Inclusive Neutrino Cross Section Ratios on Different Nuclei at MINERvA

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Rutgers, The State University of New Jersey

Joint Experimental-Theoretical Physics Seminar

October 11, 2013

What do you love about MINERvA?

What do you love about MINERvA?

V Neutrino Physics

"I want to measure neutrino oscillations"

MINERvA will…

- help me understand neutrino energy reconstruction
- reduce my uncertainties from cross sections and nuclear effects

A Nuclear Physics

"I want to measure nucleon structure"

MINERvA will…

- use a probe sensitive to flavor and axial structure

Priority: σ(E_ν)
Neutrino Oscillations

- Accelerator neutrino experiments measure ν_μ disappearance (for example)

$$P(\nu_\mu \to \nu_\tau) = sin^2(2\theta_{23}) sin^2\left(\frac{1.27\Delta m^2_{23} L}{E_\nu}\right)$$

Must reconstruct the neutrino energy!

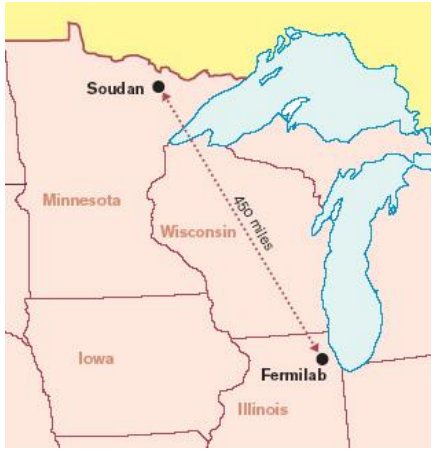
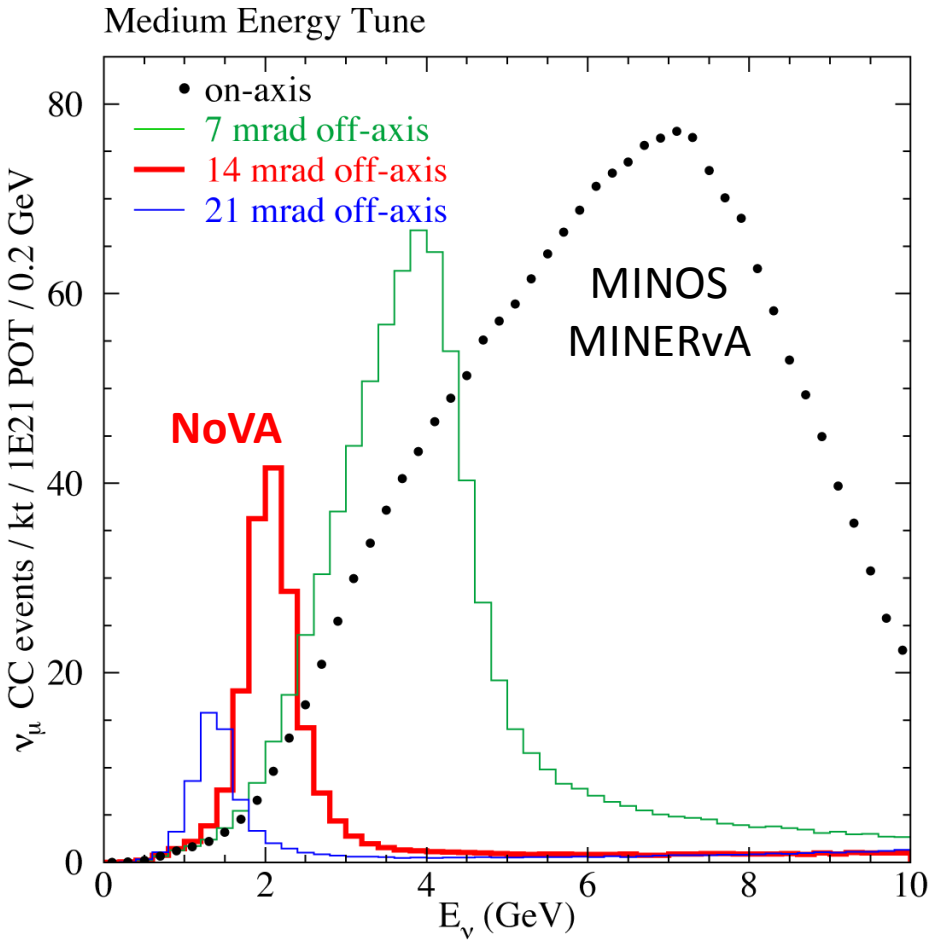


Image: symmetry May 2005

Expected event rates in NuMI



www-nova.fnal.gov/plots_and_figures

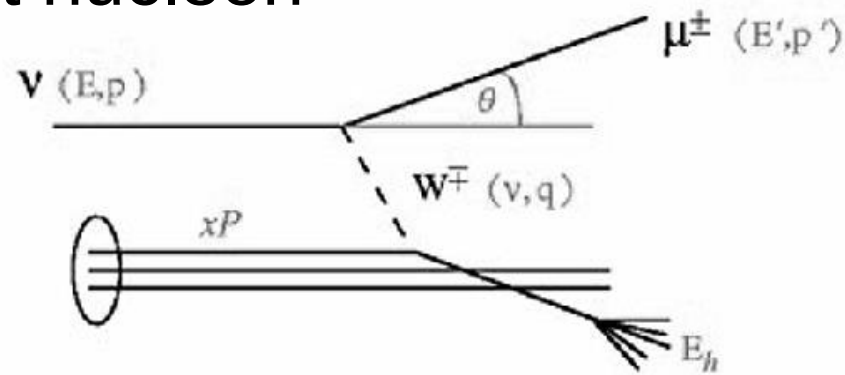
Priority: $\sigma(E_\nu)$
Neutrino-Nucleus Interactions

- Heavy nuclear targets used to get necessary statistics
  - Carbon, Iron, Lead, Water, Argon
- Nuclear effects are significant in neutrino scattering
  - Affects energy smearing and event rate
- Neutrino interaction simulation (models) rarely handle nuclear modifications well
  - They need data to test models

Must understand nuclear effects in neutrino scattering!

Probing Nucleon Structure
Deep Inelastic Scattering (DIS)

- Lepton strikes quark, breaks apart nucleon
- Cross section a function of
  - Probe (lepton) momentum
  - Interaction kinematics
  - Target (quark) momentum - Encoded in **structure functions** – F_1, F_2, F_3



$$\frac{d^2\sigma^{\nu,\bar{\nu}}}{dxdy} = \frac{G_F^2 M_n E_\nu}{\pi(1+Q^2/M_{W,Z}^2)^2}\left[\frac{y^2}{2}2xF_1(x,Q^2) + \left(1 - y - \frac{xyM_n}{2E_\nu}\right)F_2(x,Q^2) \pm y(1-\frac{y}{2})xF_3(x,Q^2)\right]$$

$$\nu = E - E'$$

$$y = E_h/E$$ Inelasticity

$$Q^2 = -q^2 = 2E\left(E' - p'cos\left(\theta\right)\right)$$

$$x = \frac{Q^2}{2M\nu}$$ Bjorken scaling variable
Fraction of nucleon's momentum carried by the struck quark

Structure Functions

$$F_2(x,Q^2) = 2\sum_{q=u,d,\ldots}\left[xq(x,Q^2) + x\bar{q}(x,Q^2)\right]$$

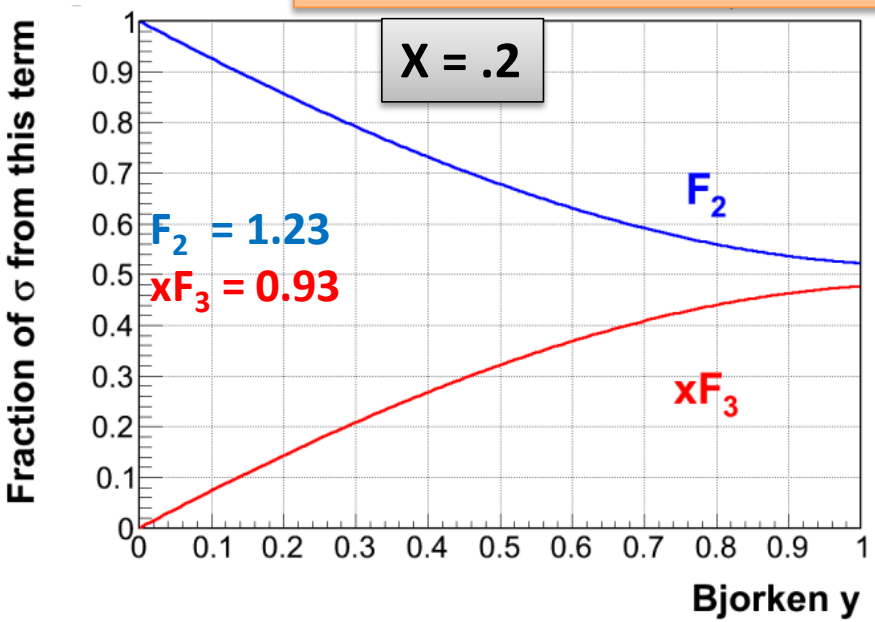
Sum of all quark and antiquark momentum

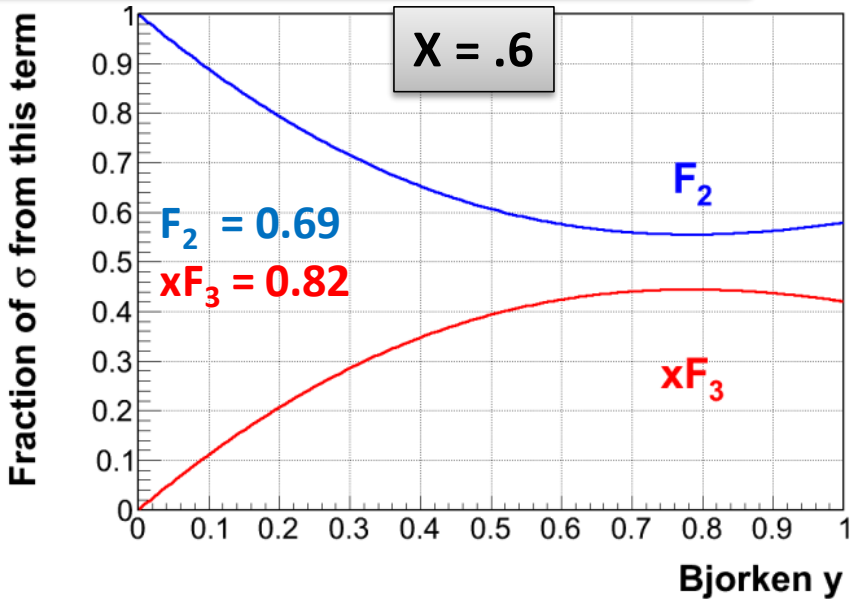
$$xF_3(x,Q^2) = 2\sum_{q=u,d,\ldots}\left[xq(x,Q^2) - x\bar{q}(x,Q^2)\right]$$

Sum of valence quark momentum

$$2xF_1(x,Q^2) = F_2(x,Q^2)\frac{1+4M^2x^2/Q^2}{1+R_L(x,Q^2)}$$

How much do they contribute to the DIS cross section?

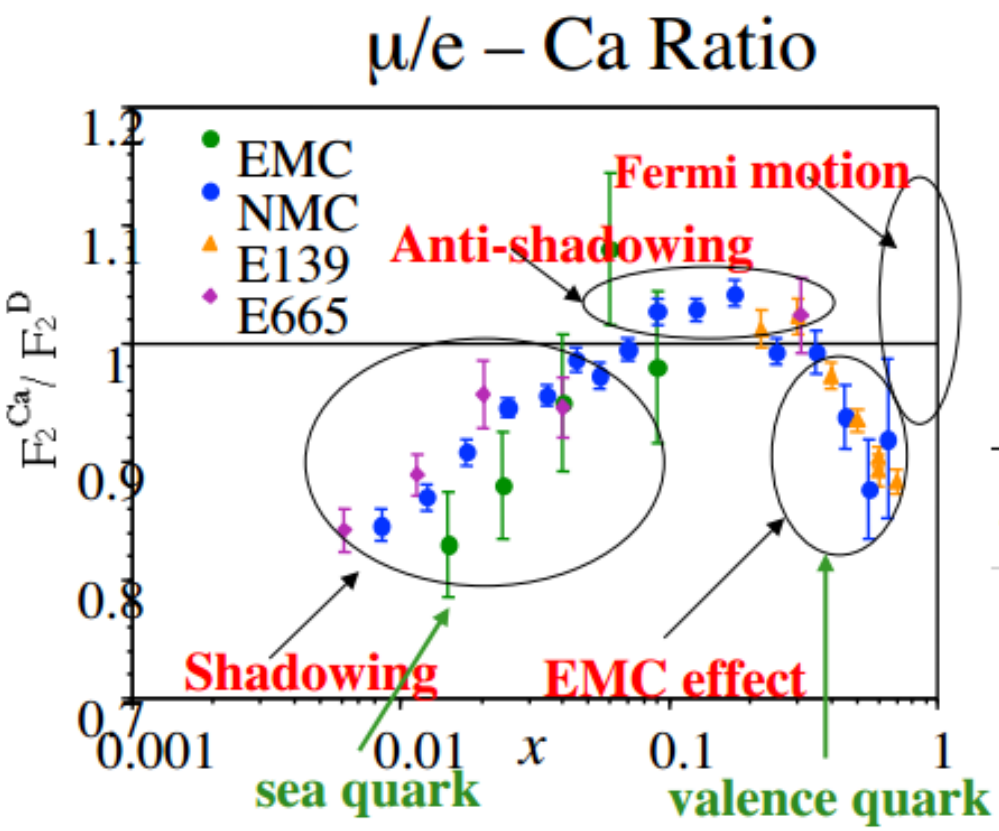




*Calculated for neutrino-neutron at Q^2 =1 GeV^2, E_ν = 4 GeV

Charged Lepton Data

Charged lepton data show structure function F_2 effectively changes when nucleon bound in nucleus



Physics Letters B
Volume 123, Issues 3–4, 31 March 1983, Pages 275–278

Abstract:
"Using the data on deep inelastic muon scattering on iron and deuterium the ratio of the nucleon structure functions $F_2(Fe)/F_2(D)$ is presented.
The observed x-dependence of this ratio is in disagreement with existing theoretical predictions. "

… much experimental and theoretical effort …

CERN COURIER

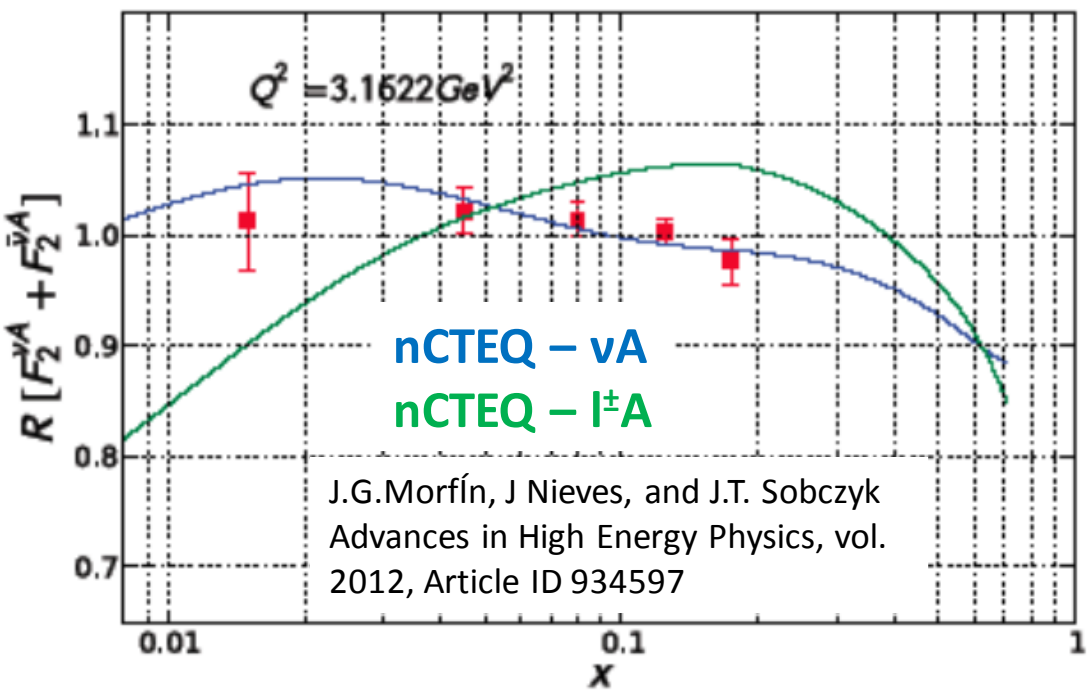
Apr 26, 2013

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.

Priority: σ(x)
No comparable neutrino data!

Plot of ratio (R) of NUTEV (ν-Fe) data to theoretical predictions of free nucleon F_2. Compared to fits to ratio from charged lepton data.



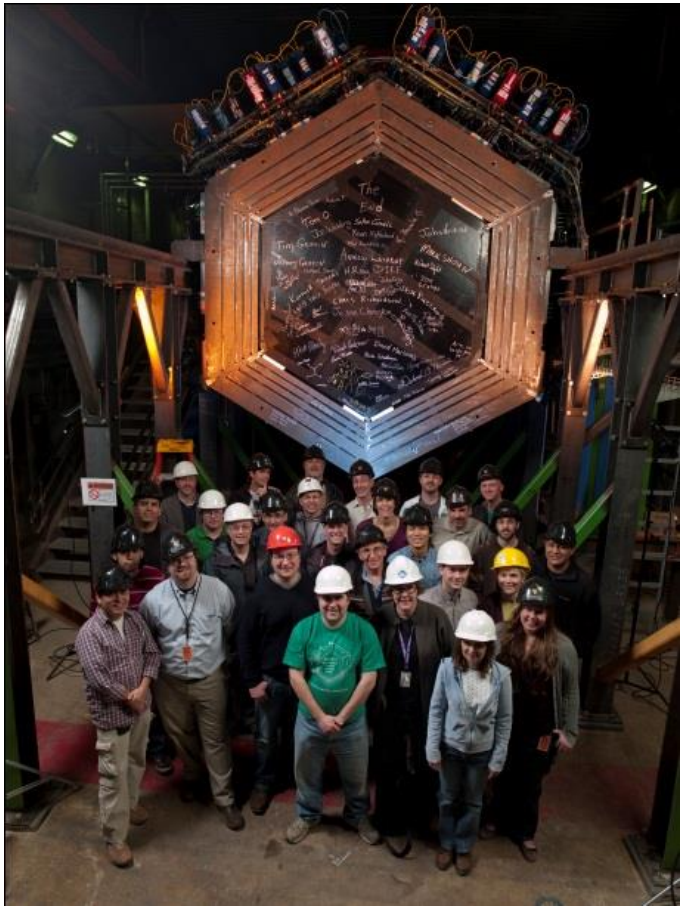
Expectations for neutrino nuclear structure function modification

- Neutrinos sensitive to structure function xF_3
  - (Charged leptons are not)
  - Gives neutrinos ability to separate valence and sea
- Neutrinos sensitive to axial piece of structure function F_2
  - (Charged leptons are not)
  - Axial effect larger at low x, low Q^2

MINERvA
Main INjector ExpeRiment v-A

- Collaboration of 80 nuclear and particle physicists

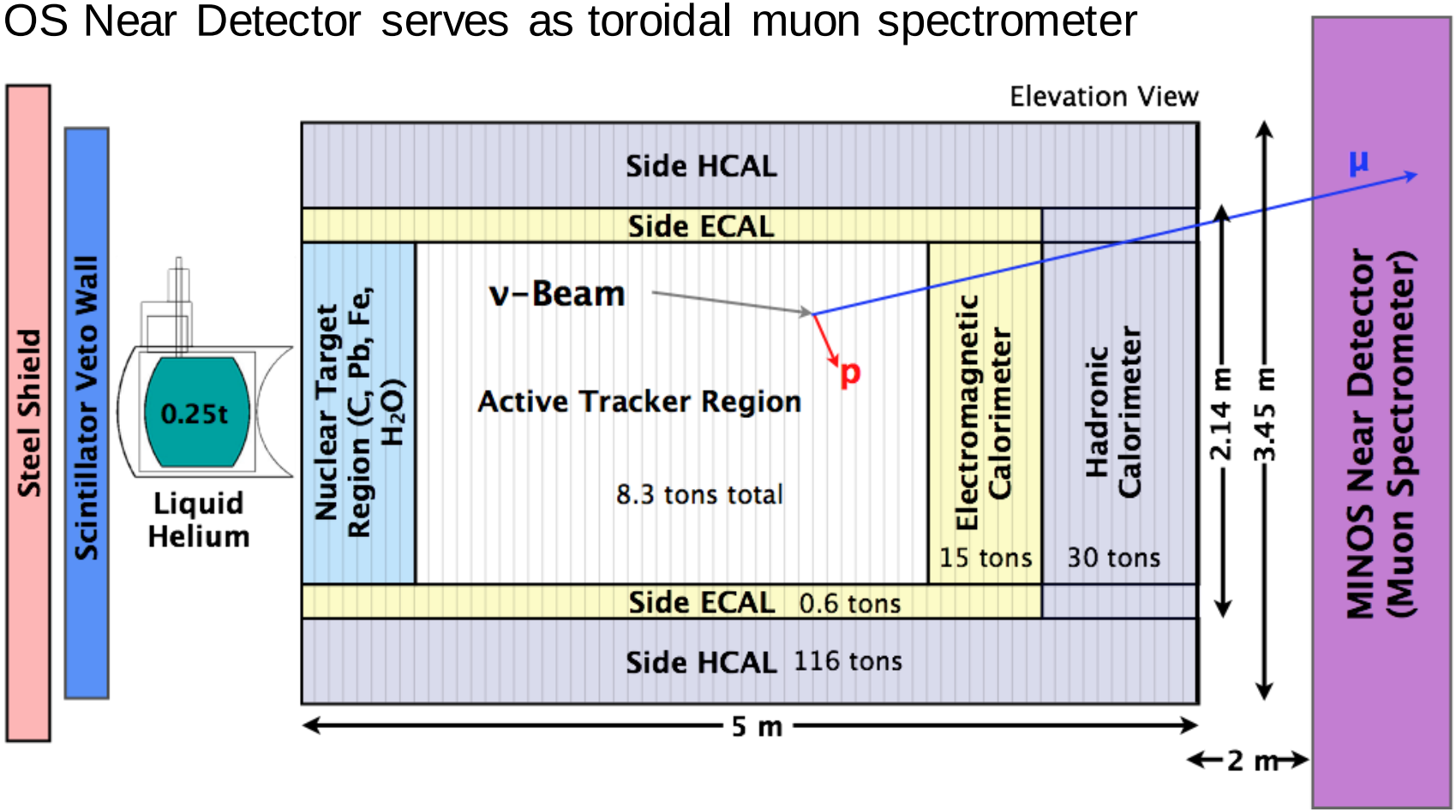
University of Athens
University of Texas at Austin
Centro Brasileiro de Pesquisas Físicas
Fermilab
University of Florida
Université de Genève
Universidad de Guanajuato
Hampton University
Inst. Nucl. Reas. Moscow
Mass. Col. Lib. Arts
Northwestern University
University of Chicago
Otterbein University
Pontificia Universidad Catolica del Peru
University of Pittsburgh
University of Rochester
Rutgers, The State University of New Jersey
Tufts University
University of California at Irvine
University of Minnesota at Duluth
Universidad Nacional de Ingeniería
Universidad Técnica Federico Santa María
William and Mary



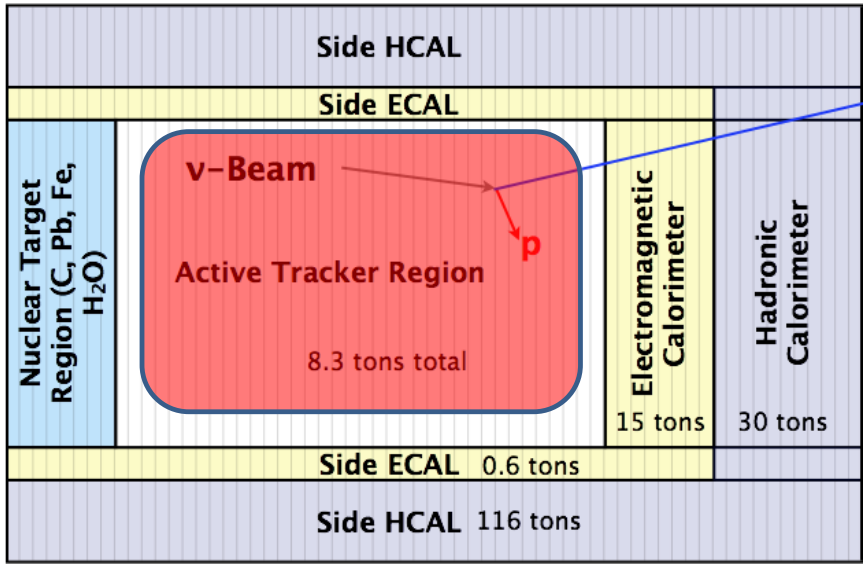
MINERvA Detector

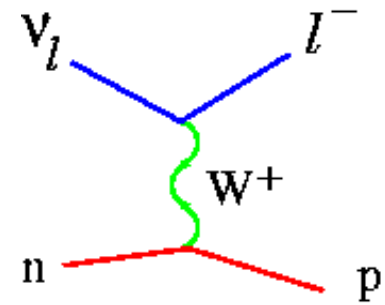
The MINERvA Detector
Calibration and Performance
arXiv:1305.5199 [physics.ins-det]

- 120 modules for tracking and calorimetry (~32k readout channels)
  - Active element is polystyrene (plastic scintillator)
- Construction completed Spring 2010. He and Water added in 2011
- MINOS Near Detector serves as toroidal muon spectrometer



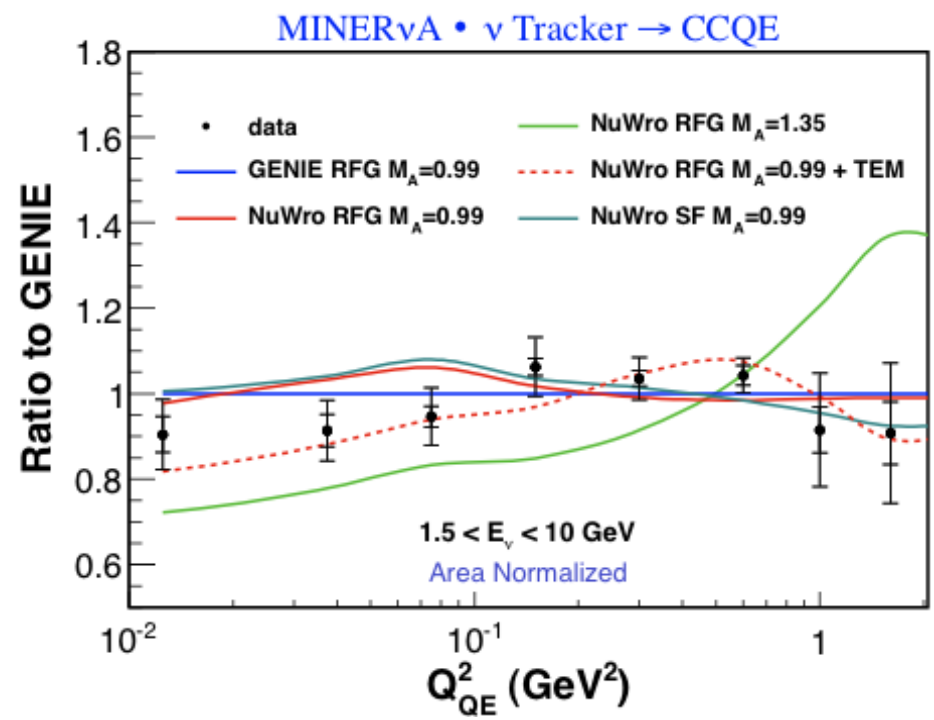
Previously from MINERvA
Quasi-Elastic Scattering on Scintillator





Quasi-Elastic (CCQE)

ν_μ CCQE

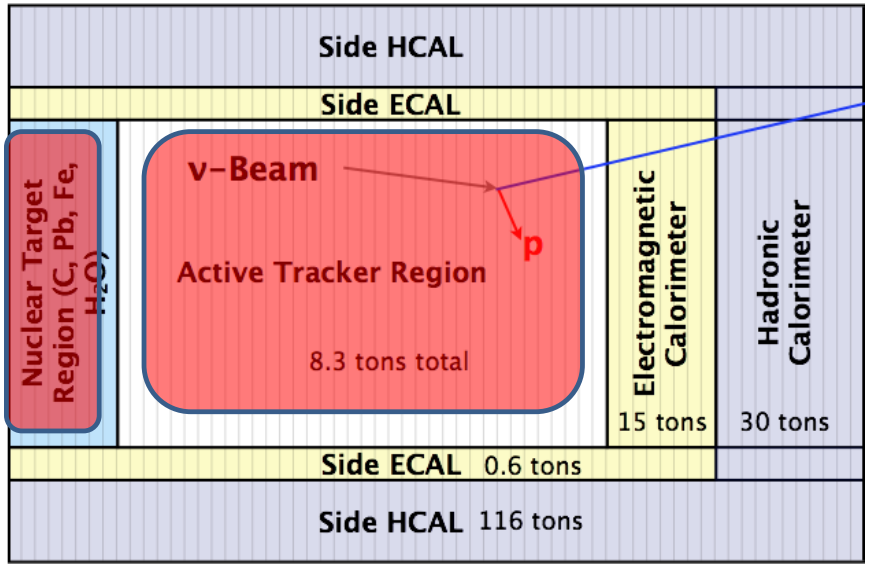


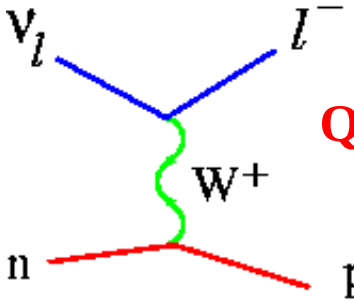
neutrino — G. A. Fiorentini *et al.* (MINERvA Collaboration) Phys. Rev. Lett. 111, 022502 (2013)

antineutrino — L. Fields *et al.* (MINERvA Collaboration) Phys. Rev. Lett. 111, 022501 (2013)

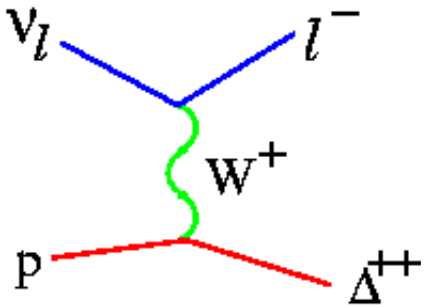
Nuclear effects are significant.
Even in this most basic interaction.

Today from MINERvA
Inclusive Scattering on Nuclear Targets



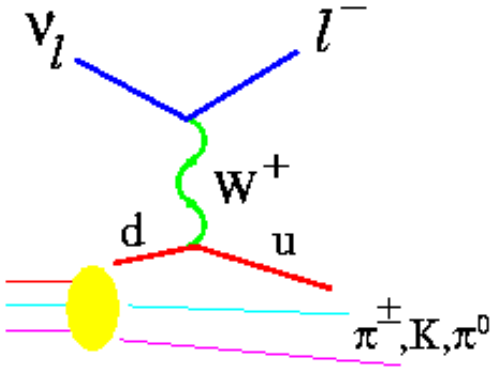


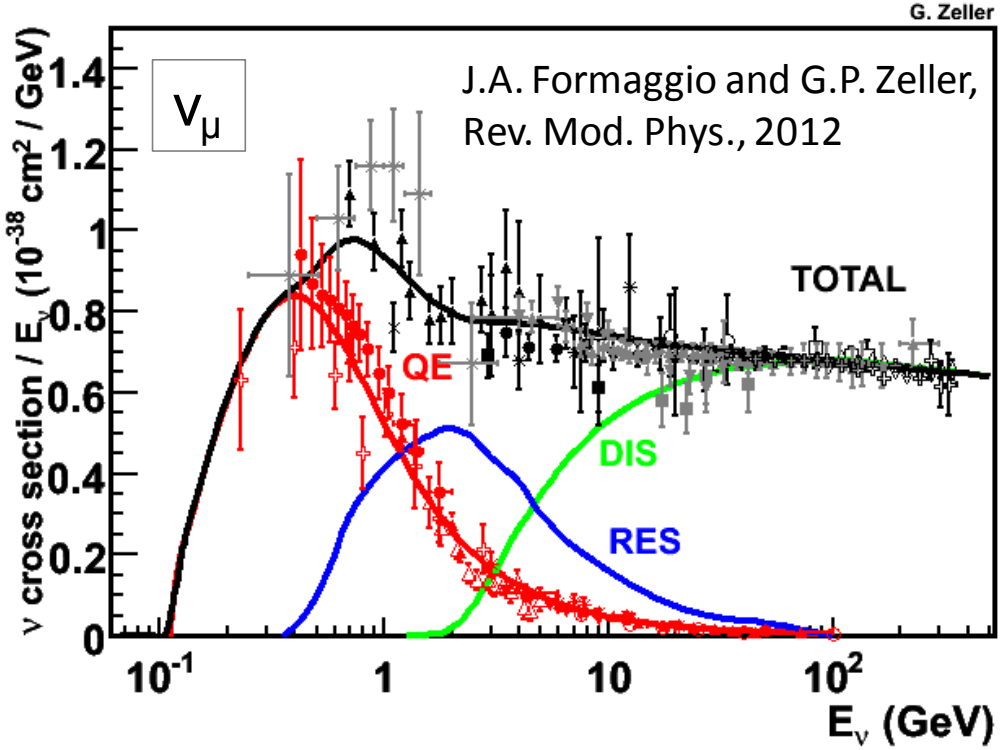
Quasi-Elastic (CCQE)



Resonance Production (CC1π)

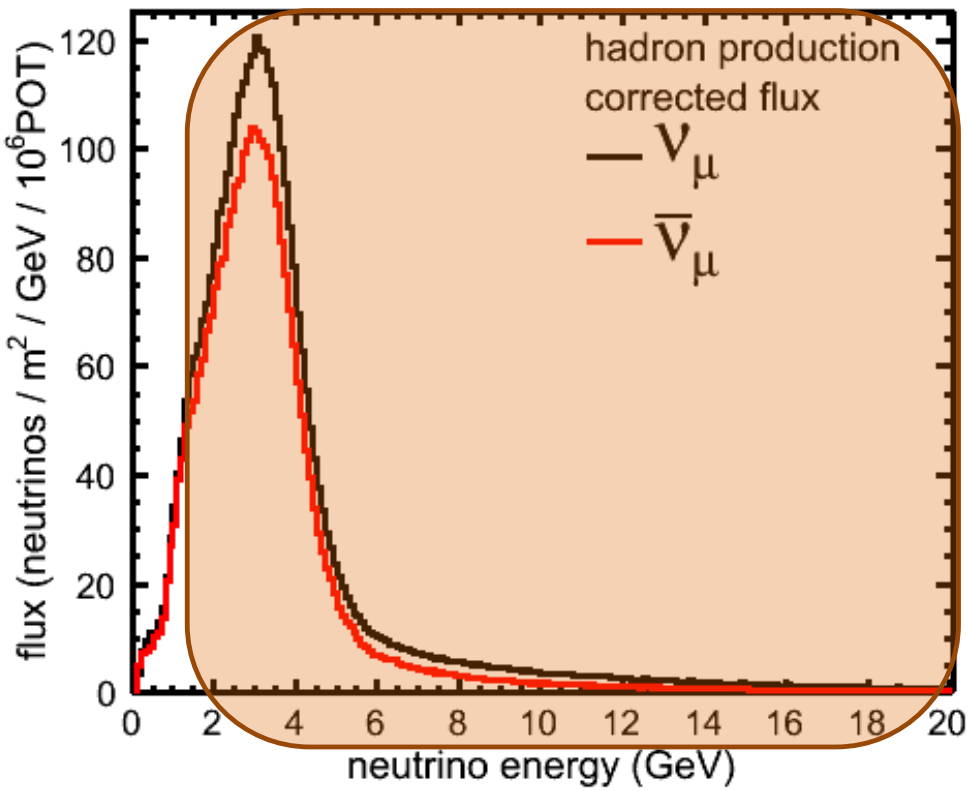
Deep Inelastic Scattering (DIS)

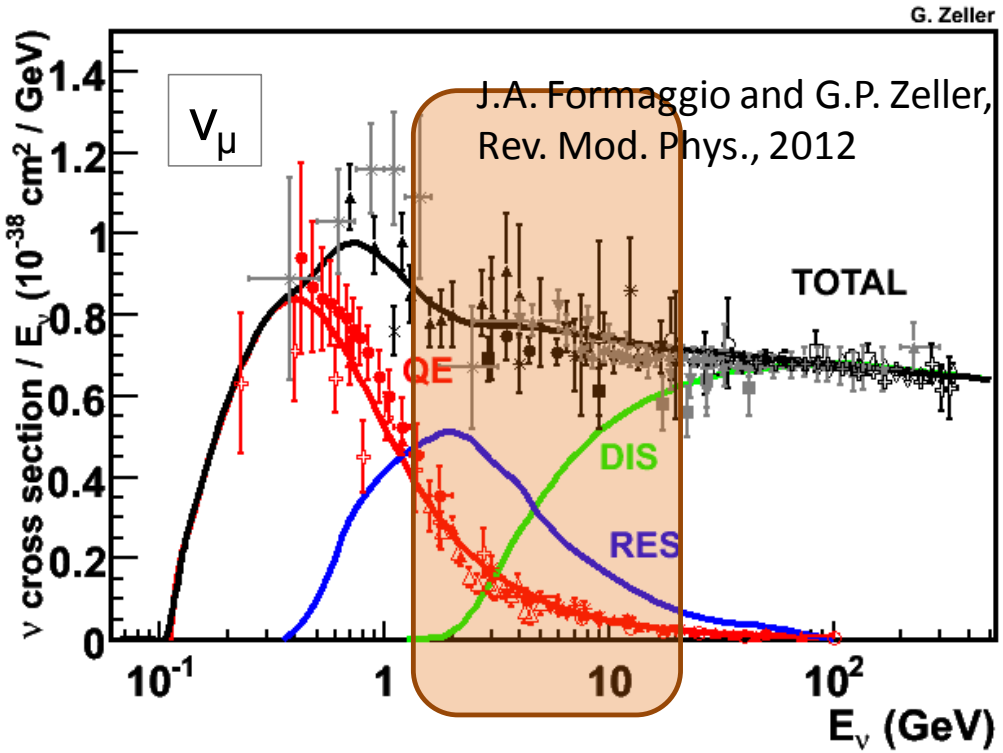




Flux, Cross Sections

NuMI Low Energy Beam Flux



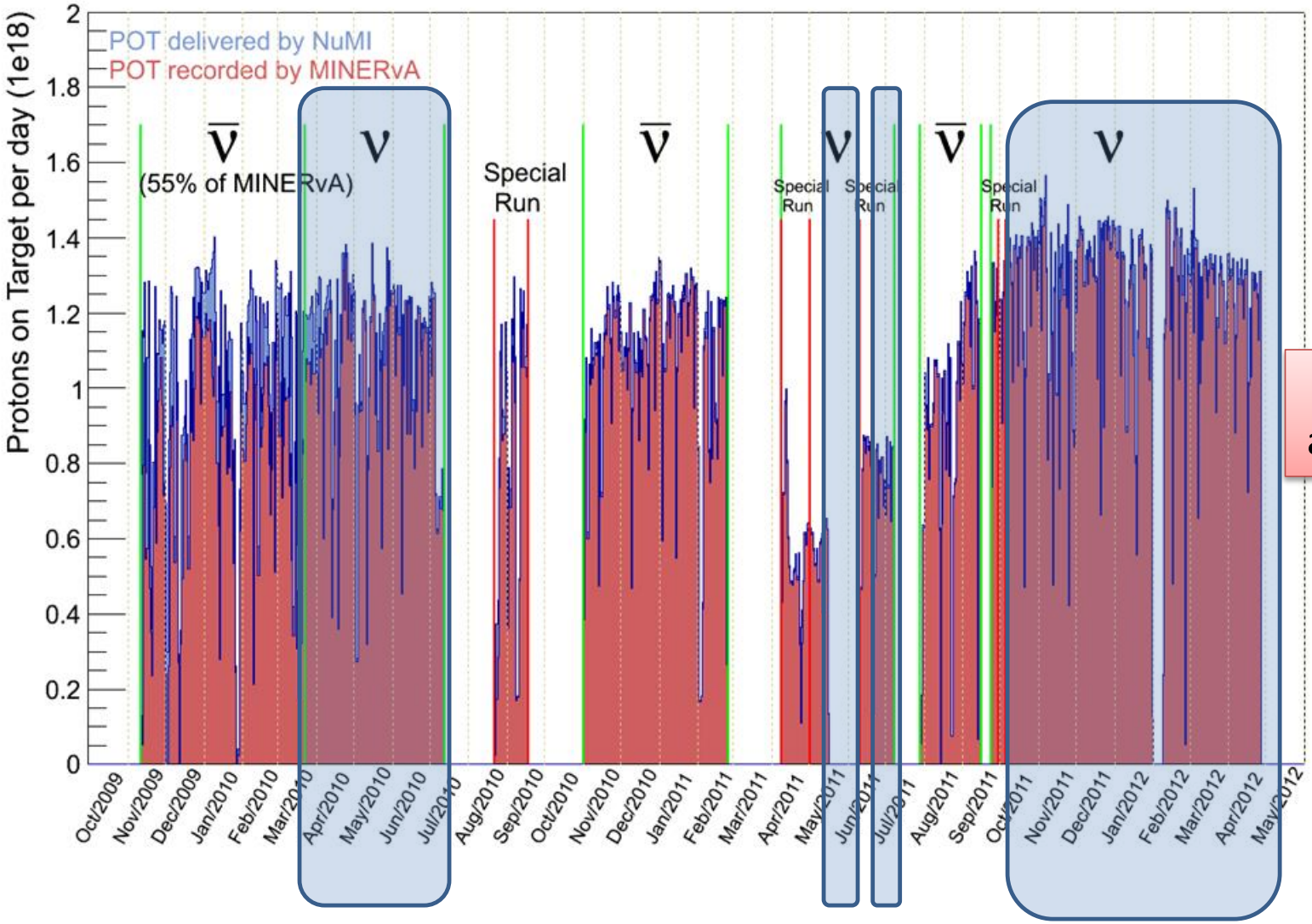


This analysis uses ν_μ only

Dataset

Thank you for the beam!

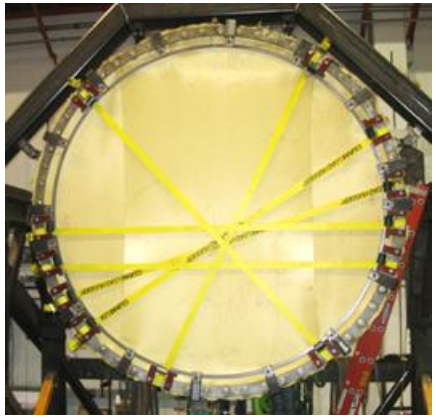
protons on target (POT) delivered
ν_μ LE - 3.98e20



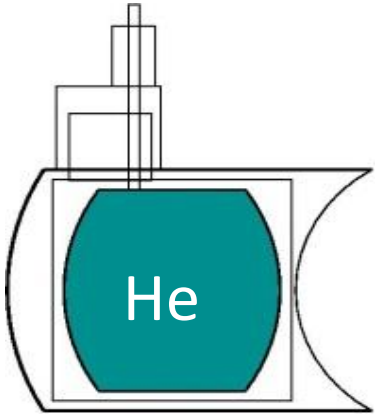
This analysis uses ALL analyzable neutrino data

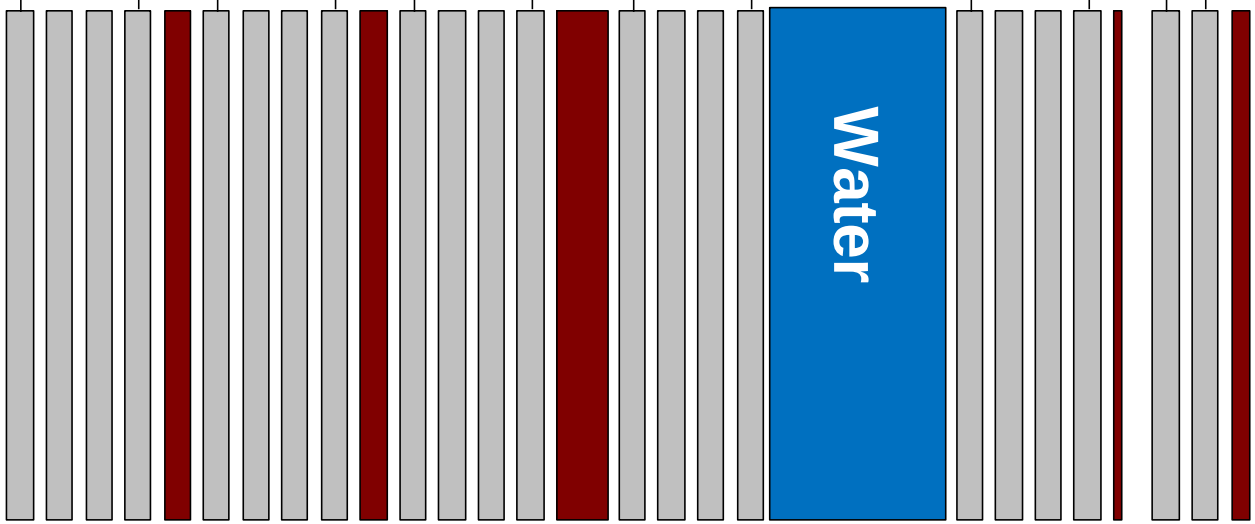
250 kg
Liquid He

500kg
Water



Active Scintillator Modules





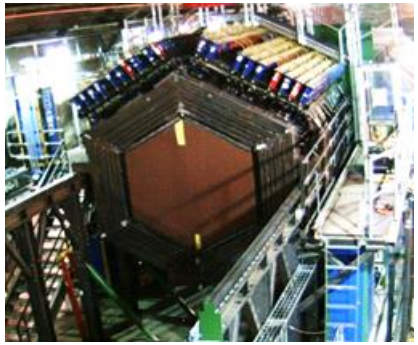
Tracking
Region

1” Fe / 1” Pb
323kg / 264kg

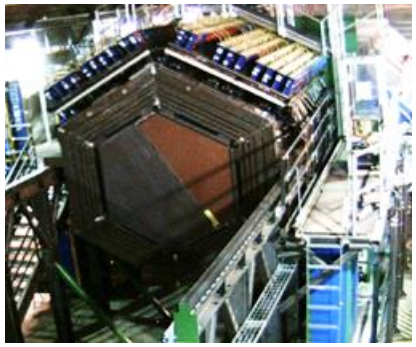
1” Pb / 1” Fe
266kg / 323kg

3” C / 1” Fe / 1” Pb
166kg / 169kg / 121kg

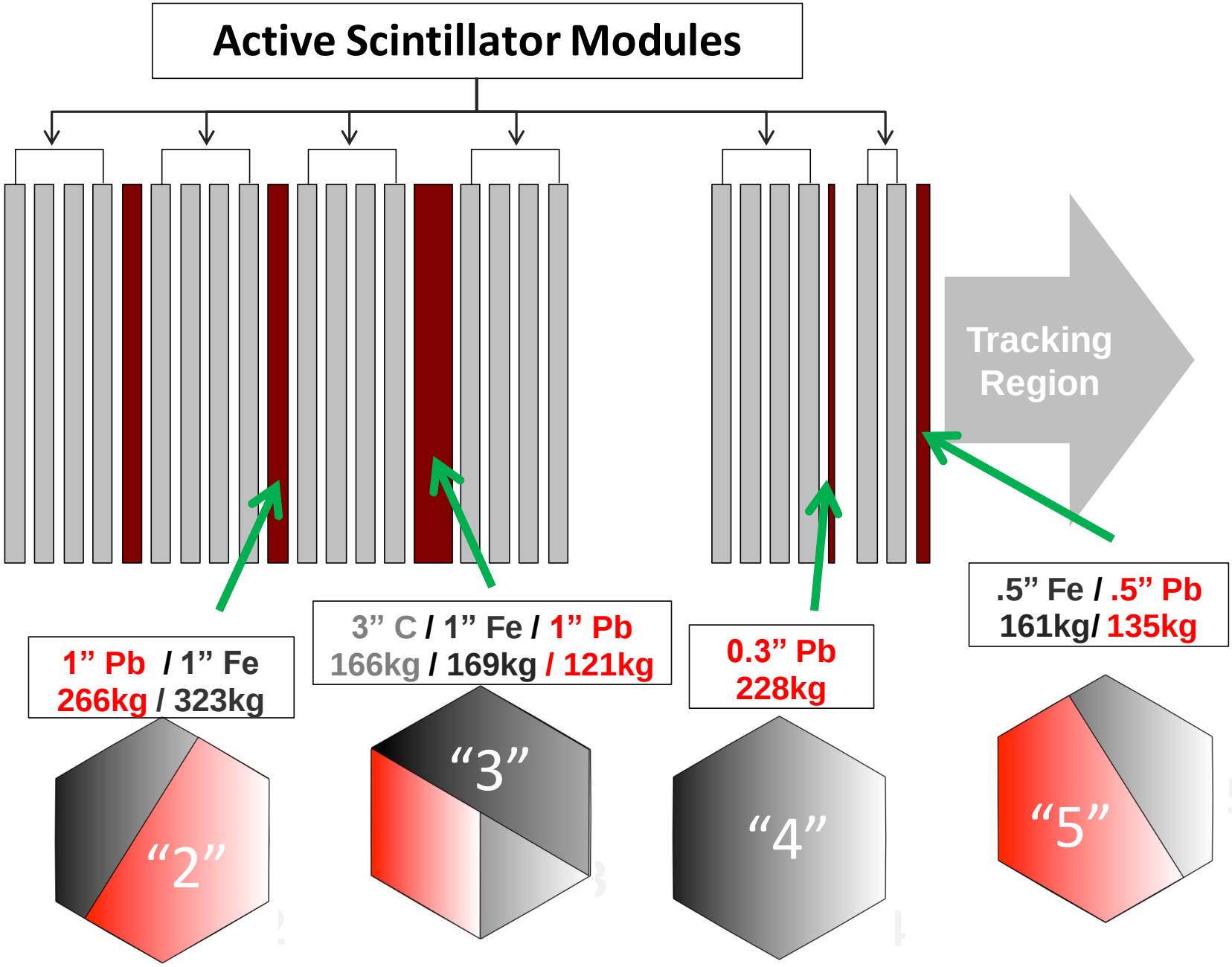
0.3” Pb
228kg



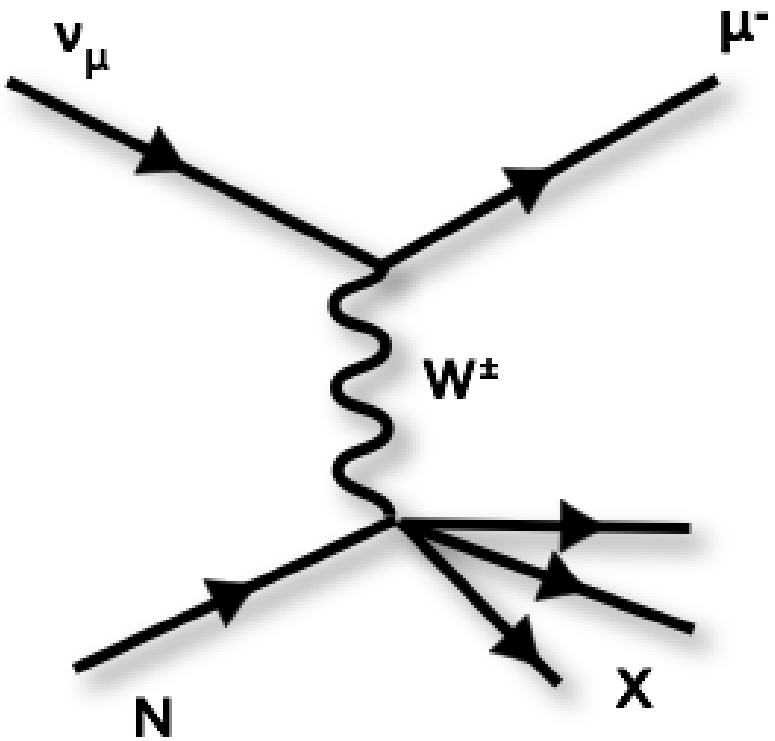
.5” Fe / .5” Pb
161kg/ 135kg



Targets used for today's result



Nuclear Target Ratios Analysis

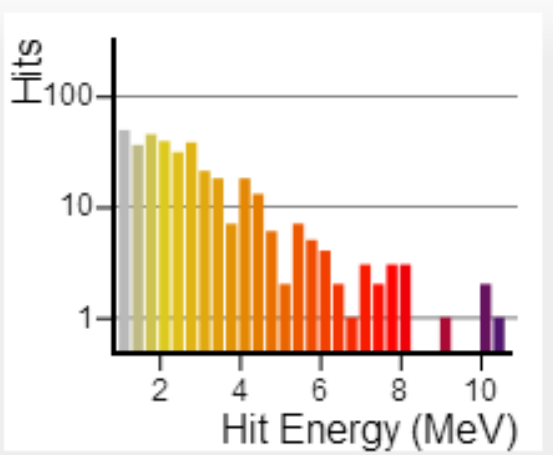


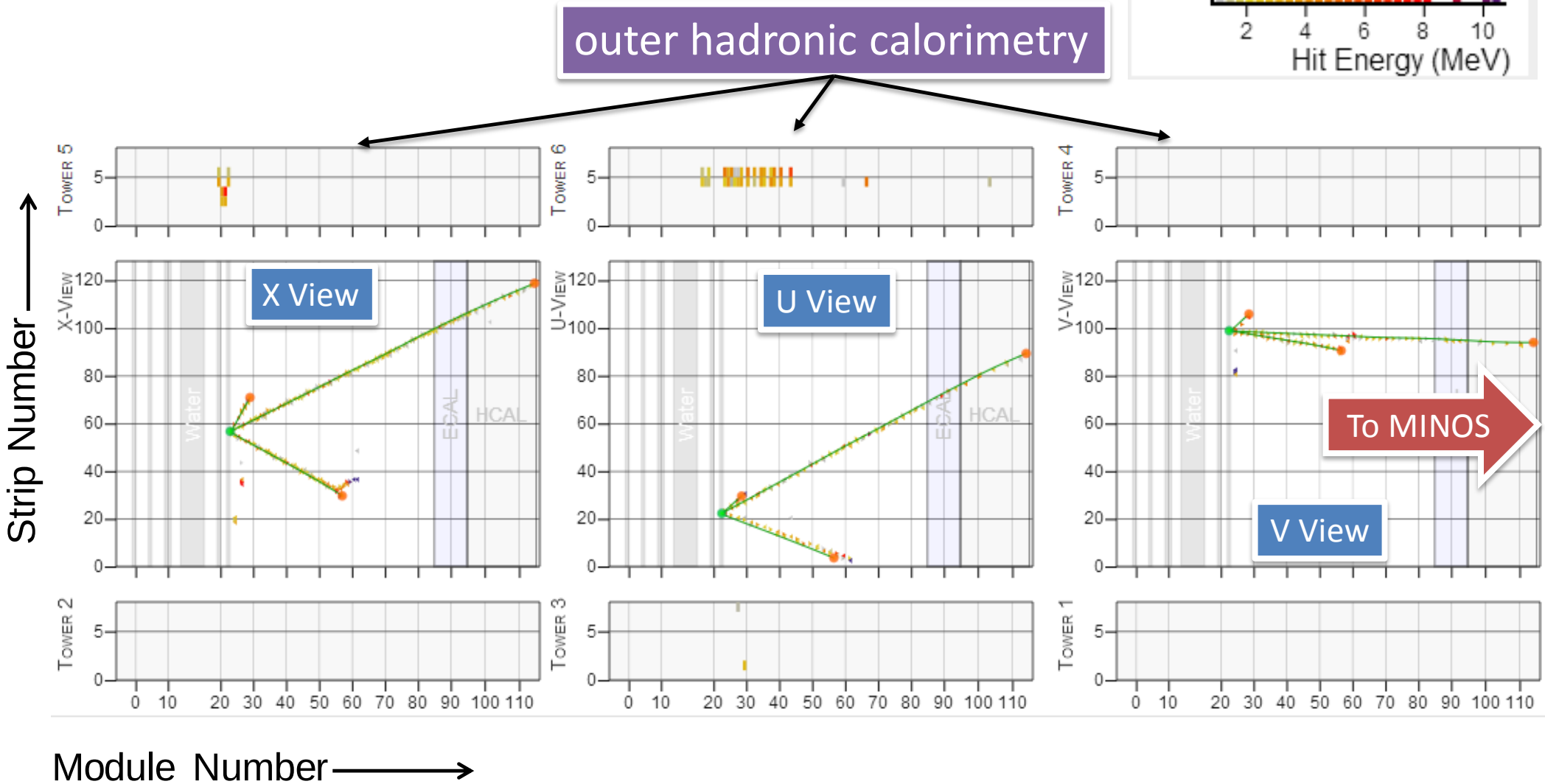
MINERvA

Main INjector ~~ExpeRiment~~ v-A

Main INjector Experiment for Ratios of v-A

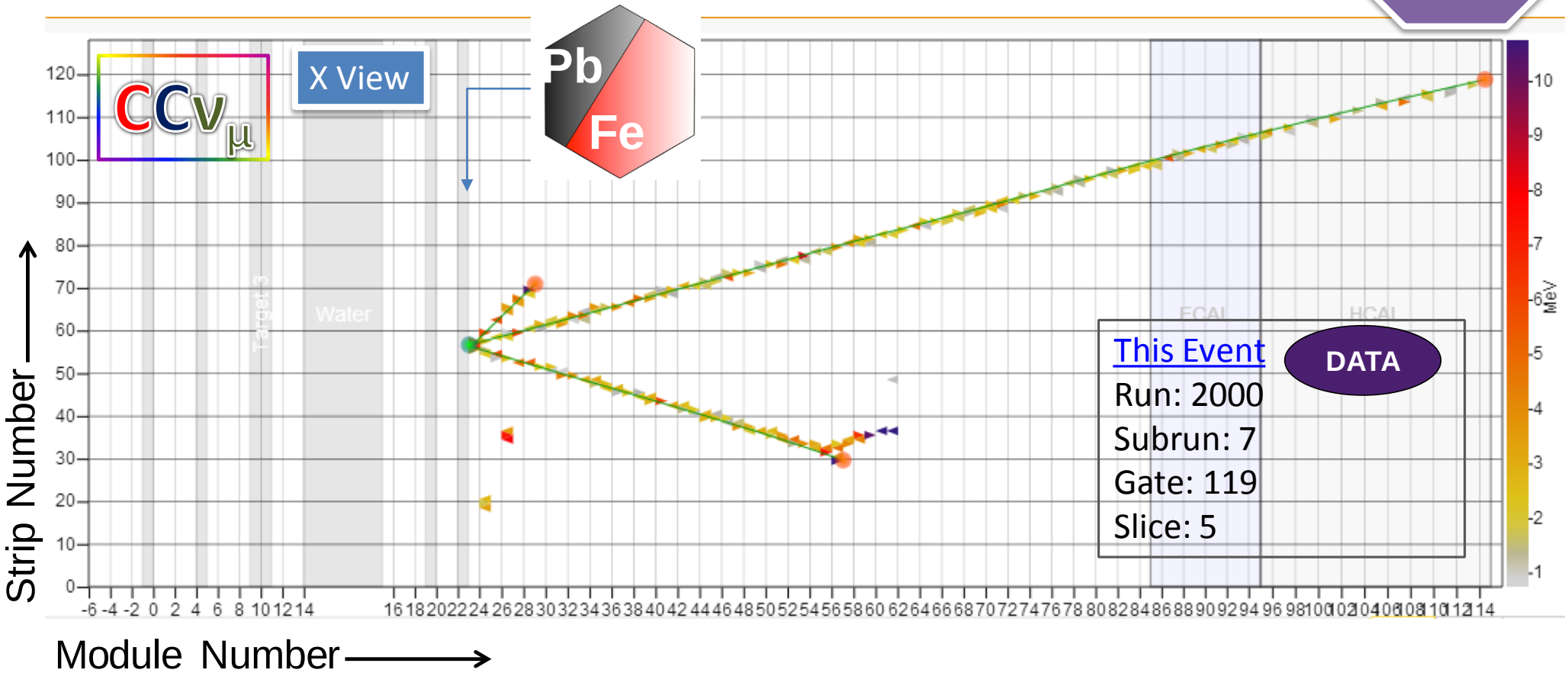
Event Display





Event Selection

Thanks MINOS!



Event Topology

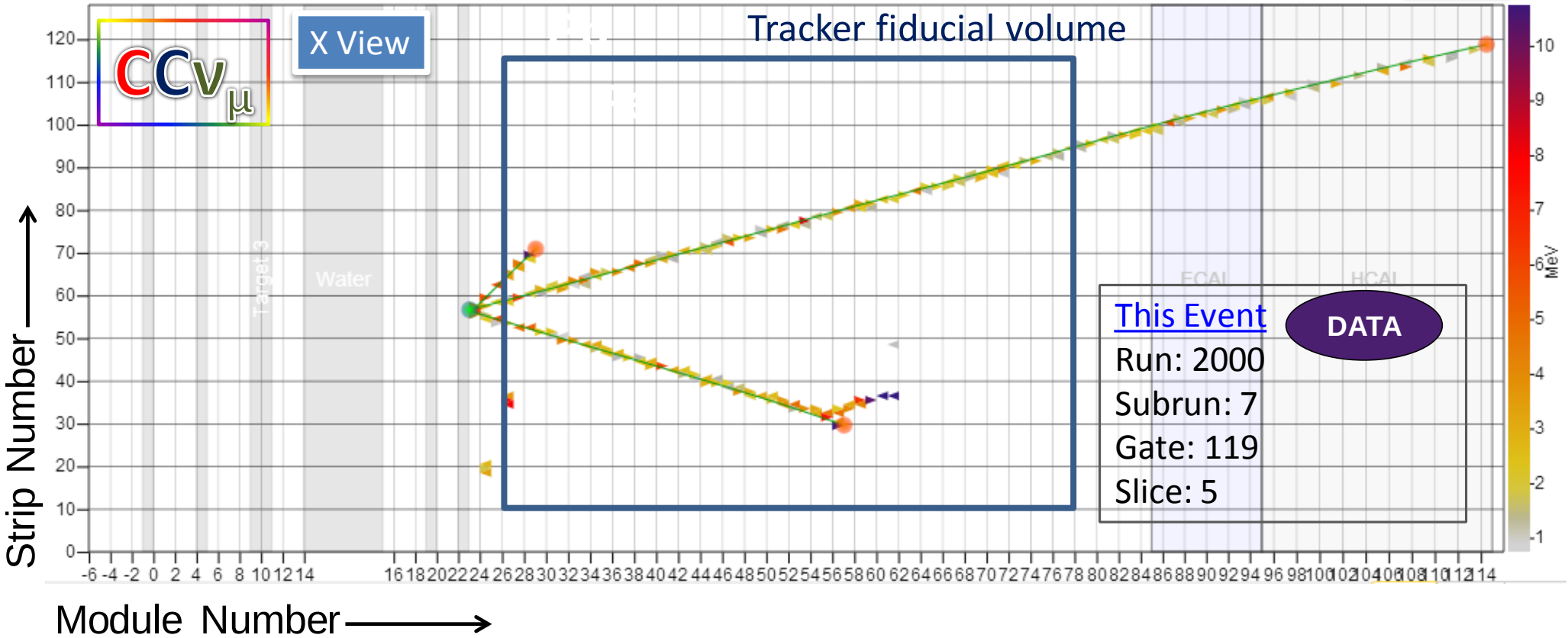
Muon must be matched to a momentum- and charge-analyzed track in MINOS ND

Interaction Material

Vertex must be in passive nuclear target or adjacent scintillator plane

Event Selection

Thanks MINOS!



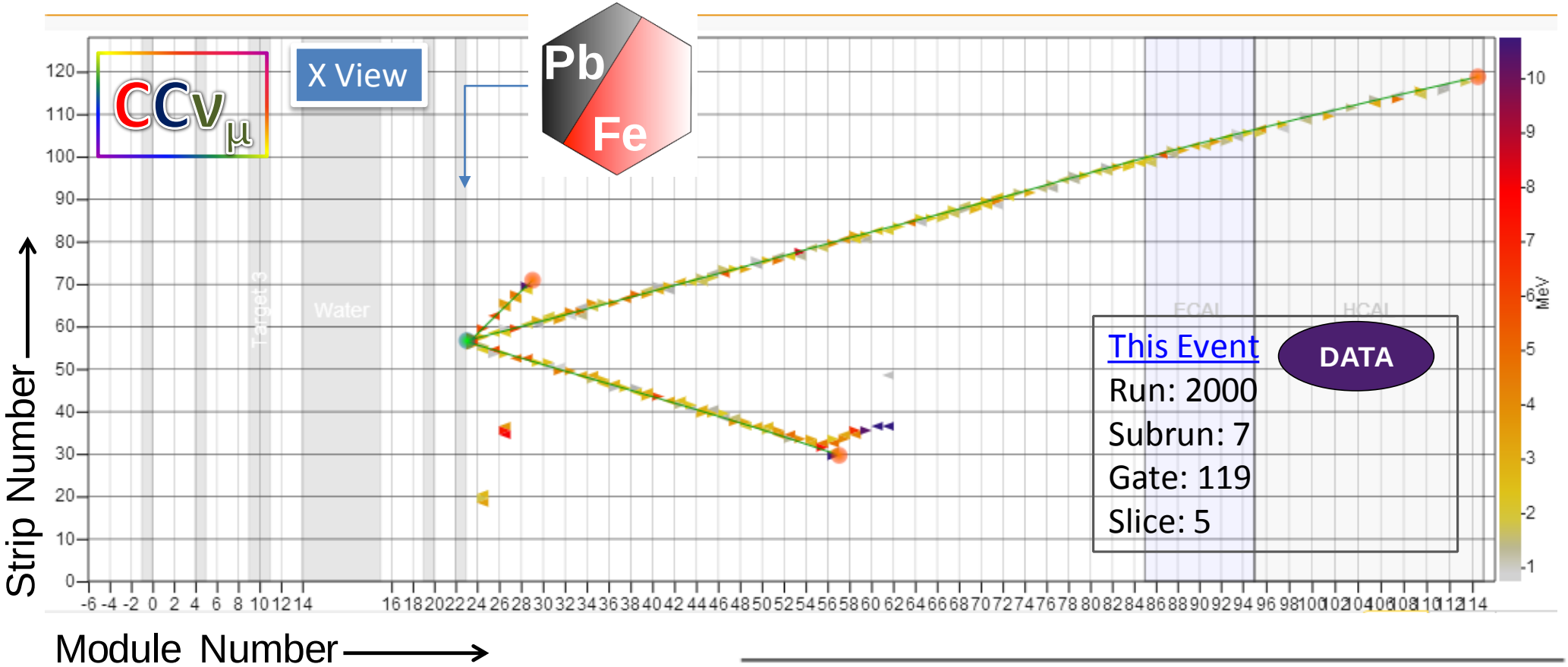
Event Topology

Muon must be matched to a momentum- and charge-analyzed track in MINOS ND

Interaction Material

Scintillator events must be in the fiducial volume of the tracker

Event Reconstruction



Vertex Location	Target 2	Target 3	Target 4	Target 5	Tracker
α	1.78	1.67	1.59	1.57	1.60

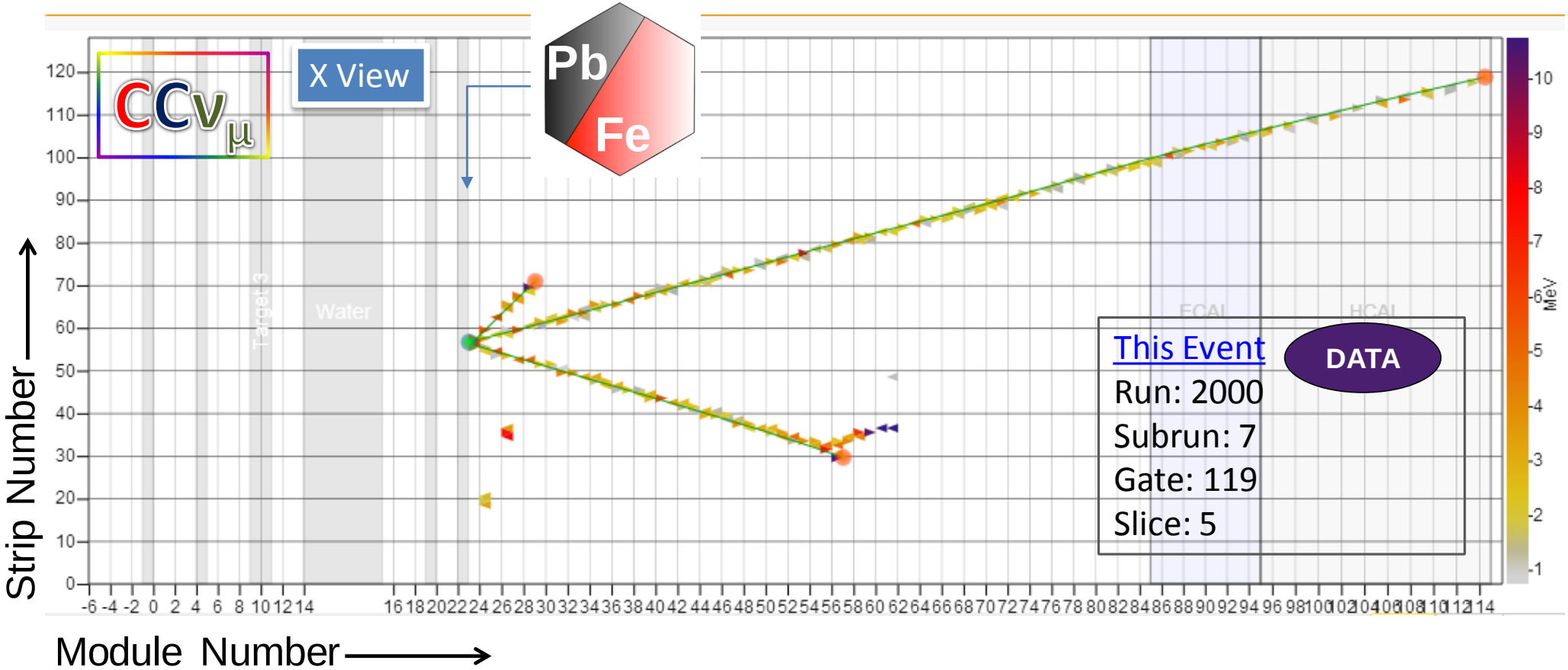
Recoil Energy

Sum of non-muon visible energy, weighted for passive material traversed

calorimetric $E_{recoil} = \alpha \times \sum_i c_i E_i$

material	Scintillator	Carbon	Iron	Lead
dEdx (MeV/ g/cm^2)	1.936	1.742	1.451	1.122

Event Reconstruction



Need to reconstruct **muon energy**, **muon angle**, **hadronic energy**

$$E_\nu = E_\mu + E_{had}$$

$$\nu = E_\nu - E_\mu$$

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

$$y = E_{had}/E_\nu$$

$$x = \frac{Q^2}{2M\nu}$$

Forming a Cross Section

$$\left(\frac{d\sigma}{dx}\right)_i = \frac{\sum_j U_{ij}(d_j - b_j)}{\epsilon_i(\Phi T)\Delta x_i}$$

- $(d_j - b_j)$ data – background = signal
- U_{ij} Unfolding matrix
  - From reco bin j to “true” bin i
- ϵ_i Efficiency for bin i
- (ΦT) Flux times target number
  - Flux may depend on bin
- Δx_i Bin width

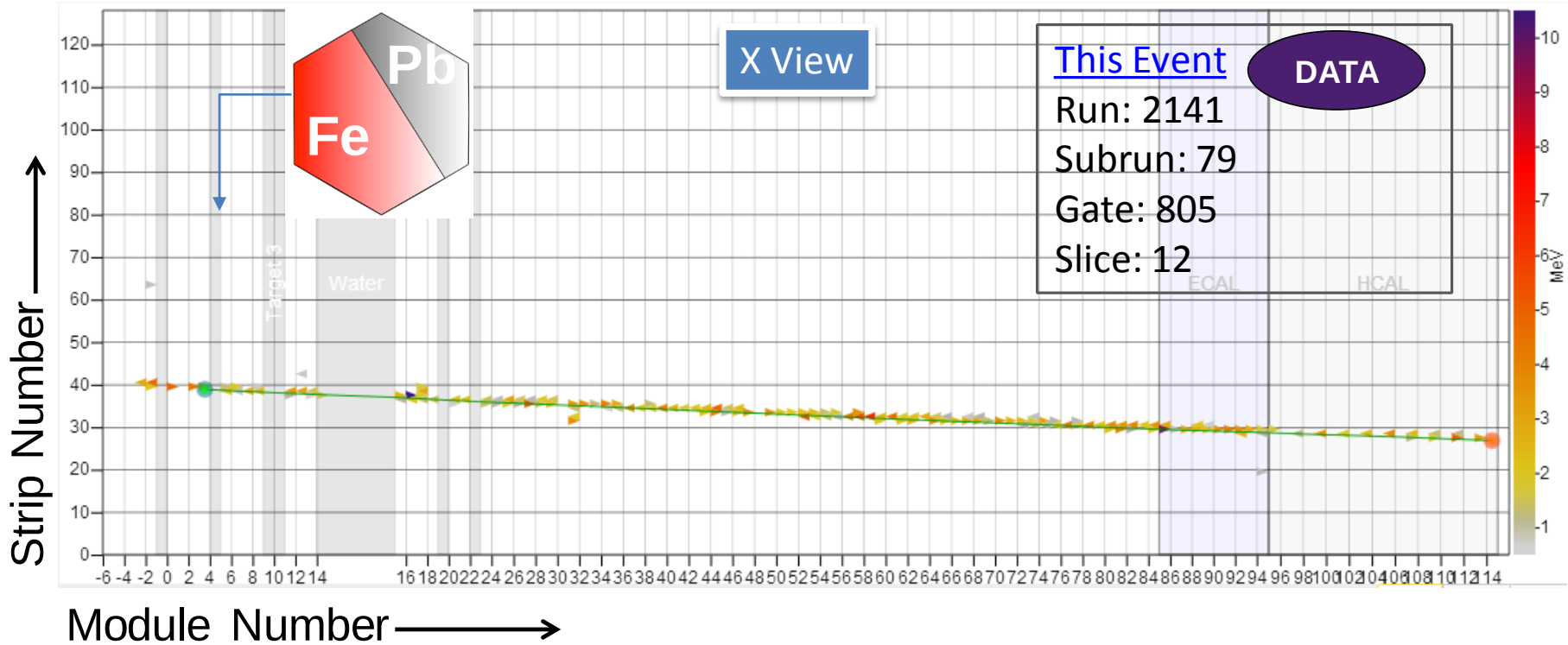
Background
1. Rock Muons

Affected only target 2 in the earliest data

Uninstrumented planes reduced tracking efficiency. Veto wall was not installed yet.

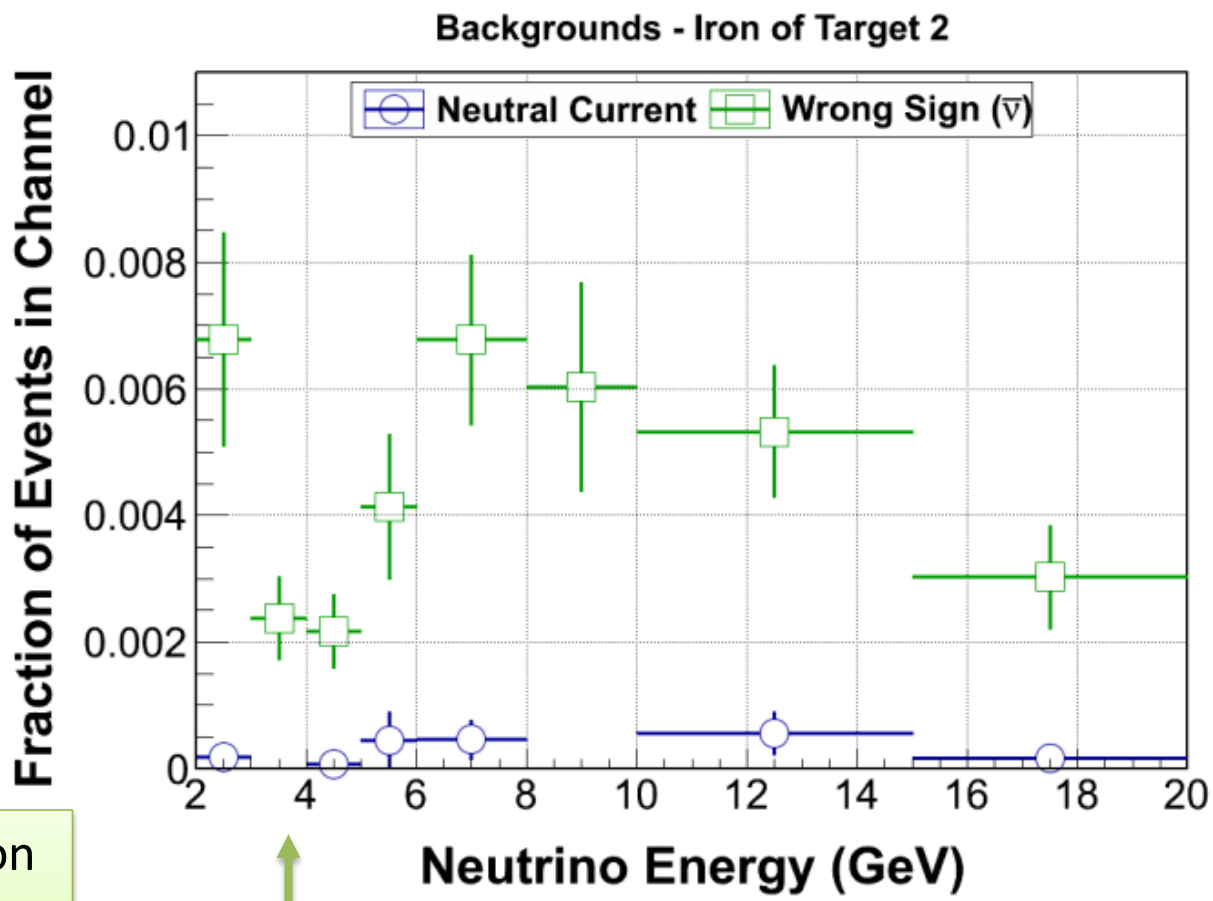
Target 2 ≈ 50% of iron, 33% of lead. Early data ≈ 30% of all neutrino data.

→ < 1% flat correction



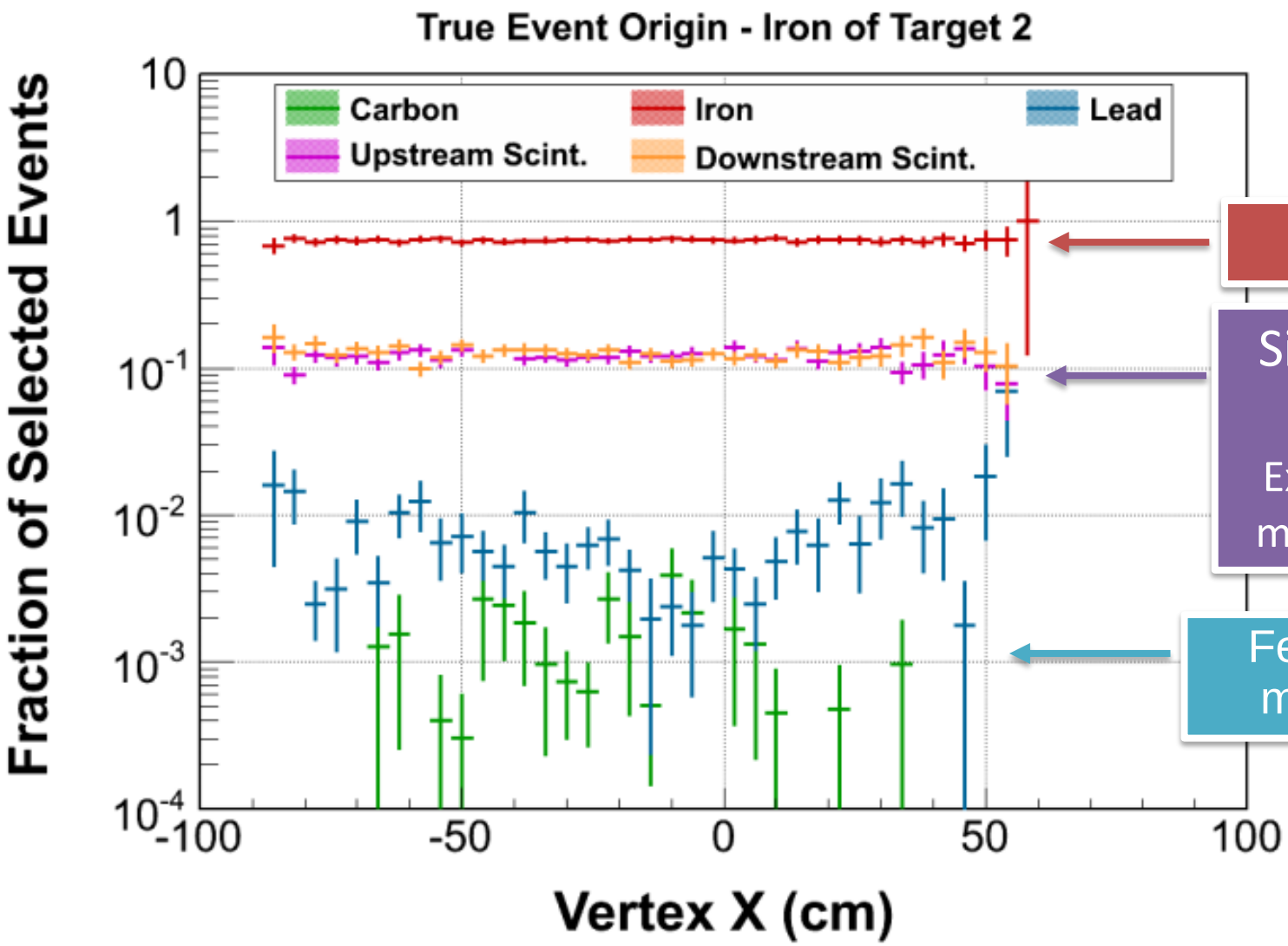
Background
2. Neutral Current and $\bar{\nu}_\mu$ Events

Small background (<0.5%). Let MC apply correction.



Wrong sign contamination is smaller in the beam's focusing beam

Background
3. Misidentified Nucleus

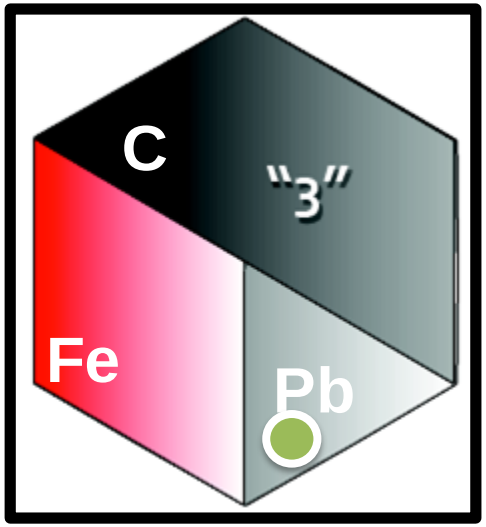


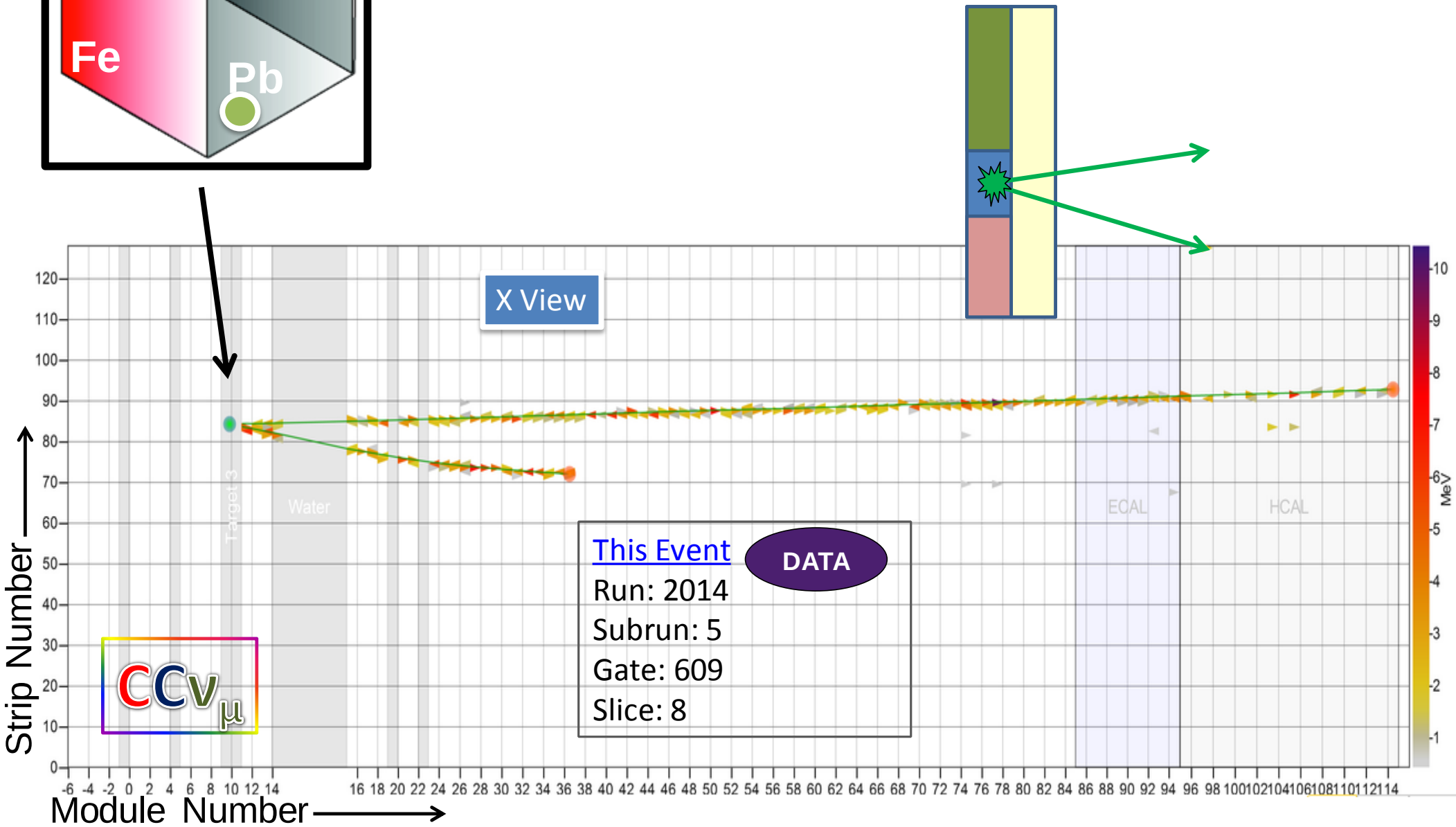
Signal

Significant impurity of scintillator events.
Expect ~23% from fiducial mass of iron vs. scintillator

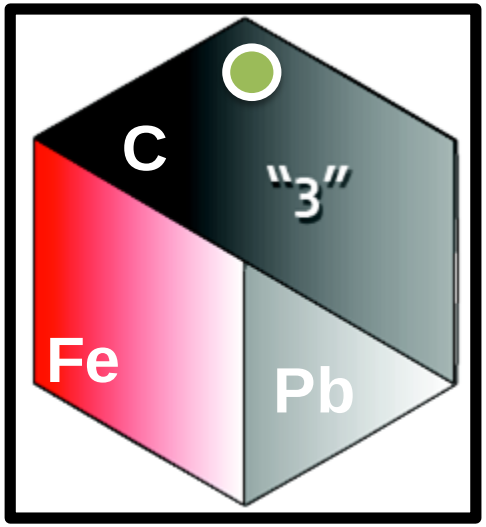
Few carbon/lead events migrating into iron sample

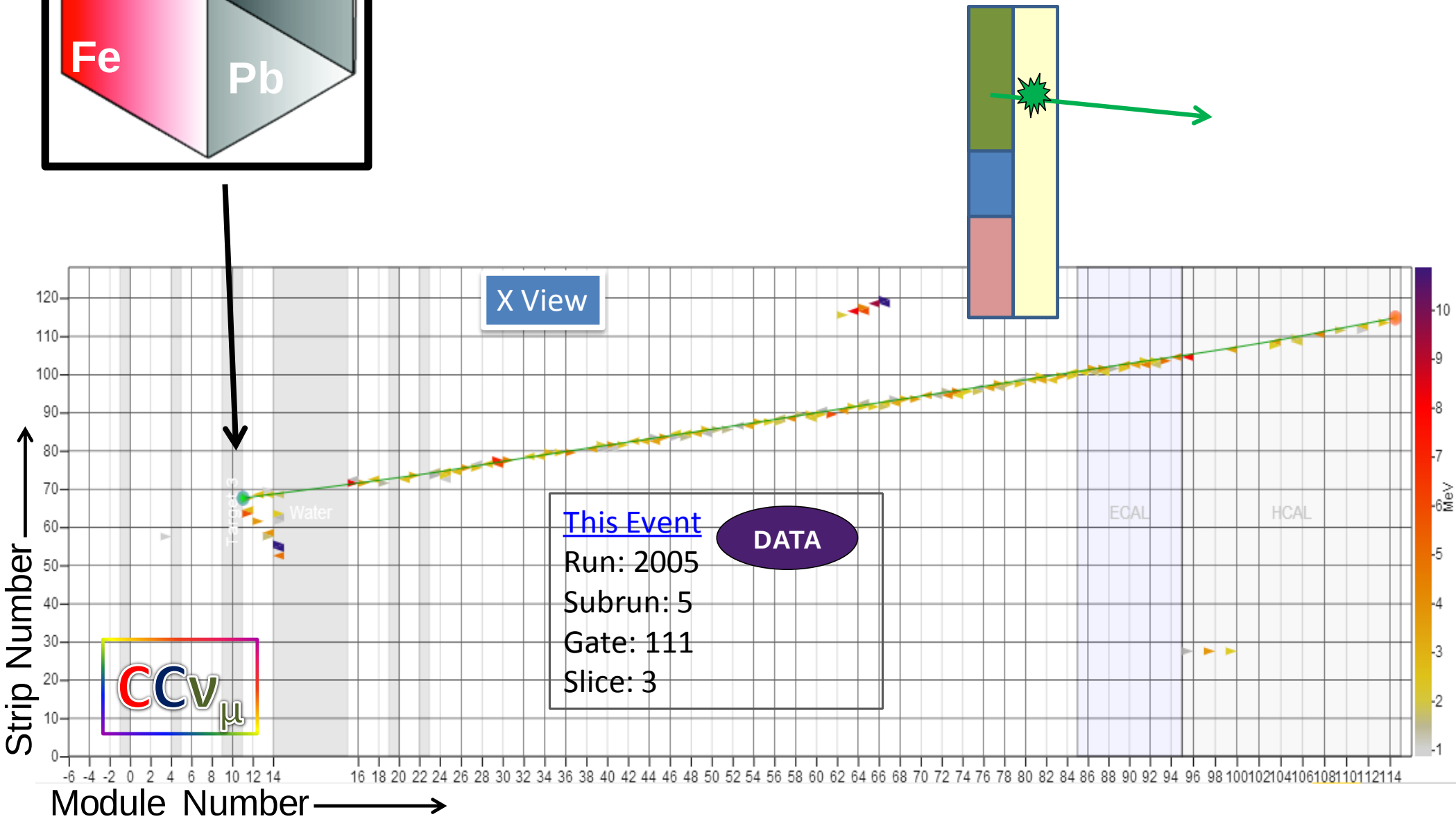
An event from target 3
Lead candidate



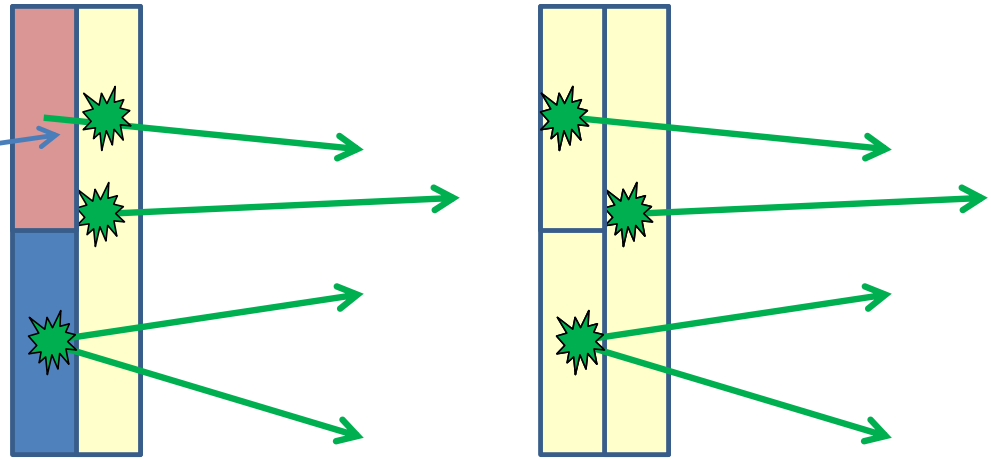


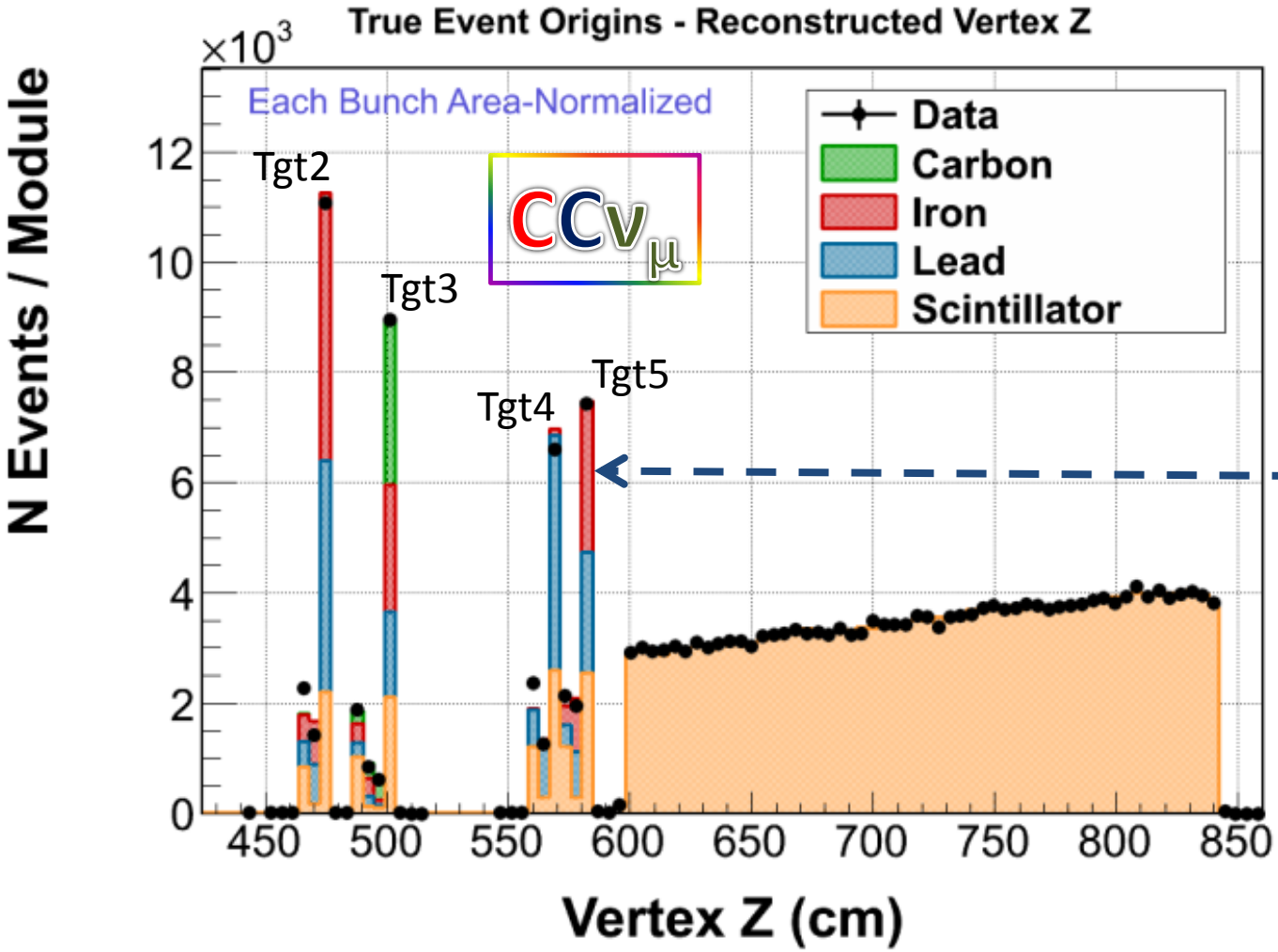
An event from target 3
Carbon candidate





One track events from passive target have a vertex in the first plane downstream of the target

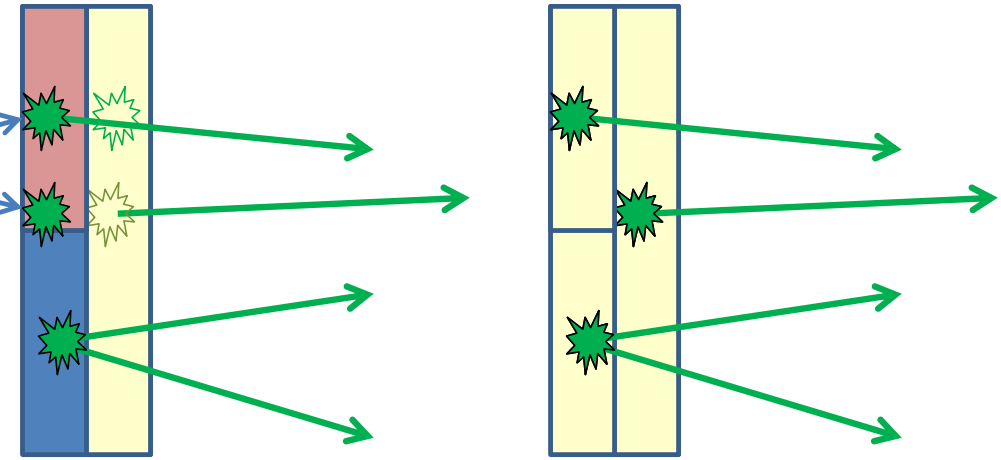


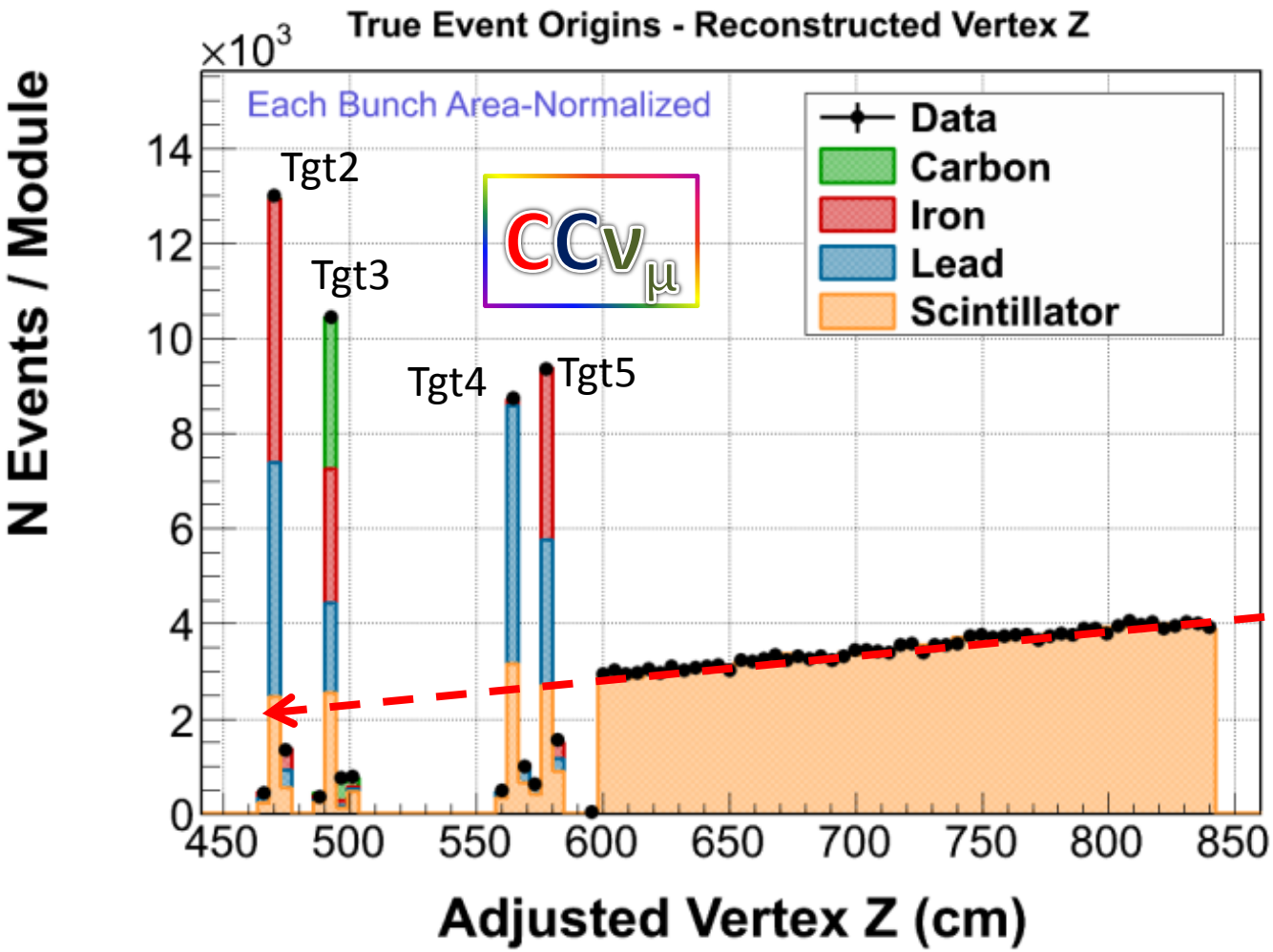


These peaks are at the location of the first module downstream of the passive targets

Project the one track events to the passive target's center in Z

This is the best guess of the vertex



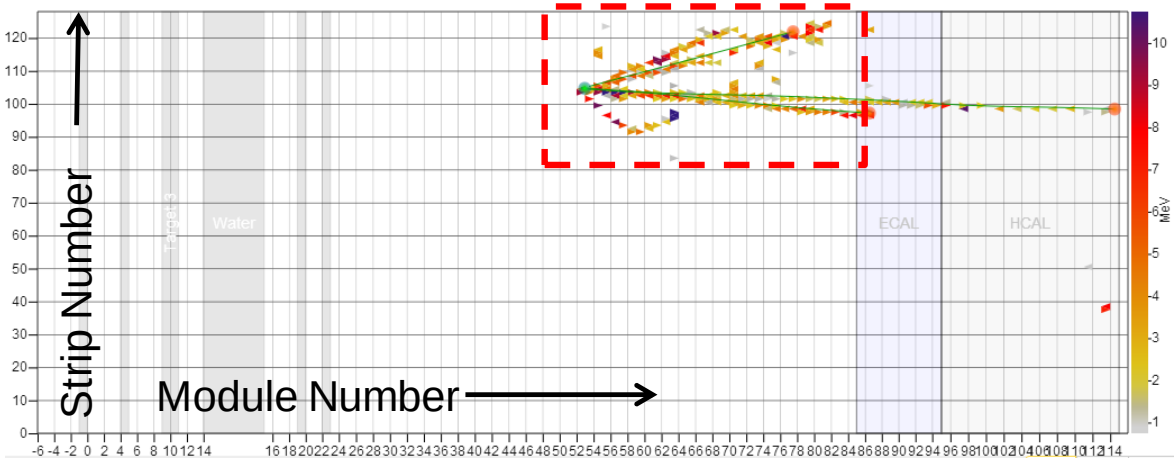


Use events in the tracker modules to predict and subtract the plastic background

Subtract the Plastic Background

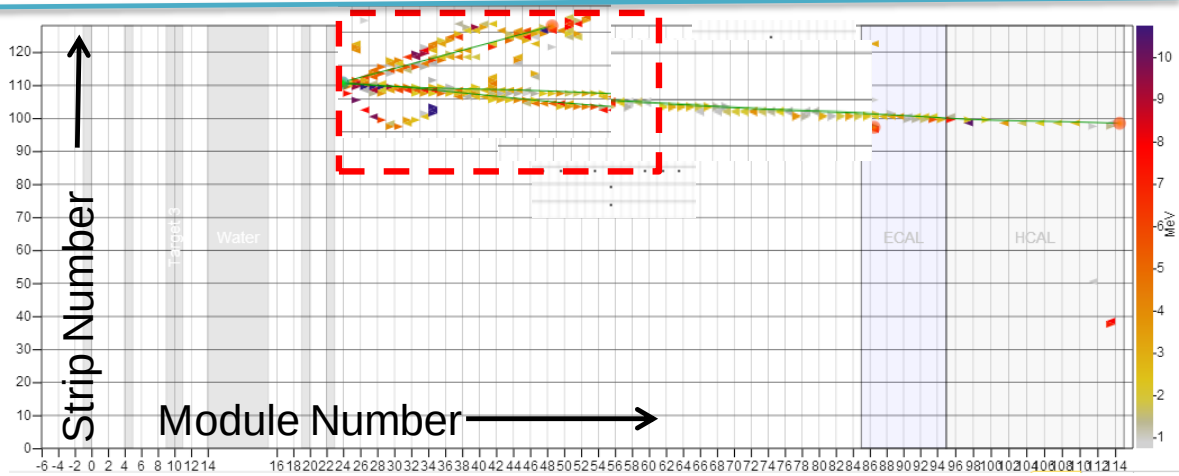
- Predict spectrum of background using:

Events in the Tracker | Geometric Acceptance | Reconstruction Efficiency



Found this event in scintillator of tracker

Pretend the same event happened in plastic background

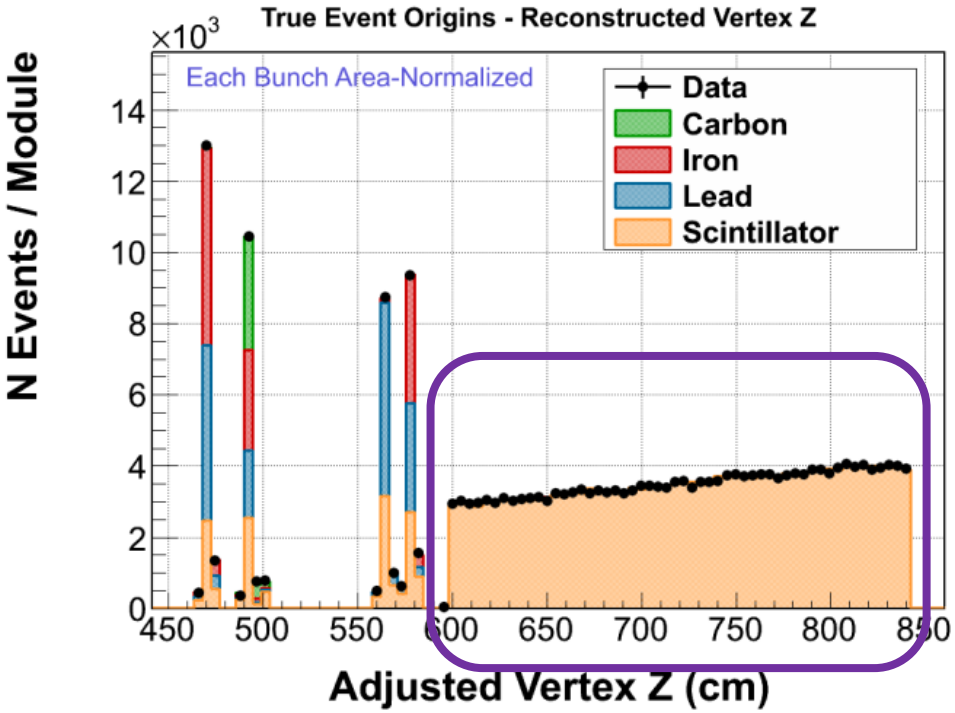


Predict spectrum of background using:

Events in the Tracker

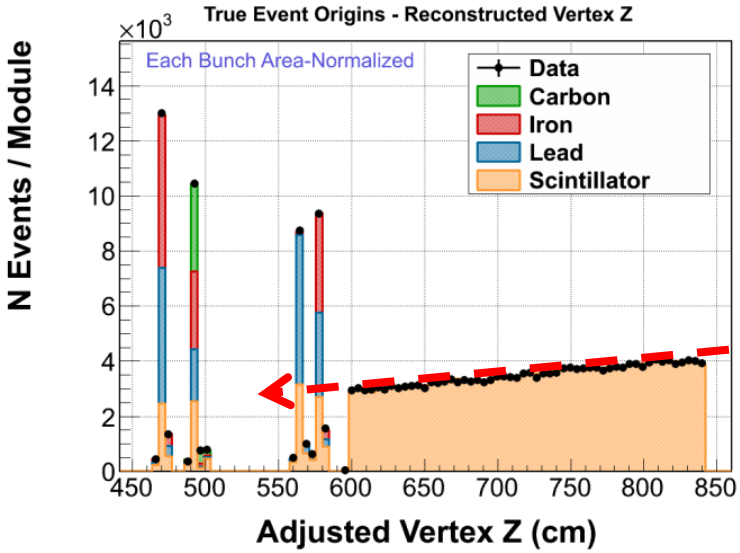
Selection of events in tracker volume done in both data.
Does not use cross section model.

Data-driven background

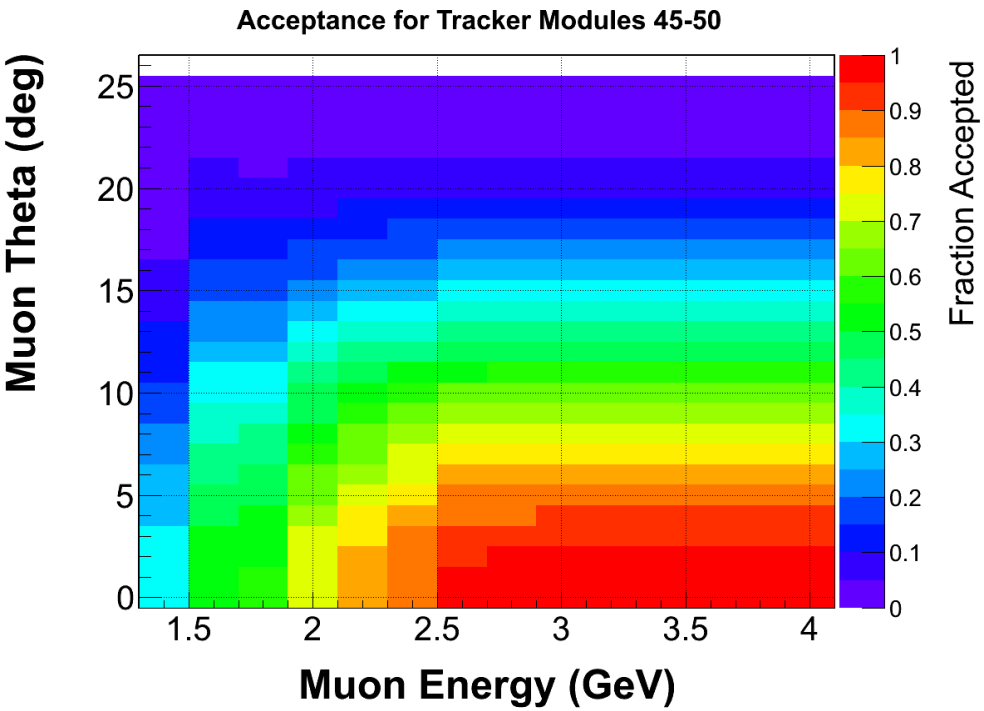


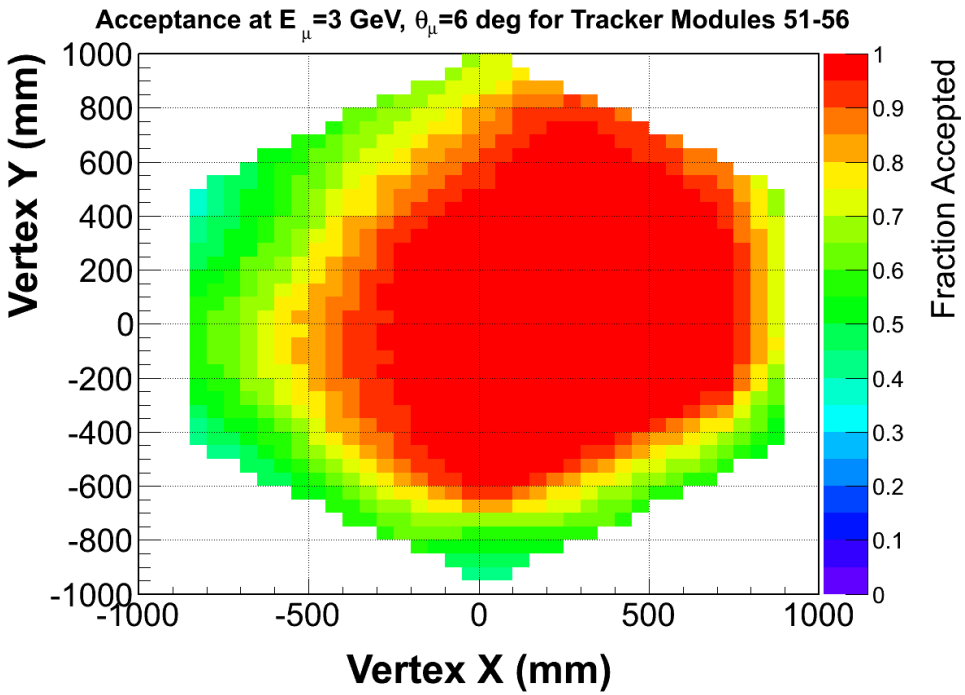
Predict spectrum of background using:

Geometric Acceptance



- Muon-only Geant4 simulation measures probability muon will hit MINOS
  - Function of muon energy, muon angle, vertex
  - Does not use neutrino interaction model





Predict spectrum of background using:

Geometric Acceptance

- Muon-only Geant4 simulation measures probability muon will hit MINOS
  - Function of muon energy, muon angle, vertex

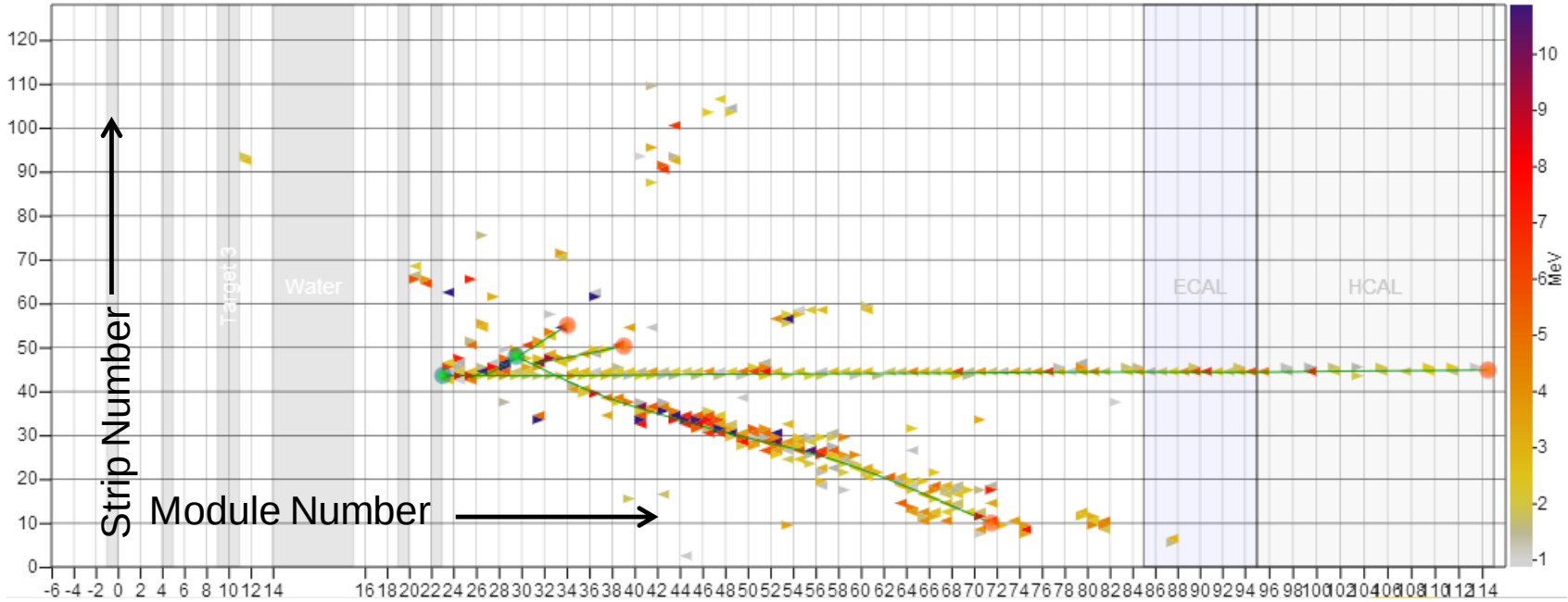
- Apply reweight factor to each event in tracker
  - "For every 1 event like this in the tracker, there will be X in the background"

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

Predict spectrum of background using:

Reconstruction Efficiency

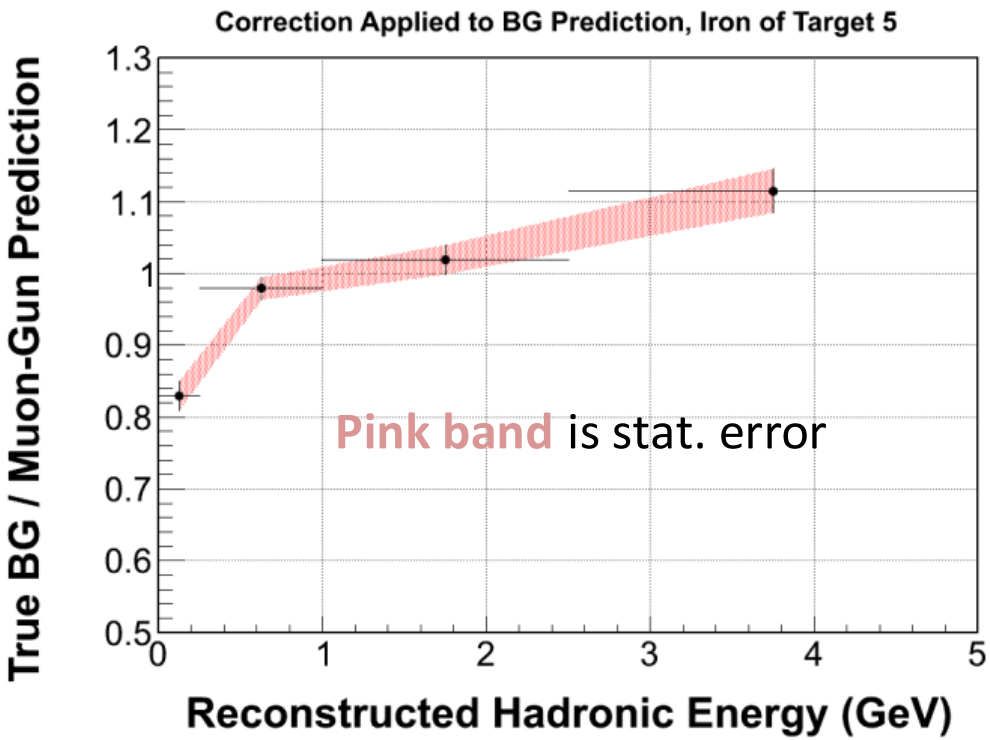
- Efficiency also depends on hadronic energy
  - Shower can obscure muon. Not addressed by geometric acceptance.
- Measure remaining efficiency with simulation
  - GENIE 2.6.2 and Geant4

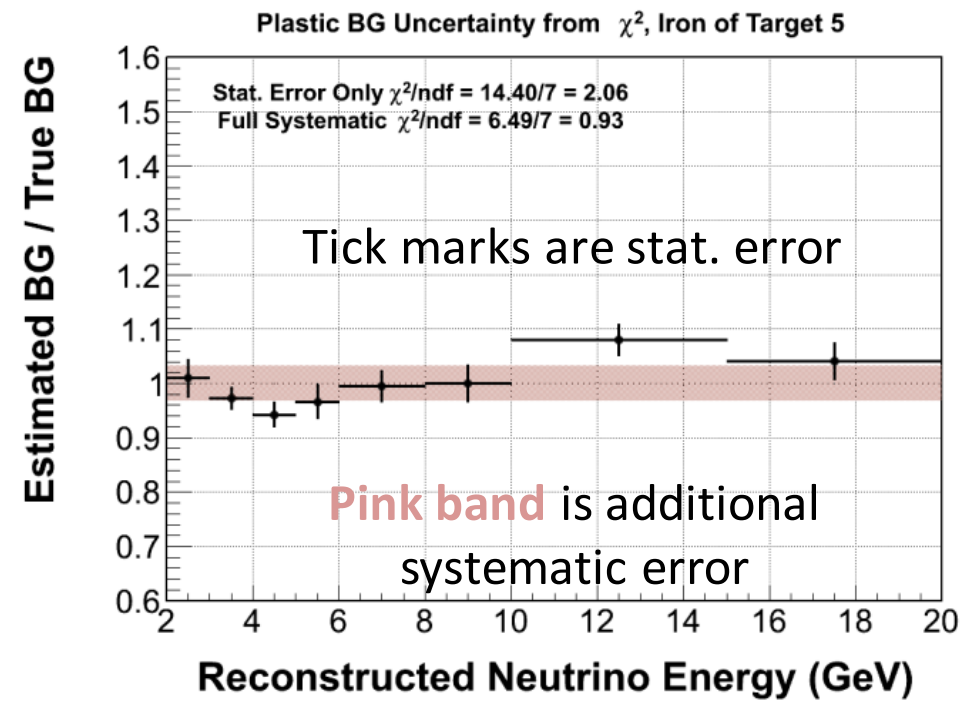


Predict spectrum of background using:

Reconstruction Efficiency

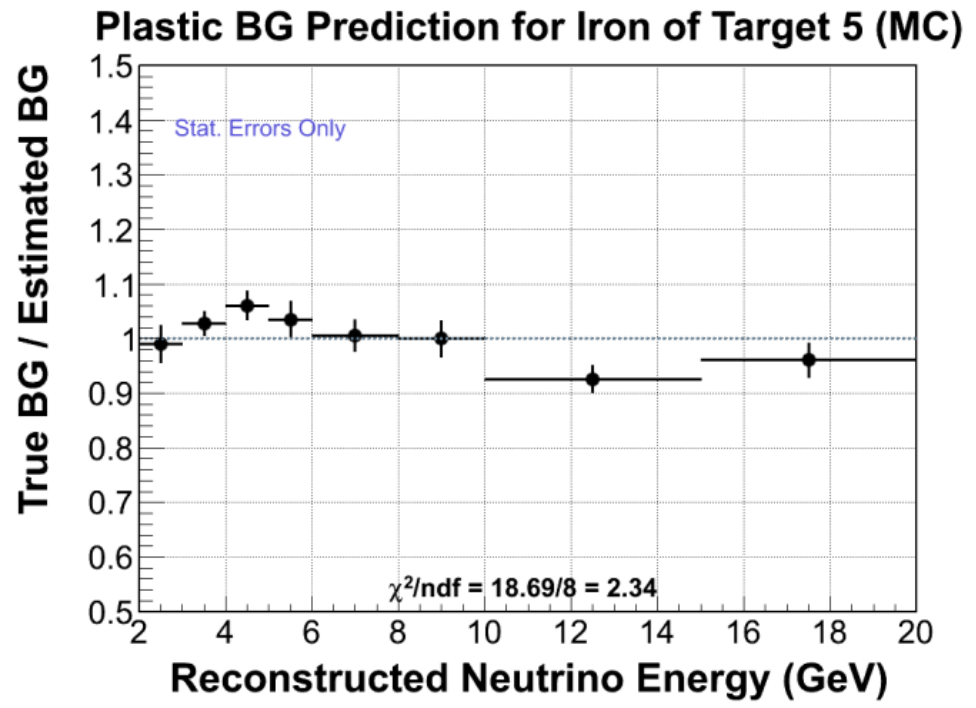
- Unique correction for each nuclear target
- Errors are MC stat. and an additional correlated error
  - Additional uncertainty scale determined by adding uncorrelated uncertainty on top of stat. until $\chi^2/dof = 1$
  - Additional uncertainty applied as correlated event-to-event and target-to-target

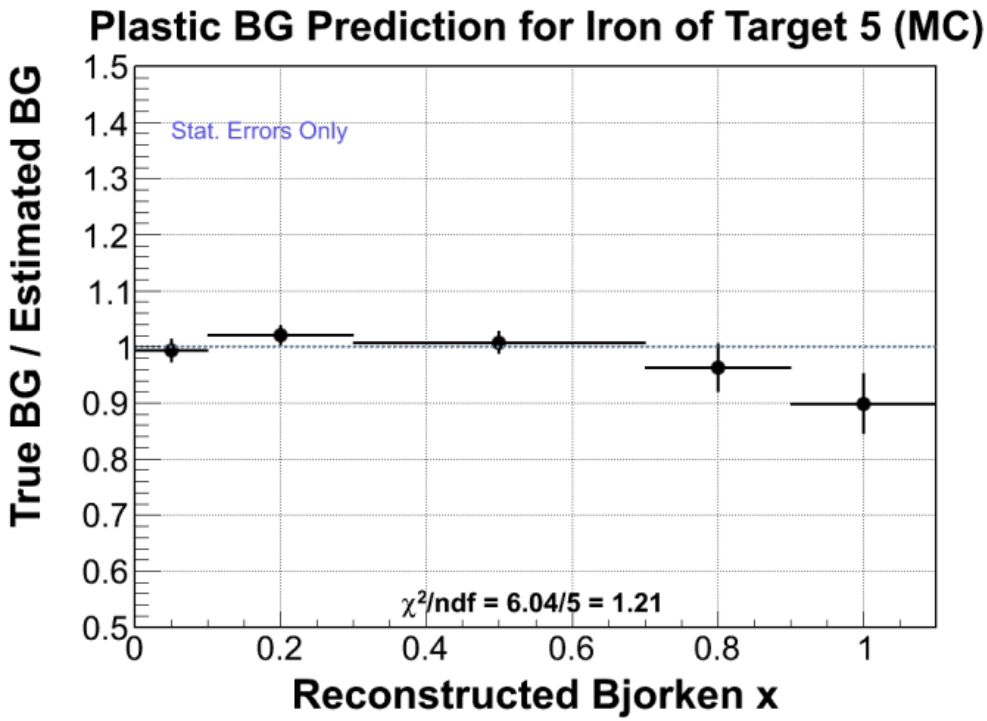




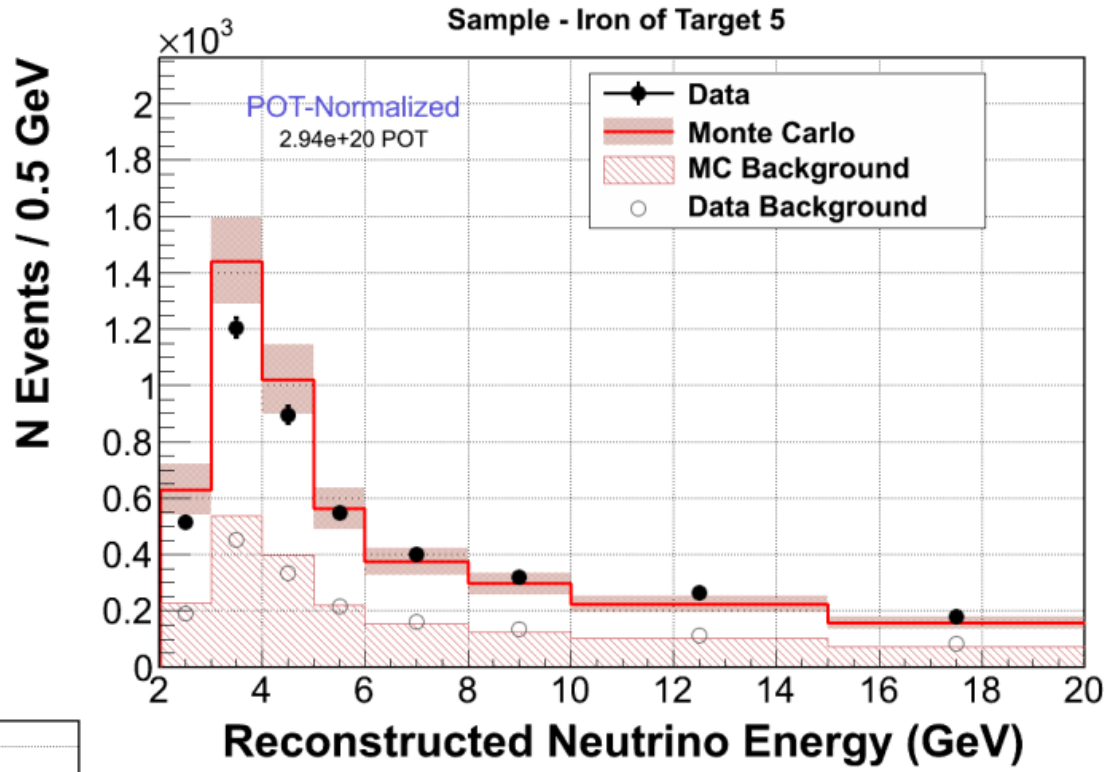
Accuracy of Background Estimation

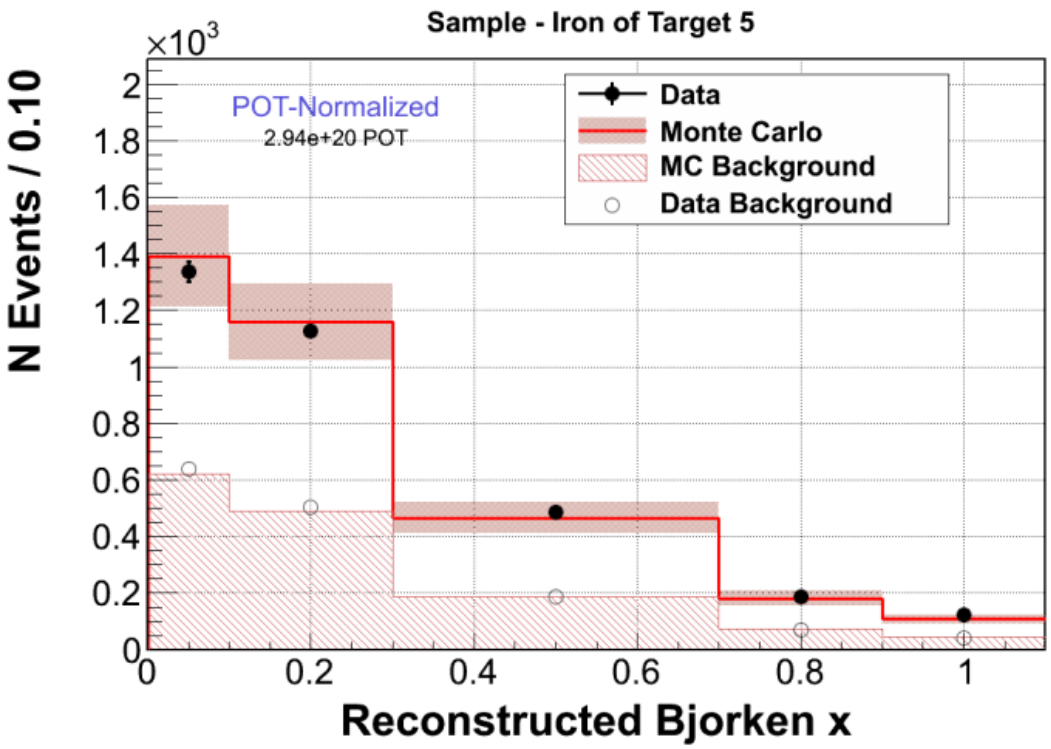
Events in the Tracker | Geometric Acceptance | Reconstruction Efficiency





$$\left(\frac{d\sigma}{dx}\right)_i = \frac{\sum_j U_{ij}(d_j - b_j)}{\epsilon_i(\Phi T)\Delta x_i}$$





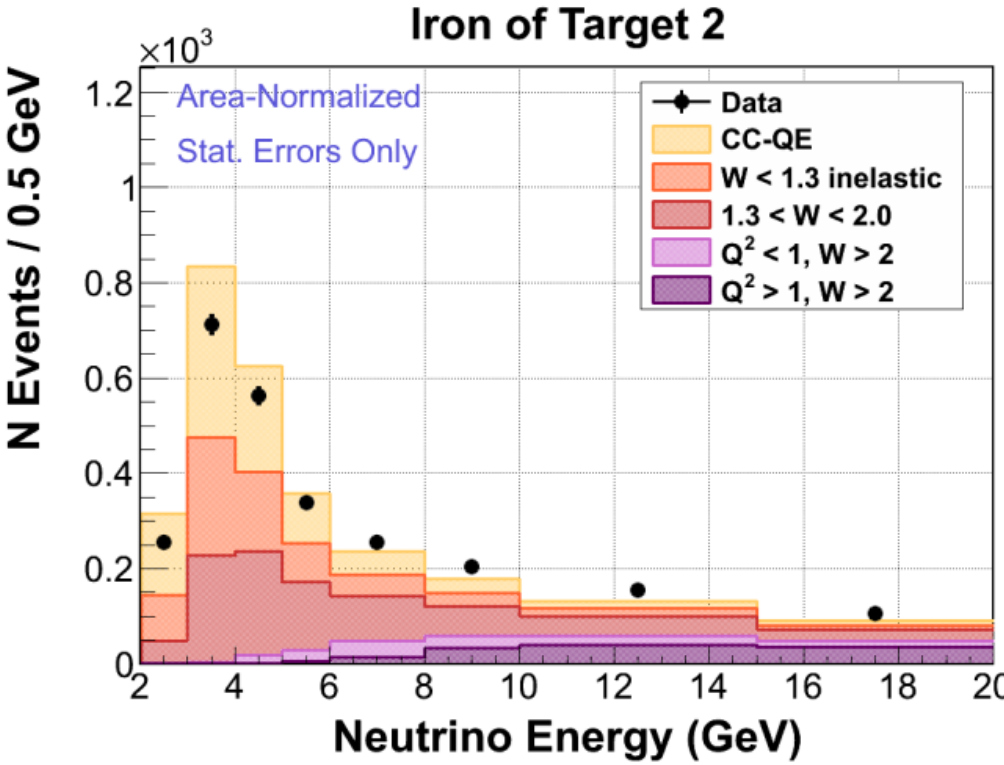
A separate estimated background for **data** and **MC**

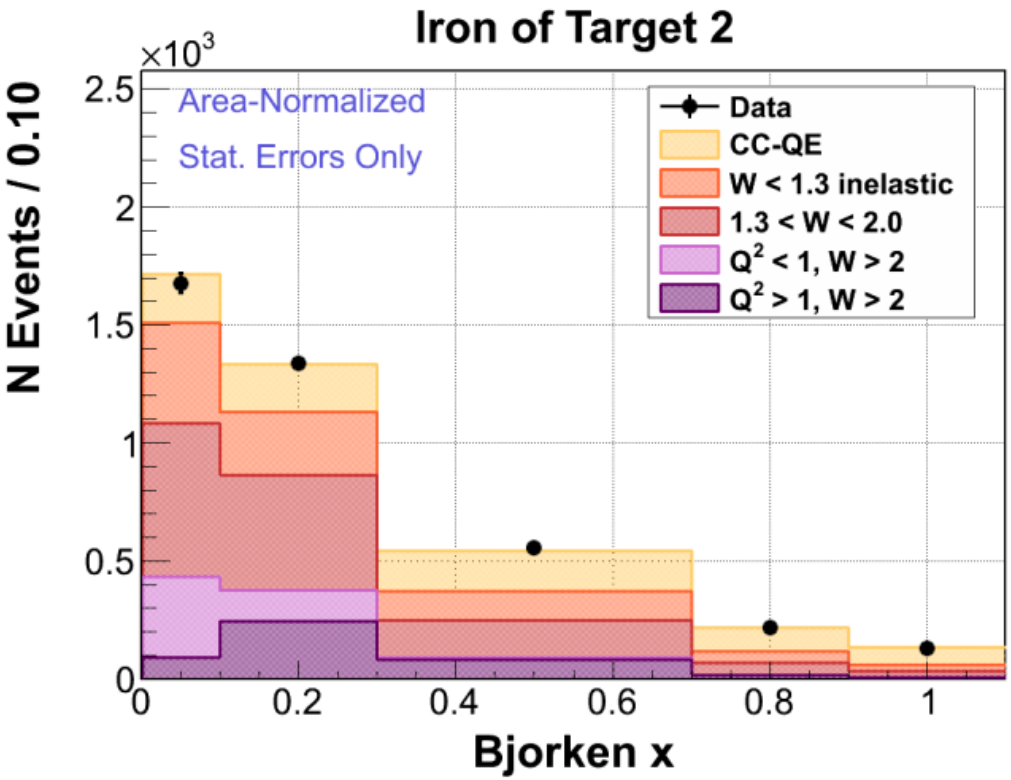
Kinematic Content

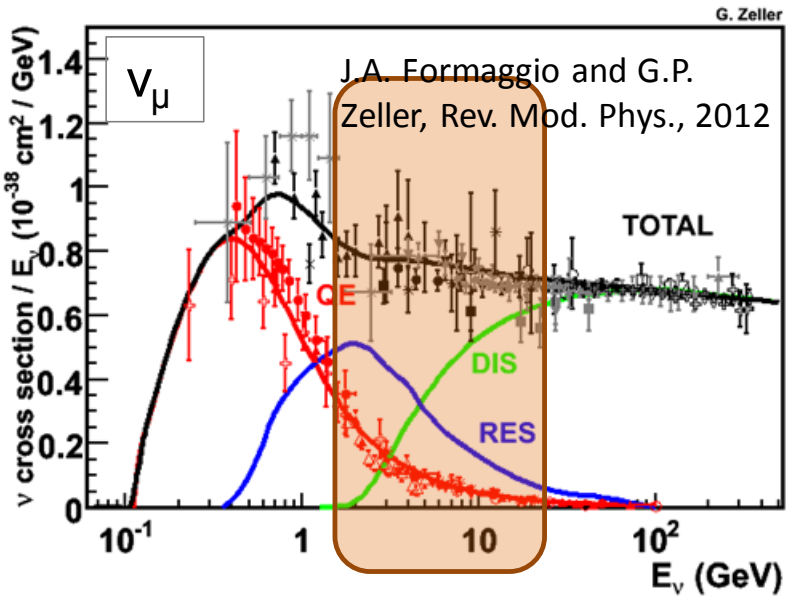
Signal Kinematics
2 < Neutrino Energy < 20 GeV
0 < Muon Angle < 17 deg

Invariant hadronic mass

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



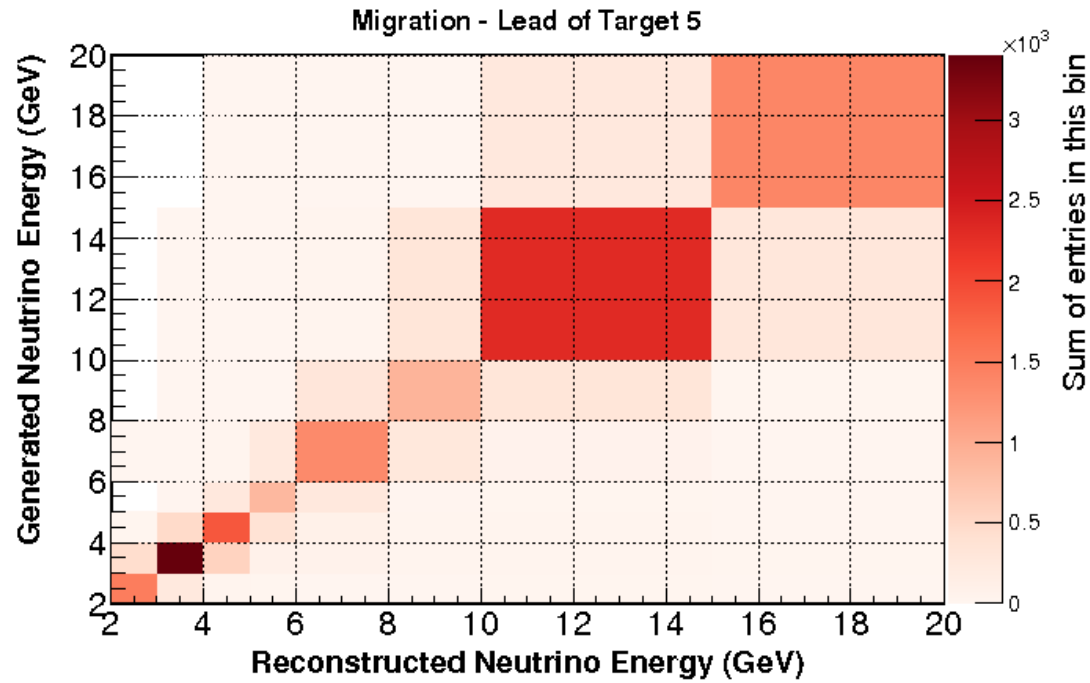




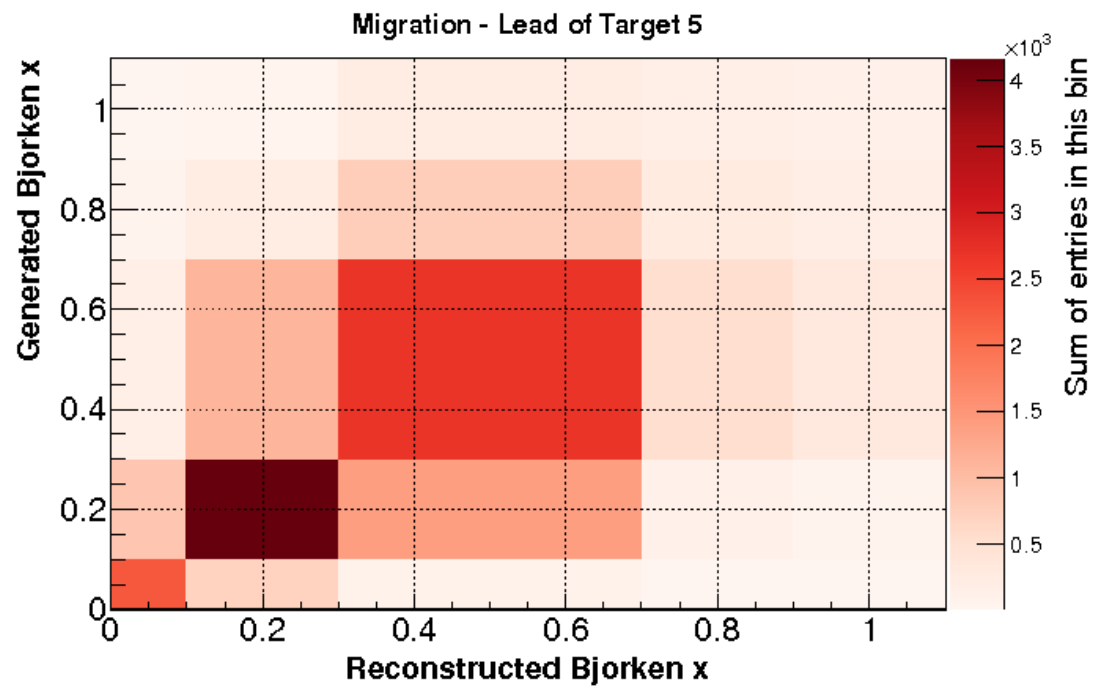
Bin Migration

$$\left(\frac{d\sigma}{dx}\right)_i = \frac{\sum_j \boxed{U_{ij}}(d_j - b_j)}{\epsilon_i(\Phi T)\Delta x_i}$$

- Unfold in neutrino energy
  - Iterative Bayesian unfolding with 4 iterations



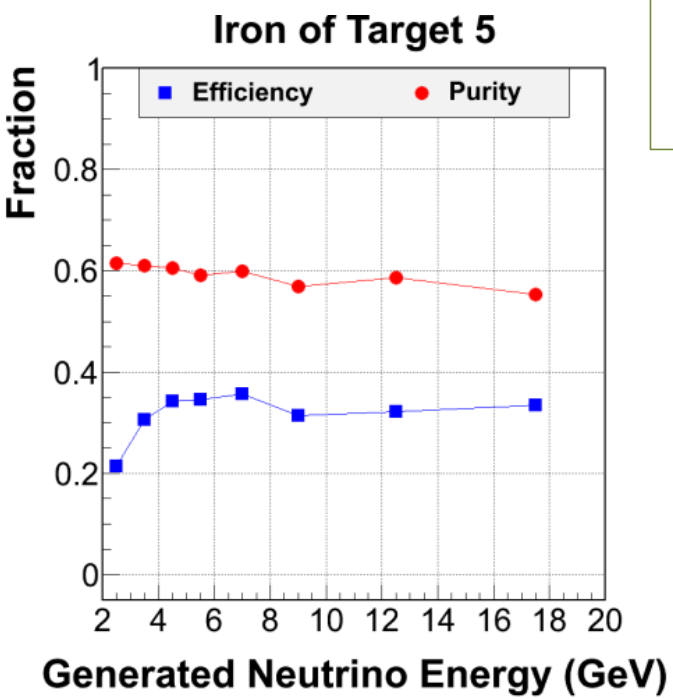
- Fold true x distributions
  - Multiply by this matrix →
  - Avoids model dependence
  - Migration in x is significant

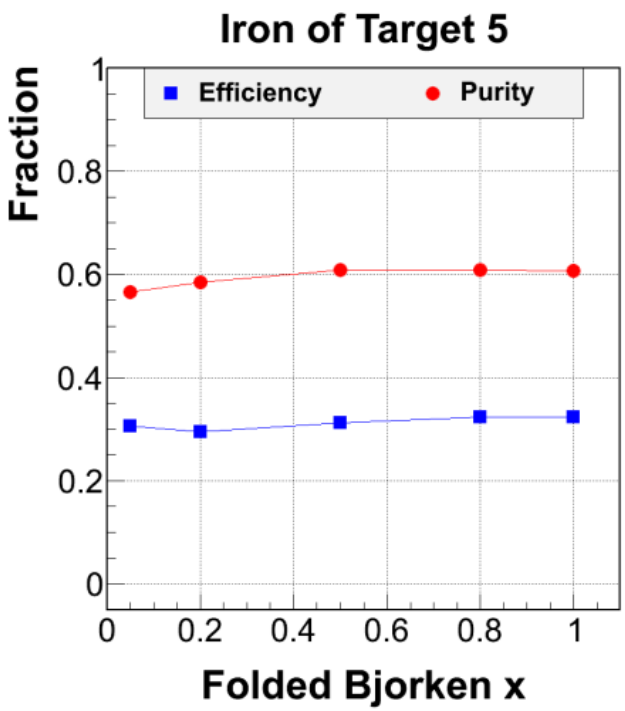


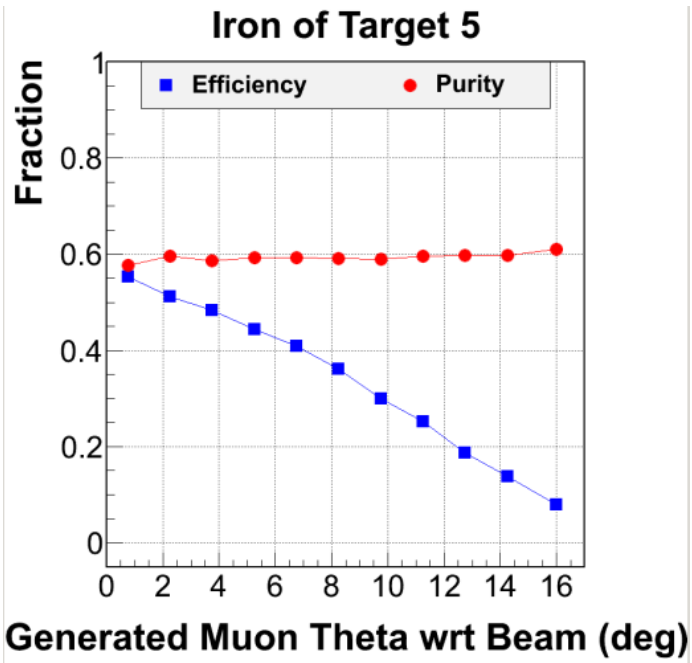
Reconstruction Efficiency

$$\left(\frac{d\sigma}{dx}\right)_i = \frac{\sum_j U_{ij}(d_j - b_j)}{\epsilon_i(\Phi T)\Delta x_i}$$

Signal Kinematics
2 < Neutrino Energy < 20 GeV
0 < Muon Angle < 17 deg







MINOS-match requirement
Muon momentum threshold ~ 2 GeV

MINOS-match requirement
Geometric acceptance primary driver for efficiency loss
Angular threshold ~ 17 deg

Systematic Uncertainties

- Muon Reconstruction
- Hadronic Energy Reconstruction
- Primary Interaction Models
- Final State Interaction Models

All very similar to recent quasi-elastic analysis

Need to reconstruct **muon energy**, **muon angle**, **hadronic energy**

$$E_\nu = E_\mu + E_{had}$$

$$\nu = E_\nu - E_\mu$$

$$y = E_{had}/E_\nu$$

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

$$x = \frac{Q^2}{2M\nu}$$

Muon Energy Scale

- All muons used in this analysis are momentum analyzed in MINOS ND

Muon momentum

scale uncertainties

MINOS range: MINOS NIM A 596, 190 (2008)

±2% for all p_μ

MINOS curvature: arXiv:1305.5199 [physics.ins-det]

±2.1% for p_μ < 1.0 GeV/c

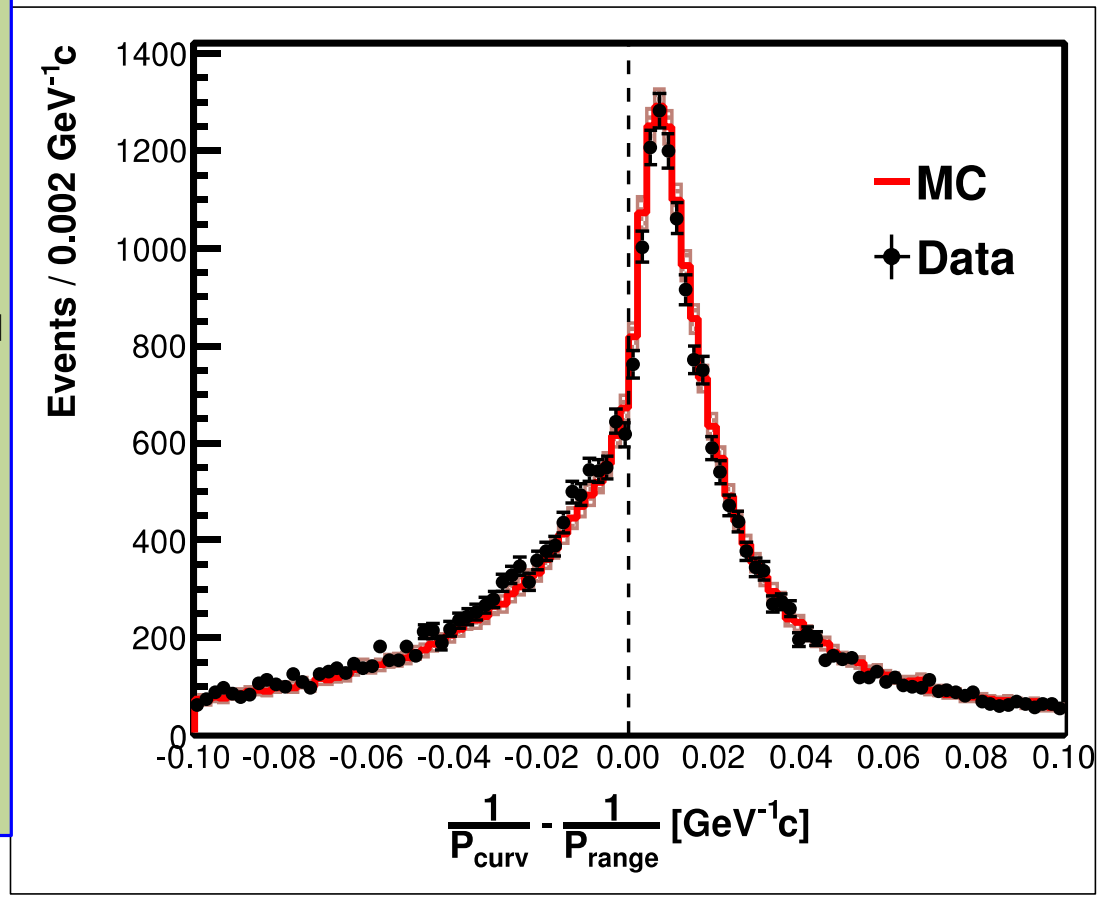
±3.3% for p_μ > 1.0 GeV/c

MINERvA Tracker (Targets)

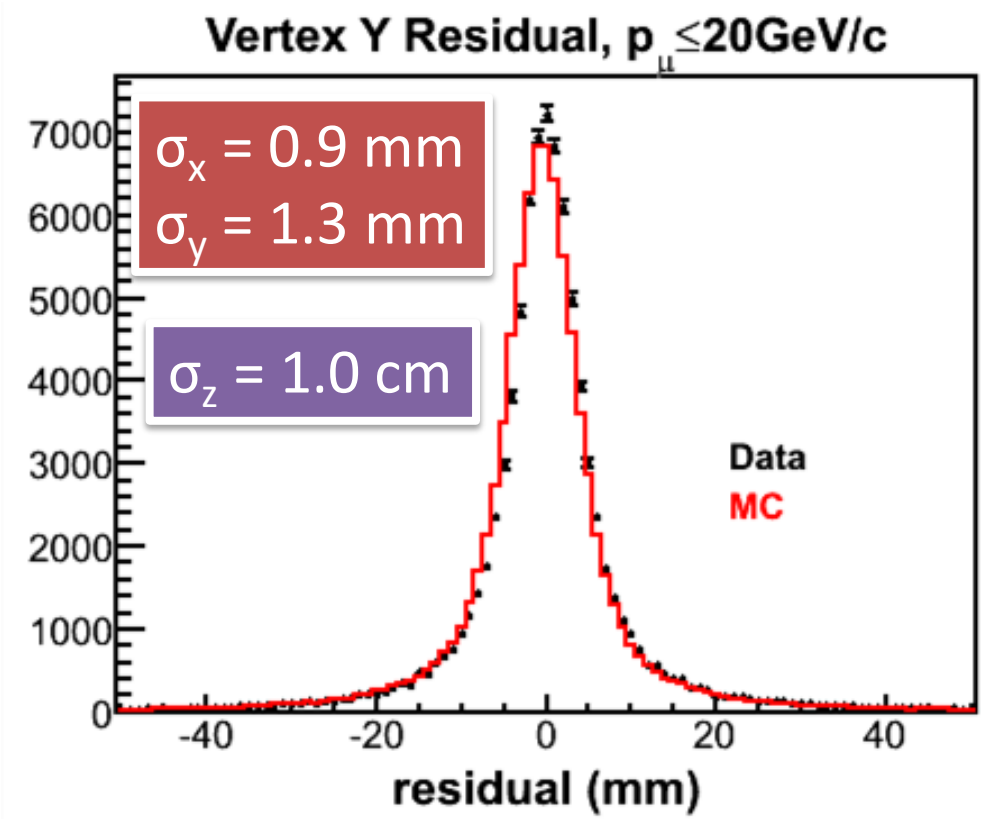
±11 (17) MeV (mass model)

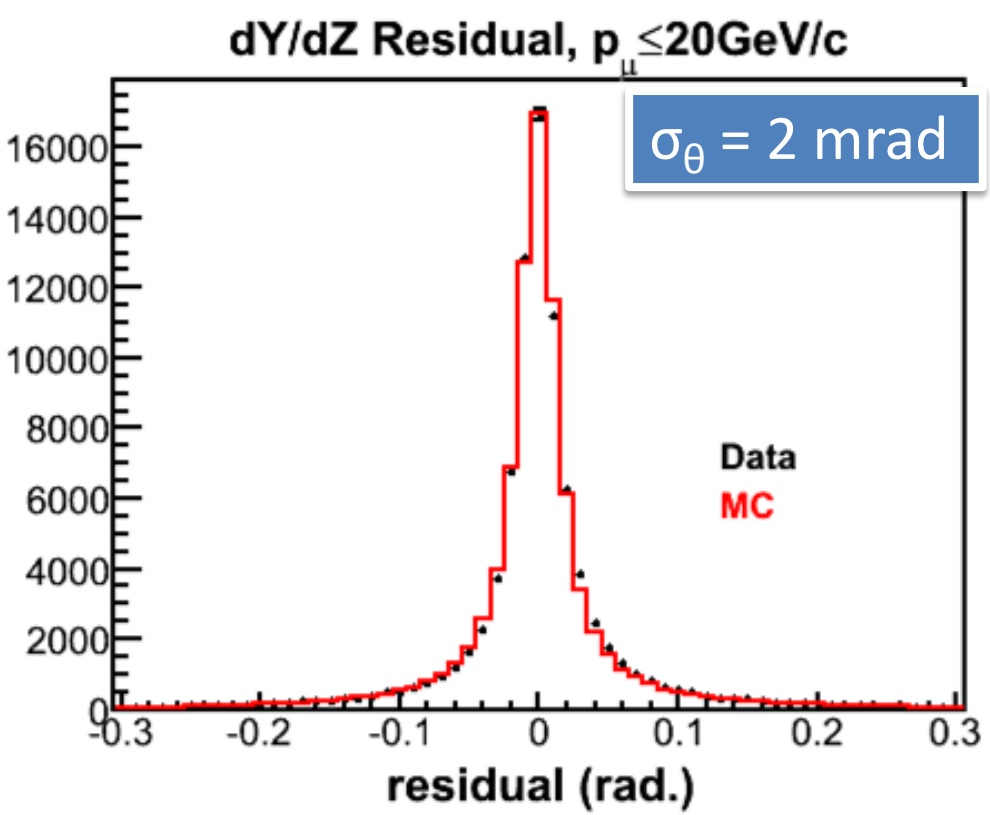
±30 (40) MeV (dE/dx)

muons lose ~0.5-1.5 GeV in MINERvA



Muon Tracking Resolutions

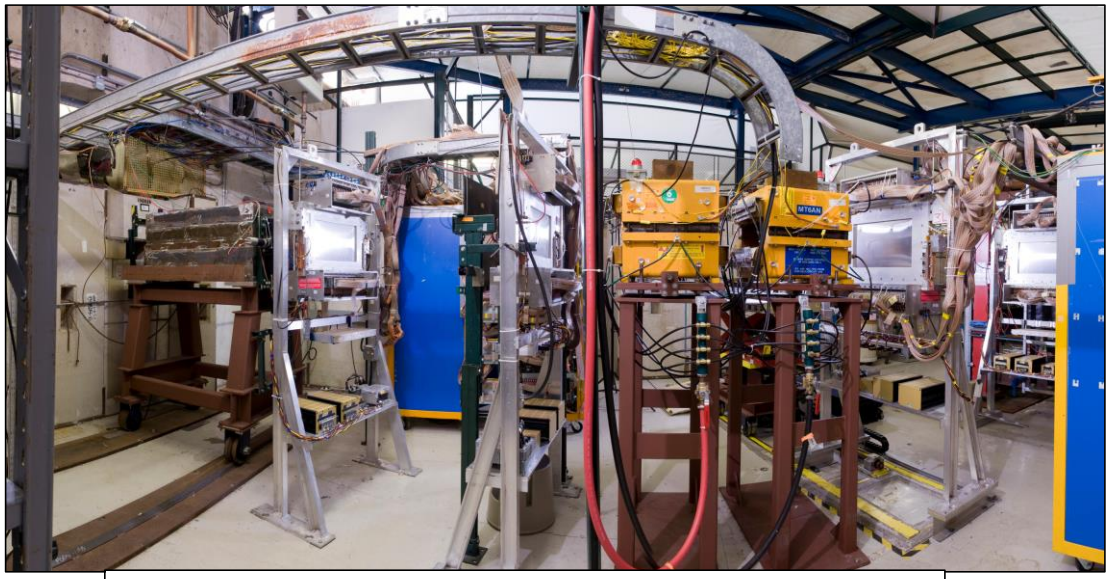


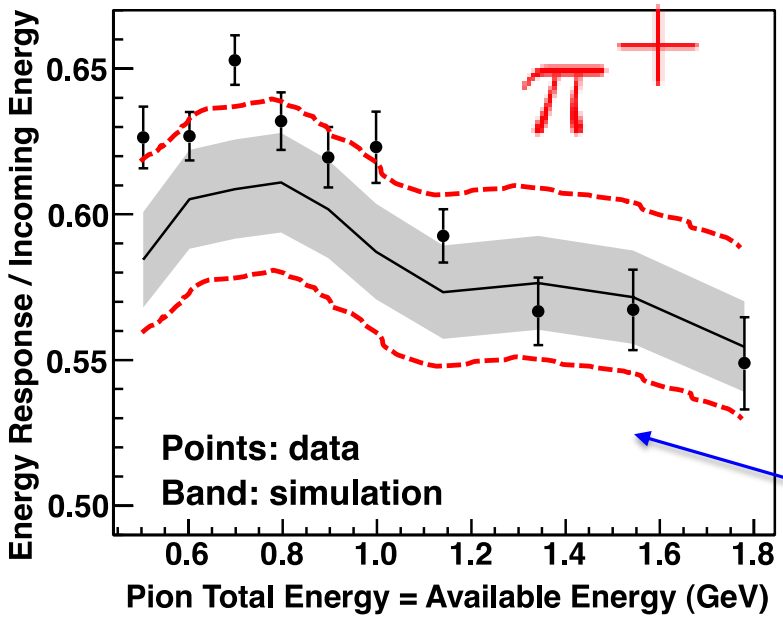


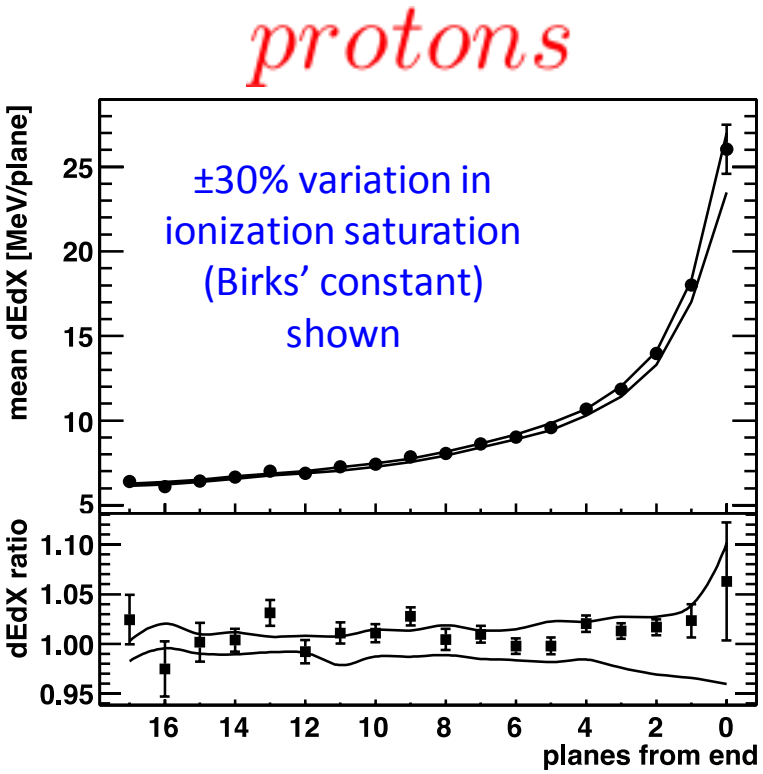
Split-track study of clean muons in tracker region

Hadronic Energy – Test Beam

Thanks to AD and MTest!



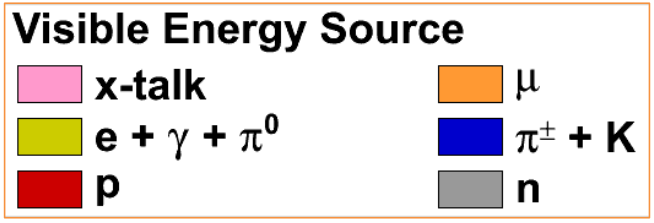


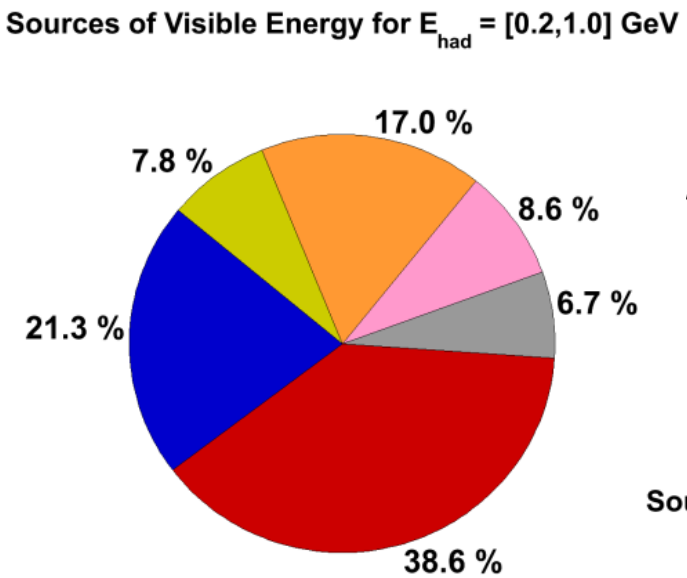


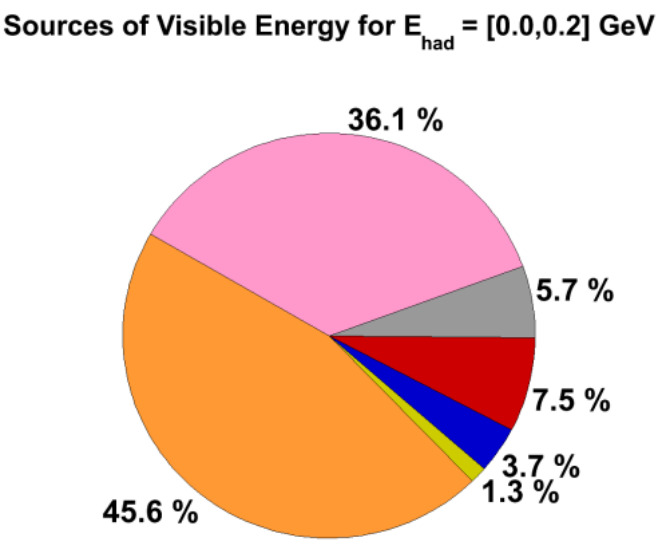
high-energy charged pion response uncertainty ≈ 5%

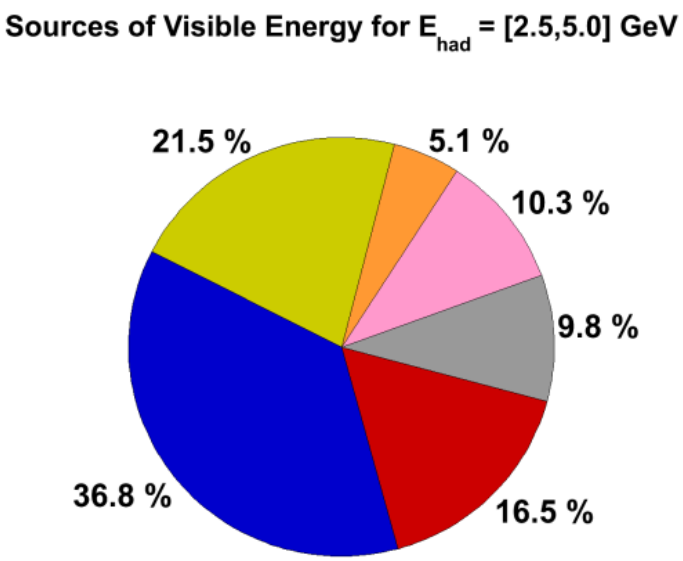
Hadronic Energy Detector Response

Energy Source	Uncertainty
Proton	3.5%
Neutron (KE <50 MeV)	25%
Neutron (50 <KE <150 MeV)	10%
Neutron (KE >150 MeV)	2%
Muon	2.4%
γ, π^0, $e^{\pm}$	10%
$\pi^{\pm}$, Kaon	5%
Cross talk	20%
Other	20 %



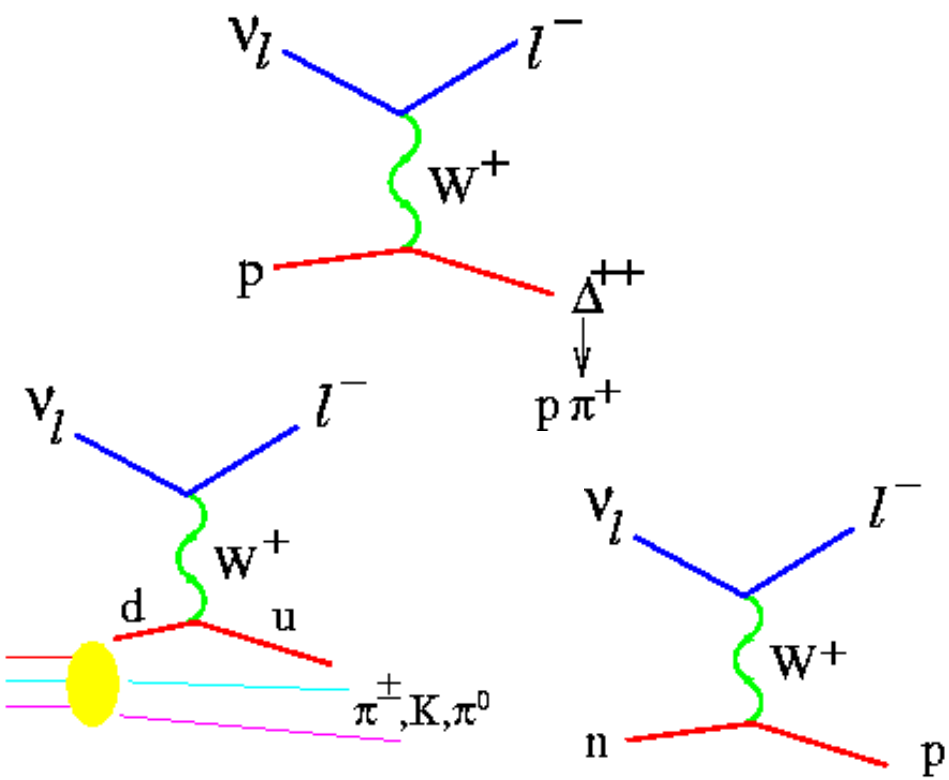


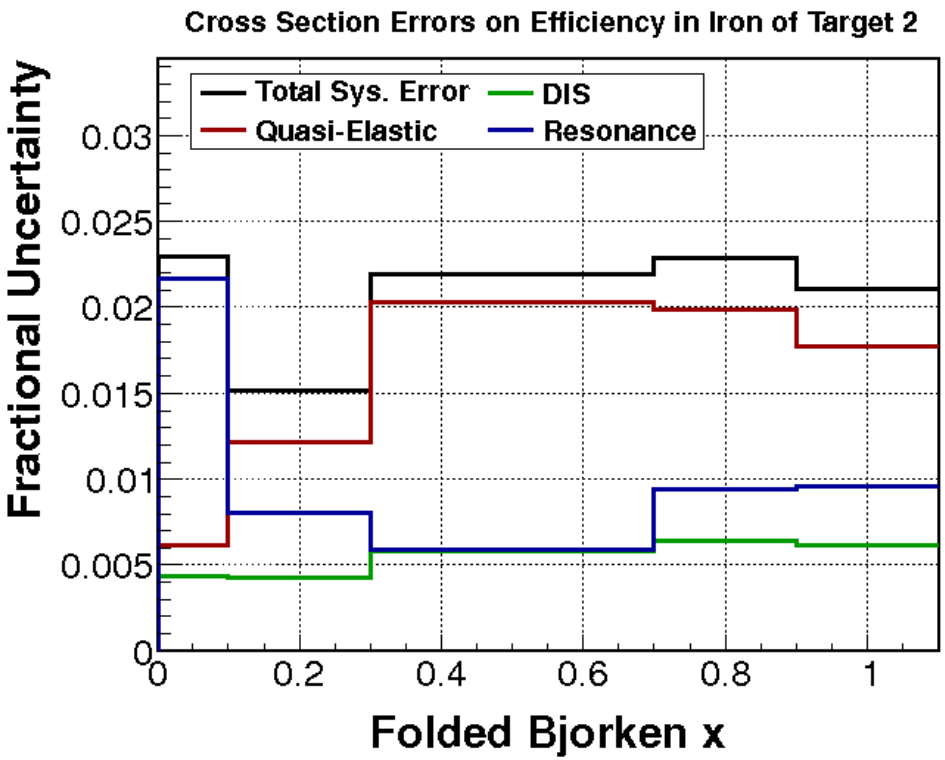




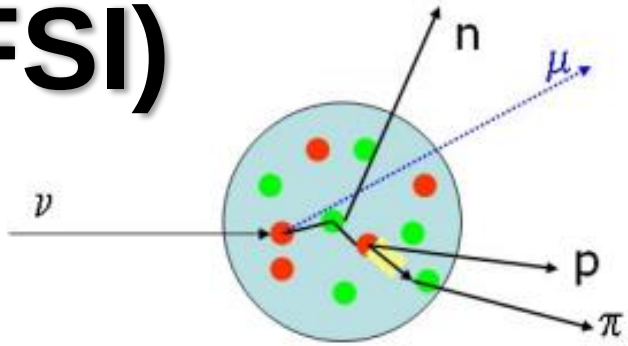
Primary Interaction Model

- Enters measurement through efficiency correction
  - Data-driven background subtraction avoids model dependence
- Efficiency calculated with GENIE 2.6.2



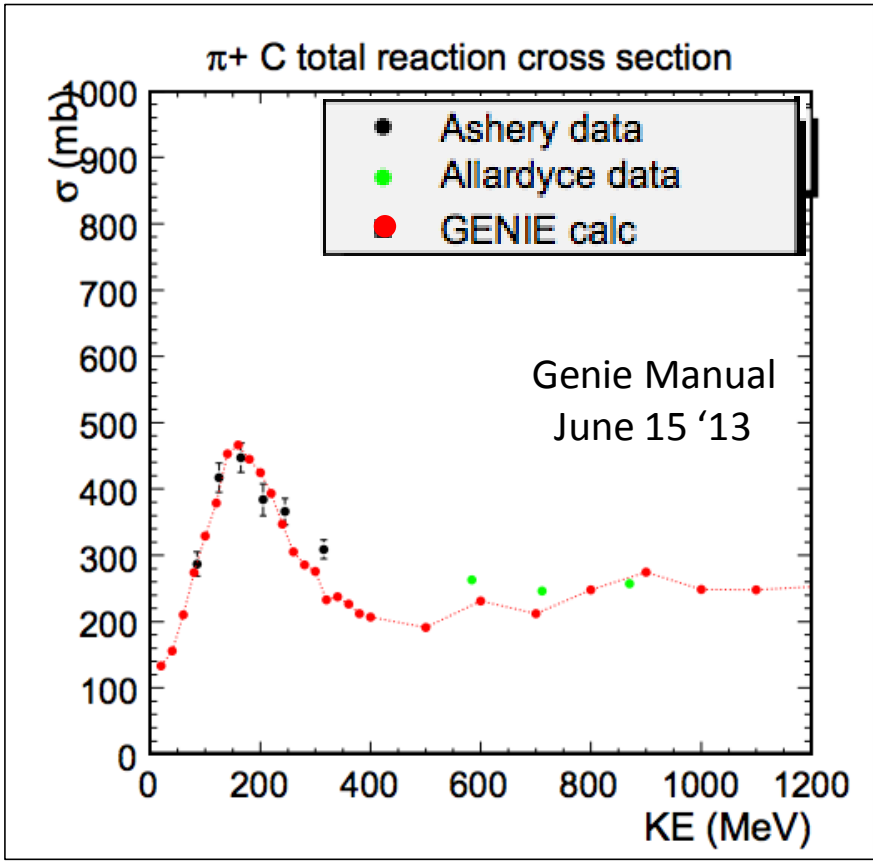


Final State Interactions (FSI)

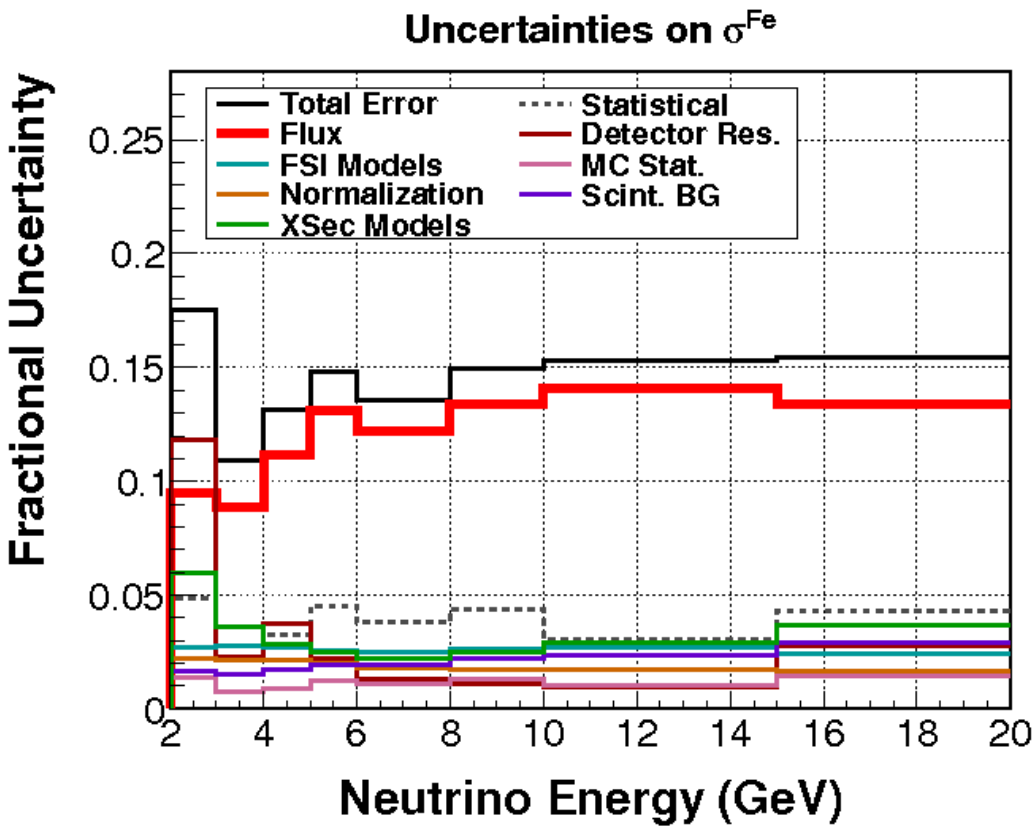


- FSI enters measurement through hadronic energy
  - Calorimetric energy scale tuned with Monte Carlo
  - Event selection not sensitive to FSI

Model parameter	uncertainty
pion/nucleon mean path	±20%
pion/nucleon charge exchange	±50%
pion absorbtion	±30%
pion/nucleon inelastic cross-section	±40%
elastic cross sections	±10-30%

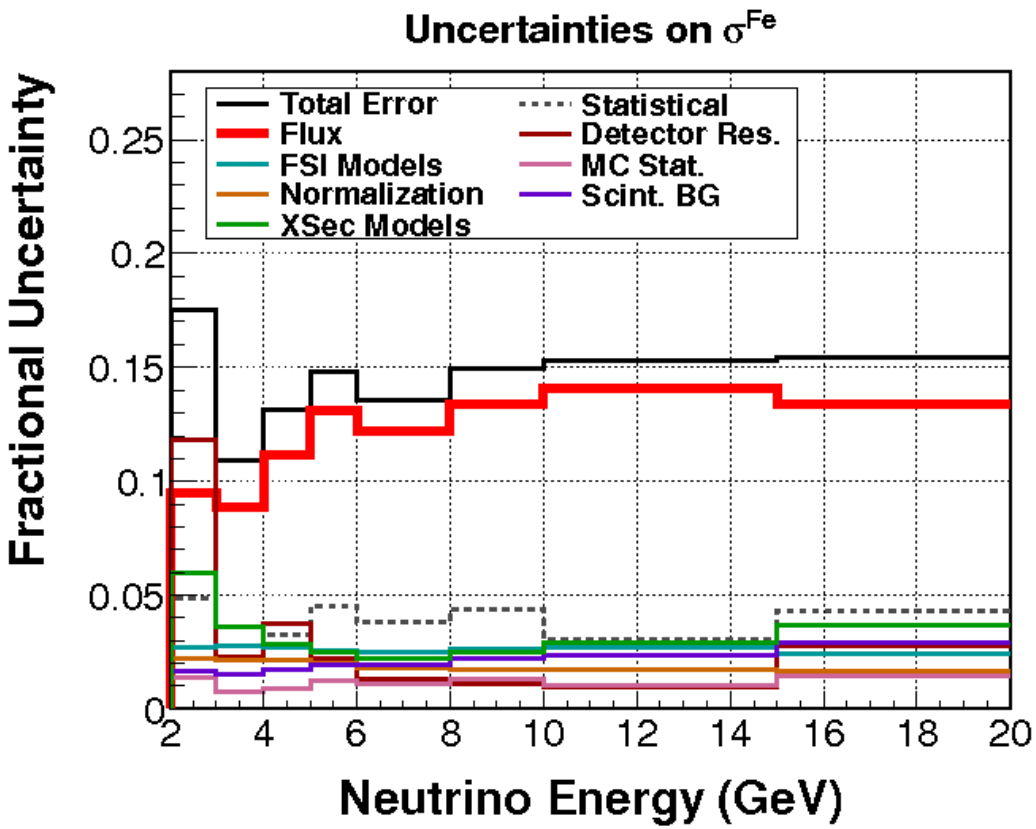


Errors on Absolute Cross Section



Flux is dominant systematic

Errors on Absolute Cross Section



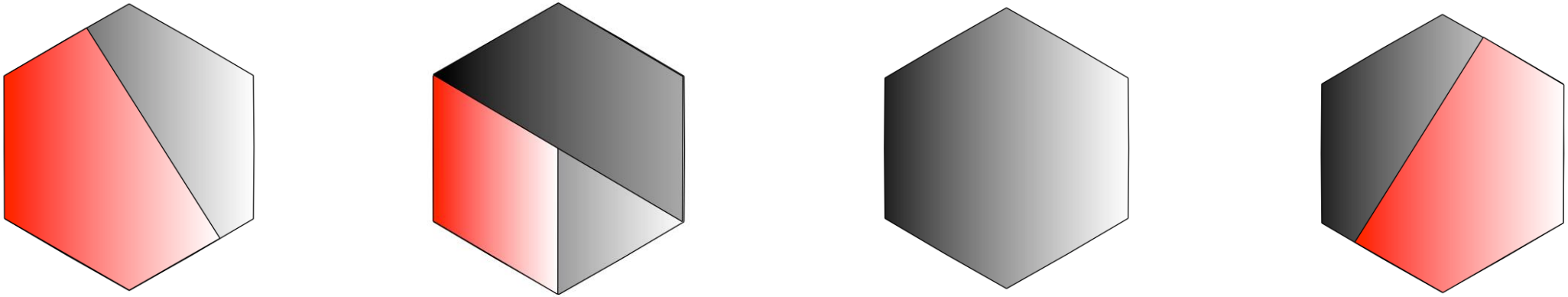
$$\frac{\left(\frac{d\sigma}{dx}\right)_i = \frac{\sum_j U_{ij}(d_j - b_j)}{\epsilon_i(\Phi T)\Delta x_i}}{\left(\frac{d\sigma}{dx}\right)_i = \frac{\sum_j U_{ij}(d_j - b_j)}{\epsilon_i(\Phi T)\Delta x_i}}$$

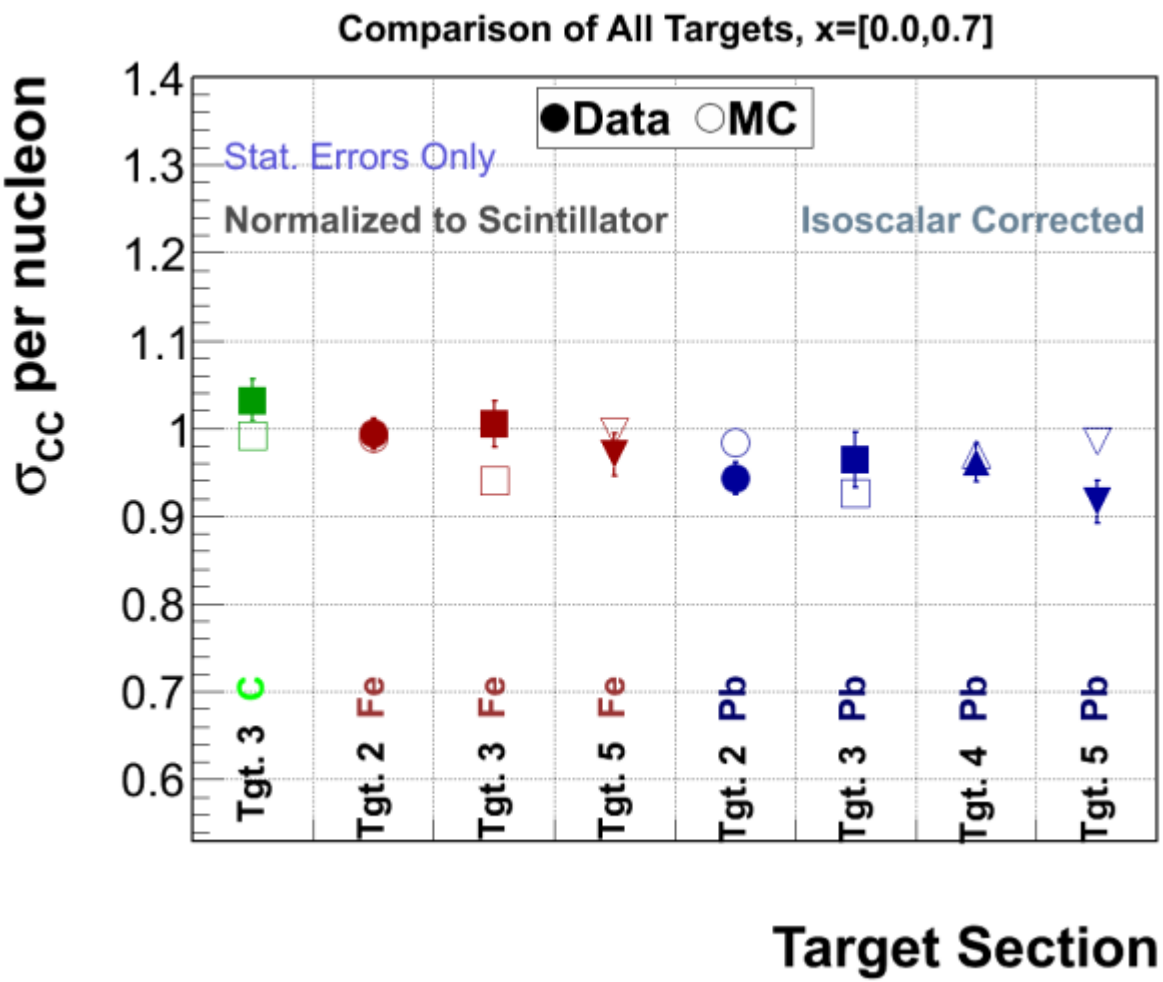
Flux is the same throughout detector

Take ratio of cross sections to ~cancel flux

Form Ratios

- Combine targets
  - E.g. Add events from all lead pieces ***after*** efficiency correction
- Divide C, Fe, Pb cross sections by scintillator cross section
  - Each nucleus divided by a statistically independent scintillator measurements
  - Scintillator measurement is specific for each nucleus, to use the same transverse area





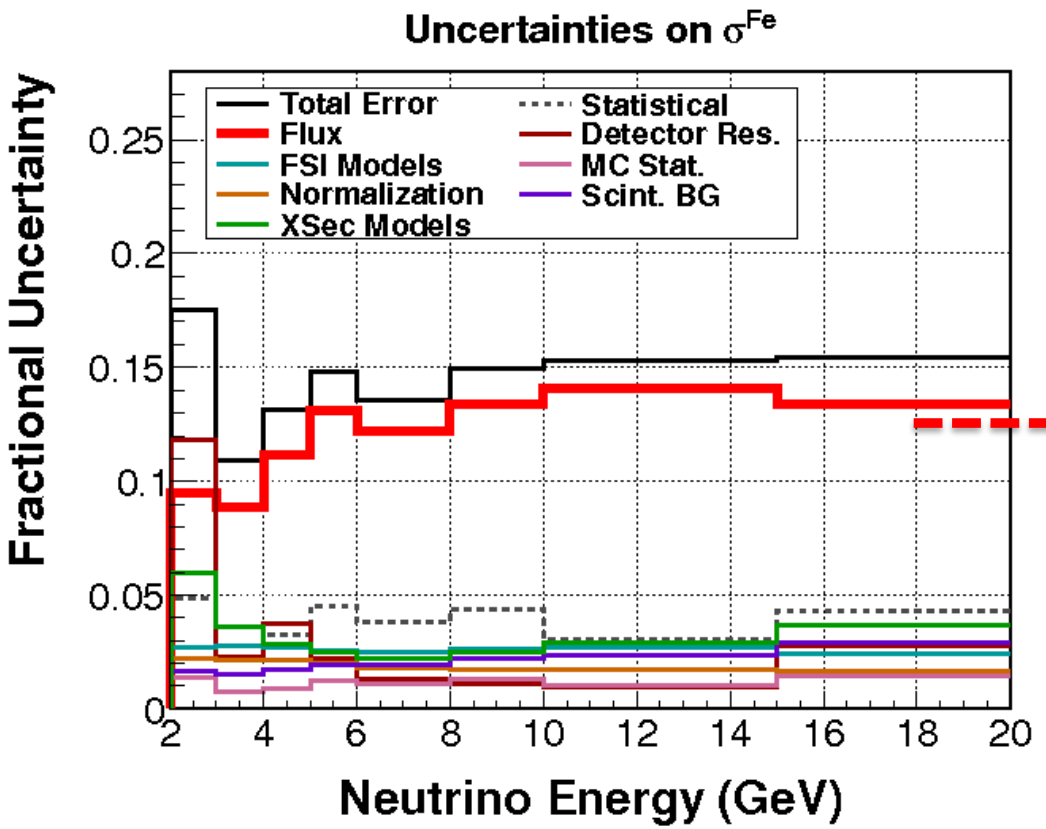
Isoscalar correction – remove effect of neutron excess.

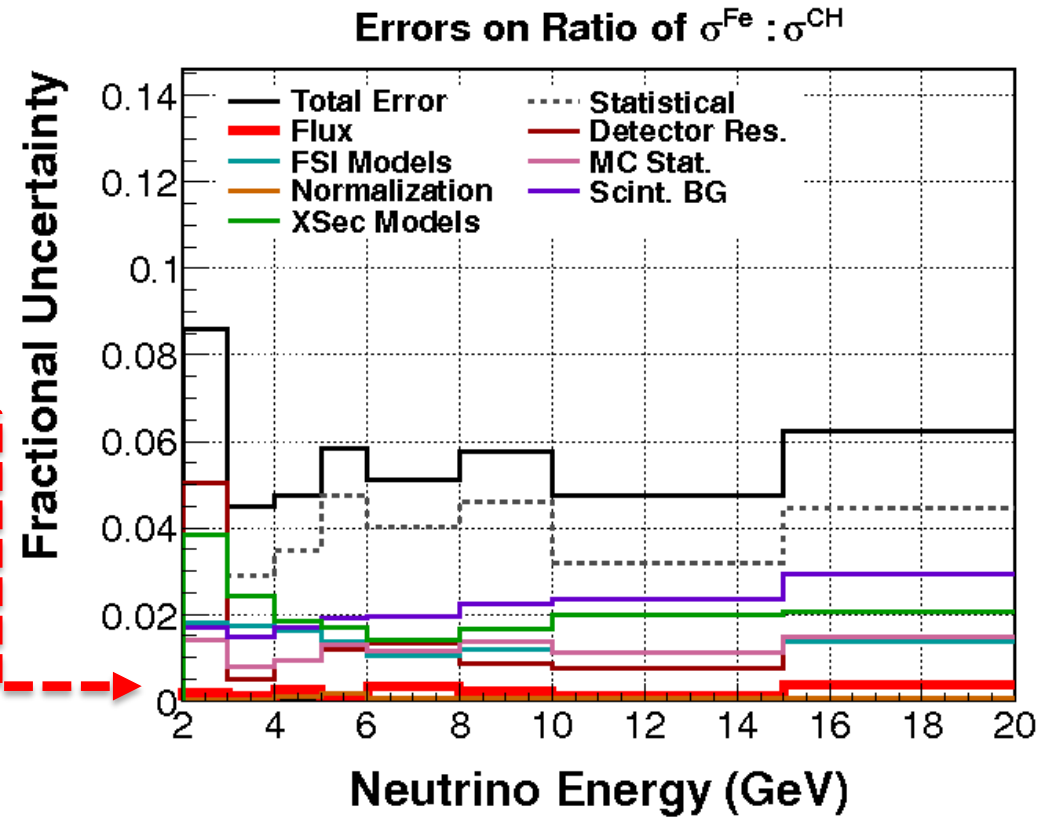
$$r(A) = \frac{Z\sigma_p + (A - Z)\sigma_n}{\sigma_p + \sigma_n}\frac{2}{A}$$

Calculated with GENIE 2.6.2

Errors on Absolute Cross Section

Errors on Ratio of Cross Sections





Results

Charged-Current Inclusive Ratios of Cross Sections

Signal Kinematics

2 < Neutrino Energy < 20 GeV

0 < Muon Angle < 17 deg

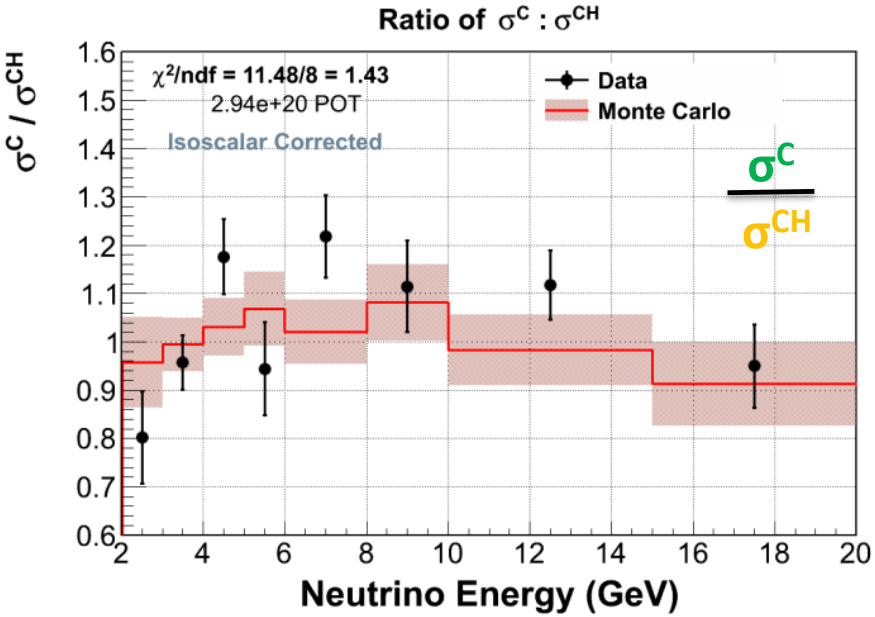
Neutrino Energy

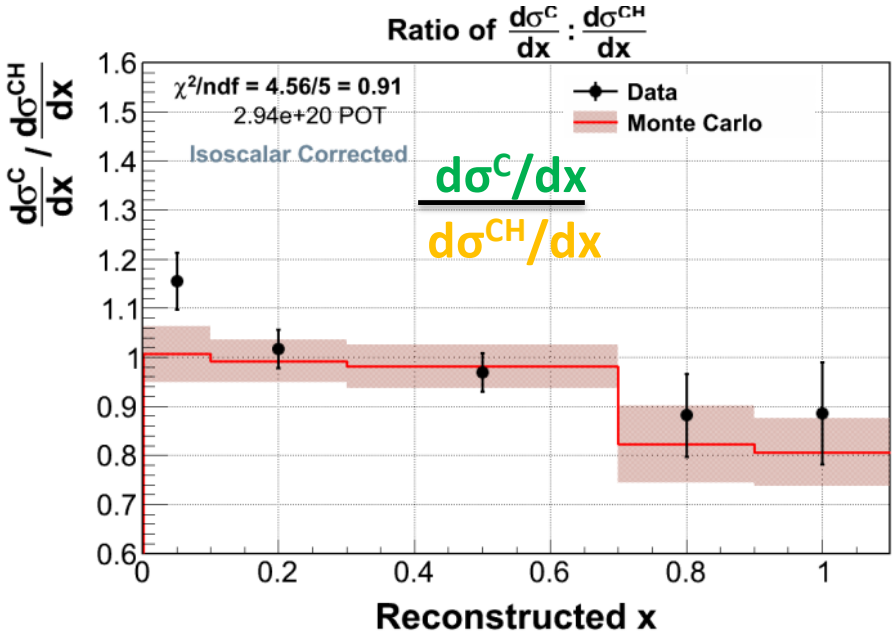
$$\frac{\sigma^{C}}{\sigma^{CH}} \qquad \frac{\sigma^{Fe}}{\sigma^{CH}} \qquad \frac{\sigma^{Pb}}{\sigma^{CH}}$$

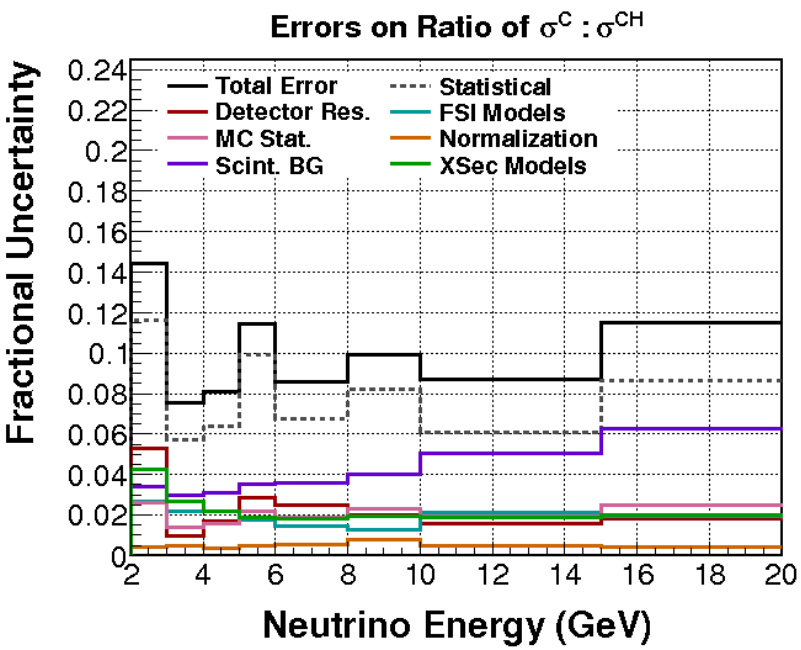
Bjorken x

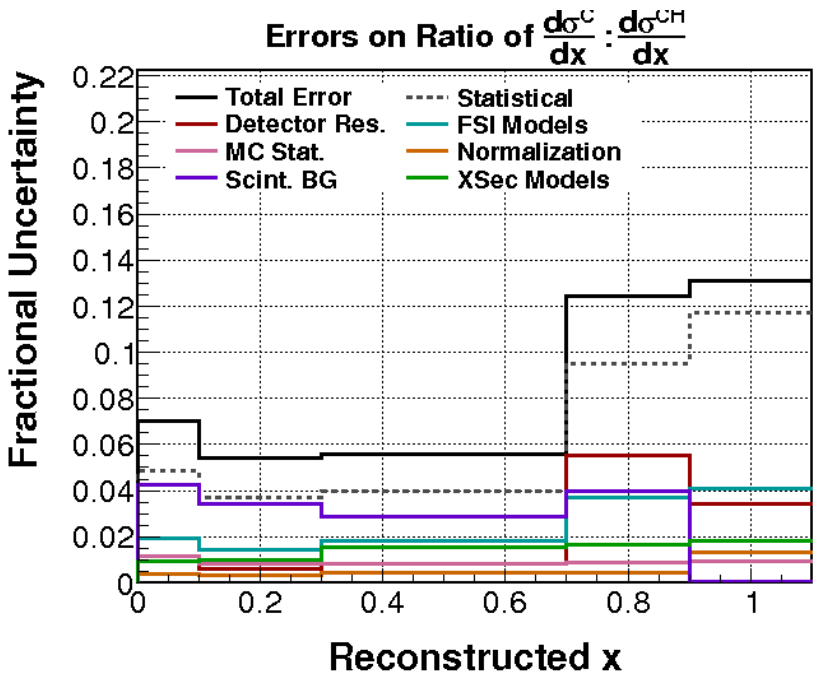
$$\frac{d\sigma^{C}/dx}{d\sigma^{CH}/dx} \qquad \frac{d\sigma^{Fe}/dx}{d\sigma^{CH}/dx} \qquad \frac{d\sigma^{Pb}/dx}{d\sigma^{CH}/dx}$$

Cross Section Ratios – Carbon

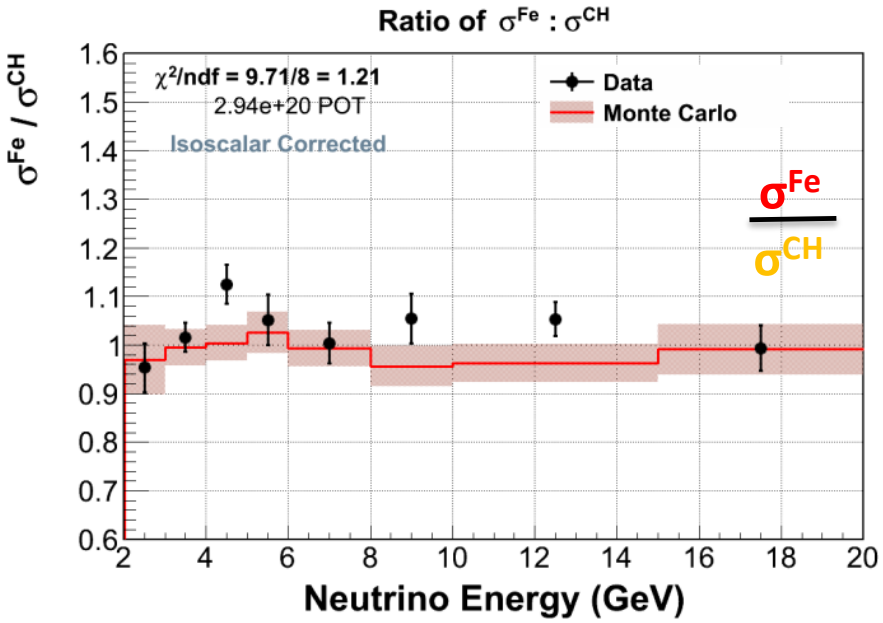


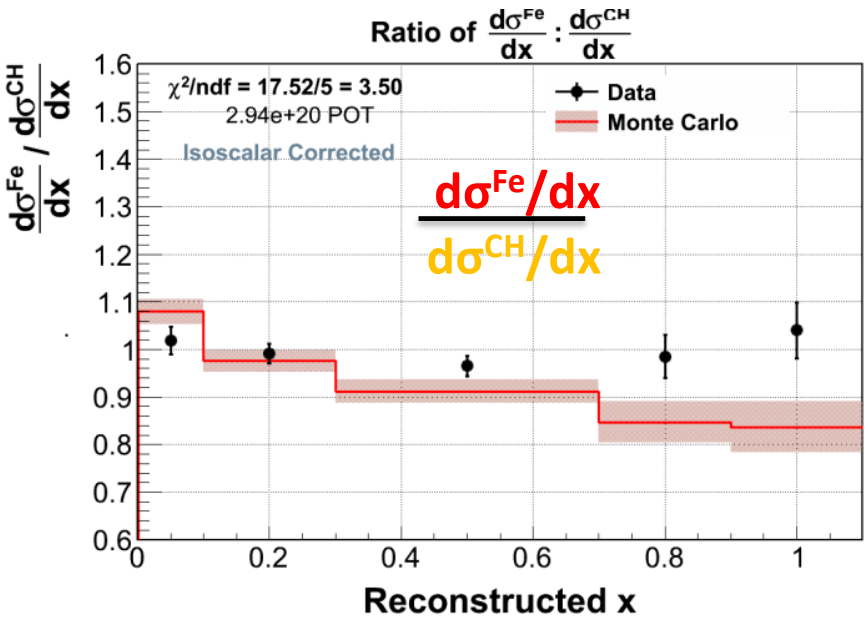


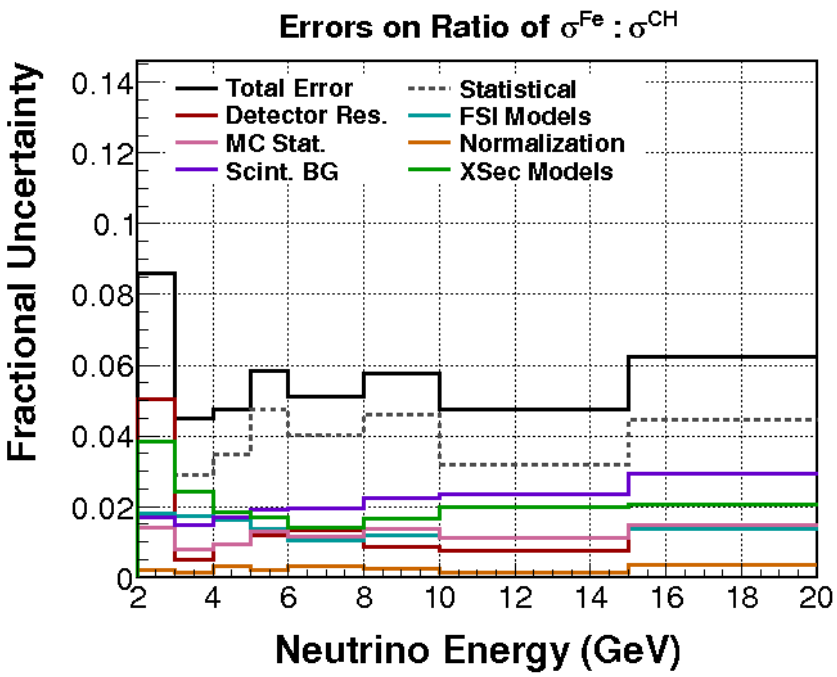


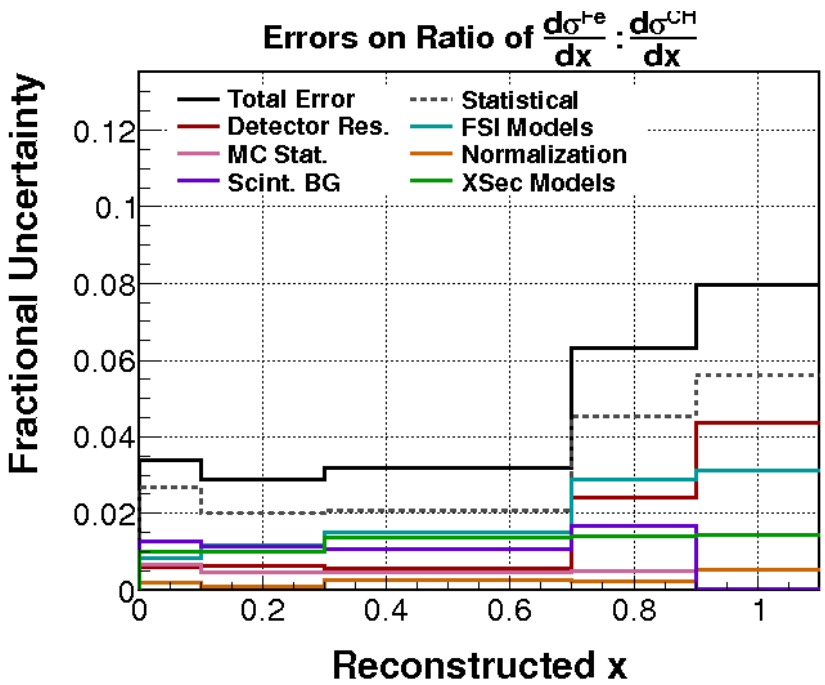


Cross Section Ratios – Iron

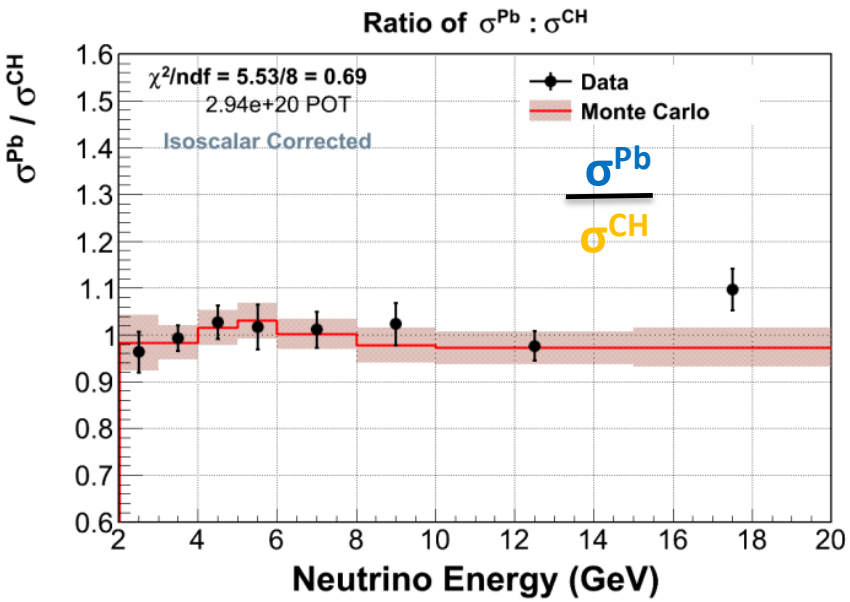


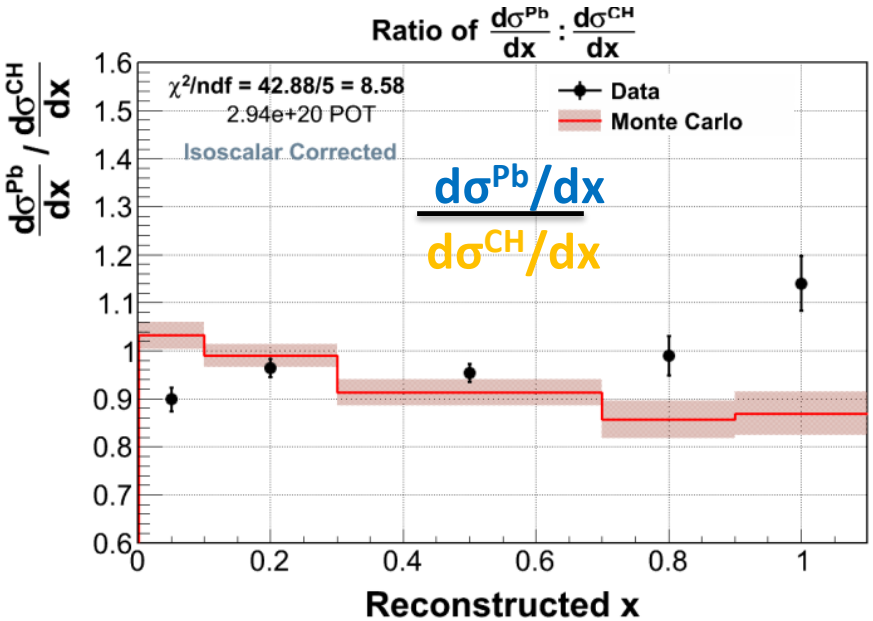


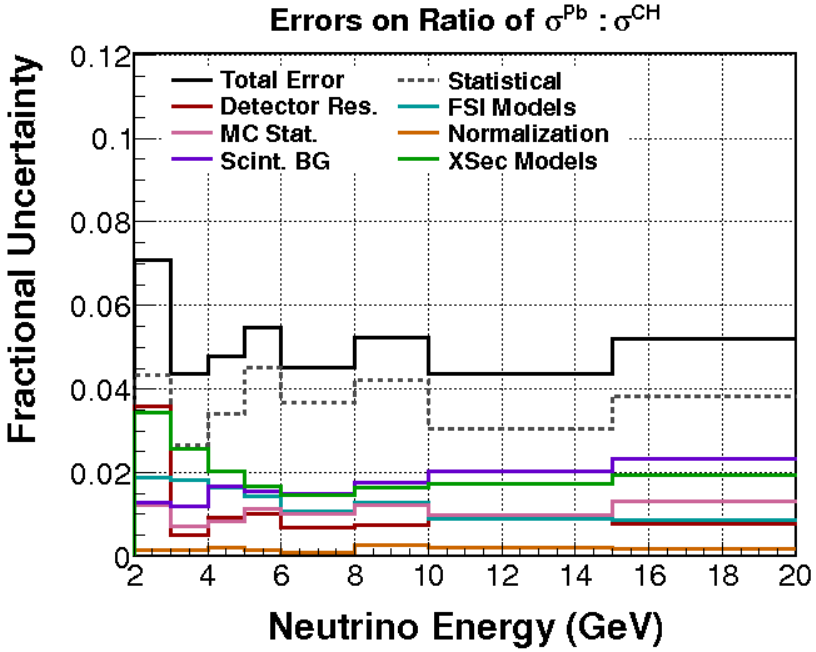


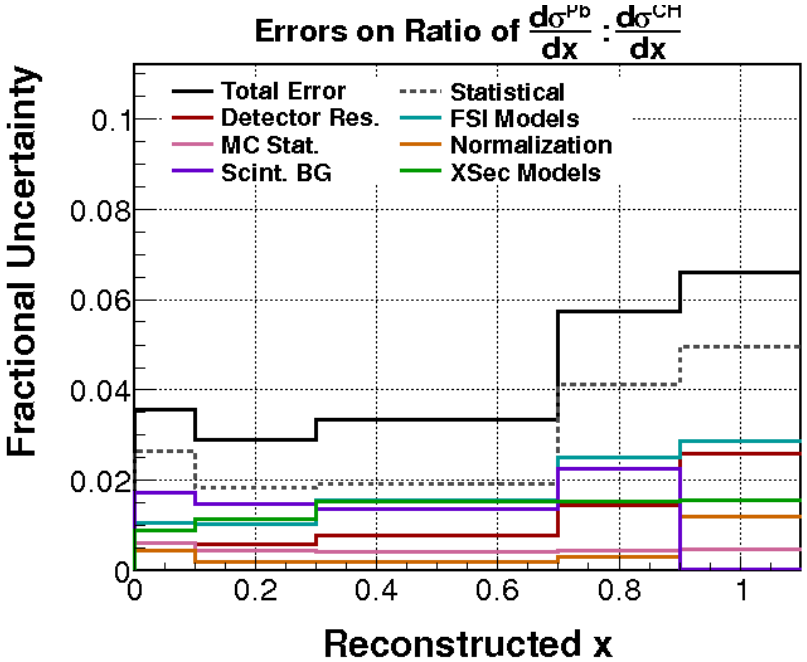


Cross Section Ratios – Lead

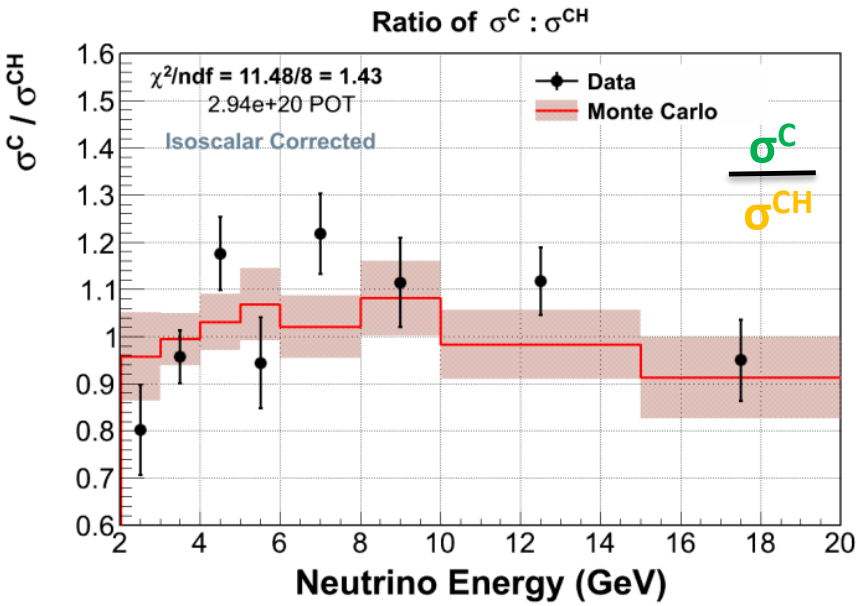




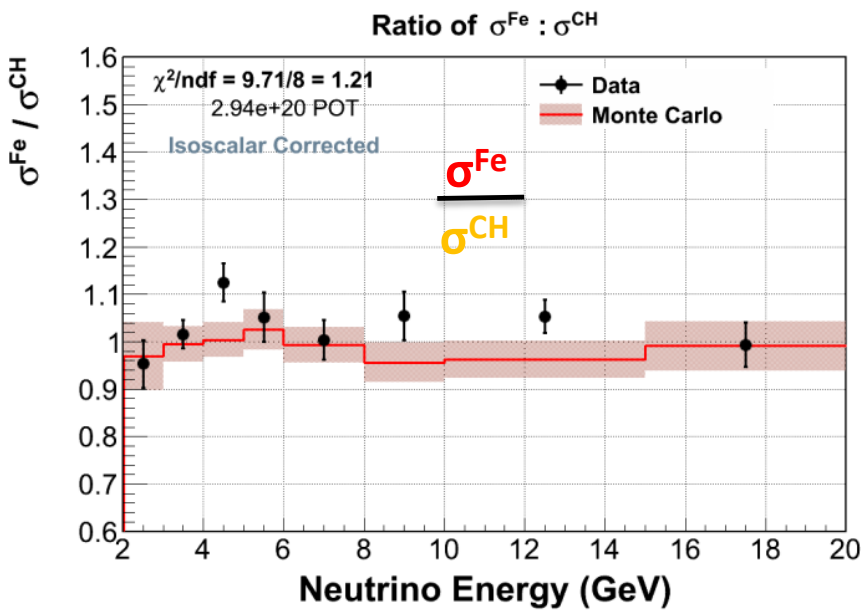


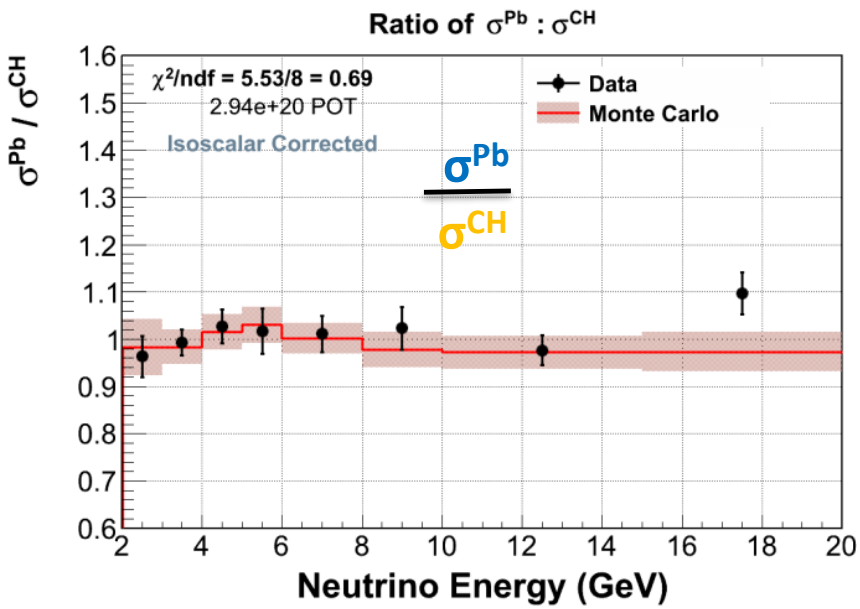


Neutrino Energy Summary



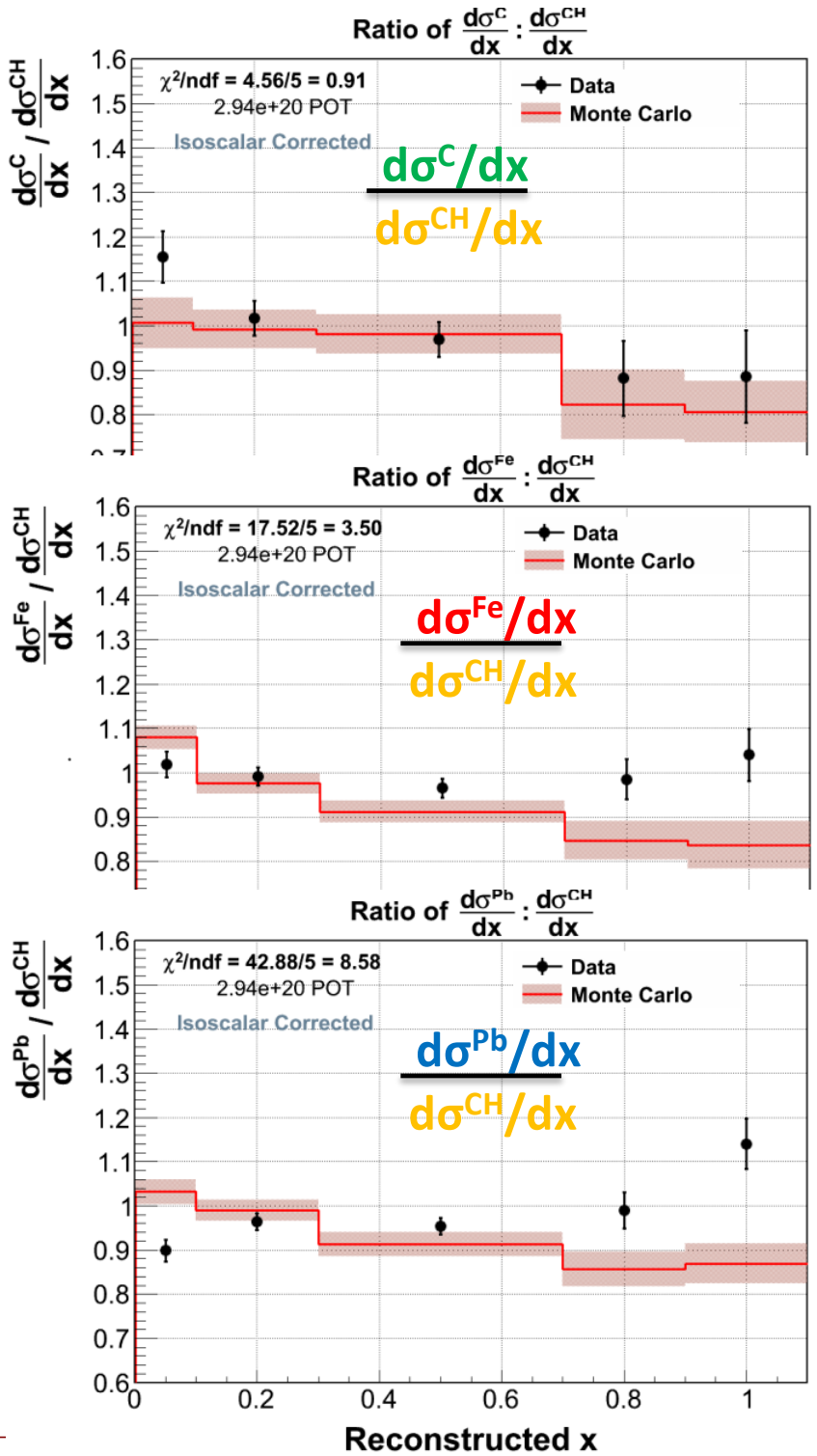
- No evidence of tension between our data and GENIE 2.6.2





High x Summary

- At x=[0.7,1.1], we observe a **excess** that grows with the size of the nucleus
- This effect is not observed in simulation



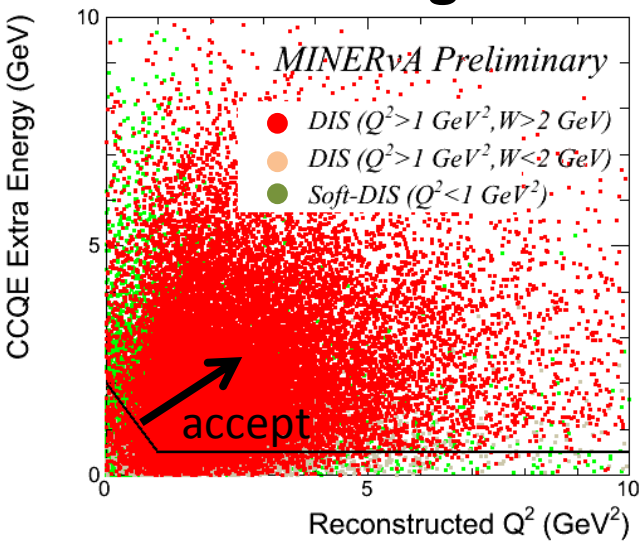
Try Removing Elastic-like Events

nuclear effects are different for elastic and inelastic channels

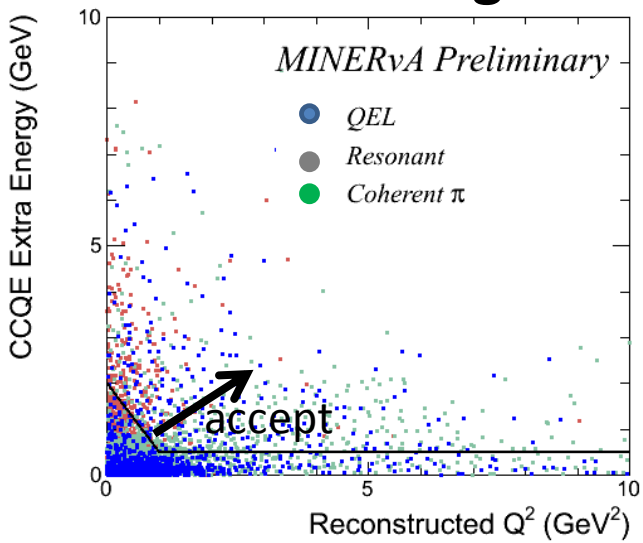
Select an **inelastic sample** (no quasi-elastic, no resonances)

Cut based on inverse of the cut we used in quasi-elastic analysis

Inelastic Signal



Inelastic Background



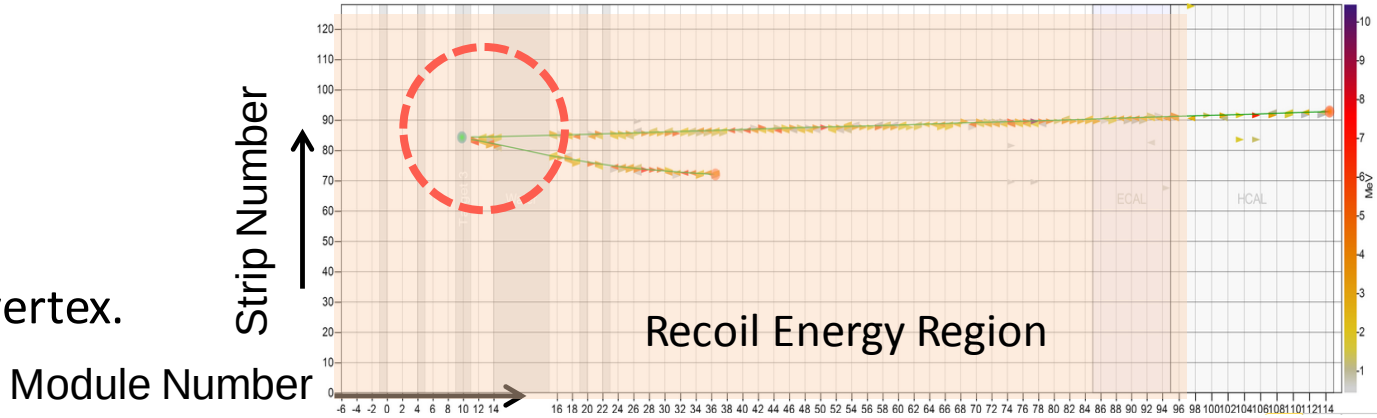
Purity – **inelastic** sample is 93% DIS (**inclusive** was 35%)

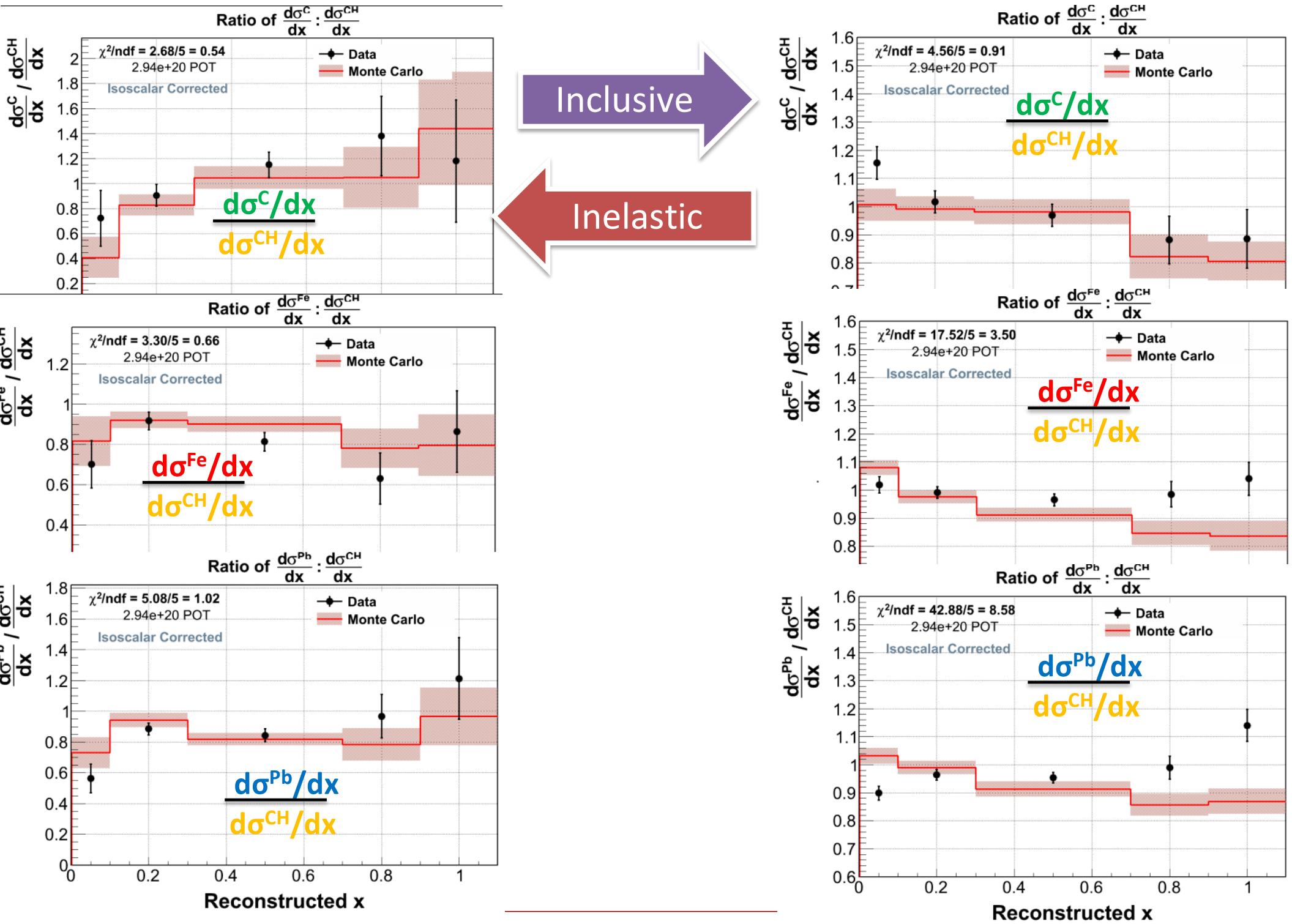
Inelastic sample is 22% size of **inclusive**

CCQE Extra Energy

Non-muon hits that are not in hadronic calorimetry.

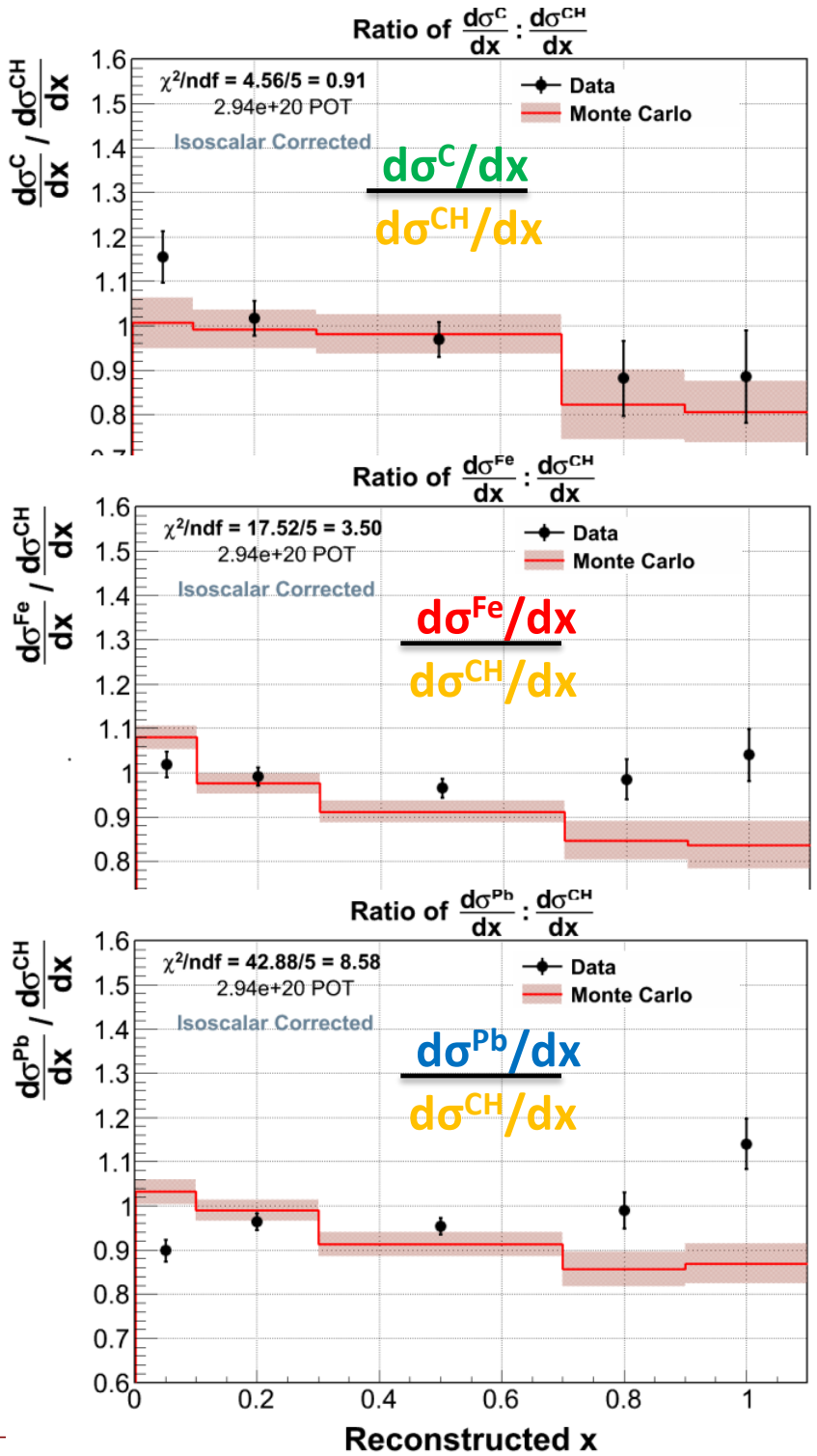
Exclude area 300mm around vertex.




Ratio of $\frac{d\sigma^C}{dx} : \frac{d\sigma^{CH}}{dx}$
χ^2/ndf = 2.68/5 = 0.54
2.94e+20 POT
Isoscalar Corrected
Data
Monte Carlo
$\frac{d\sigma^C/dx}{d\sigma^{CH}/dx}$
Inclusive
Inelastic
Ratio of $\frac{d\sigma^C}{dx} : \frac{d\sigma^{CH}}{dx}$
χ^2/ndf = 4.56/5 = 0.91
2.94e+20 POT
Isoscalar Corrected
Data
Monte Carlo
$\frac{d\sigma^C/dx}{d\sigma^{CH}/dx}$
Ratio of $\frac{d\sigma^{Fe}}{dx} : \frac{d\sigma^{CH}}{dx}$
χ^2/ndf = 3.30/5 = 0.66
2.94e+20 POT
Isoscalar Corrected
Data
Monte Carlo
$\frac{d\sigma^{Fe}/dx}{d\sigma^{CH}/dx}$
Ratio of $\frac{d\sigma^{Fe}}{dx} : \frac{d\sigma^{CH}}{dx}$
χ^2/ndf = 17.52/5 = 3.50
2.94e+20 POT
Isoscalar Corrected
Data
Monte Carlo
$\frac{d\sigma^{Fe}/dx}{d\sigma^{CH}/dx}$
Ratio of $\frac{d\sigma^{Pb}}{dx} : \frac{d\sigma^{CH}}{dx}$
χ^2/ndf = 5.08/5 = 1.02
2.94e+20 POT
Isoscalar Corrected
Data
Monte Carlo
$\frac{d\sigma^{Pb}/dx}{d\sigma^{CH}/dx}$
Reconstructed x
Ratio of $\frac{d\sigma^{Pb}}{dx} : \frac{d\sigma^{CH}}{dx}$
χ^2/ndf = 42.88/5 = 8.58
2.94e+20 POT
Isoscalar Corrected
Data
Monte Carlo
$\frac{d\sigma^{Pb}/dx}{d\sigma^{CH}/dx}$
Reconstructed x

Low x Summary

- At x=[0*,0.1], we observe a **deficit** that increases with the size of the nucleus
- This effect is not modeled in simulation



* Simulation suggests events down to 0.005
No events really at 0

Simulation of Nuclear Modification

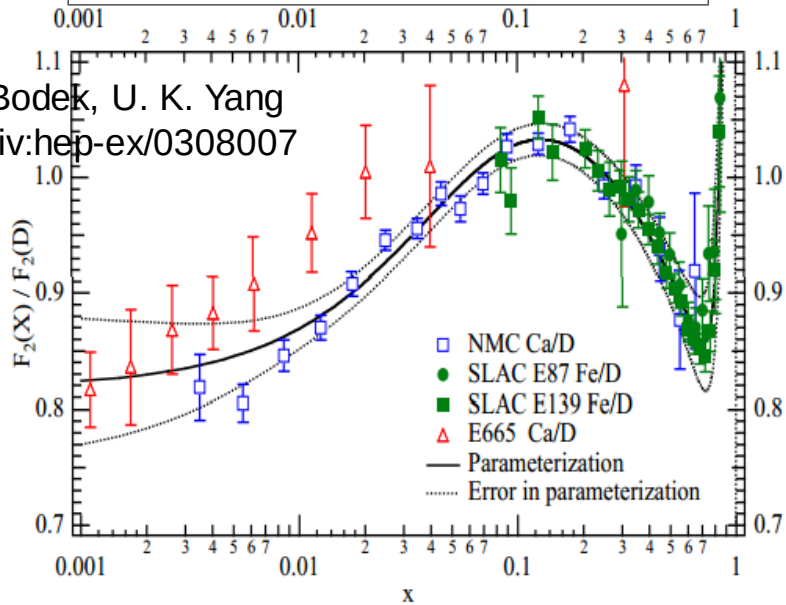
GENIE 2.6.2 | Our MC

A. Bodek, U. K. Yang
arXiv:hep-ph/1011.6592

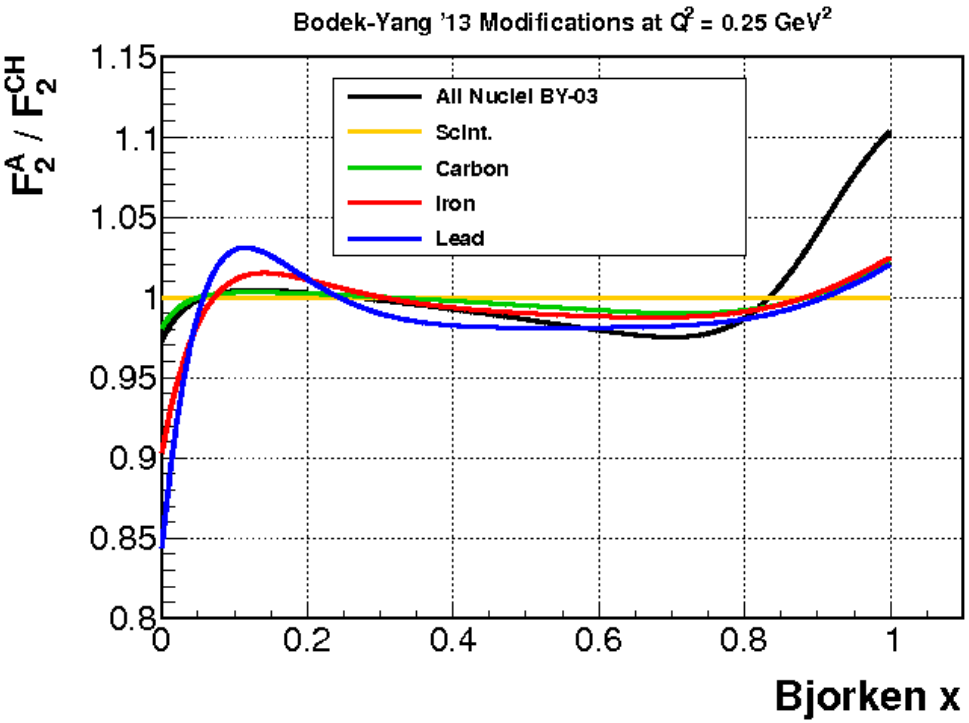
- Bodek-Yang Model (2003)
- Fit to charged lepton data
- All nuclei has same modification
  - All treated as isoscalar iron

Nuclear modification fit for iron to deuterium ratio

A. Bodek, U. K. Yang
arXiv:hep-ex/0308007



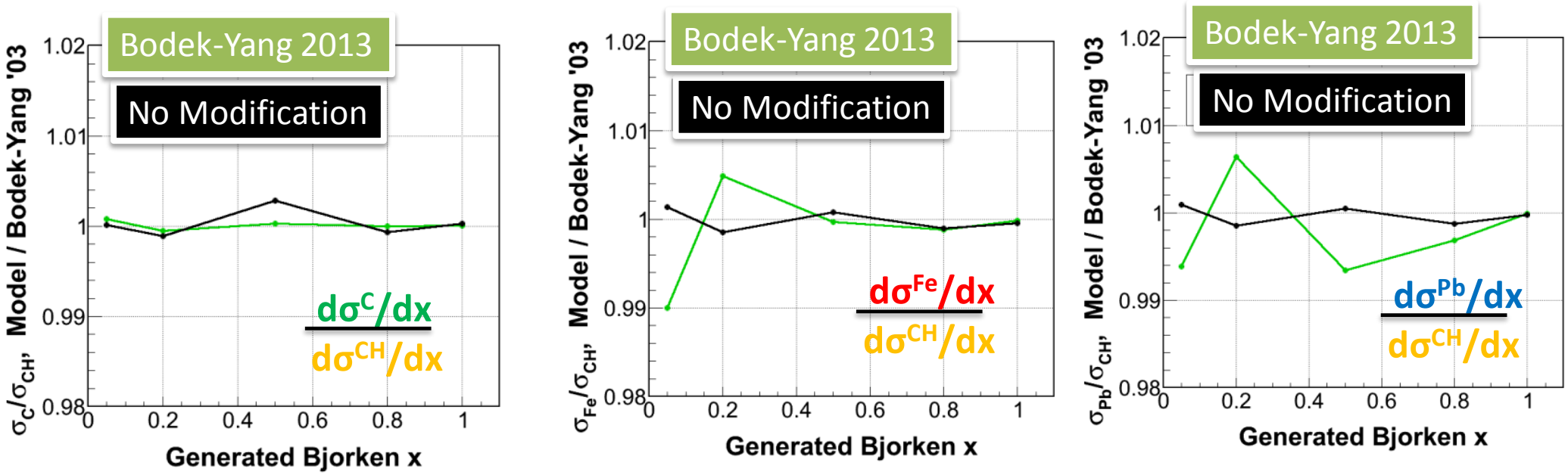
- Updated Bodek-Yang (2013)
  - Very similar to widely-used E139 fit
- Specific fits for **C**, **Fe**, **Pb**



Do our data prefer a model?

Using MINERvA bins and acceptance

Comparison of predicted for cross section **ratio**



- Charged lepton data suggest we should see < 1% effect

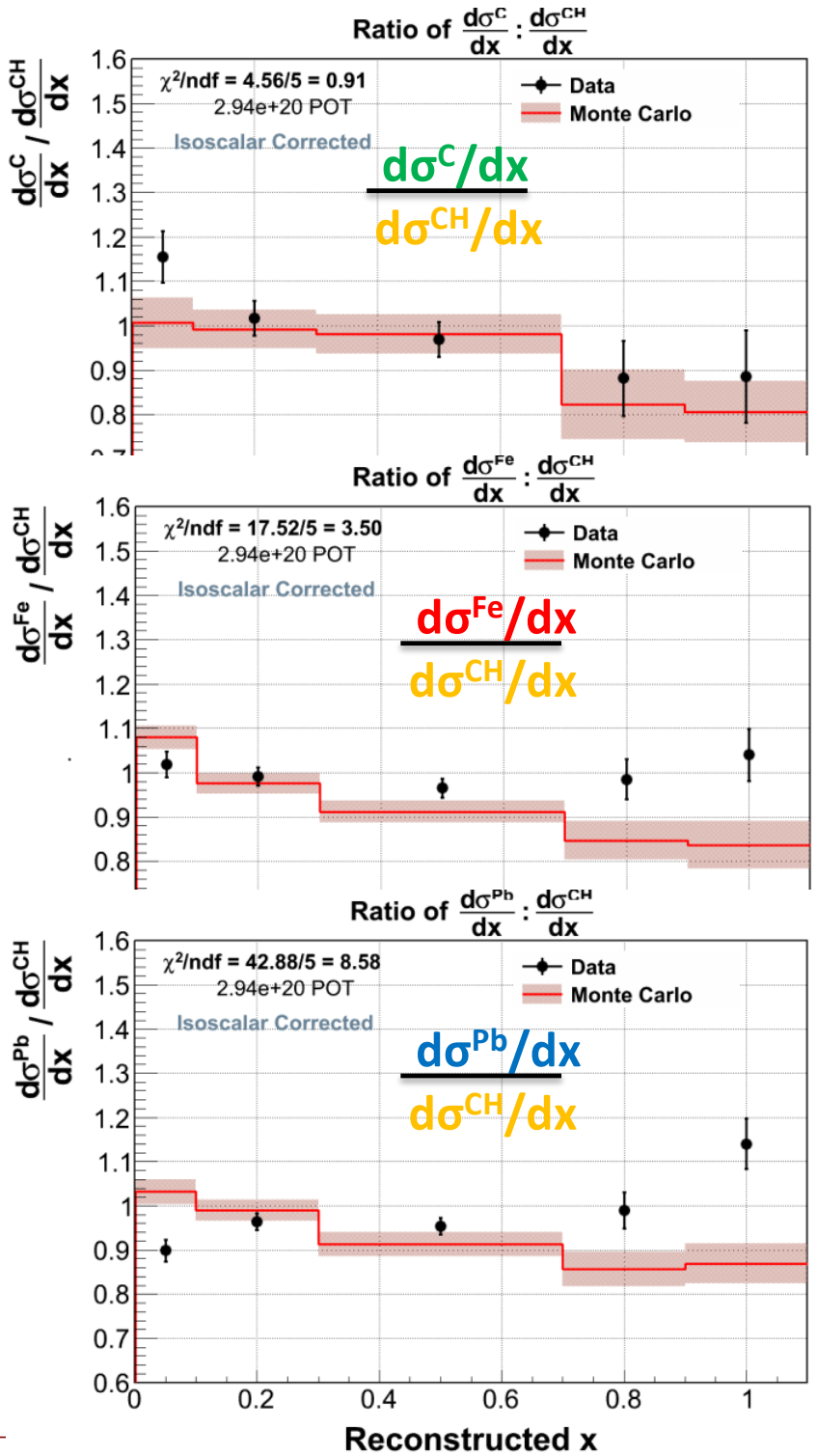
Low x Summary

- At x=[0,0.1], we observe a **deficit** that increases with the size of the nucleus
- Data show effects not modeled in simulation

Expected Neutrino Differences

Neutrinos sensitive to structure function xF_3

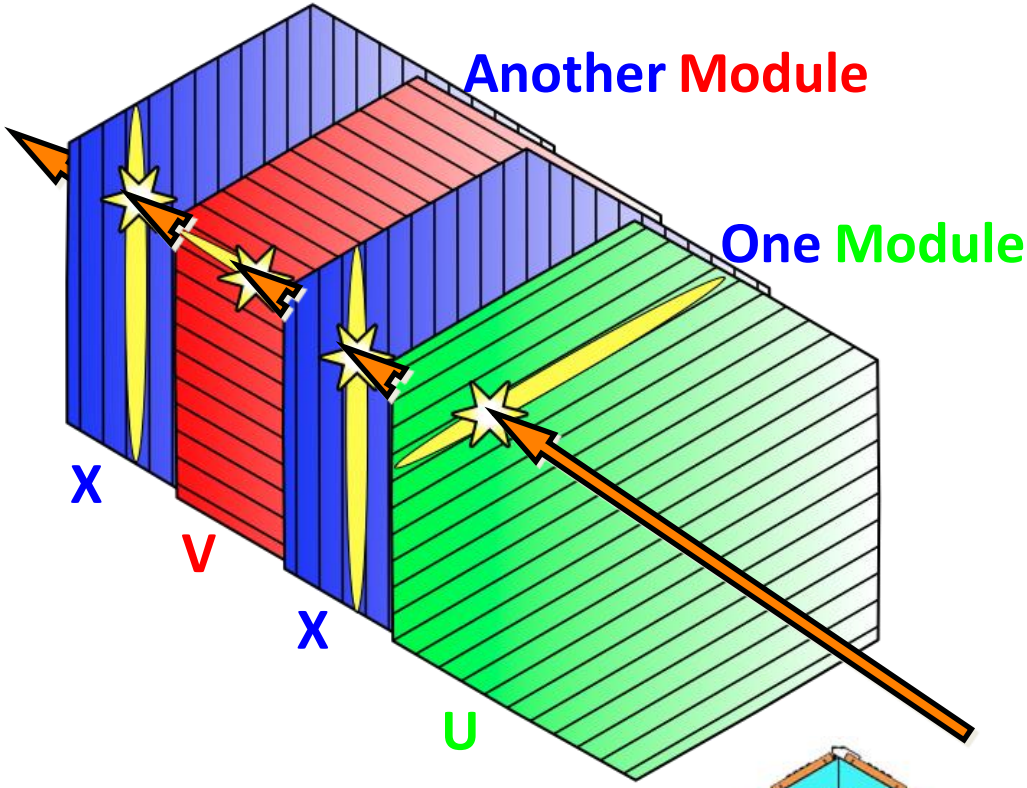
Neutrinos sensitive to axial piece of structure function F_2

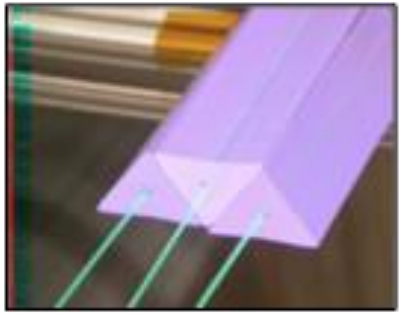


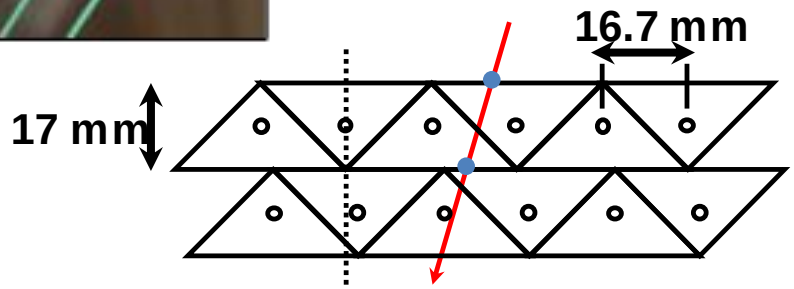
Conclusions

- First results from nuclear targets in MINERvA
- First precise direct measurement of nuclear-dependence of neutrino cross sections in the few GeV regime
- Deficit increases with A at x=[0,0.1] (**Pb** < **Fe** < **C**)
  - Not modeled in simulation
- Excess increases with A at x=[0.7,1.1] (**Pb** > **Fe** > **c**)
  - Not modeled in simulation
- Extensions of this analysis are very promising
  - Enhanced statistics (>10x) in higher energy, intensity NOvA-era beam
    - Higher energy→lower x reach. Much more DIS→extract structure functions.
  - Inelastic sample selection demonstrated. Needs more data.
  - (teaser) Combine quasi-elastic and nuclear target analyses

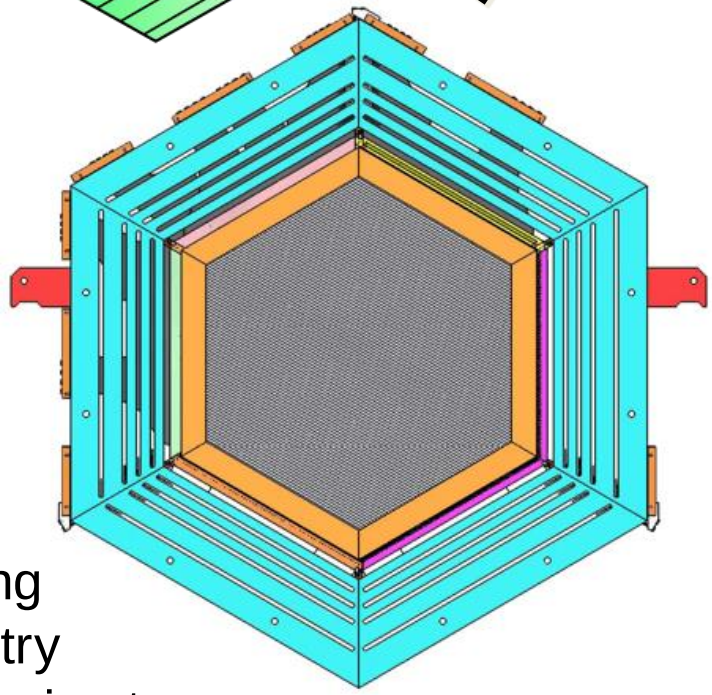
Backup

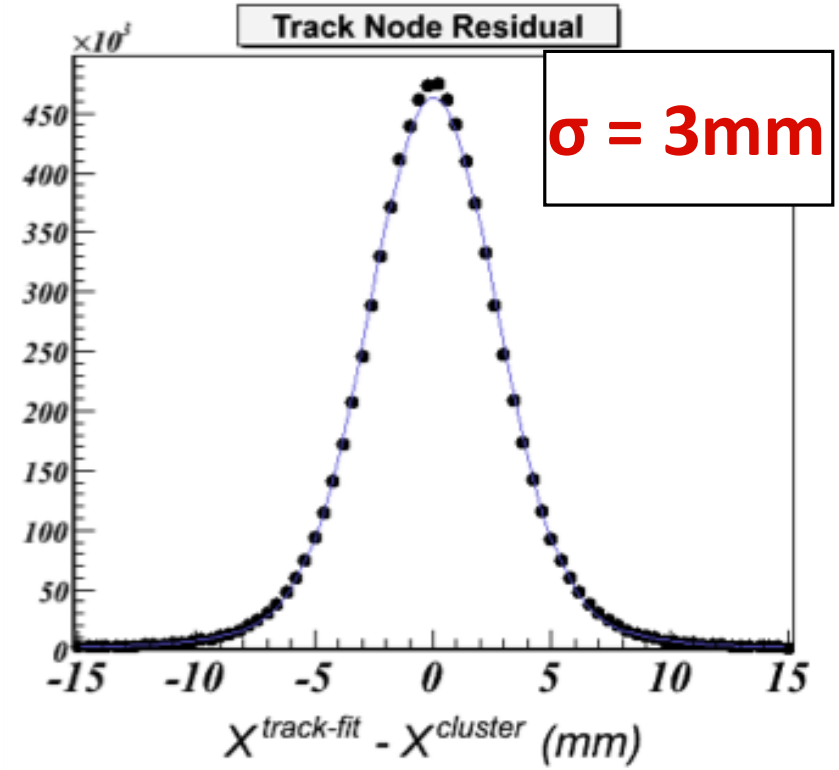




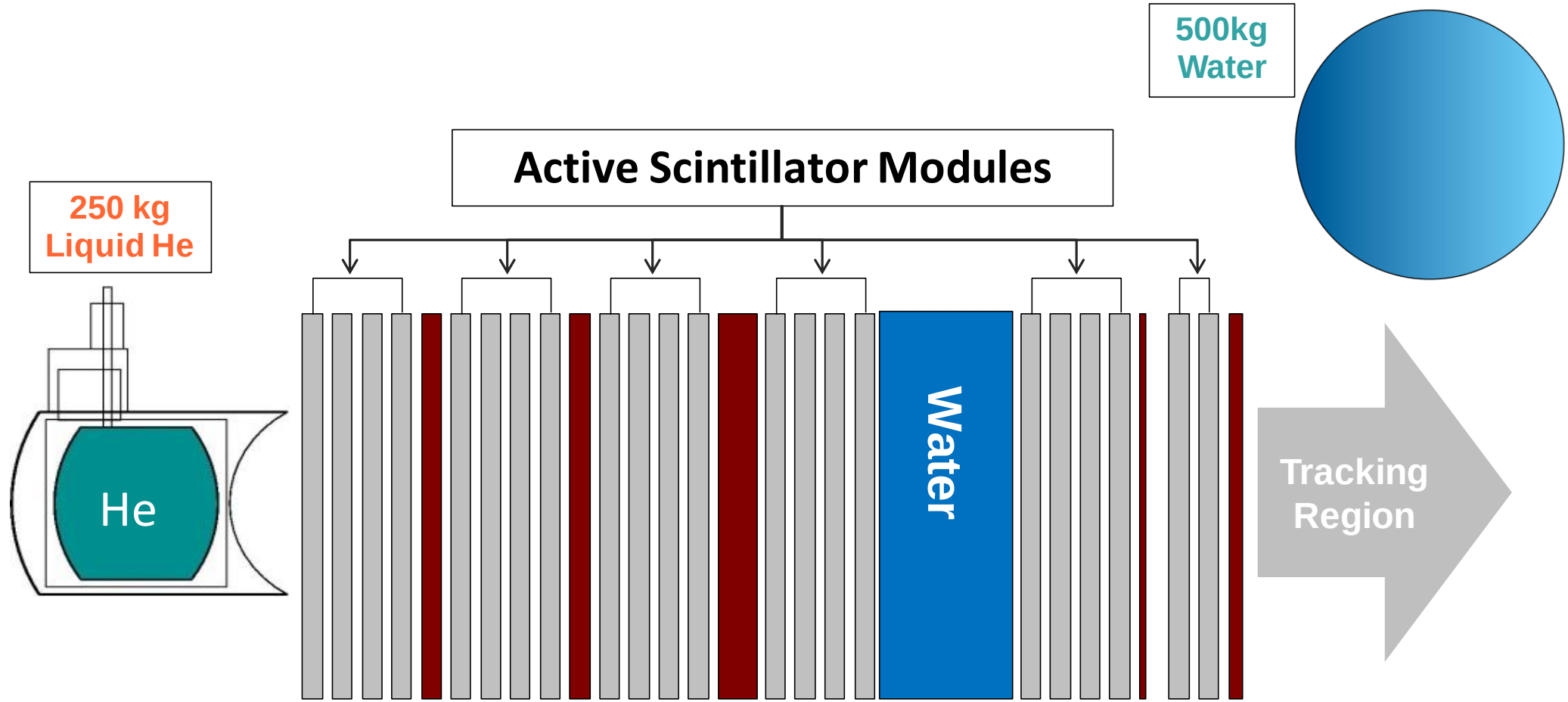


Charge sharing for improved position resolution (~3 mm) and alignment

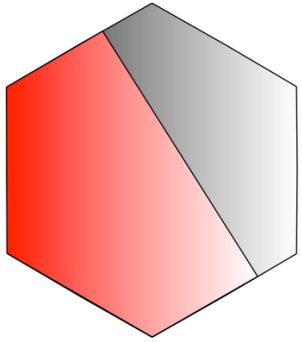




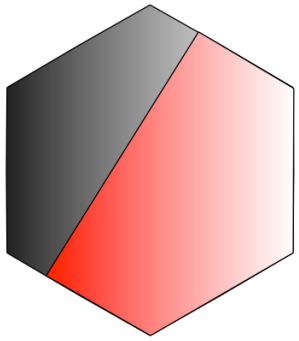
Scintillator - tracking
Lead - EM calorimetry
Steel - hadronic calorimetry



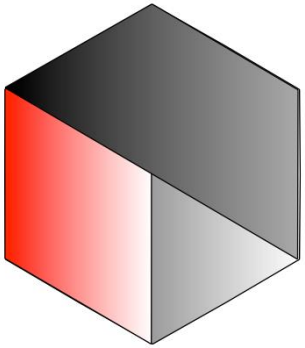
1” Fe / 1” Pb
323kg / 264kg



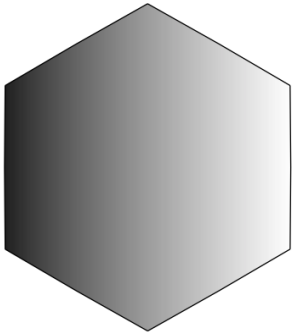
1” Pb / 1” Fe
266kg / 323kg



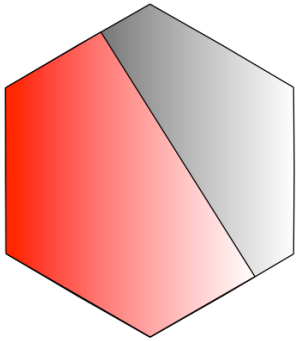
3” C / 1” Fe / 1” Pb
166kg / 169kg / 121kg



0.3” Pb
228kg

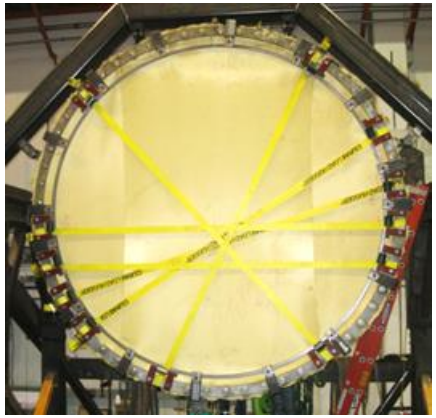


.5” Fe / .5” Pb
161kg/ 135kg

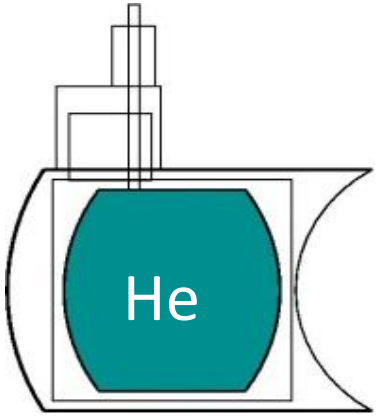


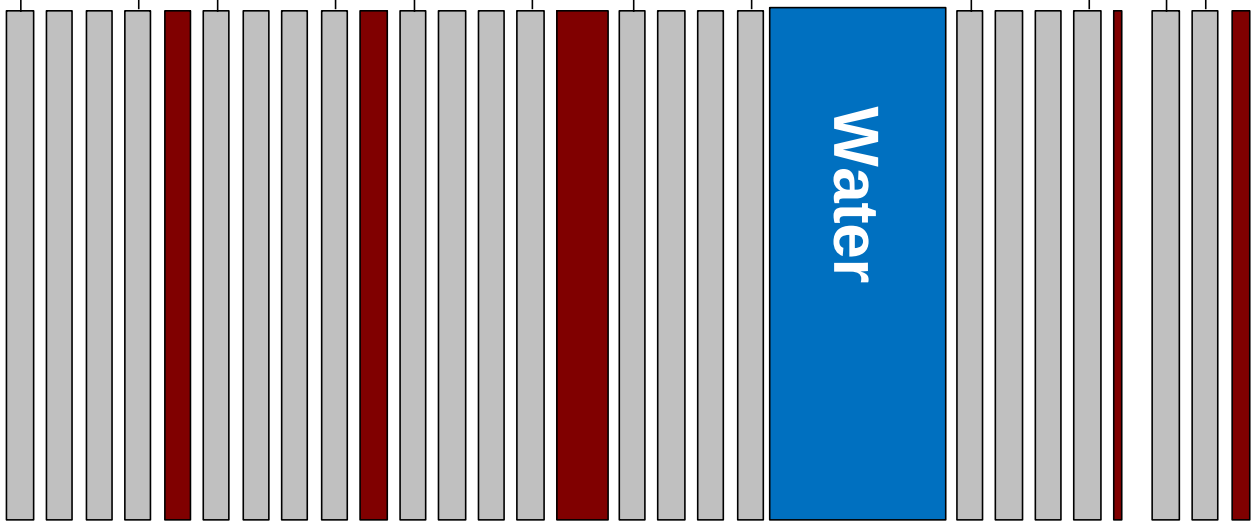
250 kg
Liquid He

500kg
Water



Active Scintillator Modules





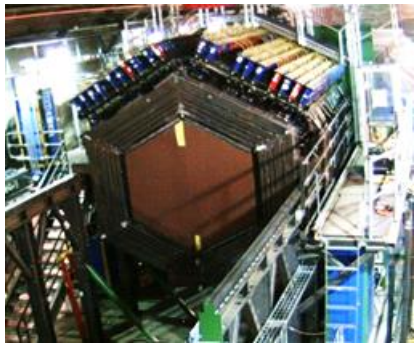
Tracking
Region

1” Fe / 1” Pb
323kg / 264kg

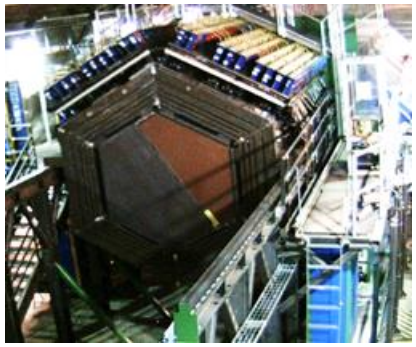
1” Pb / 1” Fe
266kg / 323kg

3” C / 1” Fe / 1” Pb
166kg / 169kg / 121kg

0.3” Pb
228kg



.5” Fe / .5” Pb
161kg/ 135kg



NuMI Beamline

Delivers ~35x10^{12} protons on target (POT) per spill at ~0.5 Hz, a beam power of 300-350 kW.

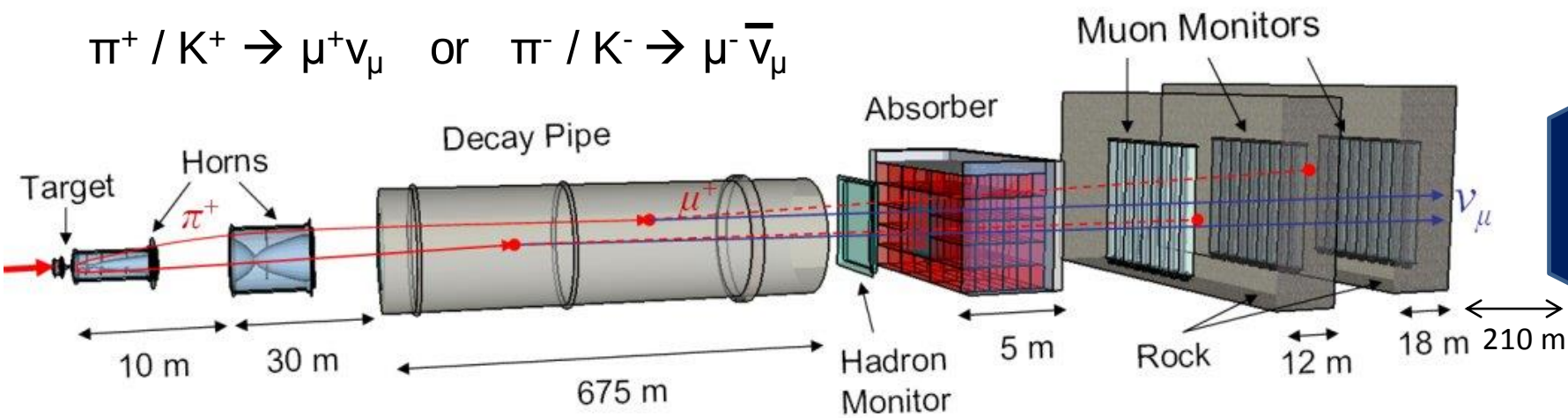
~7E9 neutrinos / m2 @ MINERvA

120 GeV proton → Carbon target

pC → $\pi^{\pm}$ and $K^{\pm}$

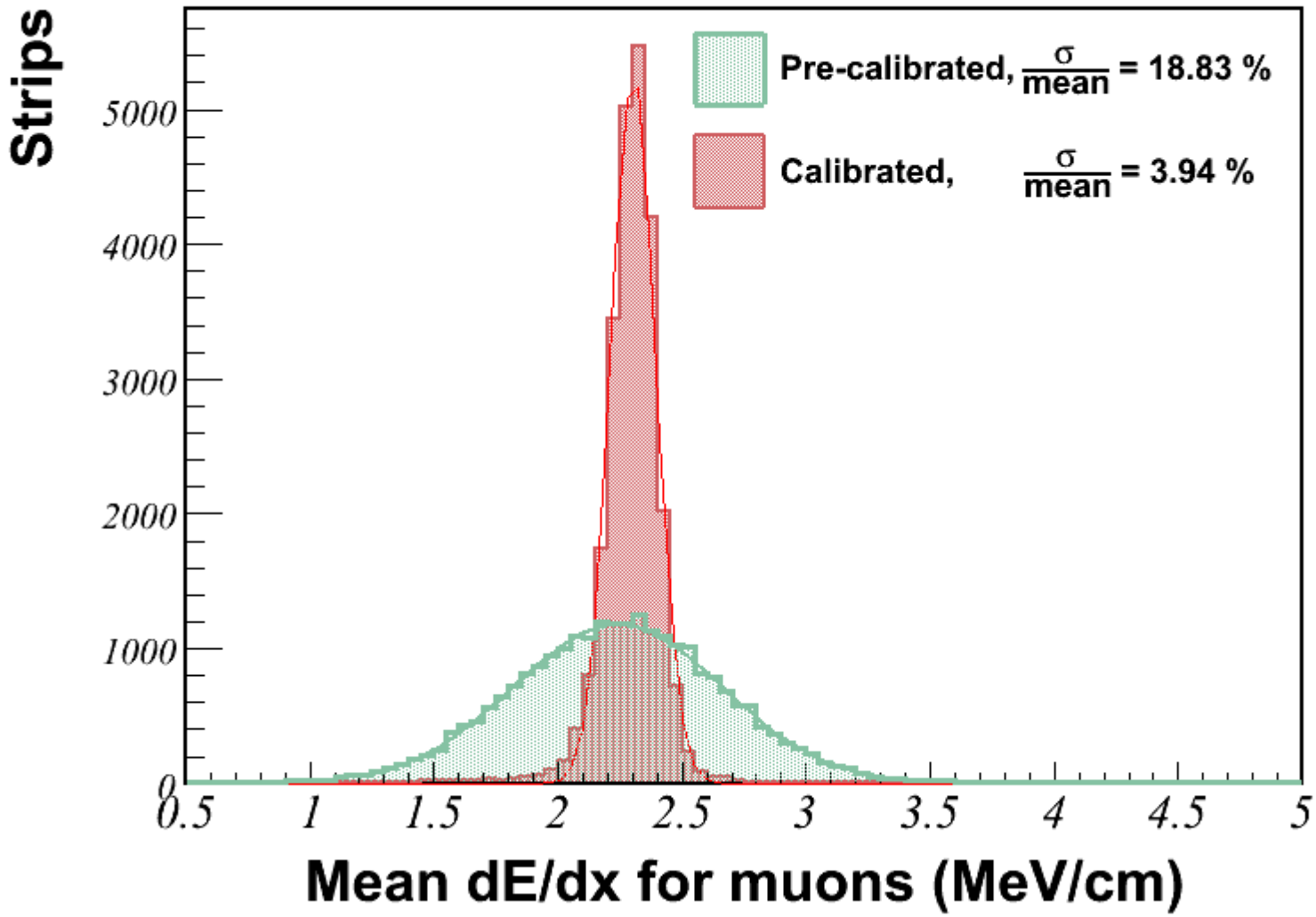
Magnetic horns focus + or -

$\pi^+ / K^+ \rightarrow \mu^+ \nu_\mu$ or $\pi^- / K^- \rightarrow \mu^- \bar{\nu}_\mu$

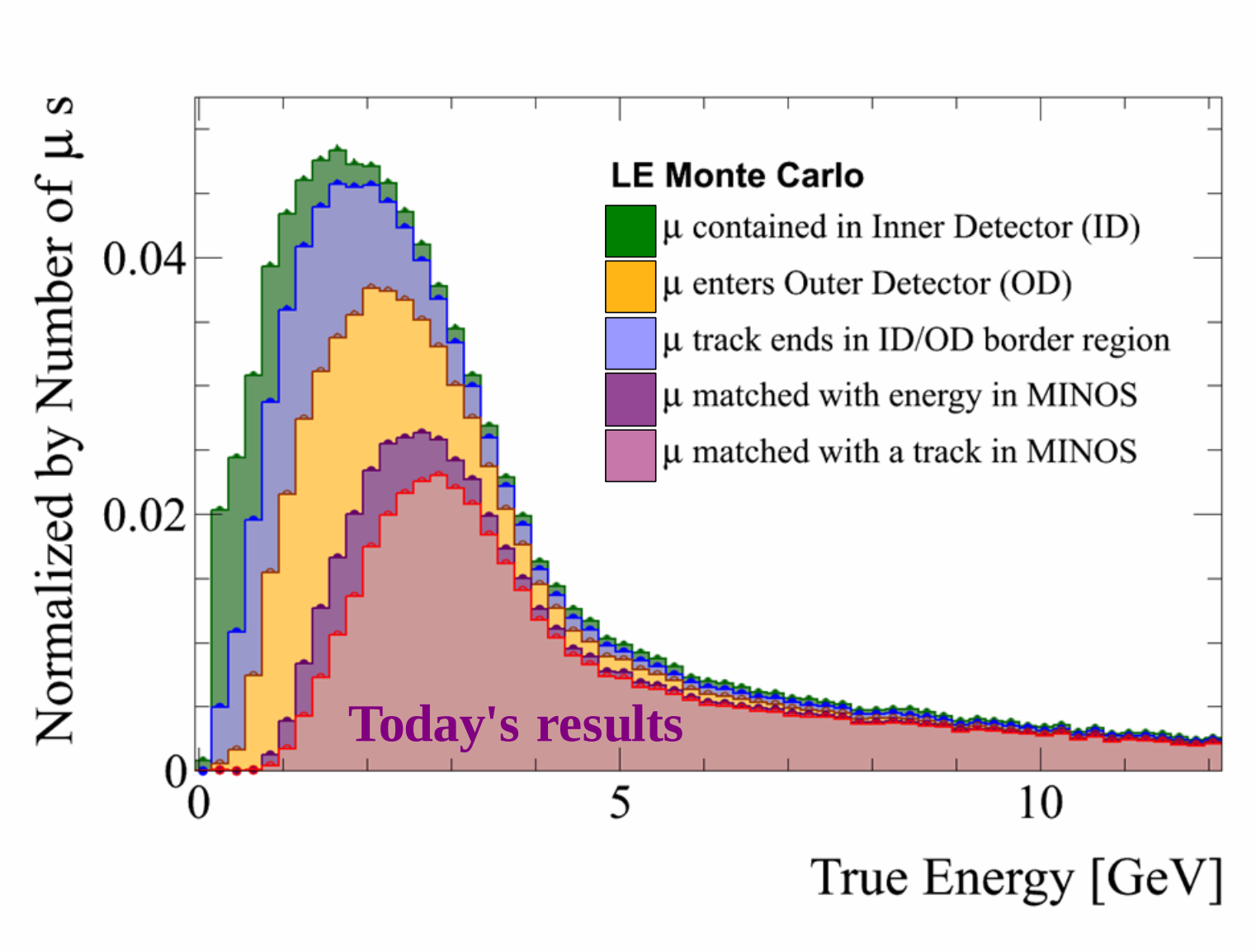


MINERvA

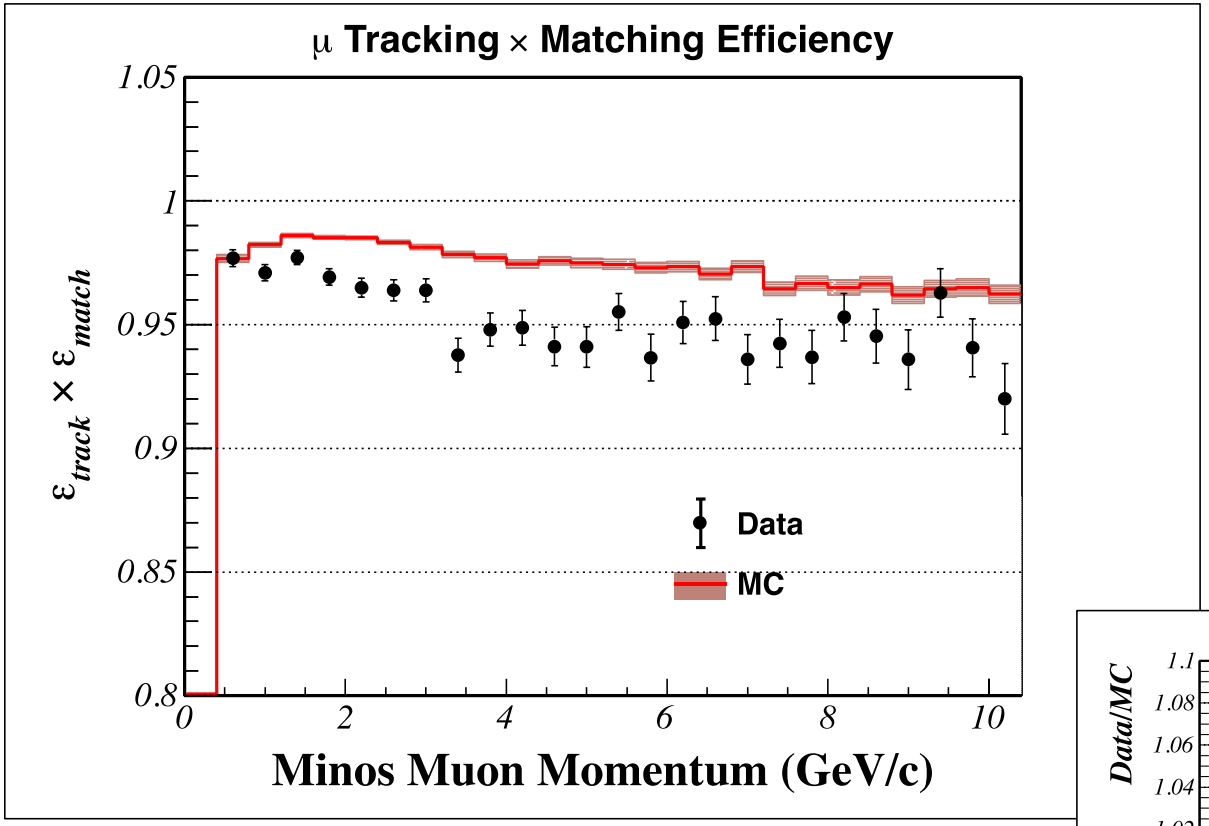
Alignment and Strip Response



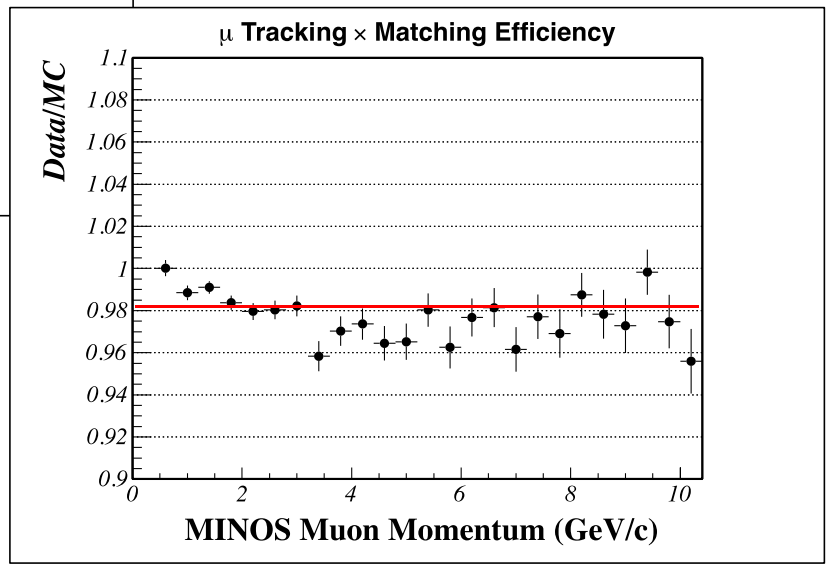
Where do the muons go?



Muon Tracking Efficiency



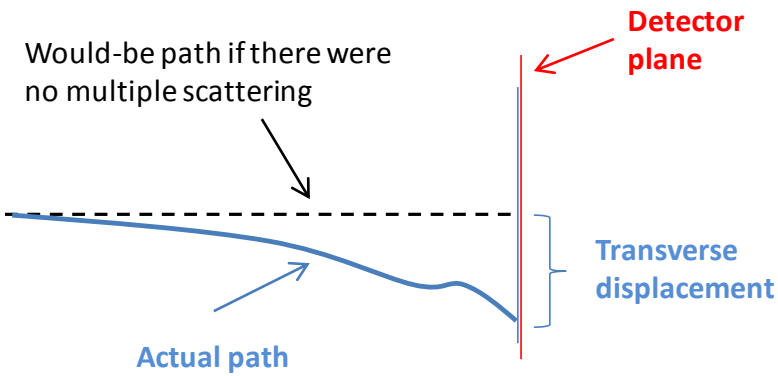
MINERvA muon tracking efficiency



Momentum provided by MINOS ND

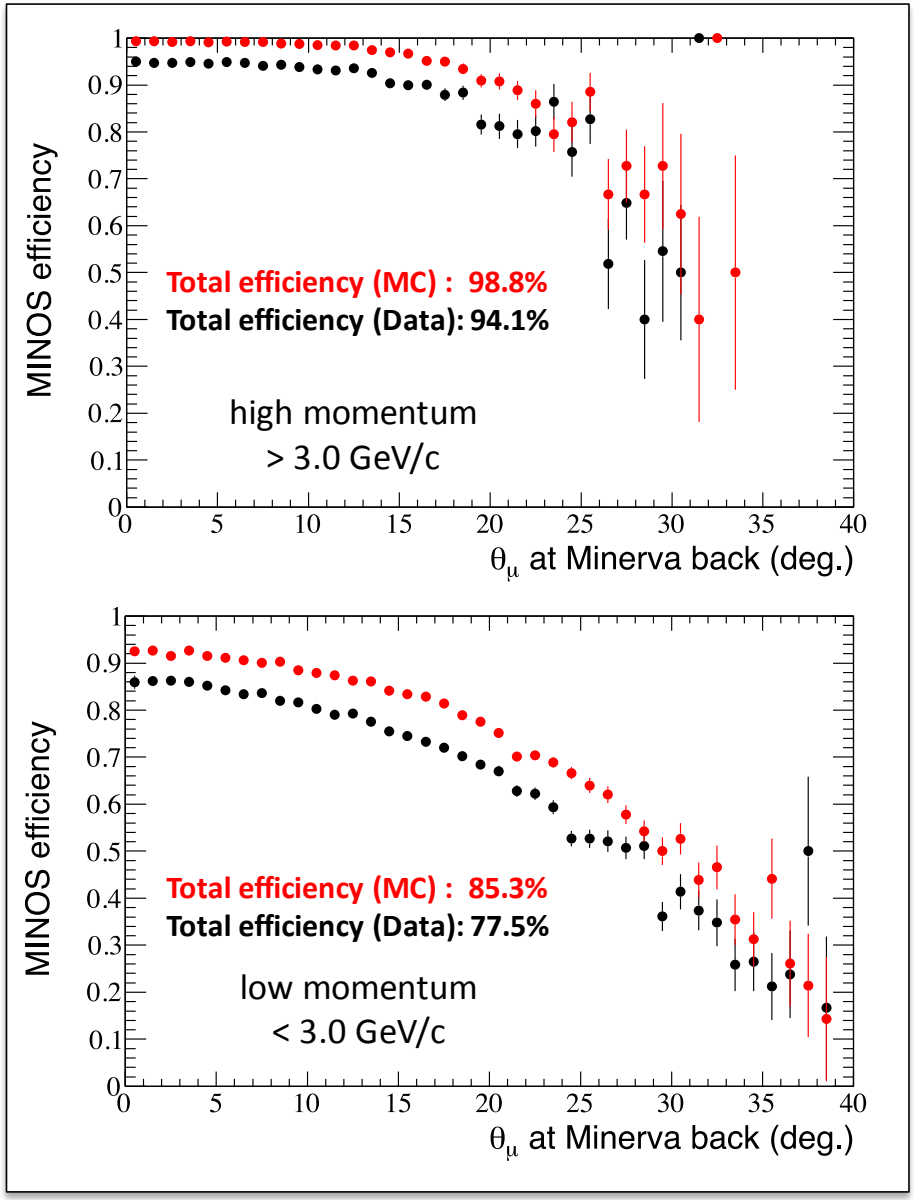
Muon Tracking Efficiency

MINOS muon tracking efficiency

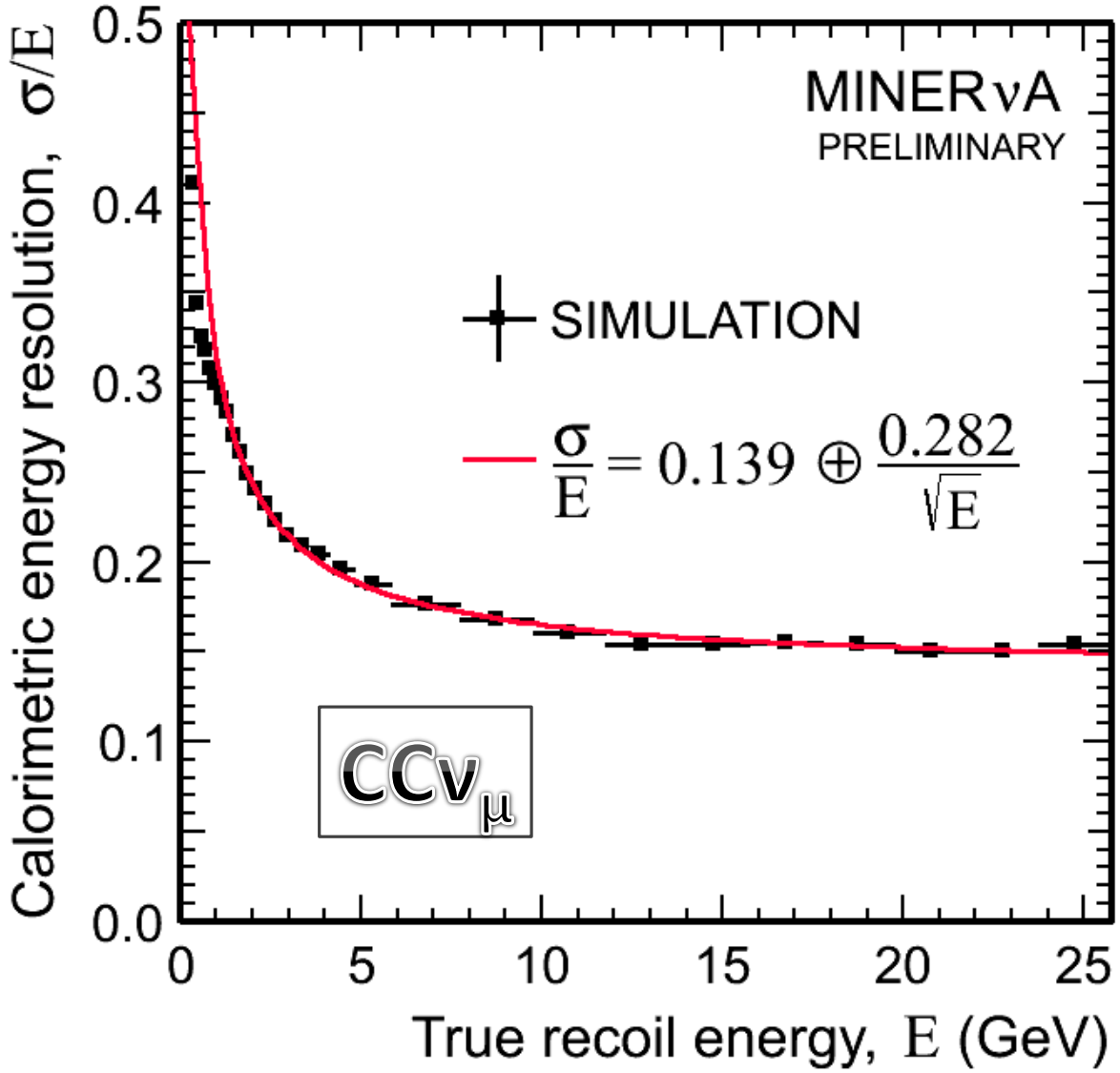


use scattering in MINERvA ECAL+HCAL to split into **high** and **low** momentum samples

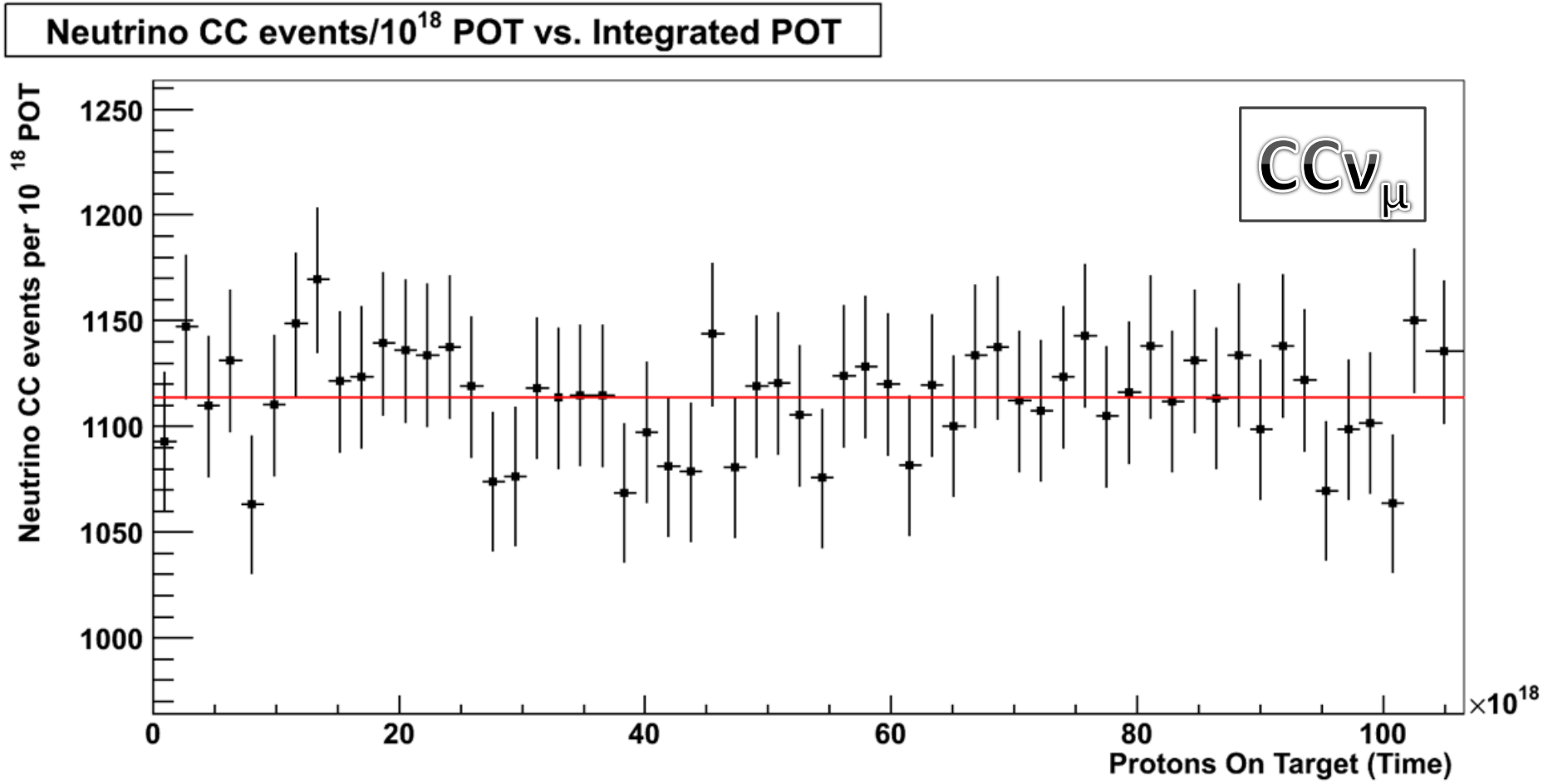
Total Corrections	neutrinos	antineutrinos
$p_\mu < 3.0$ GeV/c	(-10.1 ± 4.7) %	(-7.8 ± 3.4) %
$p_\mu > 3.0$ GeV/c	(-6.7 ± 2.6) %	(-4.5 ± 1.9) %



Recoil Energy Resolution



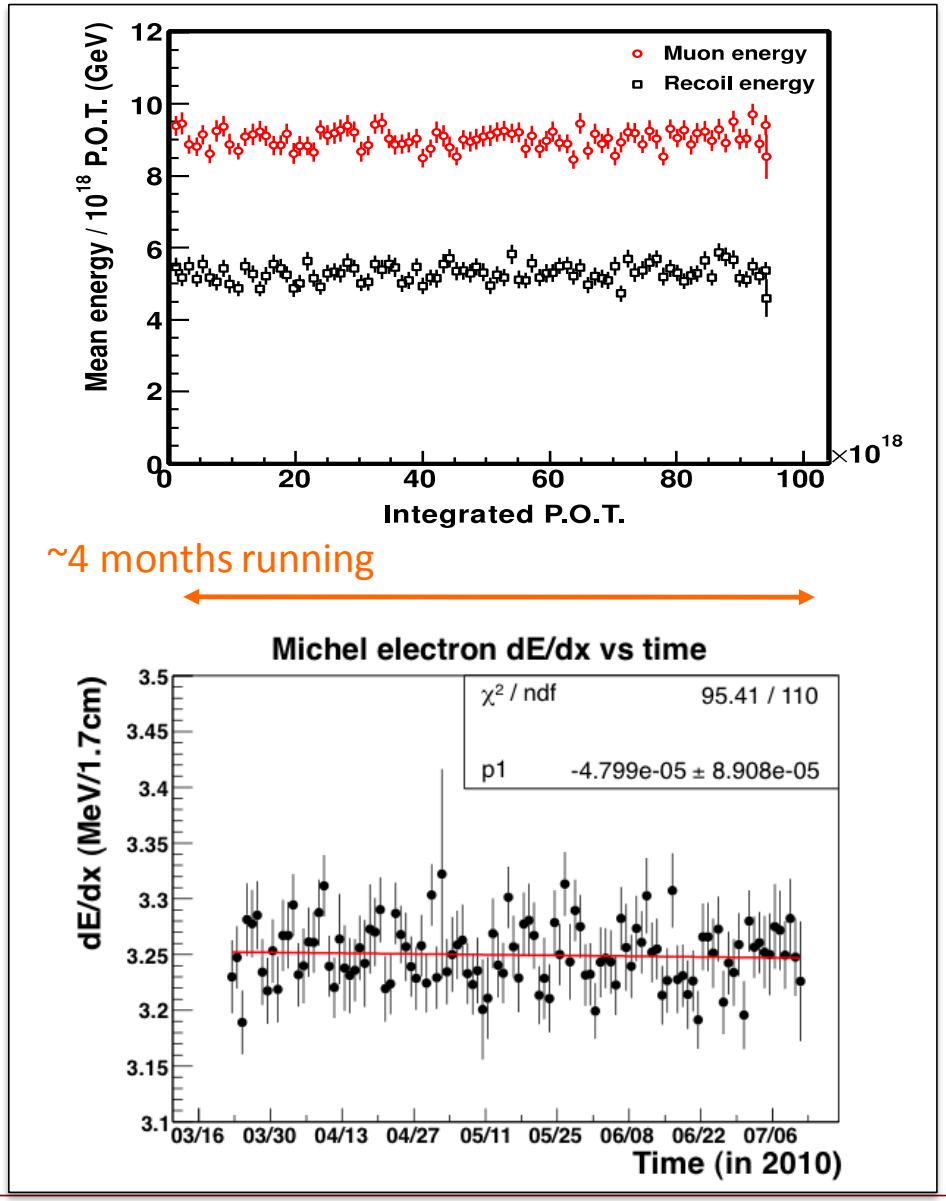
Stability



March 22, 2010

July 12, 2010

Reconstruction Stability



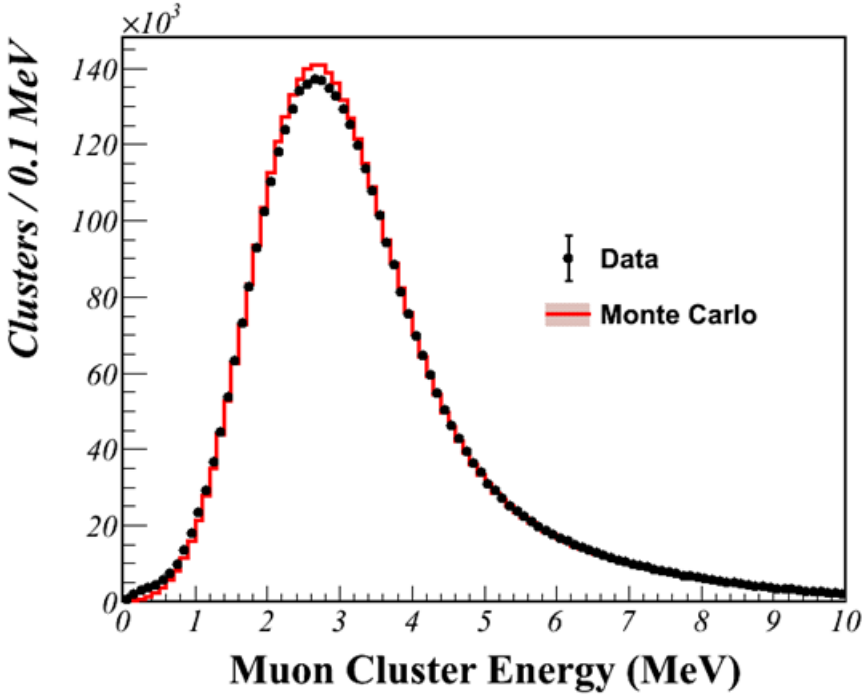
Muons

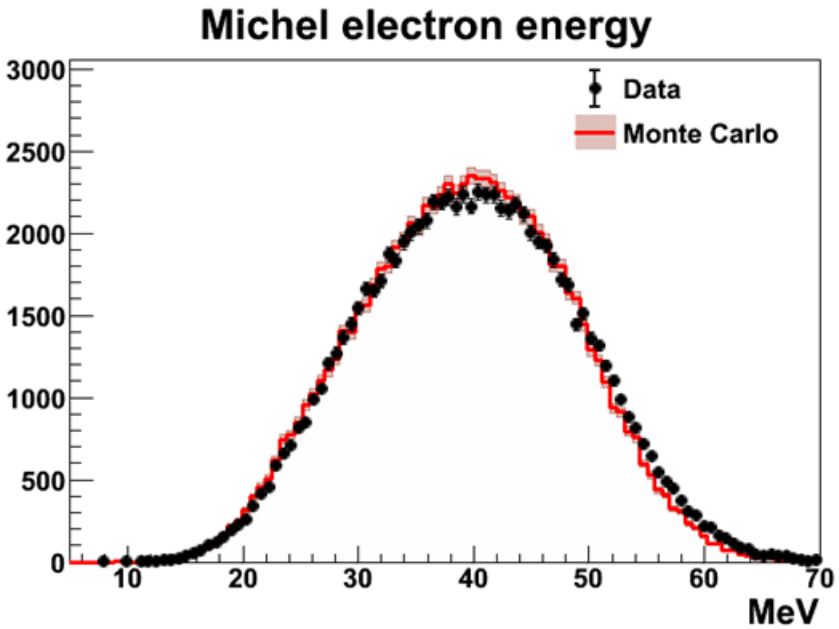
Recoil

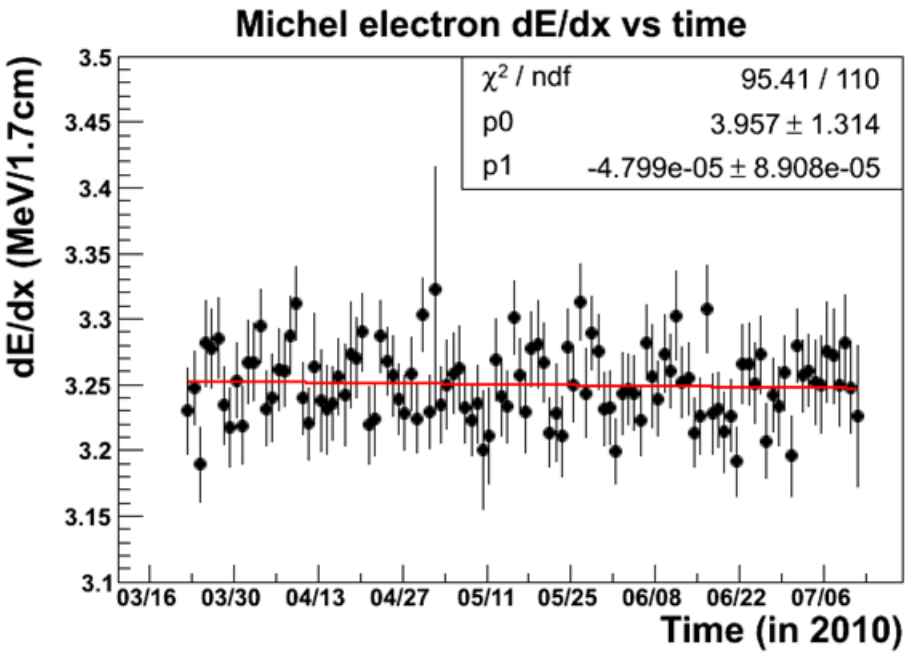
Calibrated detector
very stable
at high and low
energy scales

Electron dE/dx

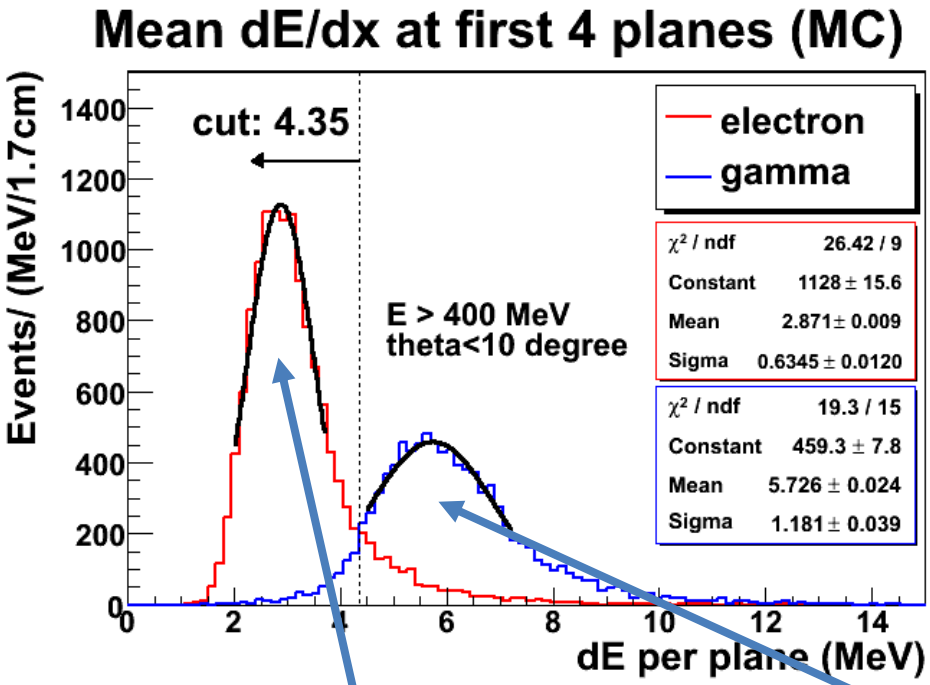
Energy Scale and Stability

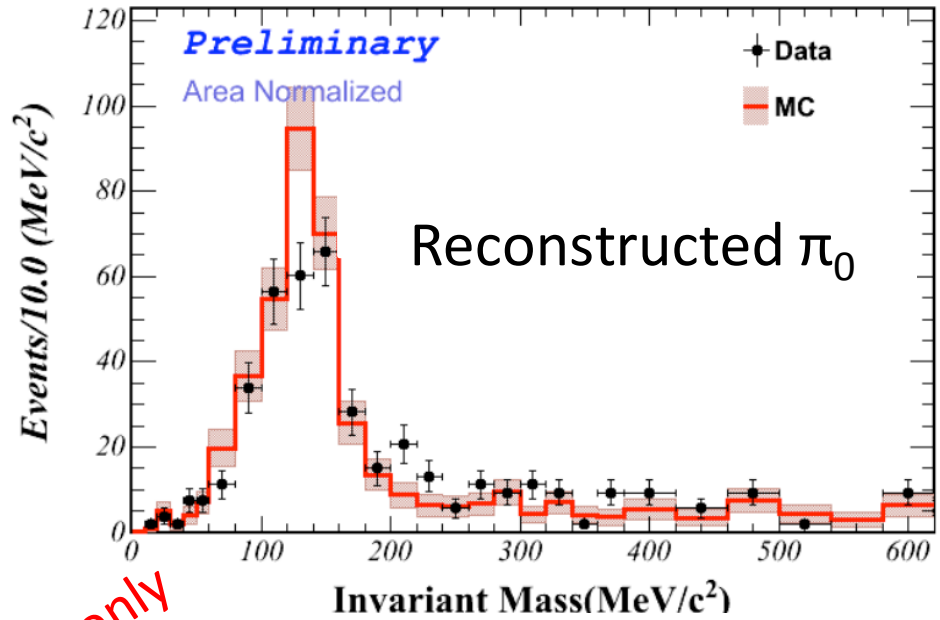




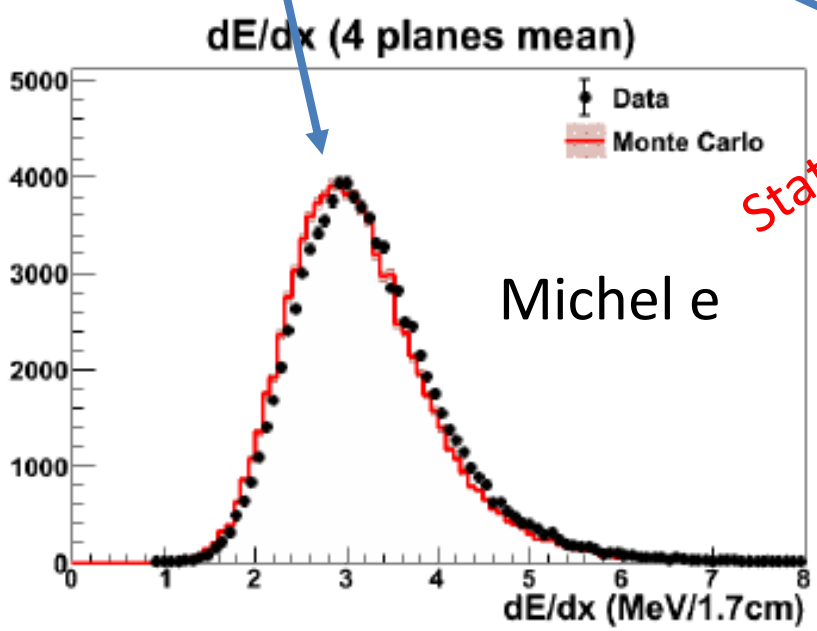


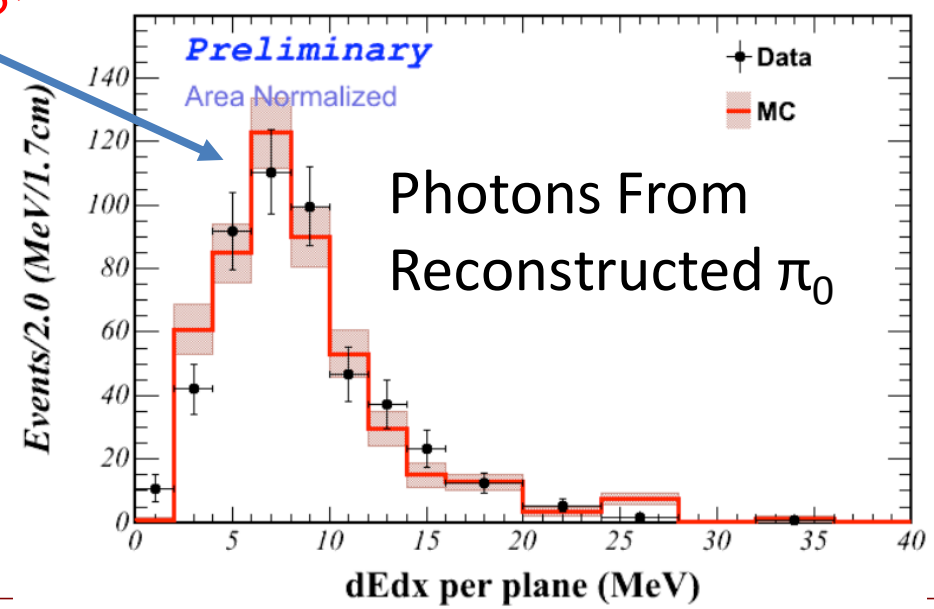
Michels, π_0 and e/γ Separation





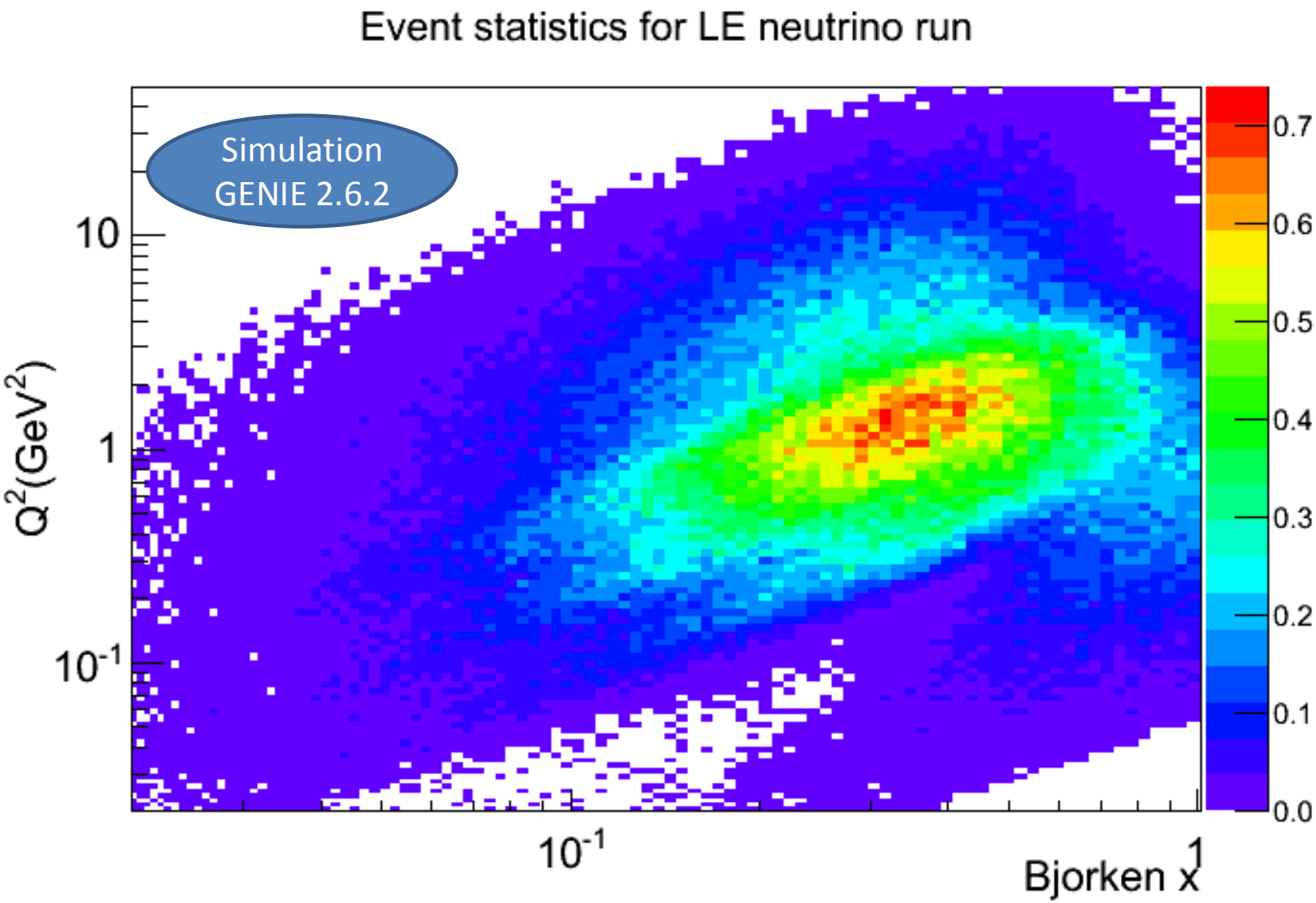
Statistical errors only





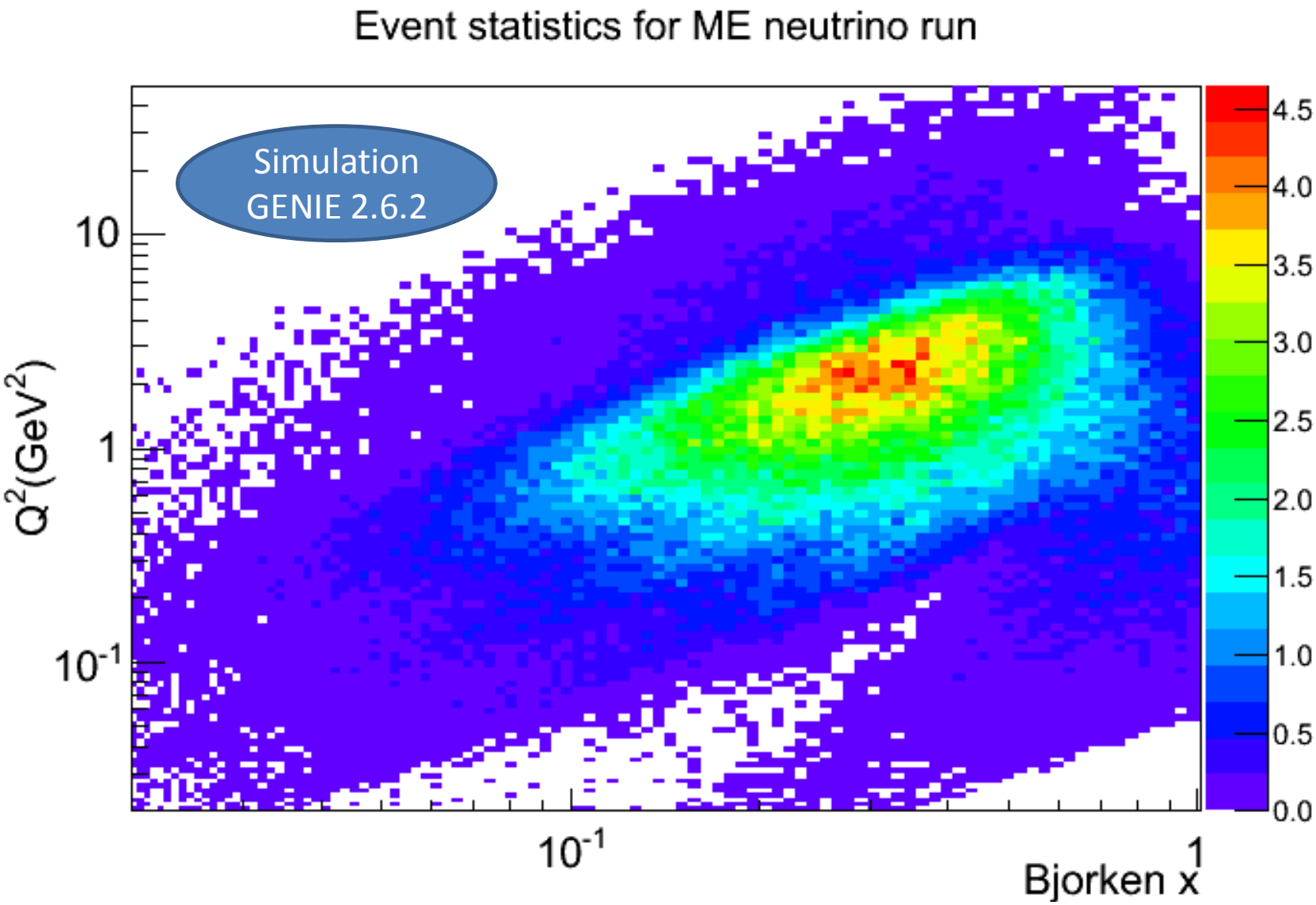
Events accepted from low energy run

Expected kinematic distribution of data shown today



Events accepted during NOvA-era run

Expected kinematic distribution of data now being collected



GENIE FSI Systematics

x_P	Description of P	$\delta P/P$
x_{mfp}^{N}	Nucleon mean free path (total rescattering probability)	±20%
x_{cex}^{N}	Nucleon charge exchange probability	±50%
x_{el}^{N}	Nucleon elastic reaction probability	±30%
x_{inel}^{N}	Nucleon inelastic reaction probability	±40%
x_{abs}^{N}	Nucleon absorption probability	±20%
x_{π}^{N}	Nucleon π-production probability	±20%
x_{mfp}^{π}	π mean free path (total rescattering probability)	±20%
x_{cex}^{π}	π charge exchange probability	±50%
x_{el}^{π}	π elastic reaction probability	±10%
x_{inel}^{π}	π inelastic reaction probability	±40%
x_{abs}^{π}	π absorption probability	±20%
x_{π}^{π}	π π-production probability	±20%

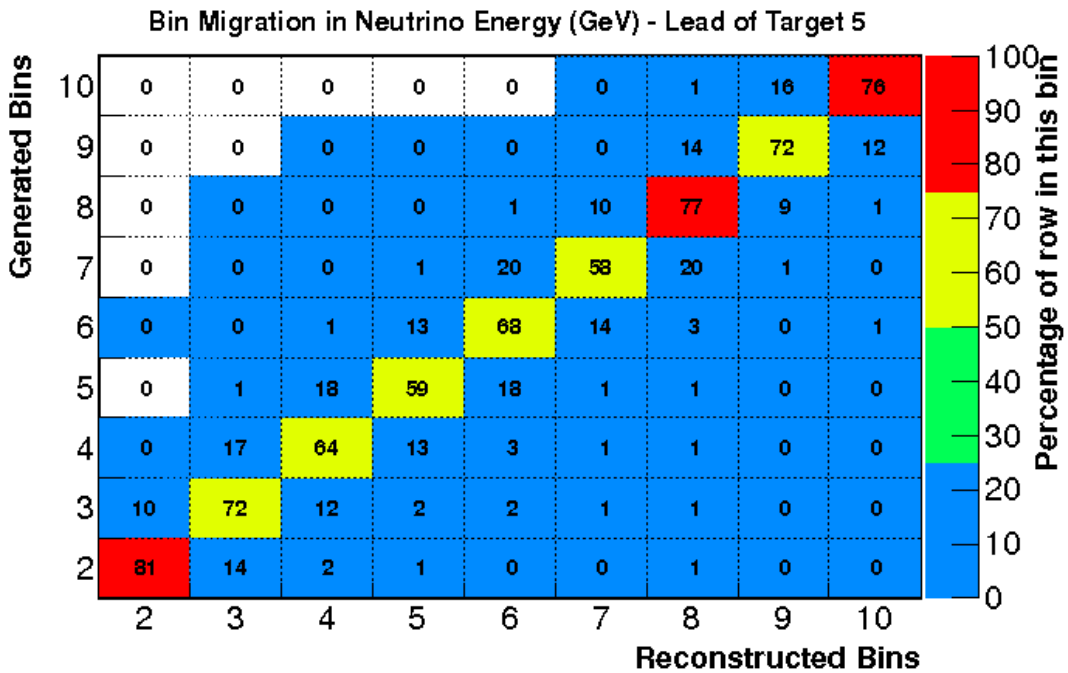
x_P	Description of P	$\delta P/P$
$x_{AGKY}^{pT1\pi}$	Pion transverse momentum (p_T) for $N\pi$ states in AGKY	-
$x_{AGKY}^{xF1\pi}$	Pion Feynman x (x_F) for $N\pi$ states in AGKY	-
x_{fz}	Hadron formation zone	±50%
$x_{\theta_\pi}^{\Delta\to\pi N}$	Pion angular distribution in $\Delta \to \pi N$ (isotropic $\leftrightarrow$ RS)	-
$x_{BR}^{R\to X+1\gamma}$	Branching ratio for radiative resonance decays	±50%
$x_{BR}^{R\to X+1\eta}$	Branching ratio for single-η resonance decays	±50%

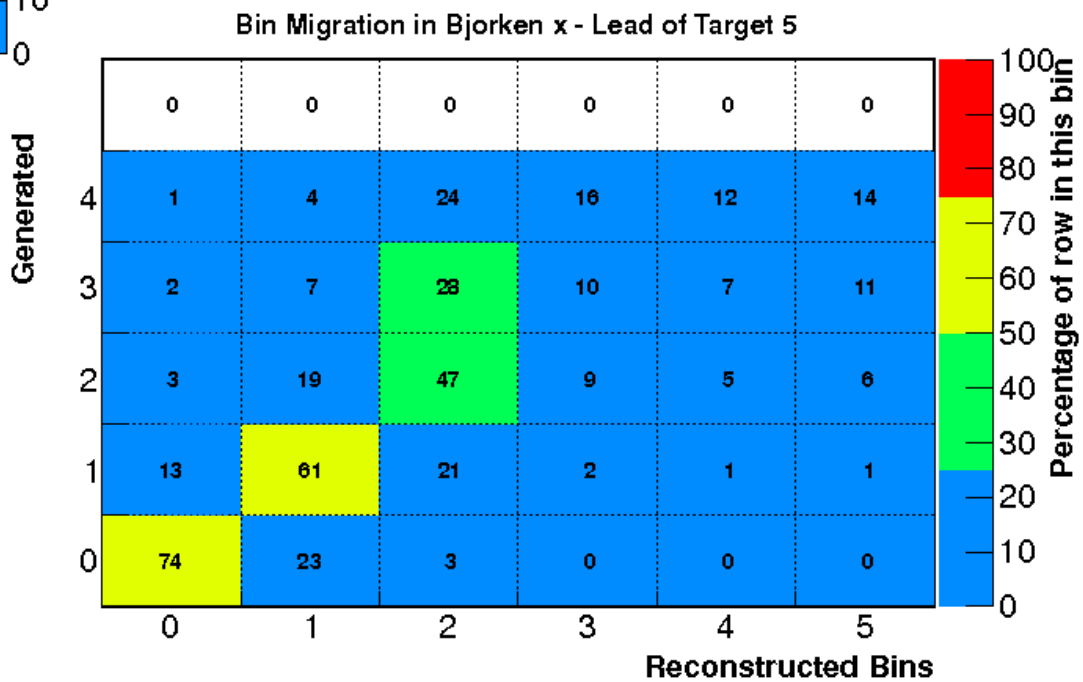
GENIE Cross Section Systematics

x_P	Description of P	$\delta P/P$
$x_{M_A^{NCEL}}$	Axial mass for NC elastic	±25%
$x_{\eta^{NCEL}}$	Strange axial form factor η for NC elastic	±30%
$x_{M_A^{CCQE}}$	Axial mass for CC quasi-elastic	-15% +25%
$x_{CCQE-Norm}$	Normalization factor for CCQE	
$x_{CCQE-PauliSup}$	CCQE Pauli suppression (via changes in Fermi level k_F)	±35%
$x_{CCQE-VecFF}$	Choice of CCQE vector form factors (BBA05 ↔ Dipole)	-
$x_{CCRES-Norm}$	Normalization factor for CC resonance neutrino production	
$x_{NCRES-Norm}$	Normalization factor for NC resonance neutrino production	
$x_{M_A^{CCRES}}$	Axial mass for CC resonance neutrino production	±20%
$x_{M_V^{CCRES}}$	Vector mass for CC resonance neutrino production	±10%
$x_{M_A^{NCRES}}$	Axial mass for NC resonance neutrino production	±20%
$x_{M_V^{NCRES}}$	Vector mass for NC resonance neutrino production	±10%
$x_{M_A^{COHpi}}$	Axial mass for CC and NC coherent pion production	±50%
$x_{R_0^{COHpi}}$	Nuclear size param. controlling π absorption in RS model	±10%

$x_{R_{bkg}^{\nu p,CC1\pi}}$	Non-resonance bkg in νp $CC1\pi$ reactions	±50%
$x_{R_{bkg}^{\nu p,CC2\pi}}$	Non-resonance bkg in νp $CC2\pi$ reactions	±50%
$x_{R_{bkg}^{\nu n,CC1\pi}}$	Non-resonance bkg in νn $CC1\pi$ reactions	±50%
$x_{R_{bkg}^{\nu n,CC2\pi}}$	Non-resonance bkg in νn $CC2\pi$ reactions	±50%
$x_{R_{bkg}^{\nu p,NC1\pi}}$	Non-resonance bkg in νp $NC1\pi$ reactions	±50%
$x_{R_{bkg}^{\nu p,NC2\pi}}$	Non-resonance bkg in νp $NC2\pi$ reactions	±50%
$x_{R_{bkg}^{\nu n,NC1\pi}}$	Non-resonance bkg in νn $NC1\pi$ reactions	±50%
$x_{R_{bkg}^{\nu n,NC2\pi}}$	Non-resonance bkg in νn $NC2\pi$ reactions	±50%
$x_{A_{HT}^{BY}}$	A_{HT} higher-twist param in BY model scaling variable ξ_w	±25%
$x_{B_{HT}^{BY}}$	B_{HT} higher-twist param in BY model scaling variable ξ_w	±25%
$x_{C_{V1u}^{BY}}$	C_{V1u} u valence GRV98 PDF correction param in BY model	±30%
$x_{C_{V2u}^{BY}}$	C_{V2u} u valence GRV98 PDF correction param in BY model	±40%
x_{CCDIS}	Inclusive CC cross-section normalization factor	
$x_{CC\bar{\nu}/\nu}$	$\bar{\nu}/\nu$ CC ratio	
$x_{DIS-NuclMod}$	DIS nuclear modification (shadowing, anti-shadowing, EMC)	

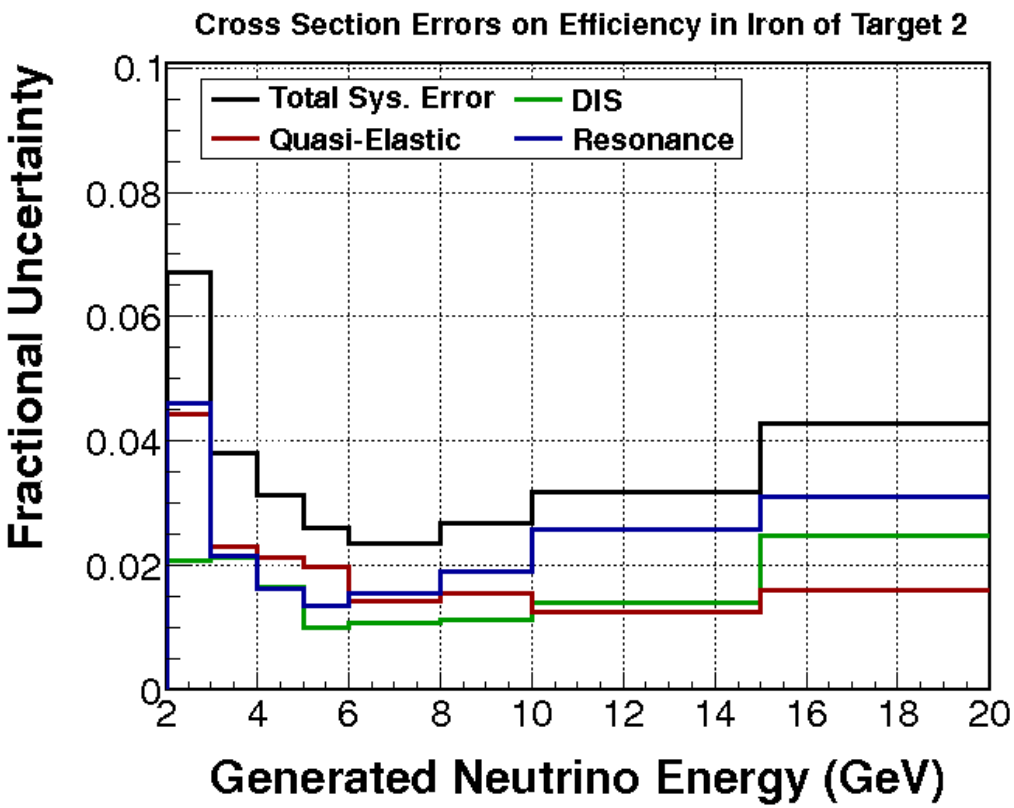
Fractional Bin Migration

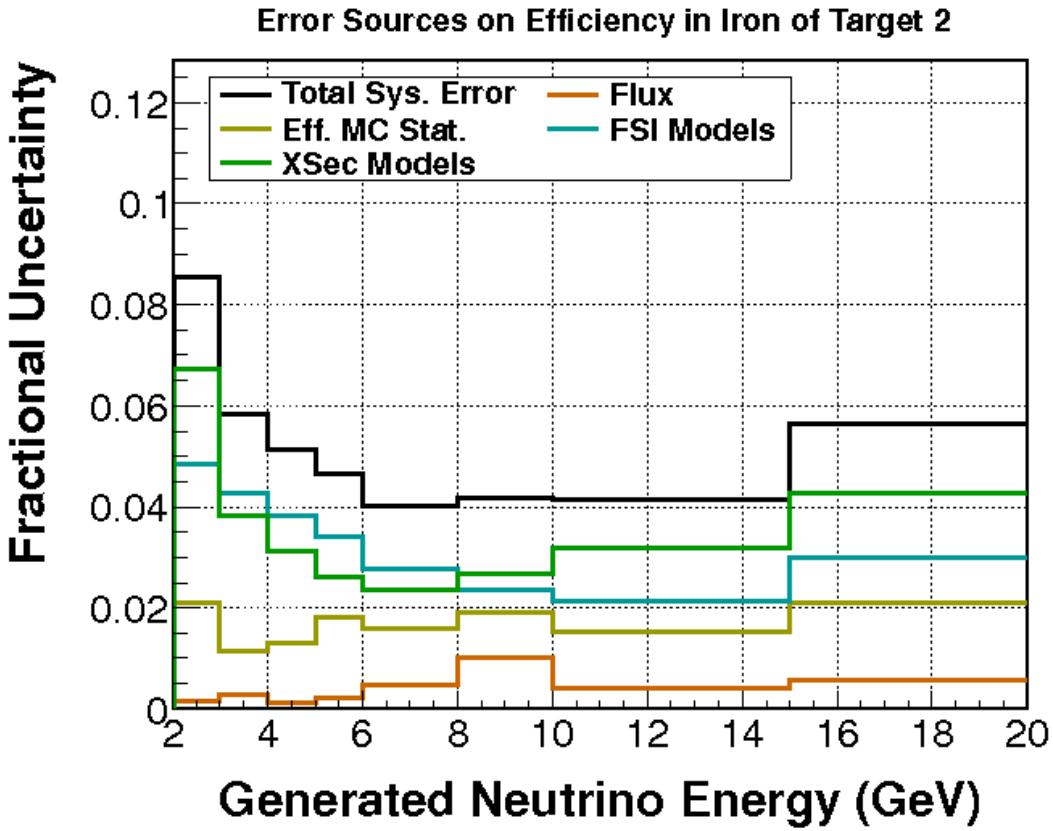




Error on Efficiency

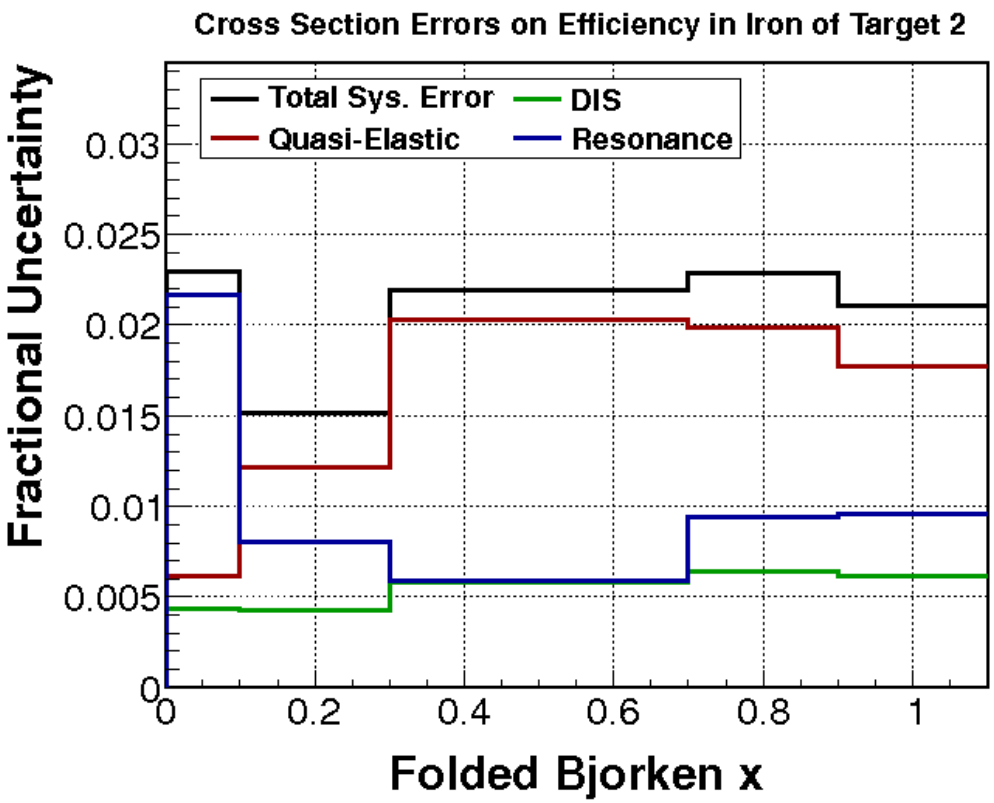
Cross section model uncertainty enters the measurement through efficiency only

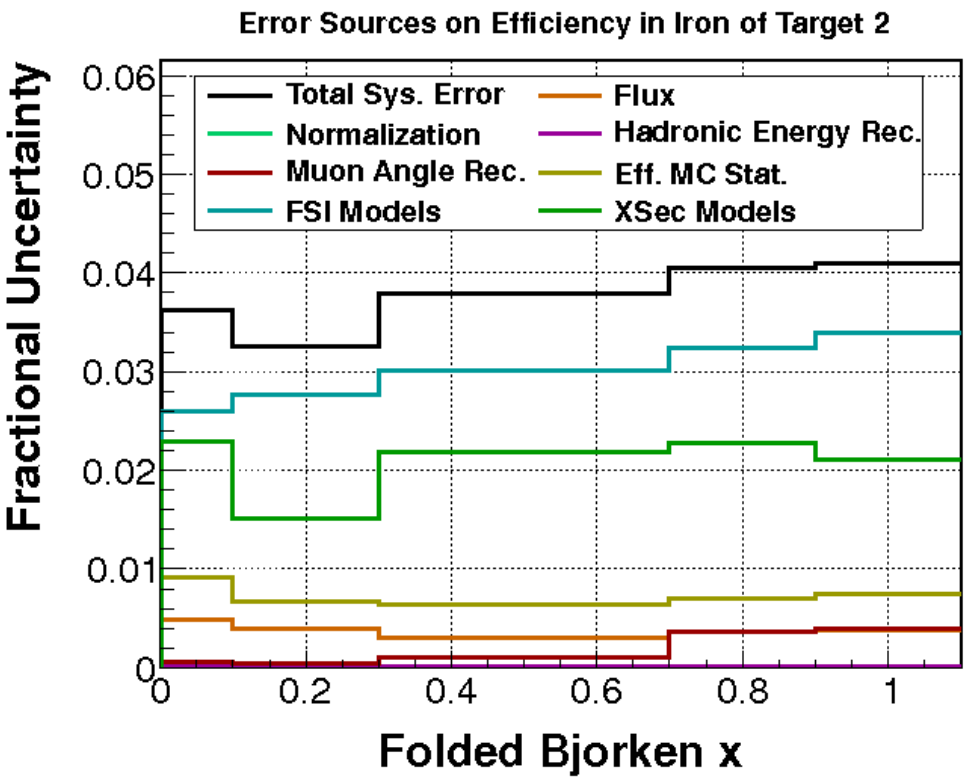




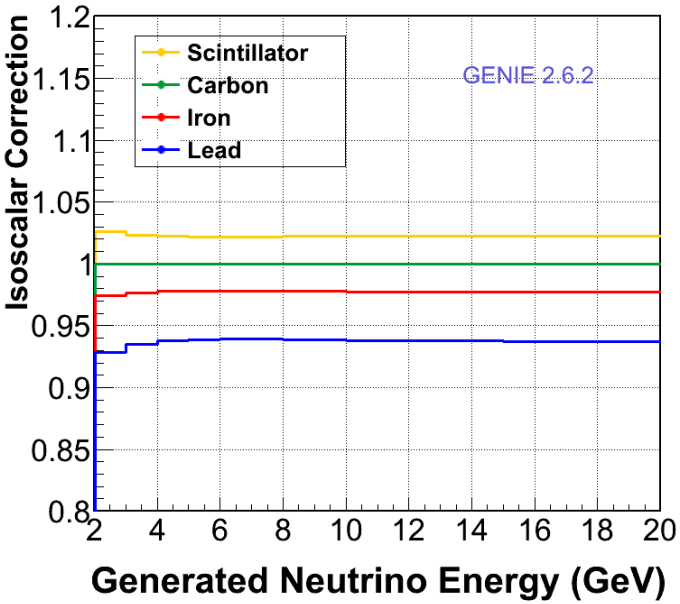
Error on Efficiency

Cross section model uncertainty enters the measurement through efficiency only

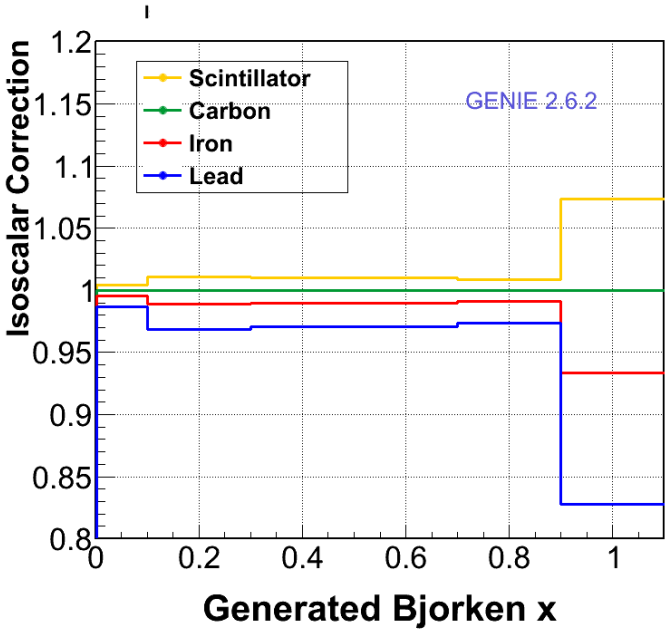




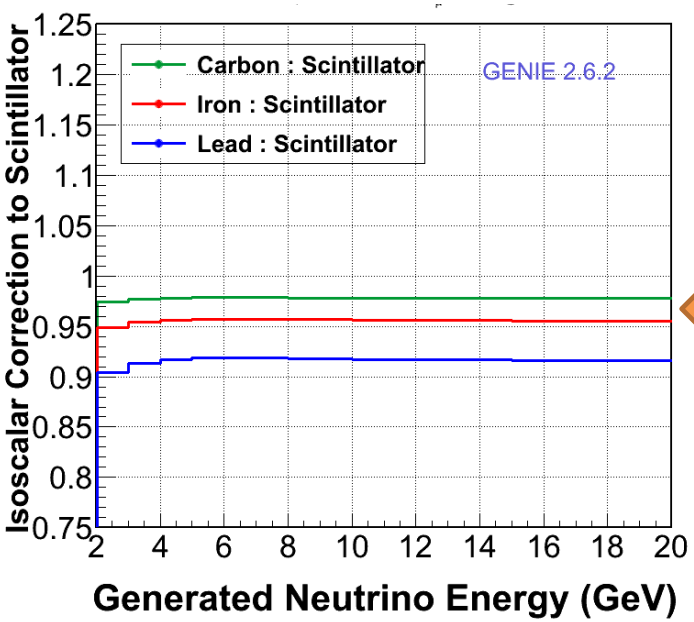
Isoscalar Corrections - Inclusive



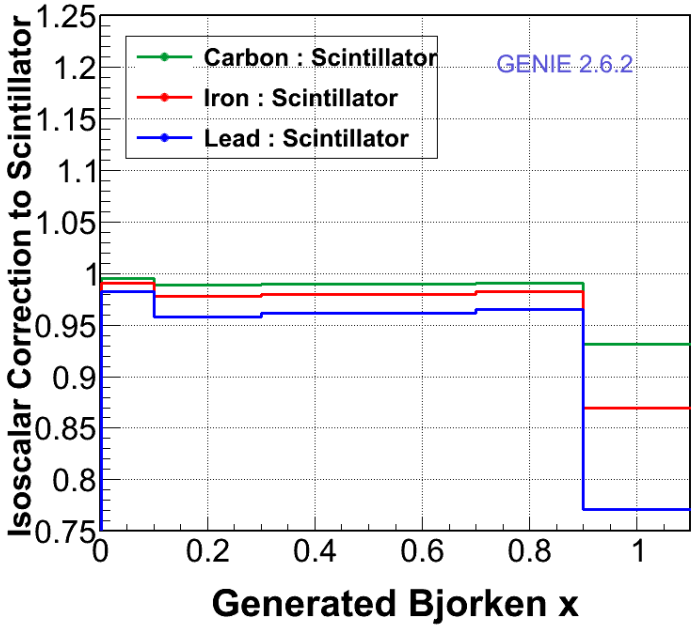
Isoscalar correction



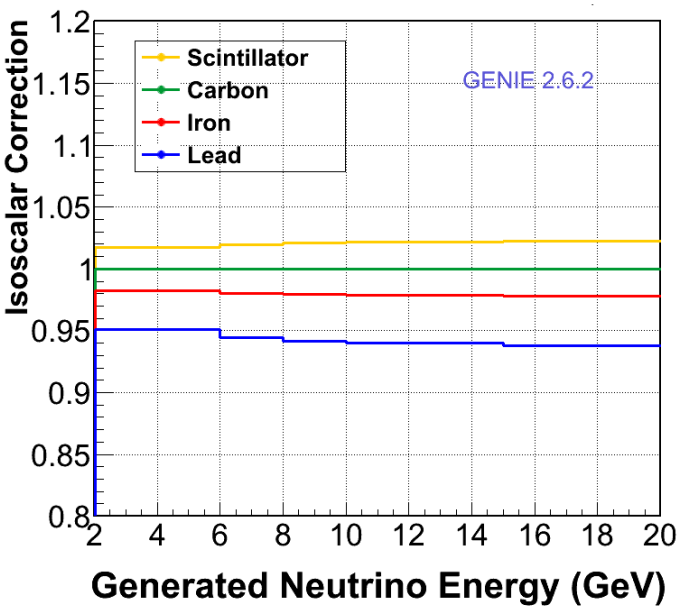
For signal kinematics
$2 < E_\nu < 20$ GeV
$\Theta_\mu < 17$ deg



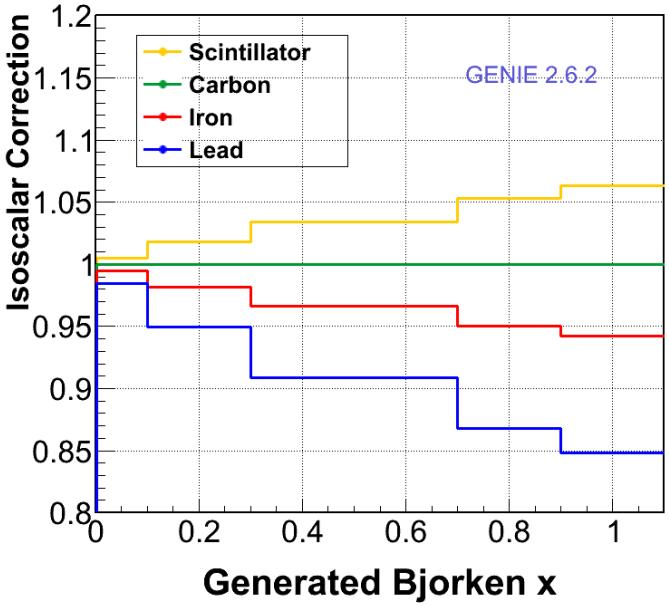
Isoscalar correction on ratio



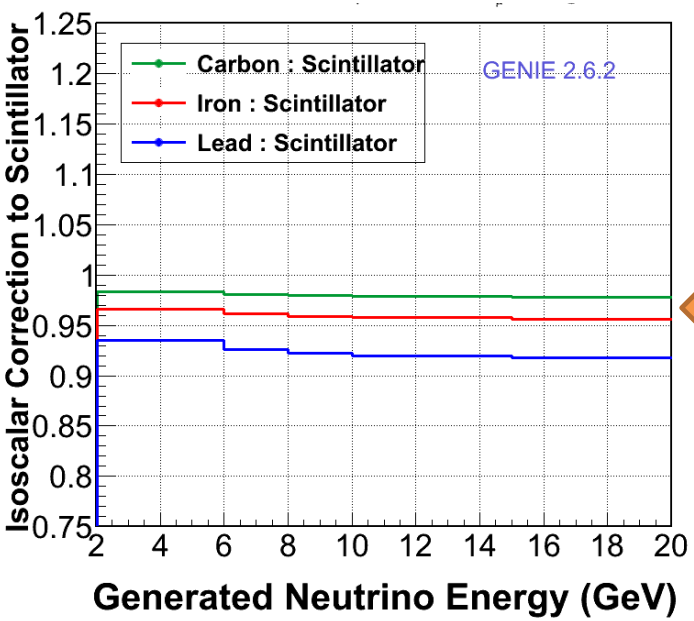
Isoscalar Corrections - Inelastic



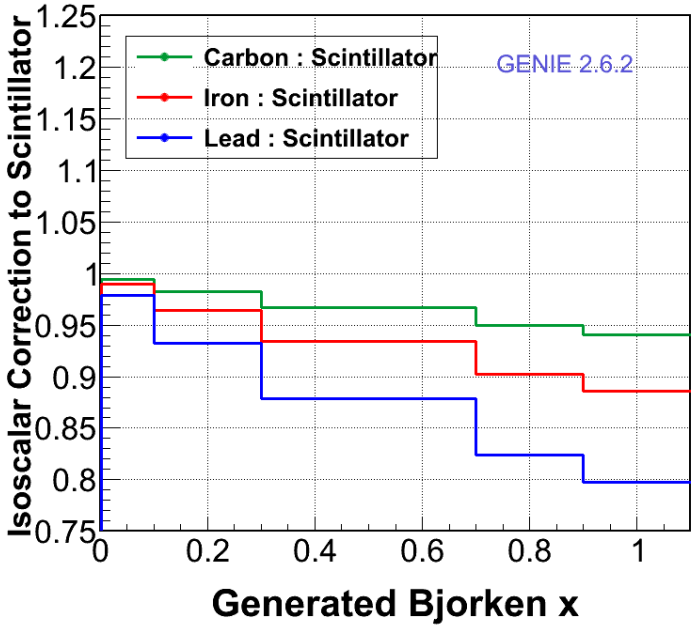
Isoscalar correction

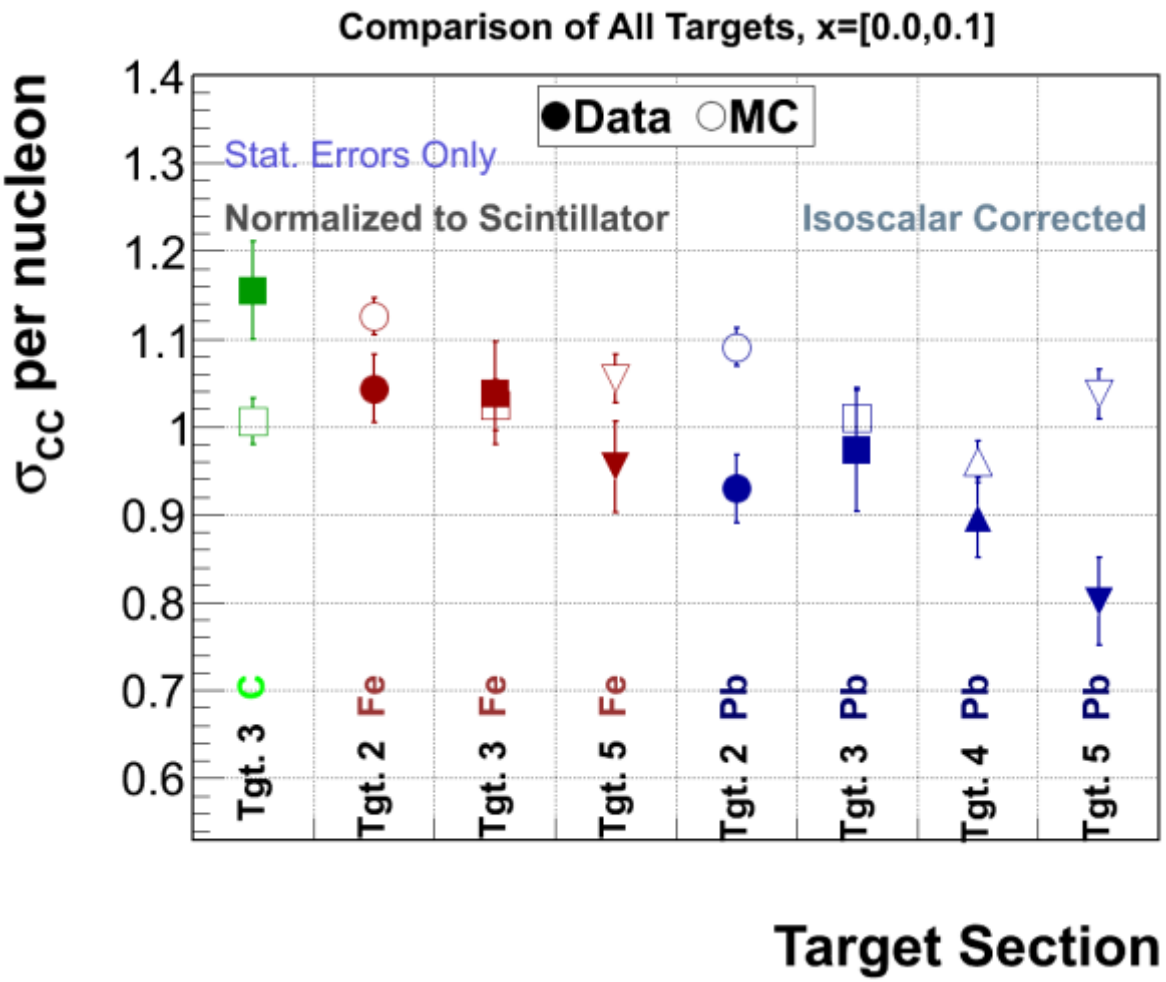


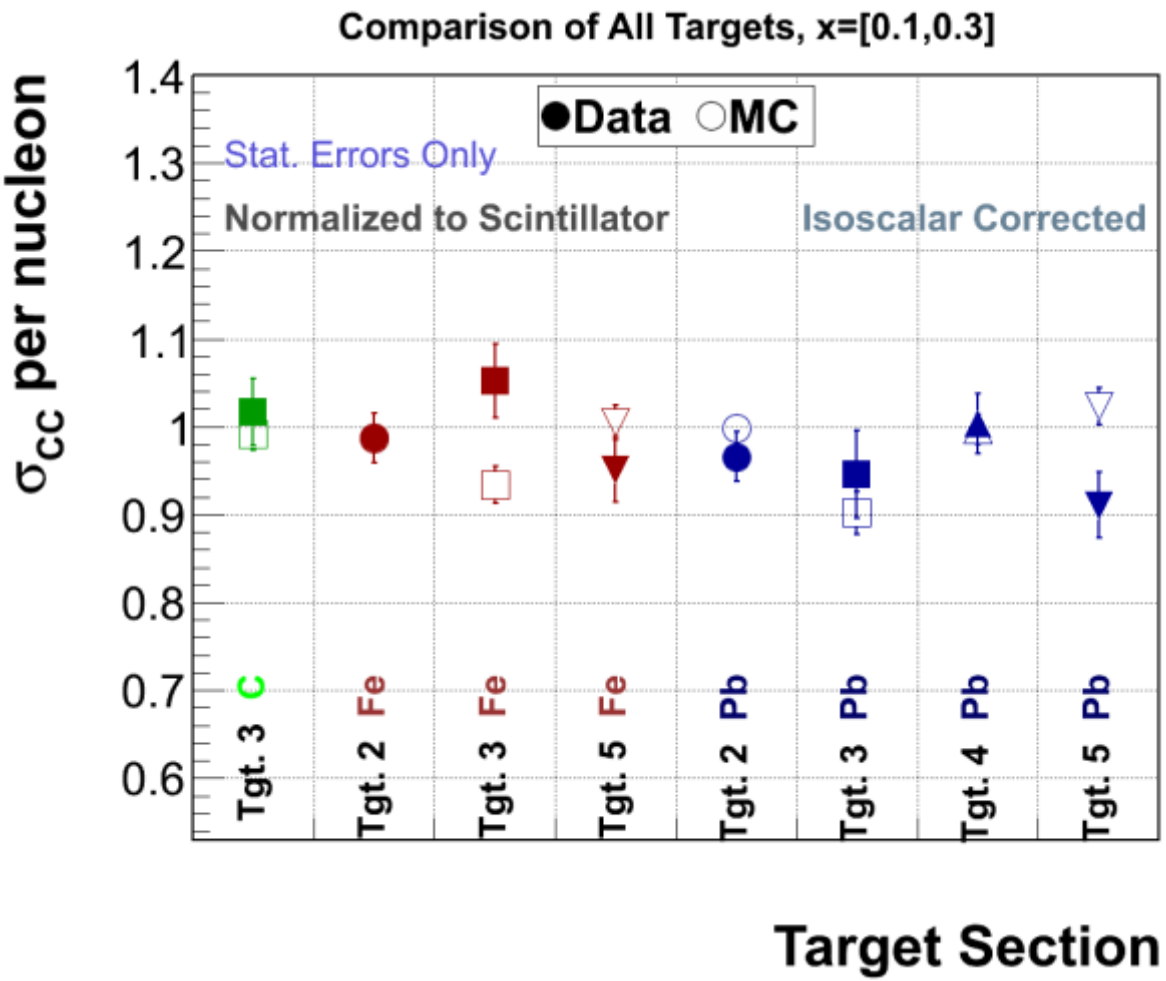
For signal kinematics
$2 < E_\nu < 20$ GeV
$\Theta_\mu < 17$ deg

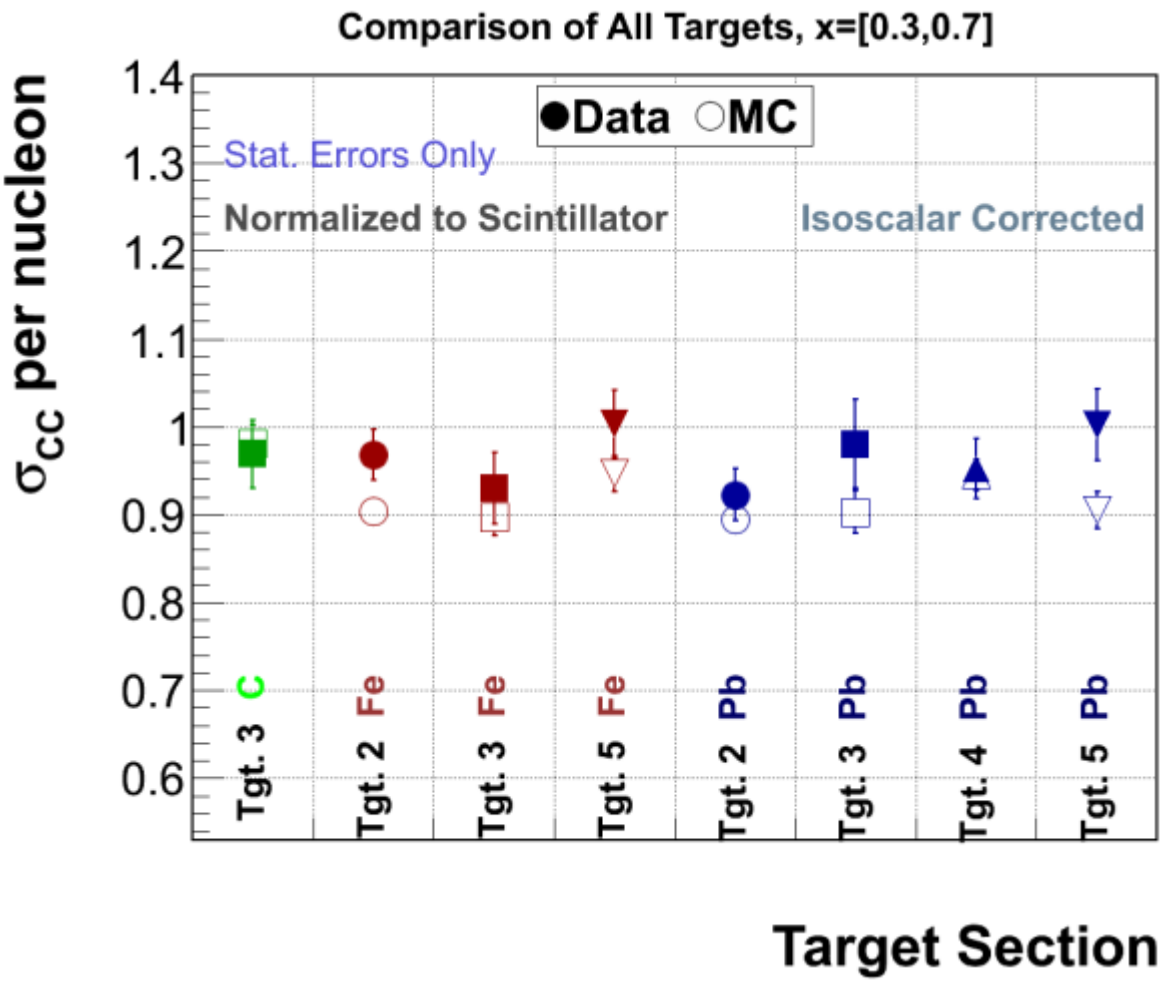


Isoscalar correction on ratio



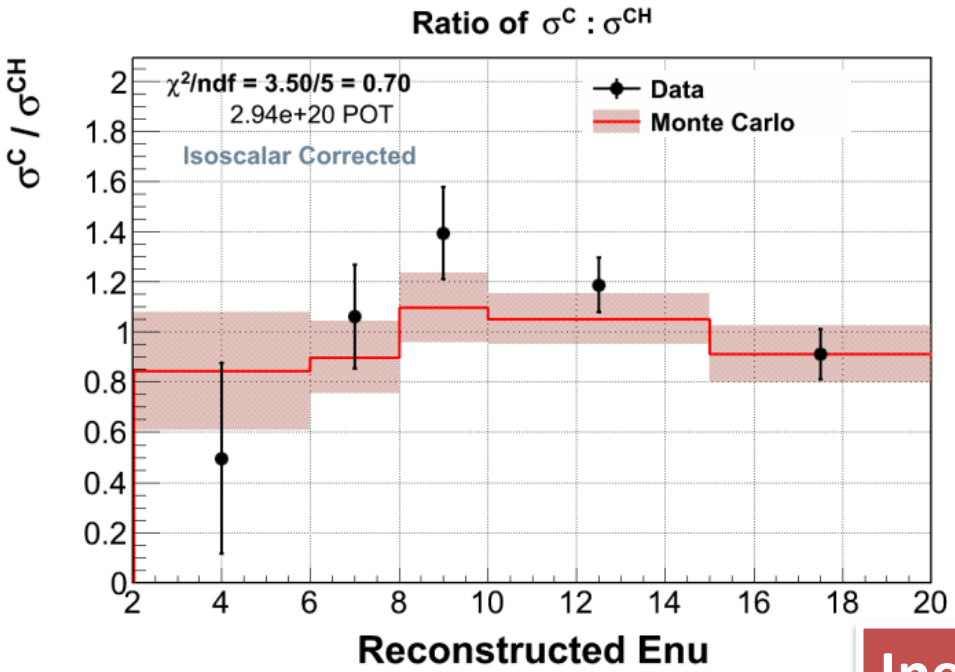

Comparison of All Targets, x=[0.0,0.1]
●Data ○MC
Stat. Errors Only
Normalized to Scintillator
Isoscalar Corrected
σ_{CC} per nucleon
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
Tgt. 3 C
Tgt. 2 Fe
Tgt. 3 Fe
Tgt. 5 Fe
Tgt. 2 Pb
Tgt. 3 Pb
Tgt. 4 Pb
Tgt. 5 Pb
Target Section

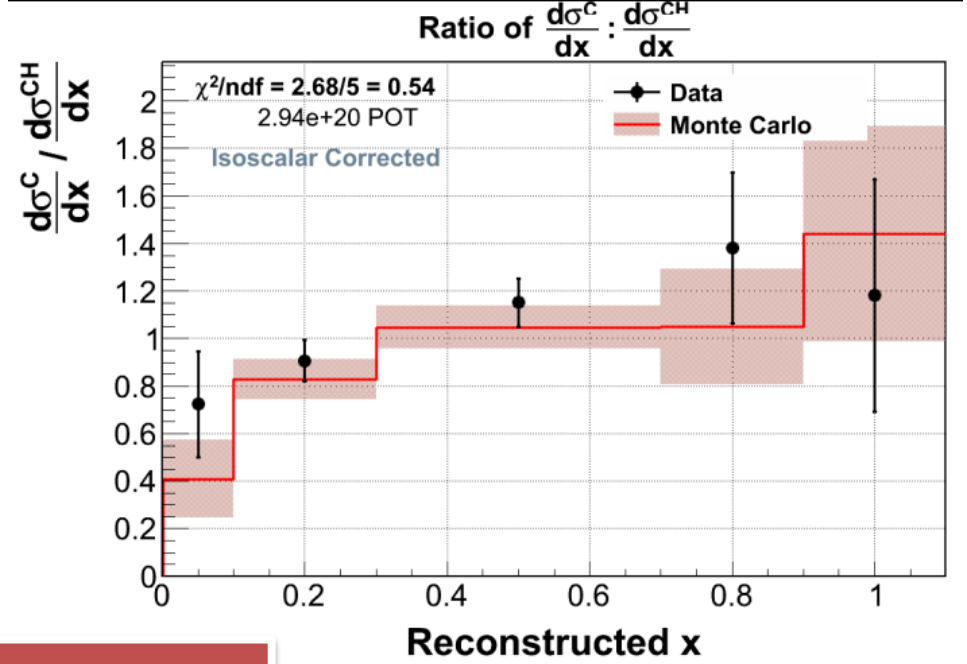

Comparison of All Targets, x=[0.1,0.3]
●Data ○MC
Stat. Errors Only
Normalized to Scintillator
Isoscalar Corrected
σ_{CC} per nucleon
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
Tgt. 3 C
Tgt. 2 Fe
Tgt. 3 Fe
Tgt. 5 Fe
Tgt. 2 Pb
Tgt. 3 Pb
Tgt. 4 Pb
Tgt. 5 Pb
Target Section


Comparison of All Targets, x=[0.3,0.7]
●Data ○MC
Stat. Errors Only
Normalized to Scintillator
Isoscalar Corrected
σ_{CC} per nucleon
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
Tgt. 3 C
Tgt. 2 Fe
Tgt. 3 Fe
Tgt. 5 Fe
Tgt. 2 Pb
Tgt. 3 Pb
Tgt. 4 Pb
Tgt. 5 Pb
Target Section

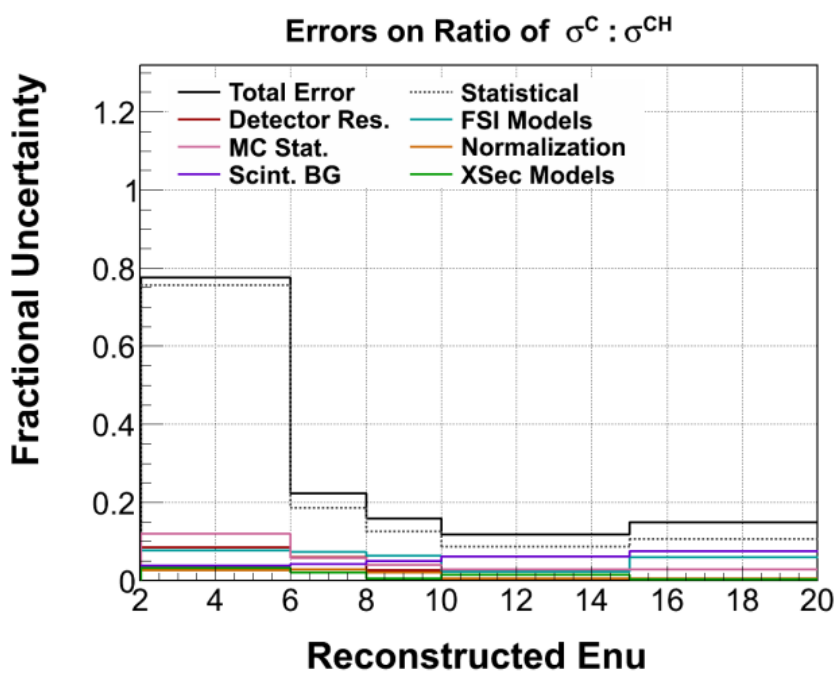
Inclusive vs. Inelastic Sample

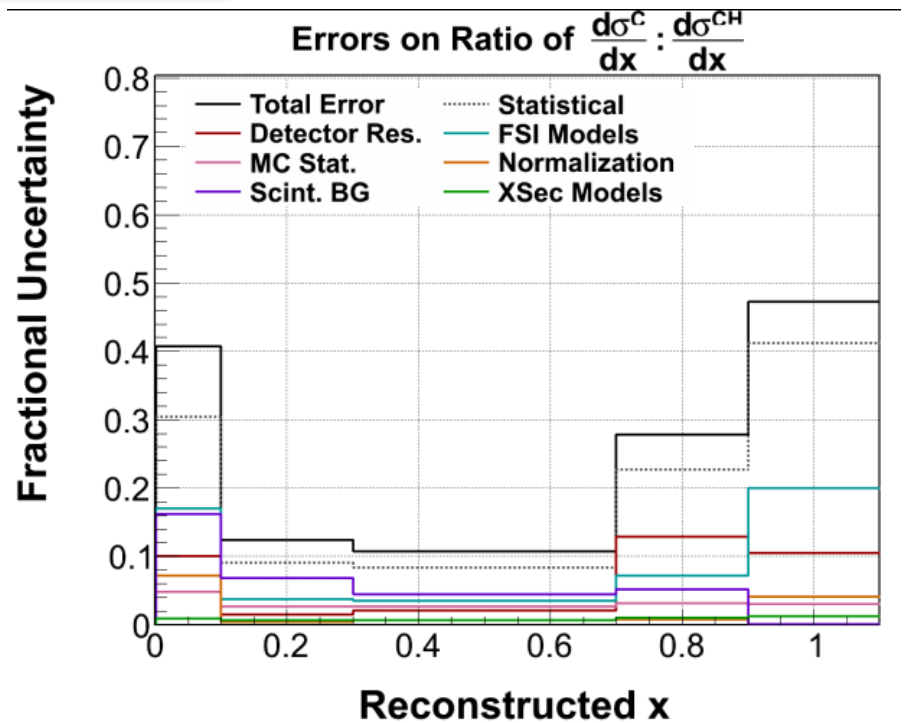
Target	data yield	QEL (%)	RES (%)	DIS, $Q^2 > 1$ $(GeV/c)^2$ (%)	DIS, $Q^2 < 1$ $(GeV/c)^2$ (%)	other (%)
Inclusive selection						
C	5400	29.67 ± 0.26	33.46 ± 0.27	12.83 ± 0.19	21.82 ± 0.24	2.23 ± 0.09
Fe	17954	29.90 ± 0.15	33.25 ± 0.15	13.68 ± 0.11	21.72 ± 0.13	1.45 ± 0.04
Pb	20488	31.43 ± 0.14	31.74 ± 0.14	13.81 ± 0.10	22.05 ± 0.12	0.97 ± 0.03
Inclusive and inelastic selections						
C	1217	1.70 ± 0.18	5.27 ± 0.31	61.83 ± 0.67	30.28 ± 0.63	0.91 ± 0.13
Fe	3699	1.45 ± 0.09	5.37 ± 0.18	66.30 ± 0.37	26.28 ± 0.34	0.59 ± 0.06
Pb	4370	1.77 ± 0.09	5.16 ± 0.16	66.03 ± 0.34	26.74 ± 0.32	0.31 ± 0.04

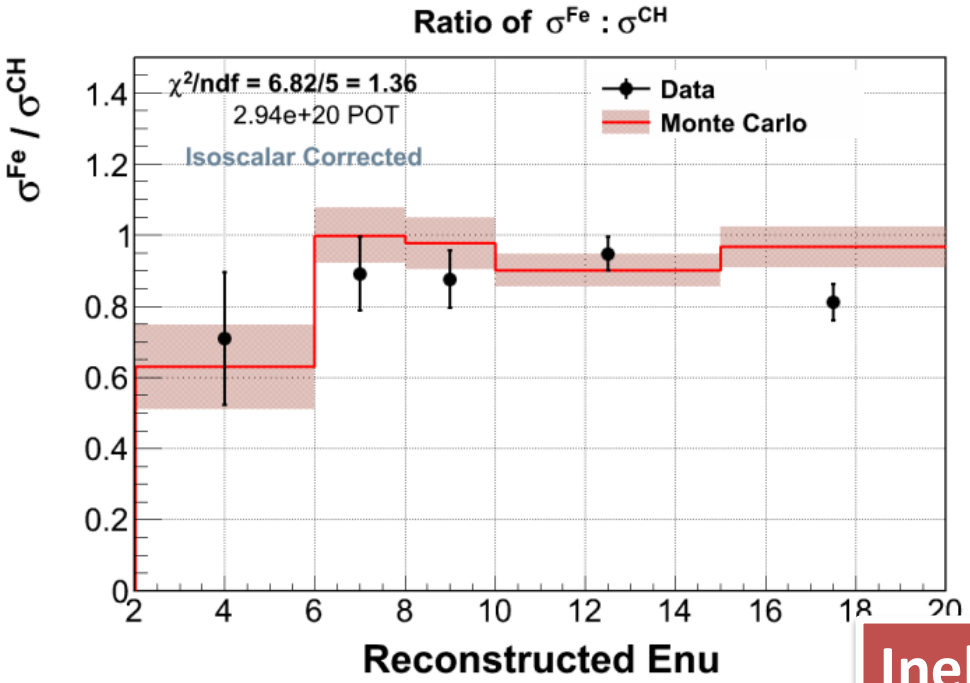


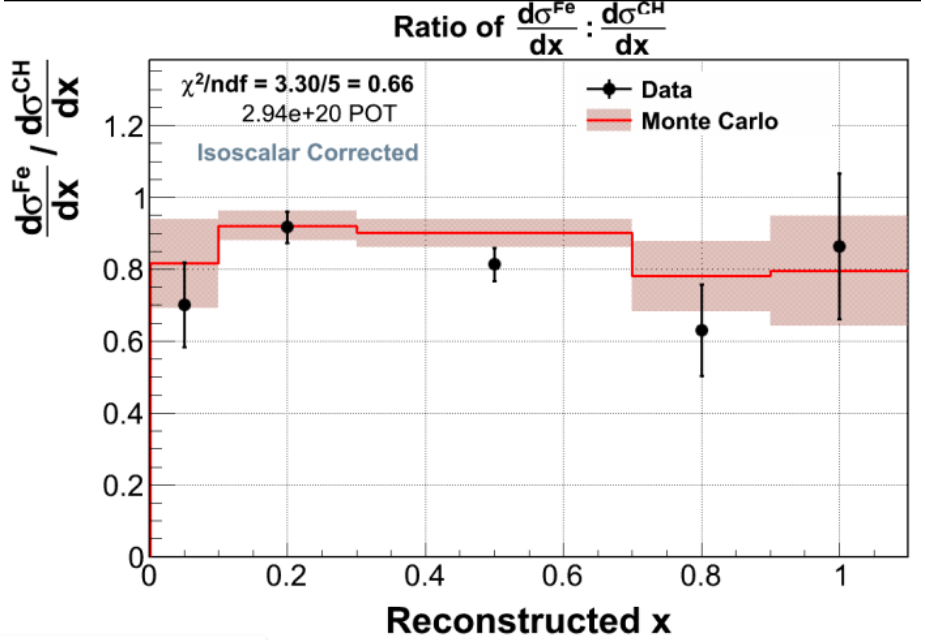


Inelastic Sample

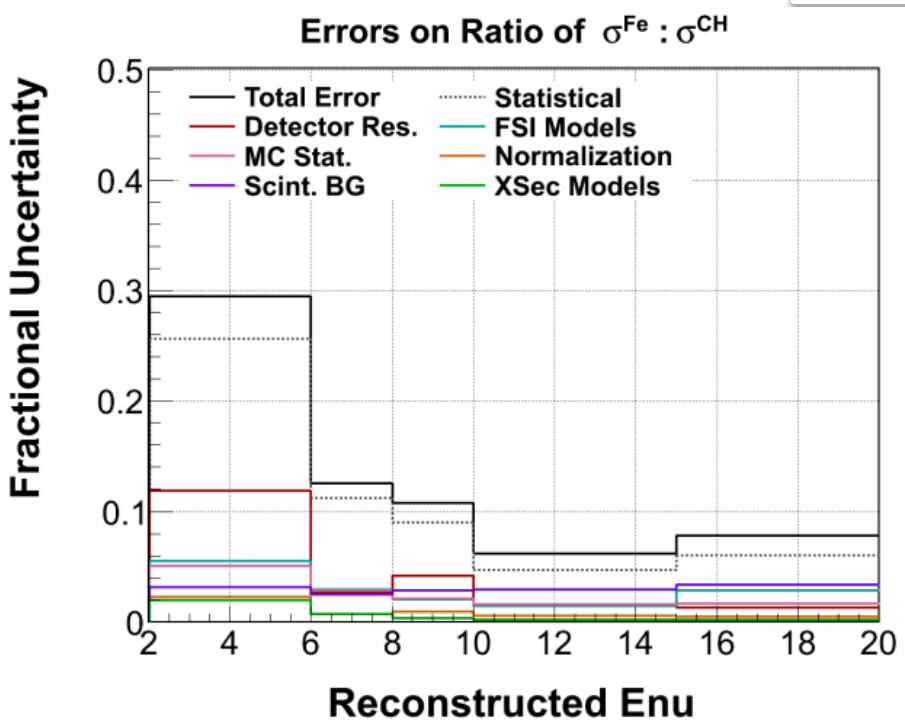


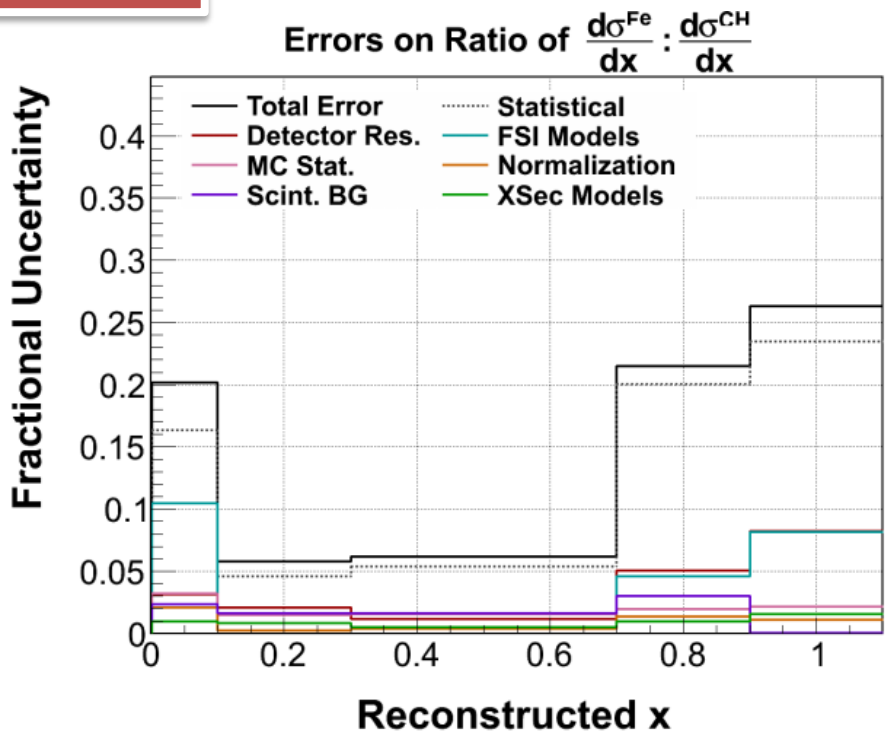


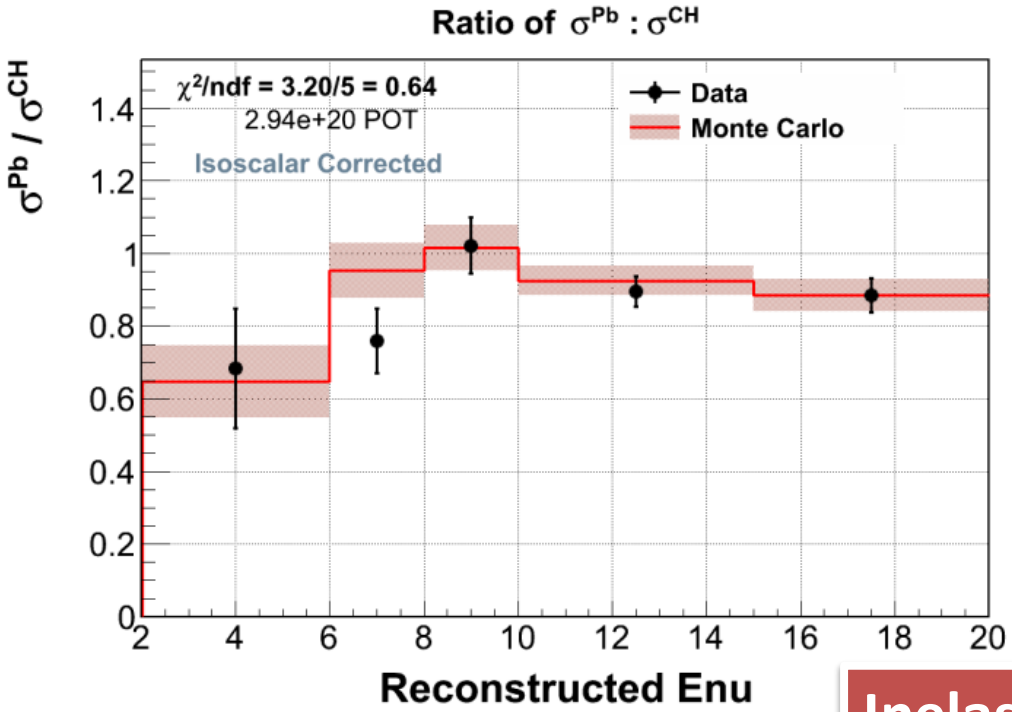


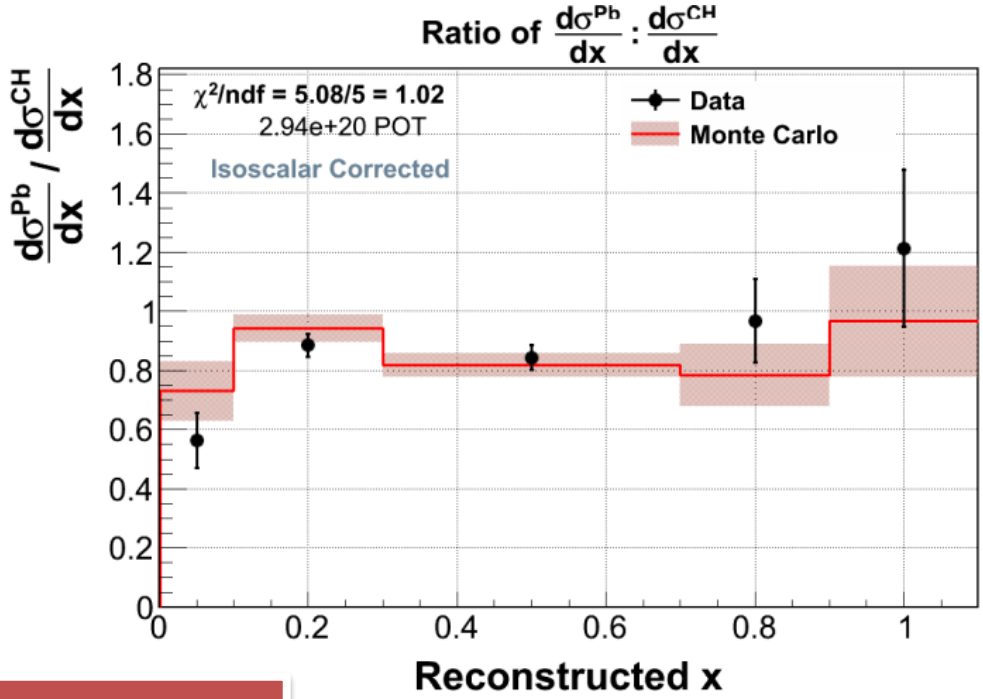


Inelastic Sample

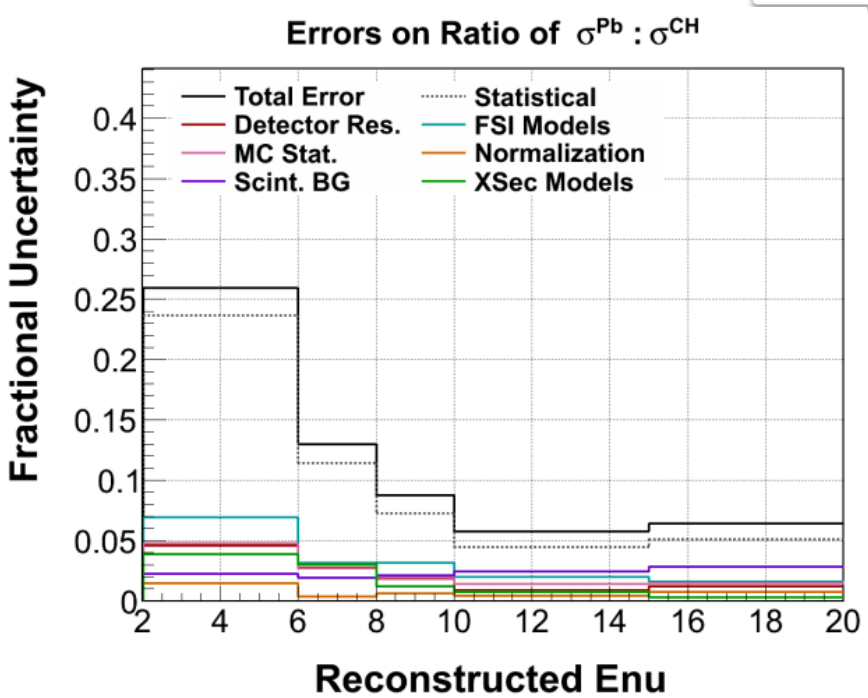


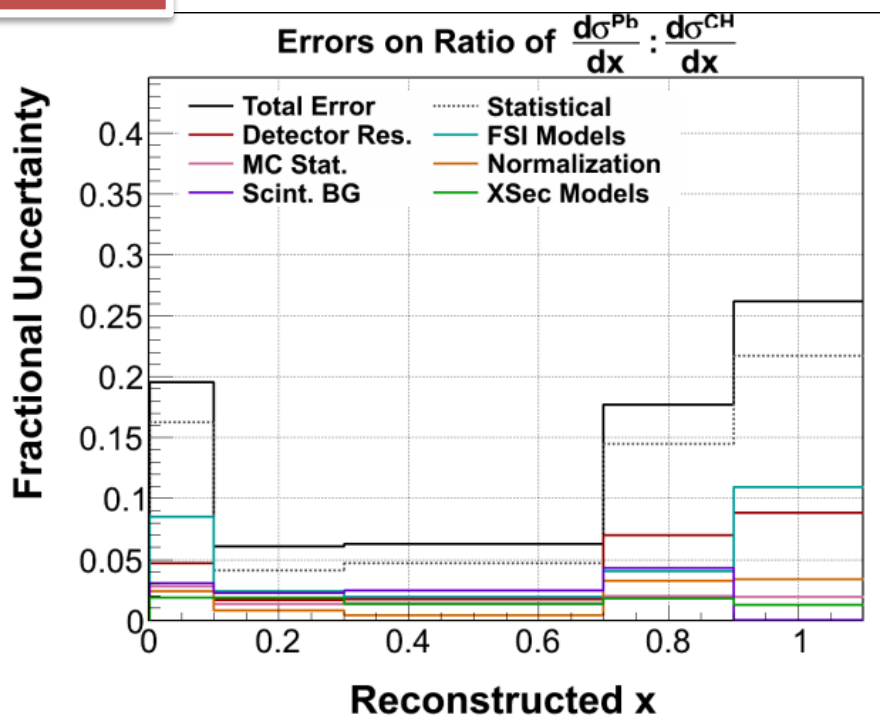




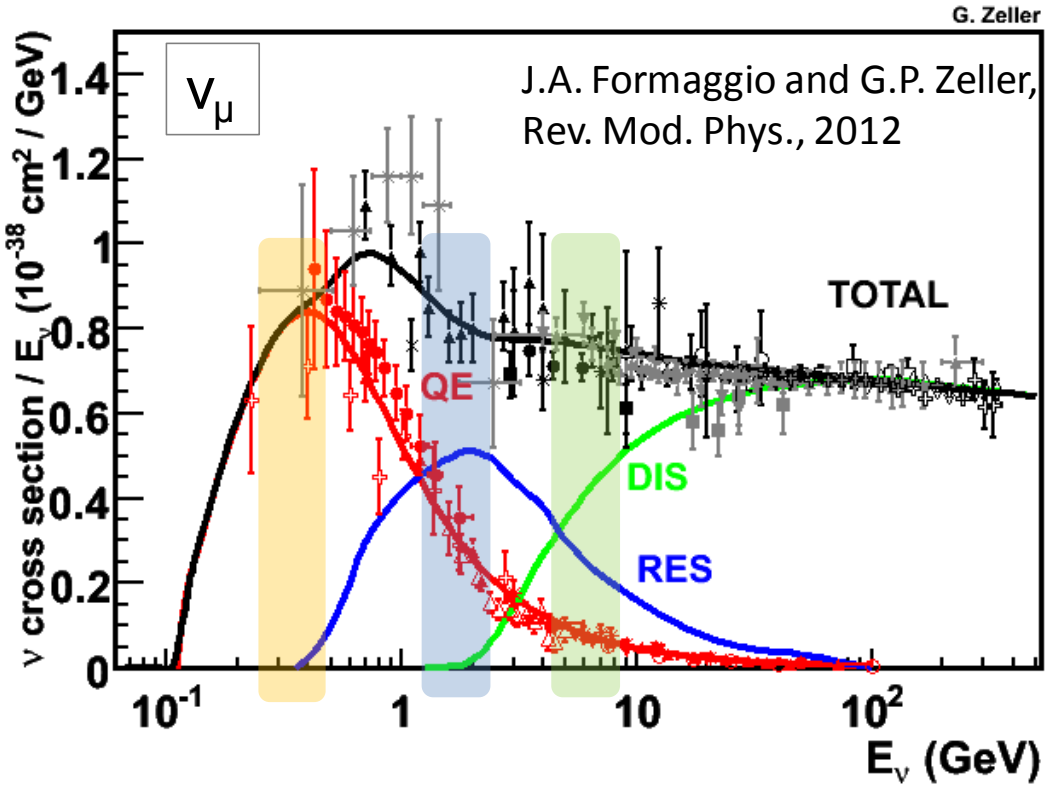


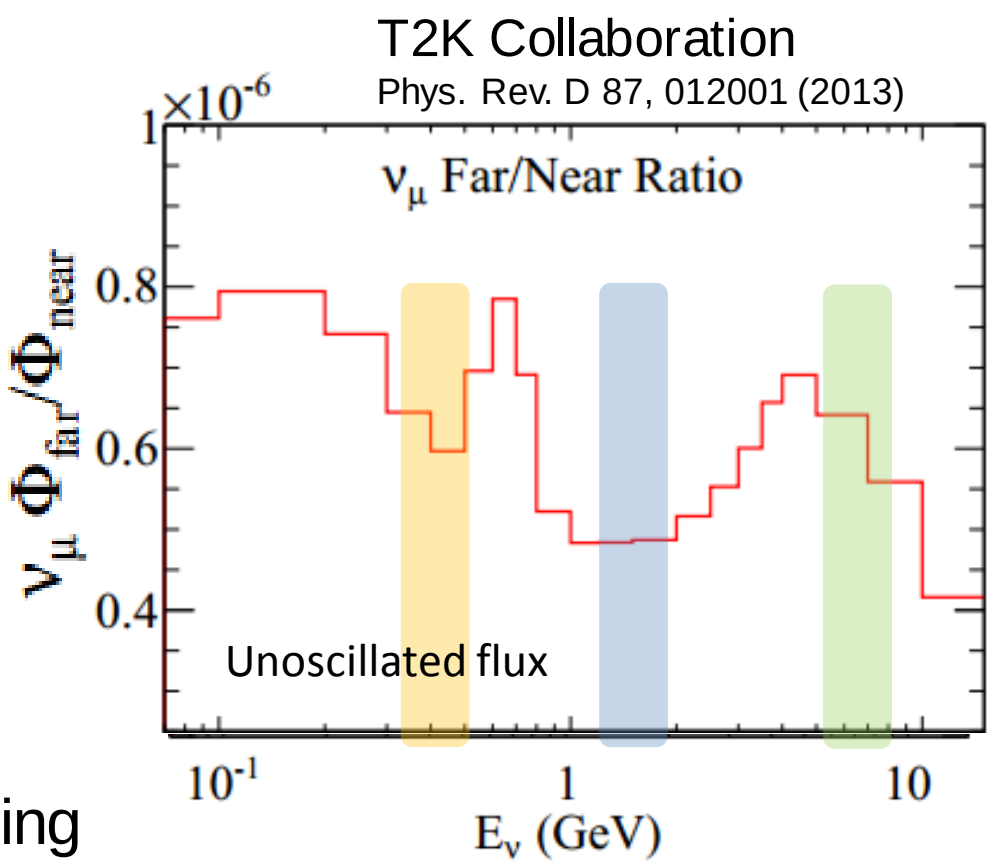
Inelastic Sample





Convolution of σ, Flux, ΔE_ν





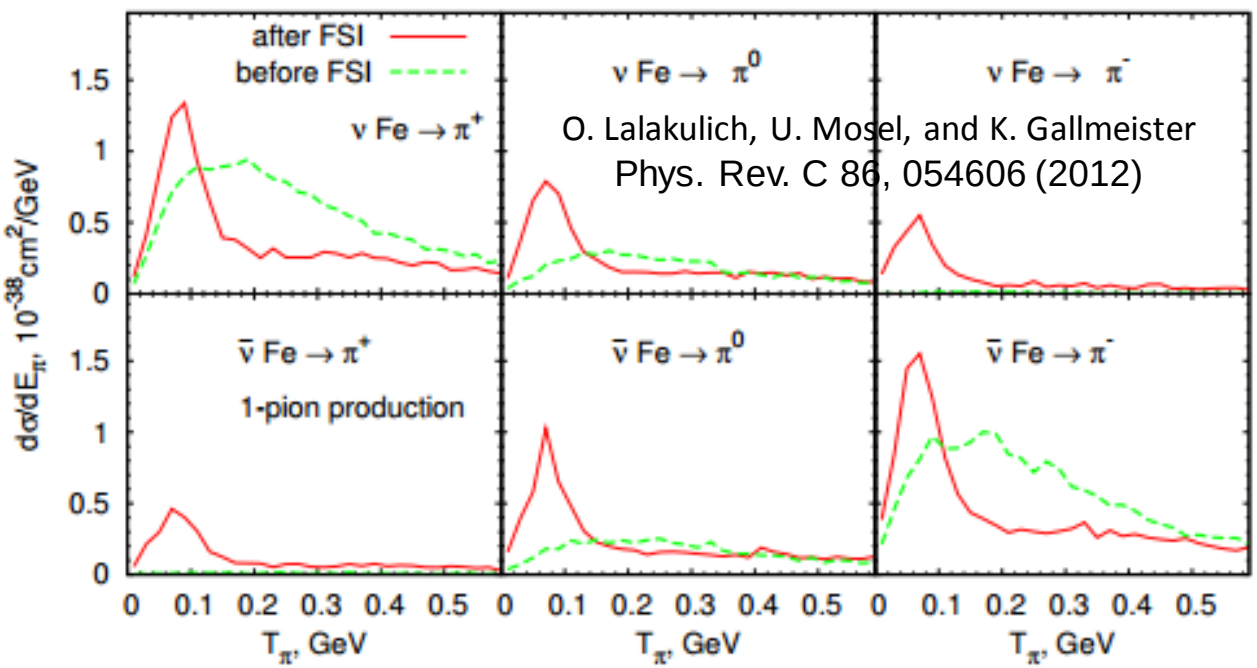
- Different flux means different sampling of interaction channels

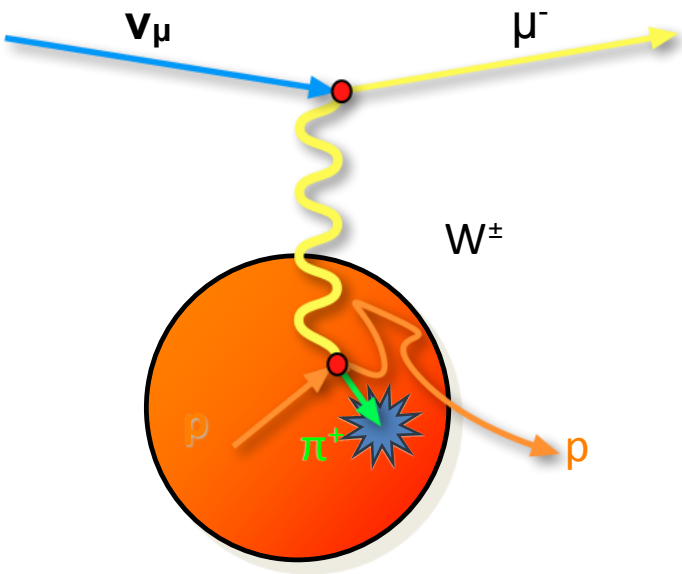
→ Energy smearing is ~ flux dependent

Energy Reconstruction Problem
Final State Interactions

- Example: Pion absorption
  - Pions can be absorbed in interaction nucleus
  - Energy and signature of pion is missing
  - Pion absorption is A-dependent

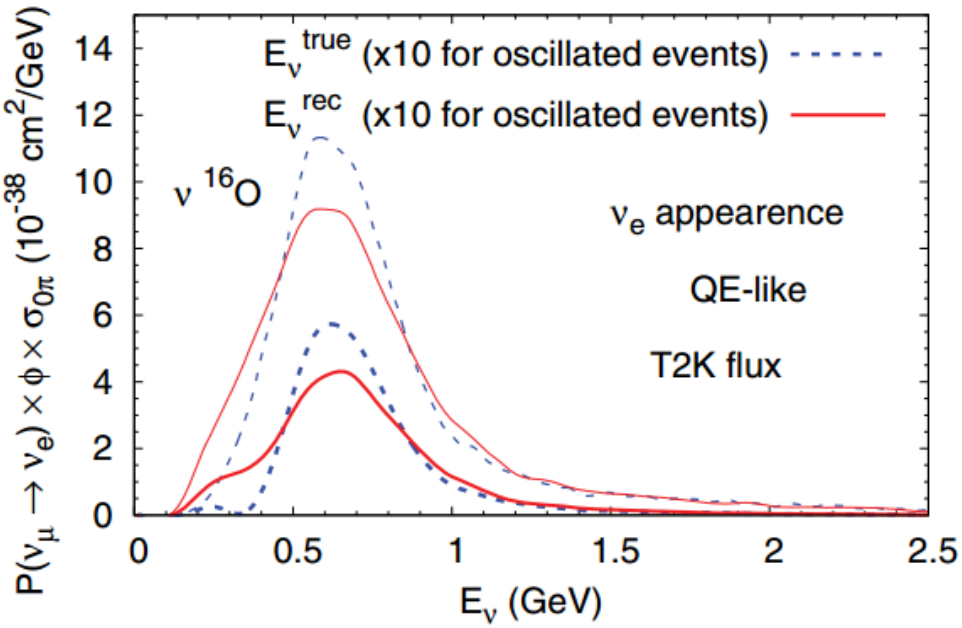
→Energy smearing is A-dependent





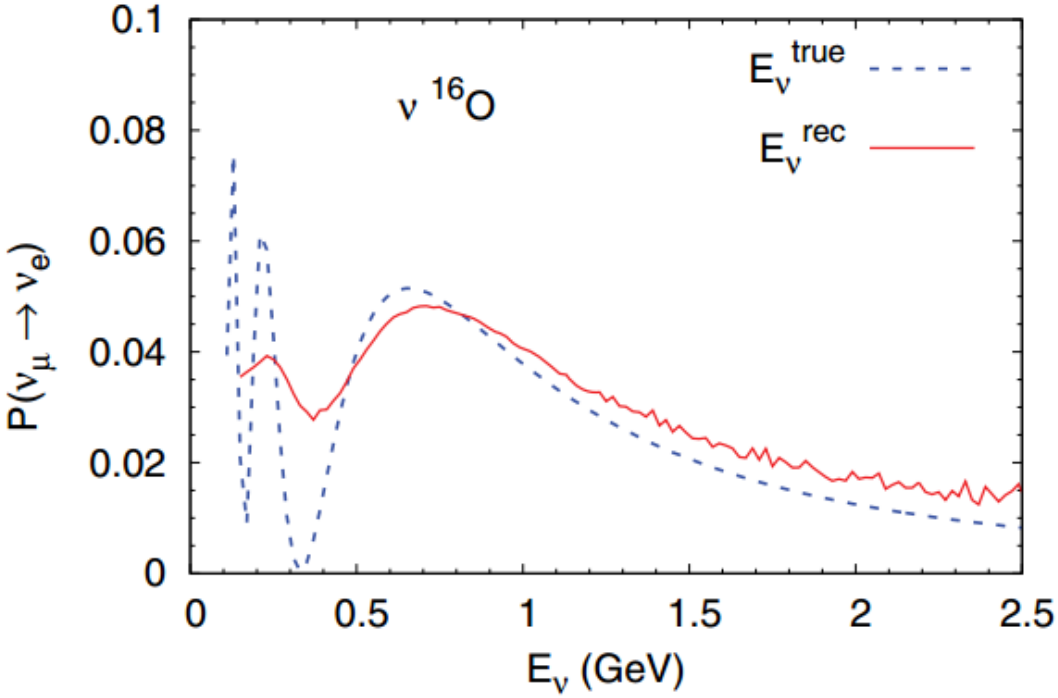
Cross section vs pion energy **before** and **after** final state interactions.

Priority: σ(E_ν)
Uncertainty on ν_e-Appearance



← Event rate for signal-type events in T2K **before** and **after** energy reconstruction

Oscillation probability **before** → and **after** energy reconstruction

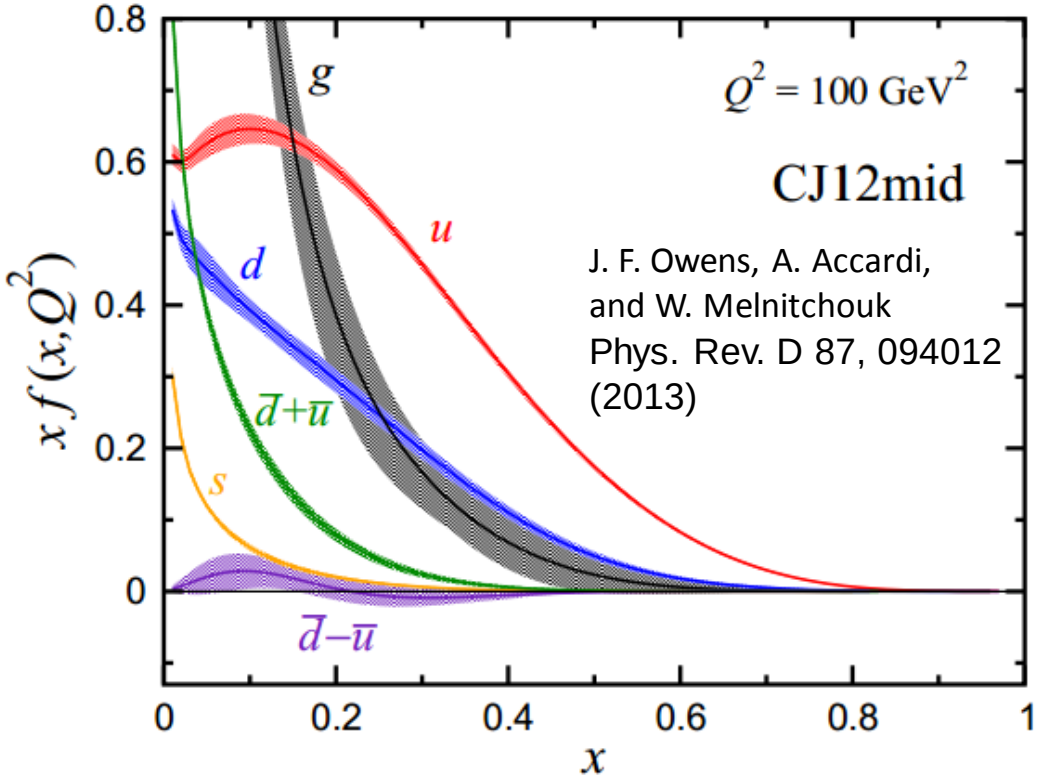


Both plots: O. Lalakulich, U. Mosel, and K. Gallmeister
Phys. Rev. C 86, 054606 (2012)

PDFs

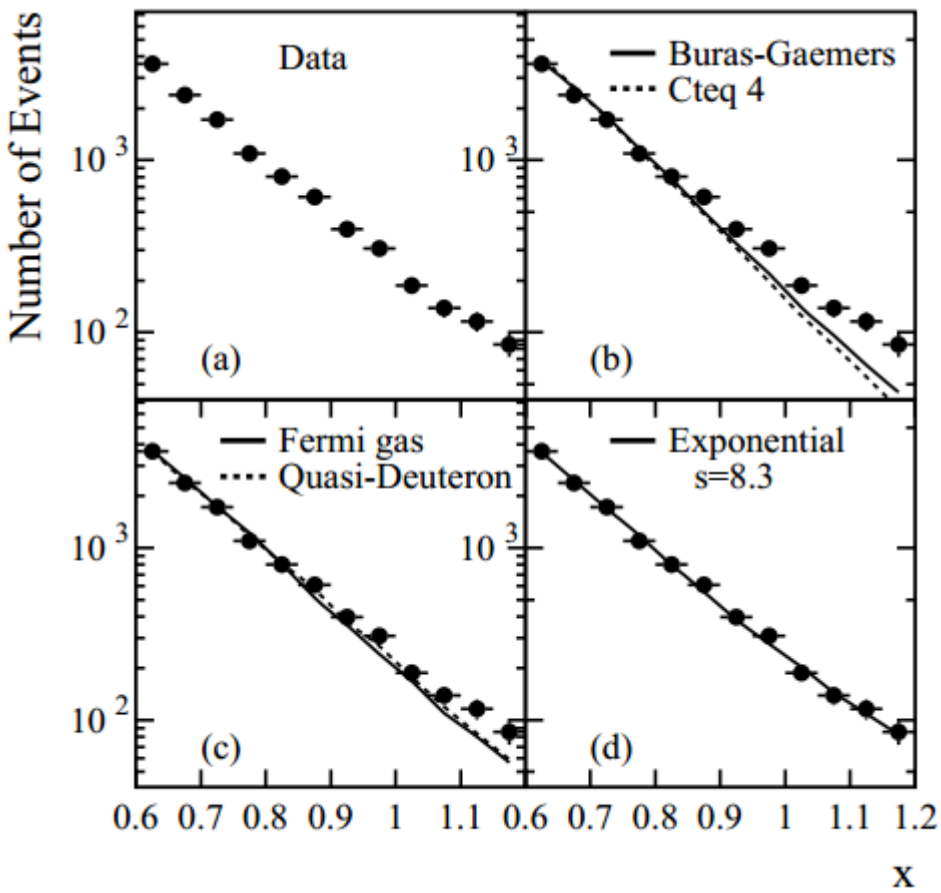
Parton Distribution Functions (PDFs)

Probability that parton in proton has this value of x, when probed at Q^2



Note: free nucleon PDFs

Neutrino Data at x>1
CCFR



M. Vakili et al. (CCFR collaboration)
arxiv:hep-ex/9905052

FIG. 2. (a) Measured x distribution. Comparison of measured x distribution and (b) distribution predicted by Buras-Gaemers structure functions and by CTEQ4M structure functions, (c) distributions predicted by a flat Fermi gas model and by the Bodek-Ritchie model, (d) distributions with an exponentially falling F_2 with s=8.3. All error bars represent only the statistical errors.

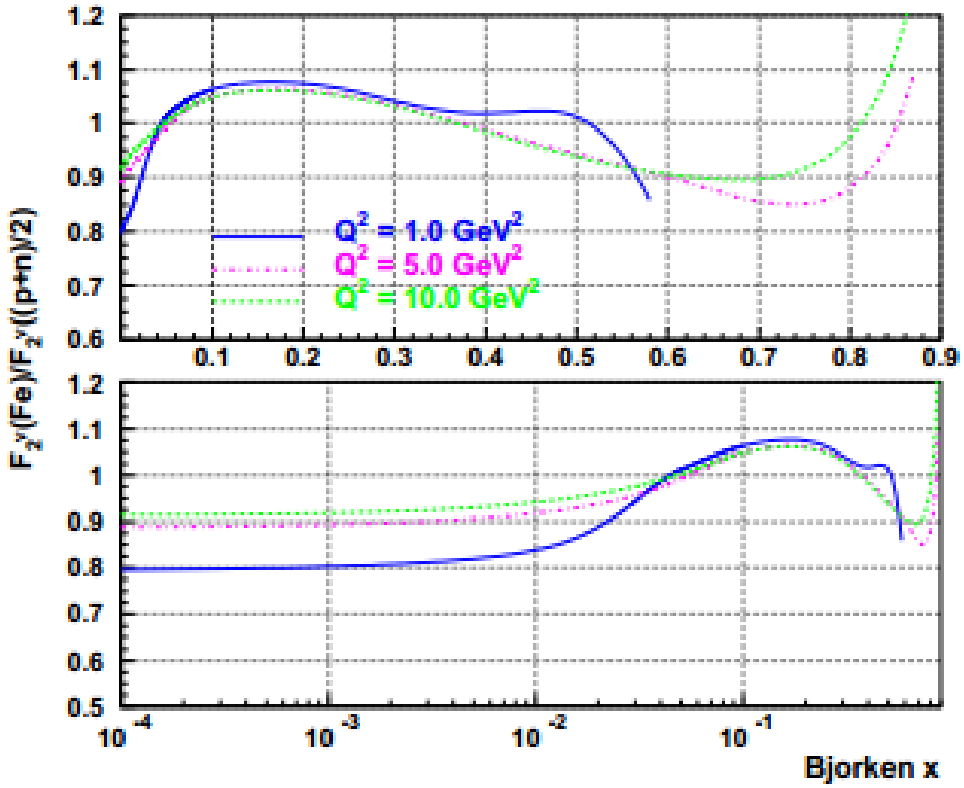
Kulagin-Petti

Comparison to our data in progress

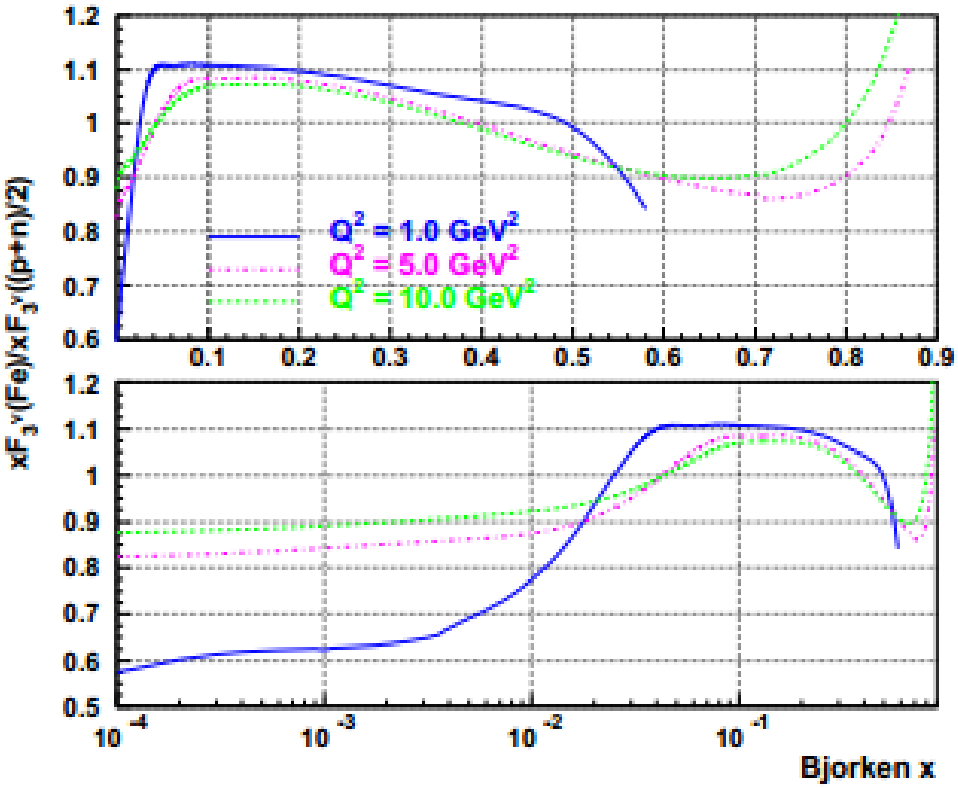
Kulagin-Petti predicts very large shadowing for neutrinos.
(large deficit at low x for heavy nuclei)

Kulagin, Sergey A., and R. Petti. "Neutrino inclusive inelastic scattering off nuclei." *Physical Review D* 76.9 (2007): 094023.

F2(Fe) nuclear modification



xF3(Fe) nuclear modification



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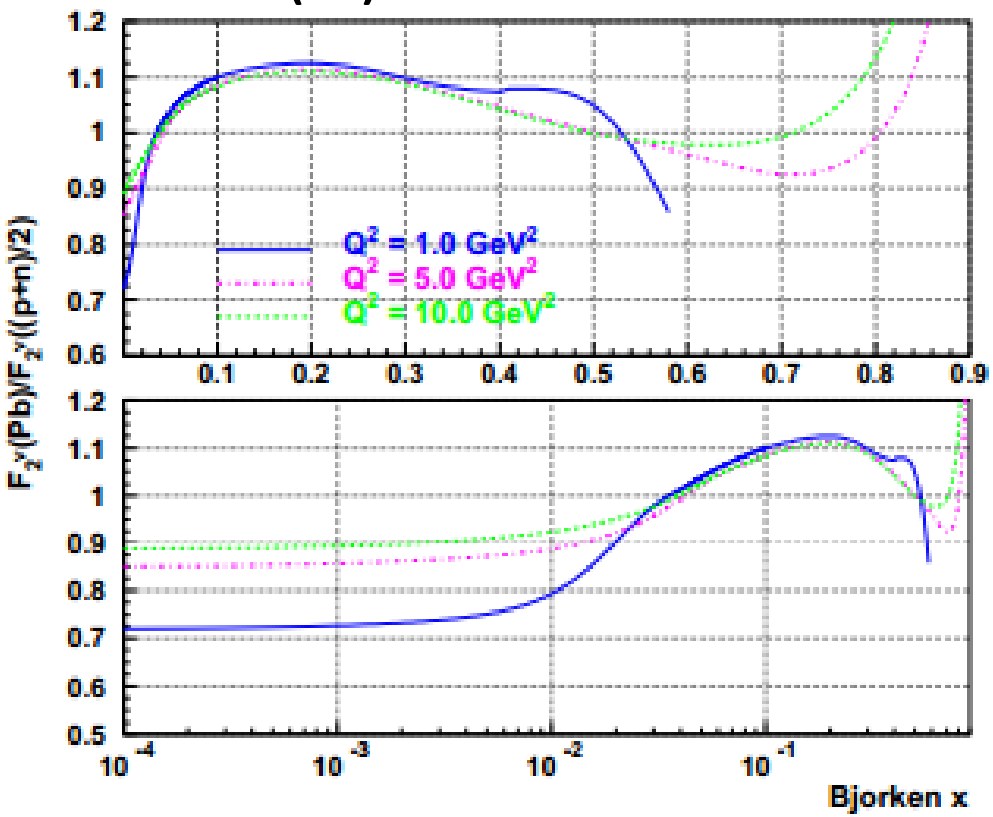
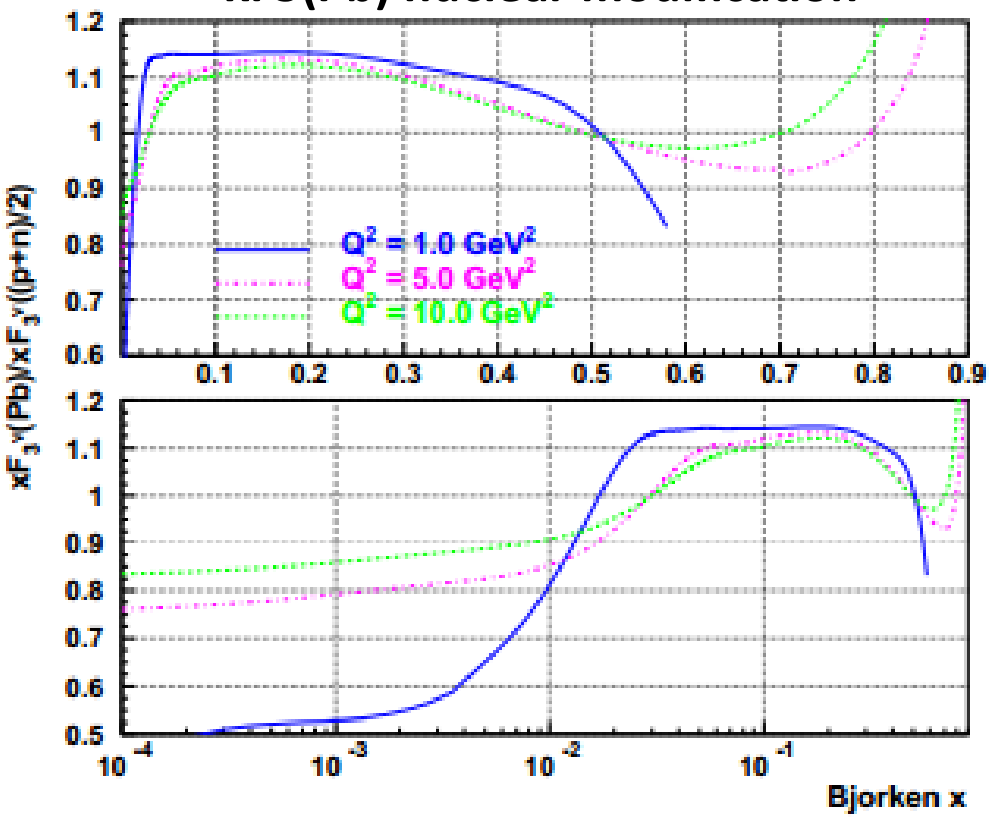
F2(Pb) nuclear modification

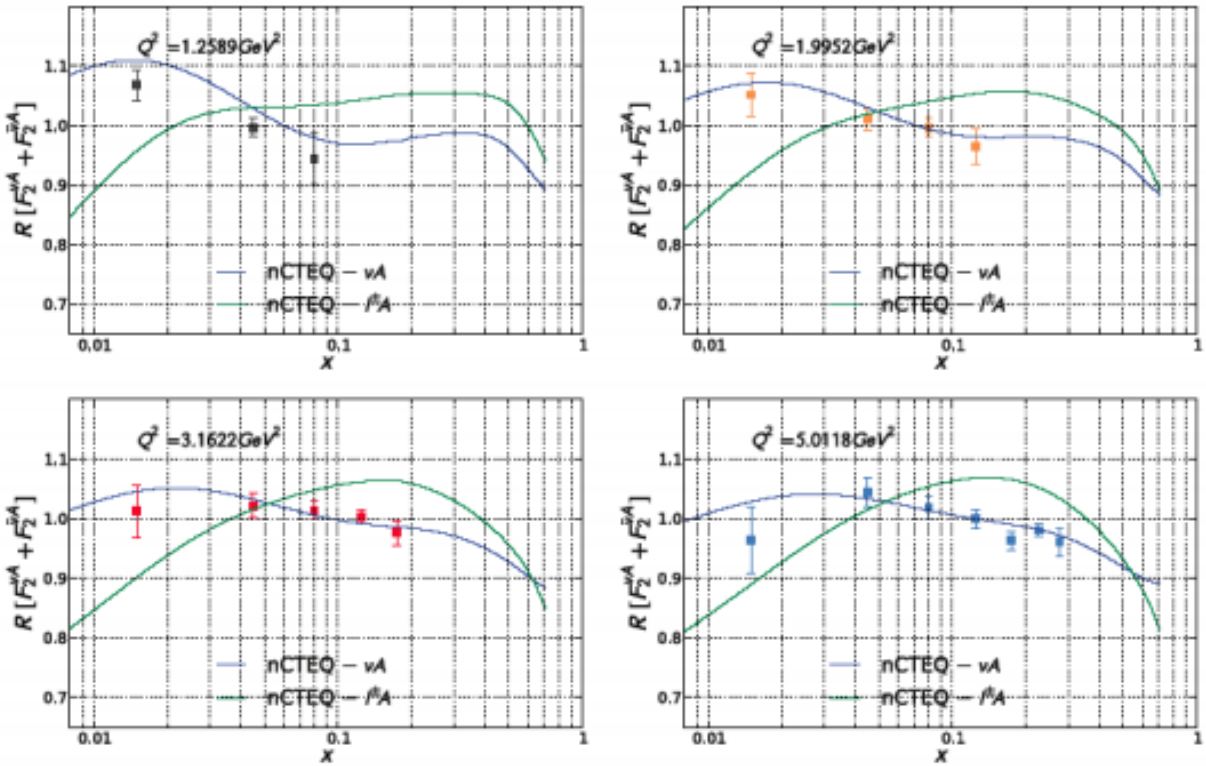


xF3(Pb) nuclear modification



A More-Detailed Look at Differences

- NLO QCD calculation of $\frac{F_2^{\nu A} + F_2^{\bar{\nu} A}}{2}$ in the ACOT-VFN scheme
  - charge lepton fit undershoots low-x data & overshoots mid-x data
  - low-Q^2 and low-x data cause tension with the shadowing observed in charged lepton data

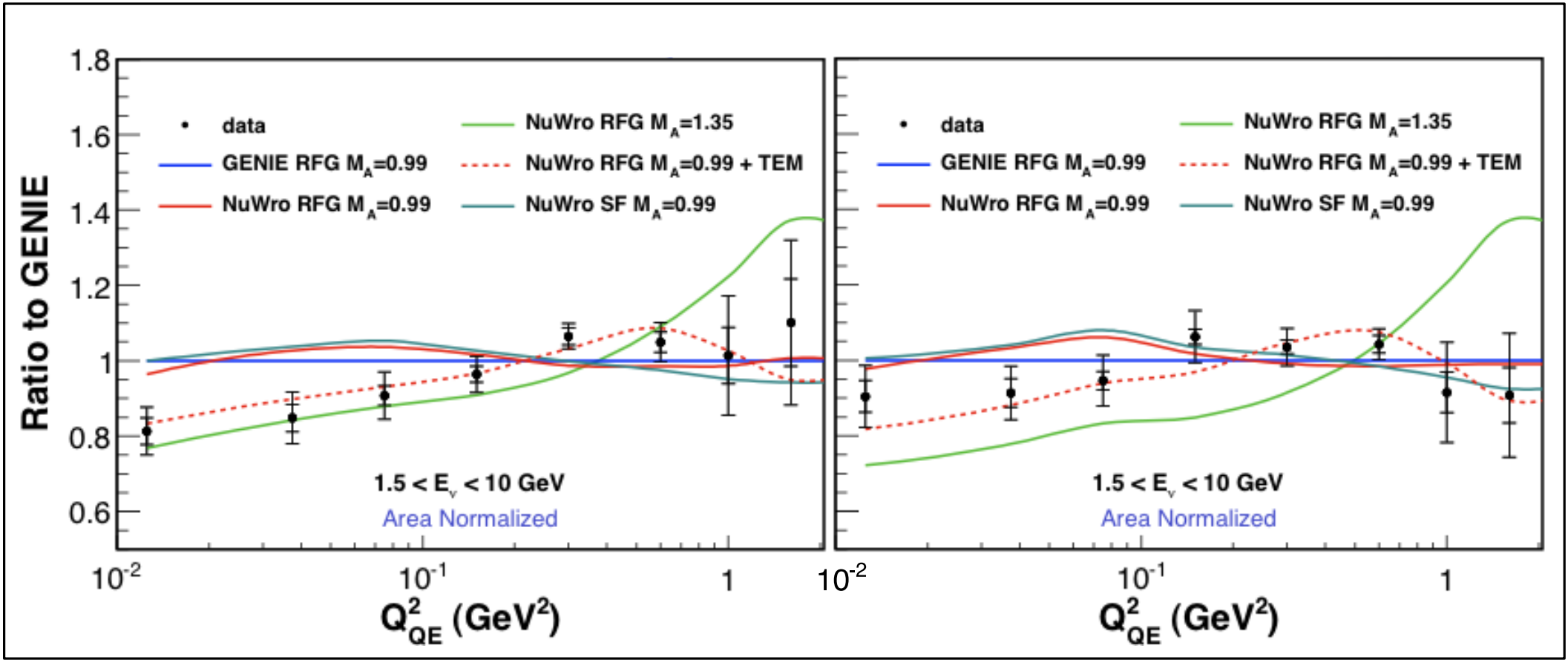


2

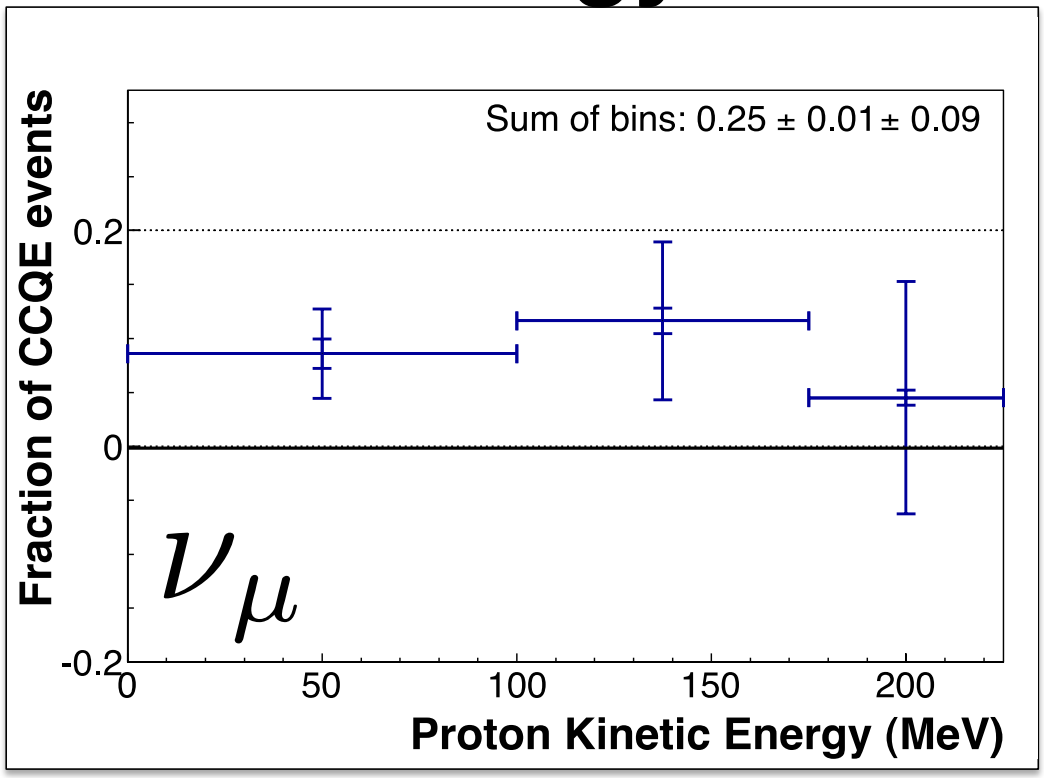
Slice courtesy of J.G.MorfÍn

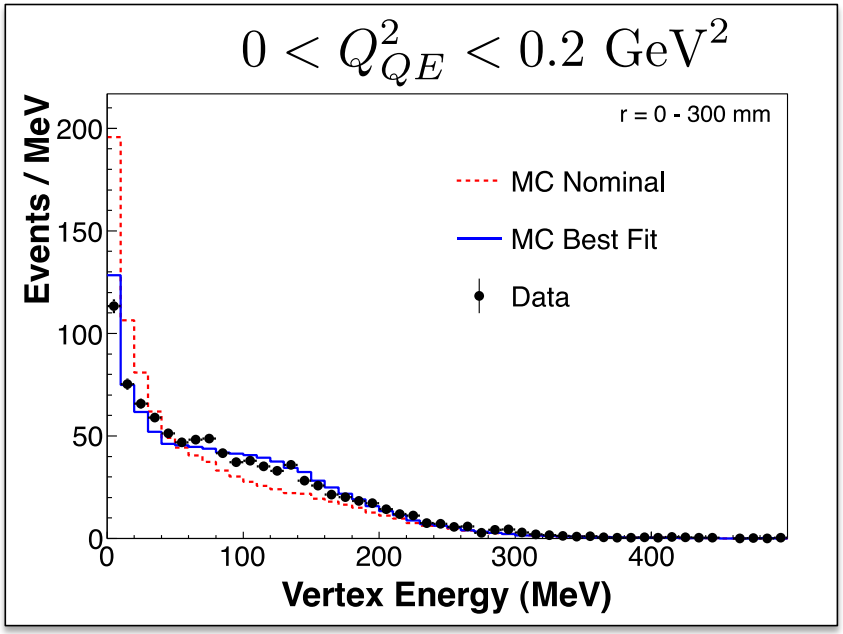
dσ/dQ² Shape

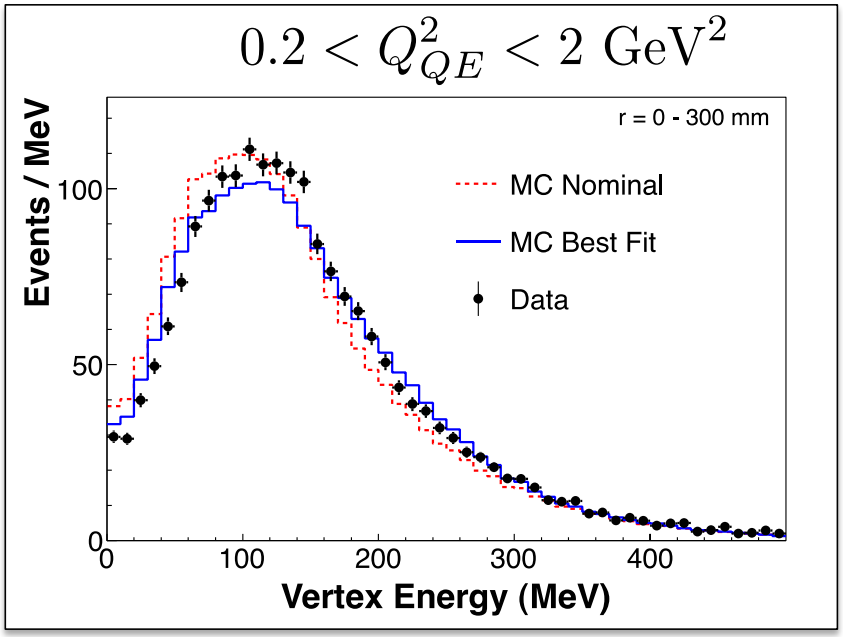
$\bar{\nu}_\mu$ CCQE ν_μ CCQE



Vertex Energy - Neutrinos

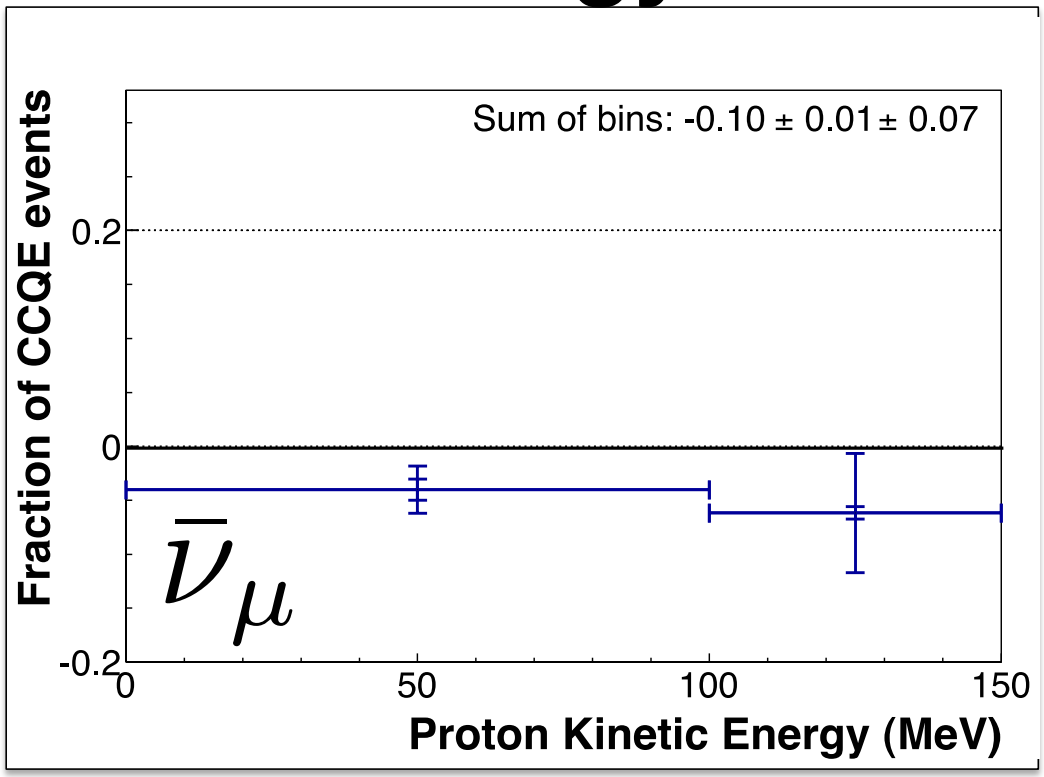


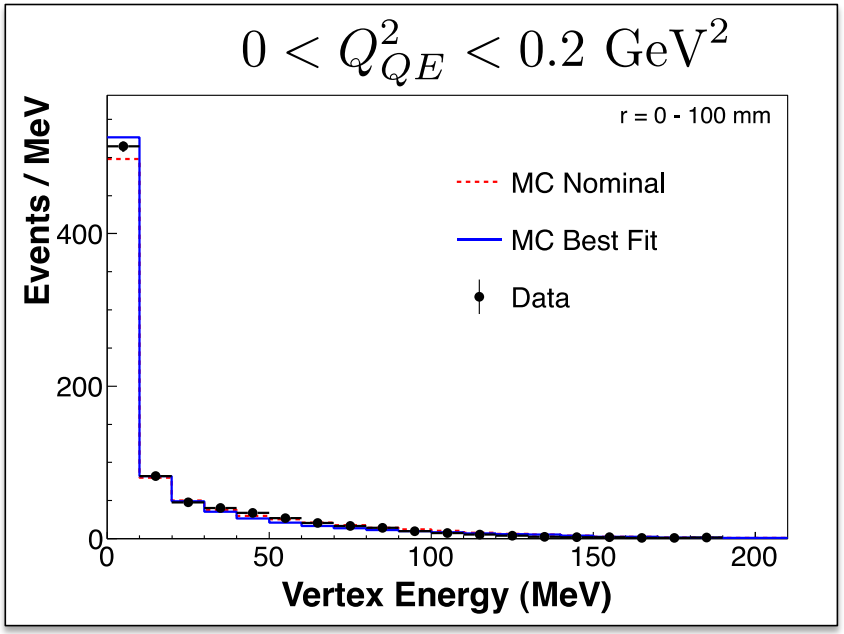


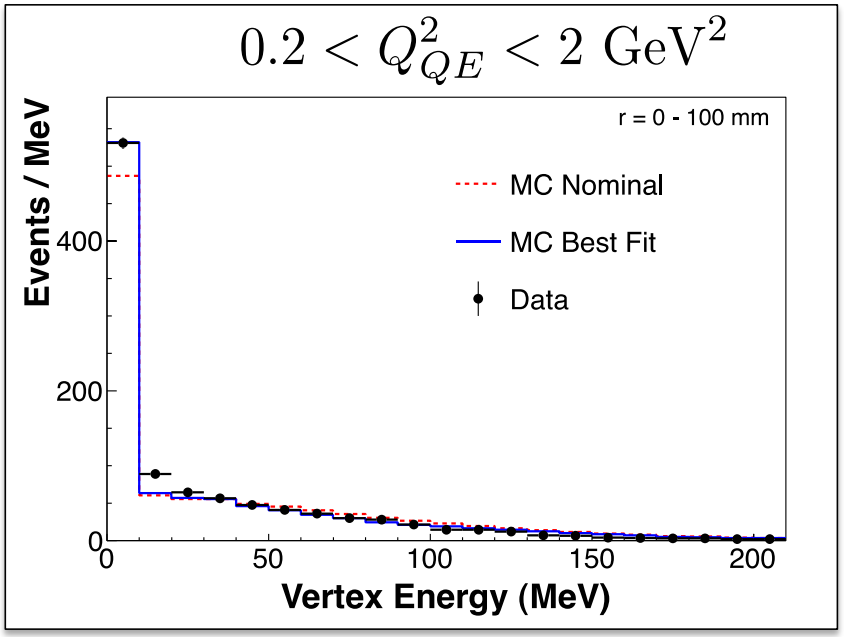


We find that adding an additional low-energy proton (KE < 225 MeV) to **(25 ± 9)% of QE events** improves agreements with data

Vertex Energy - Antineutrinos







No such addition required for antineutrinos. Slight reduction if anything.

(-10 ± 7)% of QE events