# MINERνA

## Survey of Recent Results:
## $\nu N \rightarrow$ " stuff "

**Blois 2017**

**29th Rencontres de Blois "Particle Physics and Cosmology"**

**28 May 2017 to 2 June 2017**


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University of Pittsburgh
(Representing the MINERνA collaboration)

# Outline



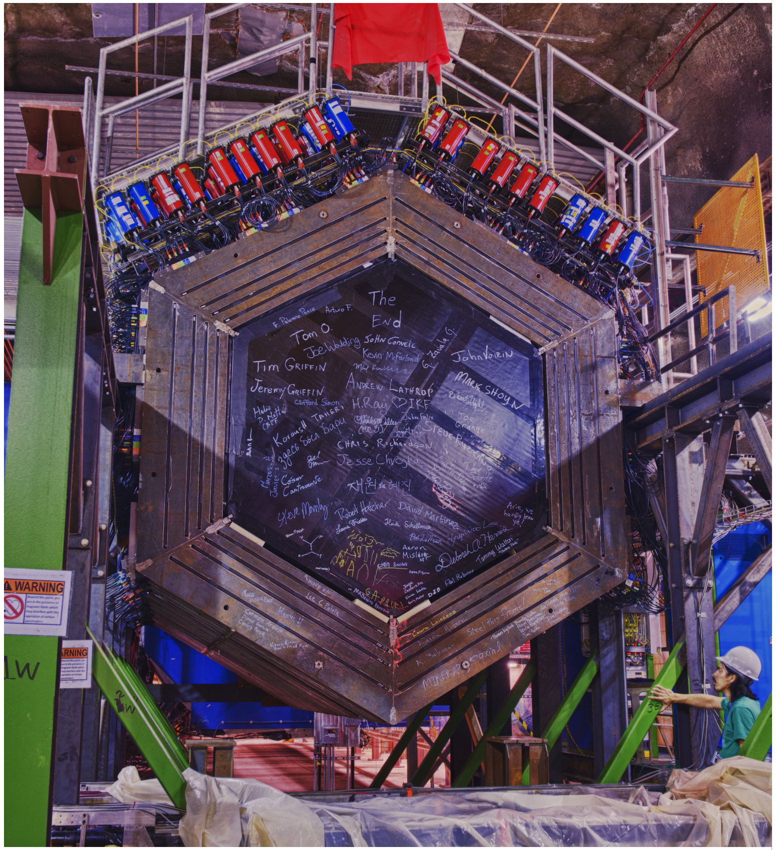
→ **What is MINERνA?**

→ **Why Measure ν cross-sections?**

→ **Recent Analysis Results.**

- Flux Constraints
- Charged-current quasi-elastic scattering
- Deep inelastic scattering on different nuclei
- Nuclear effects in neutrino-A
- Interactions at low three-momentum transfer

→ **Summary and Outlook**

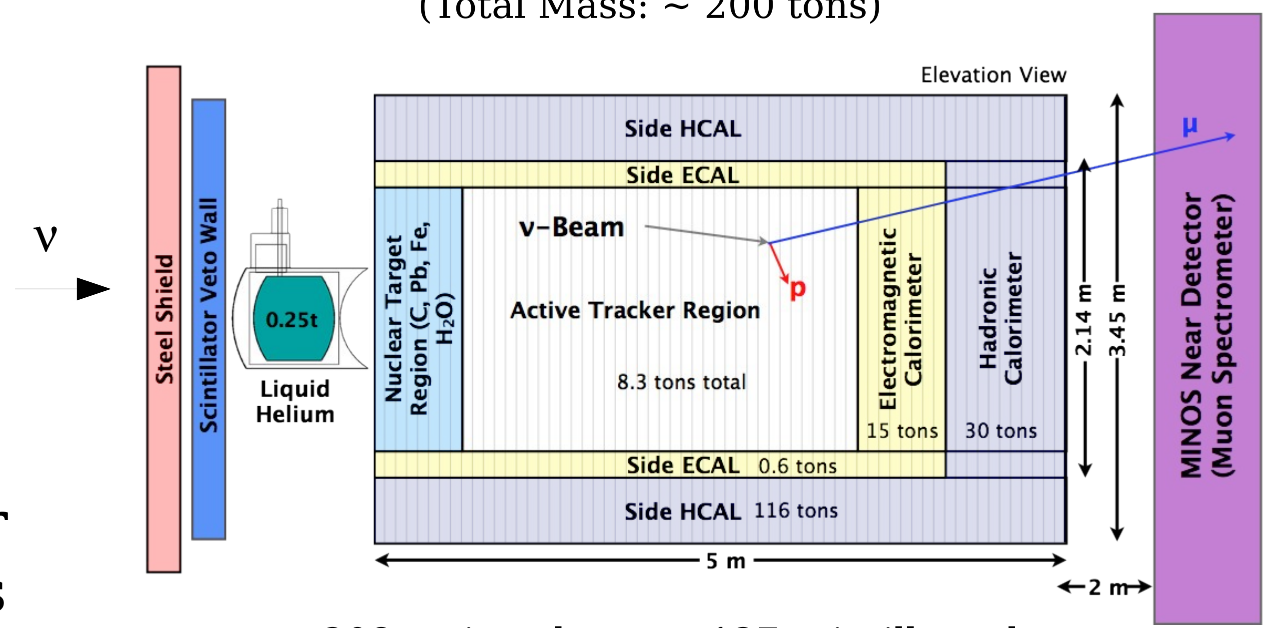


# What is MINERνA?


- 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)

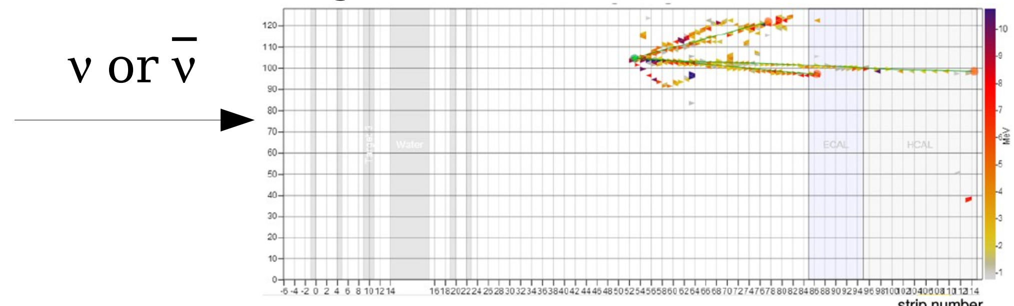
- Calorimetry for both charged hadronic particles and EM showers
  - MINERνA detector's hadronic energy response was measured using a dedicated test beam experiment at the Fermilab Test Beam Facility (FTFB)

- 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

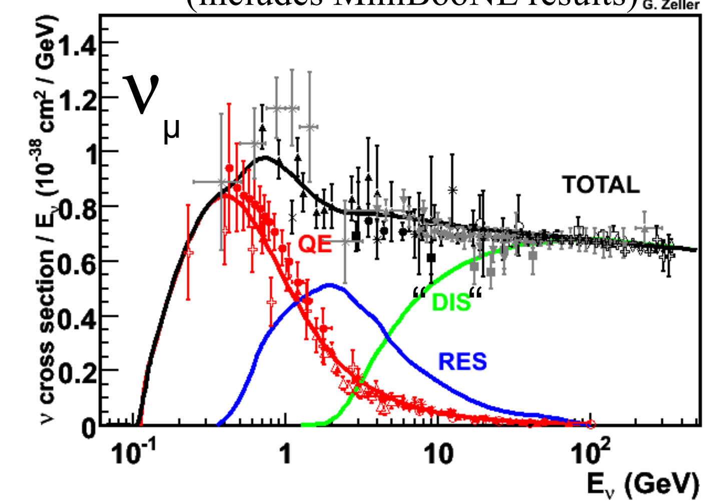
- Particle ID from dE/dx and energy+range
  - But no charge determination except muons entering MINOS

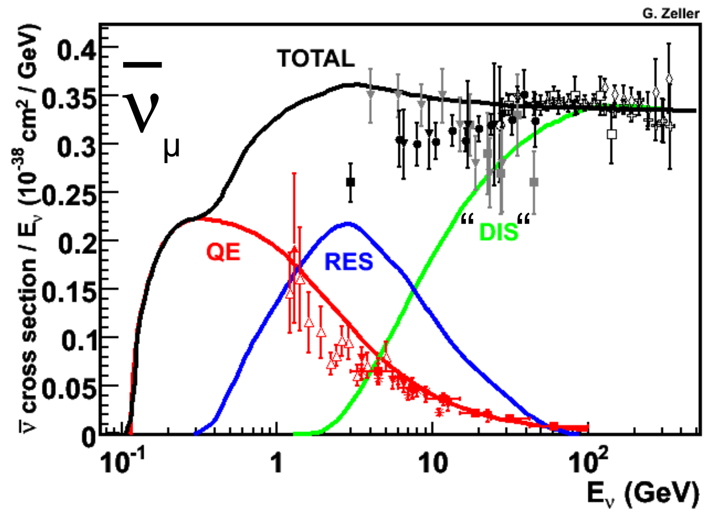


# Why is MINERνA Needed?

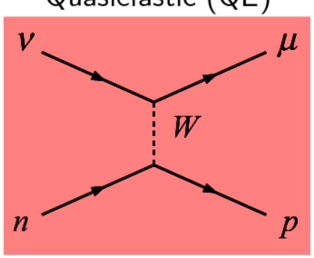

- Existing data between 1-20 GeV limited:
- Mainly bubble chamber data
- Wide band neutrino beams
  - Low statistics samples
  - Large uncertainty on flux.
  - Limited target types

Rev. Mod. Phys. 84, 1307–1341 (2012)
(includes MiniBooNE results)

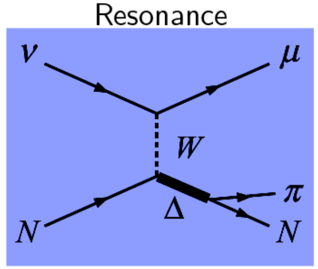


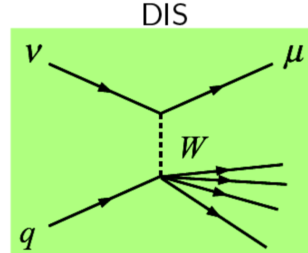

Quasielastic (QE)




Resonance




DIS



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


- **ν oscillations:**

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

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

($\nu_\mu$ disappearance example)

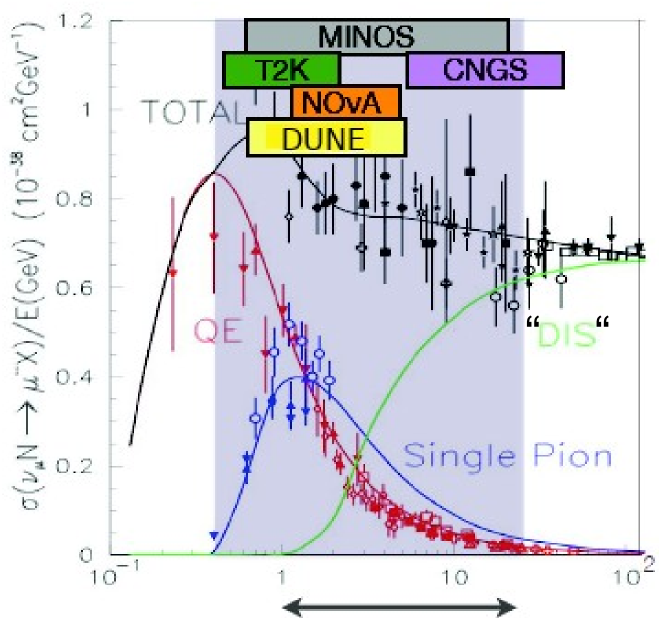
→ **Note oscillation probability depends on $E_\nu$**

- However Experiments Measure $E_{vis}$
- $E_{vis}$ depends on Flux, σ, detector response, interaction multiplicities, target type, particle type produced…

→ $E_{vis}$ not equal to $E_\nu$

→ Appearance Oscillation Measurements:

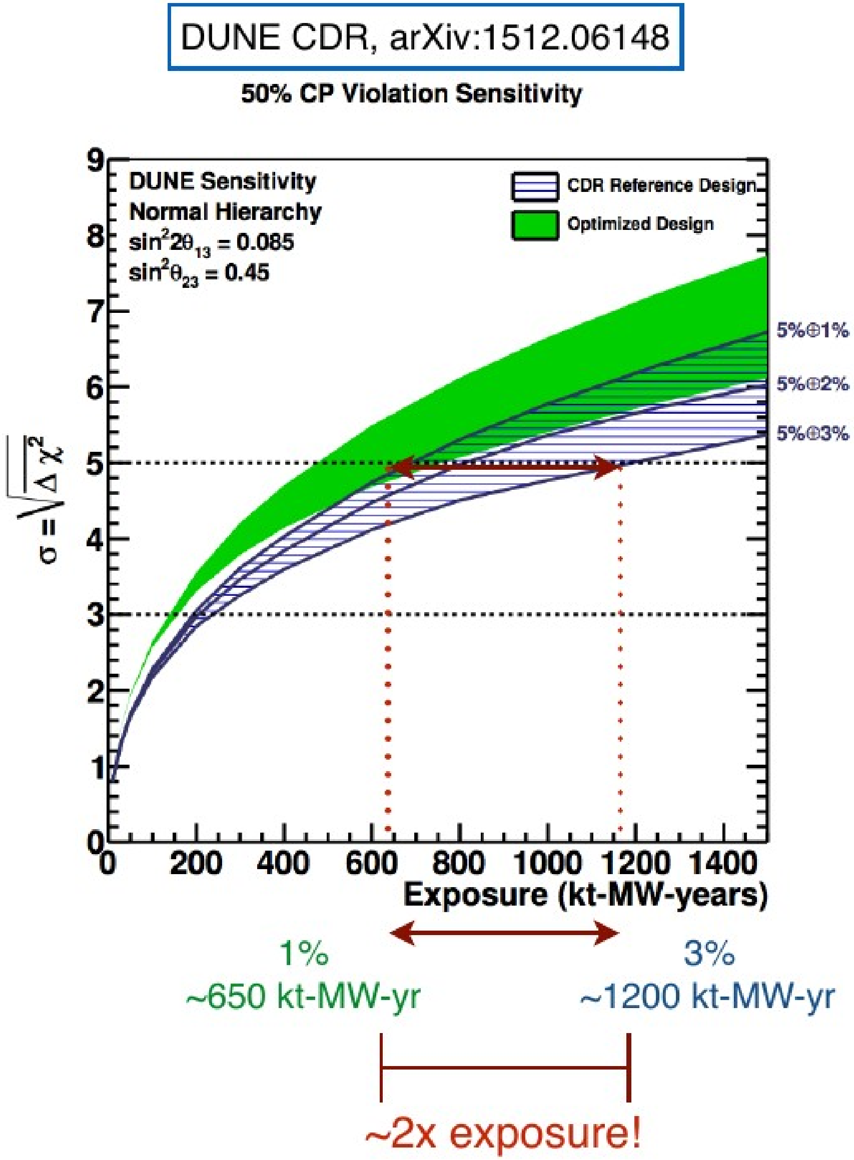
- Large $\Theta_{13}$ and CP violation - systematics important
- Need to understand backgrounds to $\nu_e$ searches:




MINERνA Energy Range

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

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

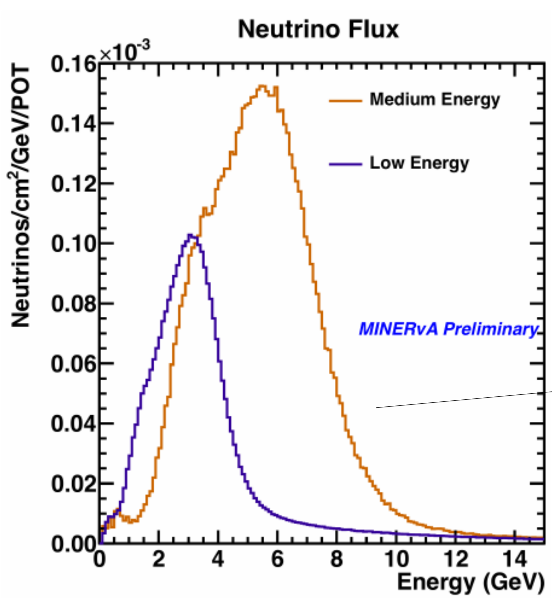

- We are now in a period of precision neutrino oscillation measurements
  - Can't ignore systematics uncertainties
  - Systematic errors due to neutrino interaction cross sections are a large fraction of the error
- Need better models (generators) based on high precision data
  - → **Enter MINERνA**

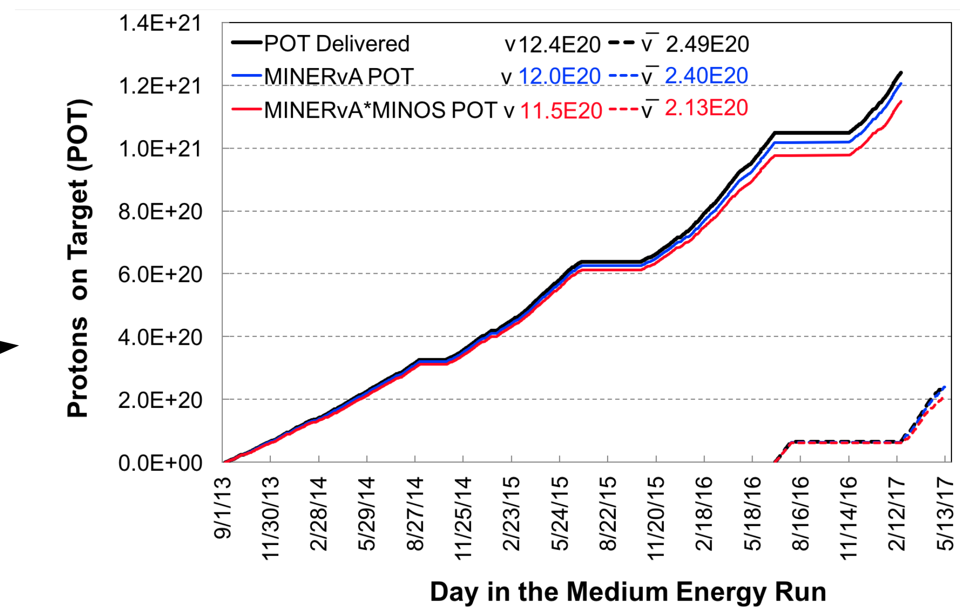
# Data Collected and Expected Sample Sizes


**Both ME and LE running :**
**→ LE > $3.98 \times 10^{20}$ POT**
**→ ME > $1.22 \times 10^{21}$ POT**

Beam Power:
LE ≈ 250kW.

Beam Power:
ME ≈ 650kW.



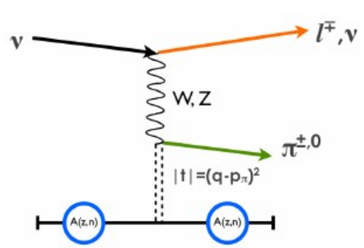

LE data taking completed in 2012 ($\nu$ and $\bar{\nu}$)
Since 2013 running in ME mode, 20/02/17 started $\bar{\nu}$

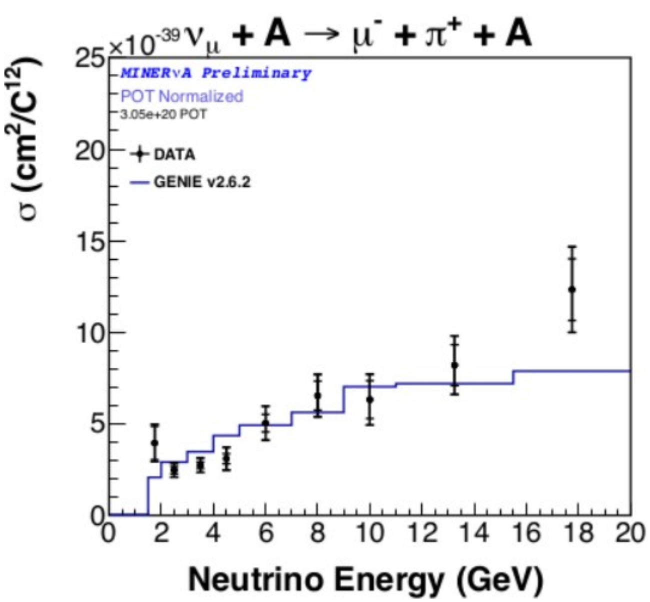
# Flux: Absolute Cross-section Errors

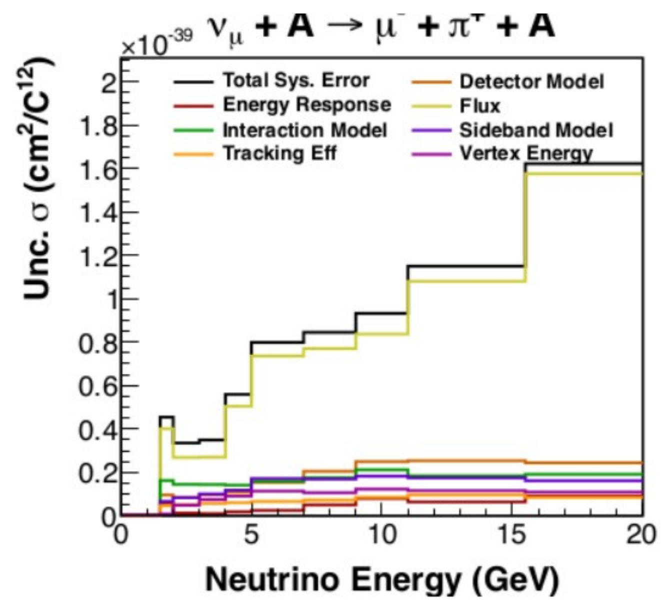

- Statistical errors are expected to be small.

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

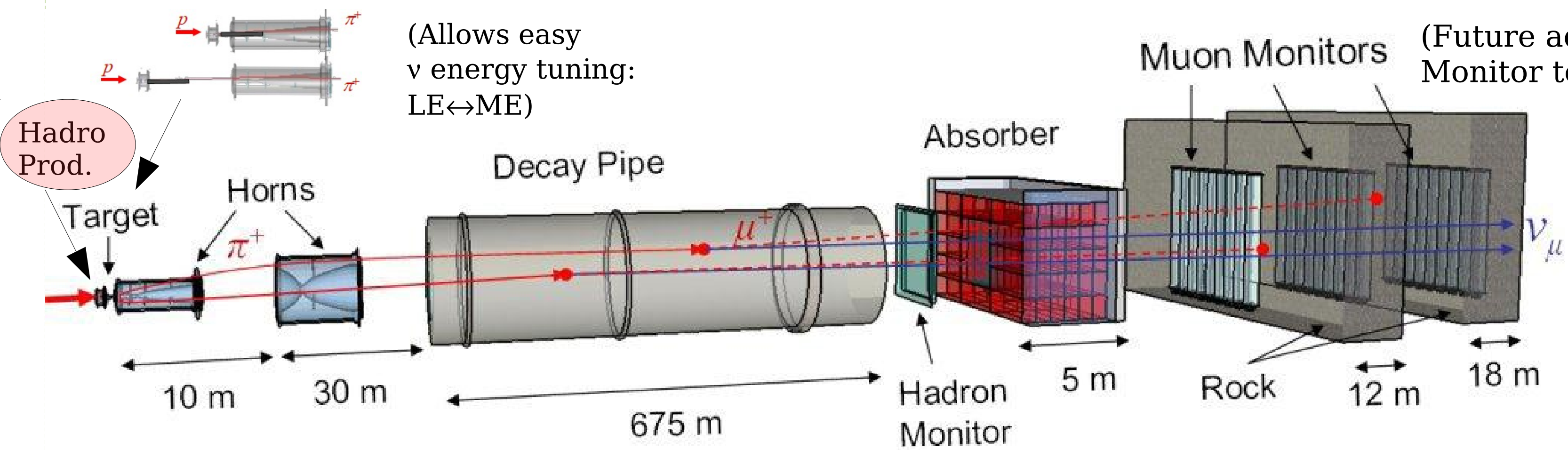
**Example:** Coherent $\pi^{\pm}$ production.
PRL 113, 261802 (2014)



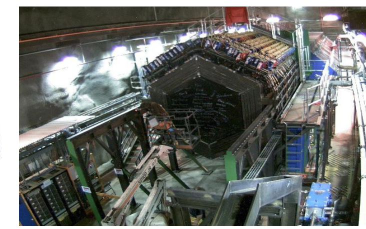



# Flux: Our ν Beam (NUMI)




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

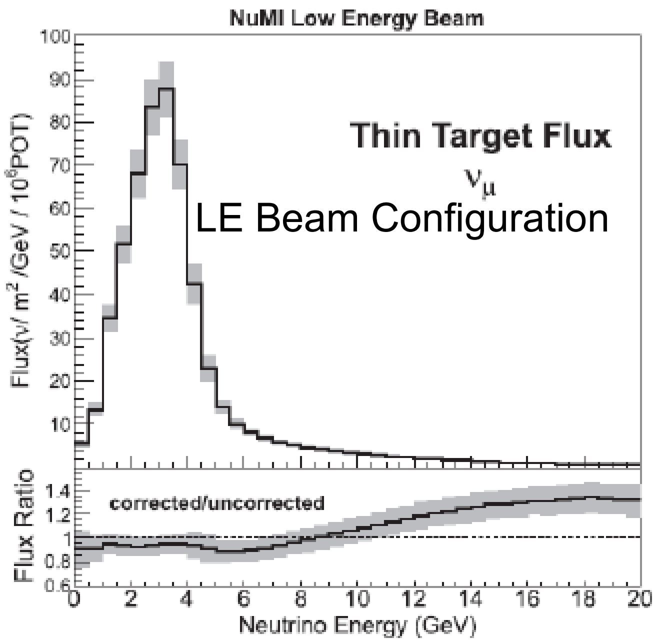


MINERνA

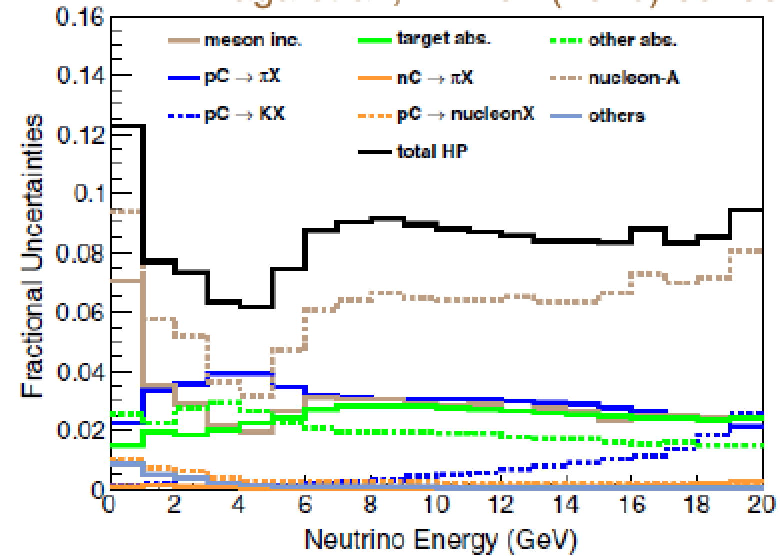
→ Magnetic horns focus pions and kaons, which then decay into muons and **neutrinos**

→ 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

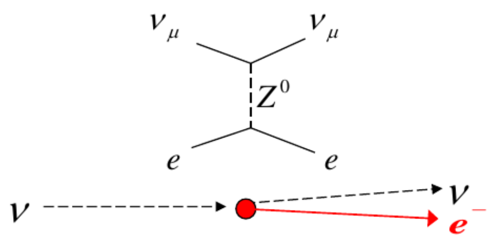

Aliaga et al., PRD94 (2016) 092005




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

- **Update to NuMI beamline simulation**
  - Includes:
    - Focusing uncertainties
    - Hadronic interactions
    - Beamline absorption
  - And used the following hadro-production data to constrain the simulation:
    - Thin target pion production (NA49)
    - NuMI target pion production (MIPP)

# Additional Flux Constraints: ν – e Elastic Scattering and Low-ν

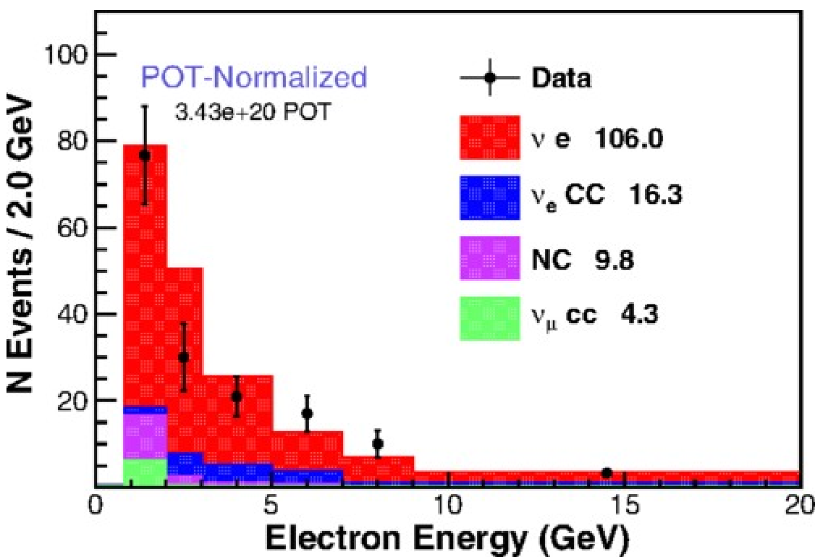




very forward single electron final state

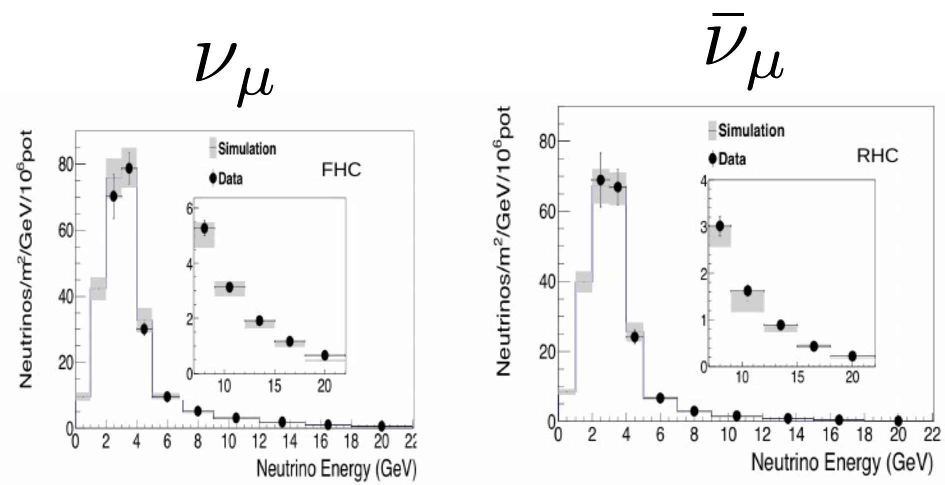
$$\frac{\mathrm{d}\sigma}{\mathrm{d}\nu} = A\left(1 + \frac{B}{A}\frac{\nu}{E_\nu} - \frac{C}{A}\frac{\nu^2}{2E_\nu^2}\right)$$

- ν – low hadronic recoil energy
- A, B, and C depend on integrals over structure functions
- **Gives a measurement of the flux shape**

Park et al., PRD93 (2016) 112007




L. Ren et al., PRD95 (2017) 072009

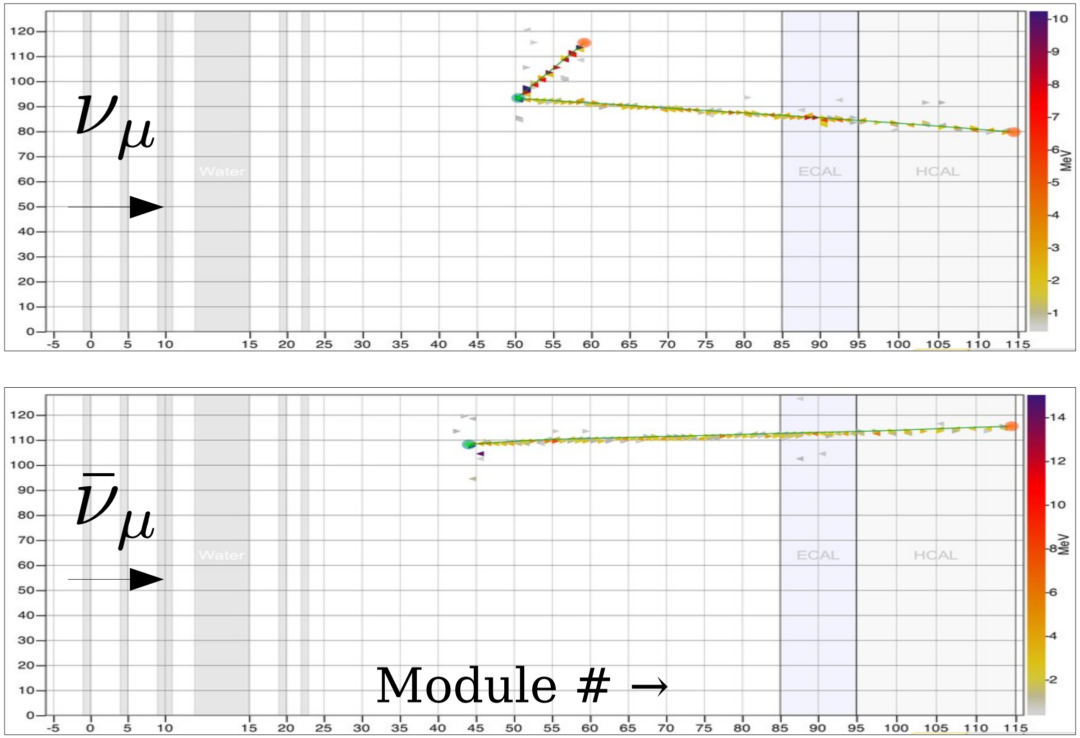



~100 events in LE sample ~6% flux constraint (in situ measurement – confirms previous hadro-production flux constraint)

Flux is normalized to extracted inclusive cross section from external measurements at high neutrino energy

# $\nu(\bar{\nu})$ 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

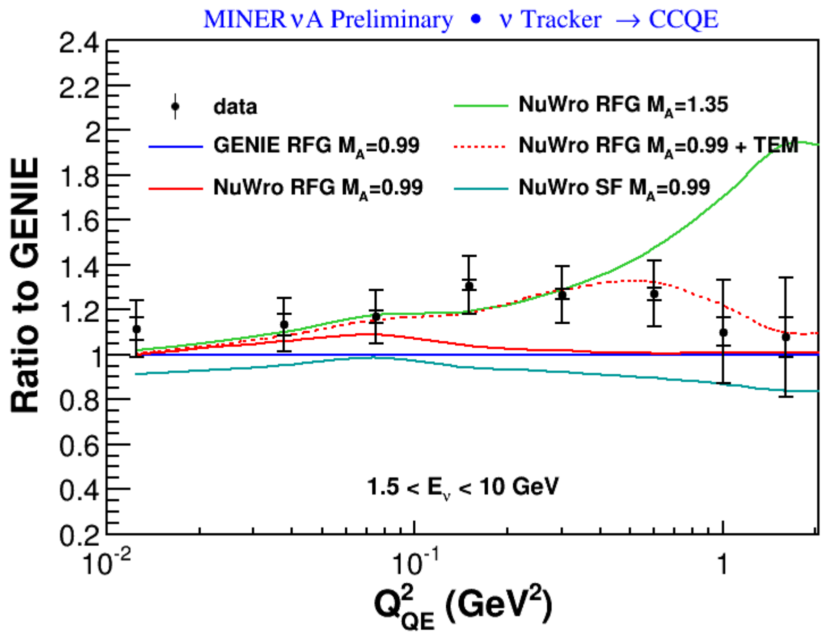
$$\nu_\mu + n \to \mu^- + p$$

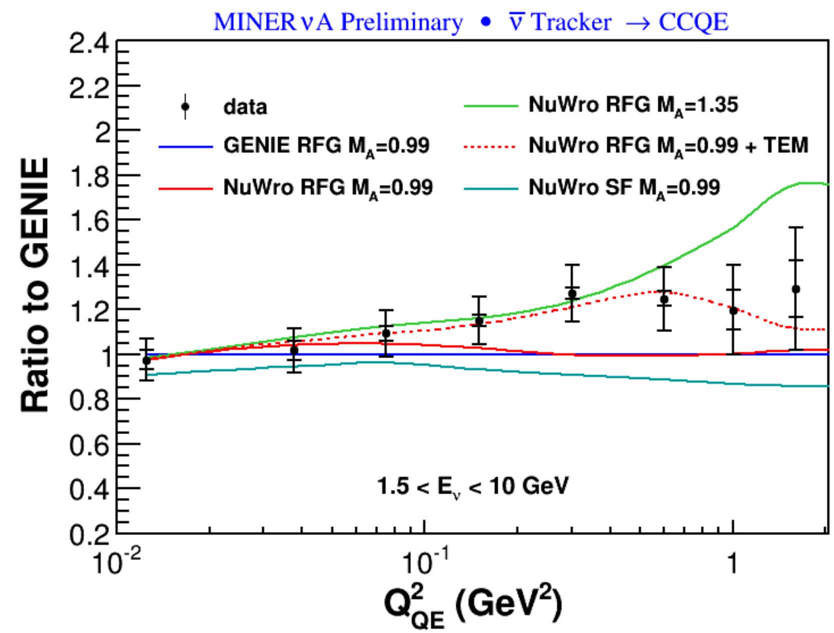
$$\bar{\nu}_\mu + p \to \mu^+ + n$$

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


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

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



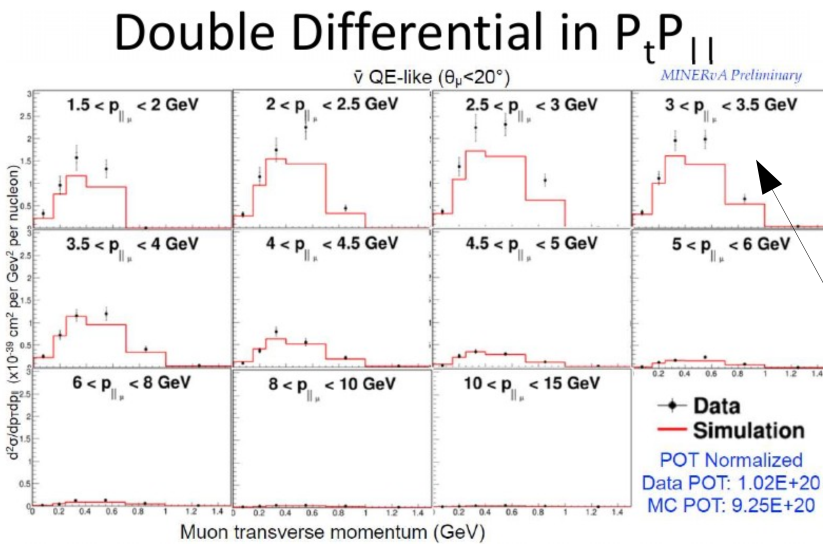

**Both results prefer models with interactions involving multi-nucleon clusters → More later**

**$M_A$ = 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

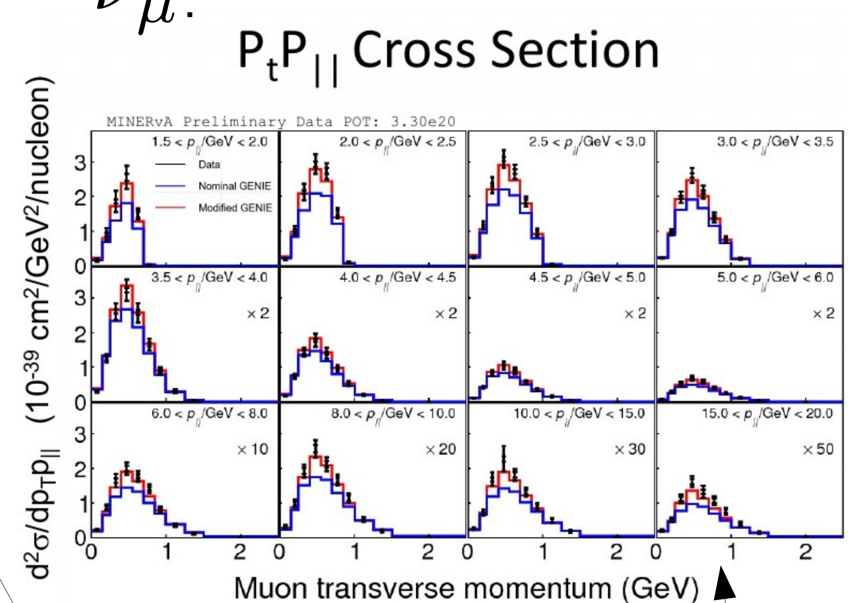
**NuWro: Golal, Jusczak, Sobczyk**
**arXiv:1202.4197**

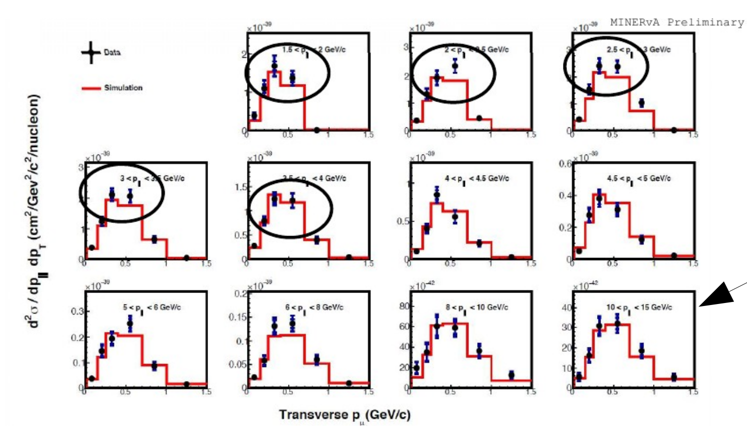
# $\nu_\mu$ & $\bar{\nu}_\mu$ CCQE: In 2D!


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




$\nu_\mu$:




Note excess at ~0.5 GeV $P_T$ :

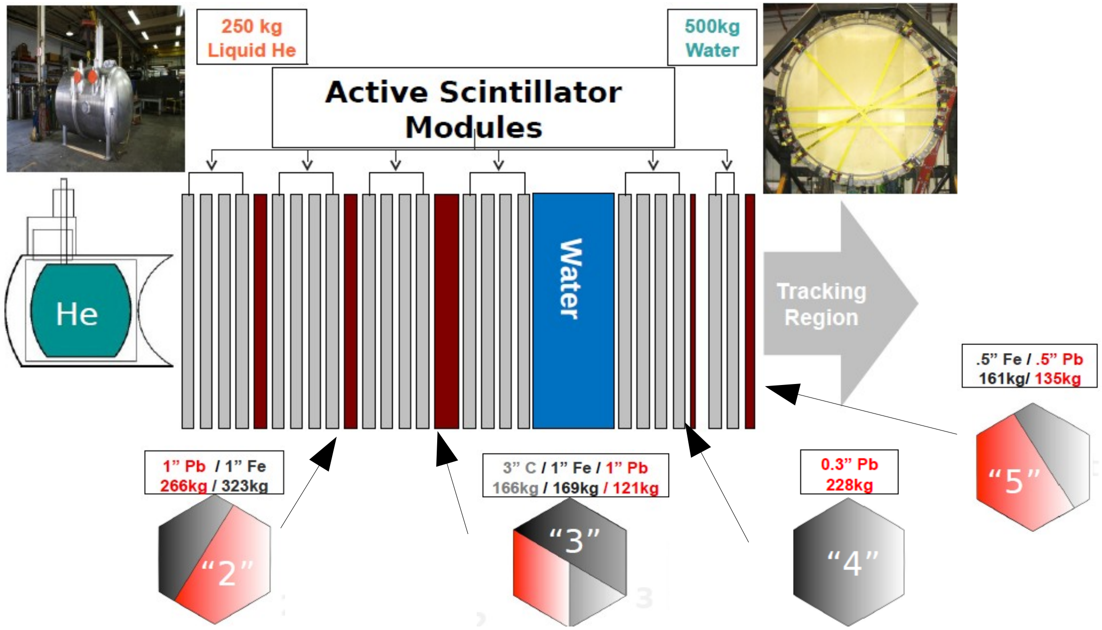
The effect maps back to excess regions in the inclusive NEUTRINO analysis:

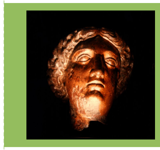
→ Genie is modified to force agreement with inclusive result and then compared with CCQE

→ Works for BOTH $\nu$ and $\bar{\nu}$ CCQE!

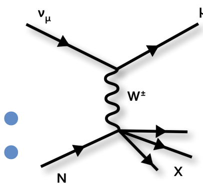
- Neutrino Oscillation experiments need a unbiased measurement of the true neutrino energy:
  - Different Experiments use Different Heavy Nuclear Targets (need mass!):
    - Carbon, Iron, Lead, Water, Argon, *etc.*
  - Nuclear effects are not small in neutrino scattering:
    - $E_{Visible} \neq E_{True}$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

Close-up of MINERvA Target Region

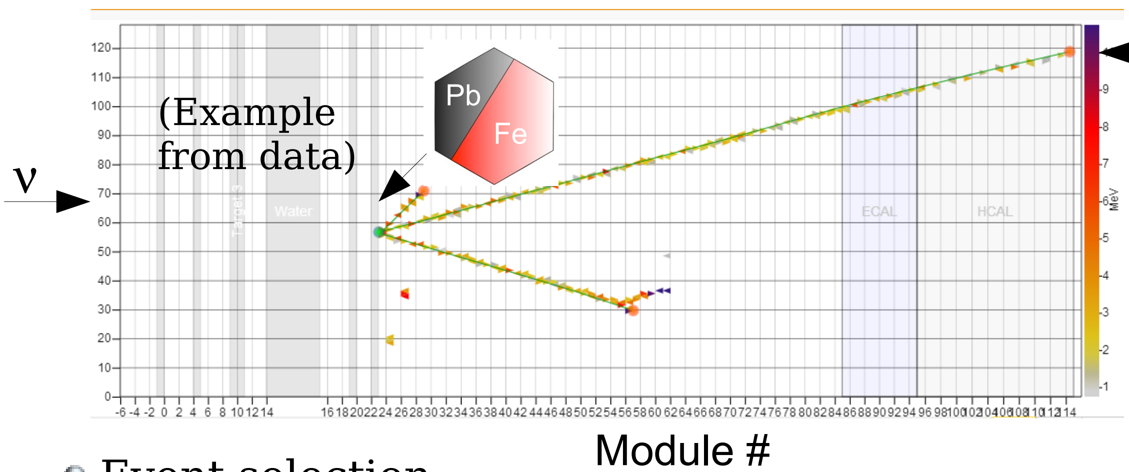




# CC ν DIS Inclusive:

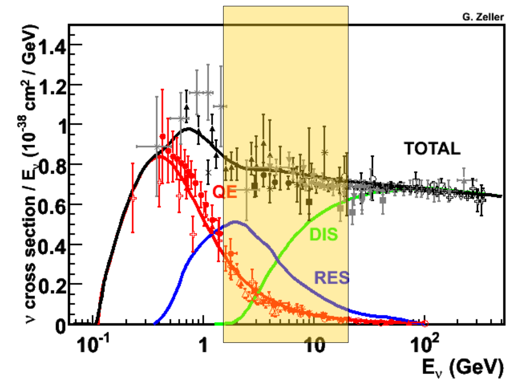







**MINOS matched Muon**

(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

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

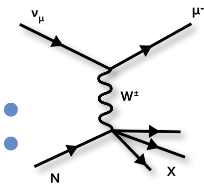
(Muon momentum and charge from MINOS ND + Sum of visible energy, weighted by amount of passive material)

- Muon angle needed for other kinematic variables:

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

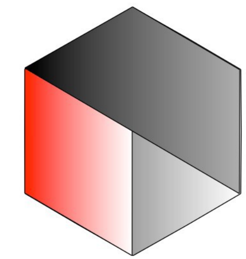
**DIS sample: $Q^2$ > 1.0 GeV$^2$ and W > 2.0 GeV**

# CC DIS Inclusive:

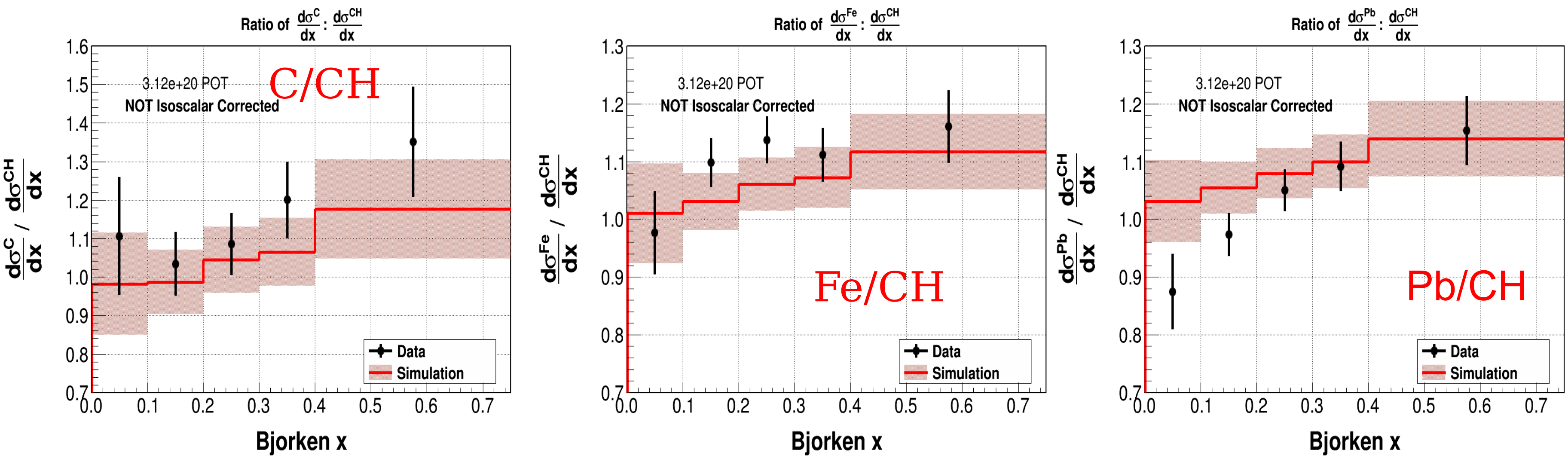




- *Divide C, Fe, Pb cross sections by scintillator (CH) cross section*
  - Each nucleus divided by a statistically independent scintillator measurements
  - Scintillator measurement is specific for each target type: use the same transverse area
    - The ratio of cross sections reduces errors by factor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

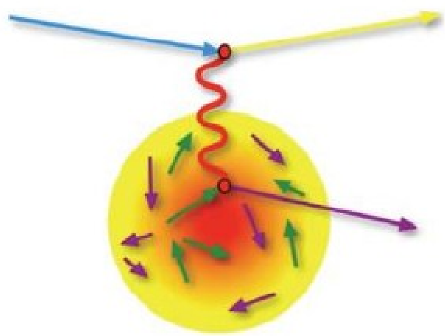


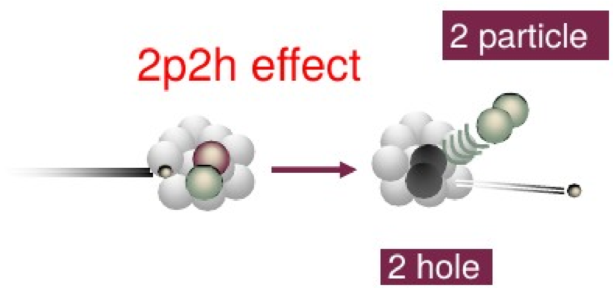
Mousseau et al., PRD93 (2016) 071101

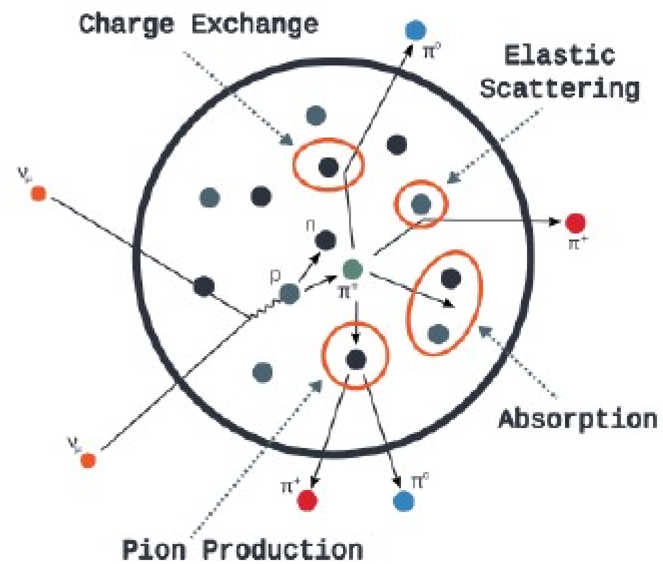



- Deficit at low x in Pb indicates additional nuclear shadowing than presently in models (Genie 2.6.2) needed
- As function of $E_\nu$(@LE): No tension between MINERνA data and GENIE simulations

# Can't Ignore the Nuclear Muck…




**There are possible short range correlations and medium range correlations:**

- Scattering off a pair of correlated nucleons – 2p2h effect

AND…

- **Long range correlations – RPA effect**

**ν interactions occur INSIDE the nucleus:**

- Produced particles have to exit out out of the nucleus to be observed
- Final state interactions (FSI)

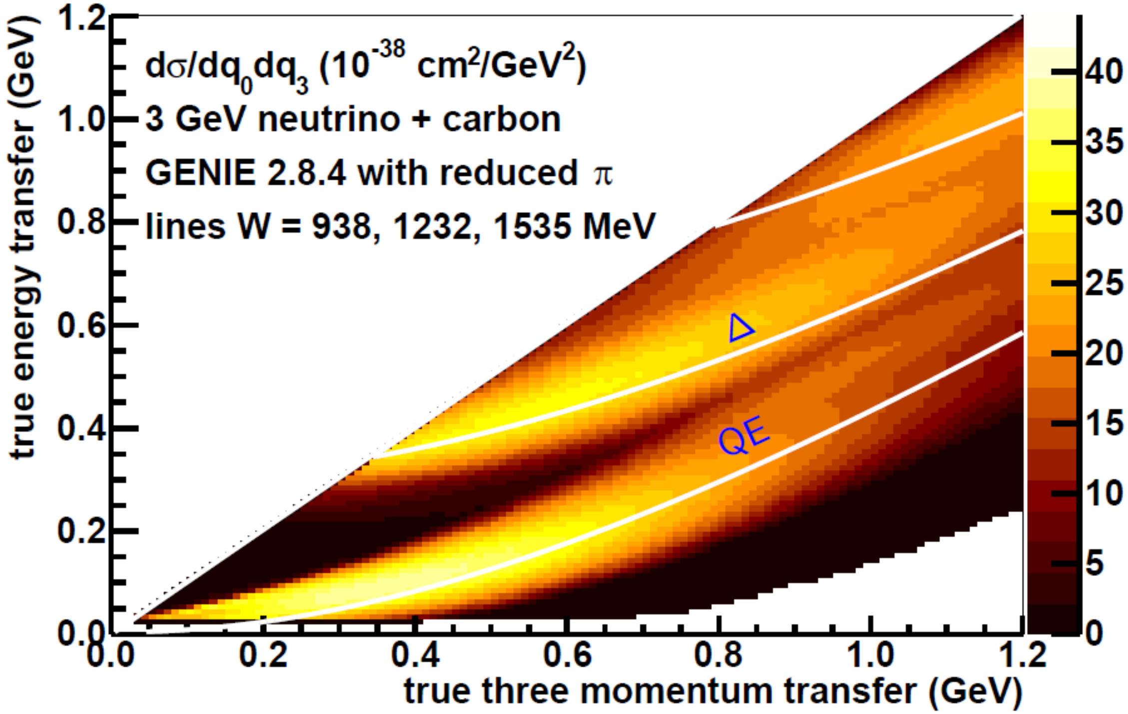
# Nuclear effects in neutrino-carbon Interactions at low three-momentum transfer

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

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

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

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



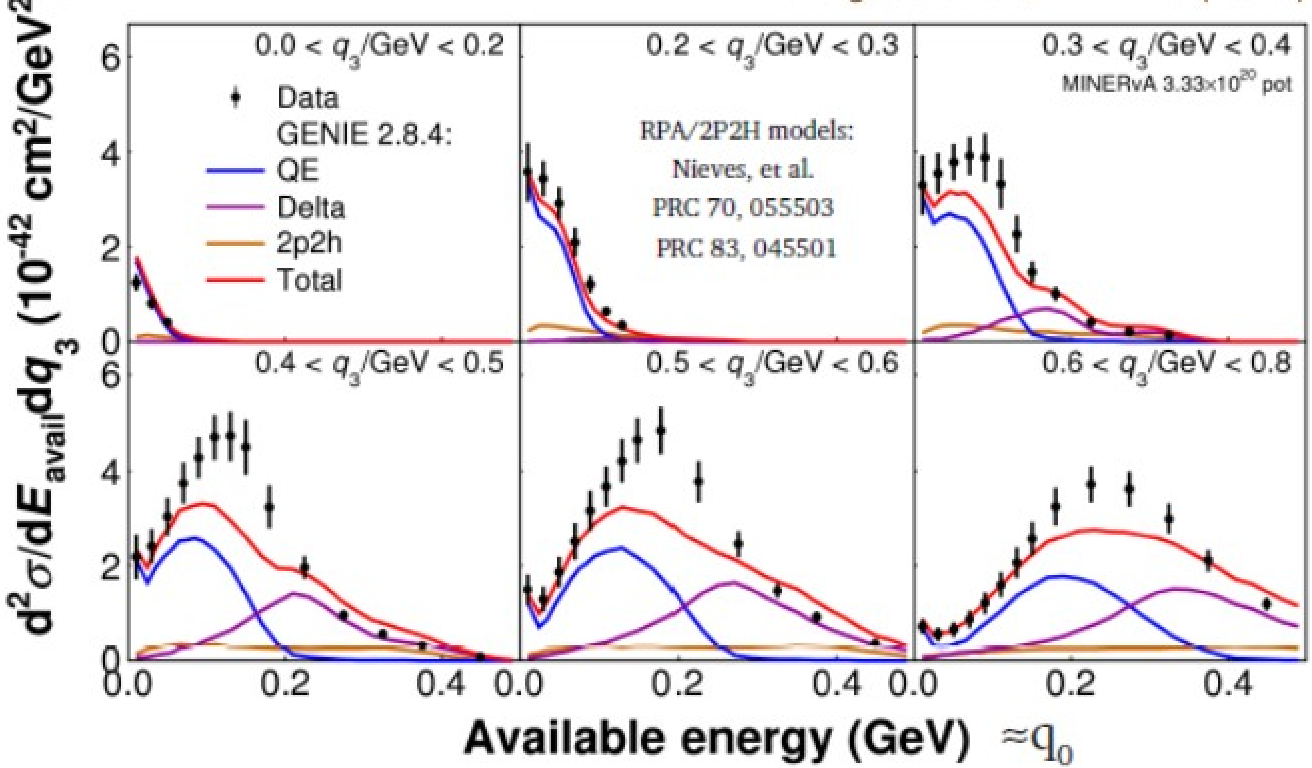

- We observe a small cross section at very low energy transfer that matches the expected screening effect of long-range nucleon correlations.

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

# $\nu_\mu$ Data in the $(q_0 - q_3)$ Plane

May 28–June 2 BLOIS

Rodrigues et al., PRL116 (2016) 071802




$$E_{\text{avail}} = \sum \text{p and } \pi^{\pm} \text{ K.E.} + \text{total energy of all other particles except n}$$

- Adding in models RPA (a charge screening nuclear effect) and 2p2h processes improves agreement in some regions, but not all...

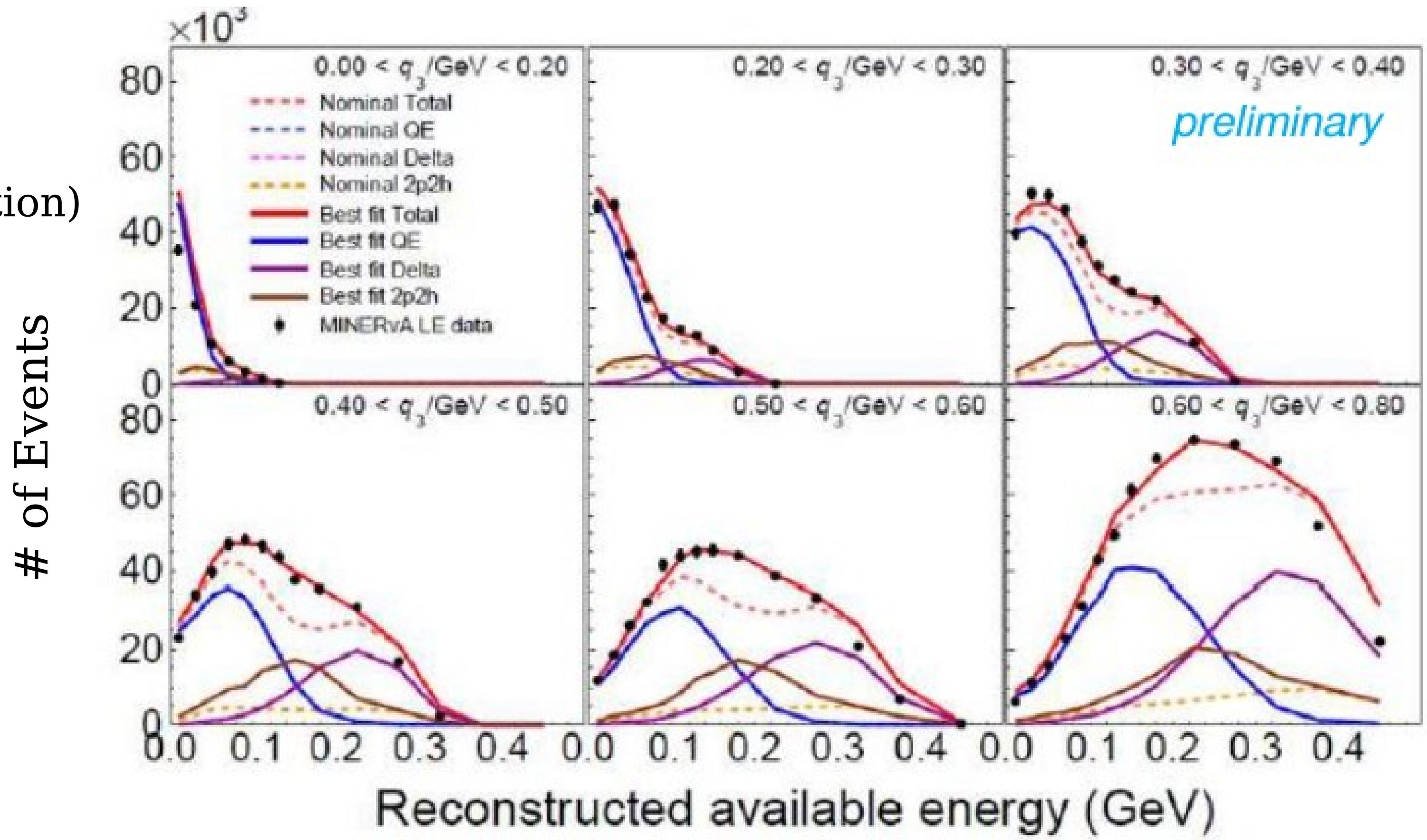
(Phys. Rev. C 83, (2011), Phys. Rev. C 70, 055503 (2004), Phys. Rev. D 88, 113007 (2013) (Valencia Model))

- Note: Excess in similar kinematic region to excess in anti-neutrino CCQE

# Now Add Re-weighted 2p2h Contribution

(Fit a 2D Gaussian in true ($q_0$, $q_3$) as a re-weighting function)

(Does not effect true QE or resonant production)




Nice Agreement!

# 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 (Valencia Model).
  - 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:
  - $\nu_{CC}$ Interactions
  - 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)!
  - Increased kinematic coverage (W and $Q^2$)

# The Collaboration Thanks You


- Aligarh Muslim University, Aligarh, India
- Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil
- College of William and Mary, Williamsburg, Virginia
- Fermi National Accelerator Laboratory, Batavia, Illinois
- Hampton University, Hampton, Virginia
- Massachusetts College of Liberal Arts, North Adams, Massachusetts
- Oregon State University, Corvallis, Oregon
- Otterbein College, Westerville, Ohio
- Pontificia Universidad Catolica del Peru, Lima, Peru
- University of Florida, Gainsville, Florida
- Universidad de Guanajuato, Mexico
- University of Minnesota-Duluth, Duluth, Minnesota
- University of Mississippi, Oxford, Mississippi
- Universidad Nacional de Ingenieria, Lima, Peru
- University of Oxford, Oxford, United Kingdom
- University of Pennsylvania, Philadelphia, Pennsylvania
- University of Pittsburgh, Pittsburgh, Pennsylvania
- University of Rochester, Rochester, New York
- Universidad Técnica Federico Santa María, Valparaíso, Chile
- University of Wrocław, Wrocław, Poland
- Rutgers University, New Brunswick, New Jersey
- Tufts University, Medford, Massachusetts

# Recent Publications


"Direct Measurement of Nuclear Dependence of Charged Current Quasielastic-like Neutrino Interactions using MINERvA" , arXiv:1705.03791

"Measurement of the antineutrino to neutrino charged-current interaction cross section ratio on carbon" Phys. Rev. D 95, 072009 (2017)

"Measurement of neutral-current K+ production by neutrinos using MINERvA" Submitted to: Phys.Rev.Lett., arXiv:1611.02224

"Measurements of the Inclusive Neutrino and Antineutrino Charged Current Cross Sections in MINERvA Using the Low-ν Flux Method" Phys. Rev. D 94, 112007 (2016)

"Neutrino Flux Predictions for the NuMI Beam" Phys. Rev. D 94, 092005 (2016)

"First evidence of coherent K+ meson production in neutrino-nucleus scattering" Phys. Rev. Lett. 117, 061802 (2016)

"Measurement of K+ production in charged-current νμ interactions" Phys. Rev. D 94, 012002 (2016)

"Cross sections for neutrino and antineutrino induced pion production on hydrocarbon in the few-GeV region using MINERvA"Phys. Rev. D 94, 052005 (2016).

"Evidence for neutral-current diffractive neutral pion production from hydrogen in neutrino interactions on hydrocarbon" Phys. Rev. Lett. 117, 111801 (2016)

"Measurement of Neutrino Flux using Neutrino-Electron Elastic Scattering", Phys. Rev. D 93, 112007 (2016)

"Measurement of Partonic Nuclear Effects in Deep-Inelastic Neutrino Scattering using MINERvA", Phys. Rev. D 93, 071101 (2016).

"Identification of nuclear effects in neutrino-carbon interactions at low three-momentum transfer", Phys. Rev. Lett. 116, 071802 (2016).

"Measurement of electron neutrino quasielastic and quasielastic-like scattering on hydrocarbon at average Eν of 3.6 GeV", Phys. Rev. Lett 116, 081802 (2016).

"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 Eνof 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).

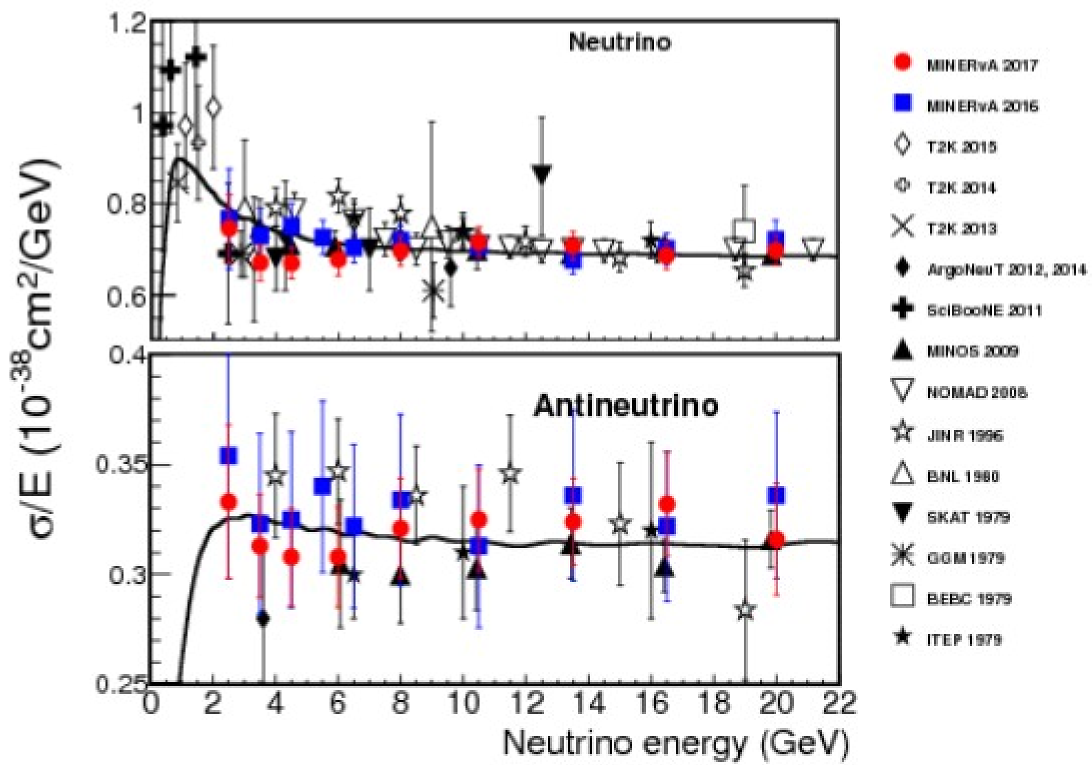
"Measurement of Coherent Production of π±in Neutrino and Anti-Neutrino Beams on Carbon from Eνof 1.5 to 20 GeV", Phys. Rev.Lett. 113, 261802 (2014).

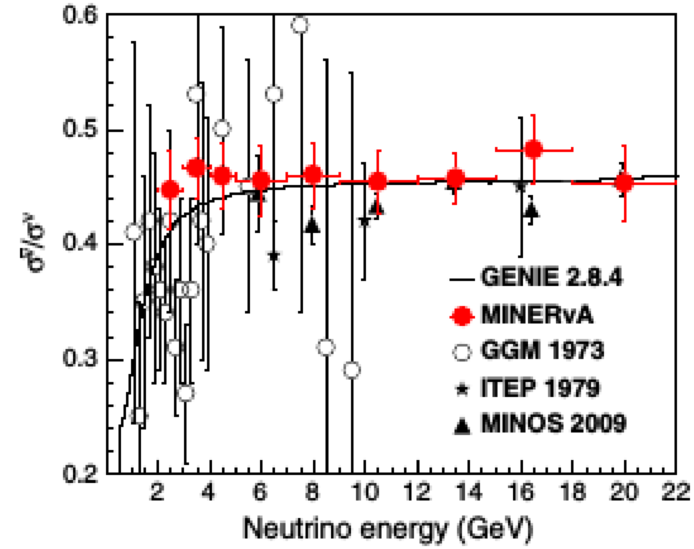
# Back-ups

# $\nu/\bar{\nu}$ Cross Sections Ratio

May 28–June 2 BLOIS

L. Ren et al., PRD95 (2017) 072009



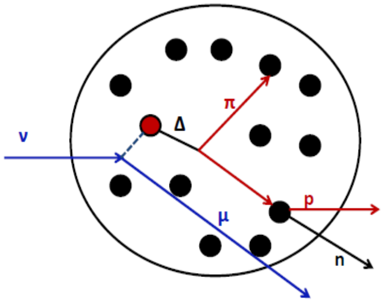




Minerva has performed the first precise measurement of the antineutrino cross sections $E_{nu}$<4 GeV.

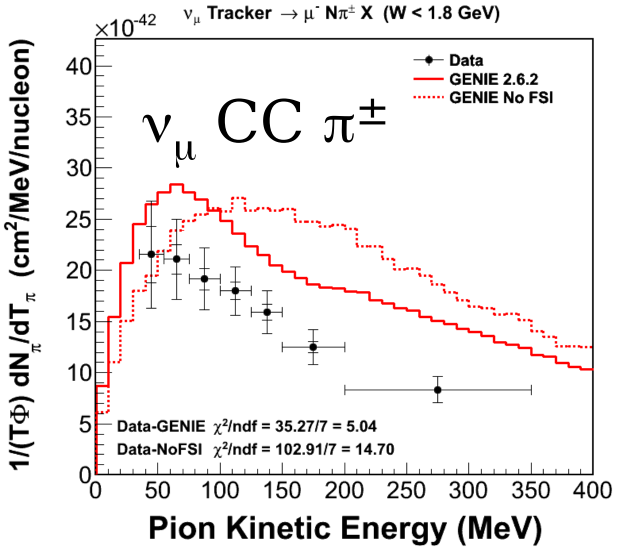
# Neutrino Oscillation Studies and Pion Production:


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

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



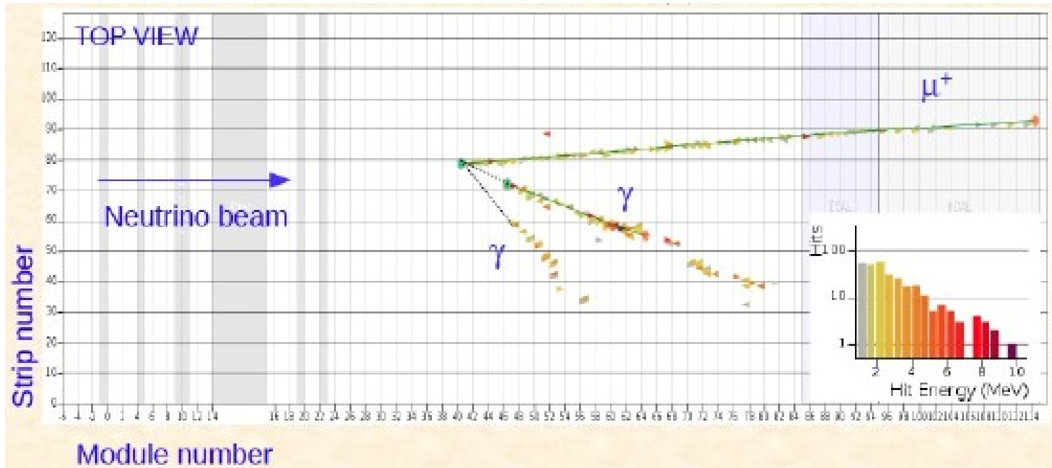

- Need a good and reliable prediction of pion spectra exiting the nucleus.

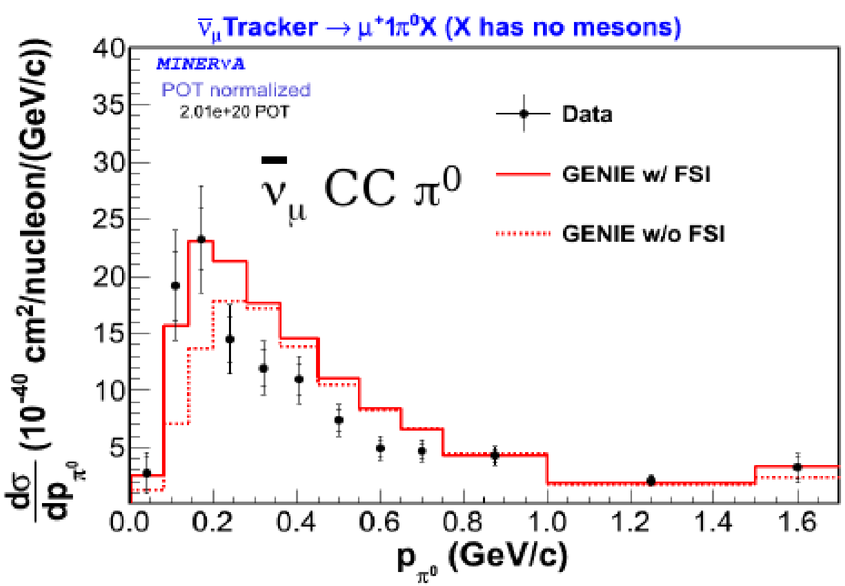



- $\pi^+$ spectrum is affected by FSI
  - FSI reduces the cross section due to pion absorption
- Cross section is over-predicted by GENIE
- Shapes agree with GENIE

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

# Pion Production: Neutral Pions



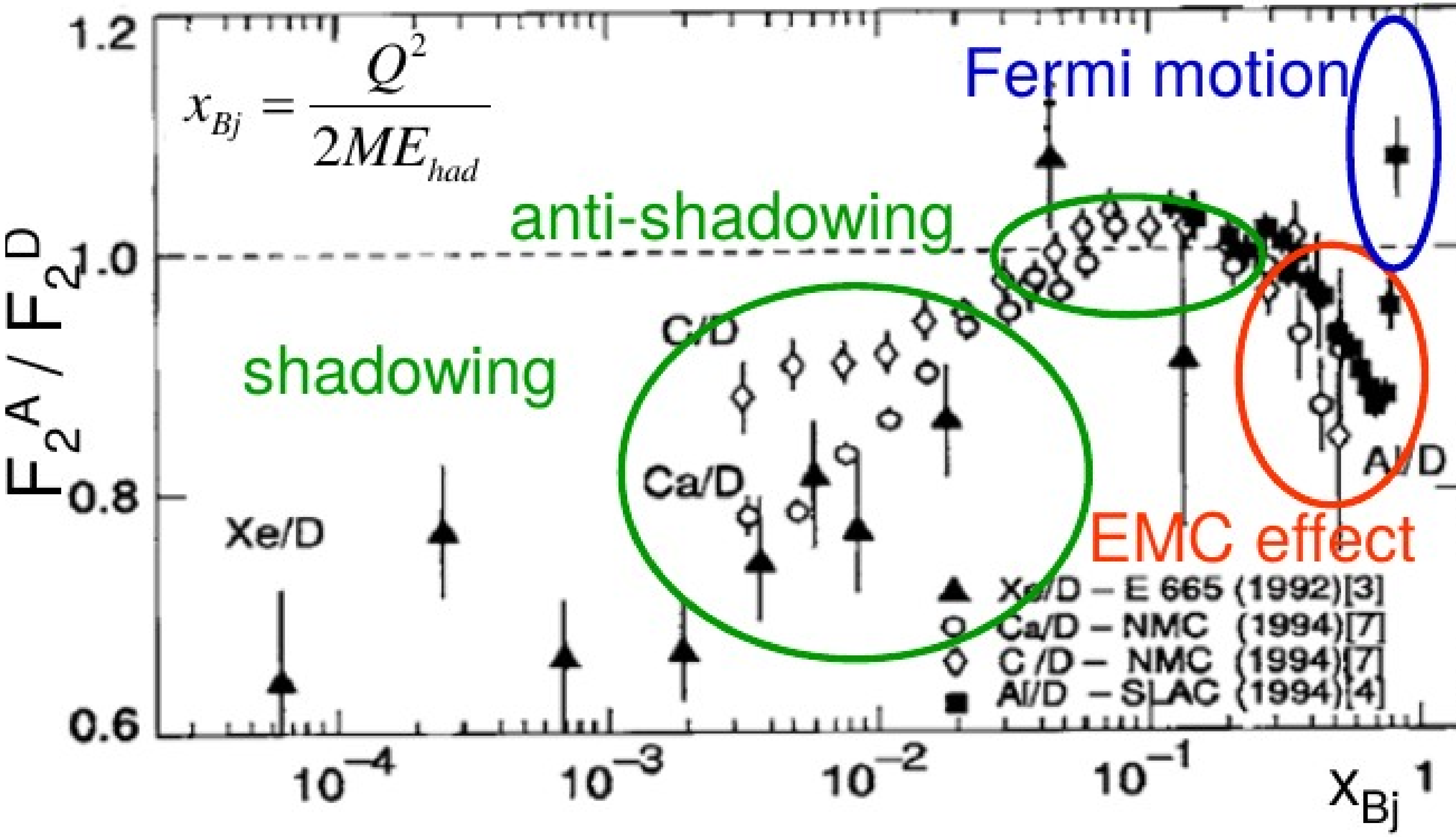




Phys.Lett. B749 (2015) 130-136

- $\pi^0$ spectrum is affected by FSI, $\mu^+$ 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)



# $\nu_e$ CCQE

**hep-ex: arXiv:1509.05729**

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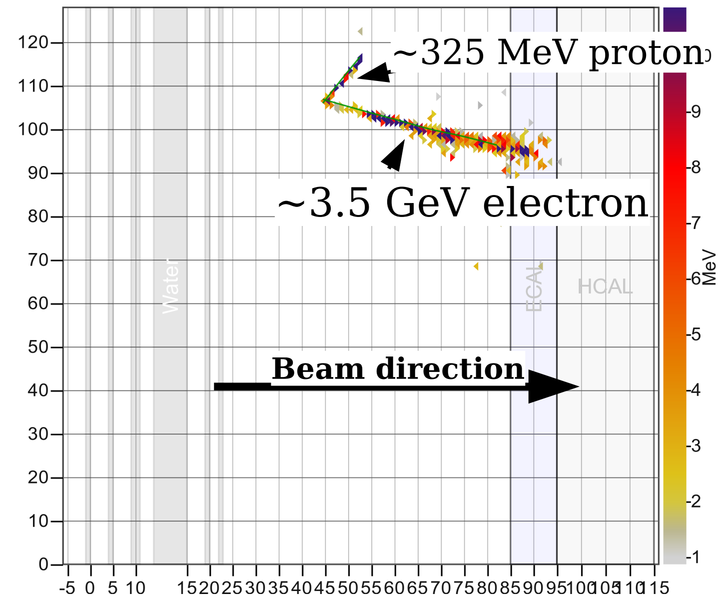
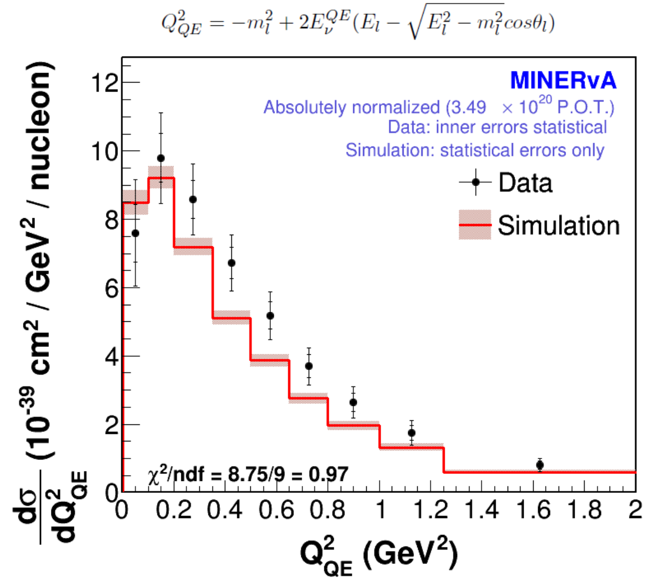
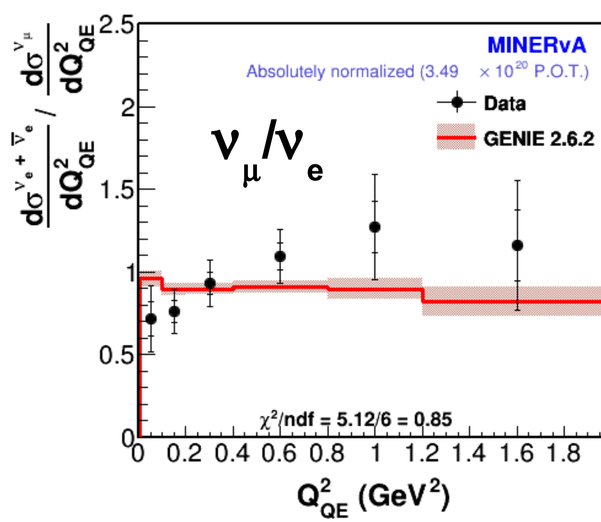


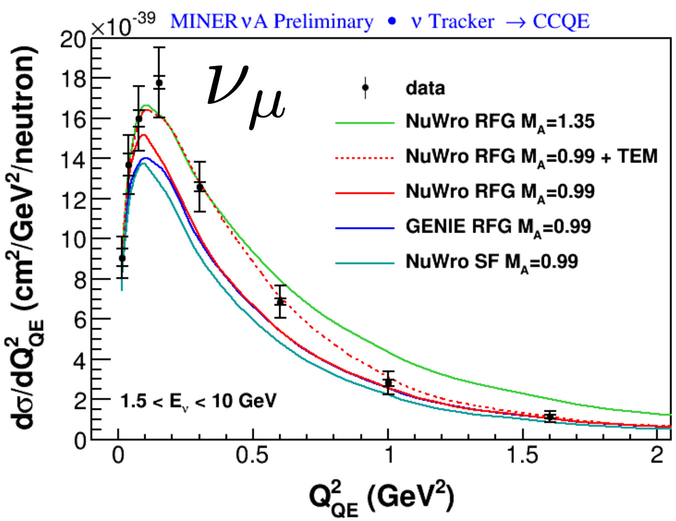

- Ratio is consistent with 1.0
- Shape is not significant due to correlated uncertainties (EM Energy Scale)

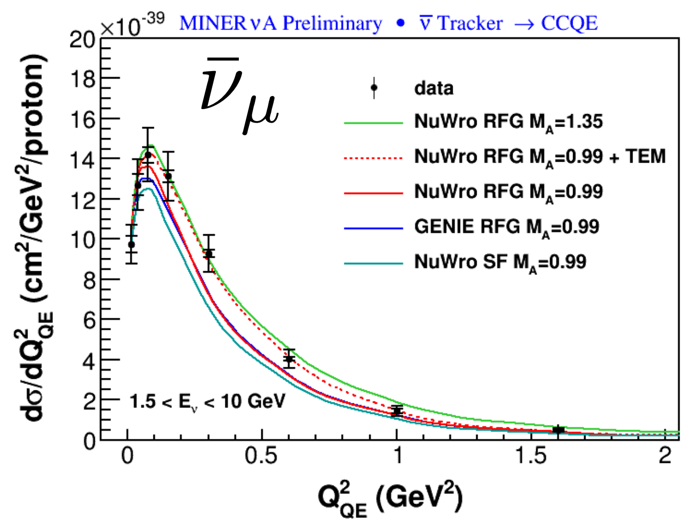
- NuMI beam contains ~1% $\nu_e$'s
- Signal: $\nu_e$ appearance experiments (T2K, NOvA, DUNE)
- Not well measured at these energies

# $\nu_\mu$ & $\bar{\nu}_\mu$ 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)