First Search for EMC Effect and Shadowing in Neutrino Scattering at MINERvA

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Fermilab Joint Experimental-Theoretical Physics Seminar

Outline:

- Motivation
- Experiment
- Reconstruction
- CCInclusive
- CCDIS
- Medium E
- Conclusions

- Motivation and background.
- The MINERvA experiment and detector.
- MINERvA calibration and event reconstruction.
- Discussion of past nuclear target charged current inclusive result.
- Nuclear target charged current deep inelastic scattering result.
- Future directions, medium energy analysis.
- Conclusions.

Motivation and Background

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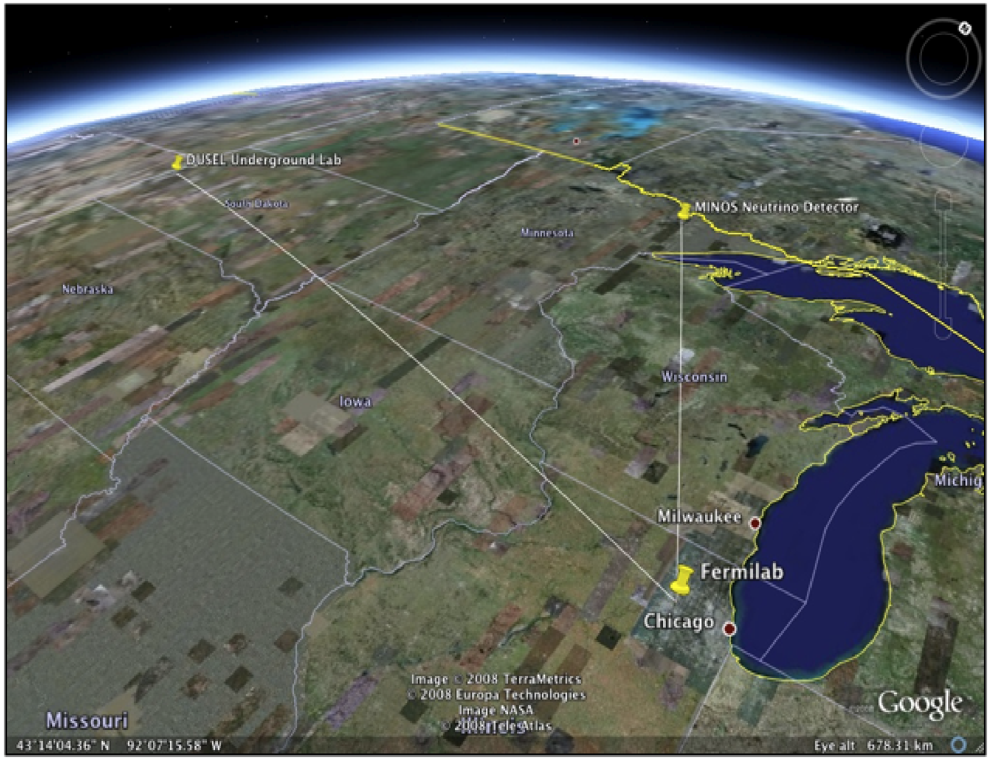


CERN COURIER

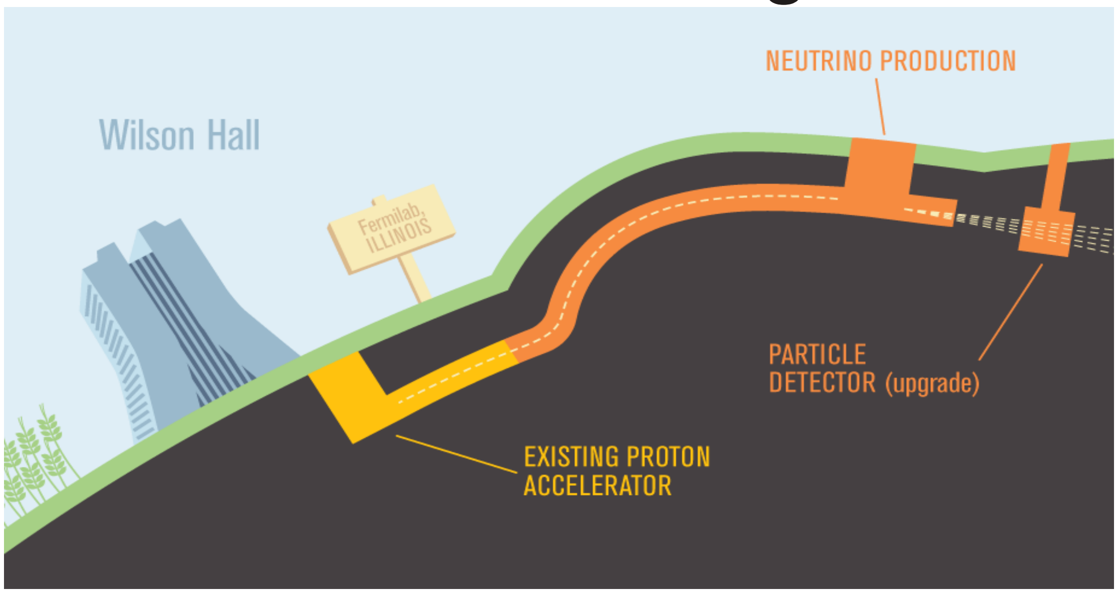
Apr 26, 2013

The EMC effect still puzzles after 30 years

Thirty years ago, high-energy muons at CERN revealed the first hints of an effect that puzzles experimentalists and theorists alike to this day.

Neutrinos: The Next Frontier

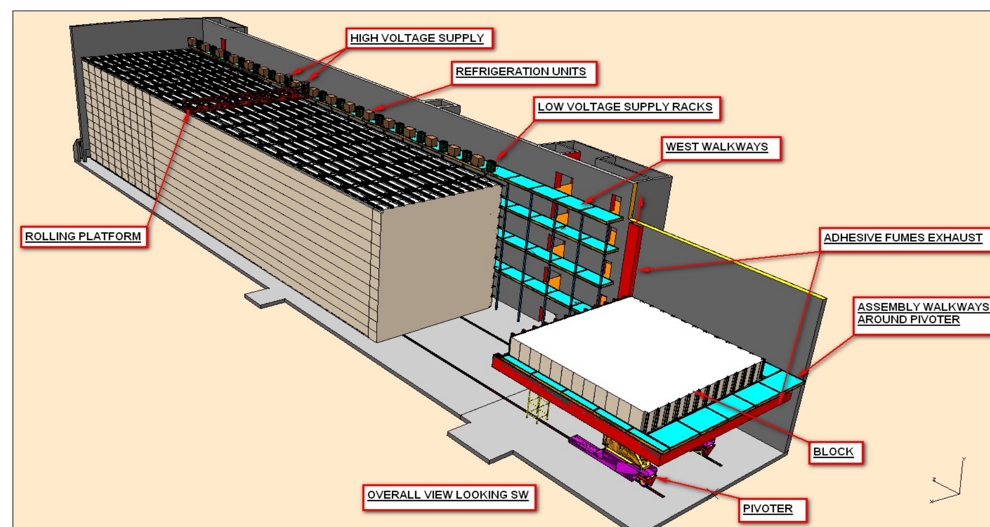
This is an exciting time for neutrino physics:



We are building more powerful beamlines (LBNF)...

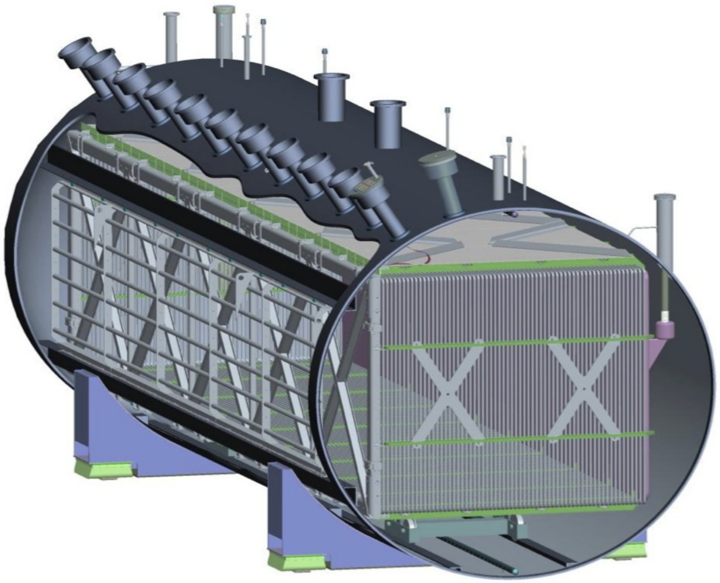
- **This is a good position to be in.**
- **We are building the tools today for a very successful physics program tomorrow.**

...And bigger detectors (NovA)!

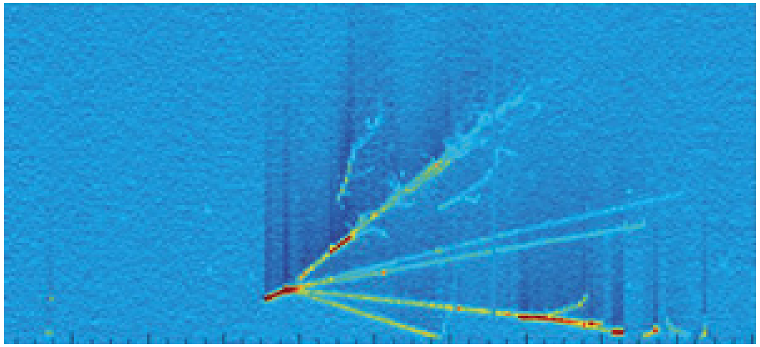


Neutrinos: The Next Frontier

- More precise detectors mean better measurements (MicroBooNE).
- Massive detectors and intense beamlines mean higher event rates (DUNE).
- Future experiments rely on the measurements we can make today if they are to reach their full potential.



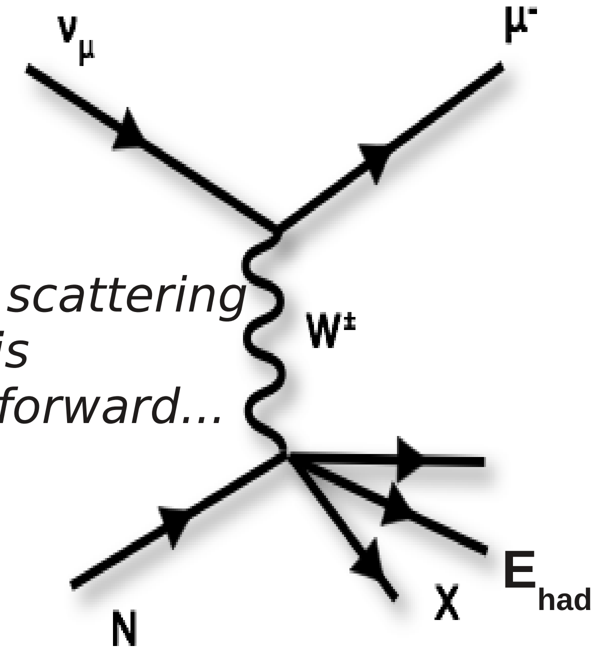
MicroBooNE TPC: excellent energy reconstruction of EM final states.



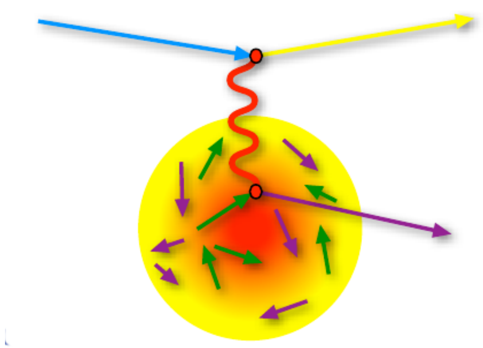
ArgoNeuT has the ability to untangle complicated final states.

Neutrinos in Nuclear Media

- One common theme of the experiments mentioned: they rely on large A materials (Fe, Ar, C, H_2O etc.)
- Problem: nuclear effects caused by nucleons bound in a nucleus distort the measured kinematics of the neutrinos.
- Two detectors will *not* solve your problem: these effects modify the near and far energy spectra differently.
- Effects not well understood in neutrino physics. General strategy has been to adapt nuclear effects from electron scattering into neutrino scattering.

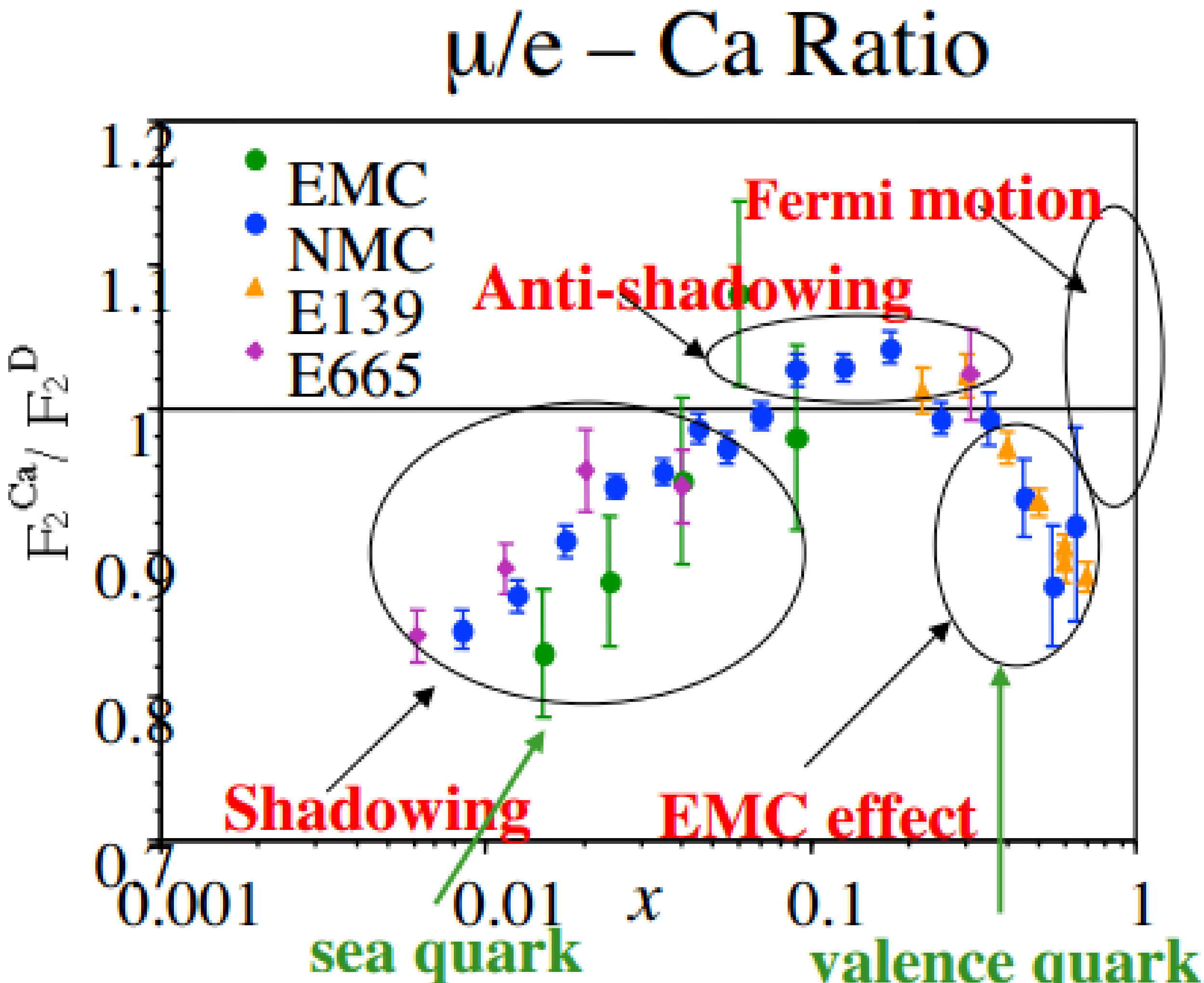


Neutrino scattering is straightforward...



...Until it's not!

Charged Lepton Nuclear Effects



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

Scaling variable Bjorken x. In the parton model, x is the fractional momentum of the struck quark

- **Shadowing and Anti-shadowing:** Depletion of cross section at low x, presumably compensated by a enhancement from x ~ 0.1 – 0.3. Shadowing is well understood experimentally and theoretically.
- **EMC Effect:** no universally accepted cause (though many theories). What *is* known is that it is a strong function of local nuclear density.
- **Fermi motion:** Each quark is allowed to have a maximum momentum of x = A, so increasing A increases maximum allowable x.

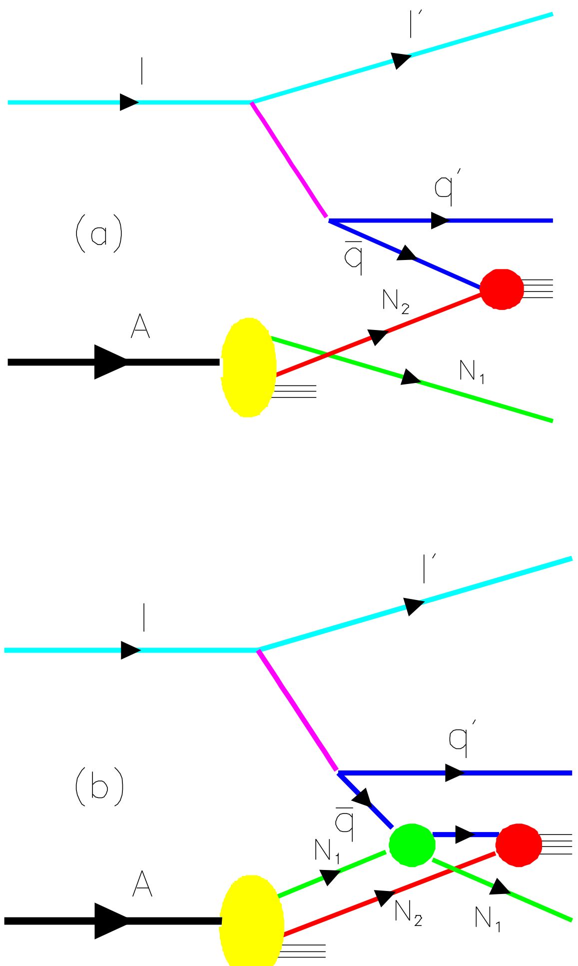
Shadowing

- Several theoretical models successfully describe the shadowing effects observed in charged-lepton nucleus scattering.

- Most are based on hadronic fluctuations of the ϒ (or W/Z for neutrinos)

- These fluctuations then undergo multiple scatterings off leading nucleons in the nucleus.

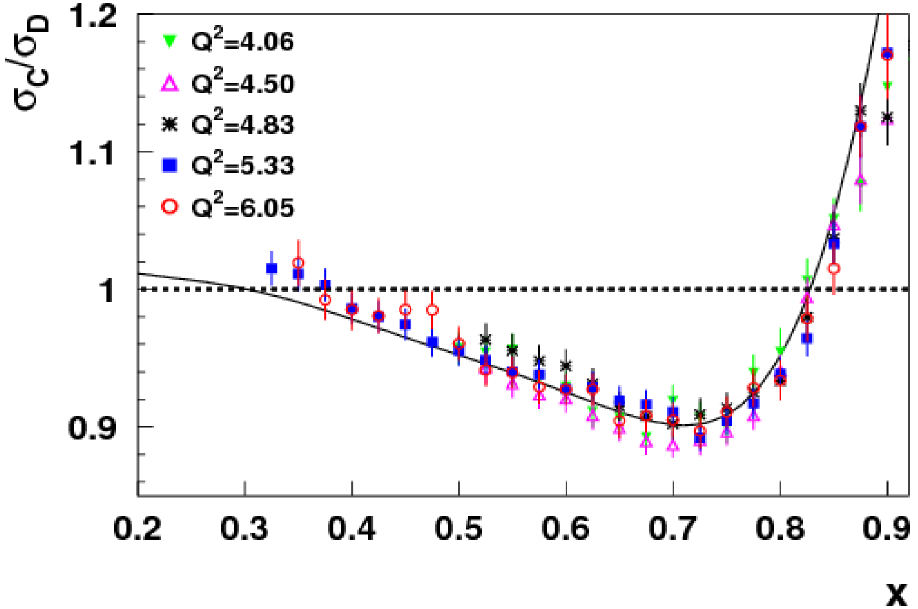
- The scattering on the leading nucleons lead to no scatters on the downstream nucleons resulting in a depletion of cross section at low values of x.



EMC Effect

- Named for the European Muon Collaboration experiment in 1983.
- Prior to EMC: a *rise* in in A / D ratio as x increases past x > 0.4 (valence quarks) was expected due to Fermi motion.
- Opposite was observed! Valence quarks in a bound nucleus carry *less* momentum than expected.
- Currently there are no agreed upon cause(s).
- But the conclusion is clear: binding nucleons together changes the momentum distribution of the quarks.

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



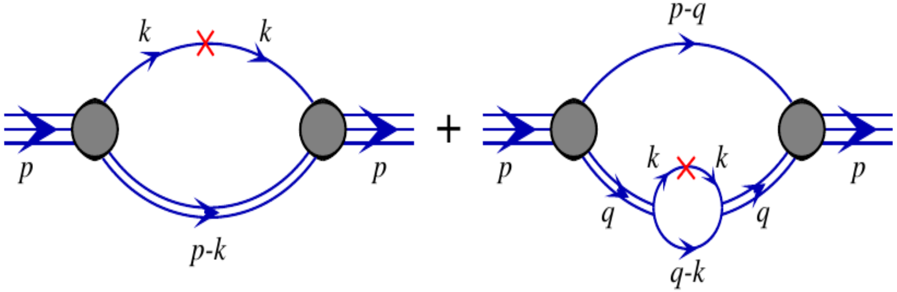
Ratio of carbon to deuterium cross section in different bins of four-momentum transfer squared (Q^2). Solid line is a fit to SLAC data. The dip above x > 0.35 is the EMC effect.

Example: Medium Modifications

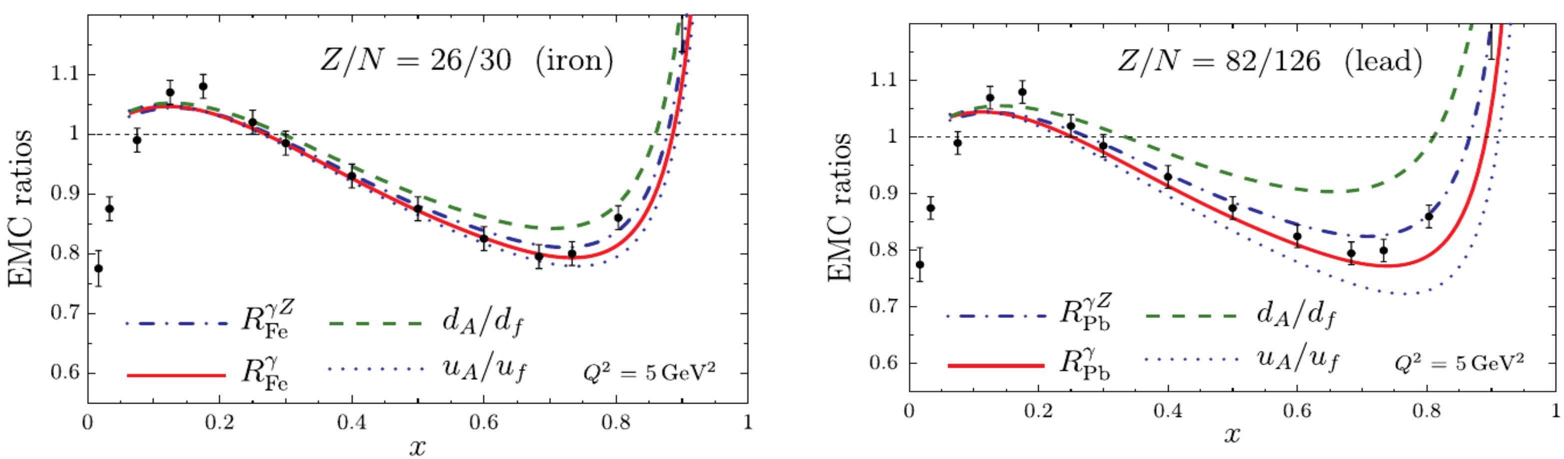
Nuclear quark distributions — *Nuclear* wave function

$$q_A(x_A) = \int_0^A dy_A \int_0^1 \delta(x_A - y_A) f_\alpha(y_A) q_\alpha(x)$$

Nucleon quark distributions



- Bound quark distributions are convoluted with the nuclear wave function.
- Treat the valence quarks as a quark – di-quark pair.
- End result is a good theoretical description of the EMC effect data on a variety of nuclei.
- Has the advantage of predicting the flavor dependence of EMC.



I. C. Cloet et. al. Phys. Rev. Lett. 109 182301 (2012)

X Dependent Nuclear Effects

- There is no one theory which explains all of these effects.
- MINERvA is the first chance to see x-dependent effects in neutrinos!
- Neutrino nucleus deep inelastic scattering data can provide some power to distinguish between different models.
- It is also a way to probe the fundamental physics differentlly.
- For example, neutrinos are sensitive to the axial and vector components of xF_3 and F_2. Charged leptons are only sensitive to the vector component.

The MINERvA Experiment

- Motivation
- Experiment
- Reconstruction
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- Medium E
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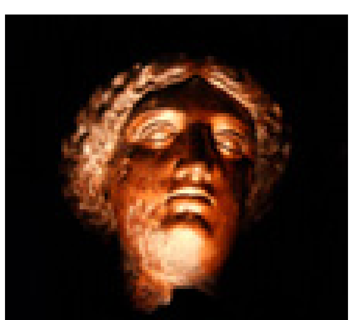
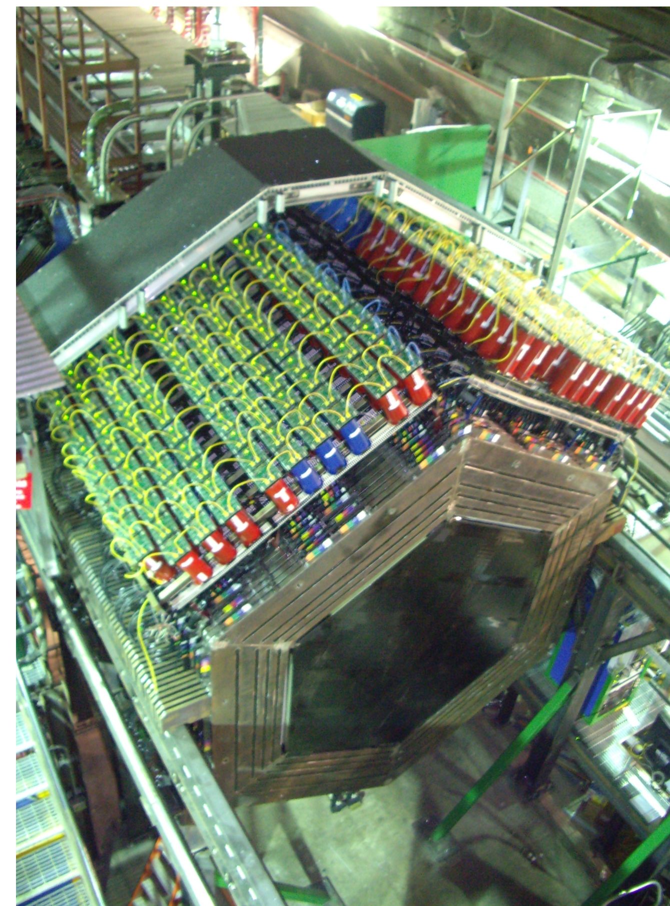
MINERvA

You are here



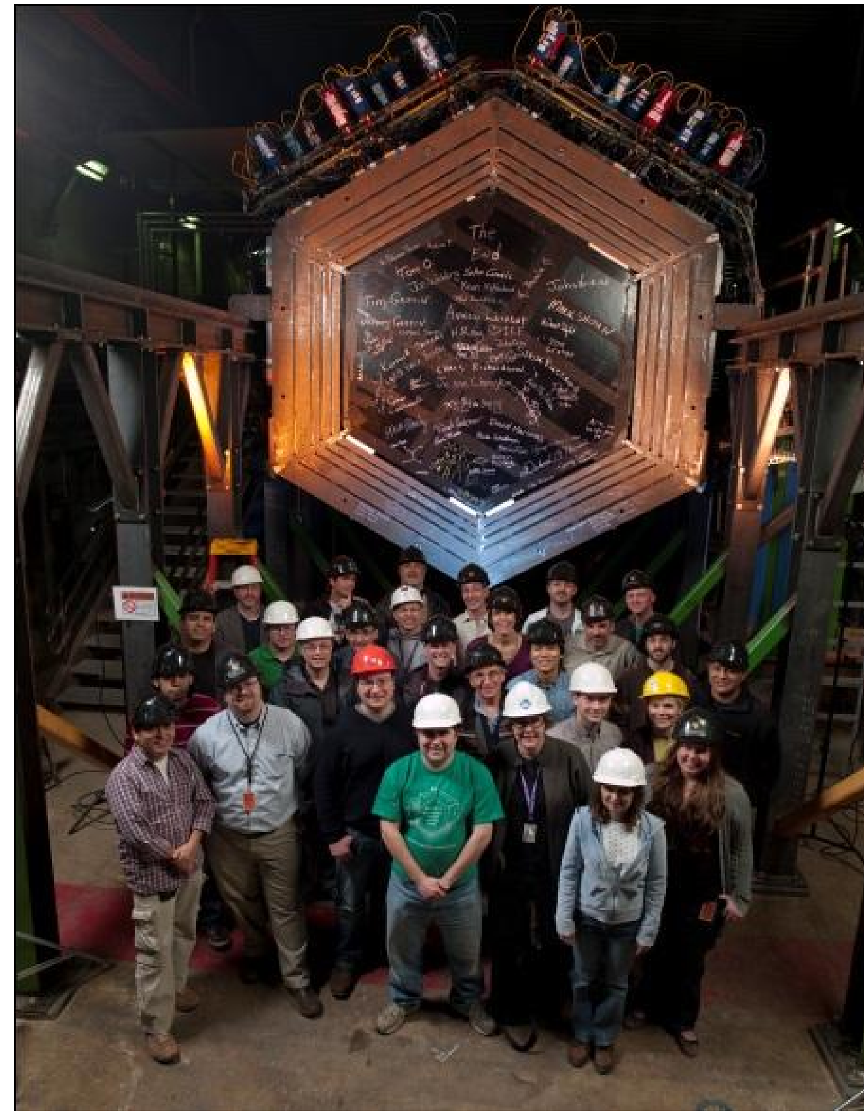
MINERvA under construction



MINERvA Collaboration

Collaboration of ~65 Nuclear and Particle Physicists

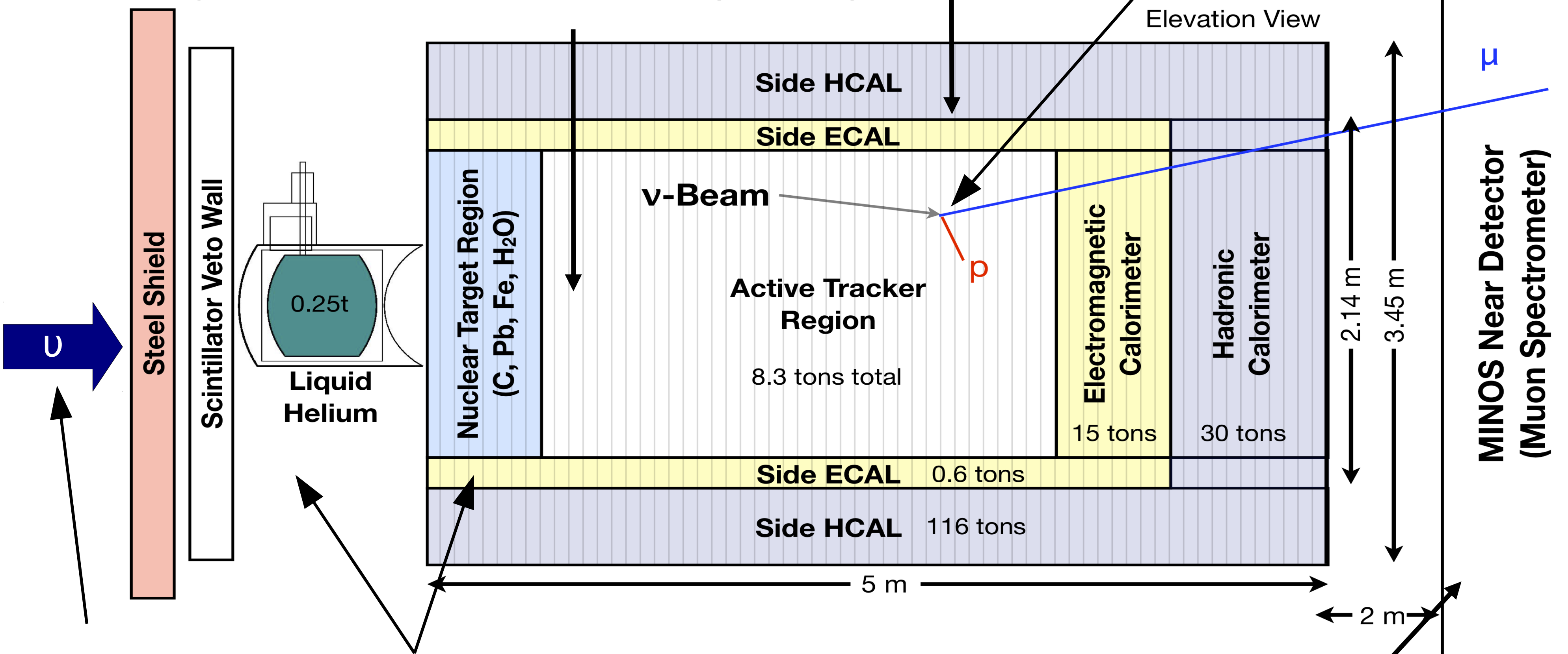
- University of California at Irvine
- Centro Brasileiro de Pesquisas Físicas
- University of Chicago
- Fermilab
- University of Florida
- Université de Genève
- Universidad de Guanajuato
- Hampton University
- Inst. Nucl. Reas. Moscow
- Massachusetts College of Liberal Arts
- University of Minnesota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



MINERvA Detector

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

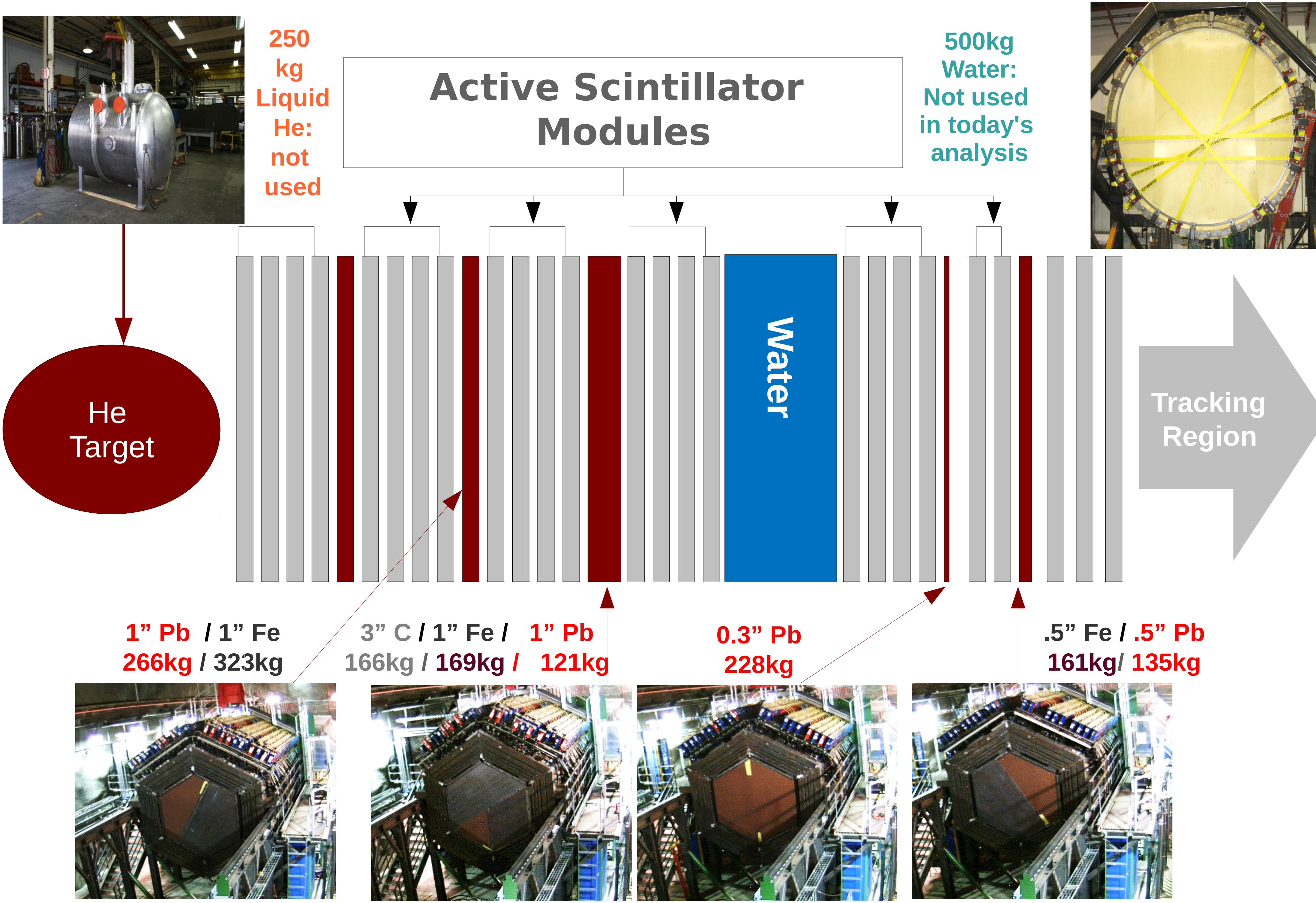
Most MINERvA Analyses happen here...



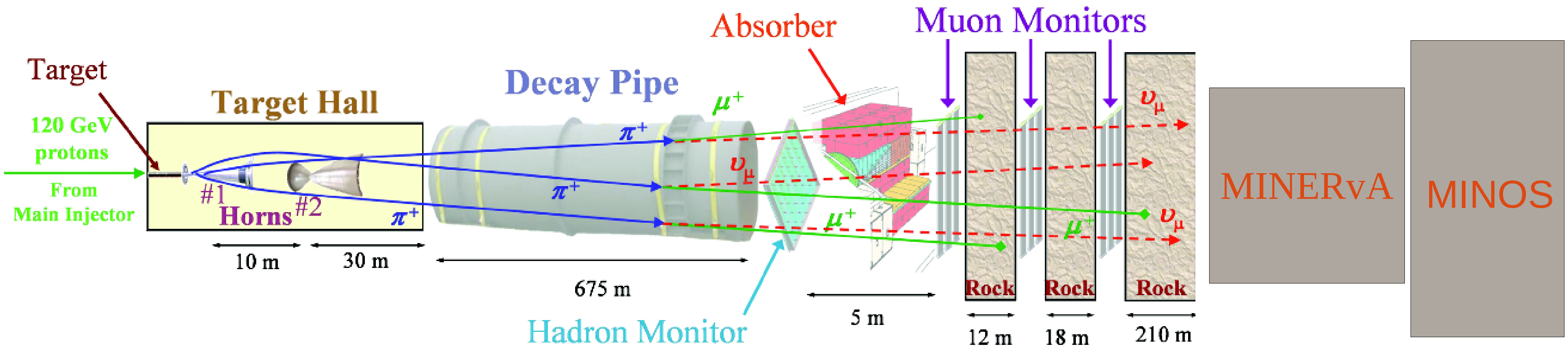
Neutrino beam created by Fermilab NuMI beamline

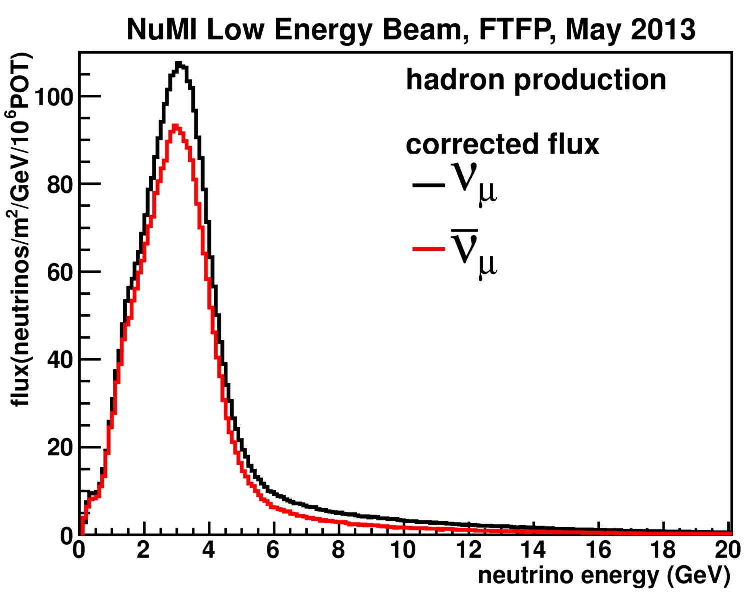
Today's result: Nuclear targets in the same neutrino beam allow MINERvA to make A-dependent physics measurements.

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

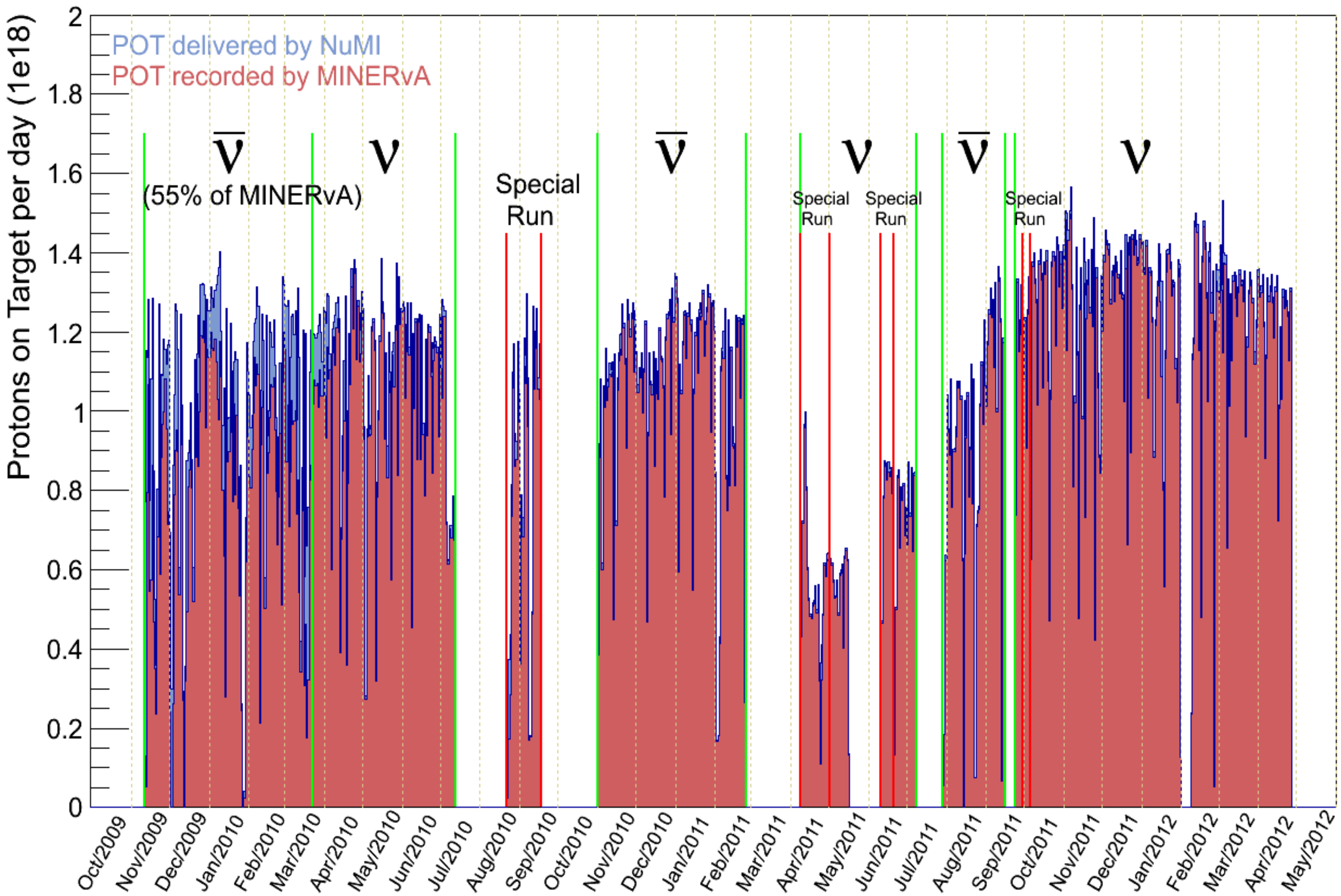
The NuMI Beamline





- MINERvA's neutrinos are produced by the NuMI beamline.
- Primary beam is 120 GeV protons from the Main Injector.
- Protons collide with a 2 λ graphite target. Decaying mesons produce a beam of 98% ν_μ.
- Modeling expected flux is difficult. Typical strategy is to use external data to model hadron production in target.
- Other *in situ* measurements possible from muon monitors, geometry runs and neutrino electron scattering are possible.

Low Energy Run Data Collected



- Low energy Physics run collected 3.98E20 POT of neutrinos from 03/2010 until 05/2012.
- Today's analysis uses 3.12E20 POT of neutrino data.
- Currently, have collected 5.50E20 POT of Medium Energy data (not used today)
- We extend our thanks to AD for the years of reliable beam!

Event Reconstruction

- •Motivation
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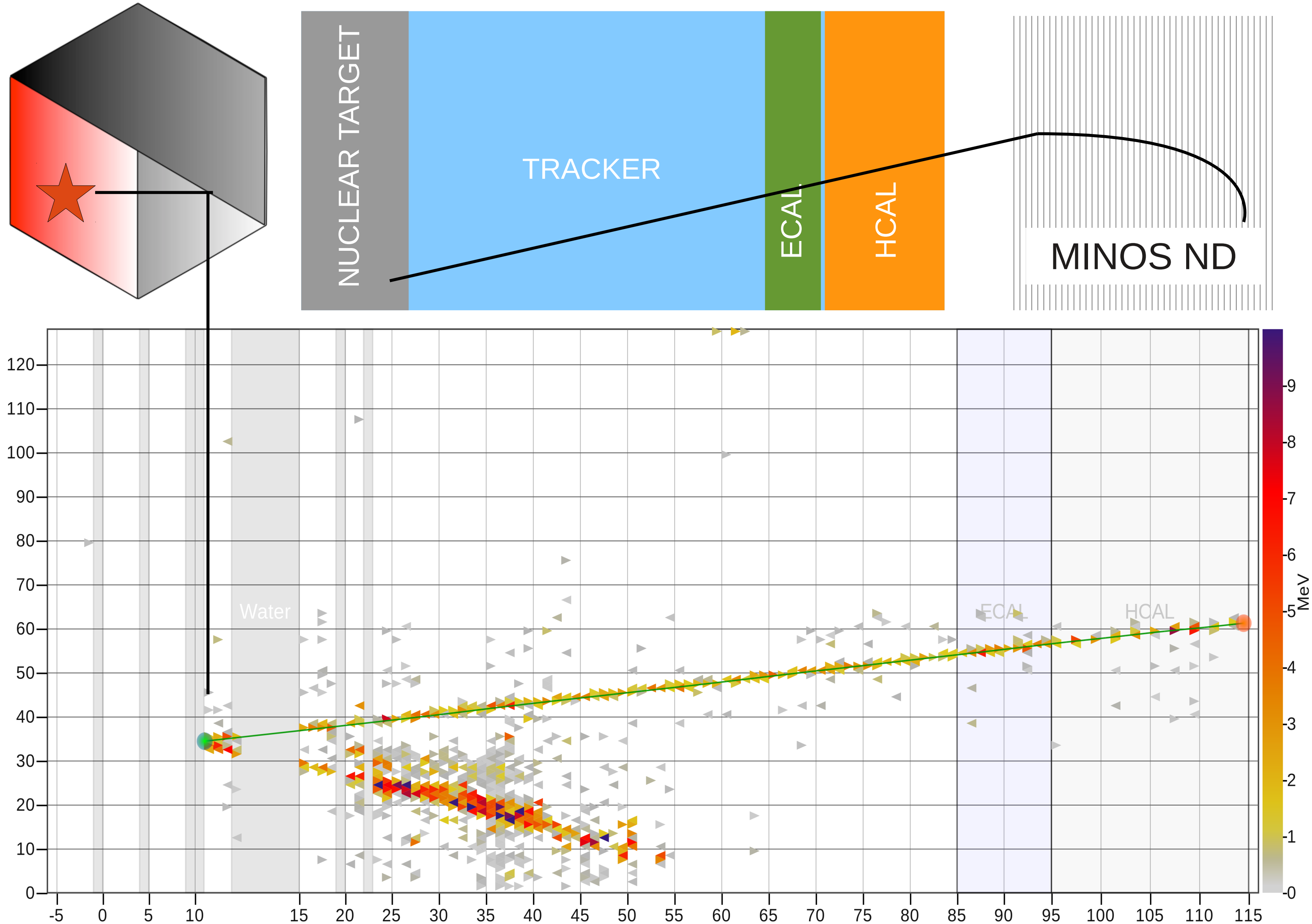
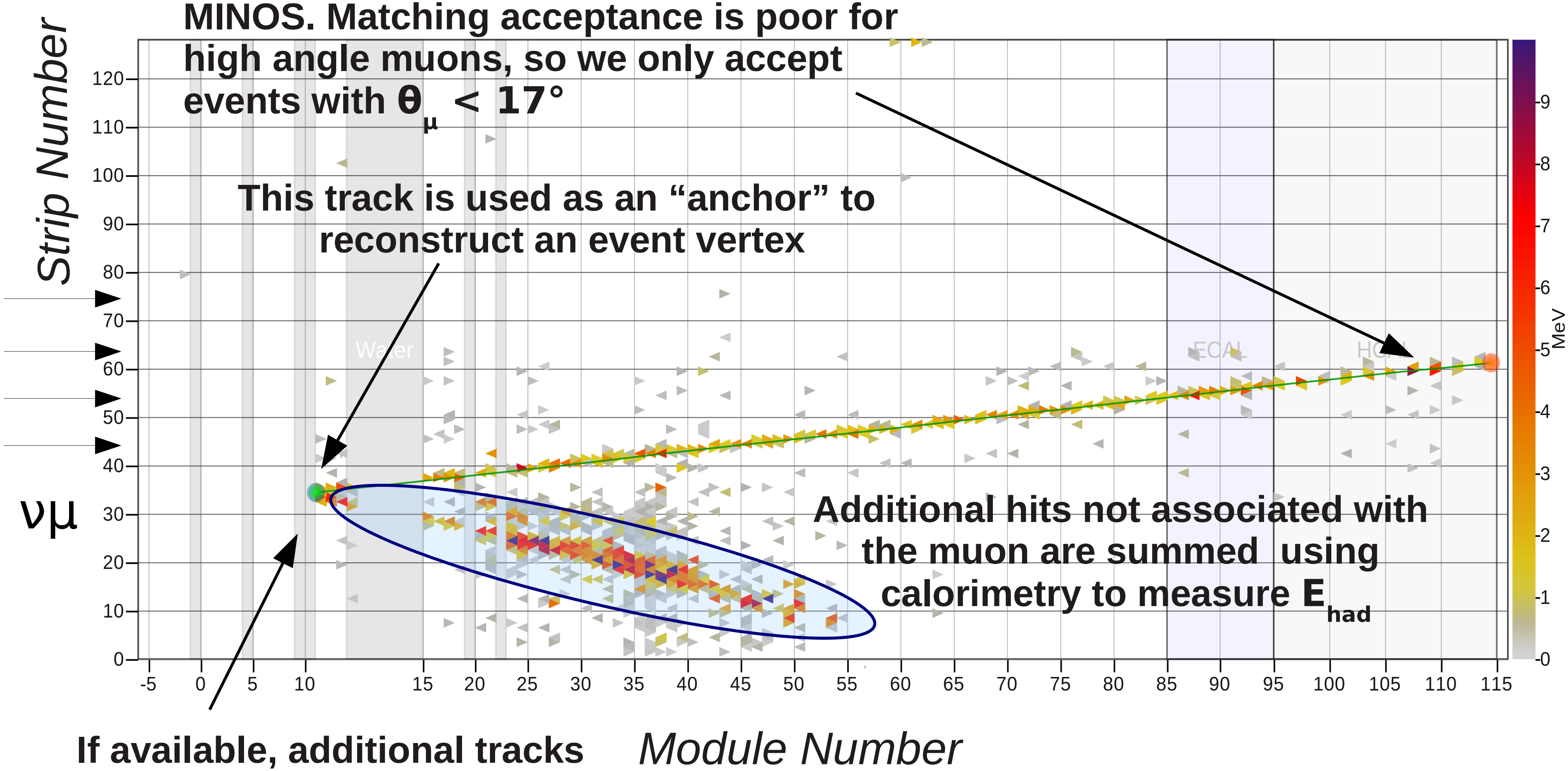
- •CCInclusive
- •CCDIS
- •Medium E
- •Conclusions



Event Selection and Reconstruction

Primary Muon track is matched to MINOS. Matching 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

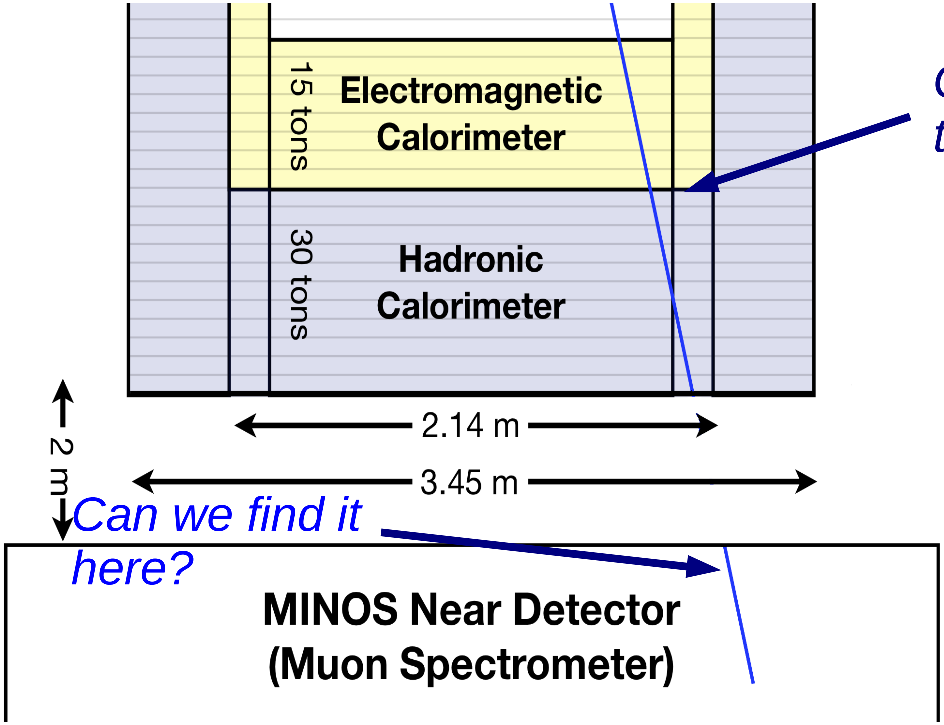


Additional hits not associated with the muon are summed using calorimetry to measure E_{had}

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

MINOS Reconstruction

- High energy muons in MINOS will not range out in the near detector
- Muons must be reconstructed by curvature in the B field of MINOS.
- Curvature algorithms break down as the particle approaches the MINOS magnetic coil, or exit from the sides of MINOS.
- High energy MINERvA analyses are statistics limited; we cannot afford to be as conservative with coil radius cuts compared to MINOS.



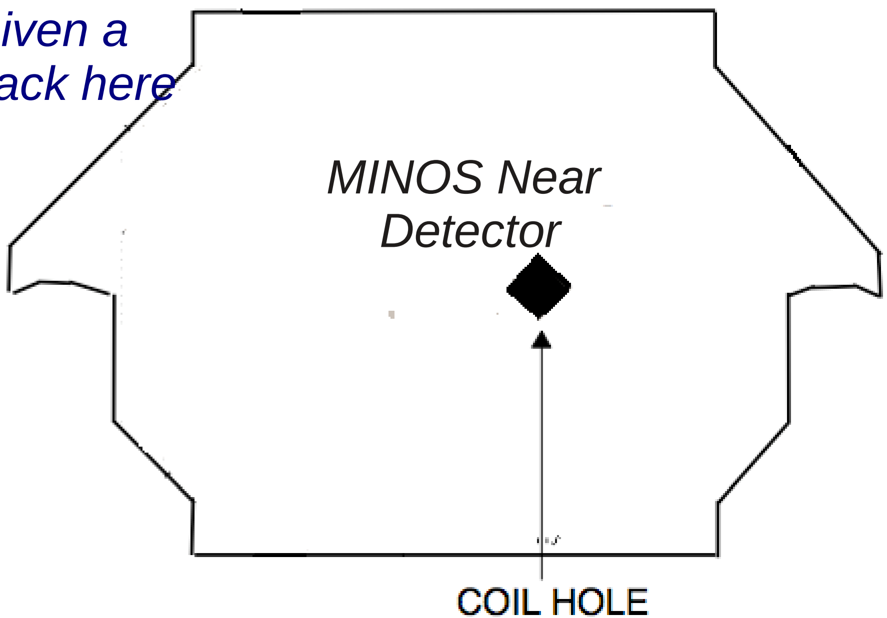
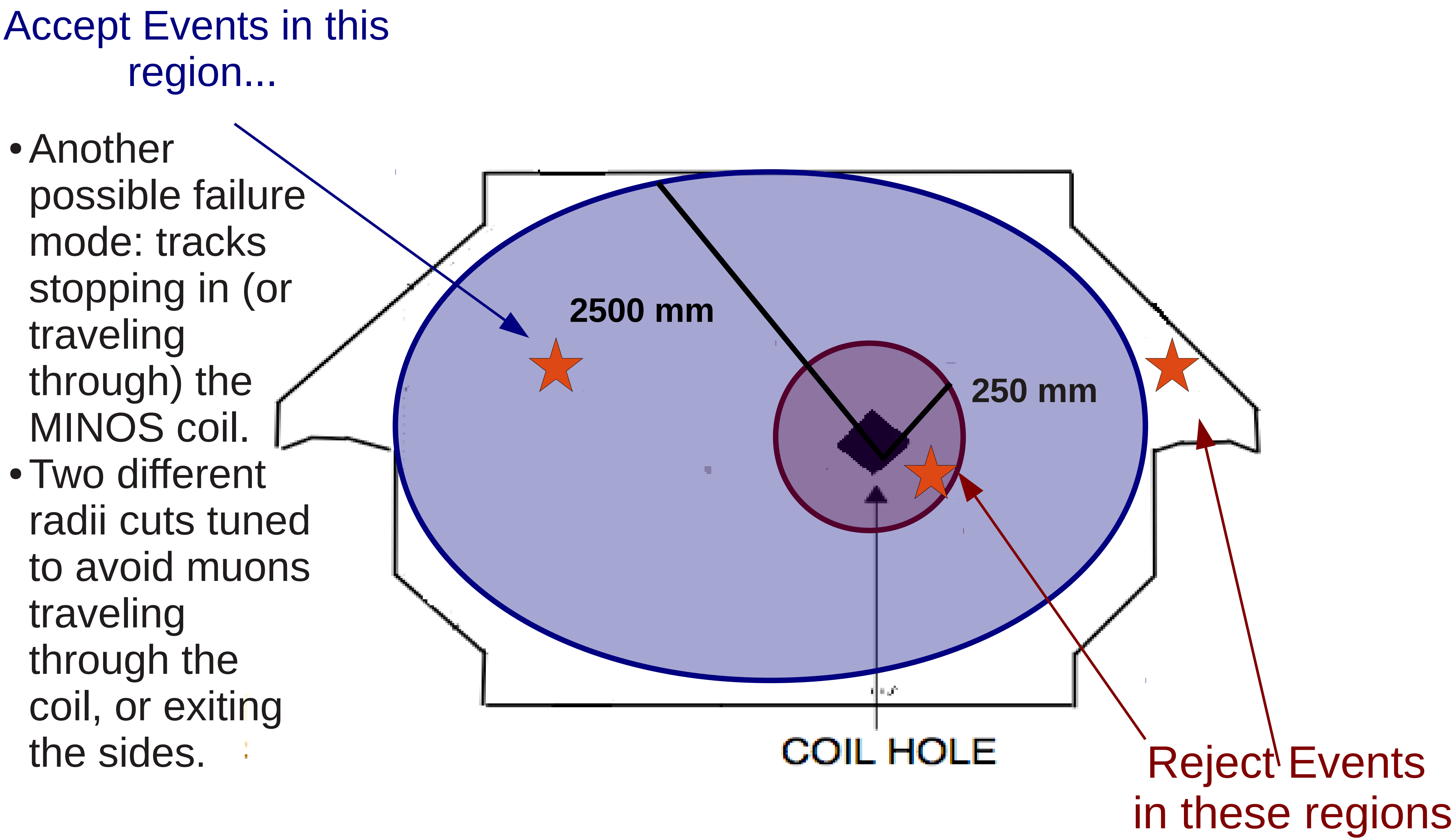


Figure adapted from P. Adamson et. al. Phys.Rev. D91 (2015) 012005

MINOS Coil Cuts

- Another possible failure mode: tracks stopping in (or traveling through) the MINOS coil.
- Two different radii cuts tuned to avoid muons traveling through the coil, or exiting the sides.



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).

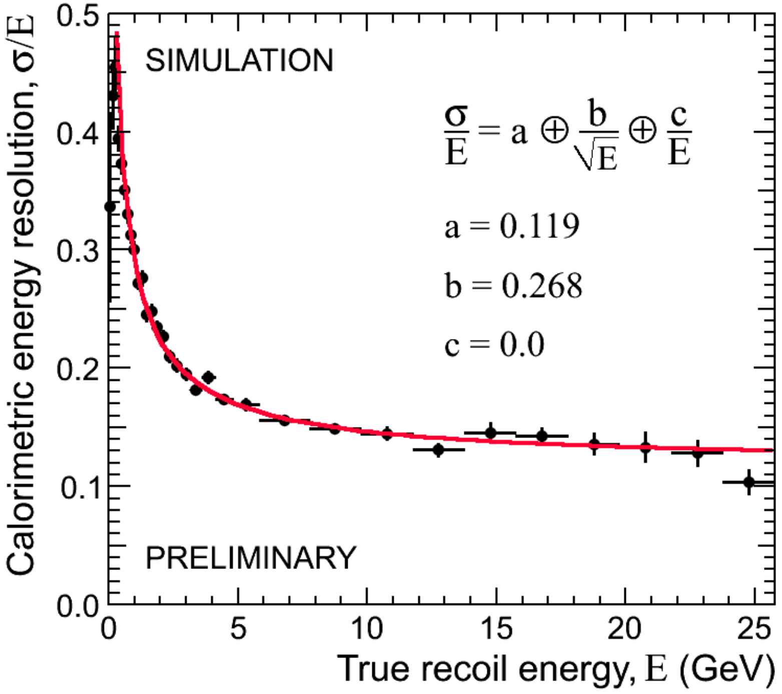
Energy lost by a minimum ionizing particle in each material

Material	CH	C	Fe	Pb
dE/dx (MeV/g/cm2)	1.96	1.74	1.45	1.12

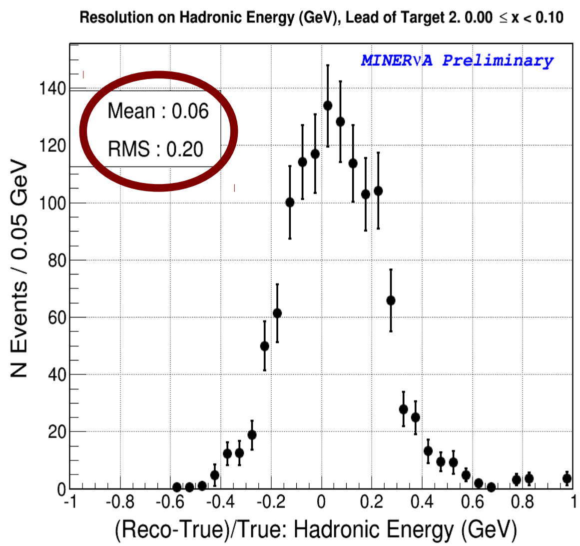
Overall scale factor (α) computed from simulation

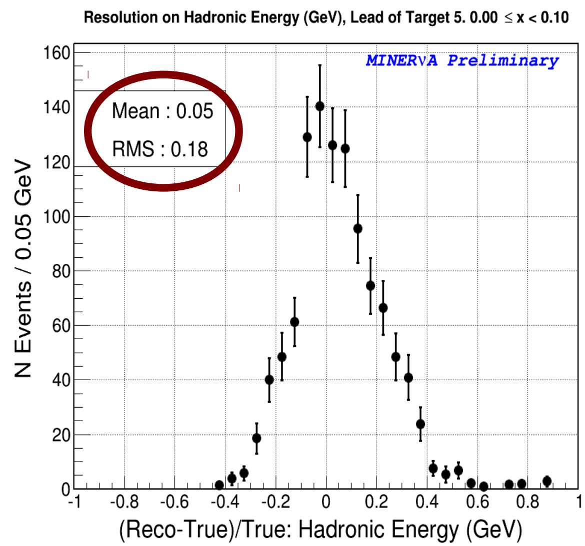
vertex	Tgt 2	Tgt 3	Tgt 4	Tgt 5	Trk
α	1.81	1.71	1.60	1.59	1.62

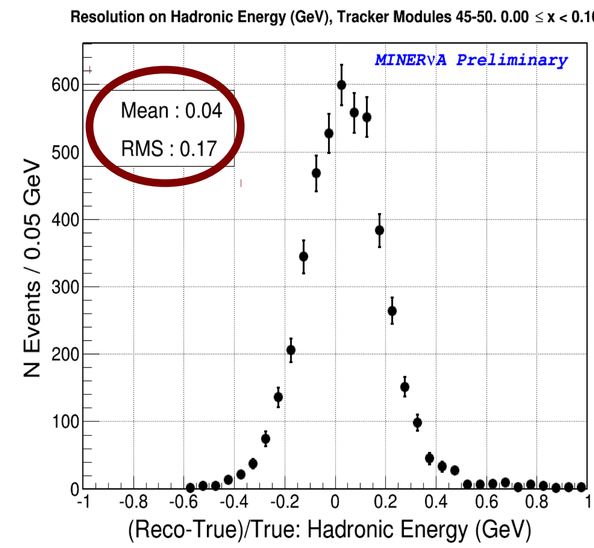
Recoil energy resolution in scintillator



Hadronic Energy Resolution





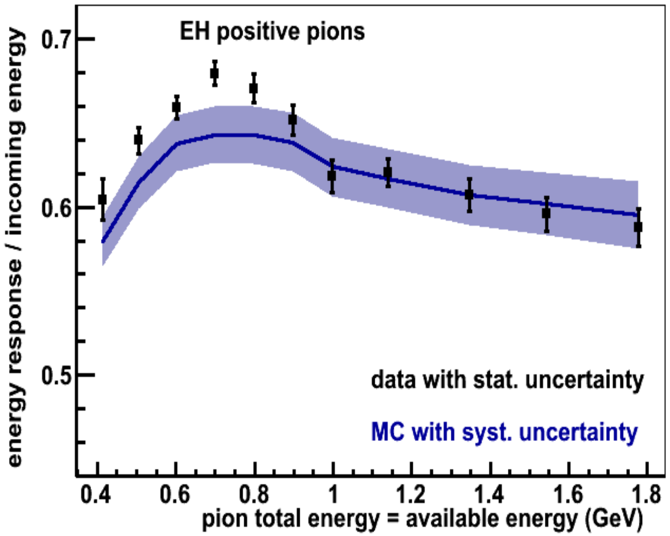


Downstream

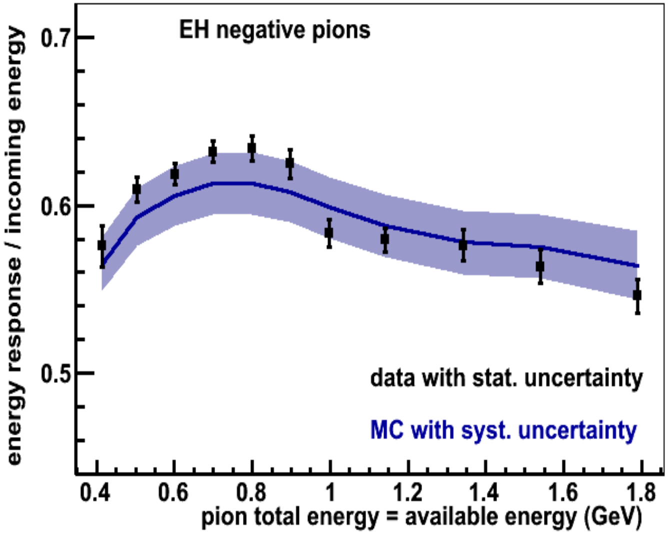
- Our event selection and ability to reconstruct x accurately is highly dependent on our hadronic energy reconstruction.
- Accuracy of high-energy, low x hadronic showers is very similar between nuclear targets and tracker modules.
- Our simulation adequately accounts for the different geometry encountered by hadronic showers, regardless of where they originate.

Test Beam

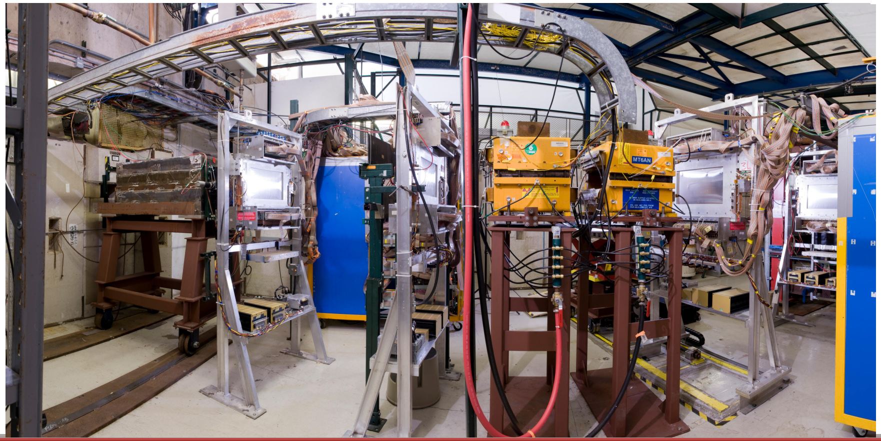
- The MINERvA detector's hadronic energy response is measured using a dedicated test beam experiment at the Fermilab Test Beam Facility (FTFB)
- Custom built beamline collected data during the summer of 2010.
- In addition to a Birk's Law calculation, hadronic energy reconstruction uncertainty is estimated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



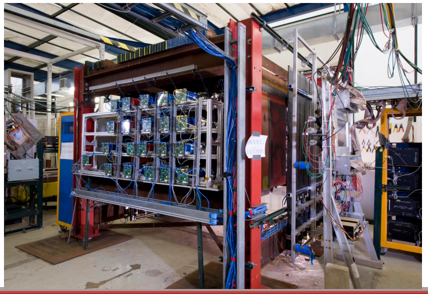
Aliaga L. et. Al. Nucl.Instrum.Meth. A789 (2015) 28- 42



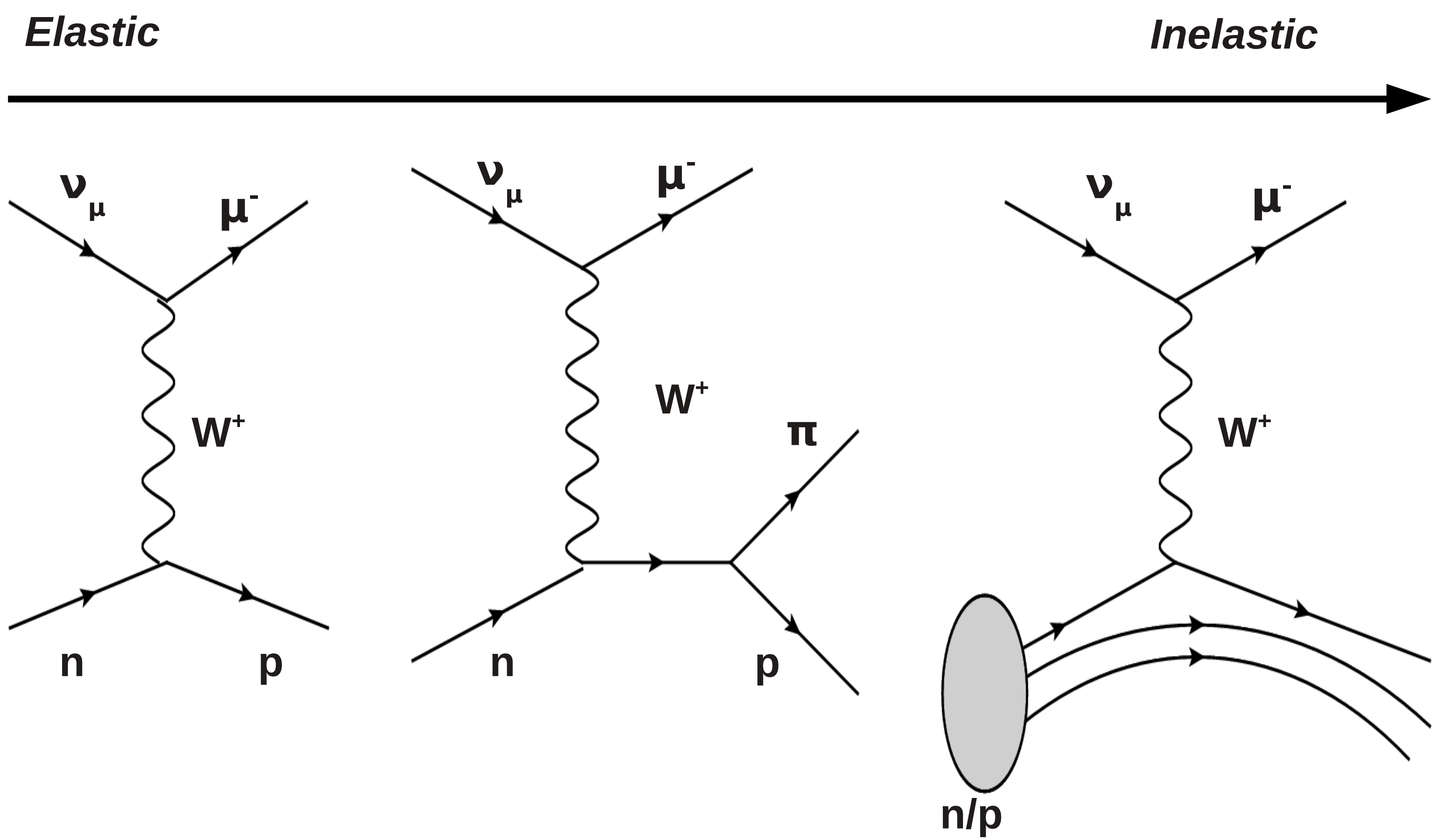
Custom built beamline



Plus miniature detector



Charged Current Inclusive Review



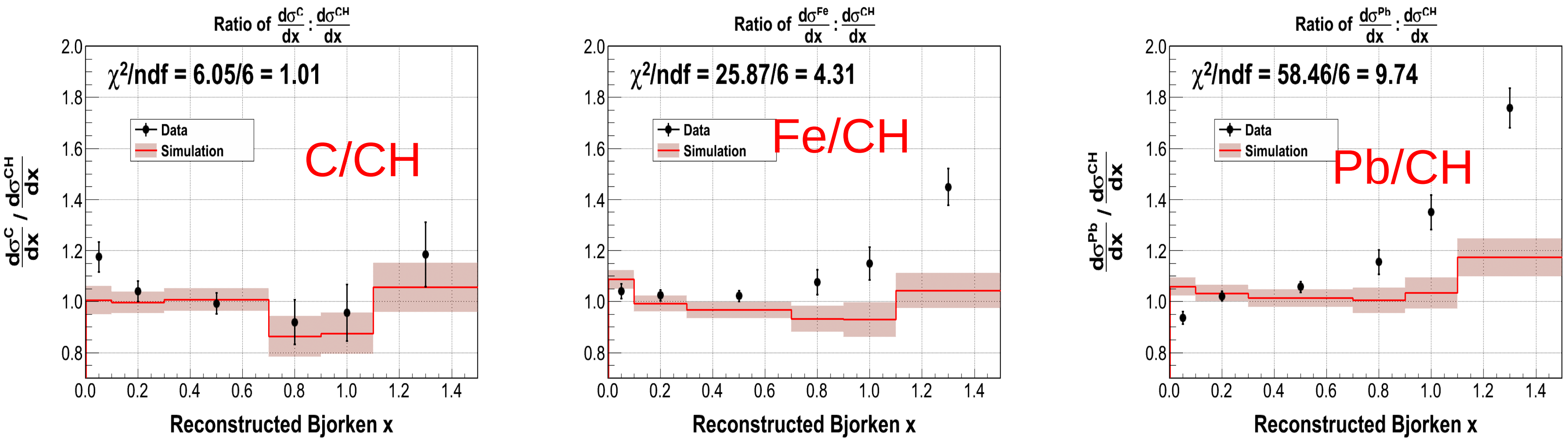
Isoscalarity

- 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.

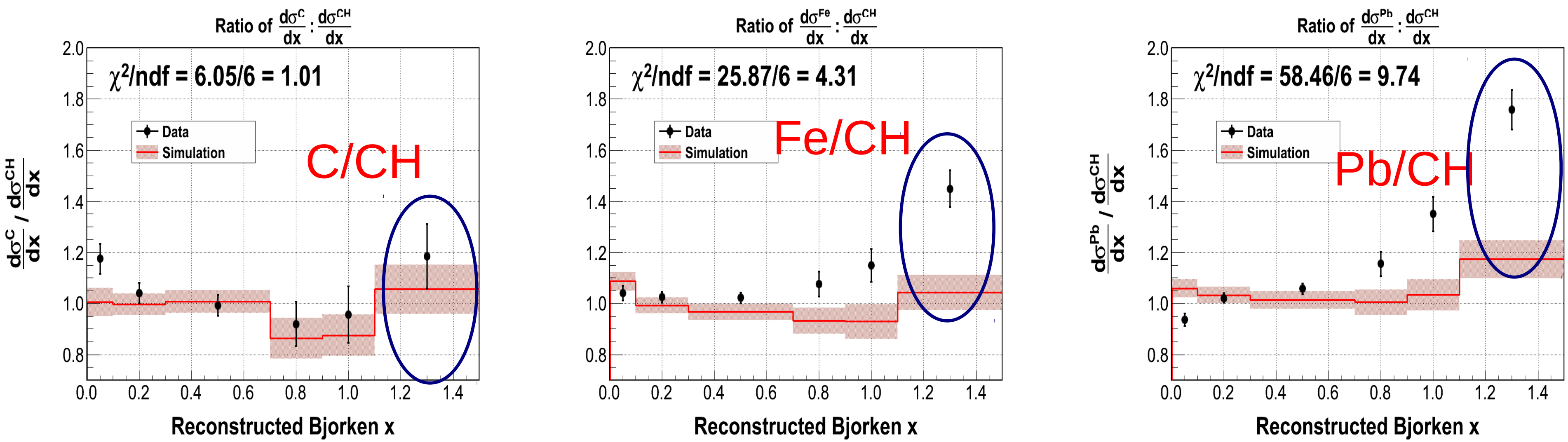
Inclusive Ratios: dσ /dx



- Data are presented in reconstructed x: we do not correct for detector smearing.
- Our neutrino interaction simulation is GENIE version 2.6.2 (*C.Andreopoulos et al., Nucl.Instrum.Meth.A614:87-104,2010.*)
- GENIE assumes an x dependent nuclear effect from charged lepton scattering, applies the same to each nuclei (C, Fe, and Pb).
- In this case, we observe an *excess* in the data at large x, and a *deficit* at low x, both of which grow with the size of the nucleus.

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

Inclusive Ratios: dσ /dx

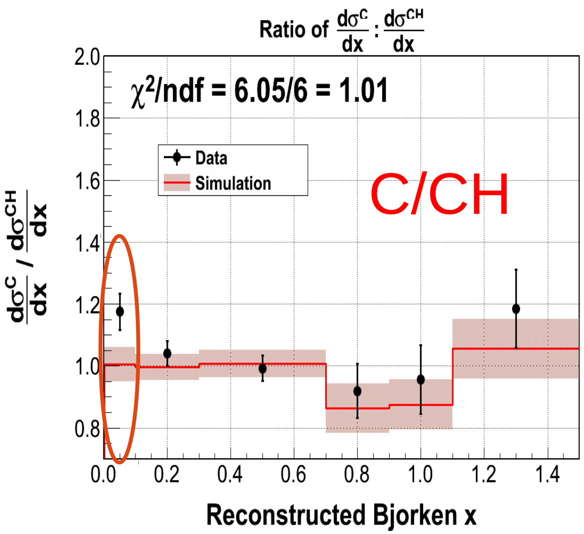


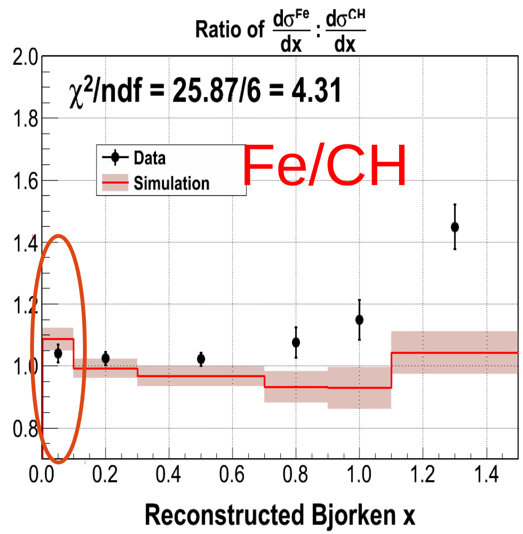
x_{bj}	QE	DIS	OTHER
0.0 – 0.1	11.3%	5.9%	77.4%
0.1 – 0.3	13.6%	16.7%	68.5%
0.3 – 0.7	32.7%	11.8%	55.3%
0.7 – 0.9	55.1%	4.3%	40.5%
0.9 – 1.1	62.7%	2.8%	34.4%
1.1 – 1.5	69.9%	1.9%	28.4%
> 1.5	79.1%	0.6%	20.2%

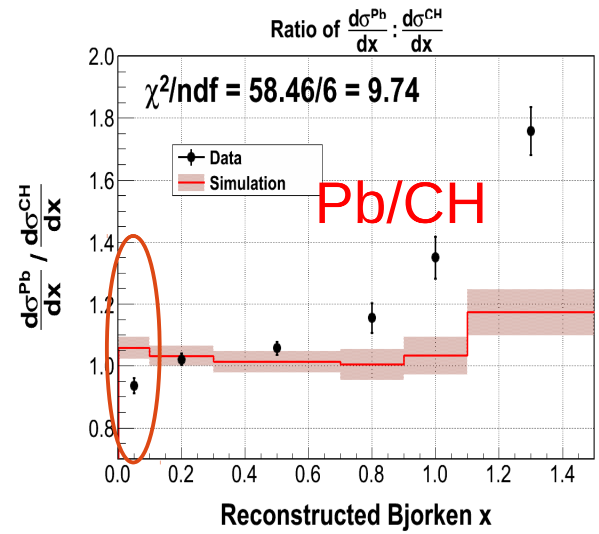
- At large x (x >0.7) we observe an excess in the data which grows with the size of the nucleus.
- These events are a mixture of CCQE and other events (see table).
- This makes interpreting this result difficult, since the physics between the CCQE and resonant events is different.

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

Inclusive Ratios: dσ /dx







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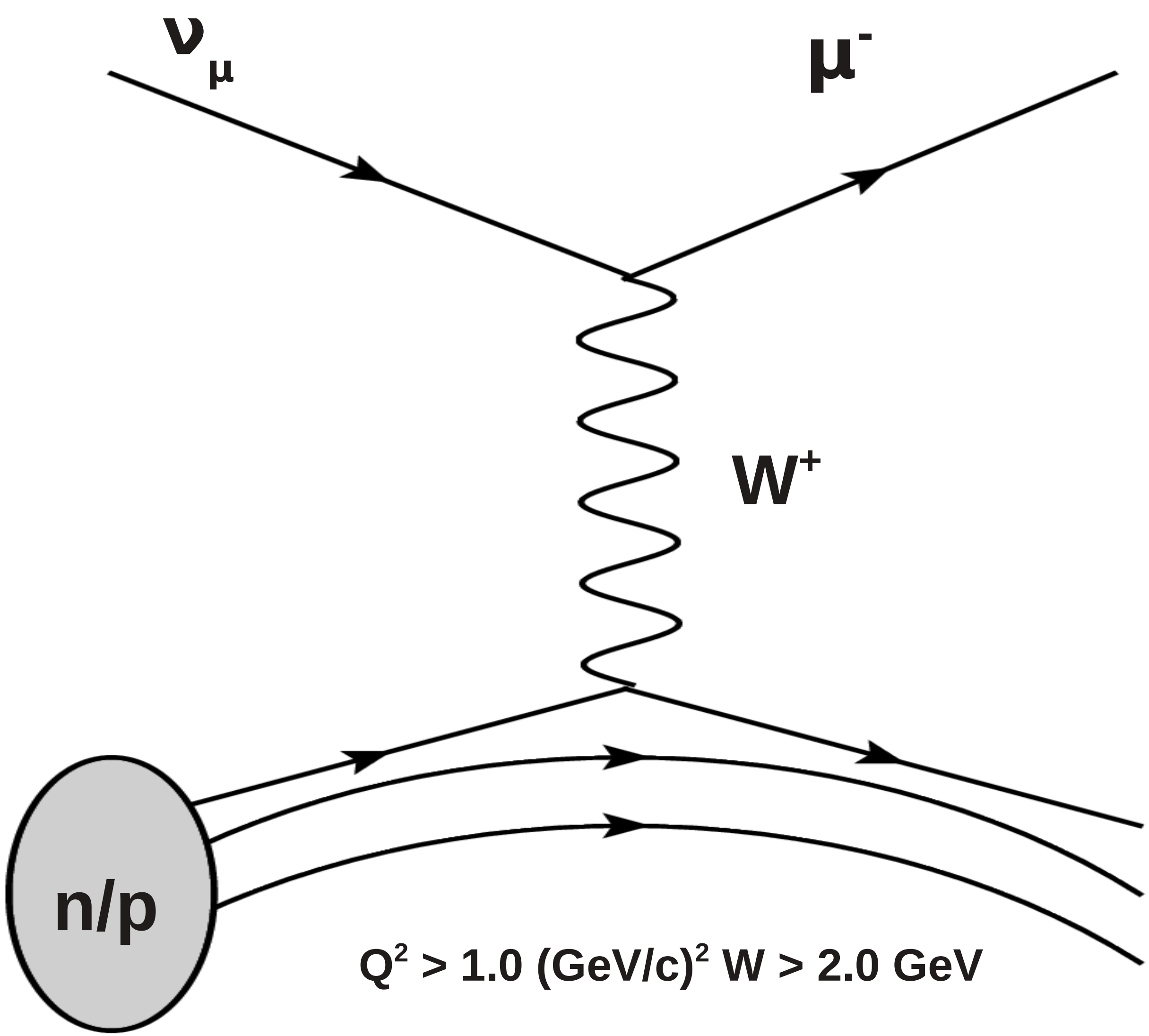
1.1 – 1.5	69.9%	1.9%	28.4%
> 1.5	79.1%	0.6%	20.2%

- At low x (x < 0.1) we observe a deficit in the data which grows with the size of the nucleus.
- This could possibly be additional nuclear shadowing in neutrino scattering.
- We can study shadowing more directly with DIS.

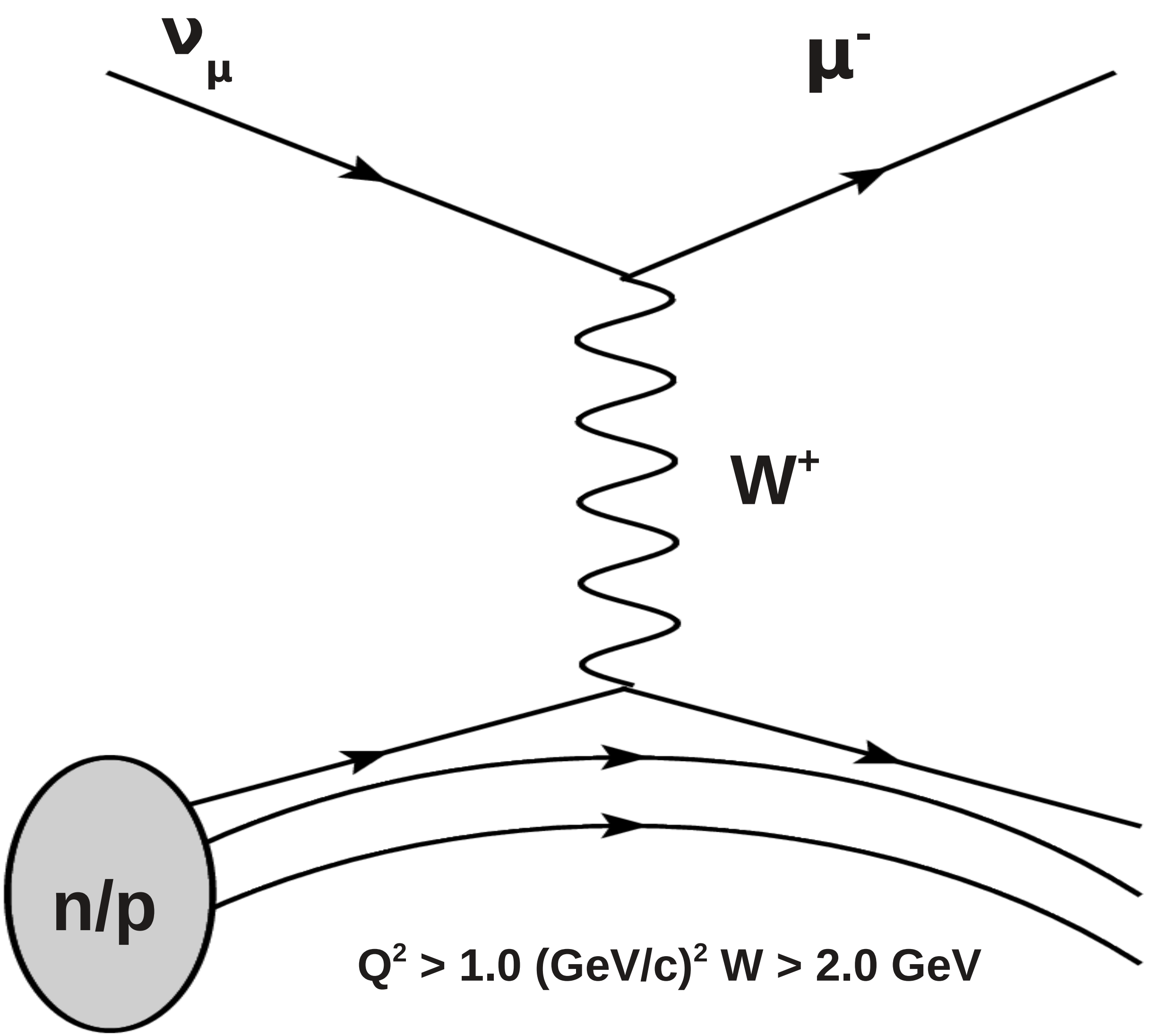
Tice, Datta, Mousseau et. al,
Phys. Rev. Lett. 112, 231801 (2014).

Charged Current DIS Analysis



$Q^2 > 1.0\ (GeV/c)^2$ $W > 2.0$ GeV

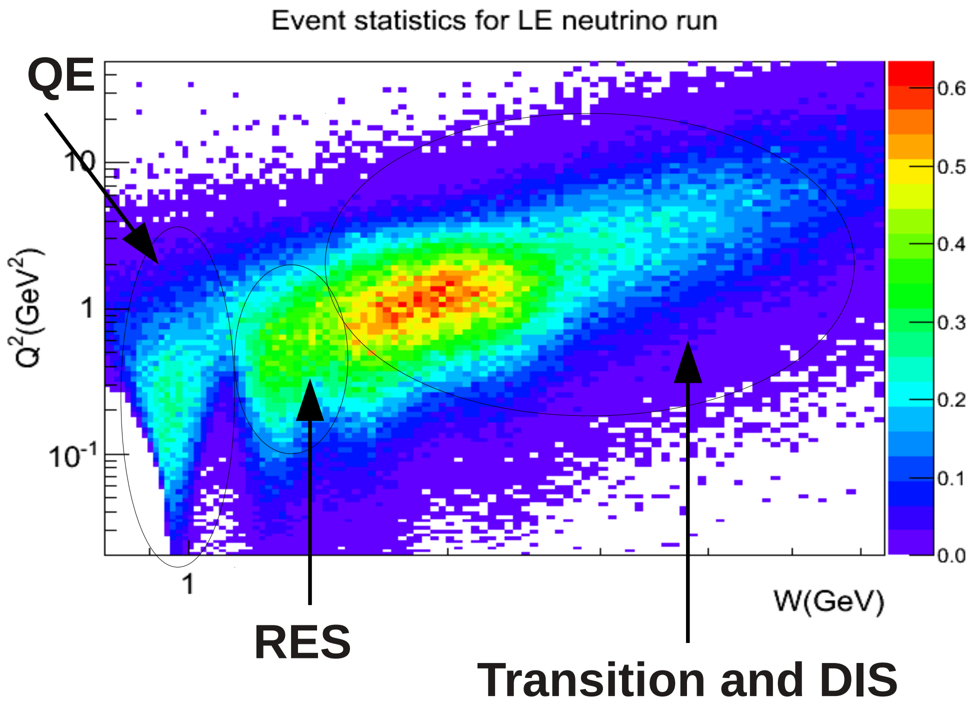
Charged Current DIS Analysis

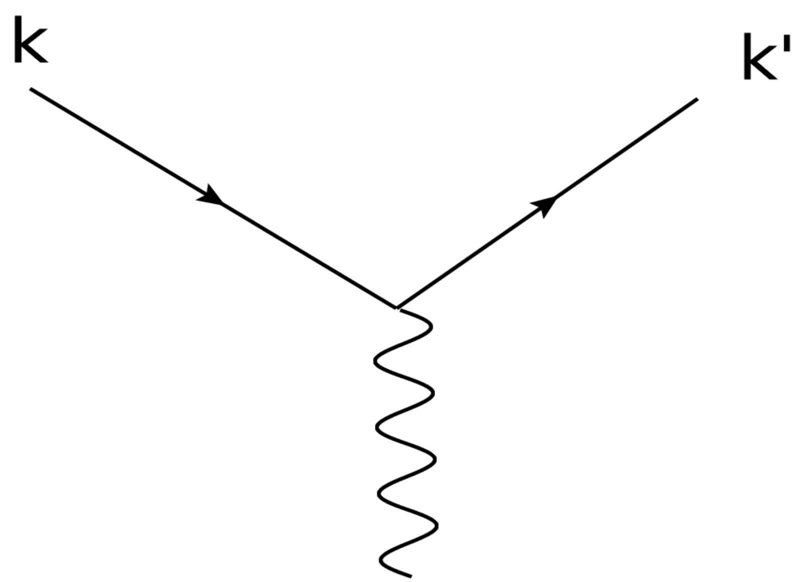


$Q^2 > 1.0\ (GeV/c)^2$ $W > 2.0$ GeV

How Deep is Your Scattering?

- The resolution of how fine you can resolve distances proportional to the *momentum transferred* between your probe and target (Heisenberg).
- The Mandelstam invariant Q^2 measures momentum transfer: $Q^2 = |k - k'|^2$.
- We consider $Q^2 > 1.0\ (\text{GeV}/c)^2$ to be enough momentum transfer to resolve the quark structure of the nucleons.

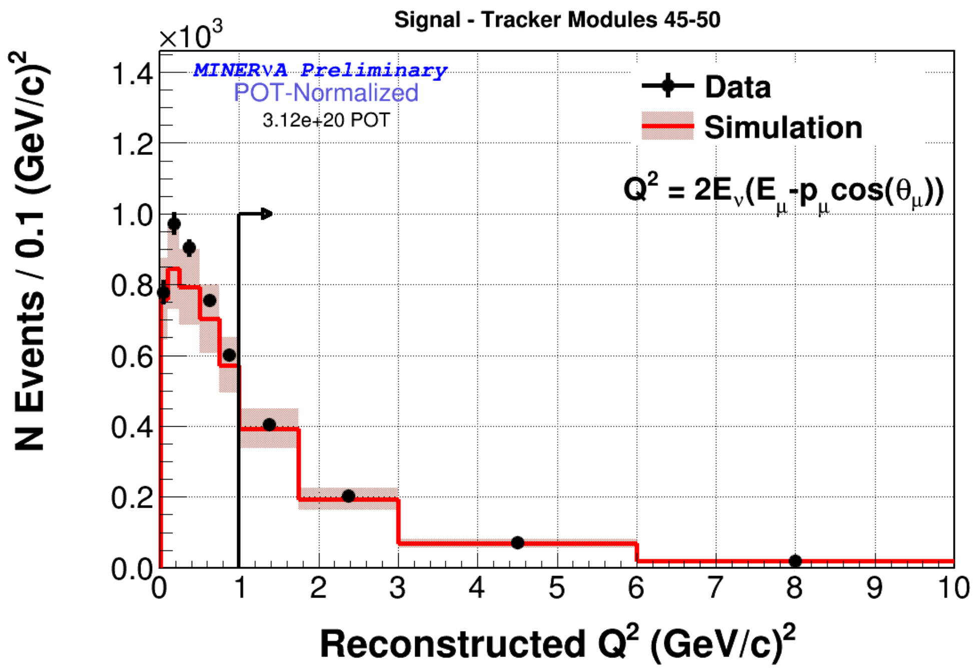


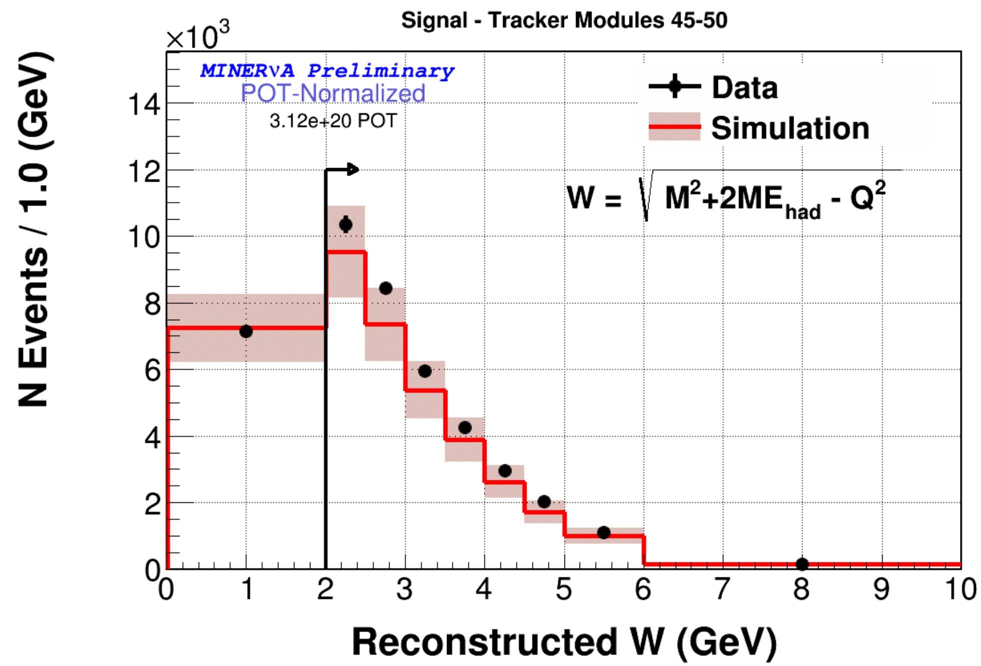


- W > 2.0 (GeV/c) safely avoids the majority of resonances, and gives us confidence the hadronic shower is from deep inelastic scattering off of a parton.

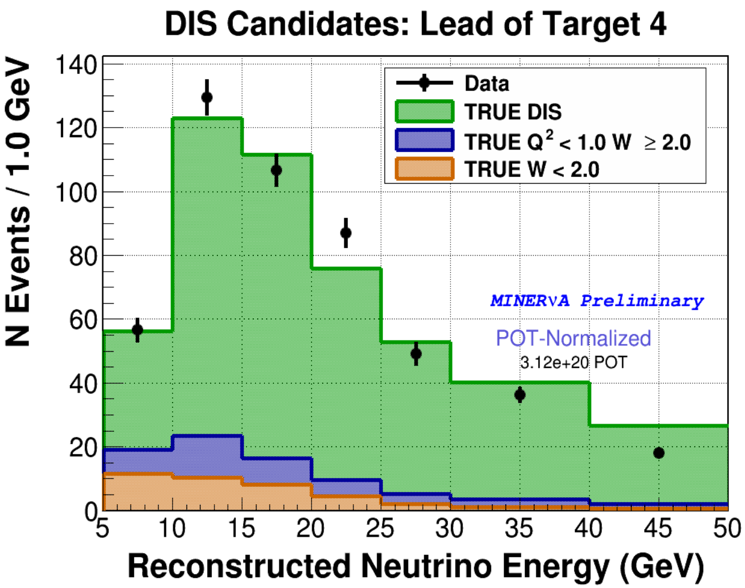
From Inclusive to DIS

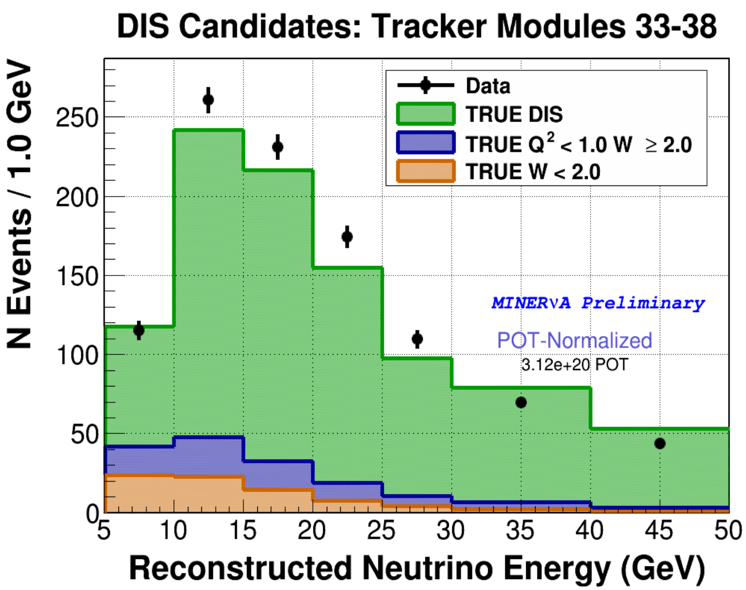
- We isolate a deeply inelastic sample from the inclusive sample by making cuts on the four momentum transfer (Q^2) and final state invariant mass (W)
- Require $Q^2 > 1.0$ (GeV / c)^2 and W > 2.0 GeV / c. These cuts remove the quasi-elastic and resonant events from the inclusive sample, and allow us 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):





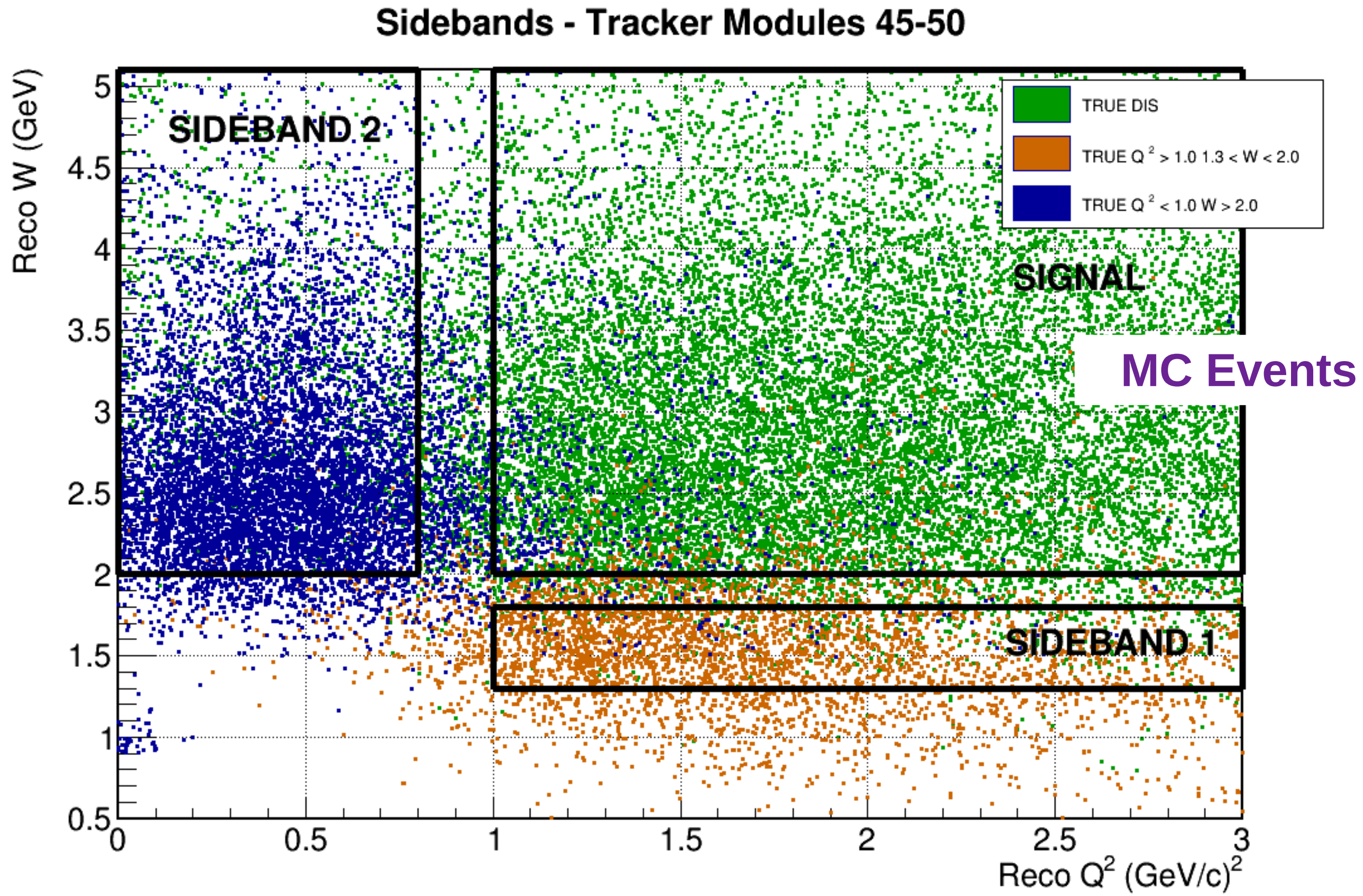
- After making kinematic cuts on Q^2 and W, we are left with a background of events with *true* $Q^2 < 1.0$ (GeV/c)^2 and W < 2.0 (GeV/c) that migrate into the sample.

- Estimate this background in the nuclear targets and scintillator using MC.

- 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).



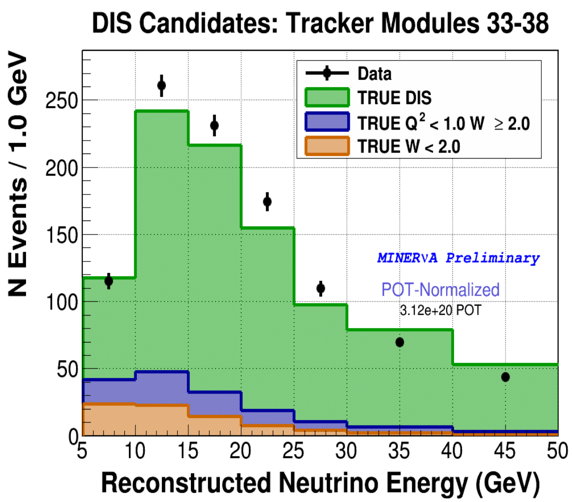
- Each sideband is tuned to limit the amount of signal in each band (green points).
- Sidebands are identical in each target.

Fitting Sidebands

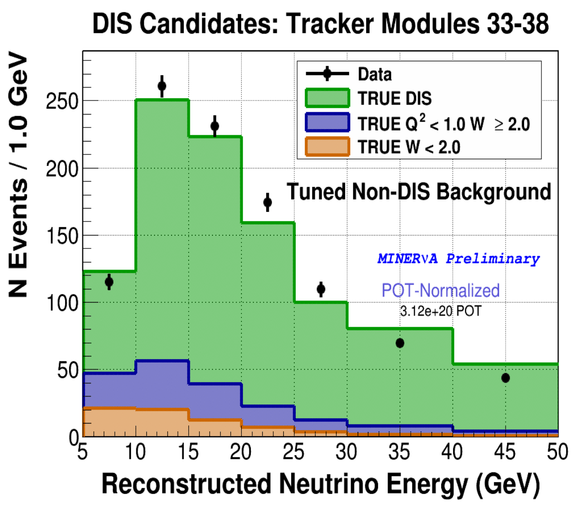
Scale factors applied to simulation (statistical error only)

A	Q2 > 1.0 1.3 < W < 2.0	Q2 < 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.

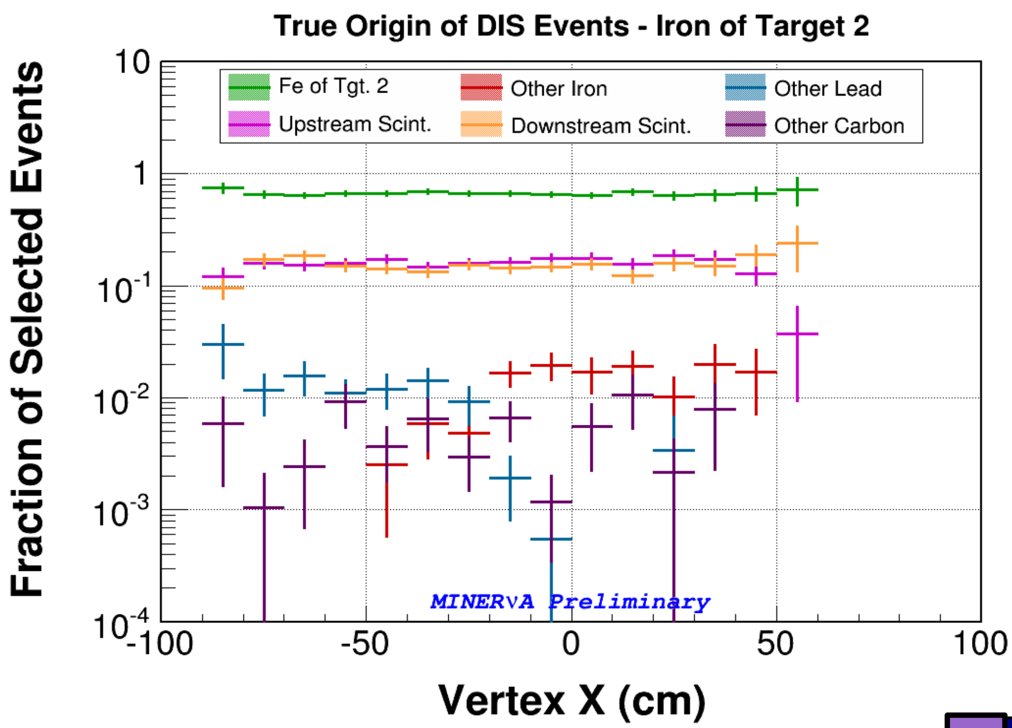


Before Fitting

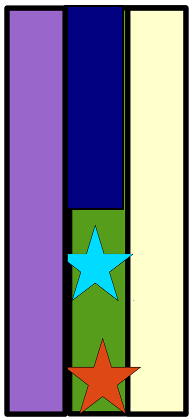


After Fitting

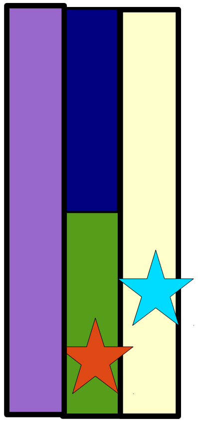
Background Events (Wrong Nuclei)



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

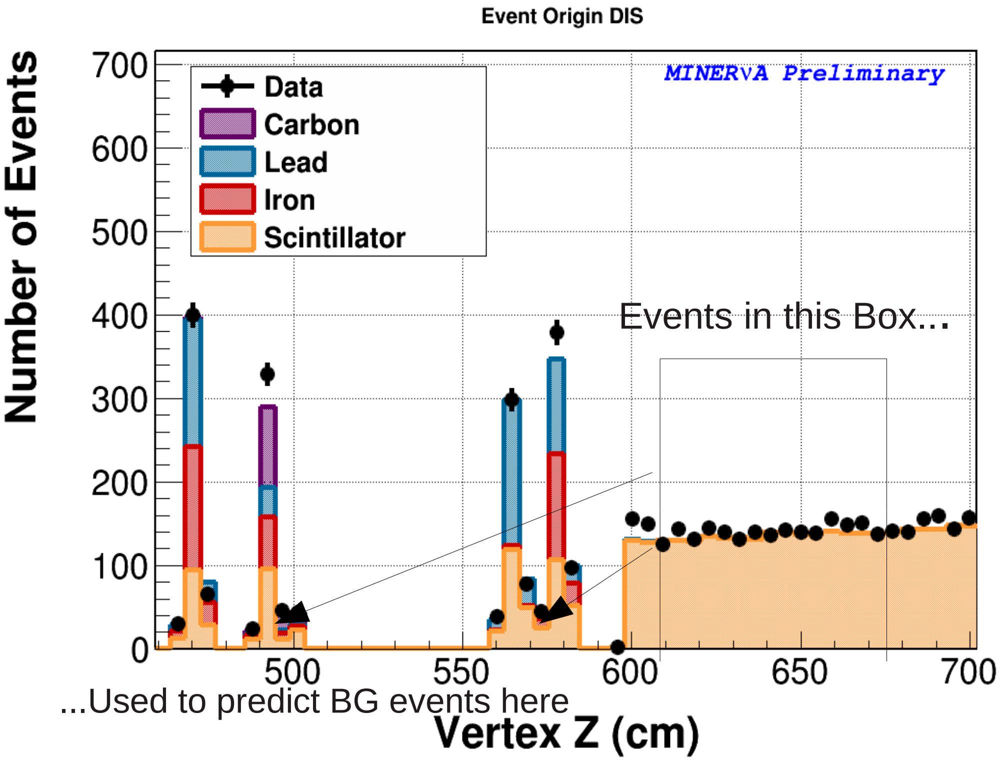


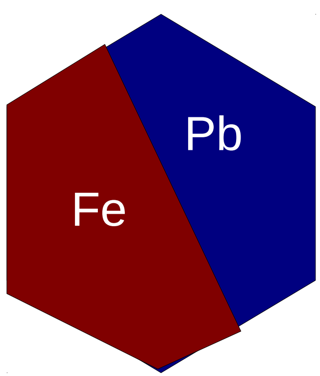
True vertex (blue star) is in the same material as the reconstructed vertex (orange star).

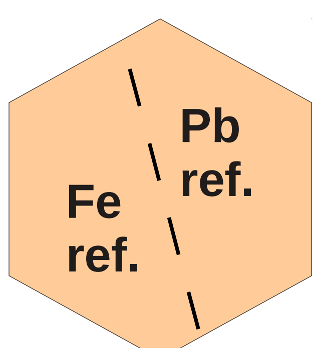


Vertex is reconstructed in the Fe (green). However, the true vertex of the event is in the scintillator (yellow).

Background Subtraction (Wrong Nuclei)

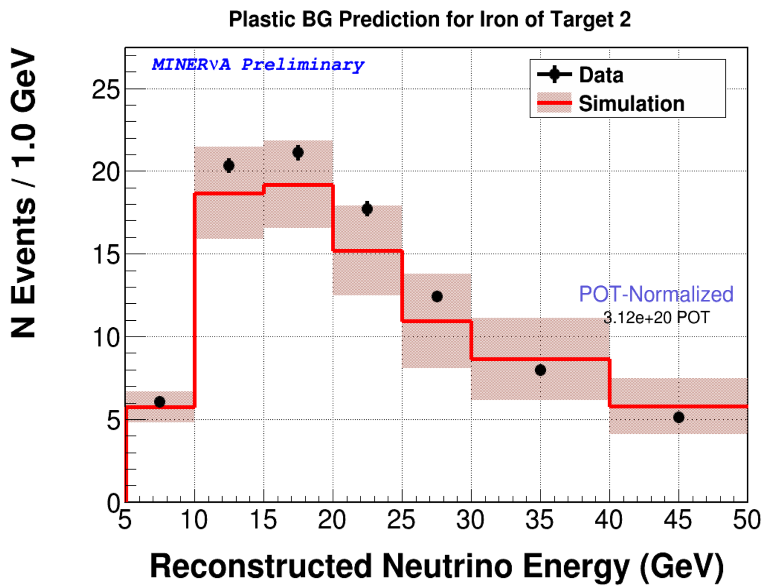




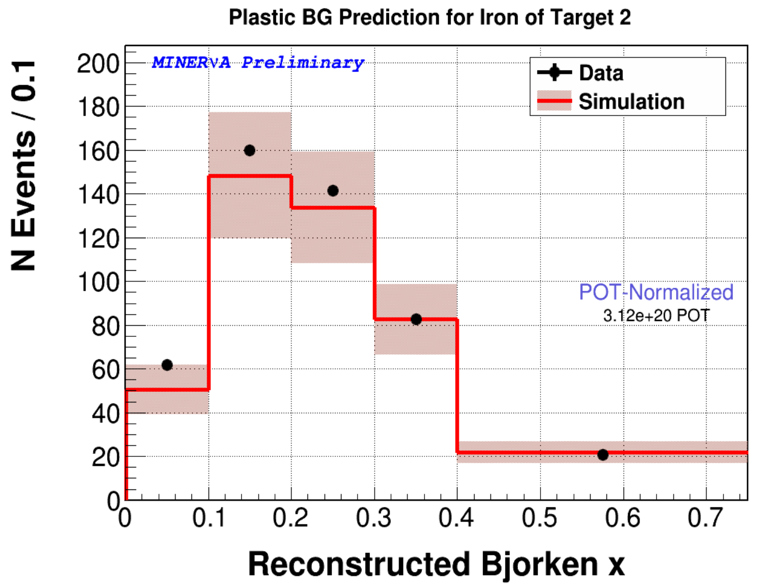


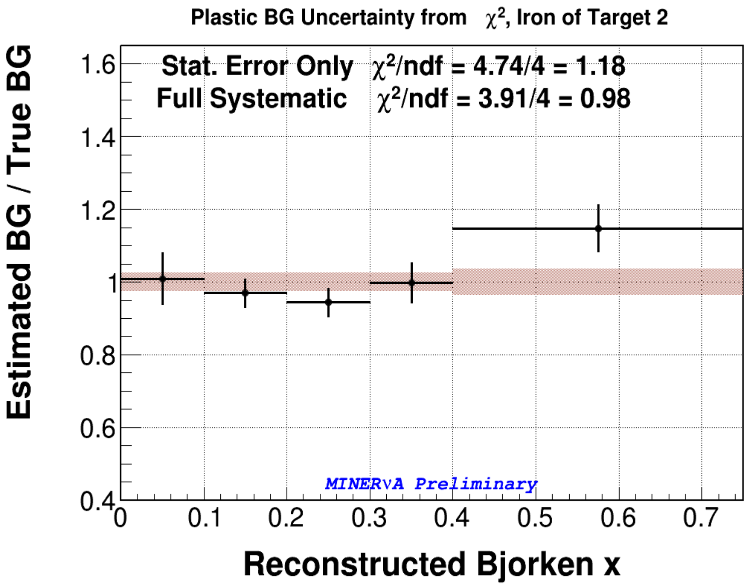
- We subtract this background by measuring the event rates in the downstream tracker, and extrapolating these events upstream to the nuclear target region.
- Downstream events are weighted for MINOS acceptance based on E_μ, θ_μ .
- Background is extracted by matching the same transverse section of the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

Wrong Nuclei BG (Data / MC)



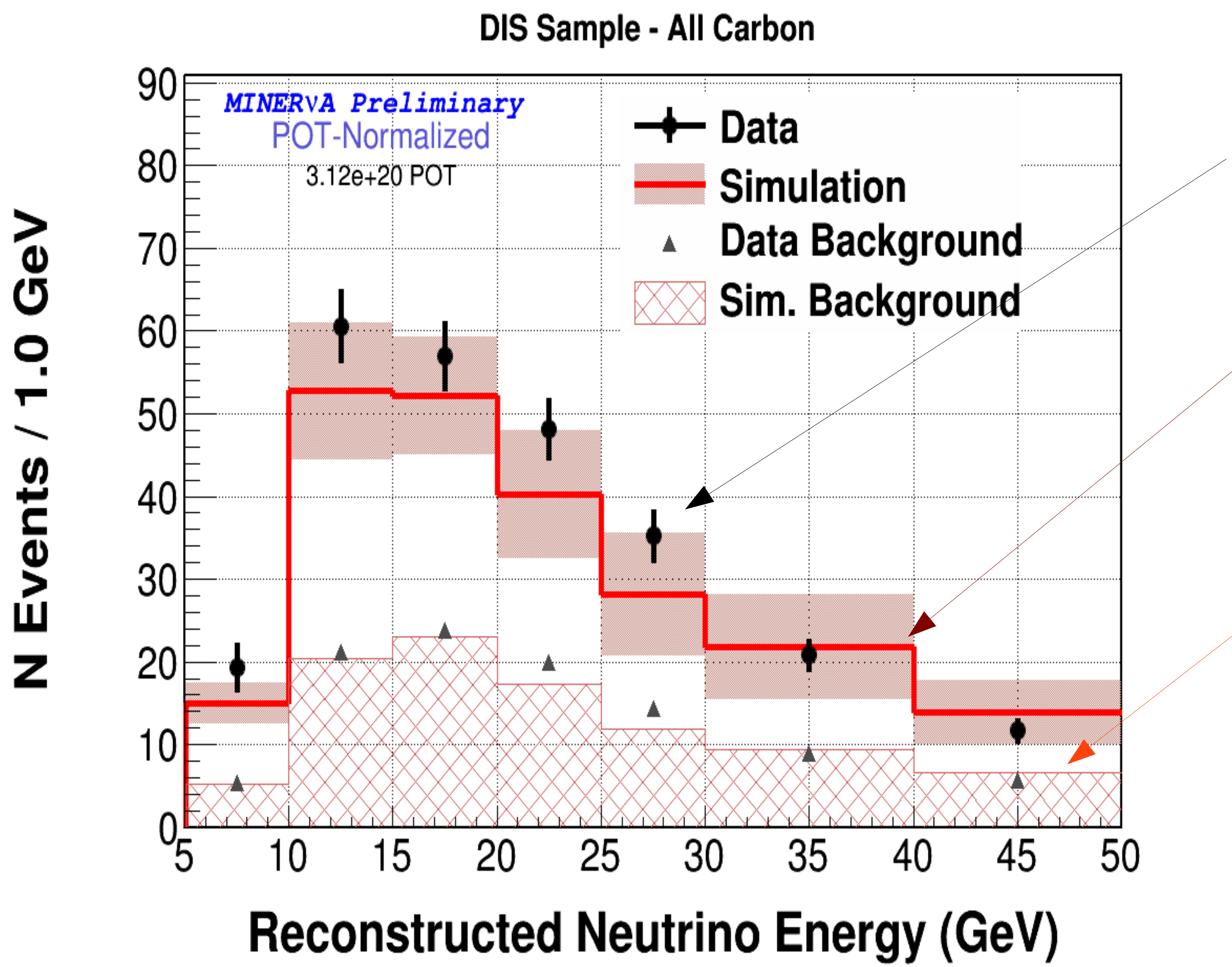
- Wrong nuclei backgrounds are extracted separately for data and MC, in each variable (E_ν, x, etc.)
- In each case, the non-DIS events have been subtracted using the procedure previously described.





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

Putting it Together



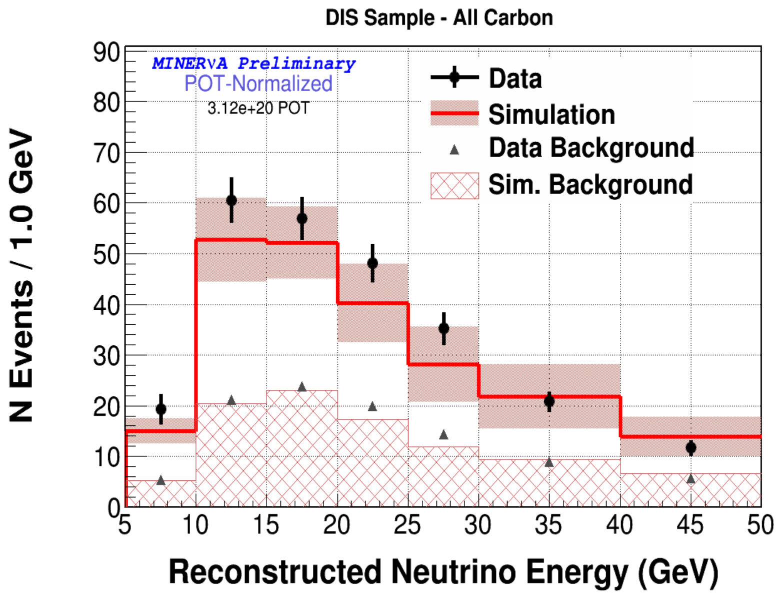
Data events reconstructed in C, with non-DIS events subtracted.

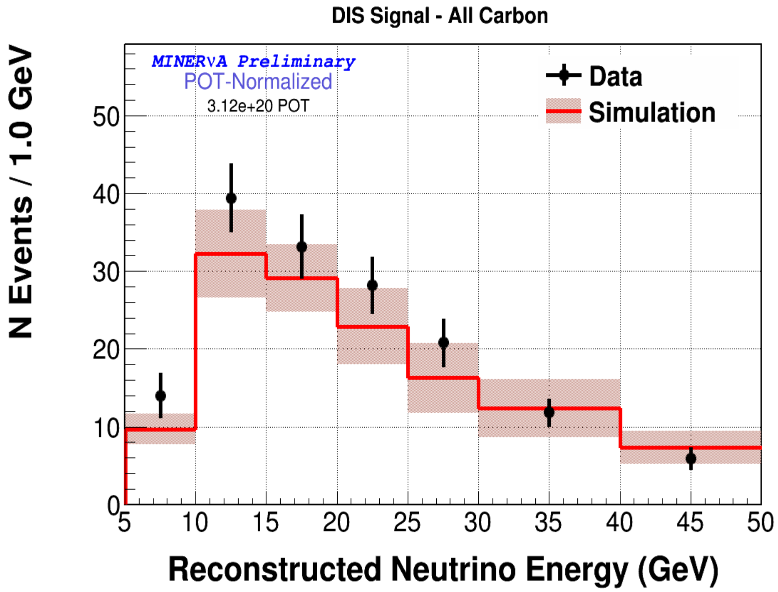
Simulated DIS events, reconstructed in C

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...



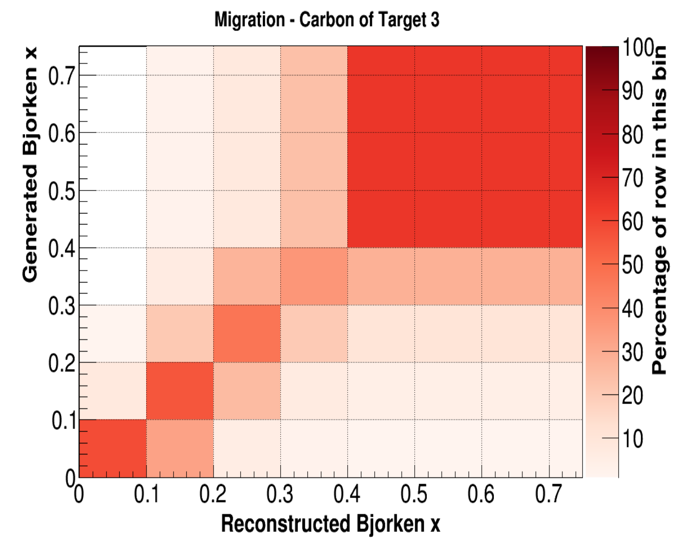


...And subtract those events to obtain a sample of DIS on carbon in data and MC. Large uncertainties in neutrino flux, measure ratios of C, Fe and Pb /CH where flux will cancel.

Migration and Unfolding

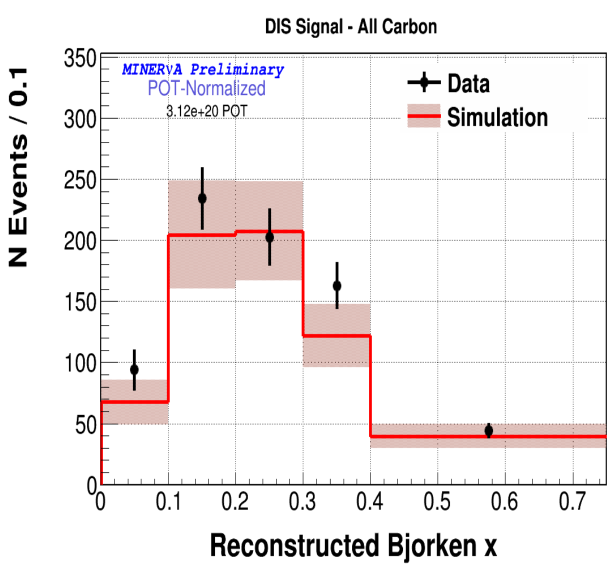
- Detector resolution smears the reconstructed values of x and E_υ from their generated quantities (right plot).

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

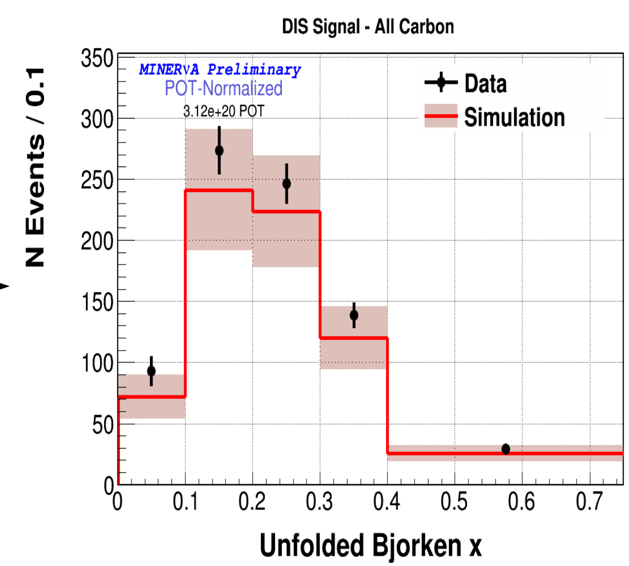


Warning! Unfolding introduces correlations between bins

Migration Matrices used as input

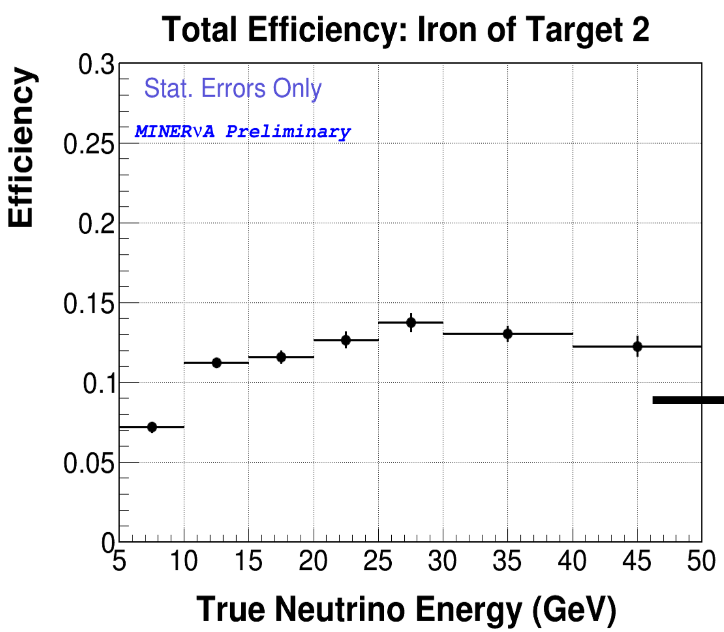


Unfold using Bayesian unfolding With 1 iteration

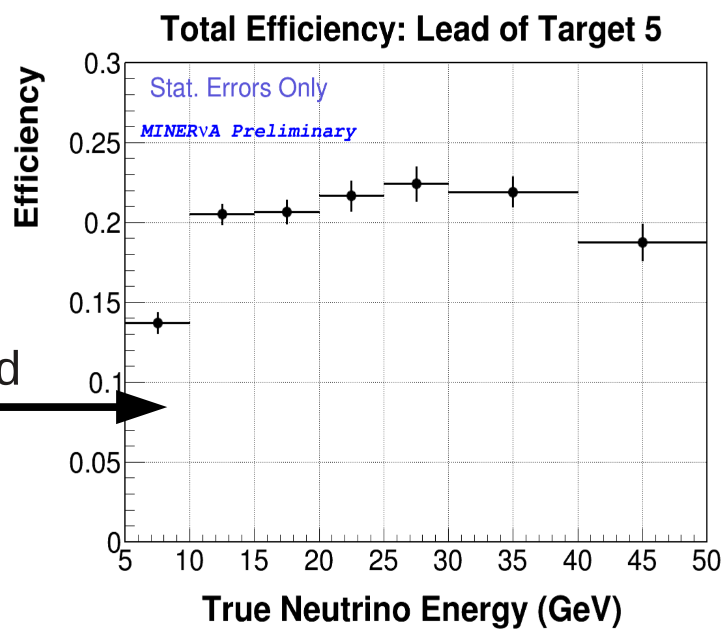


Efficiency Correction

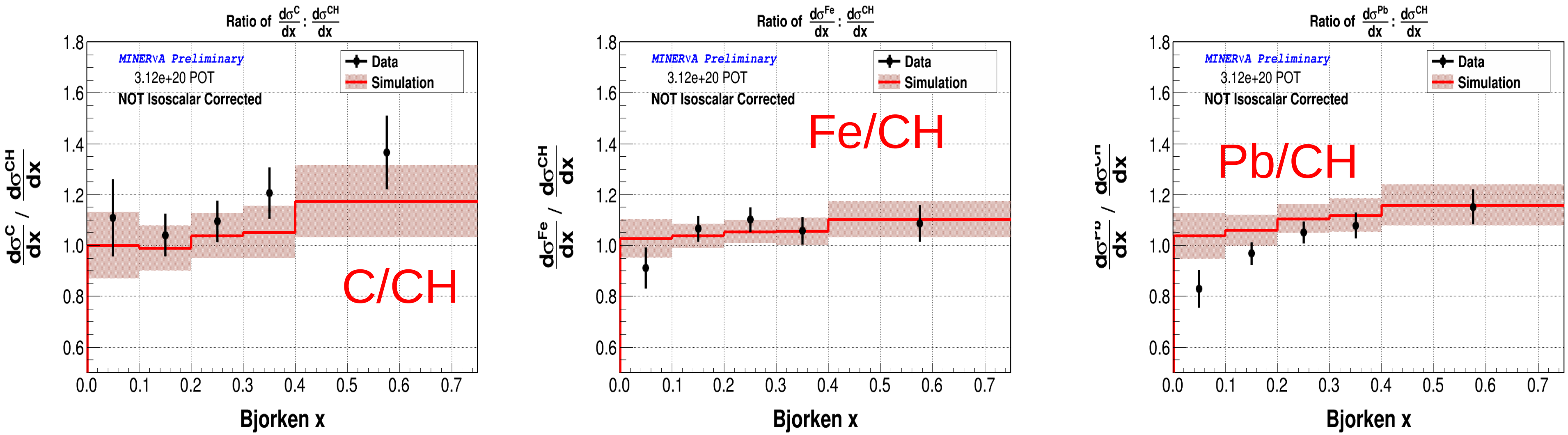
- We correct for detector acceptance, using an efficiency correction derived from the MC. However, we only correct up to E_{υ} = 50 GeV and $\theta_{\mu} < 17°$.
- Efficiency is corrected target by target, since it is a function of the distance from the target to MINOS.
- Largest source of inefficiency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



Downstream toward MINOS

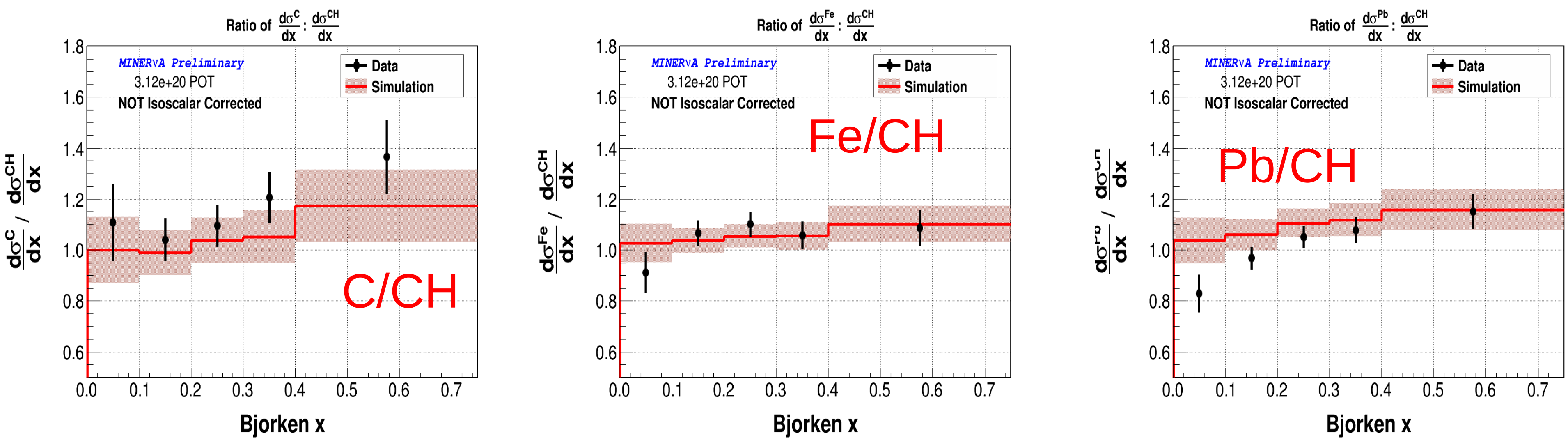


DIS Ratios: dσ /dx



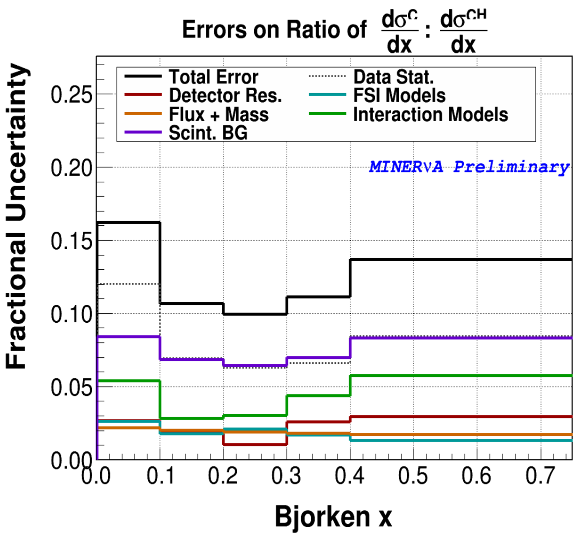
- Results are now shown for the deeply inelastic events in C, Fe, Pb and CH (not isoscalar corrected).
- X dependent ratios directly translate to x dependent nuclear effects.
- However, we cannot reach the high x events with our current beam energy.
- Currently, our simulation assumes the *same* x-dependent nuclear effects for C, Fe and Pb based on charged lepton scattering.

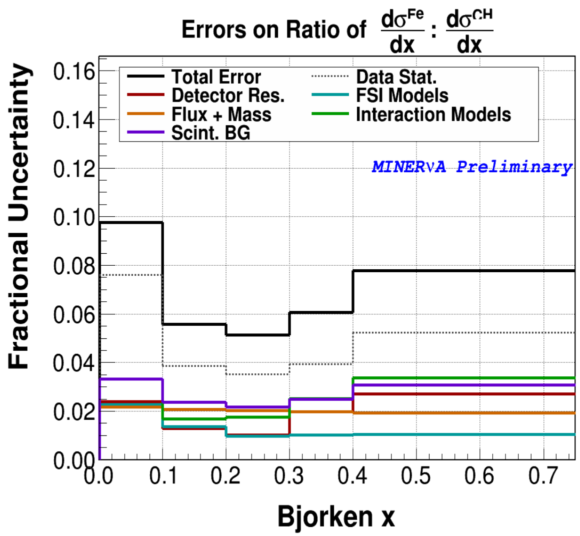
DIS Ratios: dσ /dx

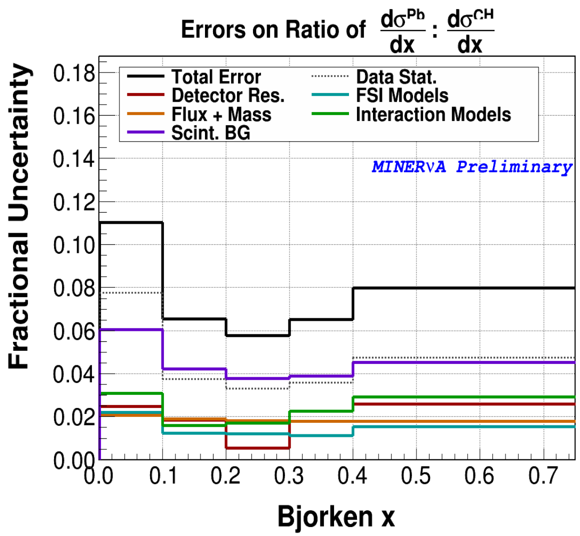


- Our data suggest additional nuclear shadowing in the lowest x bin (0 < x <0.1) than predicted in lead.
- There are some hints of this as well in Iron.
- Lowest x bin is a <x> ~ 0.07 and $<Q^2>$ ~ 2.0 $(GeV/c)^2$
- In the EMC region (0.3 < x < 0.75), we see good agreement between data and simulation.

Ratio Uncertainties

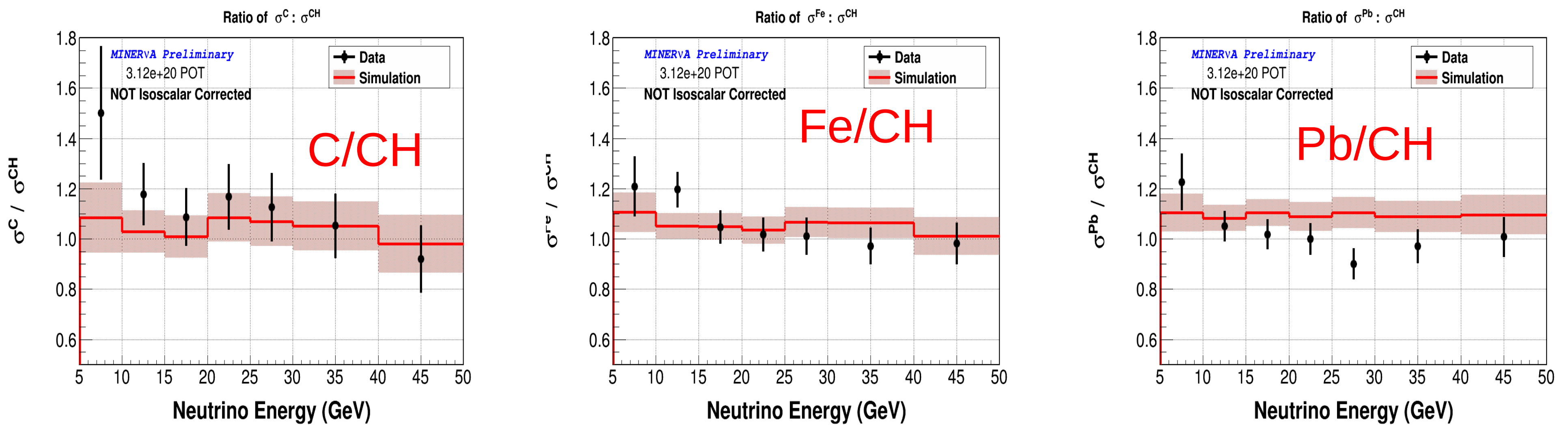






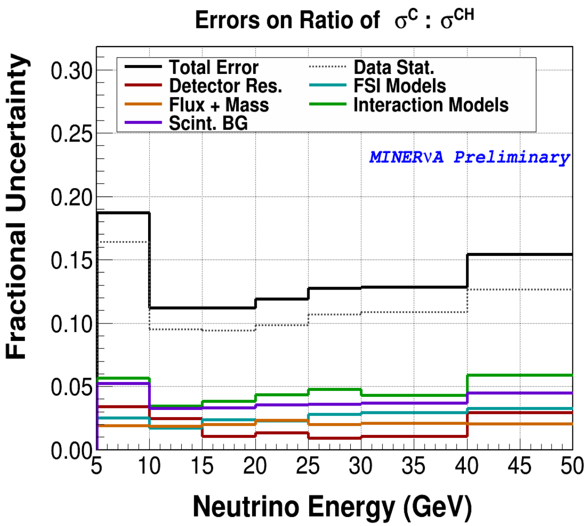
- Ratios are dominated by data statistics for the most part.
- Scintillator background is a larger uncertainty in x.
- Correlations in data introduced from unfolding are *NOT* accounted for in data stat. uncertainty.

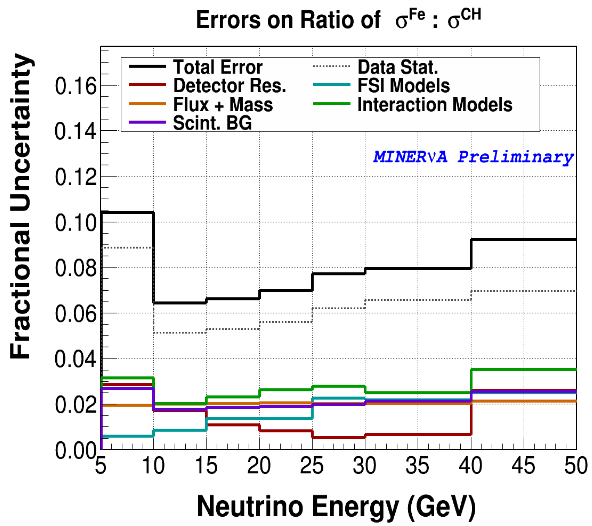
DIS Ratios: $\sigma(E_\nu)$

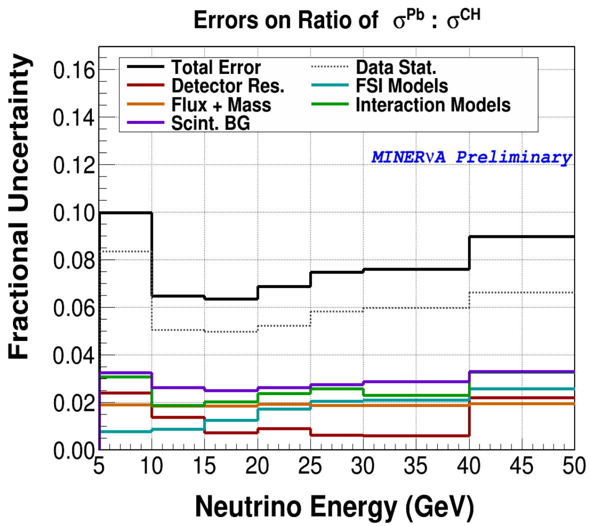


- The cross section ratios as a function of E_ν in data do not show any significant deviations from the simulation.
- GENIE does not simulate any nuclear effects as a function of E_ν.
- There is a general trend of the data being below the MC at high energy.
- This trend is larger in the lead than in the iron.

Ratio Uncertainties

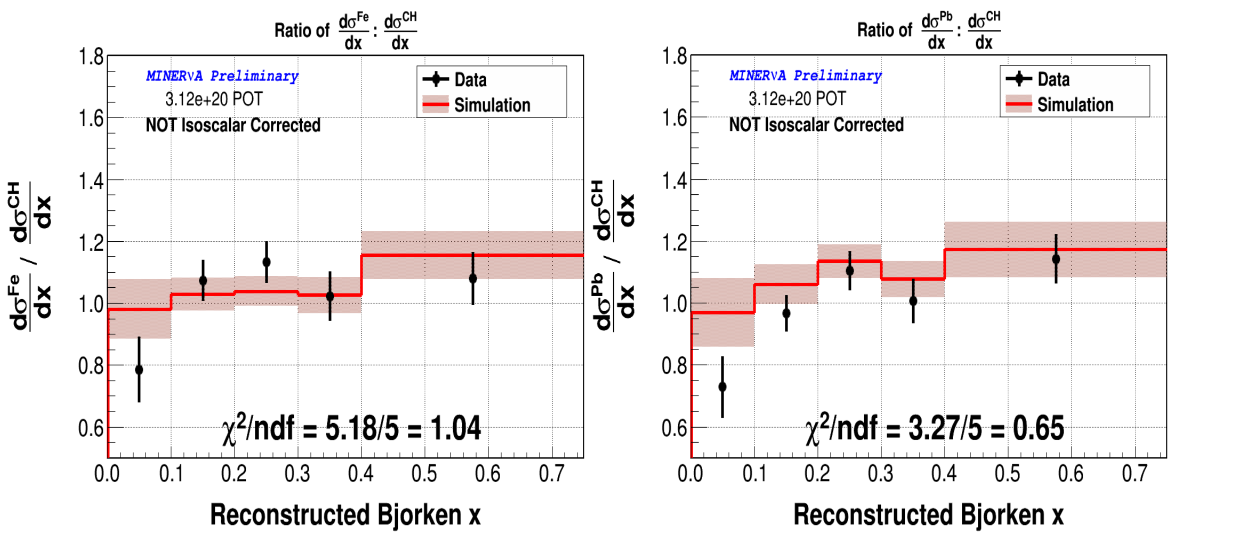




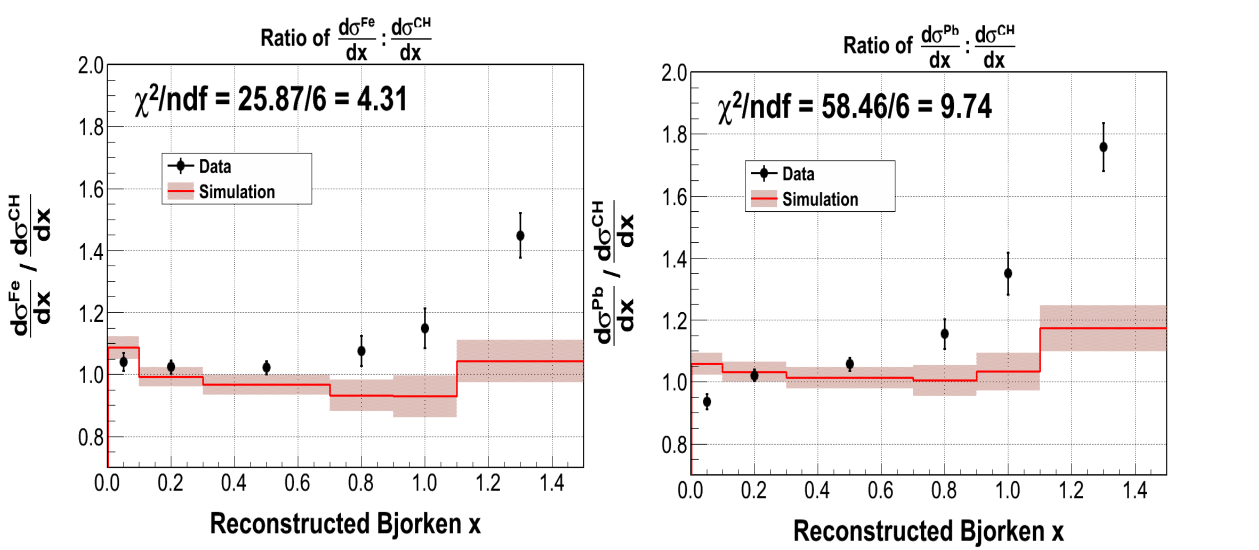


- Most of the uncertainty stems from data statistics.
- This makes the medium energy beam invaluable for this analysis.
- Correlations in data introduced from unfolding are *NOT* accounted for in data stat. uncertainty.

DIS Compared with Inclusive



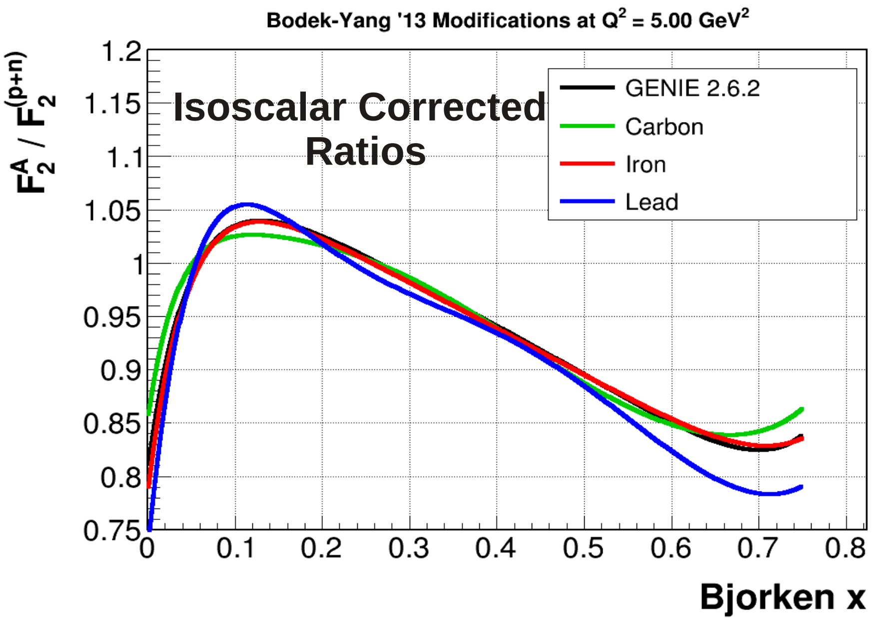
CCDIS (note different axis range)



CC Inclusive (note different axis range)

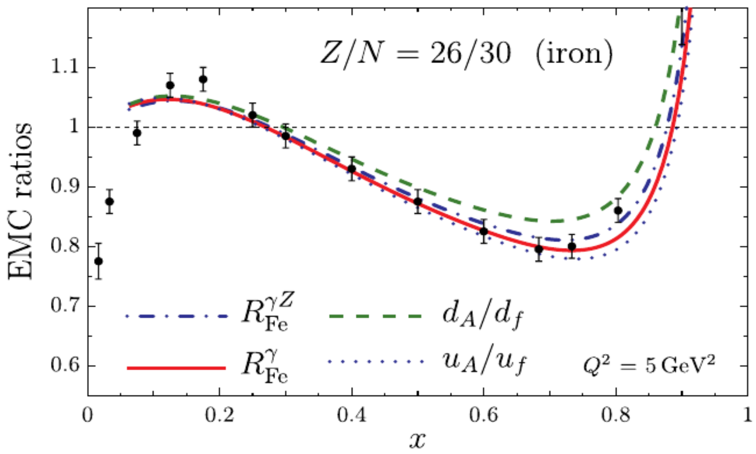
- In this case: Bjorken x is now smeared by detector effects (no unfolding).
- In both cases; we observe a deficit in low x events for the heavy nuclei (Fe, Pb) which is larger for Pb.
- There is some suggestion of a stronger effect for DIS.
- Our current neutrino energy is not sufficient to measure Fermi motion effects in DIS.

Alternative x-Dependent Models

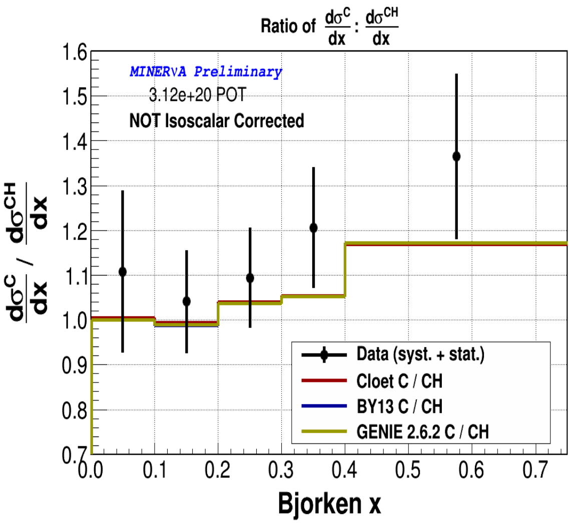


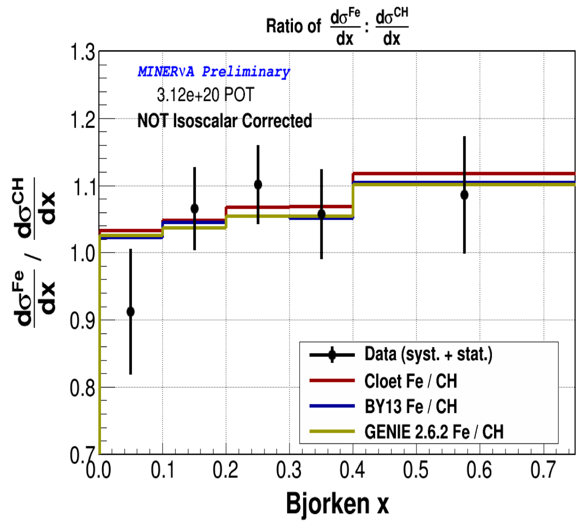
- GENIE's current parametrization of nuclear effects assumes the *same* x dependence for all nuclei heavier than He.
- Not very physically motivated. We know, for example, the EMC effect is strongly dependent on nuclear density.
- Bodek Yang 2013: update to GENIE's existing model, assumes a scaling dependent on A (top left).

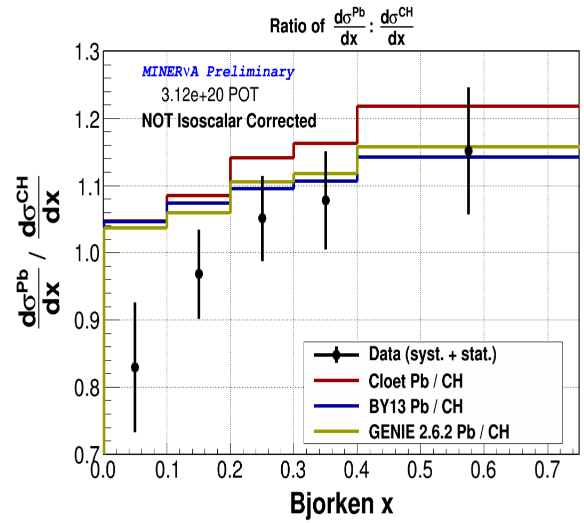
- Cloet calculation: theoretcial calculation by Ian Cloet and other Argonne collaborators of the nuclear medium modification.



Alternative x-Dependent Effects



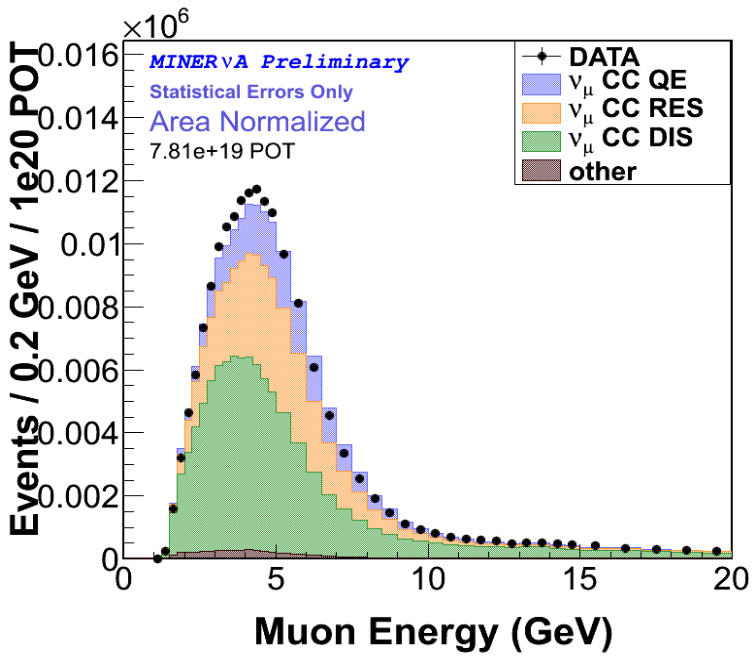


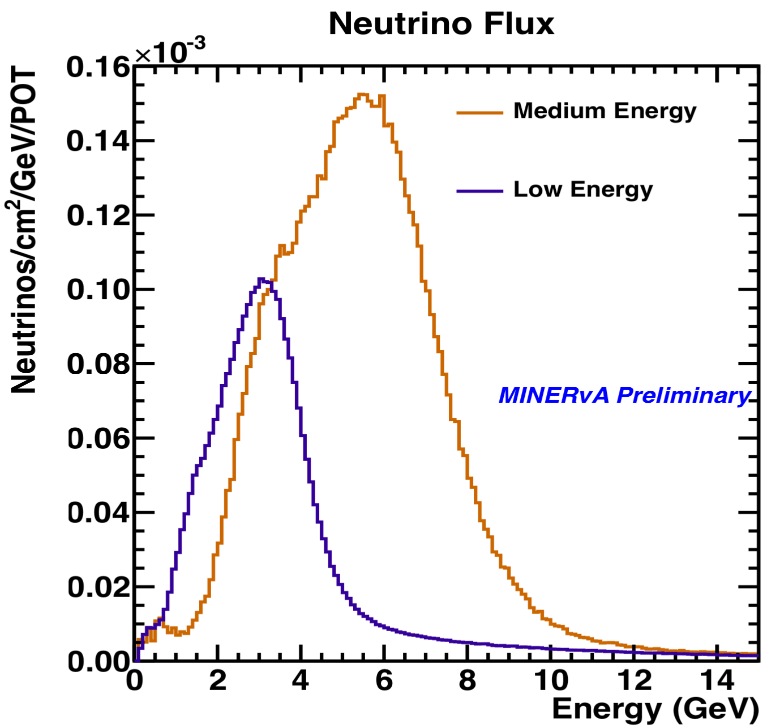


- Our data currently lacks statistical precision to differentiate between different effects, particularly on the edges of the distribution.
- But the models themselves show significant disagreements from each other, especially in the EMC region ($0.3 < x < 0.7$).
- This is strong motivation to accumulate and analyze additional medium energy neutrino and anti-neutrino data, which will be able to resolve these discrepancies.
- Additionally, better observe these differences in shadowing between e^- and ν_μ

Medium Energy

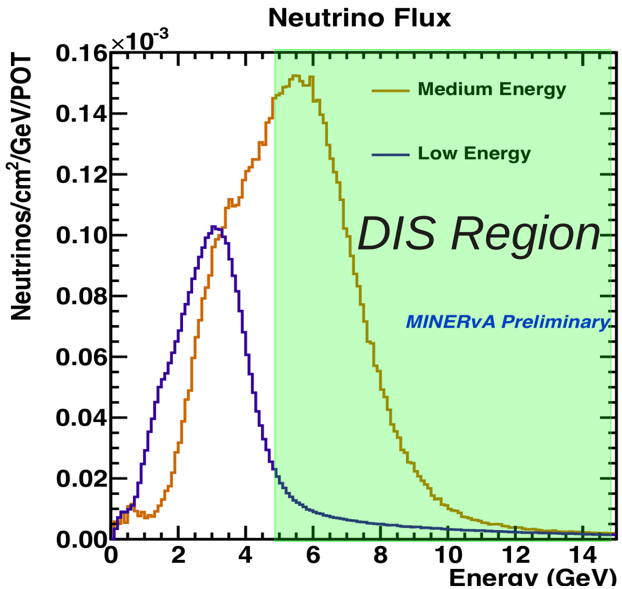
- •Motivation
- •Experiment
- •Reconstruction
- •CCInclusive
- •CCDIS
- •Medium E
- •Conclusions

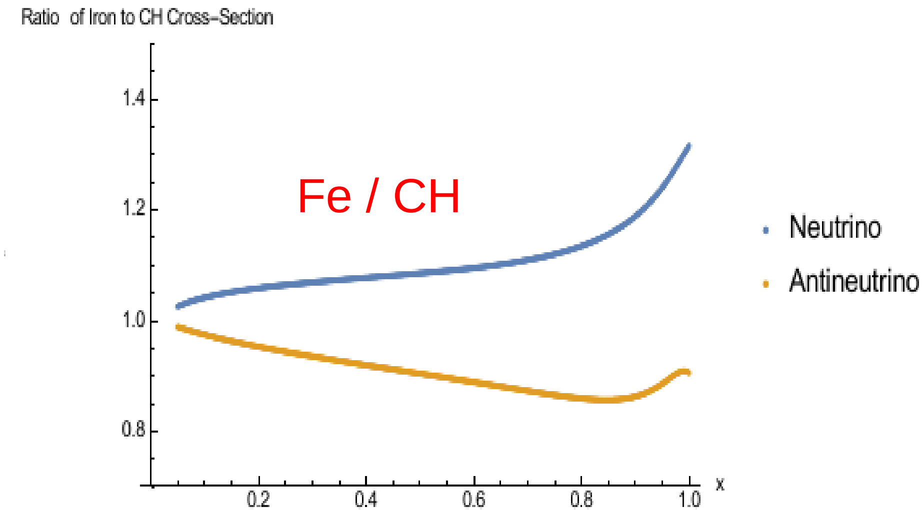




Future Directions

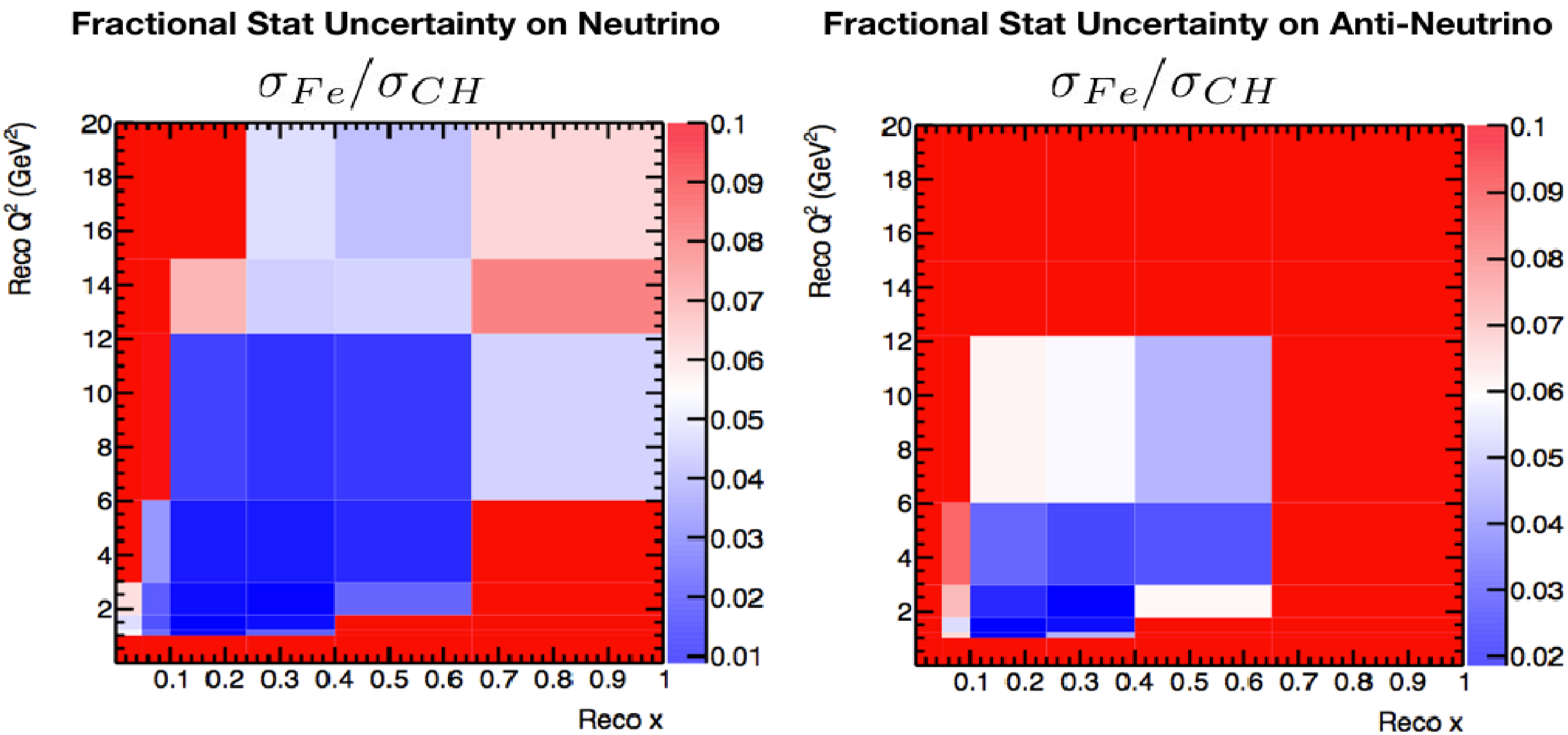
- Future studies of nuclear effects will benefit greatly from MINERvA's increased energy and intensity run, taking data as we speak.
- Expect much better sensitivity at high and low x with increased beam energy.
- Models predict a significant difference in target ratios for antineutrinos vs. Neutrinos.
- Minerva will be able to resolve these differences with ME antineutrino data!





Cloet prediction of Fe / CH for neutrinos and anti-neutrinos

Improvements to Ratios in ME



12E20 POT Exposure

- We expect the ability to analyze the high x rise (0.75 < x <1.0) with better than 10% statistical accuracy with medium energy data set.
- Significant improvement in the EMC range as well, with stat. errors on the 5% level.

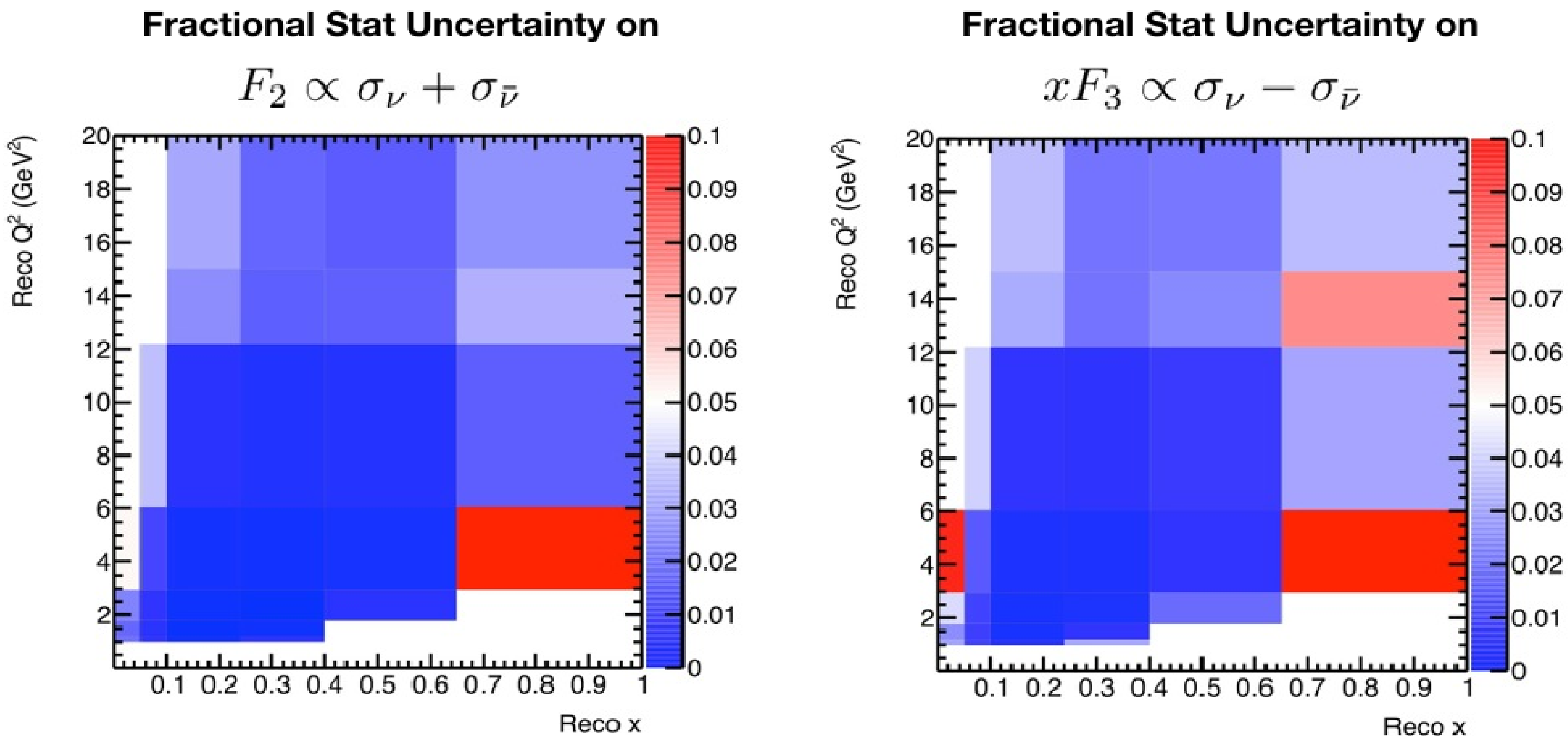
Structure Function Extraction

- Additional neutrino and anti-neutrino data provided by Medium Energy beam will allow the extraction of nuclear *structure functions* for neutrinos.
- Structure functions = form factors within the expression for the DIS cross section. They describe the distribution of quarks within the nucleon or nucleus as a function of x.
- *Structure function ratios are the most direct route to observing x-dependent nuclear effects.*
- Neutrino nuclear structure functions are also vital for future experiments and theory.

$$\frac{d^2\sigma^{\nu(\bar{\nu})A}}{dxdy} = \frac{G_F^2 M E_\nu}{\pi(1+Q^2/M_W^2)}\left[\frac{y^2}{2}2xF_1^{\nu(\bar{\nu})A} + \left(1 - y - \frac{Mxy}{2E_\nu}\right)F_2^{\nu(\bar{\nu})A} \pm y\left(1-\frac{y}{2}\right)xF_3^{\nu(\bar{\nu})A}\right]$$

Three structure functions describe the ν_μ + N and $\bar{\nu}_\mu$ + N DIS cross section

Structure Function Sensitivity



12E20 POT Exposure

- We expect better than 10% accuracy for structure function extraction.
- However, requires anti-neutrino data be taken and analyzed.

Conclusions

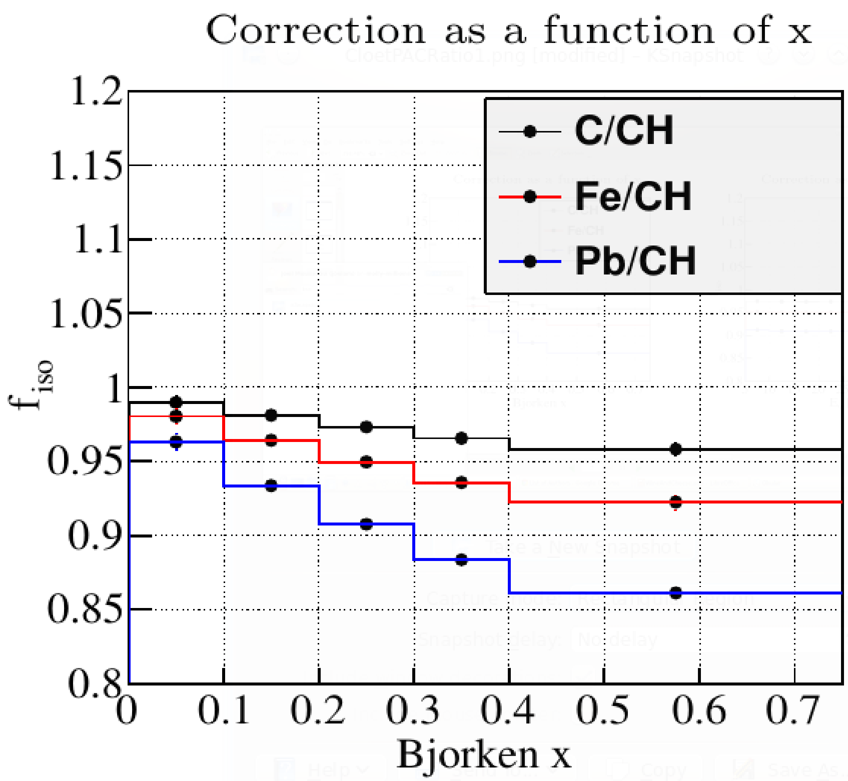
- MINERvA has made a measurement of neutrino DIS events on multiple nuclei in an identical neutrino beam.
- Unlike our previous inclusive measurements, these measurements may be interpreted directly as DIS x-dependent nuclear effects.
- We currently observe a deficit in our lead data suggestive of additional nuclear shadowing.
- Our data in the EMC region shows no deviation from theory, however we lack the precision to distinguish between different theories.
- Future higher energy measurements will be higher statistics as well as the ability to resolve larger x values.

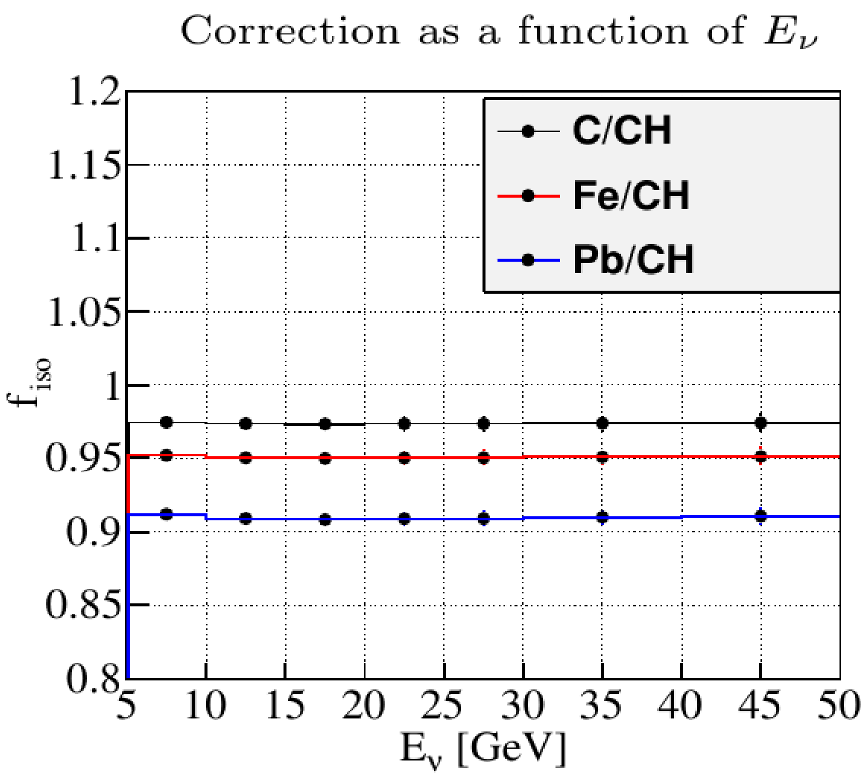
Thank you for Listening!

(

Backup Slides

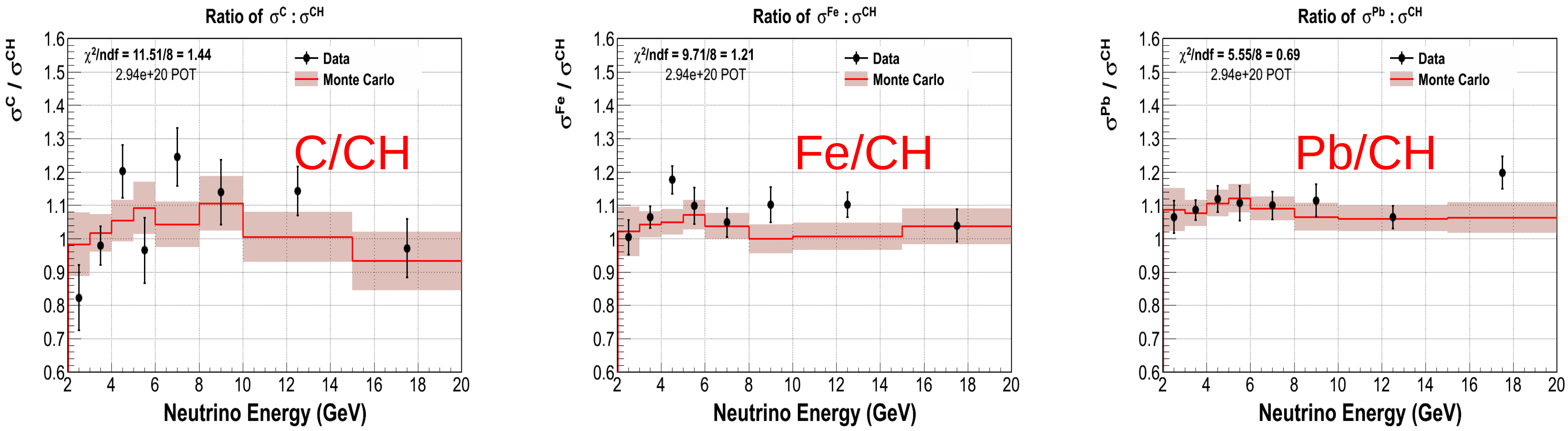
Isoscalar Correction:





- An example iso scalar correction as a function of x and E_ν
- The correction is largest at large x for lead. Note there is not much depedence on energy; the *d* quark content is dependent on x and not E_ν

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.
- As of version 2.6.2, GENIE does not simulate any E_υ nuclear effects.
- Our data tend to support that position.

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

Shadowing

- Why does shadowing occur at low x?
- The lifetime of the hadronic fluctuation has to be sufficient to allow for these multiple diffractive scatters:

$$t_c = 2_{Ehad} / (Q^2 + m^2)$$

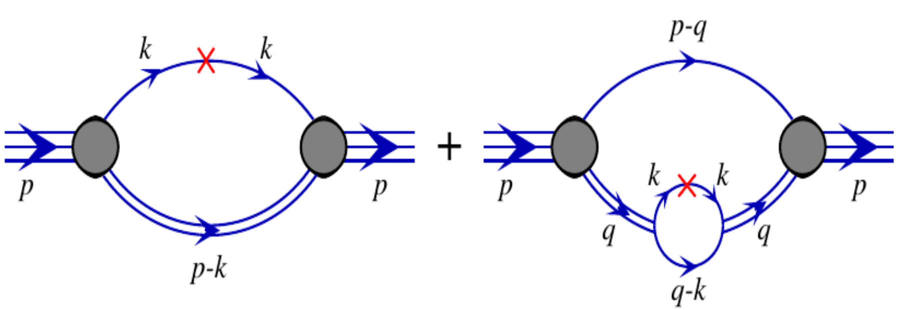
- For a given Q^2 need large E_{had} to yield sufficient tc which implies small x.
- m is larger for the vector current than the axial vector current; for a given Q^2 you need more E_{had} for the vector current than the axial vector current to have sufficient t_c.
- This implies you can have shadowing at higher x with neutrinos than with charged leptons

Explanation(s) of EMC Effect

- Nature prefers dynamic scaling?
  - Bjorken scaling isn't special; nuclear scaling may be a more complicated function of Q^2 and target mass.

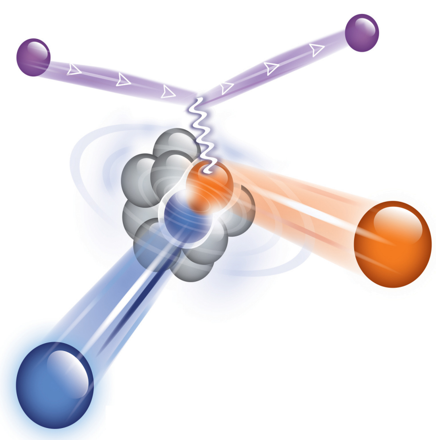
Nachtmann Scaling:

$$\xi = \frac{2x}{1+\sqrt{1+4M^2x^2/Q^2}}$$



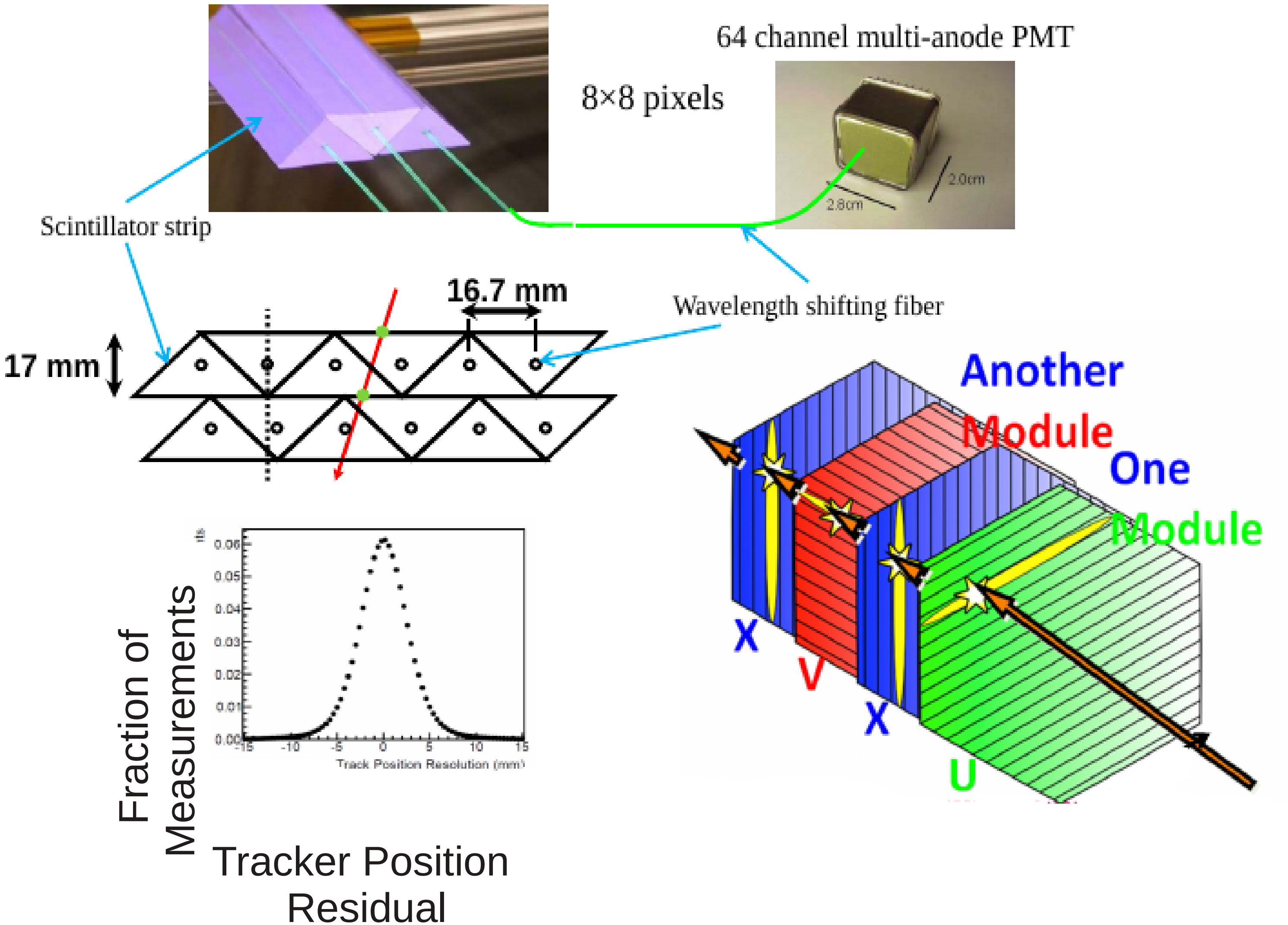
- Medium modifications to the quarks' wave functions.
  - Quarks bound inside nucleus "feel" the nucleus' wave function.

- Connection to short range correlations.
  - Lepton probe (charged or neutrino) interacts with a nucleon-nucleon pair vs. a single nucleon



Not an exhaustive list!

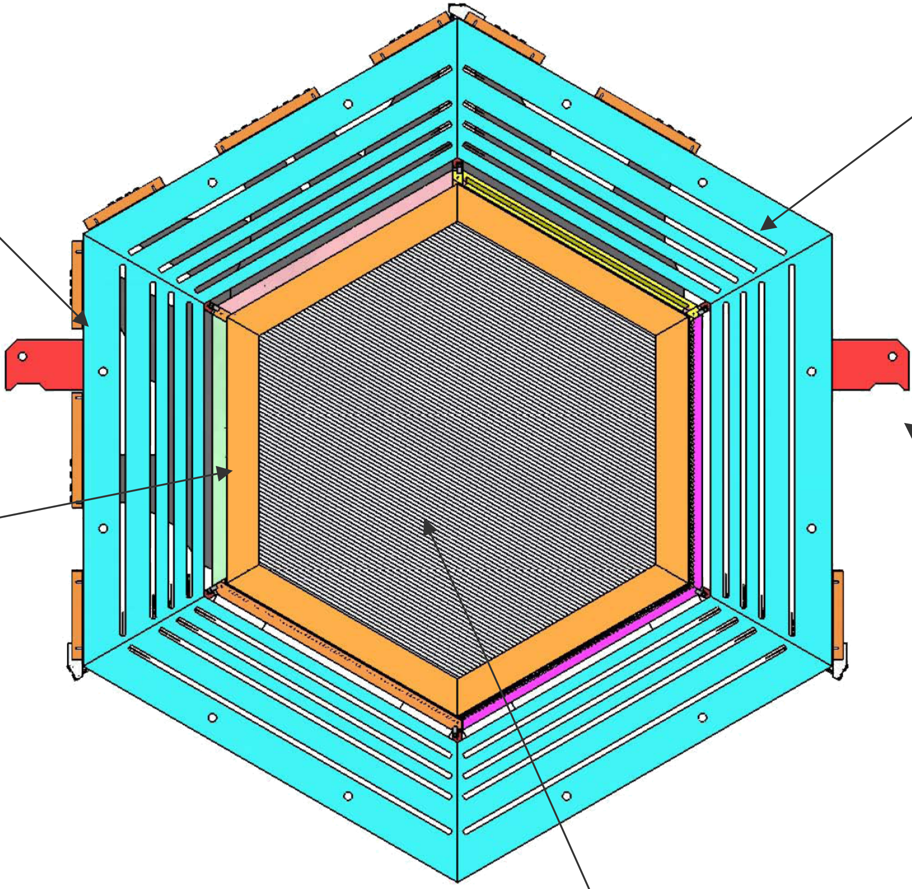
Detector Technology



A MINERvA Module

Outer Detector Frame

Scintillator Bars

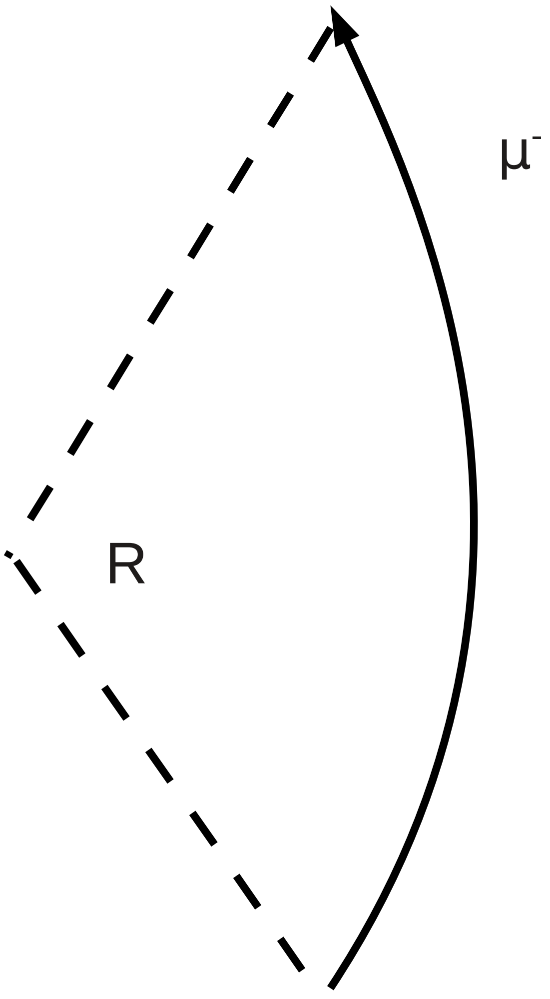


Lead collar

Steel supports used for hanging modules on rails.

Inner Detector:
Plastic scintillator strips

Curvature Significance



Muon track is curved
in the MINOS B field
$p \approx B / R$

- Muons travelling in the MINOS B bend toward the coil, the radius of the track is inversely proportional to the momentum of the muon.
- Algorithm for calculating the radius of this bend returns a *significance*, which is a measure of how curved the track is relative to a straight line.
- Higher p muons have smaller curvature; and thus poorer momentum reconstruction.
- Require at least 5 σ significance of curvature.

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

Shadowing

Anti-Shadowing

EMC

Fermi Motion

- Most of our events are in the anti-shadowing and shadowing region; but we do have a large number in the EMC region.

X-Dependent Effects from Theory

- GENIE's model for DIS and transition events is based on Bodek-Yang 2003. This includes a parametrization of identical x dependent nuclear effects for C, Fe and Pb.
- Bodek-Yang 2013. Update to 2003, incorporates separate parametrization for Fe, C and Pb.
- Kulagin-Petti. Theoretical calculation based on computed $2xF_1$, F_2 and xF_3 for each nucleus A.
- The variations from theory are too small to explain our data!

x	C/CH G	C/CH σ_{st} %	C/CH KP $\Delta\%$	C/CH BY $\Delta\%$	Fe/CH G	Fe/CH σ_{st} %	Fe/CH KP $\Delta\%$	Fe/CH BY $\Delta\%$	Pb/CH G	Pb/CH σ_{st} %	Pb/CH KP $\Delta\%$	Pb/CH BY $\Delta\%$
0.0–0.1	1.050	1.0	0.3	0.0	1.011	0.5	-0.4	1.2	1.037	0.5	-1.5	0.8
0.1–0.3	1.034	0.7	-0.3	0.0	1.017	0.3	-0.7	-0.5	1.071	0.3	-1.0	-0.7
0.3–0.7	1.049	0.8	-0.1	0.0	1.049	0.4	0.0	0.0	1.146	0.4	0.4	0.6
0.7–0.9	1.089	1.8	-0.1	0.0	0.995	0.9	0.4	0.1	1.045	0.9	0.1	0.7
0.9–1.1	1.133	2.3	-0.1	0.0	0.948	1.1	0.2	0.0	0.985	1.1	0.2	0.2
1.1–1.5	1.111	2.2	0.0	0.0	0.952	1.1	0.0	0.0	1.036	1.1	0.1	0.0

S. A. Kulagin and R. Petti, Nucl. Phys. A 765, 126 (2006)
S. A. Kulagin and R. Petti, Phys. Rev. D 76, 094023 (2007)
A. Bodek, U. K. Yang arXiv:1011.6592 (2013)