PROBING NUCLEI WITH NEUTRINOS

Jonathan Miller
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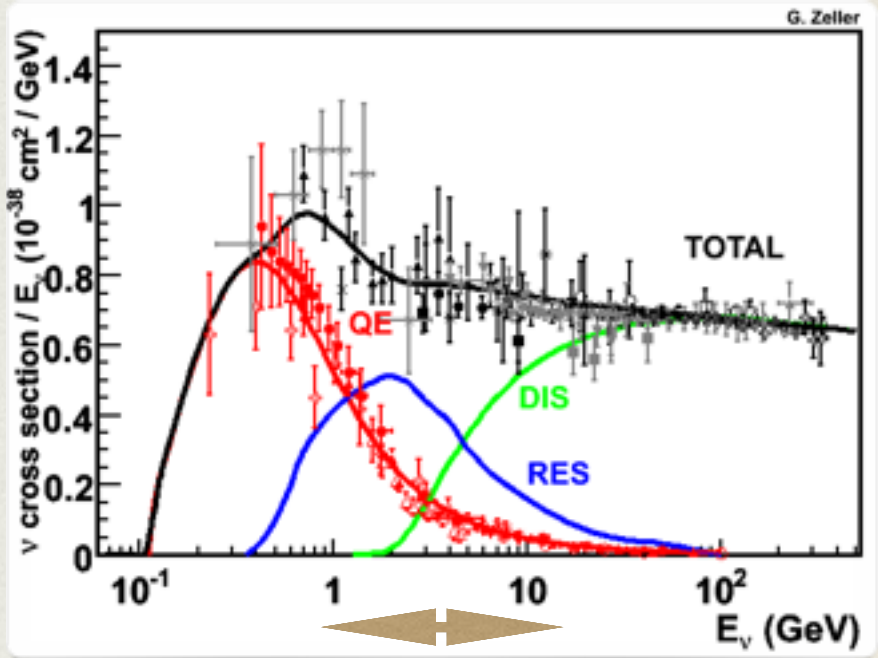
For the MINERvA Collaboration

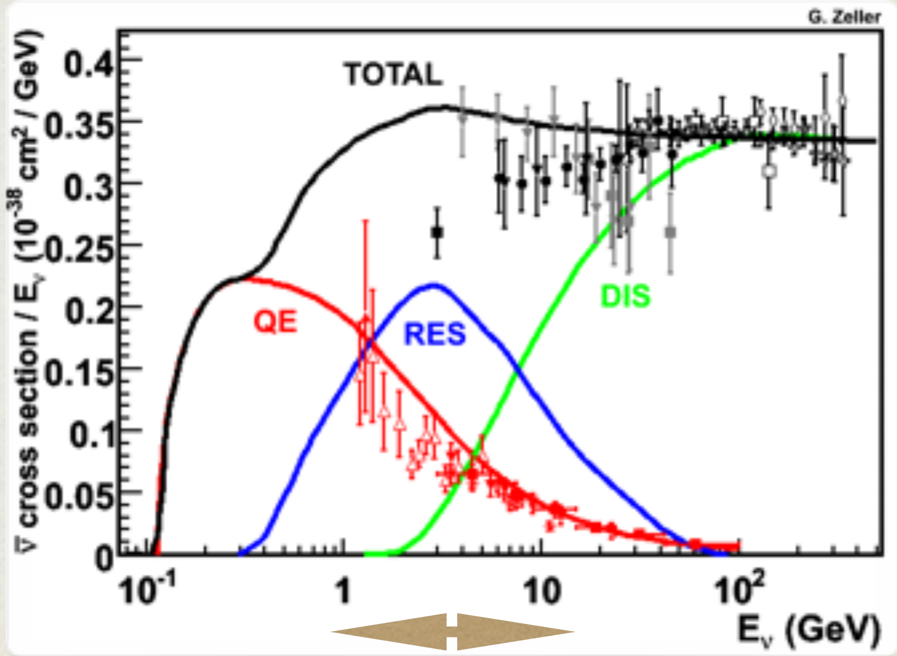
OUTLINE

- **Introduction to MINERvA**
- Neutrino Nucleus Scattering
- Quasi-Elastic Scattering
- Pion Production
    - Charged and Coherent
- Inclusive Charged Scattering
- Summary and Conclusions

neutrino



antineutrino



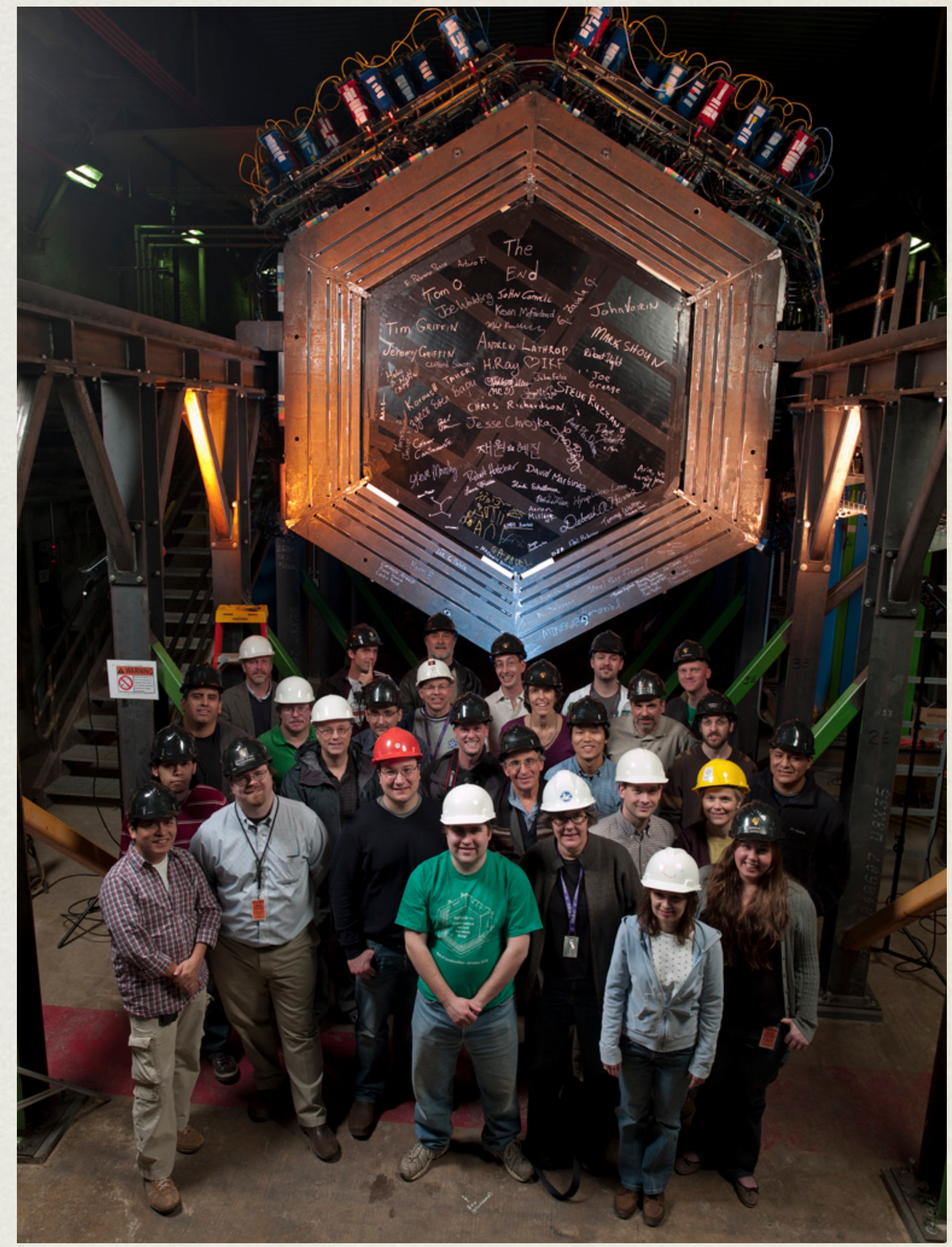
J. A. Formaggio, G.P. Zeller, Rev. Mod. Phys. 84 (2012)

MINERvA COLLABORATION

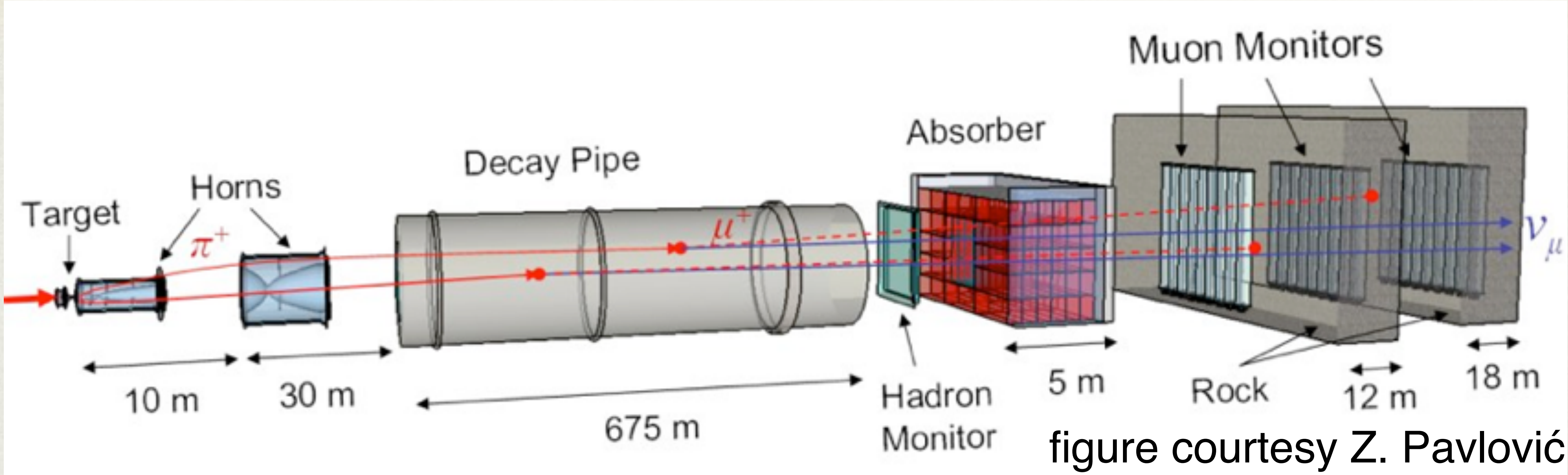
- Located underground at Fermilab, Chicago USA.

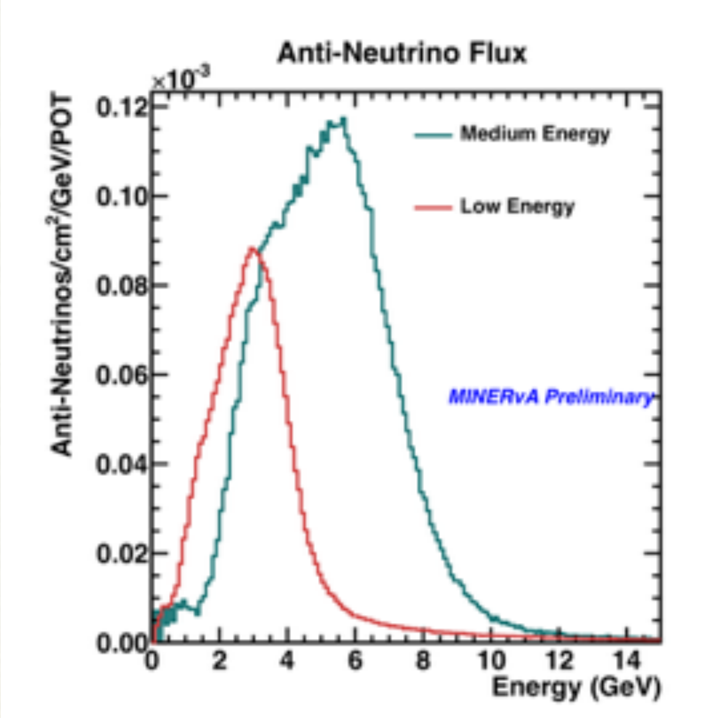
- Institutions from 9 countries with over 60 collaborators.

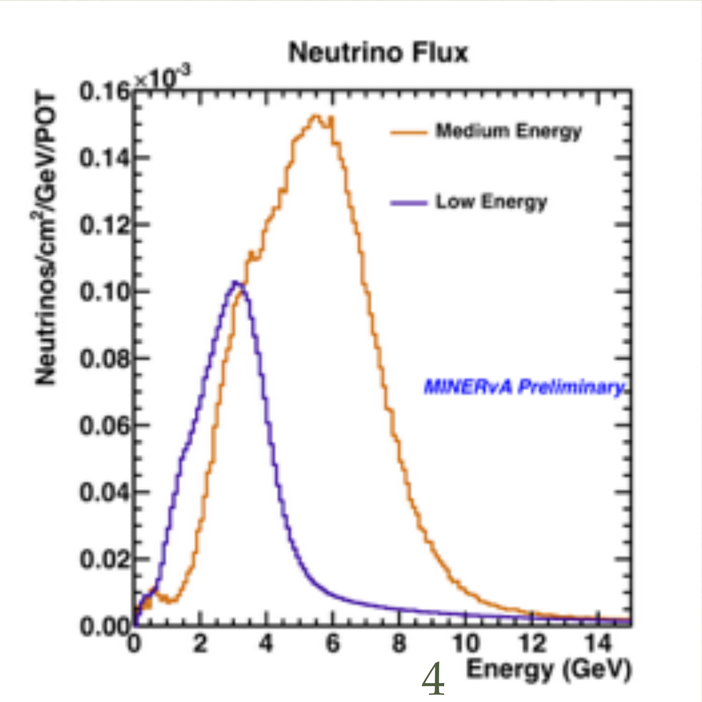
University of Athens
University of Texas at Austin
Centro Brasileiro de Pesquisas Físicas
Fermilab
University of Florida
Université de Genève
Universidad de Guanajuato
Hampton University
Inst. Nucl. Reas. Moscow
Mass. Col. Lib. Arts
Northwestern University
University of Chicago
Otterbein University
Pontificia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



NUMI BEAM



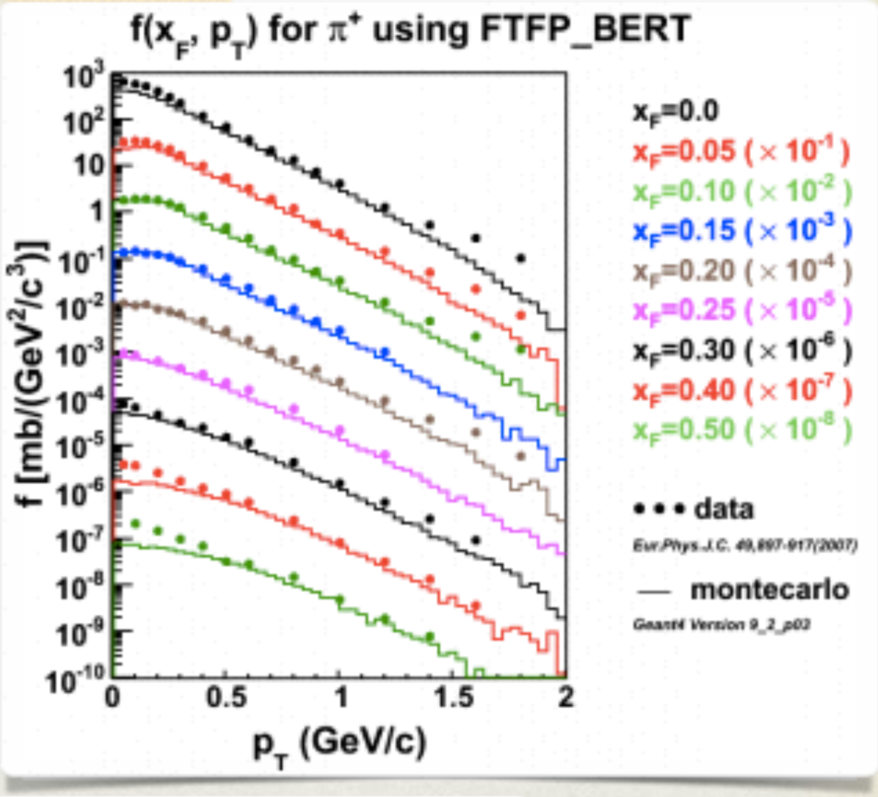


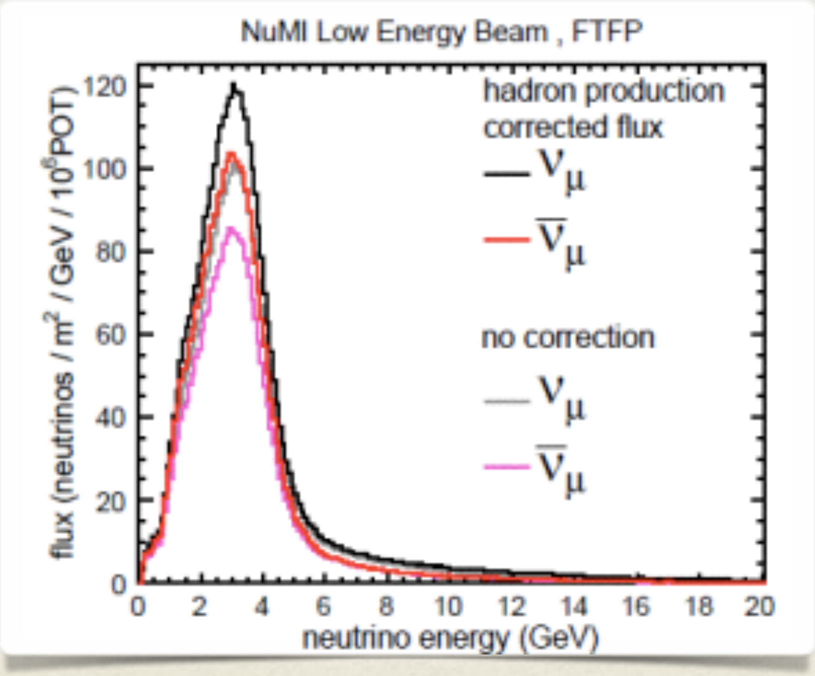


- 120 GeV/c protons from Main Injector on graphite target producing pions which decay.
- Horns focus negative or positive pions to produce ν or anti-ν (lower flux) beam.
- Medium Energy (ME) run started in September 2013 (in progress).

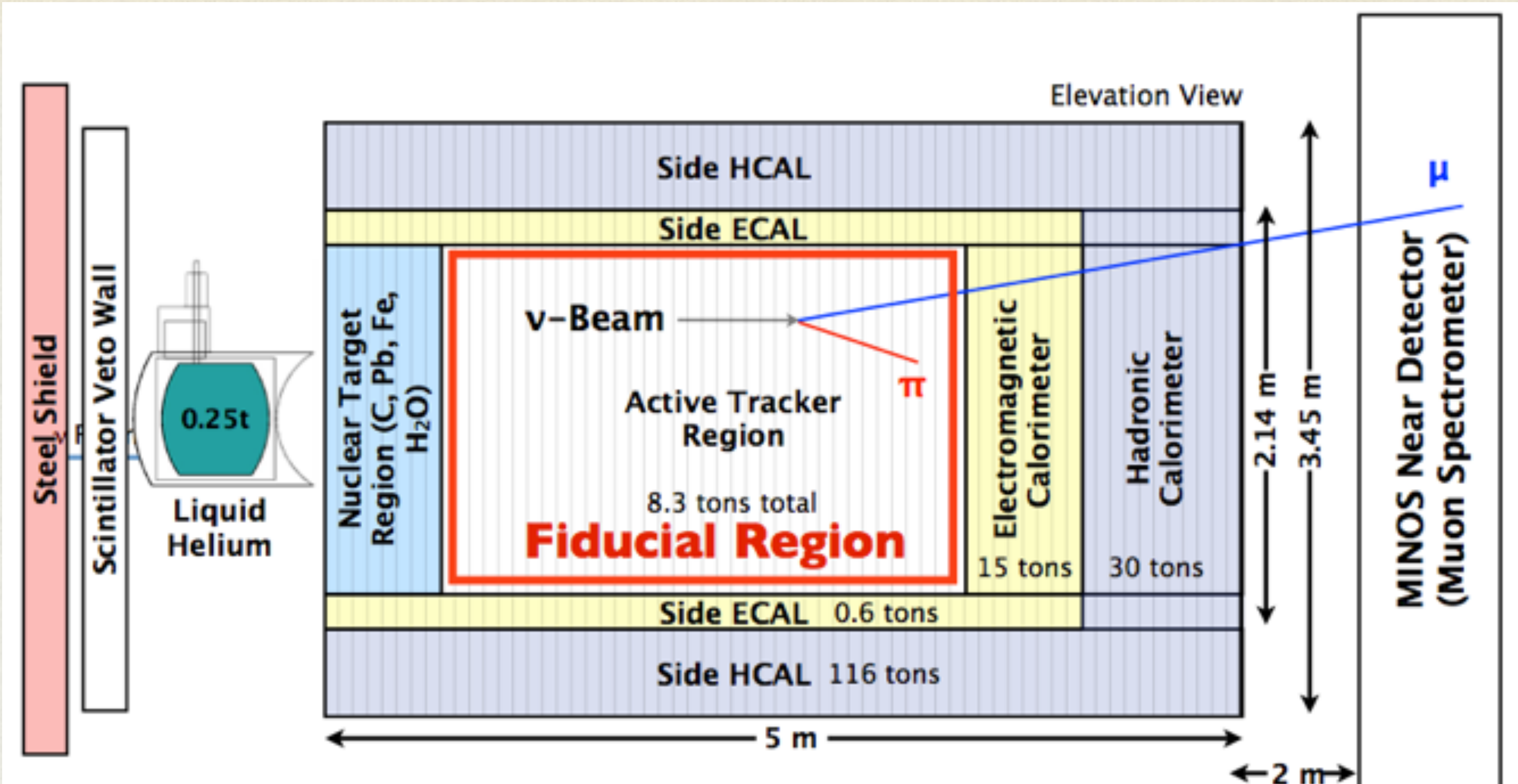
FLUX

- Understanding the neutrino flux is difficult.
- Currently flux is simulated in GEANT4 and then reweighted to match hadron production data from NA49. Recent MIPP data will help a lot.
- Using Nu-E scattering to constraint the flux (important for ME data)





MINERvA DETECTOR



Nucl. Inst. and Meth. A743 (2014) 130

- 120 (CH) modules for tracking and calorimetry (32k readout channels)
- Tracker surrounded by electromagnetic and hadronic calorimetry
- The MINOS near detector serves as a muon spectrometer
- Nuclear targets of C (166 kg), Fe (653 kg), and Pb (750 kg)

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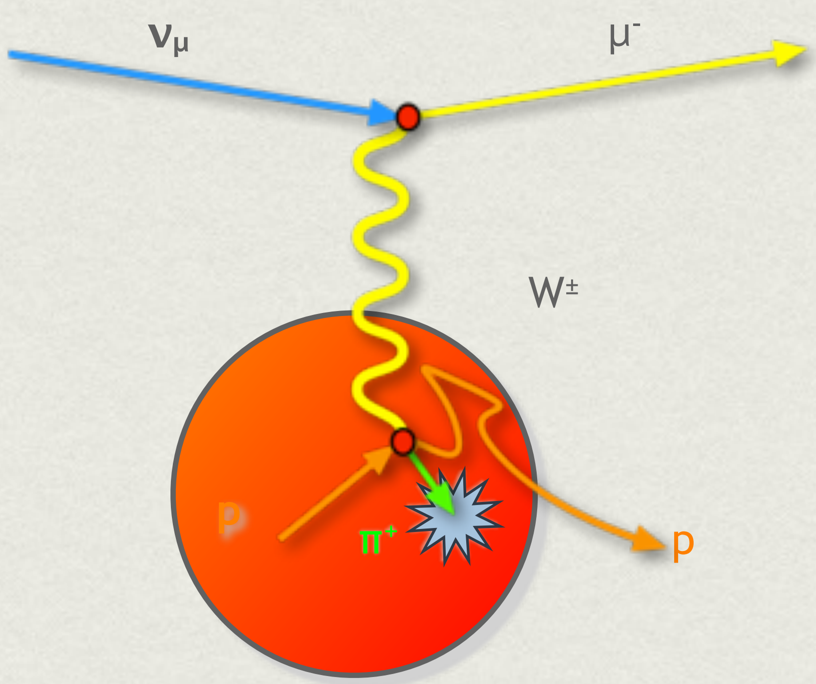


NEUTRINO NUCLEUS SCATTERING

$$Y_{c-like}(E_d) \propto \phi_\nu(E' \geq E_d) \otimes \sigma_{c,d,e,\ldots}(E' \geq E_d) \otimes \mathrm{Nuc}_{c,d,e,\ldots}(E' \geq E_d)$$

- The observed measurement (c-like topology at E_d observed energy) depends on the initial reaction but is convoluted due to flux and nuclear effects.
- Current flux uncertainties are ~10%, possibly to be improved to ~5%.
- $\sigma_{c,d,e,\ldots}(E')$ is the measured energy dependent neutrino cross section off a nucleon within the nucleus.
- $\mathrm{Nuc}_{c,d,e,\ldots}(E')$ are nuclear effects which takes the interaction of a neutrino with energy E' and channel c,d,e and then appear in our detector as an event of energy E_d and channel c.

NUCLEAR EFFECTS

- Nucleon is in motion - classical Fermi gas model or spectral functions.

- Nucleon-nucleon correlations such as Meson Exchange Currents imply multi-nucleon initial states.

Same physics different description

- Cross sections, form factors, and structure functions are modified within the nuclear environment and parton distribution functions (pdfs) within a nucleus are different than in an isolated nucleon.

- Produced topologies are modified by final-state interactions (FSI).

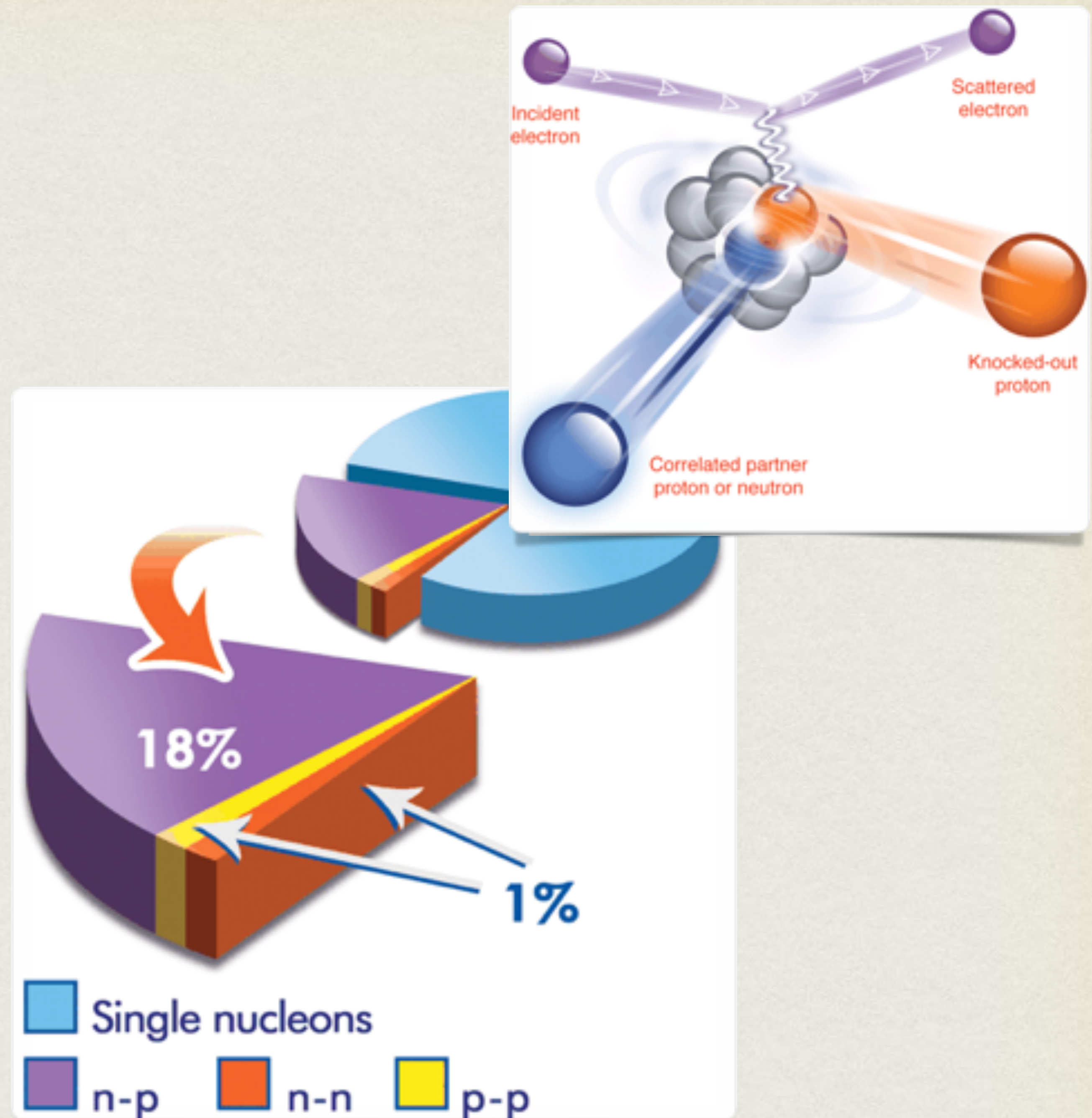
  - Convolution of $\sigma \otimes$formation zone model$\otimes\pi$-exchange/absorption

NUCLEON NUCLEON CORRELATIONS

- In electron scattering measurements on ^{12}C indicate 20% correlated nucleons.

- In neutrino scattering, initial produced state may be nn in antineutrino and pp in neutrino CC scattering due to scattering off np correlated state.

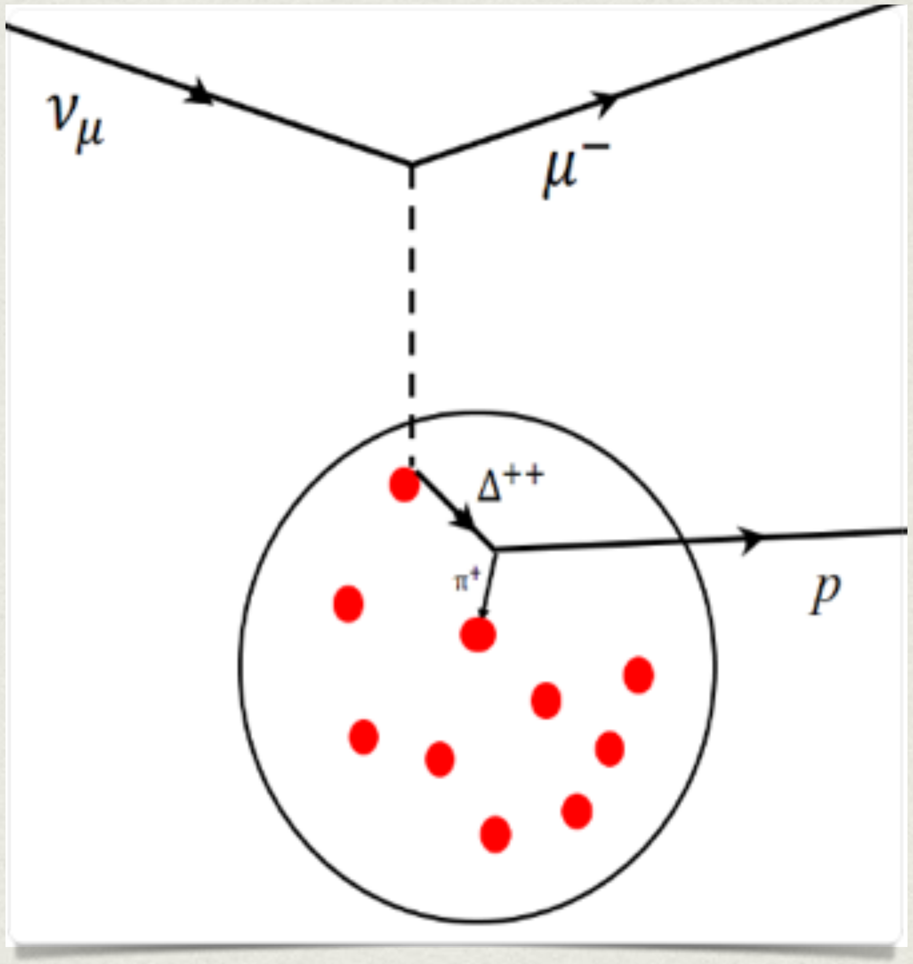
- Final observed channel and energy topology will be modified by FSI.



R. Subedi et al., Science 320, 1476 (2008)

FINAL STATE INTERACTIONS (FSI)

- Interaction between products of initial state and the rest of the nucleus, changing the final state configuration and energy (currently cascade models).
- Example 1: initial pion can charge exchange or be absorbed by pair of nucleons or nucleon can scatter producing pion.
- Example 2: Δ production where Δ scatters before decay. Pion is absorbed releasing 2 neutrons which may not be detected. Proton scatters and comes out of nucleus. Final observed states is a observed as QE-like with a lower energy than that of the neutrino.



GENERATORS

$$Y_{c-like}(E_d) \propto \phi_\nu(E' \geq E_d) \otimes \sigma_{c,d,e,\ldots}(E' \geq E_d) \otimes \mathrm{Nuc}_{c,d,e,\ldots}(E' \geq E_d)$$

- MINERvA observed events are convolutions if the interaction and nuclear effects, modelled in event generators.
  - Key to the interpretation of MINERvA measurements, giving systematic uncertainties and comparisons for background and signal if the given model is correct.
- Current Generators used by experimental community (some with many models)
  - GENIE - ArgoNeut, MicroBooNE, MINOS, MINERvA, NOvA, T2K, LBNE, IceCube
  - NEUT - SuperKamiokande, K2K, SciBooNE, T2K
  - GiBUU - Nuclear Transport Model used to check models in other generators
  - NuWRO - K2K, MINERvA as check of models in other generators

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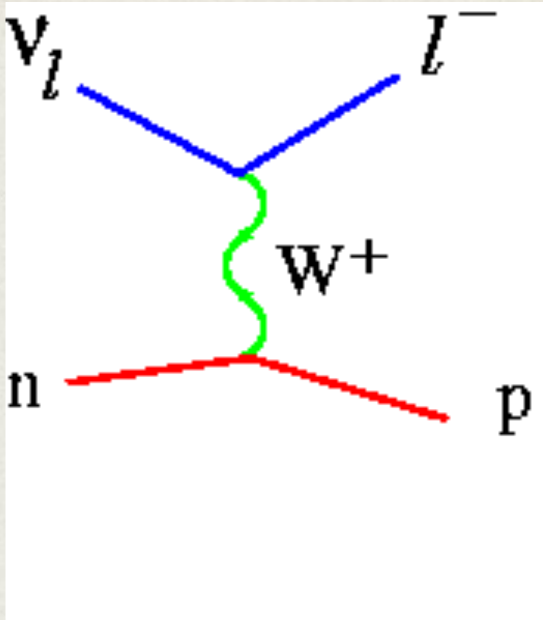


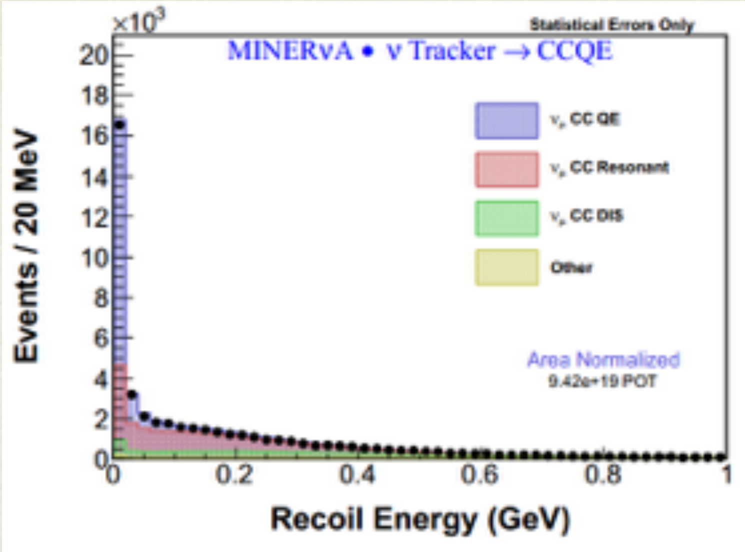
3.98e20 POT neutrinos
1.70e20 POT antineutrinos

Muon Published Phys. Rev. Lett. 111, 022502 (2013). and Phys. Rev. Lett. 111, 022501 (2013).

Hadron Published on arXiv:1409.4497

MUON EVENT SELECTION

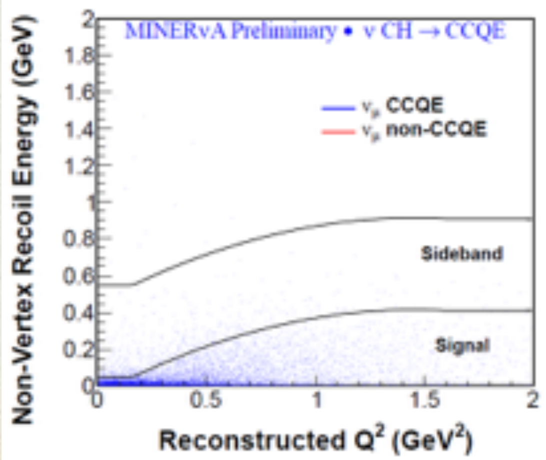
- For Muons
  - Single track with matching track in MINOS.
  - No more than 1 (2) additional blobs for anti-ν (ν).
  - Sum recoil energy calorimetrically, not including energy near vertex.



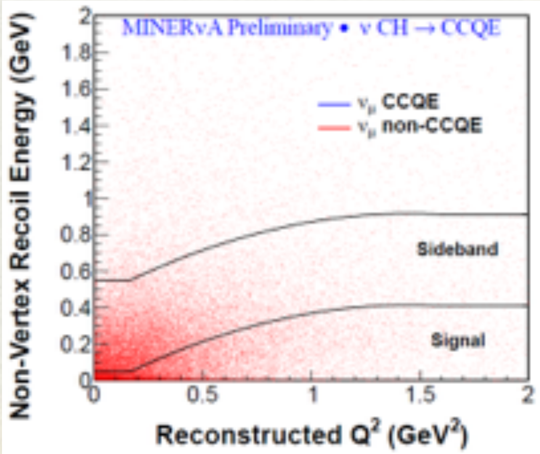
$$E_\nu = \frac{m_n^2 - (m_p - E_b)^2 - m_\mu^2 + 2(m_p - E_b)E_\mu}{2(m_p - E_b - E_\mu) + p_\mu \cos\theta_\mu}$$

$$Q^2_{QE,1-track} = 2E_\nu\left(E_\mu - p_\mu \cos\theta_\mu\right) - m_\mu^2$$

QE Signal



QE Background

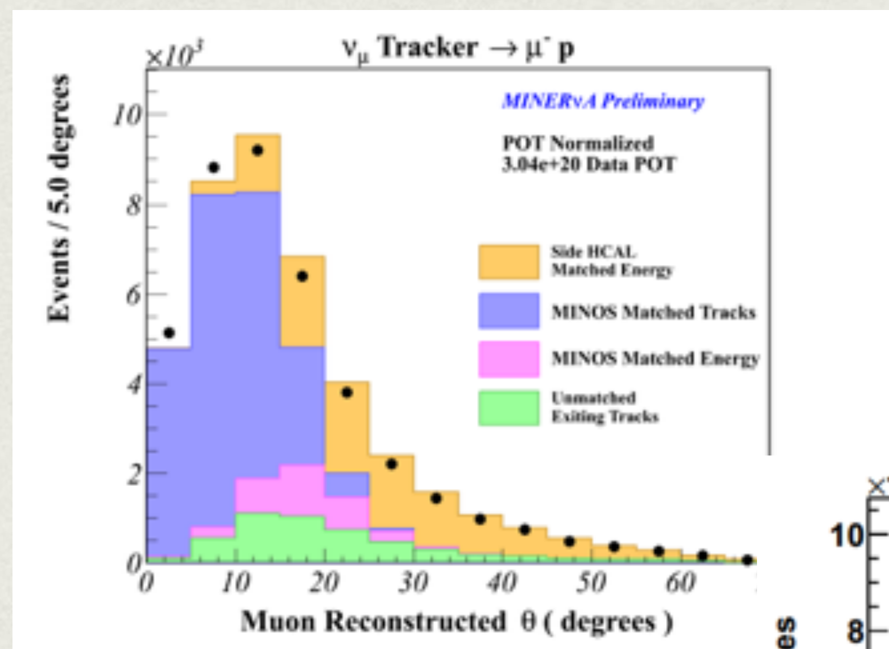


EVENT SELECTION

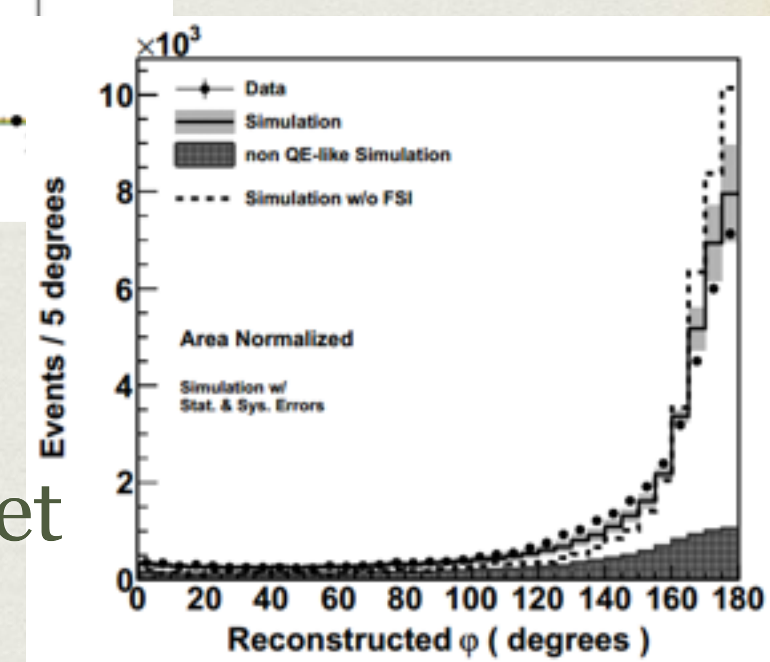
- For Protons

$$Q^2_{QE,2-track} = \left(M_n - \epsilon_B\right)^2 - M_p^2 + 2\left(M_n - \epsilon_B\right)\left(T_p - M_n - \epsilon_B\right)$$

  - Require 2 or more tracks
  - Reject events with any pion
  - Muon does not need to be in MINOS

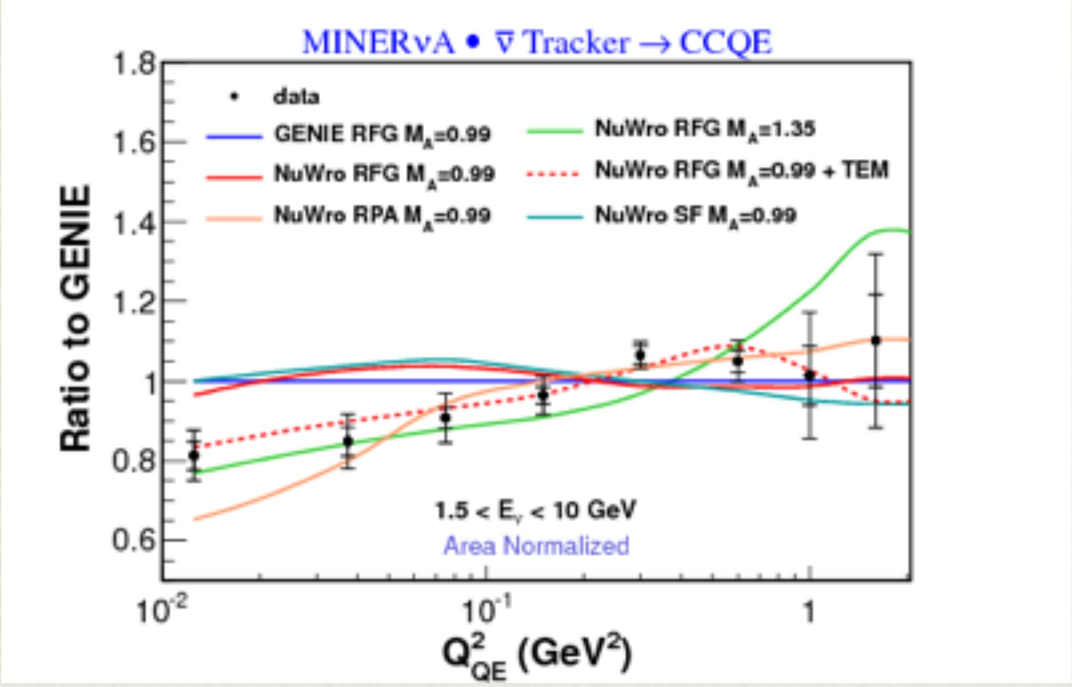


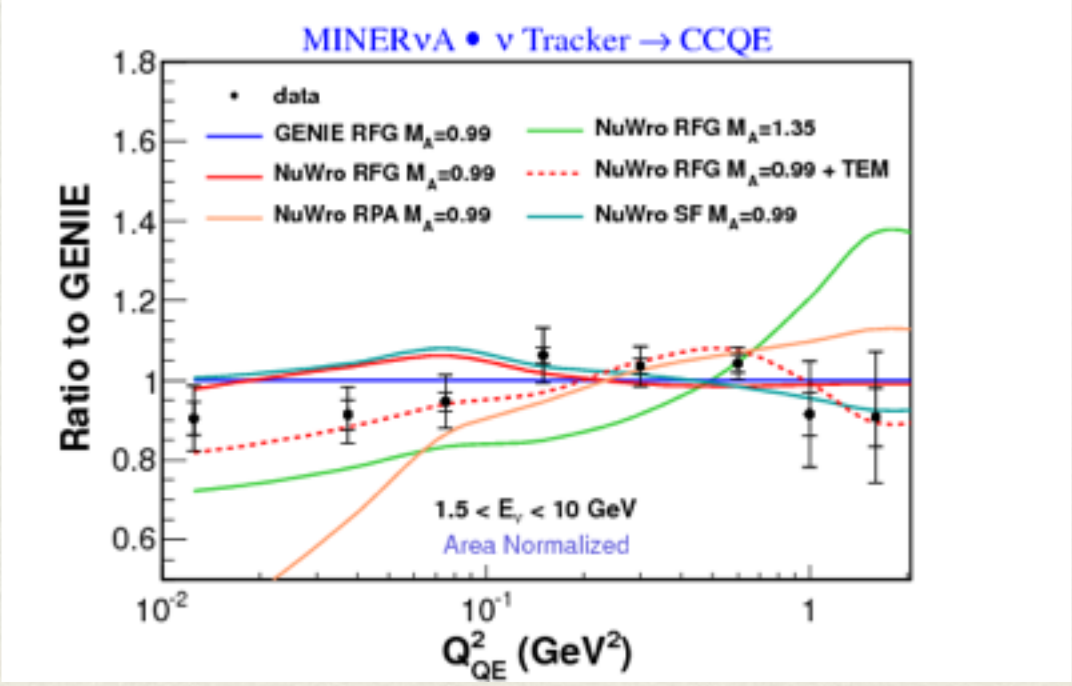
Broader dataset



MUON SELECTION RESULTS

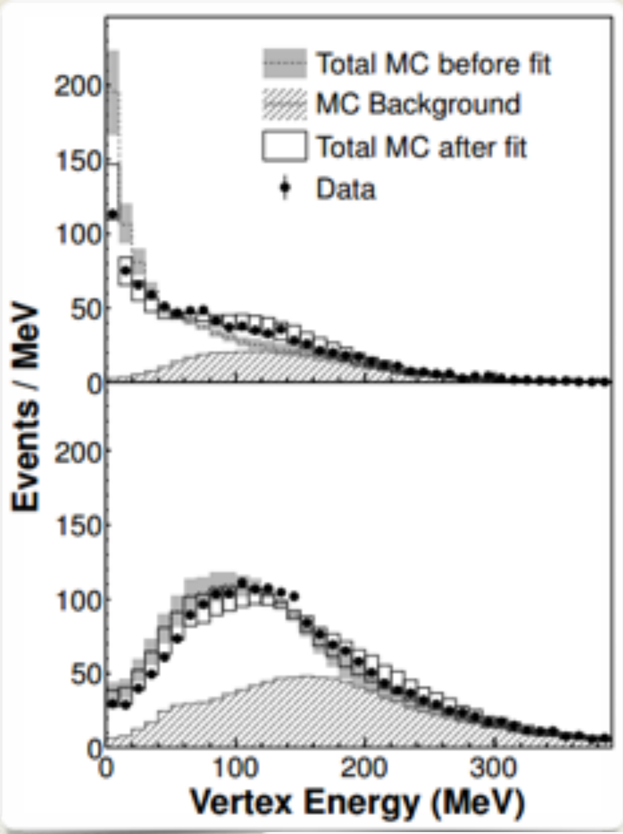
- Basic relativistic Fermi gas model disfavored.
- Increasing axial mass disfavored.
- Relativistic Fermi gas model plus Transverse Enhancement Model favored (neutrino interacts with pair of nucleons, TEM only includes vector component of axial current).



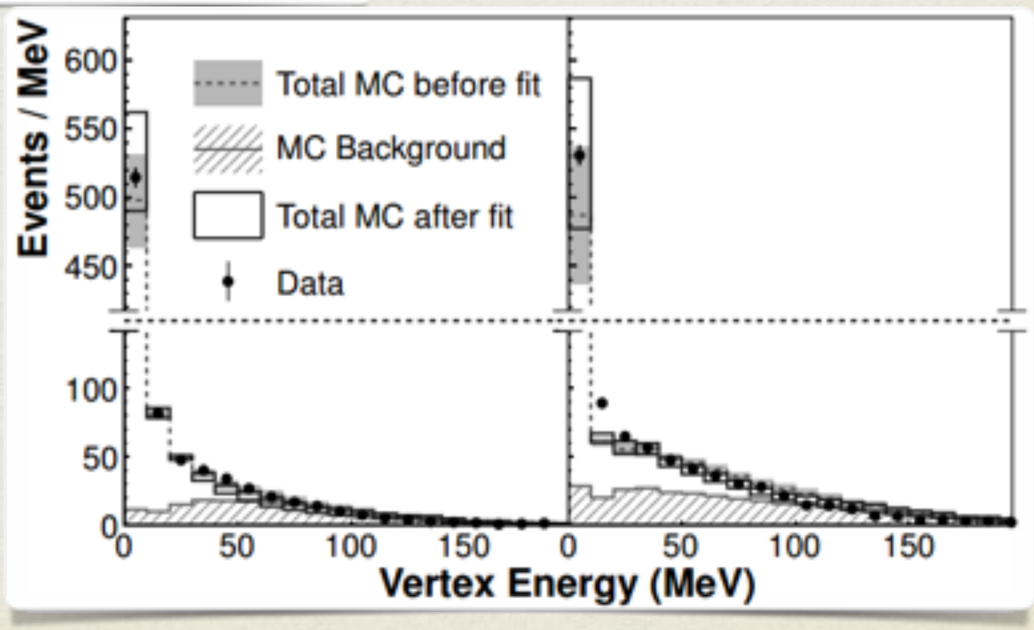


MUON VERTEX RESULTS

- Compare energy in vertex to proton simulation (assumption that additional energy is due to protons).
- Neutrino data suggests that 25% of events have additional proton.
- Antineutrino data suggests that -10% of events have an additional proton



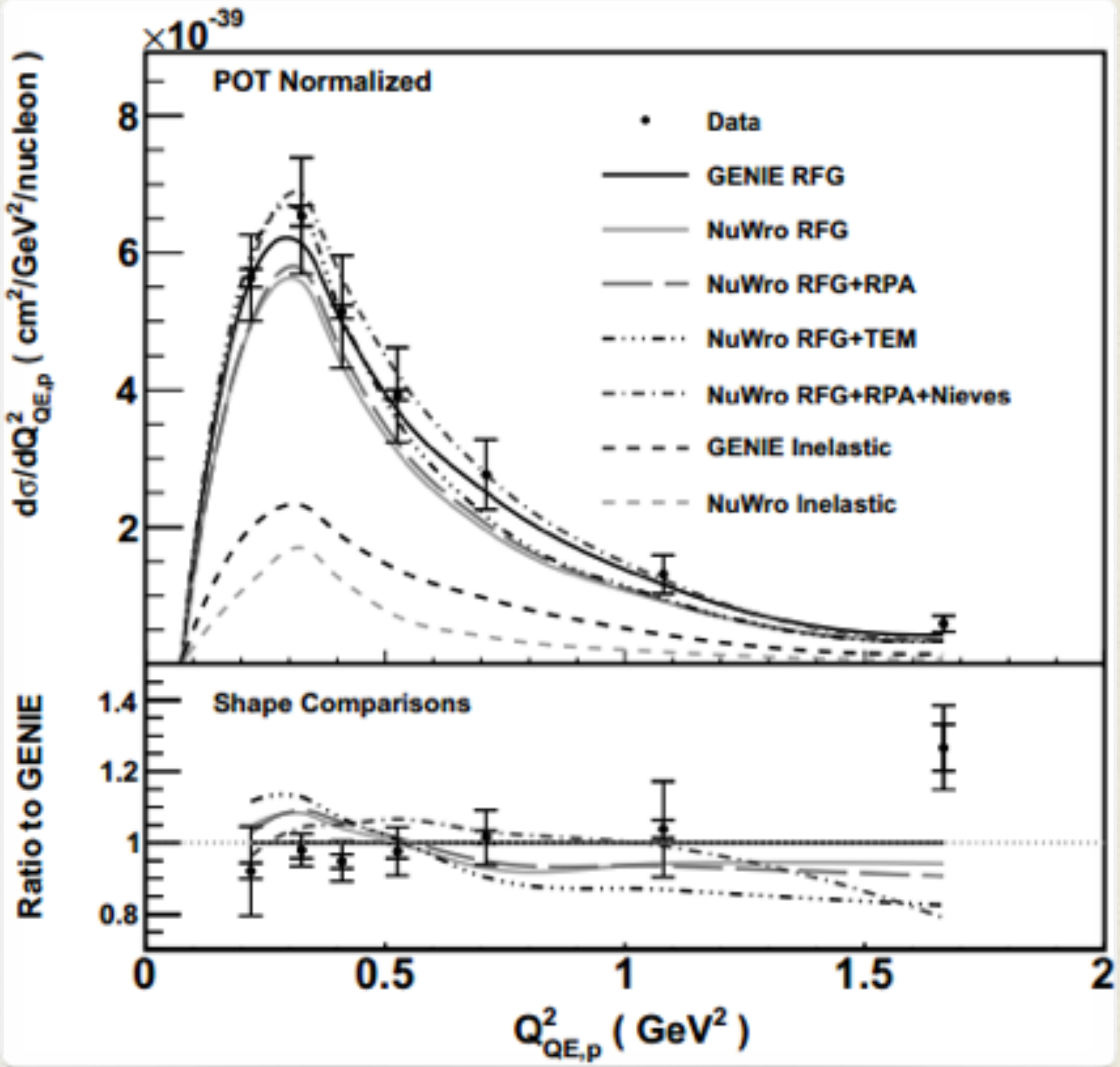
neutrino



antineutrino

HADRON SELECTION RESULTS

- Data favors the simple relativistic Fermi gas model.
- Data should be more sensitive to FSI.
- Models should explain both final state lepton and hadron.
- Discrepancy!



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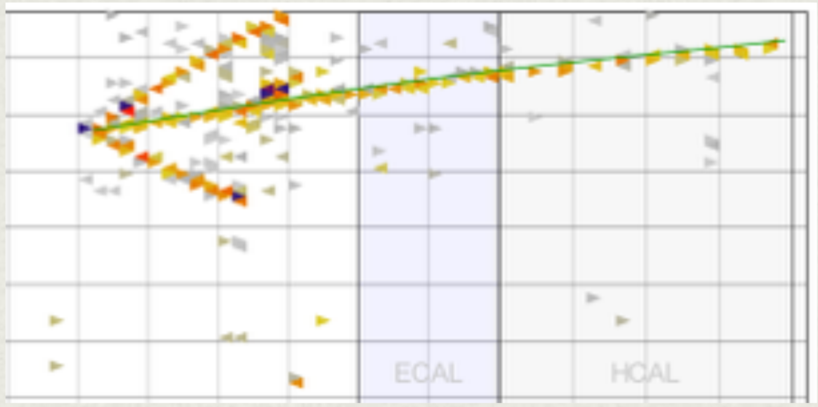
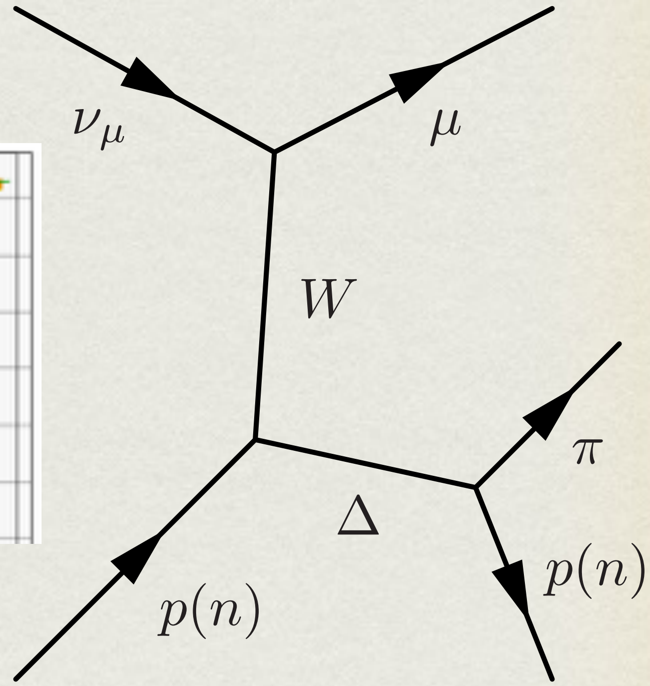


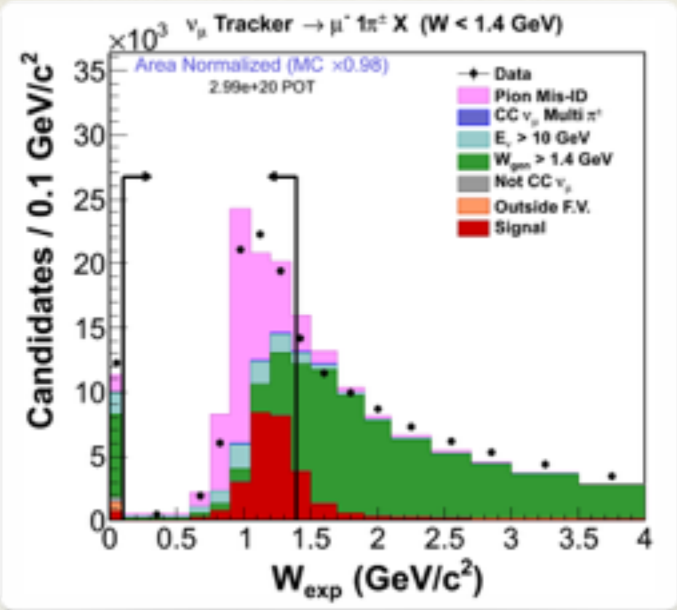


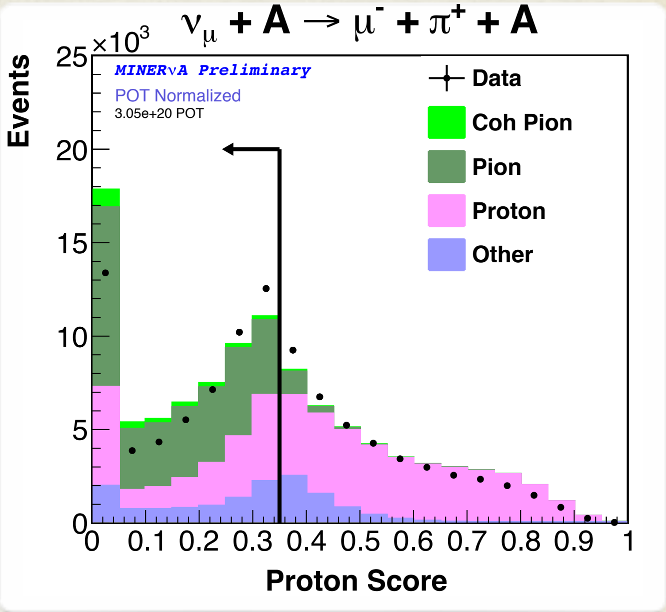
3.04e20 POT neutrinos

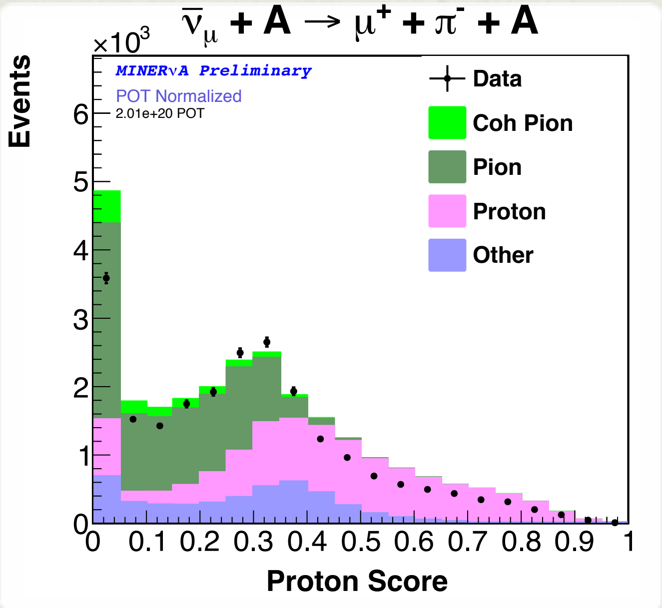
Publication forthcoming on arXiv:1406.6415

CHARGED PION EVENT SELECTION

- Events contain one muon matched in MINOS and exactly one charged pion.
- Only tracks which stop in the electromagnetic calorimeter or tracker region are accepted.
- Pions are identified by dE/dx, and the existence of a Michel electron at the end of the pion track.

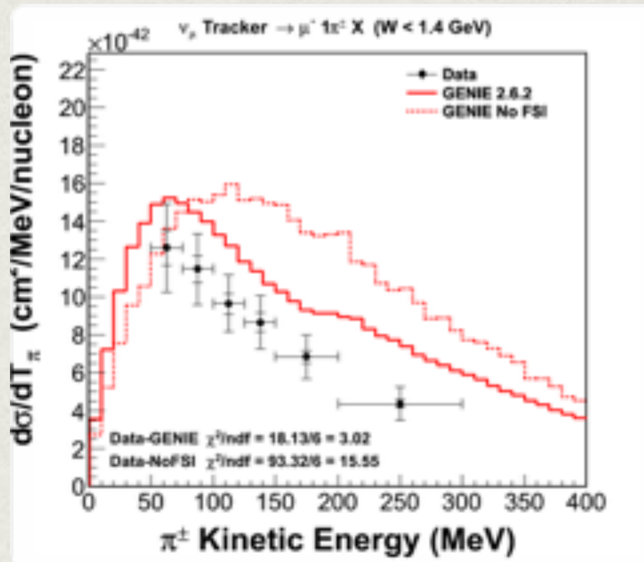


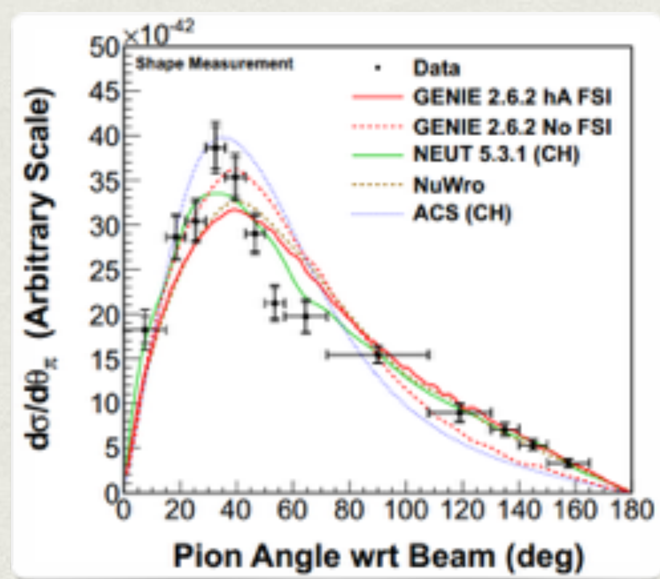


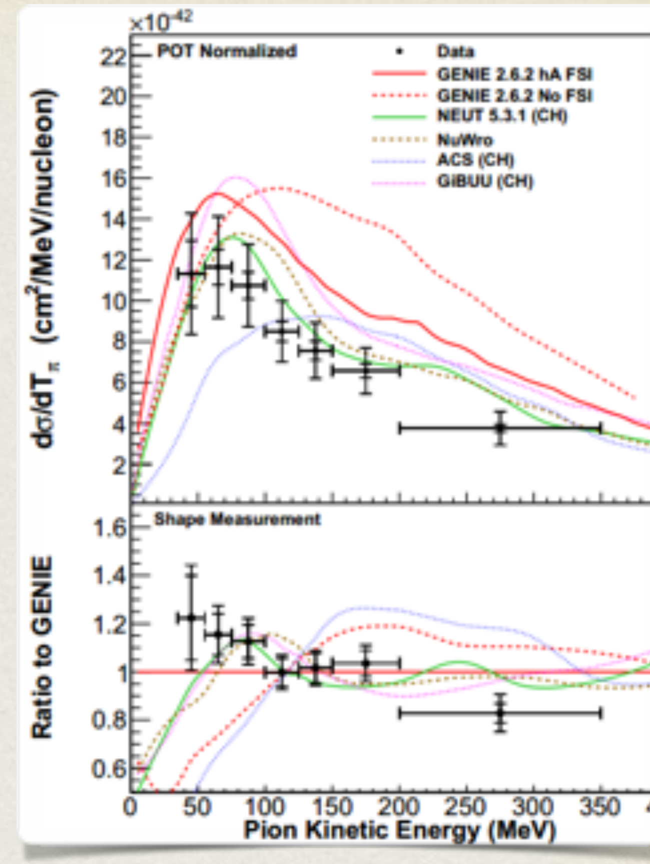


CHARGED PION RESULTS

- The shape only distributions favor GENIE with FSI included.
- The magnitude does not favor investigated GENIE models.
- Difference between MiniBooNE and MINERvA results below 100 MeV not understood.
- Energy dependence of GENIE FSI models not well modeled.







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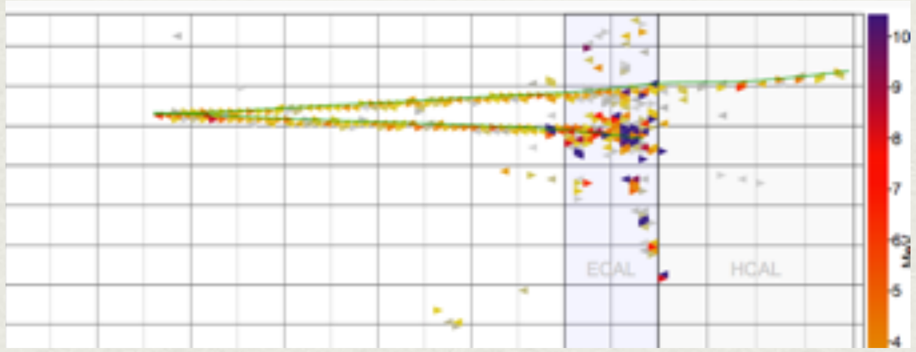
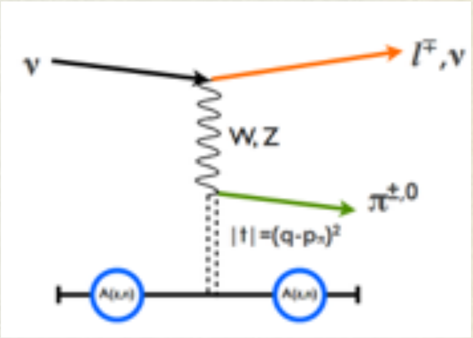




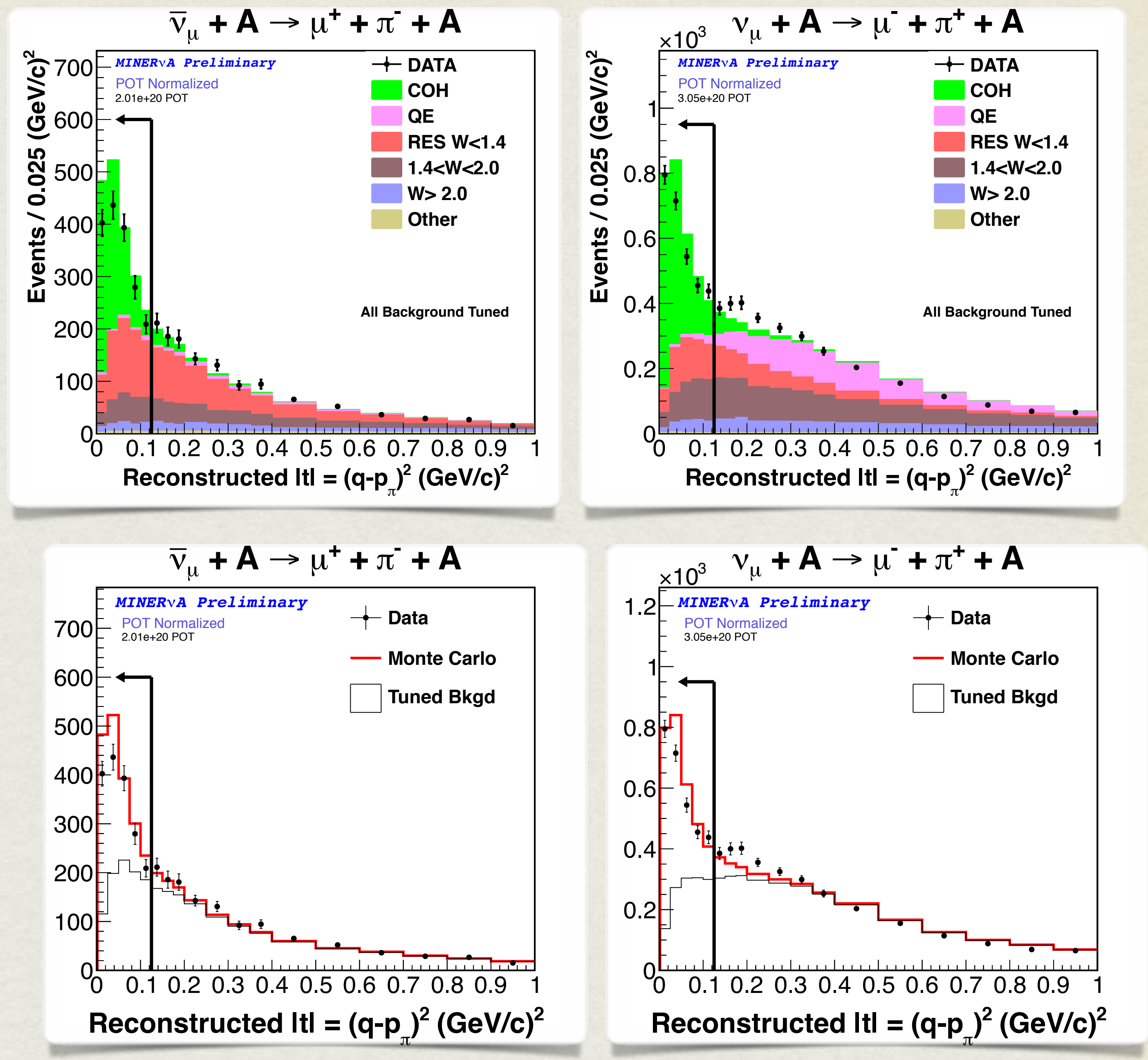
Existence of pion and muon with no nucleon breakup (quiet vertex) and low momentum transferred between nucleus and pion.

3.04e20 POT neutrinos
2.01e20 POT antineutrinos

Phys. Rev. Lett. 113, 261802 (2014) on arXiv:1409.3835

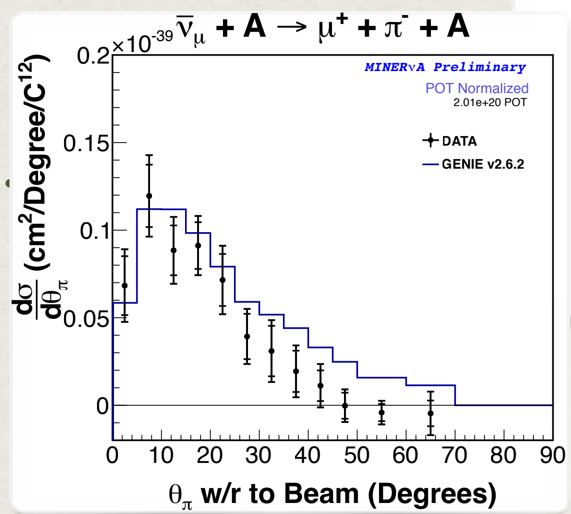
COHERENT PION EVENT SELECTION

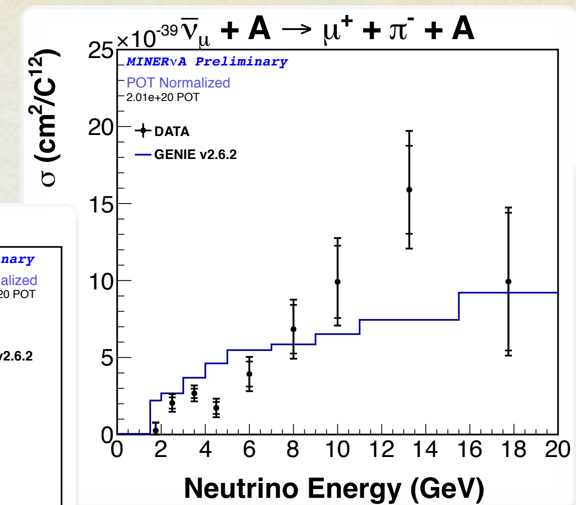
- Events have almost no vertex energy.
- Muon enters MINOS.
- Separation of coherent scattering from incoherent background by slope of |t| due to the slope being different for diffractive and resonant processes.
- Sideband is selected as the incoherent background, is tuned to MC to minimize χ2

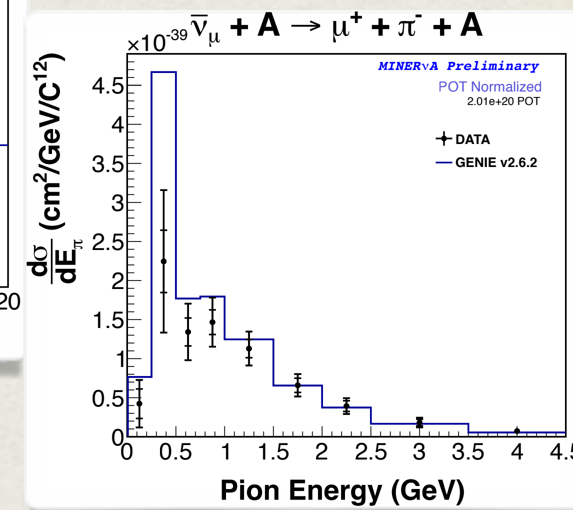


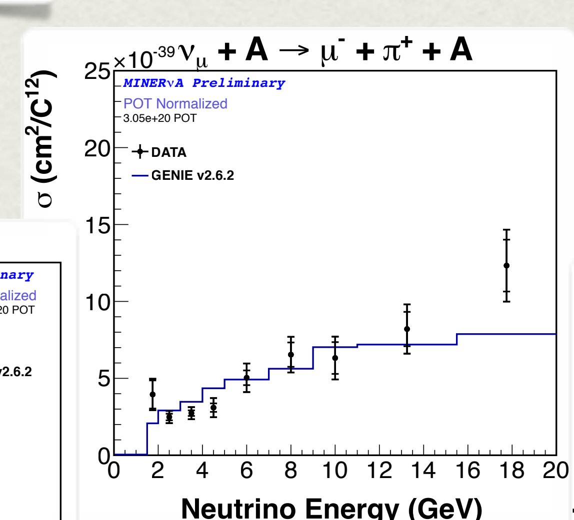
COHERENT PION RESULTS

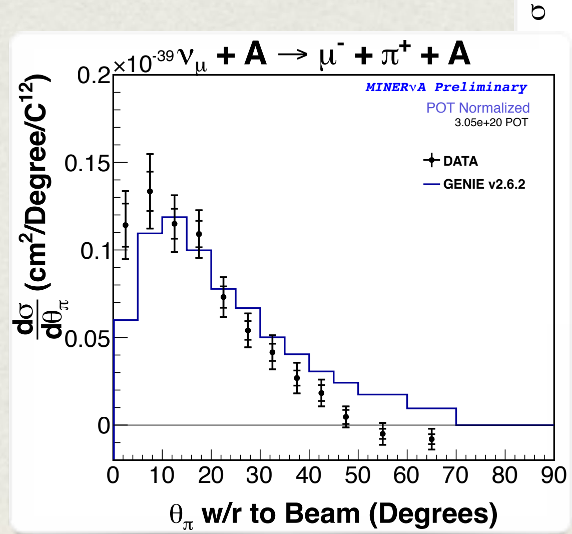
- Data shows a harder and more forward pion distribution than in GENIE.
- The selection of low |t| events allows a model independent measurement of coherent pion production.
- Disagreement at high θ_π
- 1628 neutrino and 770 anti-neutrino events

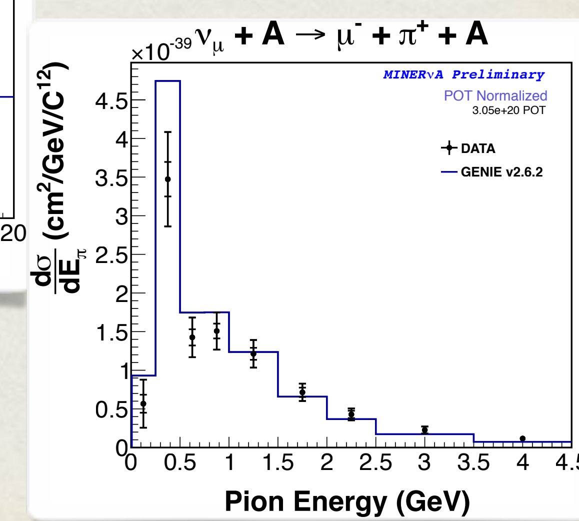




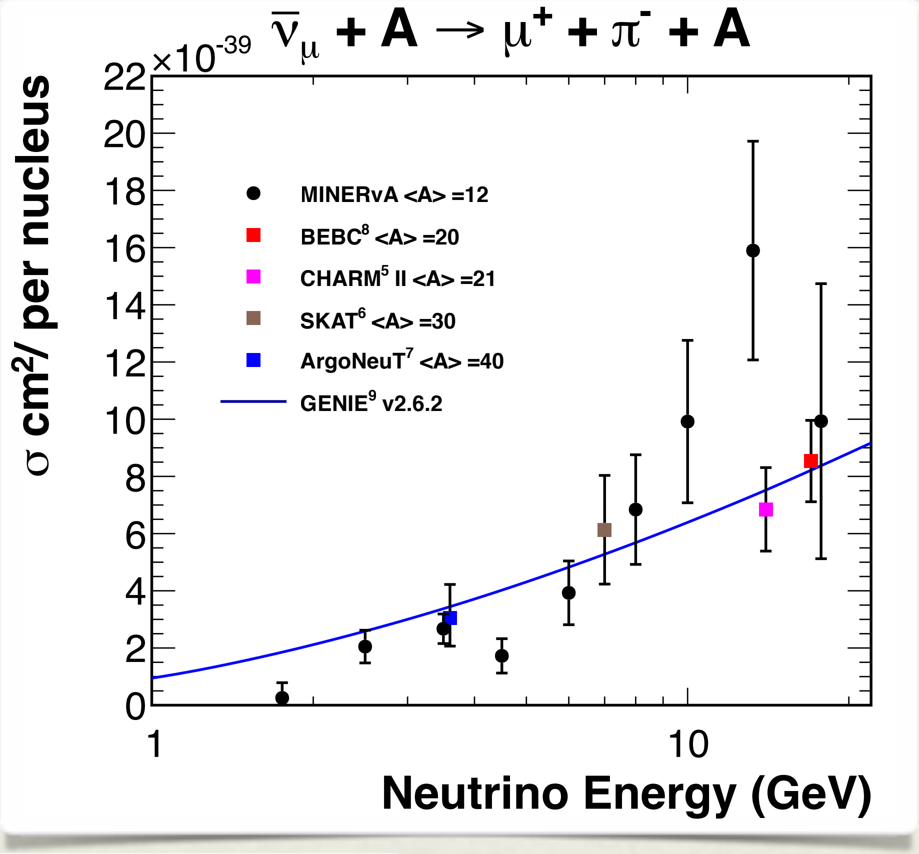


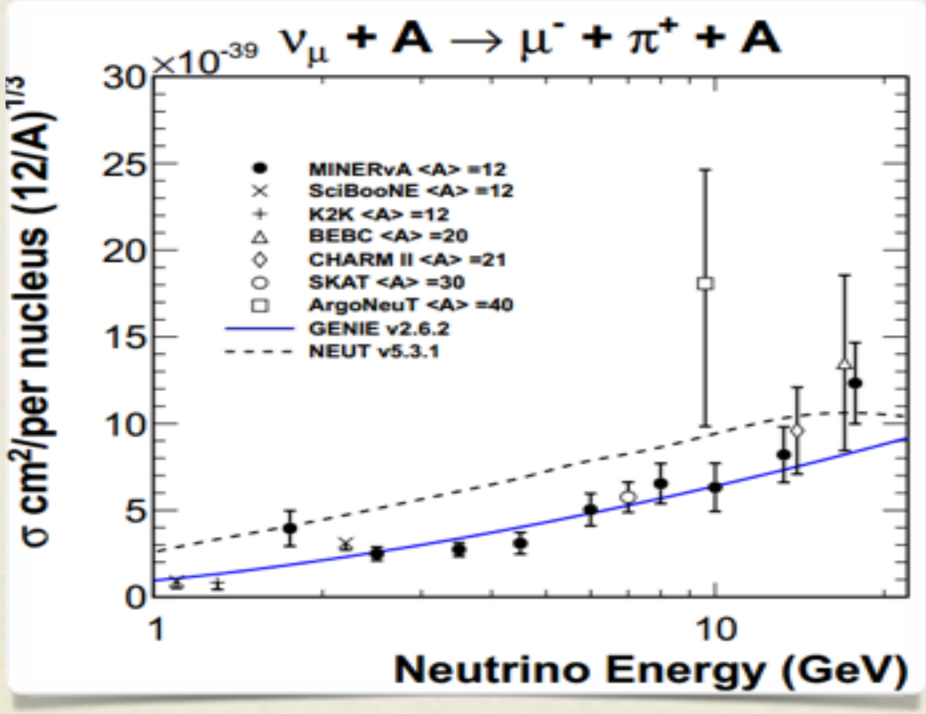




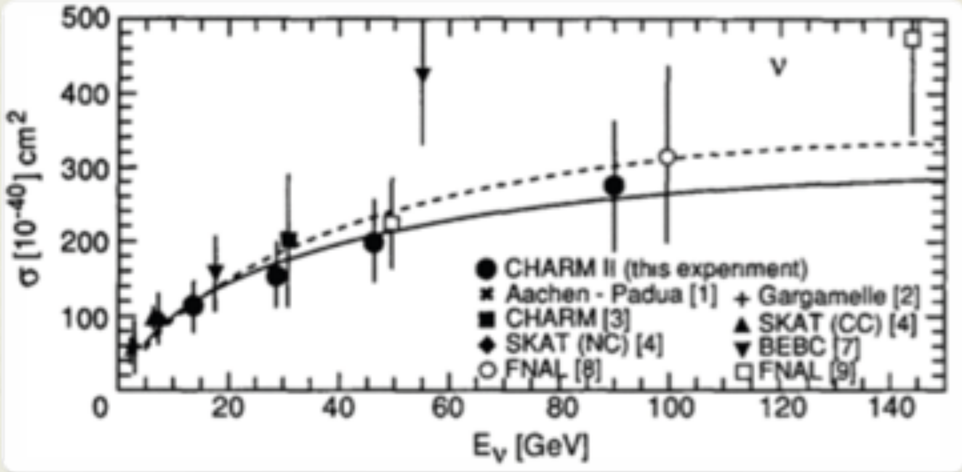


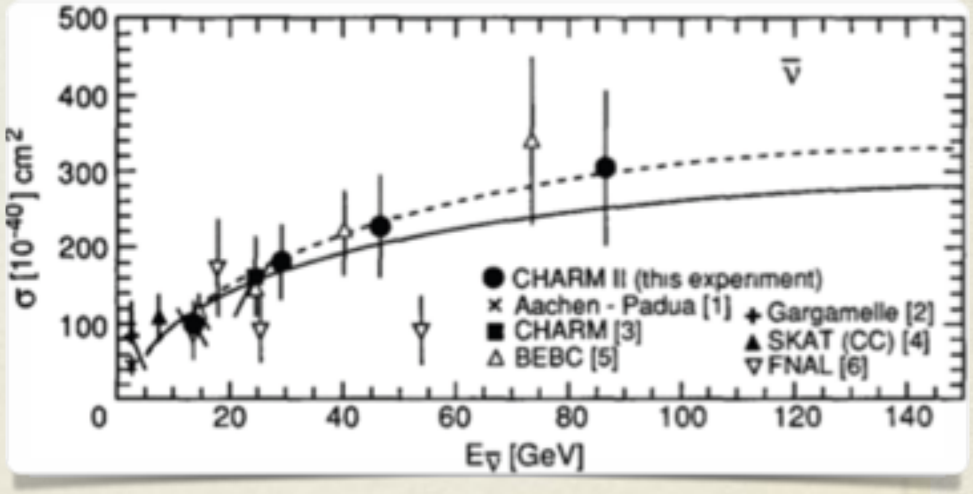
With new measurement





Prior status





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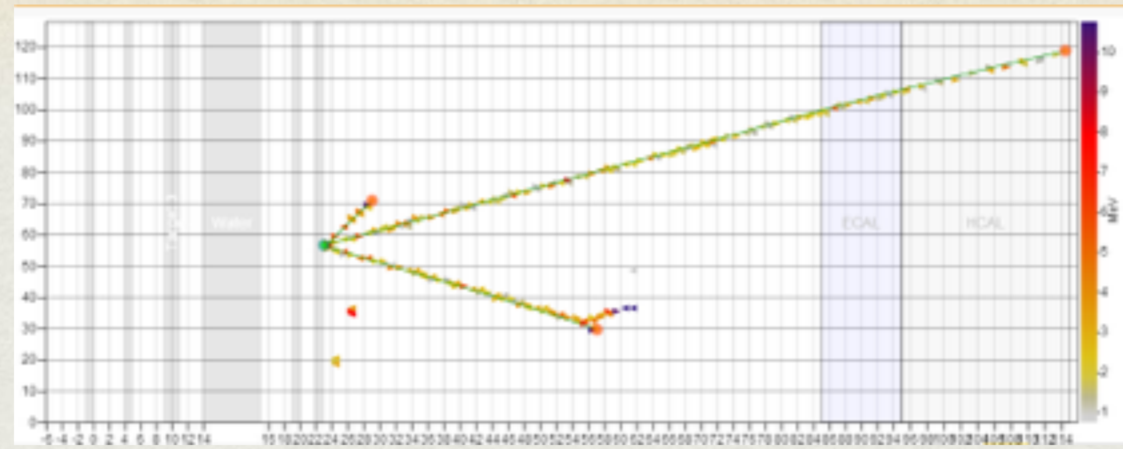
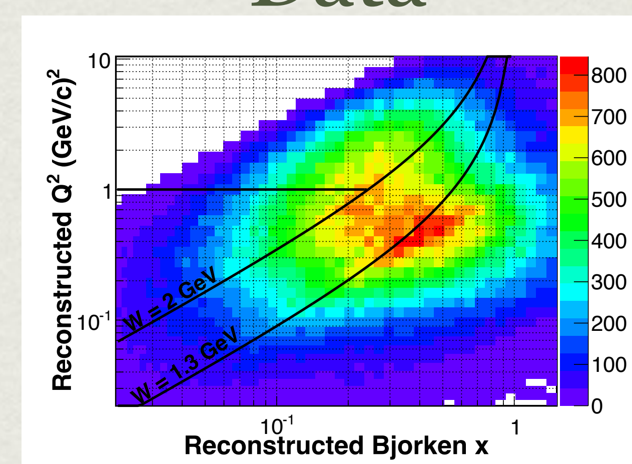


Data



2.94e20 POT neutrinos

Phys. Rev. Lett. 112, 231801 (2014)

son arXiv:1403.2103

INCLUSIVE EVENT SELECTION

- Events must have a muon in MINOS.

1” Pb / 1” Fe
266kg / 323kg

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

0.3” Pb
228kg

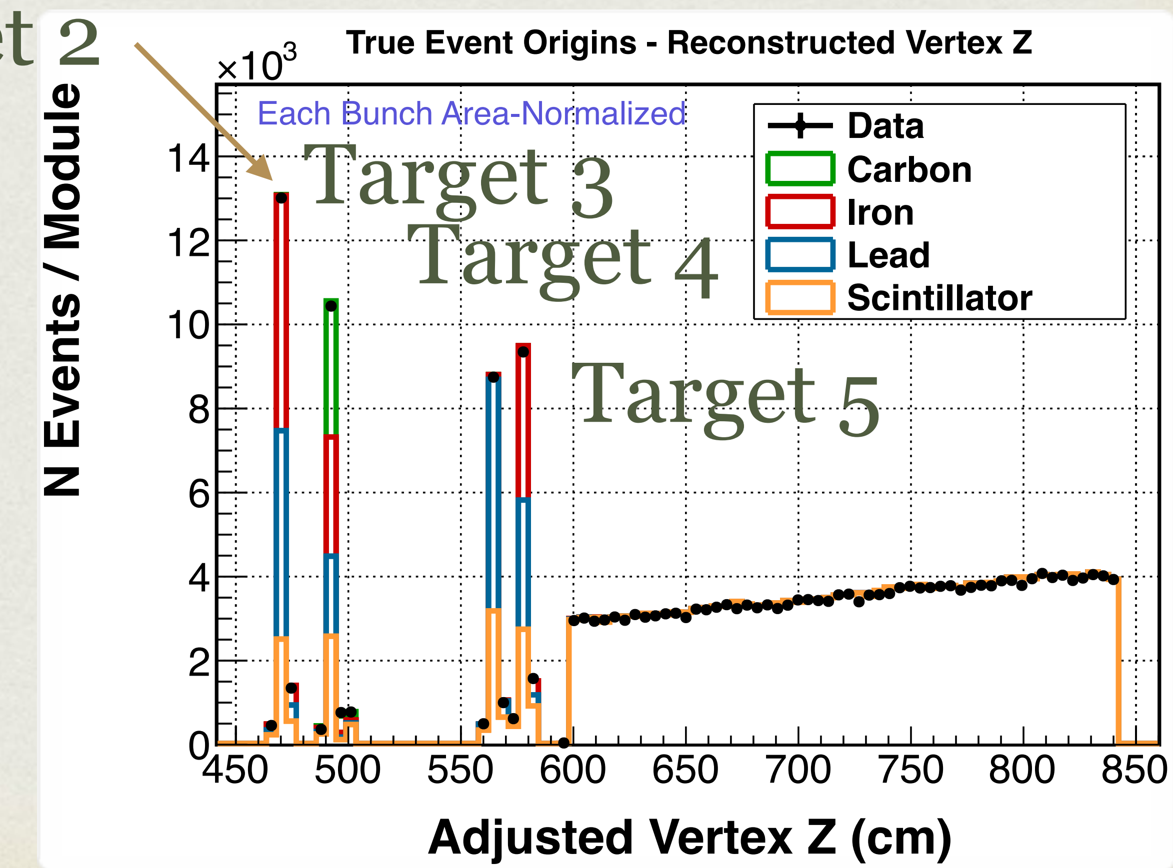
.5” Fe / .5” Pb
161kg/ 135kg

Gives MINOS acceptance (restricts kinematics).

- Target vertex must be in passive target or neighbouring scintillator.

Gives estimate of contamination from scintillator.

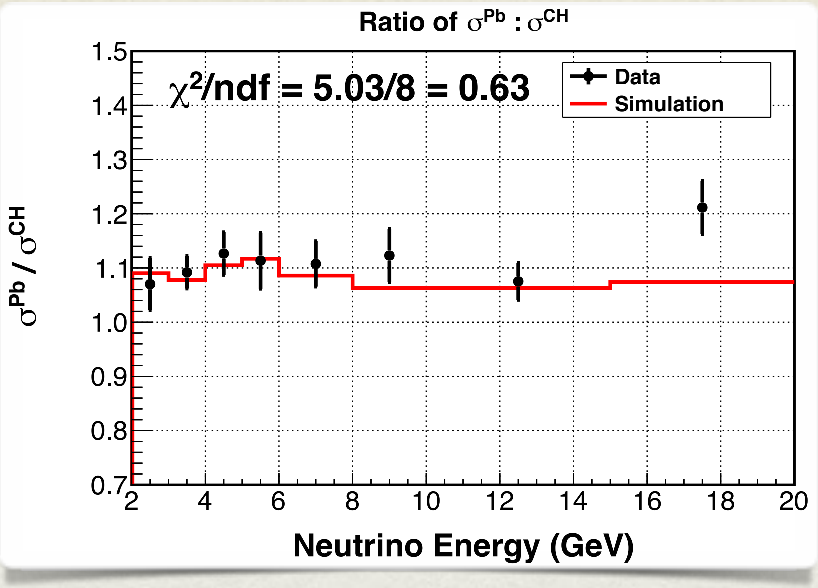
Target 2

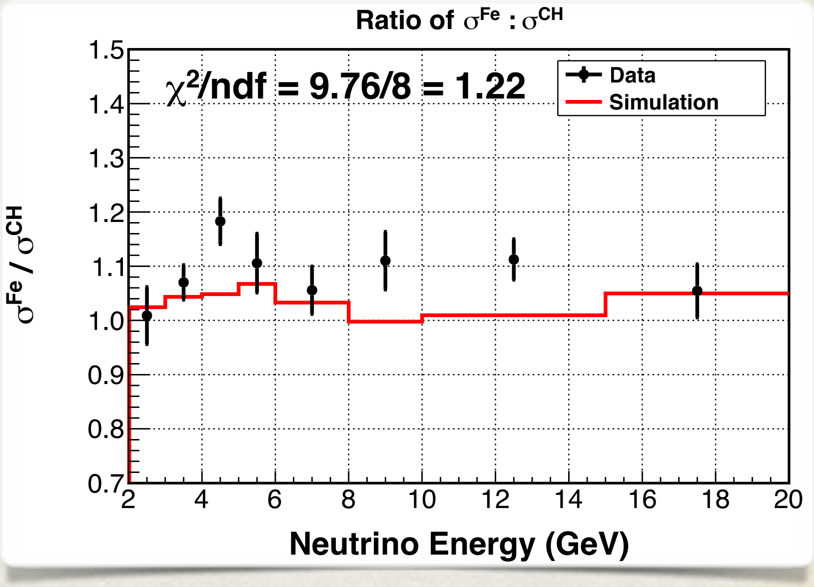


- Neutrino energy between 2 and 20 GeV.

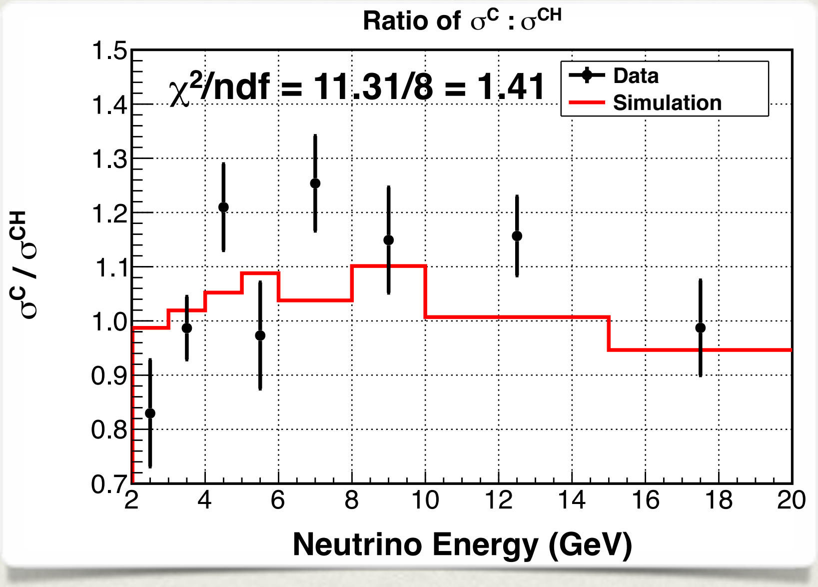
- Muon angle < 17 deg.

INCLUSIVE ENERGY RESULTS



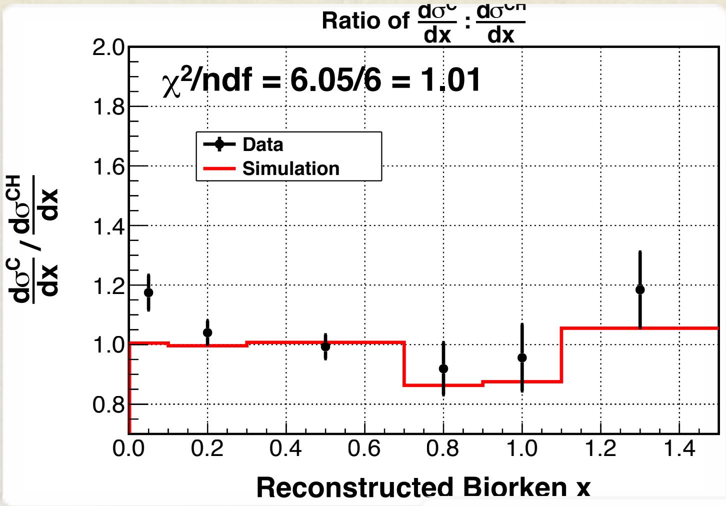


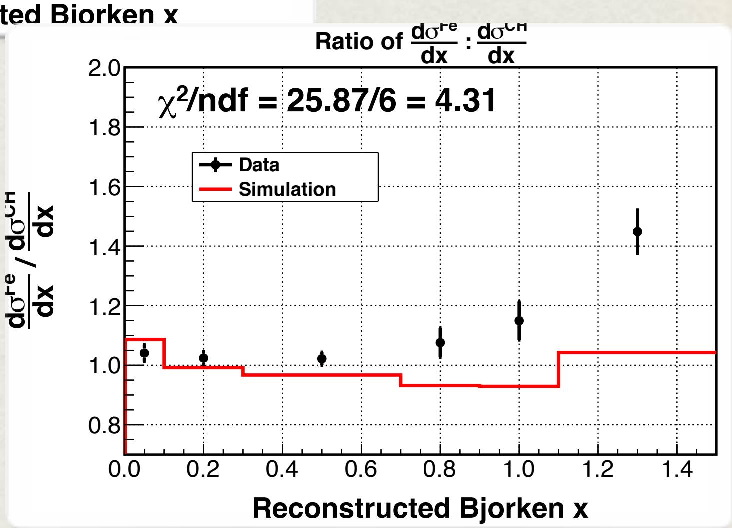
- No tension in shape between data and GENIE model.

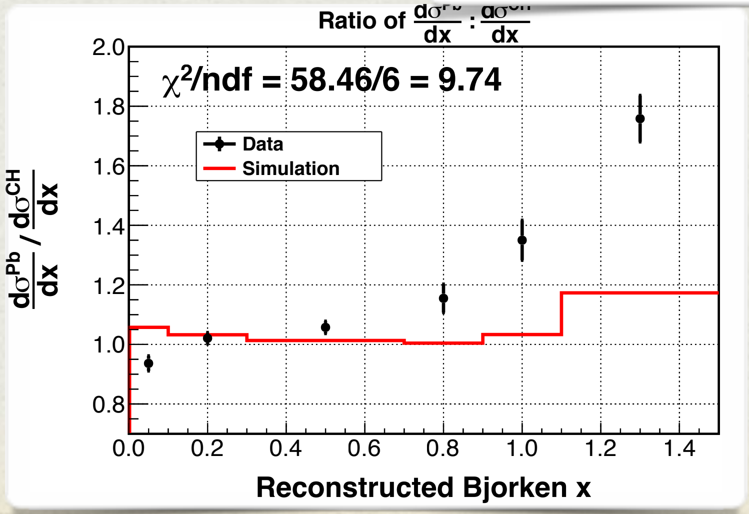


INCLUSIVE BJORKEN RESULTS

- Tension between data and GENIE at low x.
- Deficit that increases with the size of the nucleus.
- The neutrino is sensitive to xF_3 and axial component of F_2.
- Requires theory input to understand inclusive, non-DIS ratios.

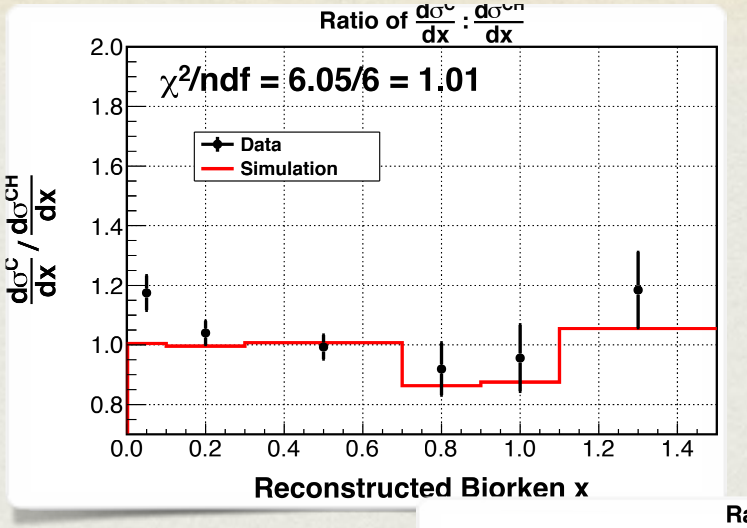


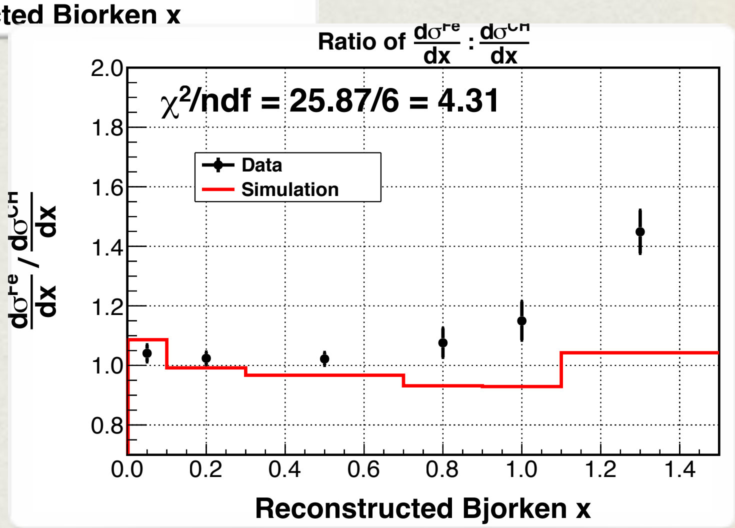


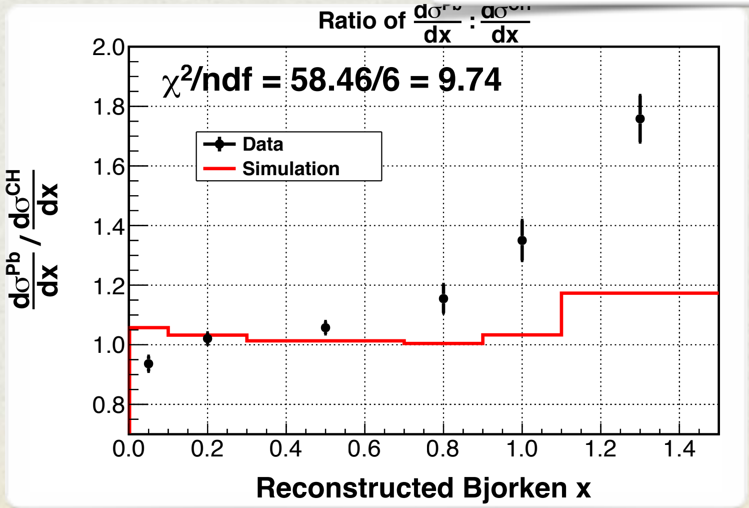


INCLUSIVE BJORKEN RESULTS

- Tension between data and GENIE at high x.
- Excess that increases with the size of the nucleus.
- High x data is ~66% quasi-elastic.
- Nuclear model in GENIE based on electron results and not neutrino predictions (ignores axial vector current).







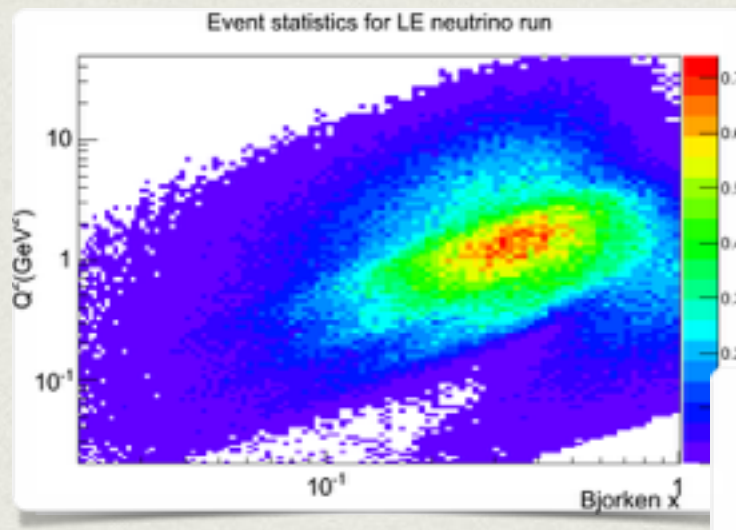
OUTLINE

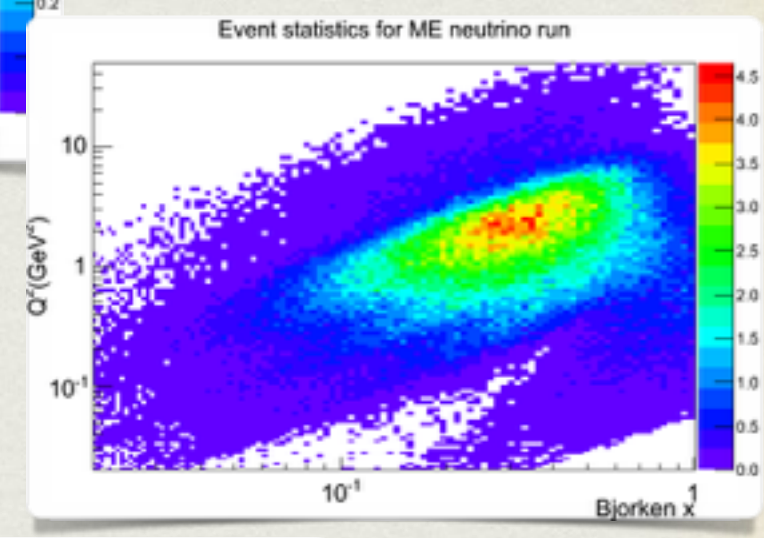
- Introduction to MINERvA
- Neutrino Nucleus Scattering
- Quasi-Elastic Scattering
- Pion Production
  - Charged and Coherent
- Inclusive Charged Scattering
- **Summary and Conclusions**

FUTURE

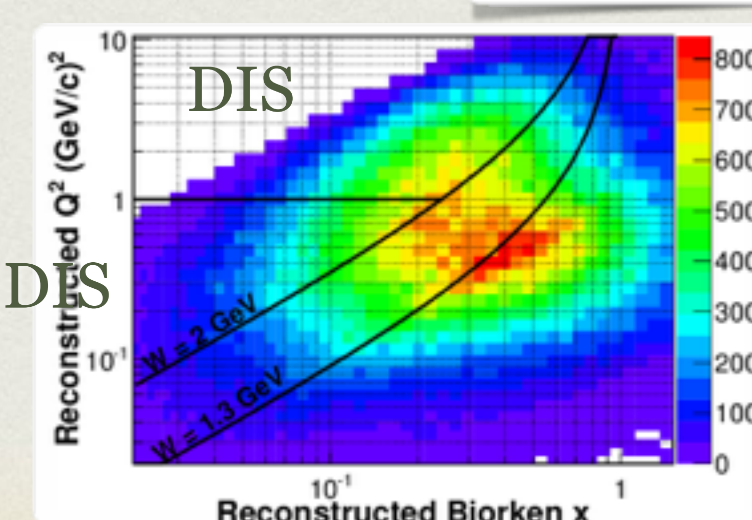
- In the ME configuration, multiple passive targets (Pb, Fe, C) will allow a measurement of A dependence in coherent pion production.
- ME gives high statistics for DIS allowing A-dependent structure functions.
- Water and Helium target analyses and exclusive target ratio analyses.
- Captain MINERvA: extension of MINERvA to include LAr target.

Simulation GENIE 2.6.2





LE Data



Soft DIS

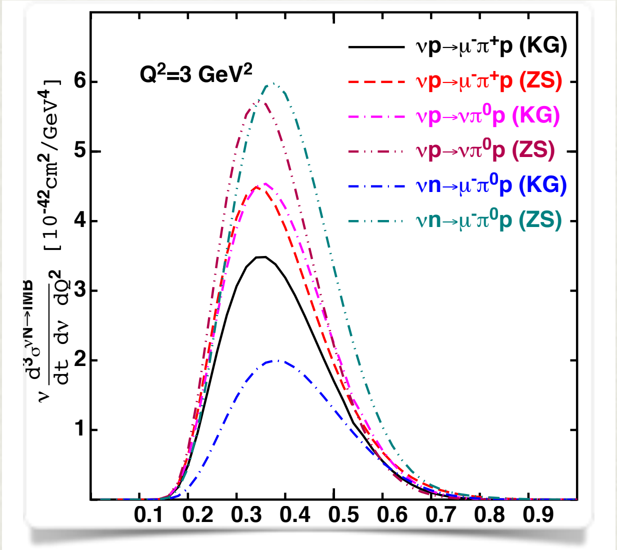
Quasi-elastic

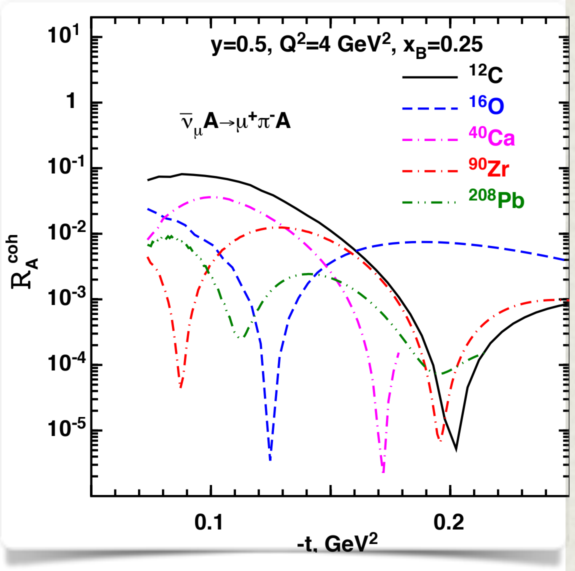
FUTURE

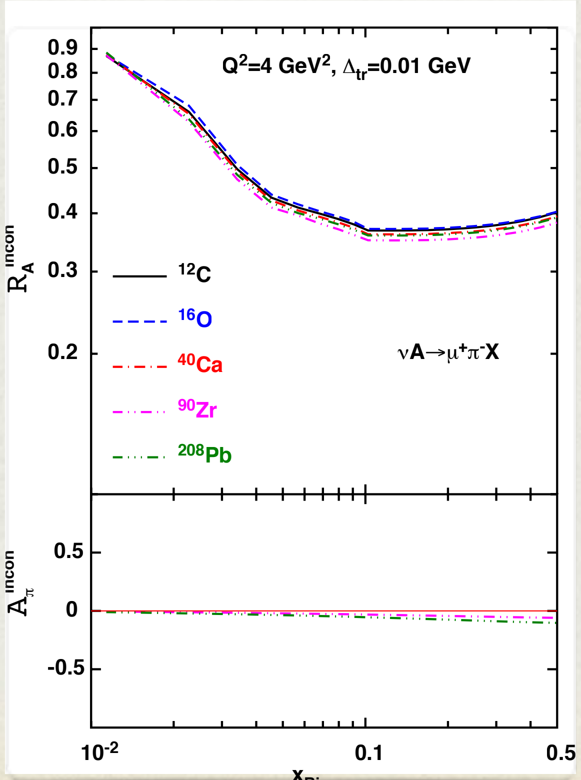
M. Siddikov and I. Smidt, 1501.04306

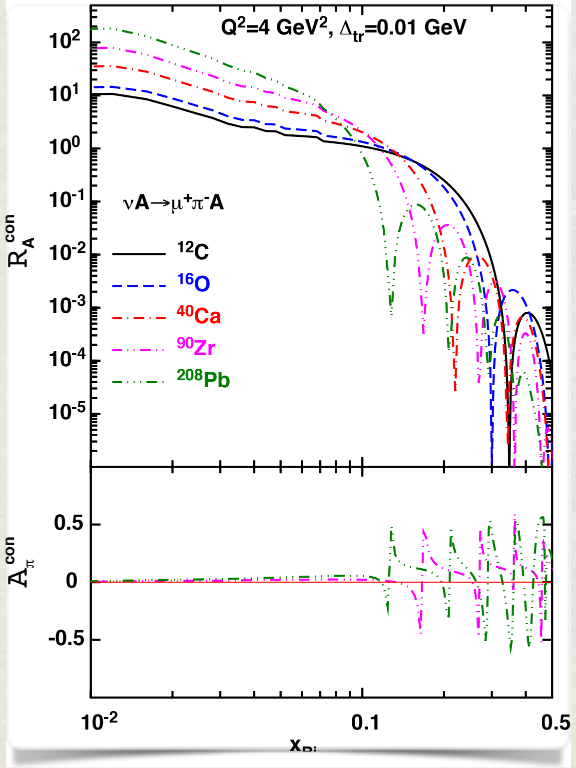
- Possibly distinguish between different GPD parameterizations in selected processes.

- GPD models give clear expectations for the coherent pion production dependence on A.









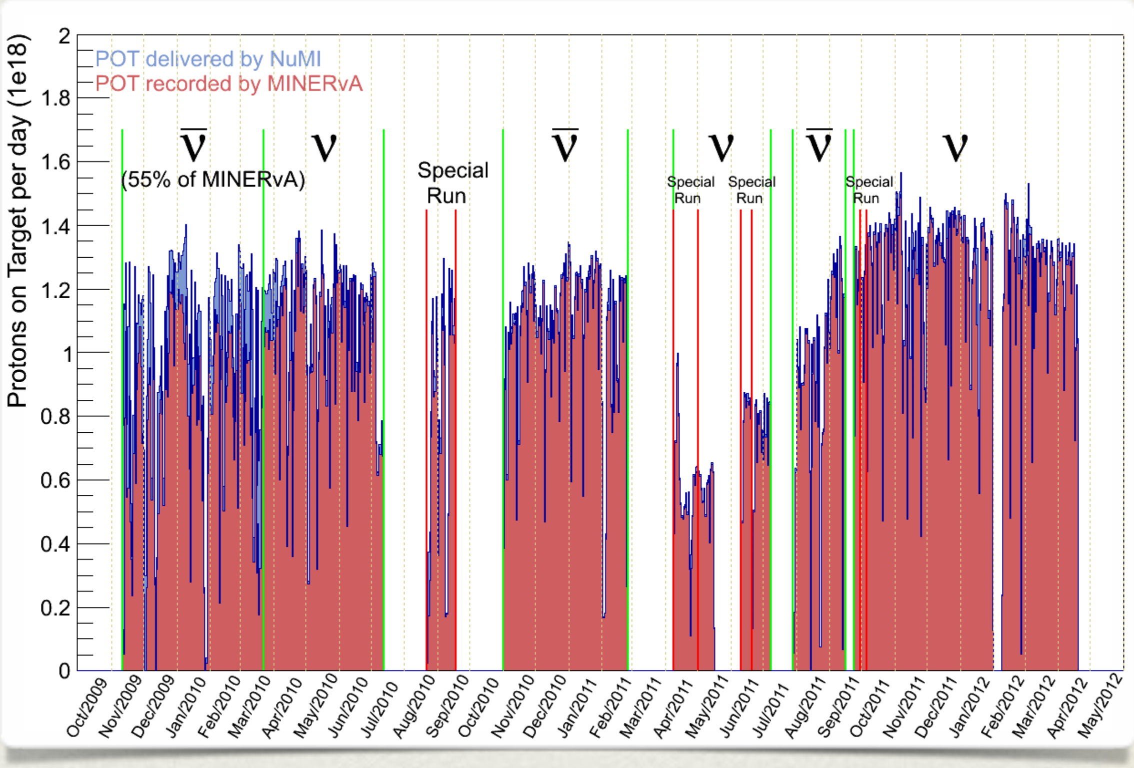
SUMMARY

- No single nuclear model fits all the data.
- Advancements require close work between experimentalists and theorists: NuSTEC
    - Next meeting in 2015 after NuINT.
- Nuclear effects mixes channels and changes energy between produced and final states requiring measurements to depend on the nuclear models considered.
    - These nuclear models require further input from theorists and should be able to serve as a generator for all lepton on hadron data.
- MINERvA has already produced exciting and challenging results about neutrino nucleus scattering, what will we show next!
    - Expect CCπ^0, K, NuE elastic later this year.

BACKUP

LOW ENERGY DATA QUALITY

- Data was collected for the low energy data run in a number of different configurations.
- Special runs existed to provide tests and calibrations.



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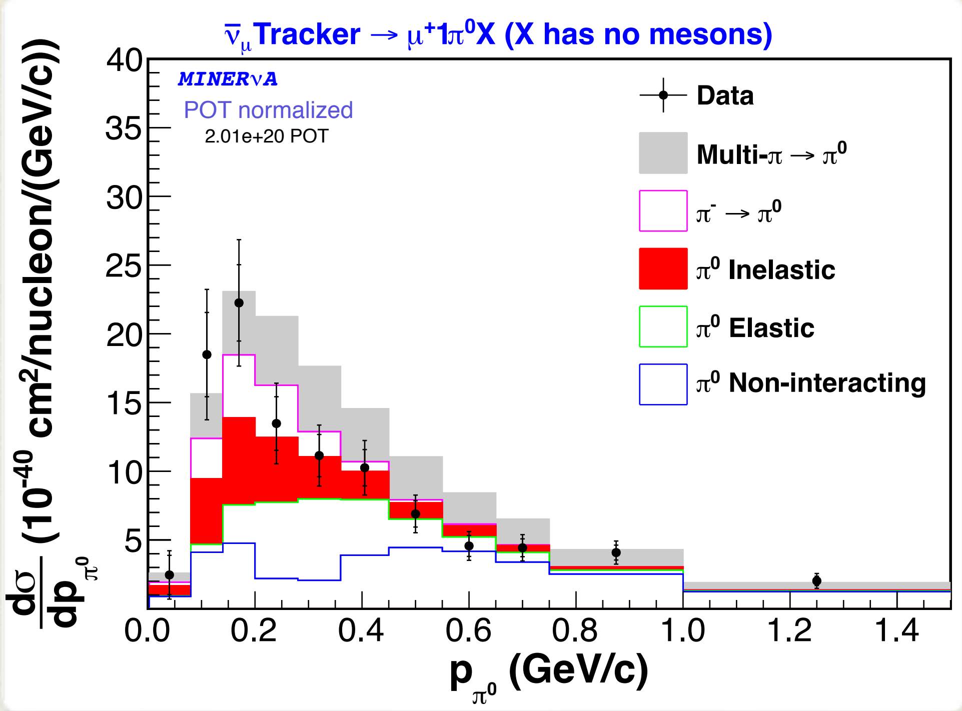
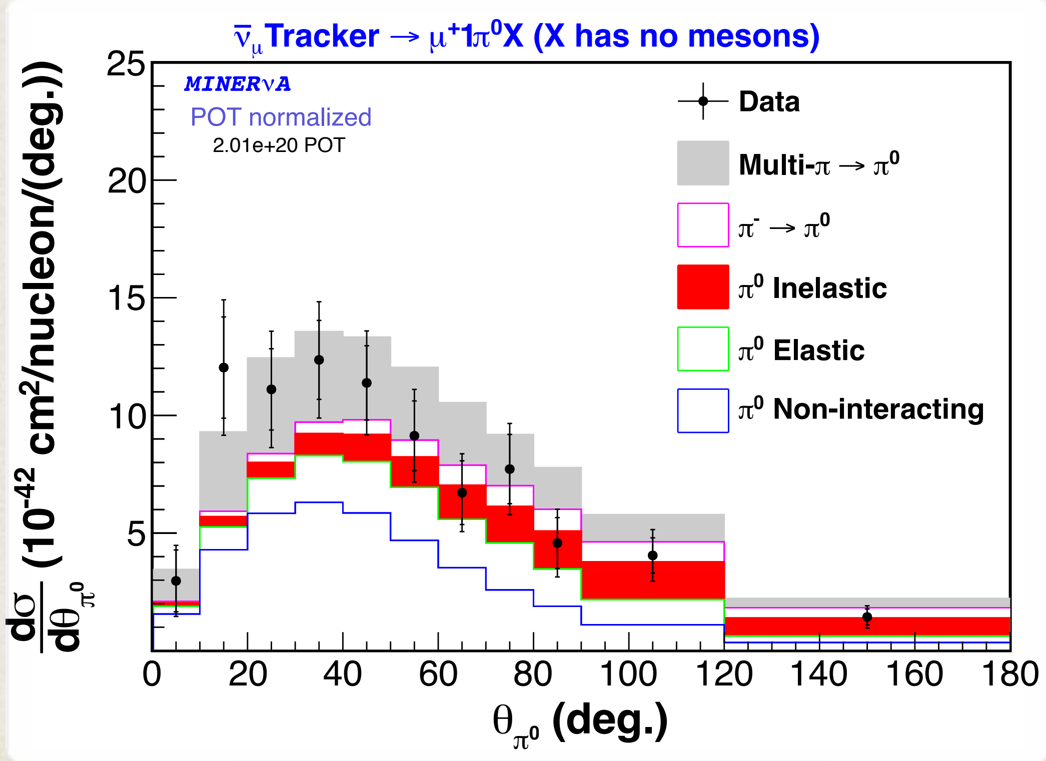
NEUTRAL PION RESULTS

- Data favours GENIE generator with FSI in both magnitude and shape.
- Analysis details forthcoming.





NUE CROSS SECTION

- We see a discrepancy between the model predictions for the NuE and NuMu ratios and observation.
- We have ruled out that this discrepancy mostly depends on the neutrino flux or on the existence of a sterile neutrino.
- Under further study.
- No further comments.