Neutrino Nucleon Deep Inelastic Scattering

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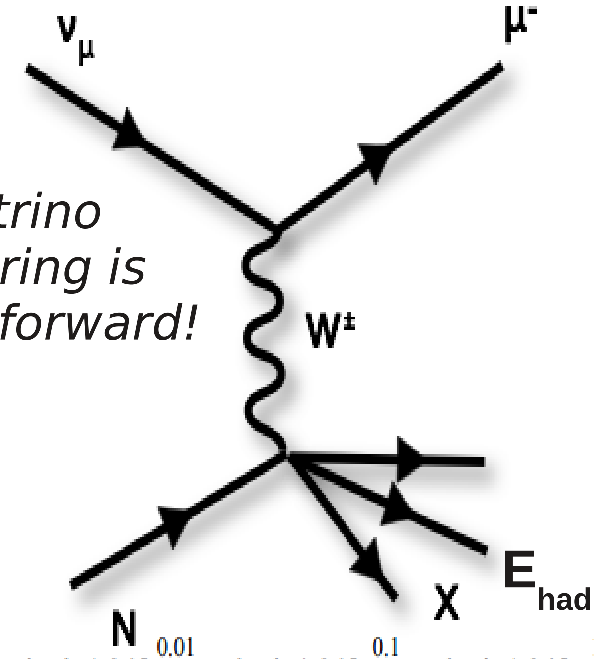
April 28th 2015
DIS 2015, Dallas, TX

Neutrinos in Nuclear Media

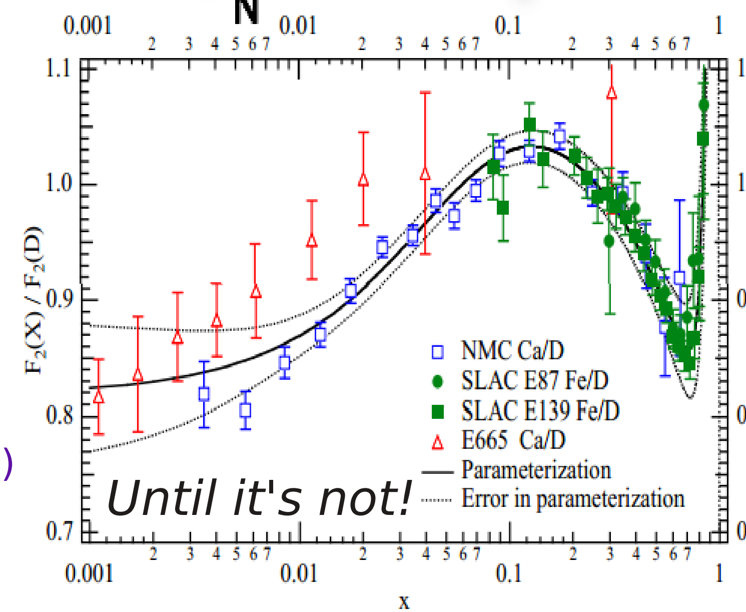
- One common theme of contemporary neutrino experiments: they rely on large A materials to supply adequate event rates (Fe, Ar, C, H_2O etc.)
- Problem: nuclear effects caused by nucleons bound in a nucleus distort the energy reconstruction of the neutrinos.
- These effects manifest in *ratios* of dσ/dx.
- Effects not well understood in neutrino physics. General strategy has been to adapt electron scattering effects into neutrino scattering theory.

$$x = \frac{Q^2}{2ME_{had}}$$

Neutrino scattering is straightforward!

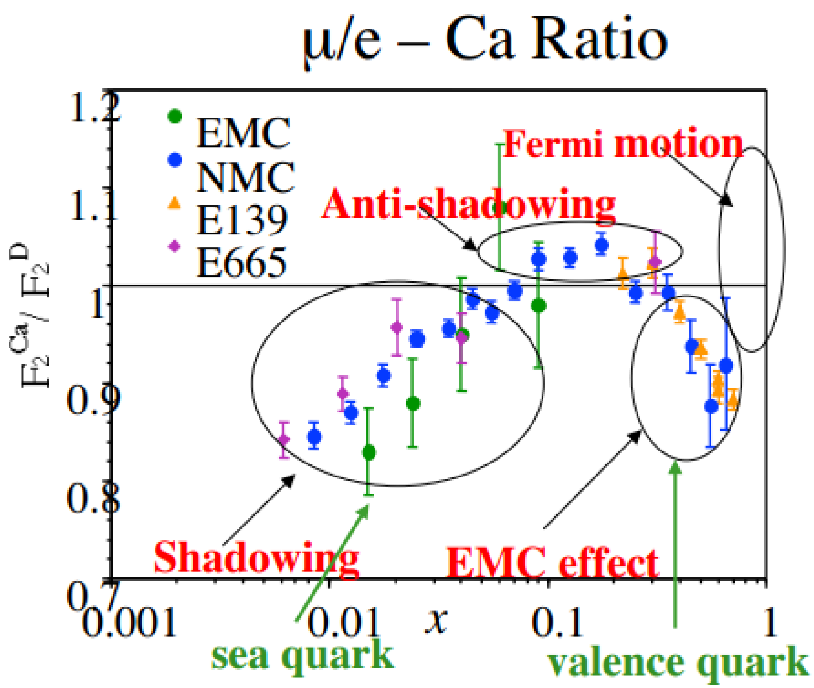


A. Bodek, I. Park, and U.-K. Yang, Nucl. Phys. Proc. Suppl. 139, 113 (2005)



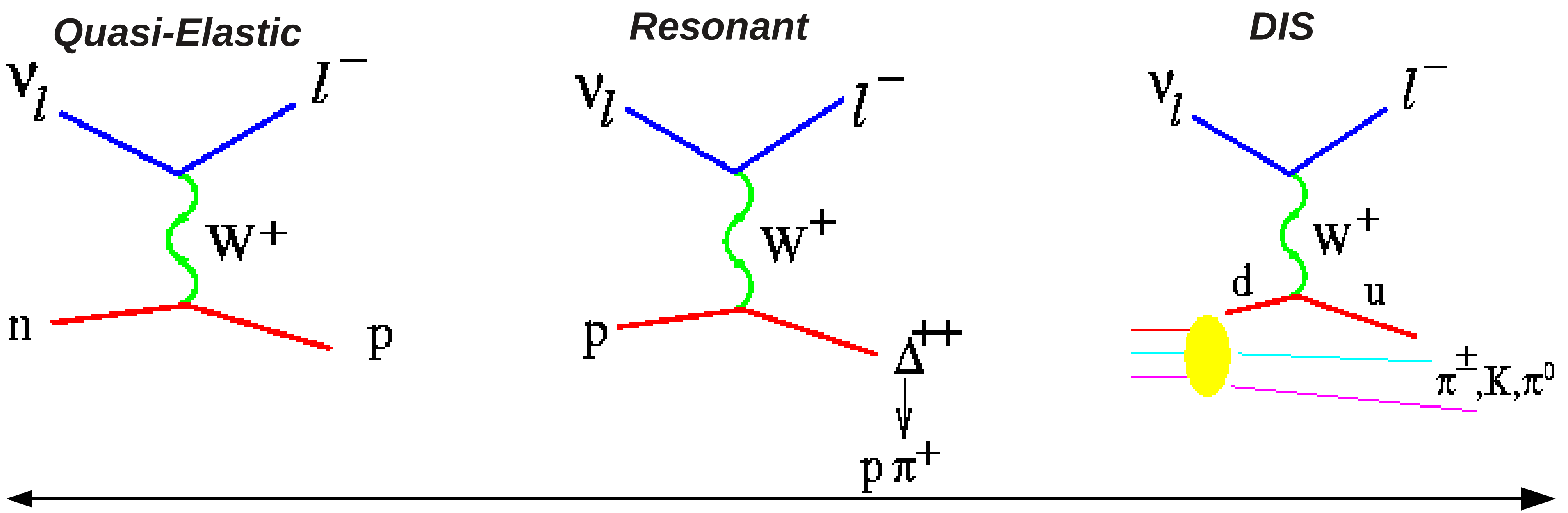
Charged Lepton Scattering

- However, there are some difficulties incorporating charged lepton data into neutrino scattering theory.
- For example, neutrinos are sensitive to the axial component of xF_3 and F_2.
- Charged lepton nuclear effects still not fully explained.



- Despite ~30 years of active research, EMC effect (0.4 < x <0.7) still not fully understood.
- MINERvA is the first chance to see the EMC effect in neutrinos!

Introduction to Neutrino Scattering



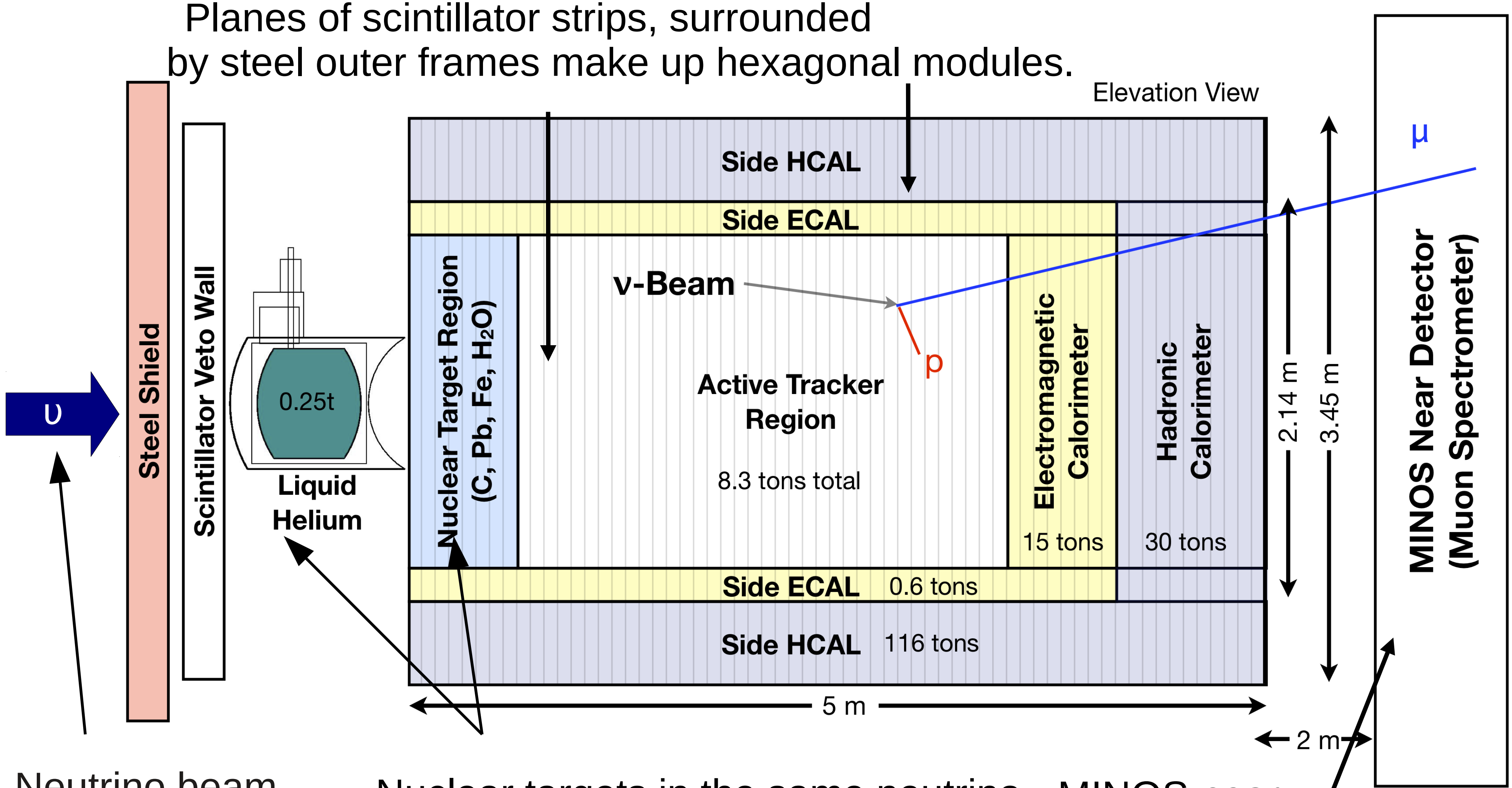
Increasing x
Decreasing E_ν

Decreasing x
Increasing E_ν

- Charged current neutrino + nucleon events are broadly categorized into quasi-elastic (single nucleon final state), resonant (multiple pion, single nucleon final state) and deeply inelastic (multiple hadron final state)
- Lower Bjorken-x implies more inelastic events.
- Total neutrino cross section dominated by quasi-elastic up to E_ν ~ 2.0 GeV

Enter MINERvA

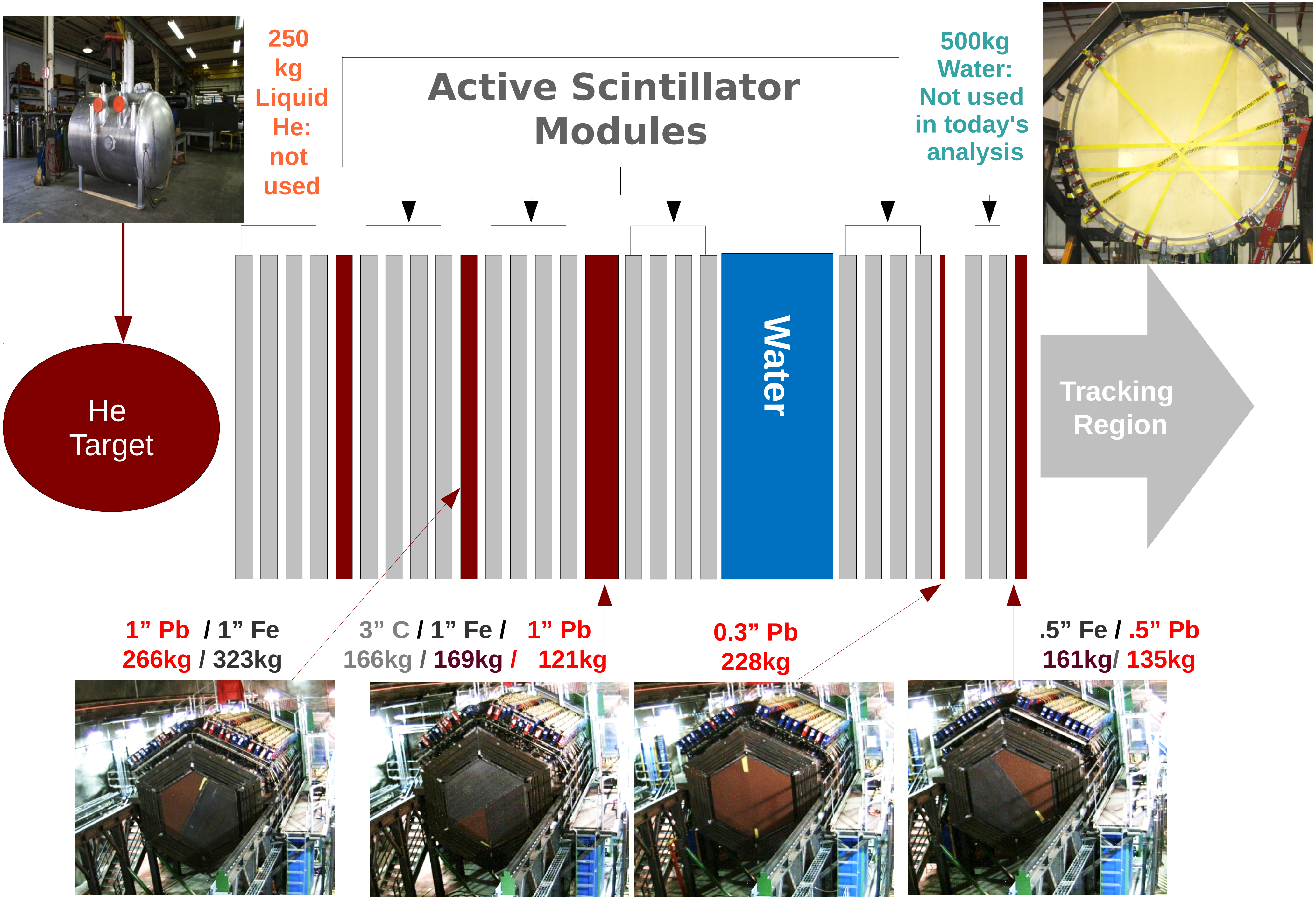
Planes of scintillator strips, surrounded by steel outer frames make up hexagonal modules.



Neutrino beam created by Fermilab NuMI beamline

Nuclear targets in the same neutrino beam allow MINERvA to make A-dependent physics measurements.

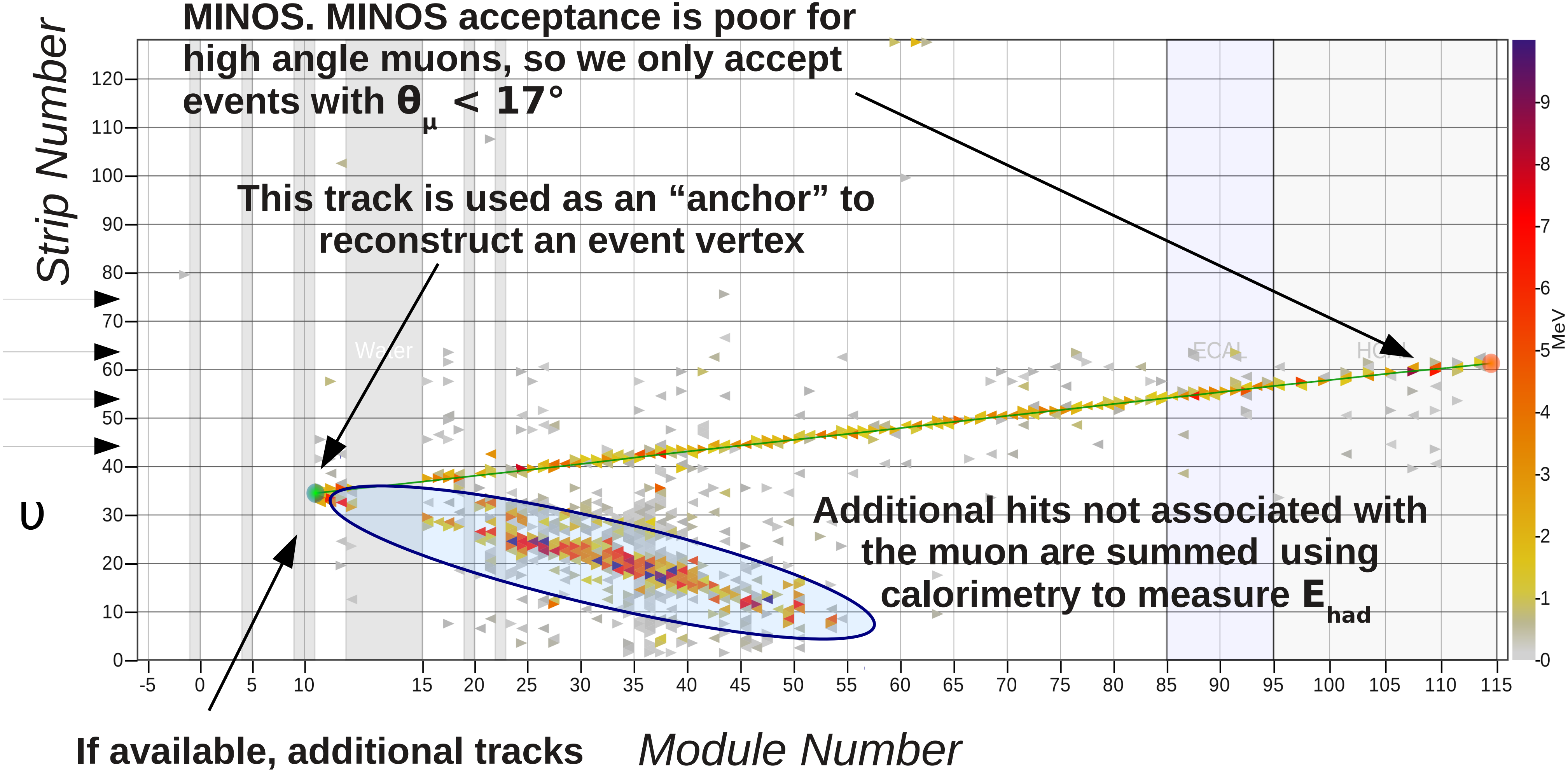
MINOS near detector used for escaping muon ID and reconstruction.


250 kg Liquid He: not used
Active Scintillator Modules
500kg Water: Not used in today's analysis
He Target
Water
Tracking Region
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

Event Selection and Reconstruction

Primary Muon track is matched to MINOS. MINOS acceptance is poor for high angle muons, so we only accept events with $\theta_\mu < 17°$

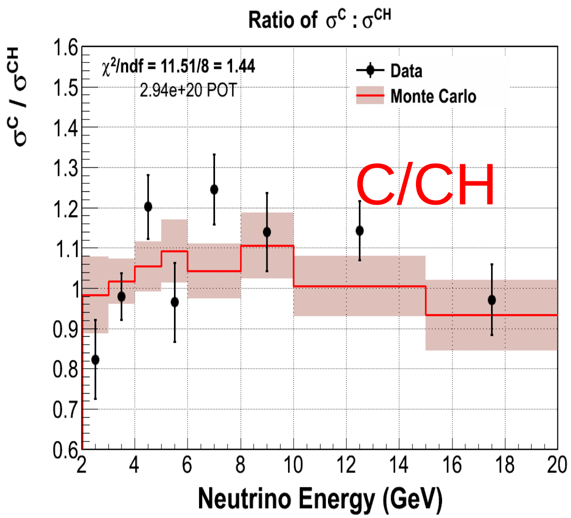
This track is used as an "anchor" to reconstruct an event vertex

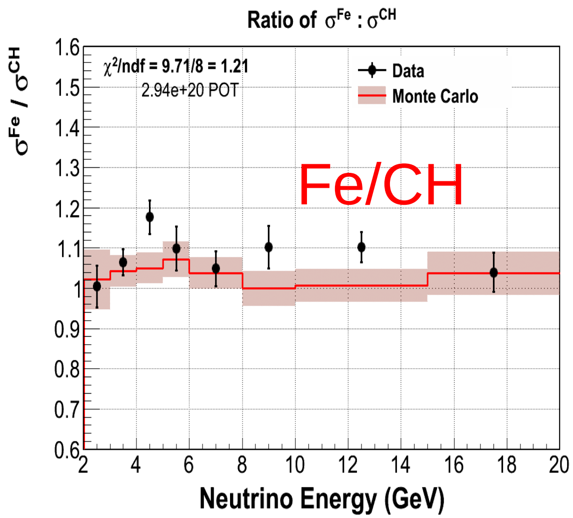


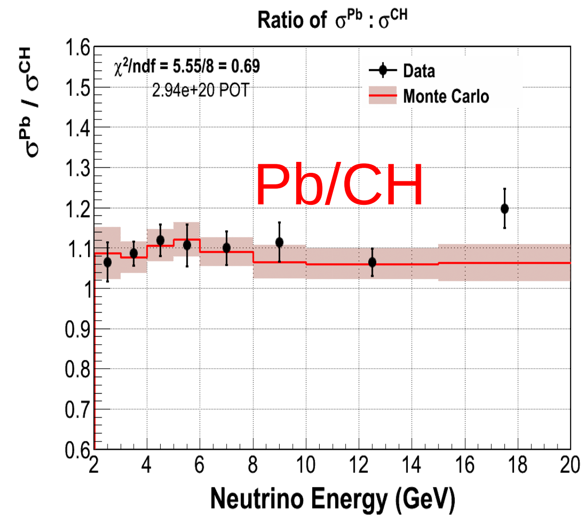
Additional hits not associated with the muon are summed using calorimetry to measure E_{had}

If available, additional tracks are used to improve the vertex fit iteratively.

Inclusive Ratios: $\sigma(E_\nu)$







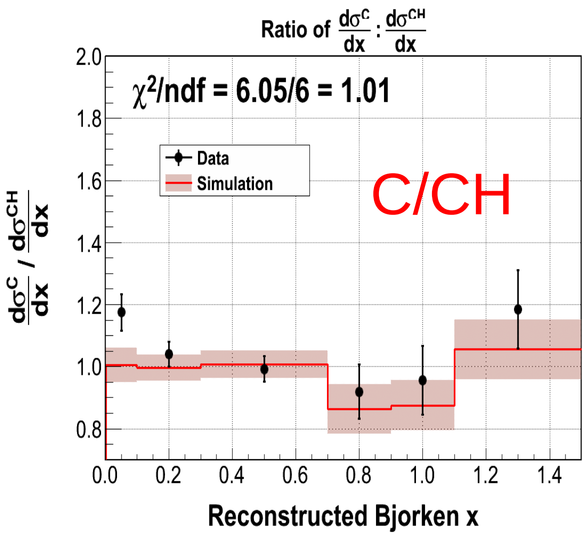
•Previously published by MINERvA; ratios of the total cross section C, Fe and Pb to CH for *all* charged-current neutrino interactions between 2 and 20 GeV.

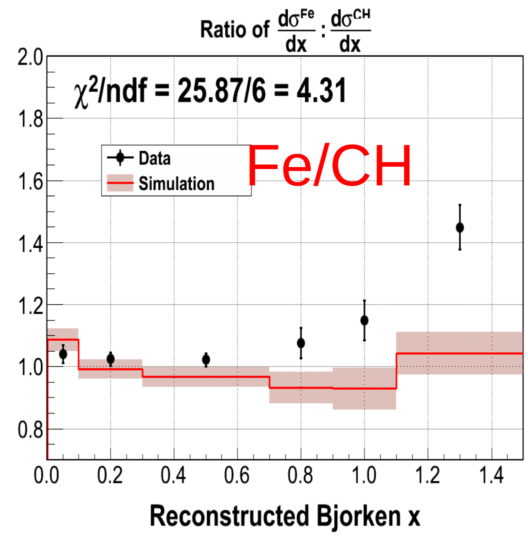
•Conclusions from this result: no evidence of unsimulated nulcear effects in total cross section *however:*

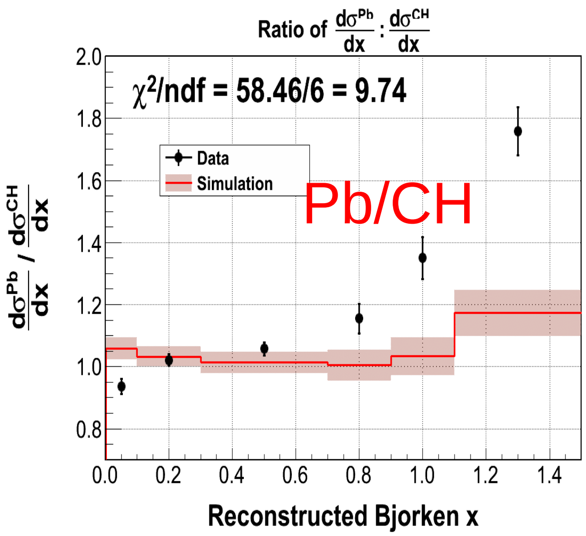
- This result reveals how the *sum* (QE, Resonant and DIS) behaves, but not the specific processes.
- Is in a Q^2 range (Q^2 ~ 1.0 $(GeV/c)^2$) where the theory is complicated.

Tice, Datta, Mousseau et. al,
Phys. Rev. Lett. 112, 231801 (2014).

Inclusive Ratios: dσ /dx







- Data are presented in reconstructed x: we do not correct for detector smearing.
- In this case, we observe an *excess* in the data at large x, and a *deficit* at low x, which grows with the size of the nucleus.
- Again the interpretation is complicated:
  - The low x events are at a low Q^2 (0.5 $(GeV/c)^2$), where the theory complicated.
  - High x events are a mixture between quasi-elastic and resonant.

It is difficult to determine the source of these discrepancies.

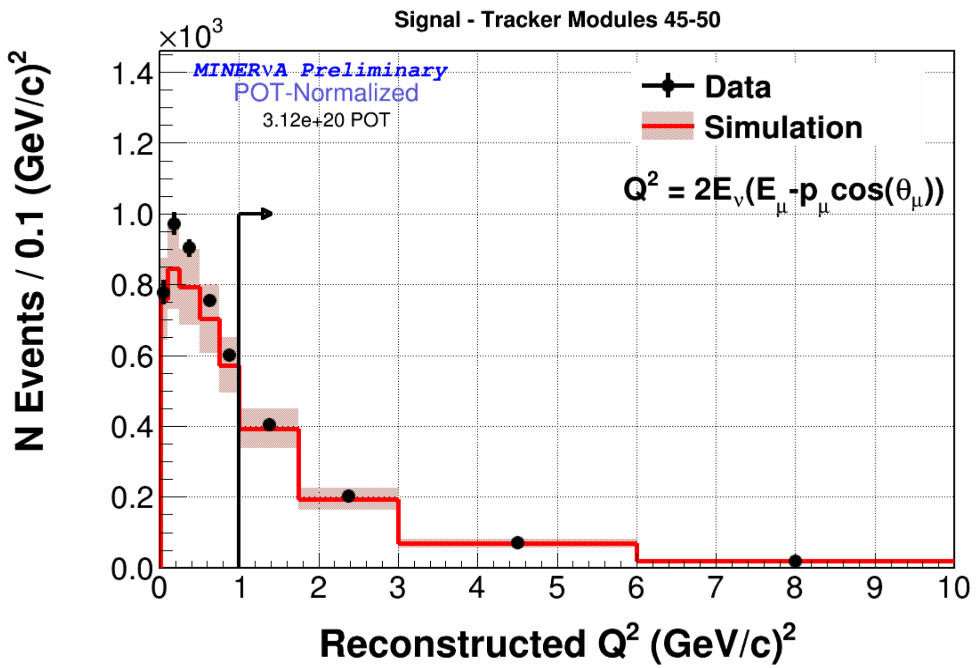
Tice, Datta, Mousseau et. al,
Phys. Rev. Lett. 112, 231801 (2014).

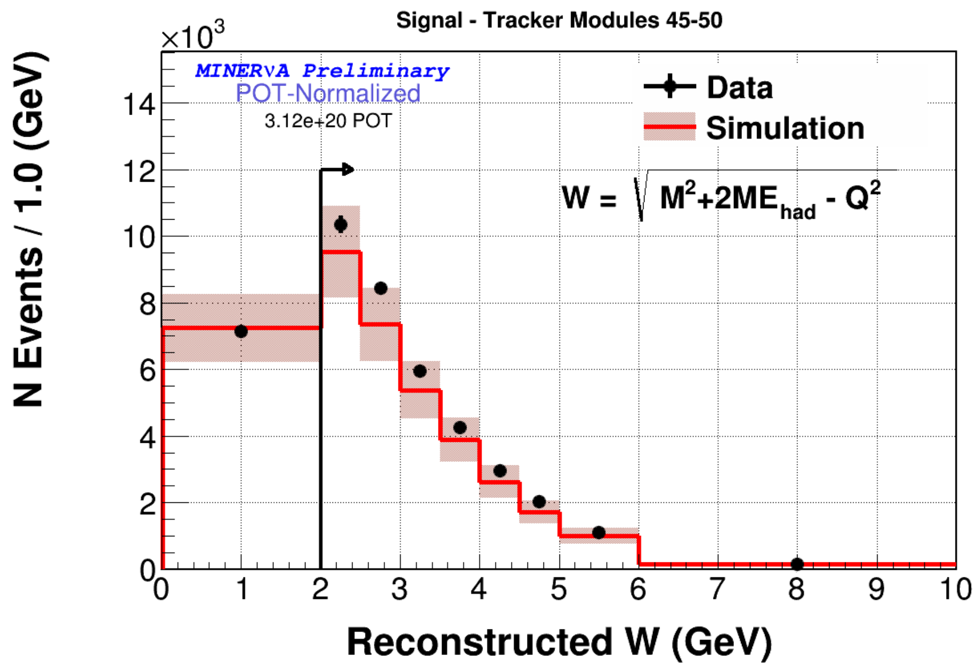
From Inclusive to DIS

•We isolate a deeply inelastic sample from the inclusive sample by making cuts on the four momentum transfer (Q^2) and final state invariant mass (W)

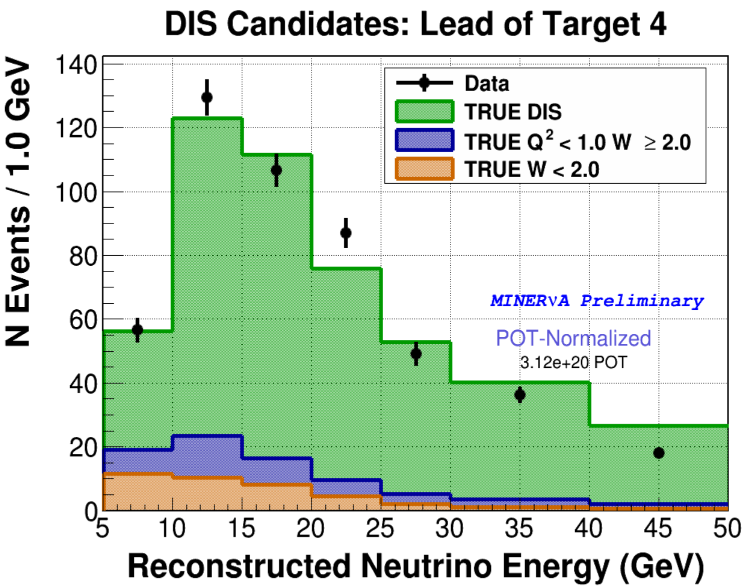
•Require $Q^2 > 1.0$ (GeV / c)^2 and W > 2.0 GeV / c. These cuts remove the quasielastic and resonant events from the inclusive sample, and allow us to interpret our data on the partonic level.

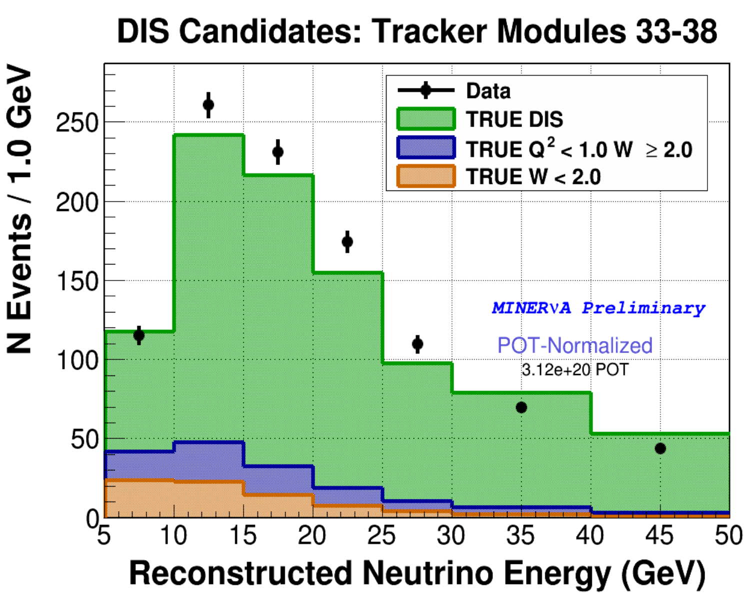
•Cuts are illustrated for CH events between 5 and 50 GeV E_υ and $\theta_\mu < 17°$.





Backgrounds (Kinematic):





- After making kinematic cuts on Q^2 and W, we are left with a background of events with *true* $Q^2 < 1.0\ (GeV/c)^2$ and $W < 2.0$ (GeV/c) that smear into the sample.

- Estimate this background in the nuclear targets and scintillator using MC (left plots).

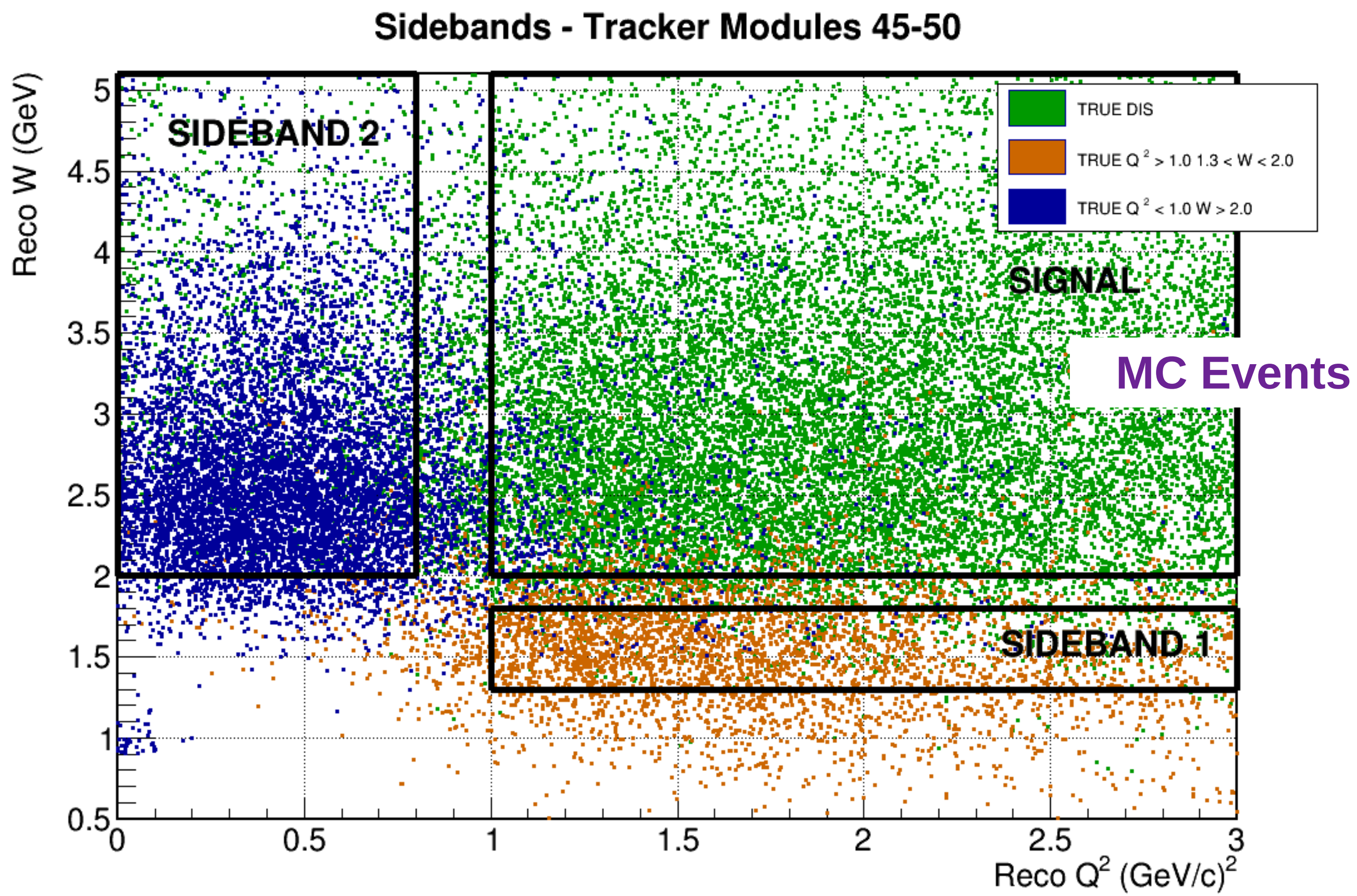
- MC is tuned to data using events adjacent to W = 2.0 (GeV) and $Q^2 = 1.0\ (GeV/c)^2$

Sidebands

•Two regions of data (sidebands) are drawn to fit background templates:

•*Reconstructed* $Q^2 > 1.0\ (GeV/c)^2$, $1.3 < W < 1.8$ GeV/c (low W)

•*Reconstructed* $Q^2 < 0.8\ (GeV/c)^2$, $W > 2.0$ GeV.c (low Q^2).



•Each sideband is tuned to limit the amount of signal in each band (green points).

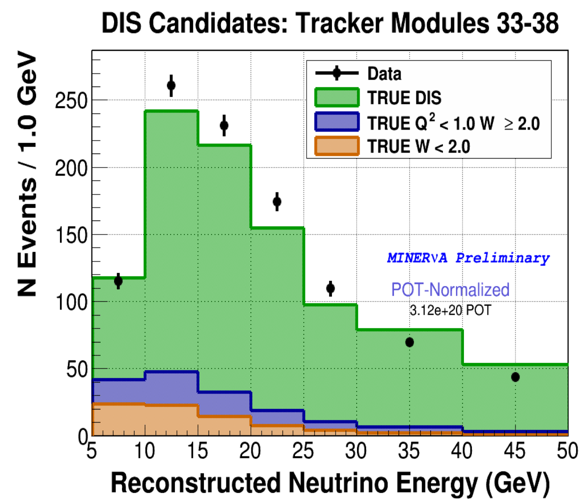
•Sidebands are identical in each target.

Fitting Sidebands

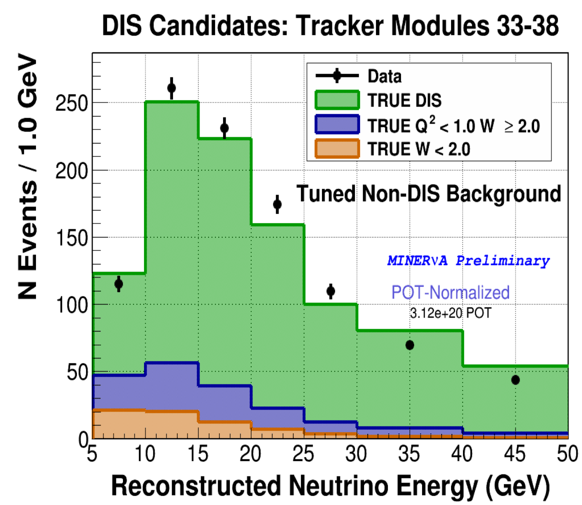
Scale Factors Applied to Simulation (stat. Error only)

A	$Q^2 > 1.0$ $1.3 < W < 2.0$	$Q^2 < 0.8$ $W > 2.0$
C	0.87±0.07	1.42±0.10
CH	0.90±0.01	1.45±0.01
Fe	0.93±0.04	1.36±0.05
Pb	0.85±0.04	1.19±0.04

- The MC of both sidebands are fit simultaneously over the region $5 < E_\nu < 50$ GeV using a χ^2 minimization.
- The data and MC of each target is summed by material prior to fitting, so we end up with a scale factor for C, CH, Fe and Pb.
- Primarily, the data prefer *more* backgrounds.

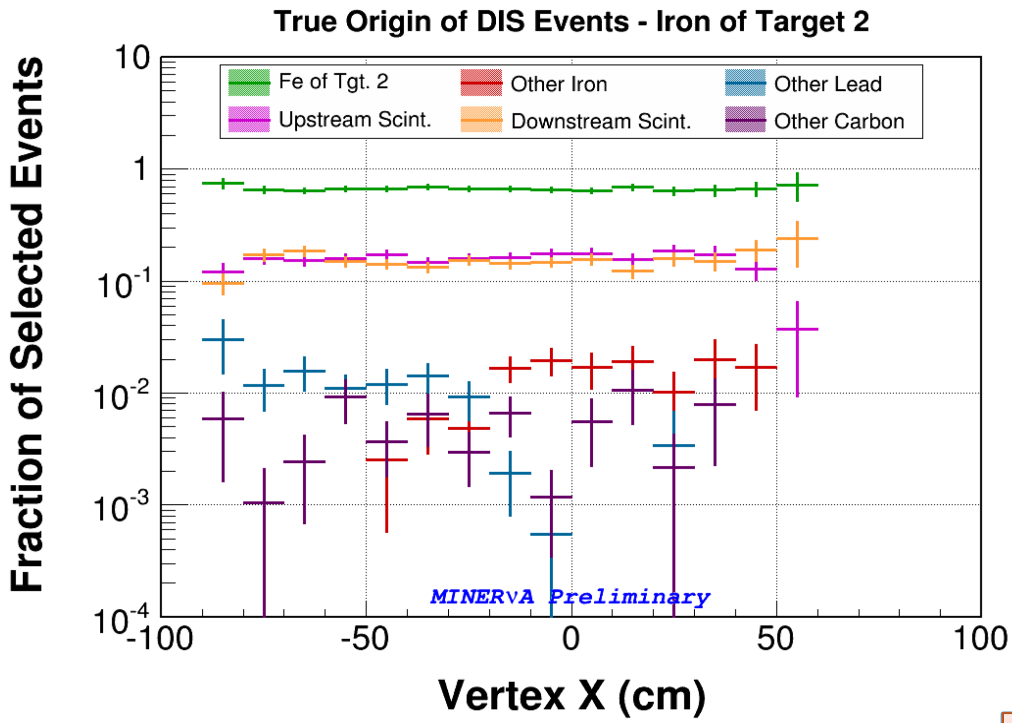


Before Fitting

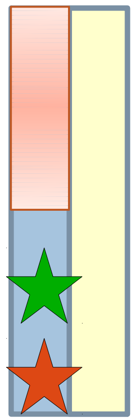


After Fitting

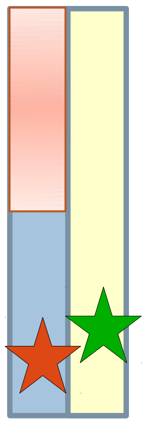
Background Events (Wrong Nuclei)



Events occasionally truly occur in the scintillator surrounding the nuclear target, but are reconstructed to the passive target. This makes up a second background.

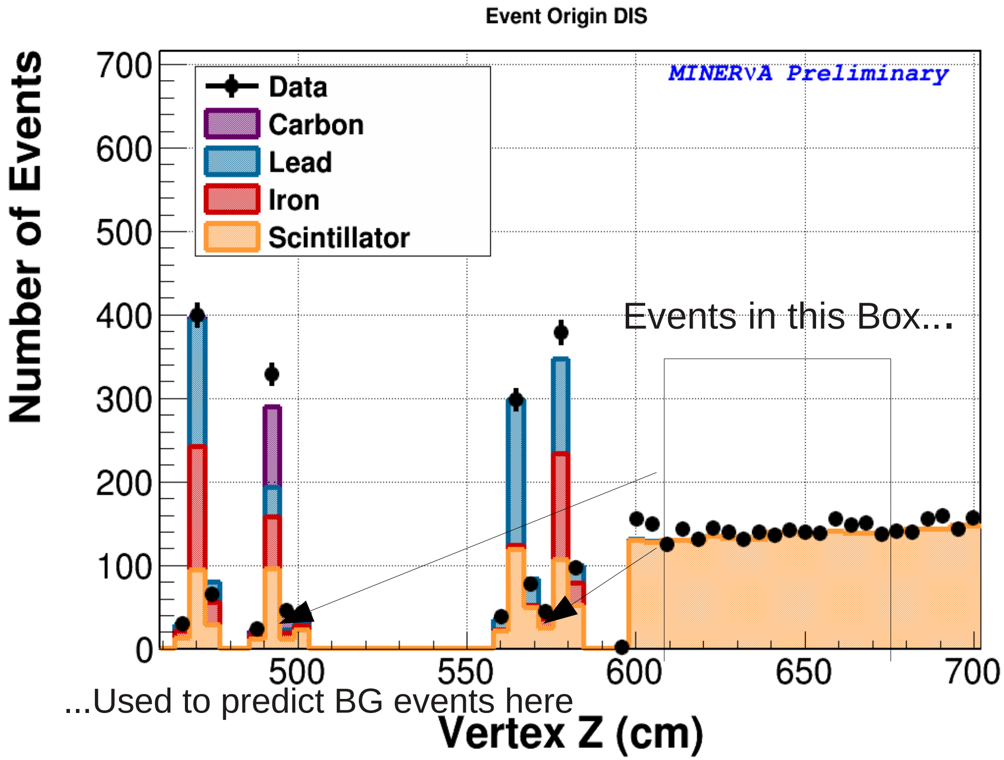


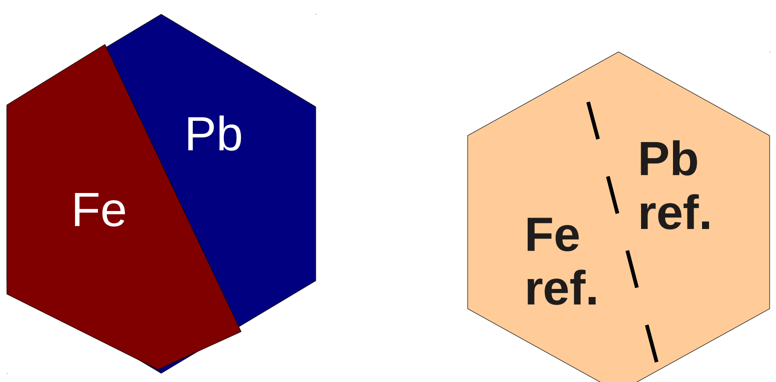
True vertex (green star) is in the same material as the reconstructed vertex (orange star).



Vertex is reconstructed in the Pb (blue). However, the true vertex of the event is in the scintillator (yellow).

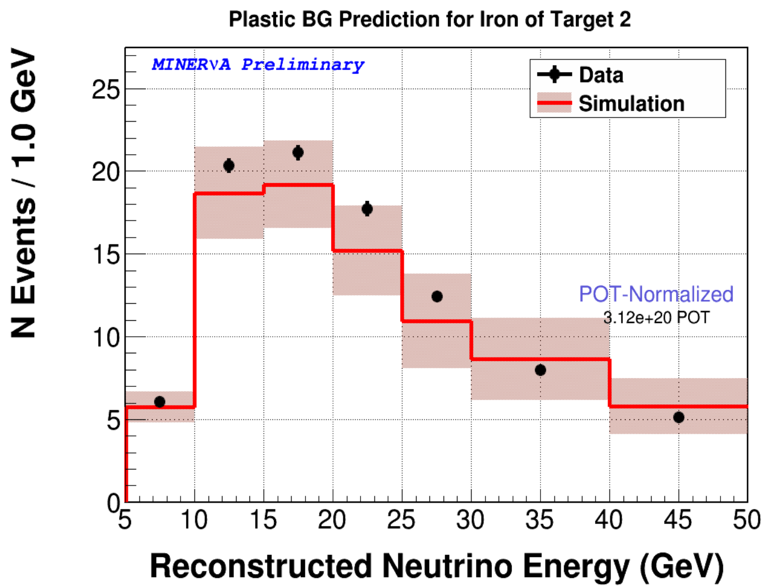
Background Subtraction (Wrong Nuclei)

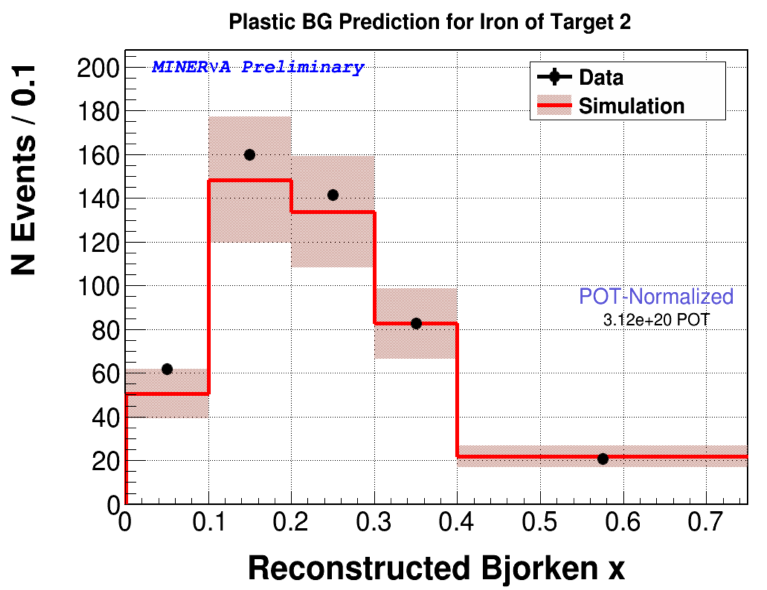




- We subtract this background by measuring the event rates in the downstream tracker, and extrapolating these events upstream to the nuclear target region.
- Downstream events are weighted for MINOS acceptance based on E_μ, θ_μ .
- Background is extracted by matching the same transverse section of the detector between modules.

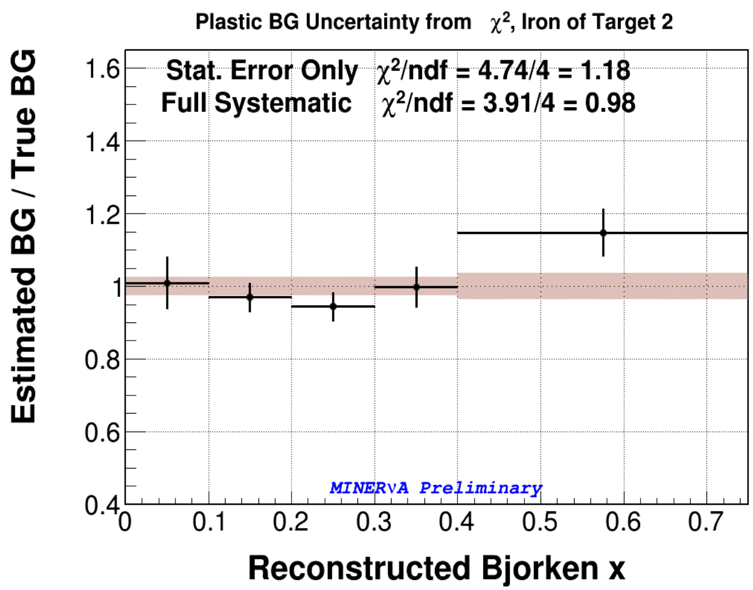
Wrong Nuclei BG (Data / MC)





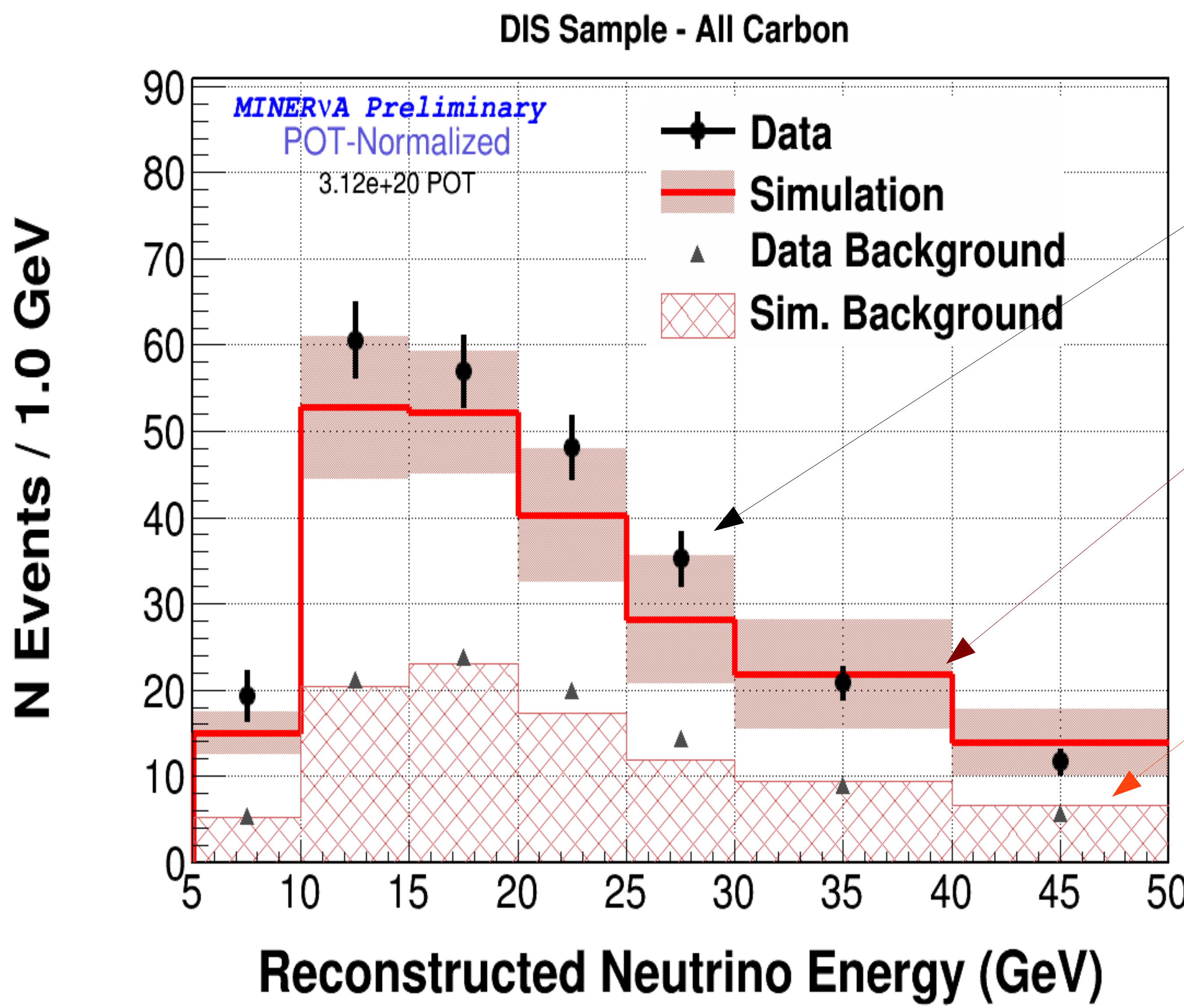
- Wrong nuclei backgrounds are extracted separately for data and MC, in each variable (E_ν, x, etc.)

- In each case, the non-DIS events have been subtracted using the procedure previously described.



- Prediction accuracy is measured from MC. Additional systematic uncertainty is calculated from the disagreement.

Putting it Together



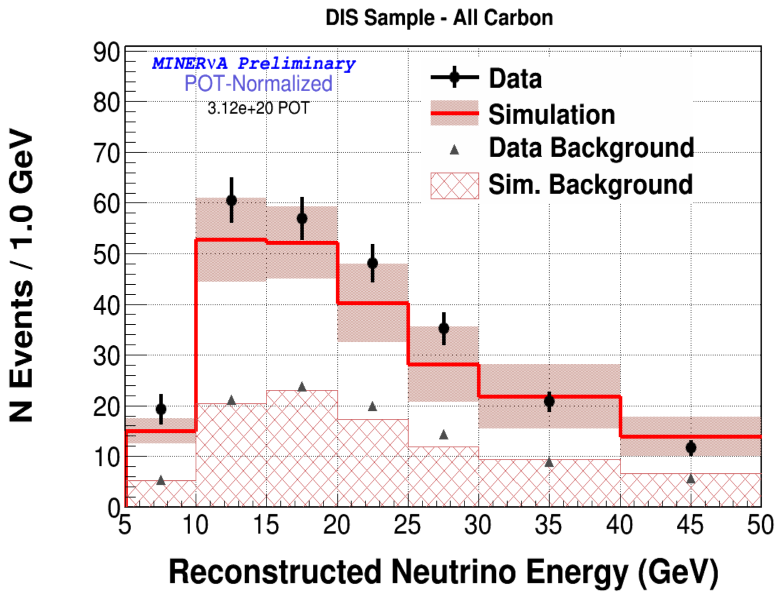
Data events reconstructed in C, with non-DIS events subtracted.

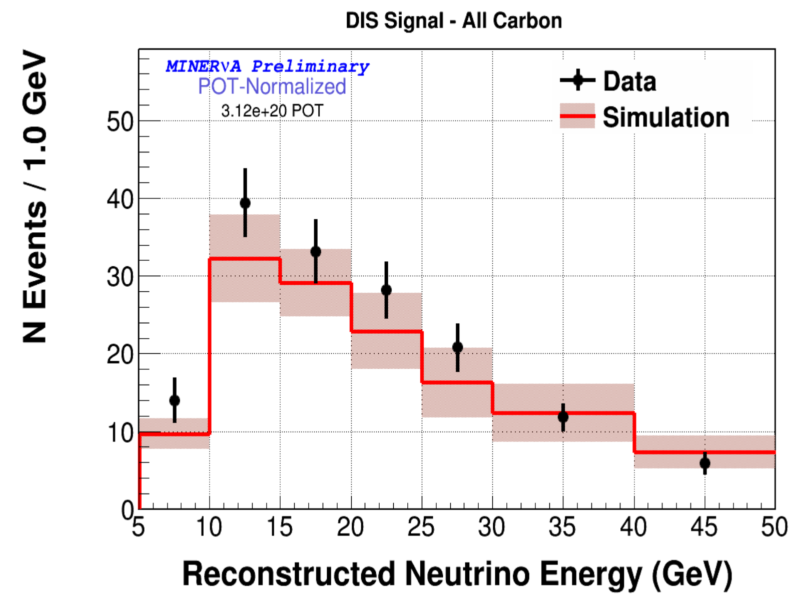
Simulated DIS events, reconstructed in C

CH events in scintillator surrounding target, with non-DIS events subtracted.

Putting it Together

Take our sample of reconstructed DIS events in carbon with CH events...



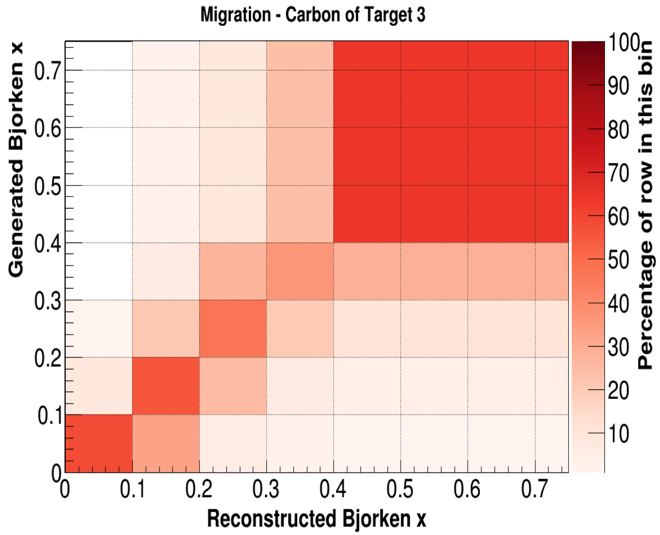


...And subtract those events to obtain a sample of DIS on carbon in data and MC. Large uncertainties on neutrino flux, measure ratios of C, Fe and Pb /CH where flux will cancel.

Migration and Unfolding

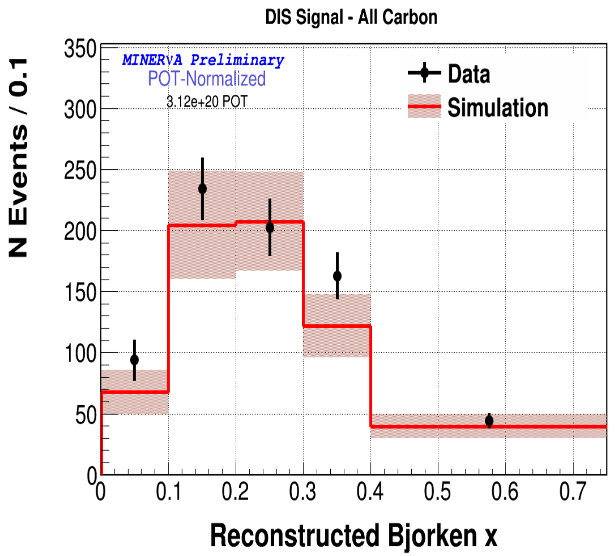
- Detector resolution smears the reconstructed values of x and E_ν from their generated quantities (right plot).

- Correct for this smearing using *unfolding* separately for each target, since detector response is slightly different.

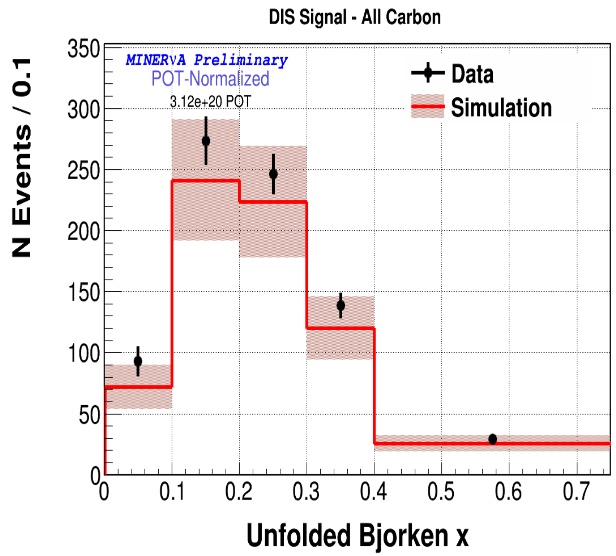


Migration Matrices used as input

Warning! Unfolding introduces correlations between bins

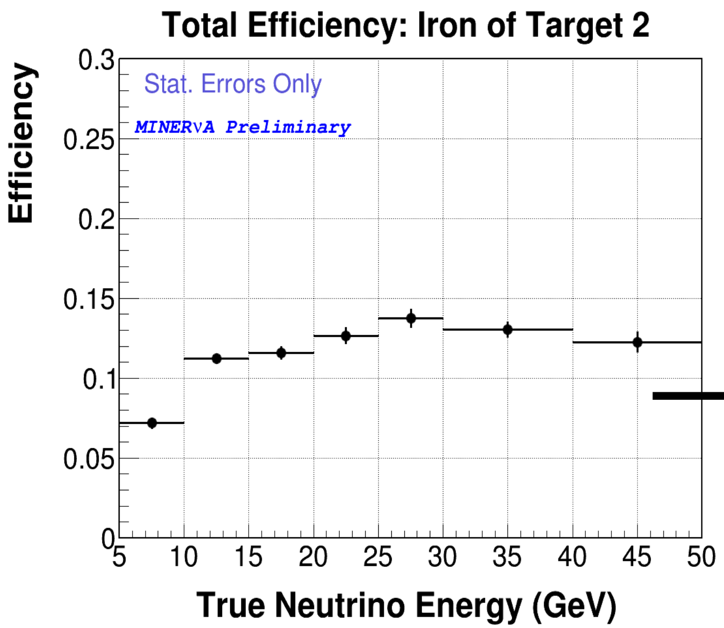


Unfold using Bayesian unfolding With 1 iteration

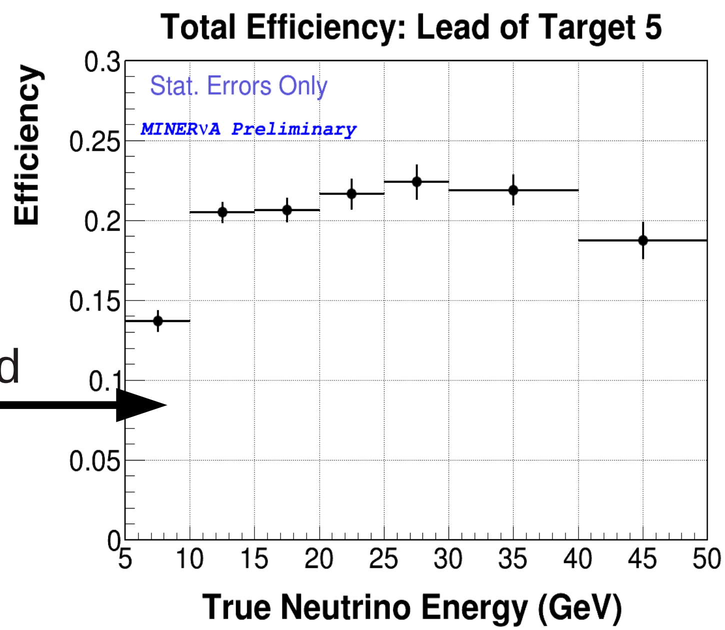


Efficiency Correction

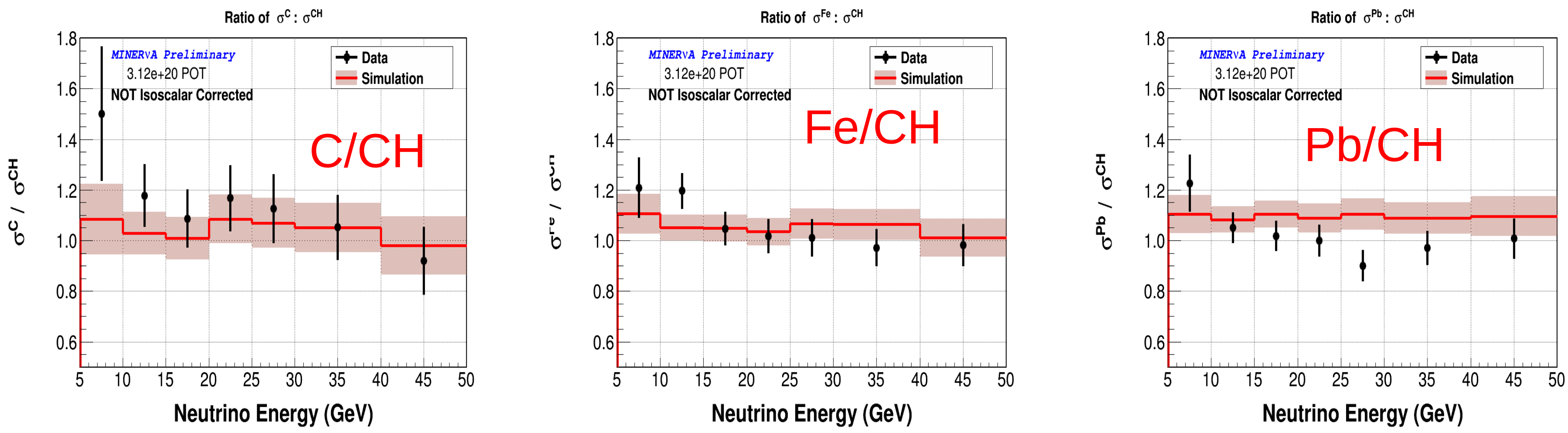
- We correct for detector acceptance, using an efficiency correction derived from the MC. However, we only correct up to E_υ = 50 GeV and θ_μ < 17°.
- Efficiency is corrected target by target, since it is a function of the distance from the target to MINOS.
- Largest source of inefficiency is MINOS matching requirement. This acceptance improves as we move downstream in the detector.



Downstream toward MINOS

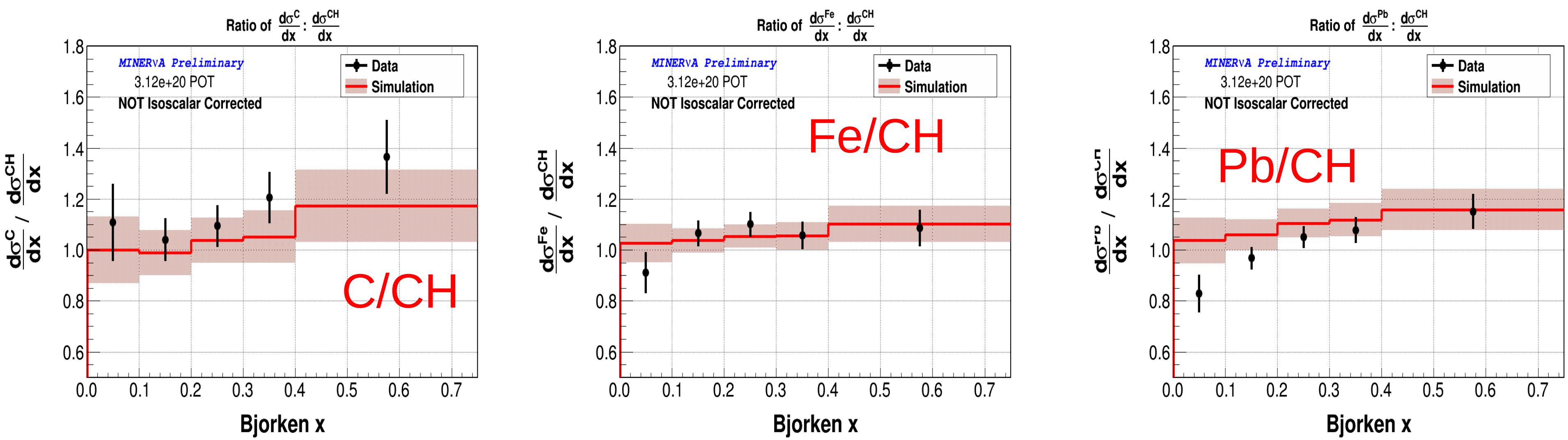


DIS Ratios: $\sigma(E_\nu)$



- Results are now shown for the deeply inelastic events in C, Fe, Pb and CH.
- As in the inclusive analysis, we measure *ratios* of cross sections to reduce systematic errors from the neutrino flux calculation.
- Ratios of the heavy nuclei (Fe, Pb) to lighter CH are evidence of nuclear effects.
- Observe no nuclear effects neutrino energy.

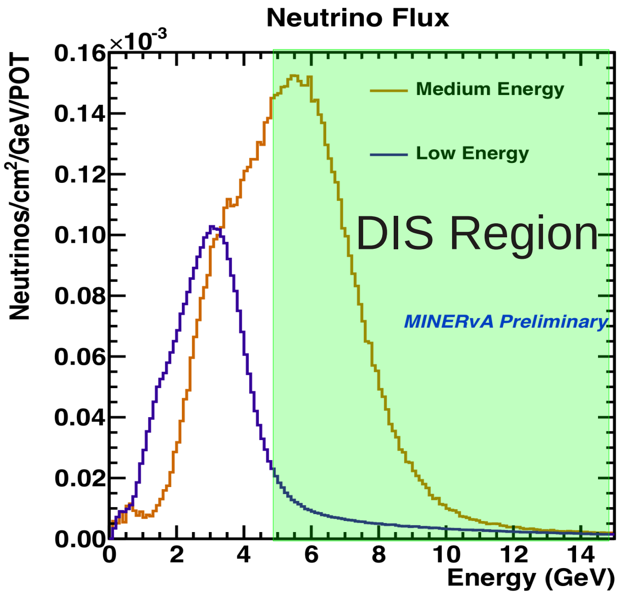
DIS Ratios: dσ /dx

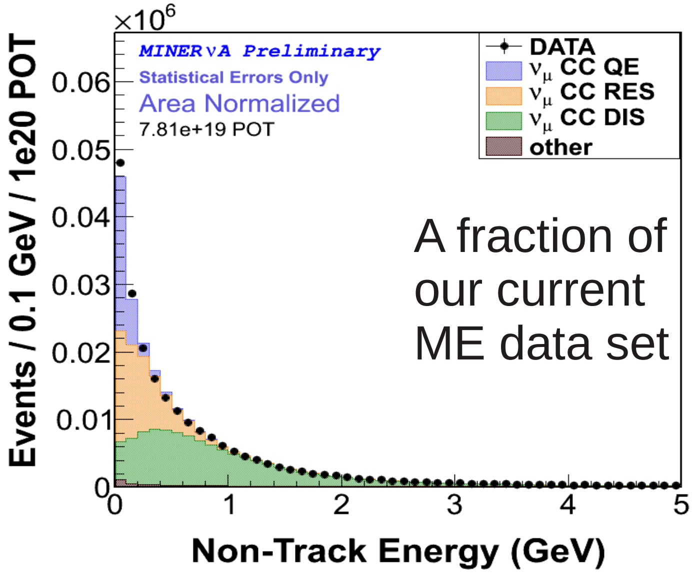


- X dependent ratios directly translate to x dependent nuclear effects.
- The events at low x are now solely deeply inelastic.
- However, we cannot reach the high x events with our current beam energy.
- Currently, our simulation assumes the *same* x-dependent nuclear effects for C, Fe and Pb.
- We observe no significant deviations from this.
- The shape of the data in low x, especially with lead is consistent with additional nuclear shadowing.

Future Directions

•Future studies of nuclear effects will benefit greatly from MINERvA's increased energy and intensity run, taking data as we speak.
Expect much better sensitivity at high and low x with increased beam energy.
•See Anne Norrick's talk on Wednesday.
•Currently have a quasi-elastic analysis in nuclear targets in progress for low energy events.
•*A bright future is expected!*





Conclusions

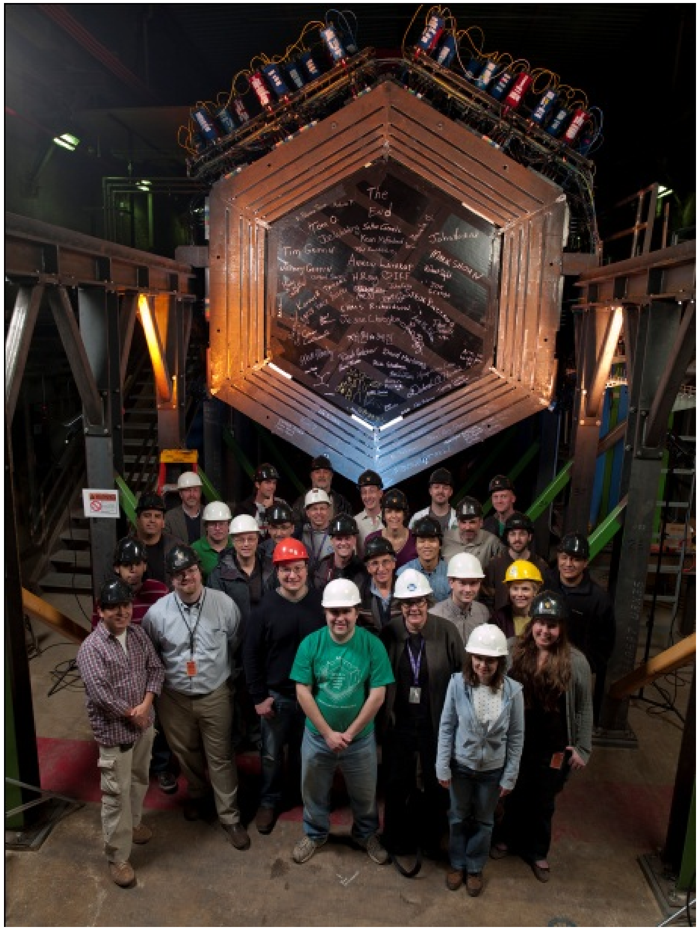
- MINERvA has made a measurement of neutrino DIS events on multiple nuclei in an identical neutrino beam.
- Unlike our previous inclusive measurements, these measurements may be interpreted directly as x-dependent nuclear effects.
- We currently observe no significant differences in x or E_ν from theory.
- Future higher energy measurments will be higher statistics as well as the ability to resolve larger x values.
- Ongoing quasielastic measurement in low energy beam will provide clues at high x.

Thank you for Listening!

The MINERvA collaboration consists of approixmately 65 Nuclear and Particle Physicists

University of California at Irvine
Centro Brasileiro de Pesquisas Físicas
University of Chicago
Fermilab
University of Florida
Université de Genève
Universidad de Guanajuato
Hampton University
Inst. Nucl. Reas. Moscow
Massachusetts College of Liberal Arts
University of Minnesota at Duluth

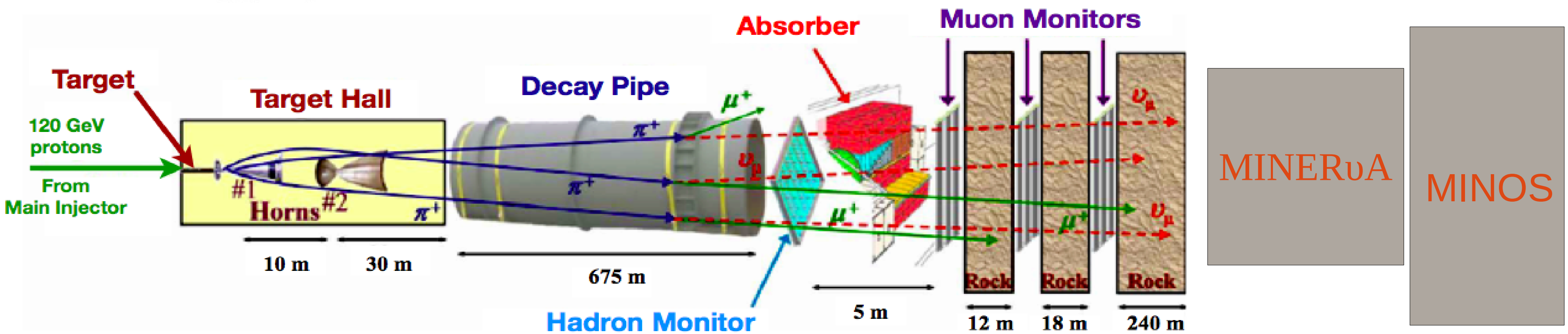
Universidad Nacional de Ingeniería
Northwestern University
Otterbein University
Pontificia Universidad Catolica del Peru
University of Pittsburgh
University of Rochester
Rutgers, The State University of New Jersey
Universidad Técnica Federico Santa María
Tufts University
William and Mary

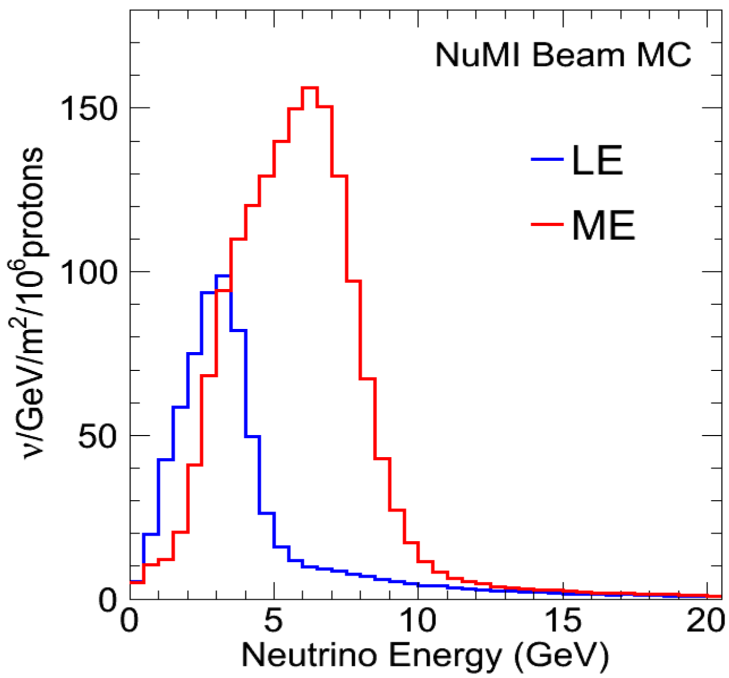


At the conclusion of detector construction

Backup Slides

The NuMI Beamline





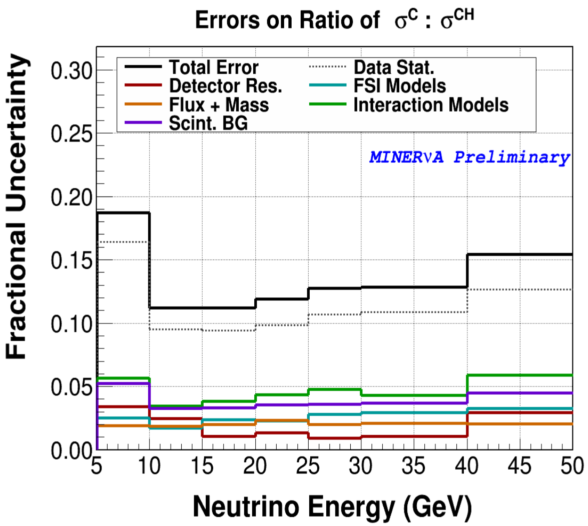
•Low energy beam (blue plot) has a peak energy of approximately 3 GeV.
•Medium energy is 7 GeV; higher beam energy means more DIS events, and access to higher x.
•Flux measurement is constrained with external hadron production data (NA49).

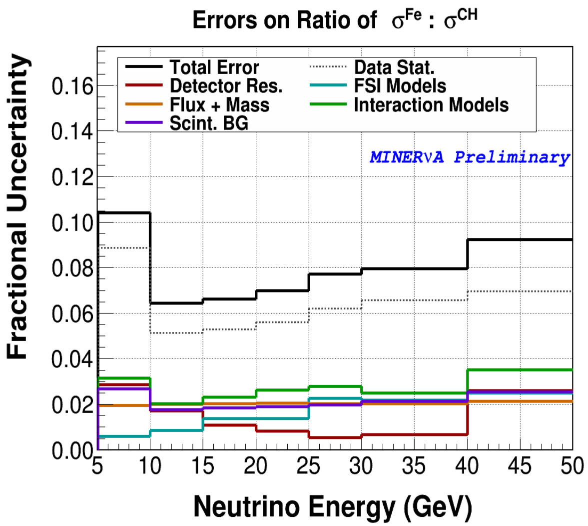
Event Table

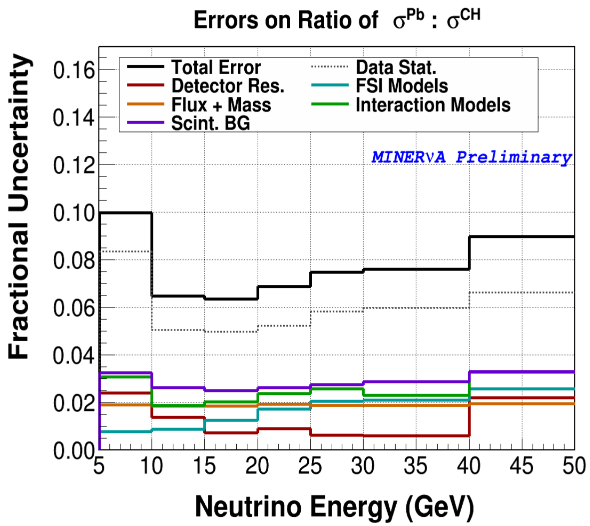
X_{bj} (unfolded)	C	Fe	Pb
0 – 0.1	90	220	230
0.1 - 0.2	270	840	930
0.2 – 0.3	250	800	940
0.3 – 0.4	140	390	520
0.4 – 0.75	100	250	350
0.75+	1	1	1
TOTAL	850	2500	2970

- Most of our events are in the anti-shadowing and shadowing region; a marginal number in the EMC region.

Ratio Uncertainties

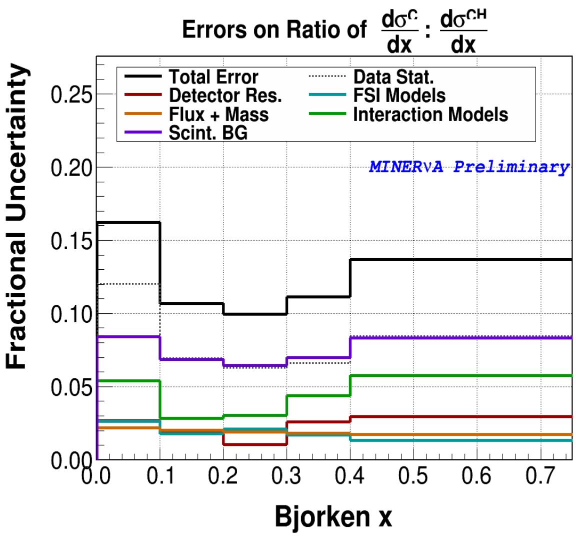


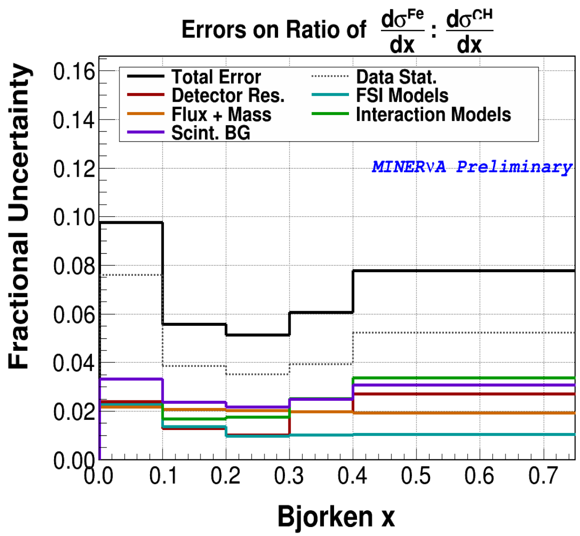


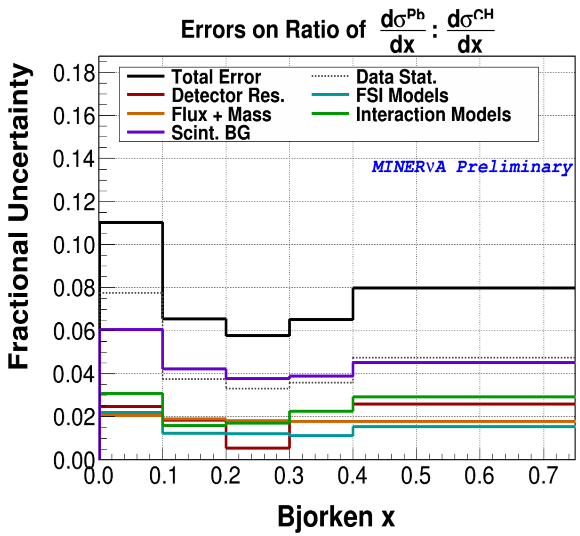


- Most of the uncertainty stems from data statistics.
- Higher intensity, higher energy beam will improve this substantially.
- Correlations in data introduced from unfolding are *NOT* accounted for in Data stat. uncertainty.

Ratio Uncertainties







- Ratios are dominated by data statistics for the most part.
- Scintillator background is a larger uncertainty in x.
- Correlations in data introduced from unfolding are *NOT* accounted for in Data stat. uncertainty.

Recoil Reconstruction

- Recoil energy = all non muon energy in a -25, 30 ns window of the vertex time.

$$E_{had} = \alpha \times \sum_{i}^{hits} c_i E_i$$

- Calibrated energy deposits (E_i) in the detector weighed by the energy lost in passive material (c_i; see table).

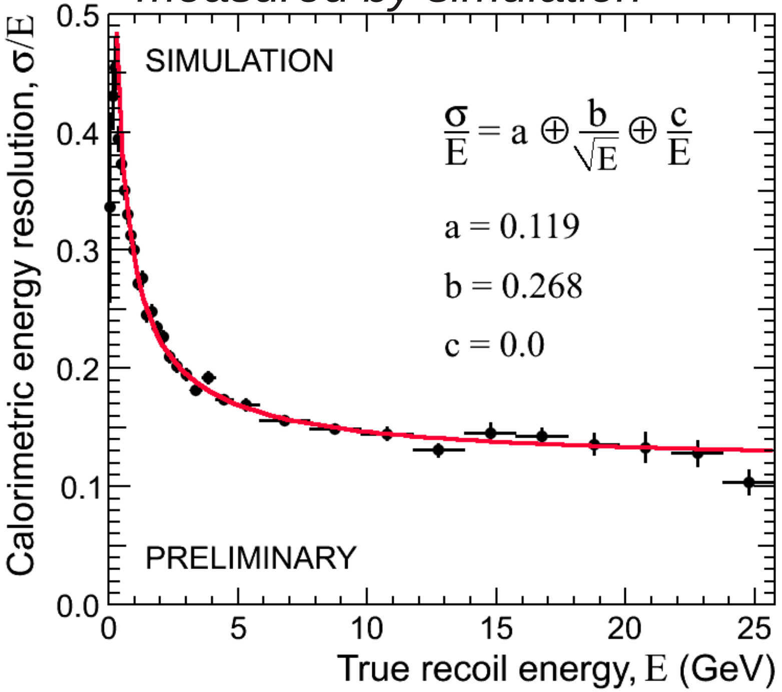
Energy lost by a mip in each material

Material	CH	C	Fe	Pb
dE/dx (MeV/g/cm^2)	1.96	1.74	1.45	1.12

Overall scale factor (α) computed from simulation

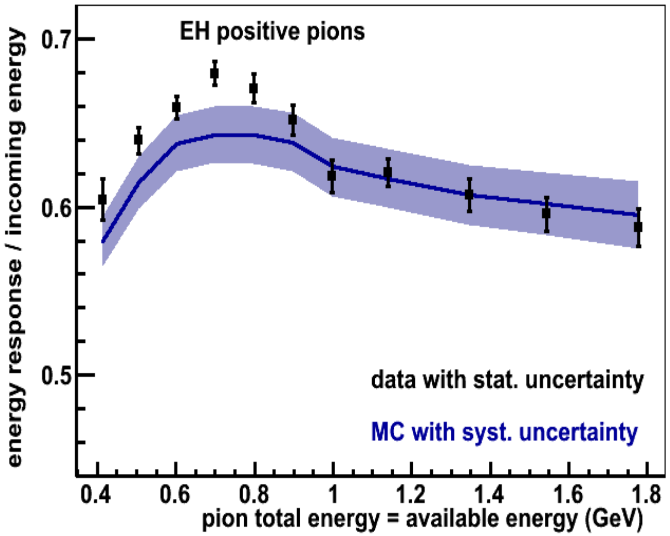
vertex	Tgt 2	Tgt 3	Tgt 4	Tgt 5	Trk
α	1.81	1.71	1.60	1.59	1.62

Tracker recoil energy resolution as measured by simulation

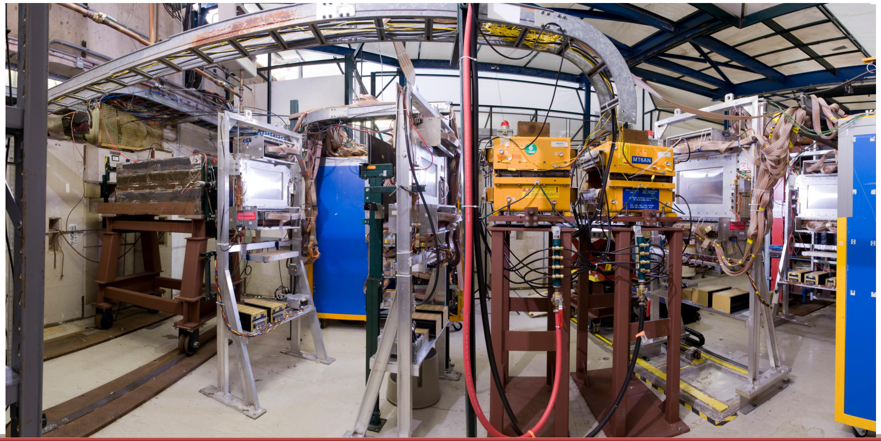


Test Beam

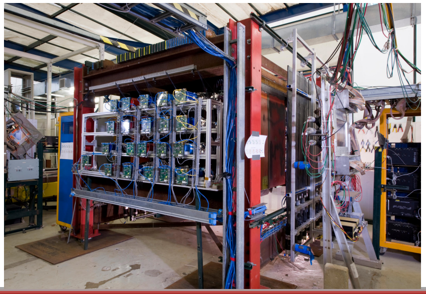
•The MINERvA detector's hadronic energy response is measured using a dedicated test beam experiment at the Fermilab Test Beam Facility (FTFB)
•Custom built beamline took data during the summer of 2010.
•In addition to a Birk's Law calculation, hadronic energy reconstruction uncertainty is esitmated from difference between test beam data and GEANT MC.

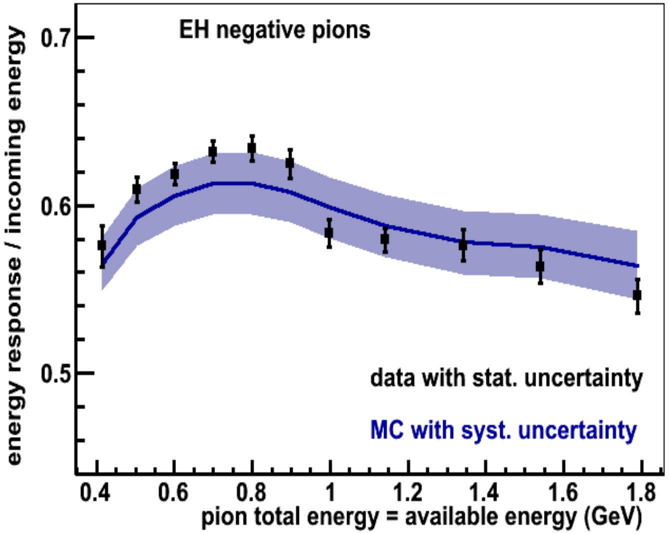


Custom built beamline

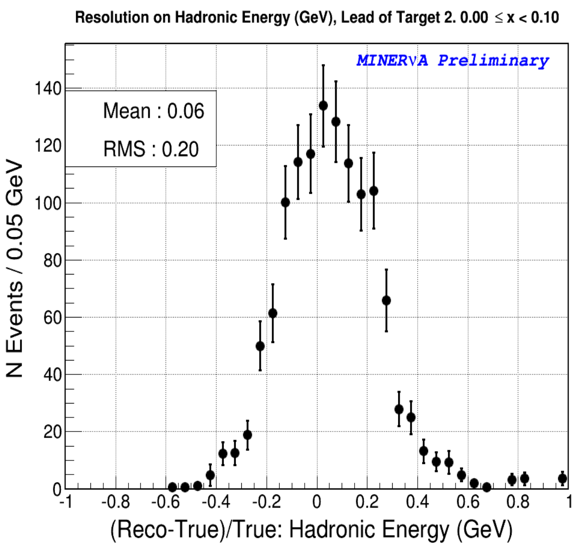


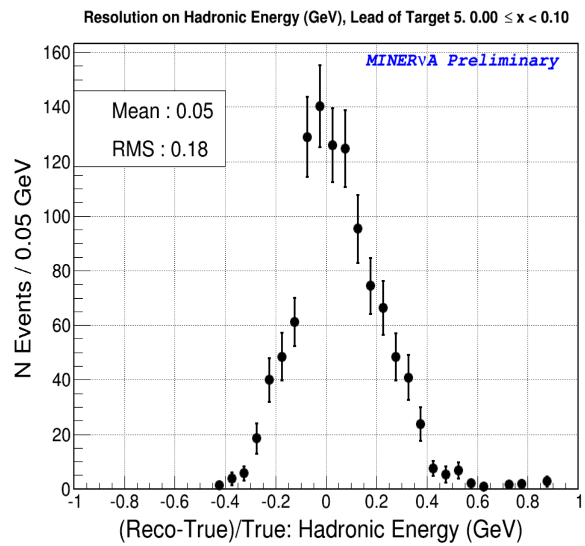
Plus miniature detector

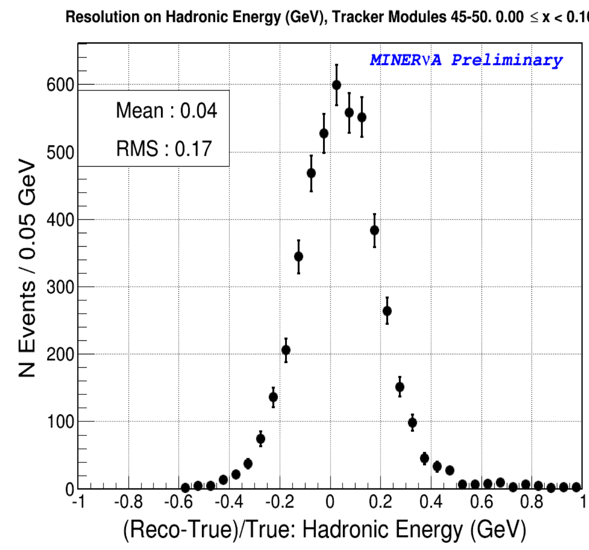




Hardonic Energy Resolution





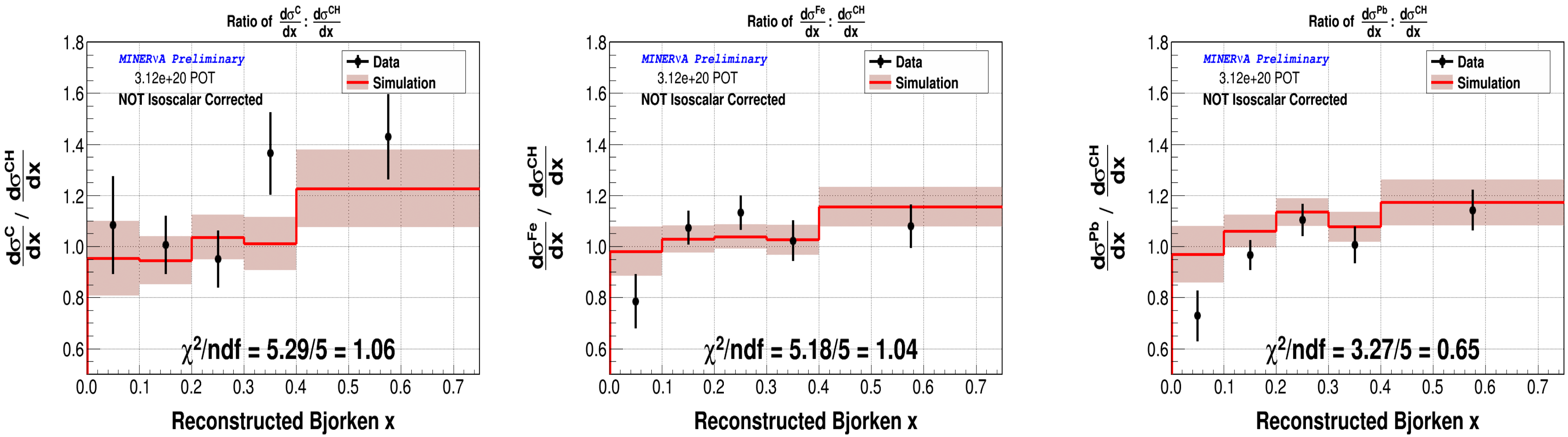


Downstream

- Accuracy of high-energy, low x hadronic showers is very similar between nuclear targets and tracker modules.

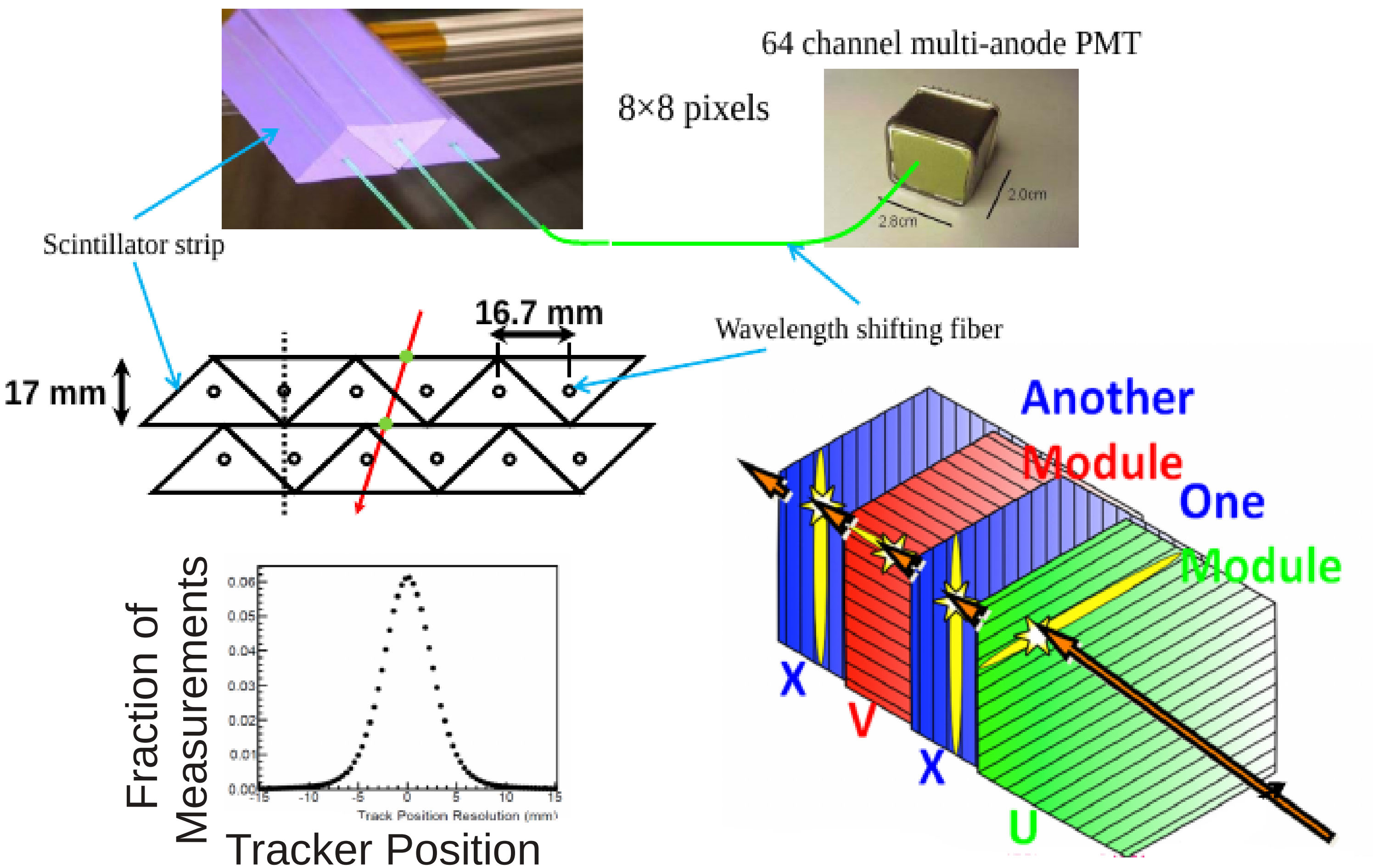
Our simulation adequately accounts for the different geometry encountered by hadronic showers, regardless of where they originate.

Ratios in Reconstructed x



- DIS ratios presented as functions of *reconstructed* x.
- These ratios are directly comparable to the Inclusive ratios.
- Similar trends are observed in the unfolded and reconstructed variable.
- Trend at low x (a deficit in data which grows with A) also comparable between DIS and inclusive.

Detector Technology



Tracker Position Residual

A MINERvA Module

Outer Detector Frame

Scintillator Bars

Lead collar

Steel supports used for hanging modules on rails.

Inner Detector: Plastic scintillator strips