Charged-Current Inclusive Cross Section Ratios with $\theta_\mu < 17°$ at MINERvA

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9th International Workshop on Neutrino-Nucleus Interactions in the Few-GeV Region
Surrey, UK
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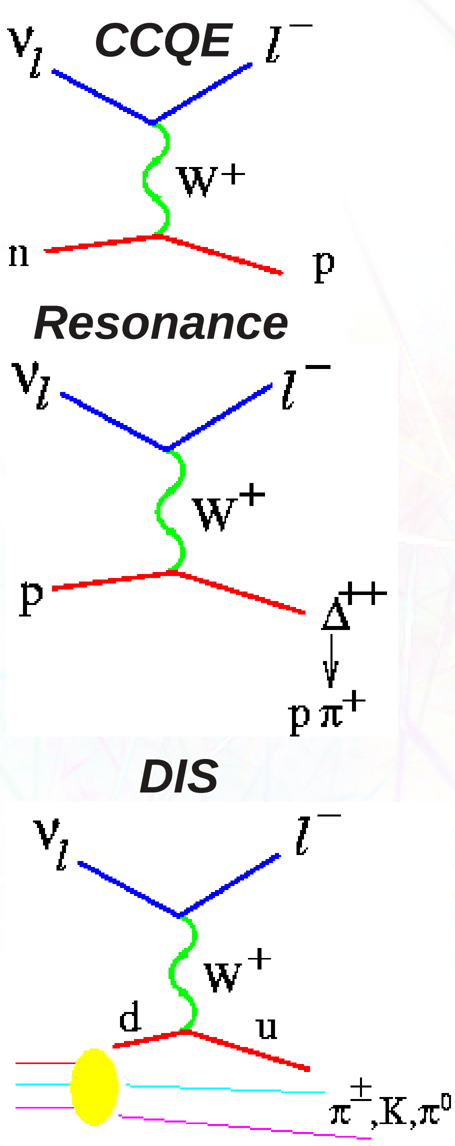
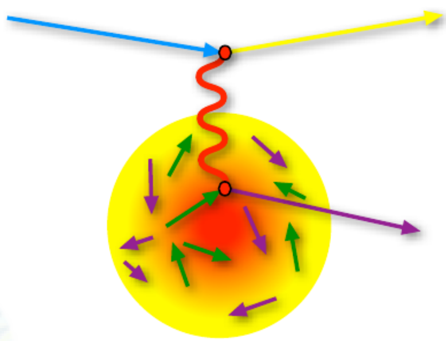
CC Inclusive Events Introduction



- Neutrino CC Inclusive: all neutrino events with a nucleon as a target mediated by the W^+ boson, regardless of specifics of the final state of the nucleus.
- Sum of CCQE + resonance + transition + DIS.
- Inclusive cross sections are commonly used for detector calibrations and to cross-check event generators.
- You need to understand the inclusive cross section before you understand specific channels!

Nuclear Effects in Neutrino Scattering

- One common theme of contemporary neutrino experiments: they rely on large A materials to supply adequate event rates (Fe, Ar, C, etc.)



Complicated physics inside the nucleus!

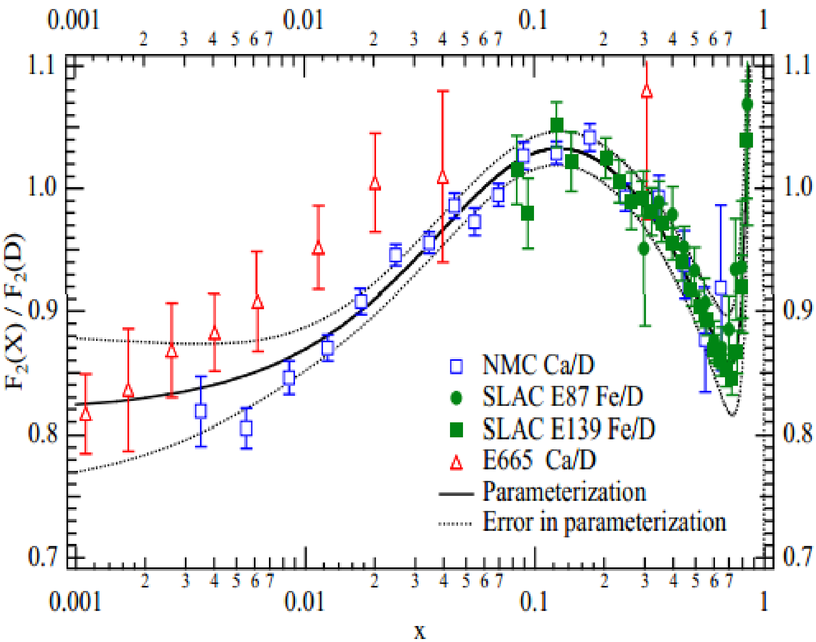
- Problem: nuclear effects caused by nucleons being bound in a nucleus distort the energy reconstruction of the neutrinos.
- Two detectors does not solve your problem! Nuclear effects are E_ν dependent, and the energy spectrum between near/far detectors is not the same.
- Effects not well understood in neutrino physics. General strategy has been to adapt electron scattering effects into neutrino event generators.

Neutrino Nuclear Effects

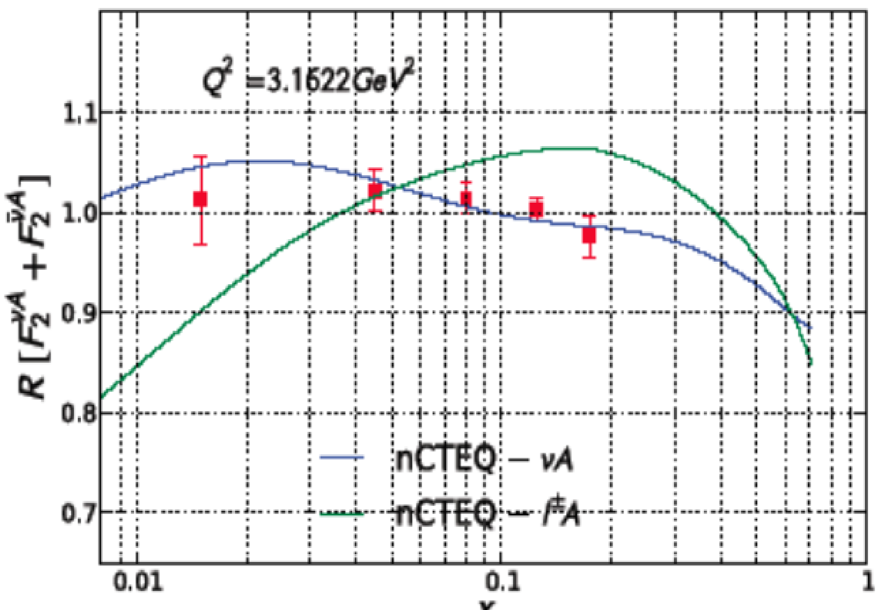
Traditional methods to incorporate x dependent nuclear effects into neutrino event generators is to adapt existing e^- scattering data... (Bodek-Yang)

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

...or use existing neutrino data + predicted pdfs to fit underlying structure functions (CTEQ).



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

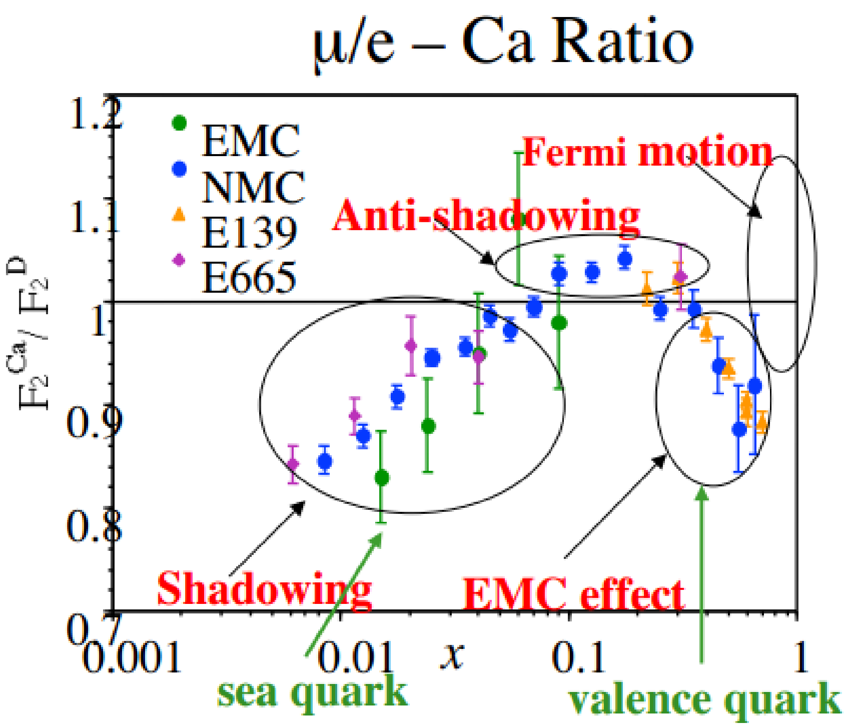


J.G.Morfĺn, J Nieves, and J.T. Sobczyk Advances in High Energy Physics, vol. 2012, Article ID 934597

In both cases, need more neutrino data to correctly model these effects!

Charged Lepton Scattering Nuclear Effects

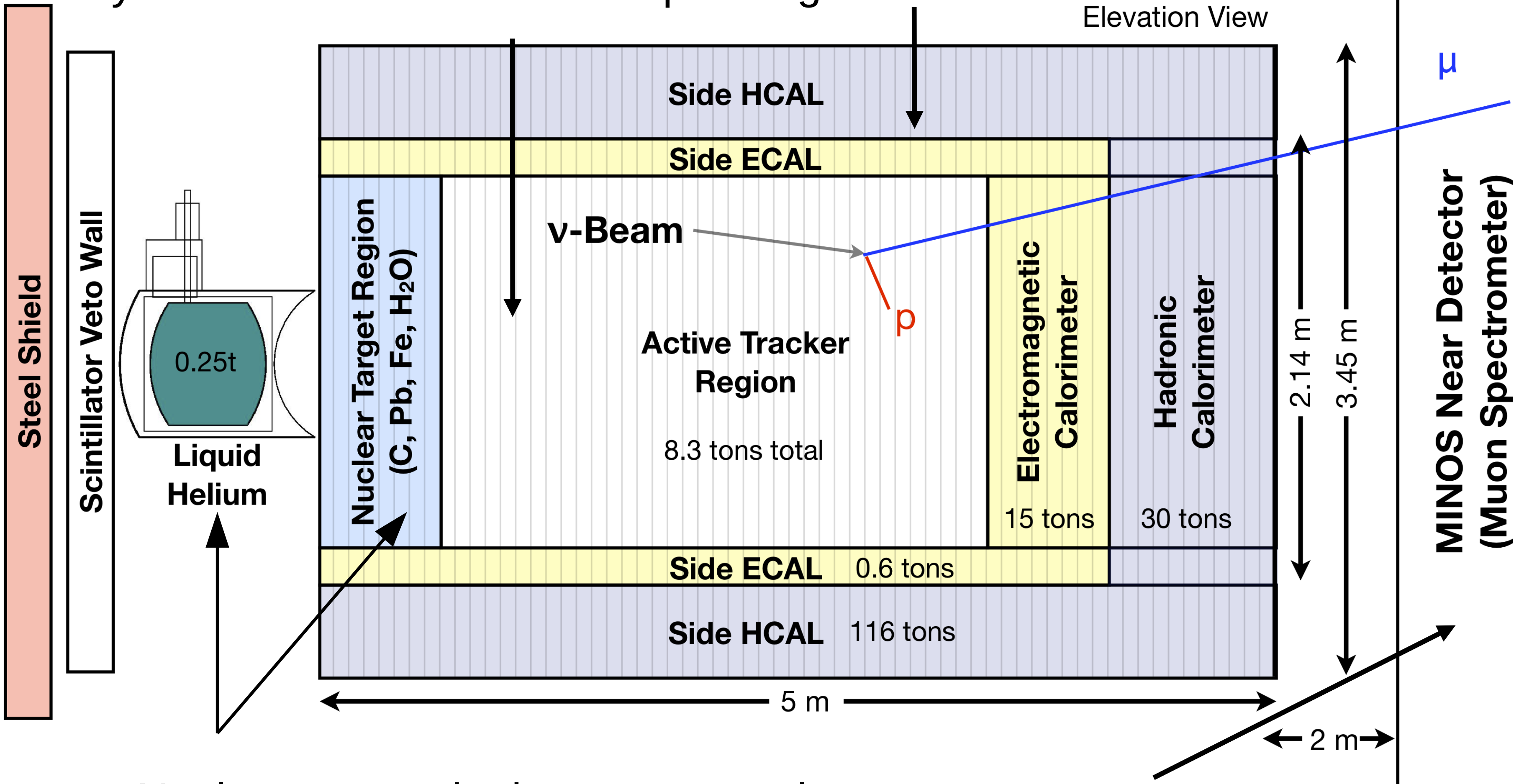
- However, there are some difficulties incorporating charged lepton data...
- For example, neutrinos are sensitive to the axial component of xF_3 and F_2.
- Charged lepton nuclear effects still not fully explained.



- Despite ~30 years of active research, EMC effect still not fully understood.
- Moral: ν + A data is needed not only to model the nuclear effects, but also understand the fundamental physics.

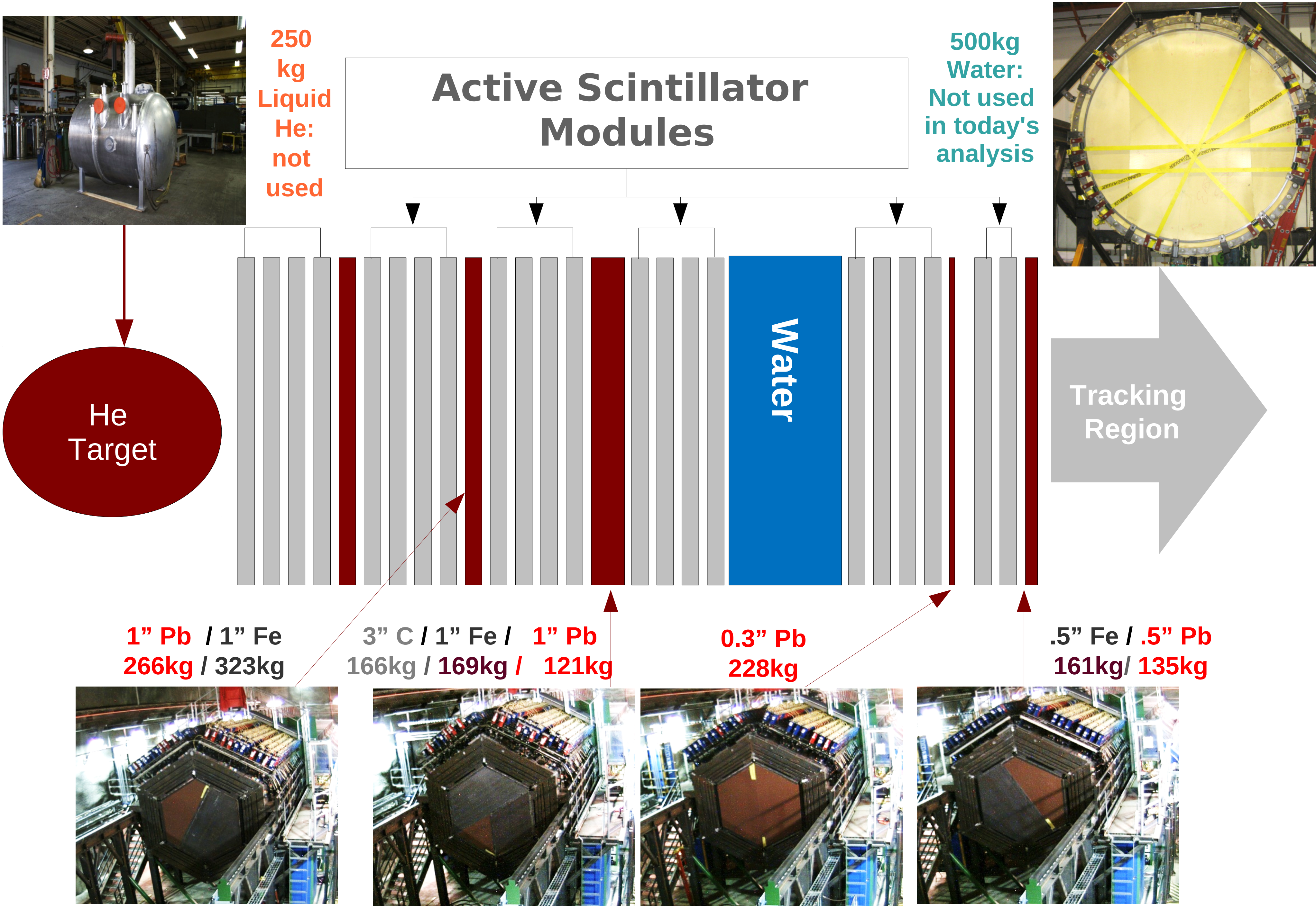
Enter MINERvA

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

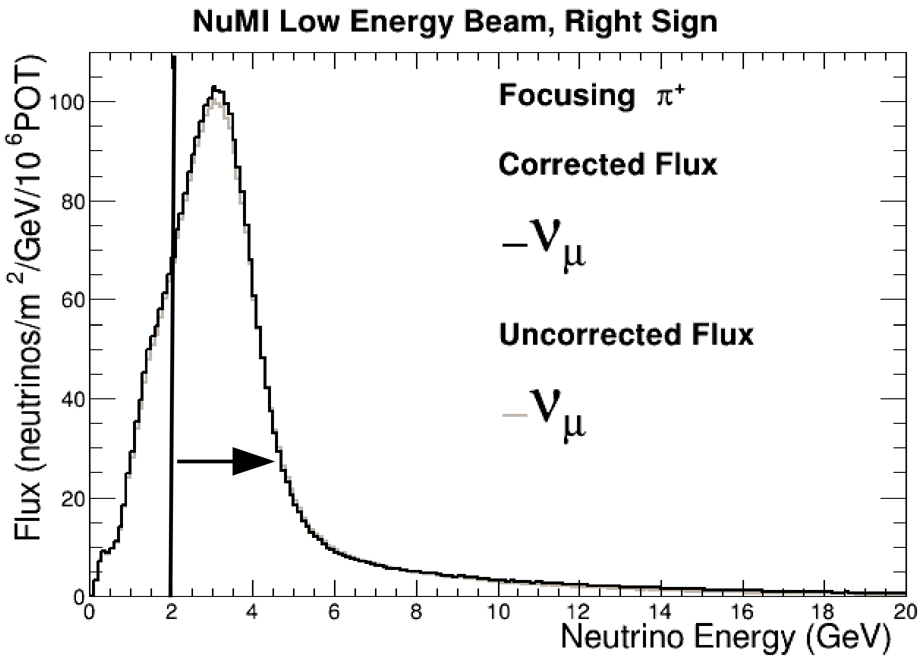


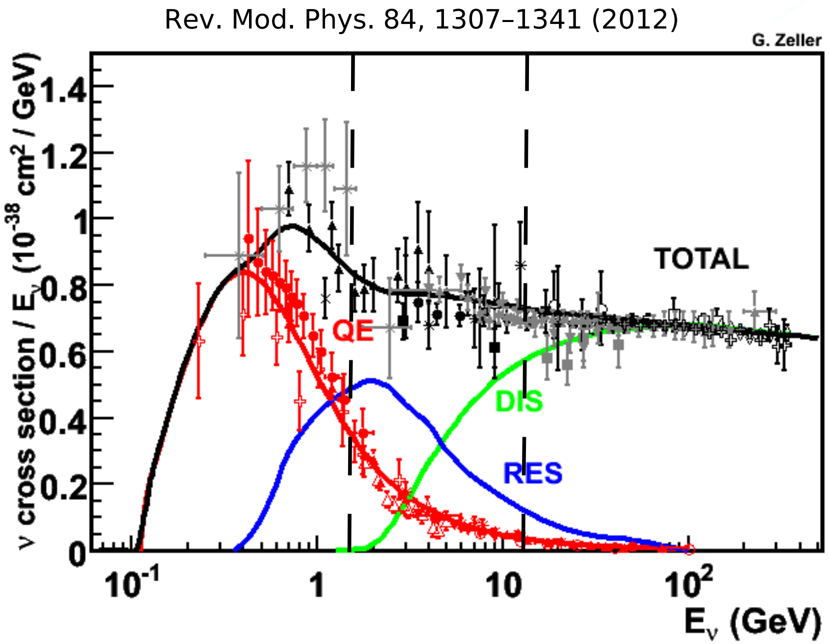
Nuclear targets in the same neutrino beam (as in EMC) allow MINERvA to make A-dependent physics measurements.

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

Neutrino Energy Range



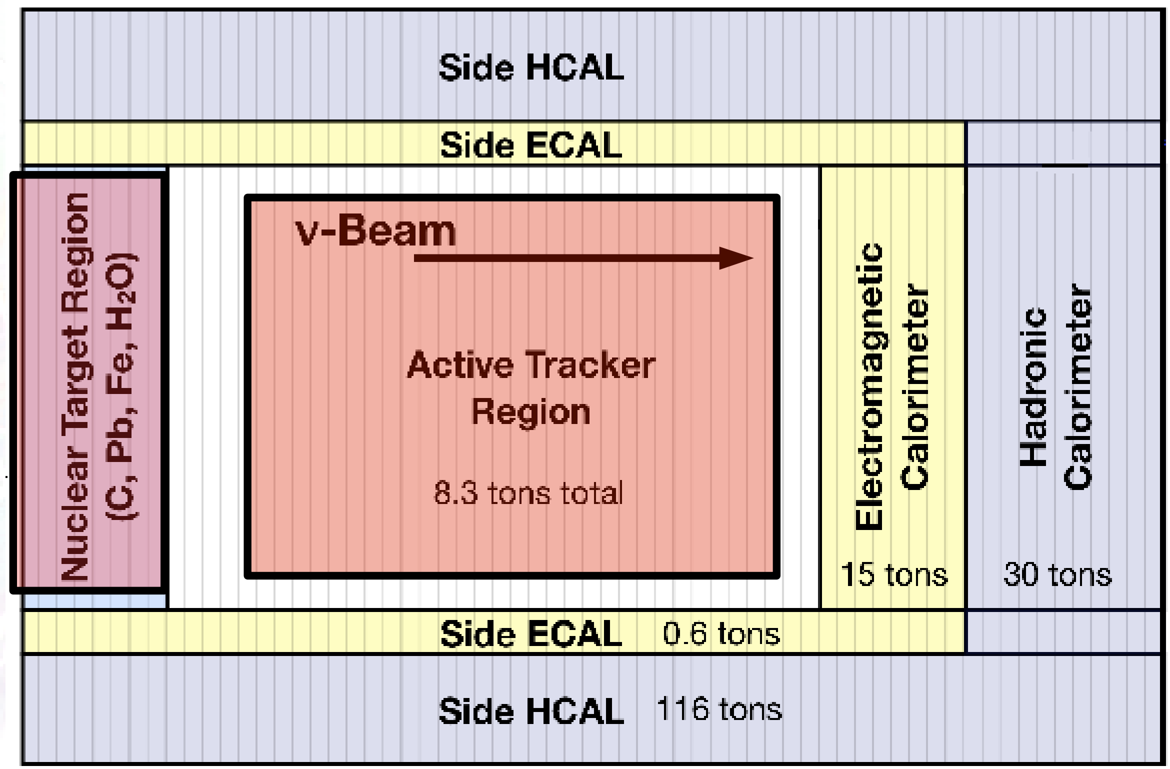


- Neutrinos are generated by the NuMI beam line at Fermilab.
- Today's presentation uses the “low energy” (peak 3 GeV) υ_μ NuMI configuration. Neutrinos with an energy between 2 and 20 GeV are analyzed.
- For more details on the NuMI beamline and how we estimate our flux, see D. A. Harris's talk on Friday.

Event Selection

Inclusive event: an event with at least on track (outgoing muon) + possible extra detector activity.

Events are selected in the passive material in the nuclear target region to form a sample of Fe, Pb and C events.

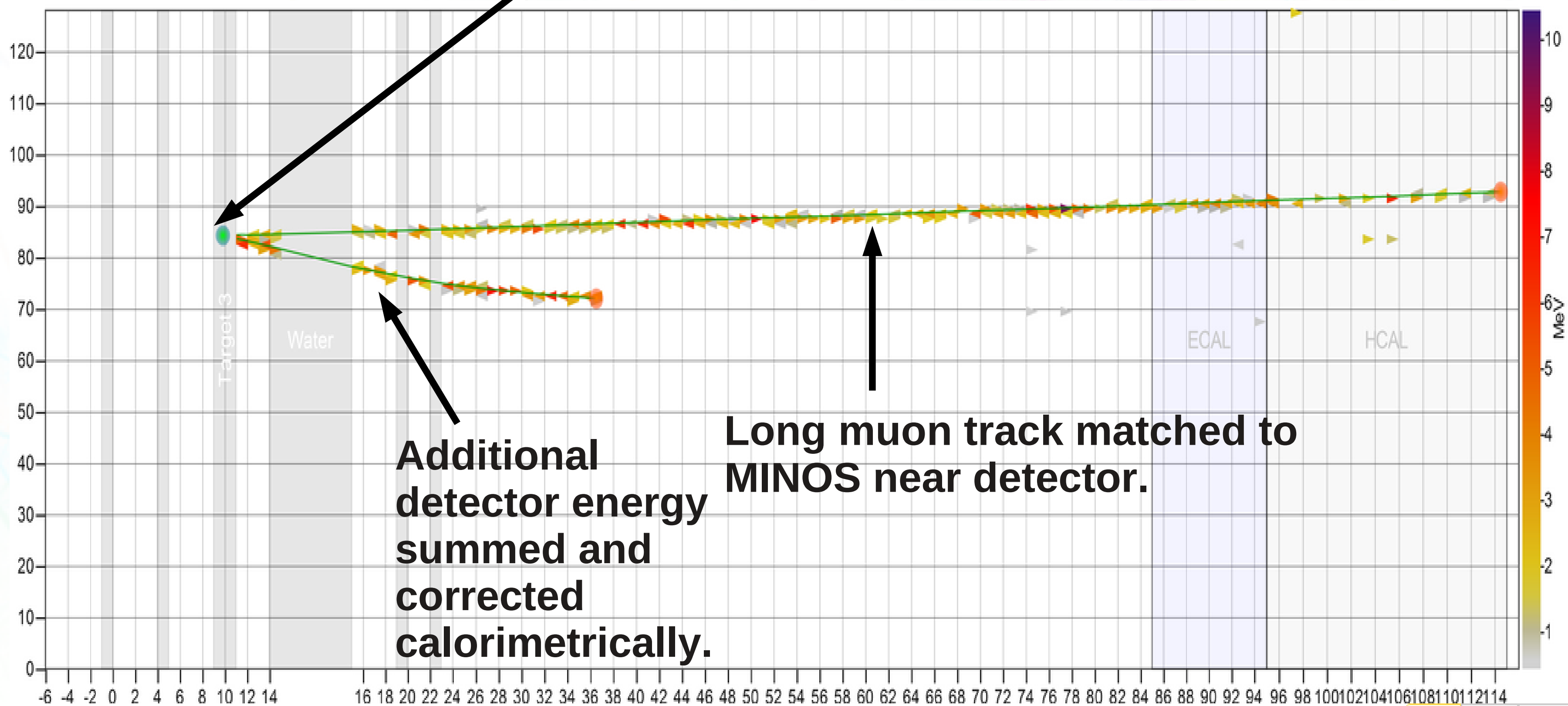


We further select events in the tracker region to from a sample of CH events.

To reduce systematic uncertainties, the σ *ratio* of C/CH, Fe/CH and Pb / CH are measured.

Reconstruction Overview

Event is reconstructed with a vertex in a nuclear target (target 3).
Both tracks in this case are used to fit the vertex.



Additional detector energy summed and corrected calorimetrically.

Long muon track matched to MINOS near detector.

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).

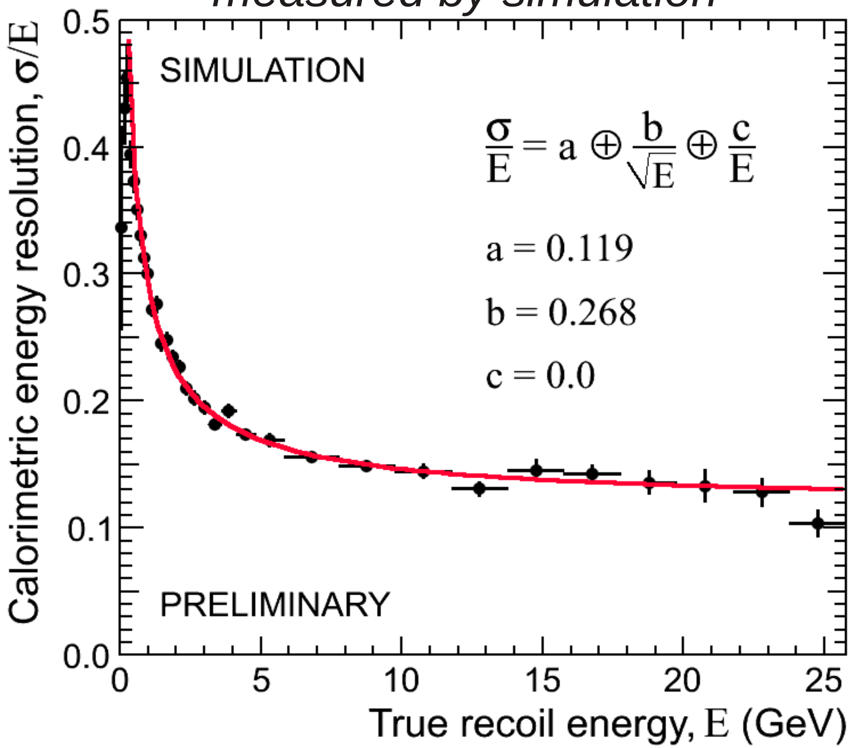
Energy lost by a mip in each material

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

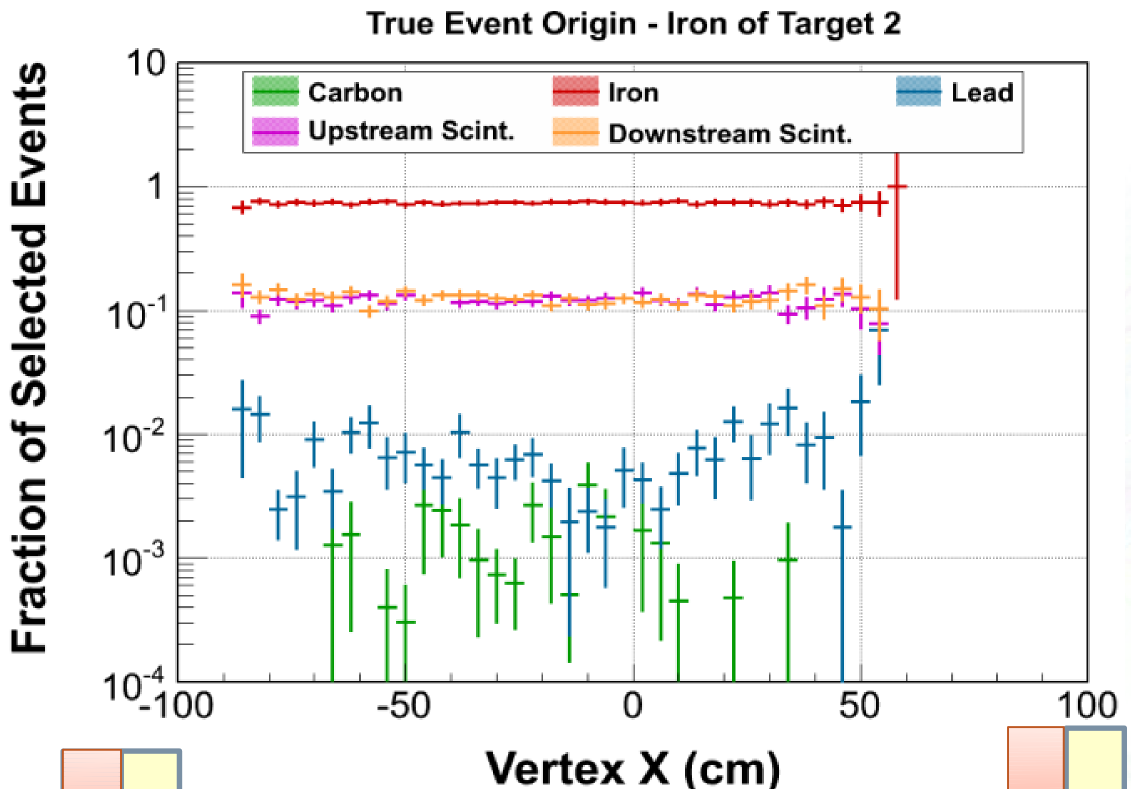
Overall scale factor (α) computed from simulation

vertex	Tgt 2	Tgt 3	Tgt 4	Tgt 5	Trk
α	1.78	1.67	1.59	1.57	1.60

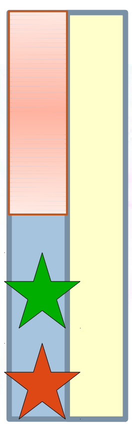
Tracker recoil energy resolution as measured by simulation



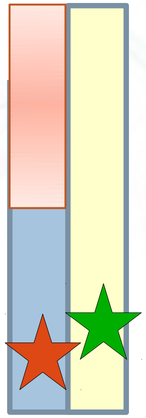
Background Events



One-track vertex events occasionally truly occur in the scintillator surrounding the nuclear target, but are reconstructed to the passive target. This makes up the largest background.

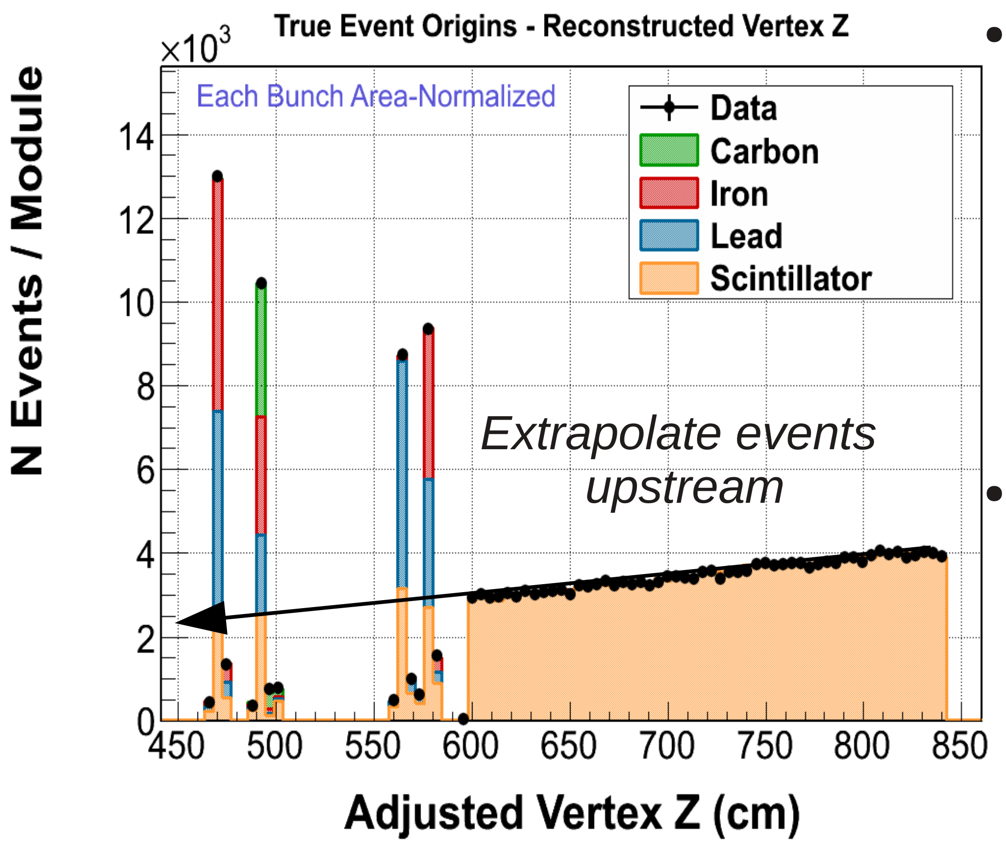


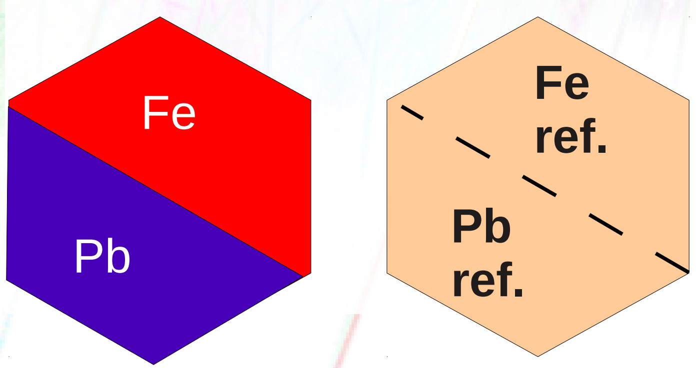
True vertex (green star) is in the same material as the reconstructed vertex (orange star).



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

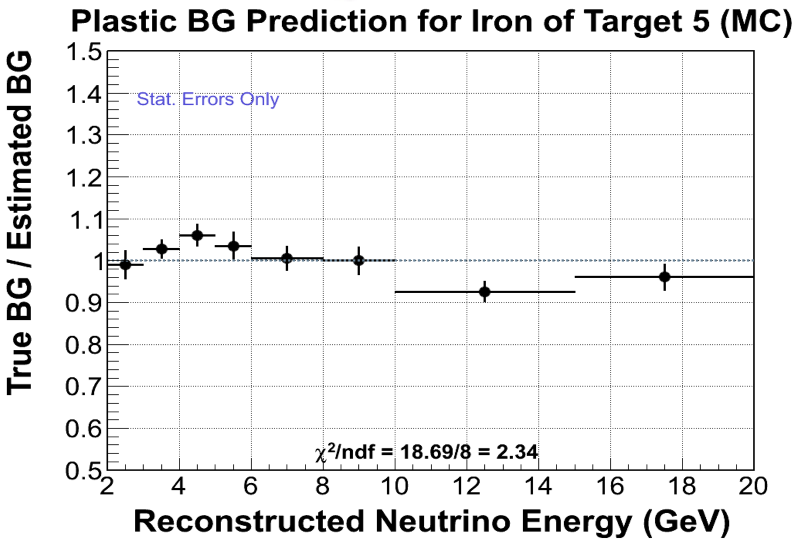
Background Subtraction

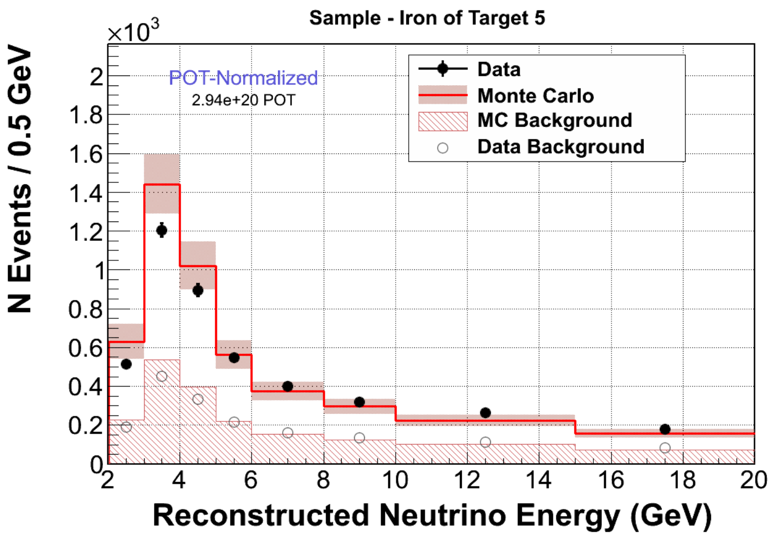




- We subtract this background by measuring the event rates in the downstream tracker, and extrapolating these events upstream to the nuclear target region.
- Downstream events are weighted for MINOS acceptance based on E_μ, θ_μ and a E_{had} based weight which accounts for tracking inefficiency.
- Extrapolation is done by matching the same transverse section of the detector between modules

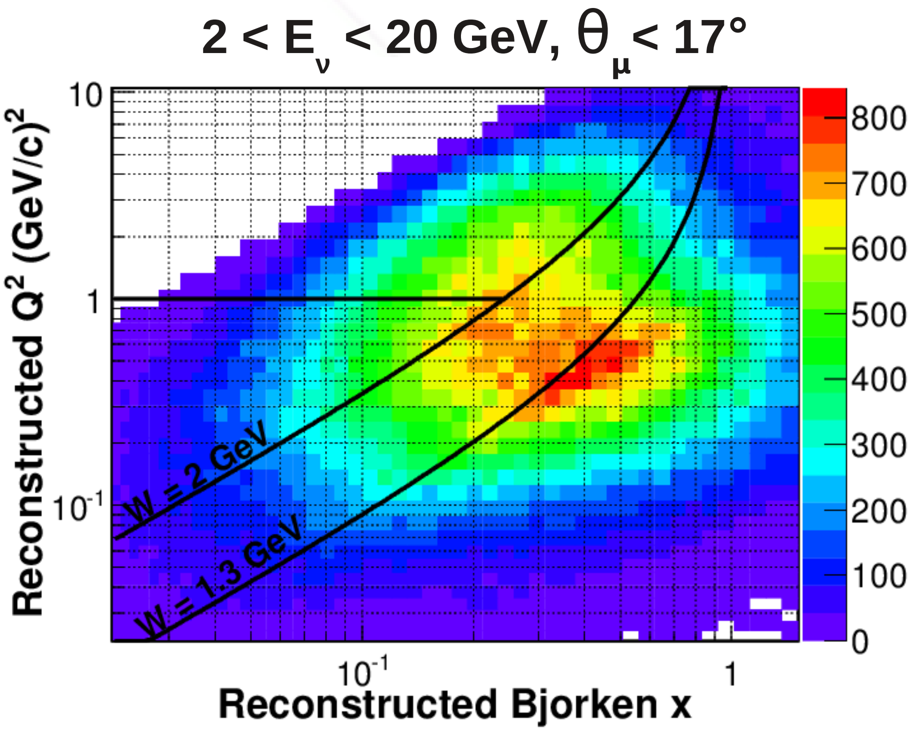
Background Subtraction Accuracy

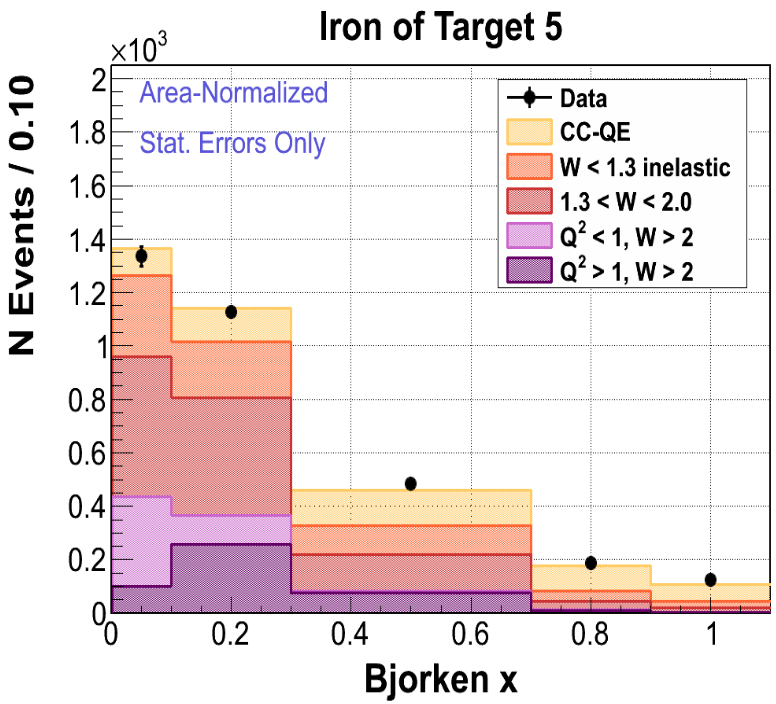




- Top plot shows the true BG from MC / estimated BG.
- Additional uncorrelated uncertainty added to this fraction until the χ^2 / dof = 1.
- Background extracted separately for data and MC, shows good agreement (bottom plot).
- Other backgrounds (wrong sign, neutral current) are < 1 %, and originate as muons mis-identified in MINOS.

Event Composition





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

$$W = \sqrt{M^2 + 2ME_{had} - Q^2}$$

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

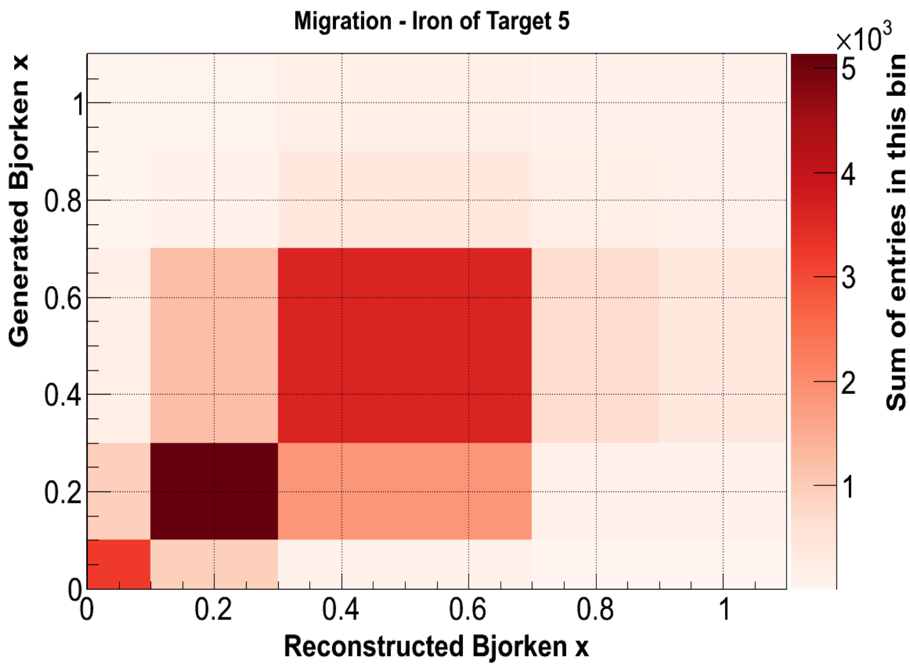
- Not truly "Inclusive" due to the θ_μ cut
- Q^2 region sculpted by MINOS acceptance: low θ_μ → low Q^2.
- Dominated by CCQE and low W events (resonance + transition).

CAUTION: Low Q^2 Ahead

- X-dependent nuclear effects are traditionally measured in an highly inelastic region ($Q^2 > 1$ GeV^2, W > 2 GeV).
- This is *not* the kinematic region of the MINERvA data set, which has a mean Q^2 between 0.23 and 1.0 GeV^2.
- This is, however, the energy and Q^2 region typical of oscillation experiments.
- What we end up measuring is a mixture of nuclear effects from CCQE, Resonance, transition and traditional DIS.

Reconstructed x	QE (%)	Res. (%)	DIS (%)	soft DIS (%)	Non-res. Inelastic Cont. (%)	Generated Q^2 (GeV^2) (Mean)
0.0–0.1	11.3	42.5	5.9	19.2	15.7	0.23
0.1–0.3	13.6	36.4	16.7	9.1	23.0	0.70
0.3–0.7	32.7	32.8	11.8	1.4	21.1	1.00
0.7–0.9	55.1	25.4	4.3	0.5	14.6	0.95
0.9–1.1	62.7	21.6	2.8	0.5	12.3	0.90
1.1–1.5	69.6	18.1	1.9	0.4	9.9	0.82
> 1.5	79.1	12.8	0.6	0.3	7.1	0.86

X Migration



Each cell is the percent of events generated in that x bin

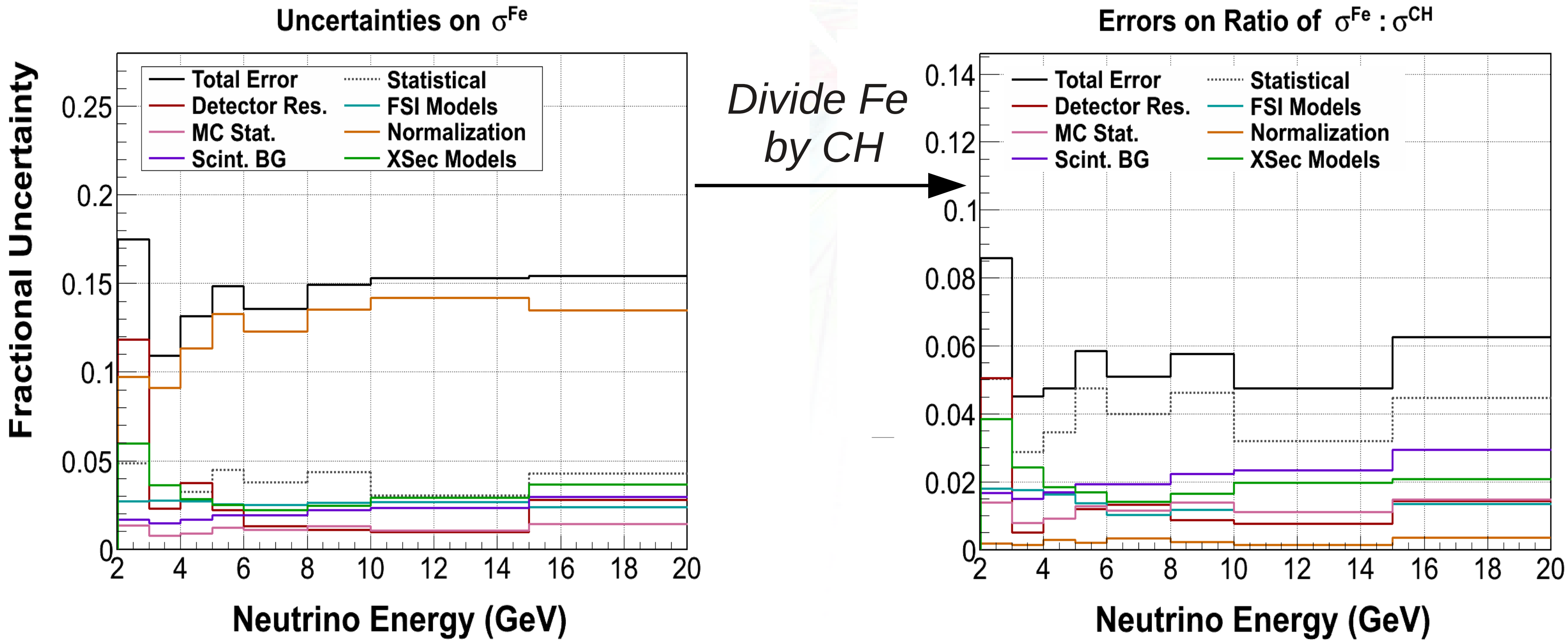
Generated x

x bin	0.0–0.1	0.1–0.3	0.3–0.7	0.7–0.9	0.9–1.1	1.1–1.5	overflow
0.0–0.1	73	23	3	0	0	0	0
0.1–0.3	12	60	23	2	1	1	2
0.3–0.7	4	20	47	9	5	6	9
0.7–0.9	2	11	30	11	9	10	26
0.9–1.1	2	8	30	12	6	10	31
1.1–1.5	3	7	21	8	8	14	38

- Migration in x is severe, especially in the x > 0.3 bins.
- Poor x resolution in this region stems from CCQE events, where calorimetry is an inappropriate technique for recoil energy reconstruction.
- Typical unfolding methods (Bayesian) do not converge with migration this severe.
- Solution is to “fold” the generated MC x distribution using the smearing matrix rather than unfold data.

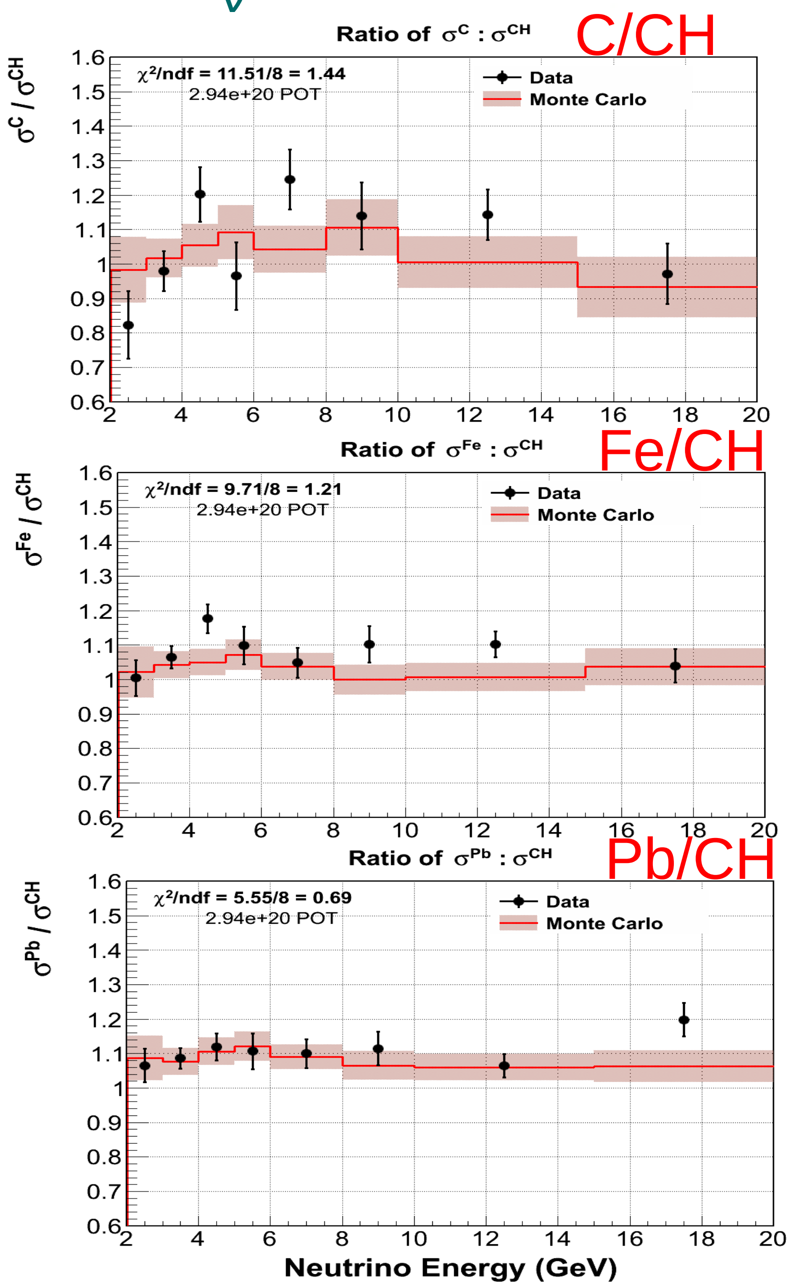
Absolute Cross Sections

- Absolute cross sections on CH, C, Fe and Pb are measured, but we present measurements of the *ratios* of C / CH, Fe / CH and Pb / CH .
- Ratio measurements reduce the systematic uncertainty substantially, especially the normalization error which is primarily the uncertainty on the flux prediction.



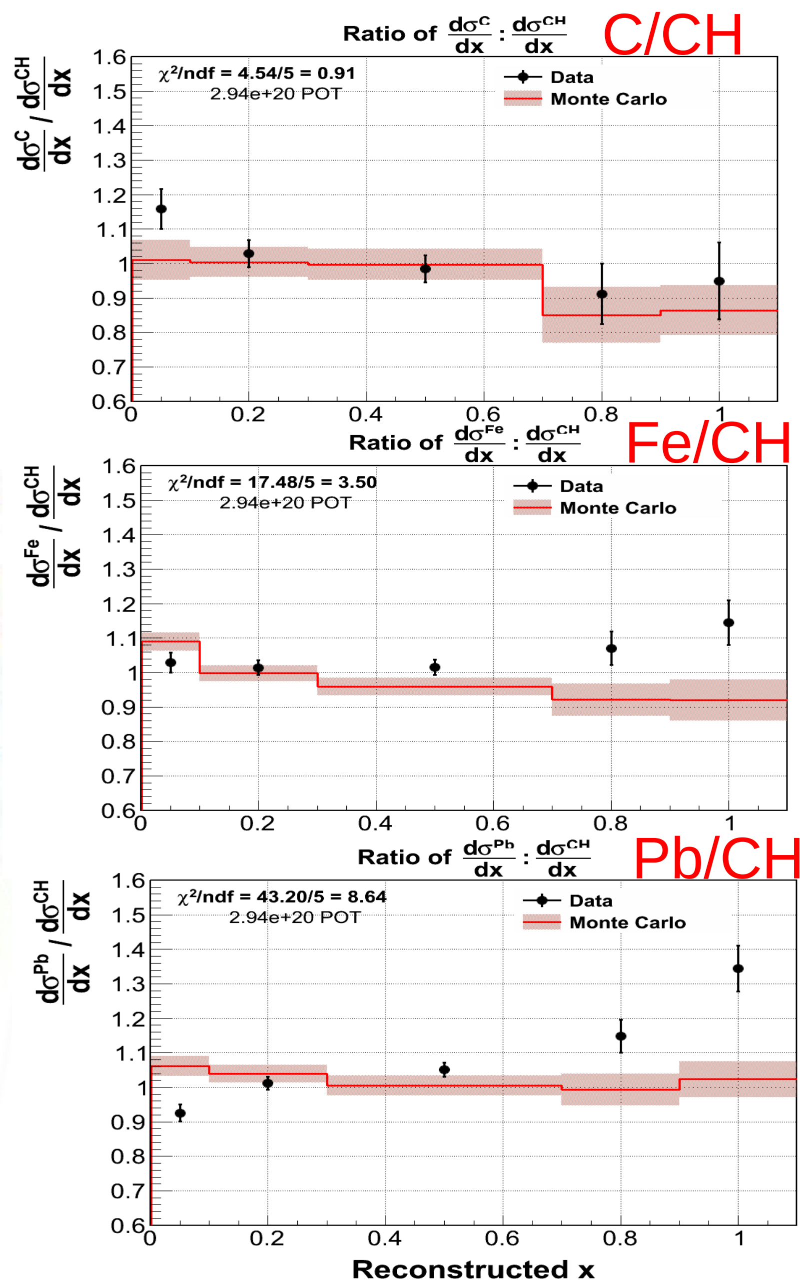
Results: $\sigma(E_\nu)$

- MC is based on GENIE version 2.6.2
- E_υ unfolded to true kinematics.
- We see good agreement between our data and MC as a function of E_ν at the 1 GeV level.
- GENIE's treatment of nuclear effects for total cross section appears to agree with data.
- However, the kinematics of the individual events could be still altered by effects not modeled in GENIE.



Results: dσ /dx

- Story very different in terms of Bjorken x.
- We observe a *deficit* of events at 0 < x <0.1 which grows with A. The size of this deficit is too large to be consistent with shadowing measured from e⁻ scattering.
- We observe an excess of events from 0.9 < x < 1.1 which grows with A.
- Neither effect is modeled by our simulation. Indicates GENIE nuclear effects are insufficient.



Modeling Nuclear Modifications

- GENIE's default nuclear model is based on BY 2003, and simulates the same x dependent nuclear effects for C, Fe and Pb .

- Alternate models / calculations:
  - Bodek-Yang 2013. Update to 2003, incorporates separate parameterization for Fe, C and Pb.
  - Kulagin-Petti. Theoretical calculation based on computed $2xF_1$, F_2 and xF_3 for each nucleus A.

- Calculations of the ratios agree with GENIE at the ~ 1% level (see table).

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)

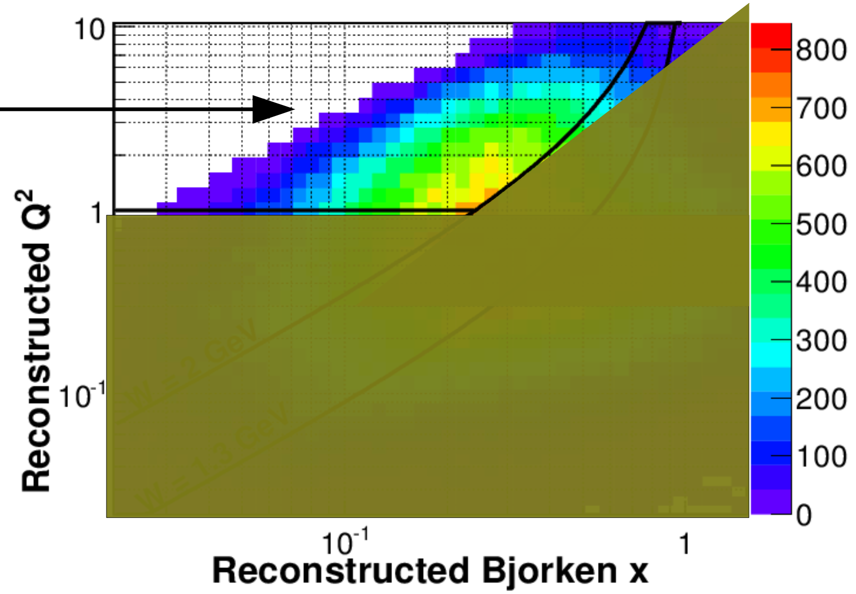
Future Nuclear Target Analyses

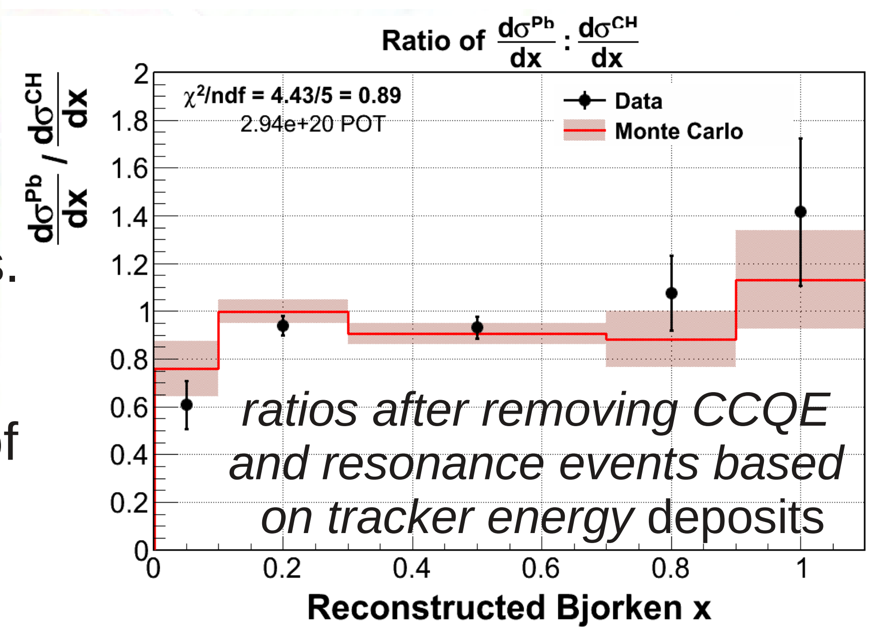
- Future analysis: isolate a DIS region from the inclusive sample.

- Should improve the x resolution by removing 99% of CCQE events, allows comparison of the data to models preferring higher Q^2.

- Initial investigation into a CCQE removed "inelastic" region has shown poor statistics. Considering increasing the energy range of analyzed events.

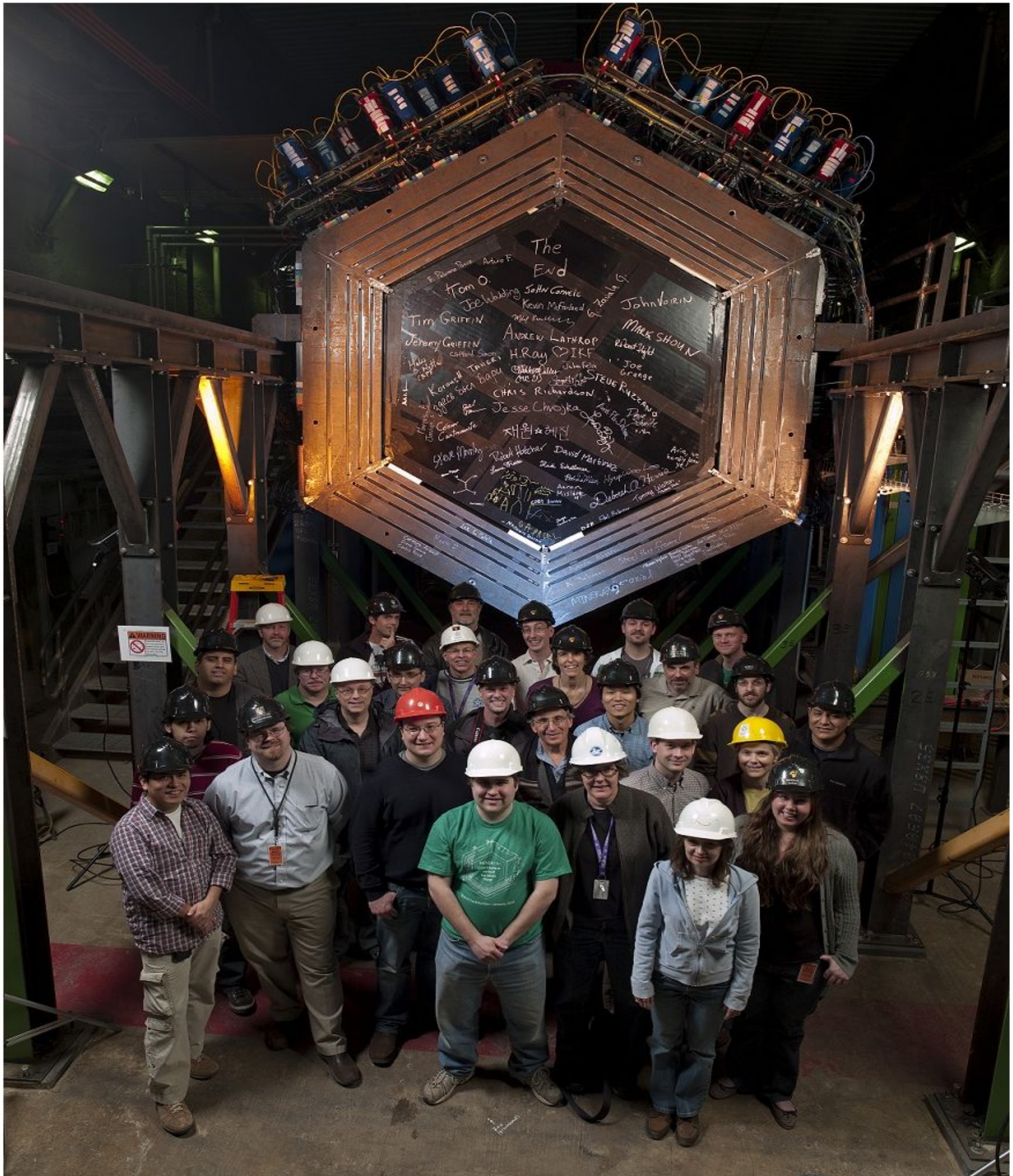
- Currently taking higher intensity ME energy data, will shift more of our events into the DIS region and improve overall statistics.





Conclusions

- MINERvA has recently measured the total and differential (as a function of x) cross section ratios of C/CH, Fe/CH and Pb / CH.
- Total cross section ratios agree well with the simulation, differential ratios show disagreements at low and high x.
- This disagreement cannot be explained by the alternate models we investigated.
- Further DIS measurements will allow cleaner comparisons at low x in the near future.



Thank you for listening!

But Wait! There's More!

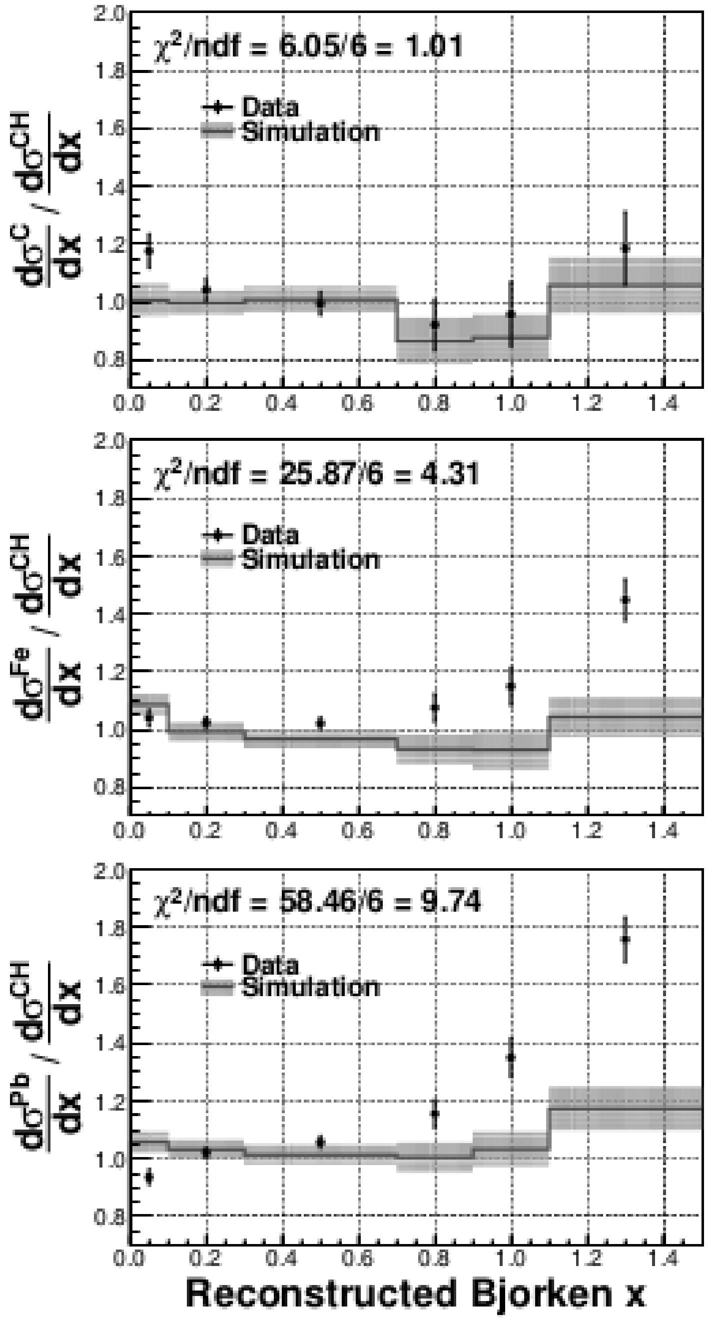
- More MINERvA Talks!
  - C. Patrick and C. McGivern, CCQE results Weds.
  - B. Eberly, Resonance Pion production. Fri.
  - A. Mislivec Coherent Pion production. Fri.
  - D. Harris, Neutrino Flux. Fri.
- MINERvA Posters!
  - C. Patrick, CCQE results
  - J. Mousseau, Inclusive Ratios (if you're not sick of me)
- ArXiv reference of Inclusive Ratio paper:1403.2103v1

Backup Slides

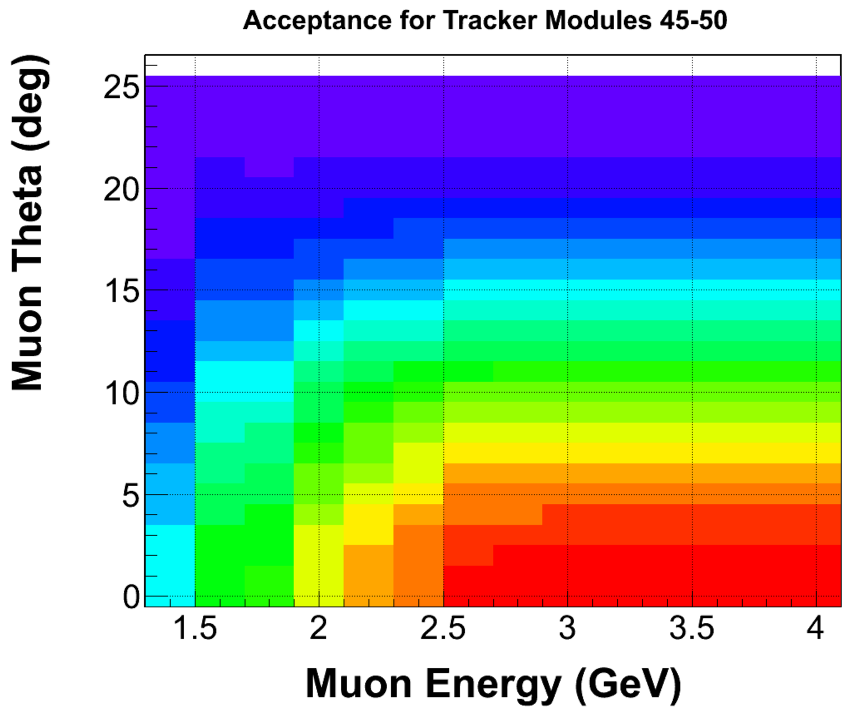
$\frac{d\sigma C/dx}{d\sigma CH\ /dx}$

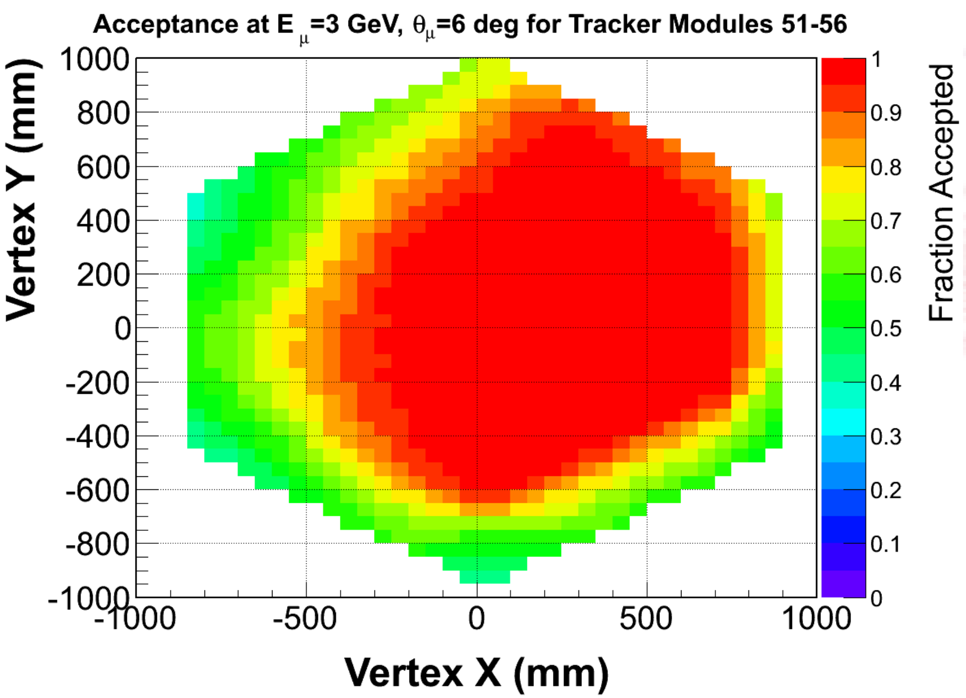
$\frac{d\sigma Fe/dx}{d\sigma CH\ /dx}$

$\frac{d\sigma Pb/dx}{d\sigma CH\ /dx}$



Background Subtraction Acceptance Weights

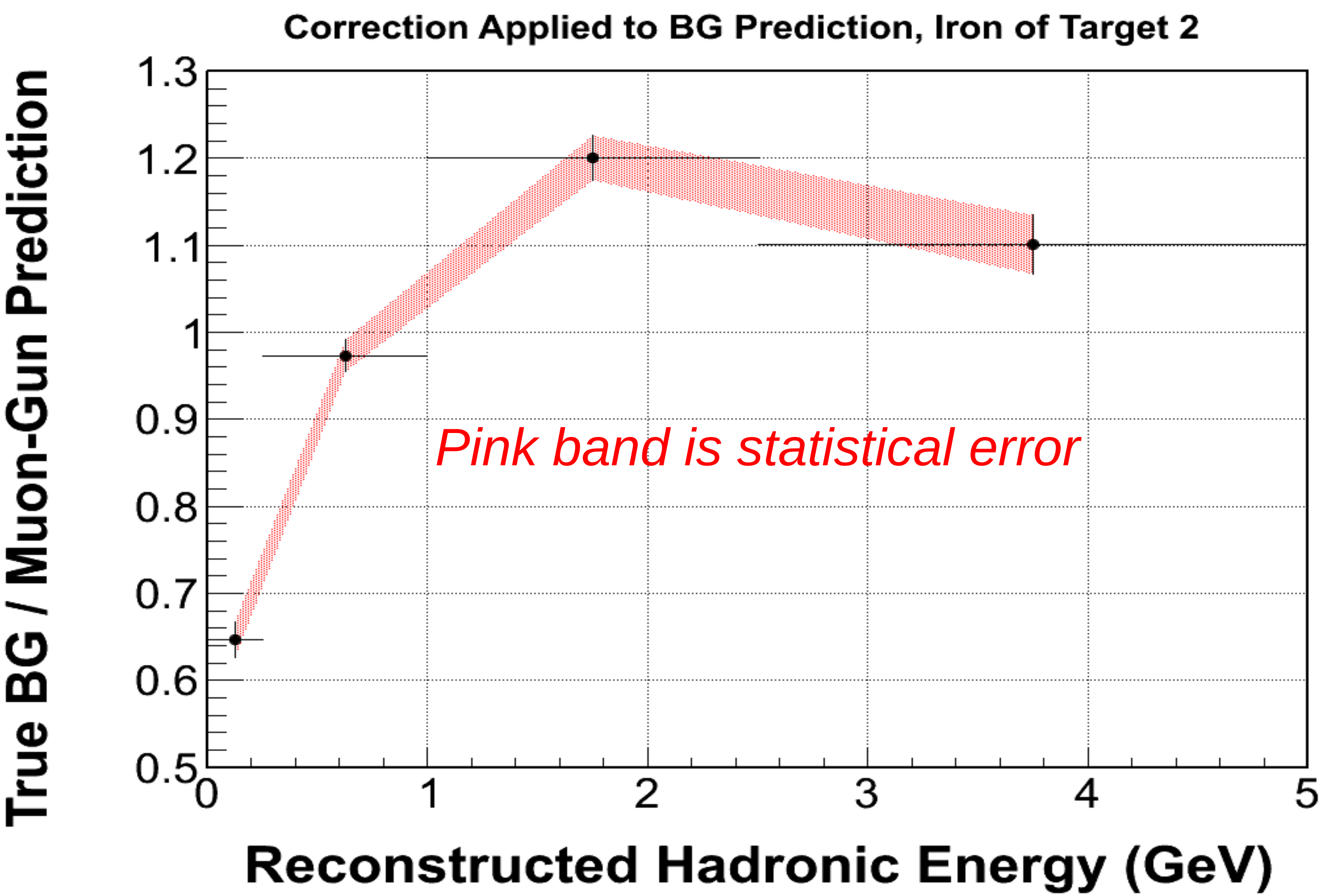




$$RW = \frac{f_{acc}^{target}(E_\mu, \theta_\mu)}{f_{acc}^{tracker}(E_\mu, \theta_\mu)}$$

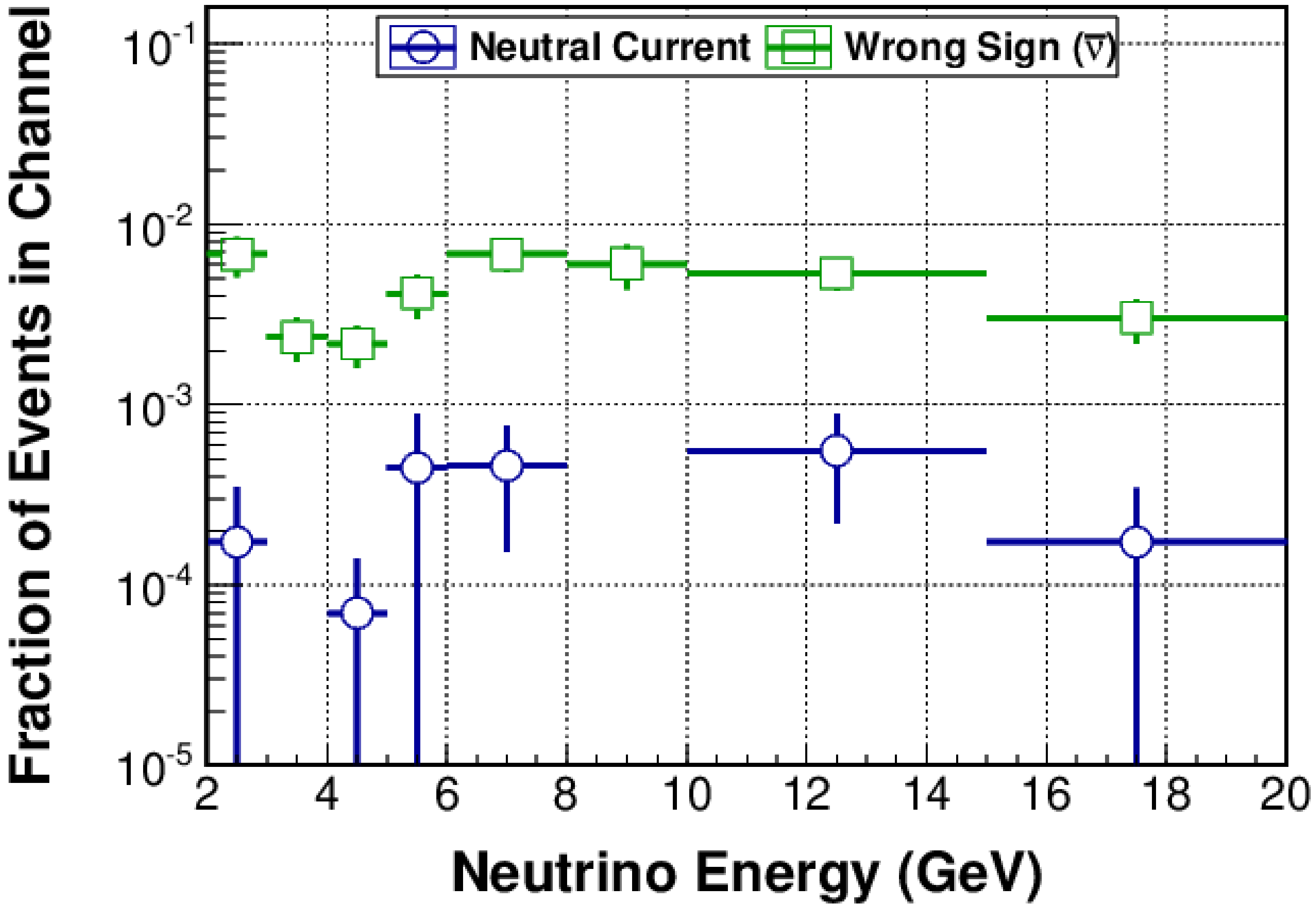
- Muon-only Geant4 simulation measures probability muon will hit MINOS

E_{had} Dependent Correction

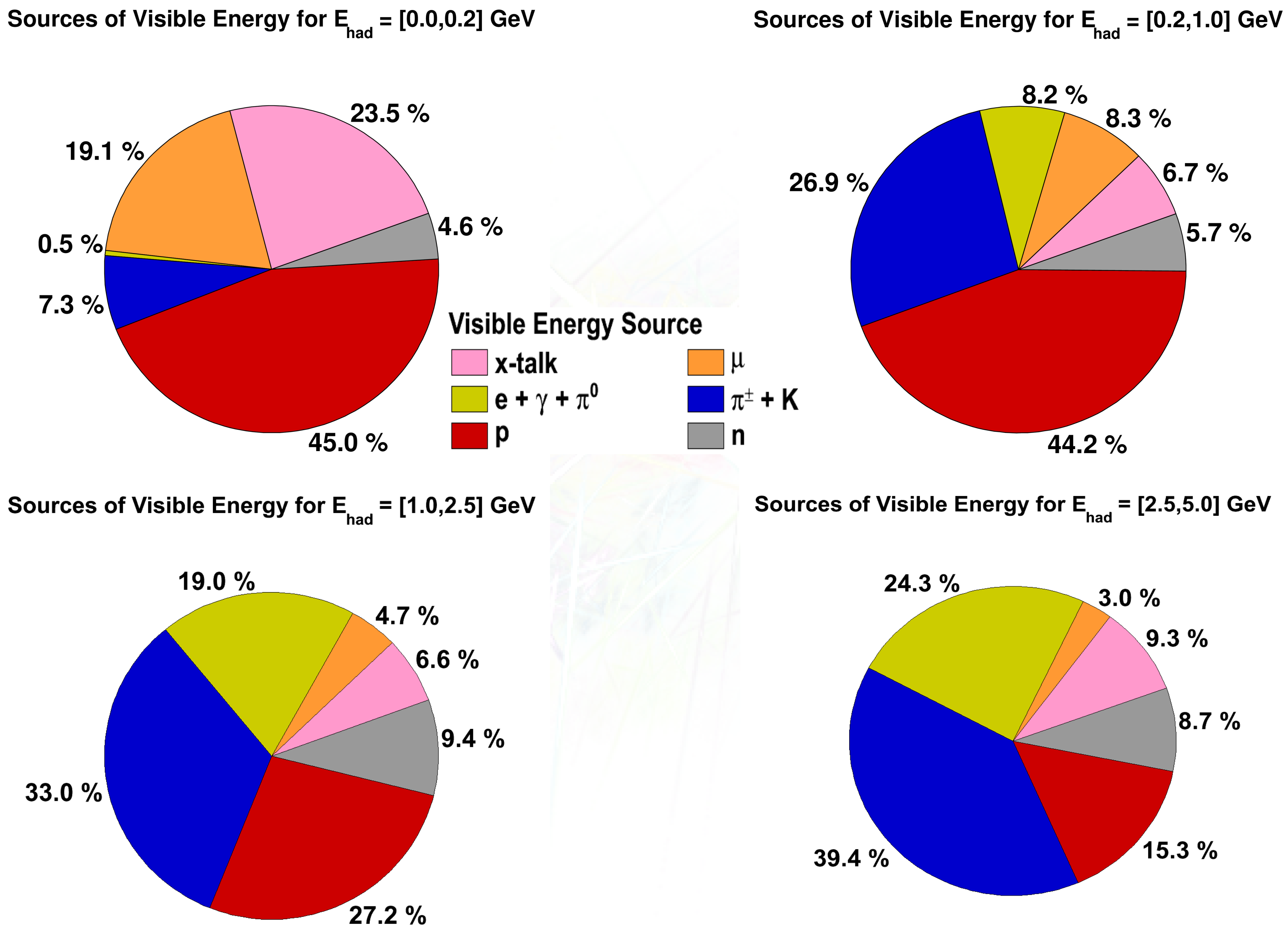


Correction accounts for tracking inefficiency due to high energy hadron showers.

Wrong Sign and Neutral Current Background



Content of Final States



Detector Technology