MINER A

An Overview of the International MINERvA Experiment

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***On behalf of MINERvA Collaboration.**
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Abstract.

A. The MINERvA collaboration (http://minerva.fnal.gov), (Main INjector Experiment for v-A), is based on a fine-grained detector operating in the Fermilab's NuMI high-intensity neutrino beam, planned to measure with high precision low energy (circa 3 GeV) and medium energy (circa 6 GeV) neutrino and antineutrino cross sections on plastic scintillator, Carbon, Fe, Pb, He and H_2O.

B. We will describe MINERvA Collaboration,

C. resume all the physics results so far achieved,

D. and show its potential for future measurements.

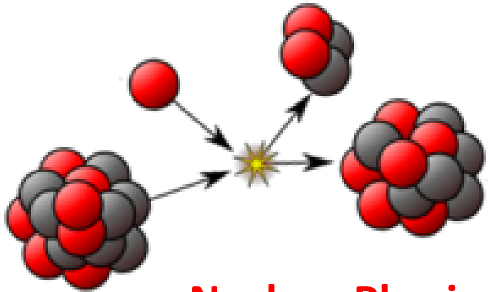
Outline

Introduction
MINERvA Motivation
MINERvA experiment
MINERvA Results
MINERvA in the near Future
Conclusions

Introduction

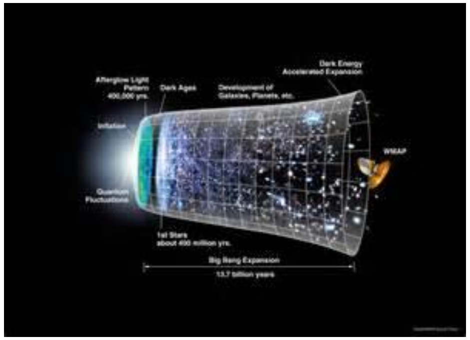
Wolfgang Pauli postulated neutrino in 1930.

E. Fermi suggested its name, about 1932.

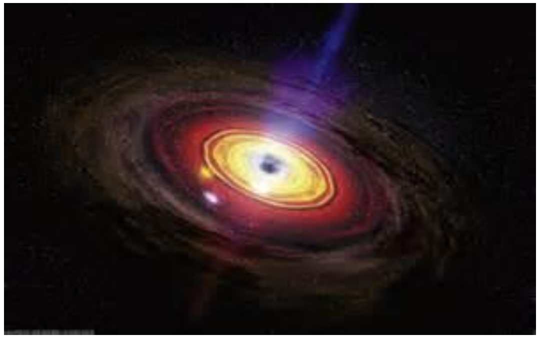


Nuclear Physics.

Particle Physics.



Cosmology.



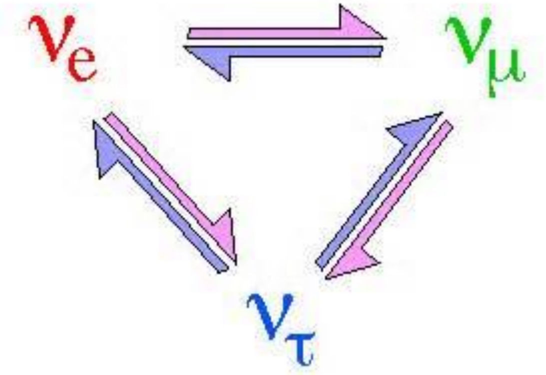
Astrophysics.

And

Cosmodynamics? (Word to be coined)

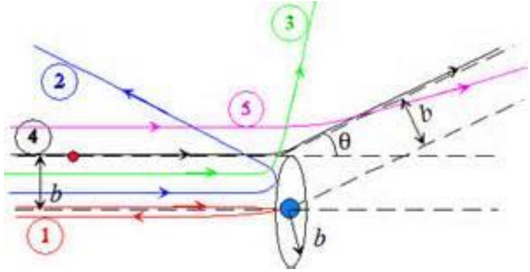
Scientists have detected and measured neutrinos.

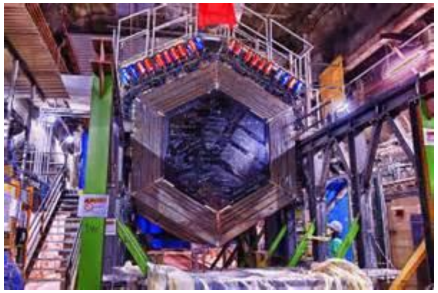
There are three neutrino flavors.



Neutrino Oscillation is a key problem

A basic question remains: how do the neutrinos interact with matter?

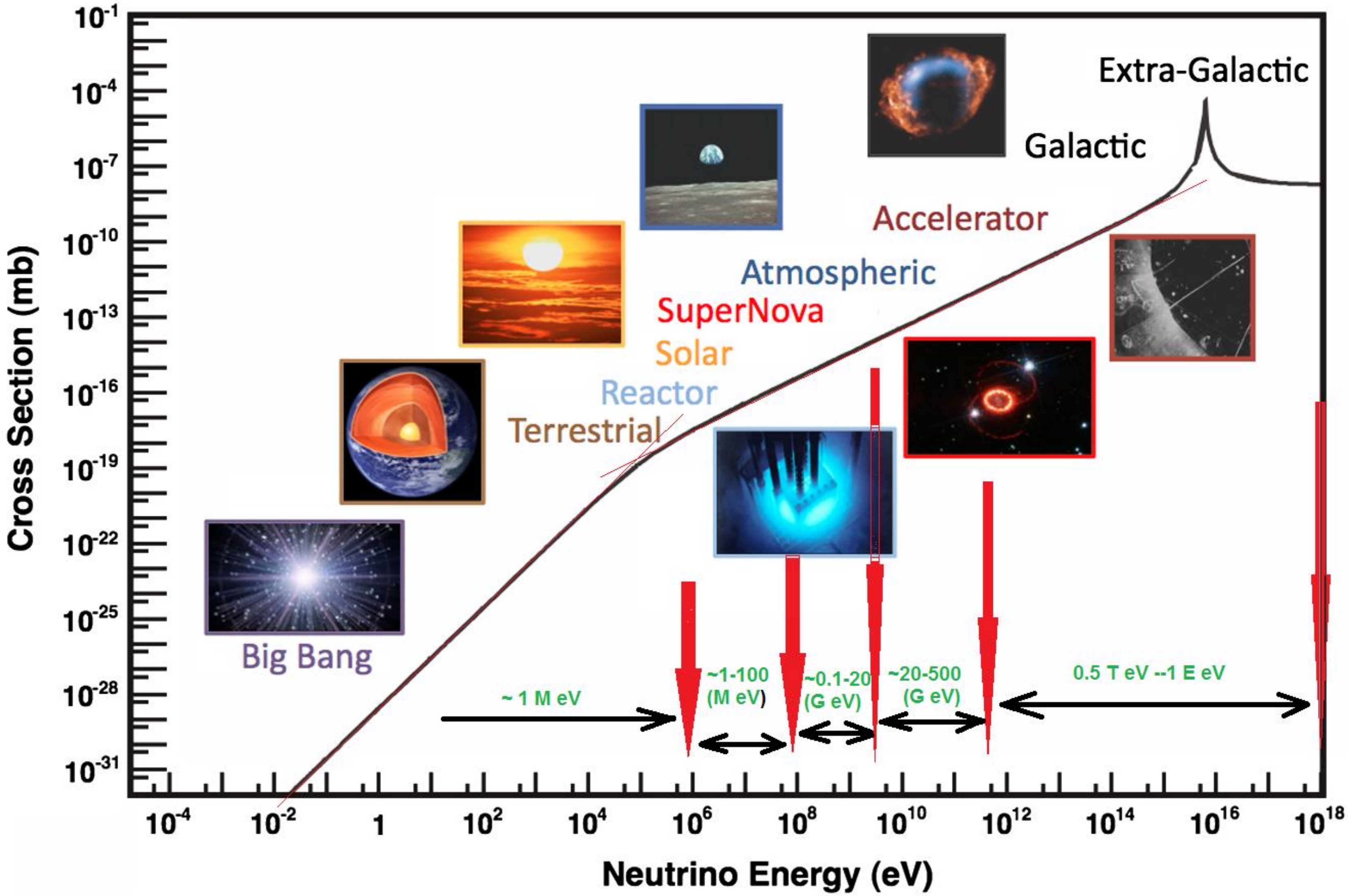




MINERvA experiment.

MINERvA Motivation

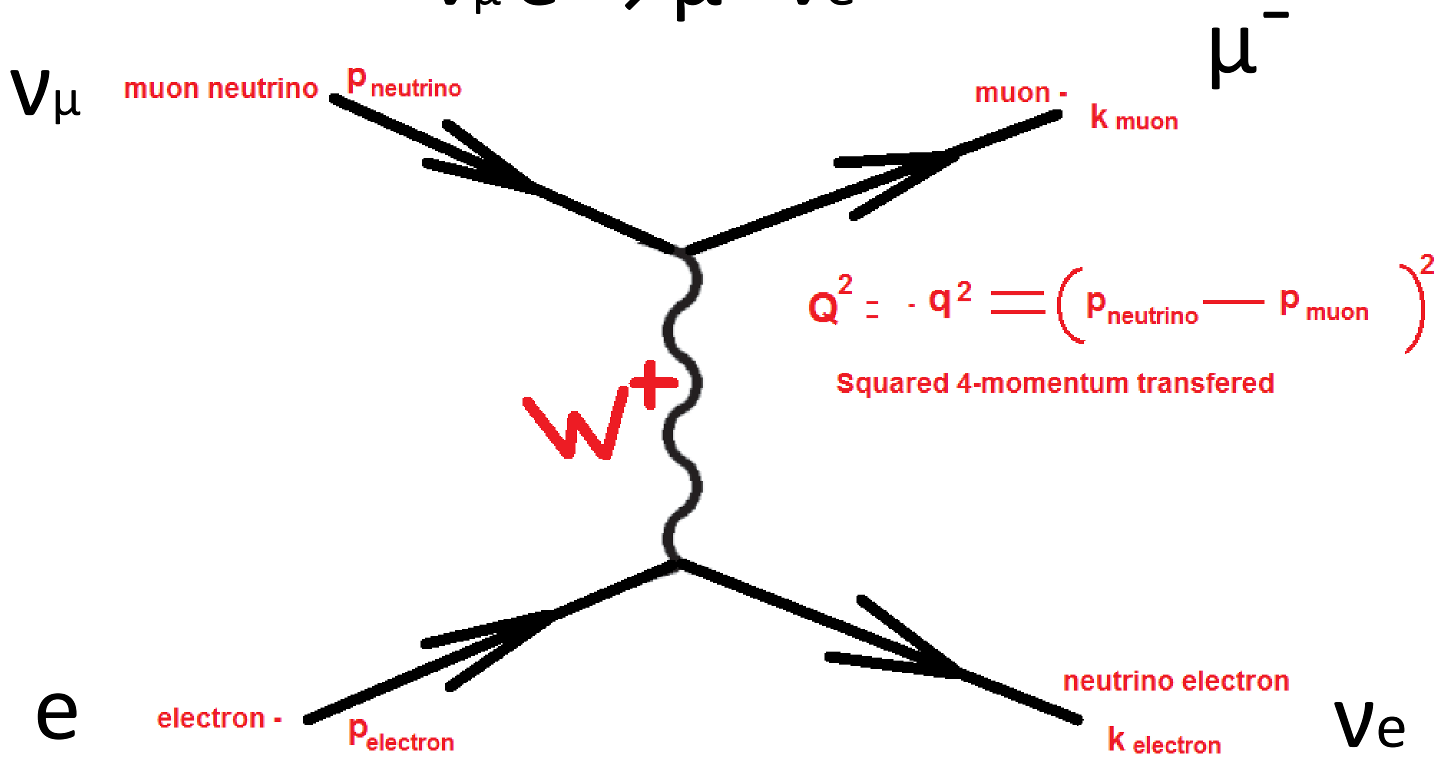
Energy regions to study interaction cross section.



Simplest case of neutrino interaction

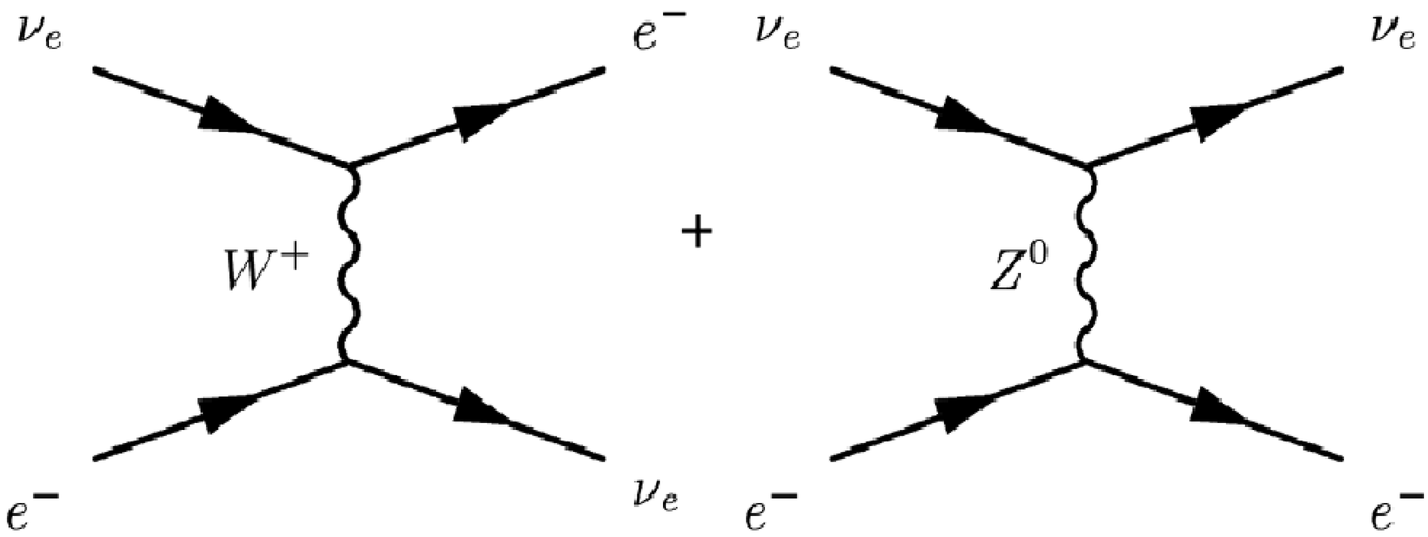
Charged Current.

$$\nu_\mu e \rightarrow \mu^- \nu_e$$



$\nu_e\, e \rightarrow \nu_e\, e$

Charged Current. **Neutral Current.**



CC and NC neutrino interactions

Neutrino Interaction depends on the energy region

THRESHOLDLESS PROCESSES: NEUTRINO ENERGY = 0–1 MeV.

A. Coherent scattering.

B. Neutrino capture on radioactive nuclei.

LOW-ENERGY NUCLEAR PROCESSES: neutrino energy = 1–100 MeV.

A. Inverse beta decay.

B. Cross section as a function of nuclear target.

INTERMEDIATE ENERGY CROSS SECTIONS: neutrino energy =0. 1–20 GeV.

Elastic and quasielastic scattering.

Resonance production.

Deep inelastic scattering.

This is the energy region where MINERvA can contribute.

This is a list of the key processes which can contribute to the total cross section at these intermediate neutrino energies:

Quasielastic,

NC elastic scattering,

resonant single pion production,

coherent pion production,

multipion production,

kaon production,

and Deep Inelastic Scattering .

HIGH-ENERGY CROSS SECTIONS: neutrino energy = 20–500 GeV

Also MINERvA can contribute to these studies up to approximately 50 GeV.

To describe DIS the following parameter is used:
the Bjorken parameter

$$x = Q^2/(2\ p_e .\ q).$$

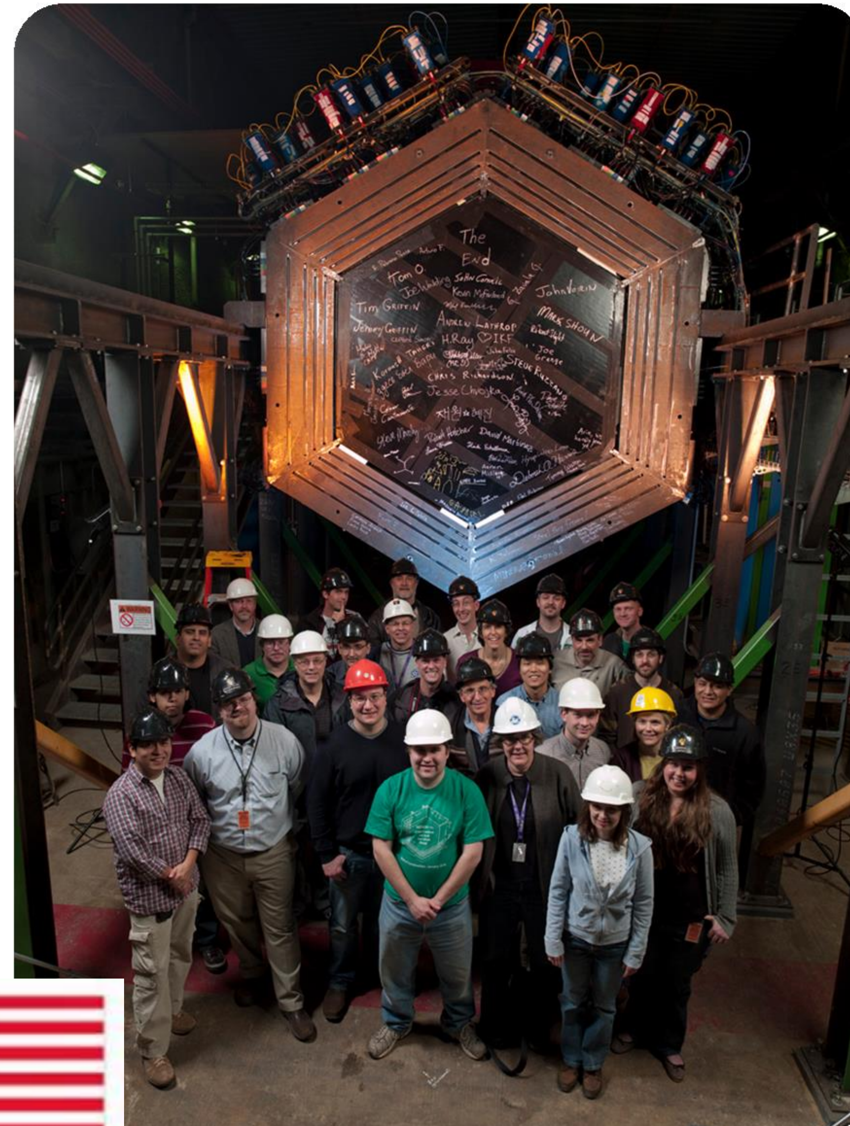
With multiple nuclear targets, in the same neutrino beam, MINERvA will also be able to complete the first detailed examination of nuclear effects in neutrino DIS.

ULTRA-HIGH-ENERGY NEUTRINOS: 0.5 TeV–1 EeV
MINERvA has not this energy. I mention it for completeness.

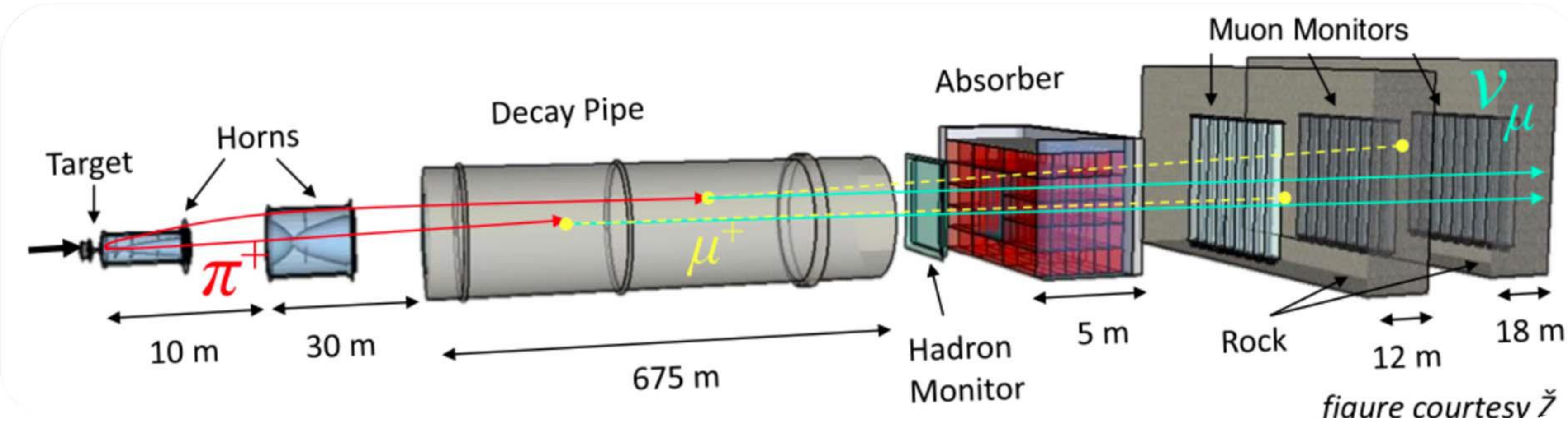
MINERvA experiment

~80 collaborators from particle and nuclear physics

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 University
Tufts University
University of California at Irvine
University of Minnesota at Duluth
Universidad Nacional de Ingeniería
Universidad Técnica Federico Santa María
College of William and Mary



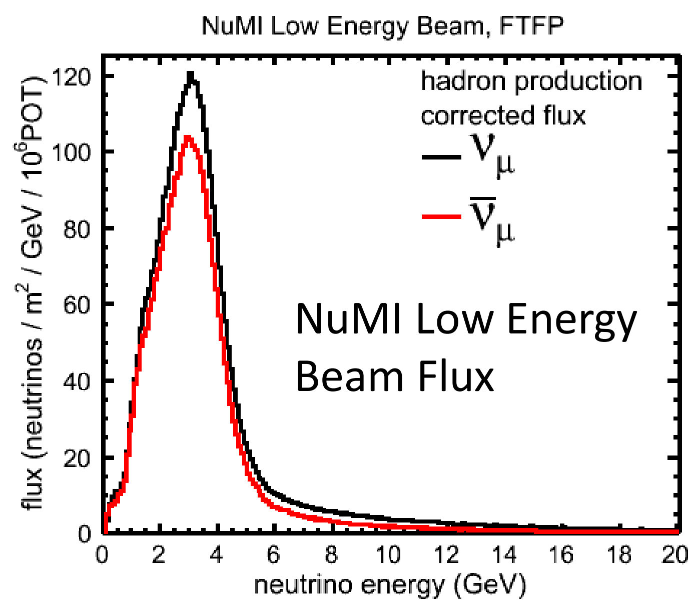
NuMI Beam (~same for MINOS, NOvA)



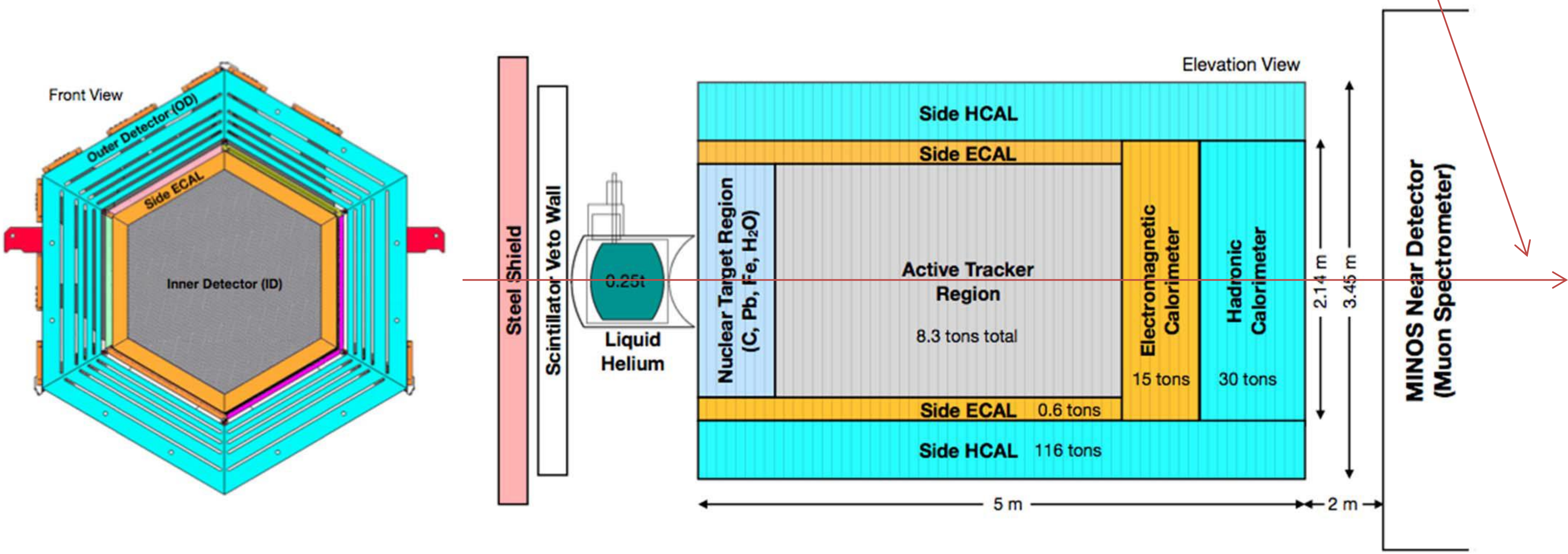
NuMI is a "conventional" neutrino beam, neutrinos from focused pions.

For MINERvA, flux must be calculated, use hadron production data.

Protons on target (POT) to MINERvA,
--neutrino (LE): 3.9E20 POT.
--anti-neutrino (LE): 1.0E20 POT.



MINERvA detector



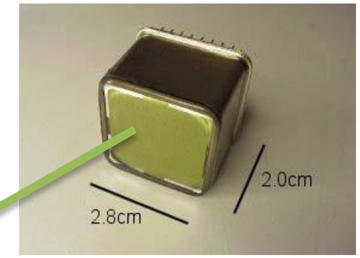
Detector comprised of **120 "modules"** stacked along the beam direction.

Central region is ***finely segmented scintillator tracker.***

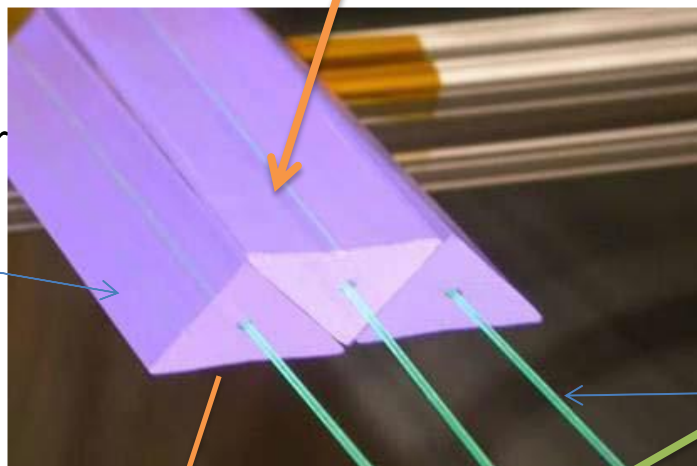
~32k plastic scintillator strip channels total.

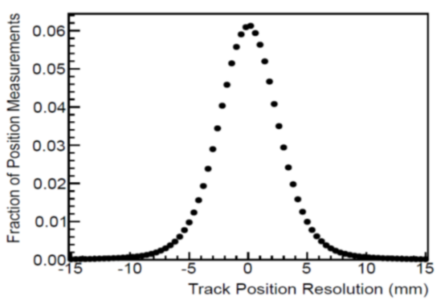
Detector Technology.
Scintillator planes in 3 orientations.

64 channel multi-anode PMT



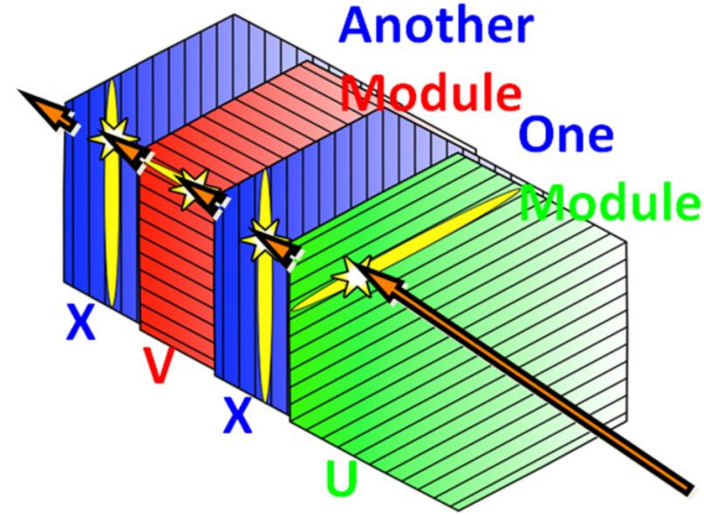
Scintillator strip



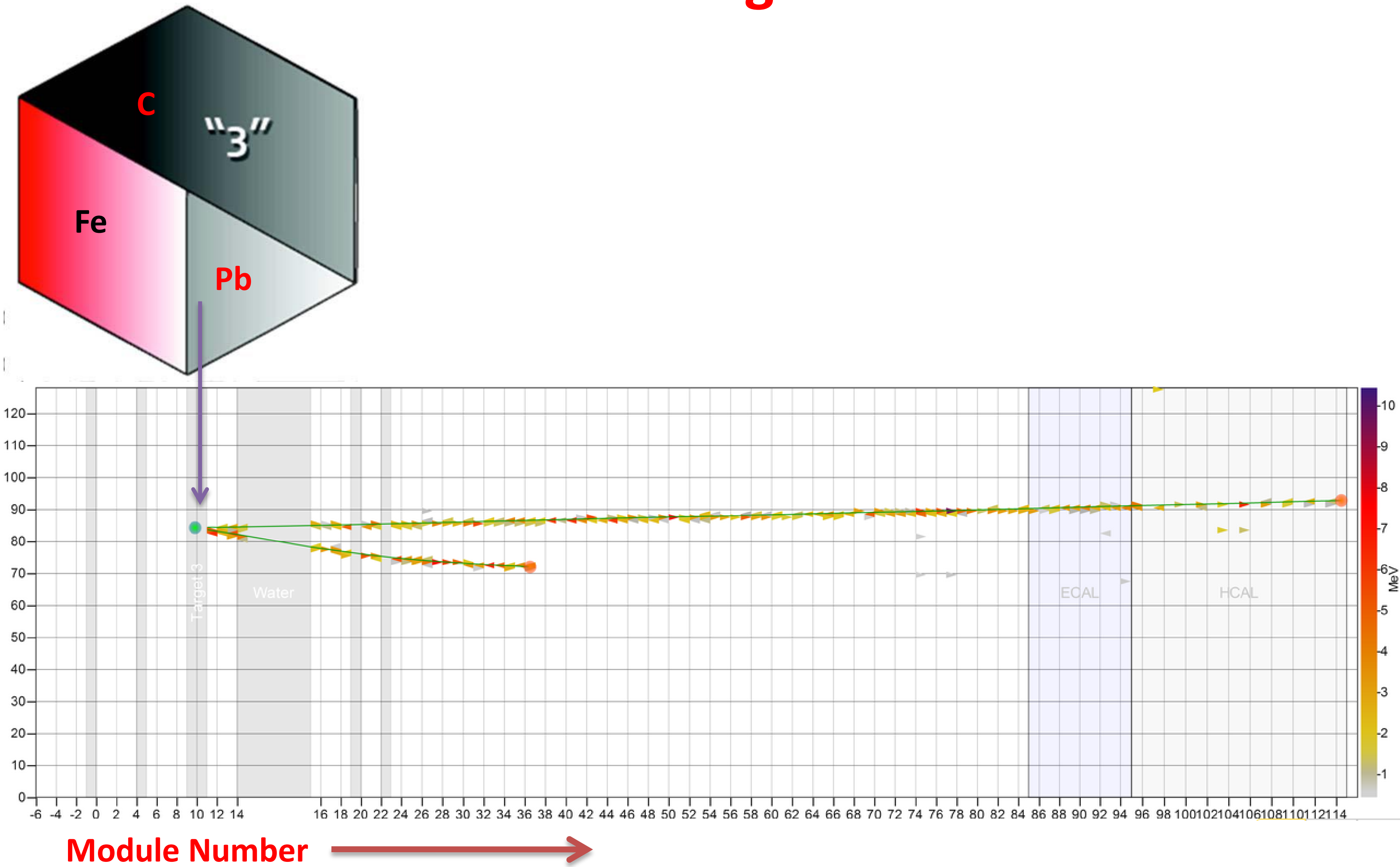


Forward-going track position resolution: 3 mm

Wavelength shifting fiber

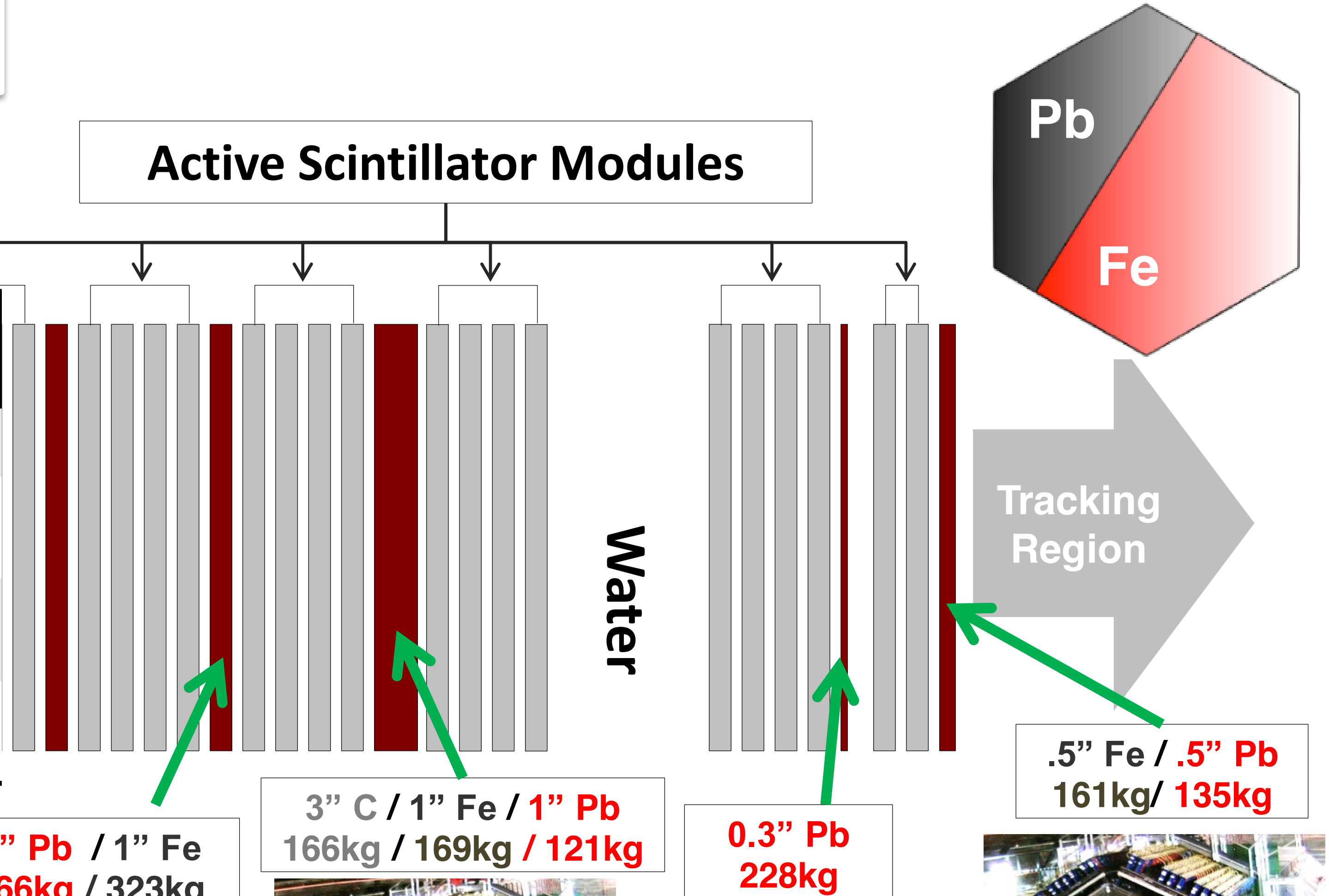


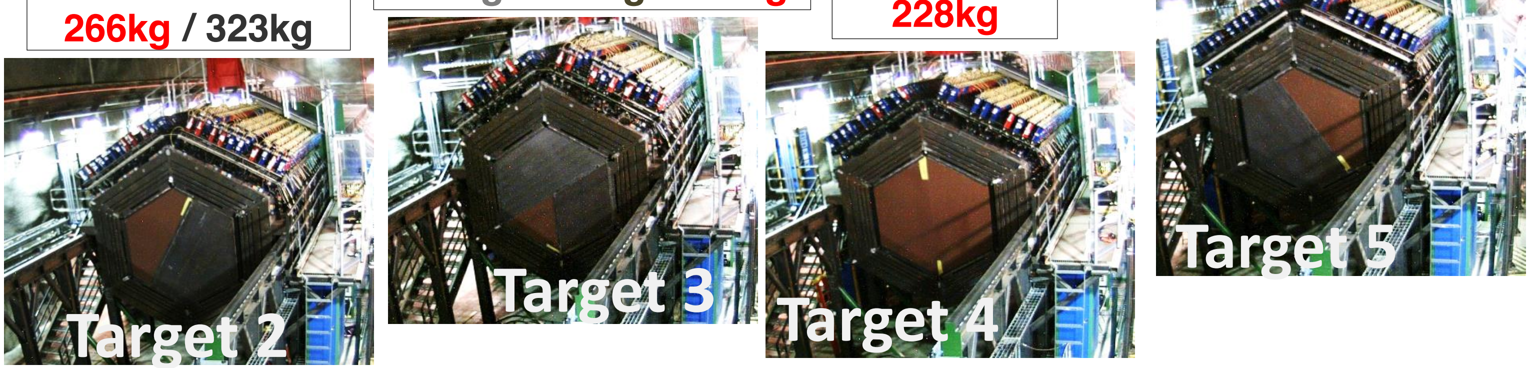
2-track event from Pb target.

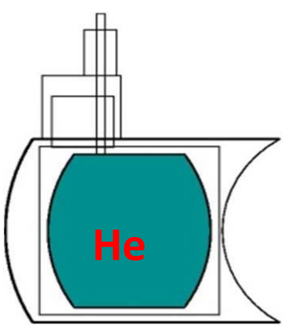


Targets used

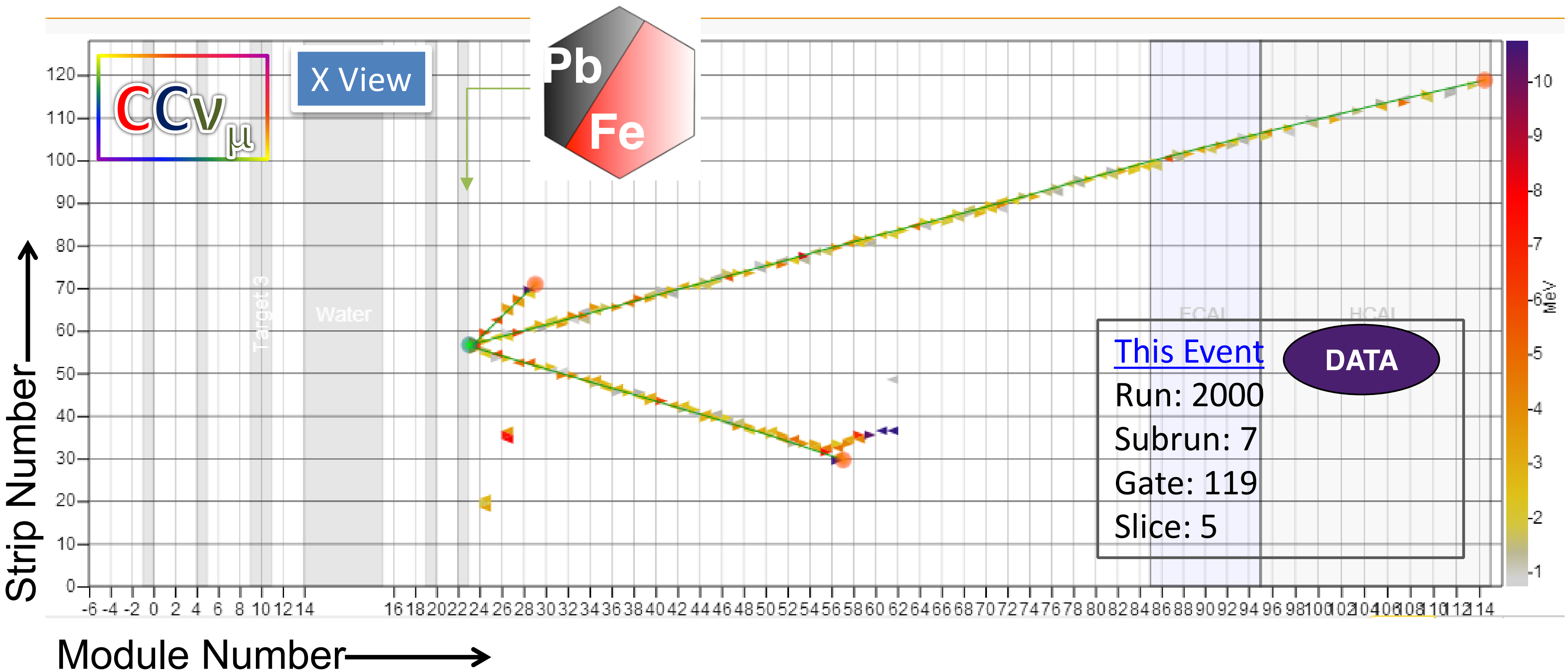
A	Mass (t)
C	0.16
Fe	0.63
Pb	0.71
CH	5.48







Another Event Sample



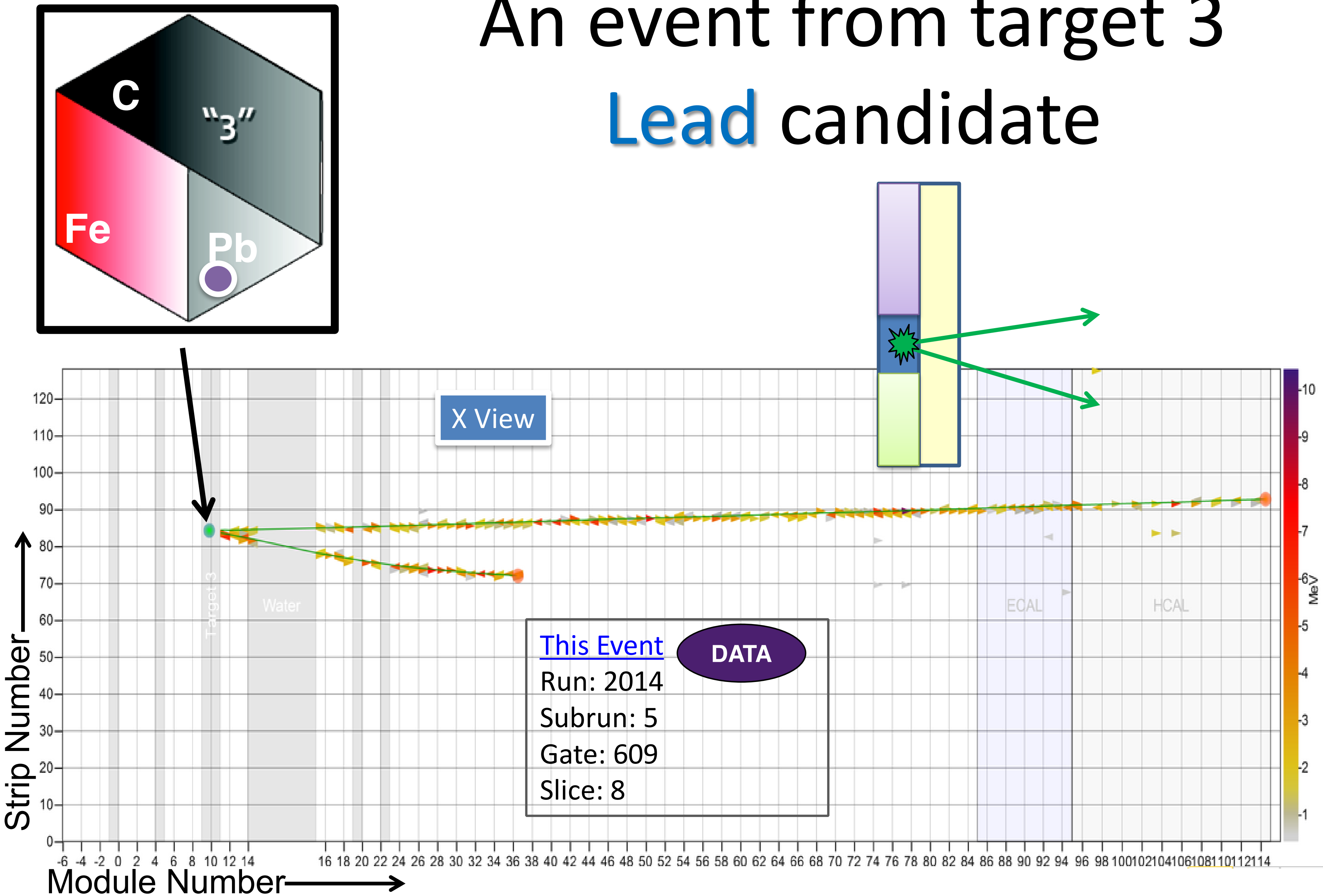
Event Topology

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

An event from target 3 Lead candidate



MINERvA Results

MINERvA Physics publications

“neutrino communications”- MPLA Vol. 27, No. 12 (2012).
0.1 Hz, 1% bit error rate.
One of top 10 physics results – Physics World – 2012.

Muon neutrino QE-like in CH - PRL 111, 022502 (2013).
Muon antineutrino QE-like in CH - PRL 111, 022501 (2013) .
Inclusive ratios (Fe:CH, Pb:CH) Phys Rev Lett 112.231801 (2014).

Many more on the way…
--Muon neutrino Single charged pion in CH (to be submitted soon!).
--Coherent charged pion – neutrino and anti neutrino CH.
-- 2-track QE muon neutrino CH, Fe, Pb (muon and p).
--neutrino-e scattering yield as beam flux calibrator (CH).
--CC pion 0 production – antineutrino CH.

Each analysis follows a particular procedure, depending on the particular physics topic.

"neutrino communications"- MPLA Vol. 27, No. 12 (2012).
0.1 Hz, 1% bit error rate.
One of top 10 physics results – Physics World – 2012.

This Demonstration is analogous of Marconi 1903 experiment.

MINERvA experiment proved the possibility of sending messages using neutrino beams.

The demonstration is based on the establishment of a low rate (0.100±0.001 bit/s) communication link using the NuMI beam line and the MINERvA detector at Fermilab, over a distance of 1035 m, including 240 m of earth.

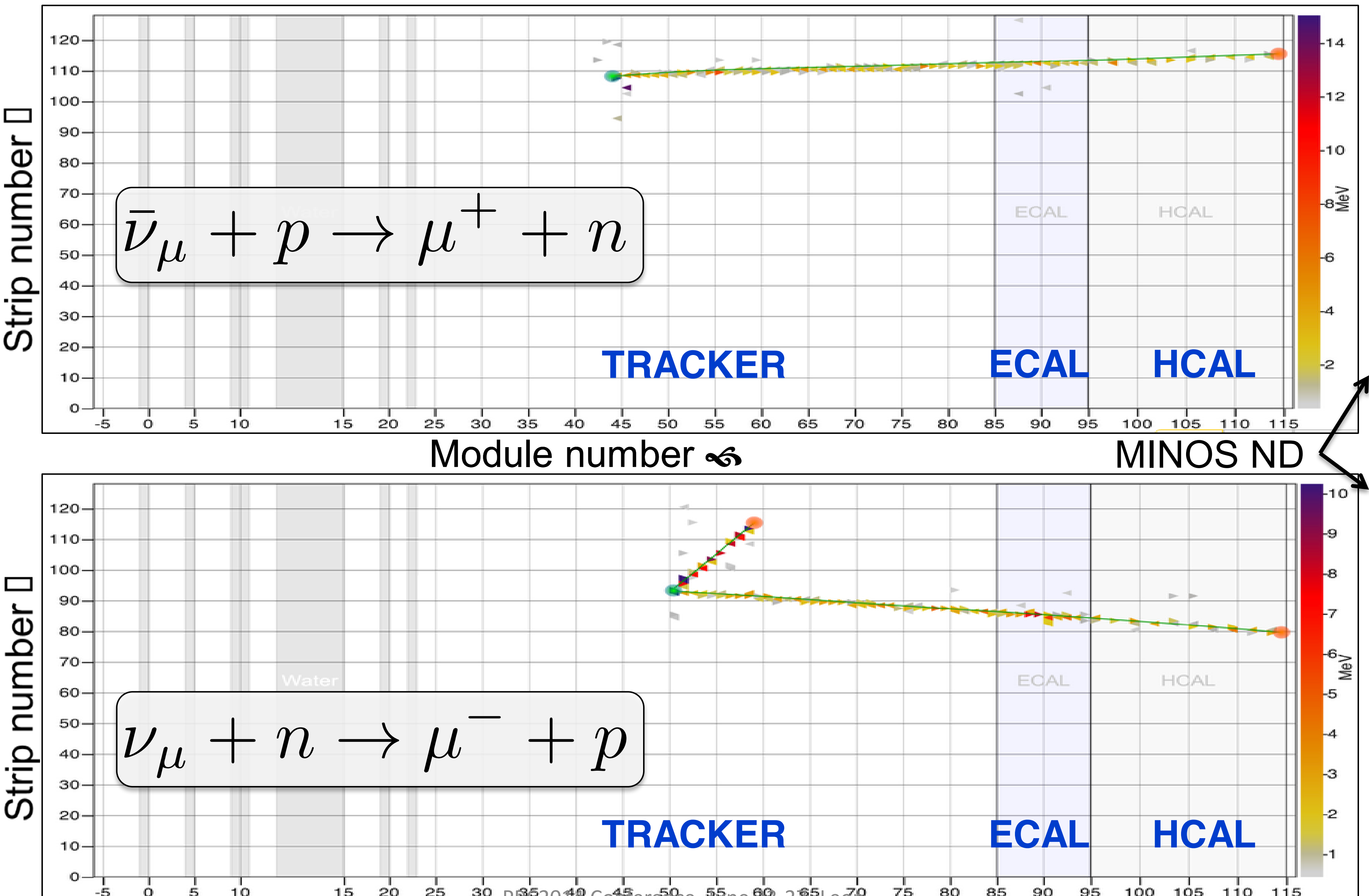
Muon antineutrino QE-like in CH - PRL 111, 022501 (2013) .

We have isolated muon antineutrino charged-current quasielastic (QE) interactions occurring in the segmented scintillator tracking region of the MINERvA detector running in the NuMI neutrino beam at Fermilab.
We measure the flux-averaged differential cross section, d(sigma)/dQ2, and compare to several theoretical models of QE scattering.

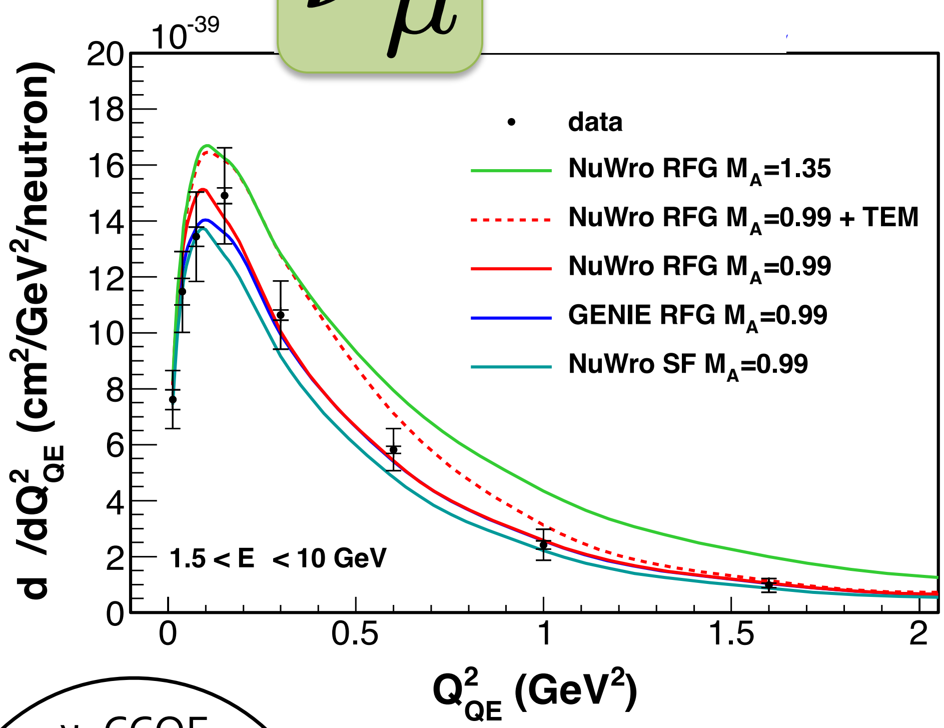
Muon neutrino QE-like in CH - PRL 111, 022502 (2013).

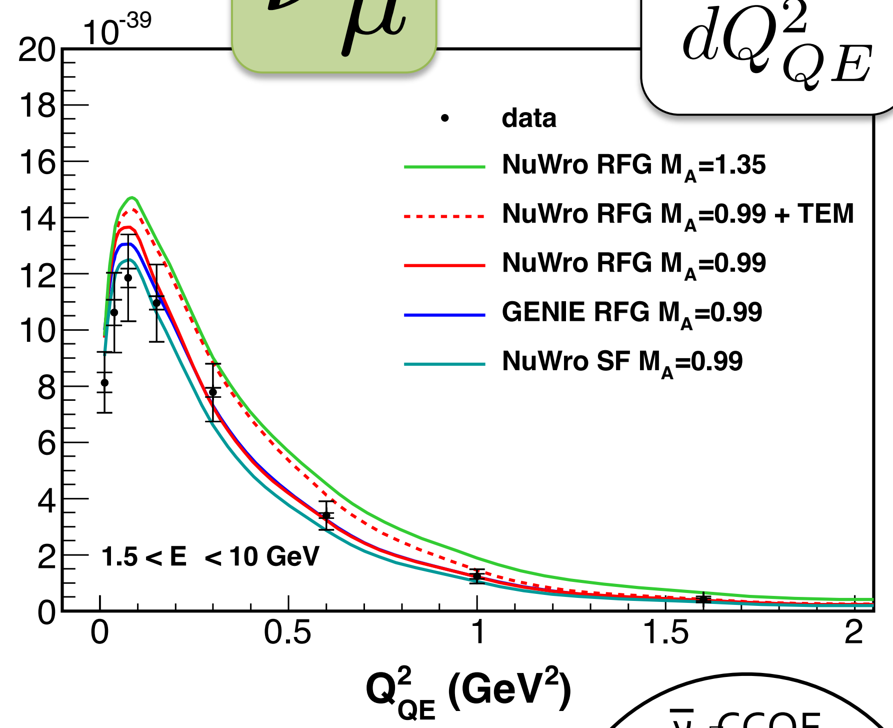
We report a study of muon neutrino charged-current quasielastic events in the segmented scintillator inner tracker of the MINERvA experiment running in the NuMI neutrino beam at Fermilab. The events were selected by requiring a muon - and low calorimetric recoil energy separated from the interaction vertex. We measure the flux-averaged differential cross section, d(sigma)/dQ2, and study the low energy particle content of the final state.

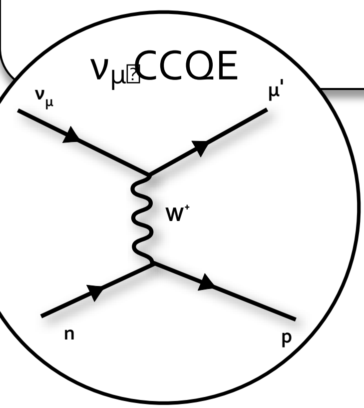
ν Beam charged-current quasi-elastic scattering



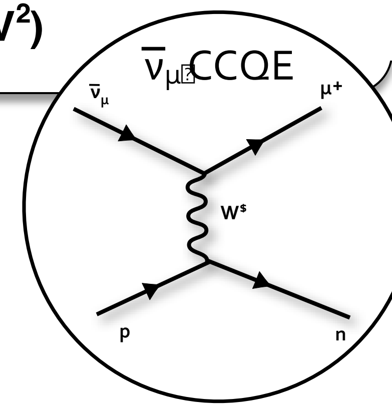
ν_μ $\bar{\nu}_\mu$ $\frac{d\sigma}{dQ^2_{QE}}$







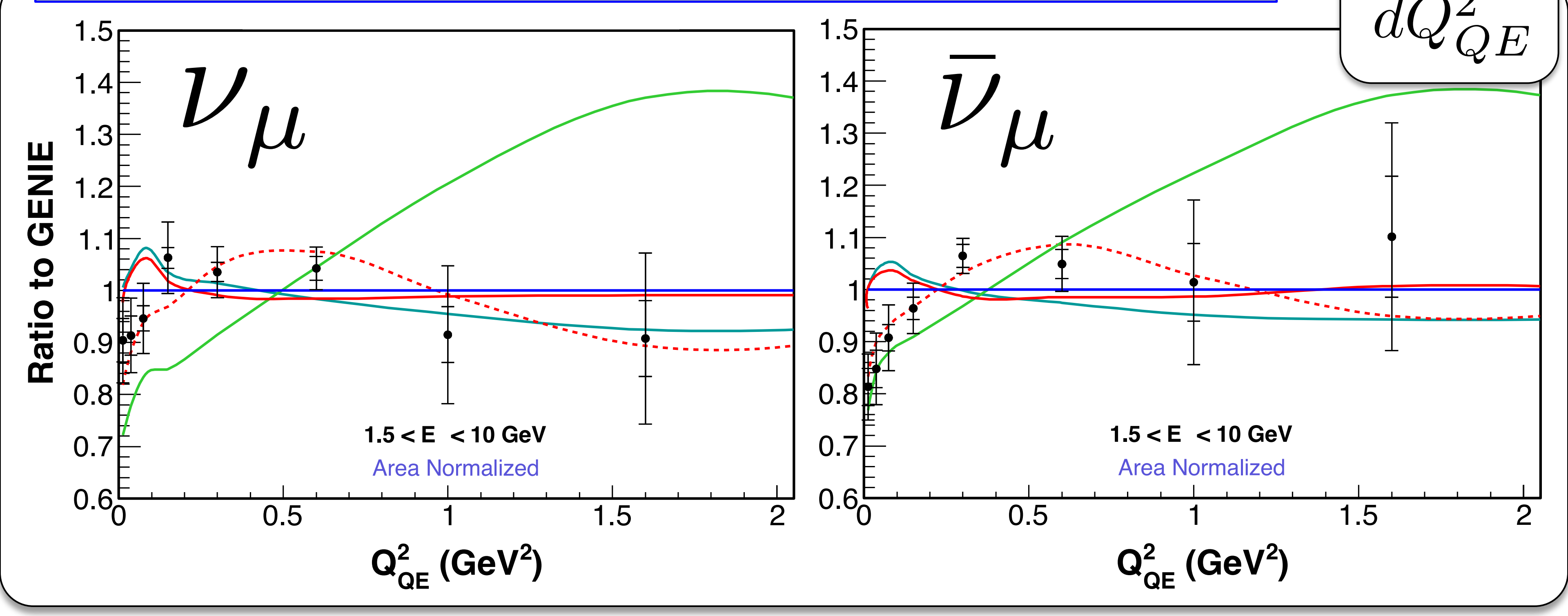
	Events	Efficiency	Purity
Neutrinos	29,620	47%	49%
Antineutrinos	16,467	54%	77%



MINER A

Emphasize Shape: Normalize each prediction and the measured cross section to GENIE prediction and form ratio

$$\frac{d\sigma}{dQ^2_{QE}}$$

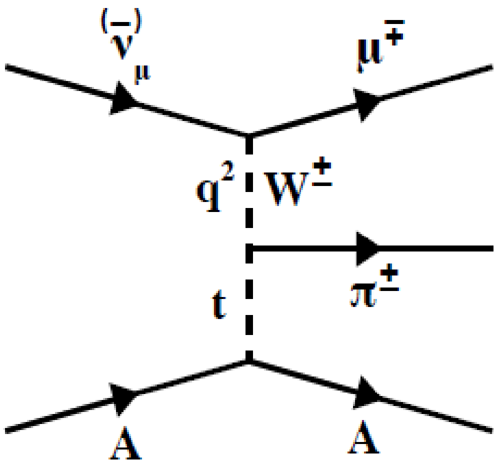


GENIE	blue solid line	independent nucleons in a mean field (M_A = 0.99 GeV).
M_A = 1.35 GeV	green solid line	best fit to MiniBooNE data.
SF	teal solid line	improved nucleon momentum-energy relation.
TEM	red dashed line	empirical model based on electron scattering data.

CC Coherent Pion Production on C

Strong contribution from Guanajuato group to this analysis.

- We are measuring neutrino and antineutrino CC coherent pion production on Carbon for 1.5 GeV < E_ν < 20 GeV
- This analysis uses the GENIE v2.6.2 event generator, which uses the Rein-Sehgal model for CC coherent pion production with lepton mass corrections
- Our signal definition:
  - a positively identified muon and pion
  - a quiet event vertex (i.e. no nuclear break-up)
  - low $|t| = |(q-p_\pi)^2|$
    - model independent, unambiguous signature of coherent scattering
    - MINERνA is the first contemporary experiment measuring |t| event-by-event



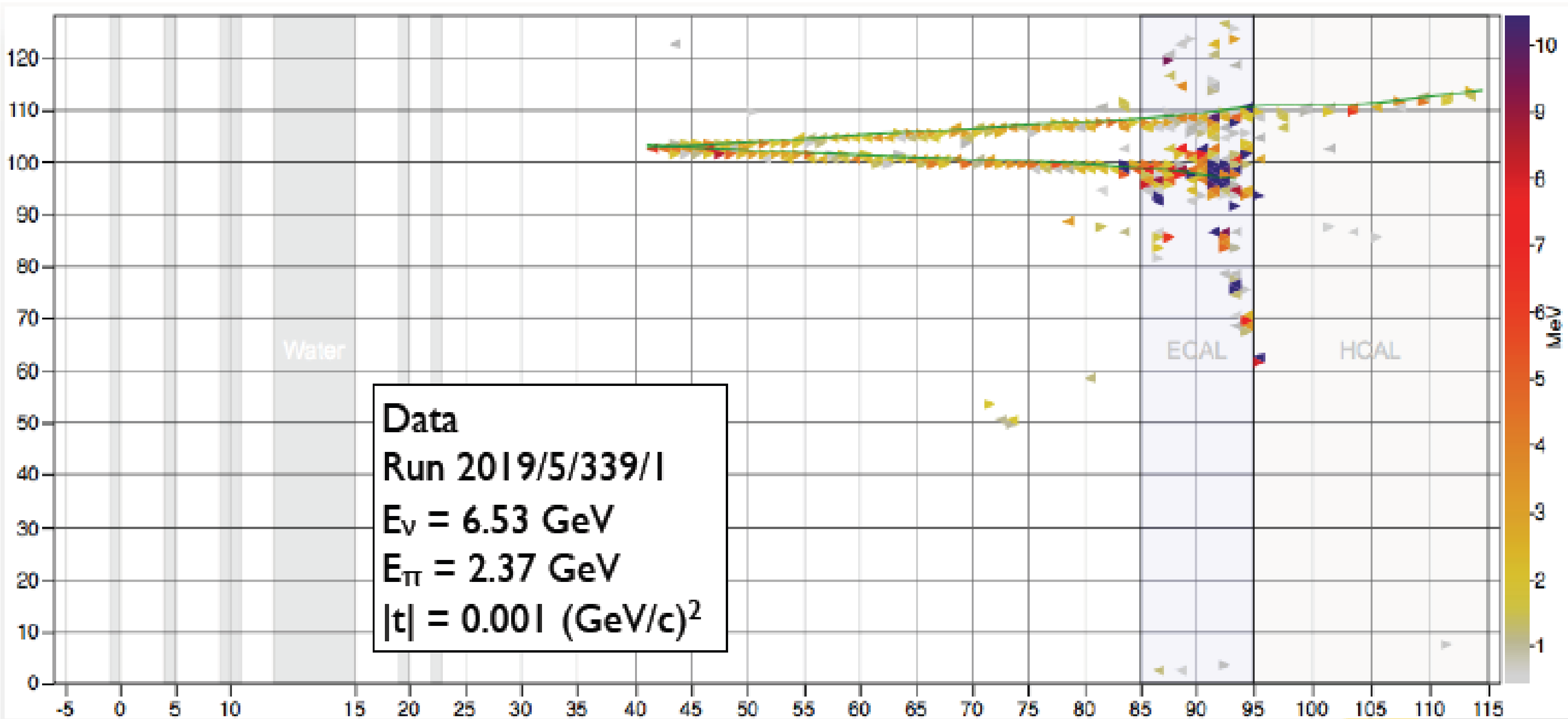
- We analyze events in our fully active central scintillator (C-H) tracker region - fine-grained for measuring μ and π direction

- Reconstructing the μ in both MINERvA and MINOS gives a measurement of p_μ and muon charge

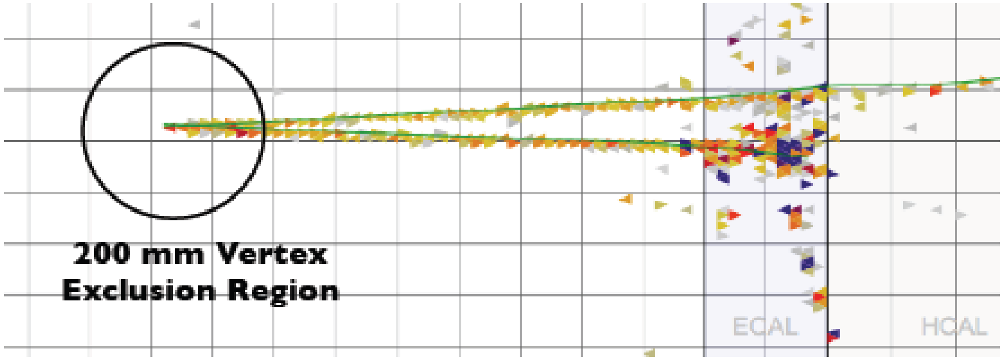
- The downstream and side calorimeters provide containment of the π for measuring E_π

- MINERvA has full access to the μ and π kinematics for measuring $|t| = |(q-p_\pi)^2|$

ν_μ CC Coherent Pion Production Candidate in MINERvA



Kinematics Reconstruction



- We accurately measure p_μ for muons reconstructed in both MINERvA & MINOS
- Since most pions interact in our detector, E_π reconstructed as:
  - total non-muon calorimetric energy > 200 mm from event vertex
  - +60 MeV estimate of single pion calorimetric energy within 200 mm from event vertex
- Excluding the vertex region minimizes sensitivity to mis-modeling vertex activity in background events
- $E_\nu = E_\mu + E_\pi$ (assumes zero energy transfer to nucleus)
- Assume neutrino direction is parallel to beam axis
- $|t| = |(q - p_\pi)^2| = |(p_\nu - p_\mu - p_\pi)^2|$

Event Selection: CC 2-Particle Sample

- Muon originates in the tracker region
- Muon is reconstructed in both MINERνA & MINOS
- Muon charge is negative for neutrinos, positive for antineutrinos
- Exactly one reconstructed hadron at the event vertex

Cross Sections

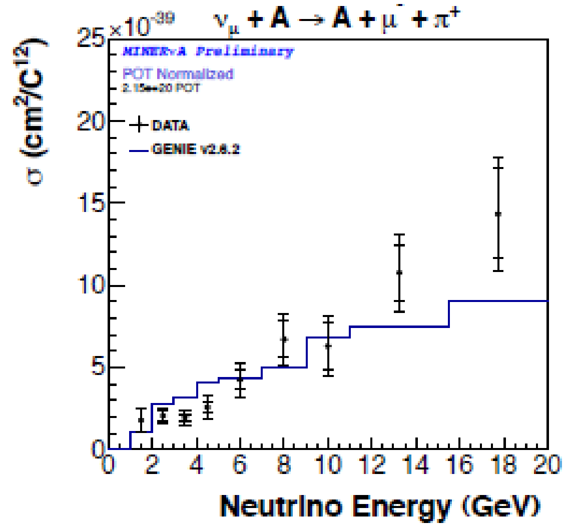
Inner error bars are systematic errors only

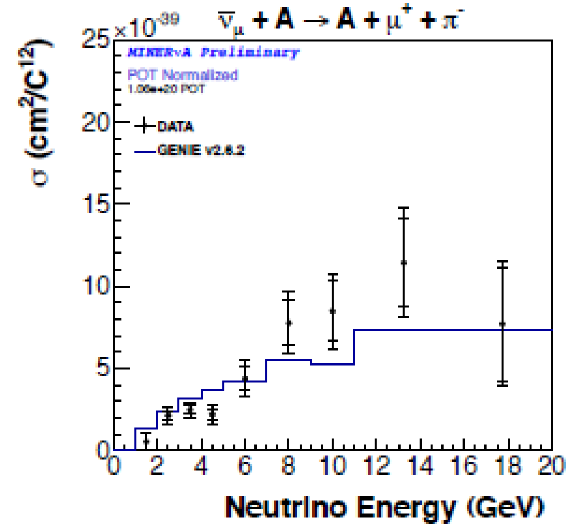
Outer error bars are systematic + statistical errors

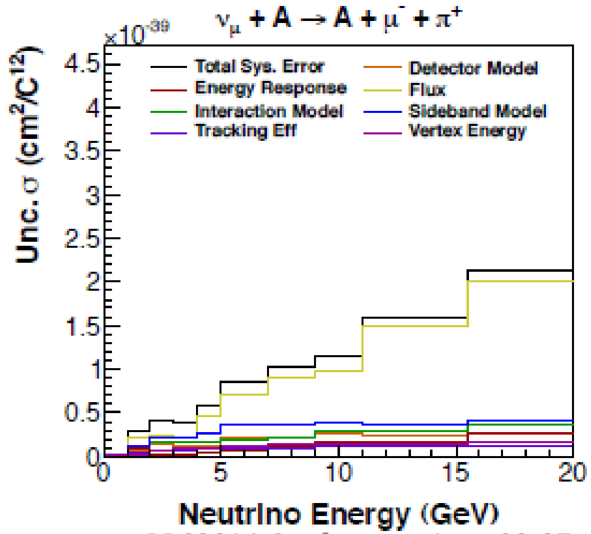
K2K and SciBooNE measurements were consistent with no CC coherent pion production for E_ν < 2 GeV

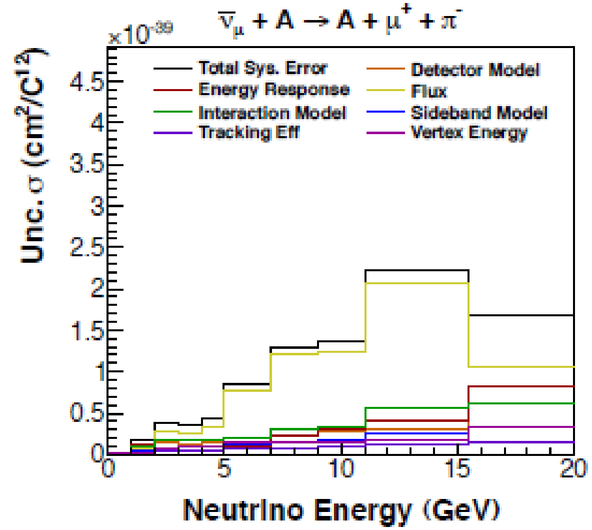
For E_ν < 5 GeV, GENIE's Rein-Sehgal model predicts a higher production rate than our data

We estimate that ~17% of our signal is diffractive scattering off Hydrogen

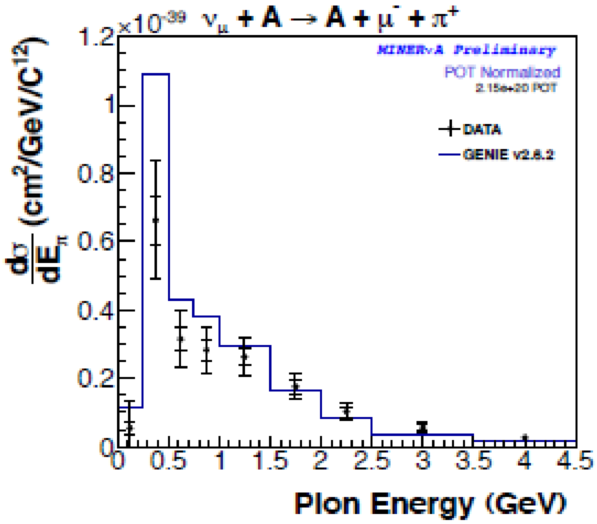


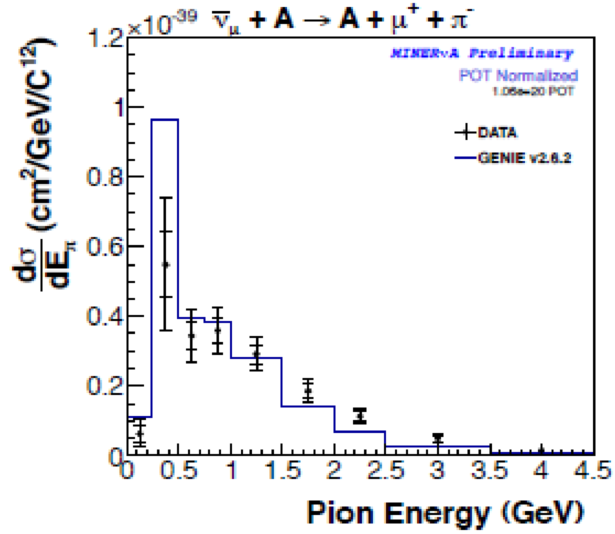


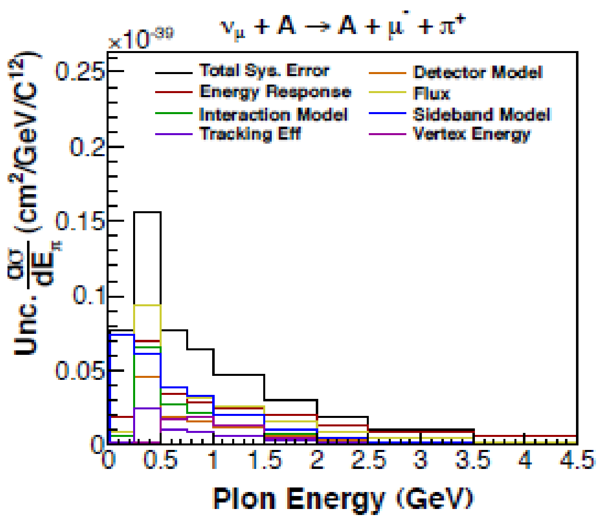


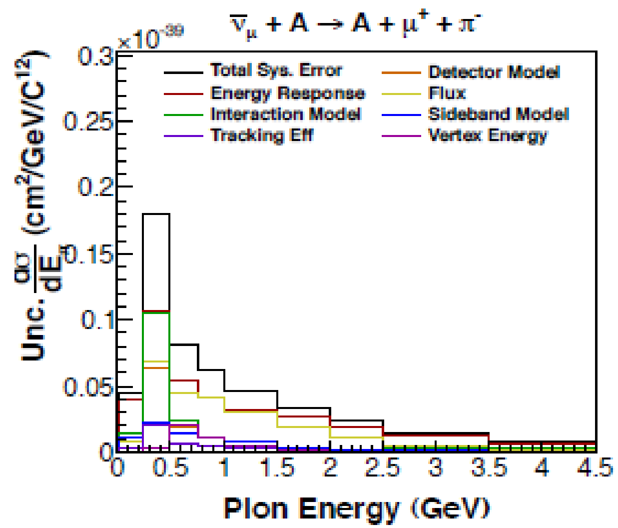


Cross Sections

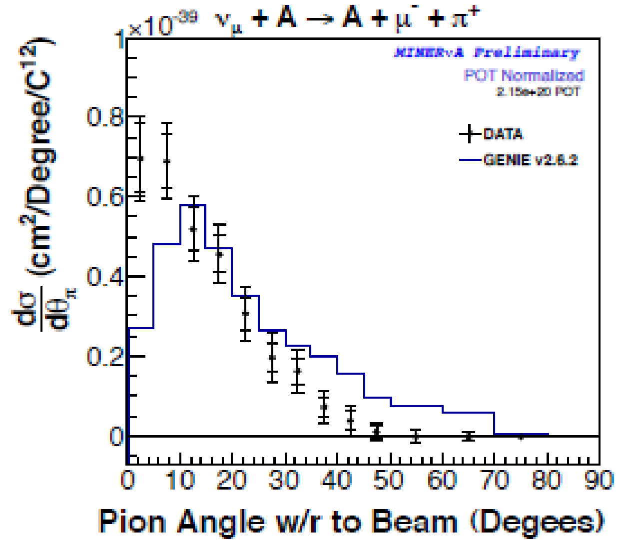


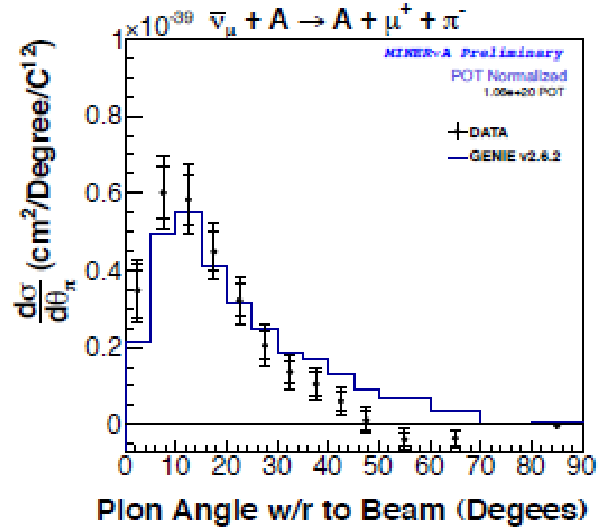


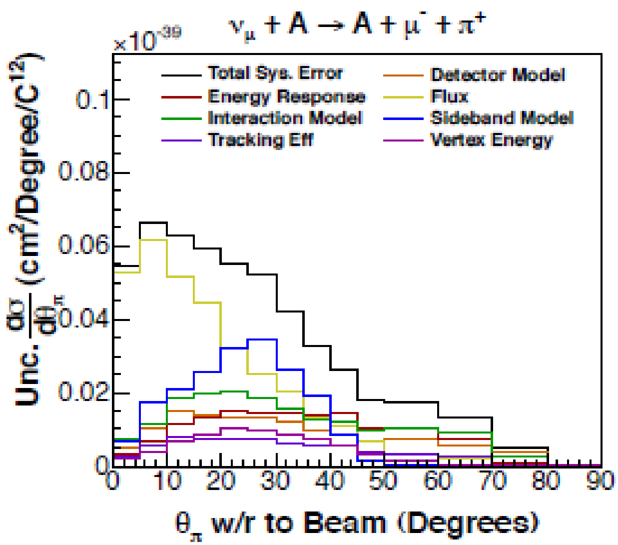


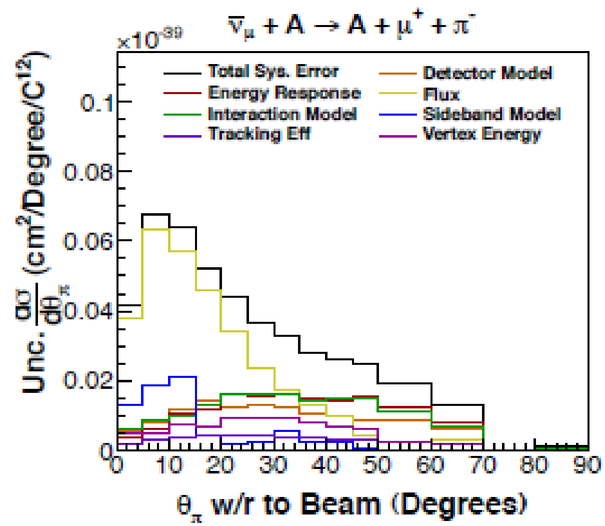


Cross Sections









Resume.

- Constraining CC coherent pion production at few GeV is needed by oscillation experiments
- MINERvA has isolated a coherent-rich sample using an event-by-event measurement of $|t| = |(q-p)^2|$
- Disagreement is observed between our data and the prediction by GENIE's implementation of the Rein-Sehgal model
- Need to compare our data with other models
- Contribution from diffractive scattering off Hydrogen needs to be considered when interpreting our data - currently estimated to be ~17% of our signal

Inclusive ratios (Fe:CH, Pb:CH) Phys Rev Lett 112.231801 (2014).

We present measurements of muon neutrino charged-current cross section ratios on Carbon, iron, and lead relative to a scintillator (CH) using the fine-grained MINERvA detector exposed to the NuMI neutrino beam at Fermilab.

The measurements utilize events of energies $2 < E_{neutrino} < 20$ GeV, with $\langle E_{neutrino} \rangle = 8$ GeV, which have a reconstructed neutrino - scattering angle less than 17 degrees to extract ratios of inclusive total cross sections as a function of neutrino energy –Eneutrino- and flux-integrated differential cross sections with respect to the Bjorken scaling variable x.

$CC\nu_\mu$ Results

Charged-Current Inclusive Ratios of Cross Sections

Signal Kinematics

2 < Neutrino Energy < 20 GeV

0 < Muon Angle < 17 deg

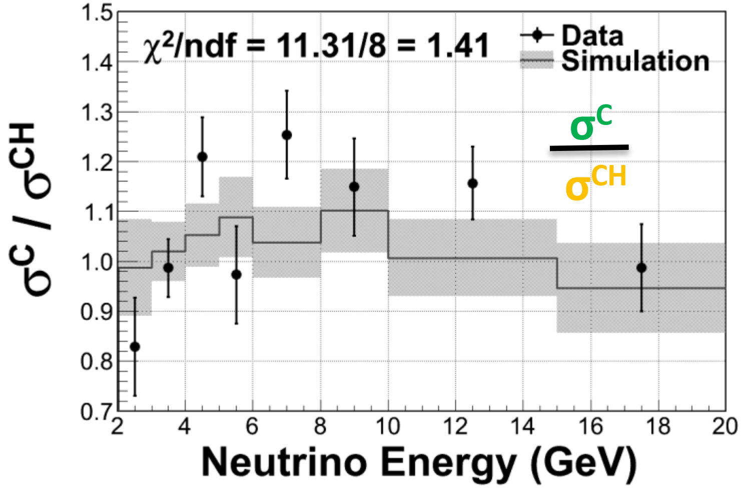
Neutrino Energy

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

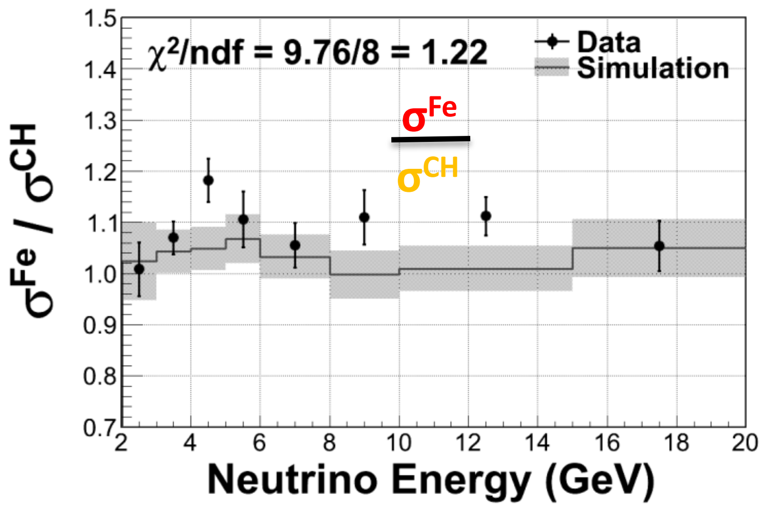
Bjorken x

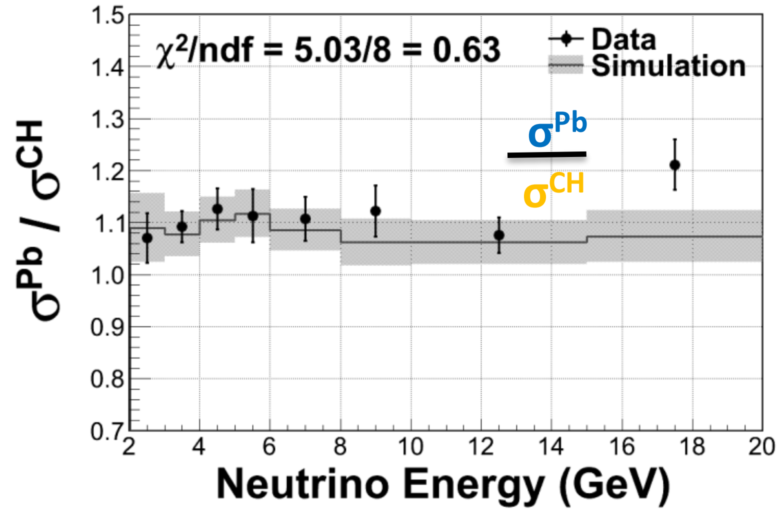
$$\frac{d\sigma^{C}/dx}{d\sigma^{CH}/dx} \qquad \frac{d\sigma^{Fe}/dx}{d\sigma^{CH}/dx} \qquad \frac{d\sigma^{Pb}/dx}{d\sigma^{CH}/dx}$$

Neutrino Energy



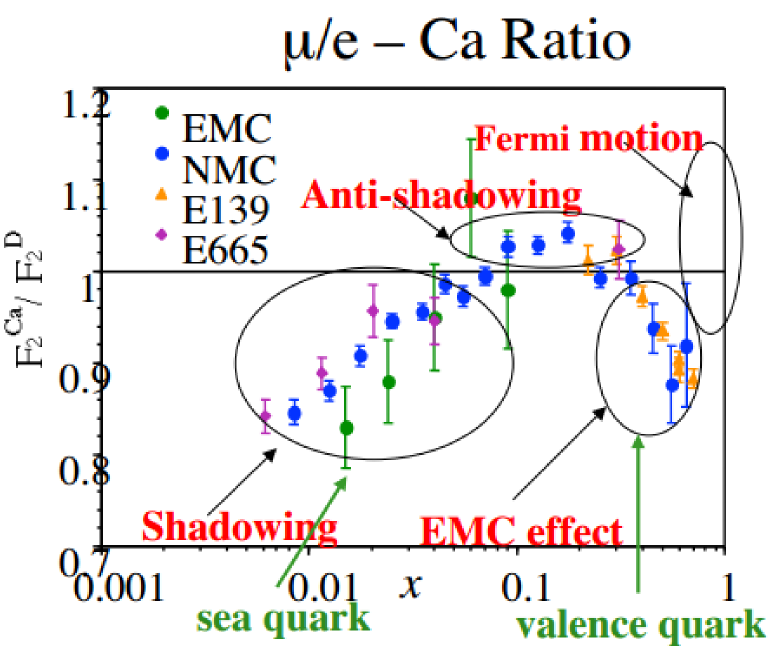
- No evidence of tension between our data and simulation here
  - Good news for oscillation experiments so far…

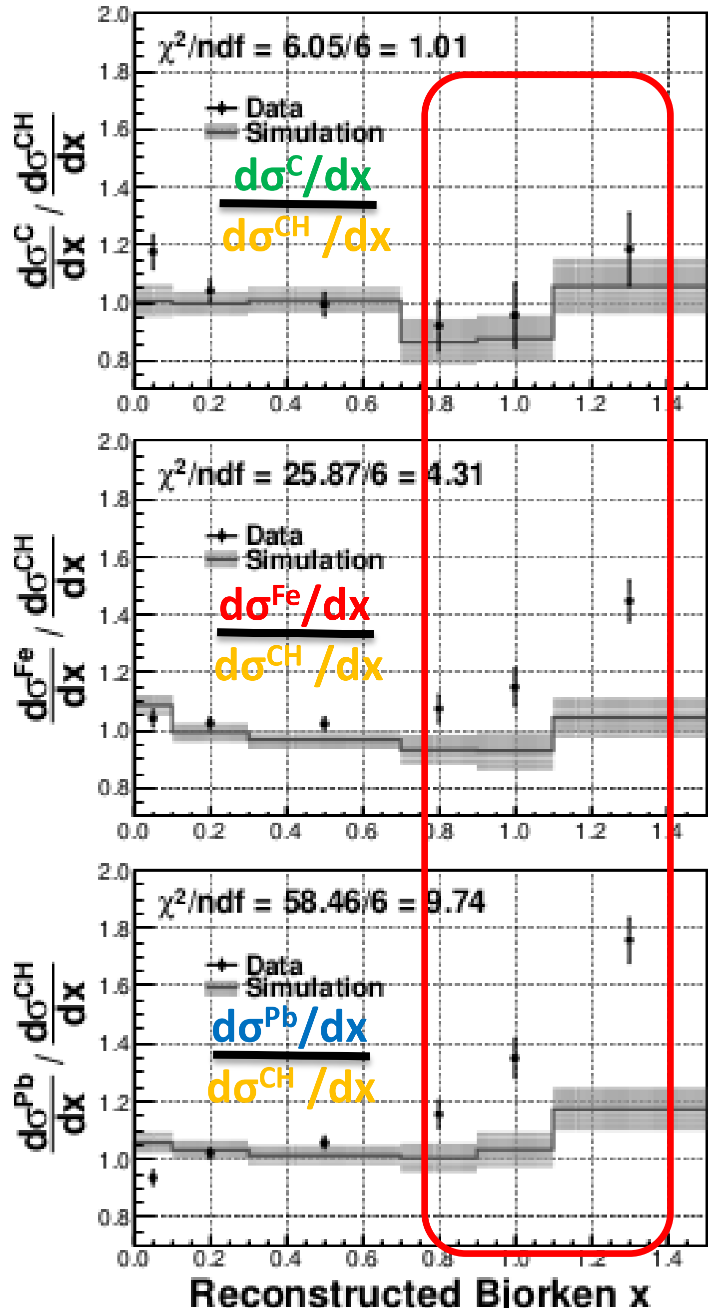




High x

- At x=[0.7,1.5], we observe a **excess** that grows with the size of the nucleus
- This effect is not observed in simulation





Low x

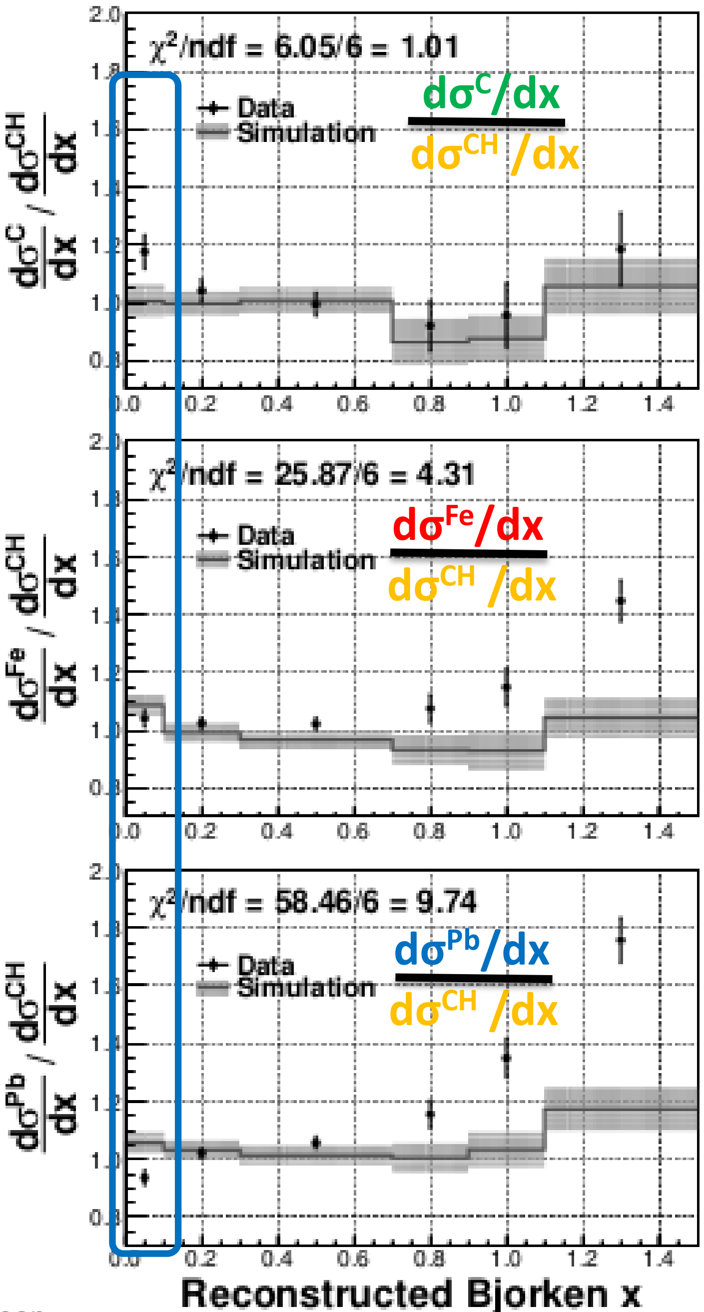
- At x=[0*,0.1], we observe a **deficit** that increases with the size of the nucleus.
- This effect is not modeled in simulation

Expected Neutrino Differences

Neutrinos sensitive to structure function xF_3

Neutrinos sensitive to axial piece of structure function F_2

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



Resume

CCν_μ

- First results from nuclear targets in MINERvA
- First precise direct measurement of nuclear dependence of neutrino cross sections in the few-GeV regime.
- Result published in PRL. Find it at arXiv:1403.2103.

Measurement of Ratios of ν_μ Charged-Current Cross Sections on C, Fe, and Pb to CH at Neutrino Energies 2–20 GeV

- Our data are not reproduced by simulation.
  - Available models differences are small compared to discrepancy
- Oscillation experiments should consider discrepancies in systematics.

- More theoretical work is needed to improve models of neutrino-nucleus scattering in all kinematic regions.

MINERvA in the near Future

Some analyses are in the way:

--Muon neutrino Single charged pion in CH (to be submitted soon!).
--Coherent charged pion – neutrino and anti neutrino CH.
-- 2-track QE muon neutrino CH, Fe, Pb (muon and p).
-- neutrino-e scattering yield as beam flux constraint (CH).
--CC pion 0 production – antineutrino CH.

More data in the Medium Energy region.

This is a list of the key processes which can contribute to the total cross section at these intermediate neutrino energies.

CC Quasielastic.
NC elastic scattering.
Resonant single pion production.
Coherent pion production.
Multipion production.
Kaon production.
DIS (Deep Inelastic Scattering).

Also MINERvA can contribute to these studies up to approximately 50 GeV., in the DIS interaction process.

Conclusions

1. **More studies of neutrino nuclei interactions are needed in all energy regions and in all interaction process.**

2. **With multiple nuclear targets, MINERvA will also be able to complete the first detailed examination of nuclear effects in neutrino DIS.**

3. **Better models of neutrino nuclei interactions are needed.**

The End, Thanks!