

Investigating Neutrino-Nucleus Interactions: Inclusive Cross-Sections Across Various Materials at MINERvA

9th April 2025

Akeem L Hart

On behalf of the MINERvA collaboration

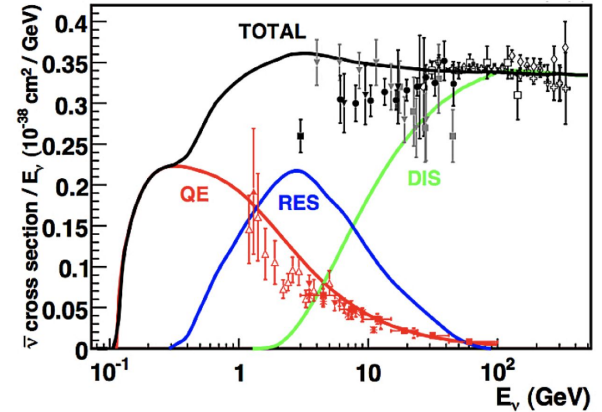
Supervisor: Dr Abbey Waldron



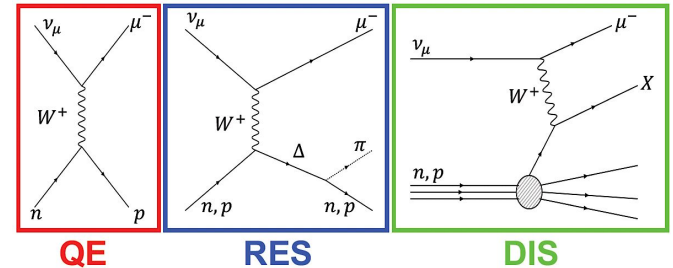
Neutrino-nucleus interactions

Different interaction modes contribute to total interaction rate dependent on E_ν

Current and future precision experiments need precise interaction reconstruction → Next-gen detectors need reduced interaction model uncertainties to achieve more ambitious physics goals



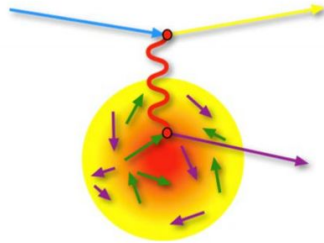
J.A. Formaggio, G.P. Zeller, Rev. Mod. Phys. 84, 1307 (2012).



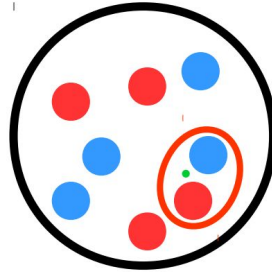
Nuclear effects

Understanding the properties of the underlying interaction from an observed event is complicated by various nuclear effects:

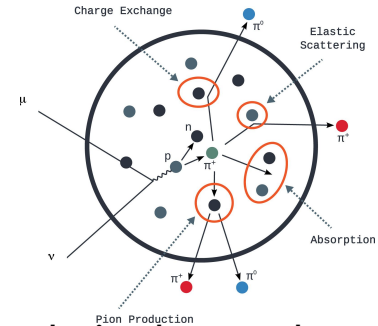
Fermi Motion



Multi-Nucleon Effects



Final State Interactions

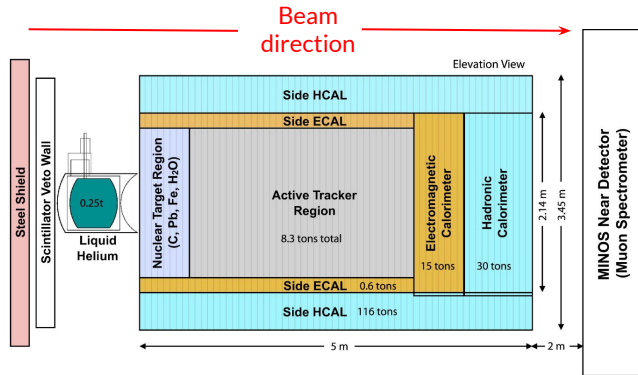
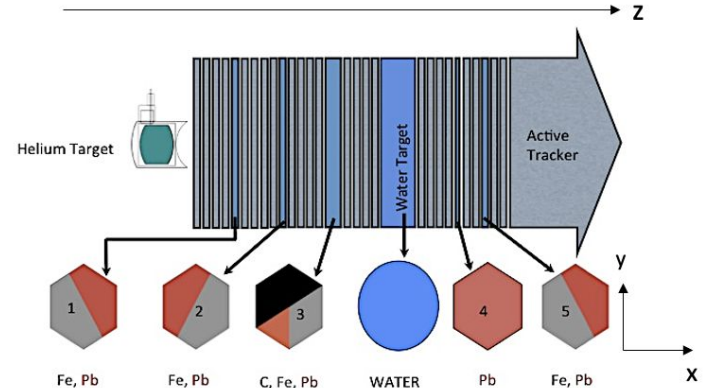
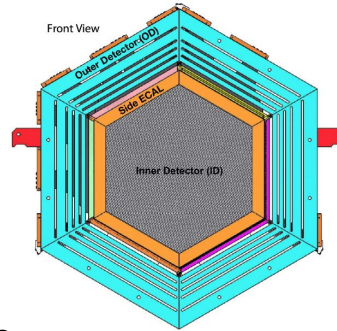


These can modify the particles present in the final state, as well as their observed kinematics

MINERvA

High statistics and finely grained detector.

Uses MINOS Near-Detector to measure muon charge and momentum.



“That’s cool, but why should I care about MINERvA?”

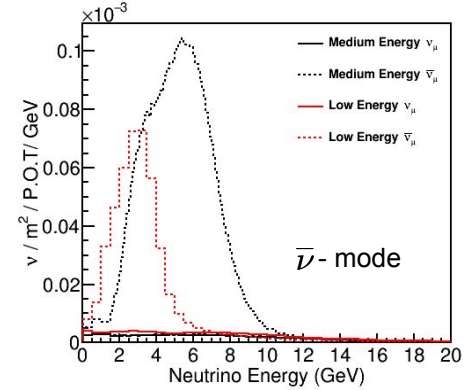
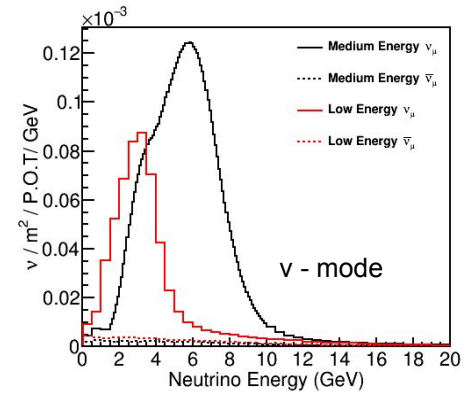
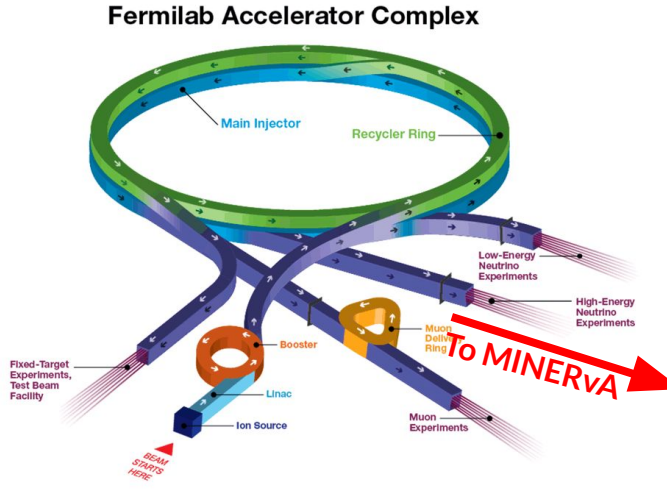
MINERvA doesn't exist in a vacuum. Neutrino physics is a broad ecosystem, a number of detectors spanning a number of different nuclei (Ar, H₂O, CH, Fe etc) means a dedicated experiment specialised in exploring nuclear effects and nuclear dependencies has significant potential to benefit wider community.



NuMI

Neutrinos at the Main Injector
@ Fermilab.

Well studied beam also used by
NOVA, MINOS & DUNE ND
Prototype “2x2”



Energy	ν - P.O.T.	$\bar{\nu}$ - P.O.T.
Low Energy “LE” - 3.5 GeV peak (2010-12)	4.0×10^{20}	1.7×10^{20}
Medium Energy “ME” - 6 GeV peak (2013-19)	<u>12.1×10^{20}</u>	12.4×10^{20}

POT/Protons-On-Target: The number of protons incident on the fixed target (C). Used as a proxy for number of neutrinos produced by the beam. Somewhat analogous to luminosity in collider experiments.



Measuring Cross Sections

$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\overbrace{\sum_j U_{j\alpha}}^{\text{Unfolding}} \overbrace{(N_{data, j} - N_{bkg, j})}^{\text{Selected Events}} \overbrace{)}^{\text{Background Subtraction}}}{\underbrace{E_\alpha}_{\text{Efficiency Correction}} \underbrace{(\phi T) (\Delta x)}_{\text{Normalisations}}}$$

x - Variable of interest

α - True Bin

j - Reconstructed bin

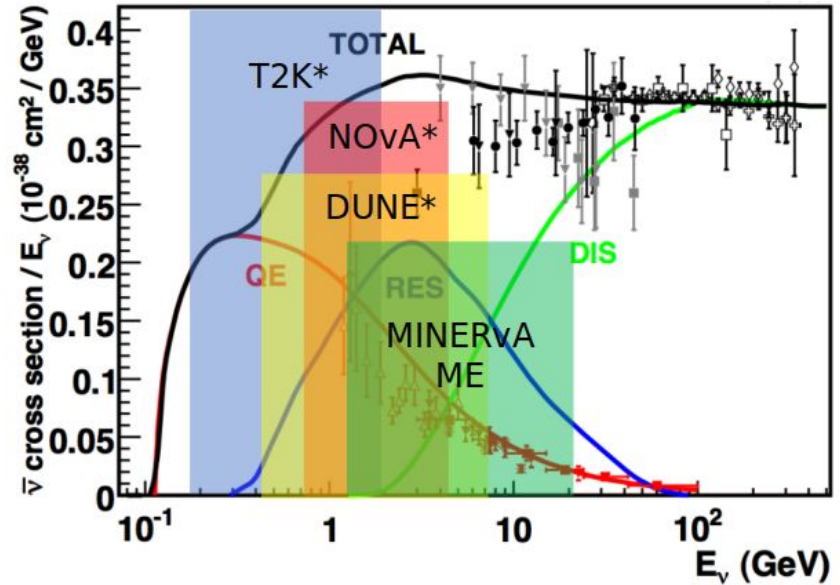
Cross section measurements can be used to refine neutrino interaction models.

Analysis overview

Charge Current Inclusive ν_μ : $\nu_\mu + X \rightarrow \mu^- + Y$
Looking for a μ^- in final state
 10.5×10^{20} useable POT

Medium Energy run (6 GeV peak) \rightarrow significant contribution from a variety of interaction channels + wide range of E_ν overlapping T2K, DUNE & NO ν A + (more)

Materials: Water + C, Fe, Pb, CH



This aims to be MINERvA's first inclusives analysis covering the water target \rightarrow Potential implications and uses with water based detectors and their associated interaction modelling.

Analysis overview

These cross sections will also be reported as ratios relative to CH → Allowing for cancellation of systematic uncertainties

Target deliverables:

1D cross sections:

Transverse muon momentum ($p_{t\mu}$), Longitudinal muon momentum ($p_{z\mu}$), Bjorken x ,
 E_{avail} & E_{μ}

2D cross sections: $\left(\frac{d^2\sigma}{dp_{||}dp_T}\right)_{\alpha} = \frac{\sum_j U_{ja}(N_{data,j} - N_{bkg,j})}{\epsilon_a(\phi T)(\Delta p_{||})(\Delta p_T)}$
 $P_{t\mu}$ vs $p_{z\mu}$

Where, $E_{avail} = \sum_{p, \pi^{\pm}} E_k + \sum_{others_{non \mu/e/n/A}} E_{Total}$ & Bjorken $x = \frac{Q^2}{2(E_{\nu} - E_{\mu})m_N}$

... and then do it 5 times (H₂O, C, Fe, Pb, CH) - Very rich analysis!



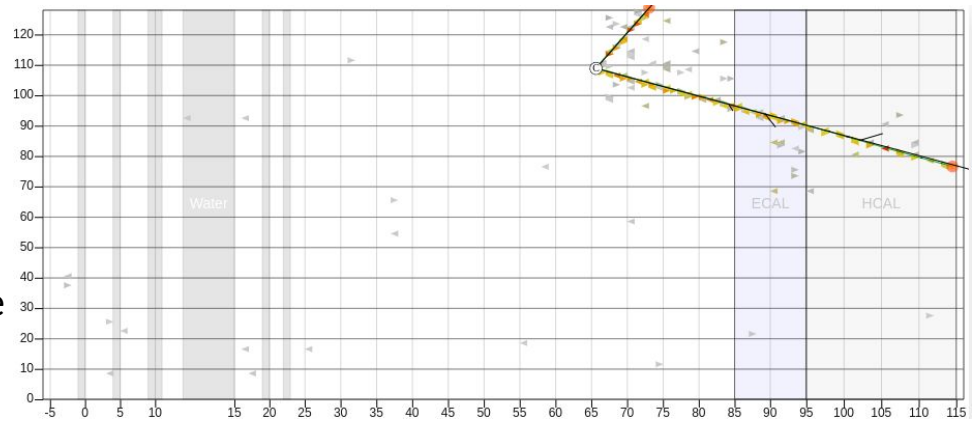
Analysis Event Selection

- Reconstructed Z Position Cut → Material/Plane disambiguation
- Various detector cuts
 - Apothem
 - Deadtime
 - ANN Reconstruction Confidence
- Muon Energy $> 2 \text{ GeV}$ and $< 50 \text{ GeV}$ → The range in which we can reconstruct well
- Muon Angle Cut → Ensure MINOS Containment
- MINOS Match
- MINOS Muon Curvature → For charge determination & calorimetry



Analysis Event Selection

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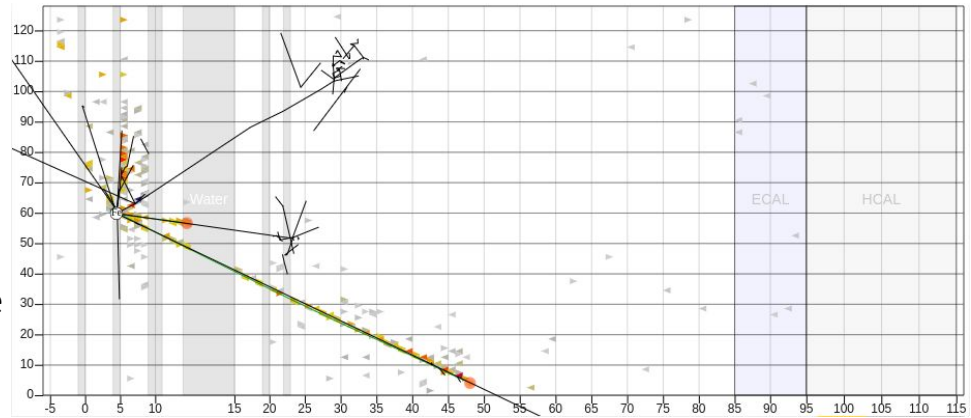


CC QE - $1 \mu^- + 1p$ ($4.5 \text{ GeV } \nu$)

Selected ✓

Analysis Event Selection

- Reconstructed Z Position Cut
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 - Deadtime
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- Muon Angle Cut
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CC RES - $1 \mu^- + 1 \pi + \text{others}$ (4.7 GeV ν)

Not Selected **X**

- Fails angle cut .'. Isn't MINOS captured

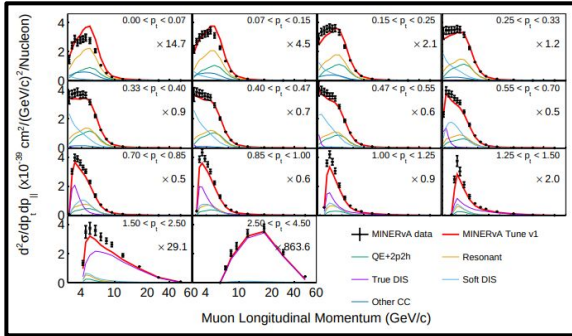
Inclusive Cross Sections at MINERvA

Inclusive cross sections are fully comprehensive tests of interaction modeling and a powerful tool to broadly understand model performance.

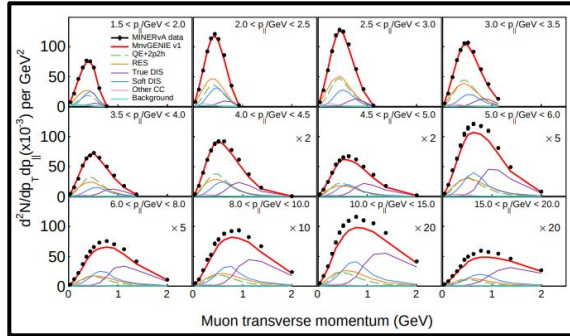
We explore **all** channels of interest **simultaneously**

We avoid detector-specific definitions

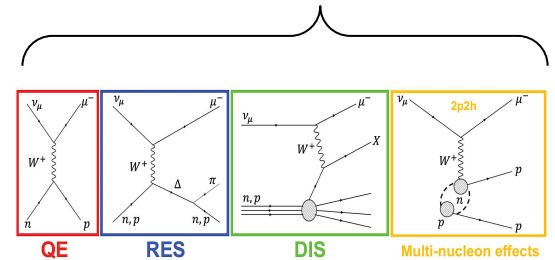
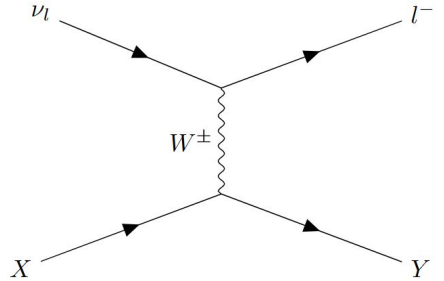
MINERvA has a rich history of inclusive cross section measurements:



doi.org/10.1103/PhysRevD.104.092007

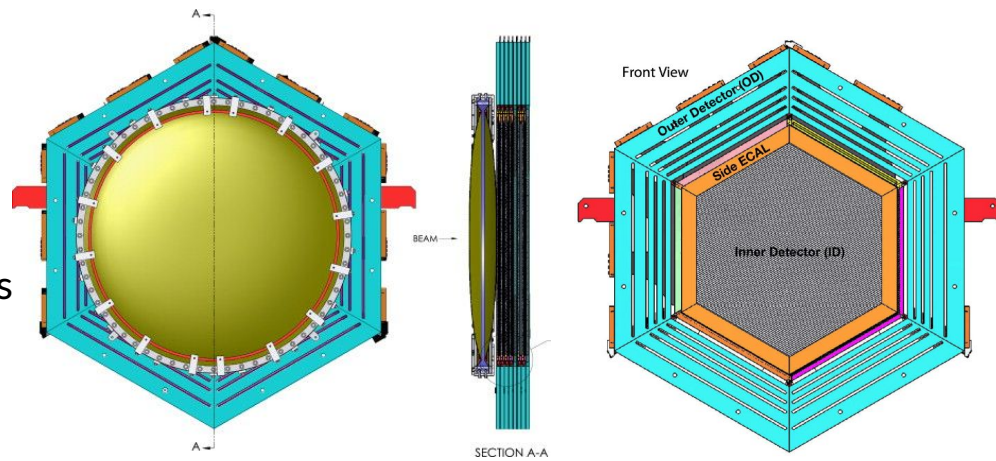


doi.org/10.1103/PhysRevD.101.112007



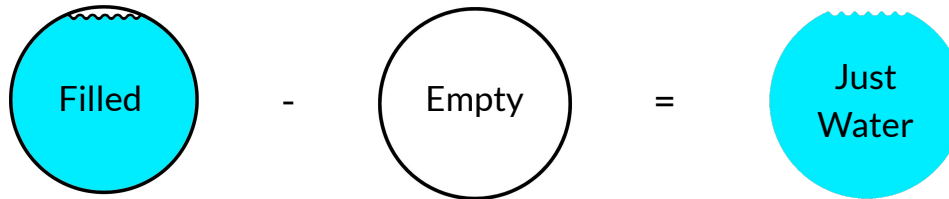
Water target

The water target has several key differences when compared with the solid targets which we need a handle on for comparisons



- Different shape (Circular tank vs hexagonal segment)
- Different materials (Water inside kevlar tank vs slab of material)

Can be drained & filled → Allows for a subtractive analysis to account for the water tank itself to 1st order:



Analysis status

- This analysis has essentially been split into 2 streams - Tracker (CH) & Nuclear targets (H_2O , Fe, Pb, C) - this is due to the special considerations required by a nuclear target analysis not present in tracker analyses

<ul style="list-style-type: none">• Tracker<ul style="list-style-type: none">○ Event Selection ○ Background subtraction ○ XSec extraction ○ Closure tests - ○ Warping Studies - ○ Model comparisons ○ Further studies...	<ul style="list-style-type: none">• Targets<ul style="list-style-type: none">○ Event Selection ○ Background subtraction ○ XSec extraction ○ Closure tests ○ Water Target Studies - / ○ Warping Studies - ○ Model comparisons ○ Further studies...
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 = Complete,  = In-Progress,  = Waiting for previous task

**Thank you for
listening!**

The End?

Jack Smalley
Tom O.
Jeremy GRIFFIN
Hugo
Kornell TANEKI
Steve Manning
F. P...
Arturo F.
John W...
John K...
H. Ray
CHAY S. Richardson
Jesse Chvojka
David...
MINERVA logo

