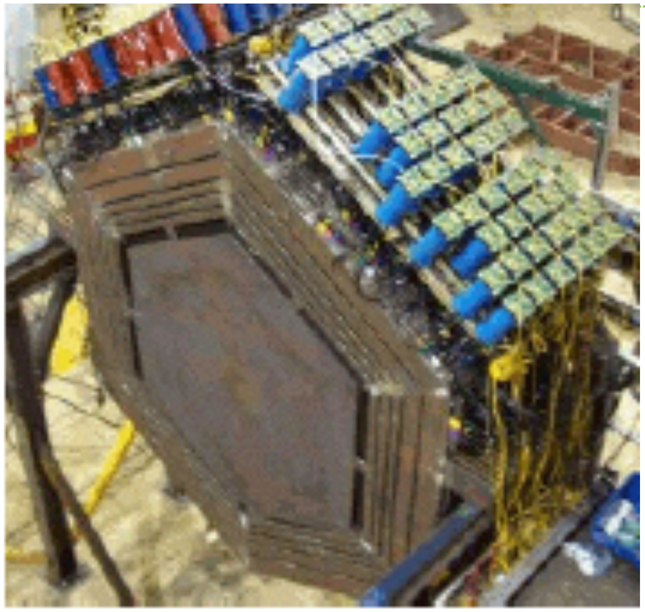
MINERνA

Selected Recent Results:
$\nu N \rightarrow$ "X"

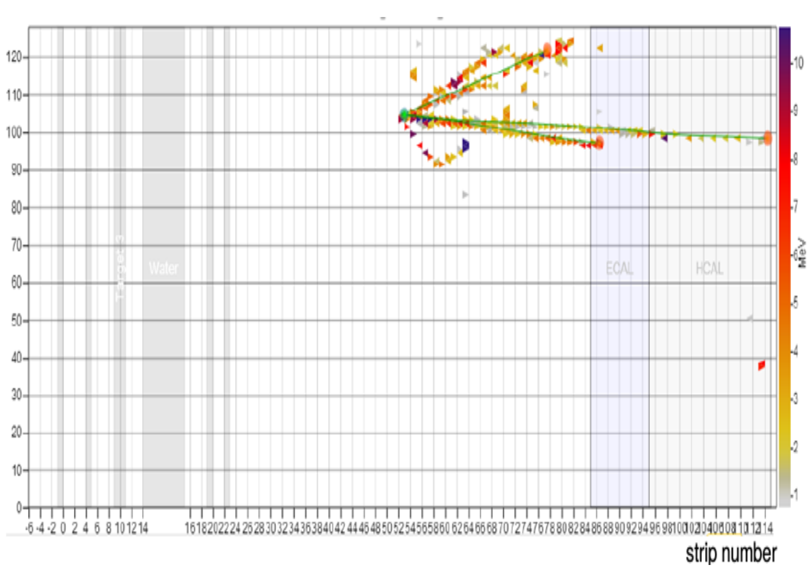


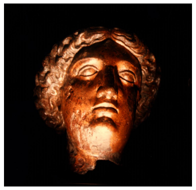
EPS Conference on High Energy Physics
Venice, Italy 5-12 July 2017

Arie Bodek
University of Rochester
Representing the MINERvA collaboration

6 Jul 2017, 12:15 15m

Room Casinò (Palazzo del Casinò)





MINERνA Detector

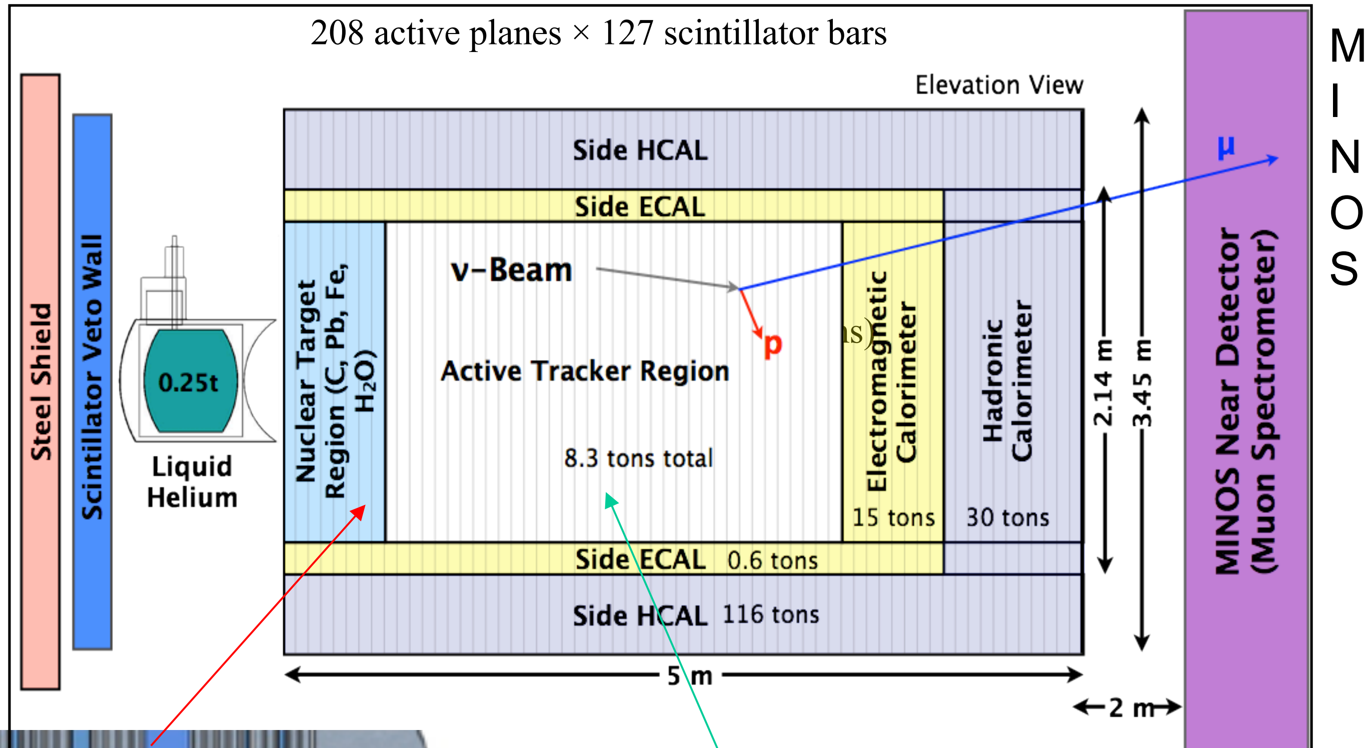
Arie Bodek, University of Rochester
EPS HEP 2017 (MINERνA Talk)

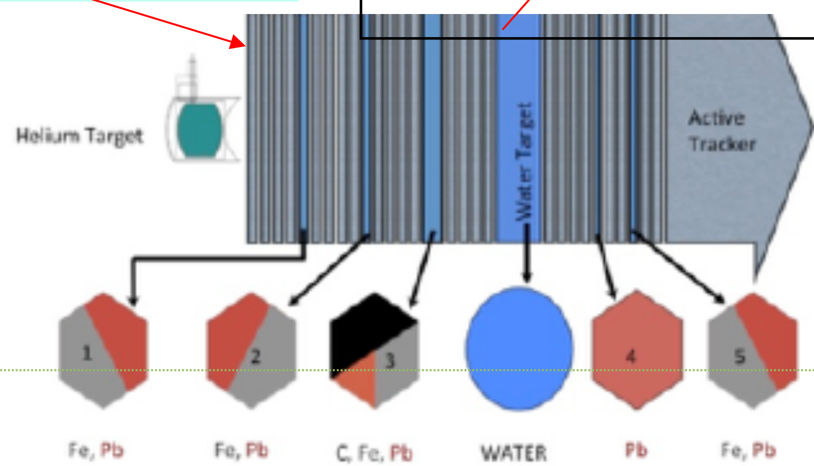
Dedicated neutrino-nucleus cross-section experiment running at Fermilab in the NuMI beamline.

120 modules of active tracker, targets, and calorimetry

- Low Energy Neutrinos
- High statistics ν

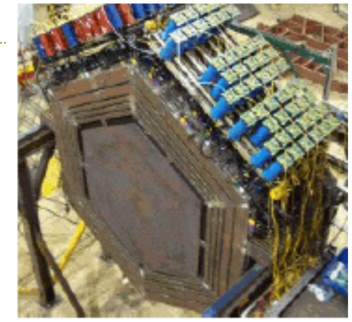
Also neutrino interactions on a variety of nuclei.
C, Fe, Pb, H_2O





Fully active, high-Resolution, scintillator-strip, target-calorimeter- tracker

Motivation: ν cross-sections are poorly known



- **ν oscillations:**

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

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

(ν_μ disappearance example)

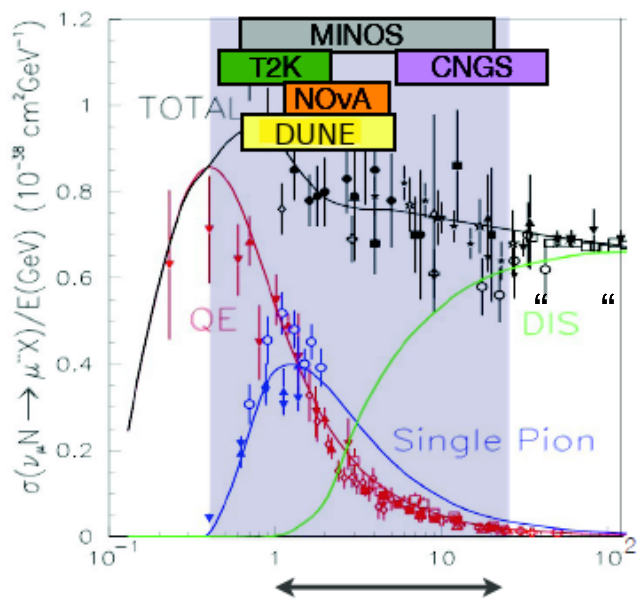
→ **Oscillation probability depends on E_ν**

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

→ E_{vis} not equal to E_ν

→ Appearance Oscillation Measurements:

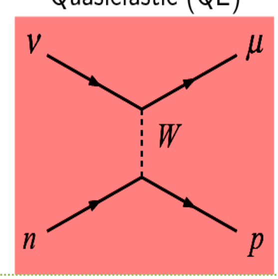
- Large Θ_{13} and CP violation - systematics important
- Need to understand backgrounds to ν_e searches:



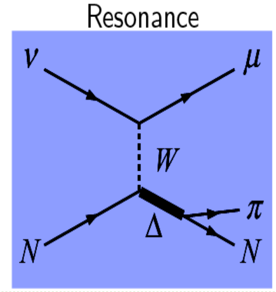
MINERnA Energy Range

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

Quasielastic (QE)



Resonance



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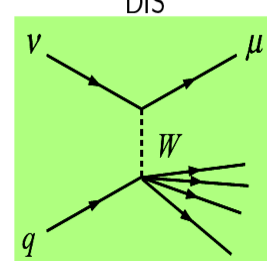
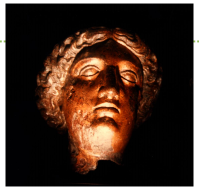




Recent Publications

"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 νμ Interactions 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).

Data Collected and Expected Sample Sizes

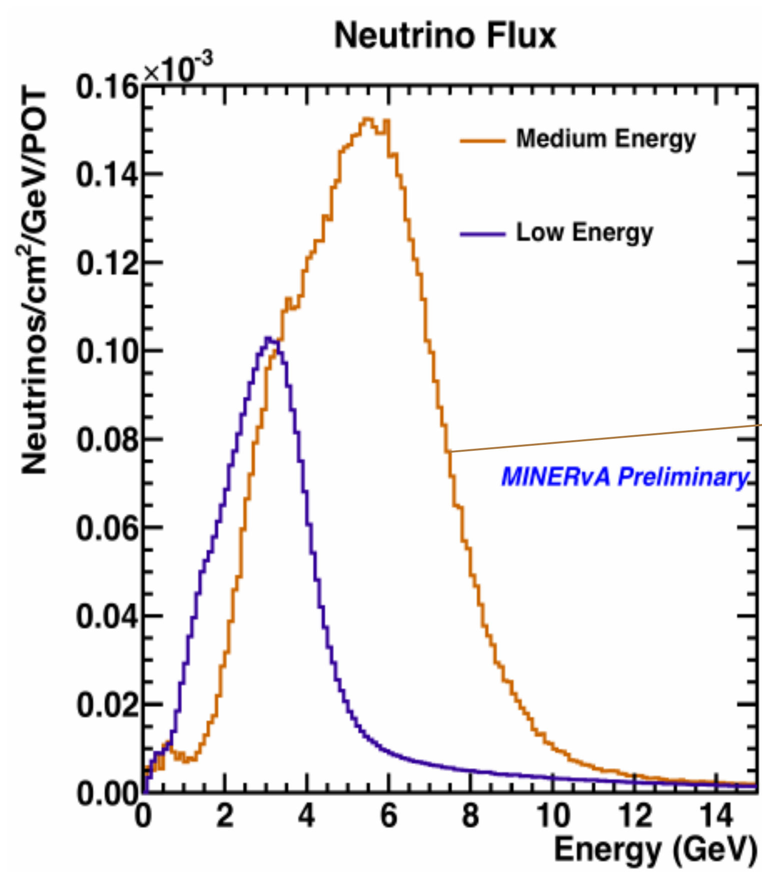
Both Medium Energy (ME) and Low Energy (LE) running:

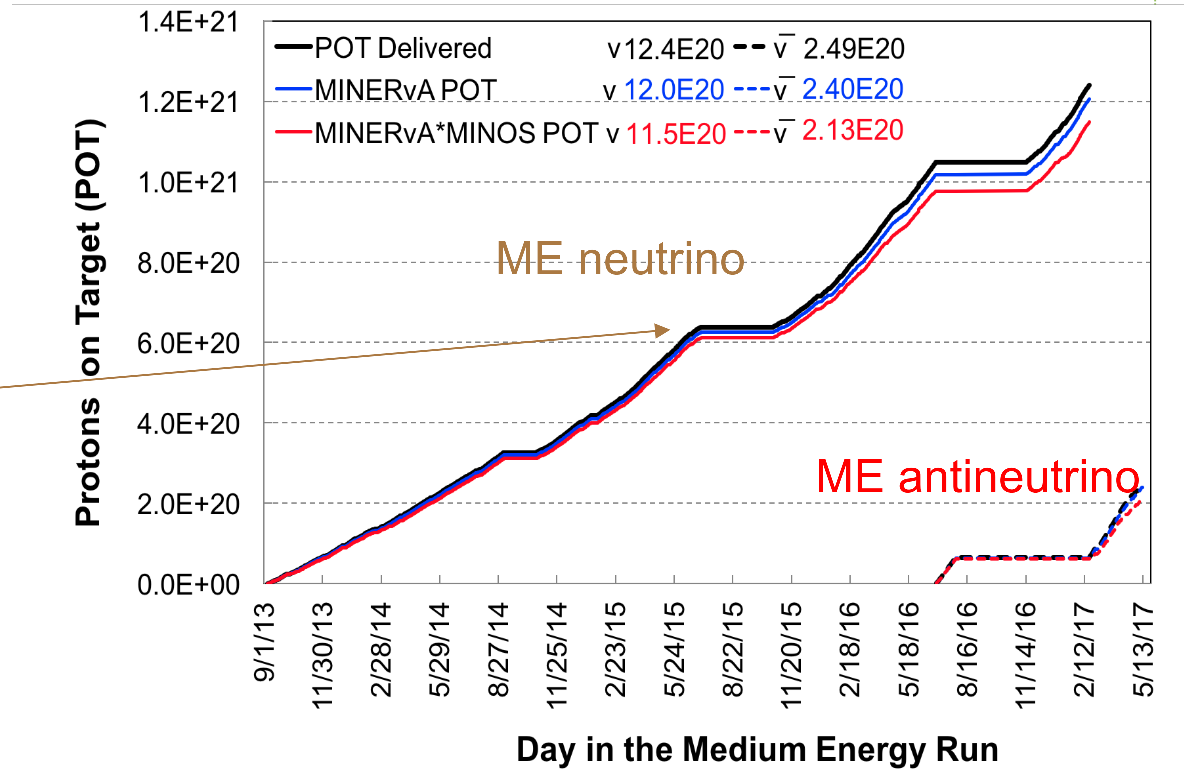
→ LE > 3.98x10^{20} POT

→ ME > 1.22x10^{21} POT

Beam Power:
LE ≈ 250kW.

Beam Power:
ME ≈ 650kW.

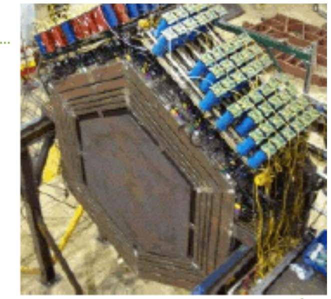


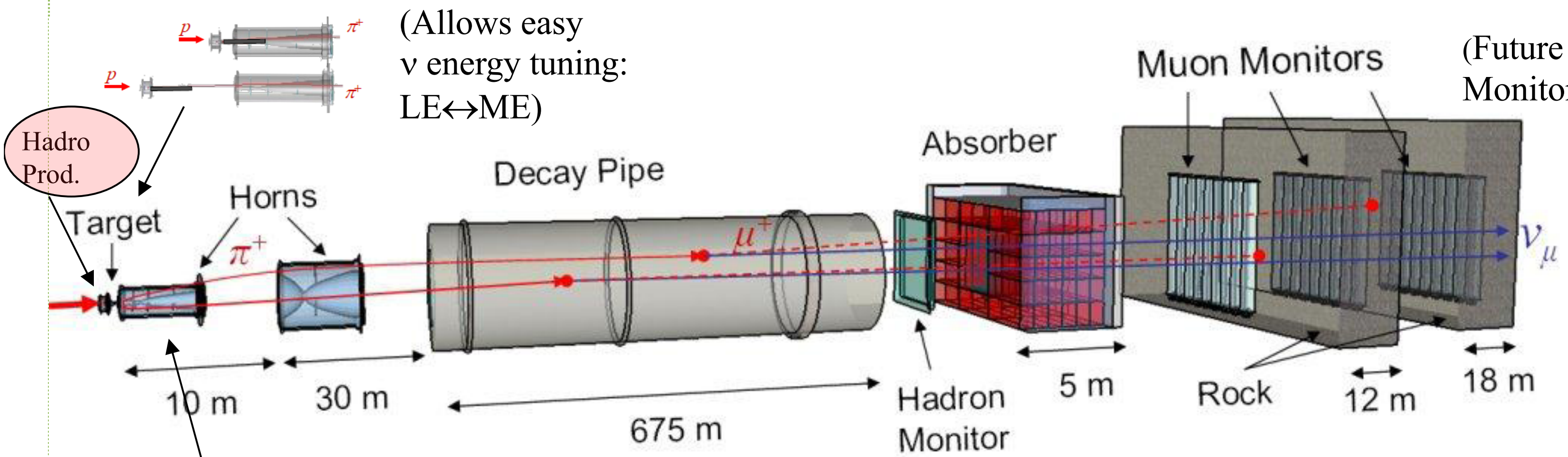


Low energy data taking completed in 2012 (neutrino and antineutrino)
Since 2013 running in Medium Energy mode, started antineutrino 2/17.

Flux: NUMI (Horn) ν Beam

(Neutrinos at the Main Injector)





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

MINERνA

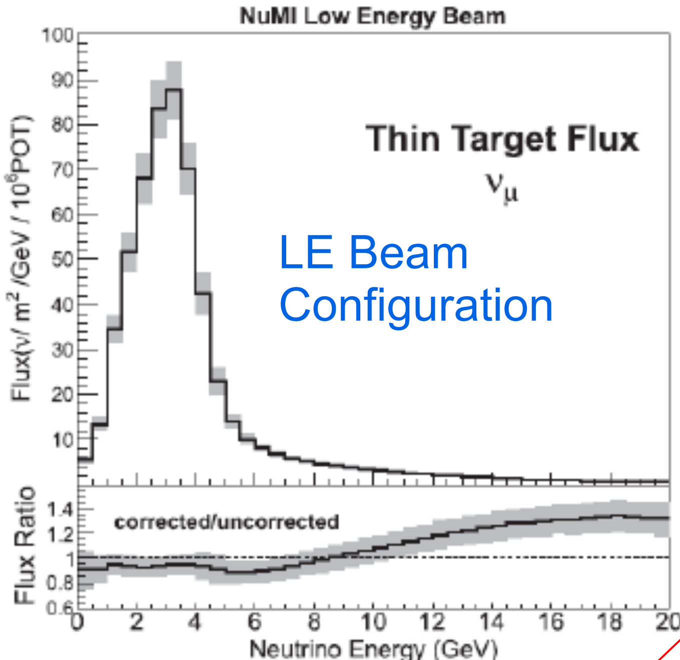
→ pions and kaons produced by a proton beam -focused by Magnetic horns - decay into muons and **neutrinos/antineutrinos**

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

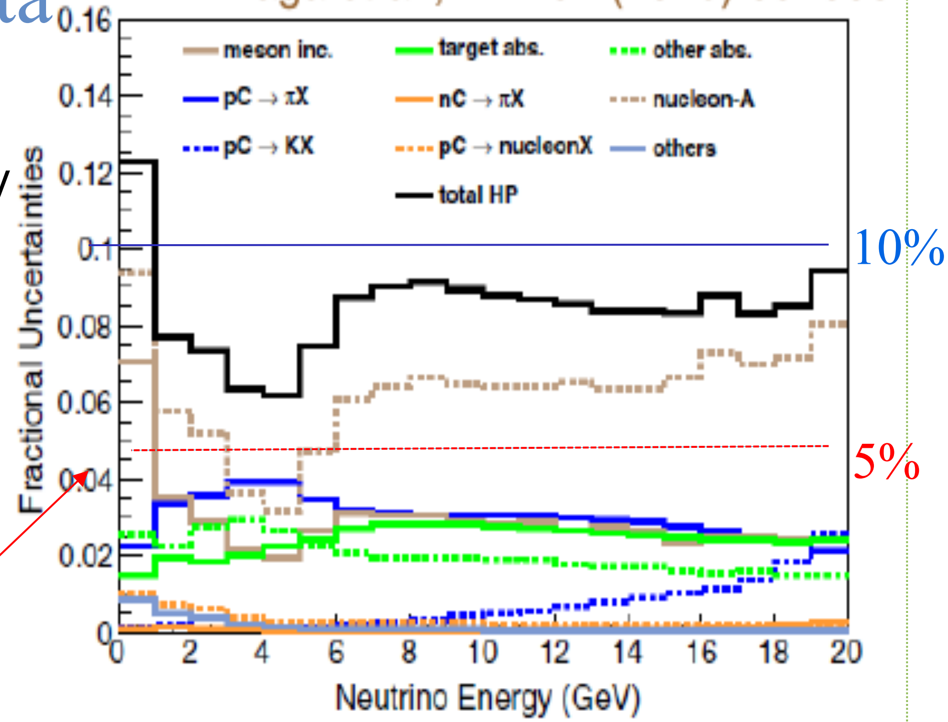
New flux Prediction Incorporating Hadron Production Data

Aliaga et al., PRD94 (2016) 092005

Flux



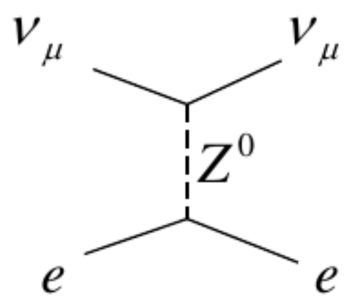
fractional uncertainty



- **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 Expt)
    - NuMI target pion production (MIPP Expt)

Aim at ~5% errors for the ME flux with the addition of two constraints from in situ measurements (ν_μ – e Elastic Scattering , Low-ν)

First in situ flux constraint



very forward single electron final state

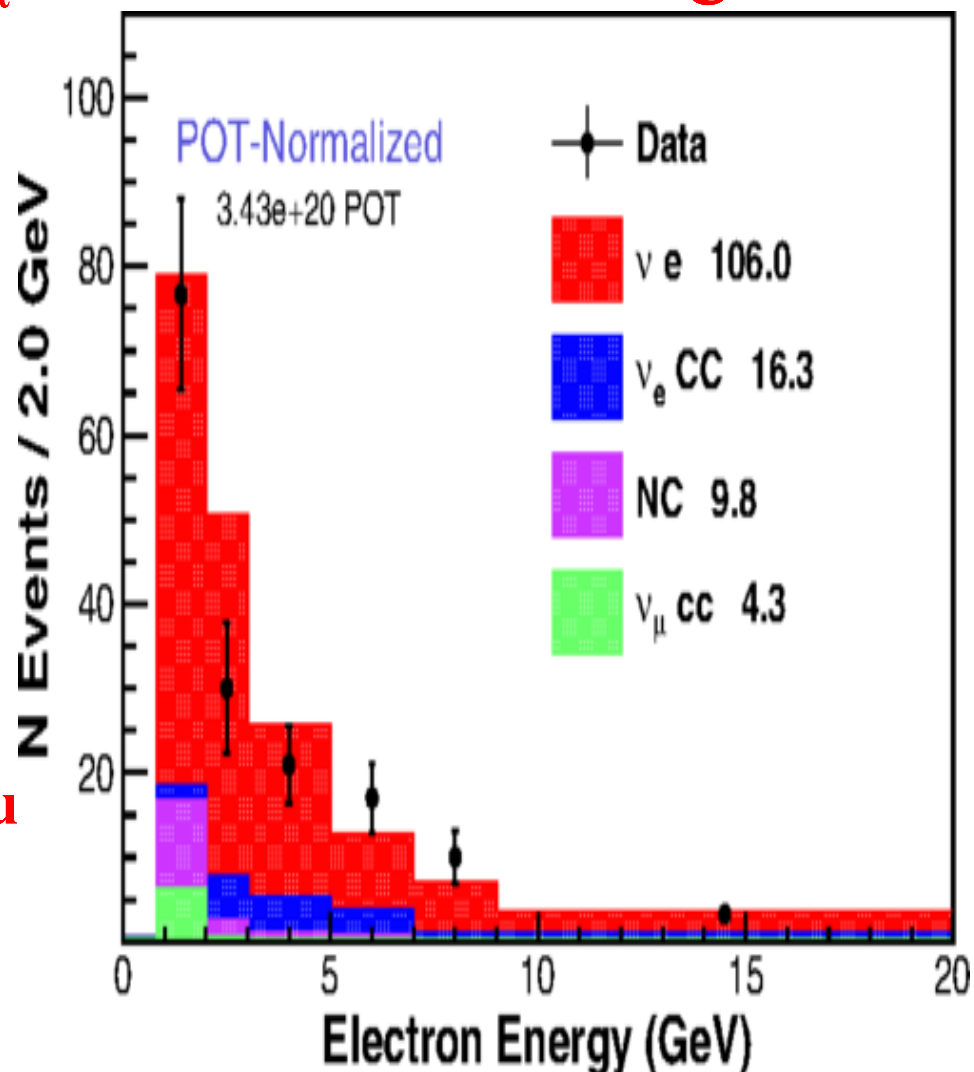
Park et al., PRD93 (2016) 112007

ν_μ – e Elastic Scattering
– point like -
Cross section is known,

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

(Many more events in ME running)

ν_μ – e Elastic Scattering



Second in situ Flux Constraints

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

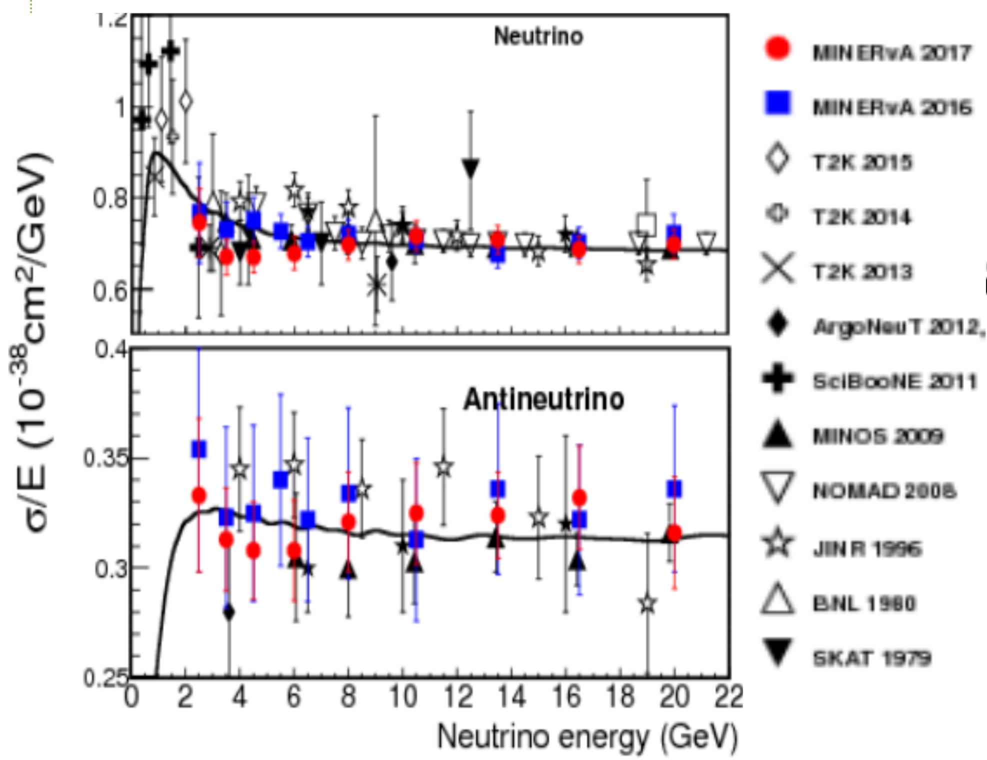
$\frac{d\sigma}{d\nu}$ ~constant for low ν

Low-ν (low hadronic energy)

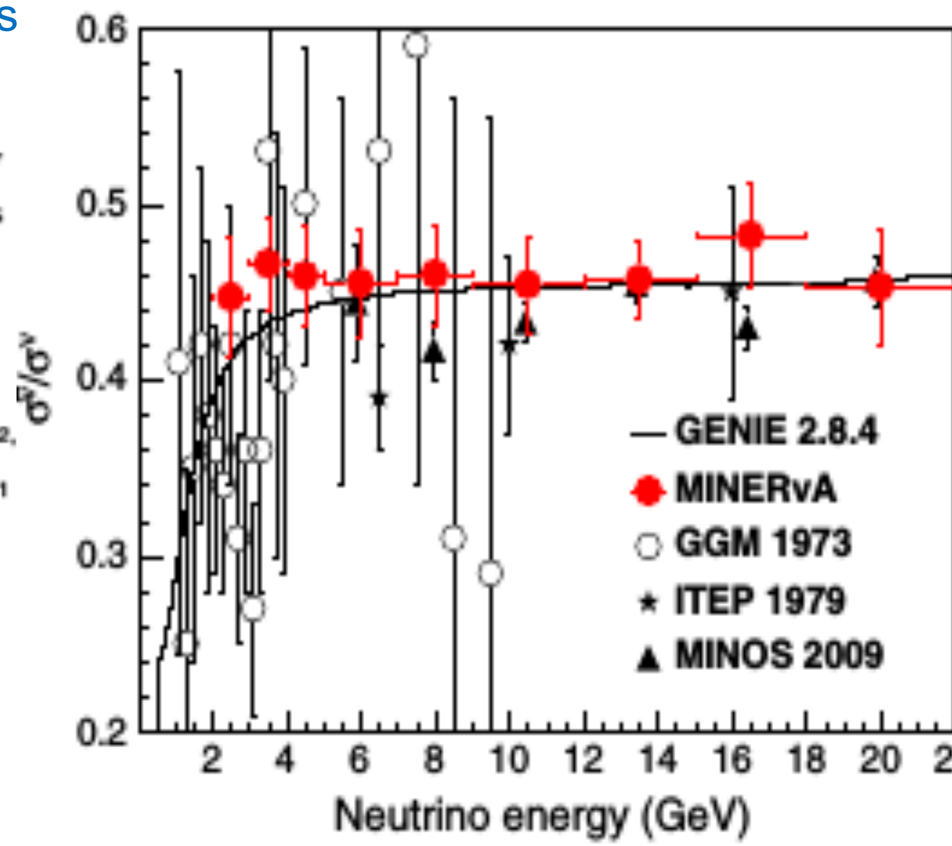
- Gives a measurement of the flux shape (relative flux) Ref: Bodek et al EPJC 72, 1973 (2012)_

Absolute Flux is normalized to other inclusive cross section measurements at high neutrino energies >20 GeV

Total neutrino and antineutrino cross sections



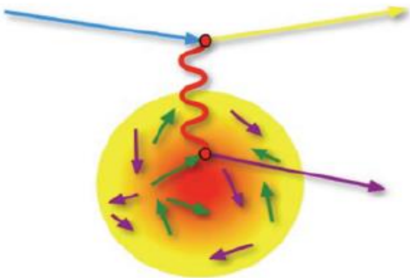
L. Ren et al(MINERvA) PRD95 (2017) 072009

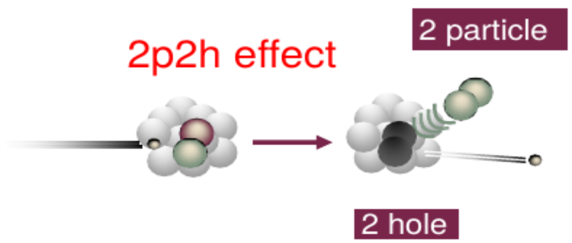


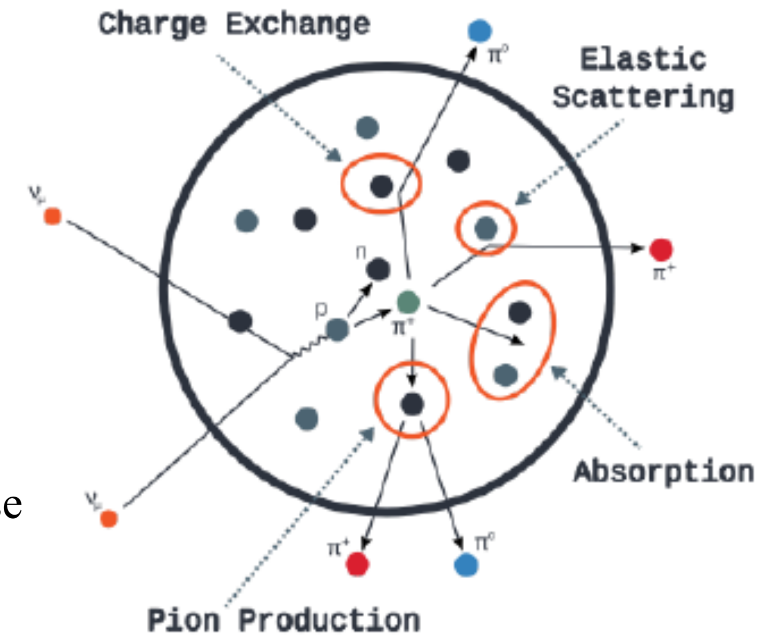
Blue MINERvA LE 2016
Red MINERvA LE 2017

Minerva has performed the first good measurement of the antineutrino cross sections for E_ν<4 GeV.

Nuclear Physics Complications SRC, 2p2h, MEC, RPA FSI







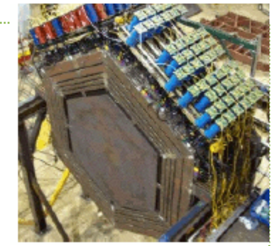
- Long range correlations – calculated using theRadom Phase Approximation, (RPA) (a charge screening nuclear effect at low Q)
- There are short range correlations (SRC) 20% observed in electron scattering experiments, Scattering off a pair of correlated nucleons (quasi-deuterons) results in 2p2h final state (2 particles 2 holes)– binding energy is larger

•2p2h also from Meson Exchange Currents (MEC)which is another process. (increases QE cross section) (increase is primarily in the transverse cross section

ν interactions occur INSIDE the nucleus:

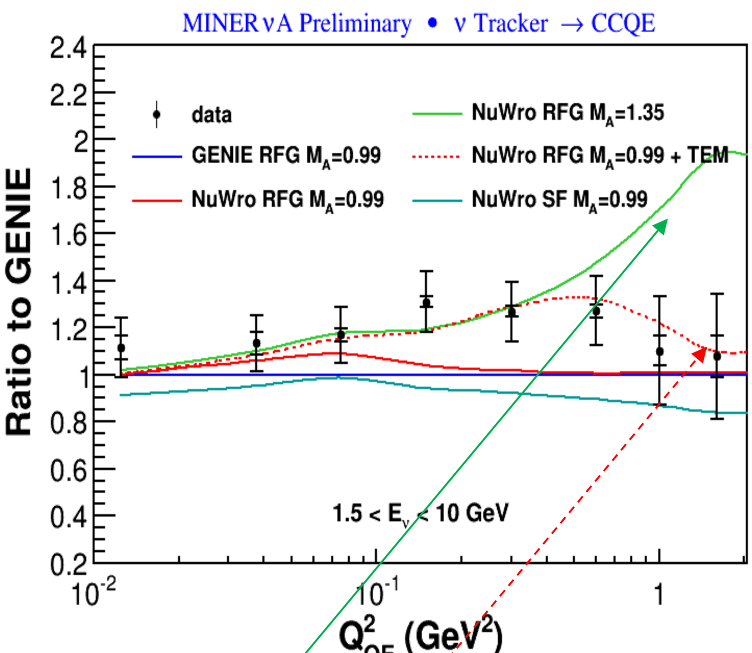
- **Produced particles have to exit out of the nucleus to be observed ****
- **Final state interactions (FSI)**

CCQE: Q^2 dist. comparison to models

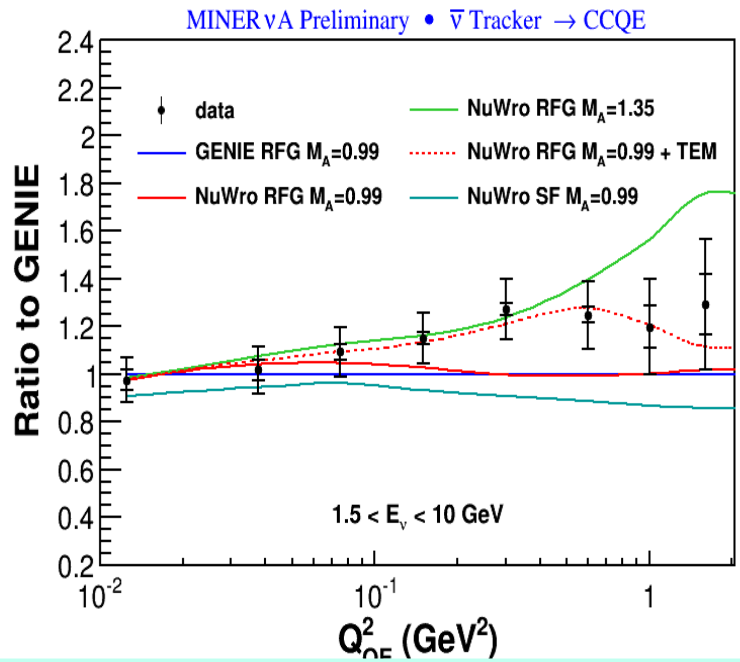


$$Q^2_{QE} = -m_l^2 + 2E_\nu^{QE}(E_l - \sqrt{E_l^2 - m_l^2} cos\theta_l)$$ **Q^2 (muon)**

CCQE neutrinos



CCQE antineutrinos



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

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

Used as the "Standard Candle" disappearance signal channel in oscillations experiments:

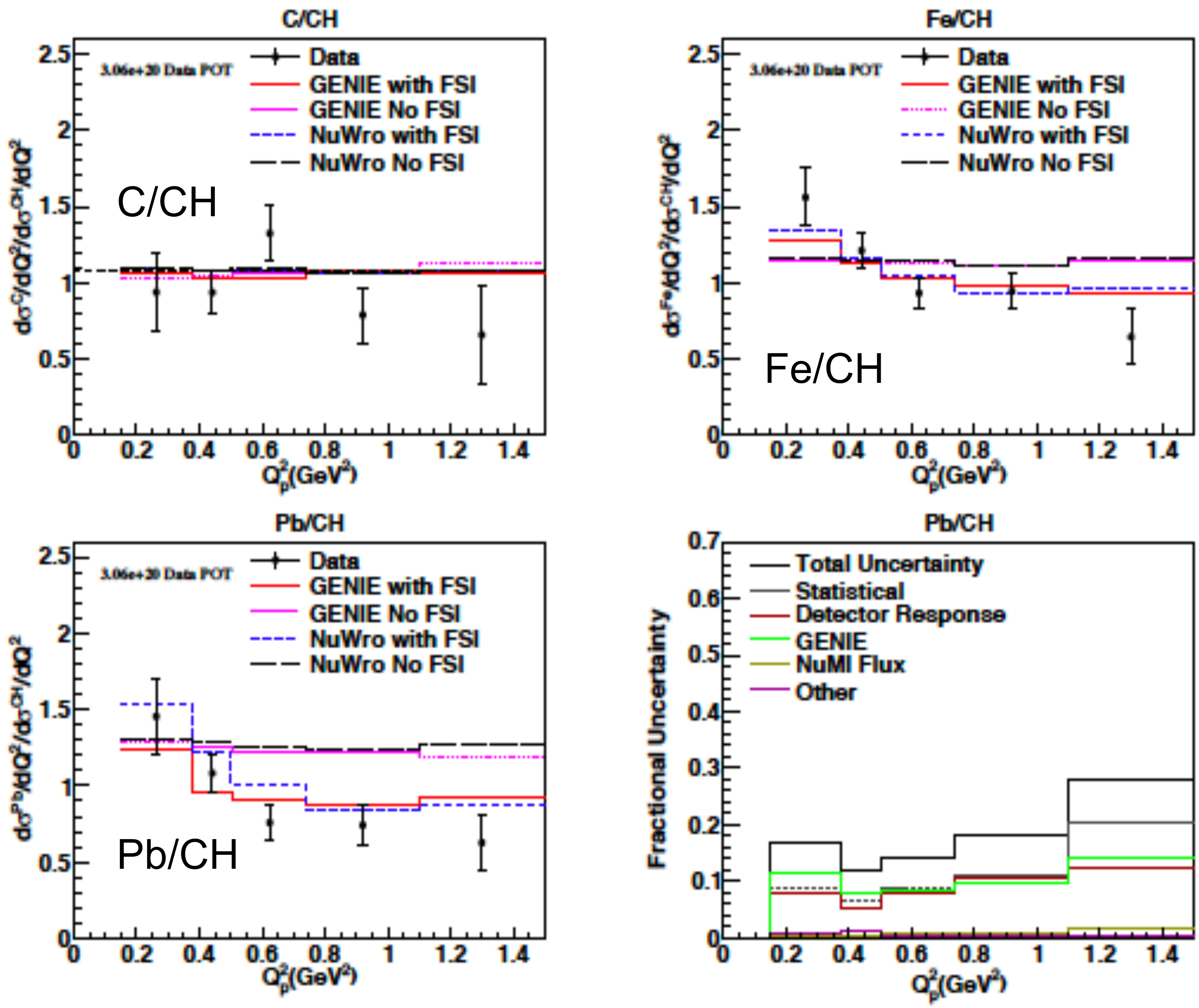
Both results prefer models with additional interactions involving multi-nucleons → More later

- **M_A = 1.35:** Fit to MiniBooNE data
- **TEM(dotted):** Transverse Enhancement Model
  → Empirical model based on electron scattering data (best description)- **2p2h final stste**
- **GENIE:** Independent nucleons in mean field
- **SF: (spectral function)** More realistic nucleon momentum-energy relation

NuWro: Golal, Jusczak, Sobczyk PhysRevC.86.015505
TEM: Bodek, Budd, Christy Eur. Phys. J. C 71 (2011) 1726

Q^2_p is sensitive to FSI effects. $Q_p^2 = (M_n - \epsilon_B)^2 - M_p^2 + 2(M_n - \epsilon_B)(T_p + M_p - M_n + \epsilon_B)$,

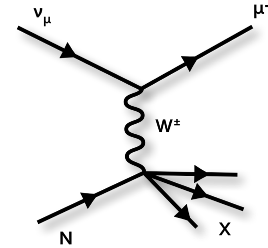
Modify CCQE GENIE model to include 2p2h (Valecia model). Now look at the Q^2 distribution of the final state proton Q^2_p for QE like events for various nuclei. arXiv:1705.03791

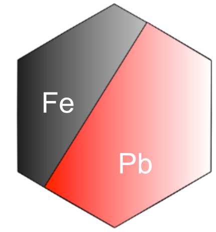


Effect of FSI clearly seen in the data.

Data calls for additional refinements in the modeling of FSI Fe and Pb in neutrino MC generators,

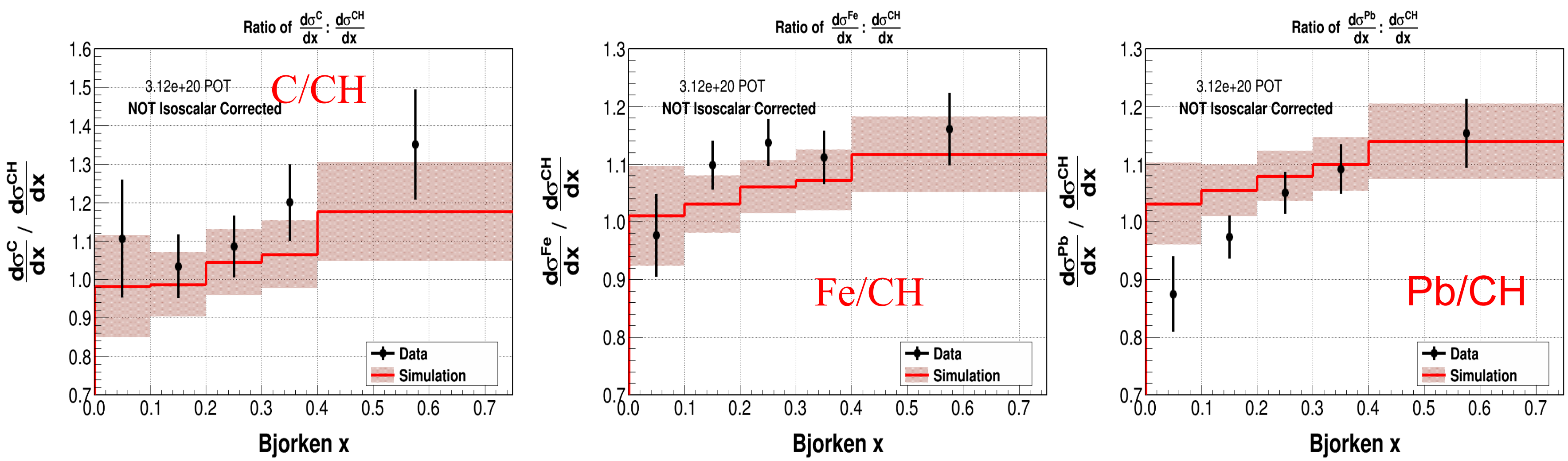
A dependence CC DIS Inclusive:





- *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 (prediction based on electron scattering data – Vector)
- As function of E_ν(@LE): No tension between MINERνA data and GENIE simulations

Selected Data to Model Comparisons

Poorly modeled nuclear effects for the QE and Δ processes, such as interactions with correlated nucleon pairs (2p2h) result in an inaccurate mapping $E_{vis} \rightarrow E_{\nu}$.

- **MINERvA data indicate that there is a need for additional processes with multiple nucleons in the final state**, such as Meson Exchange Currents (MEC - 2p2h with higher binding), leading to energy transfer between the QE and Δ peaks (Note that both: Enhanced cross section (Transverse Enhancement/MEC) and SRC have been observed in electron scattering experiments)

- **Reported on studies of nuclear effects** such as FSI and shadowing.

- **The QE cross section at low energy transfer is small**: Consistent with the effects of long range nucleon-nucleon correlations, such as charge screening computed using the Random Phase Approximation (RPA) technique.

- See list of publications for other topivs.

- **More results are forthcoming**: Medium Energy (ME) data with increased kinematic coverage (W and Q^2)

Back-ups

Overview

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

- MINERνA is improving our knowledge (and models) of:
  - ν_{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 lower systematic errors in neutrino oscillation experiments.

- Next: Higher statistics Medium Energy (ME) data with increased kinematic coverage (W and Q^2)

MINERvA Collaboration

~ 65 Particle, nuclear and theoretical physicists from 21 Institutions:

Aligarh Muslim University
Centro Brasileiro de Pesquisas Fisicas
Fermilab
University of Florida
Universite de Geneva
Universidad de Guanajuato
Hampton University
Massachusetts College of Liberal Arts
University of Minnesota at Duluth
University of Mississippi
Otterbein University

Universidad Nacional de Ingenieria
Potificia Universidad Catolica del Peru
University of Pennsylvania
University of Pittsburgh
University of Rochester
Rutgers, the State University of New Jersey
Universidad Tecnica Federico Santa Maria
Tufts University
College of William and Mary
University of Wroclaw

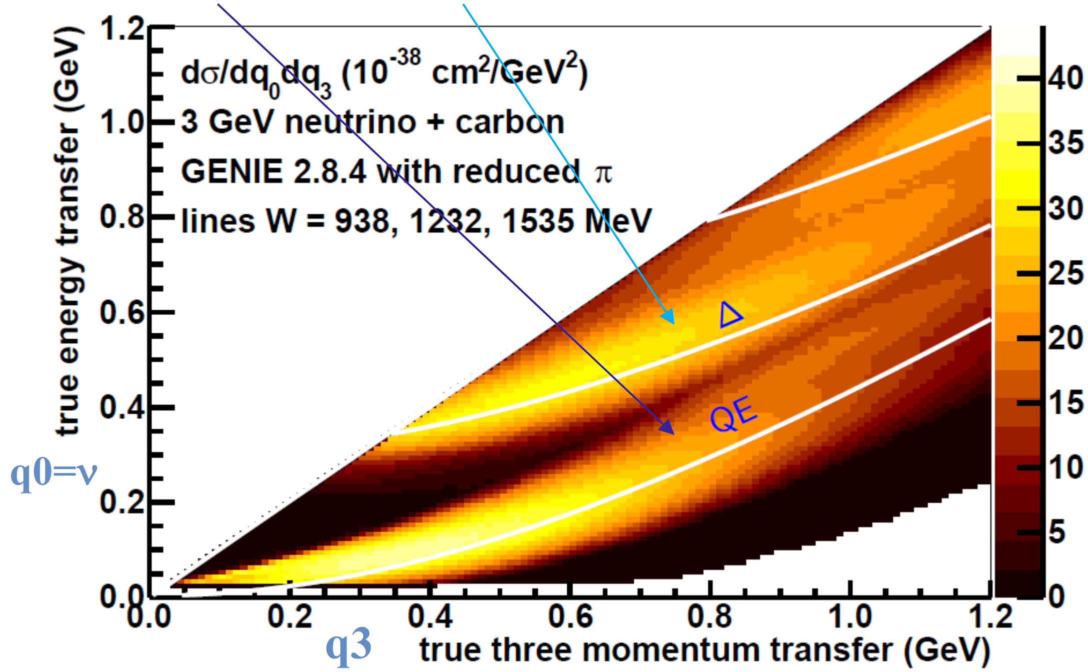
Nuclear effects in neutrino-carbon Interactions at **low three-momentum transfer. q0=ν, vs q3**

- 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:

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

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

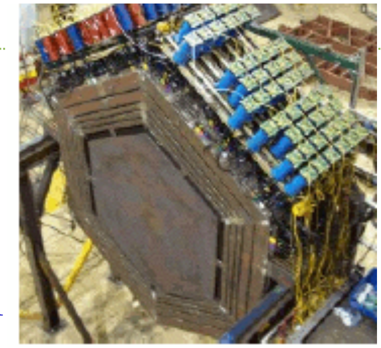
$$q_3 = \sqrt{Q^2 + q_0^2}$$



- We observe a small cross section at very low energy transfer that matches the expected *screening effect of long-range nucleon correlations*. computed using the Random Phase Approximation (RPA) technique.

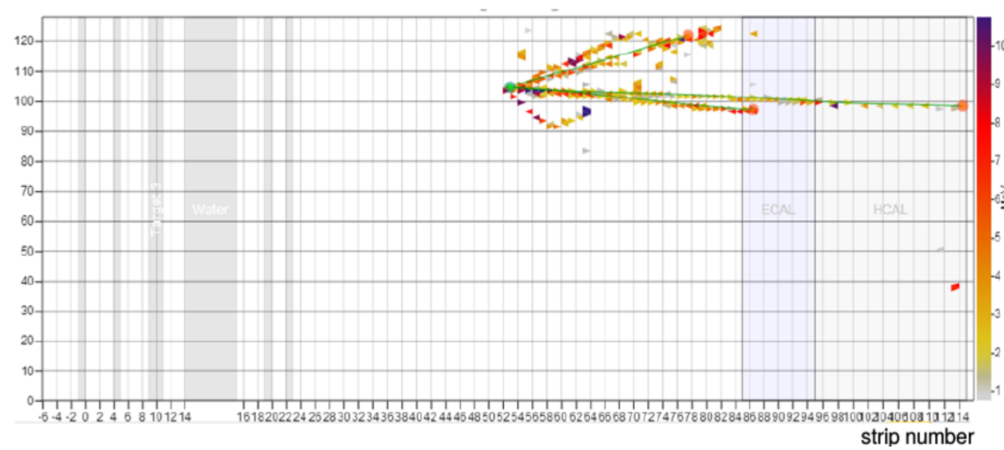
- Additional cross section in the kinematic region between the quasi-elastic and Δ resonance processes is needed to describe the data. (e.g. MEC 2p2h – larger binding)

Detector Capabilities

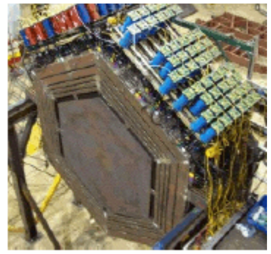


- Scintillator strip target calorimeter with Good tracking resolution
- Calorimetry for both charged hadronic particles and EM showers
  - MINERνA detector's hadronic energy response was measured using a dedicated test beam experiment at the Fermilab Test Beam Facility (FTFB)
- Timing information (few 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 + energy+range
  - But no charge determination except muons entering MINOS

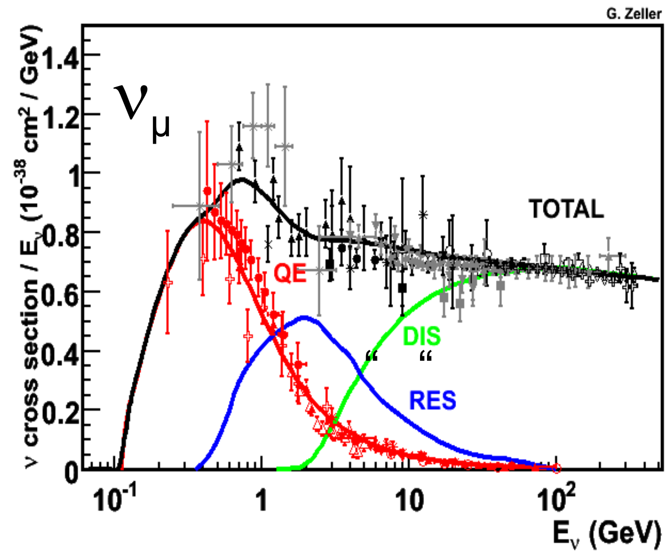
→ ν



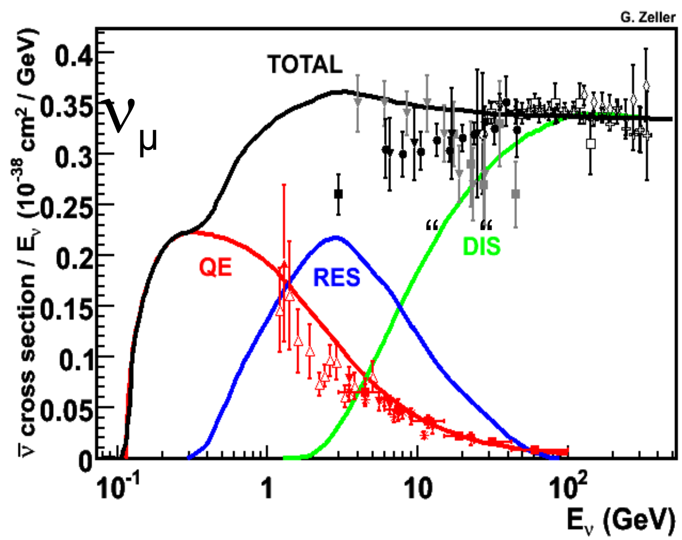
Motivation



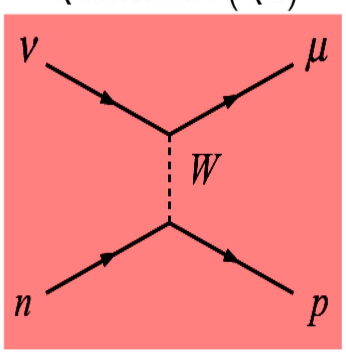
Rev. Mod. Phys. 84, 1307–1341 (2012)
(includes MiniBooNE results)



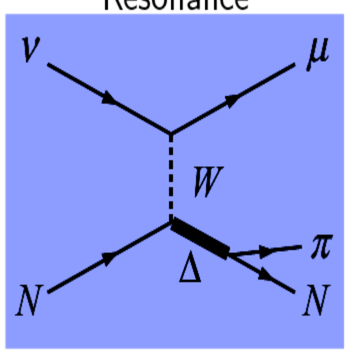
- Existing data between 1-20 GeV limited:
- Mainly bubble chamber data
- Wide band neutrino beams
  - Low statistics samples
  - Large uncertainty on flux.
  - Limited target types



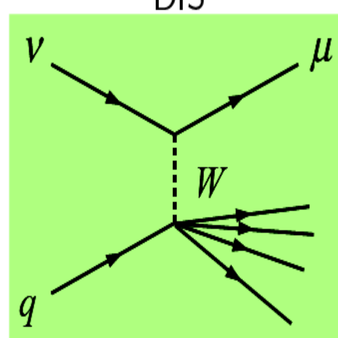
Quasielastic (QE)



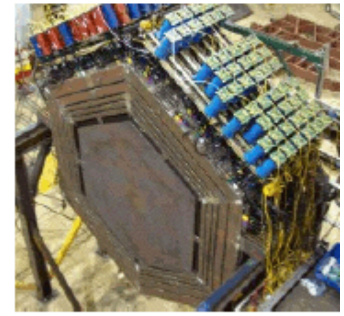
Resonance



DIS

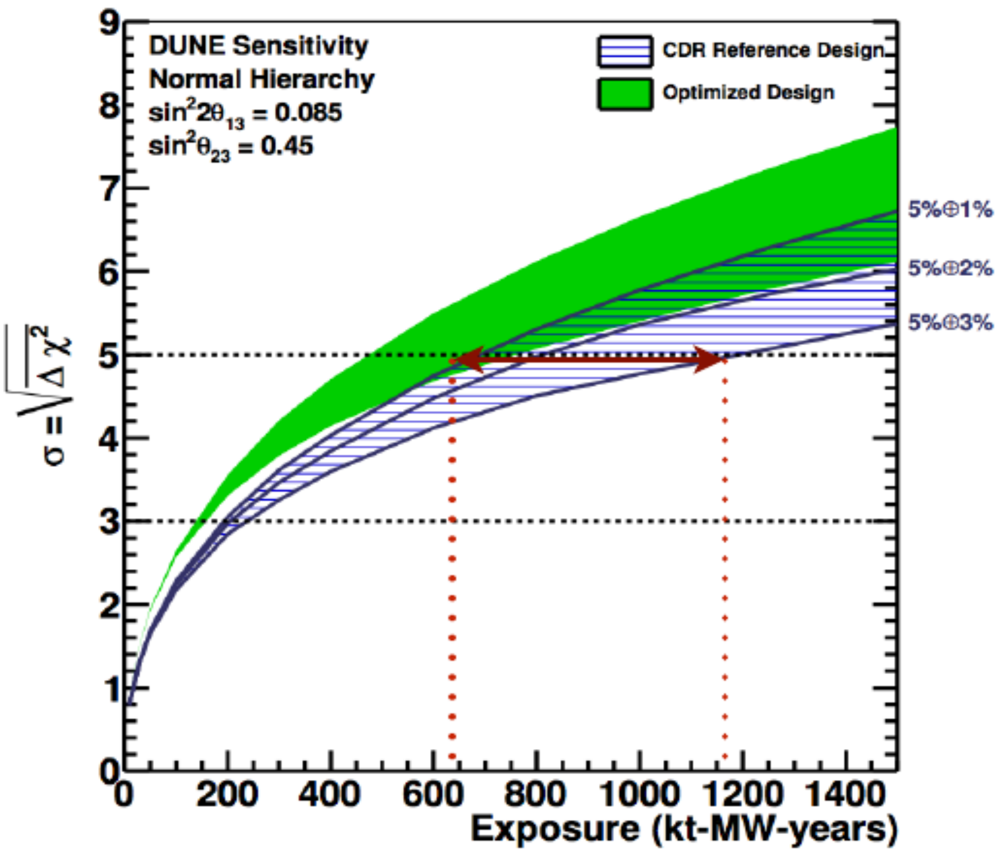


Motivation: poorly known cross-sections



DUNE CDR, arXiv:1512.06148

50% CP Violation Sensitivity



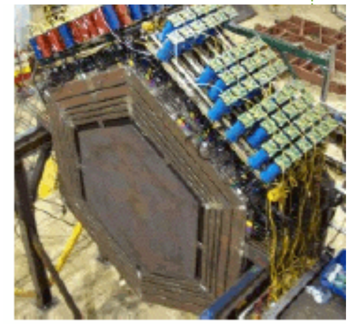
1% ~650 kt-MW-yr

3% ~1200 kt-MW-yr

~2x exposure!

- 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 significant fraction of the total error
- Need better models (generators) based on high precision data
  - → **Enter MINERνA**

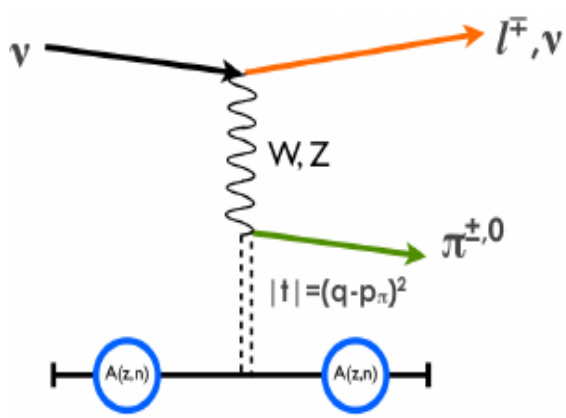
Flux: Absolute Cross-section Errors



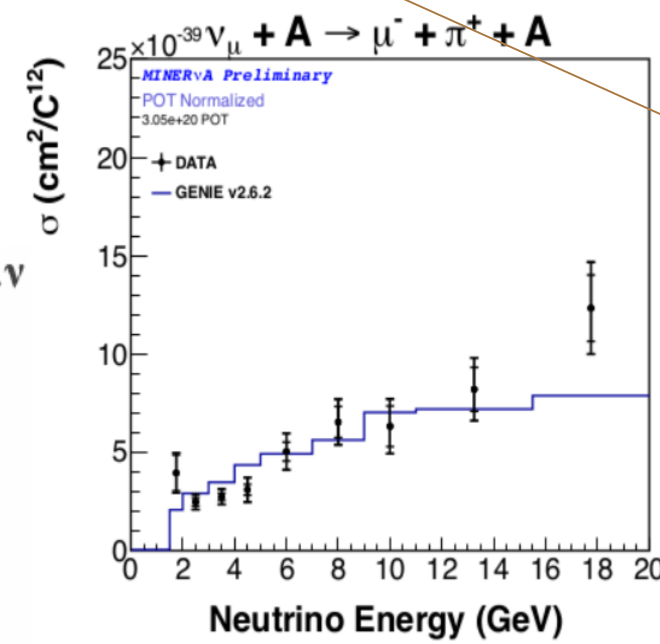
- MINERvA Statistical errors are expected to be small.
- The total error on absolute cross section measurements are dominated by the systematic error on the determination of the neutrino flux:

Example: Coherent $\pi^{\pm}$ production.

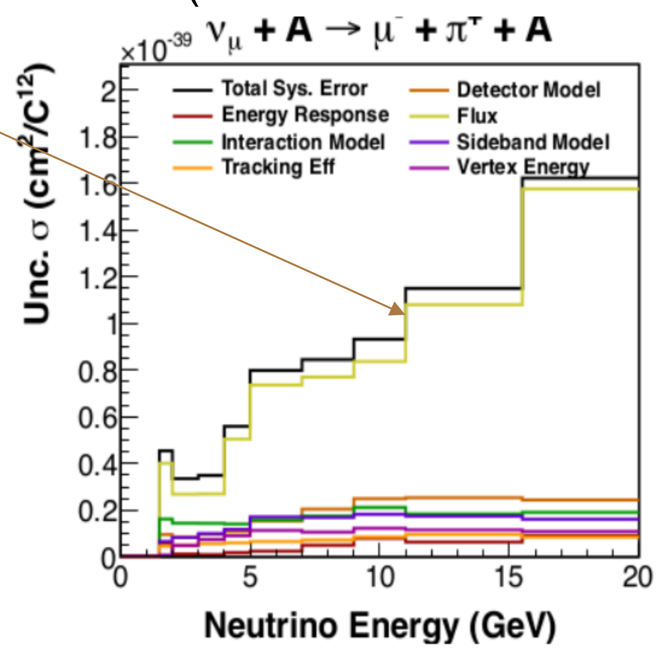
PRL 113, 261802 (2014)



Cross section (note vertical scale)



Cross section uncertainty (note vertical scale



Second in situ Flux Constraints:

Low-ν (low hadronic energy)

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

$$\frac{d\sigma}{d\nu}$$ ~constant for low ν

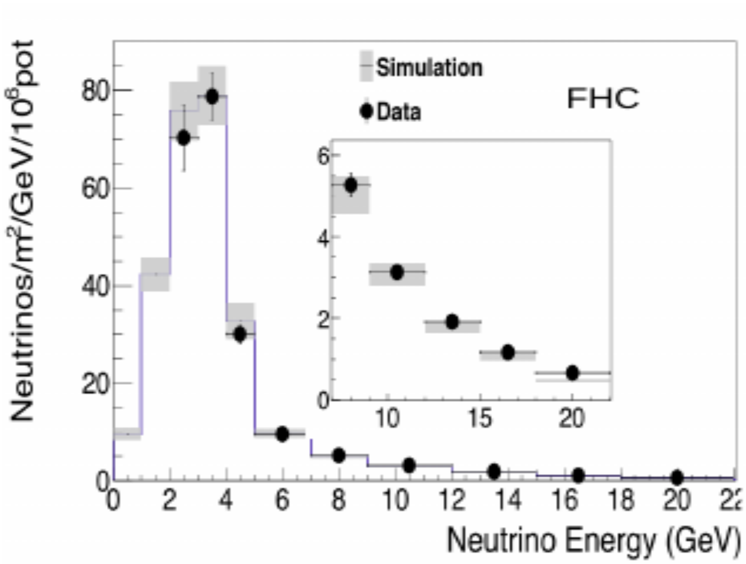
- low hadronic recoil energy
- A, B, and C depend on integrals over structure functions
- **Gives a measurement of the flux shape**

Ref: Bodek et al EPJC 72, 1973 (2012)_

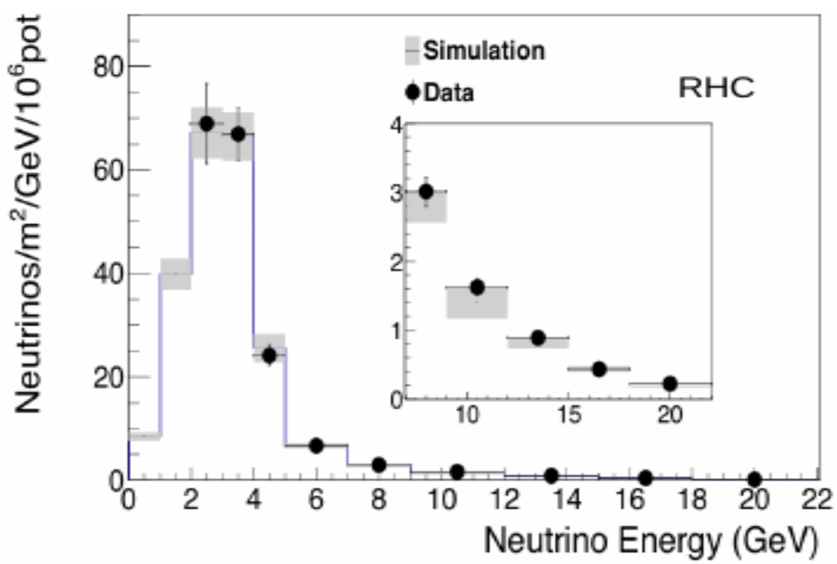
L. Ren et al., (MINERvA) PRD95 (2017) 072009

Low-ν is only a measurement of relative flux

ν_μ

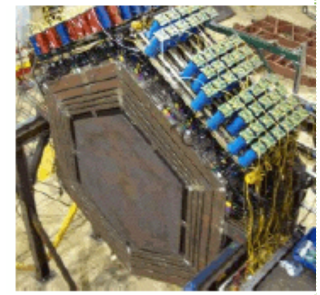


$\bar{\nu}_\mu$

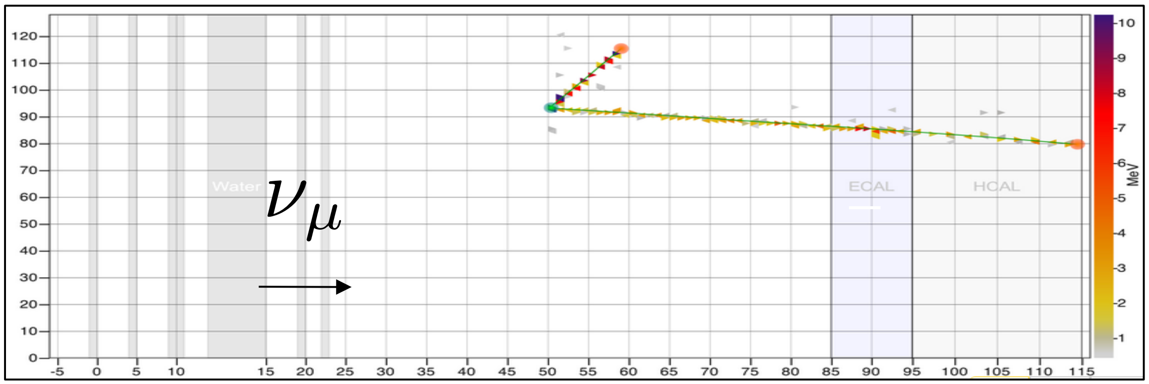


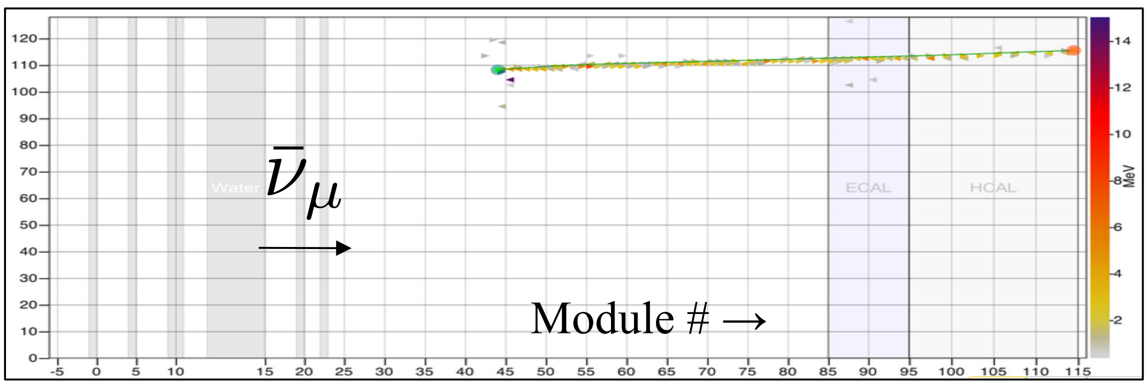
Flux is normalized to inclusive cross section from other measurements at high neutrino energy.

$\nu(\bar{\nu})$ CC Quasi-Elastic Scattering (CCQE):



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





Hit Energy in MeV

Charged Current (CC)

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

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

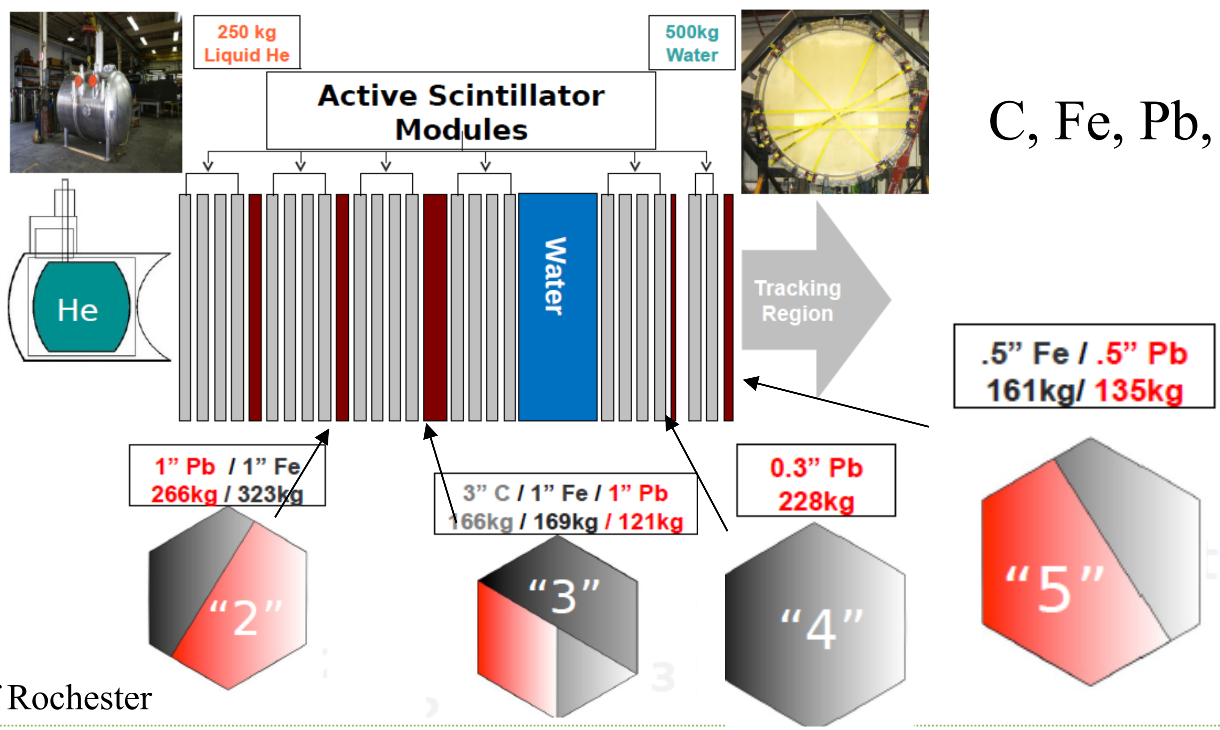
A-dependence of CC ν Cross Section

Neutrino Oscillation experiments need unbiased measurement of neutrino energy:

- **Different Experiments use Different Heavy Nuclear Targets (need mass!):**
  - Carbon, Water, Argon (now) and previously Iron, Lead, Calcium.
- **Nuclear effects are not small in neutrino scattering**:
  - $E_{Visible} \neq E_{True}$ and Interaction Rate can be target dependent
- **Neutrino interaction models do not simulate these effects well**
  - A dependence provides a check on nuclear models

C, Fe, Pb, H_2O

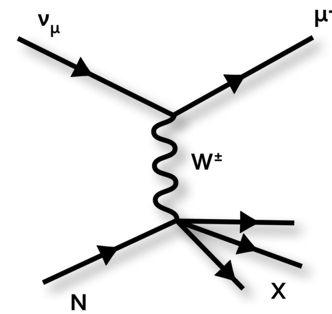
Close-up of MINERνA Target Region



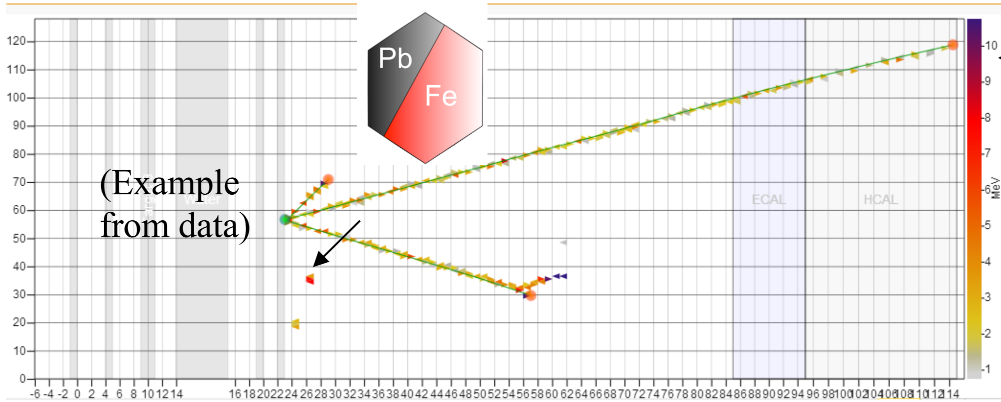
EPS HEP 2017
(MINERνA Talk)

Arie Bodek, University of Rochester

CC ν Inelastic (DIS) Inclusive:

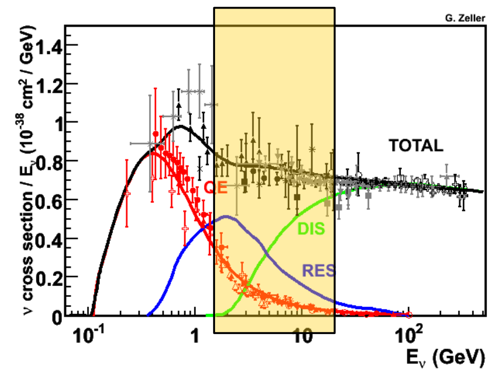


ν



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 the downstream magnetized MINOS Near Detector (ND)
  - 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)

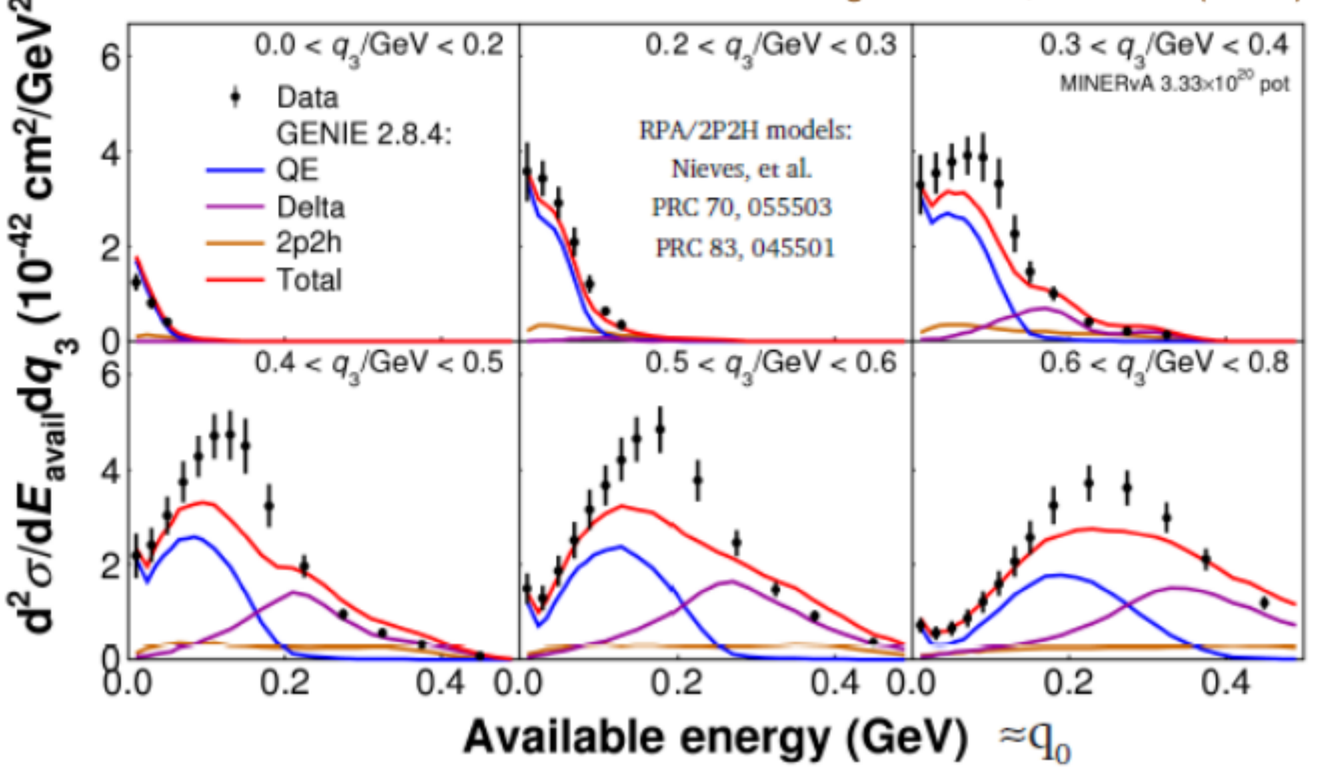
- Muon angle needed for other kinematic variables:

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

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

ν_μ CCQE data in the $(q_0 - q_3)$ plane

Rodrigues et al., PRL116 (2016) 071802



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

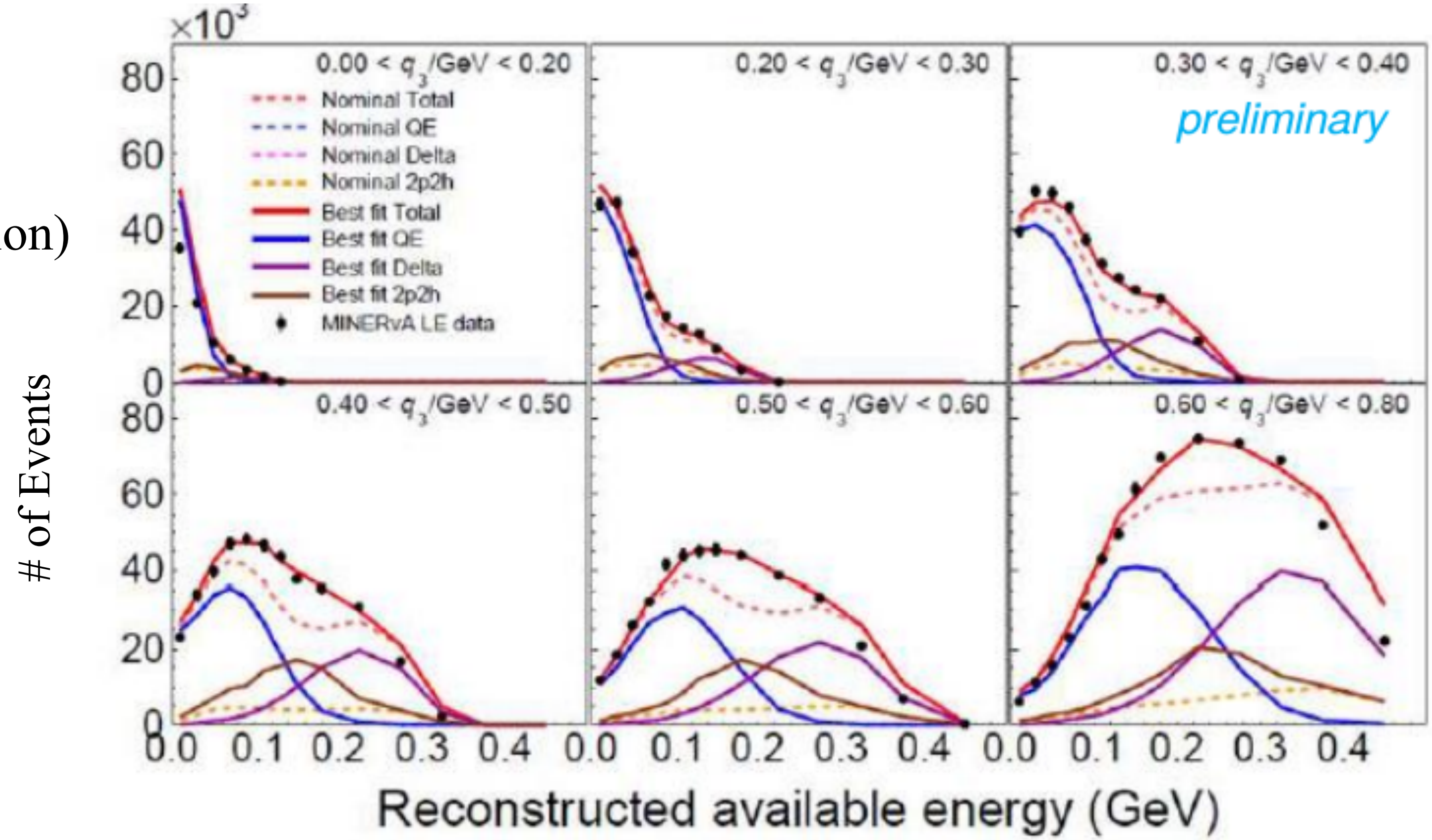
- Adding in models RPA= Random Phase Approximation (a charge screening nuclear effect) and MEC 2p2h processes improves agreement in some regions, but not all...
  (Phys. Rev. C 83, (2011), Phys. Rev. C 70, 055503 (2004), Phys. Rev. D 88, 113007 (2013) (Valencia Model))

- 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!