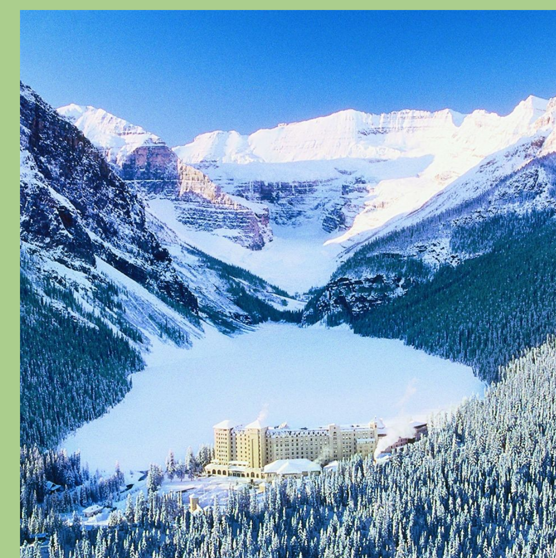
MINERνA

Status and Results

Lake Louise
Winter Institute
Chateau Lake Louise
2016 February 7 to 13



Vittorio Paolone
University of Pittsburgh
(Representing the MINERνA collaboration)

Outline

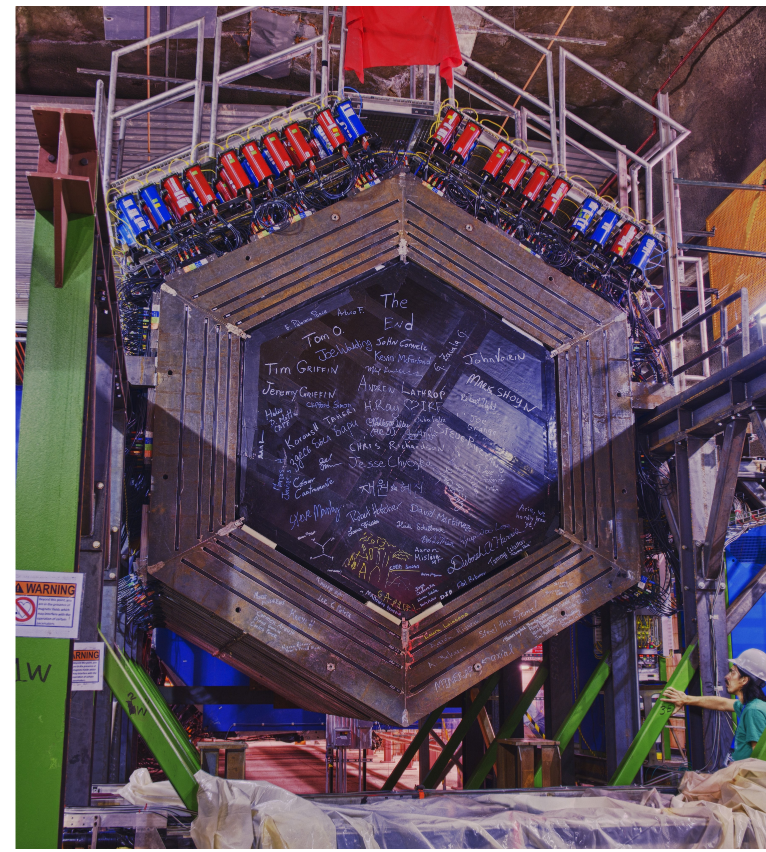
→ **What is MINERνA?**

→ **Why Measure ν cross-sections?**

→ **Recent Analysis Efforts.**

- Flux Constraints
- Charged-current quasi-elastic scattering of muon and electron neutrinos
- Deep inelastic scattering on different nuclei
- Nuclear effects in neutrino-carbon interactions at low three-momentum transfer

→ **Summary and Outlook**



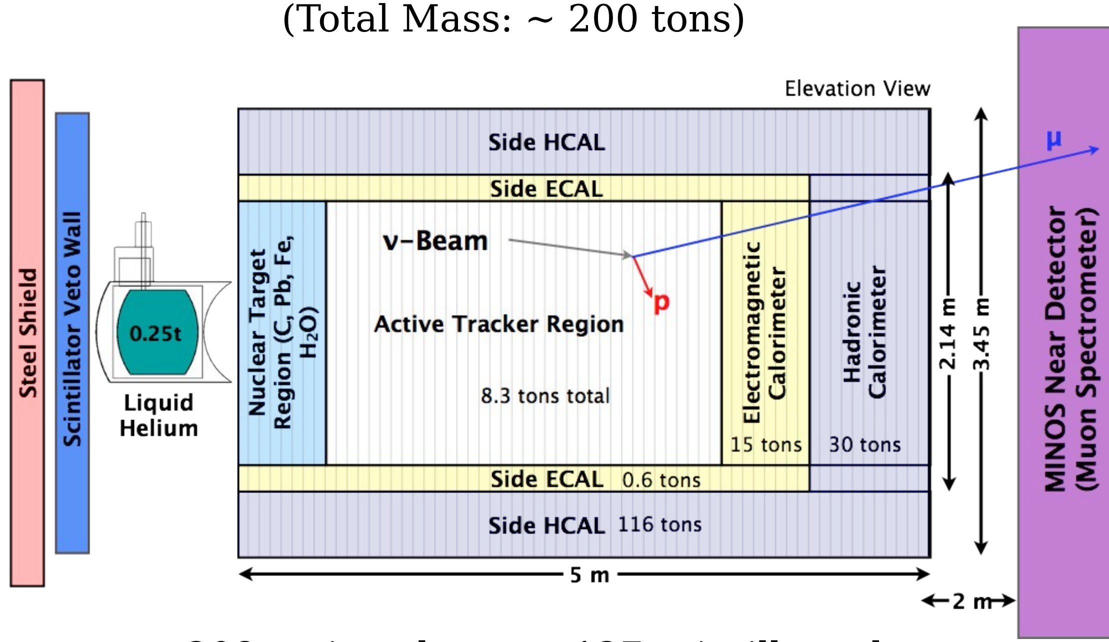
What is MINERνA?

- Dedicated neutrino-nucleus cross-section experiment running at Fermilab in the NuMI beamline.

  - Has performed detailed study of neutrino interactions on a variety of nuclei.
  - Using Low Energy Neutrinos
    - Visualized with a fully active, high resolution detector and large statistics

120 modules of tracker, targets, and calorimetry

(Total Mass: ~ 200 tons)



208 active planes × 127 scintillator bars

Detector Capabilities

- Good tracking resolution (~3 mm)

- Calorimetry for both charged hadronic particles and EM showers
  - MINERνA detector's hadronic energy response was measured using a dedicated test beam experiment at the Fermilab Test Beam Facility (FTFB)

- Timing information (few ns resolution) - untangle multiple ν interactions in same spill, decays

- Containment of events from neutrinos up to several GeV (except muon)

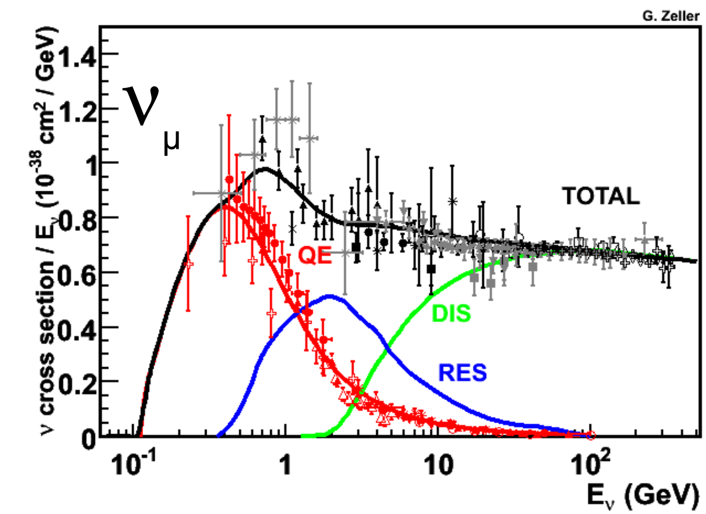
- Muon energy and charge measurement from MINOS

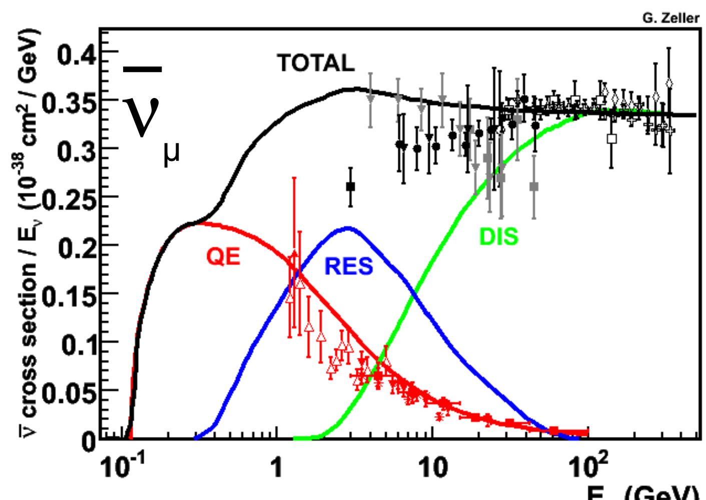
- Particle ID from dE/dx and energy+range
  - But no charge determination except muons entering MINOS

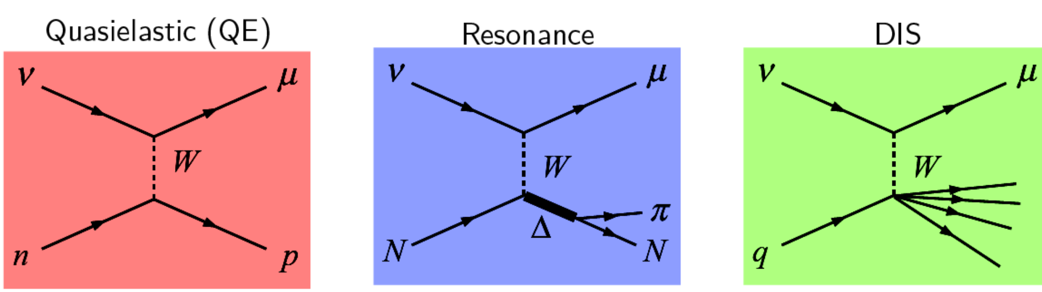
Why is MINERνA Needed?

- Existing data between 1-20 GeV limited:
- Mainly bubble chamber data
- Wide band neutrino beams
  - Low statistics samples
  - Large uncertainty on flux.
  - Limited target types

Rev. Mod. Phys. 84, 1307–1341 (2012)







Why do we care that the cross-sections are poorly known?

- **ν oscillations:**

→ We are now in a period of precision neutrino oscillation measurements

$$P(\nu_\mu \rightarrow \nu_\tau) = sin^2(2\theta_{23})sin^2\left(\frac{1.27\Delta m^2_{23}L}{E_\nu}\right)$$

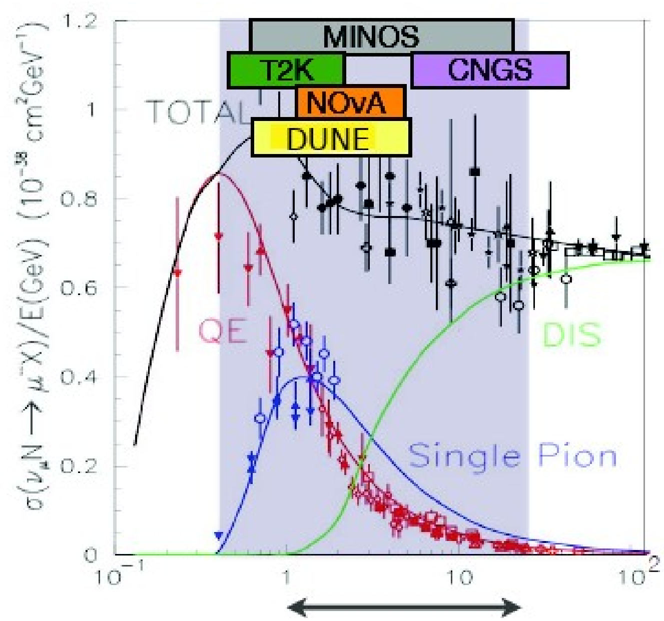
(ν_μ disappearance example)

→ **Note oscillation probability depends on E_ν**

- However Experiments Measure E_{vis}
- E_{vis} depends on Flux, σ, detector response, interaction multiplicities, target type, particle type produced and final state interactions: E_{vis} not equal to E_ν

→ Appearance Oscillation Measurements:

- Large Θ_{13} and CP violation - systematics important
- Need to understand backgrounds to ν_e searches:

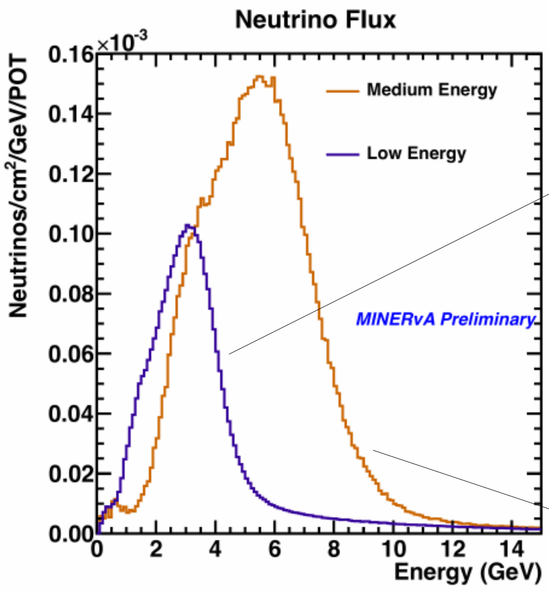


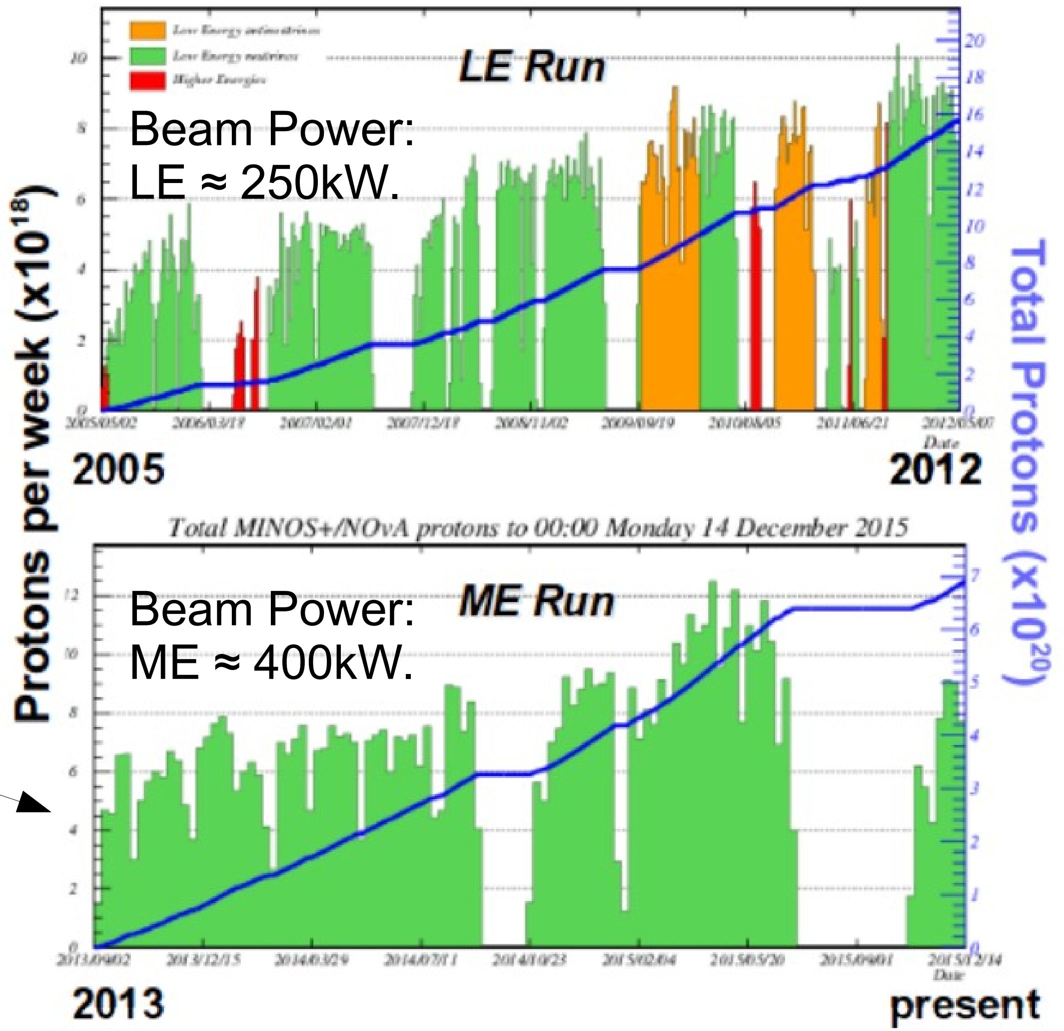
MINERνA Energy Range

- **Need Precision understanding of Low energy (Few GeV) ν_μ & $\bar{\nu}_\mu$ cross sections to improve models.**

Data Collected and Expected Sample Sizes

Results presented here based on LE running :
→ Neutrino mode 3.98×10^{20} POT
→ Anti-neutrino mode 1.7×10^{20} POT





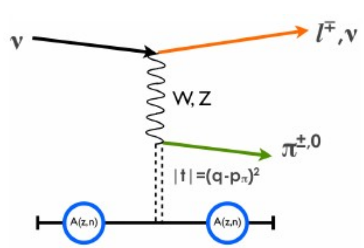
In LE mode sample size in excess of 1M events

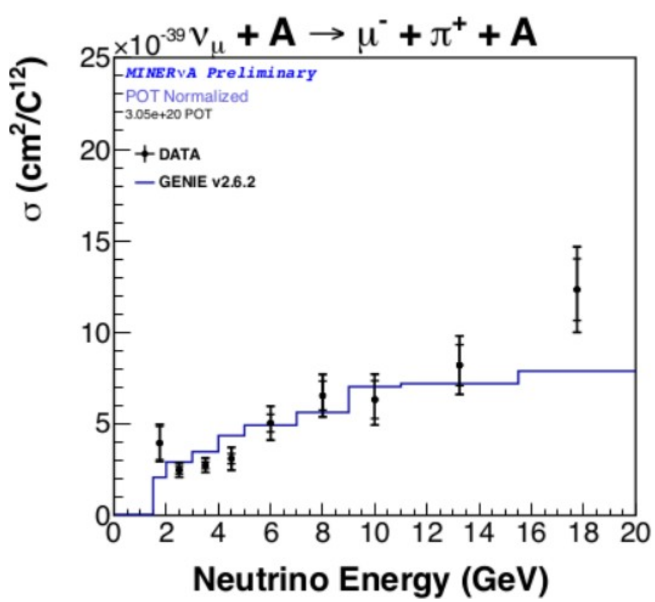
Flux: Absolute Cross-section Errors

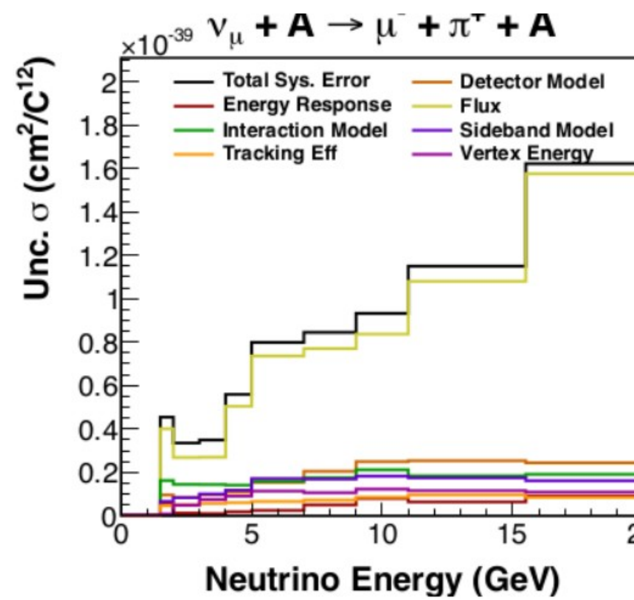
- Statistical errors are expected to be small.

- The total error on absolute cross section measurements will be dominated by the systematic error on the determination of the neutrino flux:

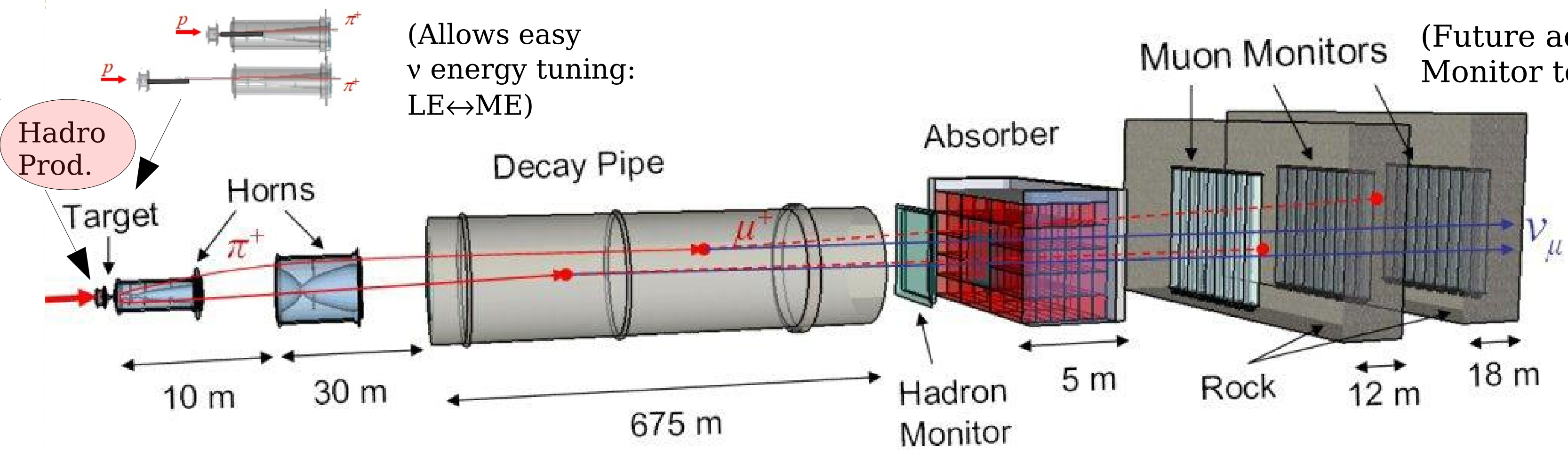
Example: Coherent $\pi^{\pm}$ production.
PRL 113, 261802 (2014)



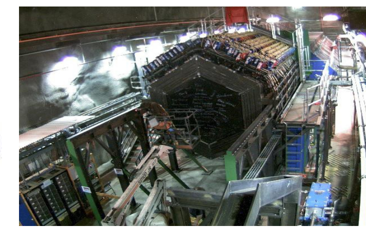




Flux: Our ν Beam (NUMI)



(Future addition of 4th Muon Monitor to study tail of ME beam)

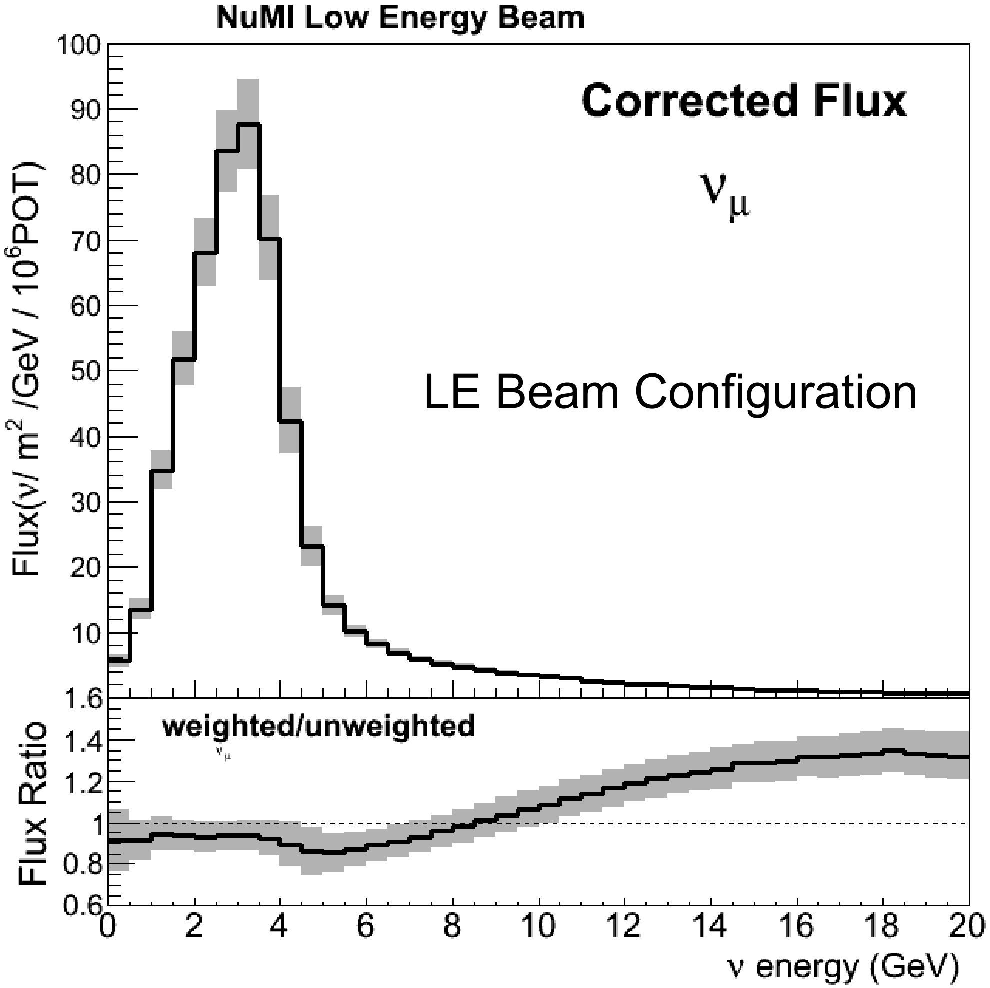


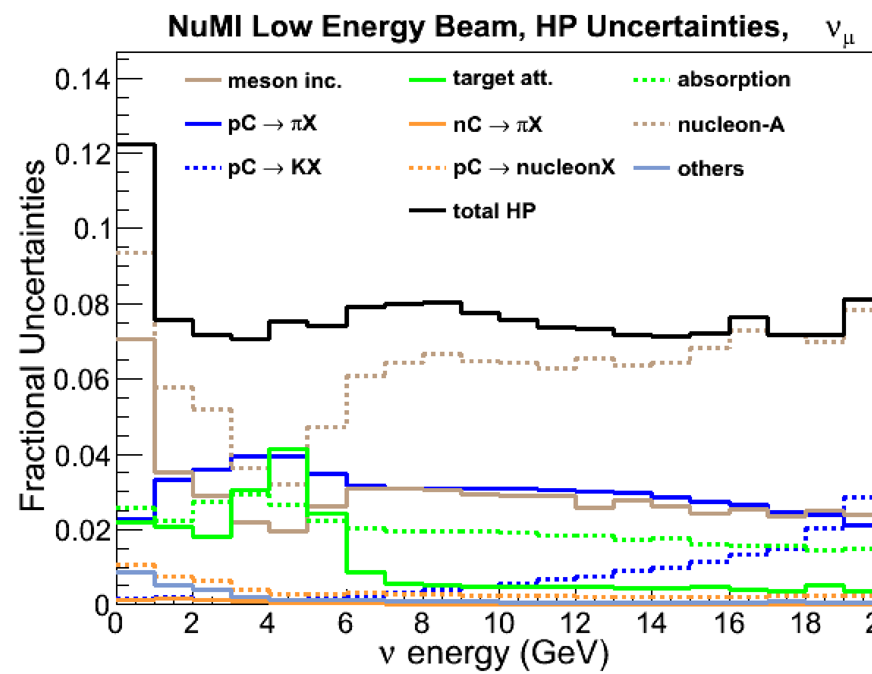
MINERνA

→ Magnetic horns focus pions and kaons, which then decay into muons and **neutrinos**

→ Good measurements of the production of pions and kaons are critical inputs to a precise flux prediction

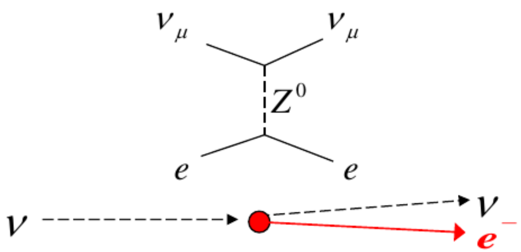
New flux Prediction Incorporating Existing Hadron Production Data





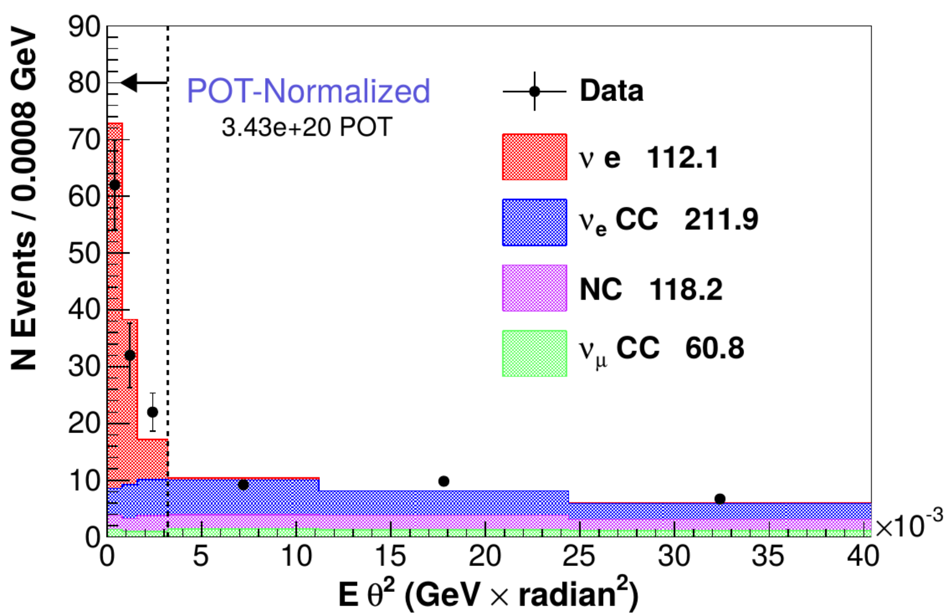
We expect ~5% errors for the ME with the addition of constraints from in situ measurements

Additional Flux Constraint: ν – e Elastic Scattering

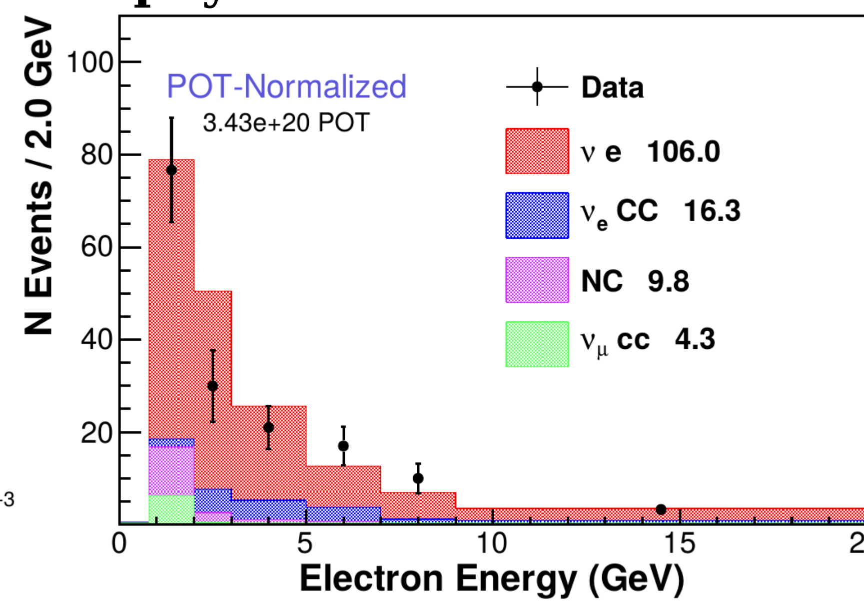


very forward single electron final state

Only true "standard candle" in neutrino scattering



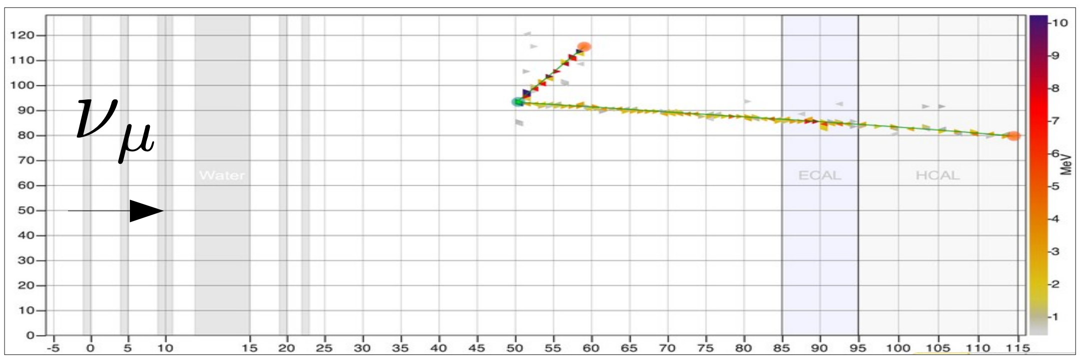
physics: arXiv:1512.07699



~100 events in LE sample ~10% flux constraint (in situ measurement – confirms previous hadro-production flux constraint – Combined LE flux errors ~6%)

ν(ν̄) CC Quasi-Elastic Scattering (CCQE):

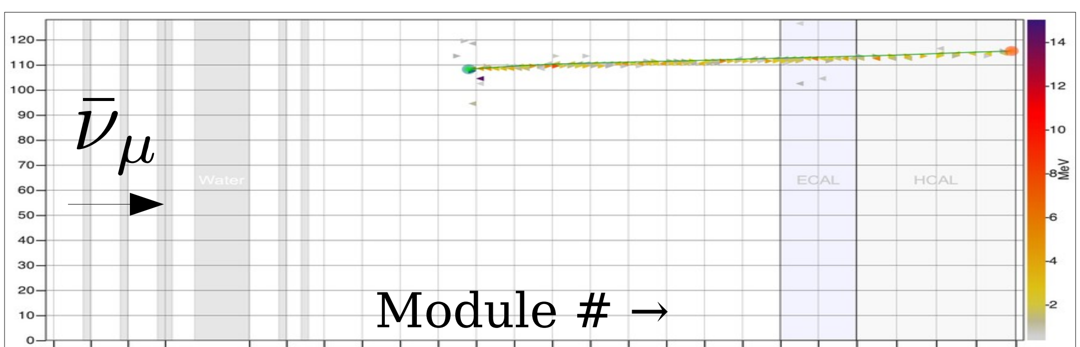
- Used as the "Standard Candle" disappearance signal channel in many oscillations experiments:
  - Assumed to be a "clean" experimental signature



Hit Energy in MeV

$$\nu_\mu + n \rightarrow \mu^- + p$$

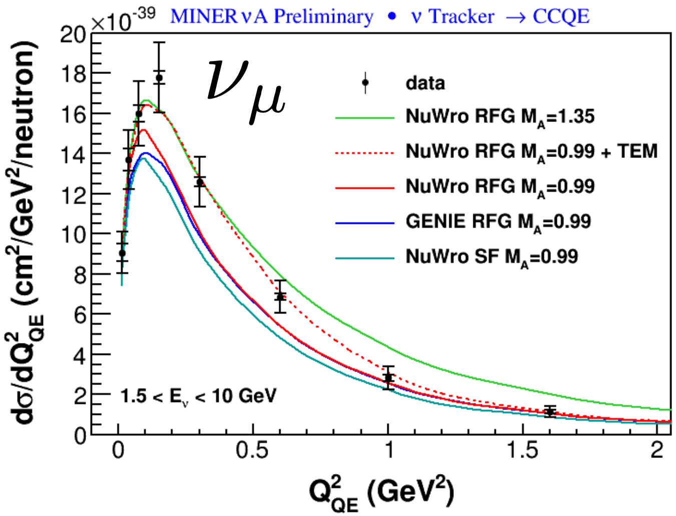
$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$$

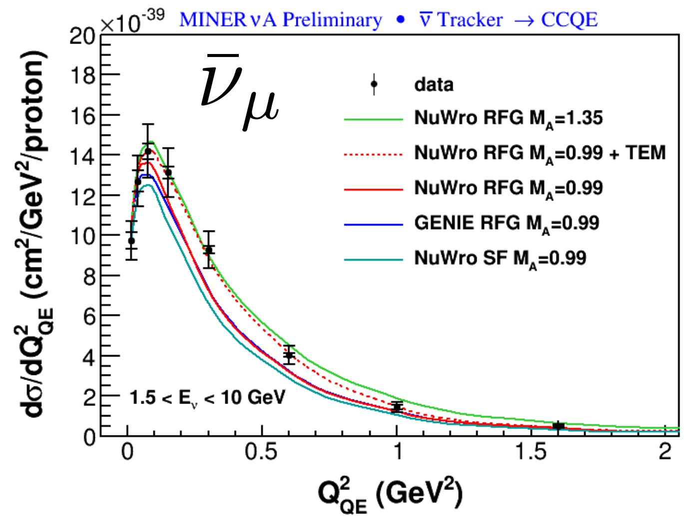


ν_μ & $\bar{\nu}_\mu$ CCQE: Results

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

$$Q^2_{QE} = -m_l^2 + 2E_\nu^{QE}(E_l - \sqrt{E_l^2 - m_l^2}cos\theta_l)$$



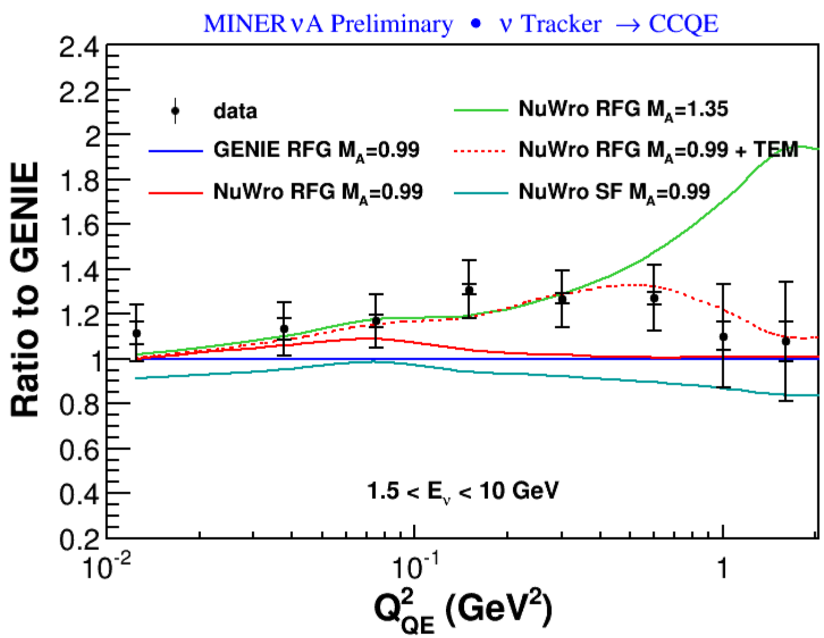


- These new results use our updated flux prediction and supersede our previous published results:

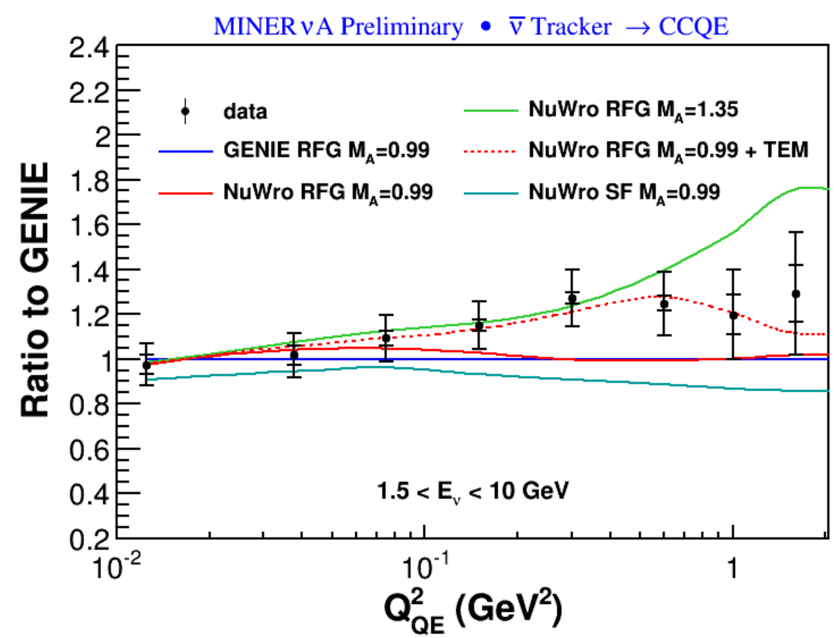
  Phys. Rev. Lett. 111, 022501 (2013)
  Phys. Rev. Lett. 111, 022502 (2013)

ν_μ & $\bar{\nu}_\mu$ CCQE: Comparison to Models

CCQE ν_μ



CCQE $\bar{\nu}_\mu$

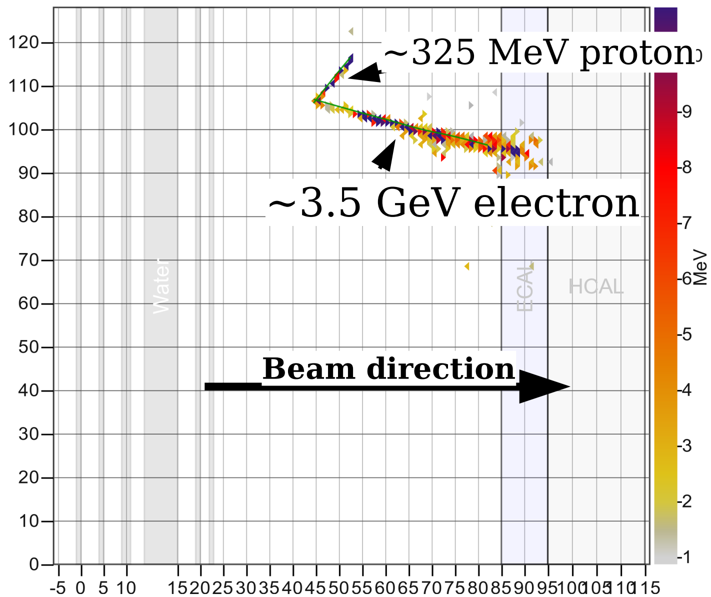


M_A = 1.35: Fit to MiniBooNE data
TEM(dotted): Transverse Enhancement Model
→ Empirical model based on electron scattering data
GENIE: Independent nucleons in mean field
SF: More realistic nucleon momentum-energy relation

NuWro: Golal, Jusczak, Sobczyk arXiv:1202.4197

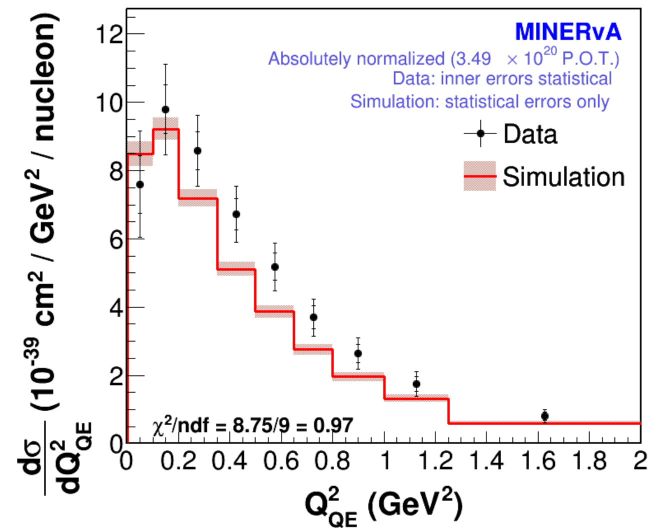
ν_e CCQE

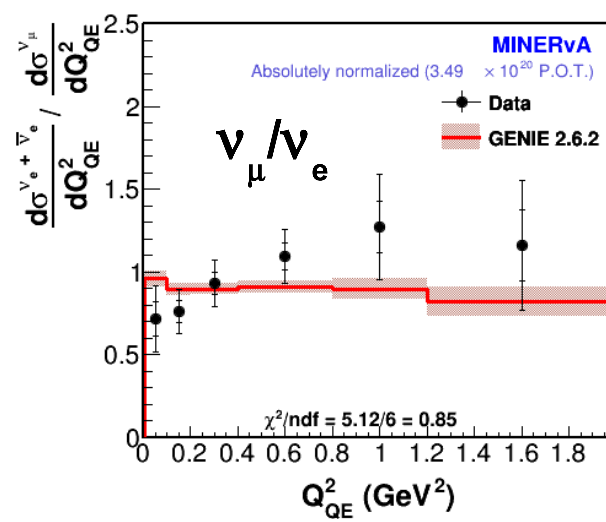
hep-ex: arXiv:1509.05729



- NuMI beam contains ~1% ν_e's
- Signal: ν_e appearance experiments (T2K, NOvA, DUNE)
- Not well measured at these energies

$$Q^2_{QE} = -m_l^2 + 2E_\nu^{QE}(E_l - \sqrt{E_l^2 - m_l^2}cos\theta_l)$$



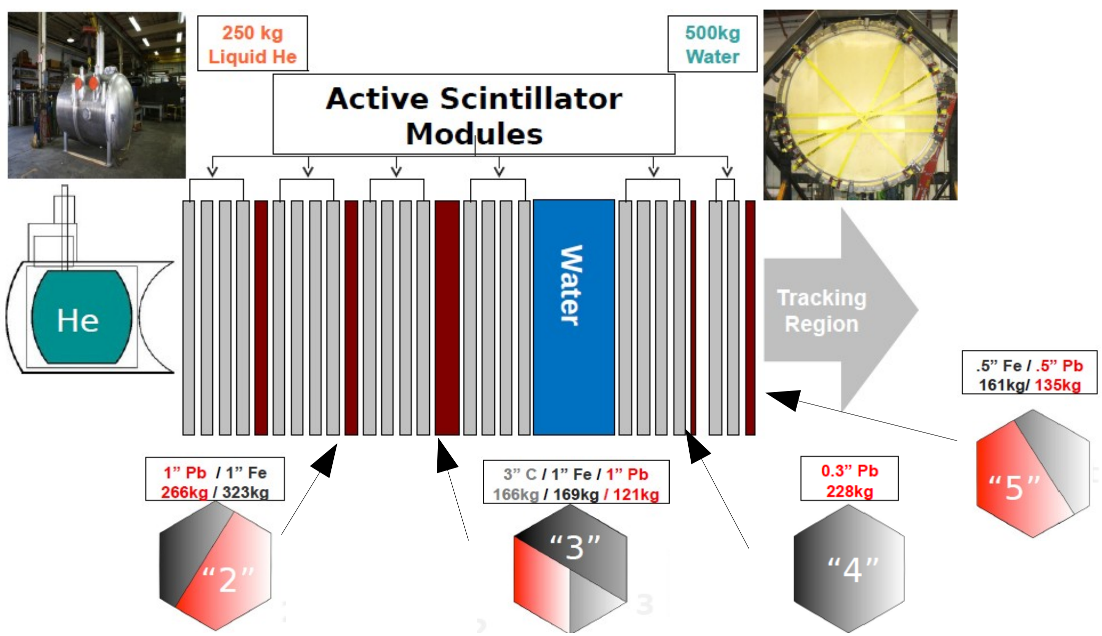


- Ratio is consistent with 1.0
- Shape is not significant due to correlated uncertainties (EM Energy Scale)

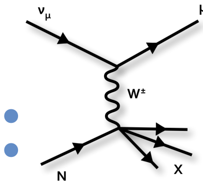
Inclusive CC ν Cross Section Ratios: A-dependence

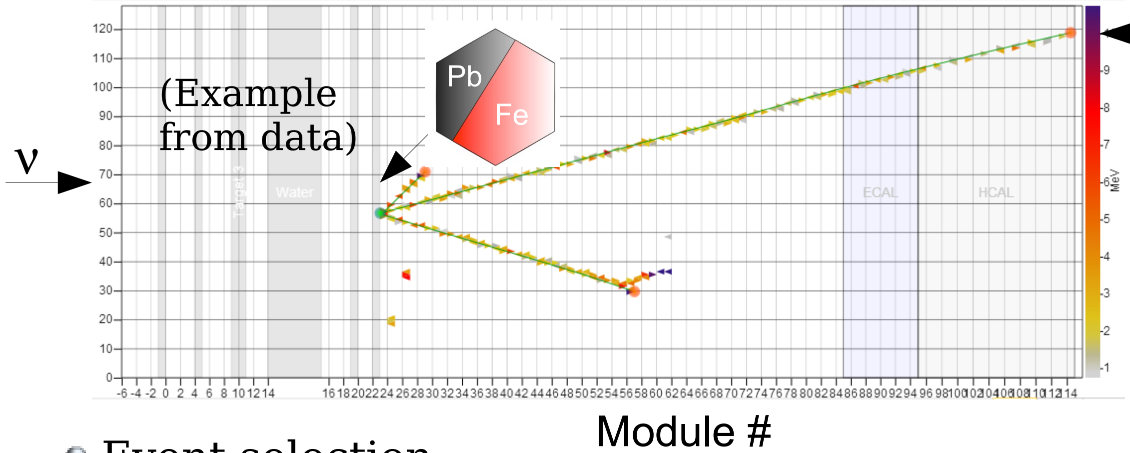
- Neutrino Oscillation experiments need a unbiased measurement of the true neutrino energy:
  - Different Experiments use Different Heavy Nuclear Targets (need mass!):
    - Carbon, Iron, Lead, Water, Argon, *etc.*
  - Nuclear effects are not small in neutrino scattering:
    - $E_{Visible} \neq E_{True}$ and Interaction Rate
  - Neutrino interaction models do not simulate these effects well
    - More data is needed to improve models

Close-up of MINERνA Target Region →



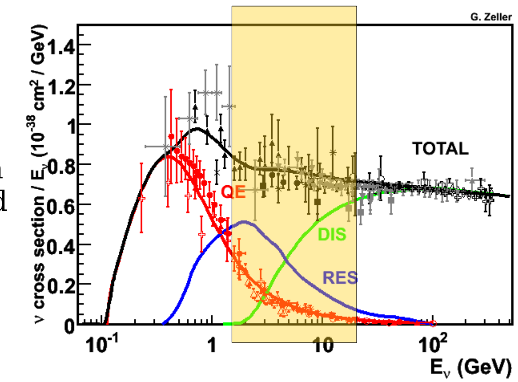
CC ν DIS Inclusive:





MINOS matched Muon

(Requiring a MINOS match somewhat reduces our energy coverage – If sign of muon not critical can use range and extend our coverage)



- Event selection:
  - Muon must be matched in MINOS Near Detector
  - Vertex in passive nuclear target

$$E_\nu = E_\mu + E_{had}$$

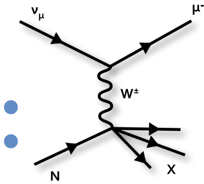
(Muon momentum and charge from MINOS ND + Sum of visible energy, weighted by amount of passive material)

- Muon angle needed for other kinematic variables:

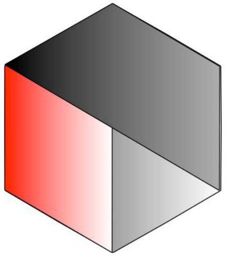
$$Q^2 = 2E_\nu\left(E_\mu - p_\mu cos\left(\theta_\mu\right)\right) \qquad x = \frac{Q^2}{2M\nu} \qquad y = E_{had}/E_\nu \qquad \nu = E_\nu - E_\mu$$

DIS sample: Q^2 > 1.0 GeV² and W > 2.0 GeV

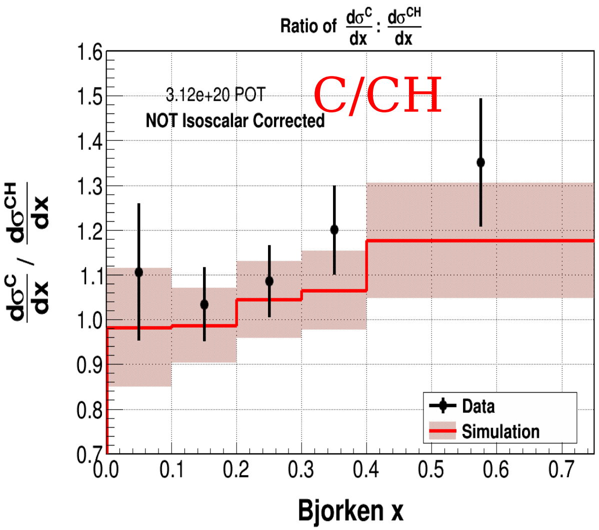
CC DIS Inclusive:

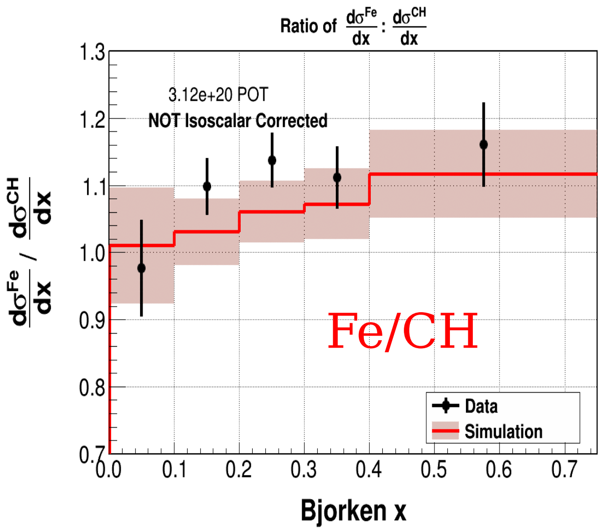


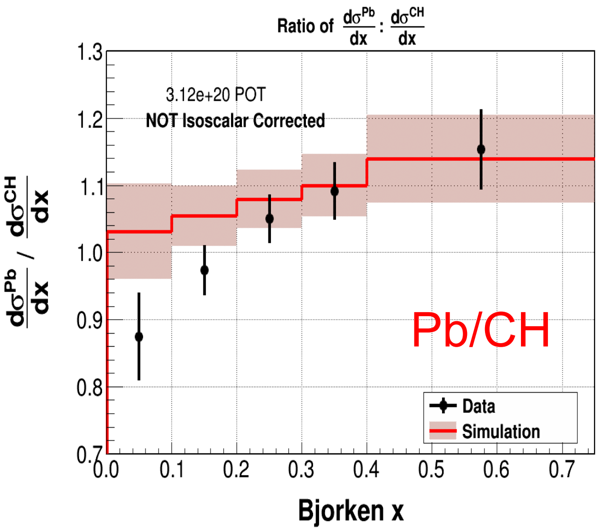
- *Divide C, Fe, Pb cross sections by scintillator (CH) cross section*
  - Each nucleus divided by a statistically independent scintillator measurements
  - Scintillator measurement is specific for each target type: use the same transverse area
    - The ratio of cross sections reduces errors by factor of ~2 (~5%):



hep-ex: arXiv:1601.06313







- Deficit at low x in Pb indicates additional nuclear shadowing than presently in models (Genie 2.6.2) needed
- As function of E_ν: No tension between MINERvA data and GENIE simulations

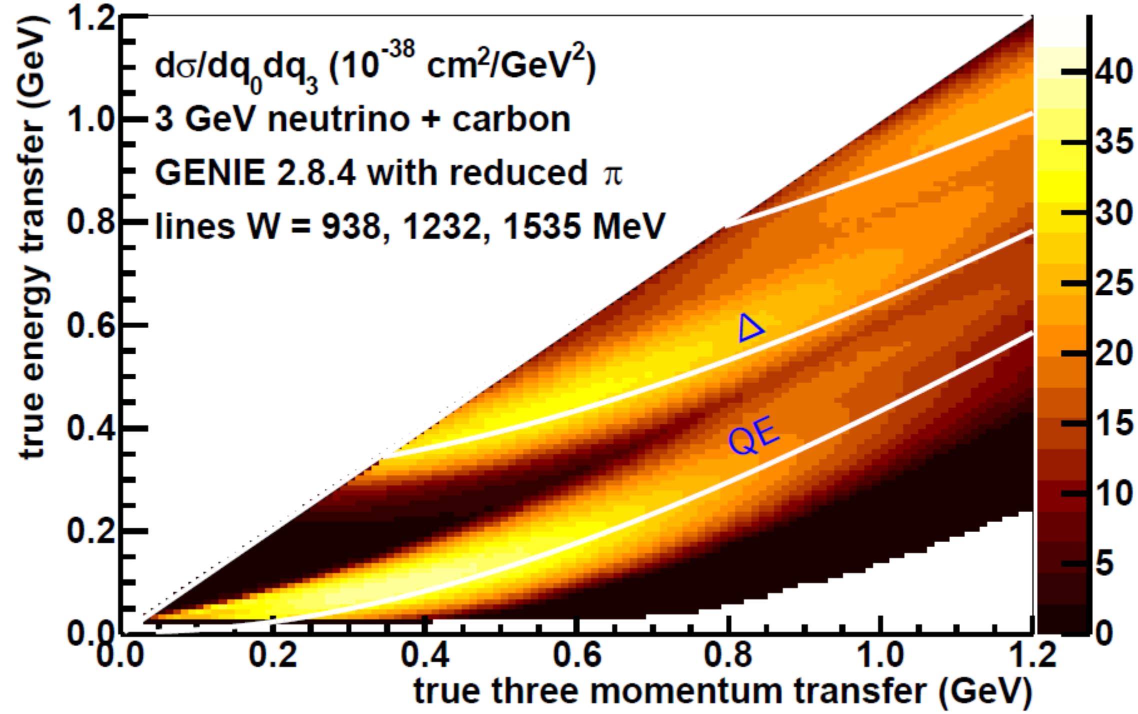
Nuclear effects in neutrino-carbon Interactions at low three-momentum transfer

- The observed hadronic energy in charged-current ν_μ interactions is combined with muon kinematics to permit separation of the quasi-elastic and Δ(1232) resonance processes:

$$E_\nu = E_\mu + q_0$$

$$Q^2 = 2E_\nu(E_\mu - p_\mu \cos\theta_\mu) - M_\mu^2$$

$$q_3 = \sqrt{Q^2 + q_0^2}$$

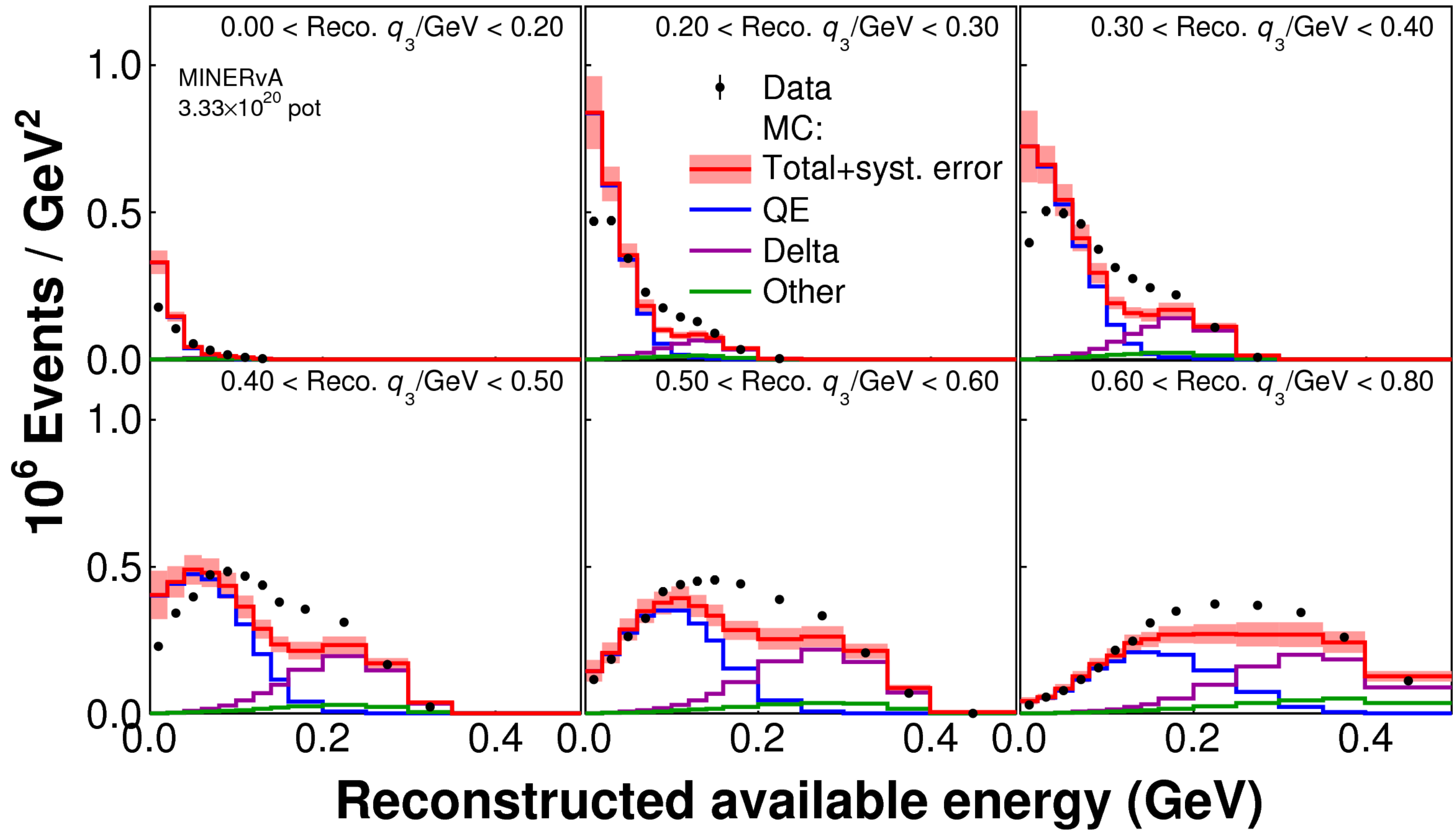


- We observe a small cross section at very low energy transfer that matches the expected screening effect of long-range nucleon correlations.

- Additions to the event rate in the kinematic region between the quasi-elastic and Δ resonance processes are needed to describe the data.

Comparison with GENIE

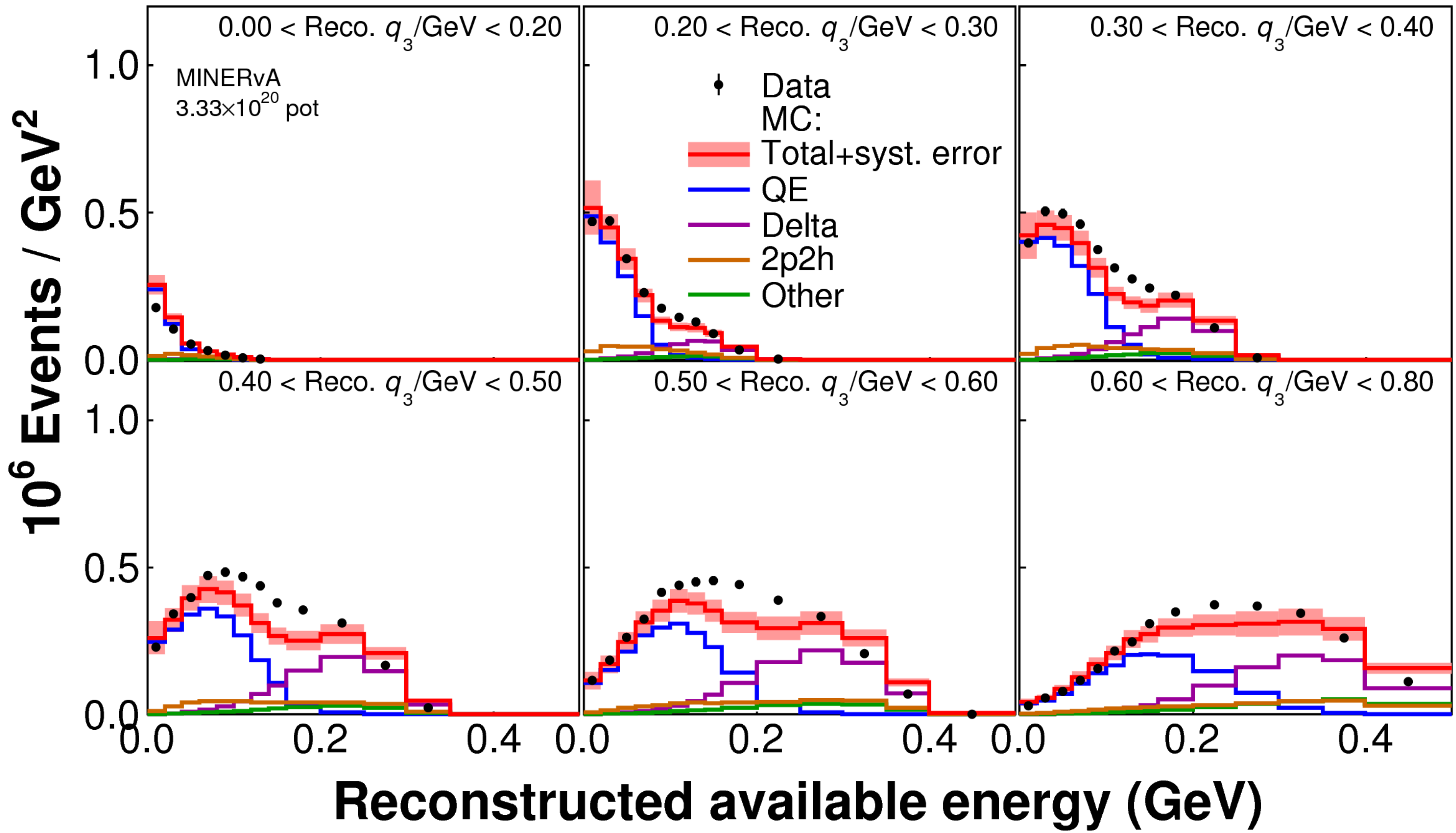
π production reduced to agree with MINERvA data



Now Add 2p2h, RPA effects

(Phys. Rev. C 83, (2011), Phys. Rev. C 70, 055503 (2004), Phys. Rev. D 88, 113007 (2013).)

arXiv:1511.05944 (PRL)



Data to Model Comparisons

- Current and future accelerator-based experiments requires accurate prediction of the neutrino energy spectrum.
- Poorly modeled nuclear effects for the QE and Δ processes, or absence of an entire process such as interactions with correlated nucleon pairs will result in an inaccurate mapping $E_{vis} \rightarrow E_{\nu}$.
- These data from the MINERvA experiment exhibit a process with multiple protons in the final state, such as those predicted by scattering from two particles leaving two holes (2p2h), with energy transfer between the QE and Δ reactions.
  - Also, the cross section at low energy transfer is small:
    - Consistent with the effects of long range nucleon-nucleon correlations, such as those computed using the Random Phase Approximation (RPA) technique.

Conclusions

- MINERνA will and has precisely studied neutrino interactions in the 1-20 GeV region:
  - Using a fine-grained, high-resolution, detector
  - Using the high flux NuMI beam in multiple energy configurations.

- MINERνA is improving our knowledge (and models) of:
  - Pion production
  - Neutrino cross sections at low energy, low Q^2.
  - A-Dependence in neutrino interactions (Targets He, C, Fe, Pb and H_2O)

- These results will help resolve longstanding discrepancies between experiments and will be important for minimizing systematic errors in oscillation experiments.

- More results are forthcoming (ME Results)!

The Collaboration Thanks You

- Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil
- UC Irvine, Irvine, CA
- University of Chicago, Chicago, IL
- Fermi National Accelerator Laboratory, Batavia, IL
- University of Florida, Gainsville, IL
- Université de Genève, Genève, Switzerland
- Universidad de Guanajuato, Ganajuato, Mexico
- Hampton University, Hampton, VA
- Mass. Col. Lib. Arts, North Adams, MA
- University of Minnesota-Duluth, Duluth, MN
- Northwestern University, Evanston, IL
- Oregon State University, Portland, OR
- Otterbein College, Westerville, OH
- University of Pittsburgh, Pittsburgh, PA
- Pontificia Universidad Católica del Perú, Lima, Peru
- University of Rochester, Rochester, NY
- Rutgers University, Piscataway, NJ
- Universidad Técnica Federico Santa María, Valparaiso, Chile
- Tufts University; Medford, MA
- Universidad Nacional de Ingeniería, Lima, Peru
- College of William & Mary, Williamsburg, VA

Recent Publications

Measurement of Partonic Nuclear Effects in Deep-Inelastic Neutrino Scattering using MINERvA

Identification of nuclear effects in neutrino-carbon interactions at low three-momentum transfer, to appear in Phys. Rev. Lett. (2016)

Measurement of electron neutrino quasielastic and quasielastic-like scattering on hydrocarbon at average Evof 3.6 GeV, to appear in Phys. Rev. Lett. (2016)

Measurement of Neutrino Flux from Neutrino-Electron Elastic Scattering

"Single neutral pion production by charged-current anti-νμ interactions on hydrocarbon at average Eν of 3.6 GeV", Phys.Lett. B749 130-136 (2015).

"Measurement of muon plus proton final states in νμInteractions on Hydrocarbon at average Eν of 4.2 GeV"Phys. Rev. D91, 071301 (2015).

"MINERvA neutrino detector response measured with test beam data", Nucl. Inst. Meth. A789, pp 28-42 (2015).

"Measurement of Coherent Production of π± in Neutrino and Anti-Neutrino Beams on Carbon from Eν of 1.5 to 20 GeV", Phys. Rev.Lett. 113, 261802 (2014).

"Charged Pion Production in νμ Interactions on Hydrocarbon at average Eν of 4.0 GeV" , Phys.Rev. D92, 092008 (2015).

"Measurement of ratios of νμ charged-current cross sections on C, Fe, and Pb to CH at neutrino energies 2–20 GeV", Phys. Rev. Lett. 112, 231801 (2014).

"Measurement of Muon Neutrino Quasi-Elastic Scattering on a Hydrocarbon Target at Eν~3.5 GeV", Phys. Rev. Lett. 111, 022502 (2013).

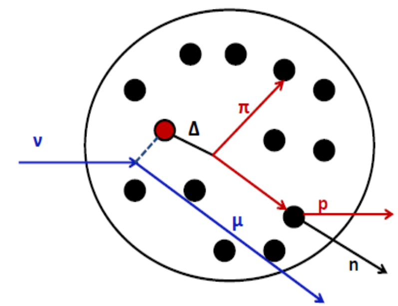
"Measurement of Muon Antineutrino Quasi-Elastic Scattering on a Hydrocarbon Target at Eν~3.5 GeV", Phys. Rev. Lett. 111, 022501 (2013).

Back-ups

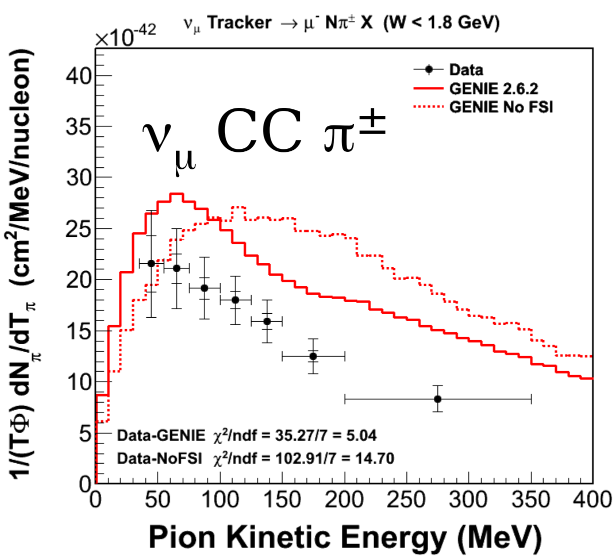
Neutrino Oscillation Studies and Pion Production:

- Pion backgrounds to ν_e oscillation searches:
  - CC ν_μ events with π^0 and "lost" μ
  - NC π^0: $\nu_{\mu/e} + N \rightarrow \nu_{\mu/e} + N + \pi^0$
  - Stopping charged π's

- Hadrons can interact with nucleons before exiting the nucleus: Final State Interactions (FSI)



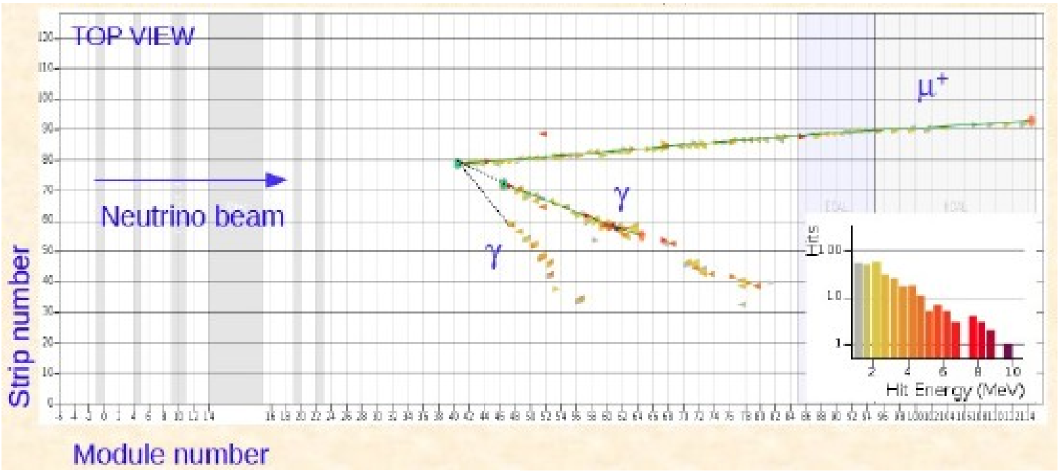
- Need a good and reliable prediction of pion spectra exiting the nucleus.

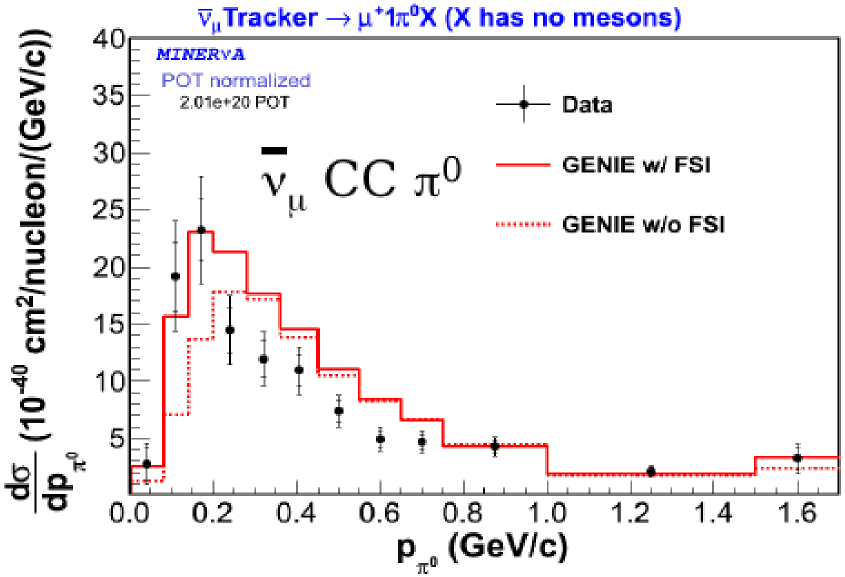


- π^+ spectrum is affected by FSI
  - FSI reduces the cross section due to pion absorption
- Cross section is over-predicted by GENIE
- Shapes agree with GENIE

(Phys. Rev. D 92, 092008 (2015))

Pion Production: Neutral Pions



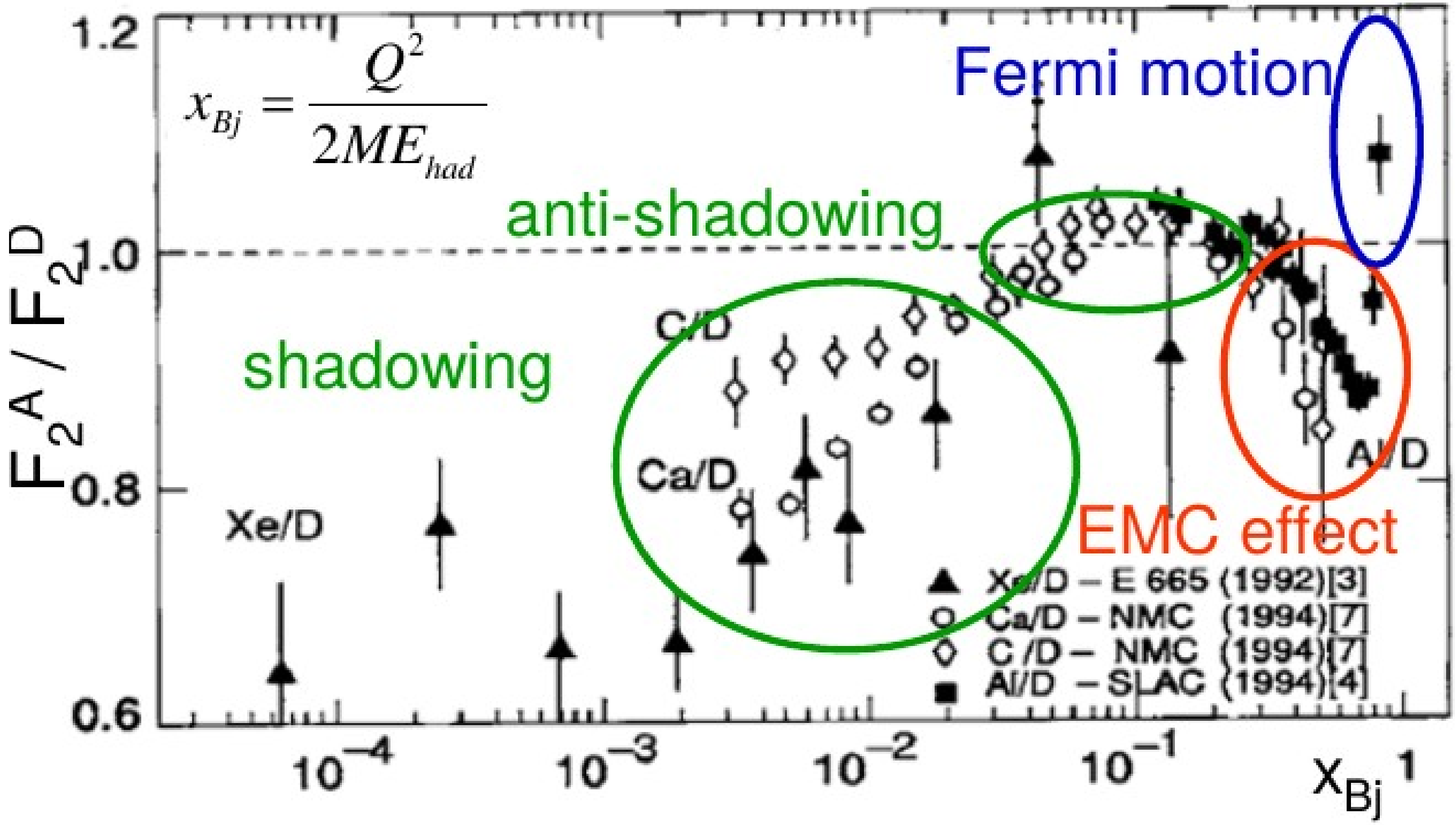


Phys.Lett. B749 (2015) 130-136

- π^0 spectrum is affected by FSI, μ^+ spectrum is not
  - FSI enhances the cross section due to $\pi^\pm$ charge exchange
- Shape agrees with GENIE

Shadowing

A / D Ratio (e / μ DIS)



New flux Prediction Incorporating Existing Hadron Production Data