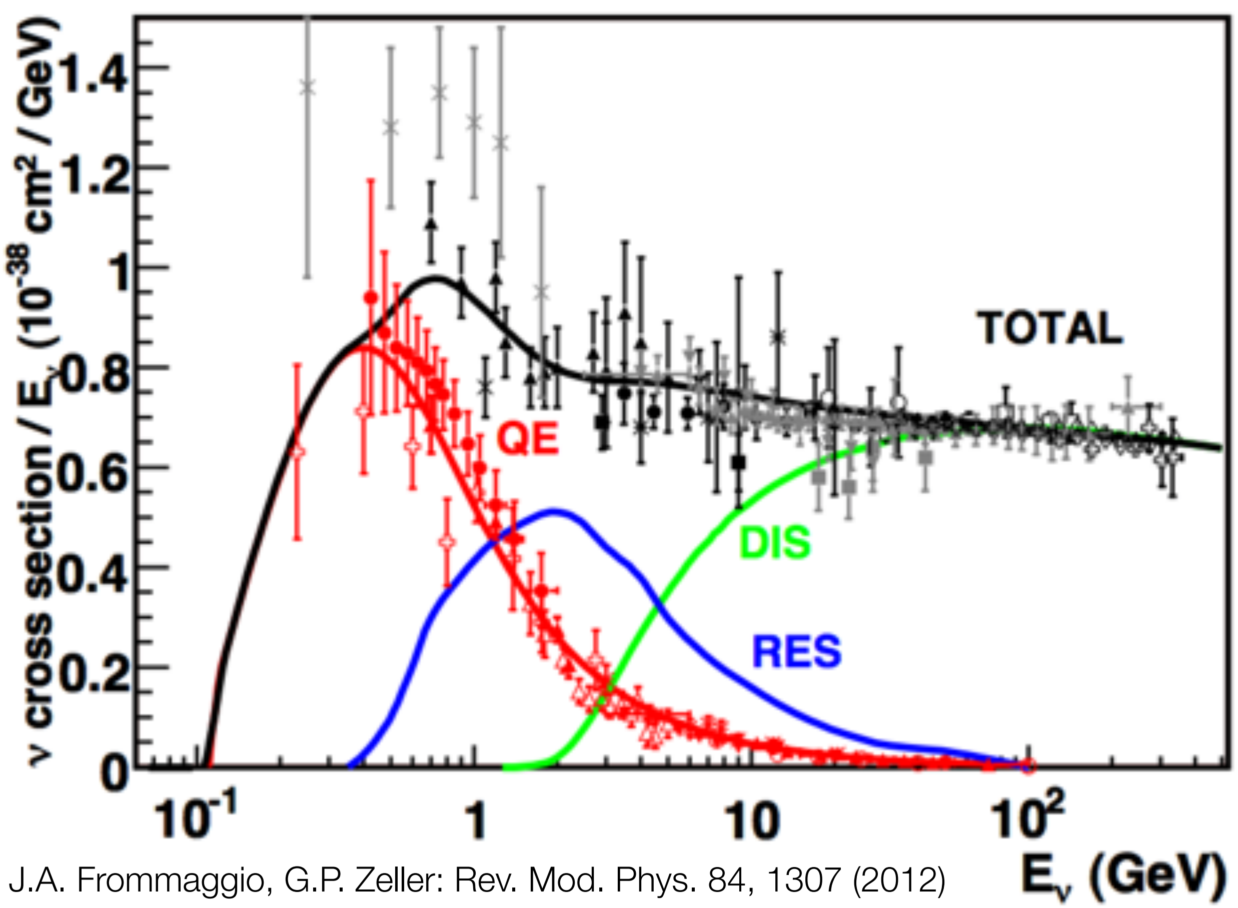
- The Nuclear Structure Function analyses use the difference and sums of neutrino and anti-neutrino cross sections.
- These are two dimensional analyses, where we need to look at the cross section with respect to x and Q^2.
- This means that we require high statistics in order to have reasonable statistics across the accessible x and Q^2 range.
- Particularly important for future CP violation experiments that will require both neutrinos and anti-neutrinos. Any differences in the way that neutrinos and anti-neutrinos interact with nuclei become important when doing precision science.



Results from the NuTeV Experiment for both F_2 and xF_3

NuTeV Cross Section and Structure Function Measurements, ***D. Naples, NuTeV (NuTeV)***, arXiv:hep-ex/0307005, 2003. DIS03, St. Petersburg, Russia, April 2003.

Neutrino Interaction Types

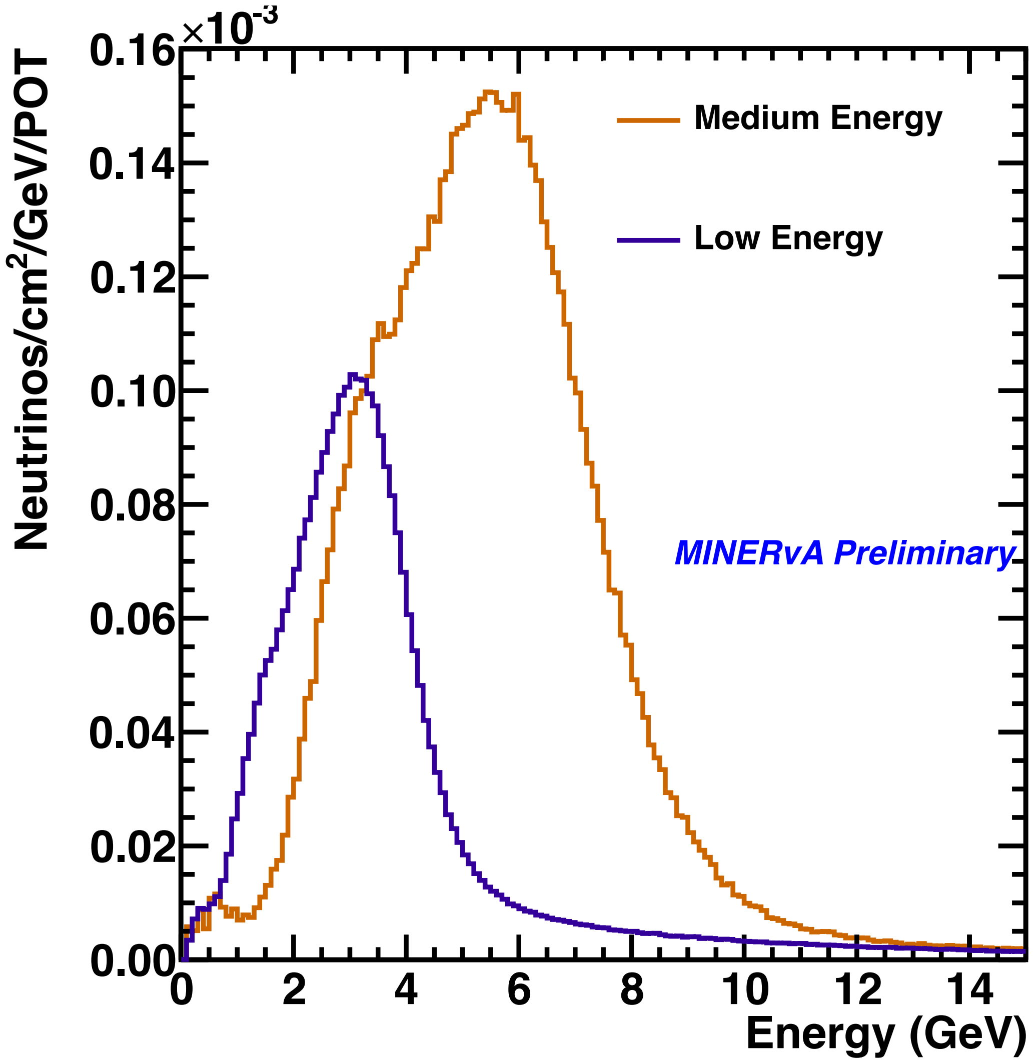


J.A. Frommaggio, G.P. Zeller: Rev. Mod. Phys. 84, 1307 (2012)

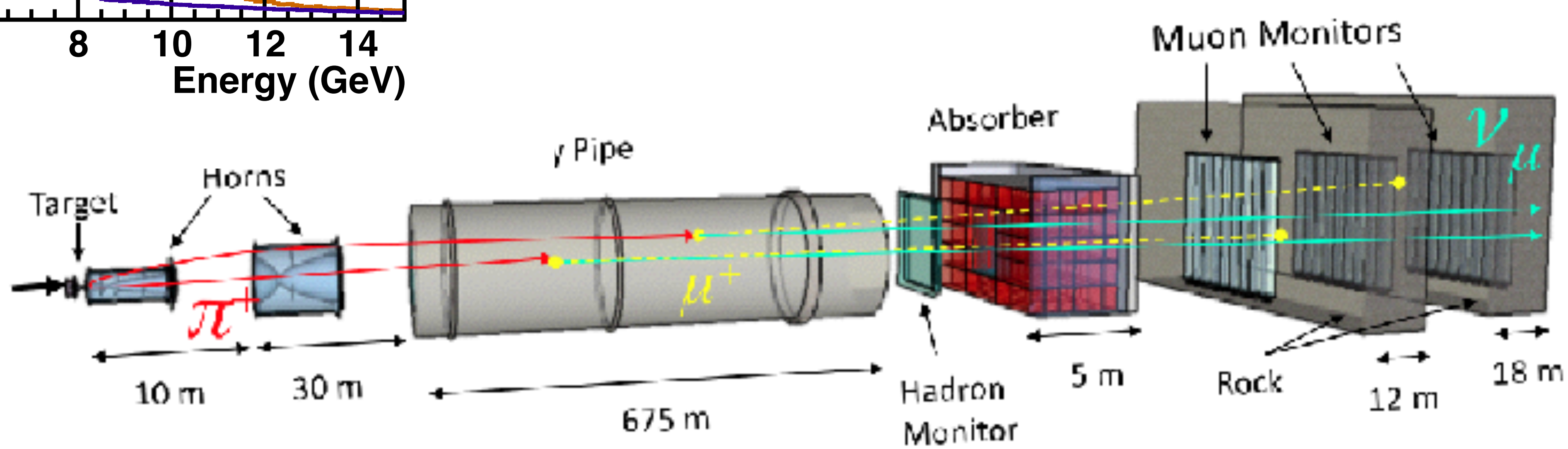
- Quasi-Elastic Scattering: Varying experimental definitions, but well measured over a range of energies.
- Inclusive Cross Sections: measurements taken at higher energies.
- Notably absent are measurements of the Resonant or DIS cross sections in the ~2-20 GeV region

NuMI Beam at Fermilab

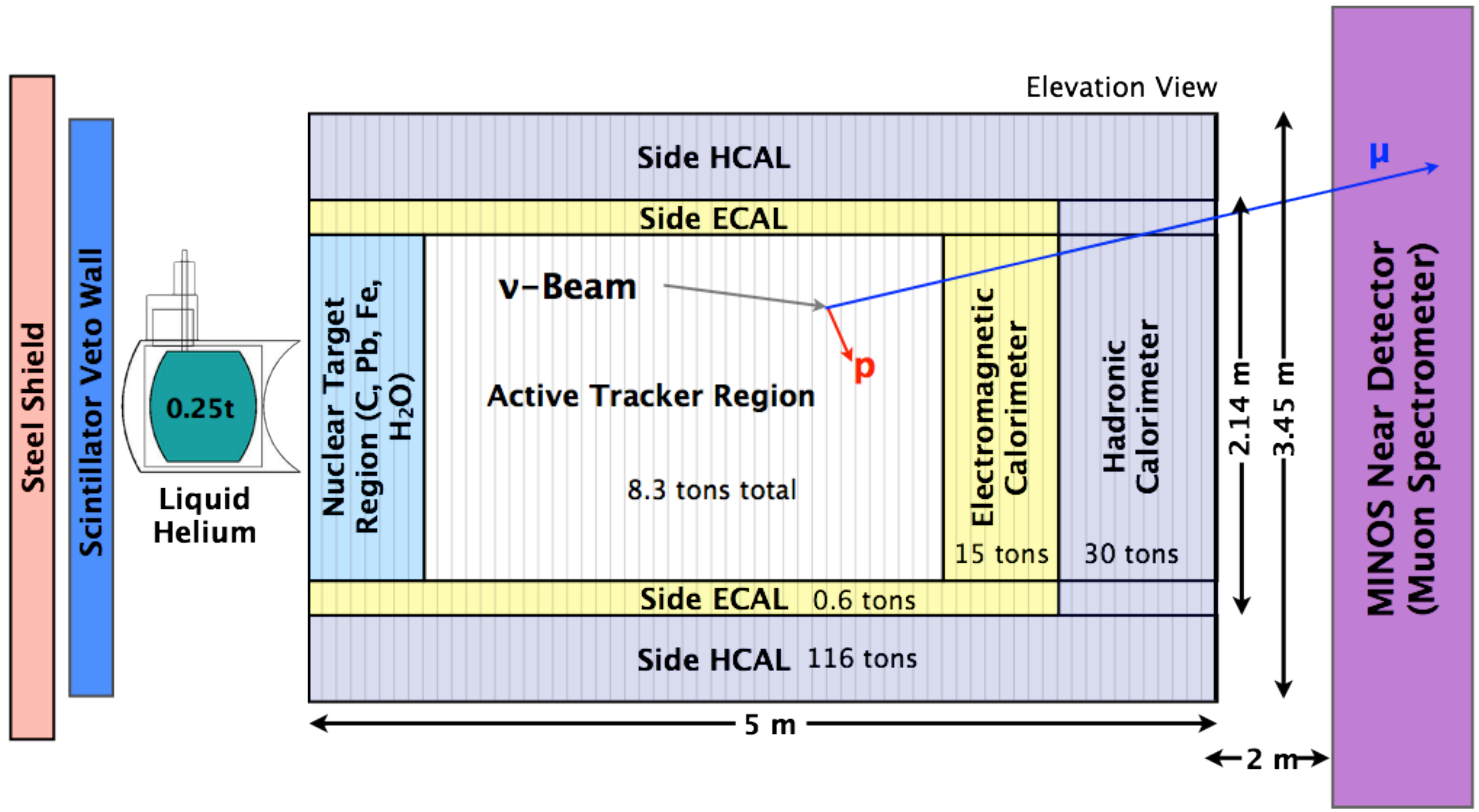
MINERvA Neutrino Flux Spectrum



- 120 GeV Protons from the Main Injector collide with a ~1m graphite target.
- Both the target and the second magnetic horn can be moved to change the energy of the beam.



The MINERvA Experiment

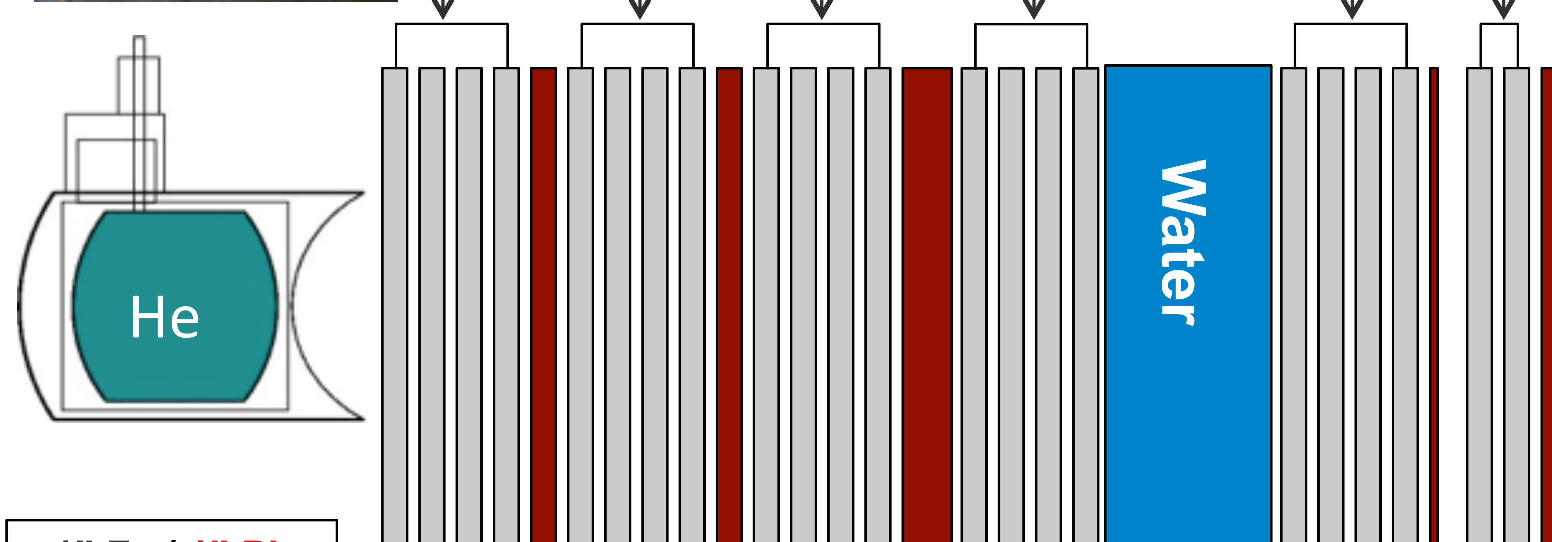


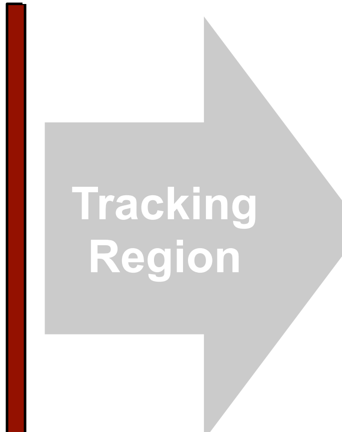
- MINERvA is a fine-grained tracking detector located in the NuMI beam line at Fermilab.
- We aim to precisely measure neutrino cross sections on multiple nuclear targets to better understand nuclear structure, and to reduce systematics for oscillation measurements.
- Multiple nuclear targets at the front of our detector allow us to make simultaneous measurements on different nuclei in the same detector, and the same beam line.
- MINERvA took data in the Low-Energy beam configuration from 2010-2012. We started taking data in the Medium Energy configuration in 2013.

Nuclear Target Regions

With our tracker region, we will be able to make a high statistics measurements of neutrino cross section on scintillator. ~500 kg in tracker.

250 kg
Liquid He





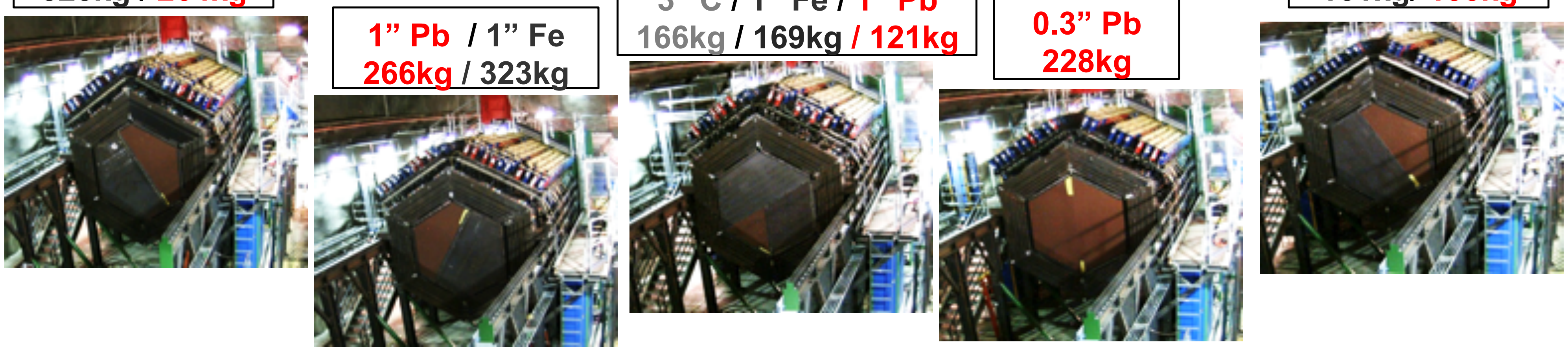
1” Fe / 1” Pb
323kg / 264kg

1” Pb / 1” Fe
266kg / 323kg

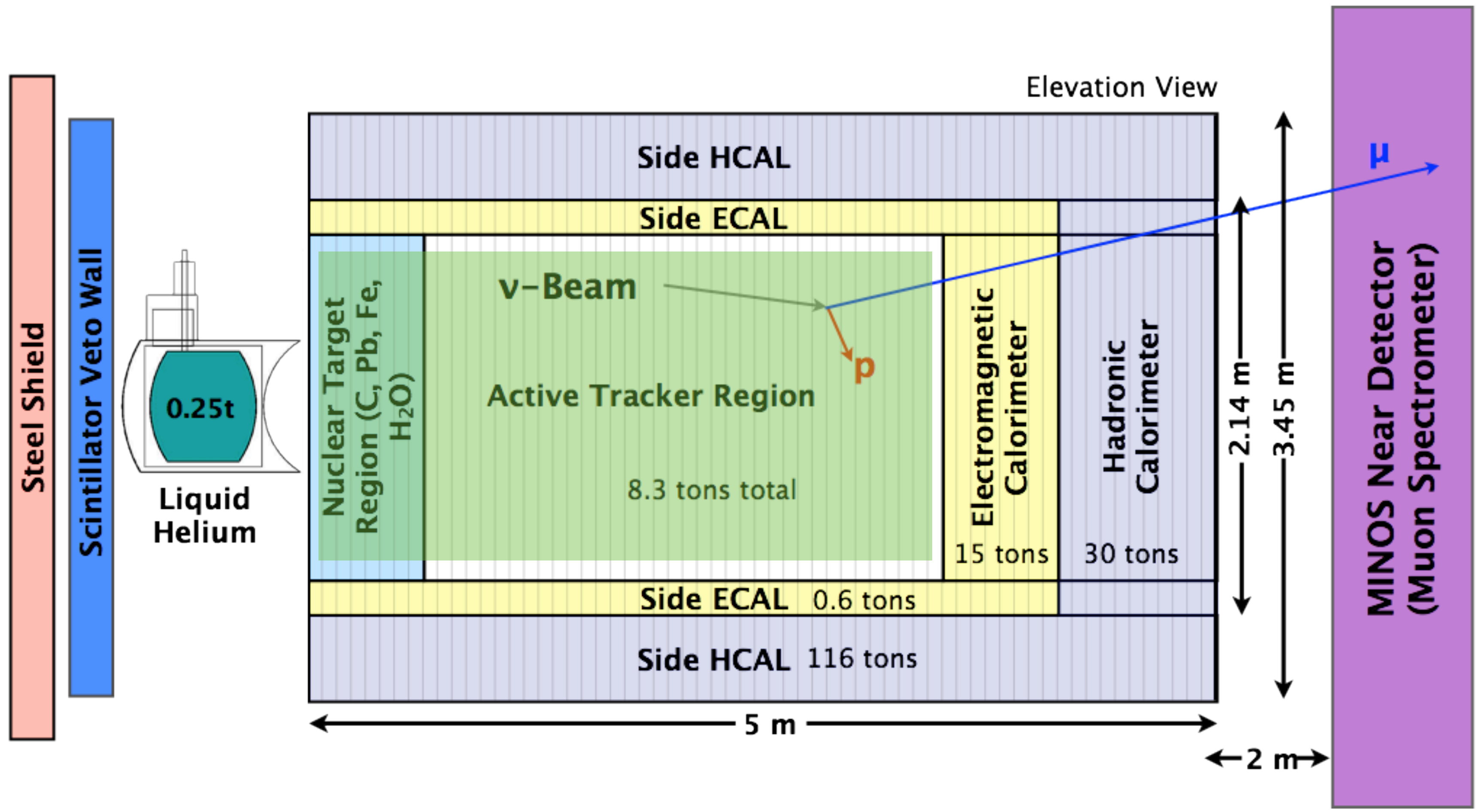
3” C / 1” Fe / 1” Pb
166kg / 169kg / 121kg

0.3” Pb
228kg

.5” Fe / .5” Pb
161kg/ 135kg



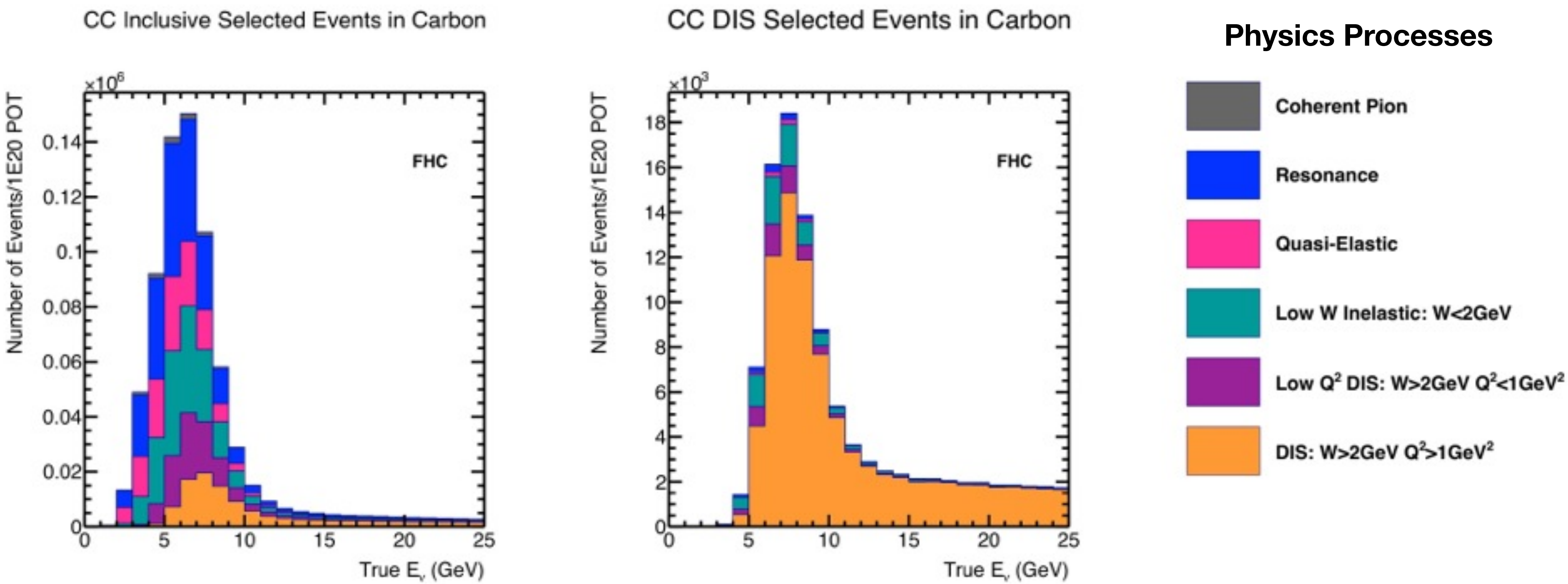
Sample Selection



- Fiducial Volume Cut: Events away from the edges
- Muon produced in the event must leave our detector and be charge and momentum selected in the MINOS spectrometer.
- Momentum transfer $Q^2 > 1$ GeV^2
- Invariant Hadronic Mass $W > 2$ GeV

Deep Inelastic Scattering in MINERvA

True Composition of the Sample



All Events

Selected DIS

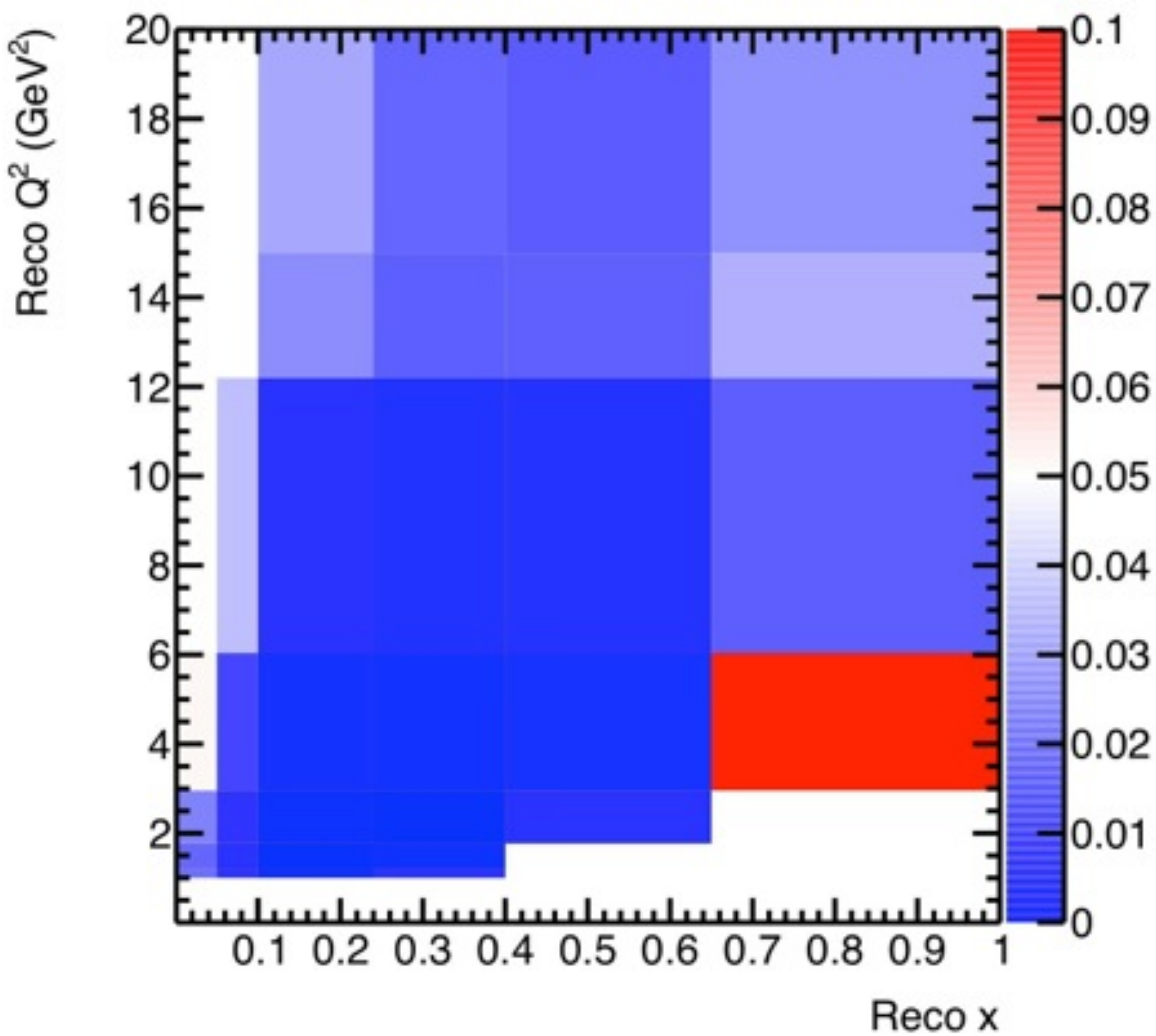
Reconstructed $Q^2 > 1$ GeV^2

Reconstructed $W > 2$ GeV

Nuclear Structure Function Errors: Iron

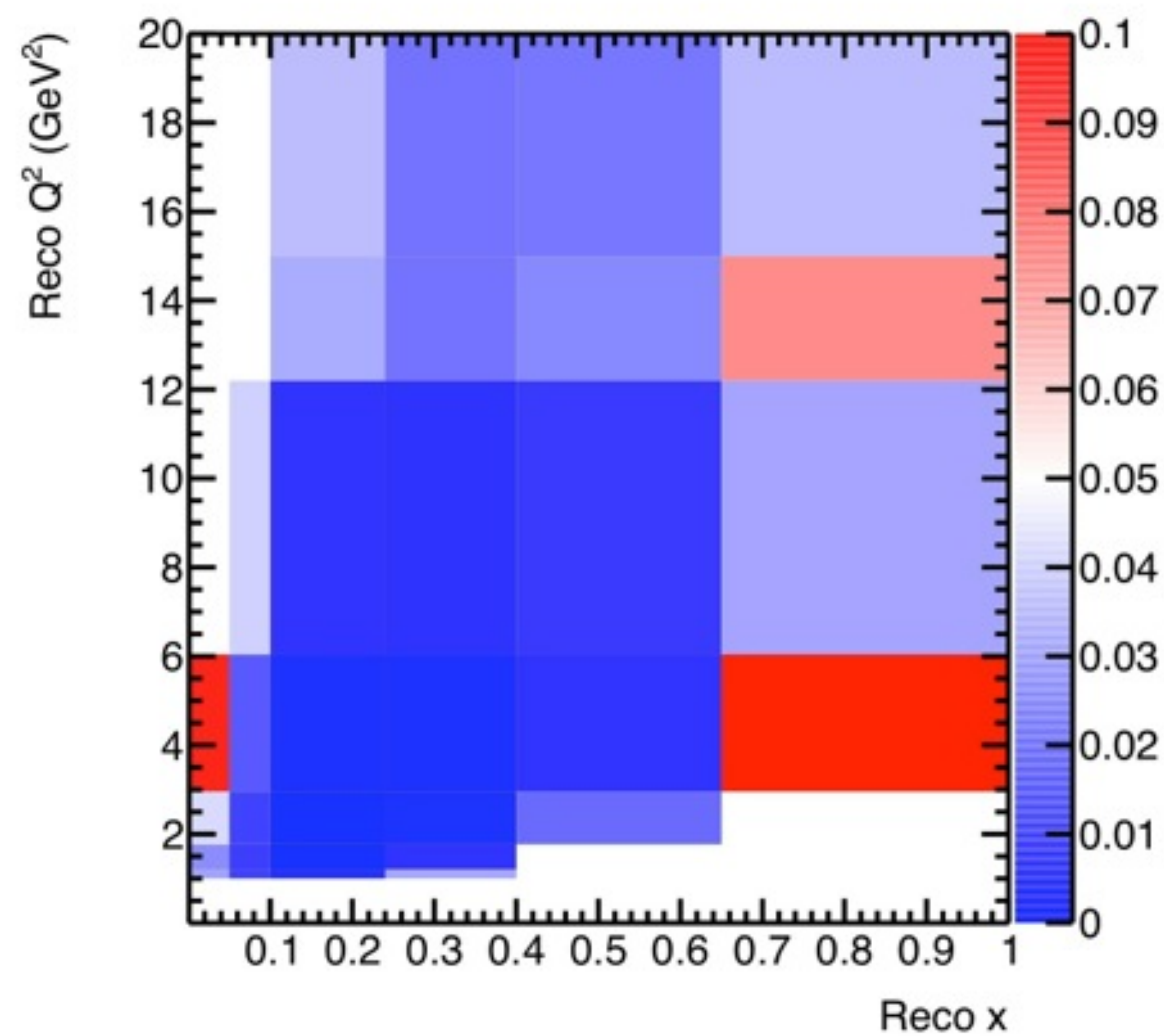
Fractional Stat Uncertainty on

$$F_2 \propto \sigma_\nu + \sigma_{\bar{\nu}}$$



Fractional Stat Uncertainty on

$$xF_3 \propto \sigma_\nu - \sigma_{\bar{\nu}}$$



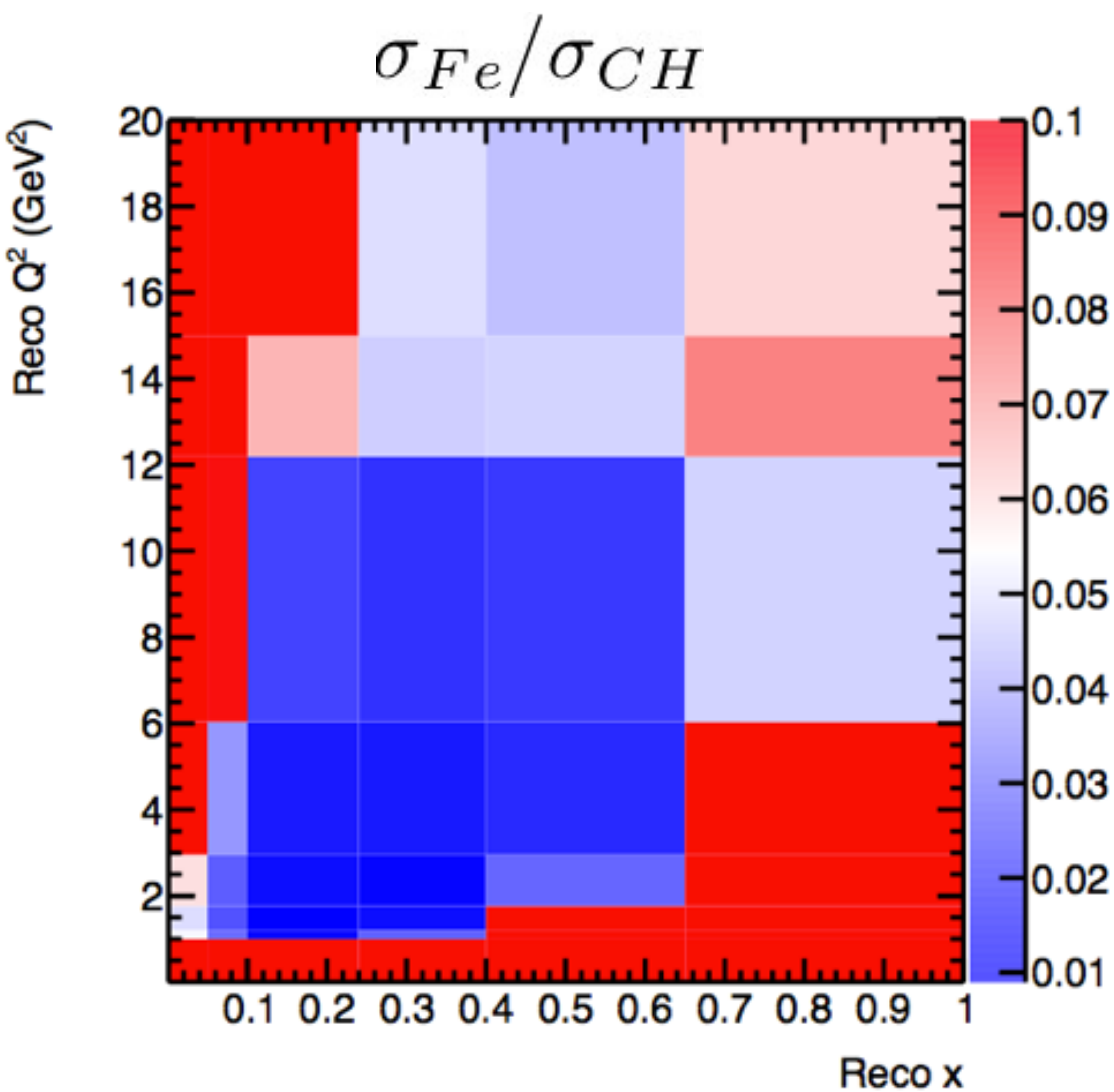
12E20 POT Exposure

Ratio Analysis

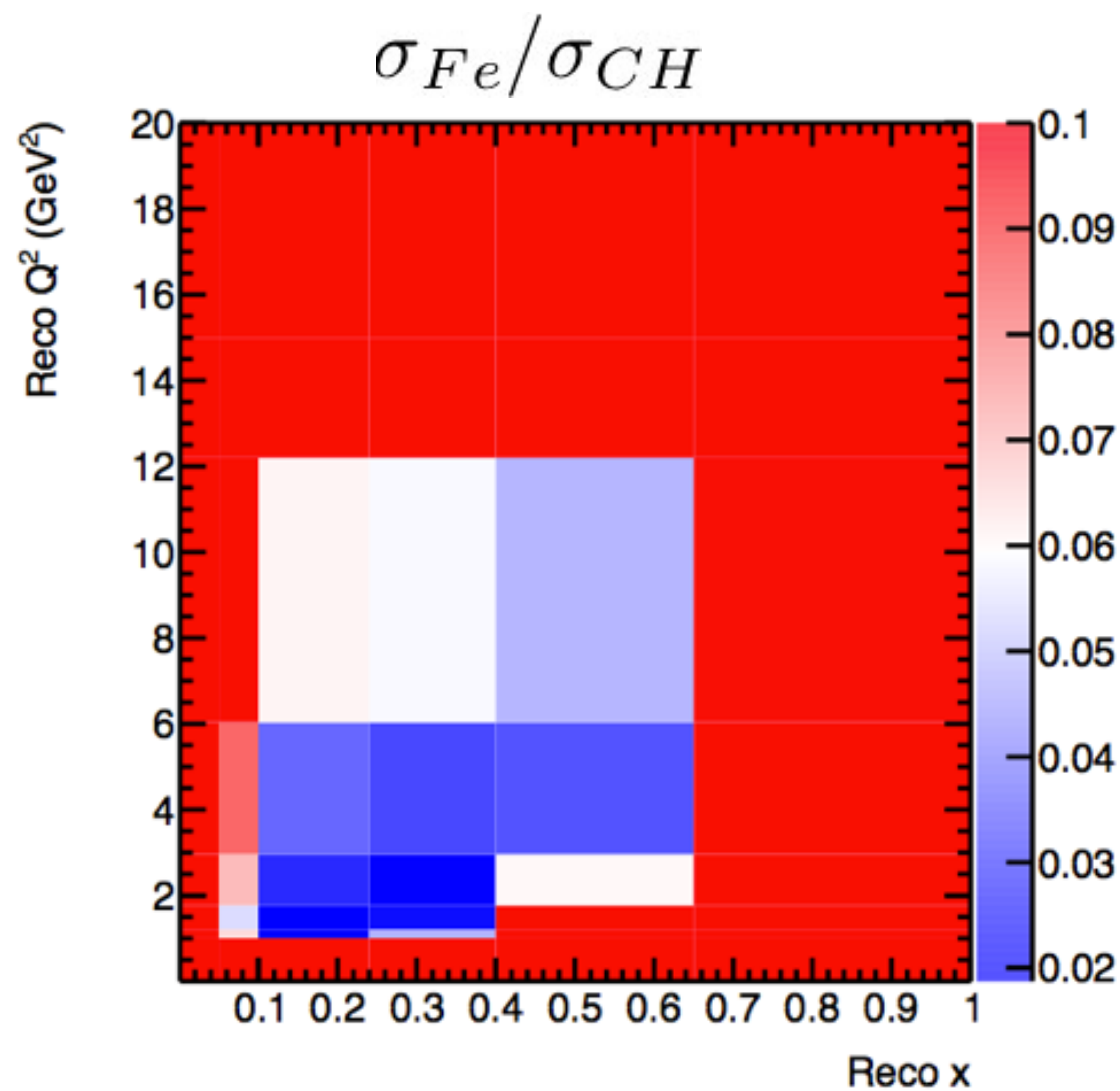
- Taking a ratio of our cross sections allows us to cancel many of our systematic errors, such as the error on our flux.
- This also allows us to compare more directly with data from charged lepton scattering experiments.

Ratio Analysis: Iron

Fractional Stat Uncertainty on Neutrino

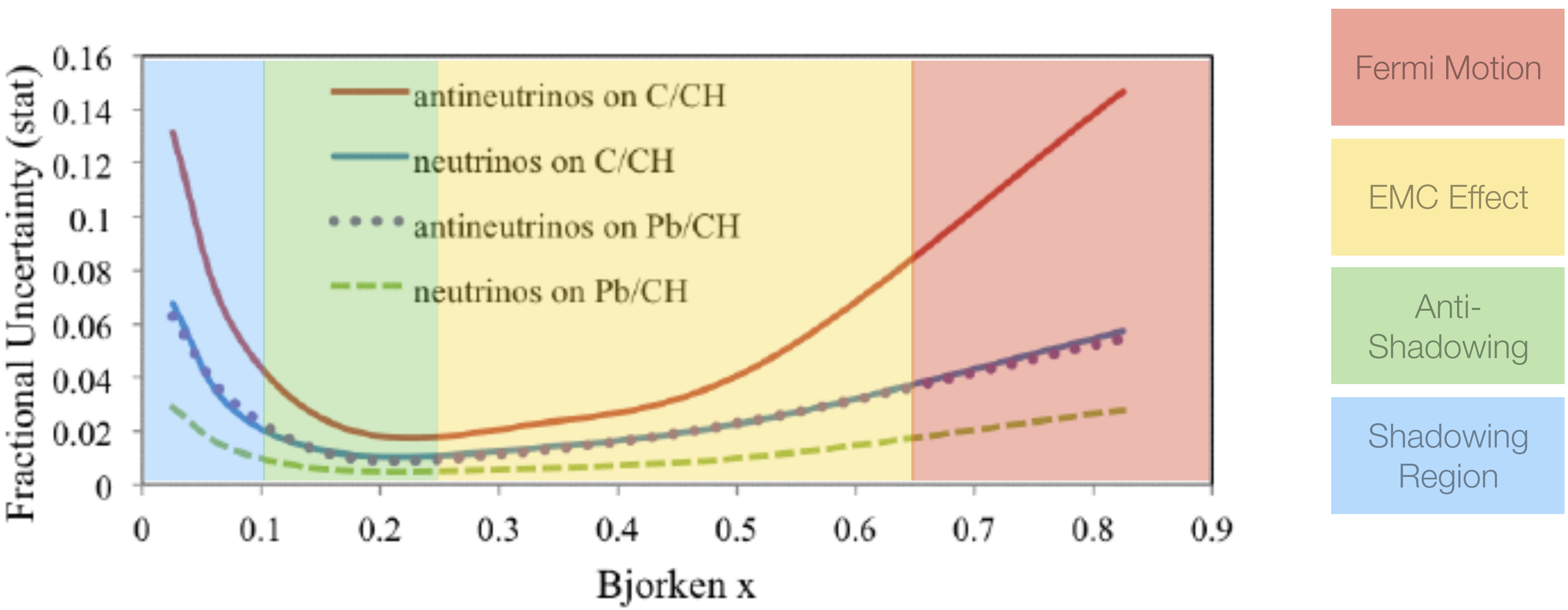


Fractional Stat Uncertainty on Anti-Neutrino



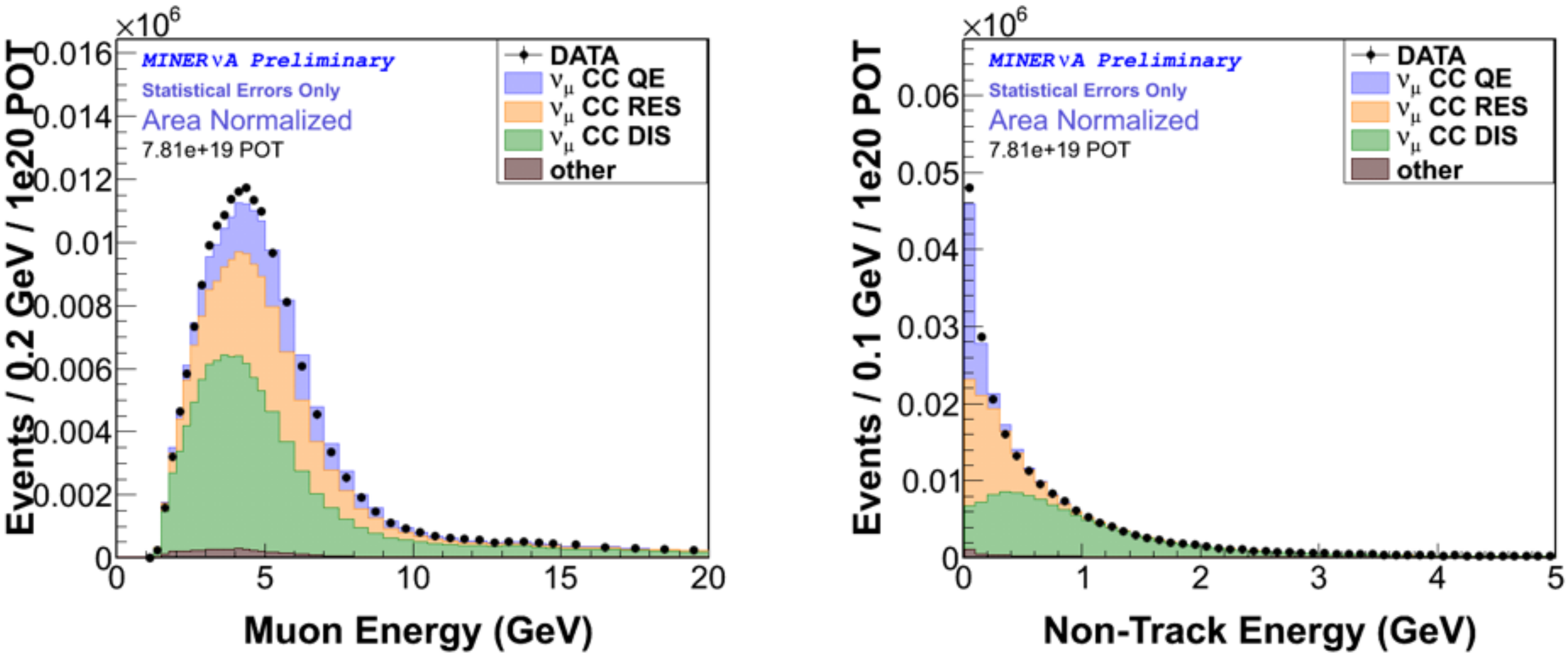
12E20 POT Exposure

Ratio Analysis: Iron



Integrated over Q^2, we can see that the fractional statistical error is less than 10% over a large range of Bjorken x, including the Anti-Shadowing and EMC Effect Region.

Where are we now?

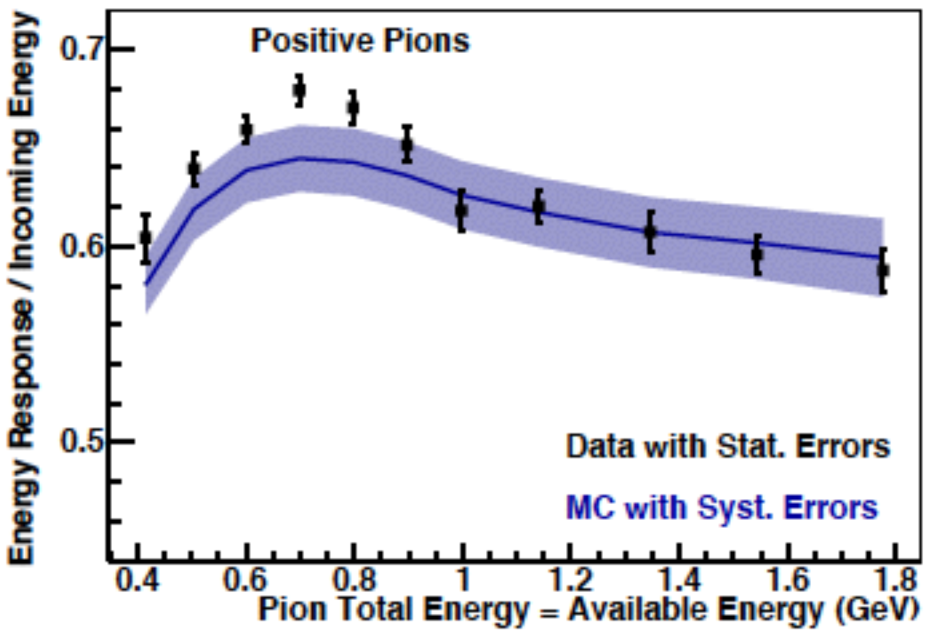


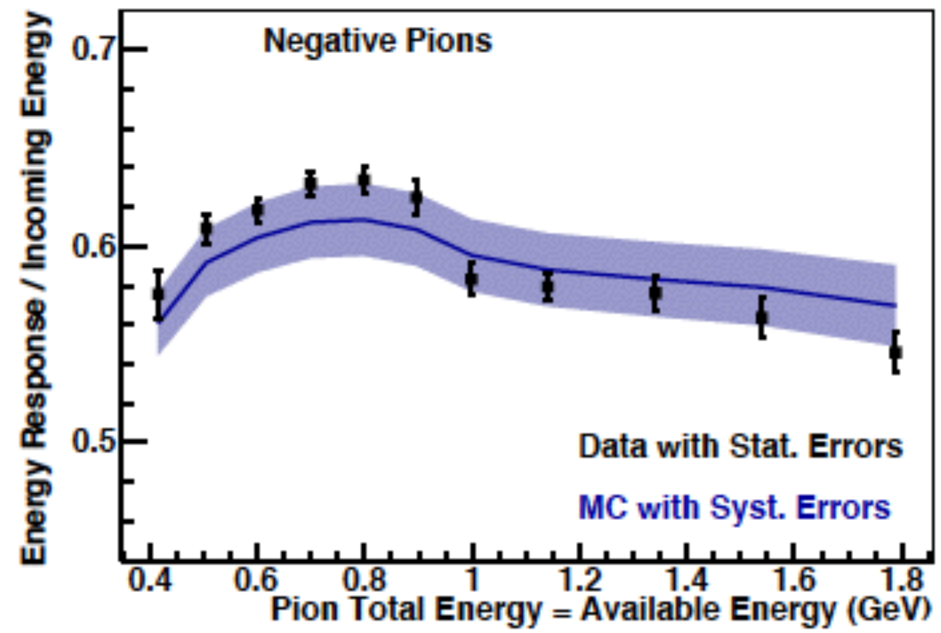
We already have over a million events taken in the Medium Energy Beam!

And we are on the way to more.

We continue a program to reduce our systematic error.

Test Beam Program

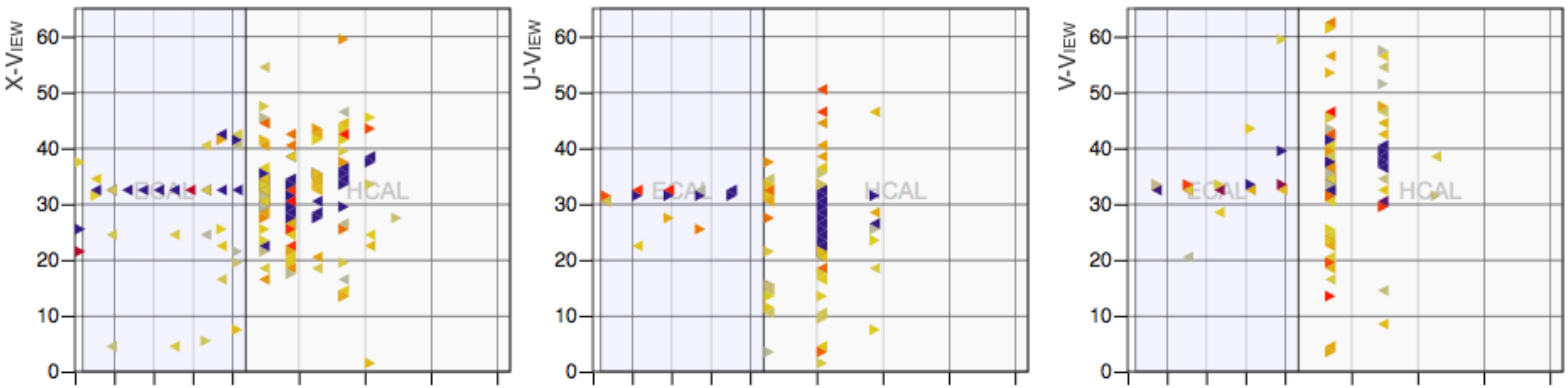




MINERvA neutrino detector response measured with test beam data, Nuclear Inst. and Methods in Physics Research, A 789 (2015), pp. 28-42

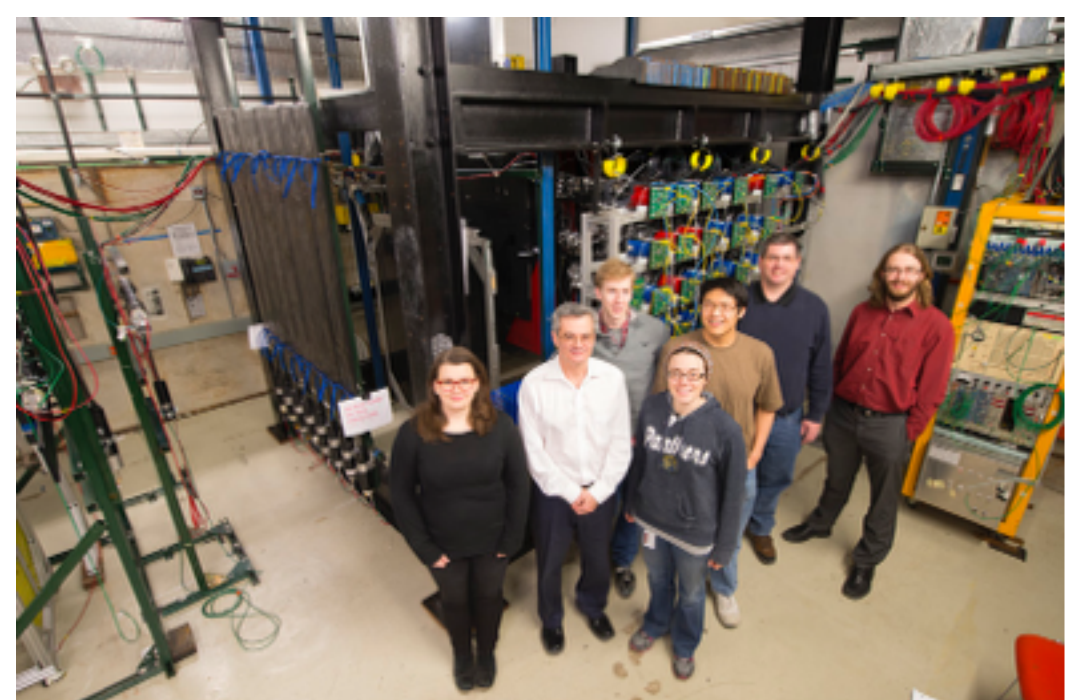
- As the energy of our beam increases, the average energy of the particles in our detector increases. Understanding the behavior of these particles in our detector is going to be very important to our Medium Energy Physics.
- We take data with a small version of our detector in a hadron beam at Fermilab.
- In 2010, we ran this detector to look at the response of our detector to pions, protons and electrons. However, that data was pions, protons and electrons less than 2 GeV in energy.
- We are currently running another test beam program with the same detector to look at higher energy particles, up to 8 GeV.

Test Beam Events



Test Beam Pion Event in the HCAL

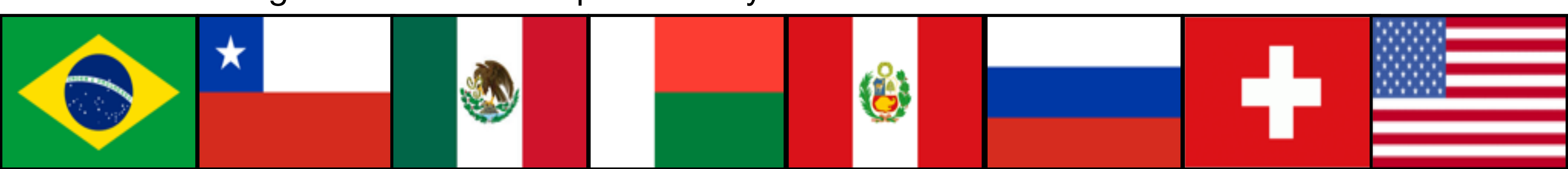
- Take a beam of hadrons of known type and momentum and use them to study our overall hadronic energy scale and to study the shower shapes of pions, protons and electrons.



Conclusion

- This is the first experiment that is able to do precision measurements studying neutrino deep inelastic scattering simultaneously on multiple nuclear targets.
- We are currently taking neutrino scattering data using the Medium Energy beam. We have half of the necessary neutrino data on disk, and hope to start taking anti-neutrino data in the next year. We continue to work on reducing our systematic uncertainties.
- Stay tuned for our future results!
- **Acknowledgements**

    - Thank you to my advisor Professor Jeffrey Nelson, and the entire MINERvA collaboration.
    - Our collaboration consists of approximately 80 nuclear and particle physicists from 22 institutions on three continents.
    - Funding for MINERvA is provided by the Department of Energy.
    - Funding for this work was provided by the National Science Foundation

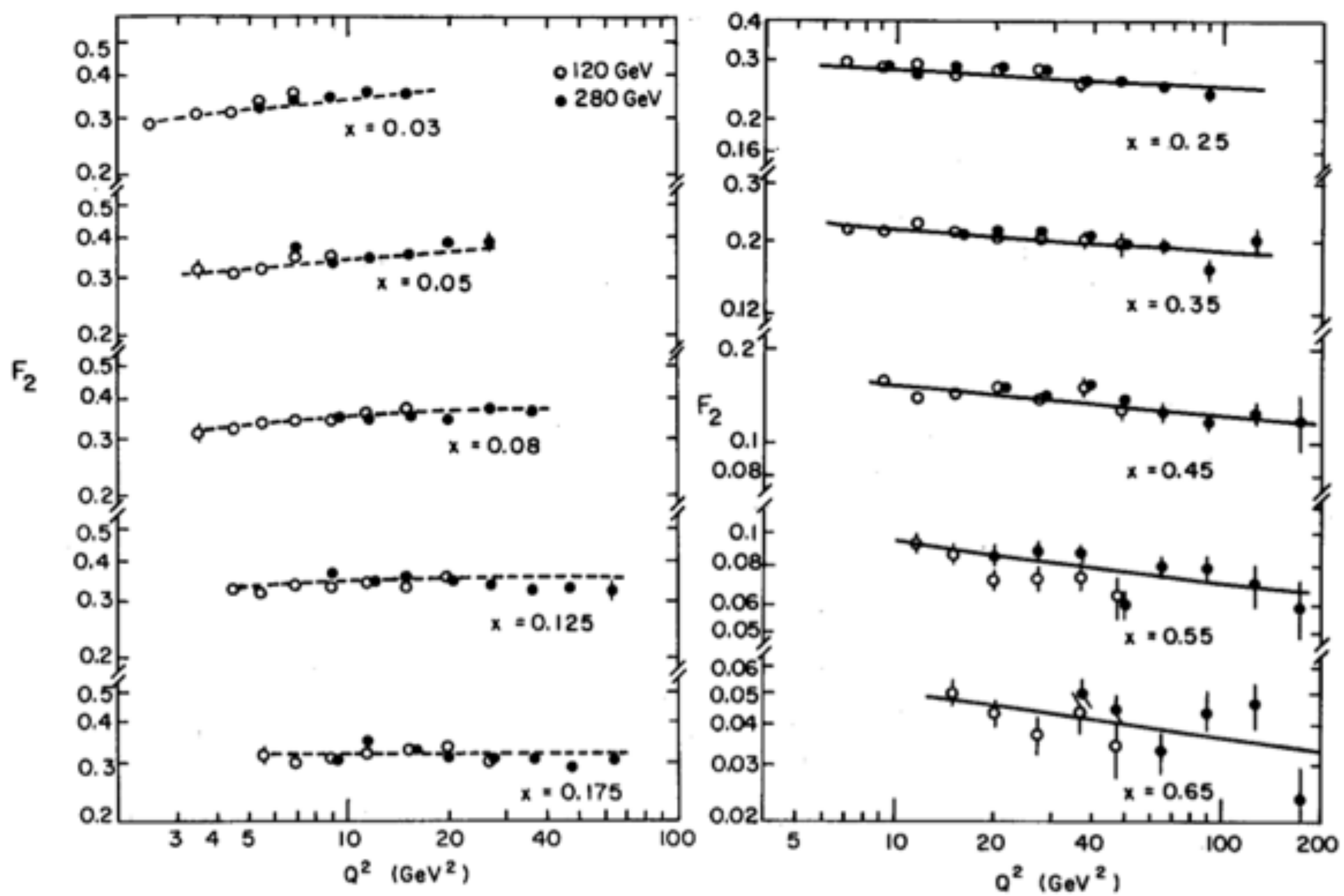


Backup

MINERvA Publications

- Single Neutral Pion Production: http://arxiv.org/abs/1503.02107
- Muon+Proton Final State: http://arxiv.org/abs/1409.4497
- Detector Response in Test Beam: http://arxiv.org/abs/1501.06431
- Coherent Pion Production: http://arxiv.org/abs/1409.3835
- Charged Pion Production: http://arxiv.org/abs/1406.6415
- Inclusive Nuclear Ratios: http://arxiv.org/abs/1403.2103
- Muon Neutrino Quasi-Elastic Scattering on Hydrocarbon: http://arxiv.org/abs/1305.2243
- Muon Anti-Neutrino Quasi-Elastic Scattering on Hydrocarbon: http://arxiv.org/abs/1305.2234

EMC Proton Structure Function Data

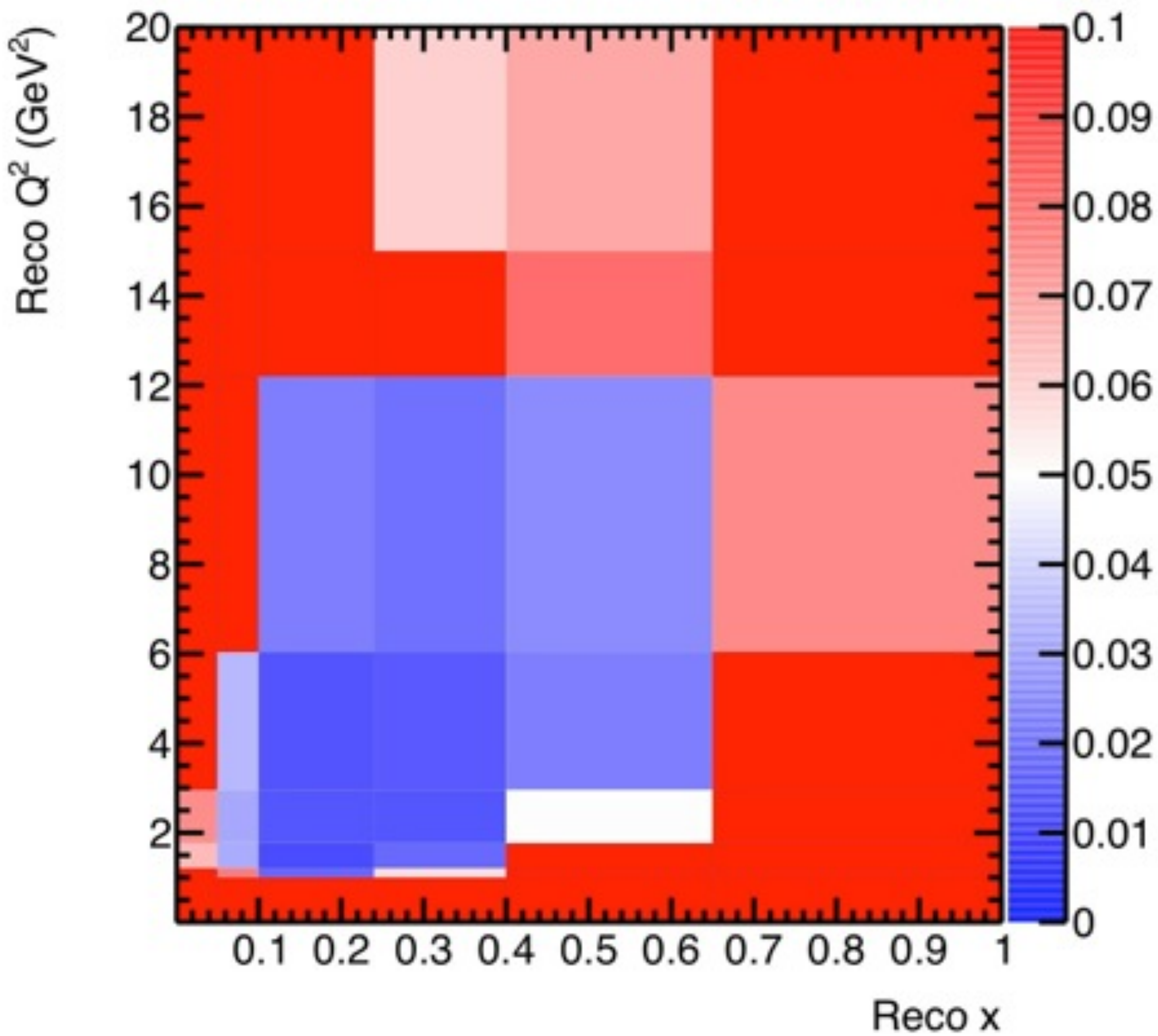


Data from the EMC paper showing the proton structure function, F_2 across a range of x and Q^2.

Structure Function Errors: Lead

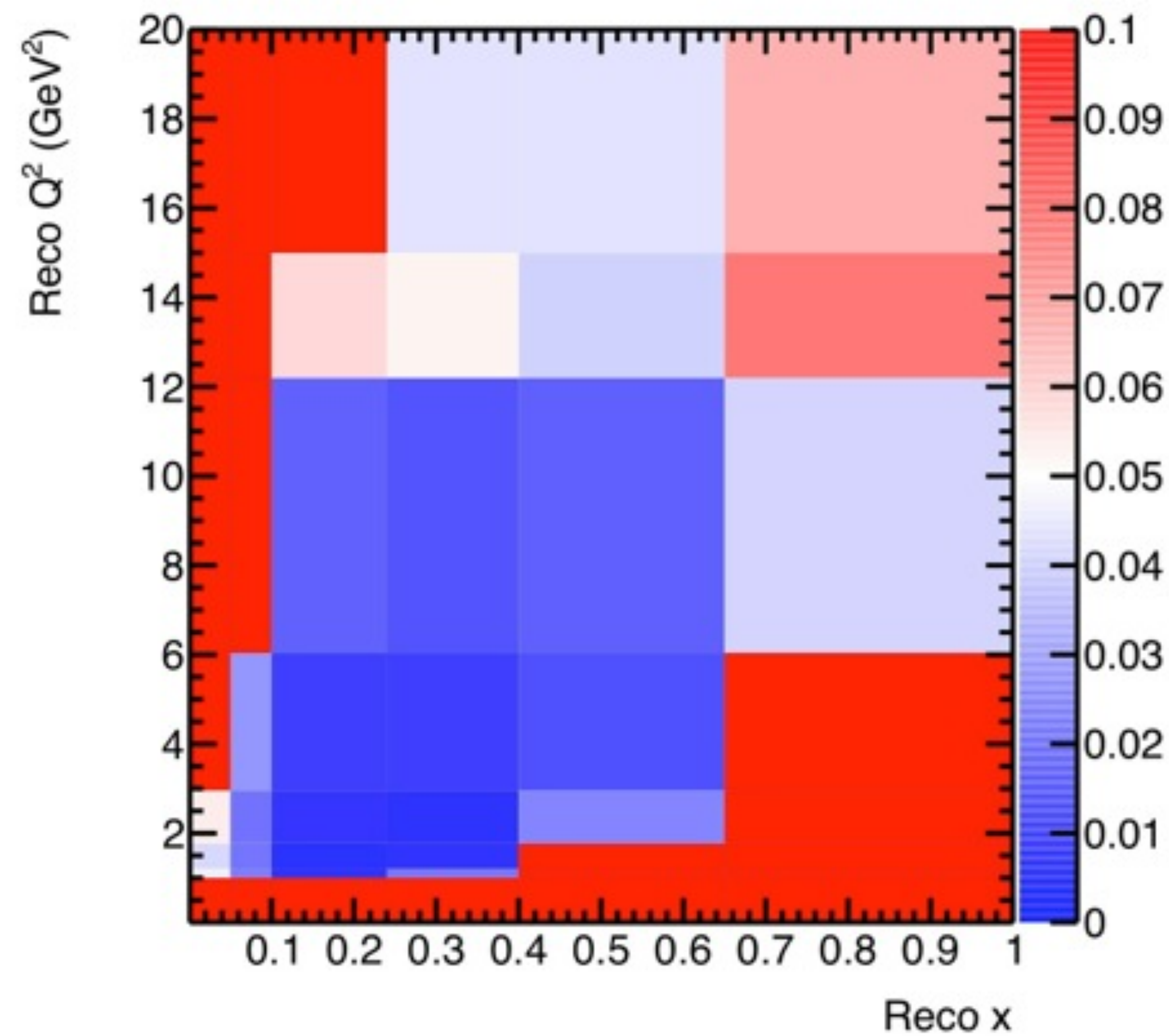
Fractional Stat Uncertainty on

$$F_2 \propto \sigma_\nu + \sigma_{\bar{\nu}}$$



Fractional Stat Uncertainty on

$$xF_3 \propto \sigma_\nu - \sigma_{\bar{\nu}}$$

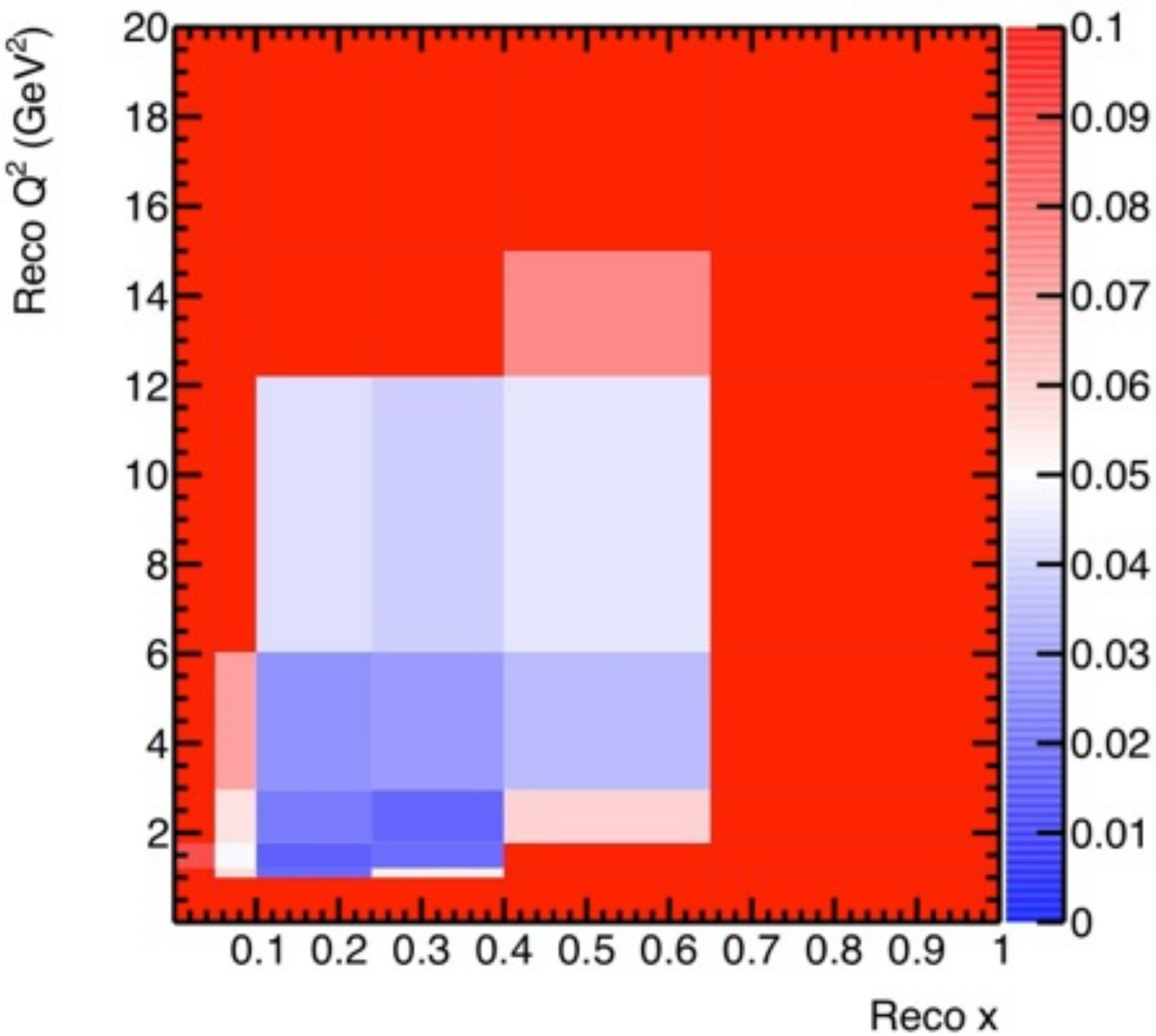


12E20 POT Exposure

Structure Function Errors: Carbon

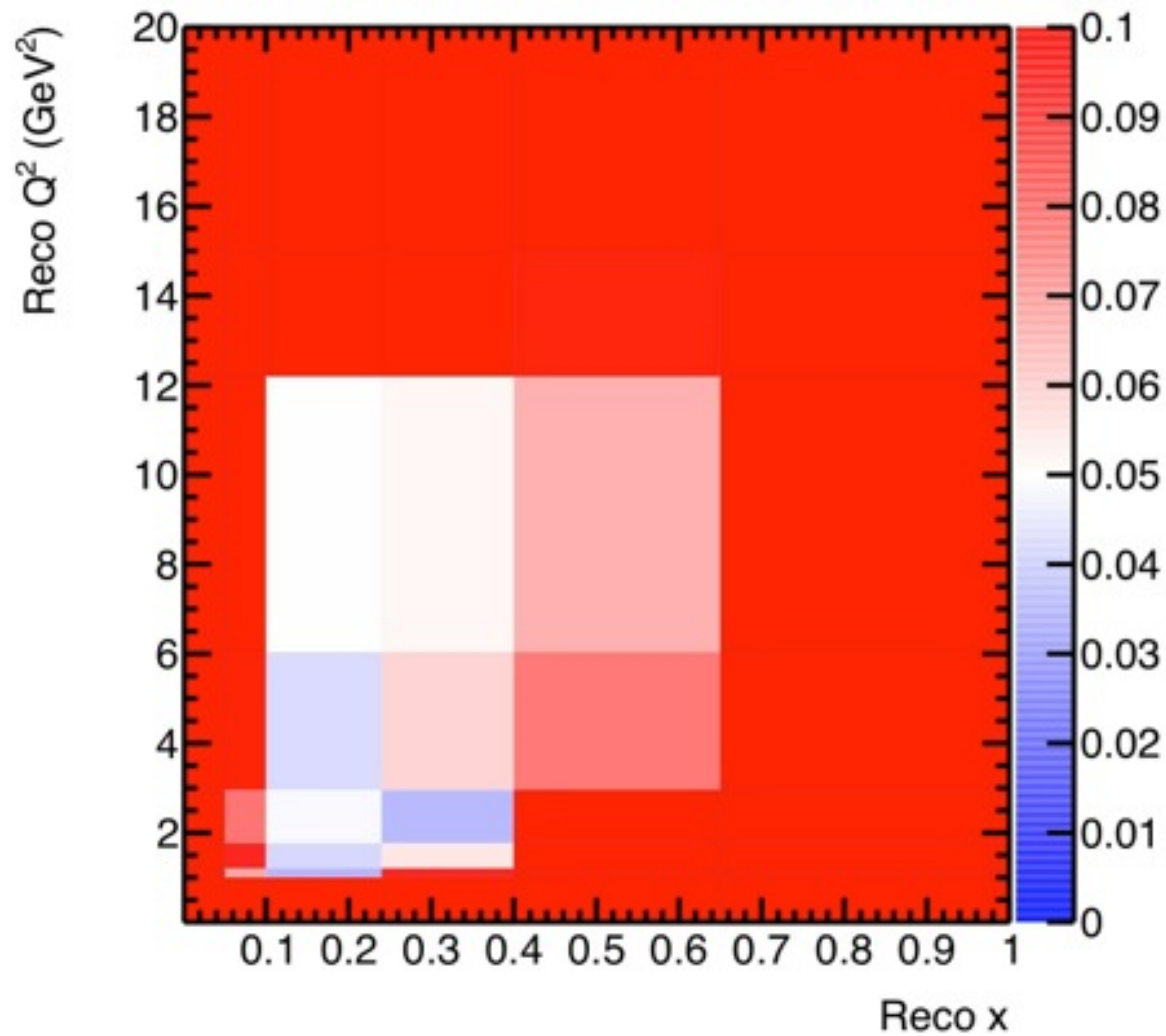
Fractional Stat Uncertainty on

$$F_2 \propto \sigma_\nu + \sigma_{\bar{\nu}}$$



Fractional Stat Uncertainty on

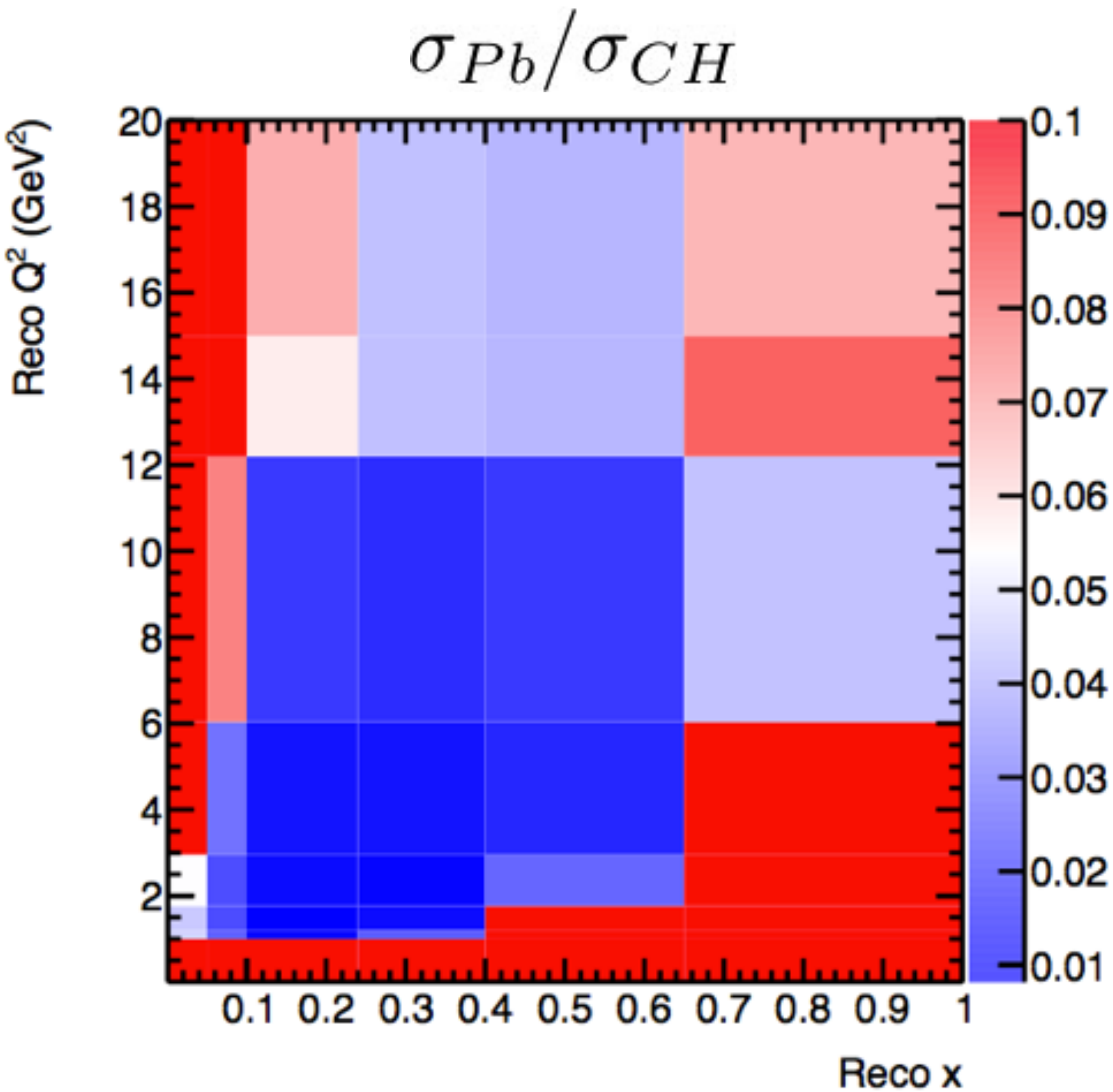
$$xF_3 \propto \sigma_\nu - \sigma_{\bar{\nu}}$$



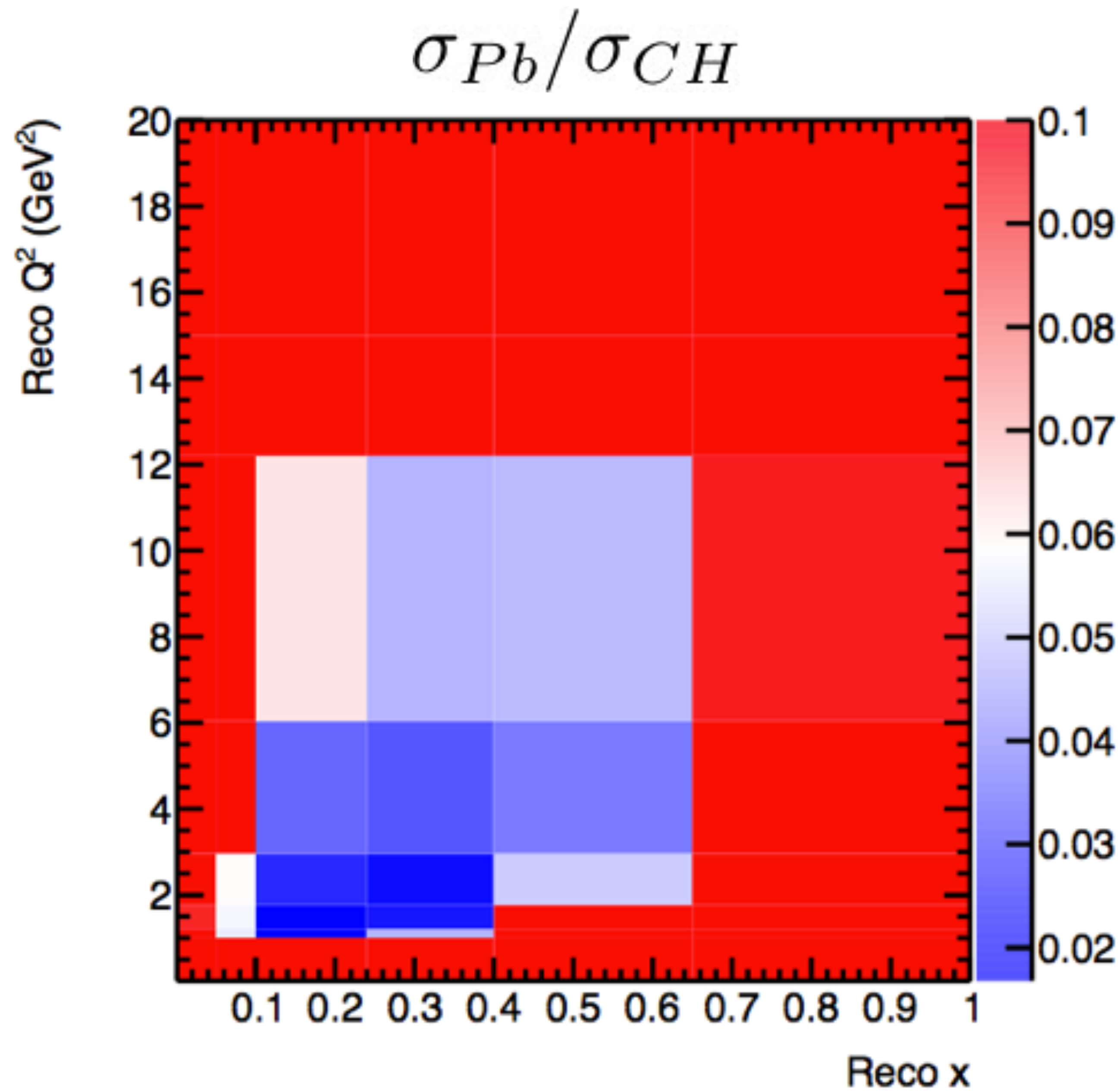
12E20 POT Exposure

Ratio Analysis: Lead

Fractional Stat Uncertainty on Neutrino



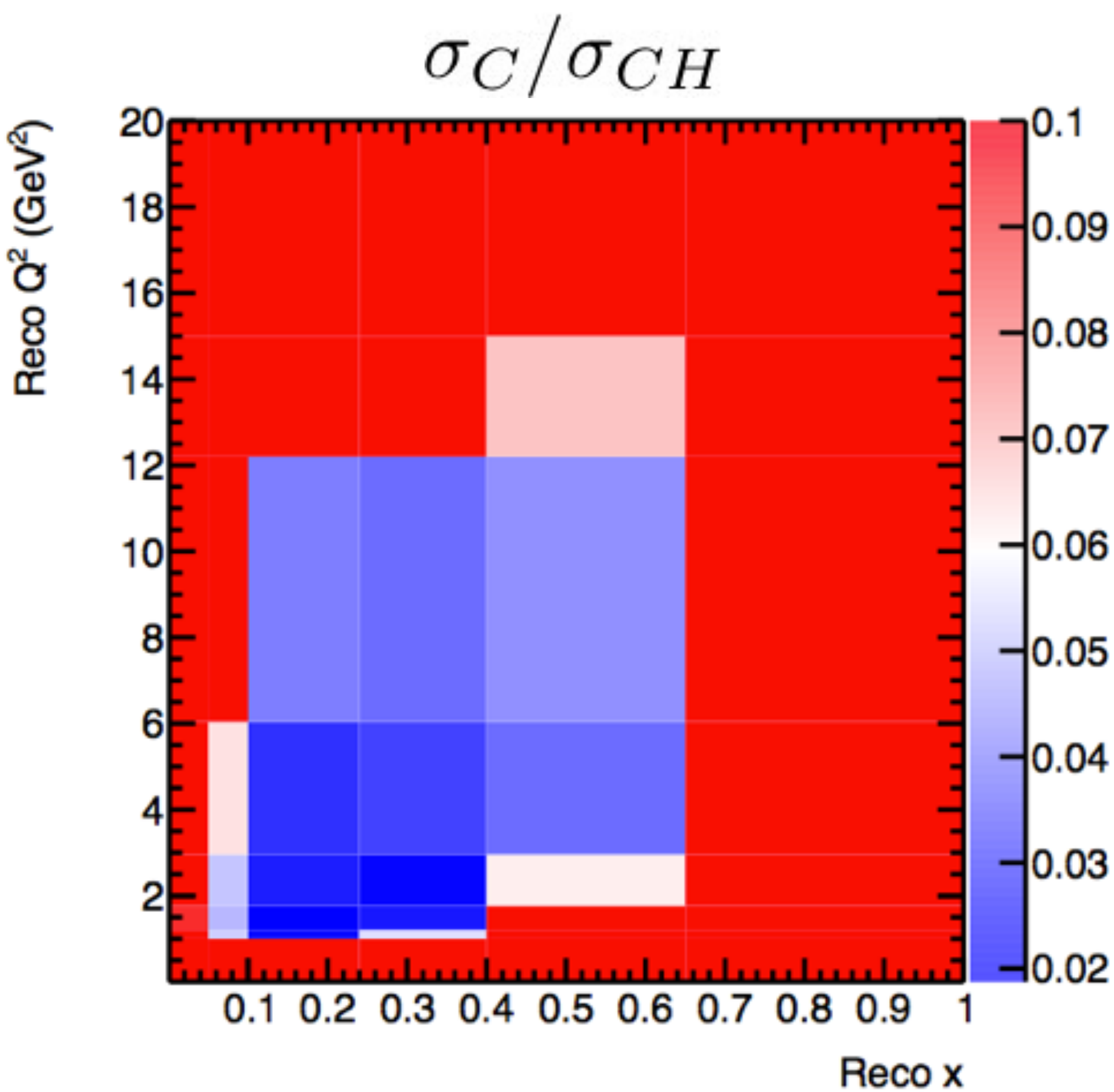
Fractional Stat Uncertainty on Anti-Neutrino



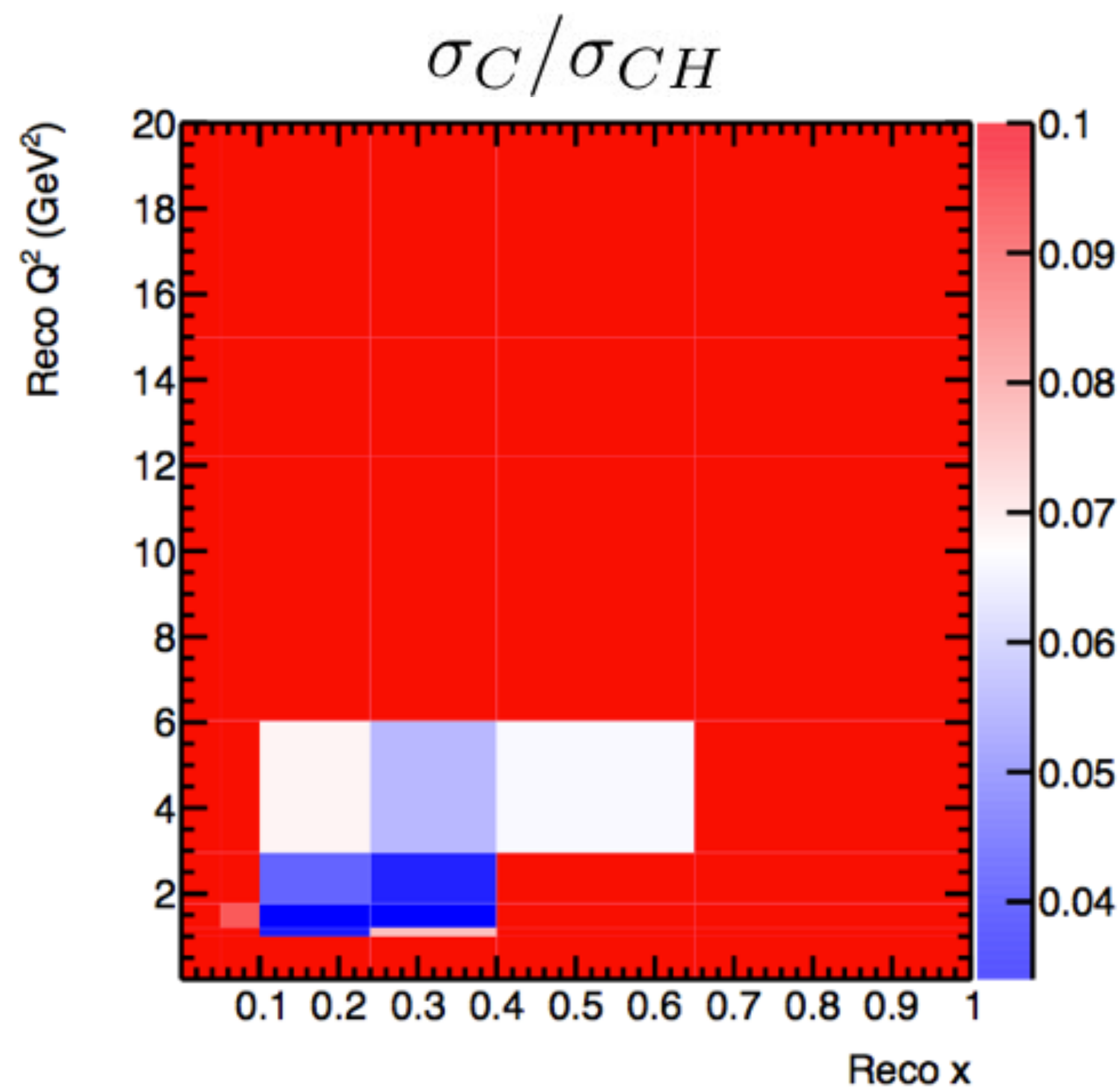
12E20 POT Exposure

Ratio Analysis: Carbon

Fractional Stat Uncertainty on Neutrino



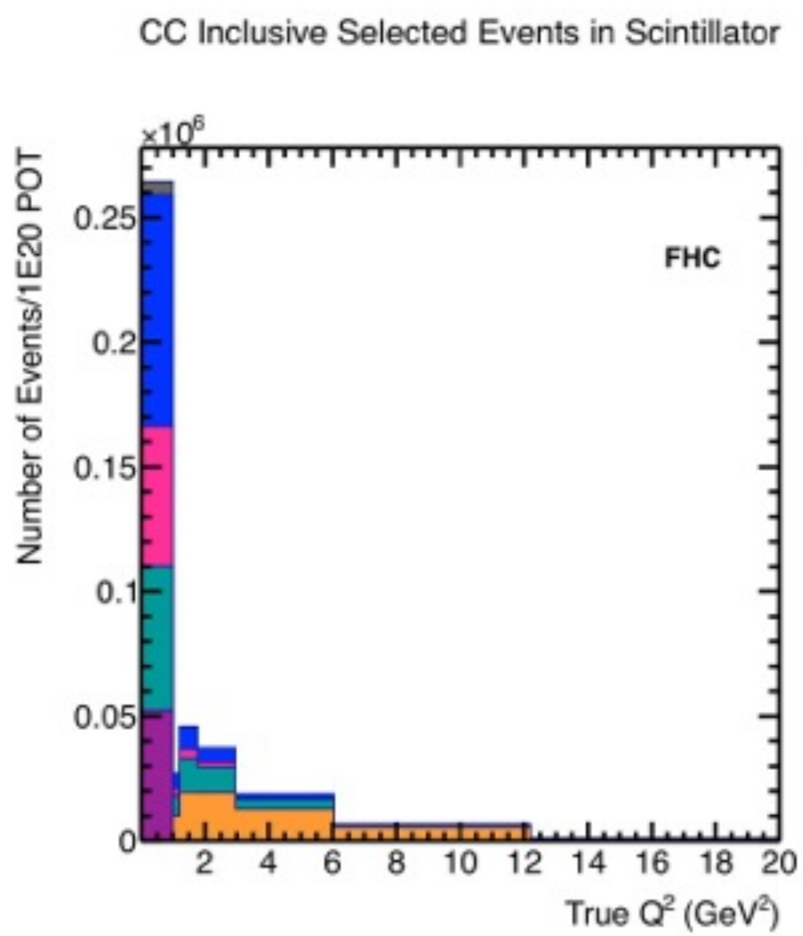
Fractional Stat Uncertainty on Anti-Neutrino



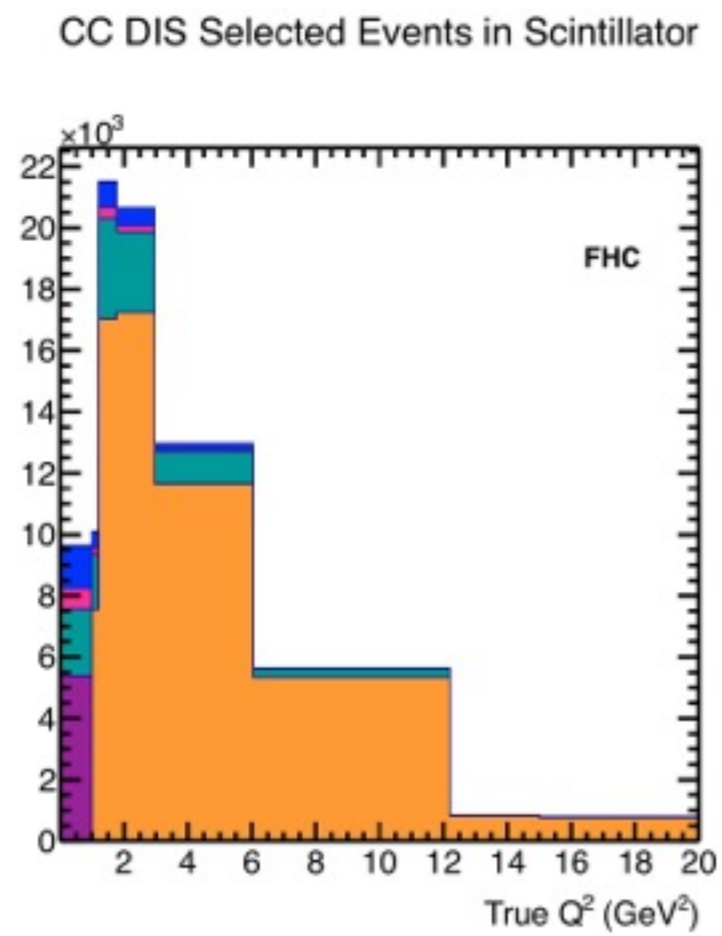
12E20 POT Exposure

Deep Inelastic Scattering in MINERvA

True Composition of the Sample



All Events



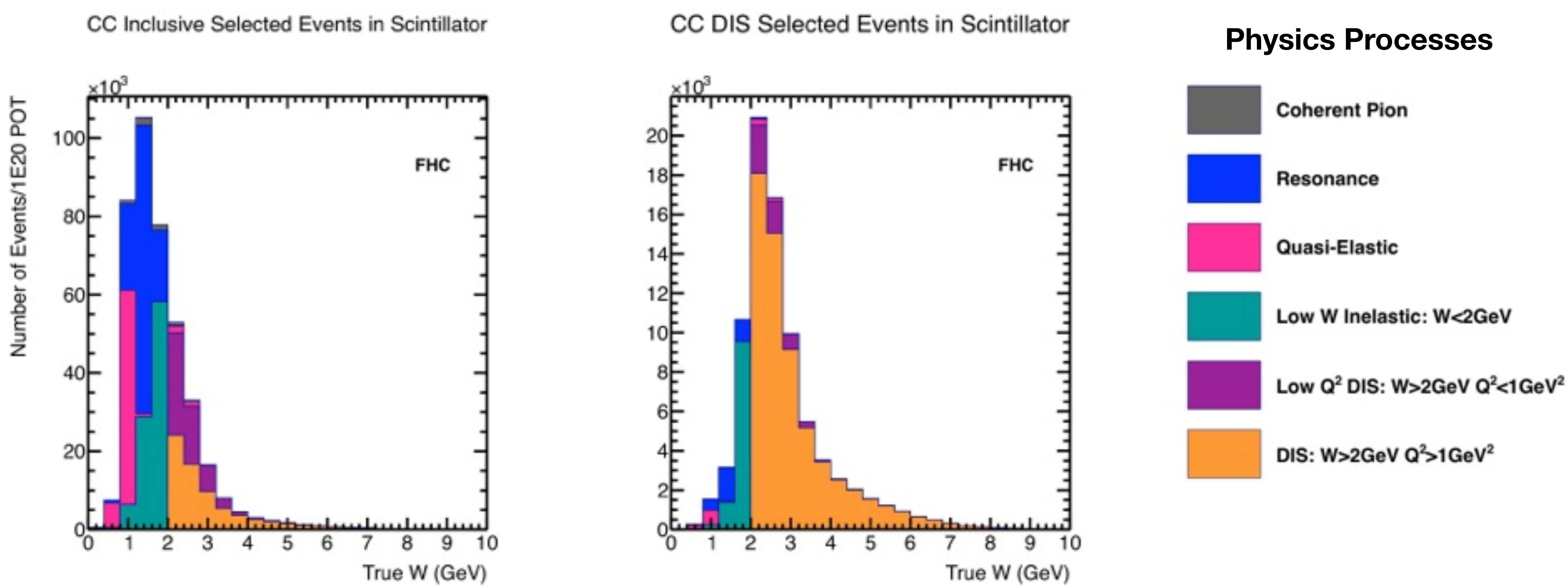
Selected DIS

Reconstructed $Q^2 > 1$ GeV^2

Reconstructed $W > 2$ GeV

Deep Inelastic Scattering in MINERvA

True Composition of the Sample



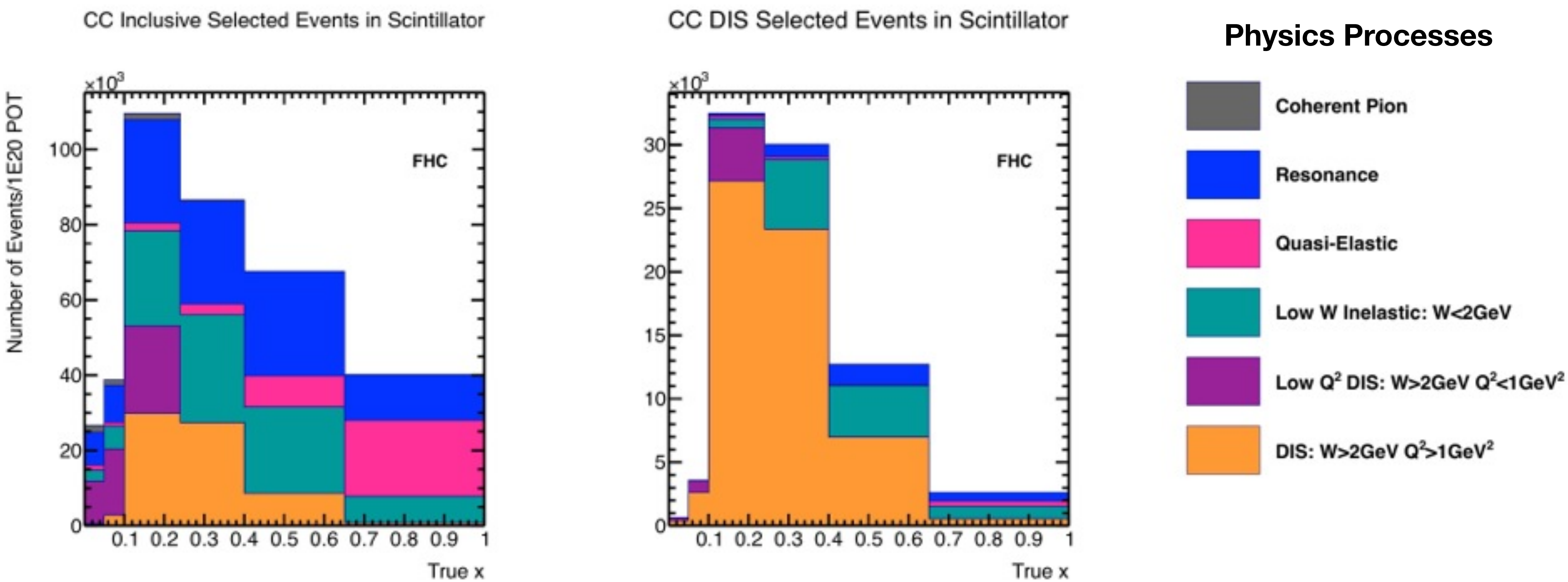
All Events

Selected DIS

Reconstructed $Q^2 > 1$ GeV^2
Reconstructed $W > 2$ GeV

Deep Inelastic Scattering in MINERvA

True Composition of the Sample



All Events

Selected DIS

Reconstructed $Q^2 > 1$ GeV^2

Reconstructed $W > 2$ GeV