MINERvA Antineutrino Running

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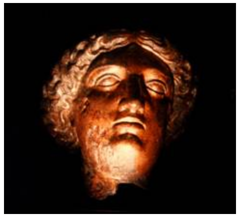
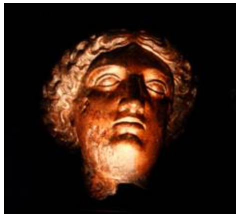
Physics Advisory Committee Meeting
June 23, 2015



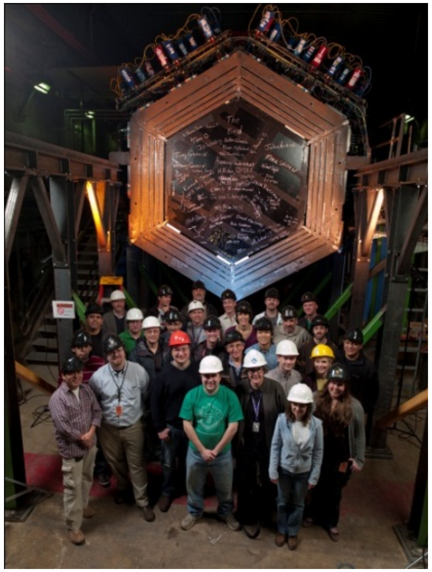
Outline

- MINERvA Overview
- Brief History of MINERvA
- Low Energy Run Physics Output
- Medium Energy Physics Goals
- Current status of Medium Energy Data
- Need for Anti-neutrinos in ME Run

Physics Overview



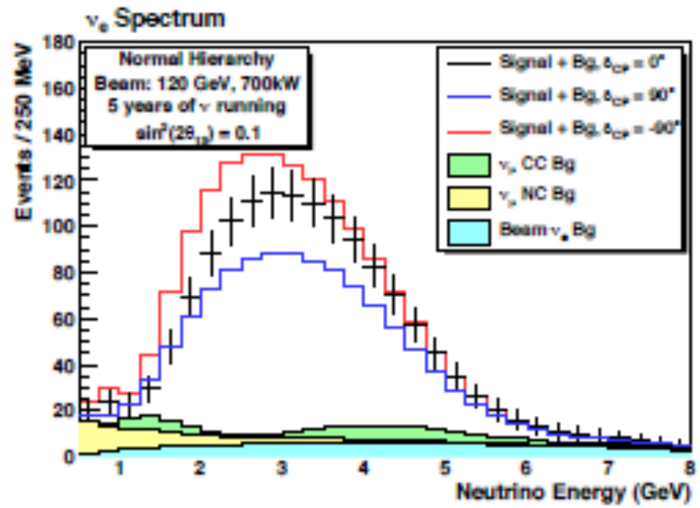
- MINERvA is studying neutrino interactions in unprecedented detail on many nuclei – He, C, CH_2, H_2O,Fe,Pb
  - Critical for model-buliding
  - Measure nuclear effects on exclusive final states
    - As function of a measured neutrino energy
    - Study differences between ν and anti-ν

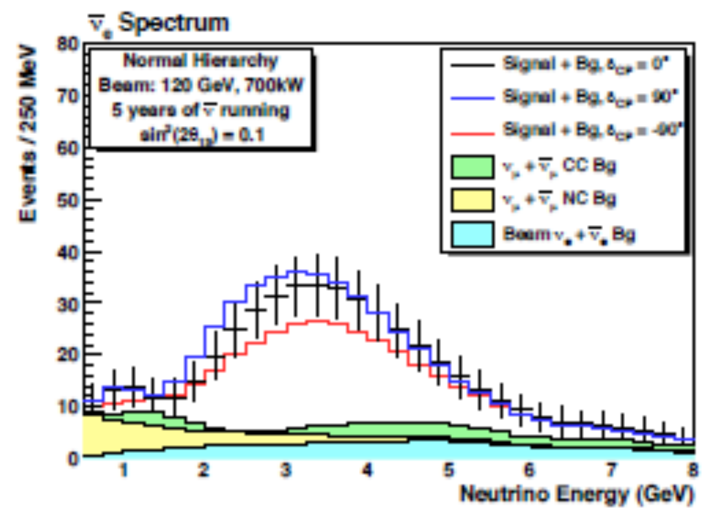


- Low Energy (LE) Beam Goals:
  - Study both signal and background reactions relevant to oscillation experiments
  - Measure exclusive channel cross sections and dynamics
- Medium Energy (ME) Beam Goals:
  - Structure Functions on various nuclei
  - Study high energy backgrounds to oscillation experiments

Oscillation Physics and Neutrino Interactions

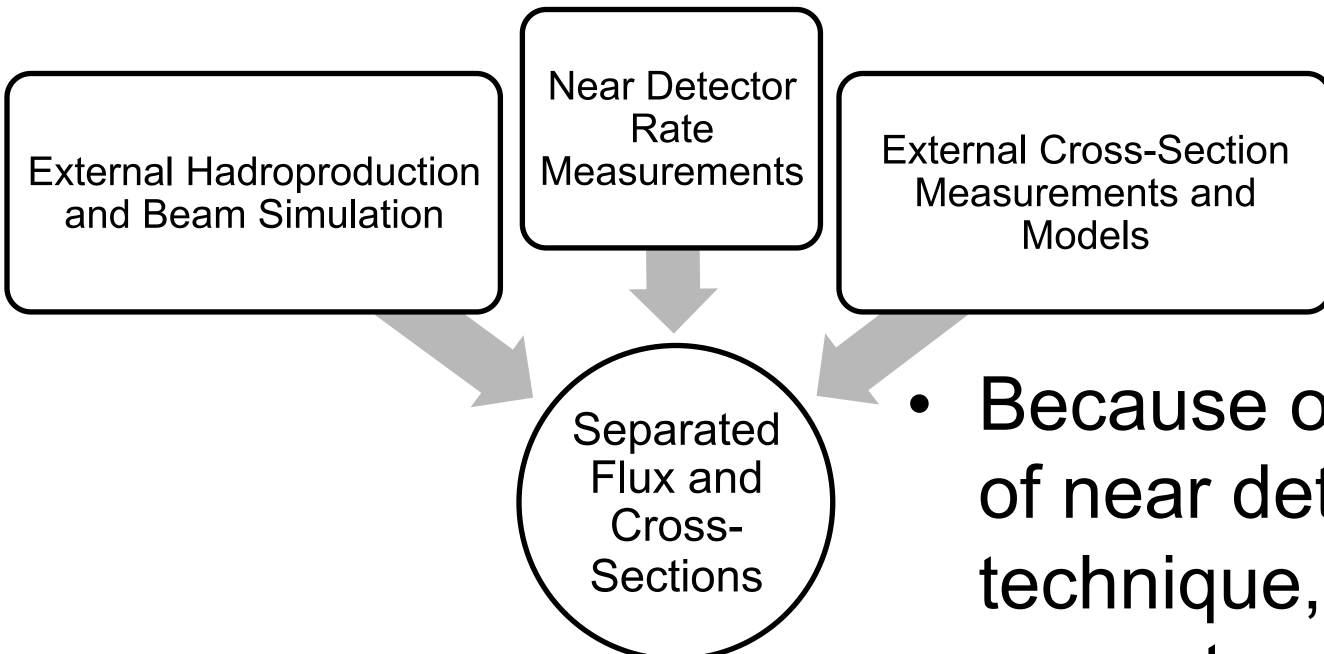
- Possible LBNE Far Detector Event Spectra shown above, Red and Blue are difference between two extremes of CP violation (±90°)
- Now Imagine what a Near Detector sees:
  - Most events are muon neutrino events
  - Intrinsic Electron Neutrino Events have completely different spectrum
  - Background Electron Neutrino events are coming from different mix of interactions
  - Still don't have a "true neutrino energy", can only measure final state particles
  - How can we get past this?
    - Have to break the degeneracy between flux and cross sections





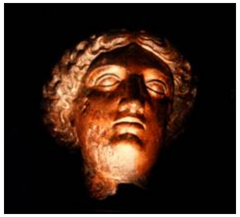
Breaking the Flux/Cross Section Degeneracy

- Experiments have a more or less universal scheme for using the near detector data to get flux and cross-section



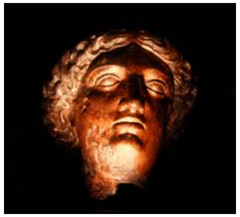
- Because of limitations of near detector technique, these rely on accurate models:
- Enter MINERvA

History of MINERvA Run Plan

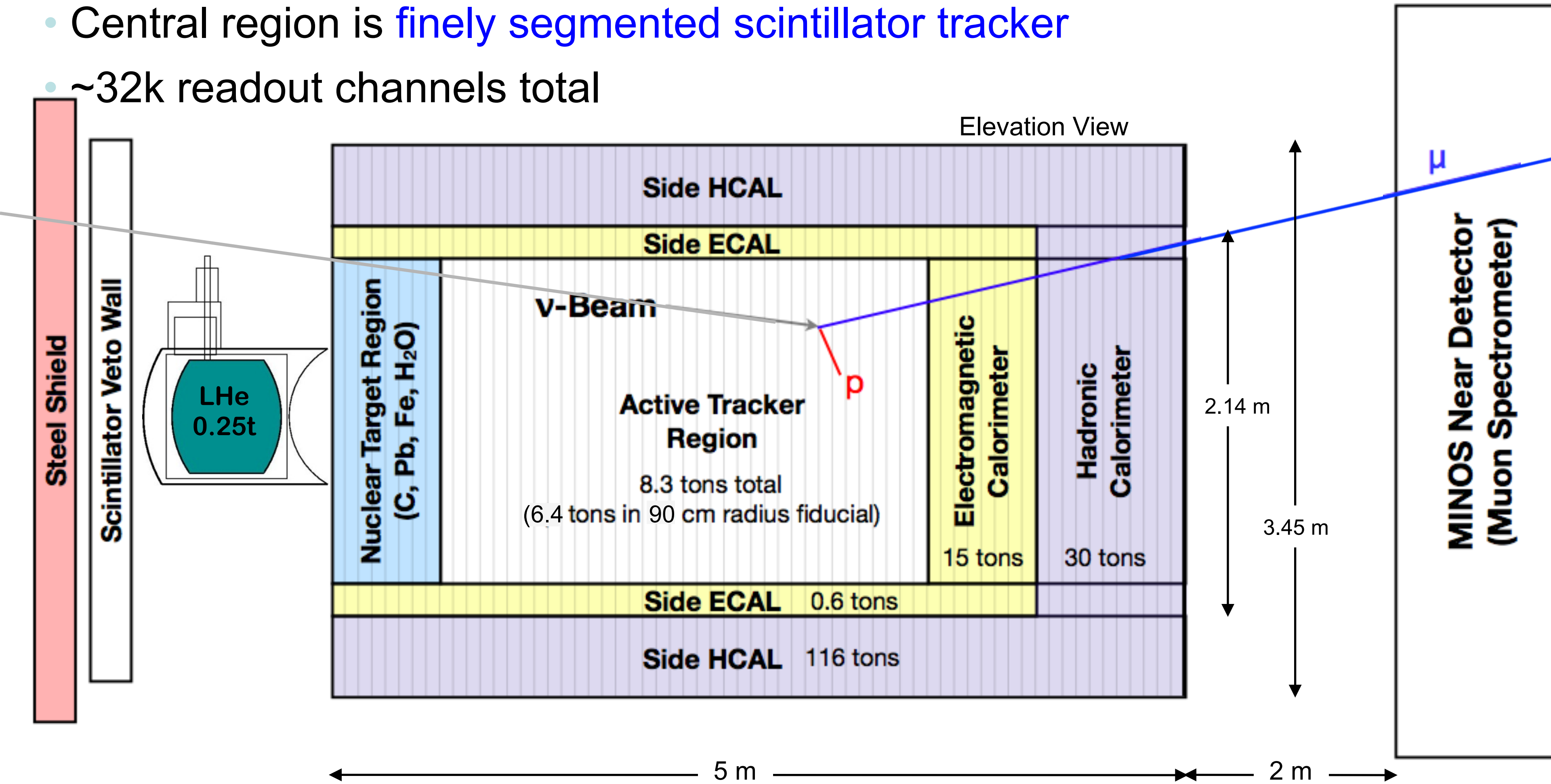


- Proposal to do MINERvA Experiment: February 2004 arXiv:hep-ex/0405002
- Stage I Approval: April 2004
- MINERvA CD-0: June 2006
- MINERvA CD-1,2,3a: March 2007
  - Technical Design Report: "1 year running parasitically with MINOS, 3 years running parasitically with NOvA, 4e20 POT per year" (ν only)
    - 4E20 POT in LE beam
    - 12E20 POT in ME beam
  - Medium Energy Beam considered the main source of events
- MINERvA Detector and solid targets Complete: March 2010
- Low Energy Run ends: April 2012, integrated 4E20POT, ν and anti-ν
- Medium Energy Run begins: September 2013
  - Integrated 6E20 POT already, expect >10E20 by 8/2016
- Case for 12E20 in antineutrino running presented at 1/2014 PAC meeting
  - Document submitted for 1/2015 meeting giving more detail

MINERvA Detector

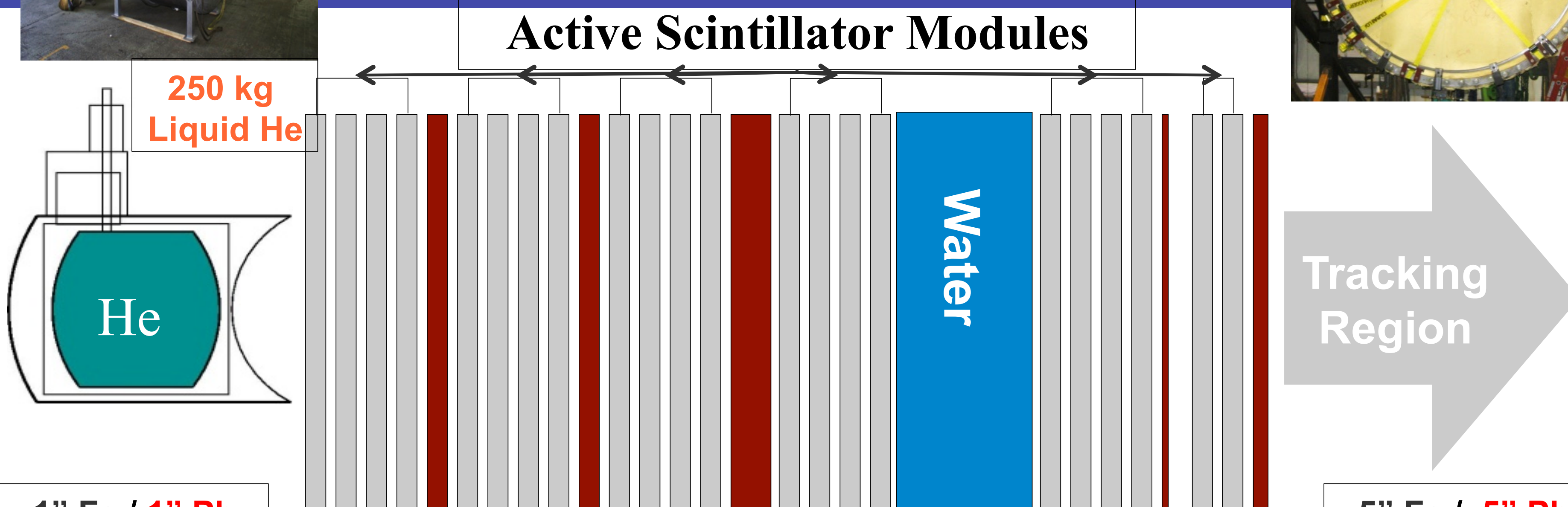


- Detector comprised of 120 “modules” stacked along the beam direction
- Central region is finely segmented scintillator tracker
- ~32k readout channels total

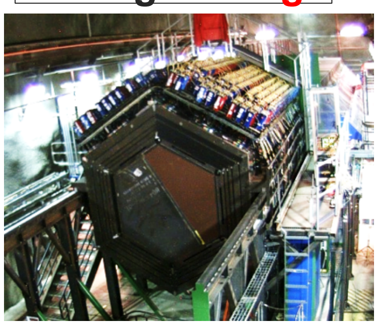


See NIMA 743 (2014) 130 for details

Nuclear Targets

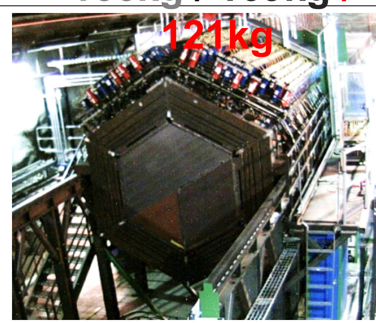


1” Fe / 1” Pb
323kg / 264kg

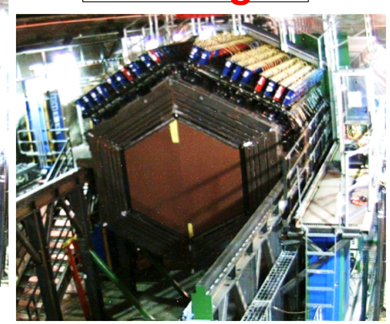


1” Pb / 1” Fe
266kg / 323kg

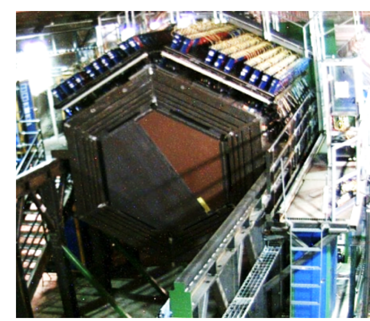
3” C / 1” Fe / 1” Pb
166kg / 169kg / 121kg



0.3” Pb
228kg

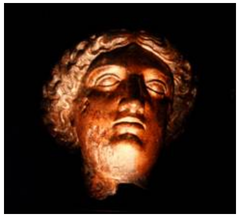


.5” Fe / .5” Pb
161kg/ 135kg



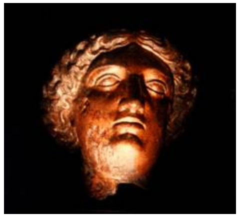
LOW ENERGY RUN RESULTS

Low Energy Physics Highlights (so far)

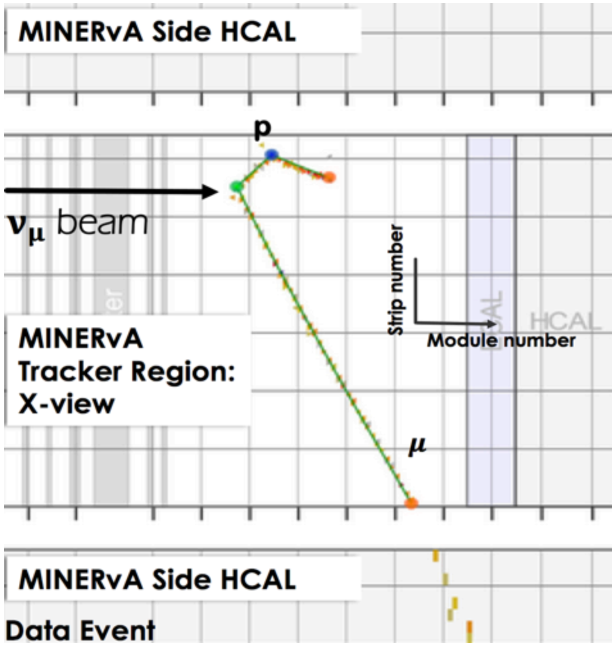


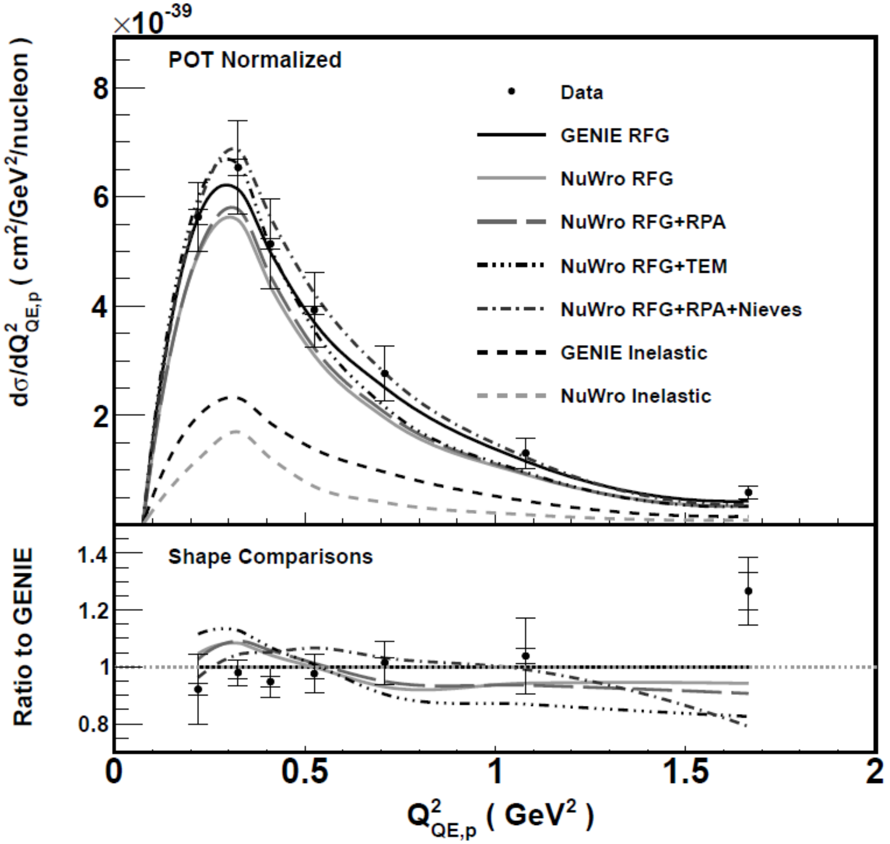
- Quasi-elastic results in neutrino and antineutrino mode, published back to back PRL's in June 2013
  - PRL 111, 022502 & PRL 111, 022501
- Nuclear Target Inclusive Cross Section Ratios
  - PRL 112, 231801 (2014)
- Since you last heard from us
  - Proton Kinematics in Quasi-elastic Interactions (ν)
    - PRD 91, 071301 (2015)
  - Charged Pion Production cross sections (ν)
    - arXiv:1406.6415
  - Coherent Pion Production (ν and anti-ν)
    - PRL 113, 261802 (2014)
  - Neutral Pion Production cross sections
    - arXiv:1503.02107
  - Nuclear Target Deep Inelastic Scattering Ratios
    - Fermilab JETP in May, paper in preparation
  - Complete analyses from Low Energy Test Beam Run
    - Nucl.Instrum.Meth. A789 (2015) 28-42

CCQE with Observed Proton



- Momentum transfer (Q^2) can be measured from proton energy
- Require proton track and cut on dE/dx
- Data-driven background subtraction
- Signal defined as “CCQE-like”



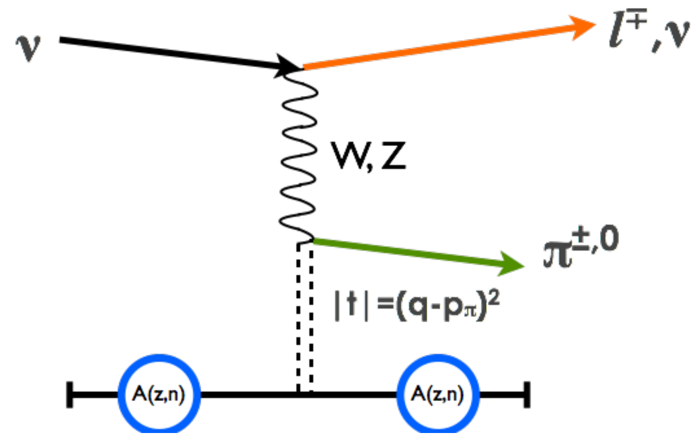


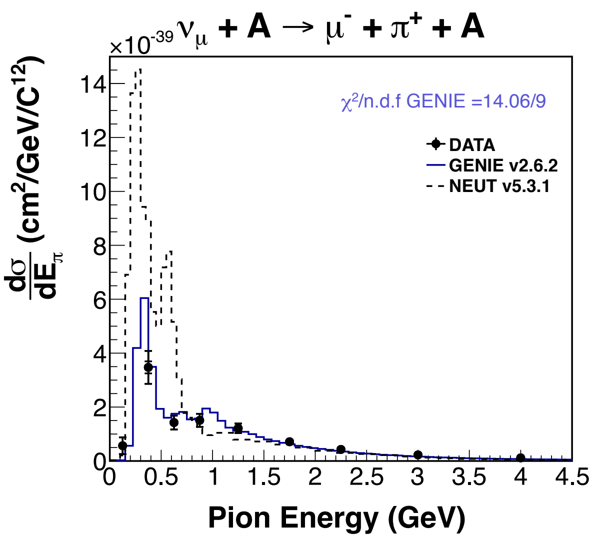
Best model for μ kinematics is not the same as the one that best describes the proton kinematics

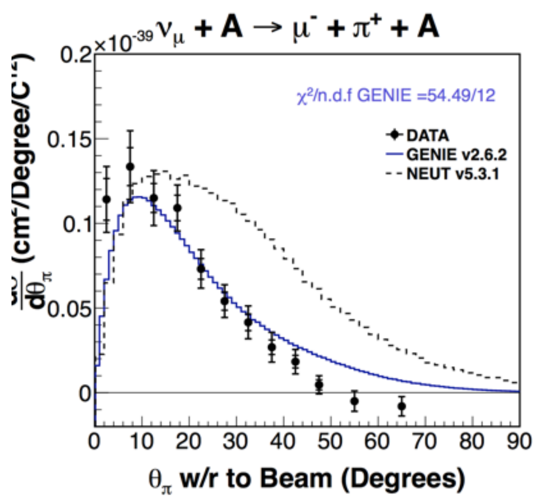
Walton et al, PRD 91, 071301 (2015)

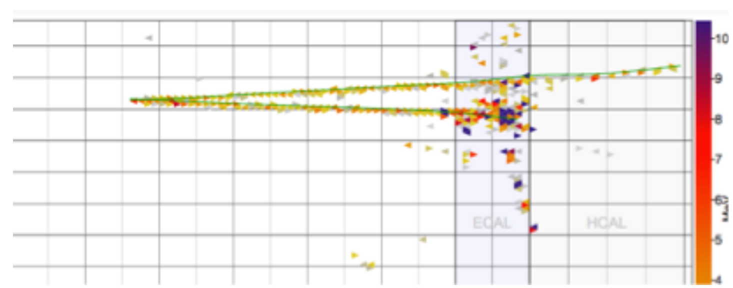
Coherent Pion Production

- Low multiplicity process is a troublesome background for oscillation experiments and previous low energy data is confusing
- Model independent selection and high statistics allows test of pion kinematics
- O(1000) coherent neutrino (antineutrino) events: largest samples collected yet





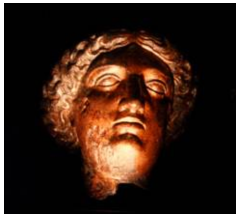




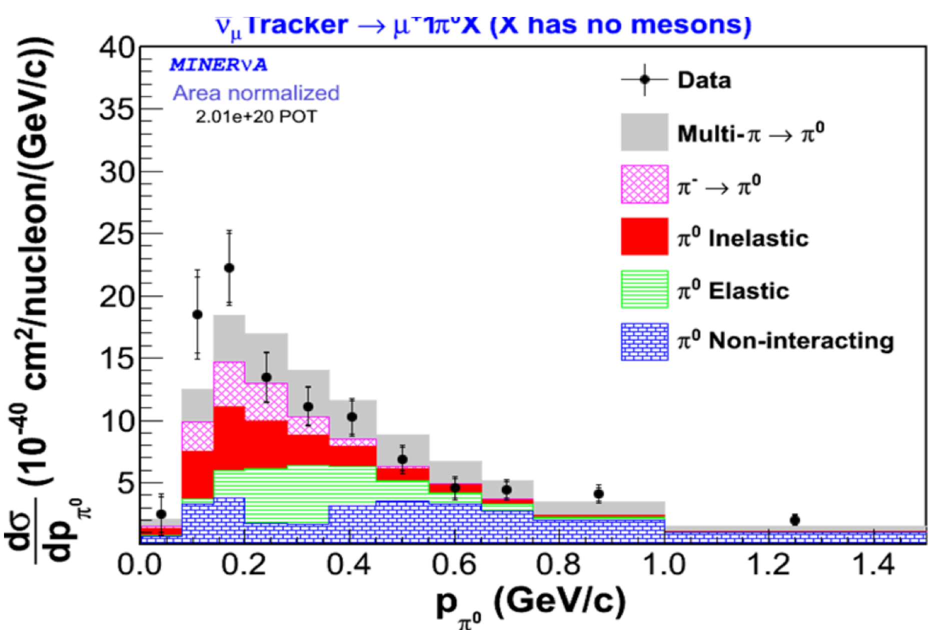
PRL 113, 261802 (2014)

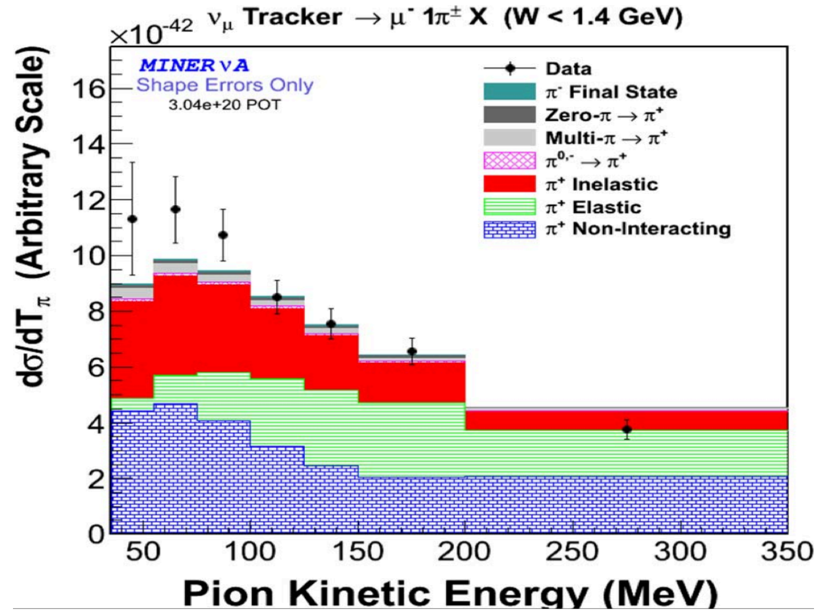
Current generators don't model process well at LBNF energies

Charged Current Pion Production Results

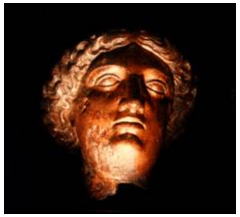


- Two ways to look at pion production
  - π^+ production by ν, π^0 production by anti-ν
  - Probe different nuclear effects in same energy beam
- Gives more complete picture of final state interactions
- See more low energy pions than current generators predict
- Charged current pion production significantly lower than expected





Upcoming LE Results

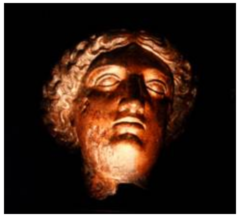


- Electron Neutrino Quasi-elastic interactions
  - Signal process for T2K and much of NOvA
- Total ν_μ Cross Section and in situ Flux Measurement
  - Important proof of principle that can serve DUNE
- We will also expand our earlier measurements
  - Charged and Neutral Pion production muon kinematics
  - Coherent pion production muon kinematics
  - Quasi-elastic scattering in nuclear targets

Impact of LE Results

- We do know some of the uses of the results because of interactions with other experiment collaborations or theory groups
- T2K uses external data (mostly MiniBooNE so far) to down-select alternative models and to fit parameters in those models. Near detector constraint is applied after this model constraint step.
  - Now fitting MINERvA's CCQE results to select multi-nucleon model.
  - Use inclusive and coherent $CC\pi^+$ MINERvA results
  - Starting to implement $CC\pi^0$ results
- Two main efforts from theory side asking questions about our data
  - Extended kinematics multi-nucleon calculation (Nieves et al)
  - Groups interested in final state interactions, e.g., GiBUU

"LE" Topics in NOvA era beam

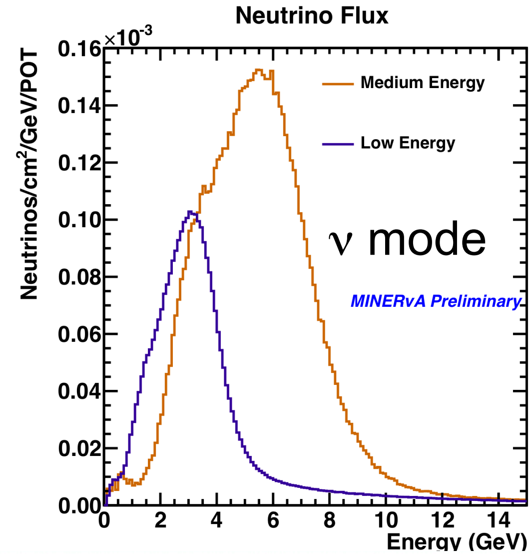


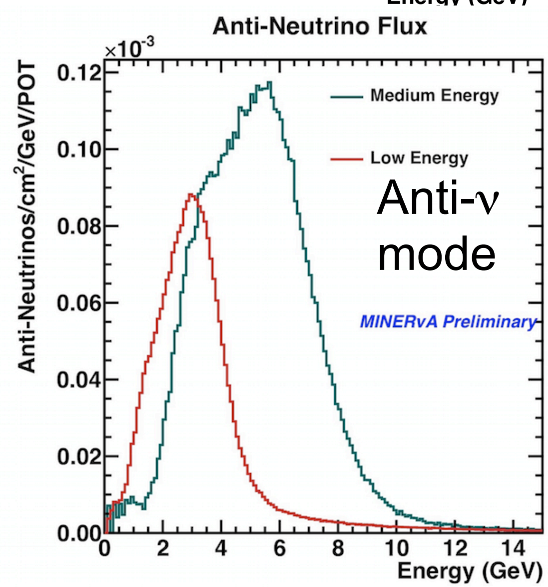
- Most of the measurements we've made in the low energy beam can be repeated in the medium energy beam without too much addition to background from high energy feeddown
  - LE beam already has a significant high energy tail, so have had to develop background rejections already to identify exclusive states
- Interests vary depending on topic
  - For flux integrated cross-sections (CCQE, pion production), integrating over a different flux is very useful. Different regions of momentum and energy transfer to target appear at different muon energy and angle.
  - For statistics challenged measurements (coherent scattering, exclusive states from nuclear targets) increased statistics will dramatically improve measurement.

STATUS OF MEDIUM ENERGY DATA

What Medium Energy Beam Brings

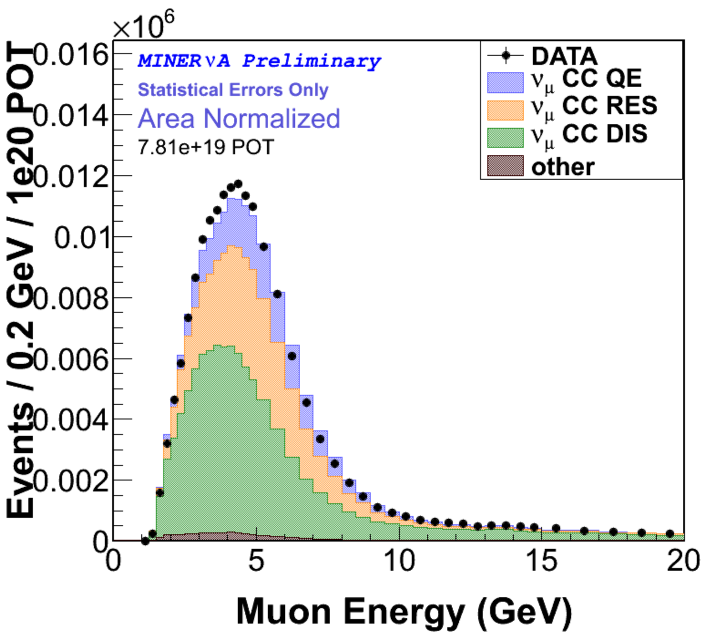
- More neutrino flux per proton on target (POT)
- More POT per year
- Higher energy ν's (often) means higher cross sections
- This means that where in LE run we could only measure events on scintillator, now we can think of getting results on nuclear targets too

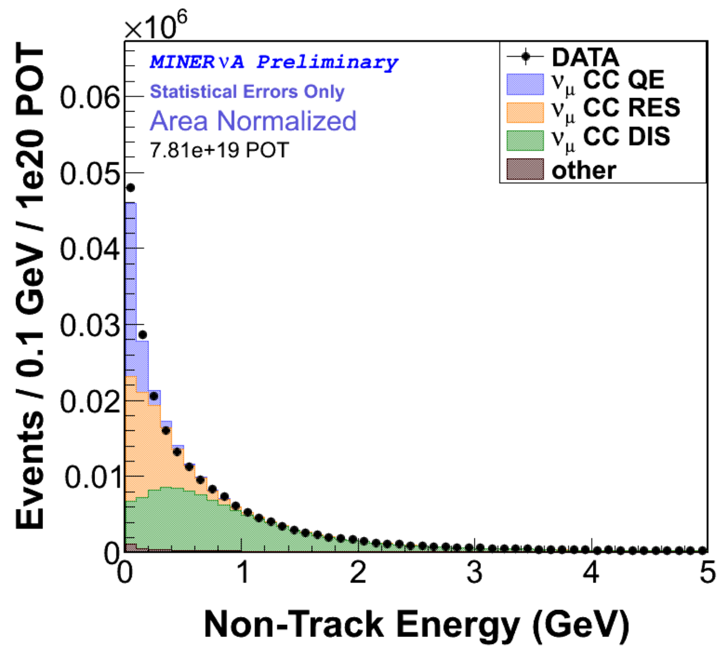




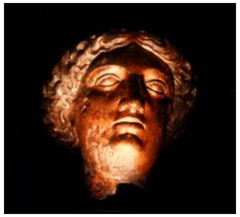
Medium Energy Run History

- Started 9/2013
- Have already collected 6E20 in Neutrino mode
- MINERvA and MINOS detectors operating at high livetimes
  - MINERvA >97% live, MINOS*MINERvA>96% live
- Event statistics meeting expectations





Medium Energy Run Collaboration



- Collaboration is small, we are limited only by people, not physics topics
- Large interest in this group for staying through CAPTAIN MINERvA

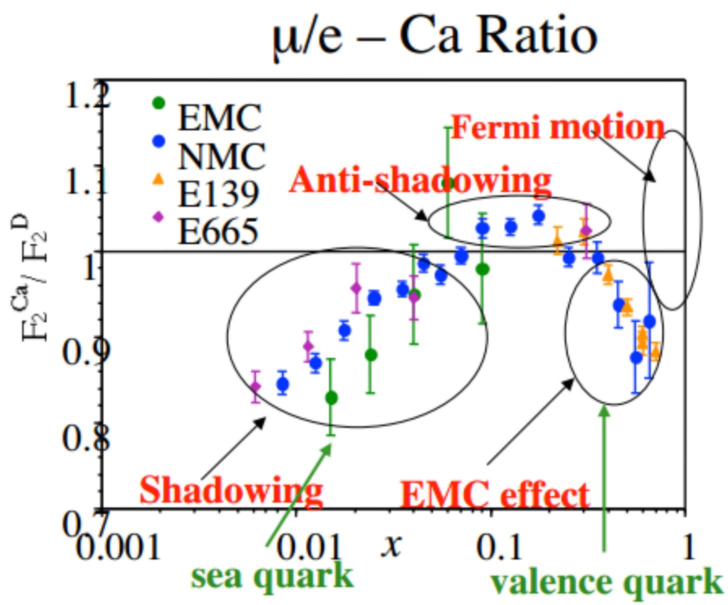
Photo from MINERvA week 2015 meeting in Rochester

EXAMPLE MEDIUM ENERGY PHYSICS GOALS

1. "EMC" effect with neutrinos
2. Inclusive Pion Production
3. Coherent scattering
4. Flux Constraint from ν-e scattering

Nuclear Effects in Inelastic Neutrino Scattering

- Nuclear Effects change momentum, and even identity of particles that leave the nucleus in a neutrino interaction
- These in turn will effect the measured or "visible" energy in a neutrino experiment
- Oscillation experiments will rely heavily on the measured visible energy
  - Event selection
  - Measurements! ($\Delta m^2 L/E_\nu$)
- Right now neutrino event generators have to rely on measurements from charged leptons
  - NO NEUTRINO DATA on these ratios prior to MINERvA
  - Field is still confused about these effects, need new probes



CERN COURIER

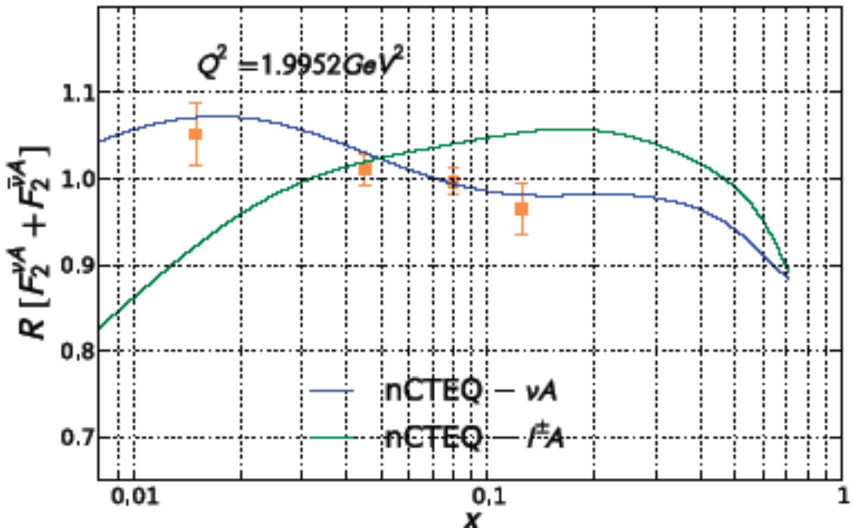
Apr 26, 2013

The EMC effect still puzzles after 30 years

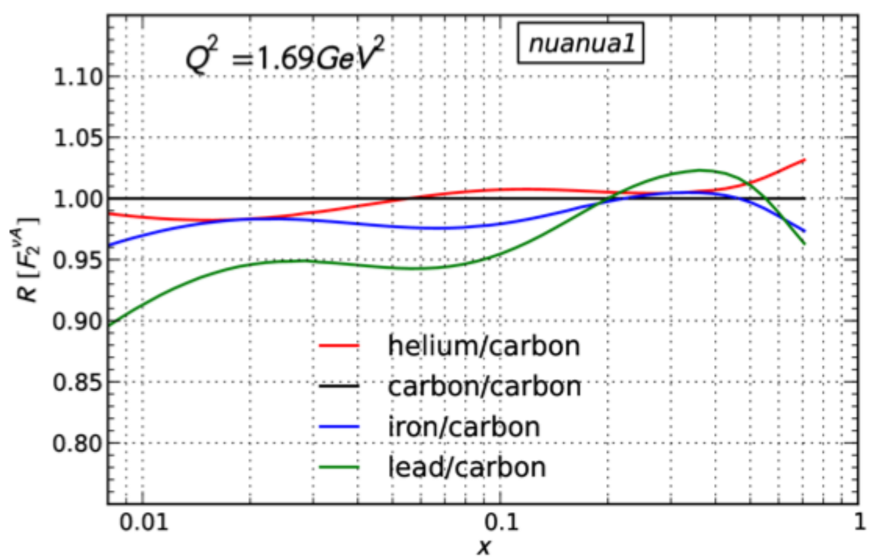
Thirty years ago, high-energy muons at CERN revealed the first hints of an effect that puzzles experimentalists and theorists alike to this day.

CTEQ Predictions from Charged Lepton and NuTeV data:

- CTEQ tries to fit for nuclear effects by comparing NuTeV structure functions on Iron to predicted “n+p” structure functions and comparing to predictions from charged lepton effects:
  - charged lepton fit undershoots low-x ν data & overshoots mid-x ν data
  - low-Q^2 and low-x ν data cause tension with the shadowing observed in charged lepton data
  - K. Kovarik et al. Phys.Rev.Lett. 106:122301,2011

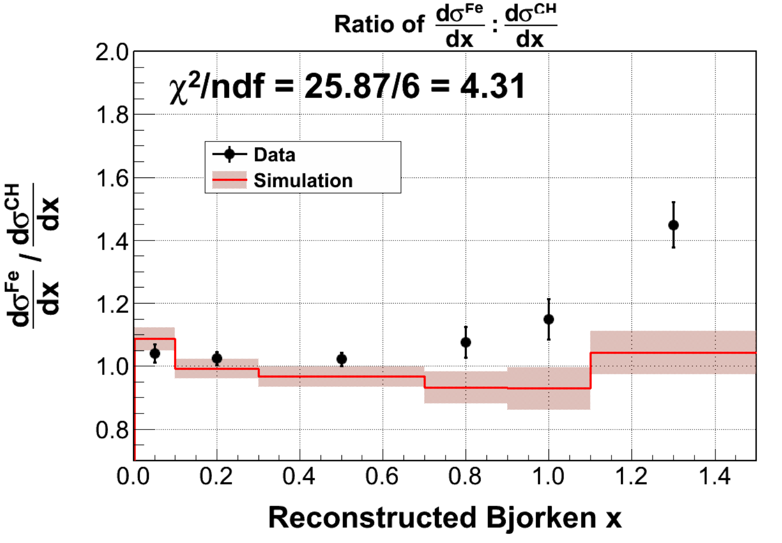


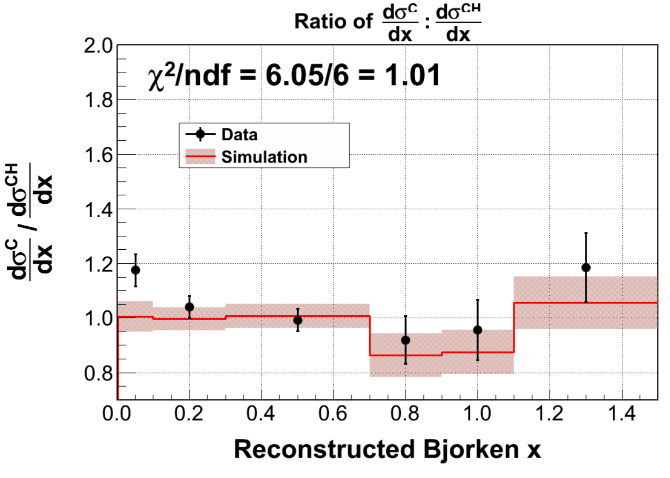
CTEQ prediction for the structure function ratios MINERvA can measure:

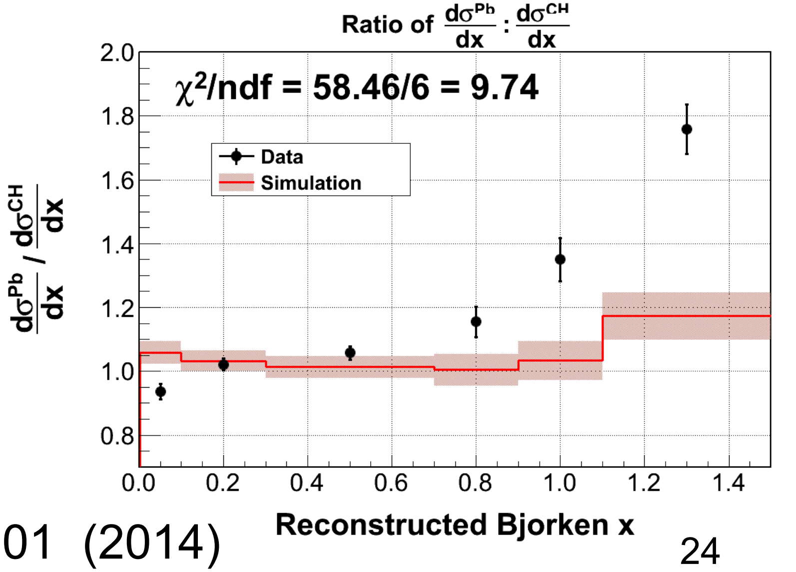


LE Cross Section Ratios as function of x

- At x=[0,0.1], we observe a deficit that increases with the size of the nucleus
- At x>0.7, we observe an excess that also increases with size of nucleus
- Data show effects not modeled in simulation
- Expectation from charged lepton data is that nuclear effects are smaller
  - But νs sensitive to xF_3
  - νs also sensitive to axial piece of F_2

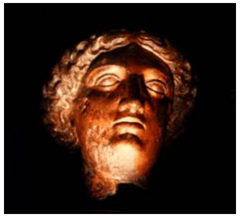




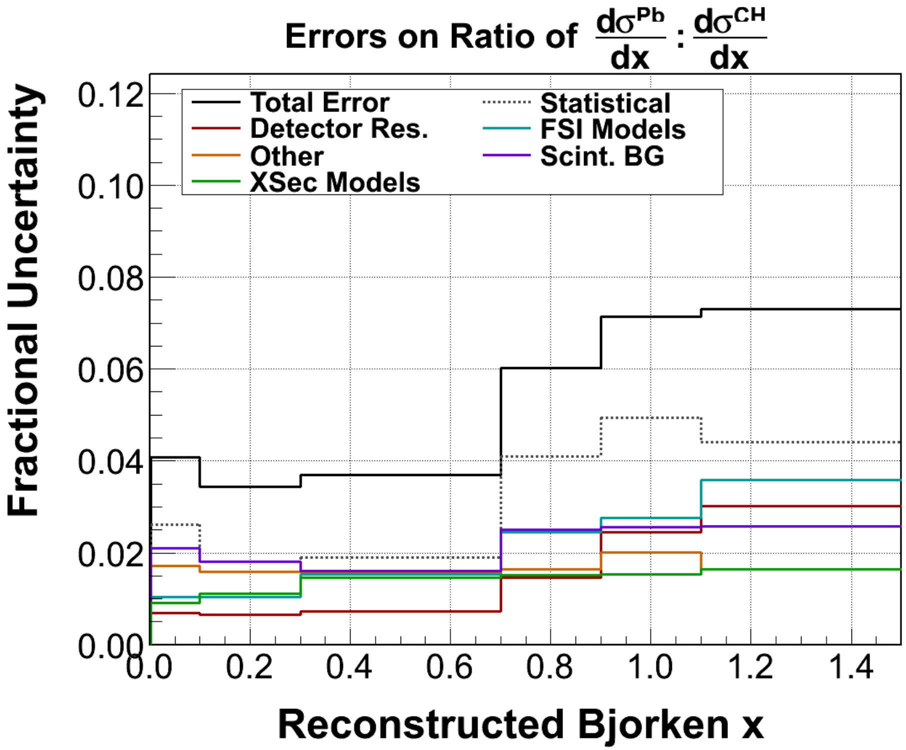


PRL 112, 231801 (2014)

LE Nuclear Target Ratio Uncertainties



- Uncertainties similar across different solid targets
- Systematics low enough to see 10% effects at low x, need Medium Energy beam to get the needed statistics

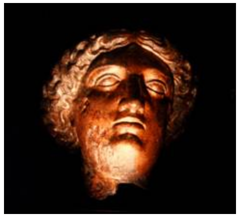


Expected Medium Energy systematic improvements:

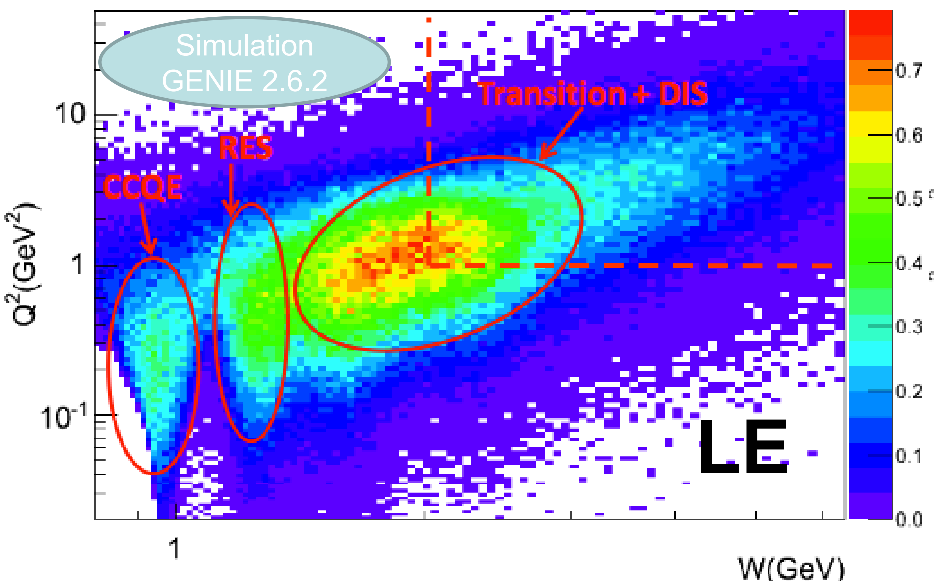
Improved Background Subtraction
Lower calorimetry systematics
Target ME systematic: 2-3%

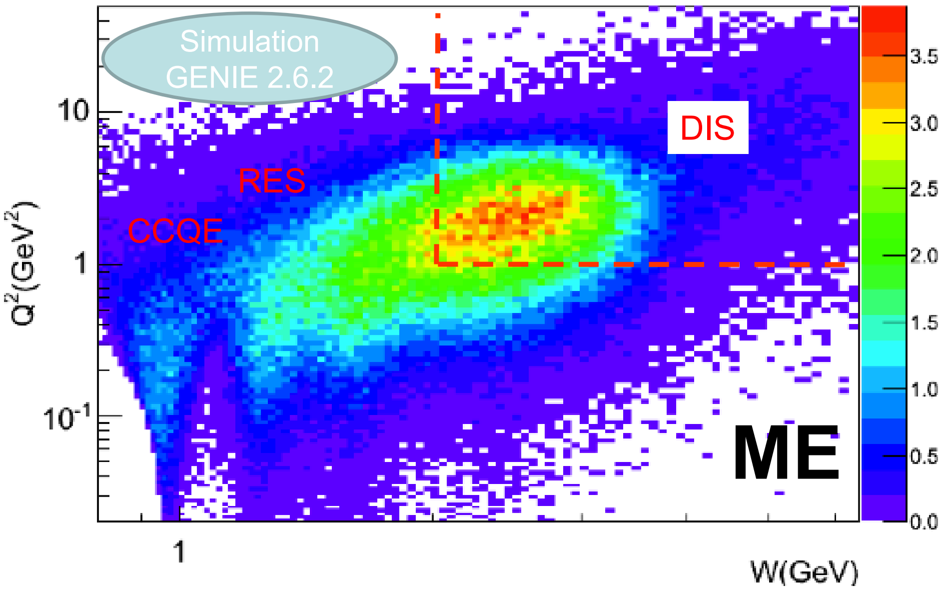
Want finer x binning, so statistics goal is 10^4 events in current binning

W, Q^2 regions in LE and ME beam

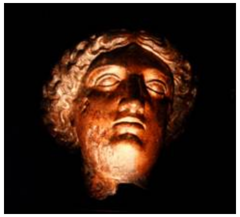


- Hadronic Invariant Mass (W) range and Q^2 both shift up
  - GENIE simulation, v2.6.2
  - Events shown have muon tracked in MINOS
  - See shift to lower x, fewer quasi-elastic and resonance events





Expected Statistics vs x: Neutrino Mode



- Full simulation on Medium Energy event sample, using cuts and reconstruction techniques from Low Energy analysis:

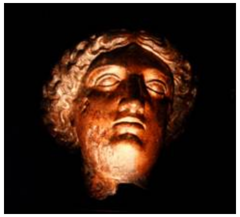
Bjorken x	0-0.1	0.1-0.3	0.3-0.7	0.7-0.9	>0.9
Carbon	7.2	14.3	10.7	2.5	7.2
Iron	36.1	70.9	55.5	10.9	36.1
Lead	39.3	83.8	66.9	13.1	39.3
Scintillator	307.1	663.0	490.4	95.1	307.1

ν Event rate **(in thousands!)** for 6E20 POT for all events vs x (reconstructed x)

Ratio of events/POT ME / LE:

Bjorken x	0-0.1	0.1-0.3	0.3-0.7	0.7-0.9	>0.9
Carbon	3.0	3.5	3.6	3.6	3.2
Iron	3.0	3.6	3.6	3.5	3.5
Lead	3.4	4.0	4.1	4.1	4.4
Scintillator	4.1	4.7	4.9	4.7	4.8

Expected Statistics vs x: Anti-Neutrino Mode



- Hit-level simulation on Medium Energy event sample, using cuts and reconstruction techniques from Low Energy analysis:

Bjorken x	0-0.1	0.1-0.3	0.3-0.7	0.7-0.9	>0.9
Carbon	4.5	7.3	6.2	1.2	4.5
Iron	20.8	34.4	27.5	5.7	20.8
Lead	21.5	37.8	28.0	6.1	21.5
Scintillator	174.3	325.0	260.6	56.3	174.3

Recall: goal of 10 kevents in these bins to be systematics dominated

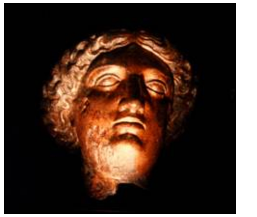
Anti-ν kEvent rate for 6E20 POT for all events vs reconstructed x

Bjorken x	0-0.1	0.1-0.3	0.3-0.7	0.7-0.9	>0.9
Carbon	0.63	0.53	0.52	0.53	0.63
Iron	0.59	0.50	0.47	0.50	0.51
Lead	0.56	0.45	0.43	0.43	0.43
Scintillator	0.61	0.52	0.50	0.50	0.52

Ratio of anti-ν/ν Per POT n ME beam as function of measured x

Goal:
12E20 in anti-ν mode

Role of Anti-neutrinos



- Having both neutrinos and antineutrinos means we do better on structure functions
- Deep Inelastic Scattering event rates, even in Medium Energy Beam, still low, especially in anti-neutrino mode

Bjorken x	0-0.1	0.1-0.3	0.3-0.7	0.7-0.9	>0.9
Carbon	0.1	3.1	1.0	0.0	0.1
Iron	0.4	9.4	3.0	0.0	0.4
Lead	0.5	11.4	3.7	0.0	0.5
Scintillator	5.5	116.0	41.0	0.1	5.5

Deep Inelastic Scattering Events
(again in thousands)
for 6E20 POT

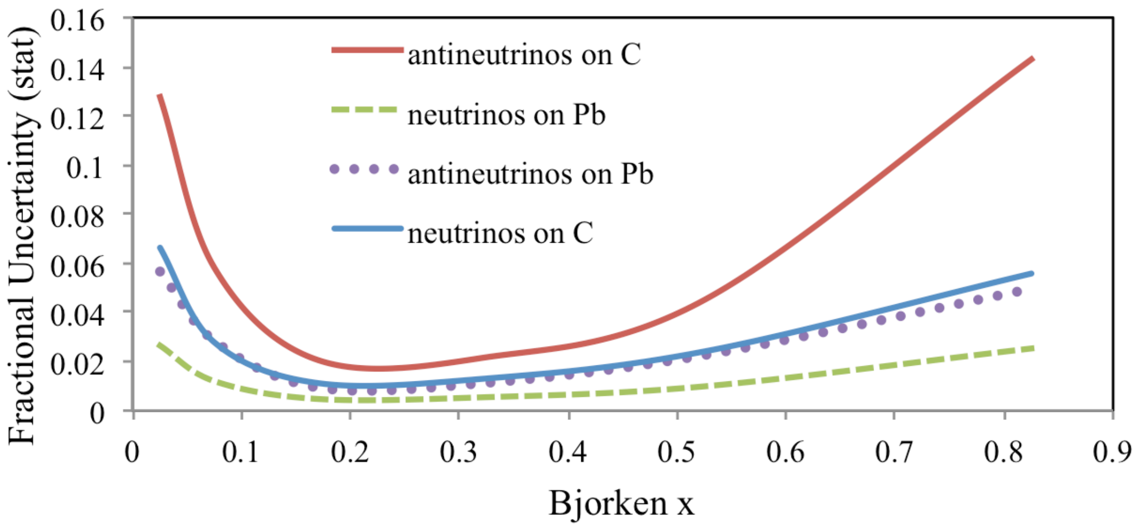
- Total event ratio (anti-ν/ν):

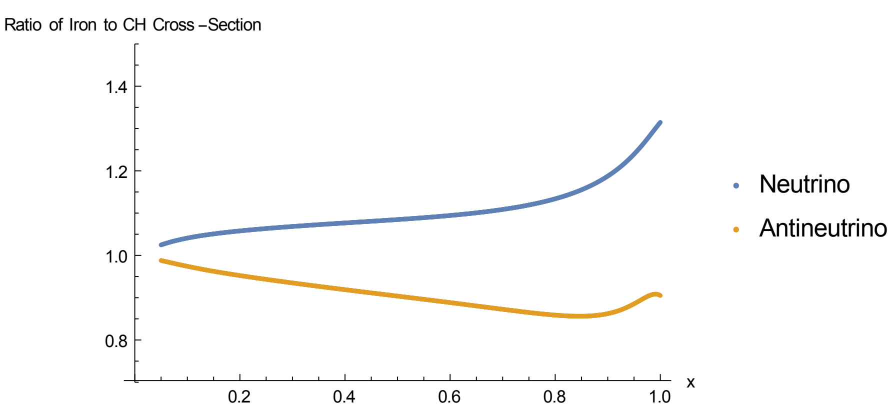
Bjorken x	0-0.1	0.1-0.3	0.3-0.7
Carbon	0.21	0.34	0.31
Iron	0.26	0.26	0.29
Lead	0.17	0.26	0.22
Scintillator	0.23	0.29	0.29

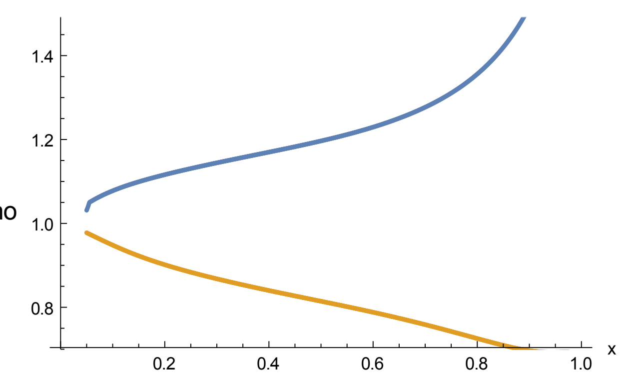
Ratio of anti-ν to ν event rates

Physics Reach on EMC Effect

- Assume 10E20 in neutrino mode, 12E20 in antineutrino mode

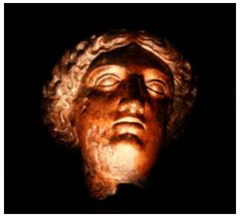




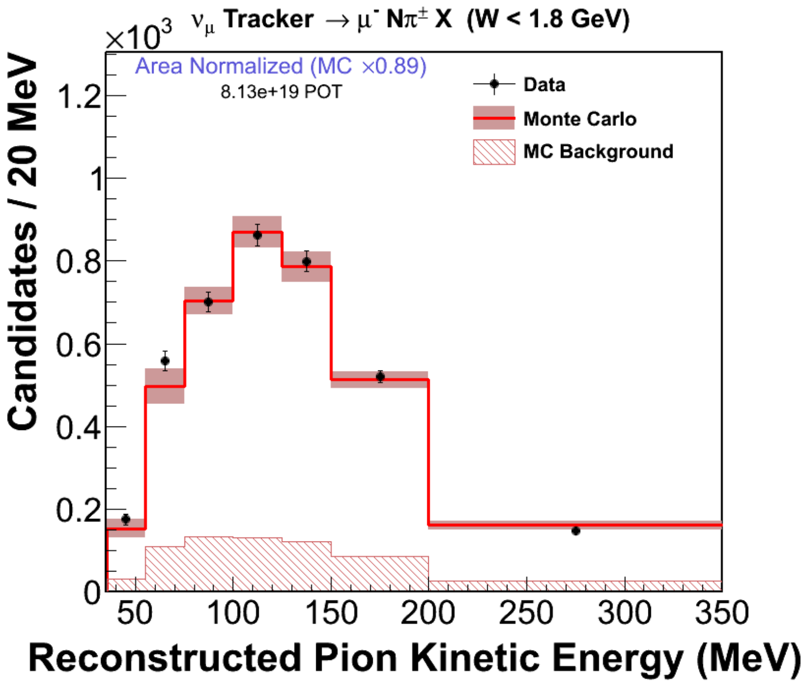


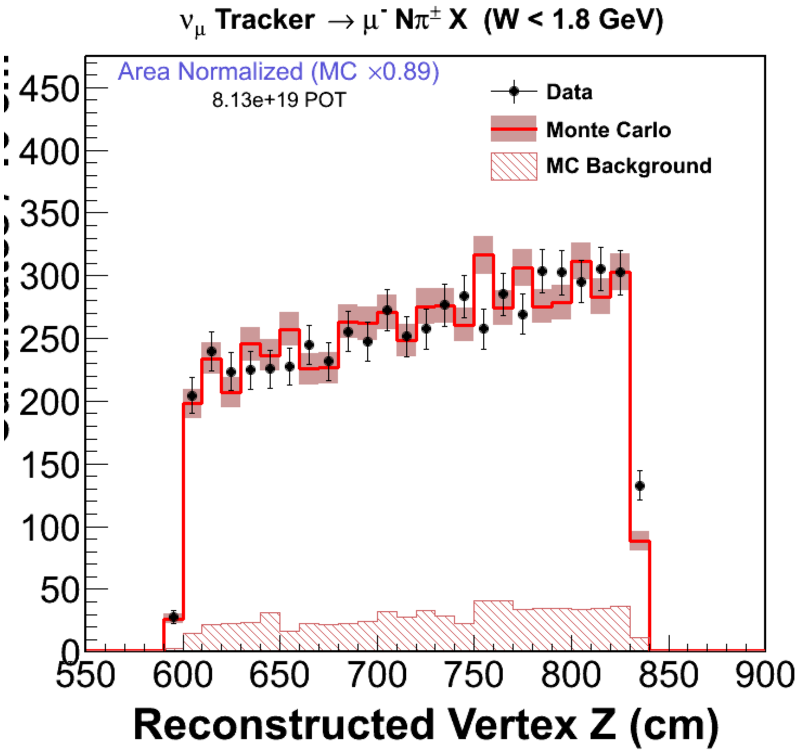
Prediction from Cloet model described in PRL 109, 182301

Pion Production on Nuclear Targets



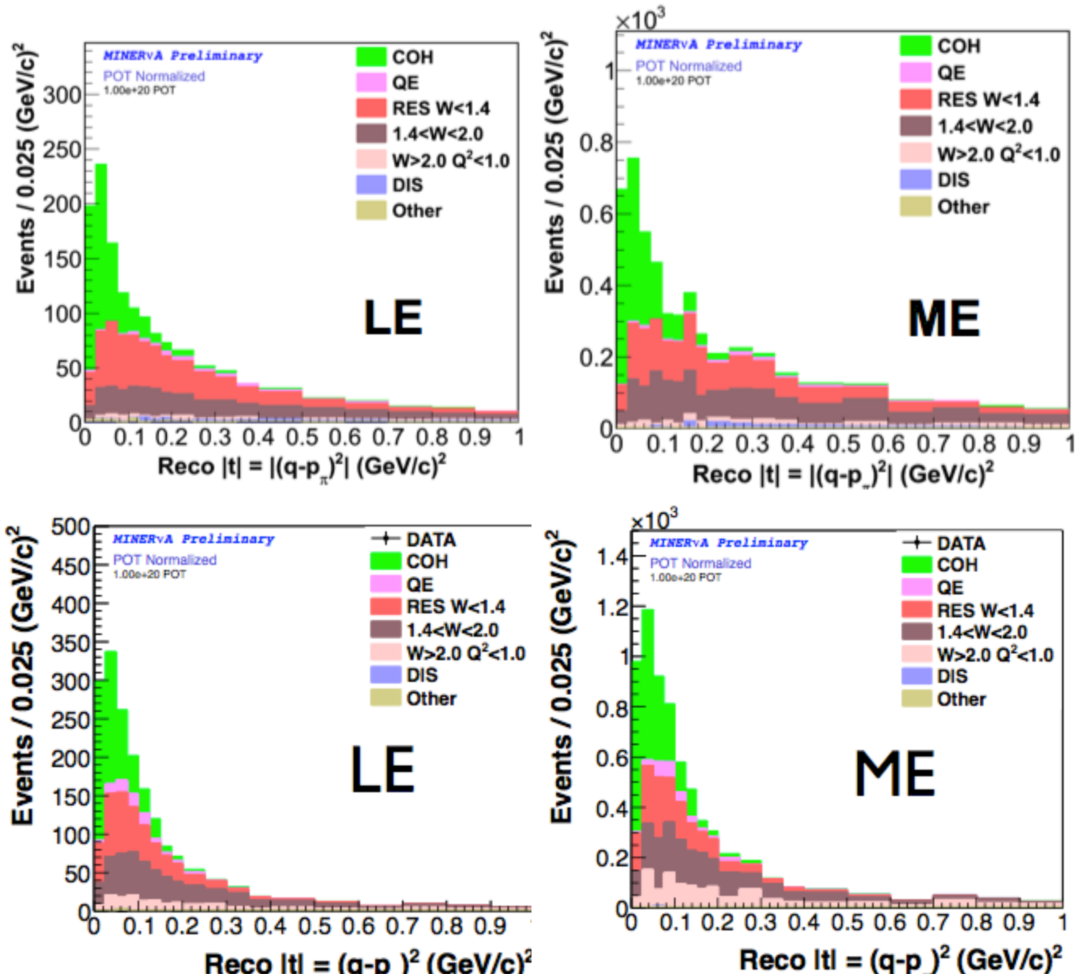
- Being able to probe FSI on different nuclei in the same beam is powerful way to constrain models
- Studies of early Medium Energy data on CH target show background rejection capability, and accurate acceptance modeling





Coherent Pion Production

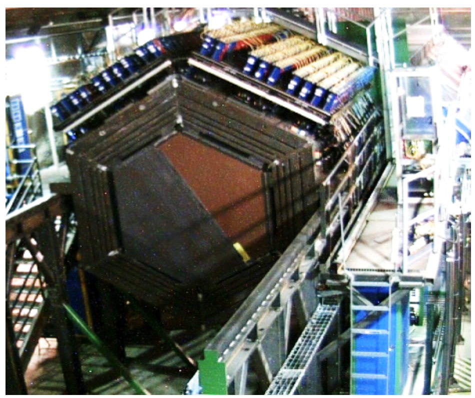
- Result in Plastic already shows that generators do not predict kinematics of this process
- Low Energy beam hit-level simulation, weighted for Medium Energy flux
- Momentum^2 transferred to nucleus distinguishes signal from background: see comparable background rejection

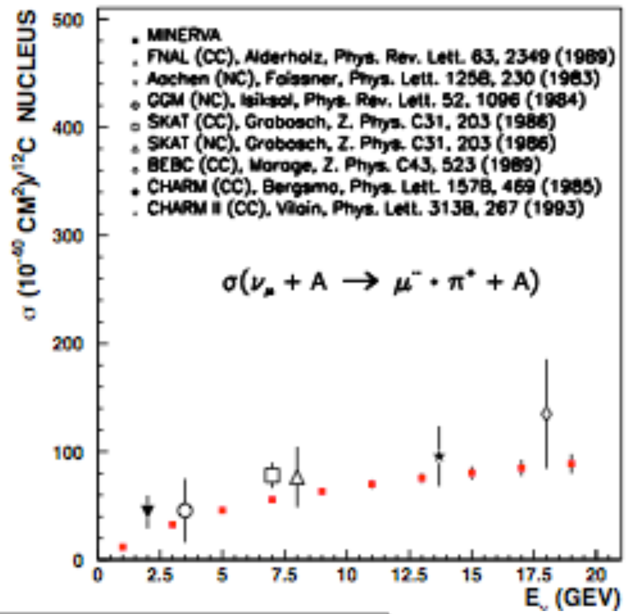


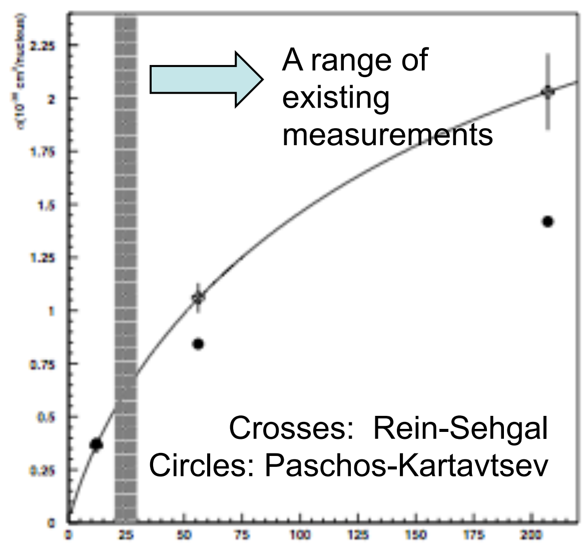
Beam Mode	Events (per 10^{20} POT)	Signal Purity	Stat error (at 10^{20} POT)
LE ν-bar	716	57%	6.5%
LE ν	1260	44%	6.4%
ME ν-bar	2430	58%	3.5%
ME ν	4480	44%	3.4%

Coherent Pion Production off Nuclear Targets

- The event rate on scintillator can be scaled to most downstream Iron/Lead target (fiducial mass of either is about 3% that of scintillator)

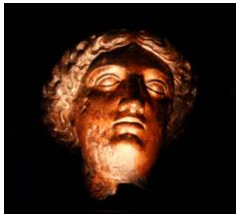




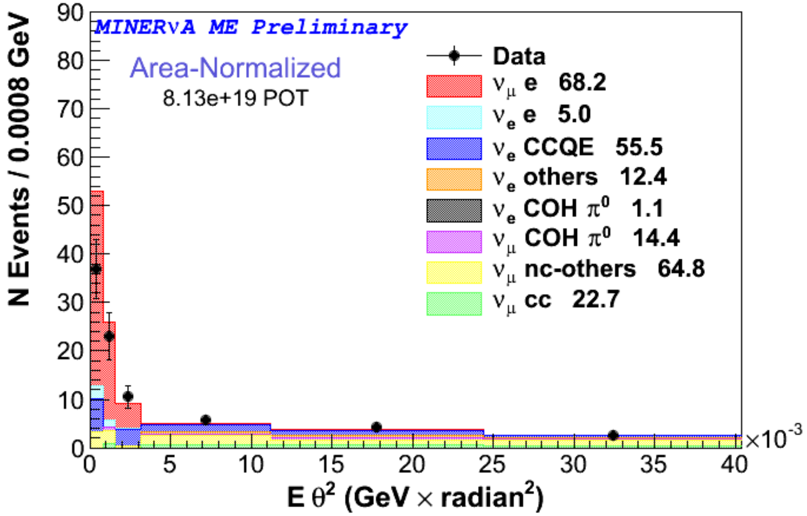


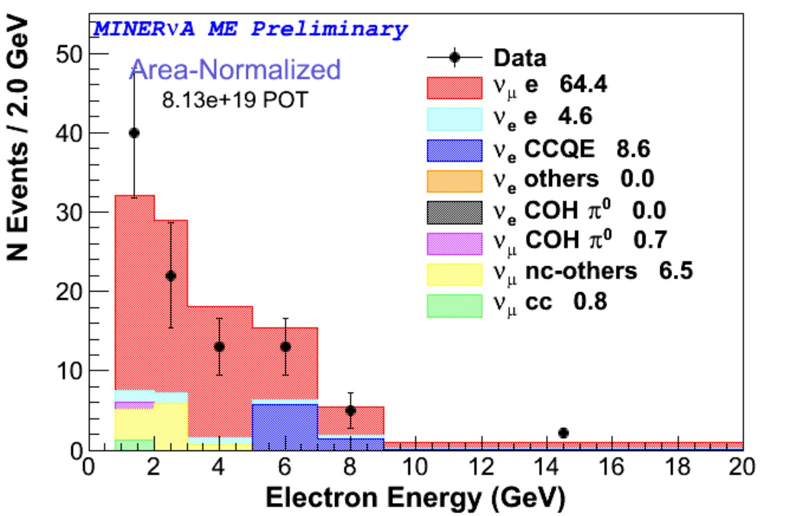
- With 6E20 POT in ν and anti-ν mode each we can make 8/9% measurements on coherent charged pion production in iron/lead (plot at right from MINERvA proposal)

Measuring Medium Energy Flux



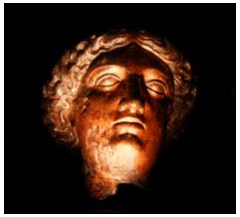
- Neutrino-electron scattering is the only “standard candle” in neutrino scattering: catch is that cross-section is extremely low
- Low energy sample produced 115 events, and 10% flux constraint, dominated by statistics
- Have repeated analysis in early Medium Energy data set and still see comparable background rejection capabilities, points to ability to achieve ~5% precision on total flux with 10E20POT in neutrino mode
- Antineutrino mode analysis will be more challenging but could still provide flux constraint





Conclusions

- MINERvA is already making important contributions to field of neutrino (oscillation) physics
  - Understanding role nucleus plays
    - Changing the interaction rates
    - Changing the final state particles
    - Changing the event reconstruction biases
  - Learning how to measure neutrino fluxes
    - New “standard candle” can be used with relatively cheap detector
- Need 12E20 POT in Antineutrino Medium Energy Beam to complete the broad physics program that we proposed to do
  - Nuclear effects on exclusive processes
    - Quasi-elastic and pion production from many angles
  - Structure functions on different nuclei
  - This exposure means we will be able to probe quark flavor dependence of nuclear effects, including EMC effect

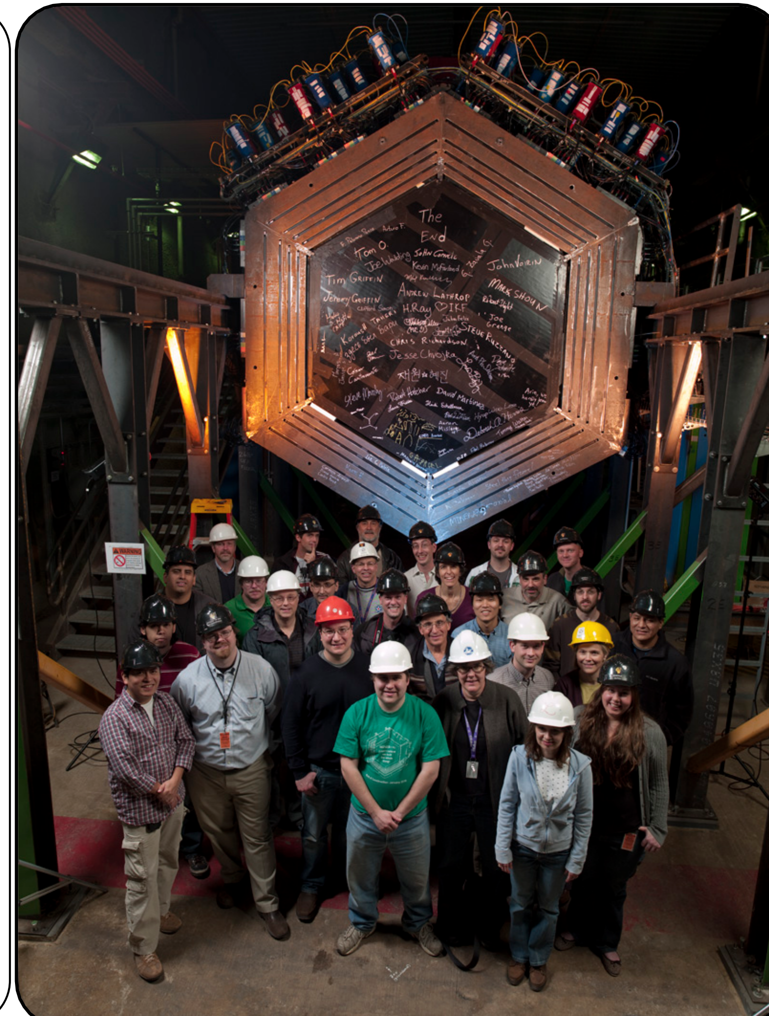


BACKUP SLIDES

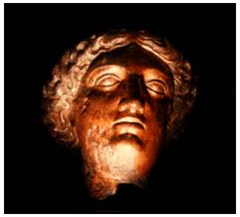
MINERvA Collaboration

~65 collaborators from particle and nuclear physics

Centro Brasileiro de Pesquisas Físicas
Fermilab
University of Florida
Université de Genève
Universidad de Guanajuato
Hampton University
Mass. Col. Lib. Arts
Northwestern University
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



How long will the Detectors Last?



- Solid scintillator normally loses light over time
- MINOS light loss at 2%/year, MINERvA light loss at 4%/year
- Event with 50% light loss, position resolution in MINERvA only worsens by 20%