Neutrino Nucleon Deep Inelastic Scattering

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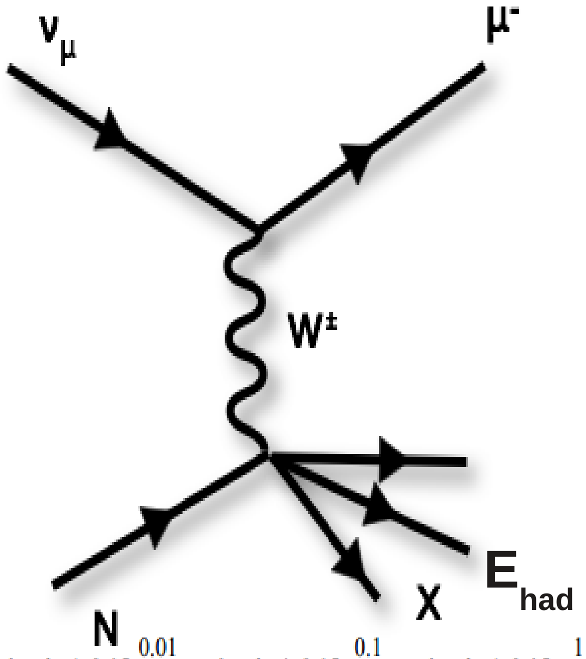
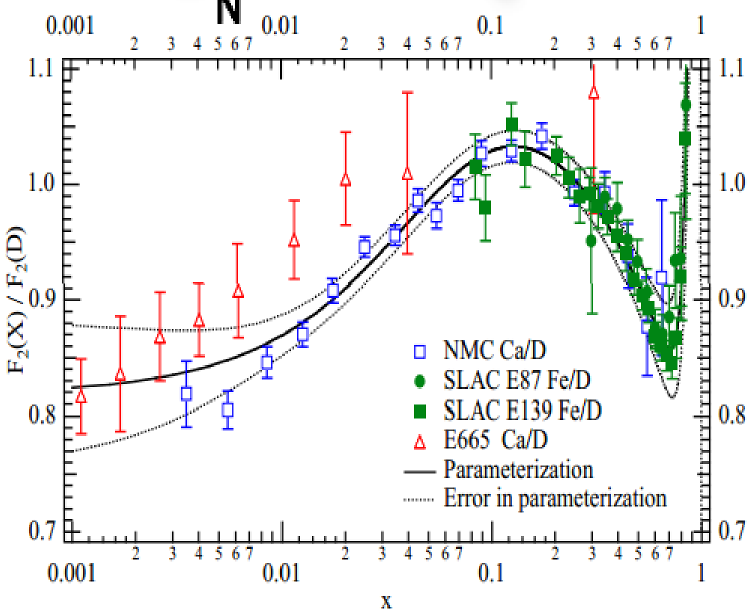
Neutrinos in Nuclear Media

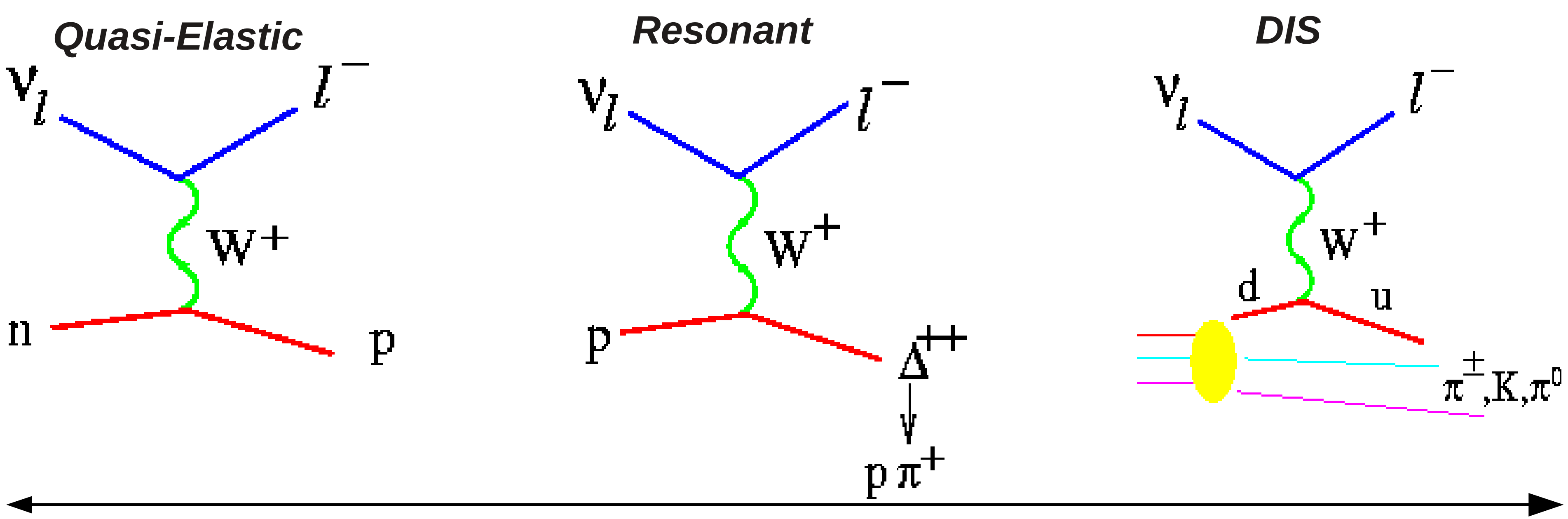
- One common theme of contemporary neutrino experiments: they rely on large A materials to supply adequate event rates (Fe, Ar, C, H_2O etc.)
- Problem: nuclear effects caused by nucleons bound in a nucleus distort the energy reconstruction of the neutrinos.
- These effects manifest in *ratios* of dσ/dx.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



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

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



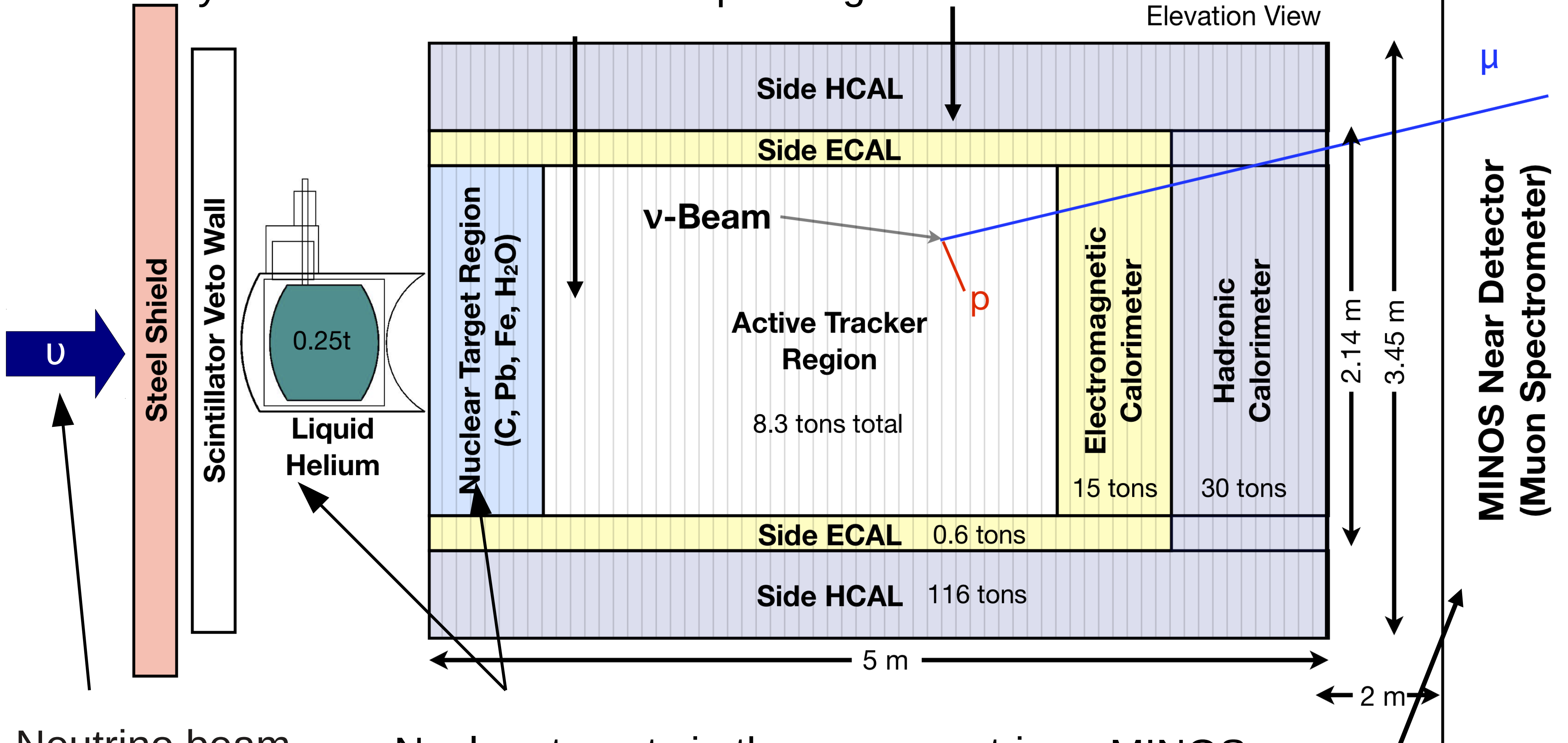


Increasing x Decreasing E_ν	Decreasing x Increasing E_ν

- 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

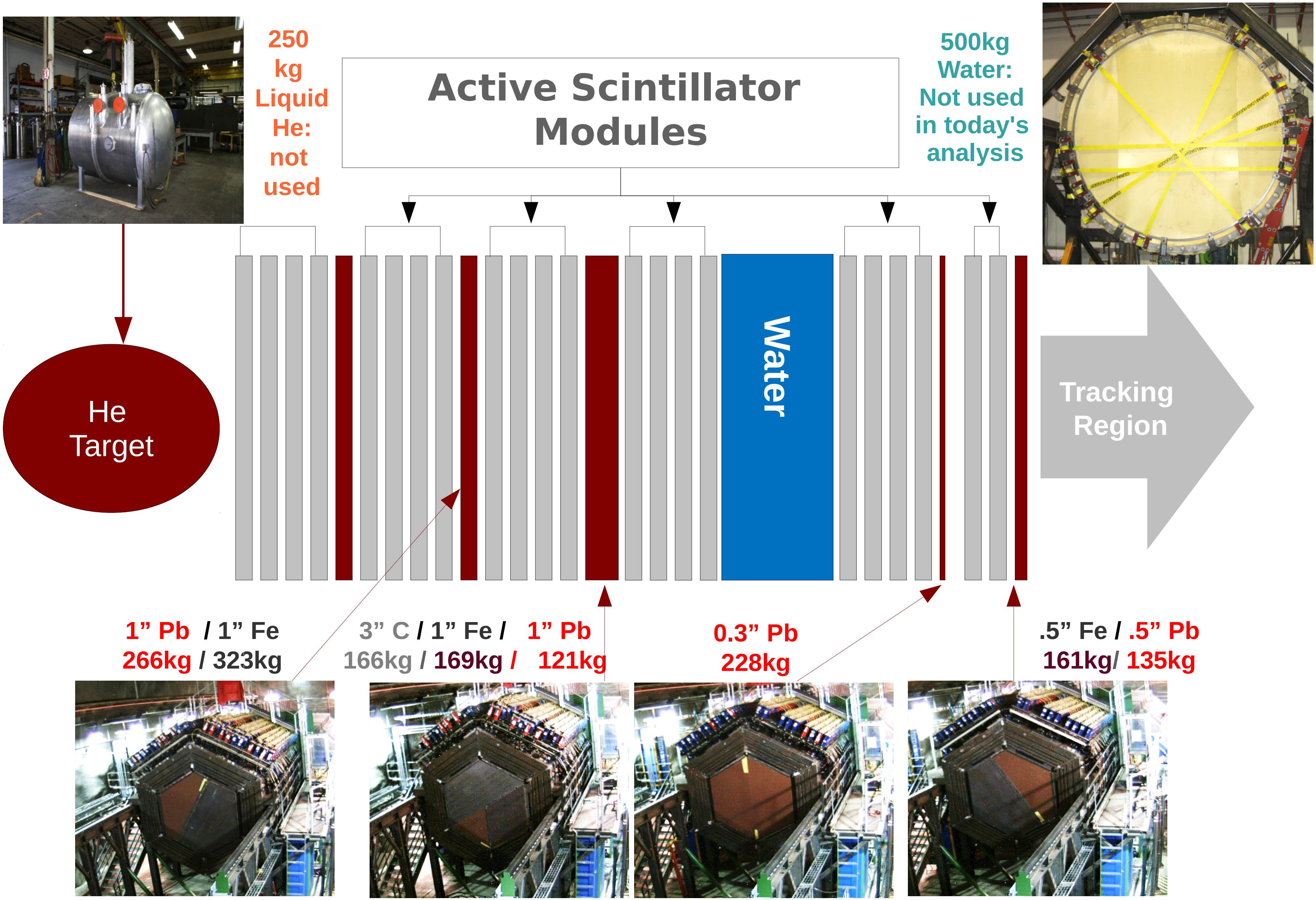
Planes of scintillator strips, surrounded by steel outer frames make up hexagonal modules.



Neutrino beam created by Fermilab NuMI beamline

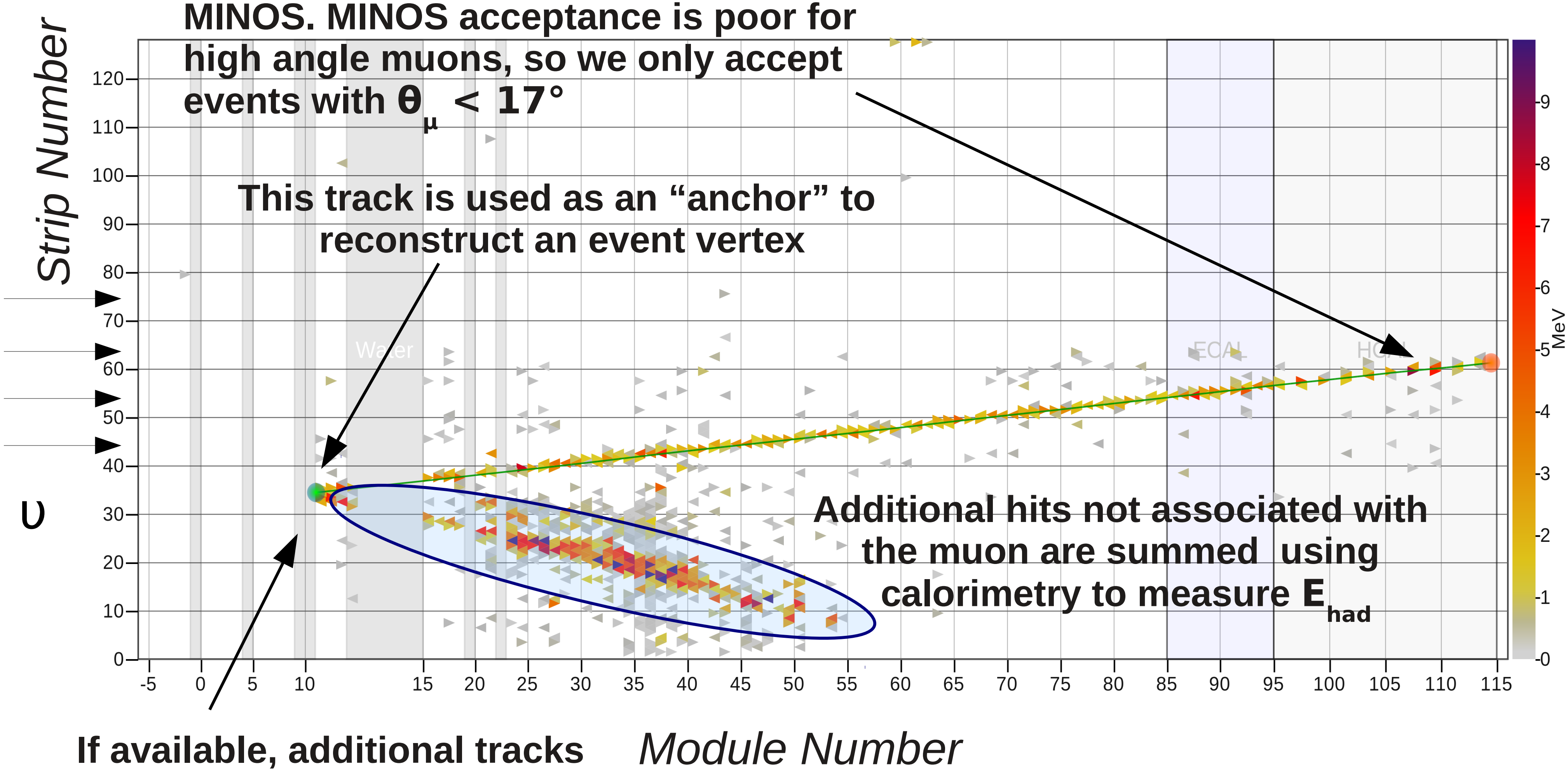
Nuclear targets in the same neutrino beam allow MINERvA to make A-dependent physics measurements.

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

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}

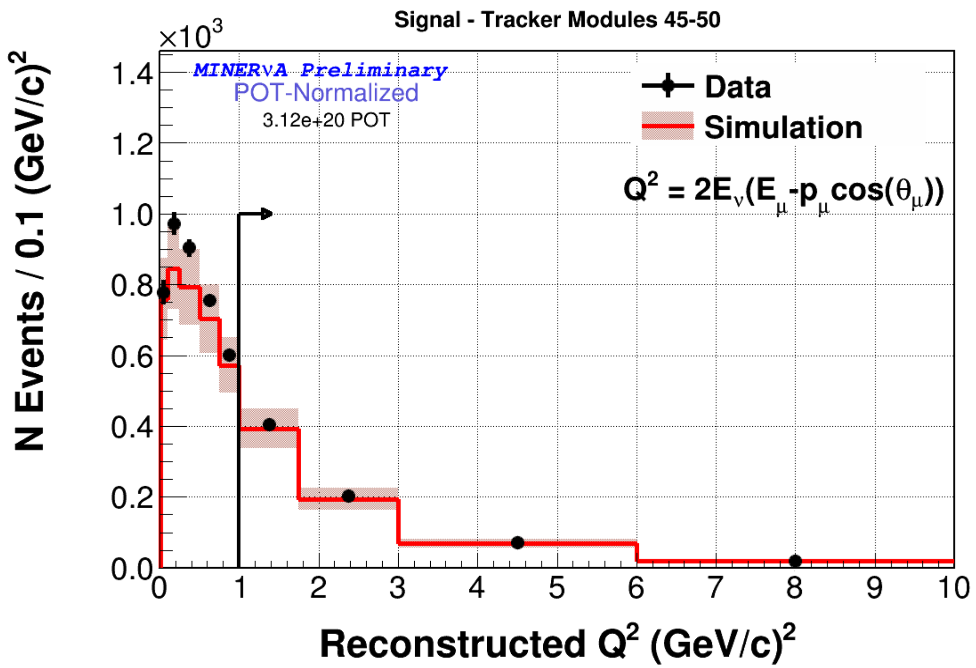
If available, additional tracks are used to improve the vertex fit iteratively.

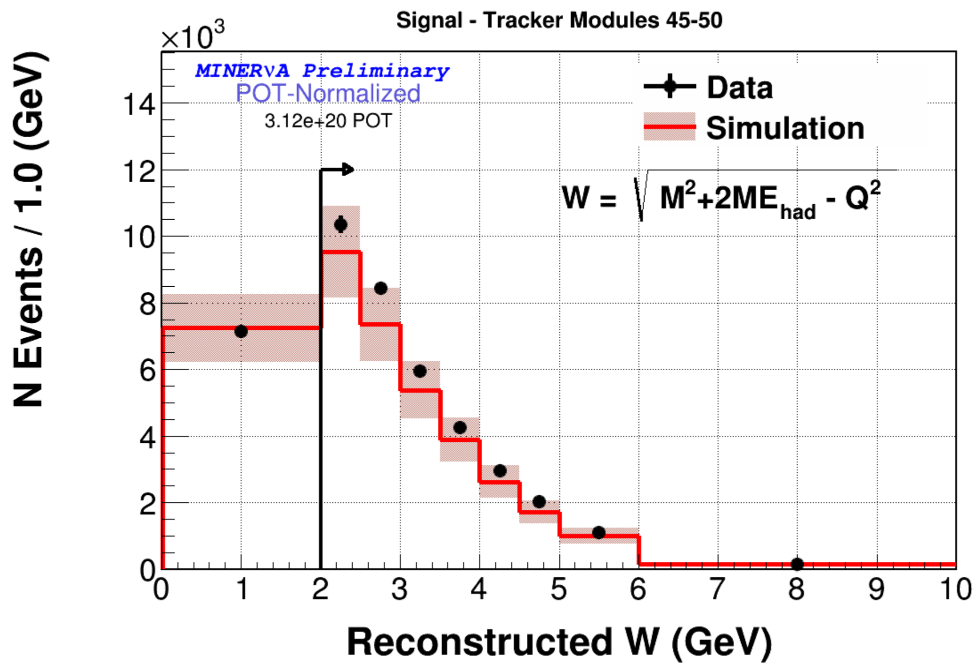
From Inclusive to DIS

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

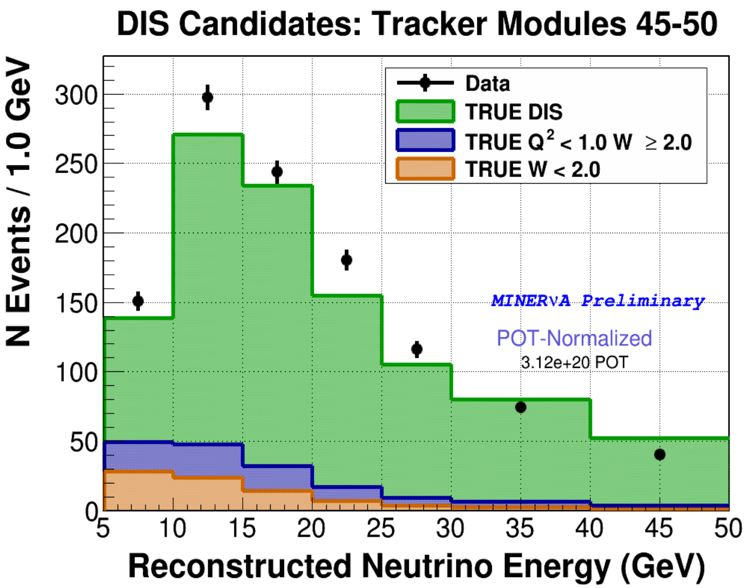
- Require $Q^2 > 1.0\ (GeV / c)^2$ and $W > 2.0\ GeV / c^2$. These cuts remove the quasielastic and resonant events from the inclusive sample, and allow us to interpret our data on the quark level.

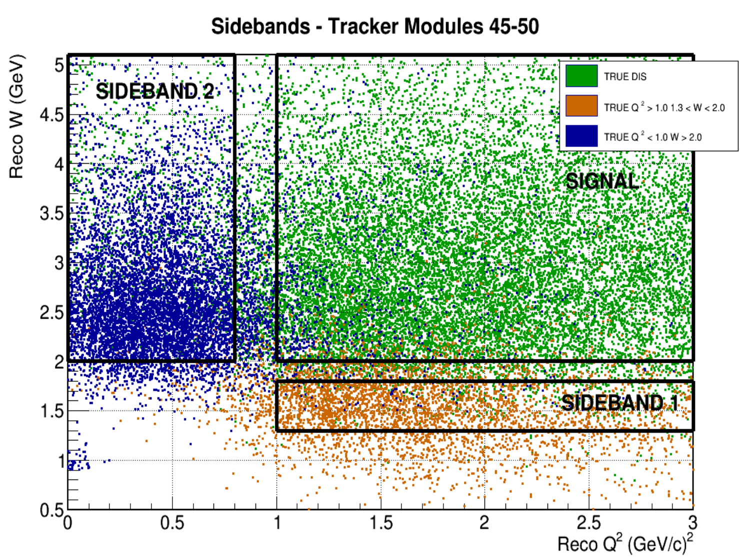
- Cuts are illustrated for CH events between 5 and 50 GeV E_υ and $\theta_\mu < 17°$.





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 $W < 2.0\ (GeV/c^2)$ that smear into the sample.

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

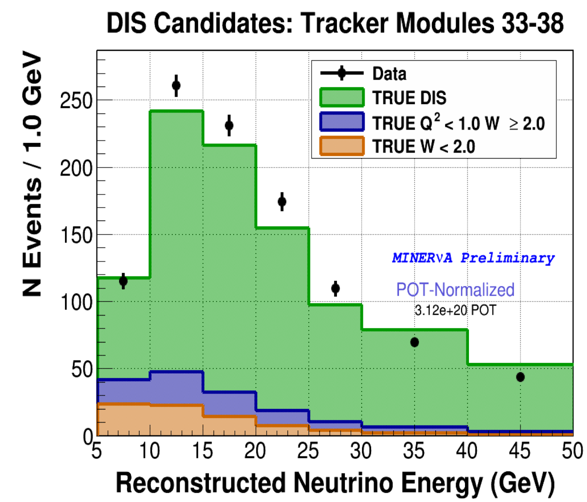
- MC is tuned to data using events adjacent to $W = 2.0\ (GeV/c^2)$ and $Q^2 = 1.0\ (GeV/c)^2$

Fitting Sidebands

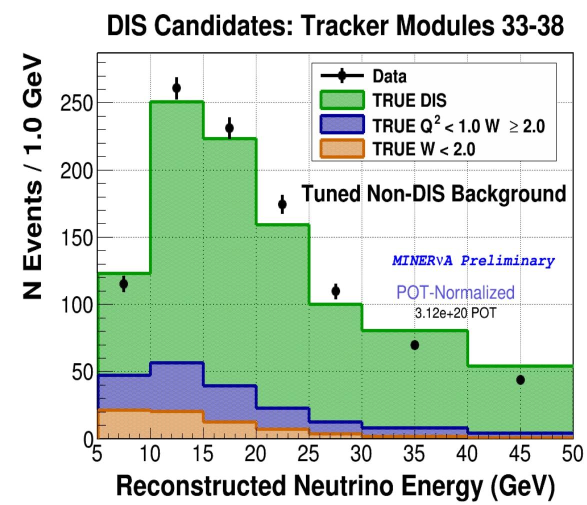
Scale Factors Applied to Simulation (stat. Error only)

A	W < 2.0	$Q^2 < 1.0$ 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.

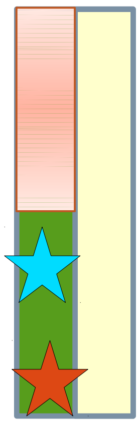


Before Fitting

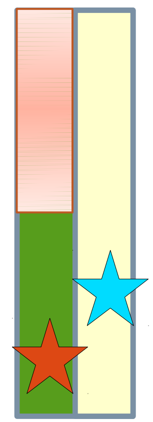


After Fitting

Background Events (Wrong Nuclei)

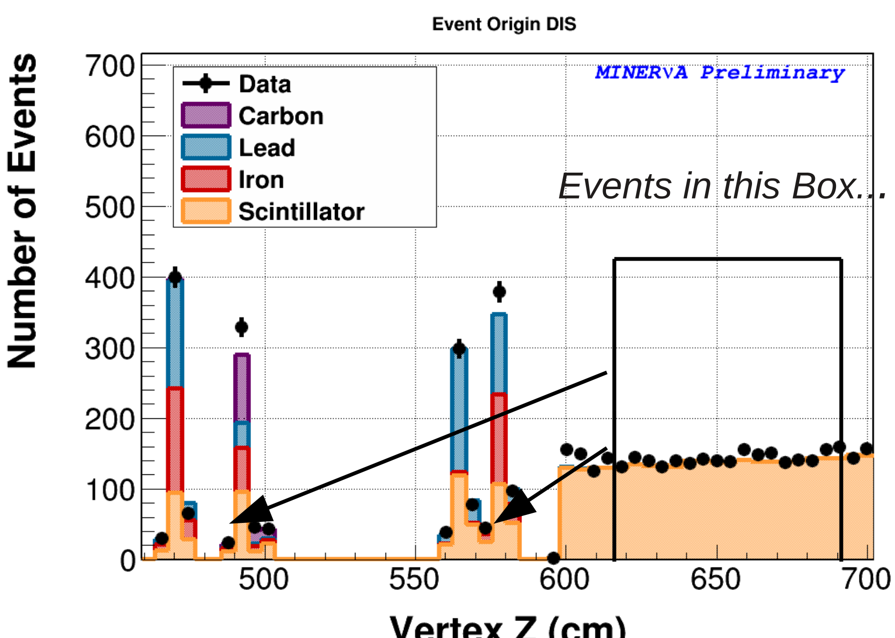


True vertex (blue star) is in the same material as the reconstructed vertex (orange star).



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

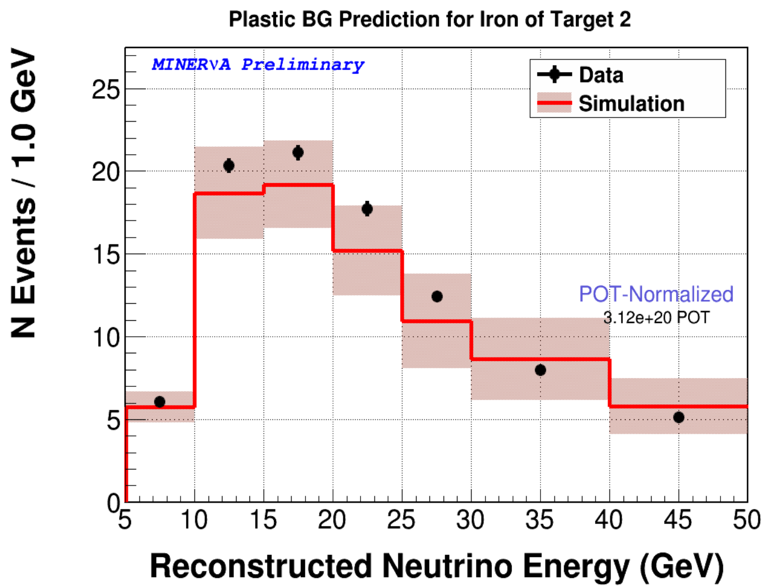
- Events occasionally truly occur in the scintillator surrounding the nuclear target, but are reconstructed to the passive target. This makes up a second background.



...Used to predict BG events here

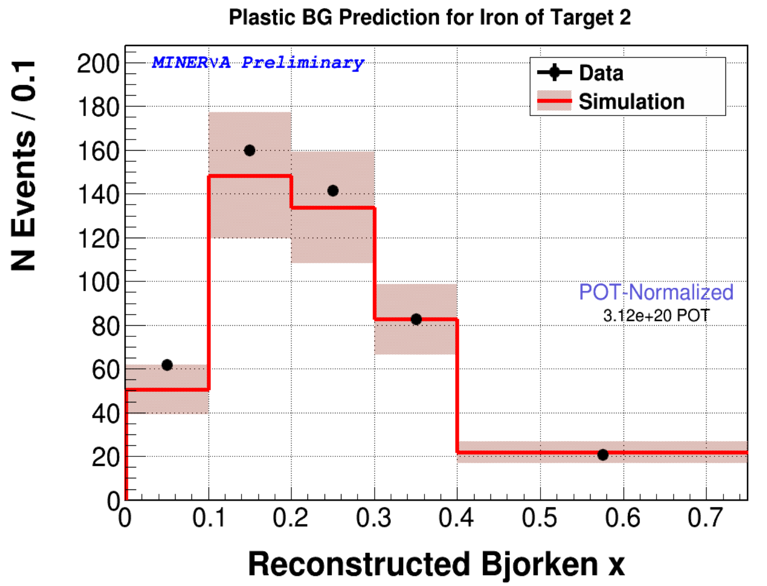
- We subtract this background by measuring the event rates in the downstream tracker, and extrapolating these events upstream to the nuclear target region.
- Downstream events are weighted for MINOS acceptance based on E_μ, θ_μ .

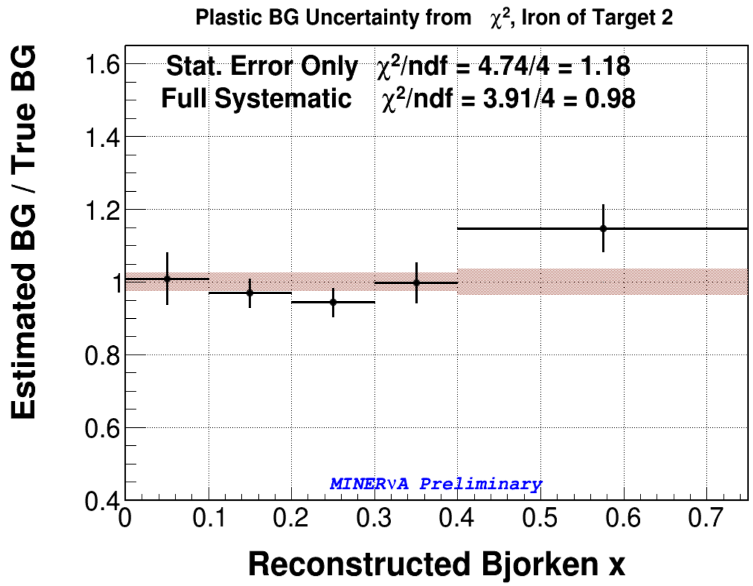
Wrong Nuclei BG (Data / MC)



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

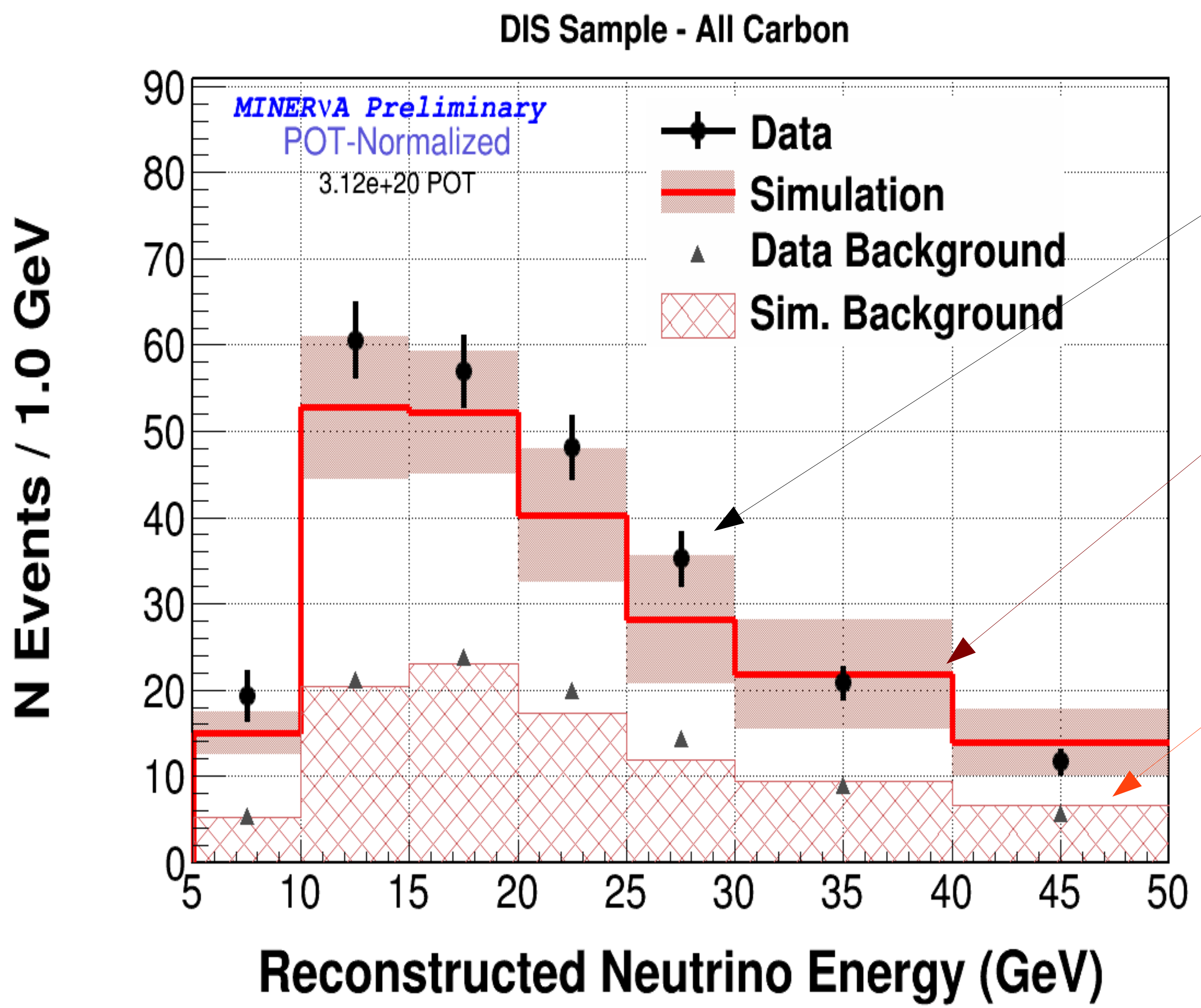
- In each case, the non-DIS events have been subtracted using the procedure previously described.





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

Putting it Together



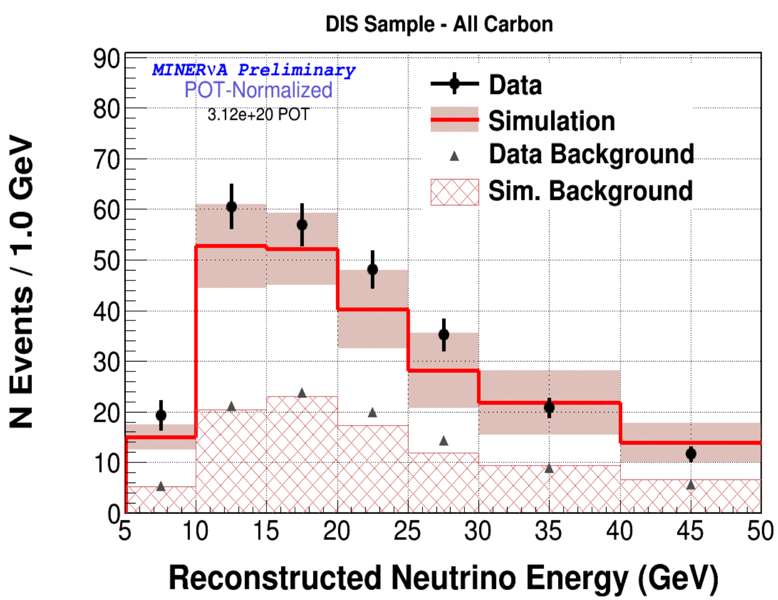
Data events reconstructed in C, with non-DIS events subtracted.

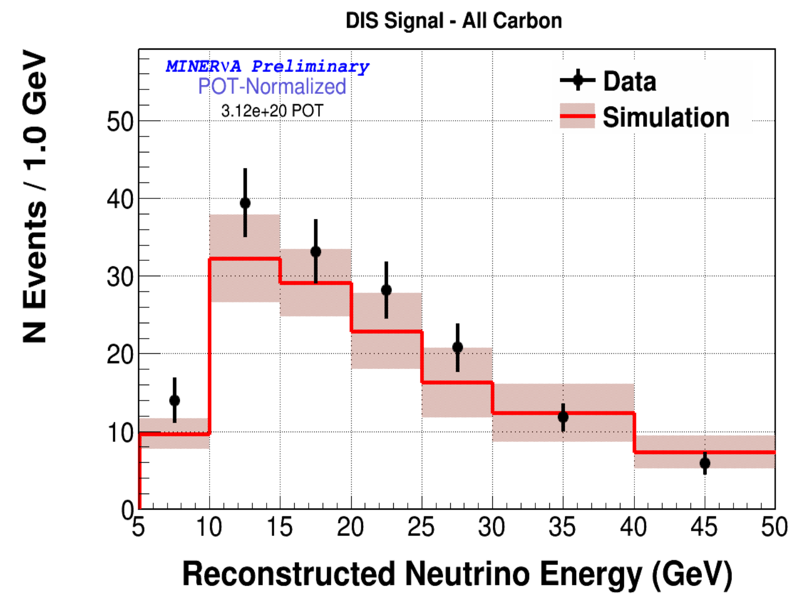
Simulated DIS events, reconstructed in C

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...

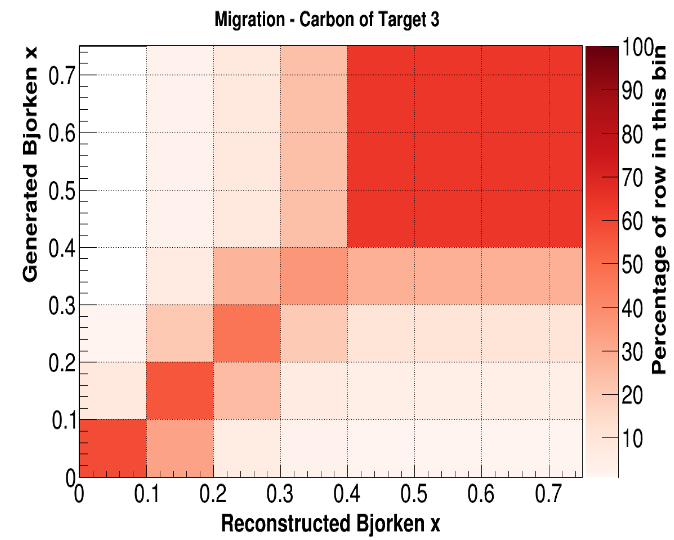




...And subtract those events to obtain a sample of DIS on carbon in data and MC. Large uncertainties on neutrino flux, measure ratios of C, Fe and Pb /CH where flux will cancel.

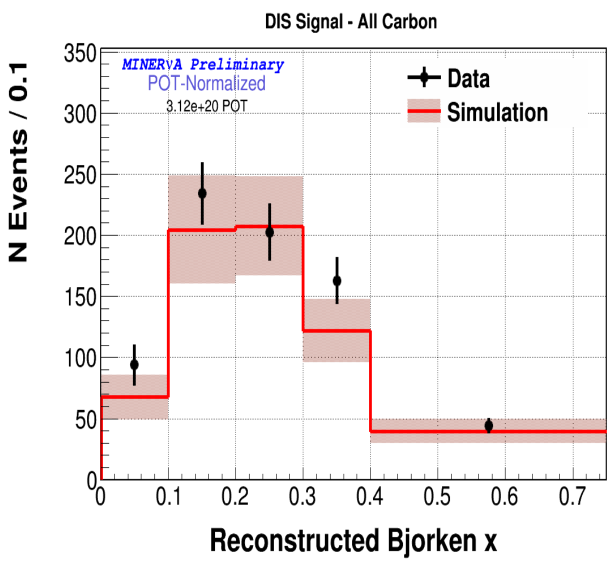
Migration and Unfolding

- Detector resolution smears the reconstructed values of x and E_ν from their generated quantities (right plot).
- Correct for this smearing using *unfolding*.
- Unfolded distributions are then efficiency corrected to account for detector effects prior to taking ratios.

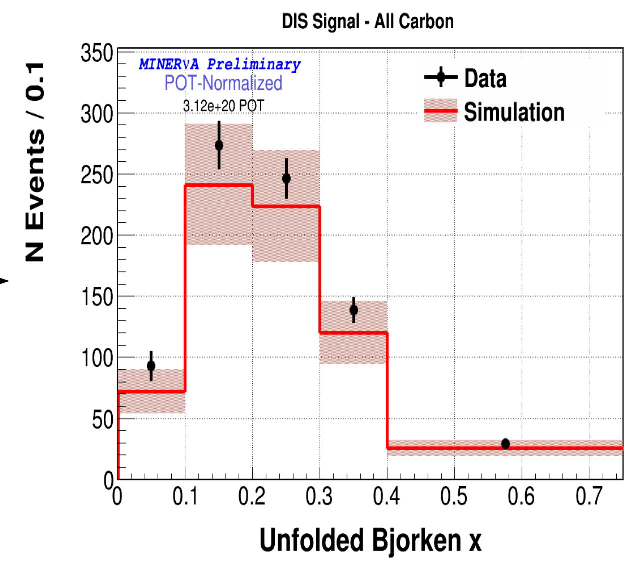


Migration Matrices used as input

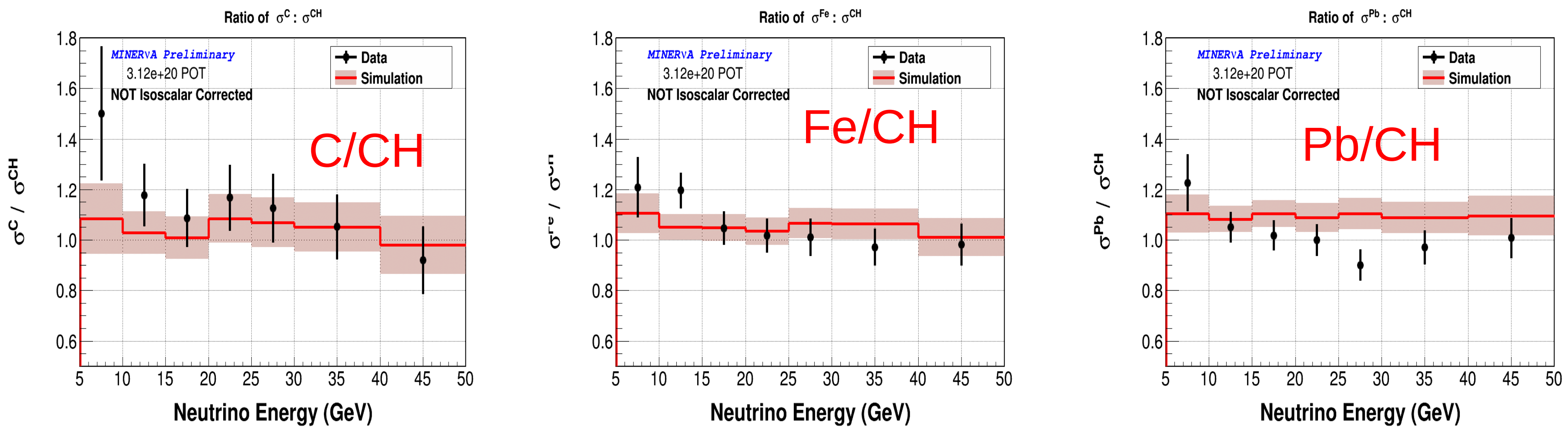
Warning! Unfolding introduces correlations between bins



Unfold

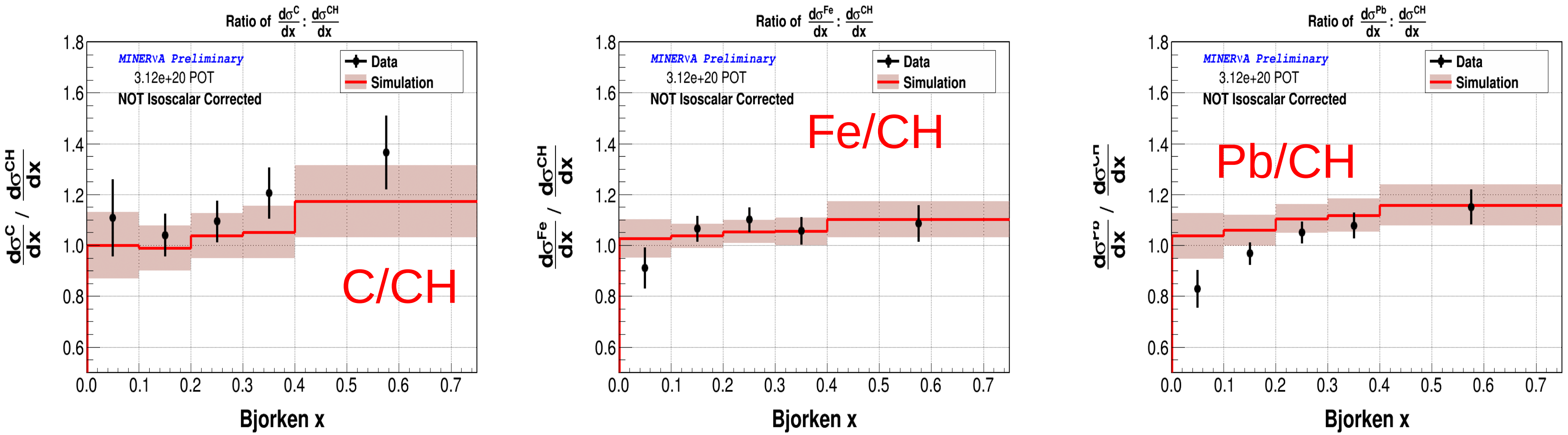


DIS Ratios: $\sigma(E_\nu)$



- 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.
- There is a general trend of the data being below the MC at high energy.
- This trend is larger in the lead than in the iron.

DIS Ratios: dσ /dx

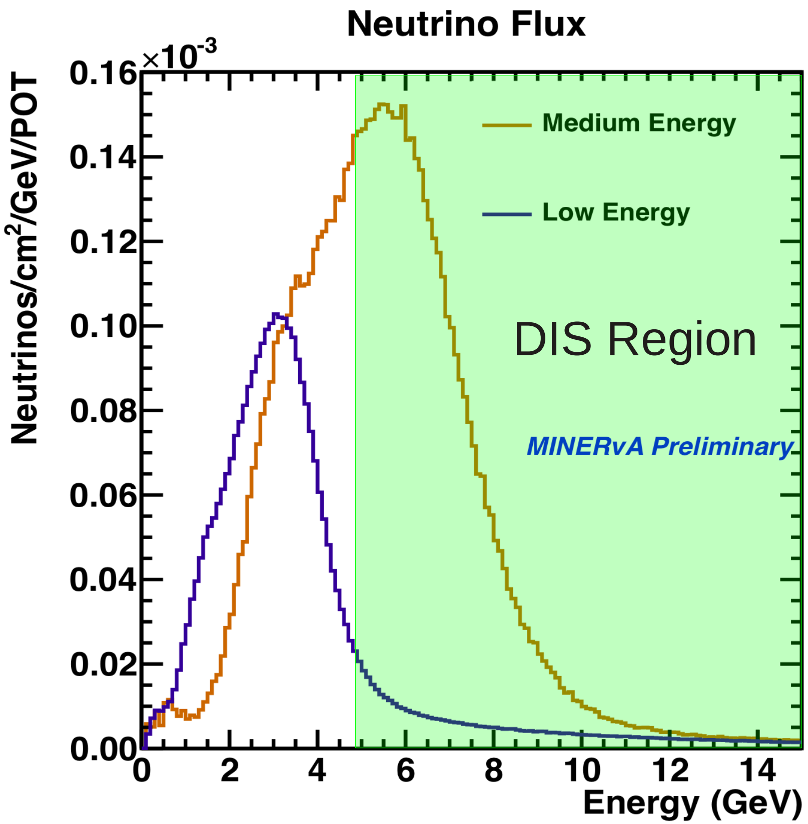


- X dependent ratios directly translate to x dependent nuclear effects.
- Currently, our simulation assumes the *same* x-dependent nuclear effects for C, Fe and Pb tuned to e^- scattering.
- The shape of the data at low x, especially with lead is consistent with additional nuclear shadowing.
- The intermediate x range of (0.3 < x <0.75) shows good agreement between data and simulation.

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.



•Currently have a quasi-elastic analysis in nuclear targets in progress for Low Energy beam

•*A bright future is expected!*

Conclusions

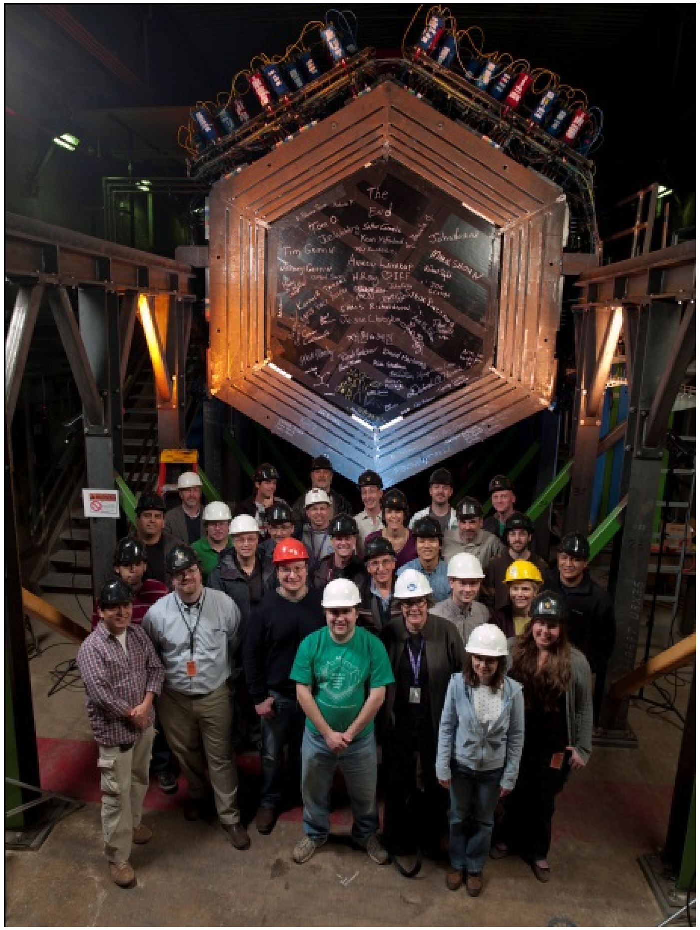
- MINERvA has made a measurement of neutrino DIS events on multiple nuclei in an identical neutrino beam.
- These measurements may be interpreted directly as DIS x-dependent nuclear effects.
- We currently observe a deficit in our lead data suggestive of additional nuclear effects.
- Our data in the intermediate x region shows no deviation from theory.
- Future higher energy measurements will be higher statistics as well as the ability to resolve larger x values ($x > 0.75$).

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

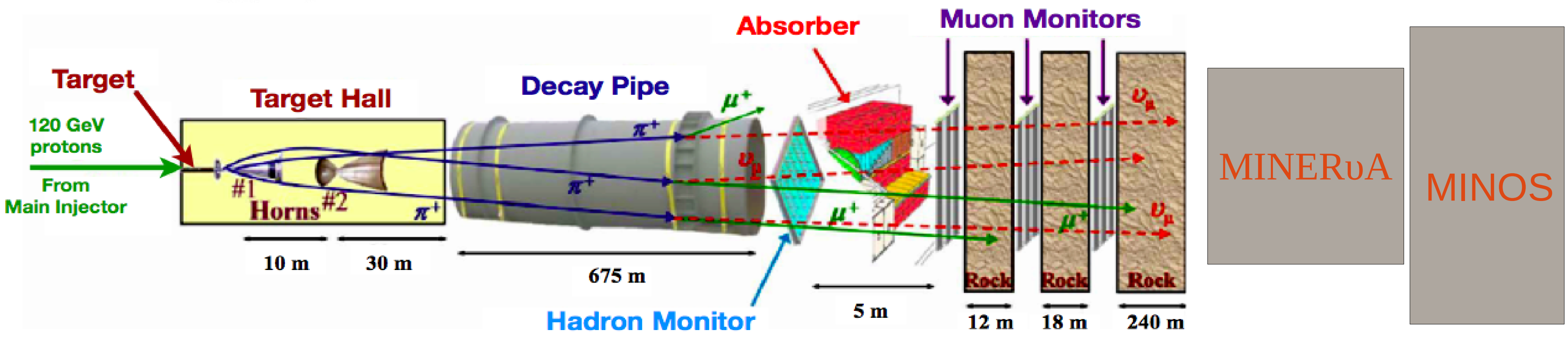
Isoscalarity

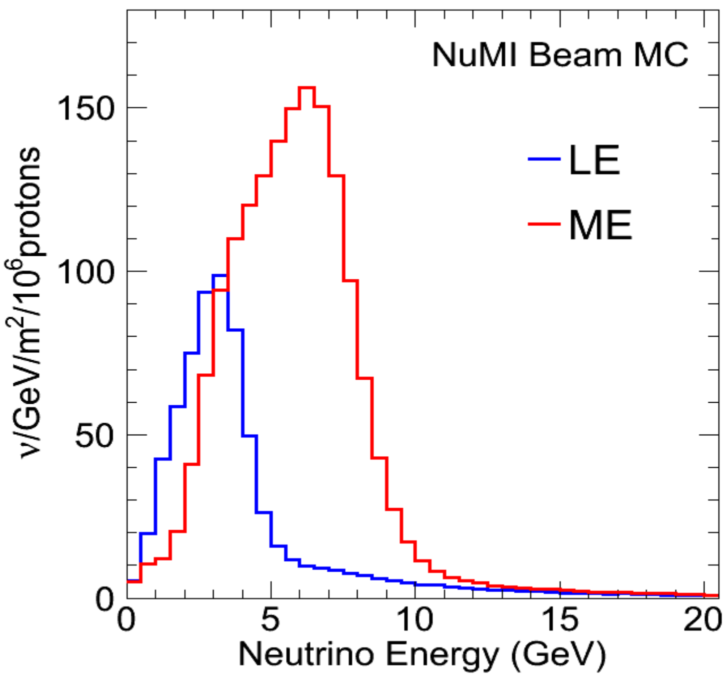
- Heavier nuclei (Fe, Pb) are composed of an unequal number of protons and neutrons (e.g. Pb: 82 protons, 125 neutrons).
- The ν_μ + N cross section is *different* for protons and neutrons; ν_μ want to couple to *d* quarks, and the neutron contains more *d* than *u* quarks.
- This effect is x dependent (higher x → more valence quarks → more *d* quarks.
- Currently, the MINERvA data does not correct for this difference; this requires some theory input.

$$f_{iso} = (A/B) \times (Z_B/Z_A) \frac{1 + (N_B/Z_B)\frac{\sigma(\nu n_f)}{\sigma(\nu p_f)}}{1 + (N_A/Z_A)\frac{\sigma(\nu n_f)}{\sigma(\nu p_f)}}$$

Isoscalar correction of two nuclei A and B with Z protons and N neutrons.

The NuMI Beamline

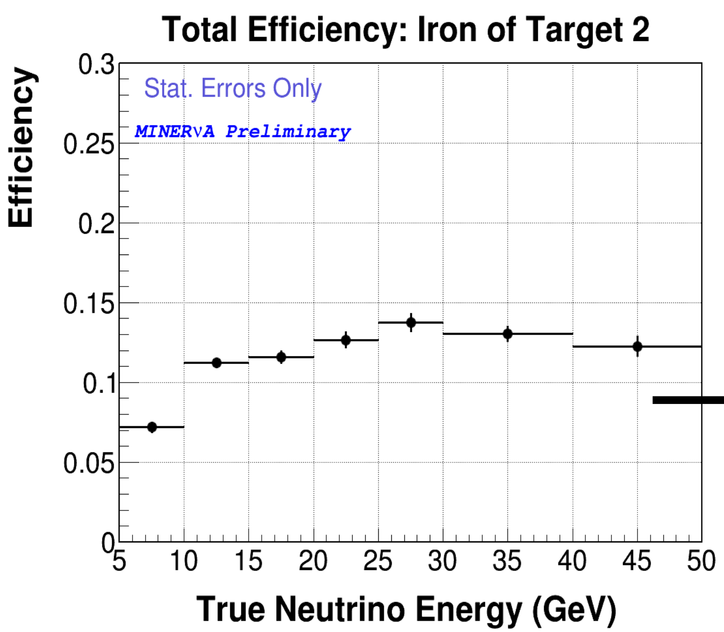




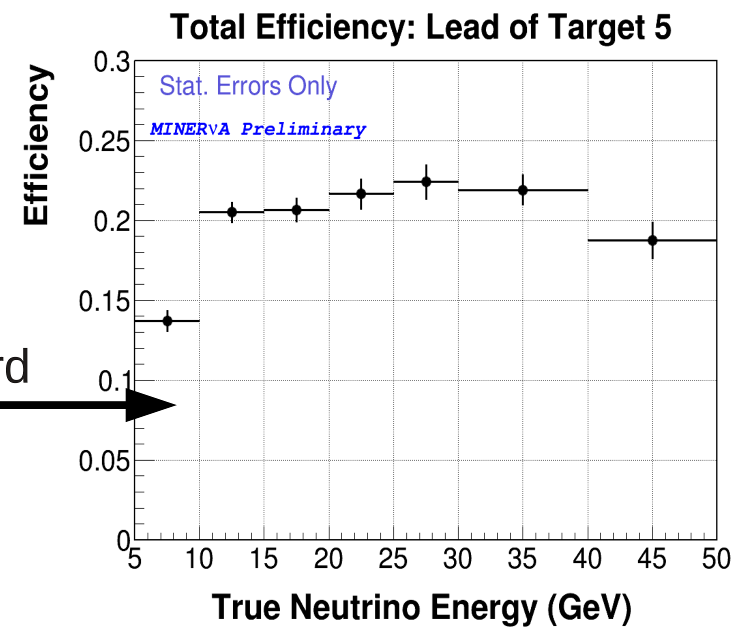
- Low energy beam (blue plot) has a peak energy of approximately 3 GeV.
- Medium energy is 7 GeV; higher beam energy means more DIS events, and access to higher x.
- Flux measurement is constrained with external hadron production data (NA49).

Efficiency Correction

- We correct for detector acceptance, using an efficiency correction derived from the MC. However, we only correct up to E_{ν} = 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

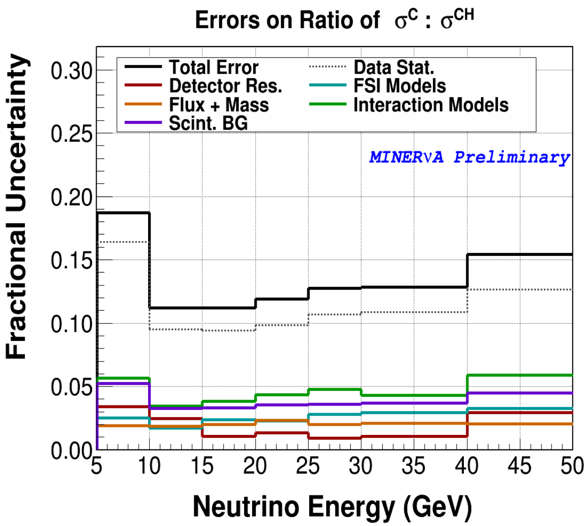


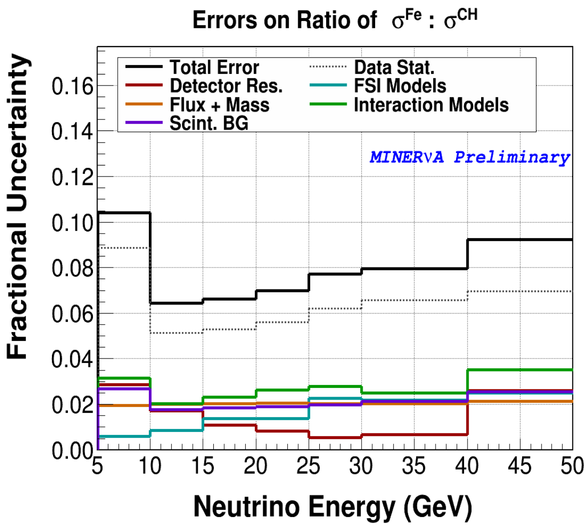
Event Table

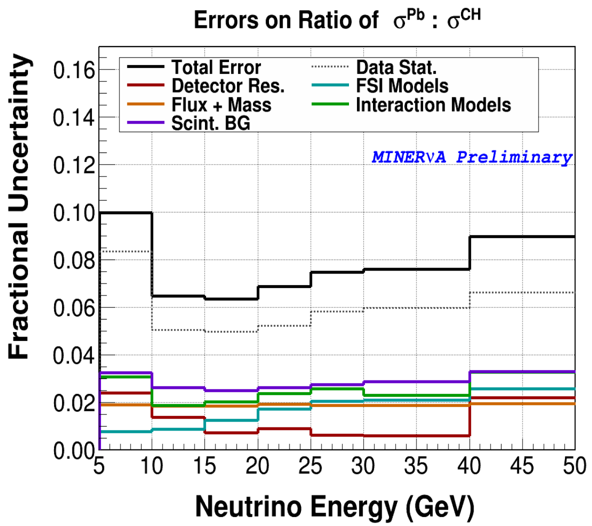
X_{bj} (unfolded)	C	Fe	Pb
0 – 0.1	90	220	230
0.1 - 0.2	270	840	930
0.2 – 0.3	250	800	940
0.3 – 0.4	140	390	520
0.4 – 0.75	100	250	350
0.75+	1	1	1
TOTAL	850	2500	2970

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

Ratio Uncertainties

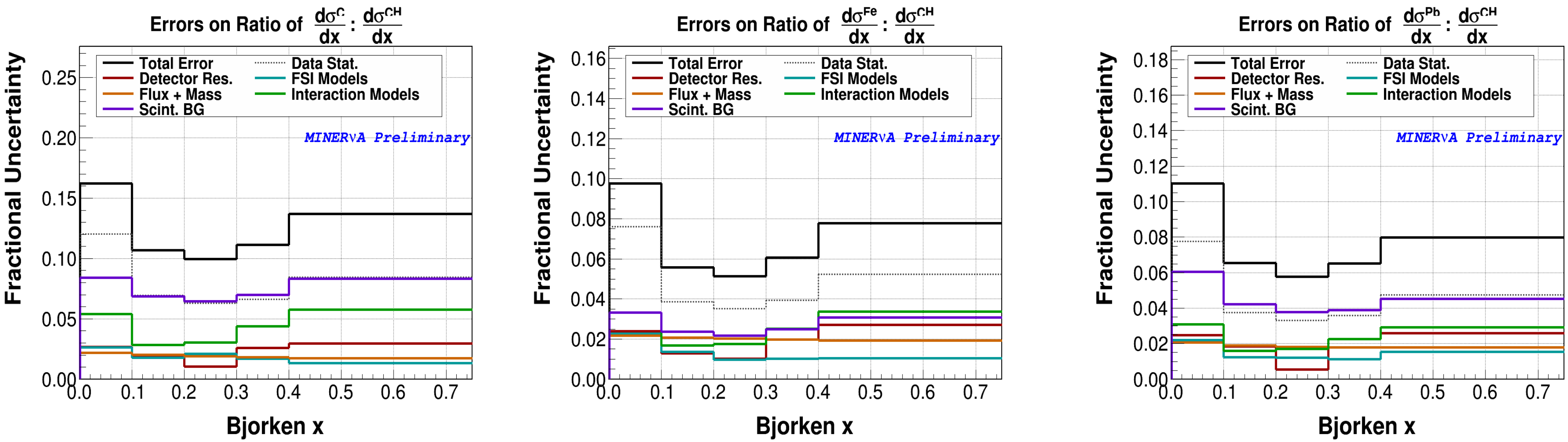






- Most of the uncertainty stems from data statistics.
- Higher intensity, higher energy beam will improve this substantially.
- Correlations in data introduced from unfolding are *NOT* accounted for in Data stat. uncertainty.

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).

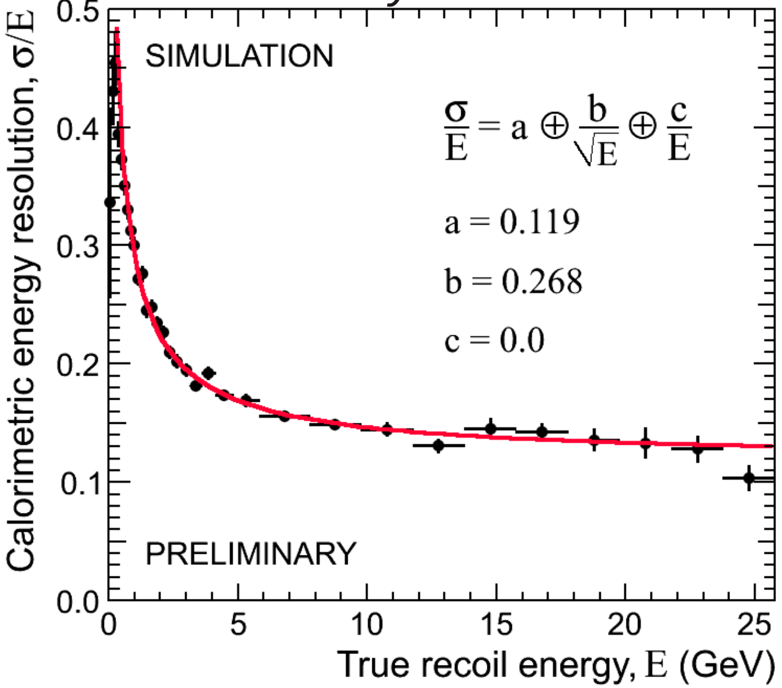
Energy lost by a mip in each material

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

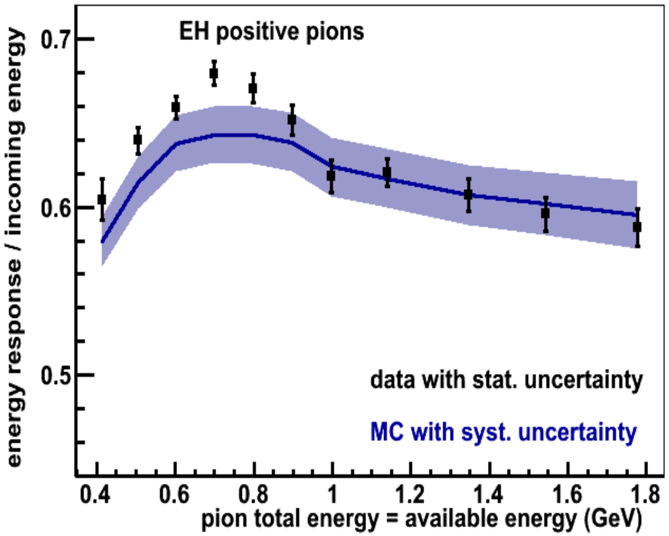
vertex	Tgt 2	Tgt 3	Tgt 4	Tgt 5	Trk
α	1.81	1.71	1.60	1.59	1.62

Tracker recoil energy resolution as measured by simulation

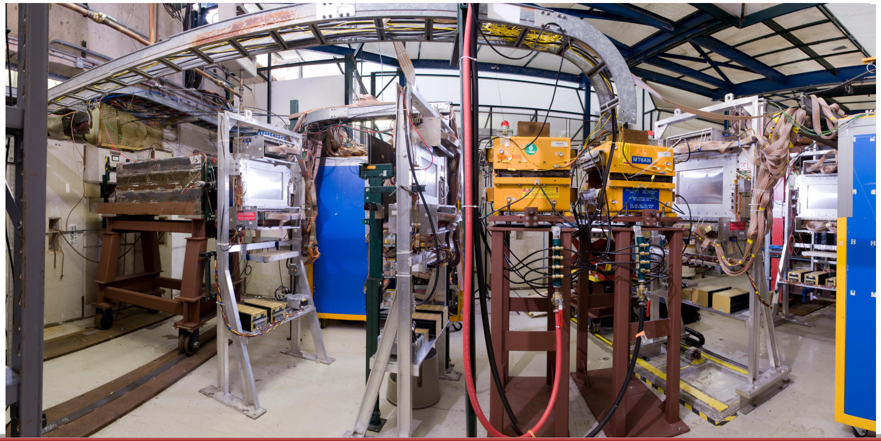


Test Beam

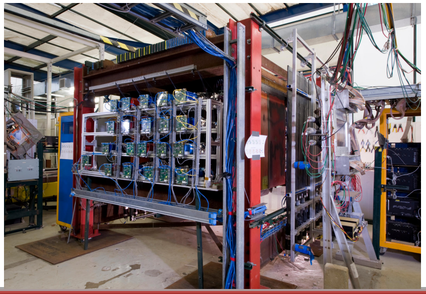
- The MINERvA detector's hadronic energy response is measured using a dedicated test beam experiment at the Fermilab Test Beam Facility (FTFB)
- Custom built beamline took data during the summer of 2010.
- In addition to a Birk's Law calculation, hadronic energy reconstruction uncertainty is esitmated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

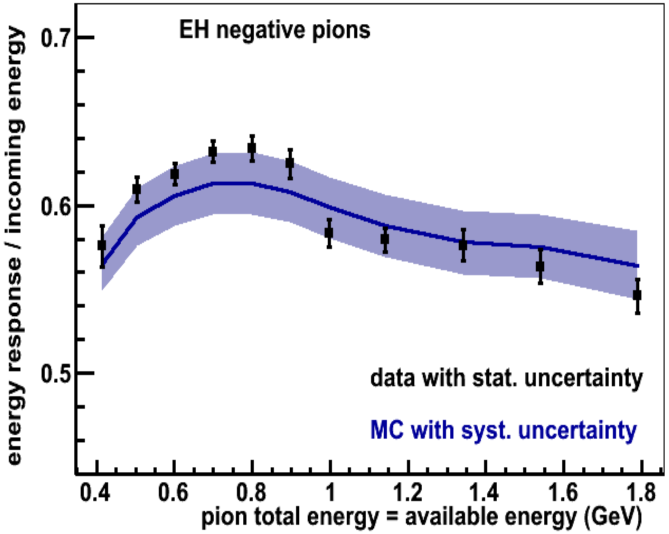


Custom built beamline

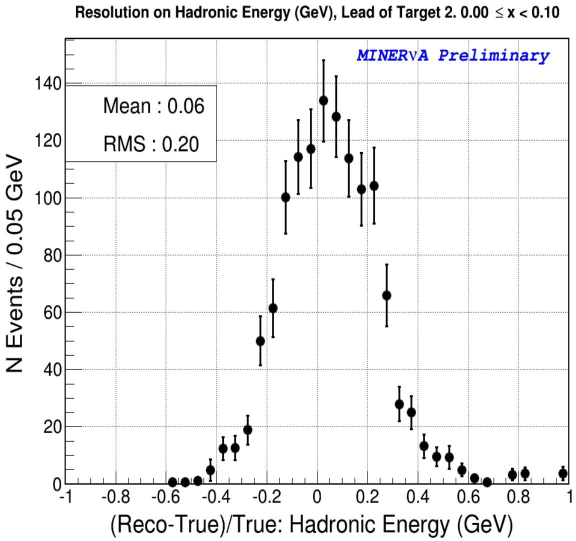


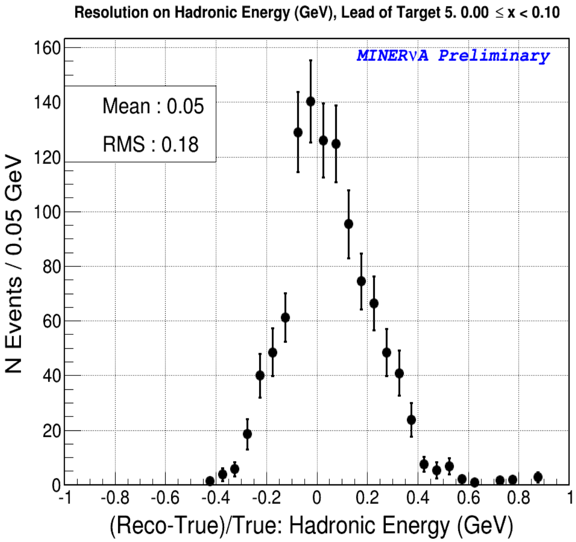
Plus miniature detector

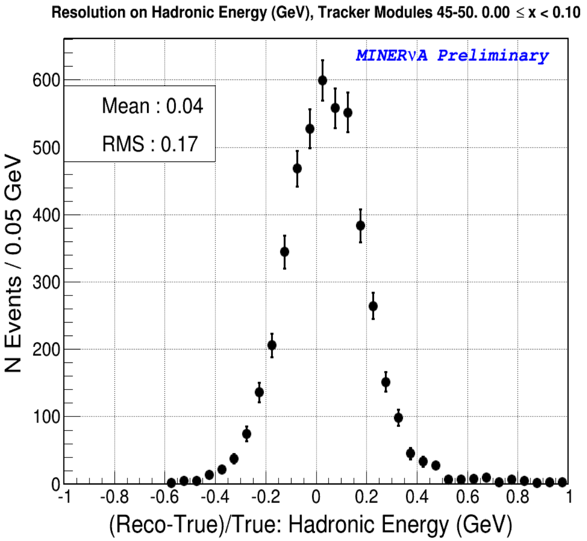




Hardonic Energy Resolution



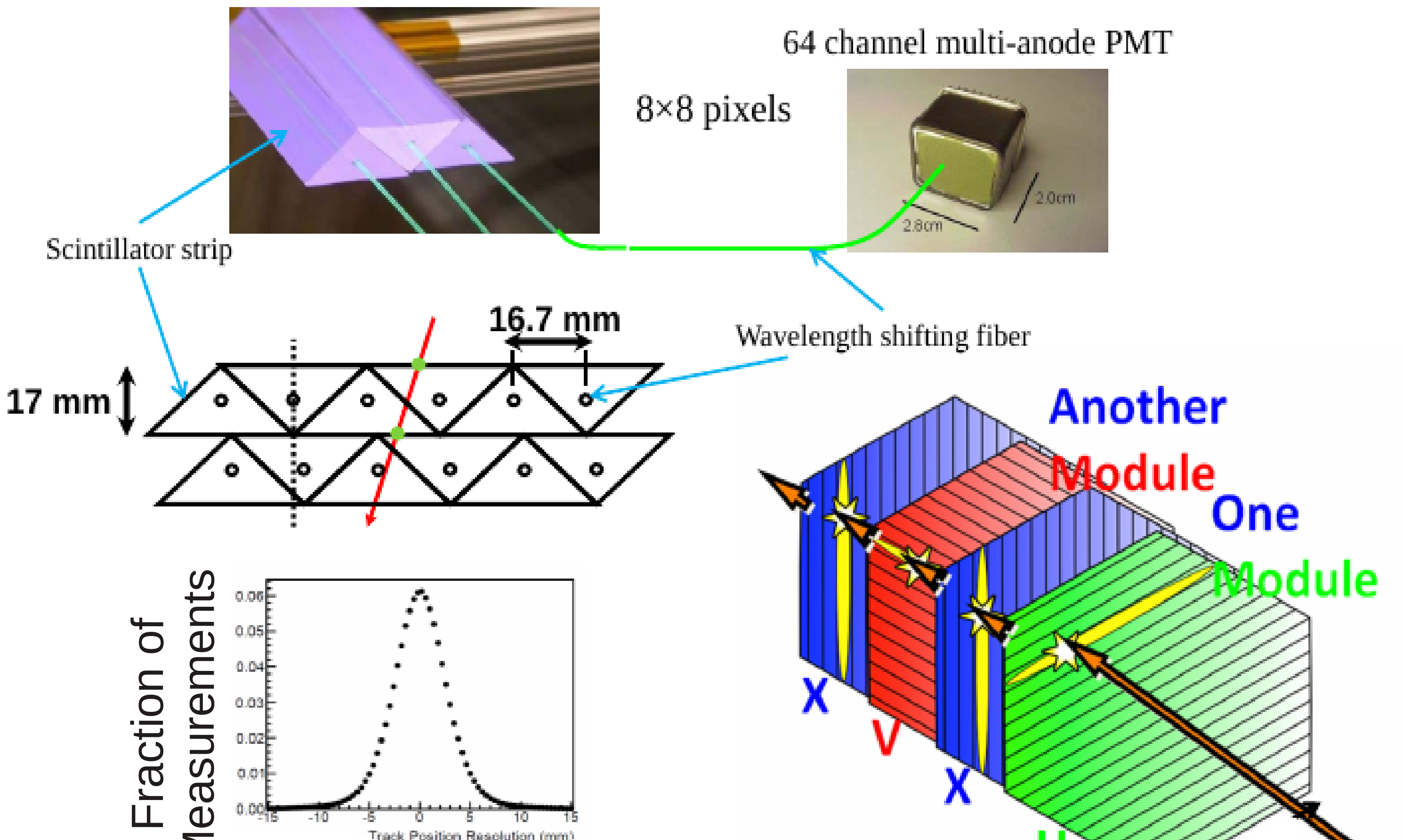




Downstream

•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.

Detector Technology



Tracker Position Residual

A MINERvA Module