$\bar{\nu}_\mu - A$ DIS cross sections for $< E_{\bar{\nu}_\mu} > \sim$ 6GeV at MINERνA

Vaniya Ansari
vansari@fnal.gov

The MINERνA Collaboration

Supervisors: Prof. M. Sajjad Athar (AMU) & Prof. Deborah Harris (YU,Canada)

Aligarh Muslim University, India

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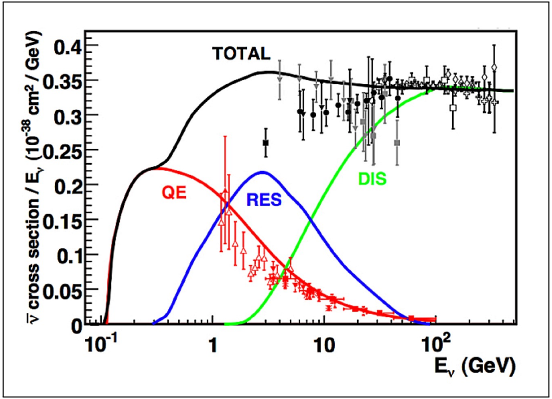
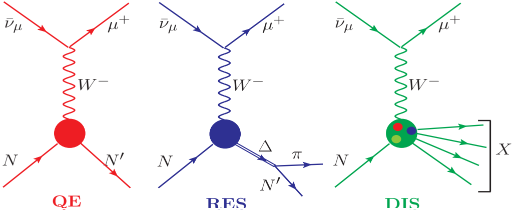
Motivation

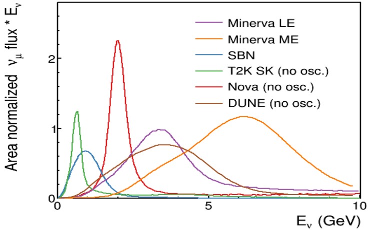
- For better understanding of neutrino properties, we require precision measurements of the oscillation parameters
- Presently, the systematics are not as large as the statistics but future generations are planning large increase in statistics, need to improve systematics also
- $\nu/\bar{\nu} - N$ and $\nu/\bar{\nu} - A$ cross section measurements are crucial for tuning neutrino interaction simulations

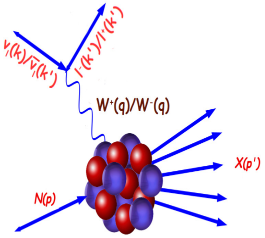
ν cross sections from different channels

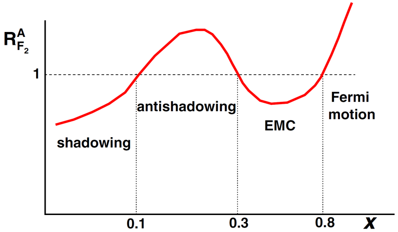
J.A. Formaggio, G.P. Zeller, Rev. Mod. Phys. 84, 1307 (2012)



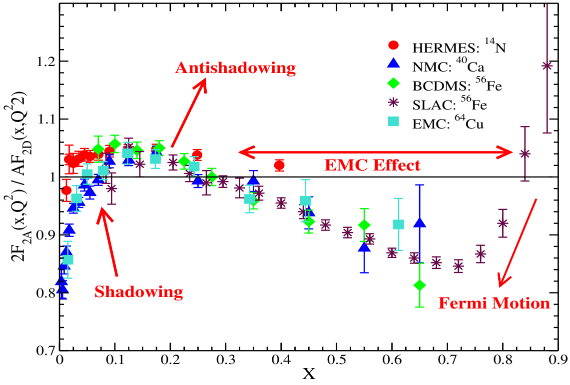








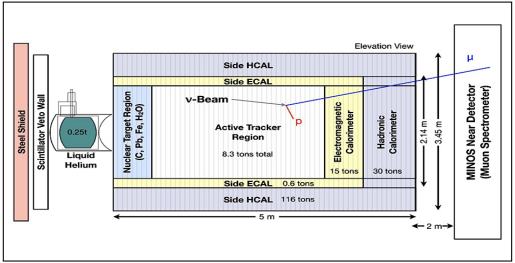
M. Sajjad Athar and S. K. Singh, The Physics of Neutrino Interactions (CUP, 2020)



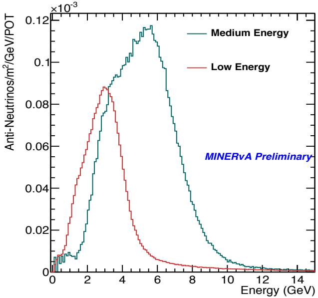
- Due to the presence of the axial-vector response function in the weak sector, the nuclear effects would be different from the electromagnetic sector
- MINERνA is a gaint step in this direction

Main INjector ExpeRiment for ν-A Scattering

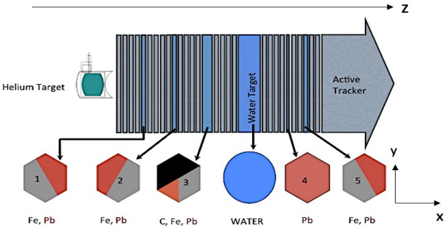
Elevation view



Located 100 meter underground, in front of MINOS detector.
Constructed of stack of hexagonal modules, supported on a frame along the beam axis



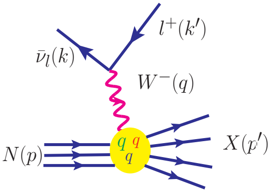
- High intensity $\nu_\mu/\bar{\nu}_\mu$ beam from NuMI beamline at Fermilab
- High statistics precision studies of $\nu-$A cross sections
- Passive nuclear targets: C, Fe, He, H_2O and Pb
- Active tracking region: Constructed of solid scintillator (CH)
- MINOS detector: muon spectrometer
- LE flux peaks $\sim$ 3.5 GeV and ME flux peaks $\sim$ 6 GeV



In ME mode of MINERνA, where DIS contribution is large and statistics is high, we expect precise nuclear effects information than our low energy results **Phys. Rev. D 93, 071101 (2016)**

Analysis Goal

$$\bar{\nu}_\mu + A \rightarrow \mu^+ + X$$



- The aim is to extract the single differential cross sections for different nuclear targets (C, Fe and Pb) and to obtain the antineutrino cross section ratios of the passive nuclear targets (C, Fe, Pb) to the scintillator (CH) in the medium energy mode
- The energy of the incoming antineutrino: $E_{\bar{\nu}} = E_{had} + E_\mu$
- Bjorken variable "x" is the fraction of momentum carried by the struck parton
  $x = \frac{Q^2}{2p \cdot q} = \frac{Q^2}{2M_N E_{had}}$
- $\theta_\mu < 17^o$ and $2 < E_\mu < 50\ GeV$
- DIS events: $W\ > 2\ GeV$ and $Q^2\ >\ 1\ GeV^2$

Analysis Procedure

Total cross section in terms of $E_{\bar{\nu}}$

$$(\sigma)_\alpha = \frac{\sum_\beta U_{\alpha\beta}(N_\beta^{data} - N_\beta^{bkgd})}{\varepsilon_\alpha \phi_\alpha T}$$

selected events

unfolding matrix

background events

efficiency

flux

number of targets

α: true bin # β: reconstructed bin #

Differential cross section in terms of Bjorken x

$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\sum_\beta U_{\alpha\beta}(N_\beta^{data} - N_\beta^{bkgd})}{\varepsilon_\alpha (\phi T)(\Delta x_\alpha)}$$

selected events

unfolding matrix

background events

efficiency

flux

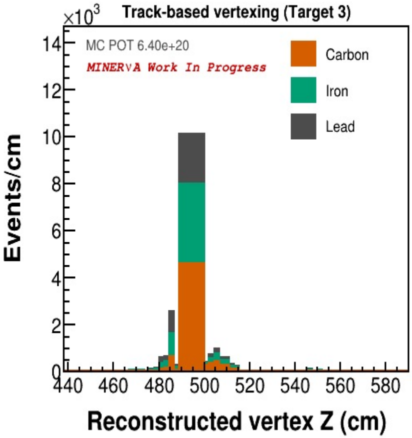
number of targets

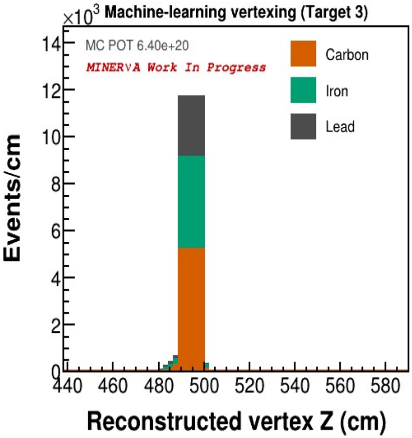
bin width α

α: true bin # β: reconstructed bin #

Machine-Learning Vertexing

- Properly reconstructing the interaction vertex of each material is important
- MINERνA uses Deep Neural Network Machine Learning algorithm to identify the event vertex in the nuclear target region. It leads to high efficiency and high purity sample

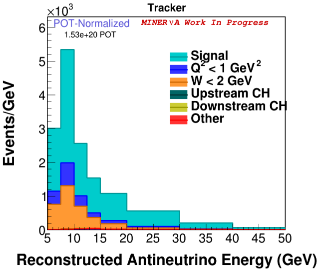


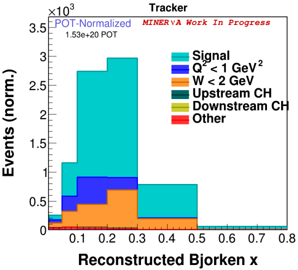


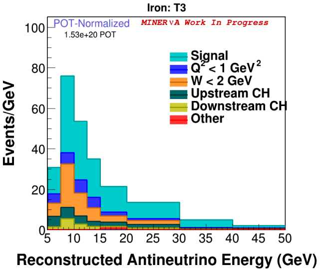
Event Selection and Background Categorization

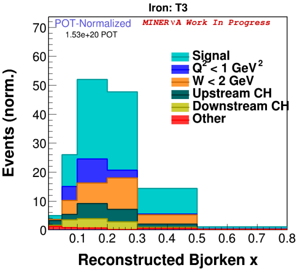
$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\sum_\beta U_{\alpha\beta}\left(N_\beta^{data} - N_\beta^{bkgd}\right)}{\varepsilon_\alpha(\phi T)(\Delta x_\alpha)}$$

- **Physics background:** Events that pass DIS cuts because of imperfect hadronic energy resolution
- **Plastic background:** Scintillator events reconstructed in targets because of imperfect detector resolution
- **Iron:** Physics background events ($\sim 28\%$) and plastic background events ($\sim 17\%$) are the main backgrounds
- **Tracker:** Physics background $\sim 33\%$
- **Other background:** Neutral current events + ν contamination ($\sim 1\%$)





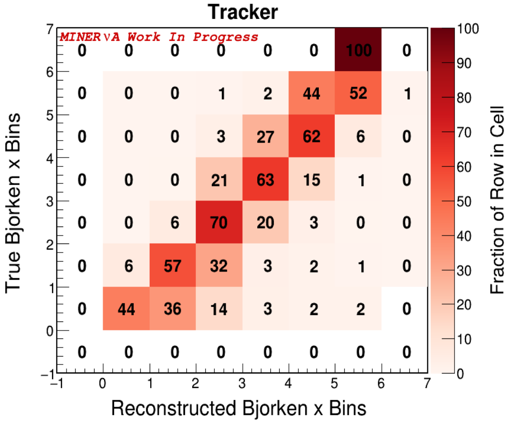


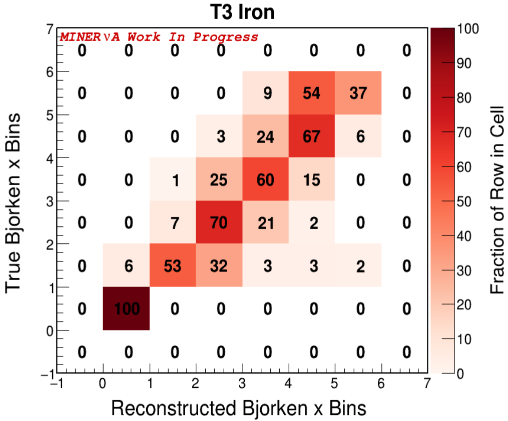


Migration Matrices ($M_{\beta\alpha}$)

$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\sum_\beta U_{\alpha\beta}(N_\beta^{data} - N_\beta^{bkgd})}{\varepsilon_\alpha(\phi T)(\Delta x_\alpha)}$$

- Finite detector resolution and imperfect reconstruction cause the reconstruction kinematics of an event to differ from its true kinematics
- For cross sections, we extract the distribution in terms of true variables $x_\alpha = M_{\alpha\beta}^{-1} x_\beta$, (where $M_{\alpha\beta}^{-1} == U_{\alpha\beta}$)
- Unfolding to true distribution: introduces model bias and statistical fluctuations
- $M_{\beta\alpha}$ is not directly invertible, so we use Bayesian unfolding method to regularize the unfolding results

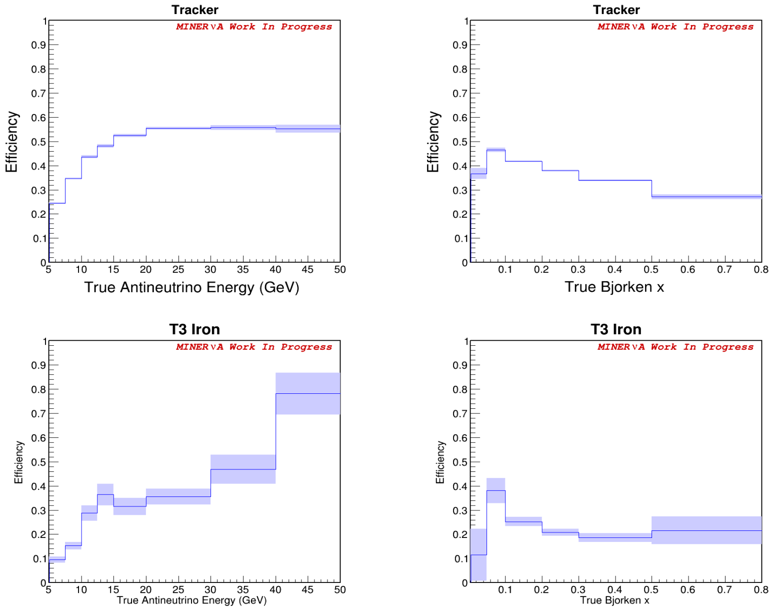




Sample Purity and Efficiency

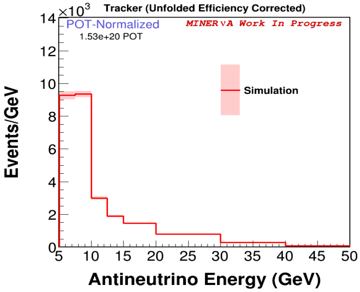
$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\sum_\beta U_{\alpha\beta}(N_\beta^{data} - N_\beta^{bkgd})}{\varepsilon_\alpha(\phi T)(\Delta x_\alpha)}$$

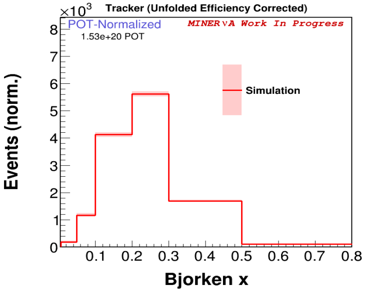
- Purity = signal / reconstructed events
- Efficiency = (true + reconstructed) / reconstructed
- Complex structure of passive target region lead to less purity and efficiency as compared to CH
- **Purity: CH** $\sim 66\%$**, Fe** $\sim 53\%$
- **Efficiency: CH** $\sim 38\%$**, Fe** $\sim 21\%$

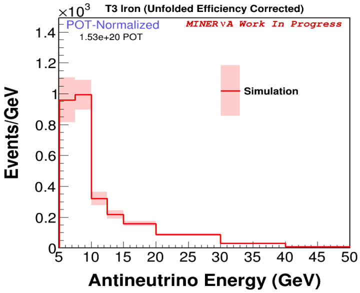


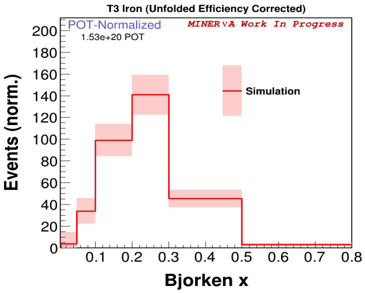
Efficiency Corrected Distributions

$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\sum_\beta U_{\alpha\beta}(N^{data}_\beta - N^{bkgd}_\beta)}{\varepsilon_\alpha(\phi T)(\Delta x_\alpha)}$$



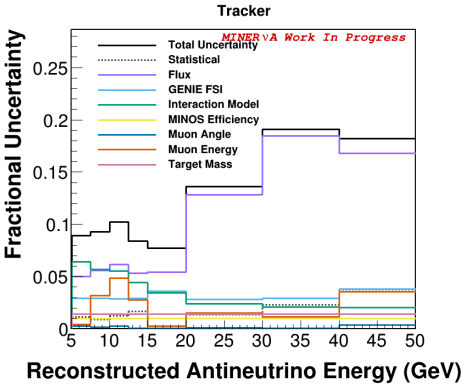


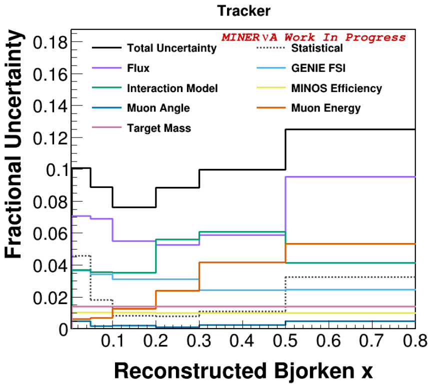




Systematic Uncertainties on Simulated Event Distributions

- Flux: (ν+$\bar{\nu}$)-electron scattering + inverse muon decay (IMD) medium energy flux constraint
- Most of the flux systematics will cancel out in cross-section ratios
- Statistical uncertainty will be reduced once we include additional data available
- Interaction model and muon reconstruction are also significant systematic uncertainties
- Hadronic energy systematic uncertainty is not included here

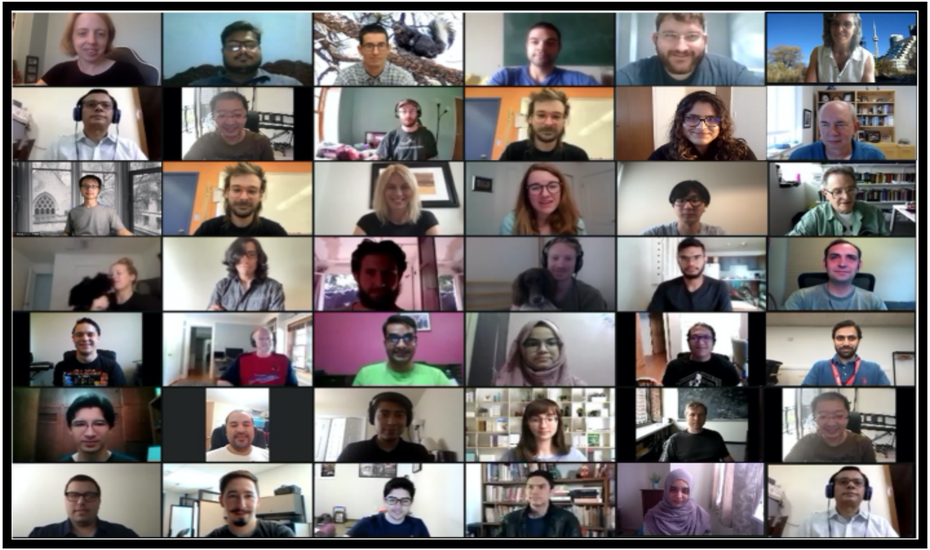




Conclusions and Next Steps

- Understand systematic uncertainties with unprecedented statistics collected
- Working to include the rest of the statistics available
- Cross sections for C, Fe, Pb and their ratios to CH are on its way
- This will be the first direct measurement of nuclear effects in DIS with antineutrinos
- Stay tuned for the exciting results!

The MINERνA Collaboration



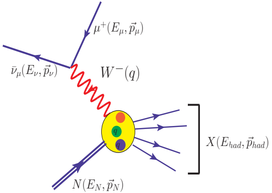
Thank you!

Backup

Sample + model information

- The aim is to extract the single differential cross sections for different nuclear targets (C, Fe and Pb) and to obtain the RHC cross section ratios of the passive nuclear targets (C, Fe, Pb) to the scintillator (CH) in the medium energy mode

$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\sum_\beta U_{\beta\alpha}(N_\beta^{data} - N_\beta^{bkg})}{\varepsilon_\alpha(\phi T)(\Delta x)} \qquad \sigma_\alpha = \frac{\sum_\beta U_{\beta\alpha}(N_\beta^{data} - N_\beta^{bkg})}{\varepsilon_\alpha(\phi_\alpha T)}$$



- **Playlist ME6A:**
  Data POT: 1.53×10^{20}
  MC POT: 3.16×10^{20}
  Antineutrinos from RHC
  With full water and He target
  Uses ML Vertexing

- **MnvGENIE v1 weighting scheme:**
  GENIE version 2.12.6
  Flux reweighter CV value (100 Universes)
  Low recoil 2p2h
  Random phase approximation
  Non resonant pion tune
- MINOS efficiency correction
- NuE (FHC+RHC) + IMD medium energy flux constraint

Reconstruction cuts

Targets

- Helicity cut (muon antineutrino)
- Fiducial volume (850 mm apothem in x, y plane)
- Atleast 25 mm distance from division between materials in targets
- Max. allowed dead time
- Antineutrino energy ($E_{\bar{\nu}} < 120$ GeV)
- MINOS curvature significance ≥ 5
- MINOS coil (210 <R<2500) mm
- Target ID cut and material cut (to ensure the vertex to be in the nuclear targets)
- Plane probability cut at 0.2
- 2 GeV $< E_{\mu} <$ 50 GeV and $\theta_{\mu} < 17^{o}$ wrt beam
- DIS cuts: $Q^2 > 1GeV^2$, $W > 2GeV$

Tracker

- Helicity cut (muon antineutrino)
- Fiducial volume (850 mm apothem in x, y plane)
- ~~Atleast 25 mm distance from division between materials in targets~~
- Max. allowed dead time
- Antineutrino energy ($E_{\bar{\nu}} < 120$ GeV)
- MINOS curvature significance ≥ 5
- MINOS coil (210 <R<2500) mm
- Target ID cut and material cut (to ensure the vertex to be within 5890 mm $< z <$ 8422 mm)
- Plane probability cut at 0.2 ?
- 2 GeV $< E_{\mu} <$ 50 GeV and $\theta_{\mu} < 17^{o}$ wrt beam
- DIS cuts: $Q^2 > 1GeV^2$, $W > 2GeV$

Truth cuts

DIS Signal

All CC antineutrino events that are in given material with muon energy 0-50GeV and passes the true DIS cuts

Targets

- CC + muon antineutrino
- Target ID cut and material cut (to ensure the vertex to be in the nuclear targets)
- 2 GeV $< E_\mu <$ 50 GeV
- DIS cuts: $Q^2 > 1GeV^2, W > 2GeV$

Note: Not using true fiducial volume cut and true muon scattering angle cut

Tracker

- CC + muon antineutrino
- Target ID cut and material cut (to ensure the vertex to be within 5890 mm $< z <$ 8422 mm)
- 2 GeV $< E_\mu <$ 50 GeV
- DIS cuts: $Q^2 > 1GeV^2, W > 2GeV$

Note: Not using true fiducial volume cut and true muon scattering angle cut

Targets: Combined iron

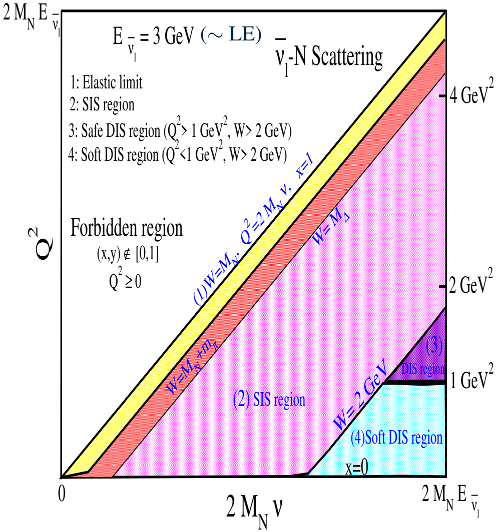
		Events	%
Reconstructed		4861	100
Signal		2593	53.34
All background		2268	46.65
total nonDIS		1361	27.99
	transition	926	19.05
	Continuum	435	8.95
	other nonDIS	0	0
Wrong material		838	17.24
	US	357	7.34
	DS	443	9.11
	Other	38	0.78
Not emu		0	
Wrong signed		66	1.35
Neutral Current		3	0.06

Tracker

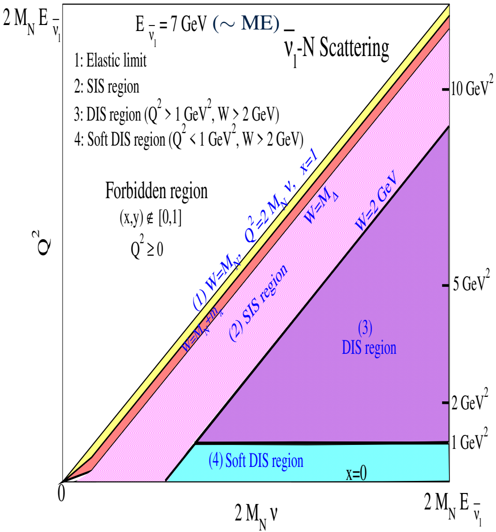
		Events	%
Reconstructed		45154	100
Signal		29713	65.80
All background		15441	34.2
total nonDIS		14752	32.67
	transition	9983	22.11
	Continuum	4769	10.56
	other nonDIS	0	0
Other material		168	0.37
Not emu		0	0
Wrong signed		476	1.05
Neutral Current		45	0.1

Kinematical Regions for $\bar{\nu}_l - N$ Scattering (DIS: $W \geq 2.0GeV$ and $Q^2 \geq 1GeV^2$)

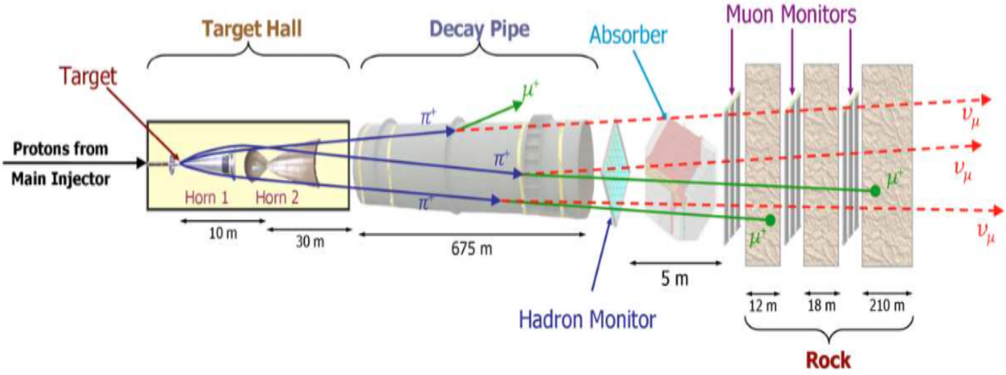
- Hadronic center of mass energy: $W = \sqrt{M_N^2 + 2E_{had}M_N - Q^2}$.



- Hadronic four momentum transfer squared: $Q^2 = -q^2 = 4E_{\bar{\nu}}E_\mu \sin^2\frac{\theta_\mu}{2}$.



NeUtrinos at Main Injector (NUMI)



DIS cross sections on C (top), Fe (center) and Pb (bottom) to CH

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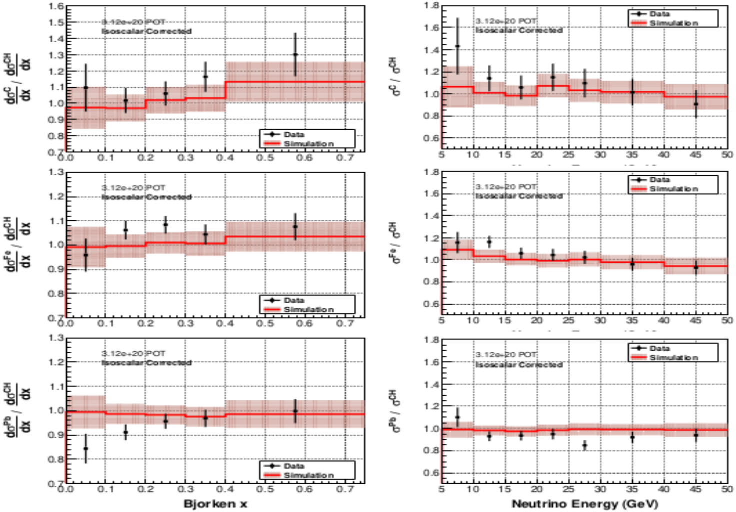
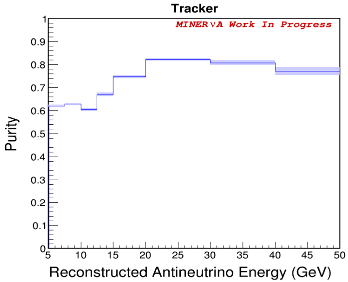
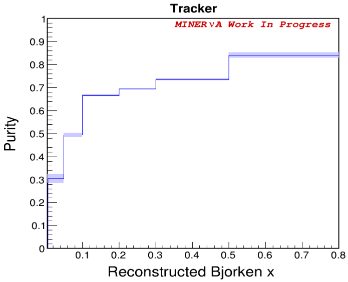
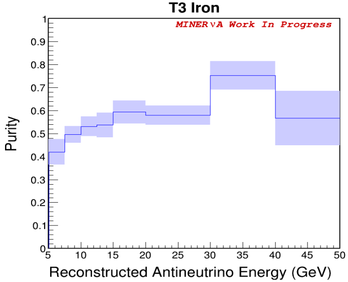
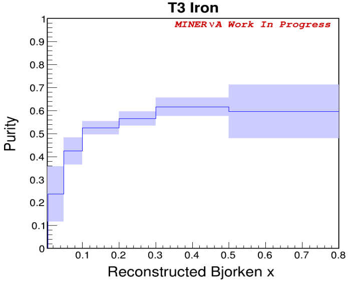


Purity


Tracker
MINERνA Work In Progress
Purity
Reconstructed Antineutrino Energy (GeV)


Tracker
MINERνA Work In Progress
Purity
Reconstructed Bjorken x


T3 Iron
MINERνA Work In Progress
Purity
Reconstructed Antineutrino Energy (GeV)


T3 Iron
MINERνA Work In Progress
Purity
Reconstructed Bjorken x

Migration Matrices for $E_{\bar{\nu}}$ ($M_{\beta\alpha}$)