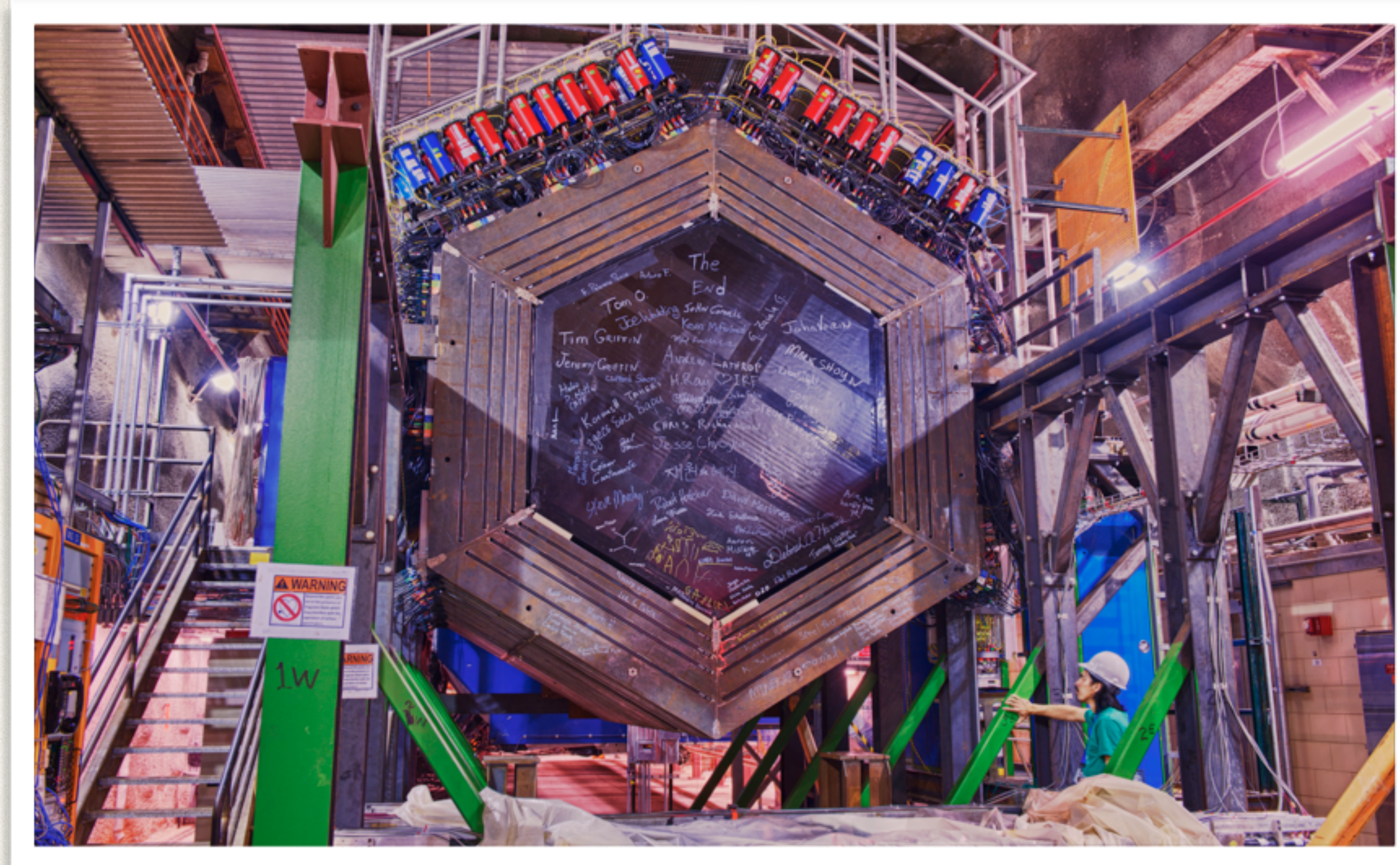


Recent Results from MINERνA

NNN ‘15

Laura Fields, Fermilab
For the MINERνA Collaboration

29 October 2015

Introduction

- Uncertainties in our models of neutrino interaction are a **major source of systematics on oscillation measurements**, even after near detector constraints:

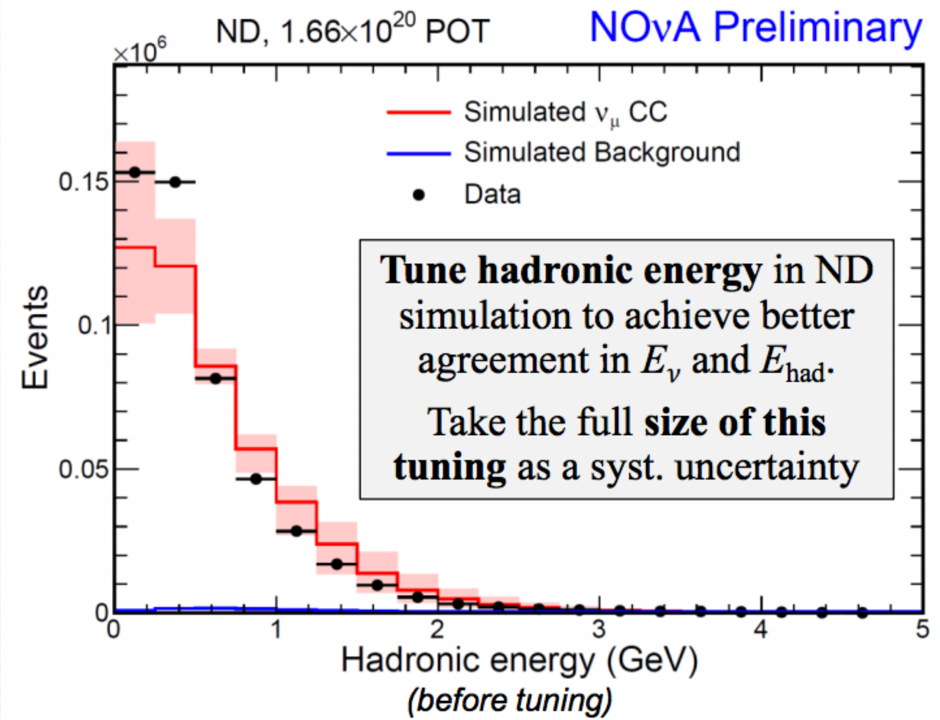
Phys. Rev. D 91, 072010 (2015)

TABLE XX: Relative uncertainty (1σ) on the predicted rate of ν_μ CC and ν_e CC candidate events.

Source of uncertainty	ν_μ CC	ν_e CC
Flux and common cross sections		
(w/o ND280 constraint)	21.7%	26.0%
(w ND280 constraint)	2.7%	3.2%
Independent cross sections	5.0%	4.7%
SK	4.0%	2.7%
FSI+SI(+PN)	3.0%	2.5%
Total		
(w/o ND280 constraint)	23.5%	26.8%
(w ND280 constraint)	7.7%	6.8%

Systematic uncertainties on **T2K's** 2015 oscillation analyses

Discrepancy in **hadronic energy in the NoVA near detector, a** significant source of systematic uncertainty on NoVA's oscillation results, possibly due to insufficiencies in neutrino interaction model



R. Patterson FNAL W&C

Introduction

- And we know that reducing systematics is increasingly important to our field:

T2K CP sensitivities with statistical and statistical + 2012-era systematic uncertainties

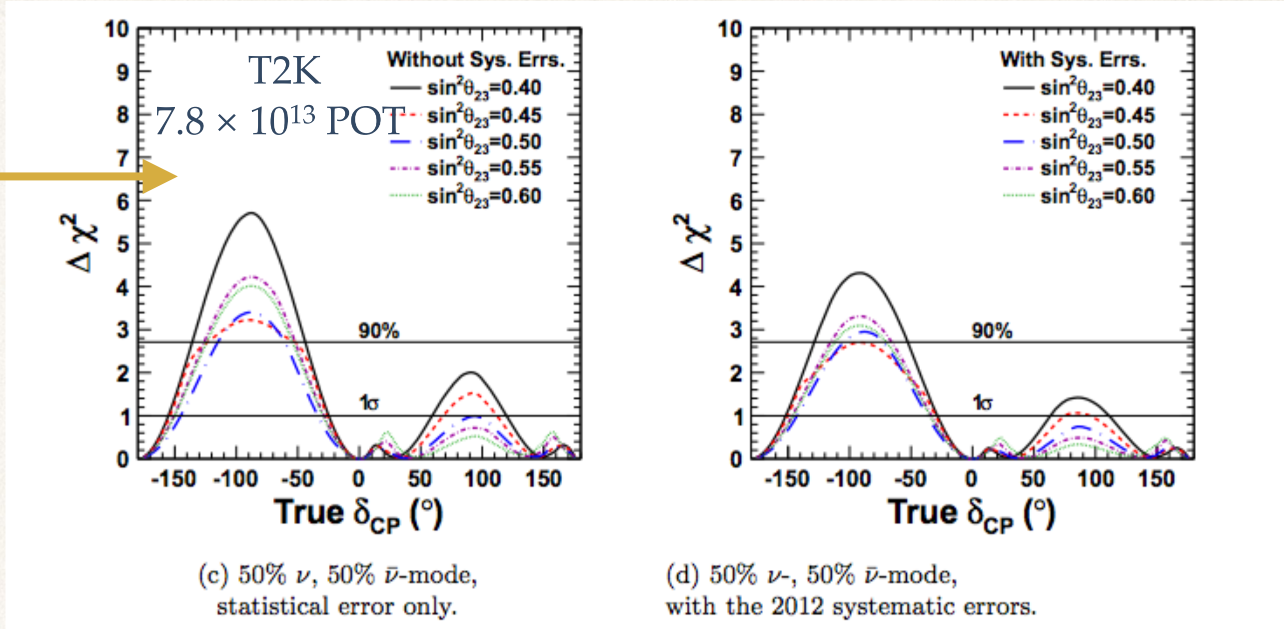
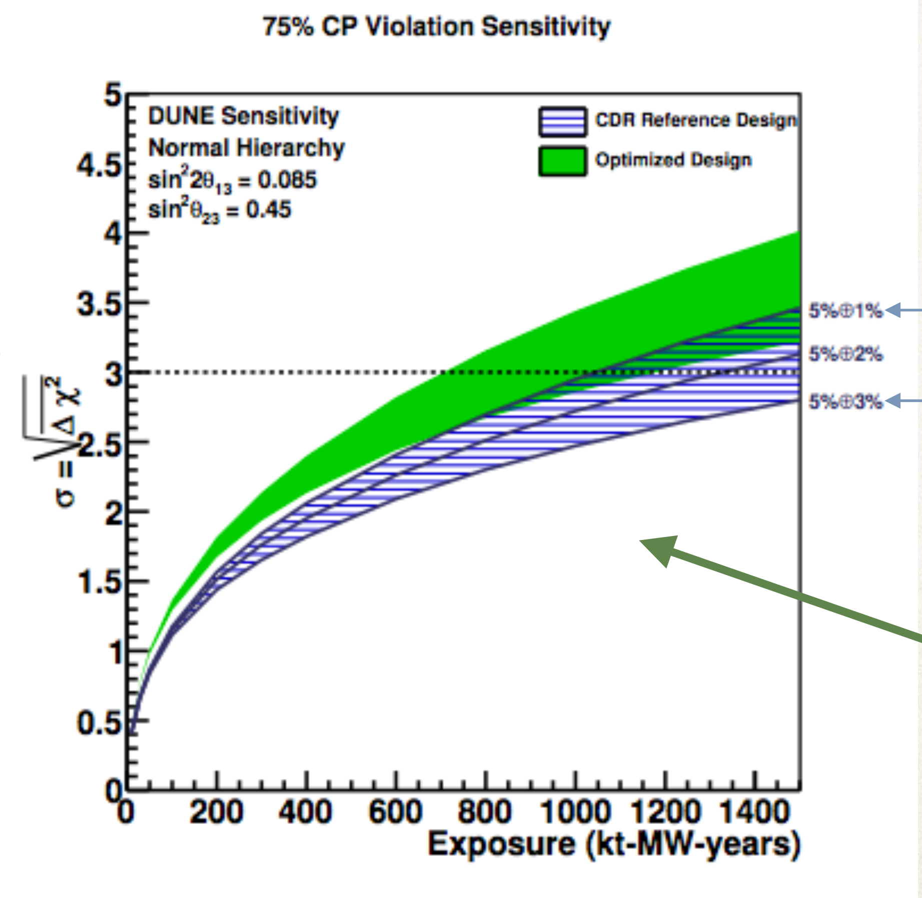


Fig. 8: The expected $\Delta\chi^2$ for the $\sin\delta_{CP} = 0$ hypothesis, plotted as a function of δ_{CP} for various values of $\sin^2\theta_{23}$ (given in the legend) in the case of normal mass hierarchy.

Prog. Theor. Exp. Phys. (2015) 043C01



DUNE Conceptual Design Report

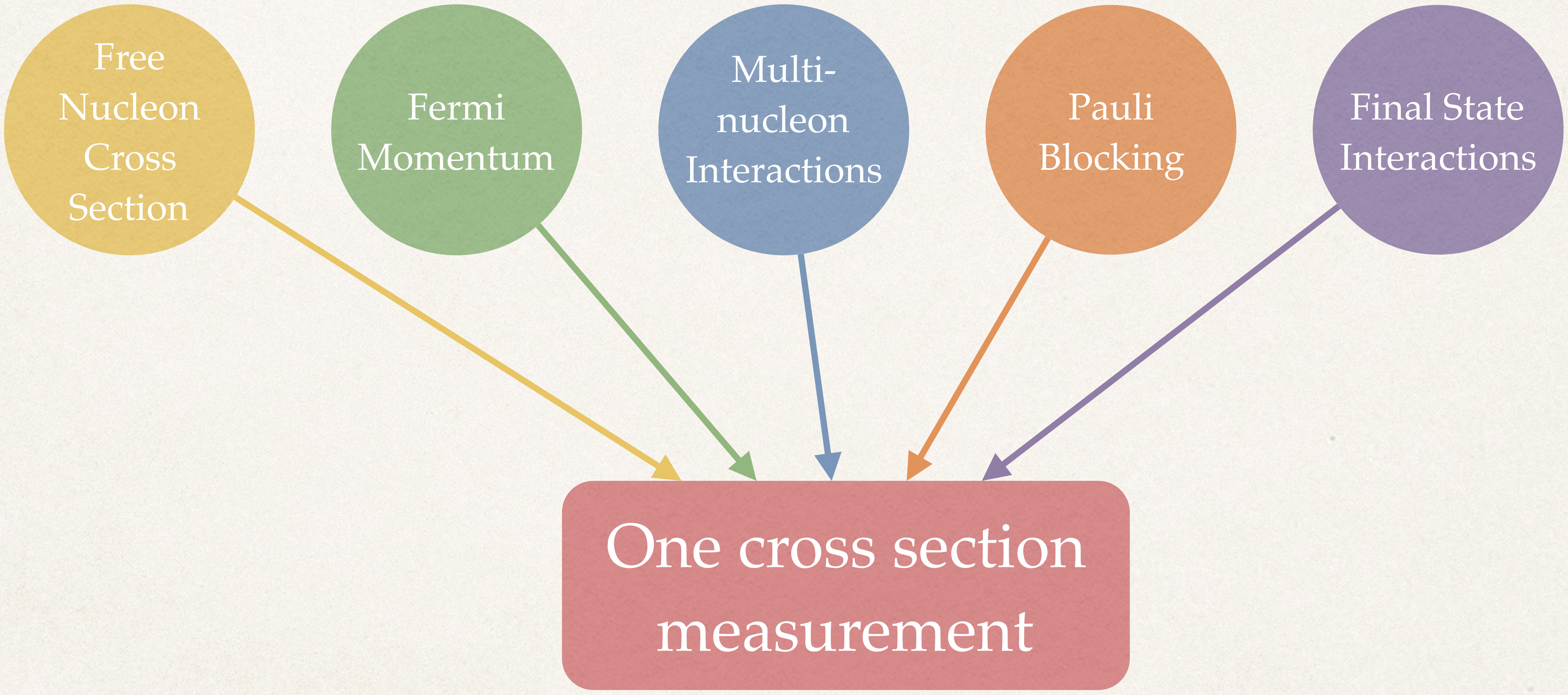
Where DUNE wants to be

Where we are now

DUNE CP sensitivities versus exposure. Band illustrates range of results for different levels of systematic uncertainty

Introduction

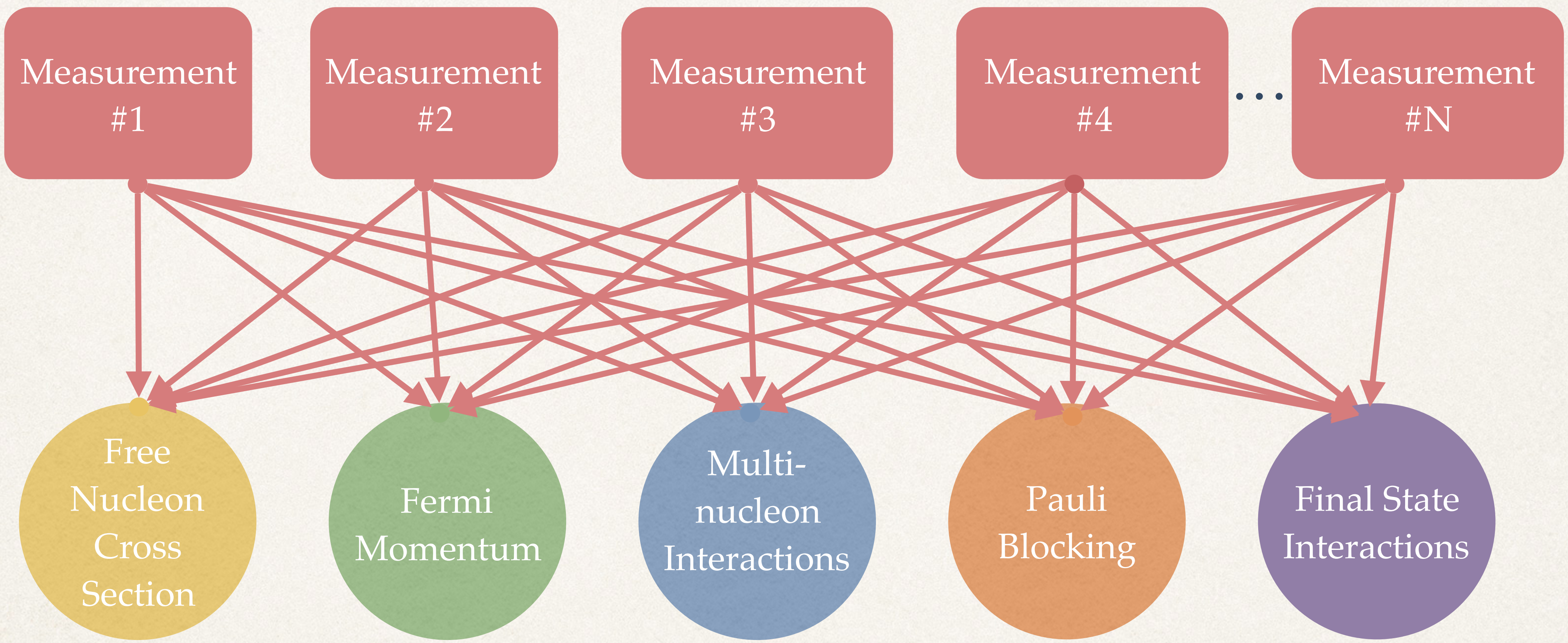
- Developing models of neutrino interactions is difficult — there are many, many unknown parameters, and we generally have to measure a bunch of them at once:



Any one cross section measurement probes the superposition of many different effects that we need to model separately for experiments like DUNE

Introduction

- We address this problem by making many different cross section measurements, where different effects have different contributions



By making measurements of different channels, on different nuclei, at different energy ranges, using different reconstruction techniques, we can disentangle the many different effects

Introduction

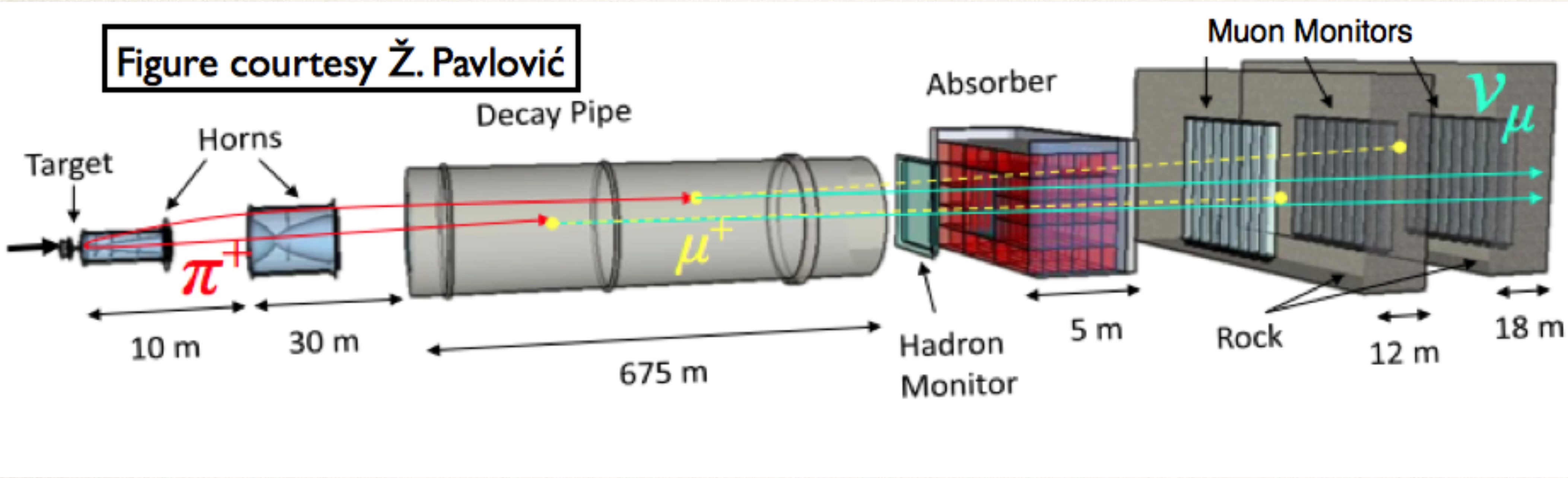
- The MINERvA detector was designed to do just this: to measure many different cross sections, to provide data constraints for models of neutrino interaction in 1-20 GeV region
- Can make measurements:
    - Using different reconstruction techniques (enabled by fine-grained detector)
    - In neutrino and antineutrino beams in several different wide-band beam tunes
    - On many different nuclei within the same beam
- Part of a broad global cross-section effort

The NuMI Beamline

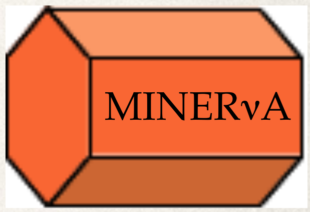
&

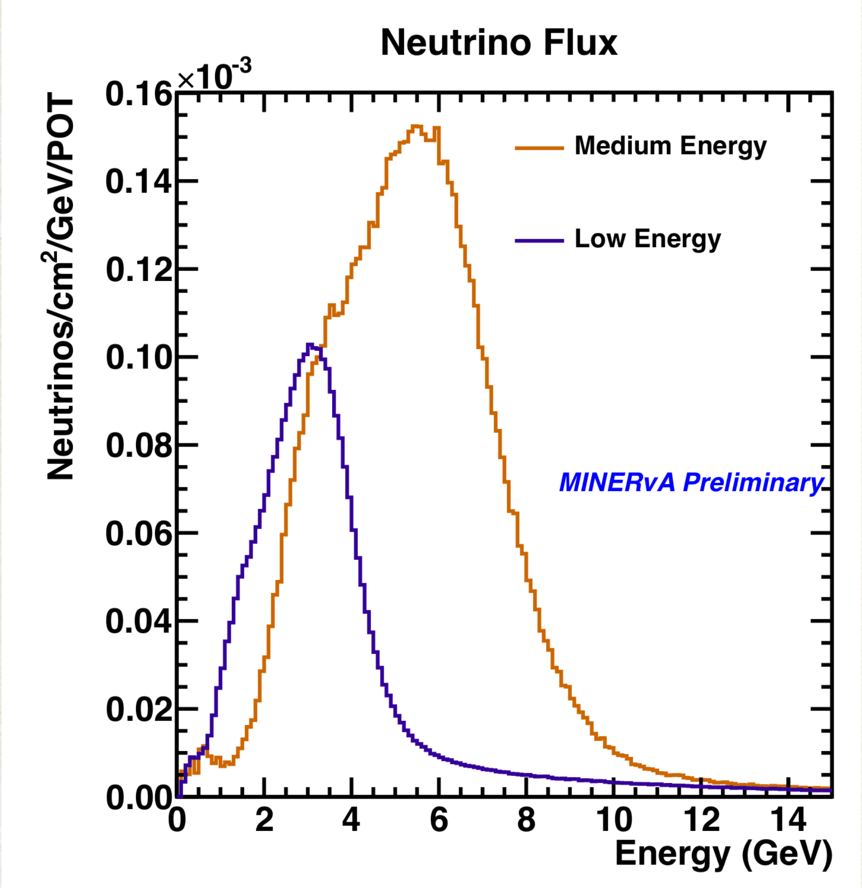
The MINERνA Detector

The NuMI Beamline



~210 m of rock





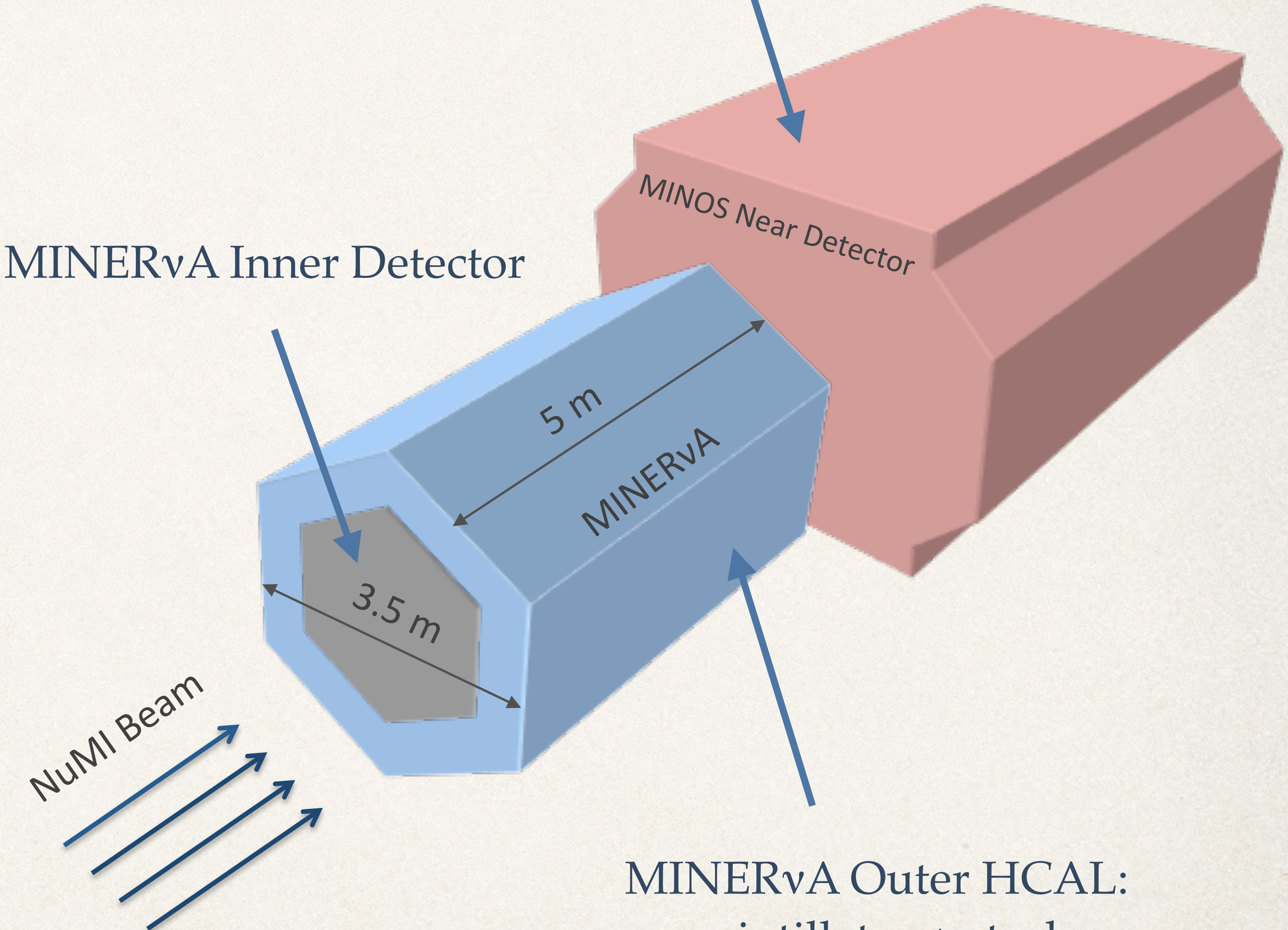
- Target/Horn spacing can be varied to produce different energy spectra
- My talk today focuses on the "Low Energy (LE)" data taken 2010-2012
- We are currently running in the "Medium (ME)" configuration of the NOνA era.

The MINERνA Detector

- MINERνA is a scintillator-based neutrino detector that sits just upstream of the MINOS near detector in the NuMI beam

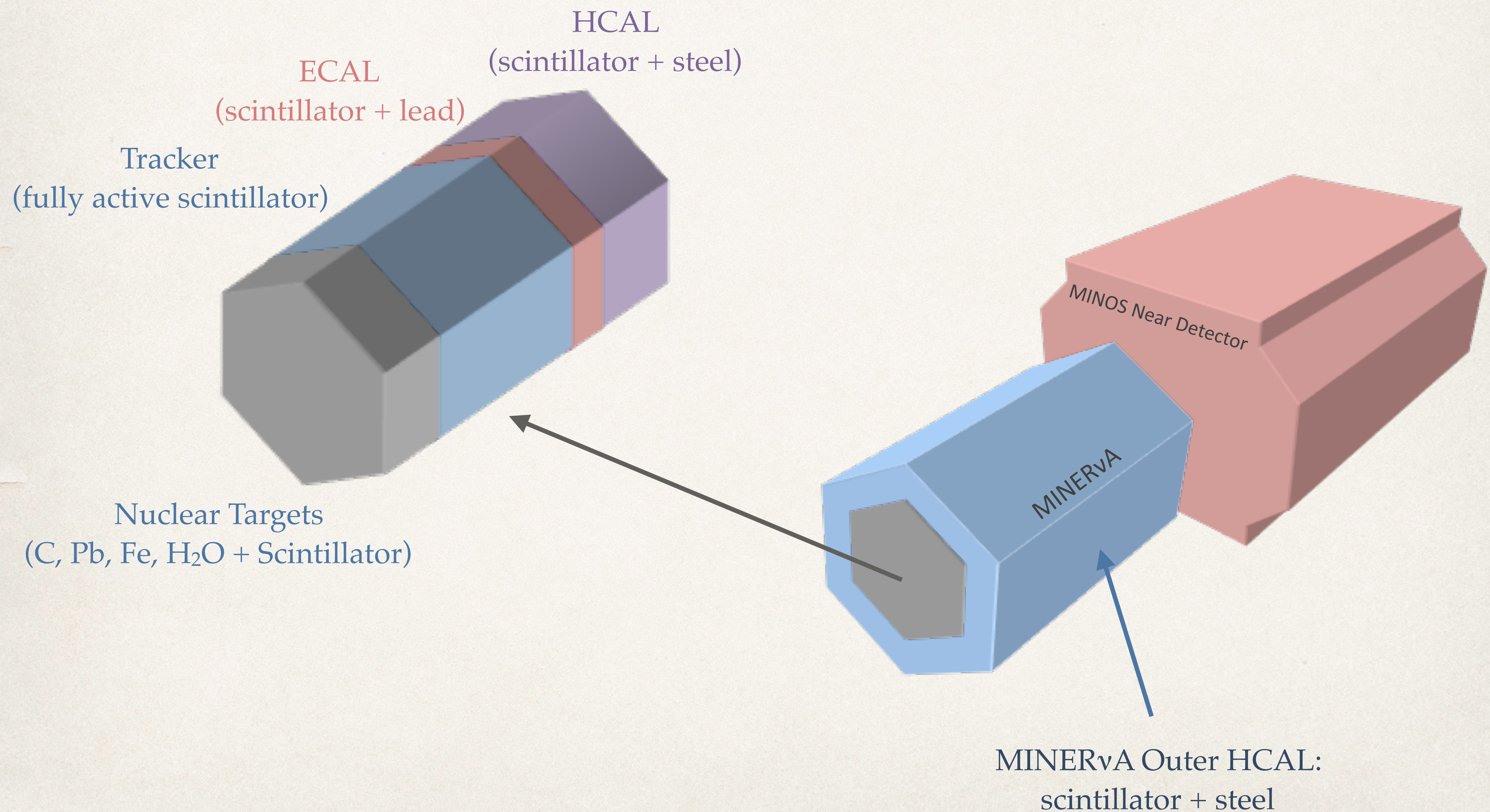
MINOS Near Detector: measures charge and momentum of muons that exit the back of MINERνA

MINERνA Inner Detector

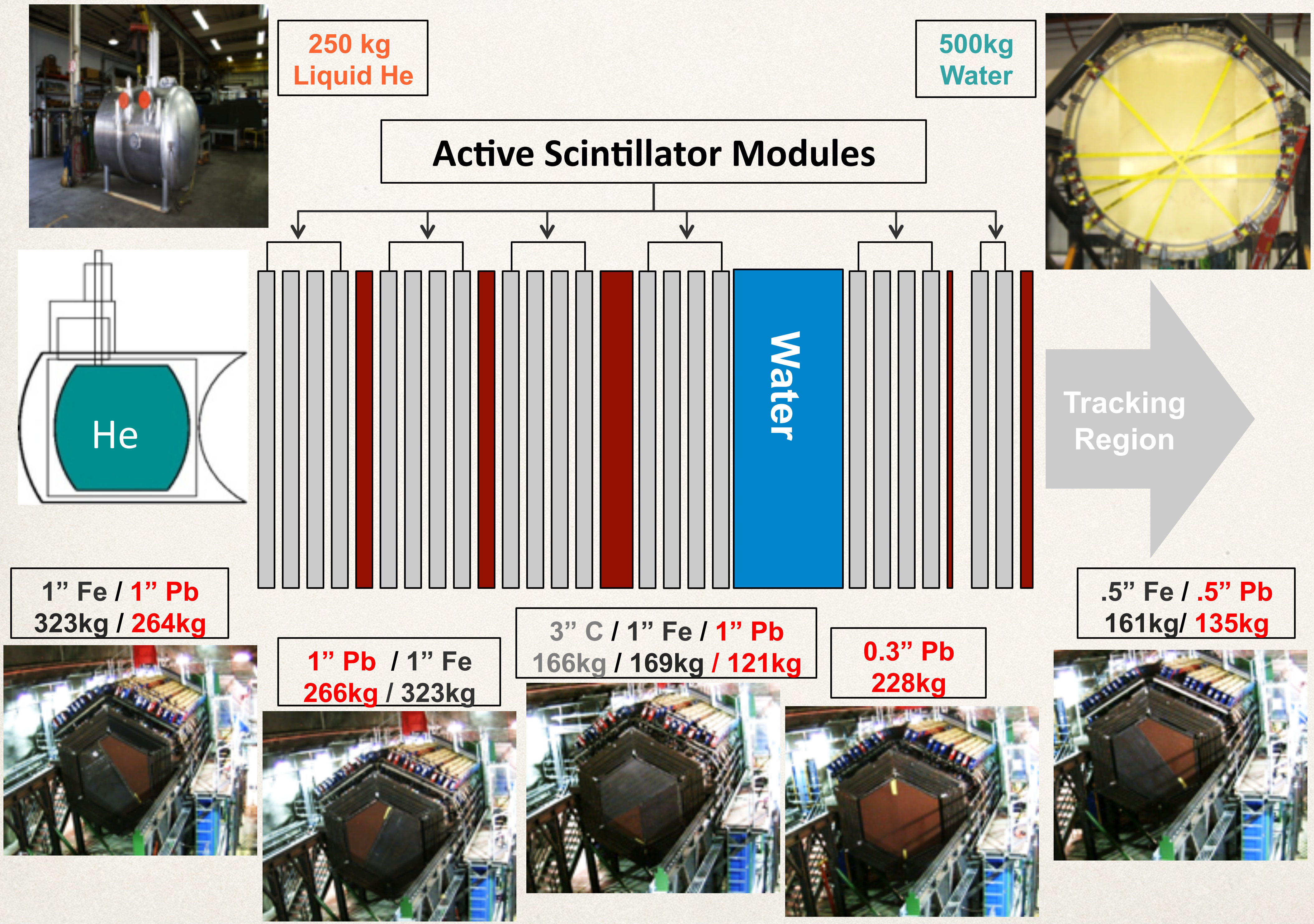


MINERνA Outer HCAL: scintillator + steel

The MINERνA Detector



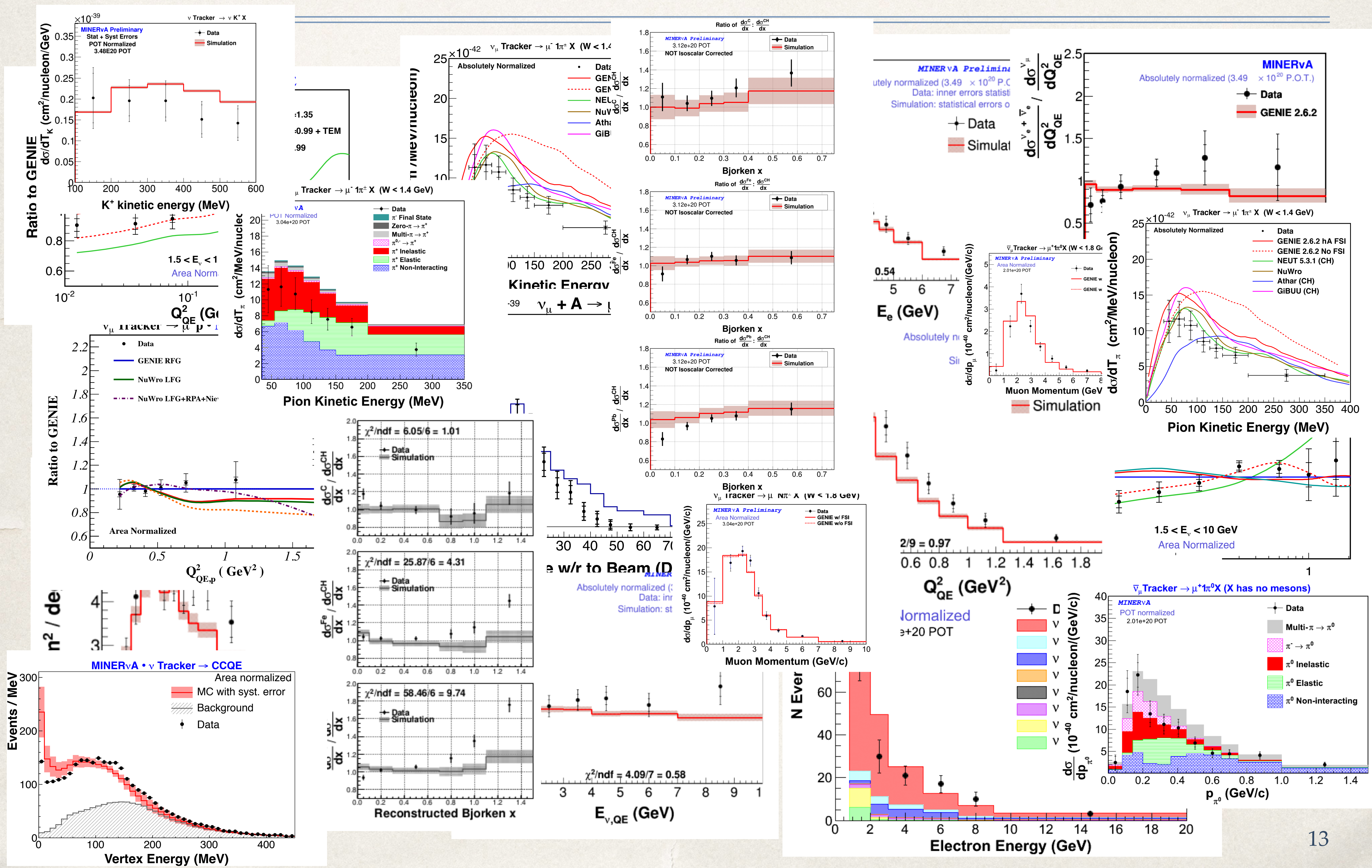
The MINERνA Detector



Targets material includes: solid iron, lead, and carbon; liquid helium and water

MINERνA Results

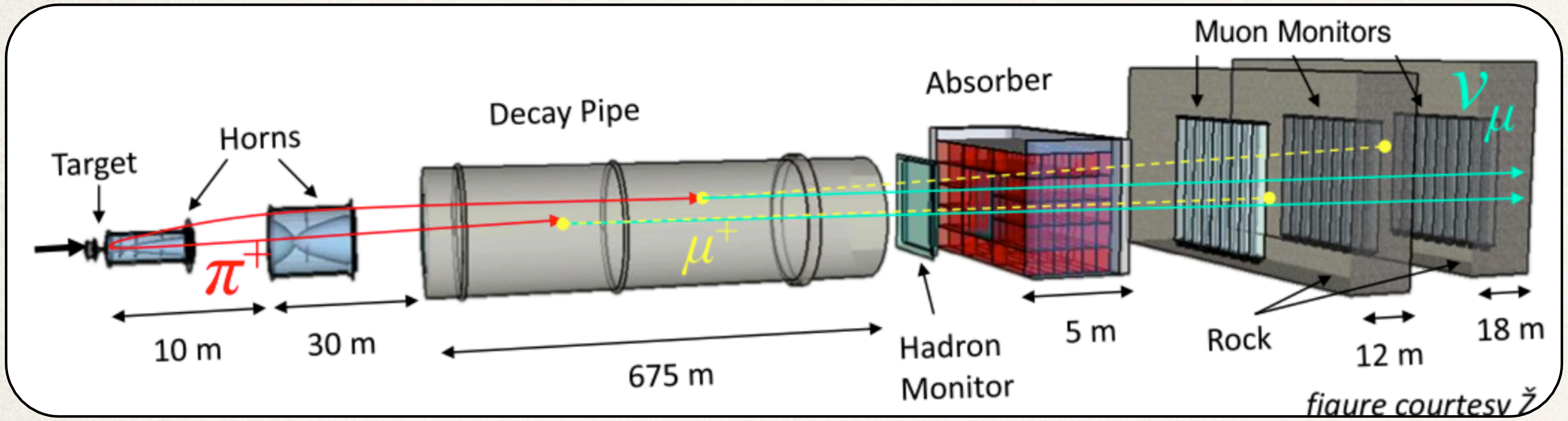
Some of MINERvA's 2013-1015 Results



Results — Overview

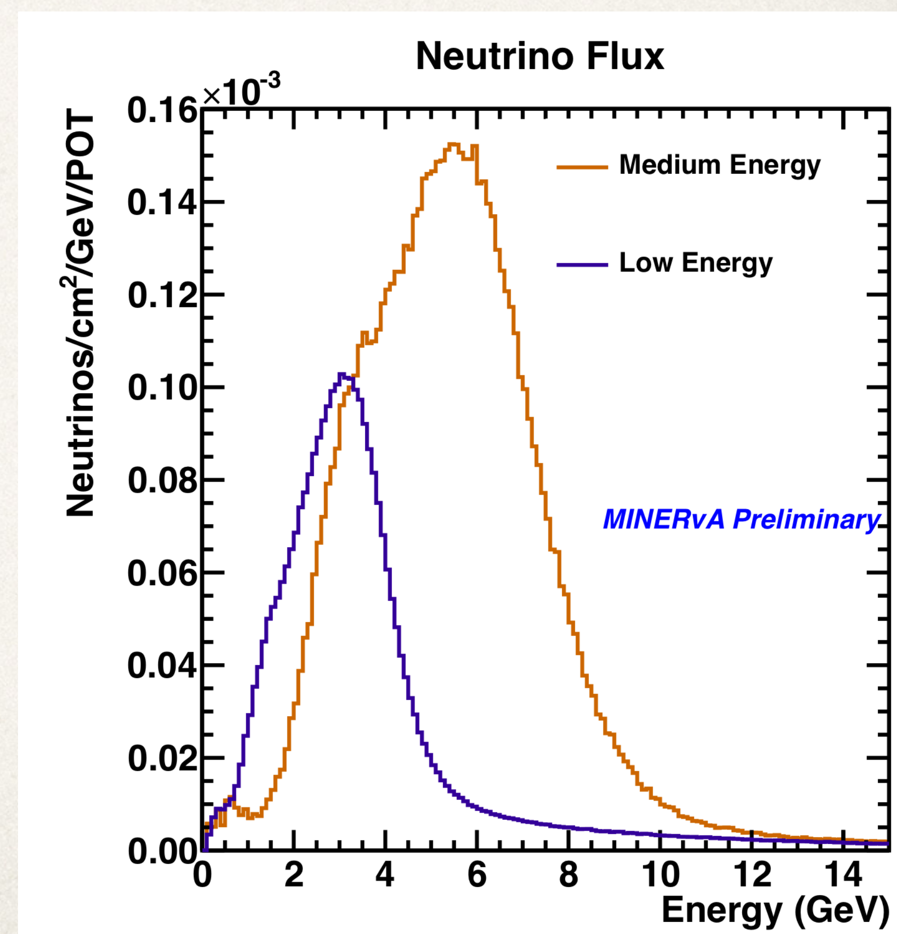
- Today I'm going to discuss a subset of our 2015 results:
  - ν_e CCQE
  - Charged and neutral CC pion production
  - NC Kaon production
  - DIS nuclear target ratios

Results: Flux

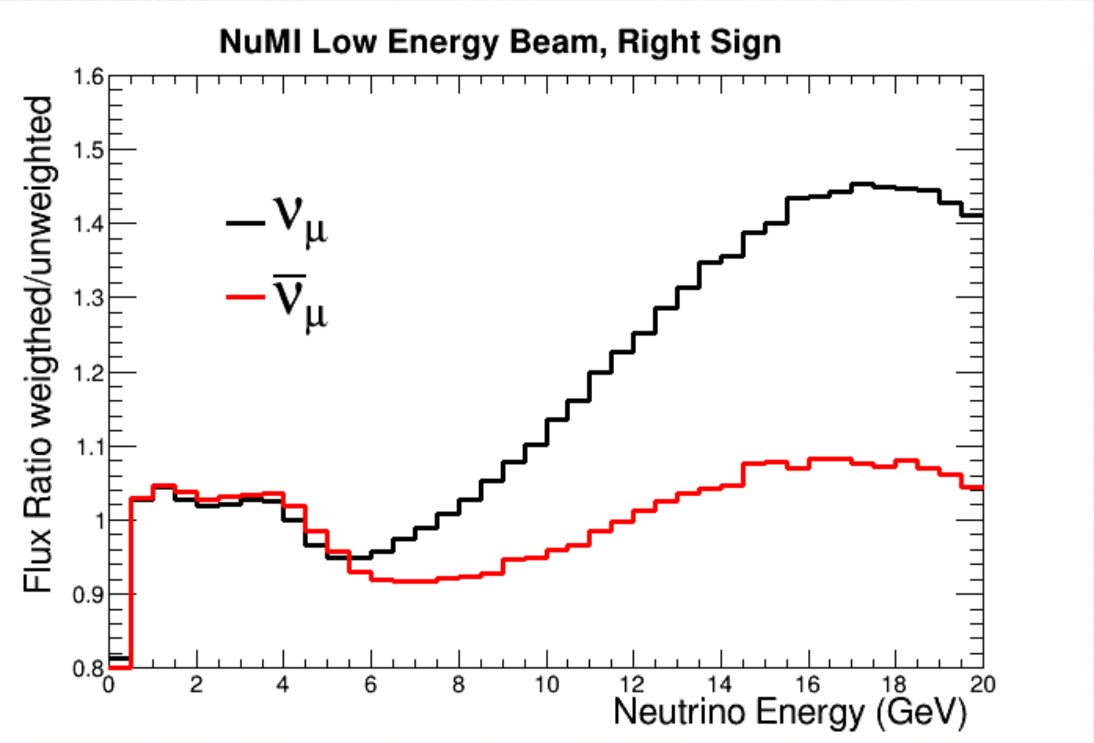


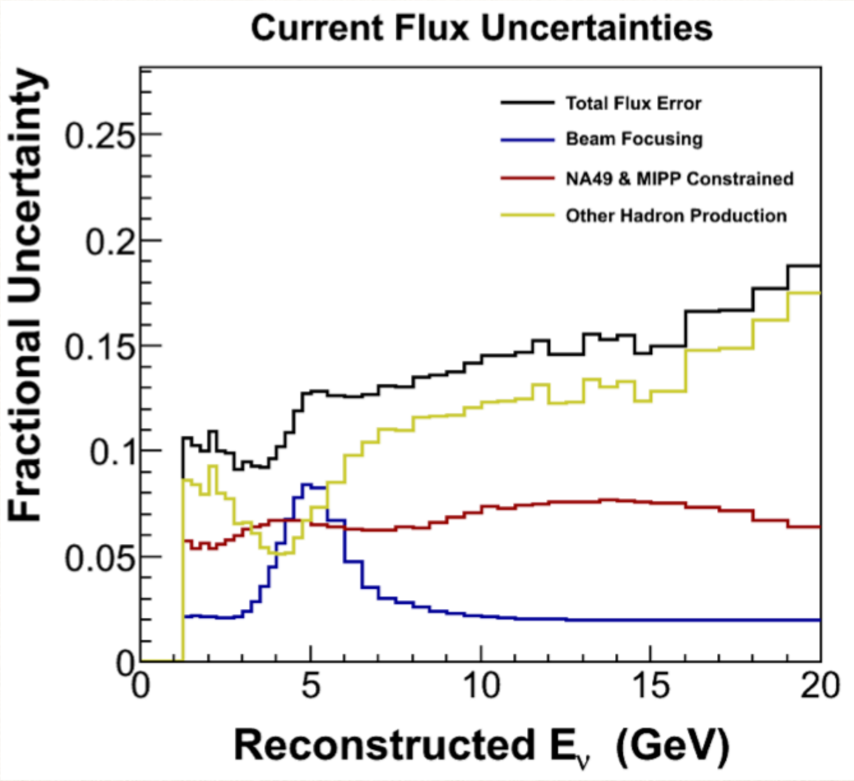
MINERvA

- It turns out neutrino interaction cross sections isn't the only way that MINERvA can help oscillation experiments
- We are also testing many of the flux constraint techniques
- Our flux estimate starts with a Geant4-based simulation of the NuMI beam line

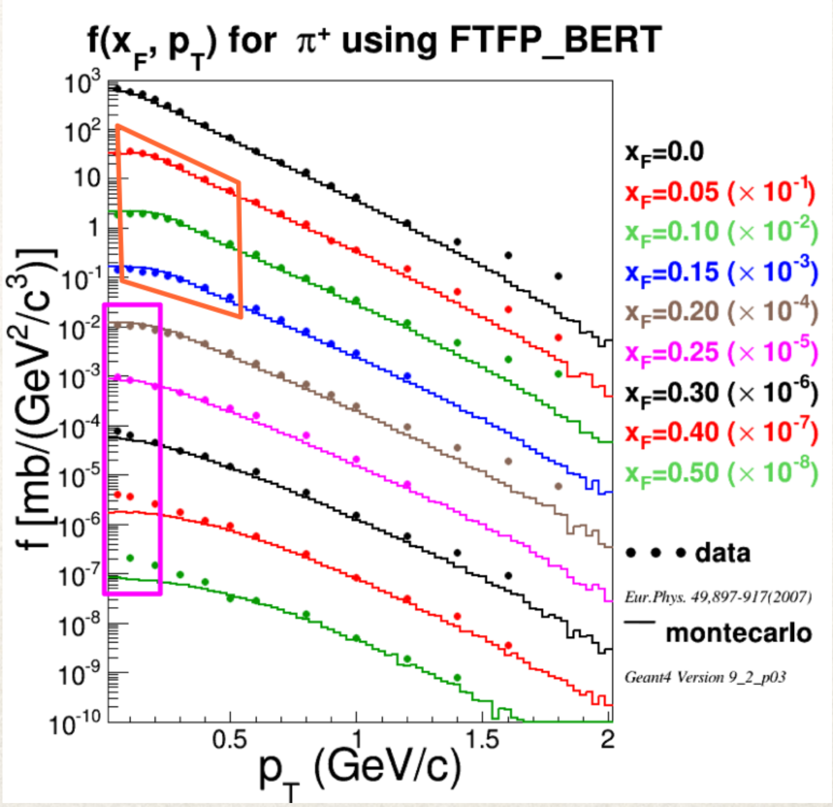


Results: Flux



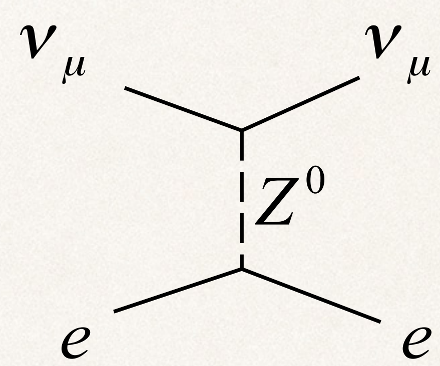


- Geant4 model constrained by NA49 and MIPP (pi/k ratio only); current flux has ~10% uncertainties in focusing peak

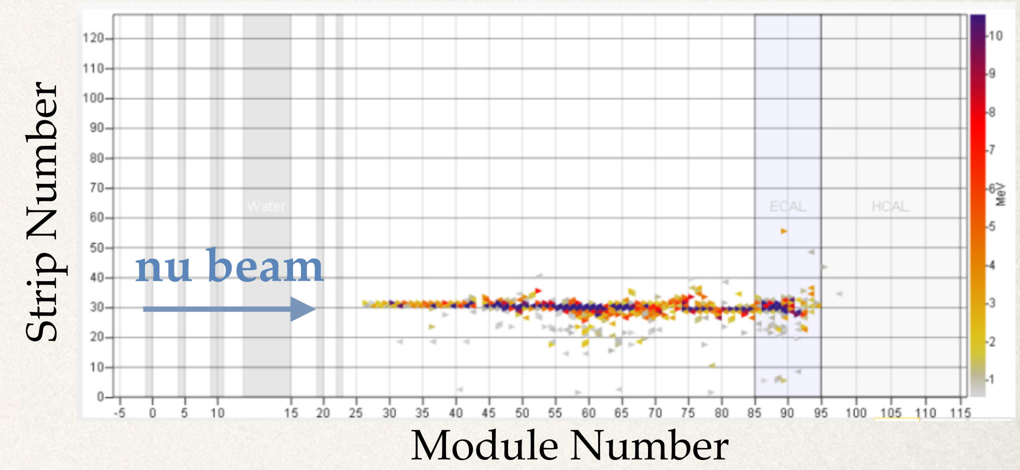


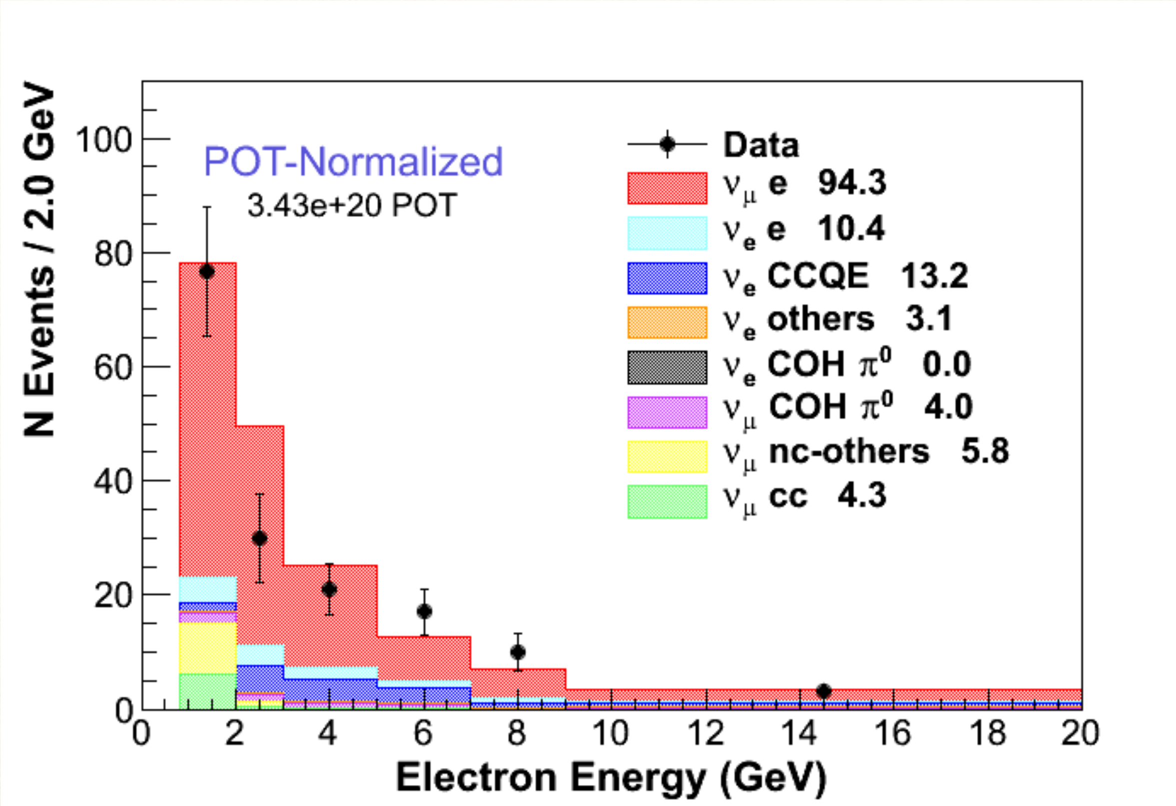
Flux: ν - e Scattering

- We are also pursuing several in situ flux constraints:
  - Neutrino scattering on electrons is a well understood electroweak process
  - Signal in MINERνA is a single electron moving in beam direction
  - Process cross section is smaller than nucleus scattering by a factor of 2000→ statistically limited



MINERνA Data



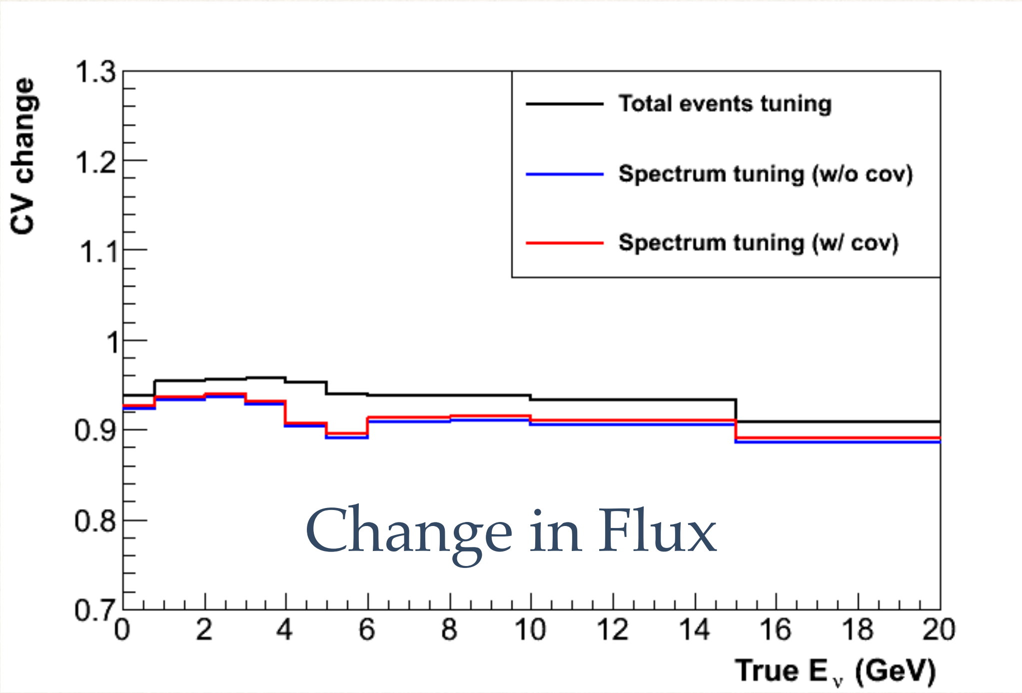


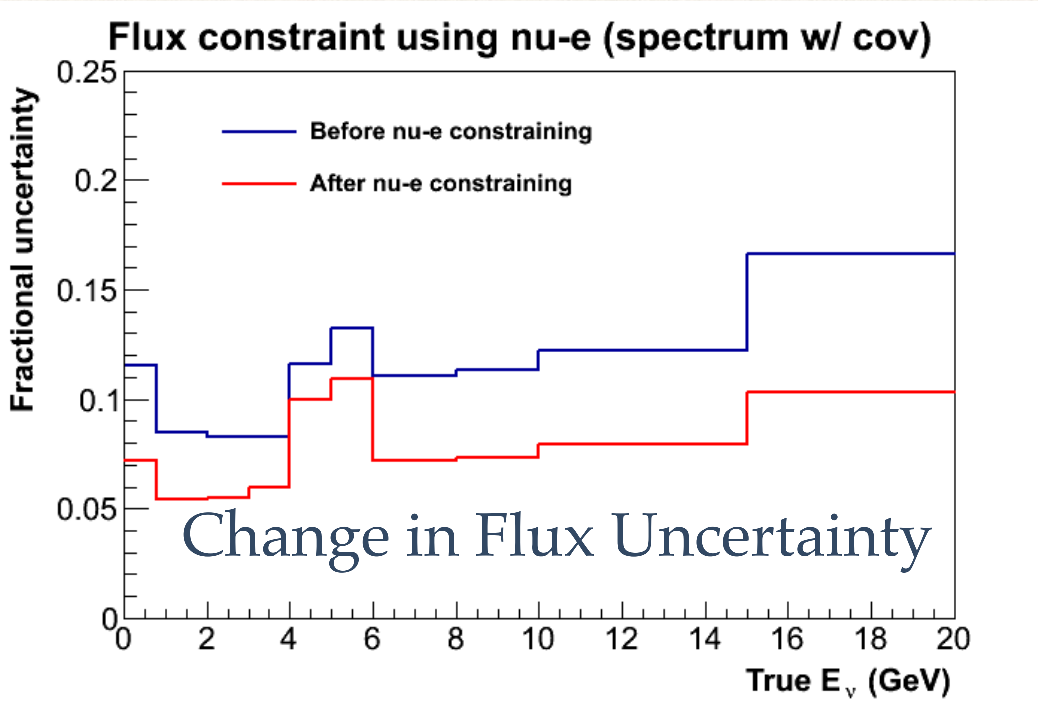
96 events observed; 108 expected

Jaewon Park, FNAL JTEP, Dec 2013

Flux: ν - e Scattering

- Effect of neutrino-electron scattering constraint:



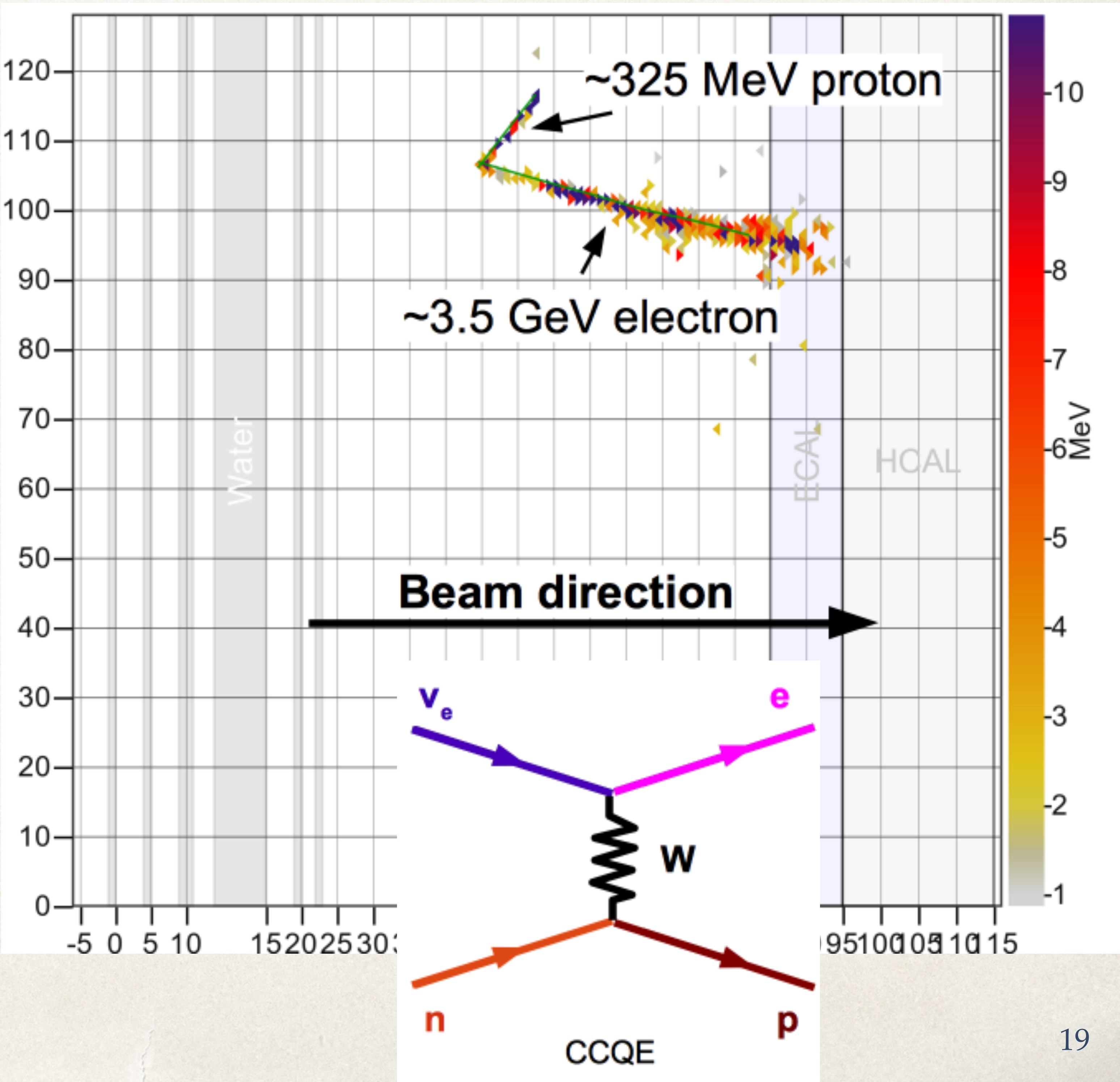


Net effect on flux FHC ν_μ flux between 0 and 8 GeV:
Lowers prediction by 5%
Lowers fractional uncertainty from 8.7 to 5.8%

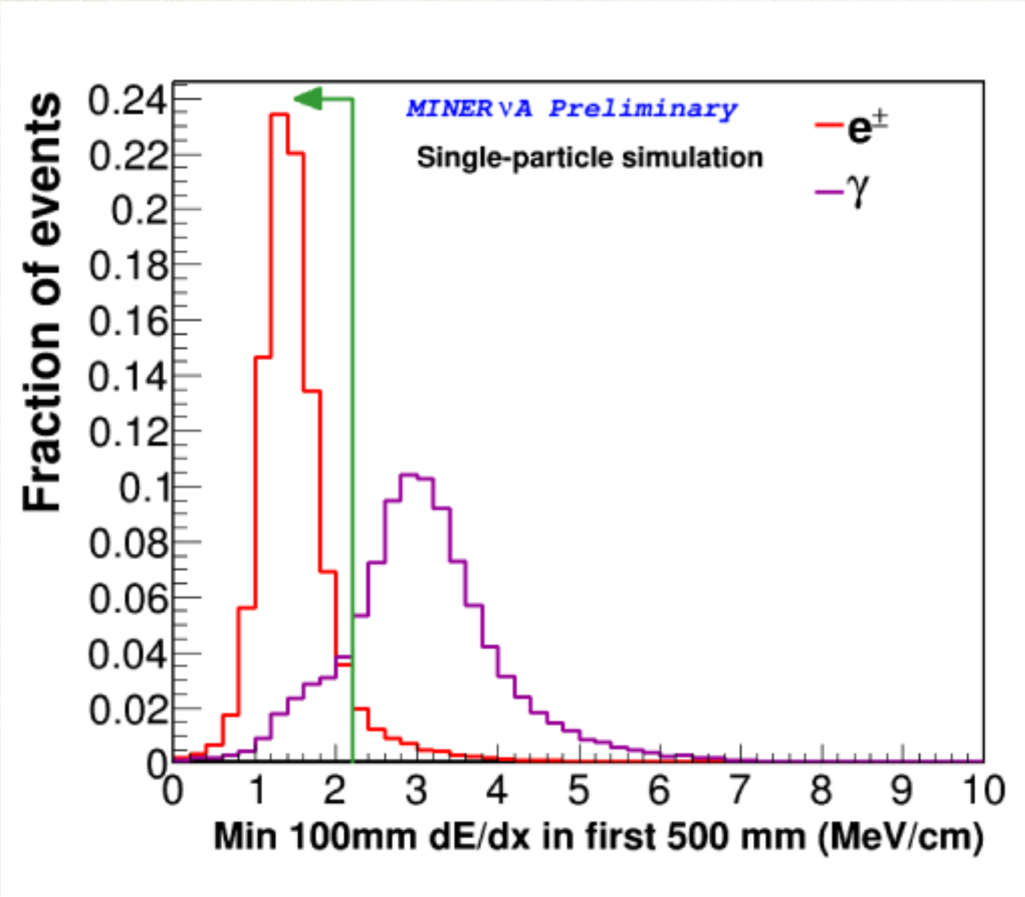
- We also expect two major flux updates before the end of 2015, incorporating more external data and a demonstration of the low-nu technique

Results: Electron Neutrino CCQE

- ν_e Charged-Current Quasi-Elastic (CCQE) is a signal process in ν_e appearance measurements
- Models of this process are tuned using ν_μ CCQE measurements + an assumption of lepton universality
- MINERvA has made the first direct measurement of this process using the 1% ν_e component of our ν_μ beam

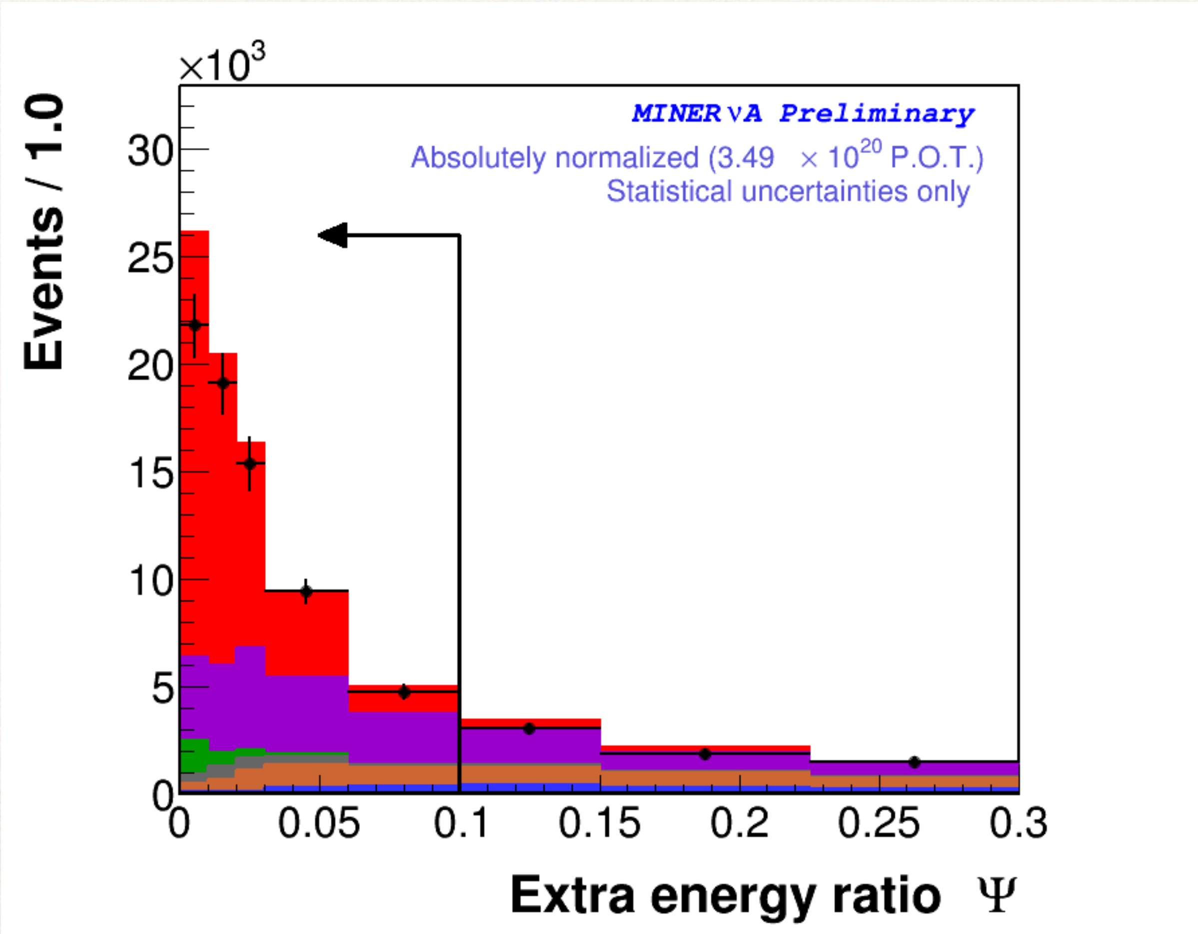


Results: Electron Neutrino CCQE



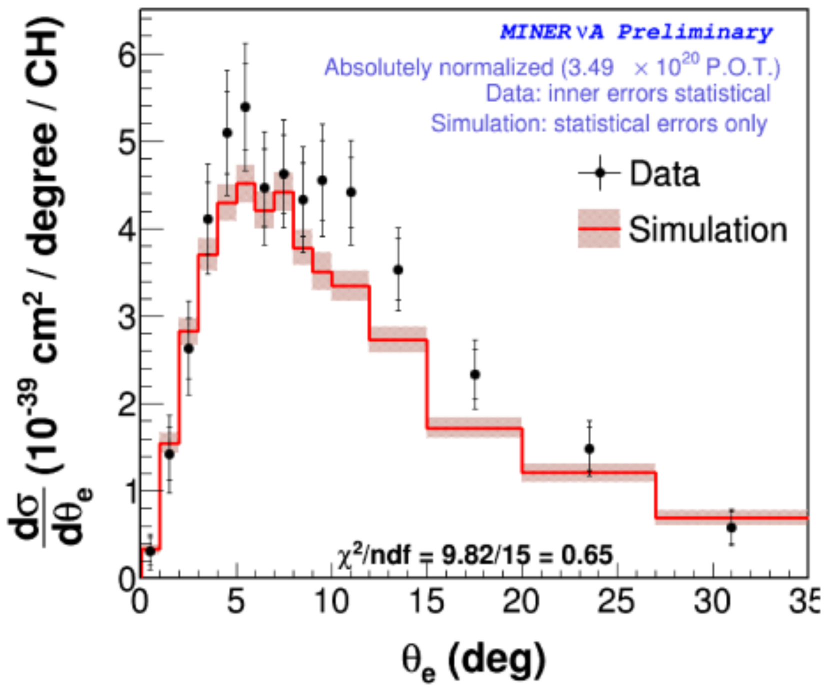
- Signal isolated by identifying electromagnetic showers with an electron-like dE/dx profile at beginning of track

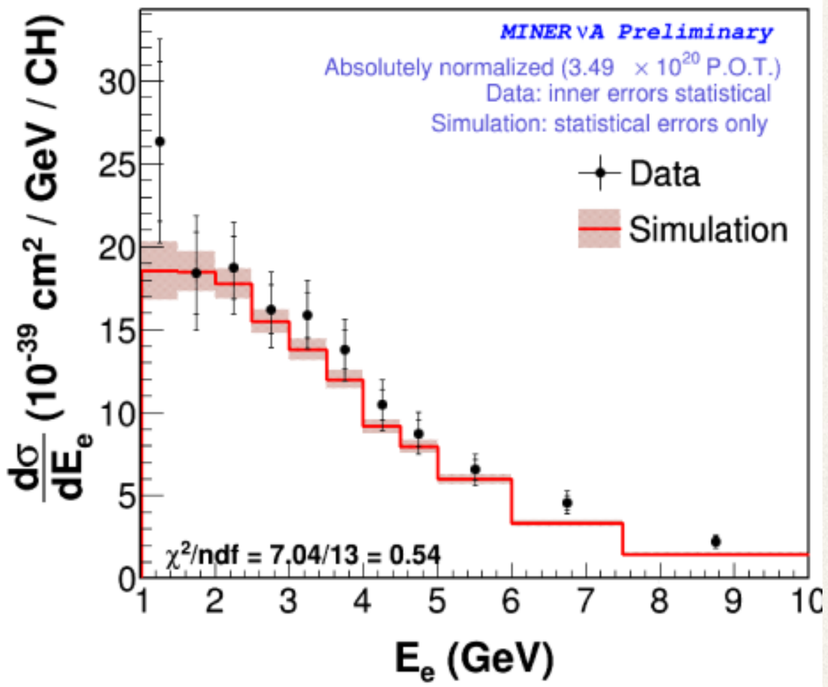
- In elastic background reduced by selecting events with low amounts of off-shower energy



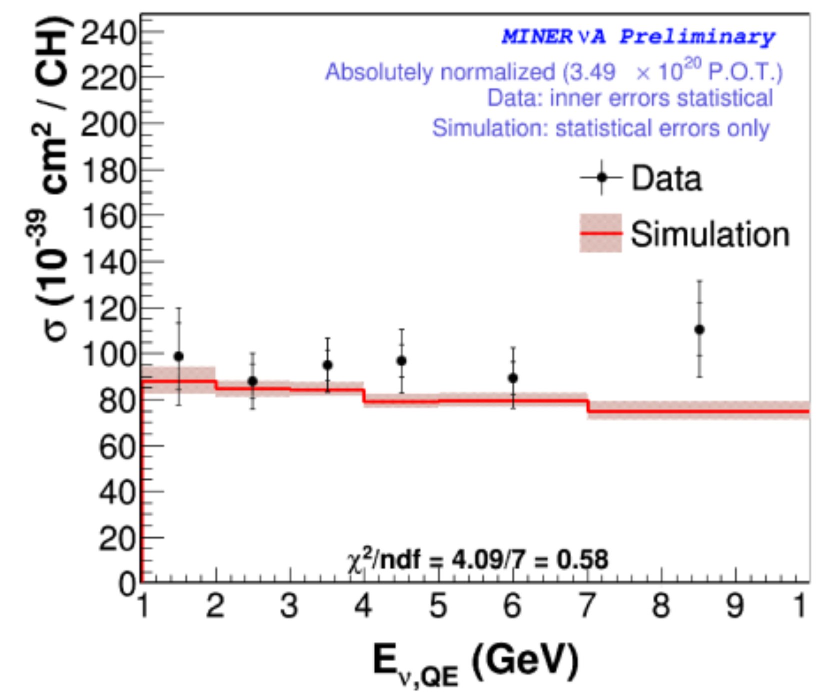
arXiv:1509.05729

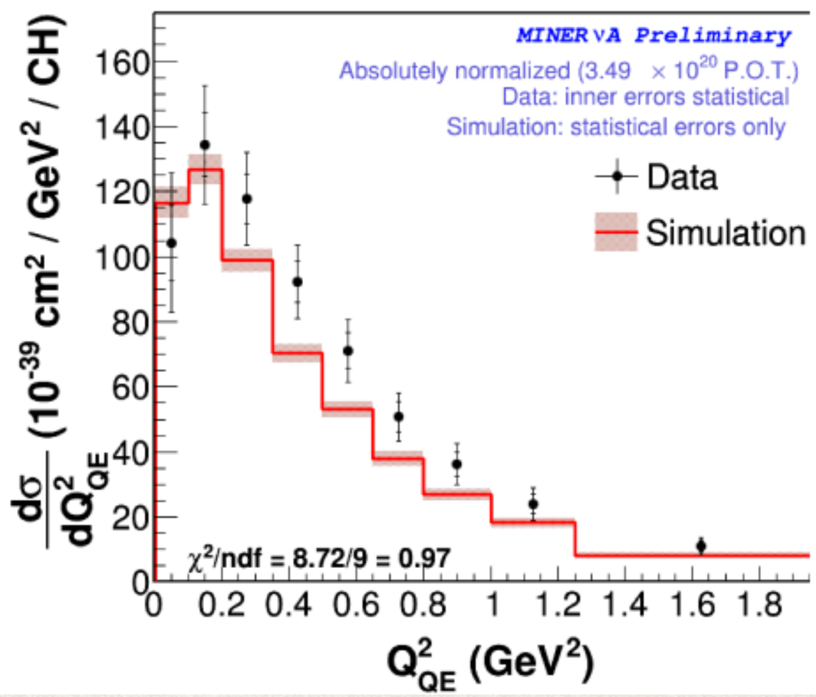
Results: Electron Neutrino CCQE





Measured cross-sections are consistent with the prediction from GENIE 2.6.2

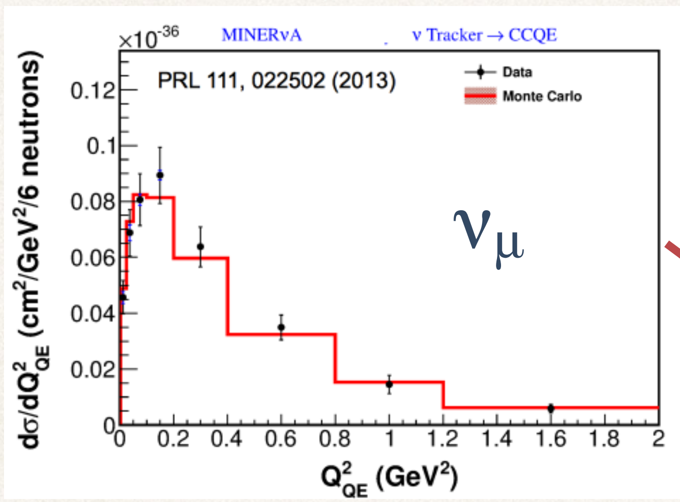


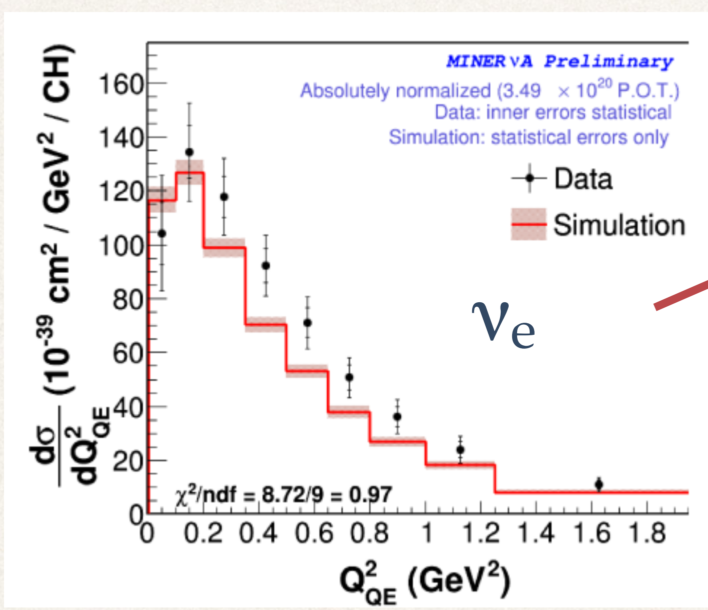


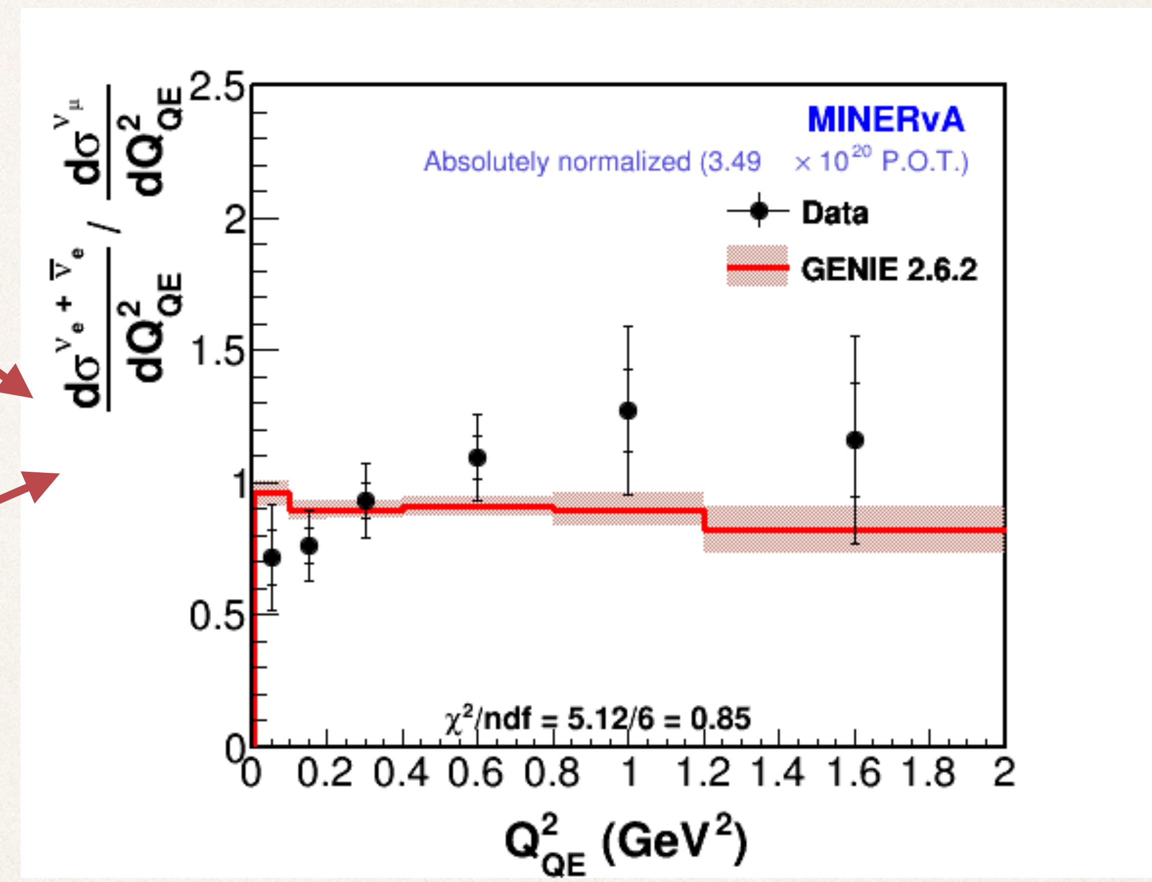
arXiv:1509.05729

Results: Electron Neutrino CCQE

- Can also directly compare electron neutrino and muon neutrino CCQE, using MINERvA's earlier ν_μ results:



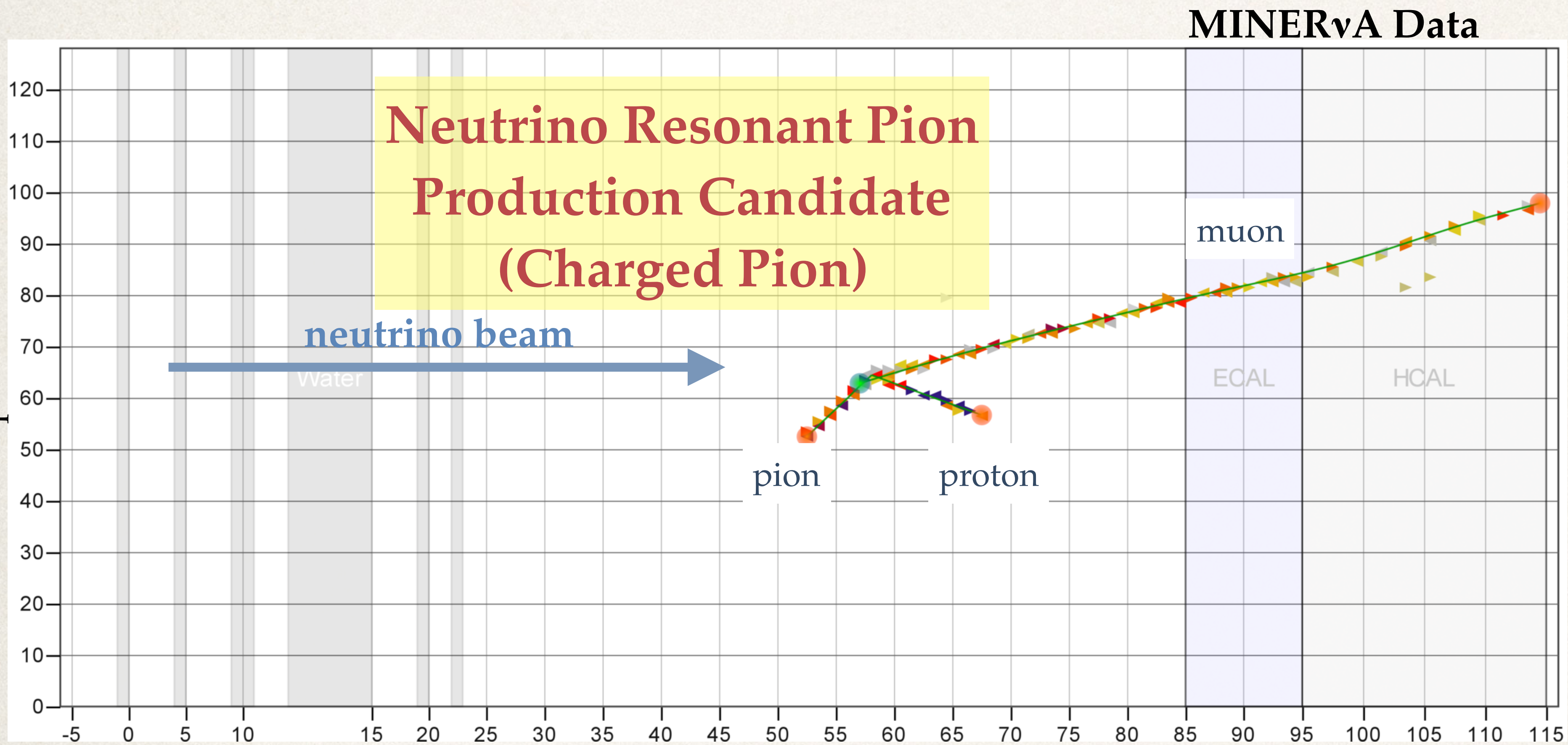


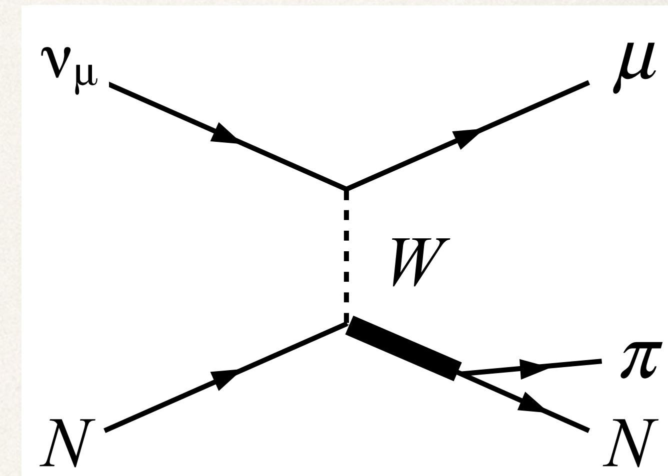


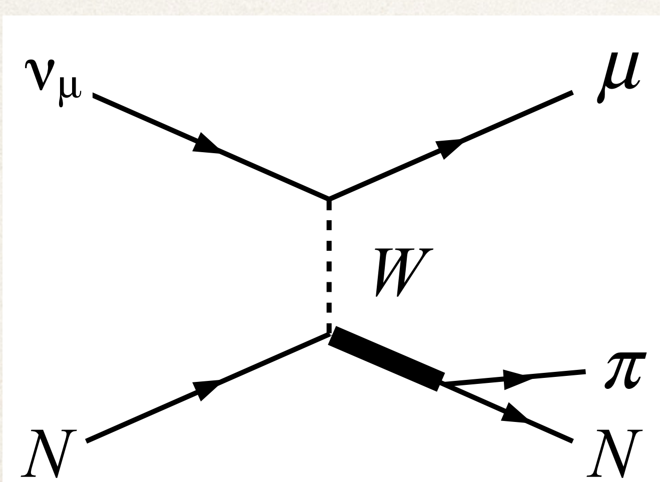
arXiv:1509.05729

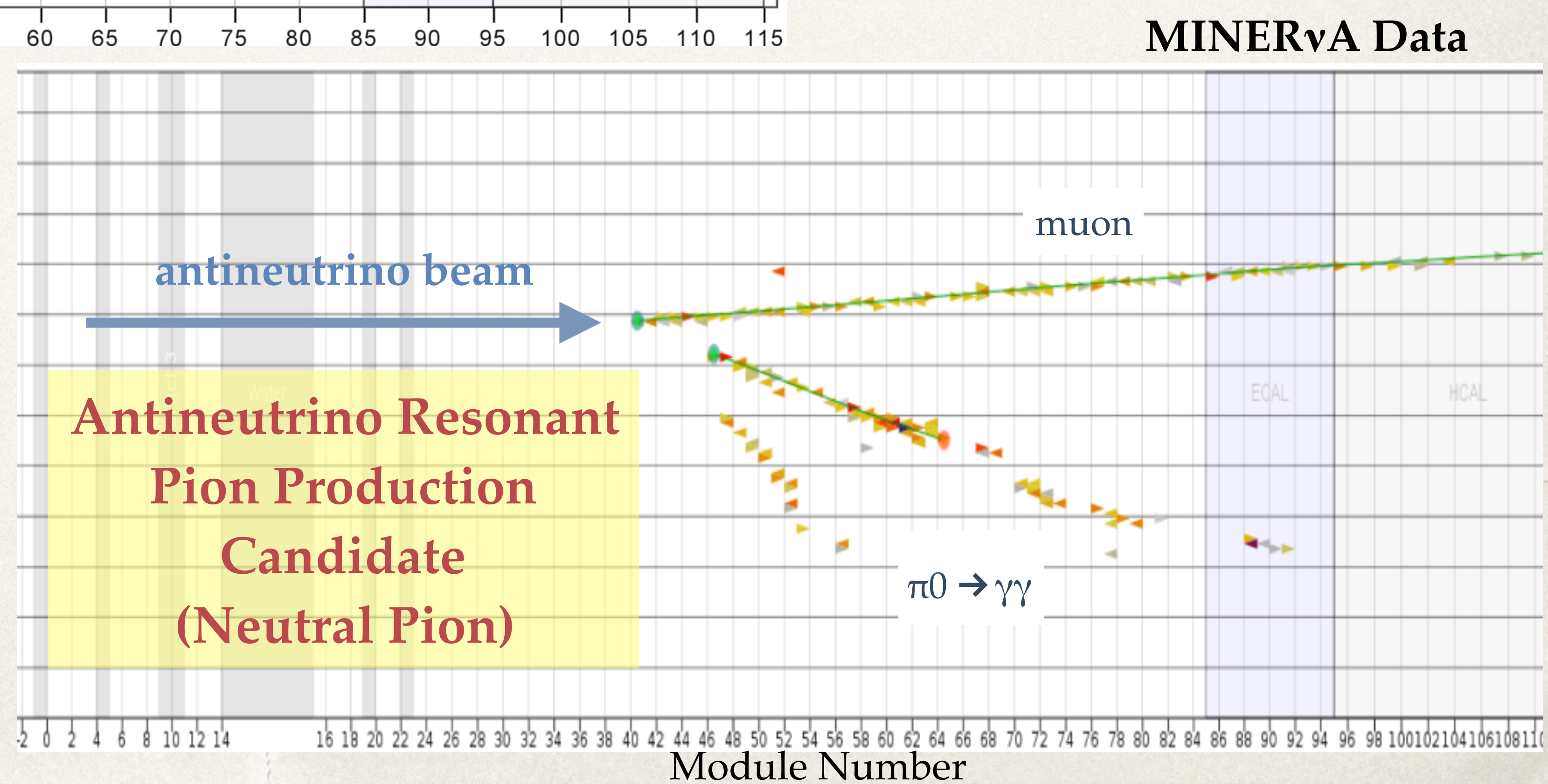
- Again, good agreement with expectation — indicates that tuning ν_e models with ν_μ data is a reasonable thing to do

Results: Charged Current Pion Production

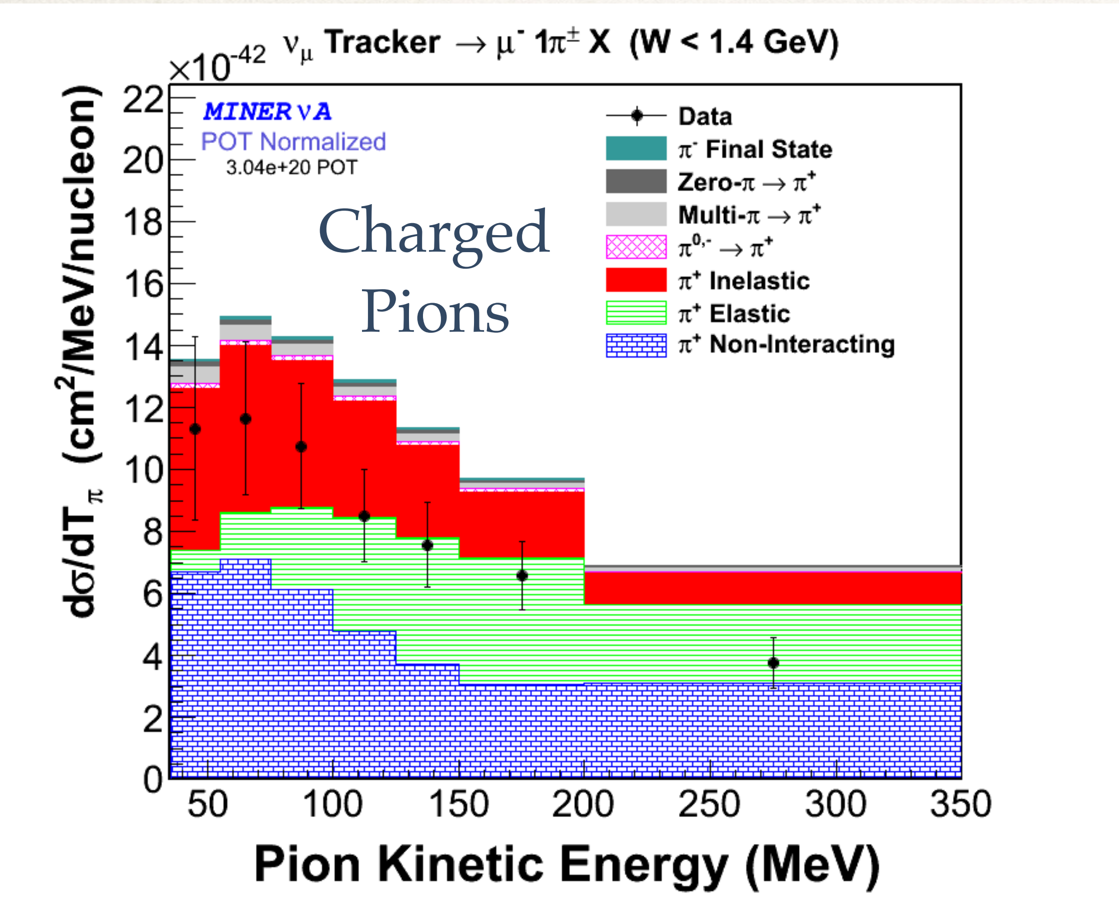




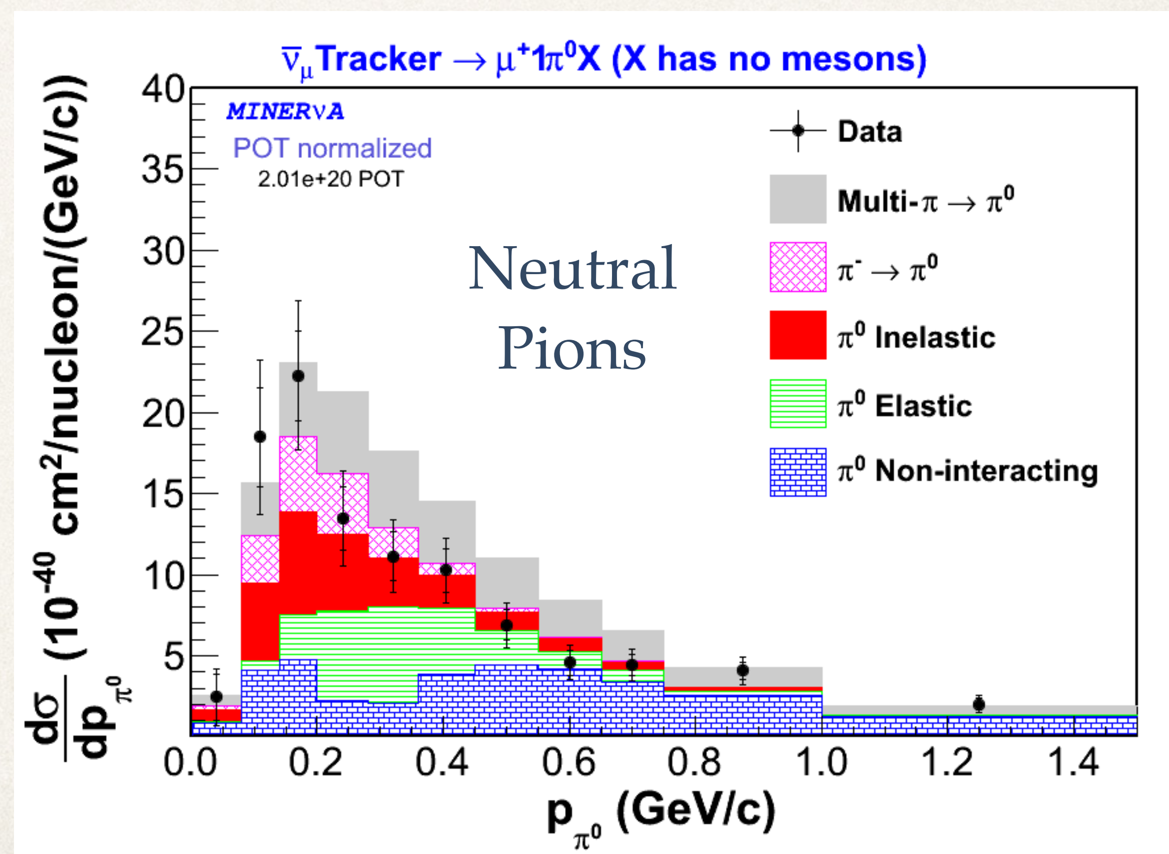




Results: Resonant Pion Production



- Pion energy distributions are heavily sculpted by final state interactions
- Sculpted in different ways for charged and neutral pions

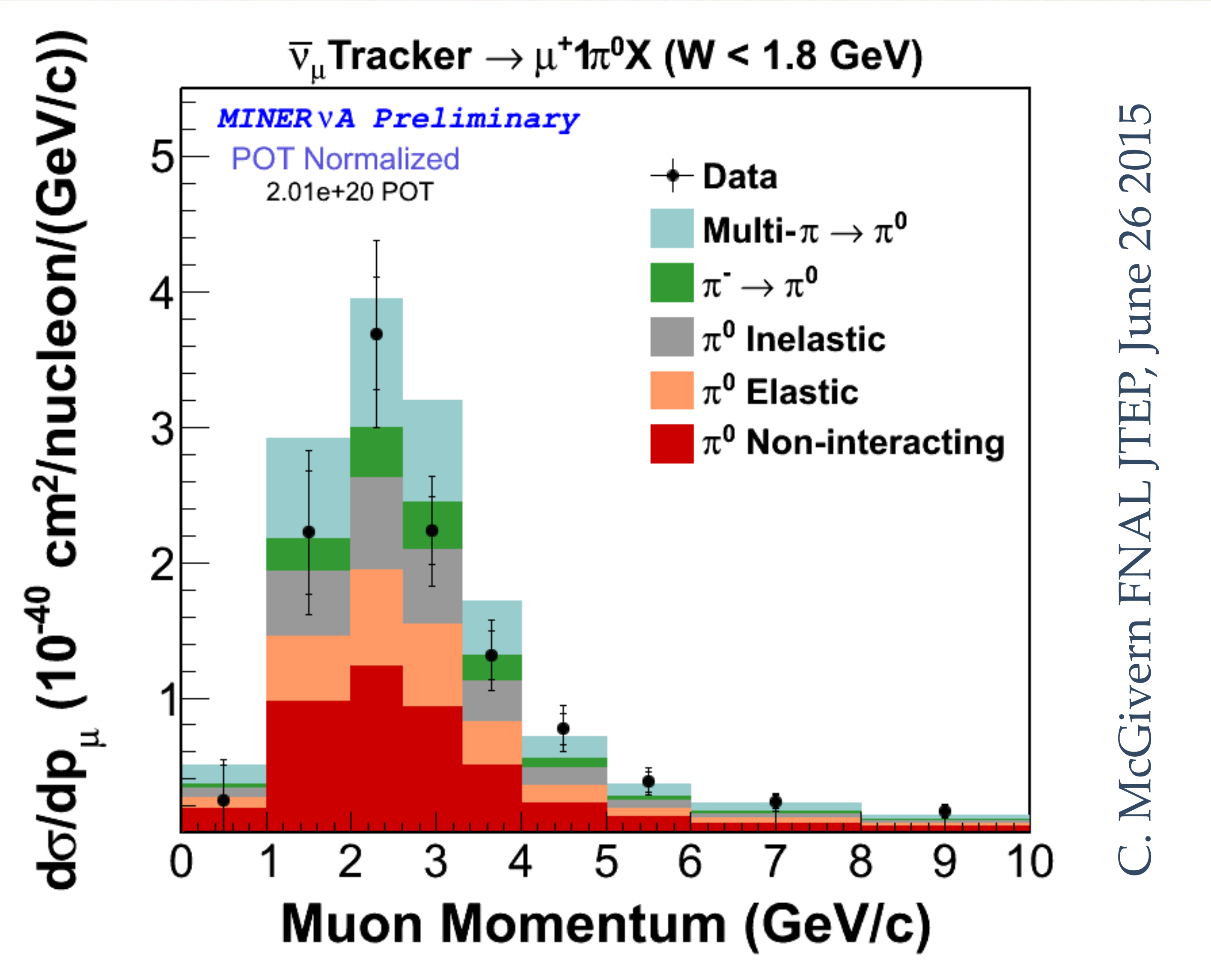


arXiv:1406.6415, accepted by PRD

- Charged pions: shape of model areas well; overall normalization off by ~30%
- Neutral pions: Good agreement seen at high energy, where FSI is rare, poor agreement at lower energy, where FSI processes dominate

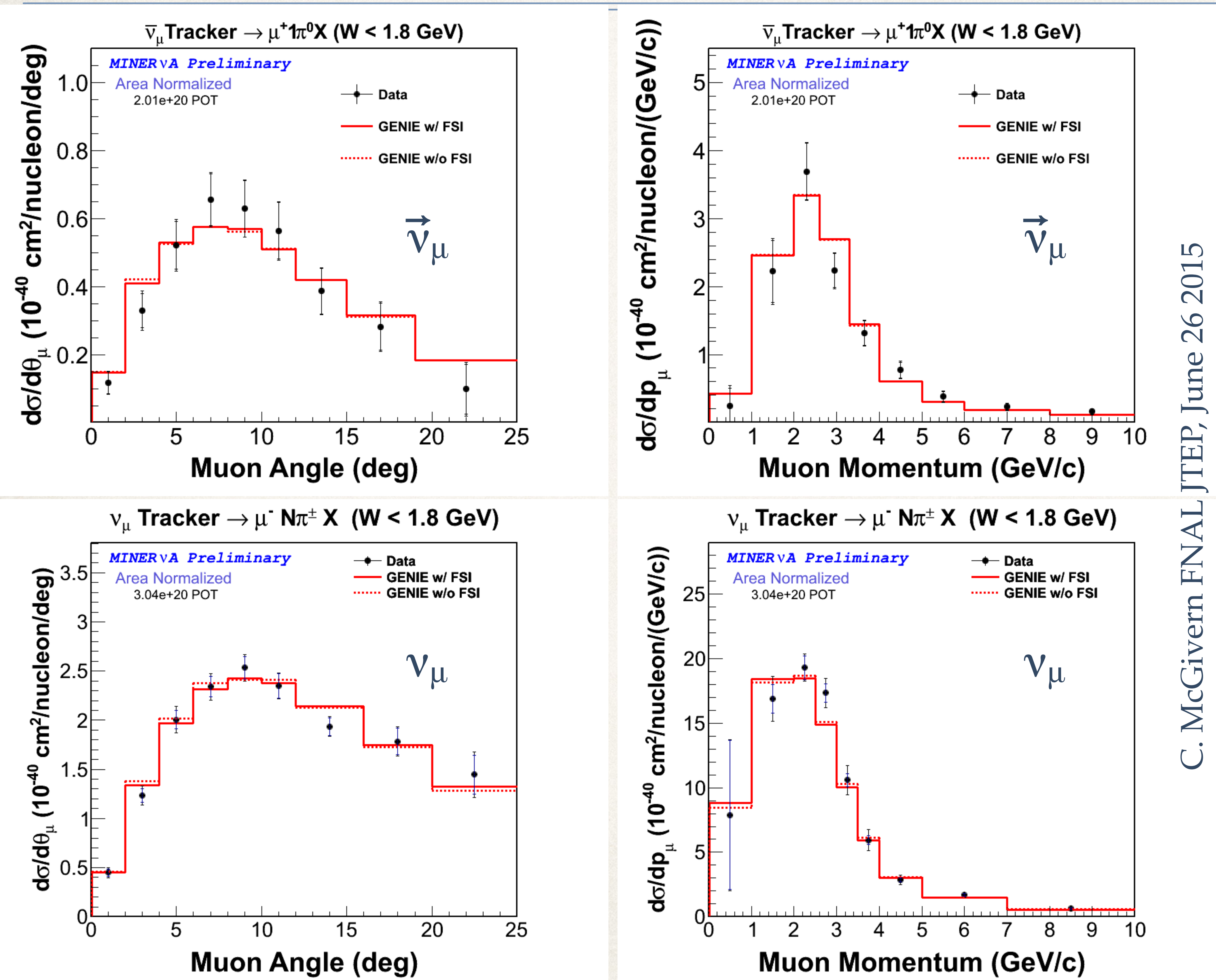
Results: Resonant Pion Production

- For muon variables, FSI impact is quite different: categories populate all regions of muon distributions evenly
- Changes to FSI models would change the normalization of these distributions, but do not affect shape
- Shape is a probe of other non-FSI interaction parameters (nuclear structure and neutrino-nucleon amplitudes)



C. McGivern FNAL JTEP, June 26 2015

Results: Resonant Pion Production



C. McGivern FNAL JTEP, June 26 2015

Muon angle and muon momentum shape agree very well!

Substantial disagreements in pion variables likely due to FSI model.

Results: NC Kaon Production

- Charged and neutral current kaon production are sensitive probes of FSI models

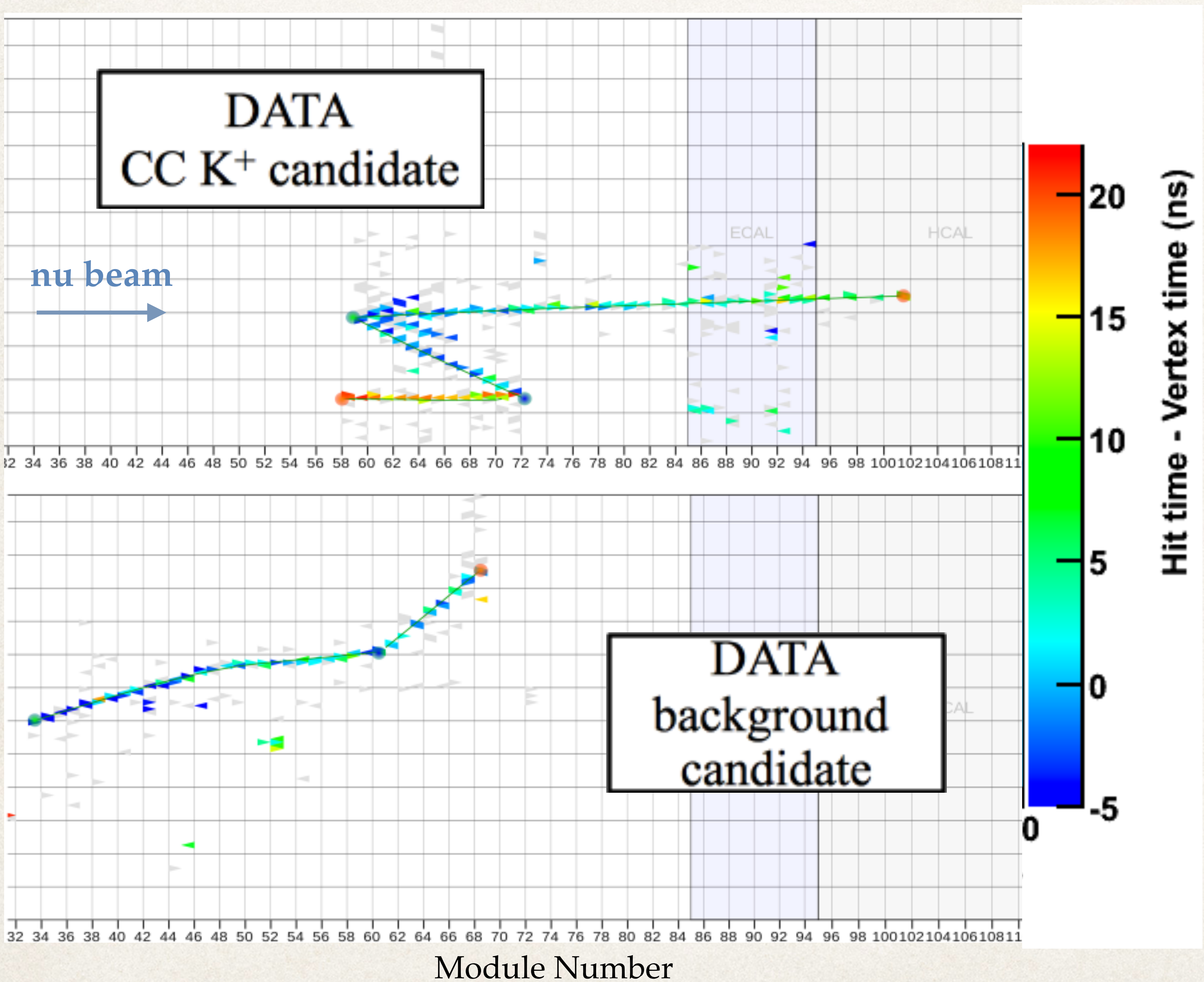
- Neutral-current reactions like
  - $\nu\, p \rightarrow \nu\, K^+\, \Lambda$
  - $\nu\, n \rightarrow \nu\, K^+\, \Sigma^-$

  are backgrounds in searches for $p \rightarrow K^+\, \nu$

- Particularly problematic for water Cherenkov detectors, where kaon is below Cherenkov threshold

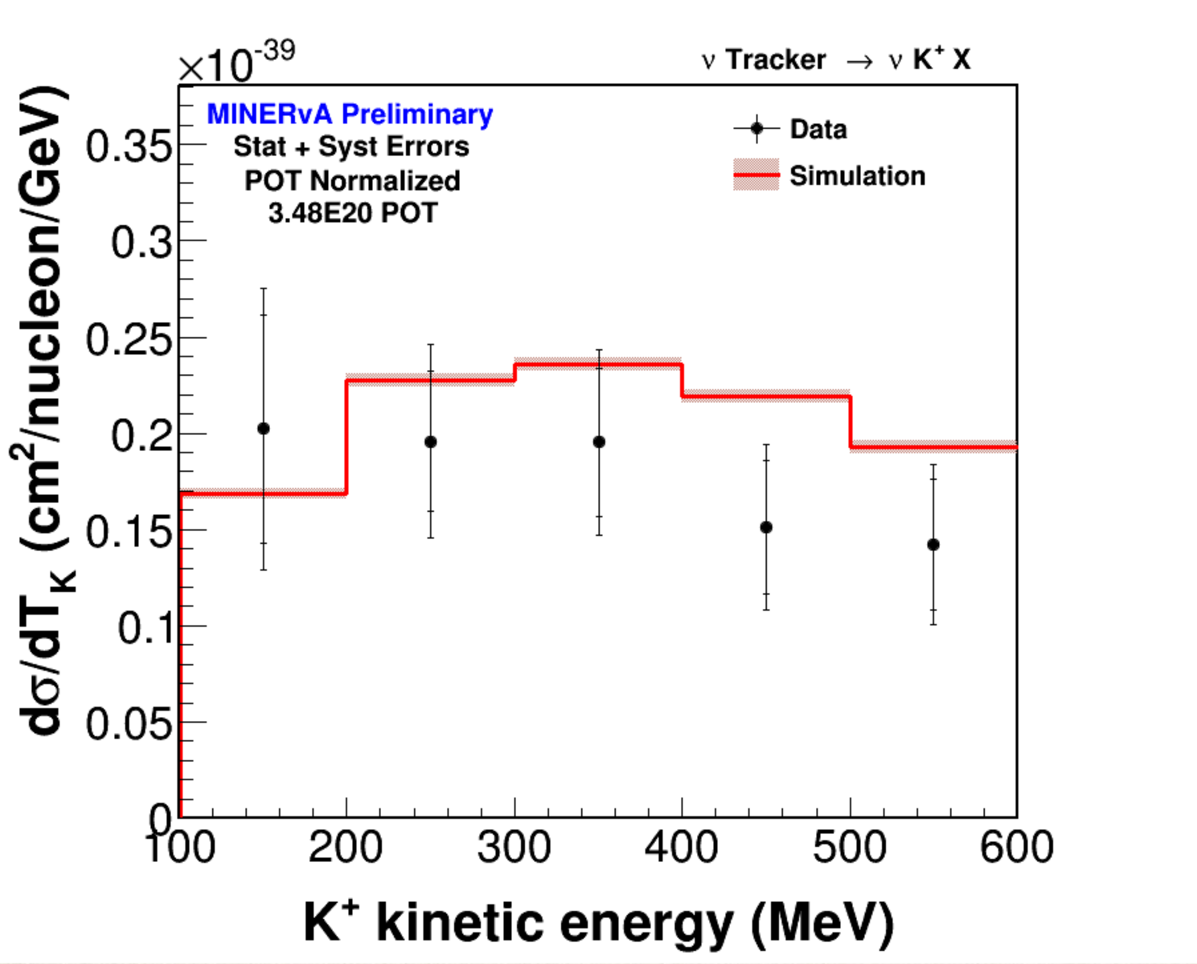
- Mismodeled rates for processes that appear as Kaon + nothing would be problematic even for liquid Argon detectors

Results: NC Kaon Production



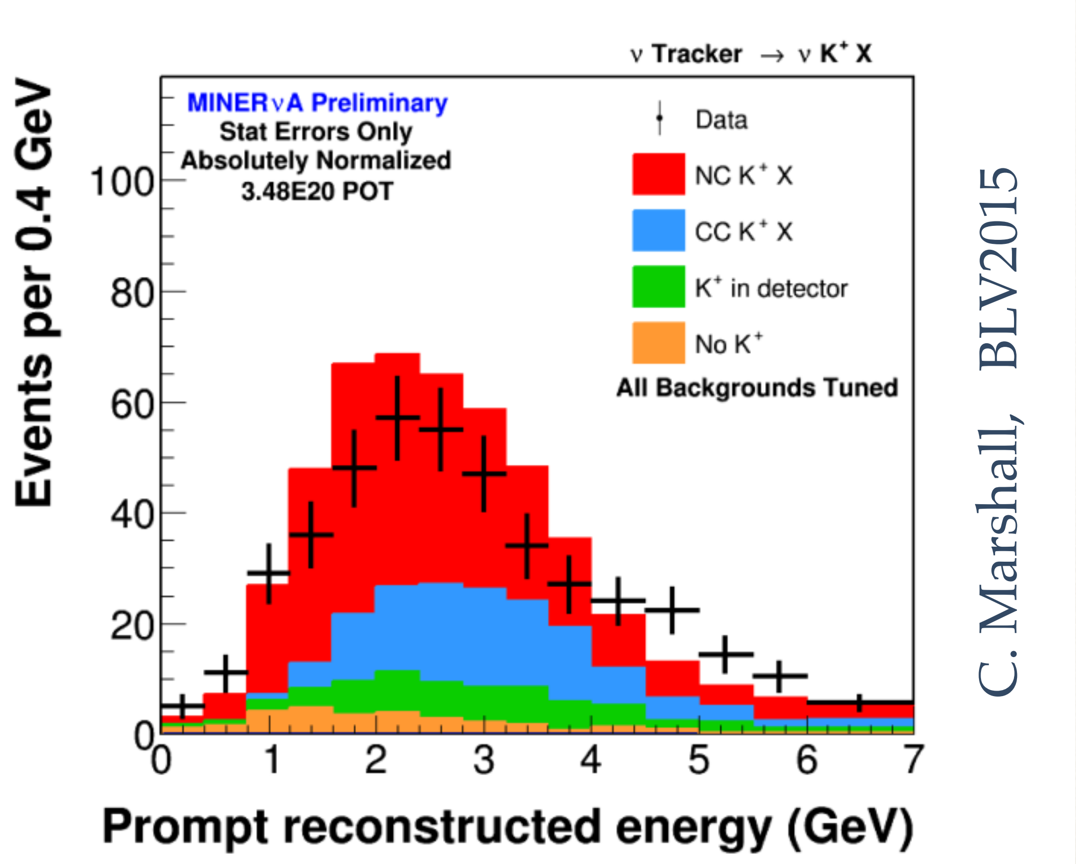
- Key distinguishing feature of kaons for MINERvA: time separation of kaon and decay products
- Here, color denotes hit time

Results: NC Kaon Production



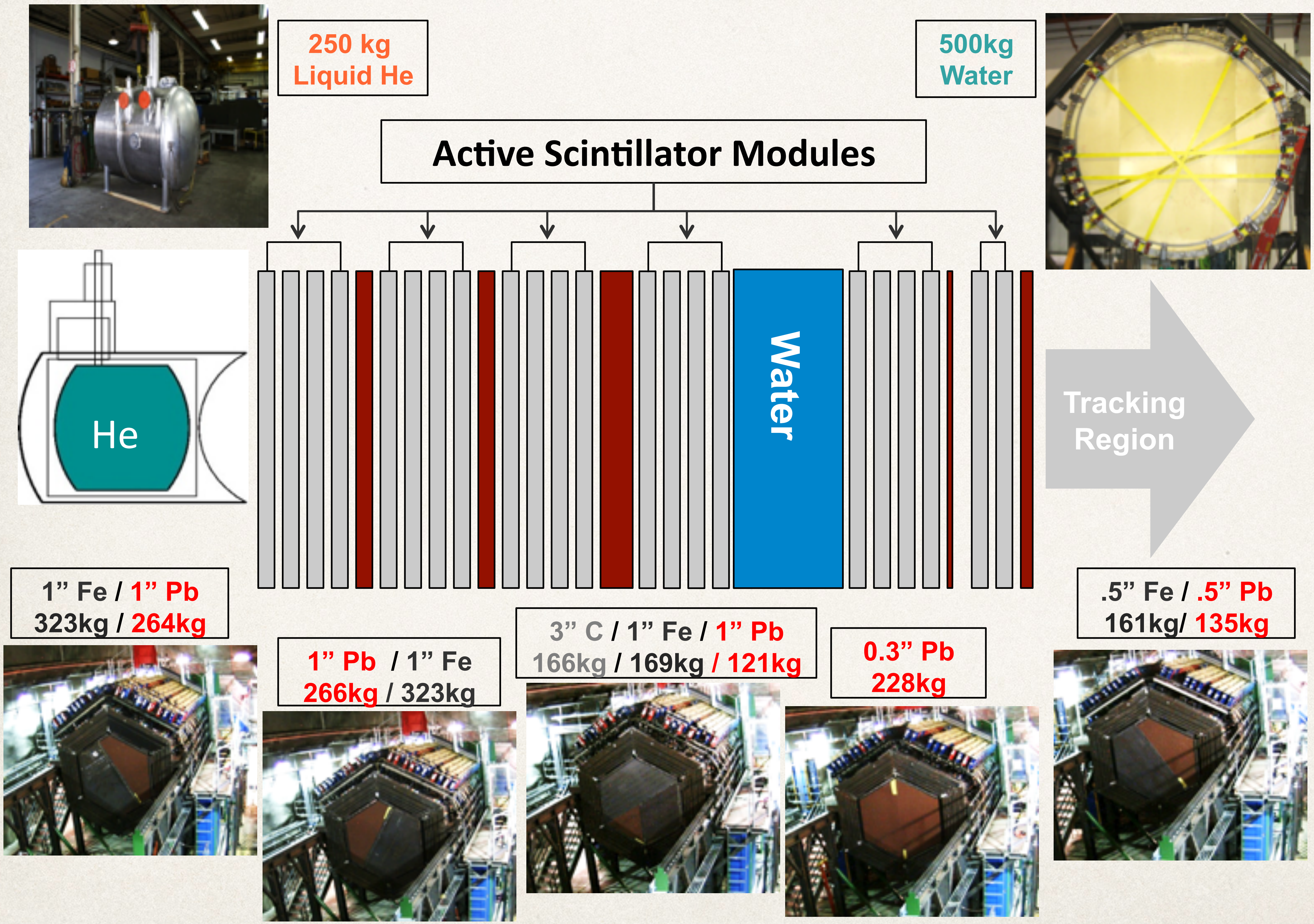
- Preliminary results from MINERvA indicate that rate and spectra are well modeled below the Cherenkov threshold

- Final results, including a companion charged current analysis (sensitive probe of FSI models) expected in next few months



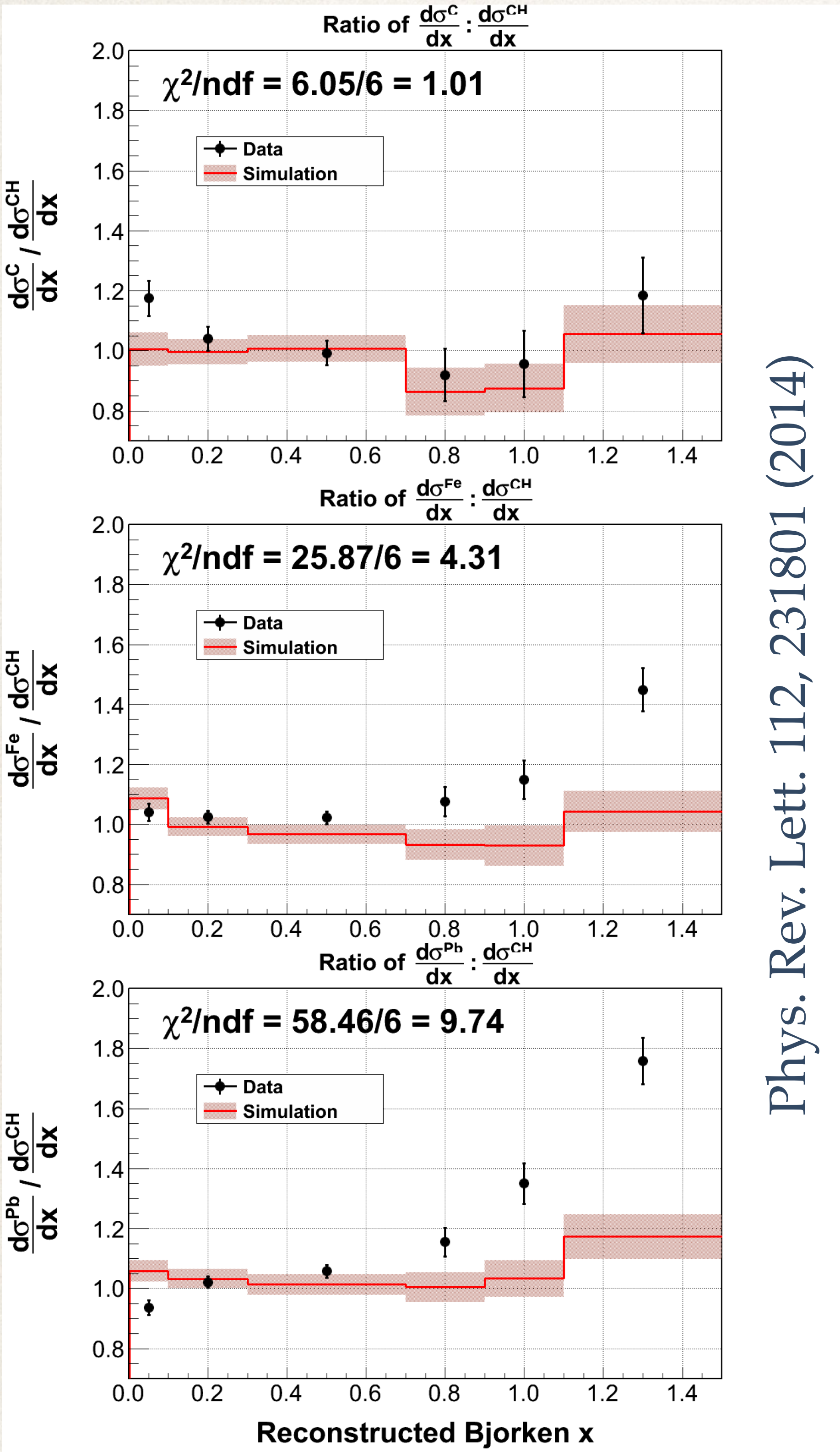
C. Marshall, BLV2015

Results: Inclusive Target Ratios



MINERvA has also begun to study the ratio of neutrino interactions on different nuclei using solid nuclear targets.

Results: Inclusive Target Ratios



Phys. Rev. Lett. 112, 231801 (2014)

Carbon

Iron

Lead

- Inclusive charged current cross section ratios of a dimensionless scaling variable called "x"
- x corresponds to the fraction of the initial nucleon's momentum that is carried by the struck quark
- Large normalization uncertainties cancel in ratios

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

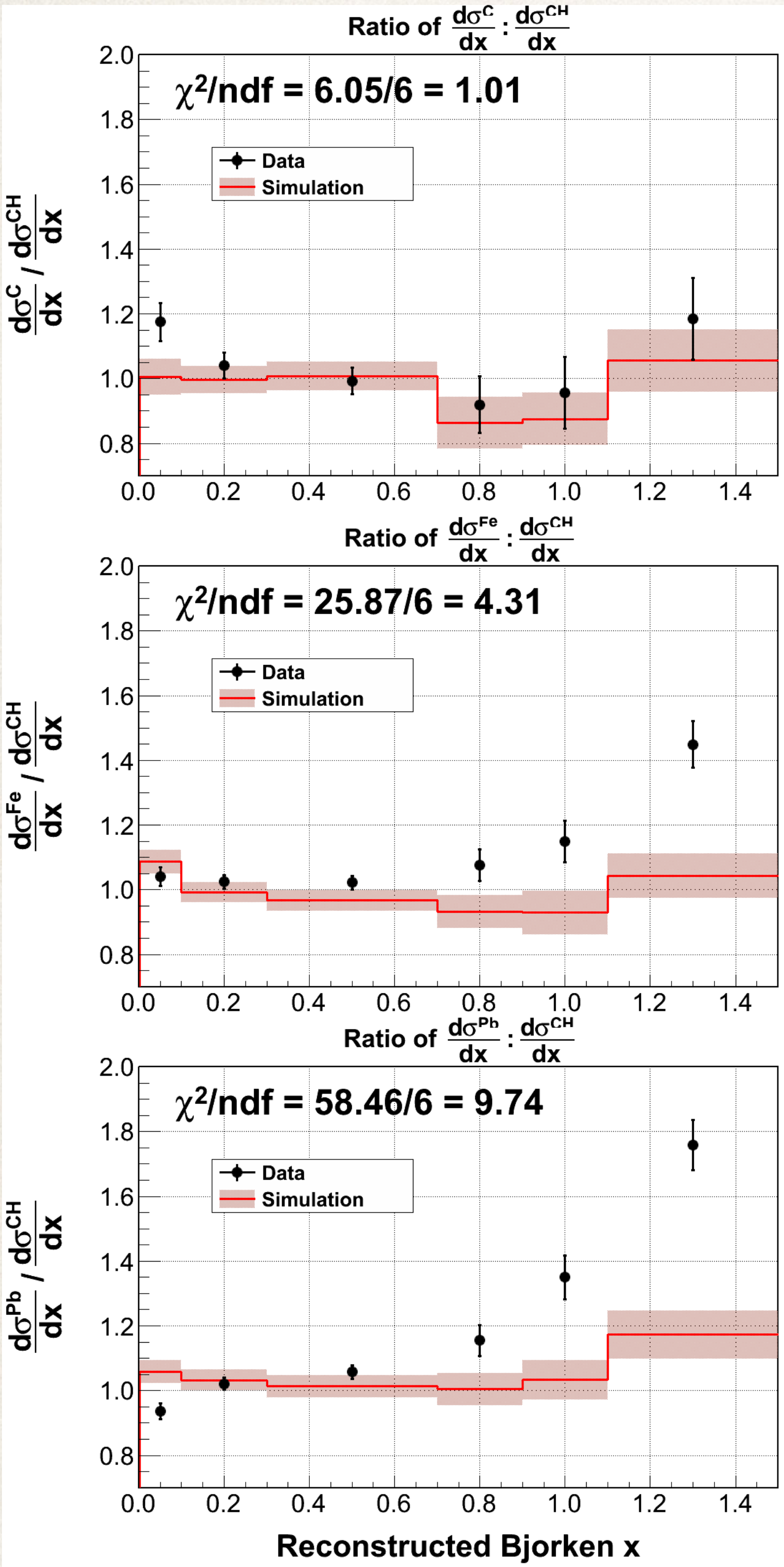
high x = more elastic

$$\nu = E_\nu - E_\mu$$

$$Q^2 = 2E_\nu\left(E_\mu - p_\mu cos\left(\theta_\mu\right)\right)$$

Phys. Rev. Lett. 112, 231801

Results: Inclusive Target Ratios



Phys. Rev. Lett. 112, 231801 (2014)

Carbon

Iron

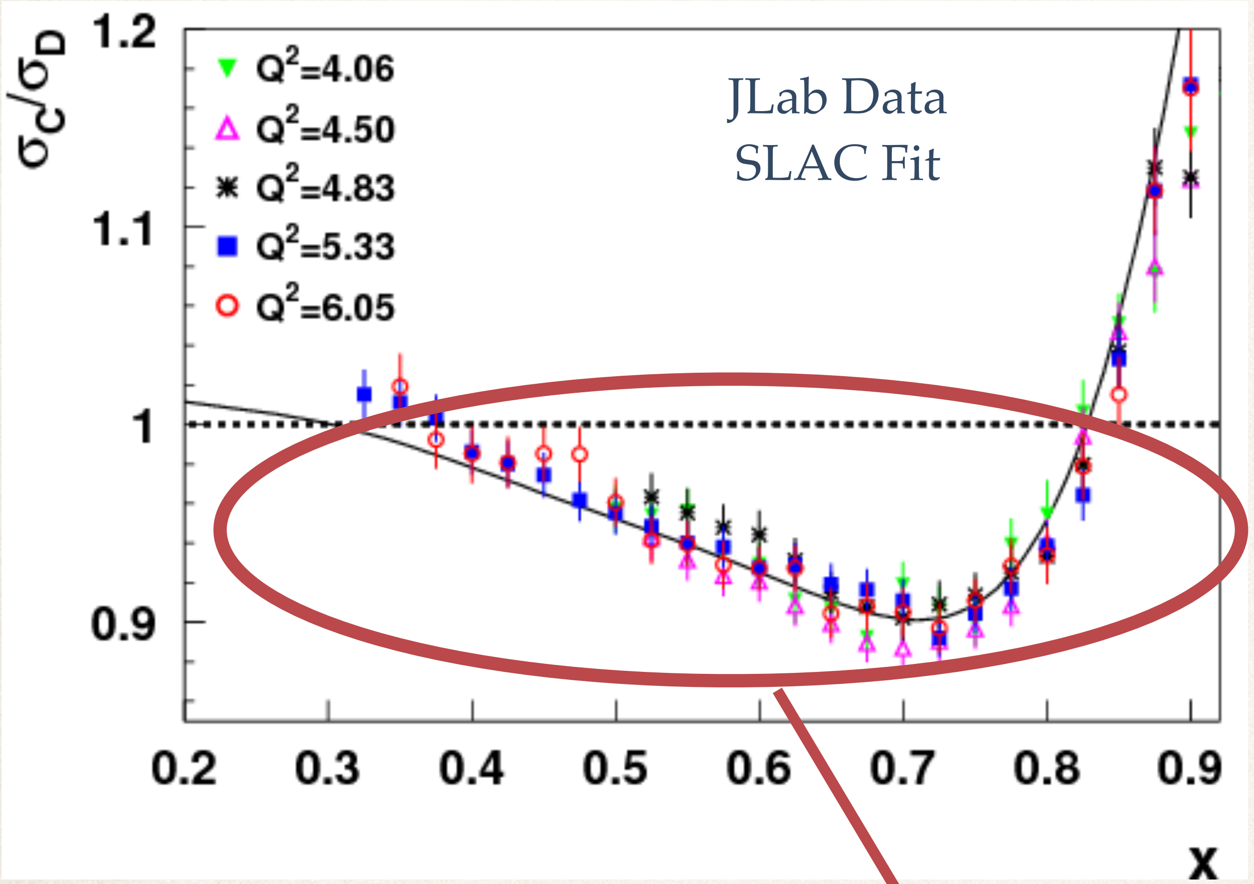
Lead

- The accepted model of nuclear effects is wrong
- And it is **increasingly wrong in heavier nuclei**
- High-x behavior implies mismodeling of A-dependence of quasi-elastic interactions

Phys. Rev. Lett. 112, 231801

Results: Inclusive Target Ratios

Seely, J. et al. Phys.Rev.Lett. 103 (2009) 202301 arXiv:0904.4448

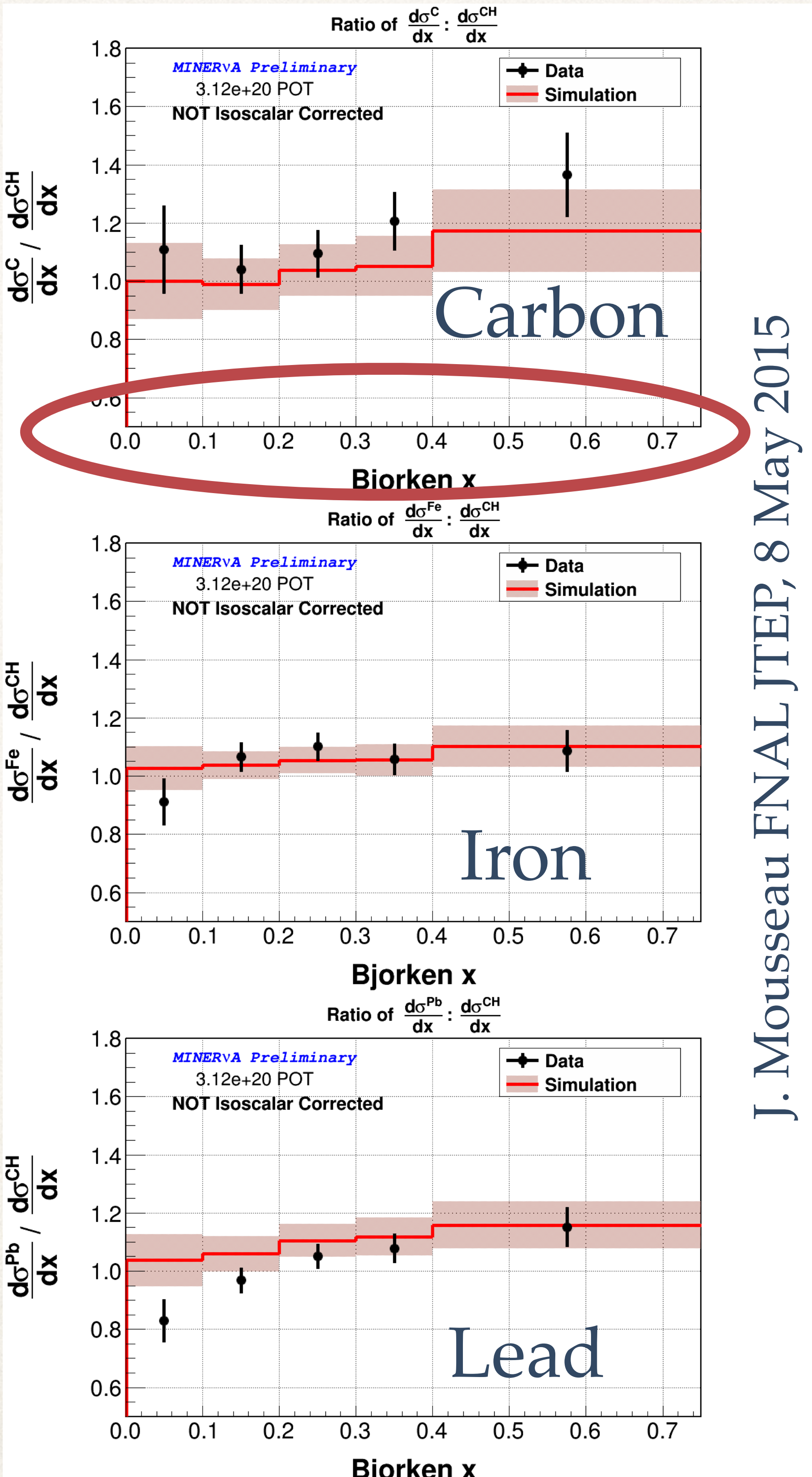


Ratio measurements like these can also be used to study a mysterious phenomenon first observed in muon scattering: the “EMC effect”

The EMC Effect:
An unexpected dip in the ratio of muon scattering cross section on heavy nuclei compared to those on deuterium between x = ~0.3 and ~0.9

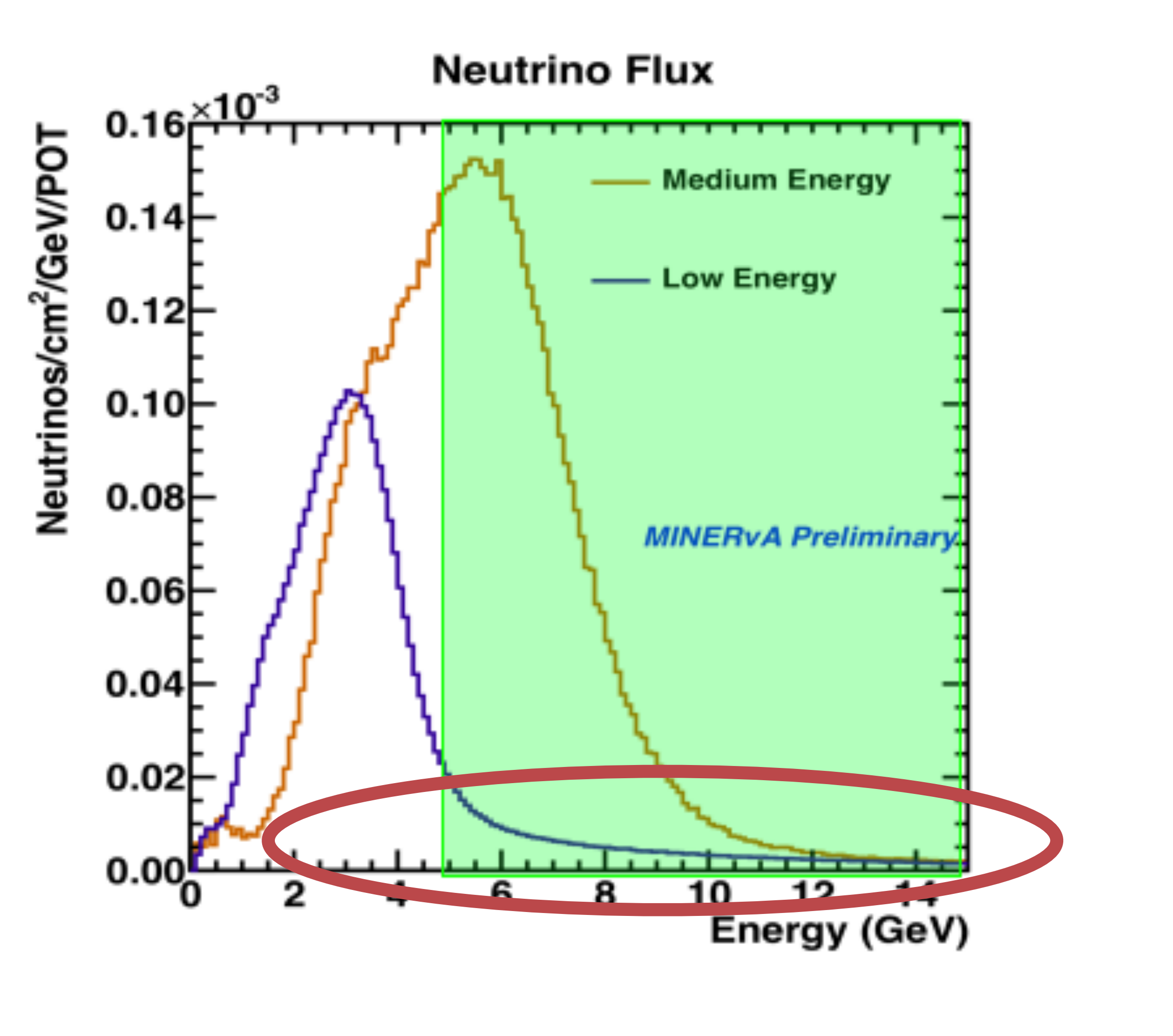
Results: DIS Target Ratios

You are now looking at a zoomed x-axis compared to the CC inclusive ratios a few slides ago



- This year, we produced our first exclusive nuclear target ratios — measuring Deep Inelastic scattering
- Simulation is GENIE, which does not include any attempt to predict impact of EMC effect on neutrino scattering
- Simulation is in good agreement with MC in the EMC region (0.3 - 0.8)

Future Plans

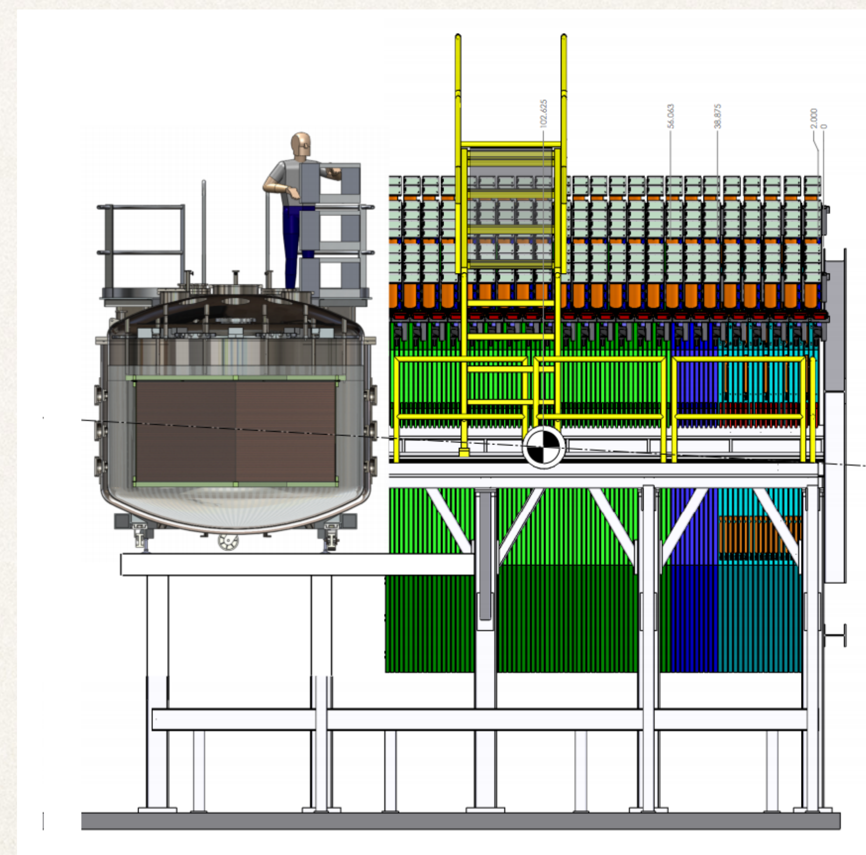


This analysis used the high energy tail of our "Low Energy" dataset. We are now accumulating many more events in the Medium Energy beam configuration

- The Medium Energy data we are taking now is rich in statistics for this and several other analyses
- Also expect ~factor of 10 more statistics for the neutrino-electron scattering flux constraint
- There are also ~ten other active not-yet-published analyses beyond what I've talked about that use low energy data

Future Plans: CAPTAIN MINERνA

- CAPTAIN MINERvA is a proposal to combine the CAPTAIN 5-ton liquid Argon detector with MINERvA in the NuMI beam



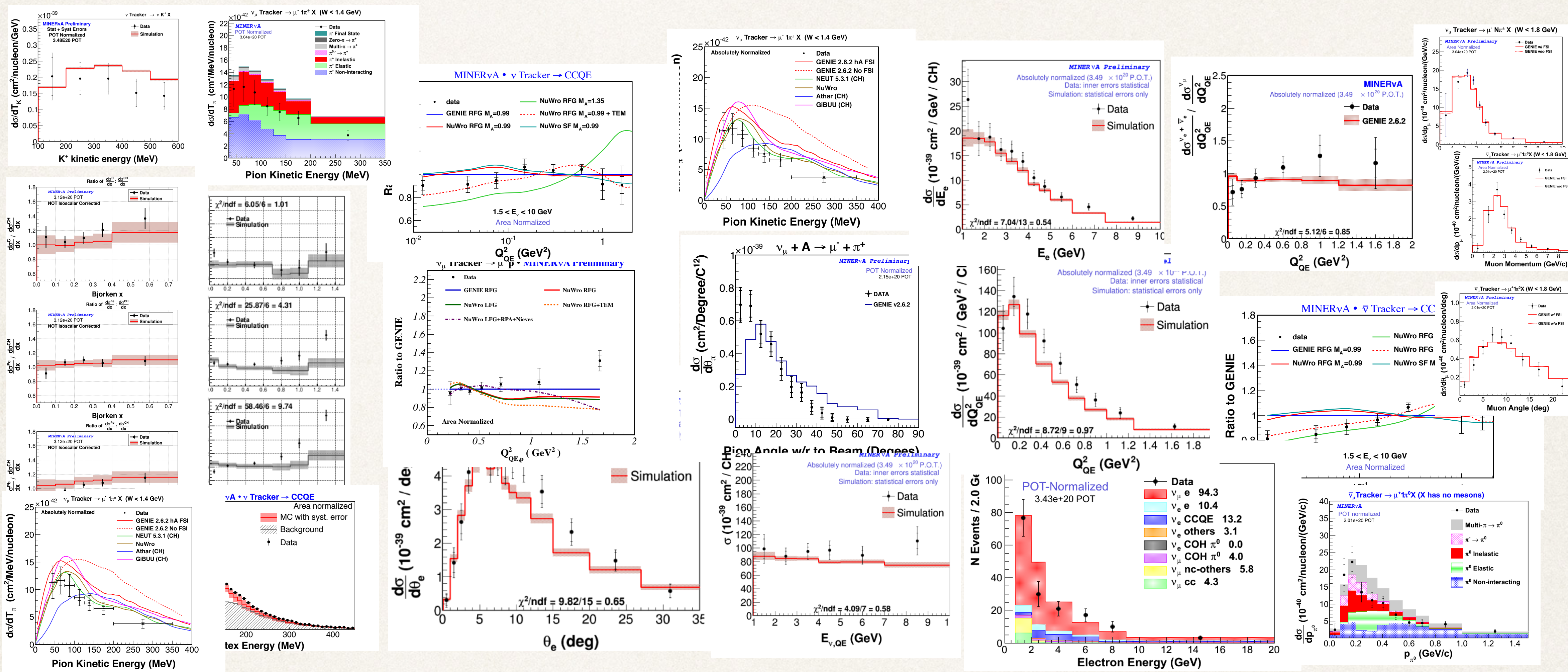
- Complements BNB cross section program by measuring higher energy portion of DUNE flux

- Allows CH/Argon measurements to untangle nuclear effects

See CAPTAIN talk from Lisa Whitehead

Conclusion

- MINERvA has become a prolific source of neutrino scattering data



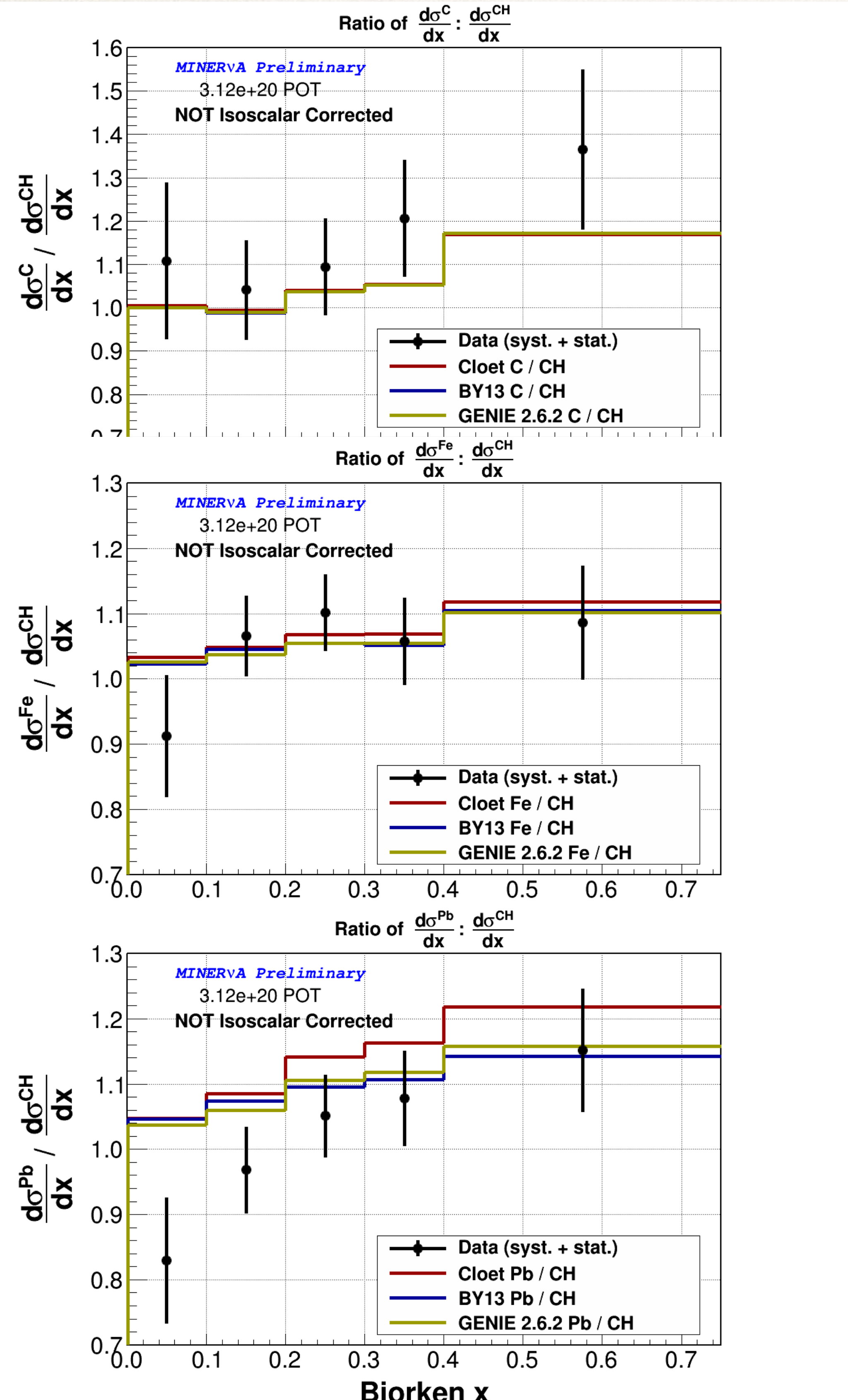
- Our data is illuminating locations where model development is needed for DUNE and beyond

- These precision measurements will provide many of the powerful constraints needed to meet the systematics goals of precision oscillation measurements

Thank You!

From the MINERvA Collaboration

Results: DIS Target Ratios



- This year, we produced our first exclusive nuclear target ratios — measuring Deep Inelastic scattering
- Simulation is GENIE, which does not include any attempt to predict impact of EMC effect on neutrino scattering
- Simulation is in good agreement with MC in the EMC region (0.3 - 0.8)

Future Plans: Model Building

- Making these measurements is the first step in developing models and event generators needed by DUNE and other oscillation experiments
- There are several organizations actively working on model development and tunes of models to global data
- There is broad overlap in collaboration between the MINERvA collaboration and these organizations
- We are actively working with them to ensure that our results are minimally model-dependent and in a format easily consumable by model developers

GENIE

FENIXS

NuSTEC

T2K