Neutrino-nucleus deep inelastic scattering with MINERvA

Joel A. Mousseau
University of Michigan /
University of Florida
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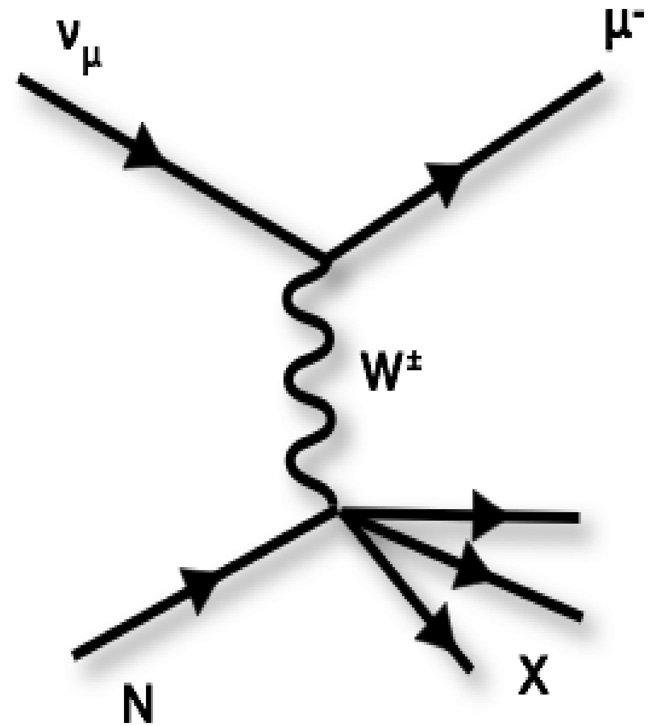
Neutrinos in Nuclear Media

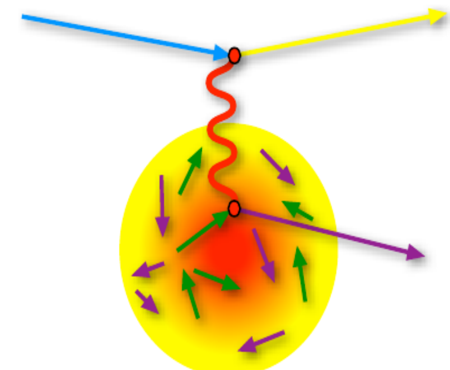
- Modern neutrino experiments rely on large A materials (Fe, Ar, C, H_2O etc.) to obtain adequate event rates.
- Nuclear effects can occur as *interactions* of intermediate particles inside the nucleus, or *partonic* effects which change the kinematics of quarks within the nucleus.
- General strategy for partonic effects has been to adapt nuclear effects from electron scattering into neutrino scattering.

$$F = q_1 + \overline{q}_1 + q_2 + \overline{q}_2 + q_3 + \overline{q}_3 + q_4 + \overline{q}_4 \rightarrow$$
$$F^N = q^N{}_1 + \overline{q}^N{}_1 + q^N{}_2 + \overline{q}^N{}_2 + q^N{}_3 + \overline{q}^N{}_3 + q^N{}_4 + \overline{q}^N{}_4$$

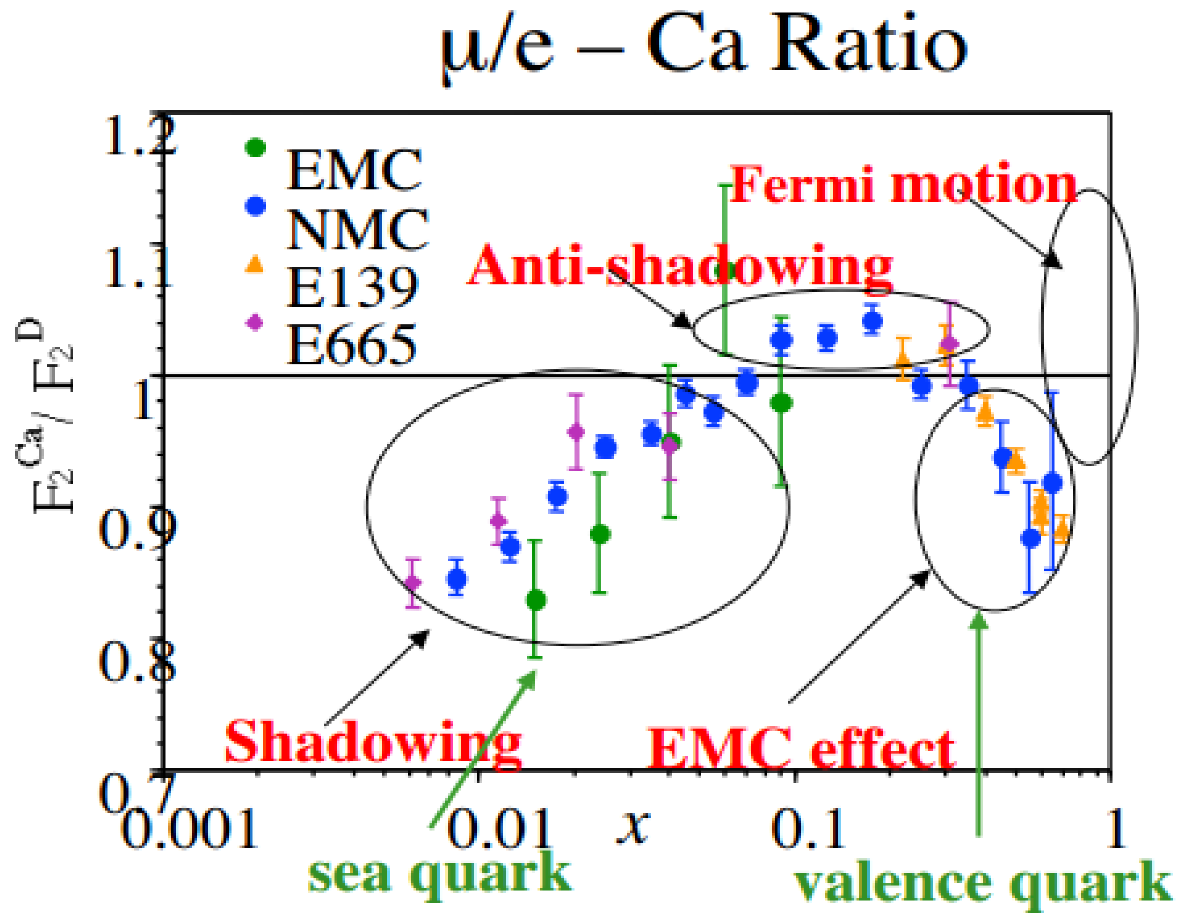
Partonic effects translate free nucleon PDFs (F) to nuclear PDFs (F^N)



Nuclei are not point-like, there are interactions between and within nucleons.



Charged Lepton Nuclear Effects

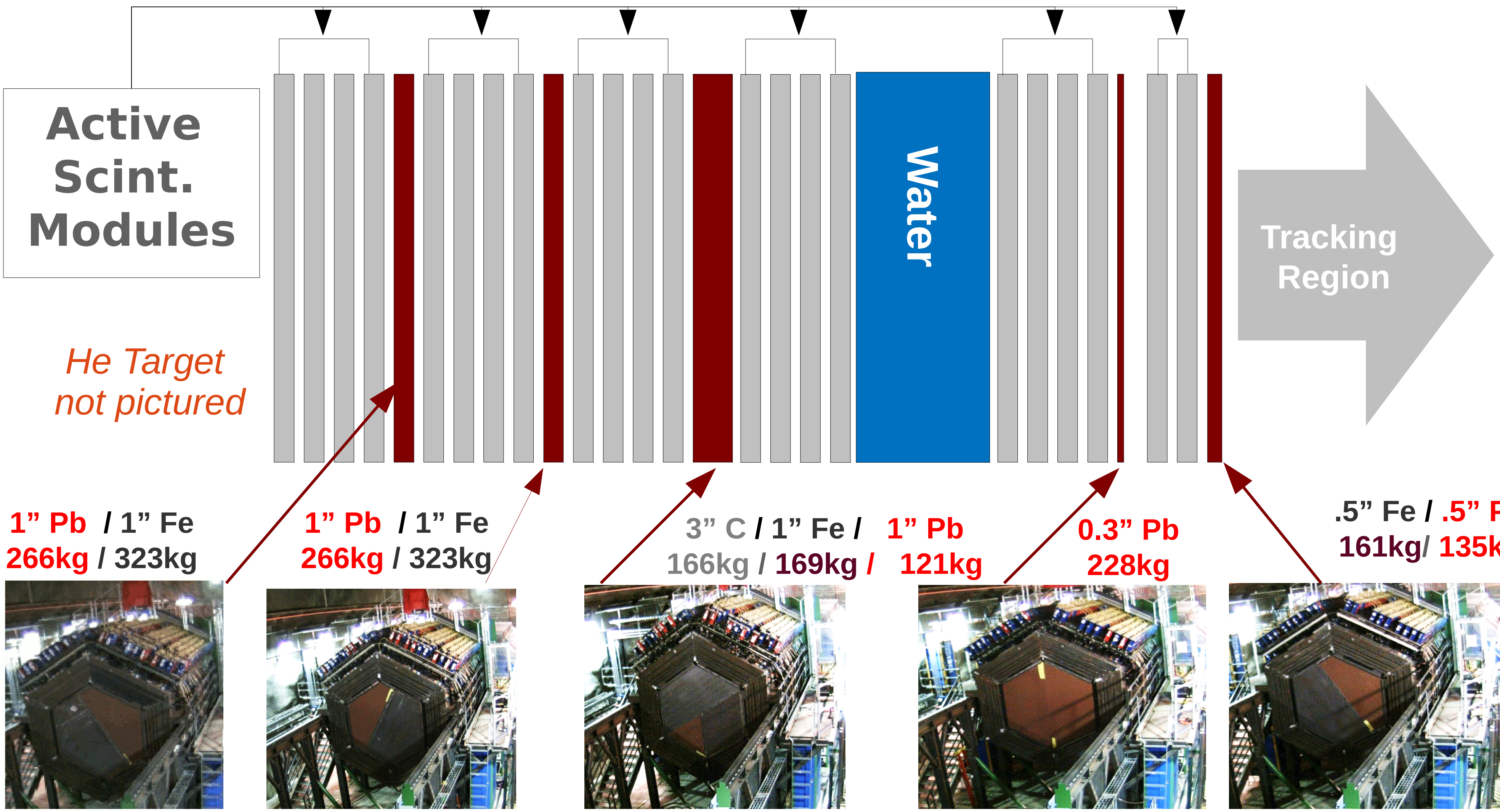


- **Shadowing and Anti-shadowing:** Depletion of cross section at low x, presumably compensated by a enhancement from x ~ 0.1 – 0.3.
- **EMC Effect:** No universally accepted cause.
- **Fermi motion:** Each quark is allowed to have a maximum momentum of x = A, so increasing A increases maximum allowable x.

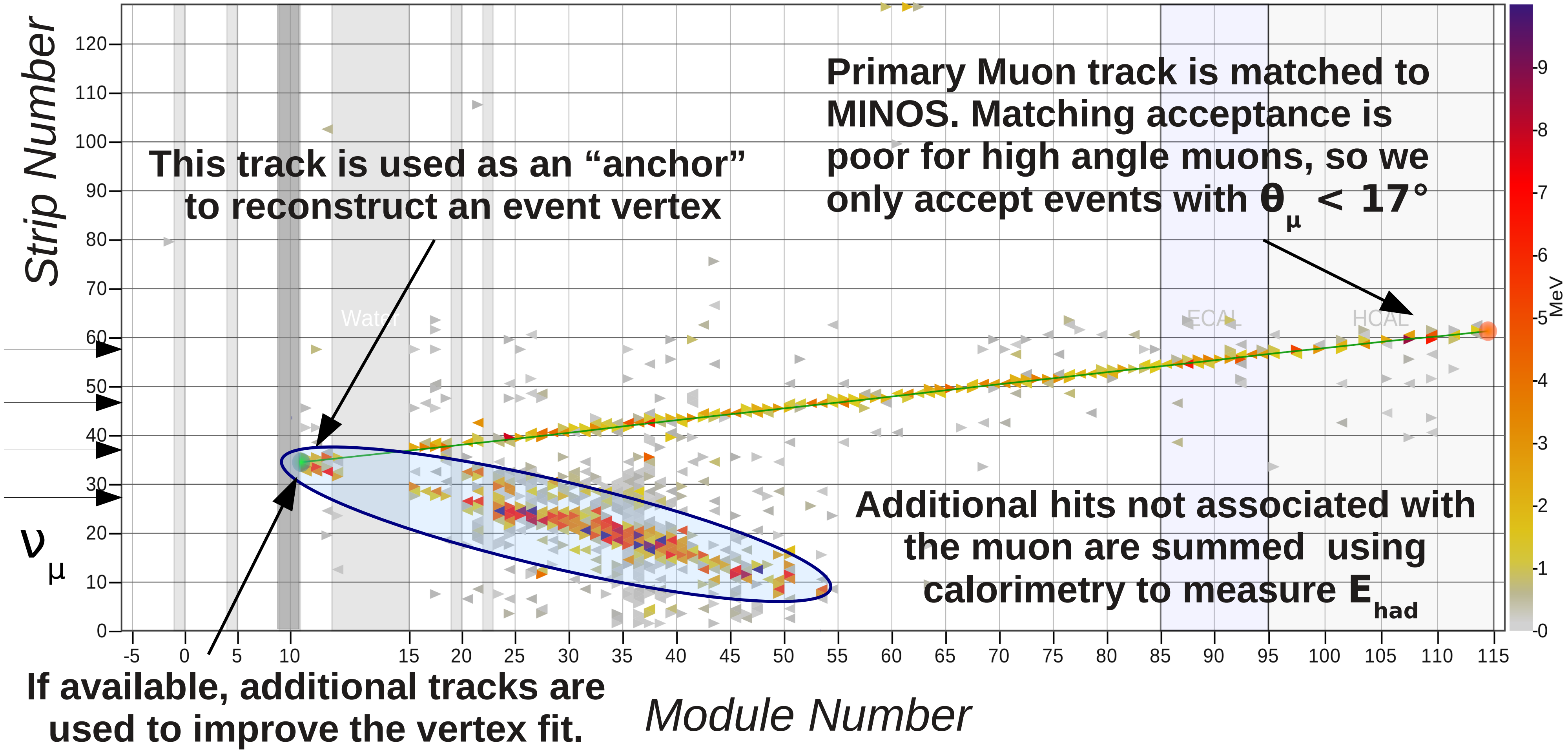
$$x = \frac{Q^2}{2ME_{had}}$$

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

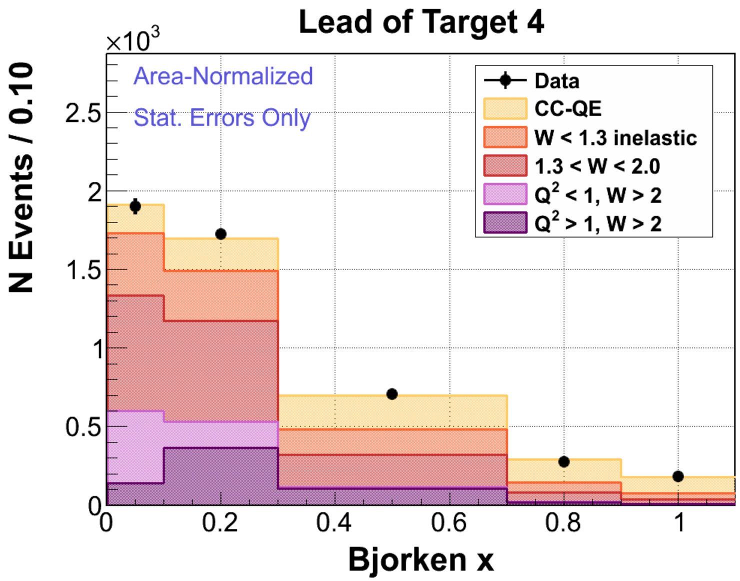
MINERvA Nuclear Targets



Event Selection and Reconstruction



From Events to Cross Sections



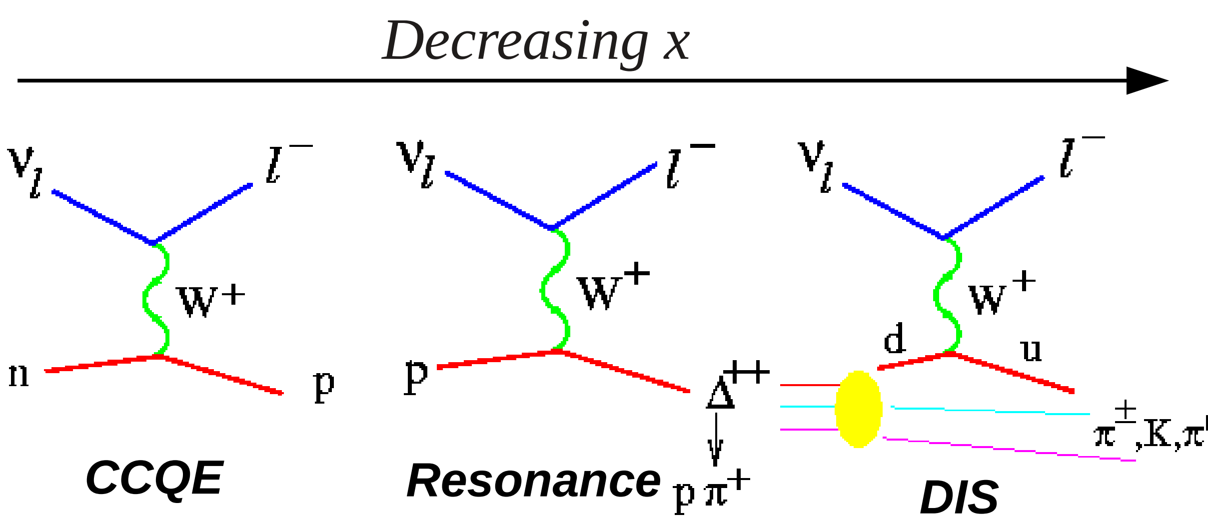
•The first step in calculating a cross section is to measure the number of signal events.

• In an inclusive cross section, count all υ_μ events regardless of channel.

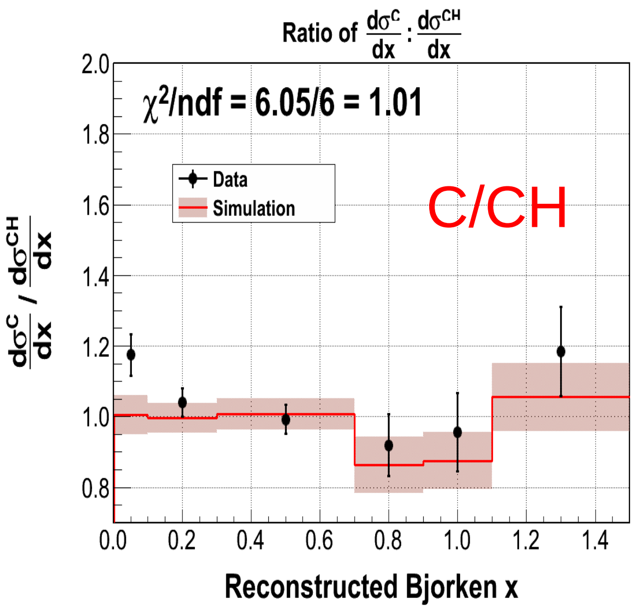
•$d\sigma/dx = U(S - B)/(\varepsilon \int \phi\, \Lambda\, T)$

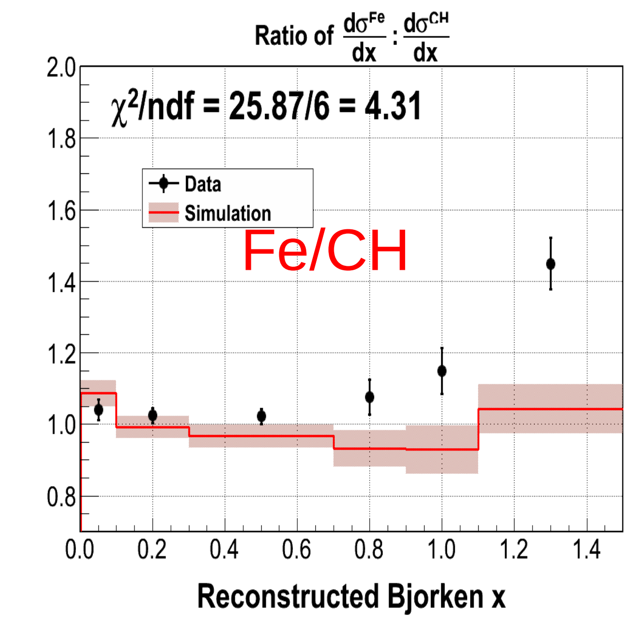
•Partonic effects between two nuclei are measured as ratios of dσ/dx.

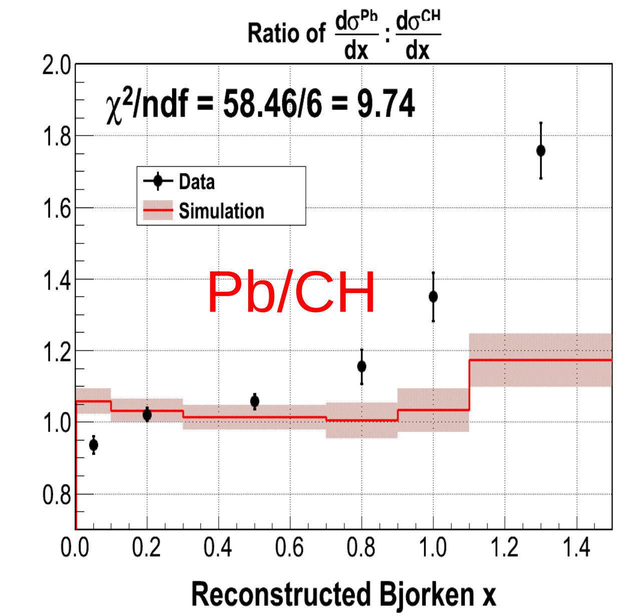
•Thus: $d\sigma^A/dx \,/\, d\sigma^C/dx \approx [\,(S^A - B^A) \,/\, (S^C - B^C)\,] * [(\varepsilon^C T^C) \,/\, (\varepsilon^A T^A)]$.



Inclusive Ratios: dσ /dx







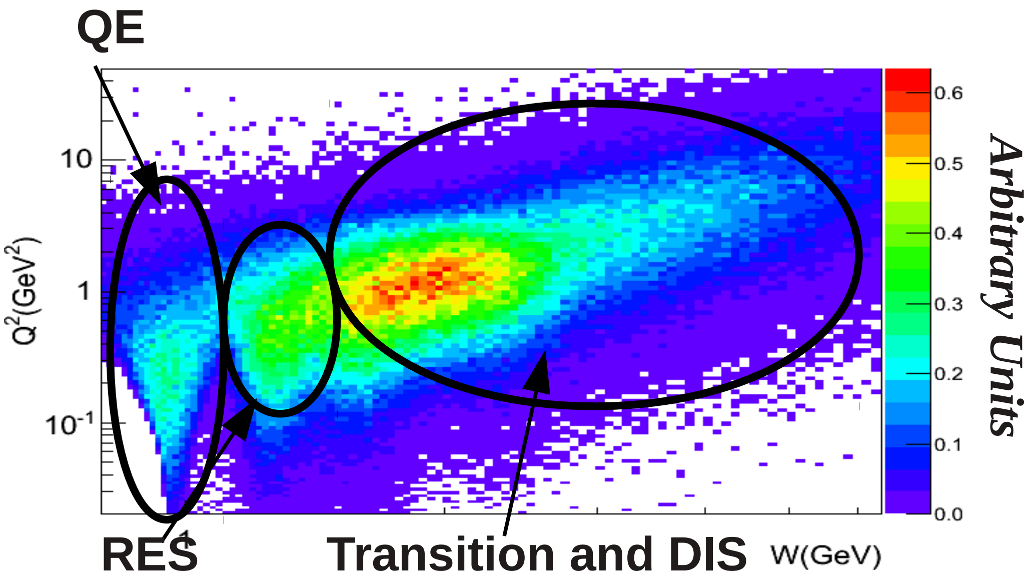
- Data are presented as differential cross-section ratios in reconstructed x: we do not correct for detector smearing.
- We observe an *excess* in the data at large x, and a *deficit* at low x, which grows with the size of the nucleus.
  - The low x events are at a low Q^2 (0.5 $(\mathrm{GeV}/c)^2$) and cannot be interpreted as quark-level interactions.
  - High x events are a mixture between quasi-elastic and resonant.

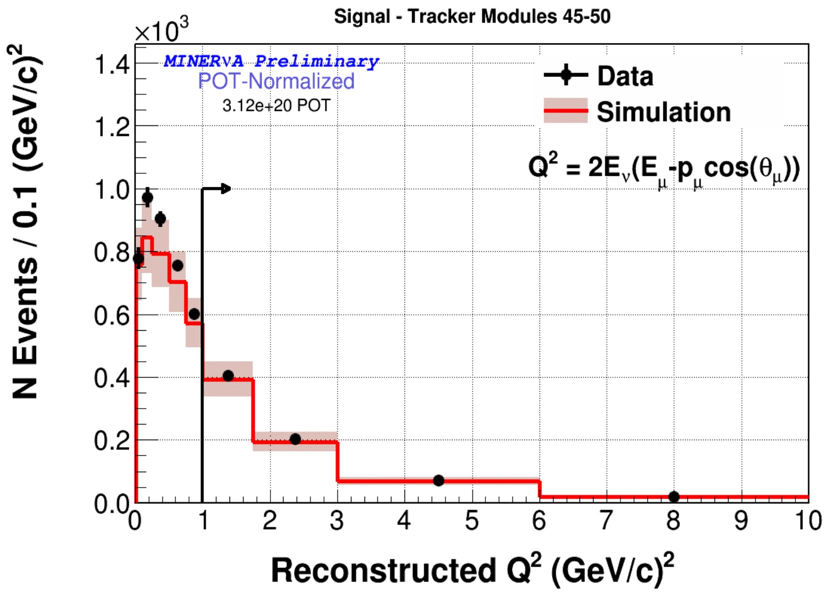
Tice, Datta, Mousseau et. al,
Phys. Rev. Lett. 112, 231801 (2014).

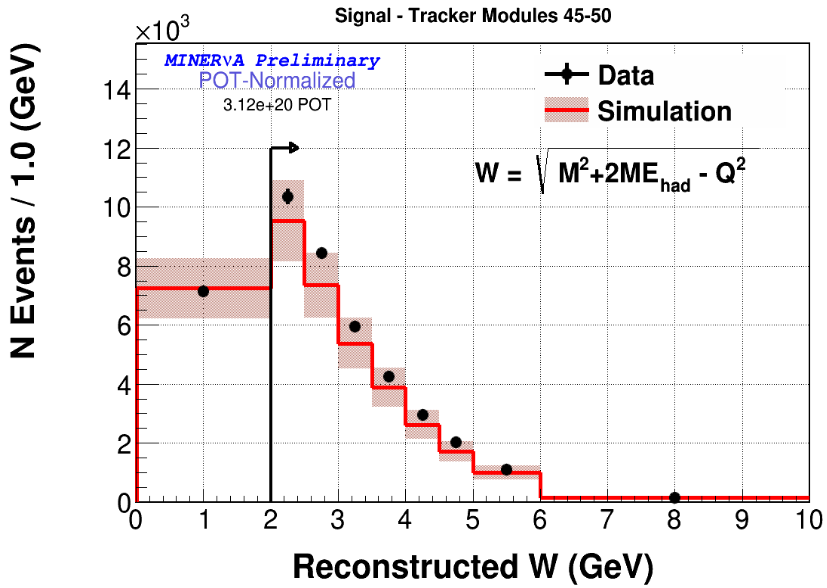
Presented at NuInt 2014
London, UK

How Deep is Your Scattering?

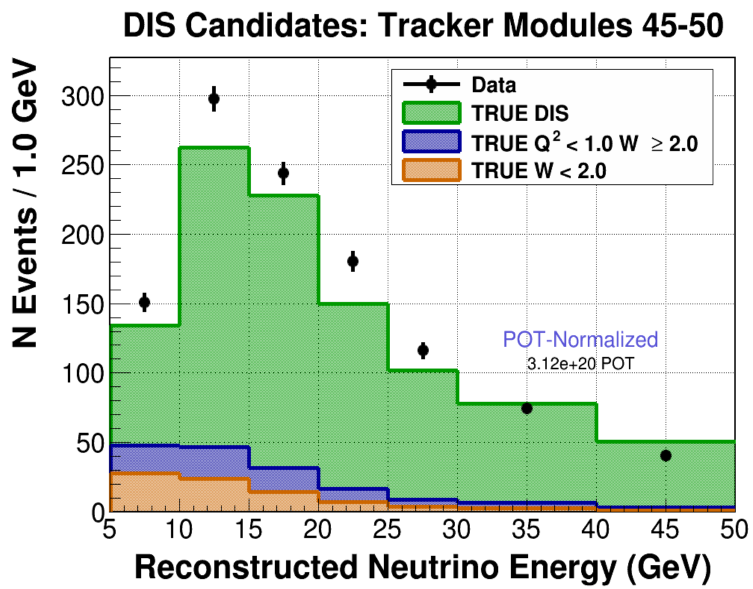
- Momentum transfer: $Q^2 = |k - k'|^2$.
- $Q^2 > 1.0$ (GeV/c)^2 to be enough momentum transfer to resolve the quark structure of the nucleons.
- $W > 2.0$ (GeV/c) safely avoids the majority of resonances.

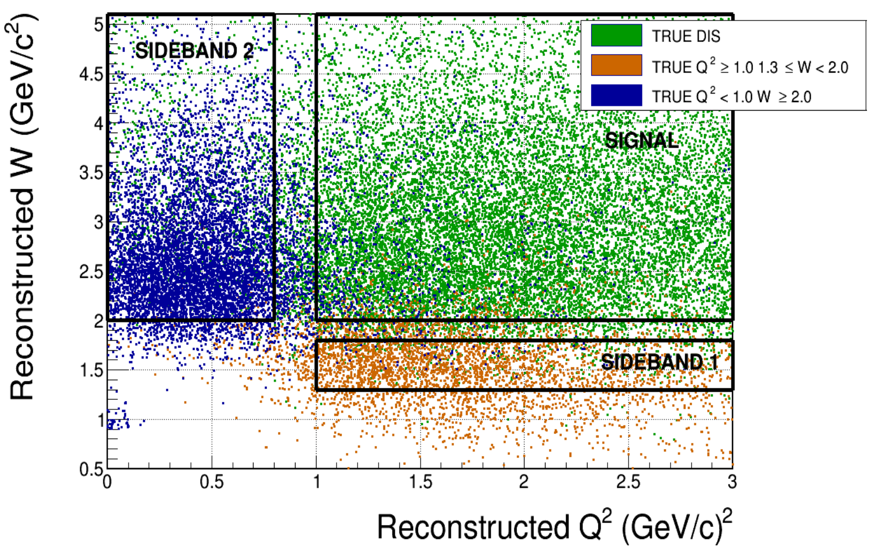






Backgrounds (Kinematic):





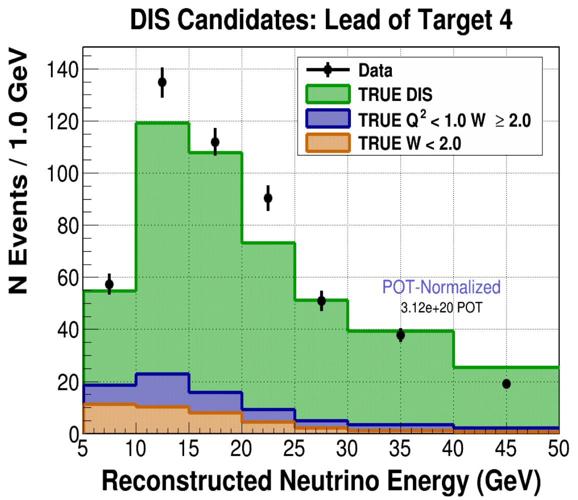
- After making kinematic cuts on Q^2 and W, we are left with a background of events with *true* $Q^2 < 1.0$ (GeV/c)^2 and W < 2.0 (GeV/c^2) that smear into the sample.
- Estimate this background in the nuclear targets and scintillator using MC (left plots).
- MC is tuned to data using events adjacent to W = 2.0 (GeV/c^2) and Q^2 = 1.0 (GeV/c)^2

Fitting Sidebands

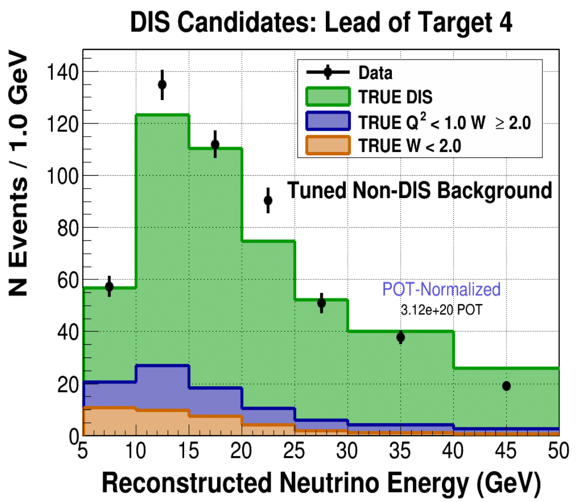
Scale Factors Applied to Simulation (stat. Error only)

A	$W_{gen} < 2.0$	$Q^2_{gen} < 1.0$ $W_{gen} > 2.0$
C	0.90±0.08	1.58±0.11
CH	0.94±0.01	1.57±0.02
Fe	0.99±0.04	1.58±0.05
Pb	0.95±0.03	1.36±0.05

- 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.

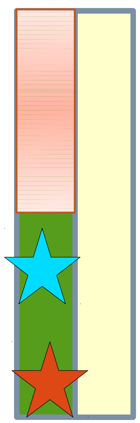


Before Fitting

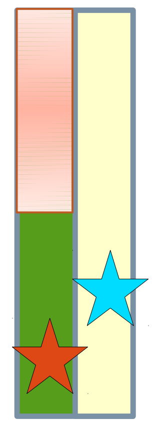


After Fitting

Background Events (Wrong Nuclei)

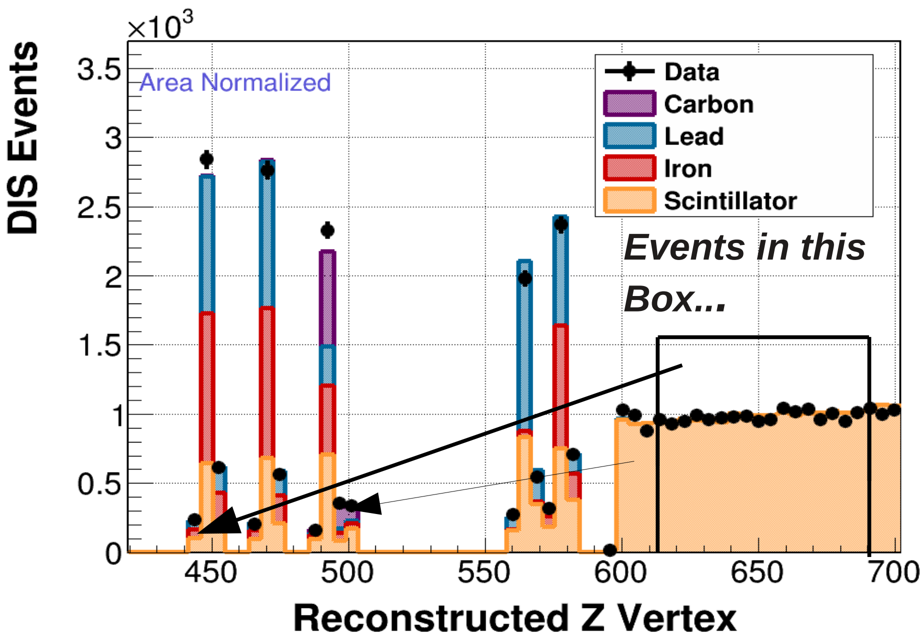


True vertex (blue star) is in the same material as the reconstructed vertex (orange star).



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.

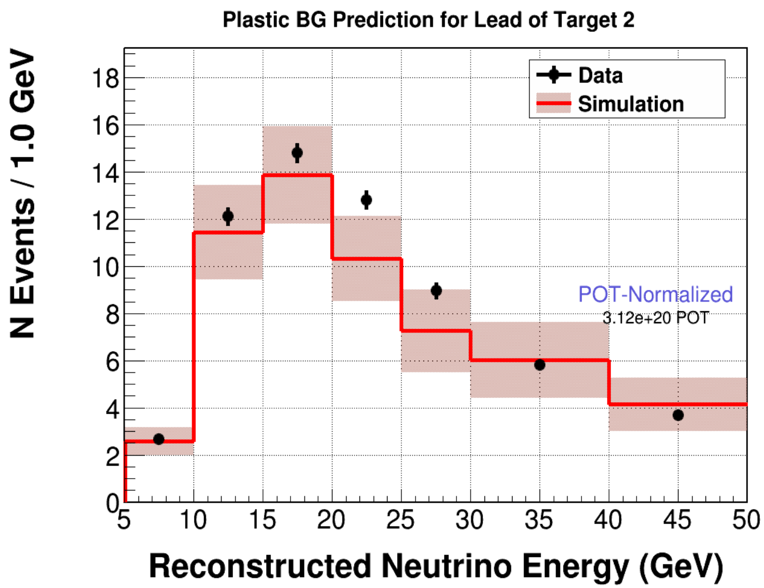


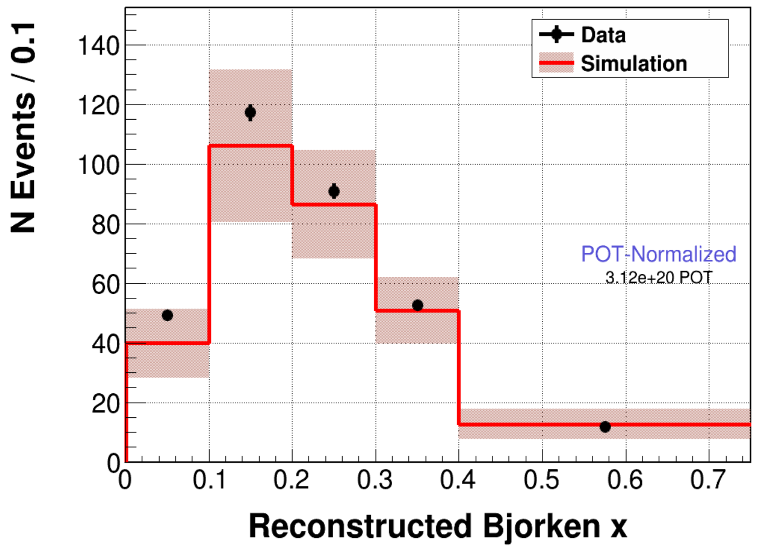
...Used to predict BG events here

- 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 .

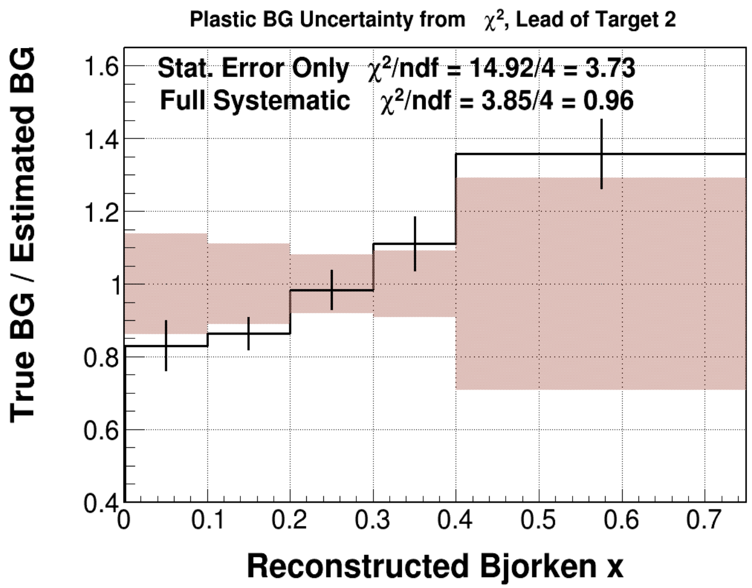
Wrong Nuclei BG (Data / MC)





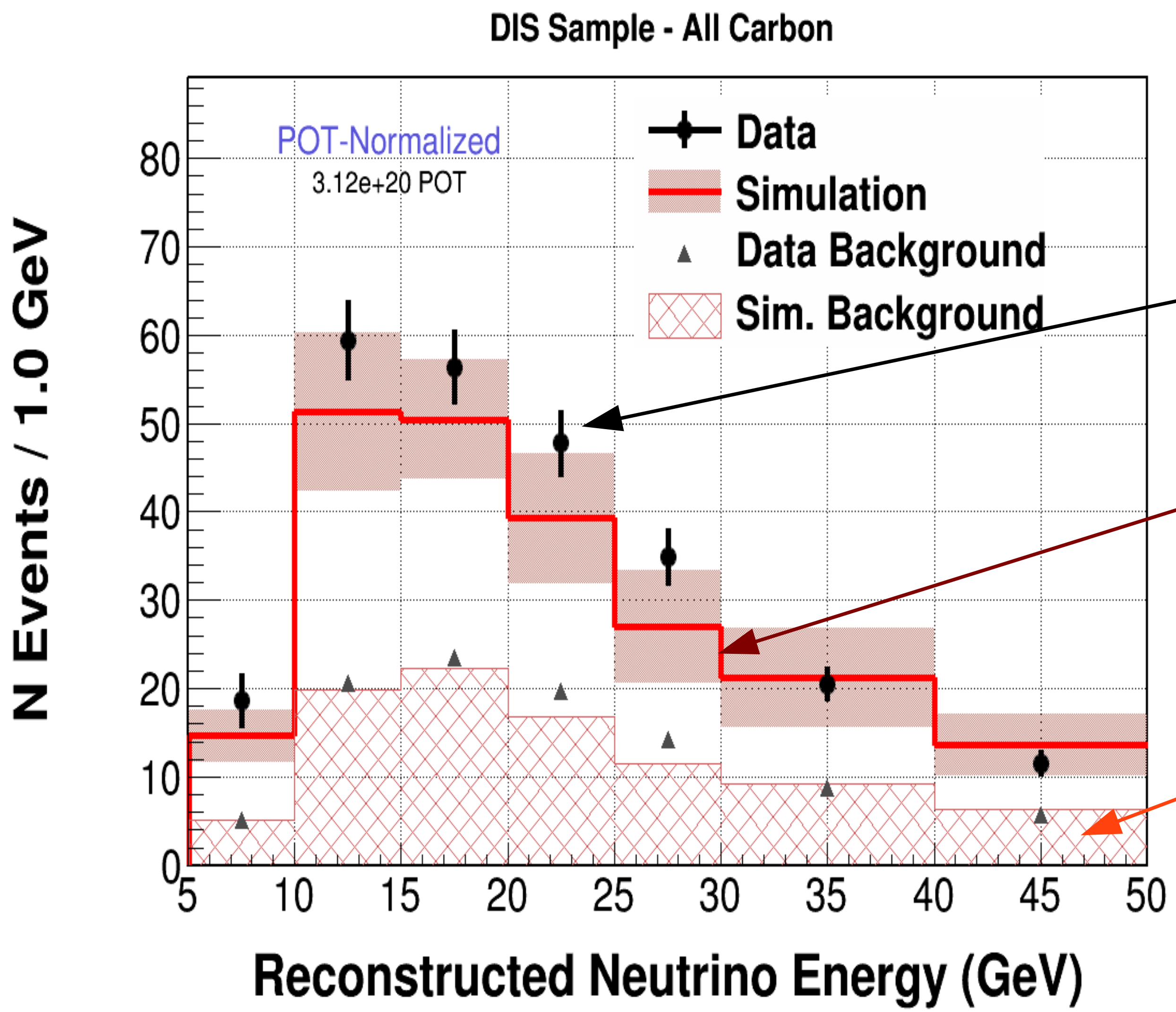
- Wrong nuclei backgrounds are extracted separately for data and MC, in each variable (E_ν, x, etc.)

- 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



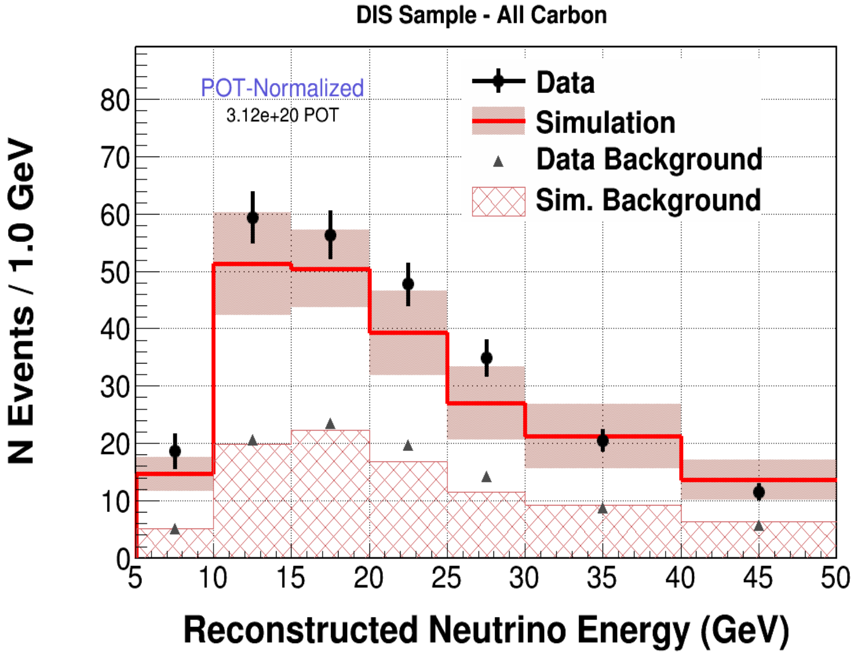
Data events reconstructed in C, with non-DIS events subtracted.

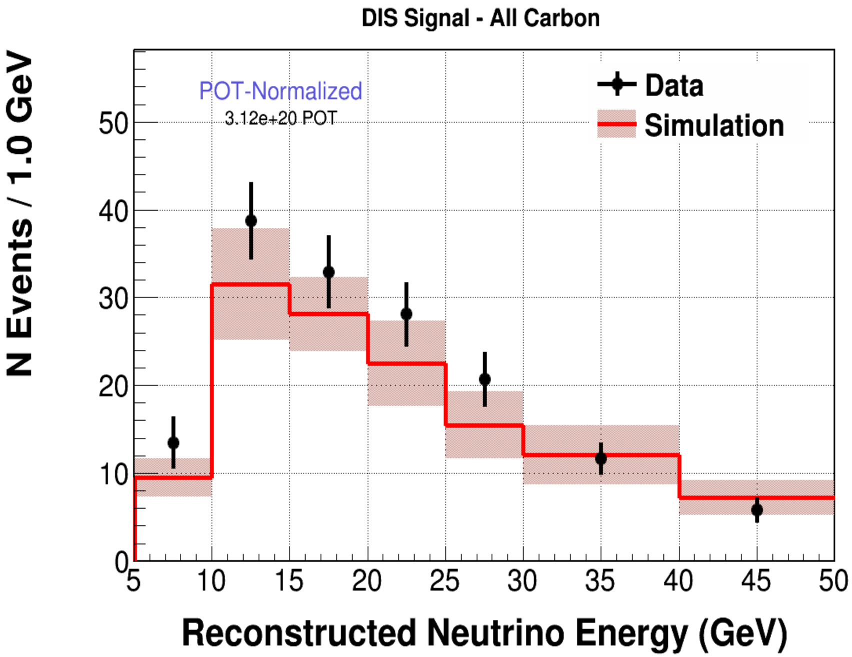
Simulated DIS events, reconstructed in C

Wrong nuclei events, with non-DIS events subtracted.

Putting it Together

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

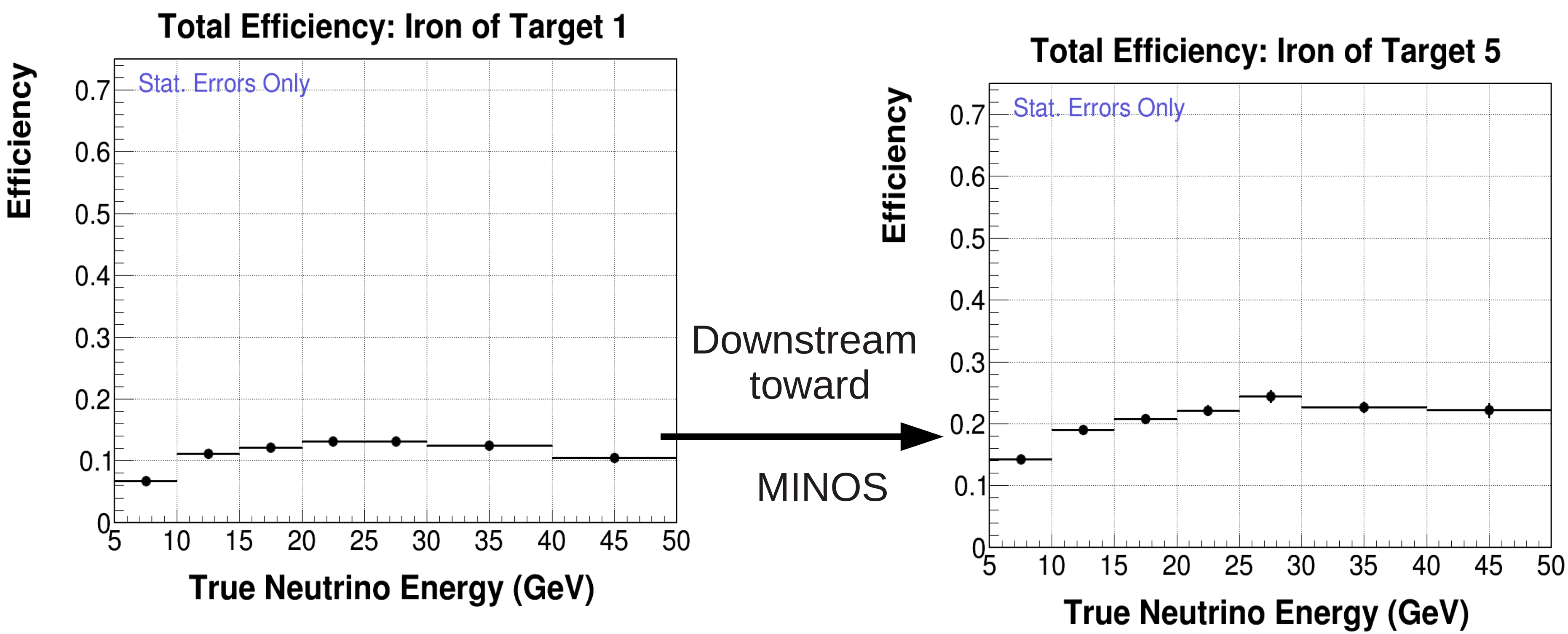




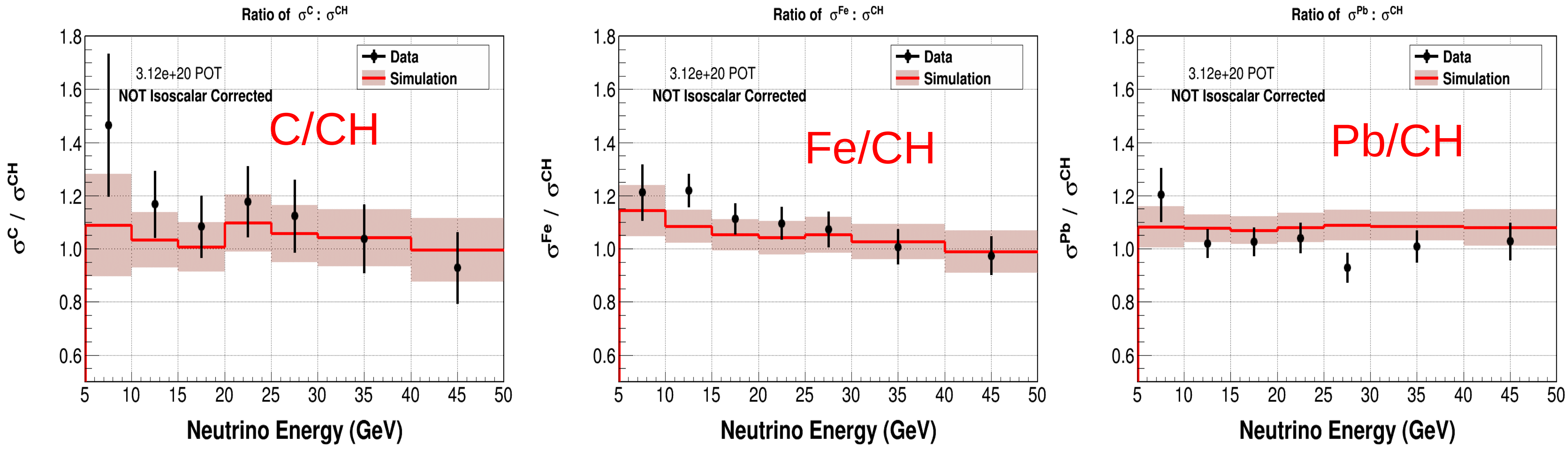
...And subtract those events to obtain a sample of DIS on carbon in data and MC. Large uncertainties on neutrino flux, measure ratios of C, Fe and Pb /CH where flux will cancel.

Efficiency and Smearing Corrections

- Detector smearing is corrected via Bayesian unfolding with one iteration.
- 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.

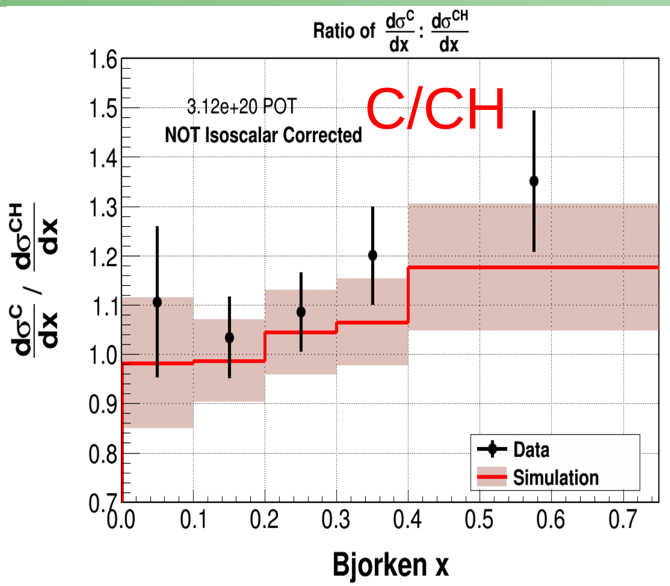


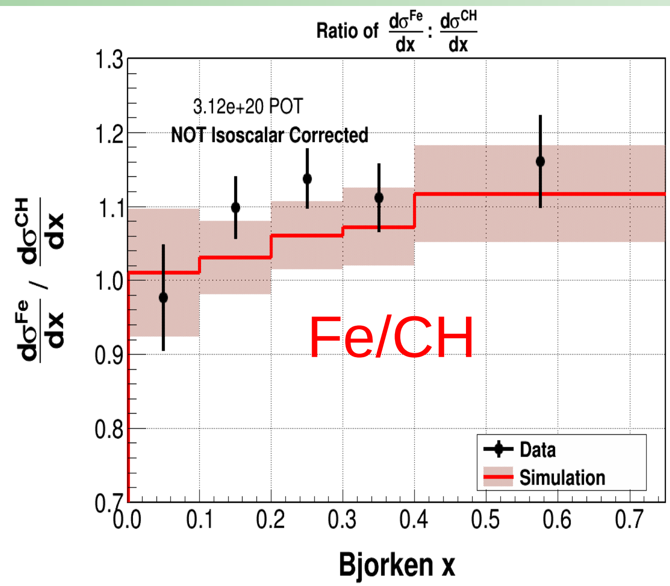
DIS Ratios: σ(E_ν)

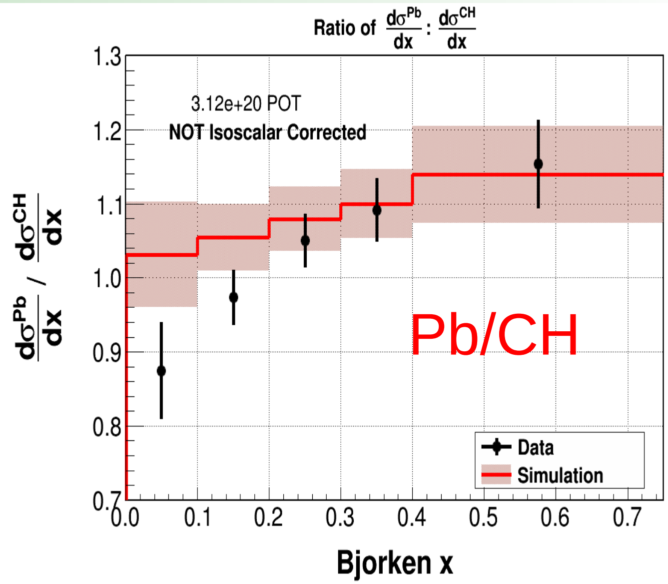


- Ratios of the heavy nuclei (Fe, Pb) to lighter CH are evidence of nuclear effects.
- Current simulation assumes the same nuclear effects for C, Fe and Pb.
- There is a general trend of the data being below the MC at high energy.
- This trend is larger in the lead than in the iron.

DIS Ratios: dσ /dx

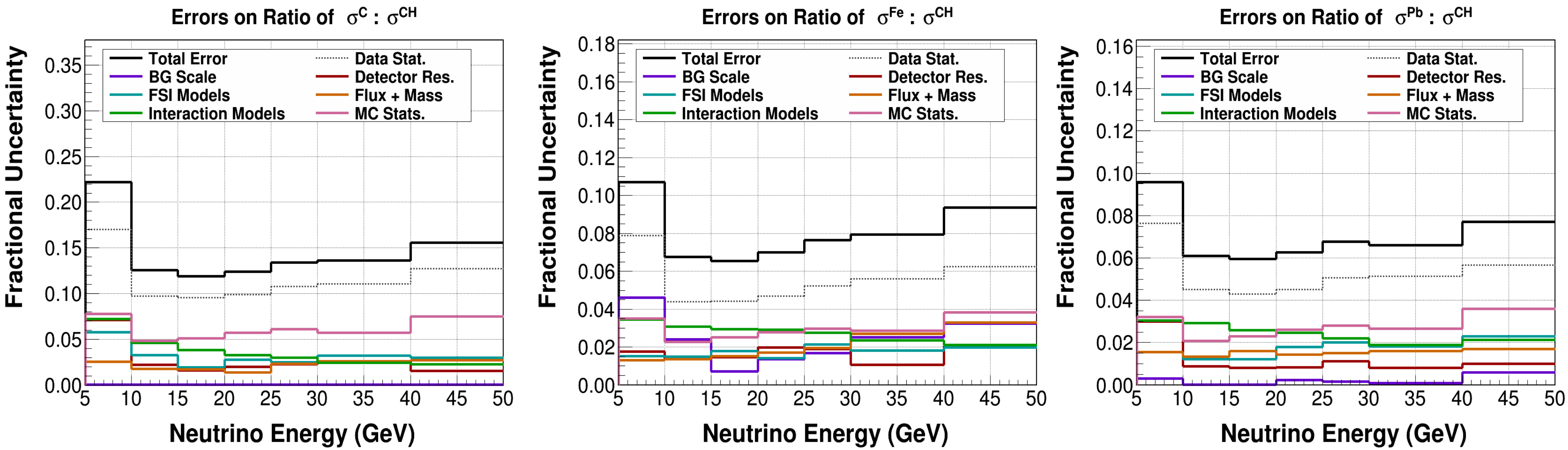






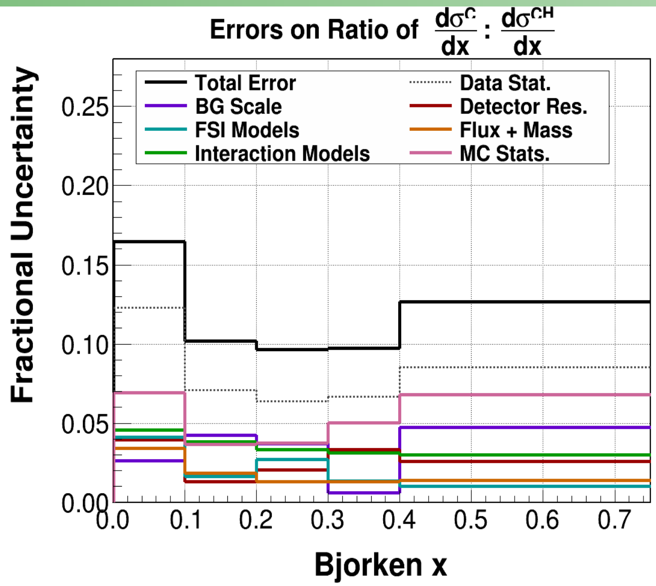
- X dependent ratios directly translate to x-dependent nuclear effects.
- Currently, our simulation assumes the *same* x-dependent nuclear effects for C, Fe and Pb tuned to e^- scattering.
- The shape of the data at low x, especially with lead is consistent with additional nuclear shadowing.
- The intermediate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

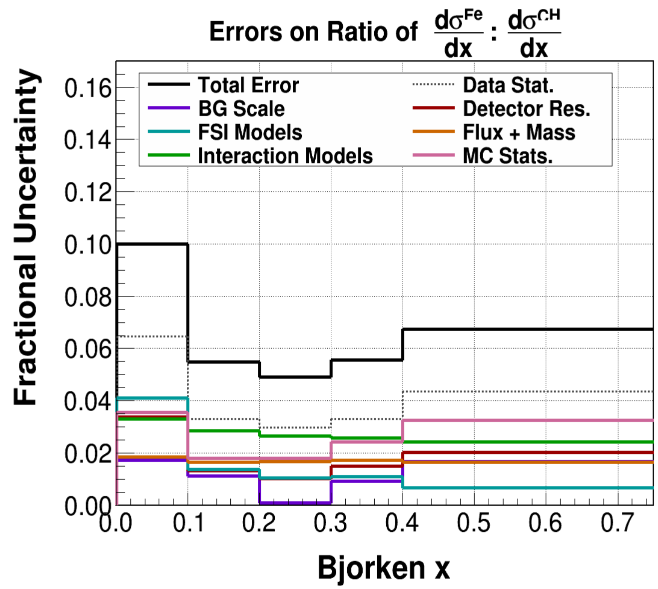
Ratio Uncertainties

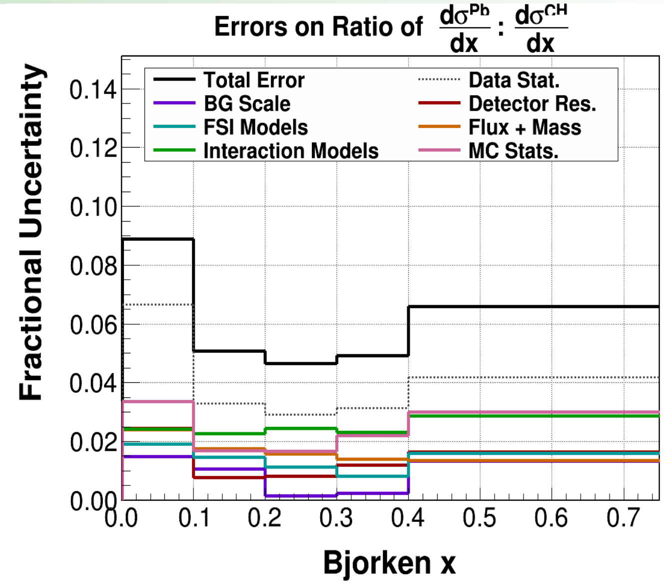


- Most of the uncertainty stems from data and MC statistics.
  - MC statistics enter during the BG subtraction and efficiency correction steps.
- Uncertainties in the Interaction model enter via the BG subtraction, and are non-trivial.

Ratio Uncertainties



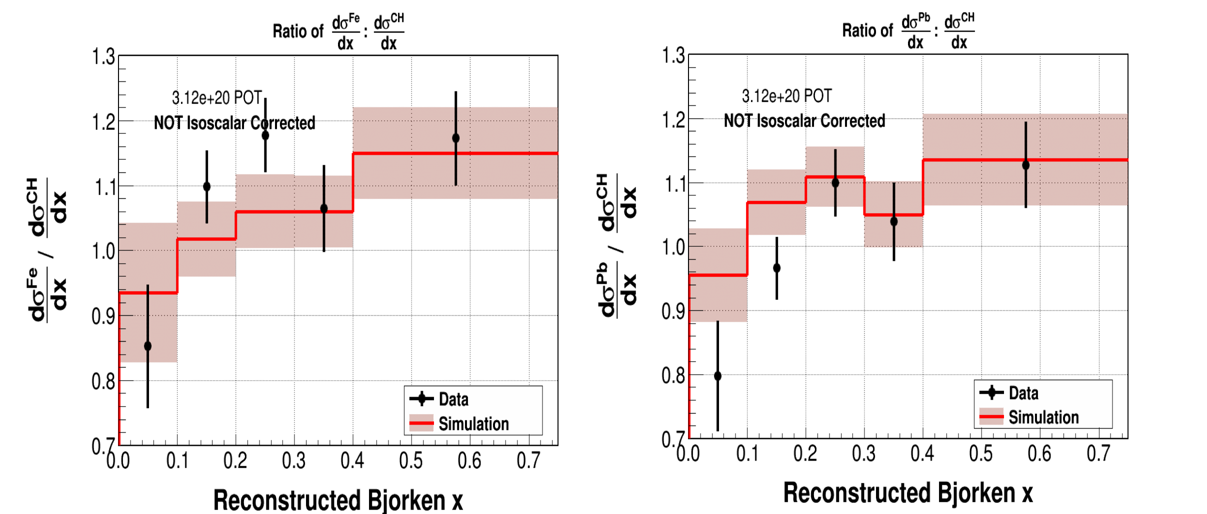




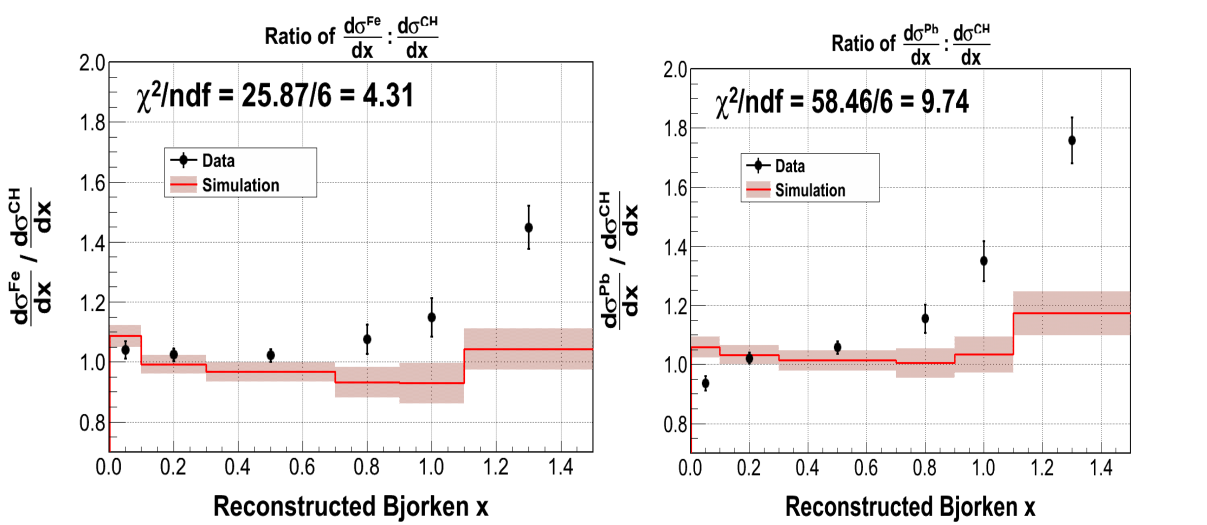
- The x-ratios are almost completely stats-dominated, especially in the shadowing ($0 < x_{bj} < 0.1$) and EMC ($0.4\ x_{bj} < 0.75$) bins.

Higher intensity, high energy data currently being taken will improve the statistical uncertainties.

DIS Compared with Inclusive



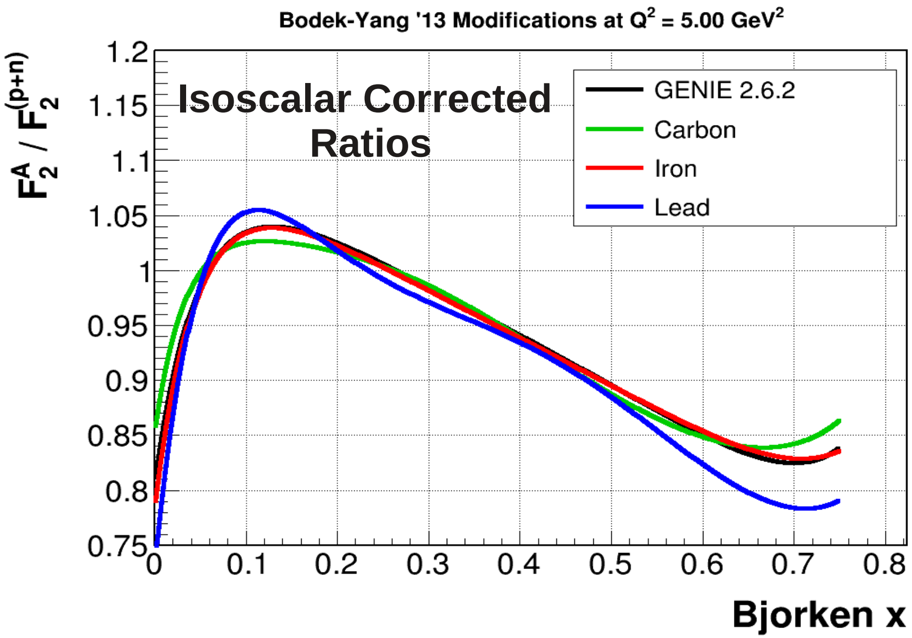
CCDIS (note different axis range)



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 and limited muon acceptance is not sufficient to measure Fermi motion effects in DIS.

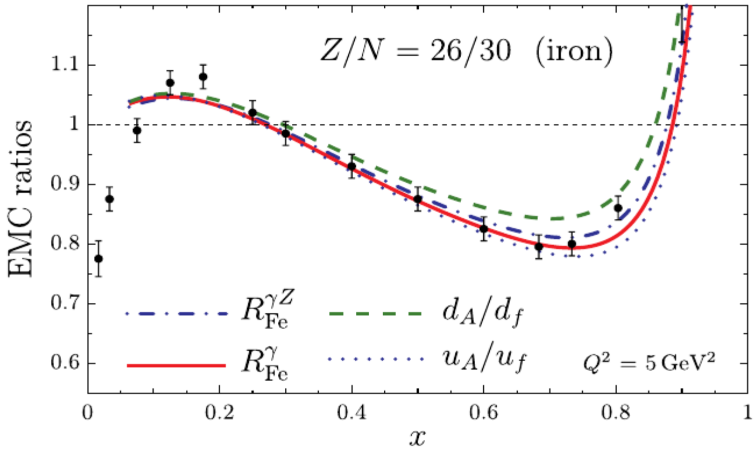
Alternative x-Dependent Models



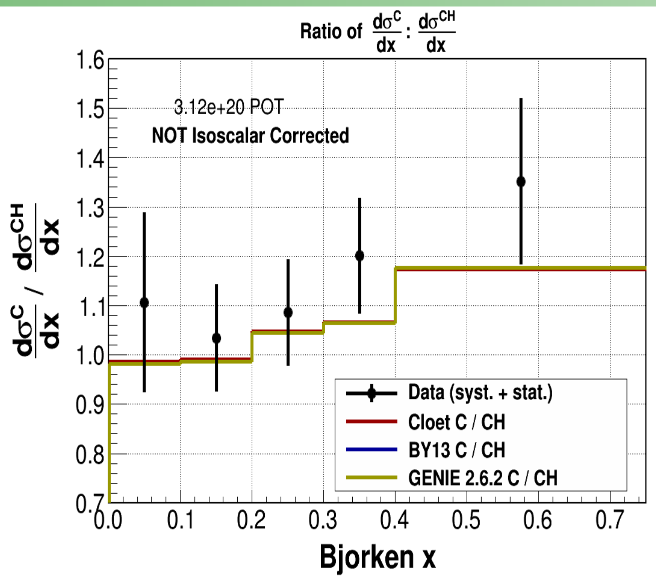
- GENIE's current parametrization of nuclear effects assumes the *same* x dependence for all nuclei heavier than He.
- Not very physically motivated. We know, for example, the EMC effect is strongly dependent on nuclear density.
- Bodek Yang 2013: update to GENIE's existing model, assumes a scaling dependent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

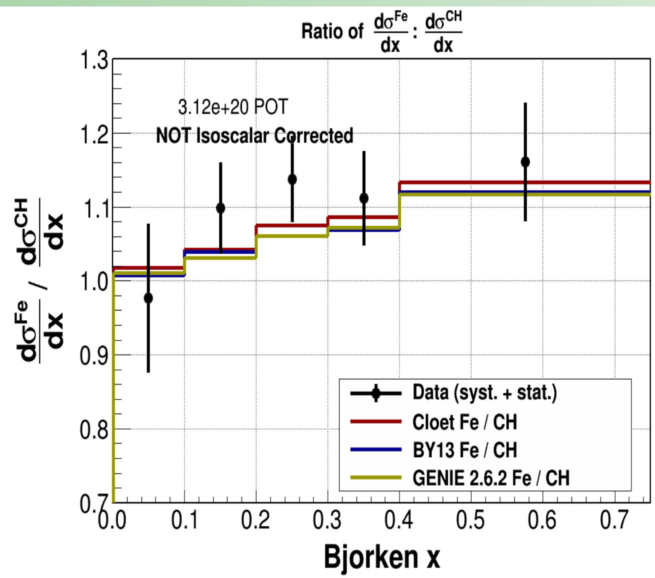
- Cloet calculation: theoretical calculation by Ian Cloet and other Argonne collaborators of the nuclear medium modification.

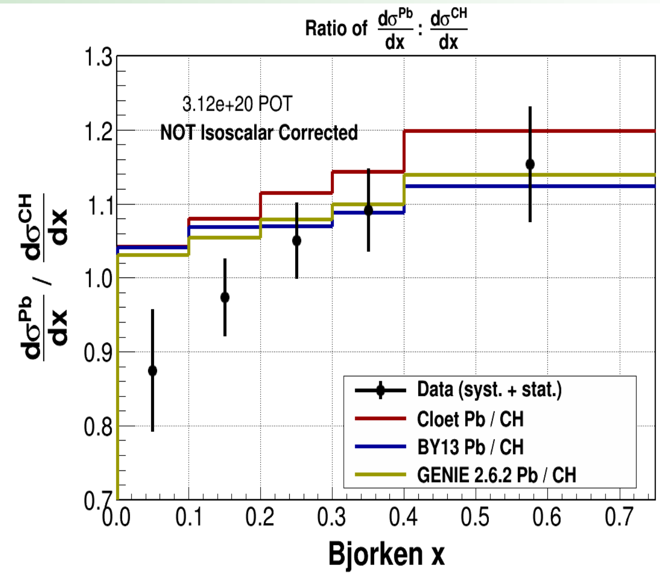
I. C. Cloet et. al. Phys. Rev. Lett. 109 182301 (2012)



Alternative x-Dependent Effects





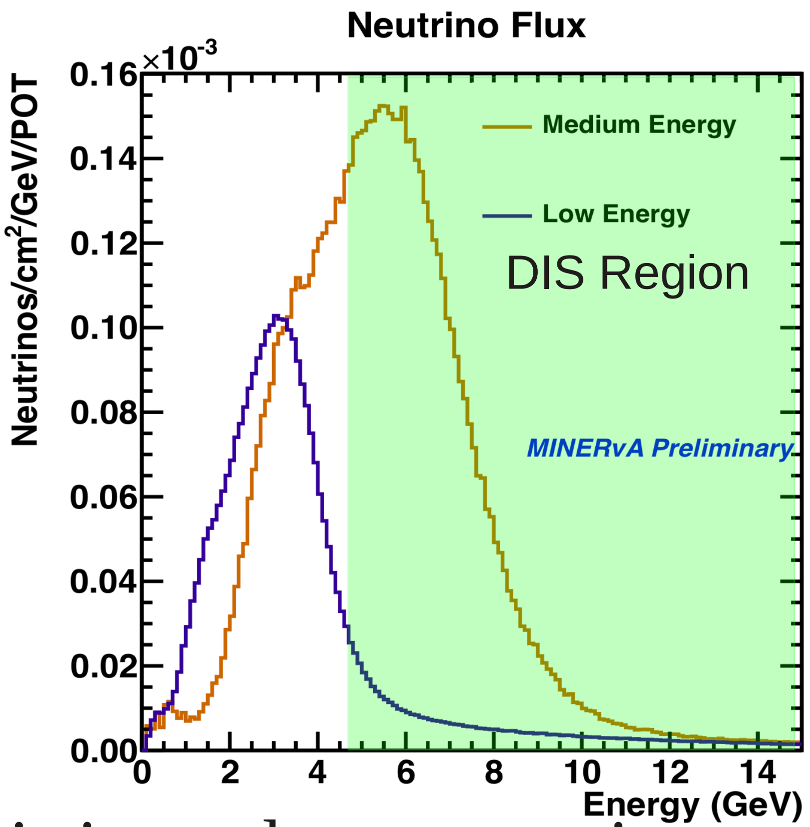


- Our data currently lacks statistical precision to differentiate between different effects, particularly on the edges of the distribution.
- But the models themselves show significant disagreements from each other, especially in the EMC region ($0.3 < x < 0.7$).
- This is strong motivation to accumulate 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

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.

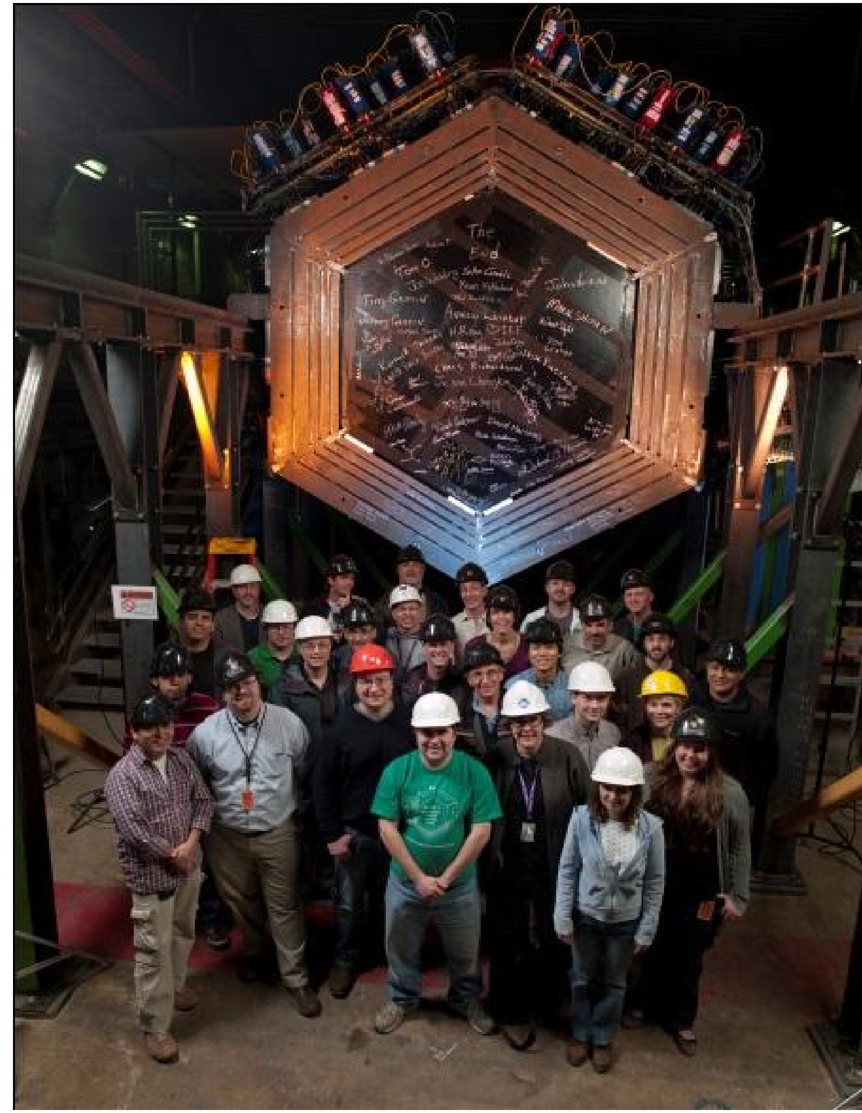
Conclusions

- 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

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



Backup

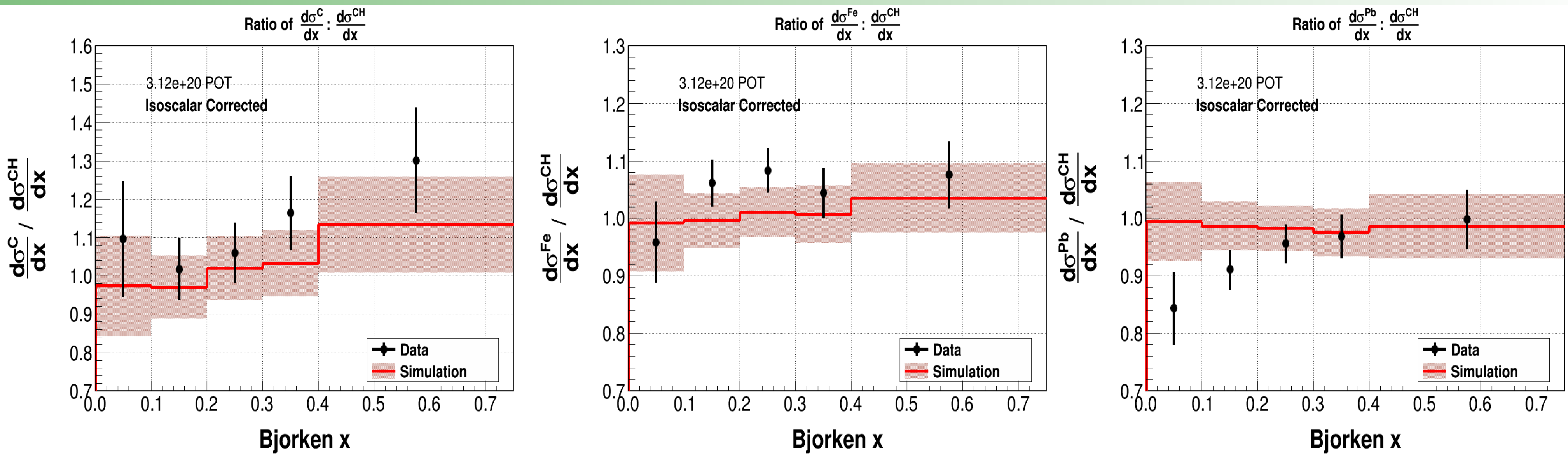
Isoscalarity

- 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.
- Correct for this using GENIE's model of neutrino free-nucleon scattering.

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

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

Isoscalar Ratios



- Ratio is reduced significantly at large x, where the valence quarks dominate.

Hadronic 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).

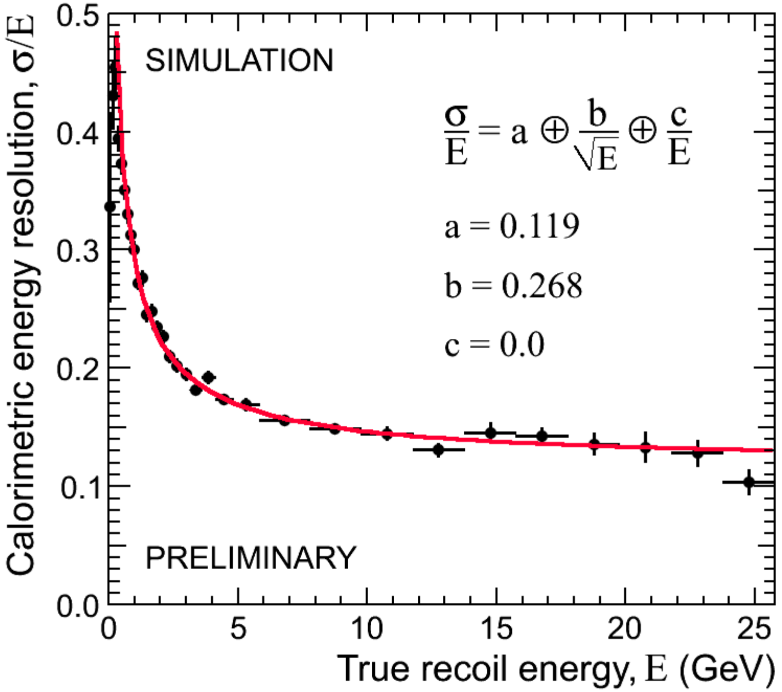
Energy lost by a minimum ionizing particle in each material

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

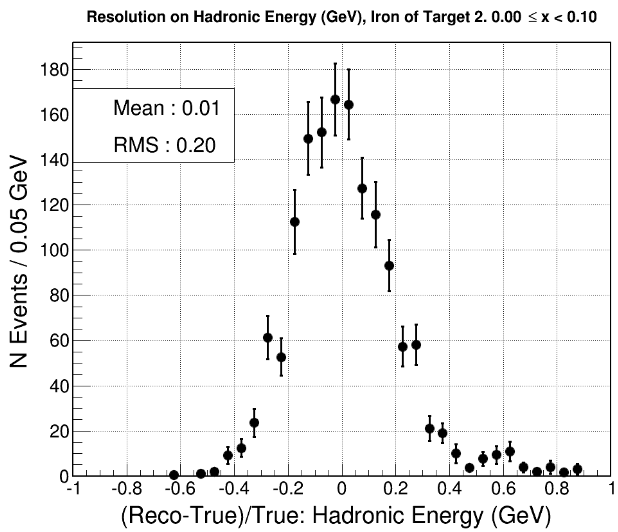
Overall scale factor (α) computed from simulation

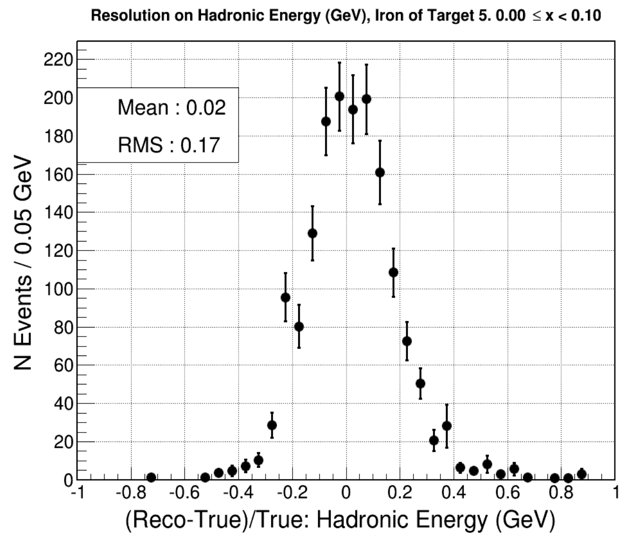
vertex	Tgt 2	Tgt 3	Tgt 4	Tgt 5	Trk
α	1.81	1.71	1.60	1.59	1.62

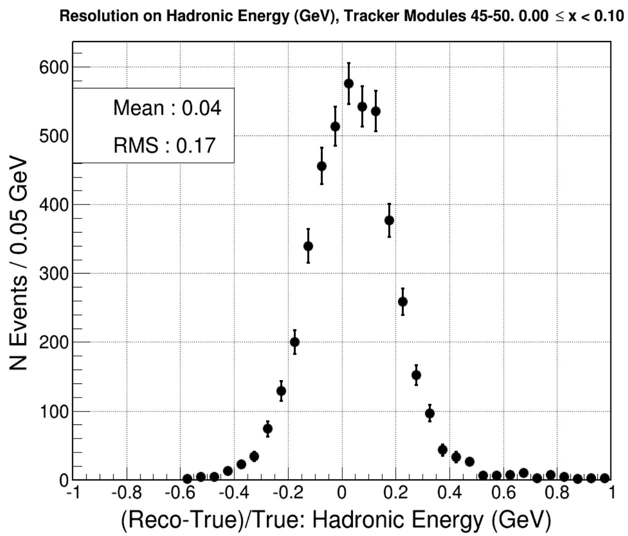
Recoil energy resolution in scintillator



Hadronic Energy Resolution





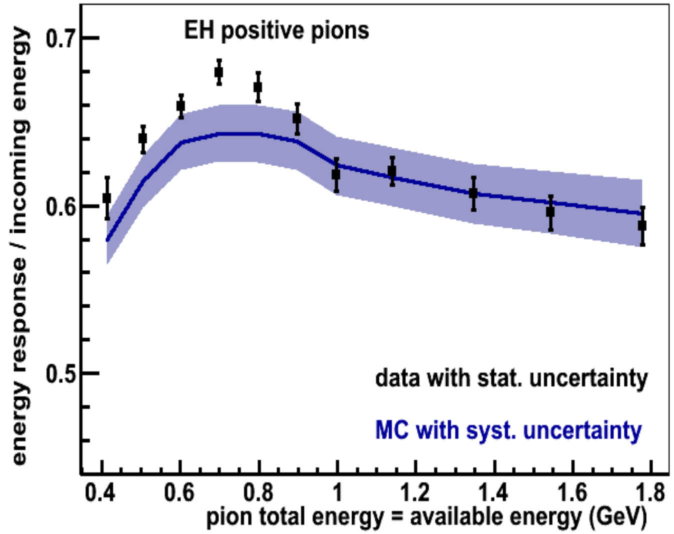


Downstream

- Hadronic energy resolution consistent across targets.
- Lowest x-bin (high energy showers).

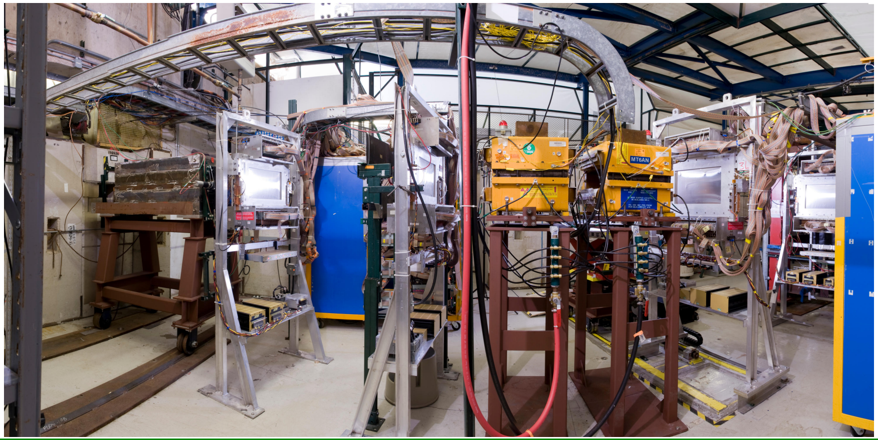
Test Beam

- 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.

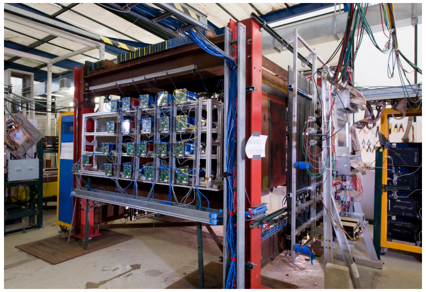


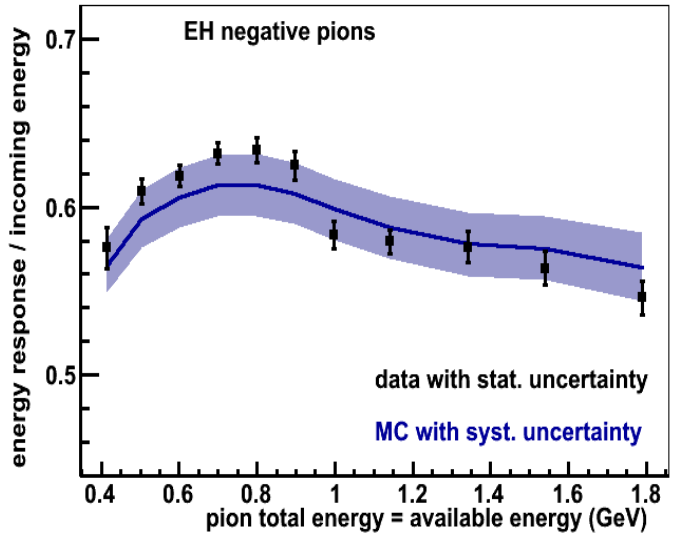
Aliaga L. et. Al. NIM A789 (2015) 28

Custom built beamline



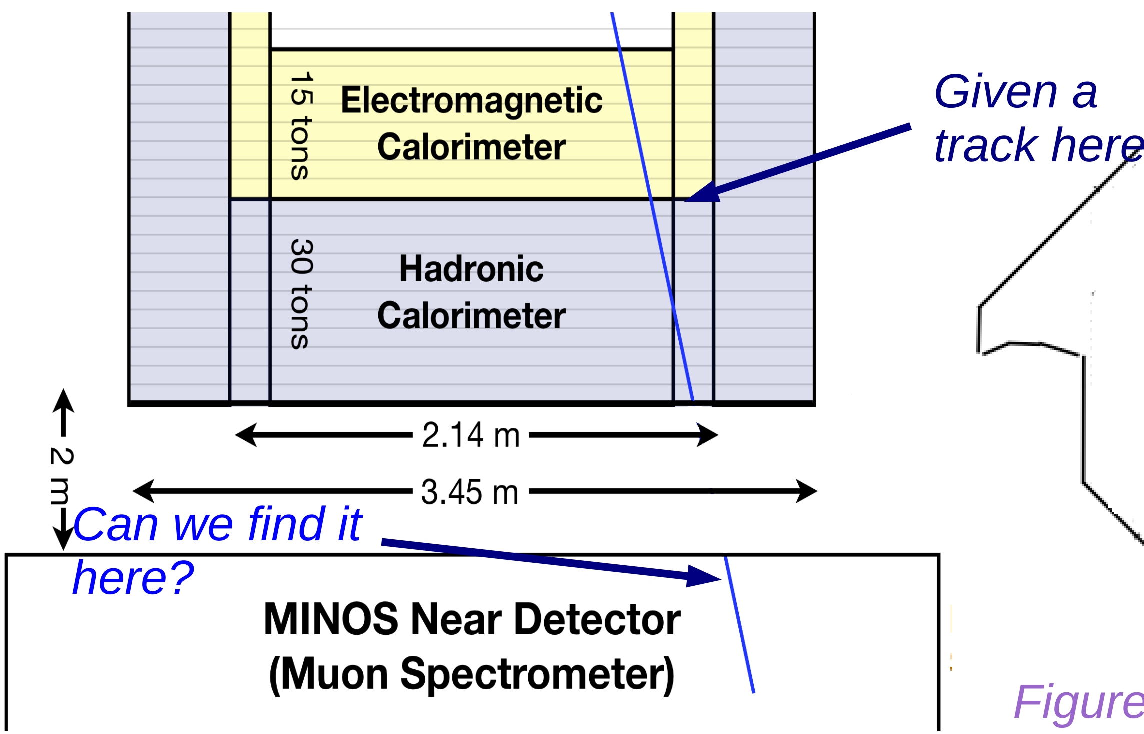
Plus miniature detector





MINOS Matching

- 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.



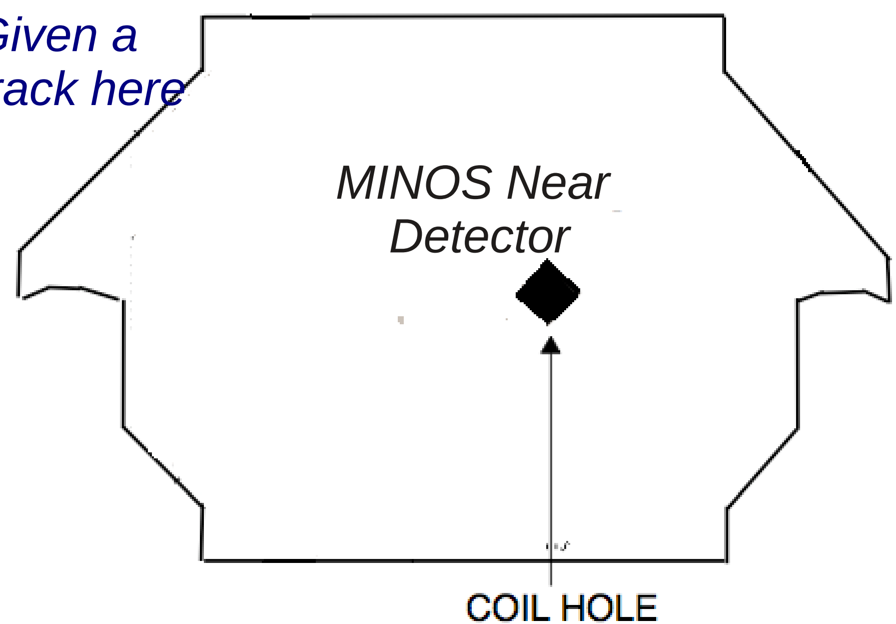
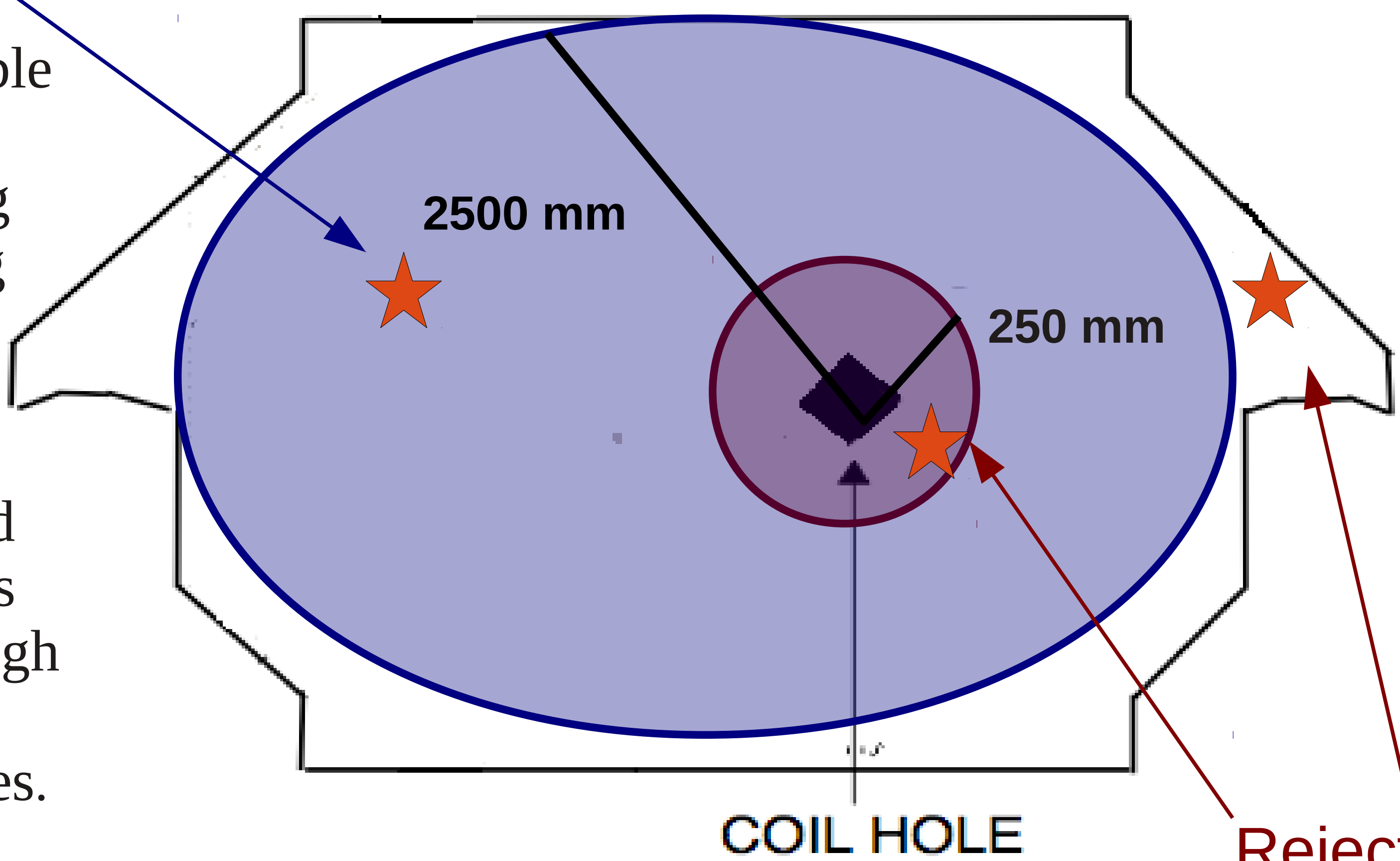


Figure adapted from P. Adamson et. al. Phys.Rev. D91 (2015) 012005

MINOS Coil Cuts

Accept Events in this region...

- 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.



Reject Events in these regions

Event Table

X_{bj} (unfolded)	C	Fe	Pb
0 – 0.1	90	310	310
0.1 - 0.2	270	1200	1220
0.2 – 0.3	250	1160	1230
0.3 – 0.4	140	580	690
0.4 – 0.75	100	390	460
0.75+	1	1	2
TOTAL	850	3640	3900

Shadowing

Anti-Shadowing

EMC

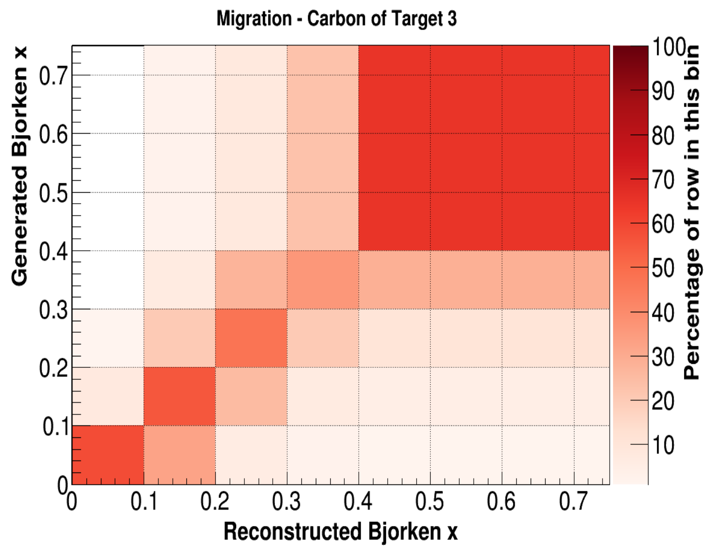
Fermi Motion

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

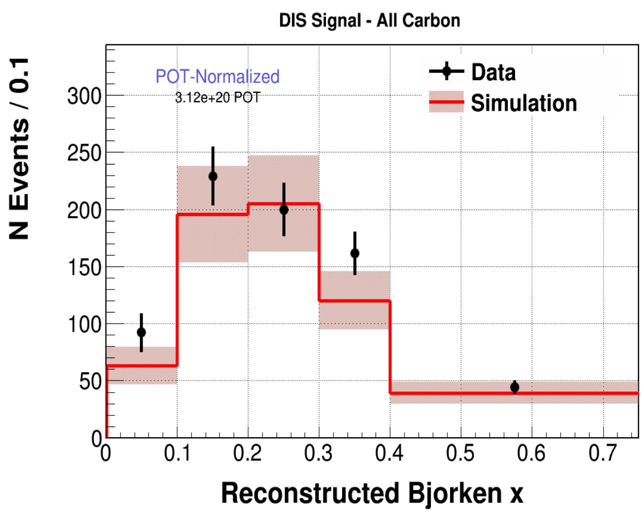
Migration and Unfolding

- 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.



Migration Matrices used as input



Unfold using Bayesian unfolding With 1 iteration