Brazilian Participation in Neutrino Scattering Experiments at Fermilab

MINERνA and CAPTAIN-MINERνA

***** Neutrino agreement for Joe Biden and Dilma Rousseff**
The Brazil Minister of Science, Technology & Innovation Rebelo signed a statement of intent that promotes collaborative R&D in neutrino physics with the US DOE. It took place during lunch hosted by VP Joe Biden in honor of President Dilma Rousseff during her official visit to the U.S. The document recalls that Brazil and the US have many decades of collaboration in HEP. Brazil has several working groups studying neutrinos and the US DOE considers this field a priority for its future particle physics program.
http://www.mcti.gov.br/ and search "neutrino"

Jorge G. Morfín - Fermilab

Manaus – August, 2015

The Scene at Fermilab

Goals of this presentation:

1) **Describe a present and future Neutrino Scattering experiments at FNAL.**
2) **Emphasize the very poor agreement between expt. and ν-A interaction models.**
3) **Invite increased Brazilian participation in neutrino scattering at FNAL.**
2) **Outline a model for Brazilian collaboration with these experiments.**

The Exquisite Goal of Oscillation Experiments

and the **Hazards** that Block our Way

Working towards that Goal….
Neutrino Experiments at Fermilab

- **Experimental Neutrino Oscillation**
  - MiniBooNE, SciBooNE and MINOS
  - **MINOS+, NOνA, MicroBooNE (soon)**
  - **SBND (with MicroBooNE and ICARUS)**
  - **LBNF/DUNE**

- **Experimental Neutrino Scattering** (***FOUR NAILS***)
  - MiniBooNE, SciBooNE
  - **MINERνA,** ArgoNeuT**, NOνA-ND,**
  - **MicroBooNE**
  - **CAPTAIN-MINERνA**
  - **SBND**
  - **DUNE-ND**

To appreciate the importance of ν-Nucleus Scattering ask "What do we observe in our detectors?"

Significant implications for Oscillation Experiments

- The events we observe in our detectors are convolutions of:

$$Y_{c\text{-like}}(E_m) \;\alpha\; \phi_\nu(E' \geq E_m) \;\otimes\; \sigma_{c,d,e..}(E' \geq E_m) \;\otimes\; Nuc_{c,d,e..\rightarrow c}(E' \geq E_m)$$

- **$Y_{c\text{-like}}(E_m)$** is the event energy and channel / topology of the event observed in the detector. It is called **c-like** at **E_m** since it is detected as channel c with energy E_m but may not have been so at interaction.

- The energy E_m is the sum of energies coming out of the nucleus that are measureable in the detector.

- That is the topology and energy measured in the detector is **not necessarily what was produced at the initial interaction. The neutrino physics analyses depend on the initial interaction.**

ν-Nucleus Scattering

Nuclear Effects Term: $Nuc_{c,d,e..\rightarrow c}(E' \geq E_d)$

Significant implications for Oscillation Experiments

- The events we observe in our detectors are convolutions of:

$$Y_{c\text{-like}}(E_d) \;\alpha\; \phi_\nu(E' \geq E_d) \otimes \sigma_{c,d,e..}(E' \geq E_d) \otimes \mathbf{Nuc_{c,d,e..\rightarrow c}(E' \geq E_d)}$$

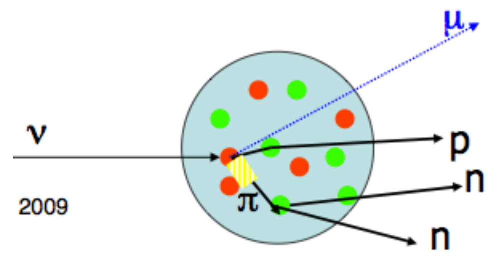
- **$Nuc_{c,d,e..\rightarrow c}(E' \geq E)$ – Nuclear Effects**
  - **The Supreme Mixer / The Grand Deceiver** – a migration matrix that mixes produced channel and energy to detected channel and energy.
  - There are many nuclear effects that have to be considered that take the interaction of a neutrino with energy E' with the bound nucleon(s) and producing initial channel d,e… that will then appear in our detector as energy E_d and channel c.
  - The physics we want to study depends on the initial interaction – not what we observe coming out of the nucleus. **How do we move detected quantities backwards through the nucleus?**

What are these Nuclear Effects **$Nuc_{c,d,e..\rightarrow c}$ (E' ≥ E)** in **ν-Nucleus Scattering**?

Could certainly use Brasilian Nuclear Theorists here!!

- Target nucleon in motion – classical Fermi gas model or spectral functions (Benhar et al.) or more sophisticated models.
- Certain reactions prohibited - Pauli suppression.
- Nucleon-nucleon correlations such as MEC and SRC and even RPA implying multi-nucleon initial states.
- Cross sections, form factors and structure functions are modified within the nuclear environment and parton distribution functions within a nucleus are different than in an isolated nucleon.
- Produced topologies are modified by final-state interactions modifying topologies and possibly reducing detected energy.
  - Convolution of $\sigma(n\pi) \otimes$ formation zone model $\otimes$ π-charge-exchange/absorption.

An Example: Final State Interactions (FSI)



- Components of the initial hadron shower interact within the nucleus changing the apparent final state configuration and even the detected energy. Currently using mainly **cascade models for FSI**.
- For example, an initial pion can charge exchange or be absorbed on a pair of nucleons.
- Final state observed is μ + p that makes this a fine candidate for QE production. We've probably also lost measurable energy.

Example numbers	**Final μ p**	**Final μ p π**
Initial μ p	90%	10%
Initial μ p π	25%	75%

ν-Nucleus Scattering
Putting it all together: The Nuclear Model

- The events we observe in our detectors are convolutions of:

effective $\sigma_{c\text{-like}}^{A}(E)$

$$Y_{c\text{-like}}(E_d) \;\alpha\; \phi_\nu(E' \geq E_d) \otimes \sigma_{c,d,e..}(E' \geq E_d) \otimes \mathbf{Nuc}_{c,d,e..\rightarrow c}(E' \geq E_d)$$

- The community models these last two terms in **event generators**:
  - Provide information on how signal and background events should **appear** in our detectors if the model is correct.
  - Provide means for estimating systematic errors on measurements.
  - One of the most important components in the analysis of neutrino experiments.
- Current Generators used by experimental community – each with their own models of the nuclear environment!
  - **GENIE** – ArgoNeut, MicroBooNE, MINOS, MINERvA, NOvA, T2K, DUNE
  - **NEUT** – SuperKamiokande, K2K, SciBooNE, T2K
  - **NuWRO** – K2K, MINERvA as check of other generators
- **GiBUU** – Nuclear Transport Model used to check other generators

Where we are depends on which nuclear model / generator we use!

Where are we?

Map at Great Wall

A Step-by-Step Two-Detector LBL Oscillation Analysis

1) Measure detected E_d and event topology in the near detector.

2) Use the **nuclear model** to take the detected E_d and topology back to the initial interaction energy E_ν and topology.

3) Project this initial interaction E_ν distribution, perturbed via an oscillation hypothesis that changes ϕ_ν at the far detector.

4) Following the initial interaction in far detector, use the **nuclear model** to take the initial E_ν and topology to a detected E_d and topology.

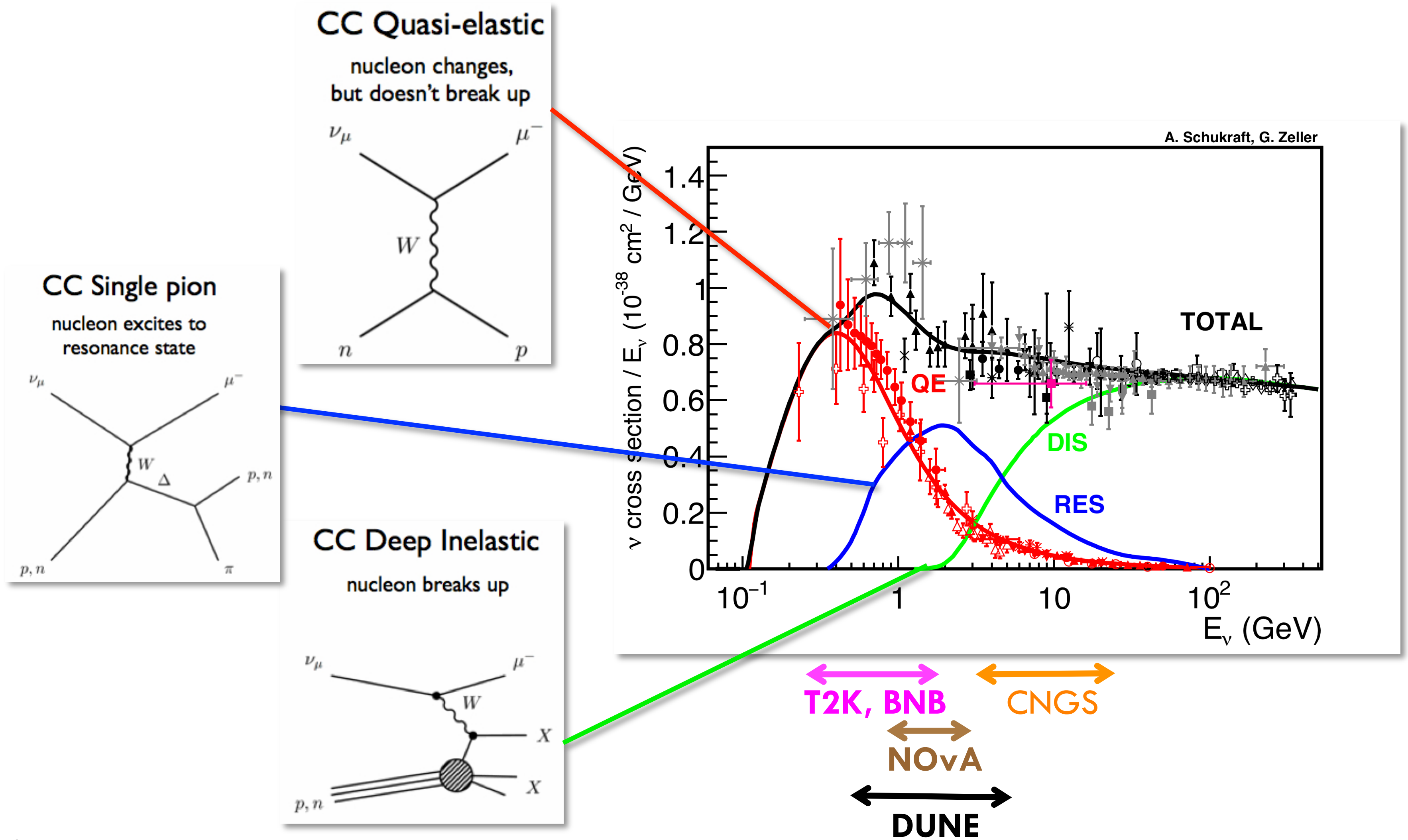
5) Compare with actual measurements in the far detector.

Critical dependence on the nuclear model <u>even with a near detector – SYSTEMATICS DO NOT CANCEL!</u>

We constrain/improve the nuclear model by measuring neutrino nucleus interactions on a variety of nuclei!

Constraining the Nuclear Model via Experimental Input

Dominant Interaction Modes



Studying Neutrino-Nucleus Cross Sections & Nuclear Effects:

The MINERνA Experiment: Five Latin American Groups

Taking Data for the past 5 years, Now and Into the Future

Collaboration of 65 nuclear and particle physicists.

Centro Brasileiro de Pesquisas Físicas. Brasil
Fermilab
University of Florida
Université de Genève
Universidad de Guanajuato, Mexico
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 Minnesota at Duluth
Universidad Nacional de Ingeniería, Peru
Universidad Técnica Federico Santa María, Chile
William and Mary

MINERνA Latin American Initiative

Latin American Students: **27 MS & 11 PhD**

CBPF, Rio de Janeiro, Brasil

Prof	Helio da Motta		
ms	Jose Palomino		
doc	Jose Palomino	Pdoc SUNY	nu pi0 production
ms	Arturo Fiorentini		
doc	Arturo Fiorentini	Pdoc York	nu CCQE xsection
ms	David Martinez		
doc	David Martinez	PDoc IIT	Ratio nu CCQE/CCInclusive
doc	Kenyi Hurtado	Pdoc Notre Dame	nu CCQE double differential xsec
ms	Cesar Sotelo		
doc	**Mateus Carneiro**		**ME nu CCQE 1 and 2 track xsec**
Pdoc	Cesar Castromonte	Prof Goiania	
PDoc	Thiago Muhlbeier		
Pdoc	Harold Yepes		
Pdoc	**Anushree Ghosh**		

PUCP, Lima, Peru

Prof	Alberto Gago	
ms	Leo Aliaga	
doc	**Leo Aliaga**	**(W&M)**
ms	Jose (Pepe) Bazo	doc DESY
ms	Carlos Perez	doc Utrect
ms	Carmen Araujo	teaching Uni Cusco
ms	Noemi Ochoa	doc Uppsala (iceCube)
ms	J.P. Velasquez	will apply for doc
ms	Gonzalo Diaz	
doc	Gonzalo Diaz	Rochester Univ.
doc	Carmen Araujo	returning to PUCP for doc
ms	M. Jose Bustamente	

UNI, Lima, peru

Prof	Javier Solano	
ms	Marcos Alania	
ms	Carlos Romero	
ms	Adolfo Chamorro	
ms	Kenyi Hurtado	doc at CBPF
ms	Antonio Zegarra	
ms	Gerald Salazar	

Guanajuato, Mexico

Prof	Julian Felix	
Prof	Gerardo Guzman	
Prof	Victor Castillo (Guadalajra)	
Prof	Zaida Urrutia (Guatemala)	
ms	Jorge Castorena	
ms	Aaron Higuera	
doc	**Aaron Higuera**	**Pdoc Houston**
ms	Alfonso Balcazar	
ms	Julio Capetillo	
ms	Zaidy Urrutia	
doc	Zaidy Urrutia	return to Fermilab
ms	Edgar Valencia	
doc	**Edgar Valencia**	
ms	**Guadalupe Barrios (Guatemala)**	

USM , Valparaiso, Chile

Prof	Will Brooks	
Prof	Jon Miller	
ms	Cristian Peña	doc Caltech
ms	Giuliano Maggi	doc VUB (IceCube)
doc	Roger Galindo	
Pdoc	Nur Nuruzzaman	

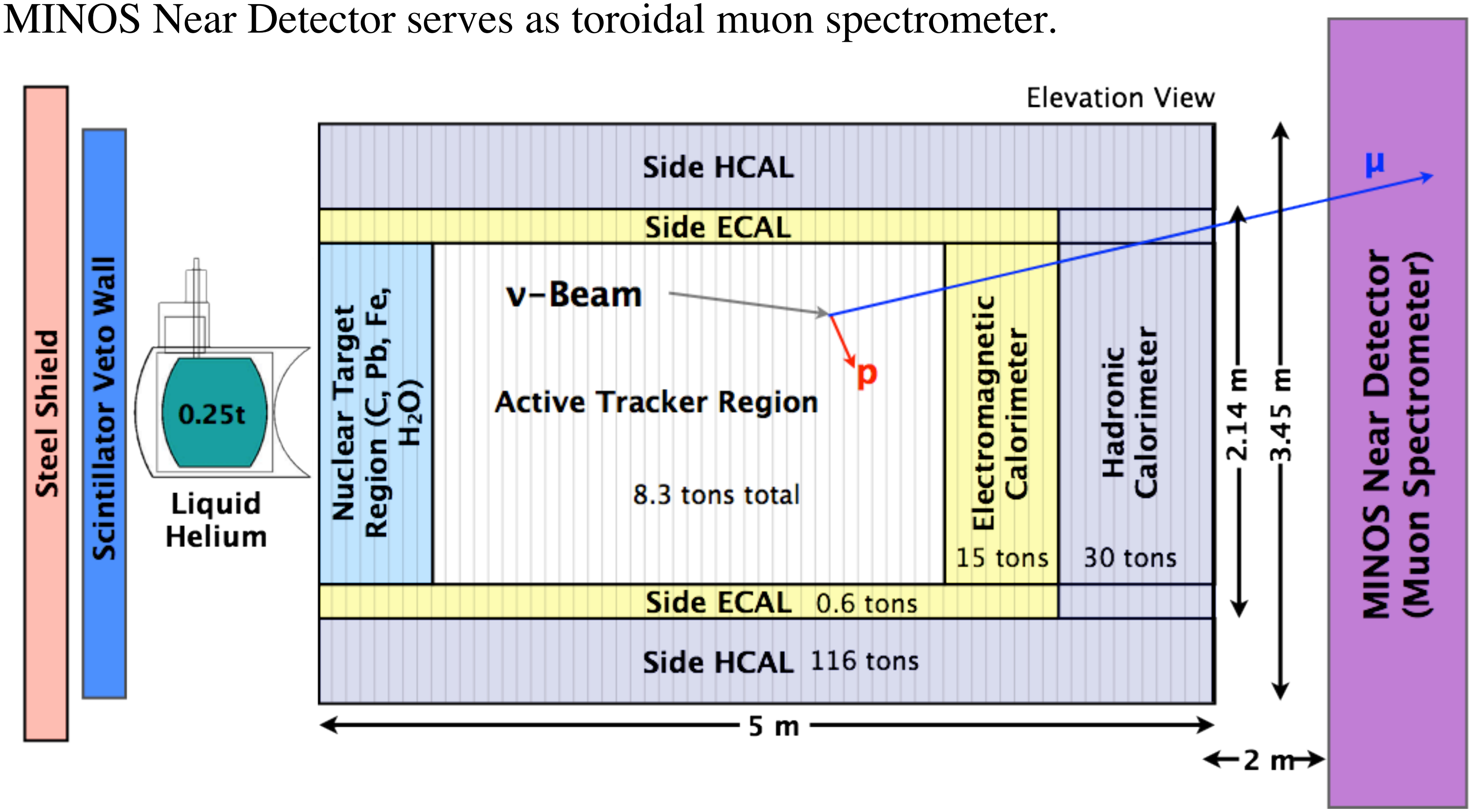
Brazilian Students on MINERνA
4 MS and 5 PhD students

CBPF, Rio de Janeiro, Brasil
Professor Helio da Motta

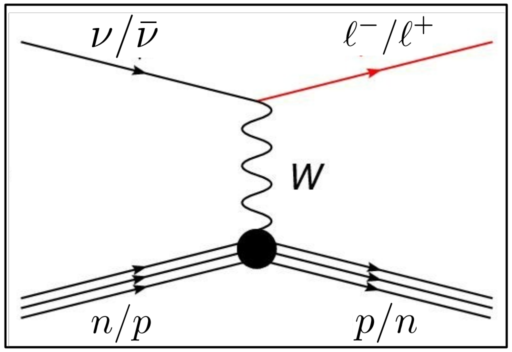
MS	Jose Palomino		
PhD	**Jose Palomino**	**PostDoc SUNY**	**nu pi0 production**
MS	Arturo Fiorentini		
PhD	**Arturo Fiorentini**	**PostDoc York**	**nu CCQE xsection**
MS	David Martinez		
PhD	David Martinez	**PostDoc** IIT	Ratio nu CCQE/CCInclusive
PhD	Kenyi Hurtado	Pdoc Notre Dame	nu CCQE double differential xsec
MS	Cesar Sotelo		
PhD	**Mateus Carneiro**		**ME nu CCQE 1 and 2 track xsec**
Pdoc	Cesar Castromonte	Staff Goiania	
PDoc	Thiago Muhlbeier		
Pdoc	Harold Yepes		
Pdoc	**Anushree Ghosh**		

MINERνA Detector

- 120 plastic scintillator modules for tracking and calorimetry (~32k readout channels).
- Construction completed Spring 2010. He and Water targets added in 2011.
- MINOS Near Detector serves as toroidal muon spectrometer.



Example Analysis Charged-current Quasi-elastic Scattering: **Led by CBPF Student!**



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

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

$$\frac{d\sigma}{dQ^2} = \frac{M^2 G_F^2 cos^2\theta_C}{8\pi E_\nu^2} \times [A(Q^2) \mp \frac{(s-u)B(Q^2)}{M^2} + \frac{C(Q^2)(s-u)^2}{M^2}]$$

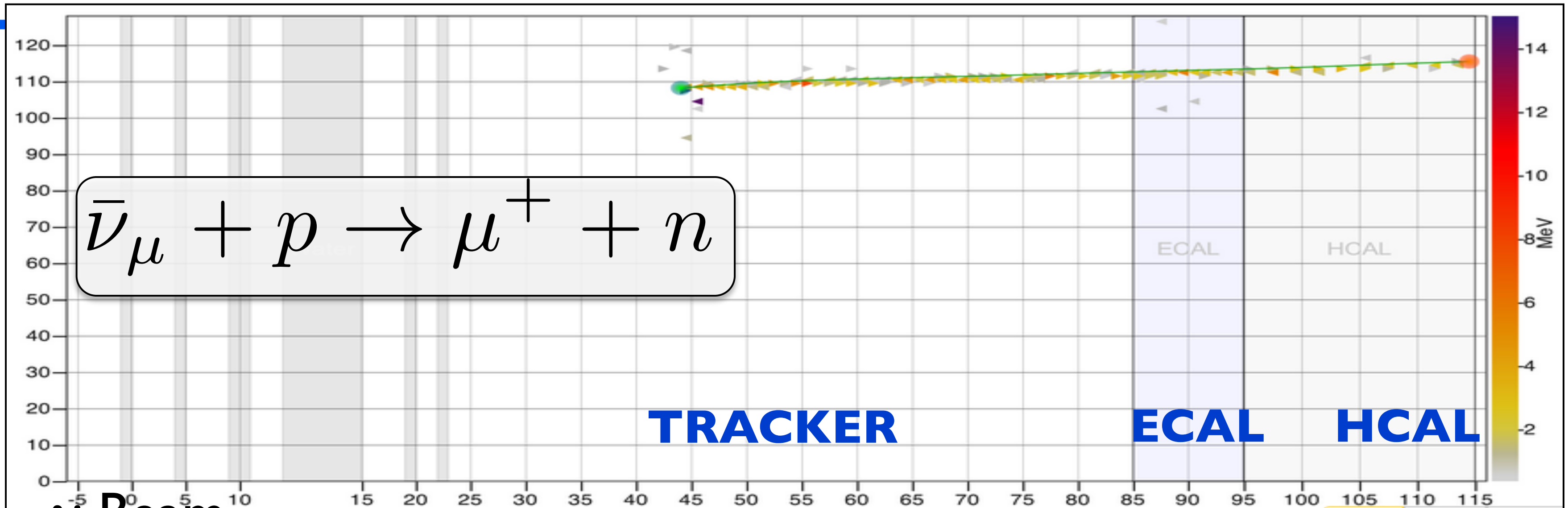
$$A(Q^2) = \frac{m_l^2 + Q^2}{M^2}[(1+\tau)|F_A|^2 - (1-\tau)|F_1^V|^2 + \tau(1-\tau)|F_2^V|^2 + 4\tau F_1^V F_2^V] - \frac{m_l^2 + Q^2}{M^2}\frac{m_l^2}{M^2}[|F_1^V + F_2^V|^2 + |F_A + 2F_P|^2 - 4(1+\tau)F_P^2]$$

$$B(Q^2) = 4\tau F_A(F1^V + F_2^V) \qquad C(Q^2) = \frac{1}{4}(|F_A|^2 + |F_1^V|^2 + \tau|F_2^V|^2)$$

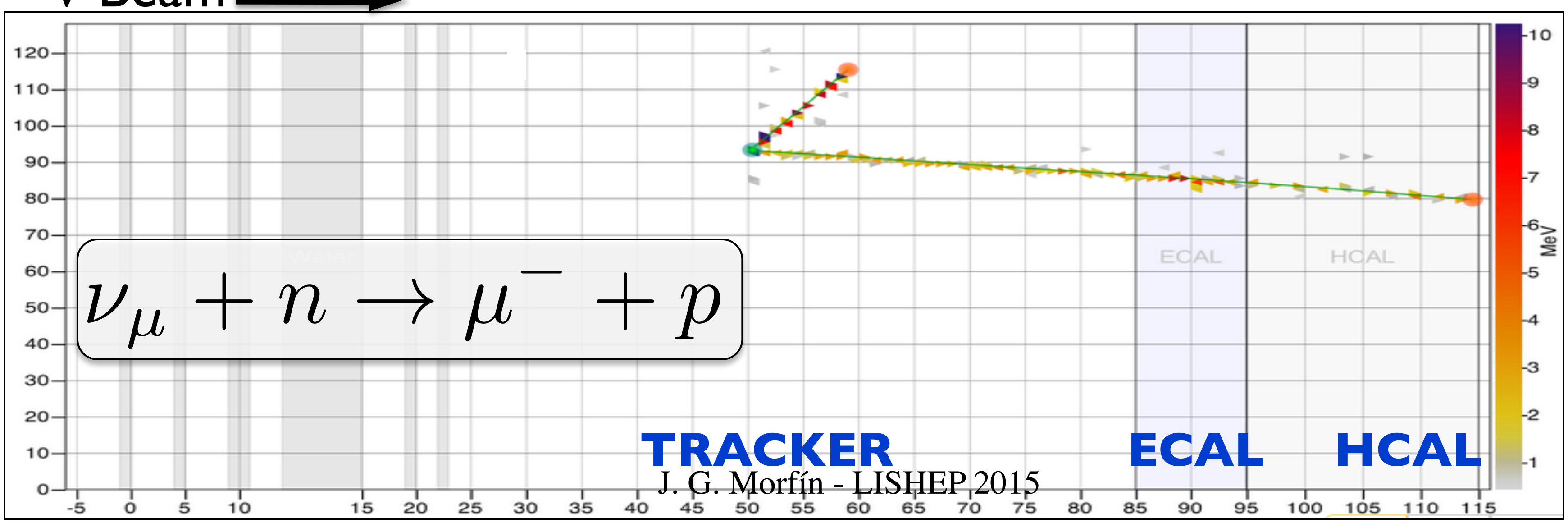
Llewellyn Smith, C.H., 1972, Phys. Rep. C3, 261.

$$F_A(Q^2) = \frac{F_A(0)}{(1 + \frac{Q^2}{M_A^2})^2}$$

Charged-current Quasi-elastic Scattering



ν Beam



MINERνA Charged-current Quasi-elastic Scattering:
Led by CBPF, Rio de Janeiro Student!

Measurement of Muon Neutrino Quasi-Elastic Scattering on a Hydrocarbon Target at $E_\nu \sim 3.5$ GeV

G.A. Fiorentini,[1] D.W. Schmitz,[2,3] P.A. Rodrigues,[4] L. Aliaga,[5,6] O. Altinok,[7] B. Baldin,[3] A. Baumbaugh,[3] A. Bodek,[4] D. Boehnlein,[3] S. Boyd,[8] R. Bradford,[4] W.K. Brooks,[9] H. Budd,[4] A. Butkevich,[10] D.A. Martinez Caicedo,[1,3] C.M. Castromonte,[1] M.E. Christy,[11] H. Chung,[4] J. Chvojka,[4] M. Clark,[4] H. da Motta,[1] D.S. Damiani,[5] I. Danko,[8] M. Datta,[11] M. Day,[4] R. DeMaat,[3,*] J. Devan,[5] E. Draeger,[12] S.A. Dytman,[8] G.A. Díaz,[6] B. Eberly,[8] D.A. Edmondson,[5] J. Felix,[13] L. Fields,[14] T. Fitzpatrick,[3,*] A.M. Gago,[6] H. Gallagher,[7] C.A. George,[8] J.A. Gielata,[4] C. Gingu,[3] B. Gobbi,[14,*] R. Gran,[12] N. Grossman,[3] J. Hanson,[4] D.A. Harris,[3] J. Heaton,[12] A. Higuera,[13] I.J. Howley,[5] K. Hurtado,[1,15] M. Jerkins,[16] T. Kafka,[7] J. Kaisen,[4] M.O. Kanter,[5] C.E. Keppel,[11,†] J. Kilmer,[3] M. Kordosky,[5] A.H. Krajeski,[5] S.A. Kulagin,[10] T. Le,[17] H. Lee,[4] A.G. Leister,[5] G. Locke,[17] G. Maggi,[9,‡] E. Maher,[18] S. Manly,[4] W.A. Mann,[7] C.M. Marshall,[4] K.S. McFarland,[4,3] C.L. McGivern,[8] A.M. McGowan,[4] A. Mislivec,[4] J.G. Morfín,[3] J. Mousseau,[19] D. Naples,[8] J.K. Nelson,[5] G. Niculescu,[20] I. Niculescu,[20] N. Ochoa,[6] C.D. O'Connor,[5] J. Olsen,[3] B. Osmanov,[19] J. Osta,[3] J.L. Palomino,[1] V. Paolone,[8] J. Park,[4] C.E. Patrick,[14] G.N. Perdue,[4] C. Peña,[9] L. Rakotondravohitra,[3,§] R.D. Ransome,[17] H. Ray,[19] L. Ren,[8] C. Rude,[12] K.E. Sassin,[5] H. Schellman,[14] R.M. Schneider,[5] E.C. Schulte,[17,¶] C. Simon,[21] F.D. Snider,[3] M.C. Snyder,[5] J.T. Sobczyk,[22,3] C.J. Solano Salinas,[15] N. Tagg,[23] W. Tan,[11] B.G. Tice,[17] G. Tzanakos,[24,*] J.P. Velásquez,[6] J. Walding,[5,**] T. Walton,[11] J. Wolcott,[4] B.A. Wolthuis,[5] N. Woodward,[12] G. Zavala,[13] H.B. Zeng,[4] D. Zhang,[5] L.Y. Zhu,[11] and B.P. Ziemer[21]

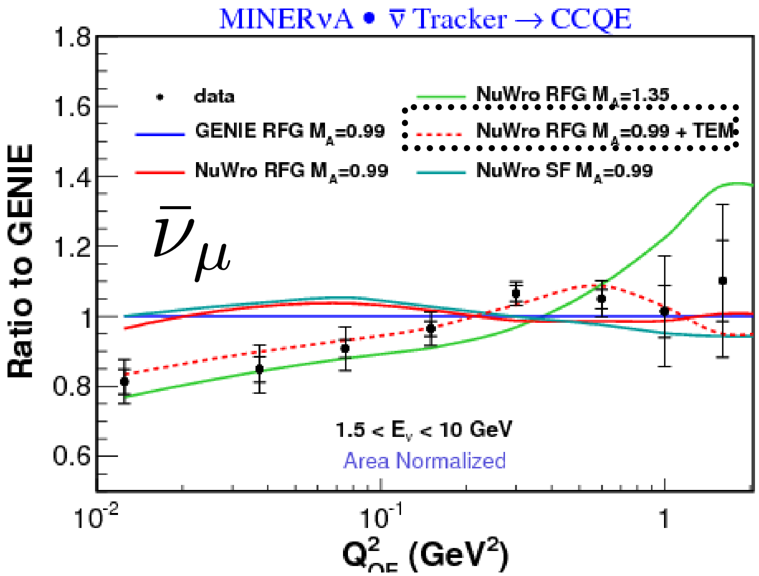
(The MINERvA Collaboration)

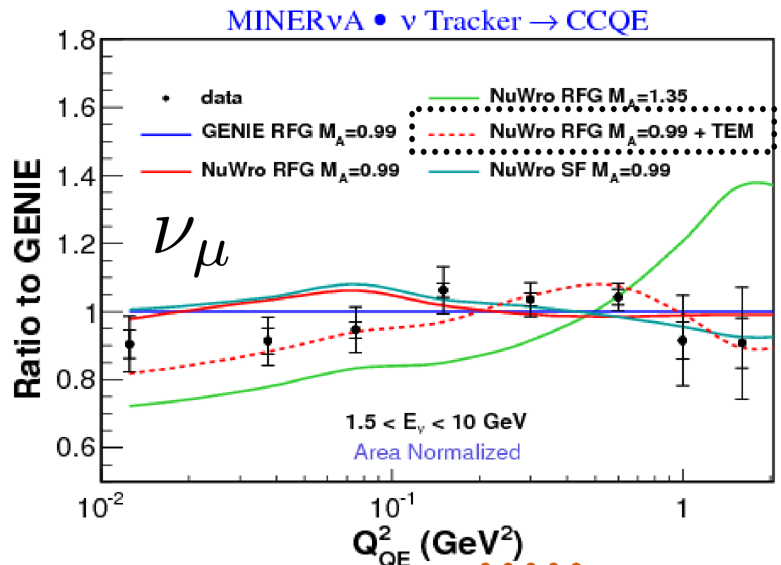
[1] *Centro Brasileiro de Pesquisas Físicas, Rua Dr. Xavier Sigaud 150, Urca, Rio de Janeiro, RJ, 22290-180, Brazil*
[2] *Enrico Fermi Institute, University of Chicago, Chicago, IL 60637 USA*
[3] *Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*

MINERvA: Single Muon QE-like Analysis

Emphasis on the Shape

- Using leptonic information only, the results favor the RFG with $M_A = 0.99$ + a Transverse Enhancement Model for NN correlations (vector current only contributions!!)





NuWro Model	RFG	RFG +TEM	RFG	SF
M_A (GeV)	0.99	0.99	1.35	0.99
Rate χ^2/d.o.f.	2.64	1.06	2.90	2.14
Shape χ^2/d.o.f.	2.90	0.66	1.73	2.99

NuWro Model	RFG	RFG +TEM	RFG	SF
M_A (GeV/c^2)	0.99	0.99	1.35	0.99
Rate χ^2/d.o.f.	3.5	2.4	3.7	2.8
Shape χ^2/d.o.f.	4.1	1.7	2.1	3.8

Conclusions of the MINERνA QE Scattering Study

- CCQE $d\sigma/dQ^2$ shape distributions disfavor a simple RFG modeling of the carbon nucleus for scattering at these energies, strengthening the call for improved modeling in (anti)neutrino scattering
- The data most prefer a model derived from an observed enhancement of the transverse part of the cross-section in electron scattering attributed to meson exchange currents, a form of long-range multi-nucleon correlation
- **NO SINGLE NUCLEAR MODEL FITS MINIBOONE and MINERVA SINGLE μ CCQE DATA.**

MINERνA: ν Charged-current Single π^0 Production:
Led by CBPF, Rio de Janeiro Student!

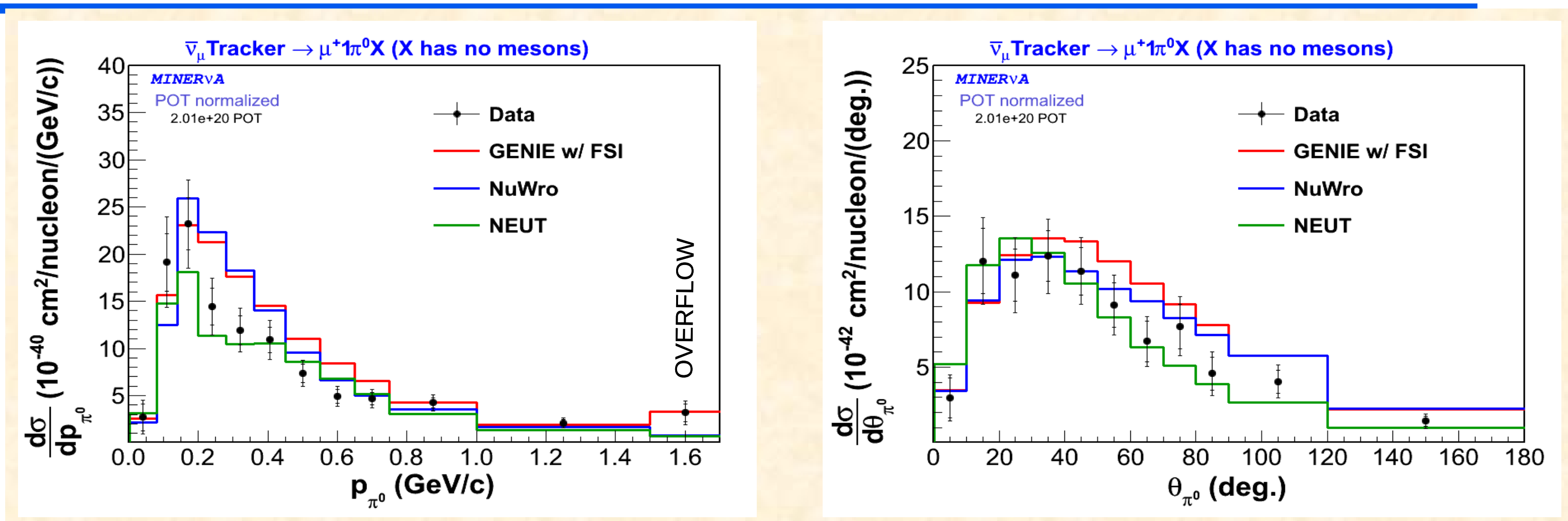
Single neutral pion production by charged-current $\bar{\nu}_\mu$ interactions on hydrocarbon at $\langle E_\nu \rangle = 3.6$ GeV

T. Le[a,*], J.L. Palomino[b], L. Aliaga[c,k], O. Altinok[d], A. Bercellie[e], A. Bodek[e], A. Bravar[f], W.K. Brooks[g], A. Butkevich[h], D.A. Martinez Caicedo[b,o], M.F.Carneiro[b], M.E. Christy[i], J. Chvojka[e], H. da Motta[b], J. Devan[c], S.A. Dytman[j], G.A. Díaz[k], B. Eberly[j], J. Felix[l], L. Fields[m], R. Fine[e], A.M. Gago[k], H. Gallagher[d], R. Gran[n], D.A. Harris[o], A. Higuera[e,l], K. Hurtado[b,s], M. Kordosky[c], E. Maher[p], S. Manly[e], W.A. Mann[d], C.M. Marshall[e], K.S. McFarland[e,o], C.L. McGivern[j], A.M. McGowan[e], J. Miller[g], J.G. Morfín[o], J. Mousseau[q], J.K. Nelson[c], A. Norrick[c], J. Osta[o], V. Paolone[j], J. Park[e], C.E. Patrick[m], G.N. Perdue[o,e], L. Rakotondravohitra[o,2], R.D. Ransome[a], H. Ray[q], L. Ren[j], P.A. Rodrigues[e], D. Ruterbories[e], H. Schellman[m], D.W. Schmitz[r,o], J.T. Sobczyk[o,3], C.J. Solano Salinas[s], N. Tagg[t], B.G. Tice[a,4], E. Valencia[l], T. Walton[i], J. Wolcott[e], H. Yepes-Ramirez[b], G. Zavala[l], D. Zhang[c], B.P.Ziemer[u]

[a]*Rutgers, The State University of New Jersey, Piscataway, New Jersey 08854, USA*

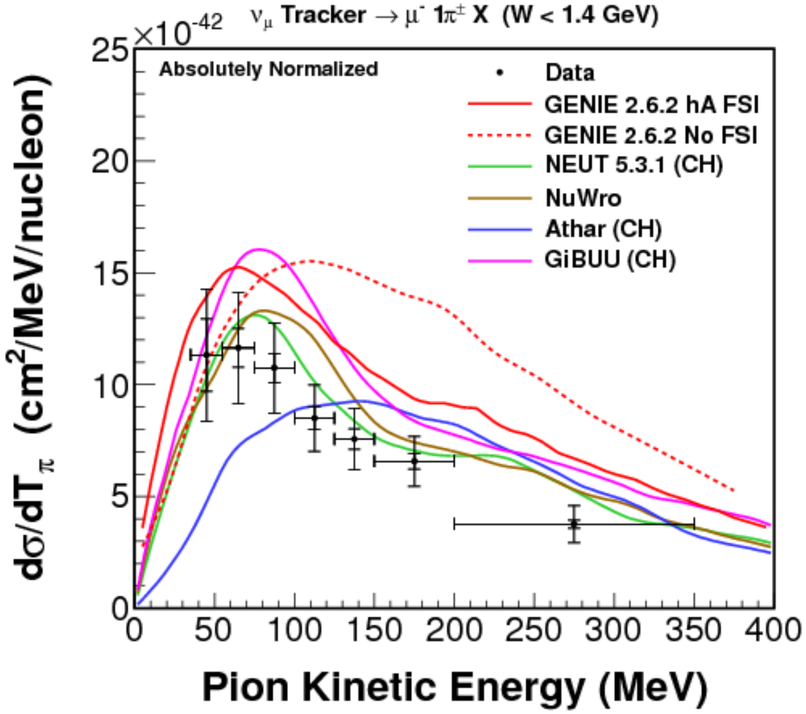
[b]*Centro Brasileiro de Pesquisas Físicas, Rua Dr. Xavier Sigaud 150, Urca, Rio de Janeiro, RJ, 22290-180, Brazil*

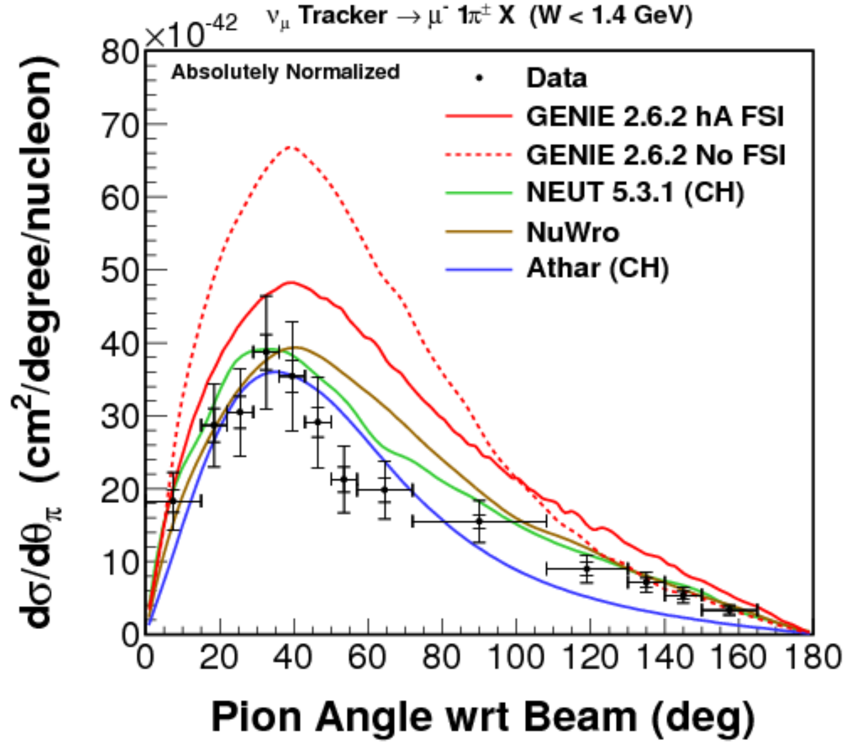
Results



- First measurement of the differential cross sections vs π^0 kinematics for this pion production channel.
- Data are in better agreement when final state interactions are included.
- **No single model describes the various results of these measurements**

More details: charged pion (W < 1.4 GeV) absolute cross section – model comparisons





- **NEUT and NuWro normalization agree the best with data.**
- **GiBUU, GENIE normalizations disfavored by a couple σ**
- **GENIE (with FSI), NEUT, and NuWro predict the data shape well**
- **Except for Athar, data is unable to distinguish different FSI models**

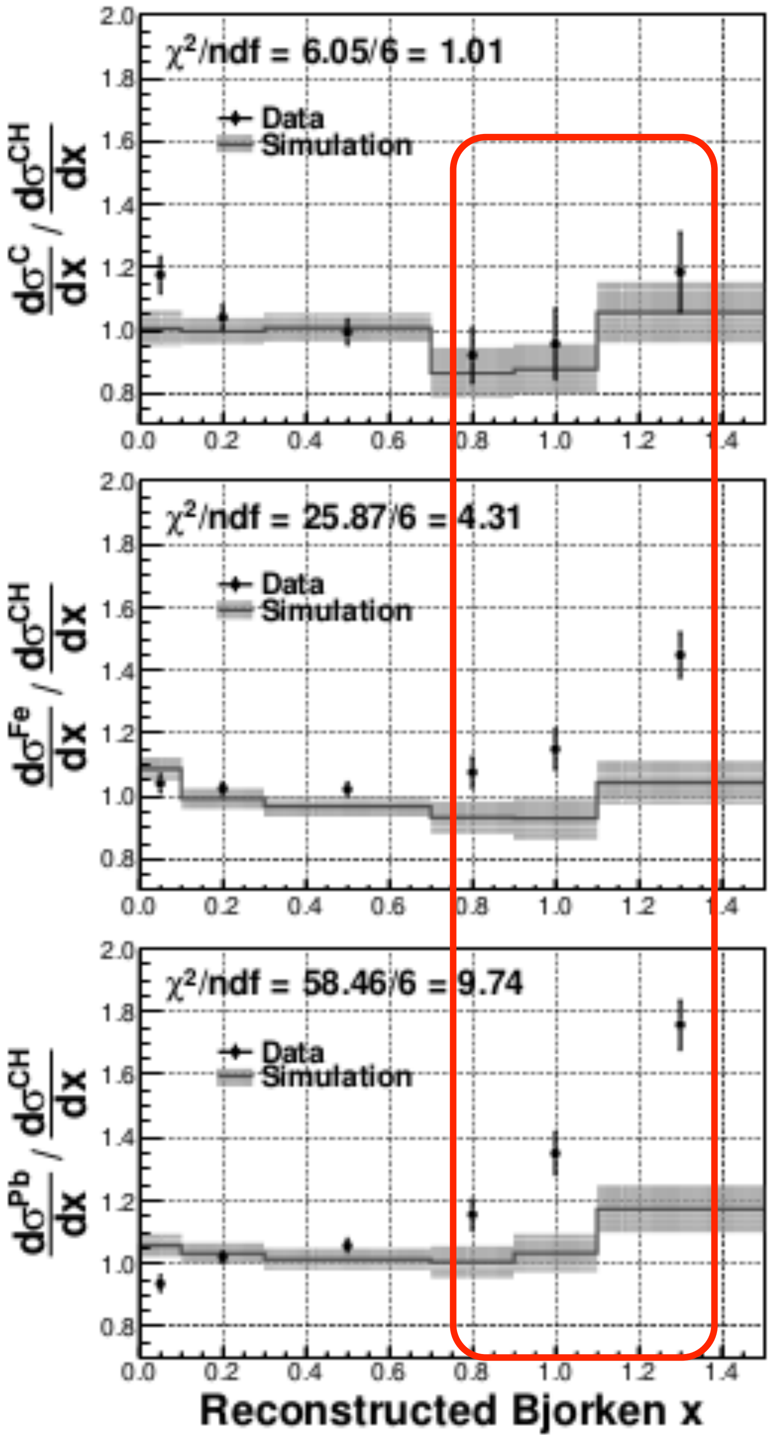
- **No single model describes the various results of these measurements!!**

INCLUSIVE RATIOS

MINERvA nuclear targets:
C (166 Kg), Fe (653 kg) and Pb (750 Kg)

- At x = [0.7,1.1], we observe an **excess** that grows with the size of the nucleus
- This effect is not modeled in the GENIE simulation.
- **Problems modeling A-dependence of CCQE – dominant in osc. expts!!**

x_{bj}	QE	DIS	OTHER
0.0 – 0.1	11.3%	5.9%	77.4%
0.1 – 0.3	13.6%	16.7%	68.5%
0.3 – 0.7	32.7%	11.8%	55.3%
0.7 – 0.9	55.1%	4.3%	40.5%
0.9 – 1.1	62.7%	2.8%	34.4%
1.1 – 1.5	69.9%	1.9%	28.4%
> 1.5	79.1%	0.6%	20.2%



In Summary: Nuclear Physics Meets Neutrino Physics

No single nuclear model comes close to fitting all of the accumulated experimental scattering data.

However, it is not a knockout – we need collaboration with the nuclear physics community and additional measurements.

NuSTEC

A Collaboration of HEP and Nuclear Experimentalists and Theorists Studying Low-energy Neutrino Nucleus Scattering **Physics**

GOALS:

- **Coordinate NP (theorist) - HEP experimentalist collaborative efforts:**
  - Coordinate theorist-experimentalist collaborative efforts to improve generators
  - Improve general understanding of the physics via enhanced theoretical background for experimentalists and ensuring theorists have the latest experimental data and correctly incorporated errors to test models.
- **Workshops:** Organize Community-wide Workshops when needed
  - Main Conference: The NuInt Neutrino Interaction Workshop (next, November 2015)
  - Organization beginning on workshop to investigate np-nh/MEC nuclear effects
- **Training Programs**: Organize and run training programs in:
  - Neutrino Scattering Event Generators: University of Liverpool, 14 – 16 May
  - Theory-oriented Neutrino-nucleus Scattering physics ocurred at Fermilab in October.
- **Global Fits**: Combine results from multiple experiments to compare with and then, if necessary, modify a theory/model framework.
- **First meeting of the NuSTEC Board in September**: Representatives of each ν-A experiment, each nuclear theory "school" and each ν event generator

CAPTAIN-MINERνA Experiment

(Measuring ν Ar Interactions) - Literally Dozens of Theses available!

- DUNE will measure neutrino oscillations in a liquid argon TPC
- One of the main systematic uncertainties in neutrino oscillation measurements is uncertainty in the neutrino interaction model
- CAPTAIN-MINERνA Goals: (Anti) Neutrino-argon cross sections, event reconstruction, and particle identification in the energy range relevant for DUNE
  - Only proposal to make neutrino-argon measurements in this energy range before DUNE!

- **CAPTAIN-MINERνA would welcome Brazilian collaborators who want to become familiar with the LAr environment before DUNE and help reduce the eventual DUNE systematics.**

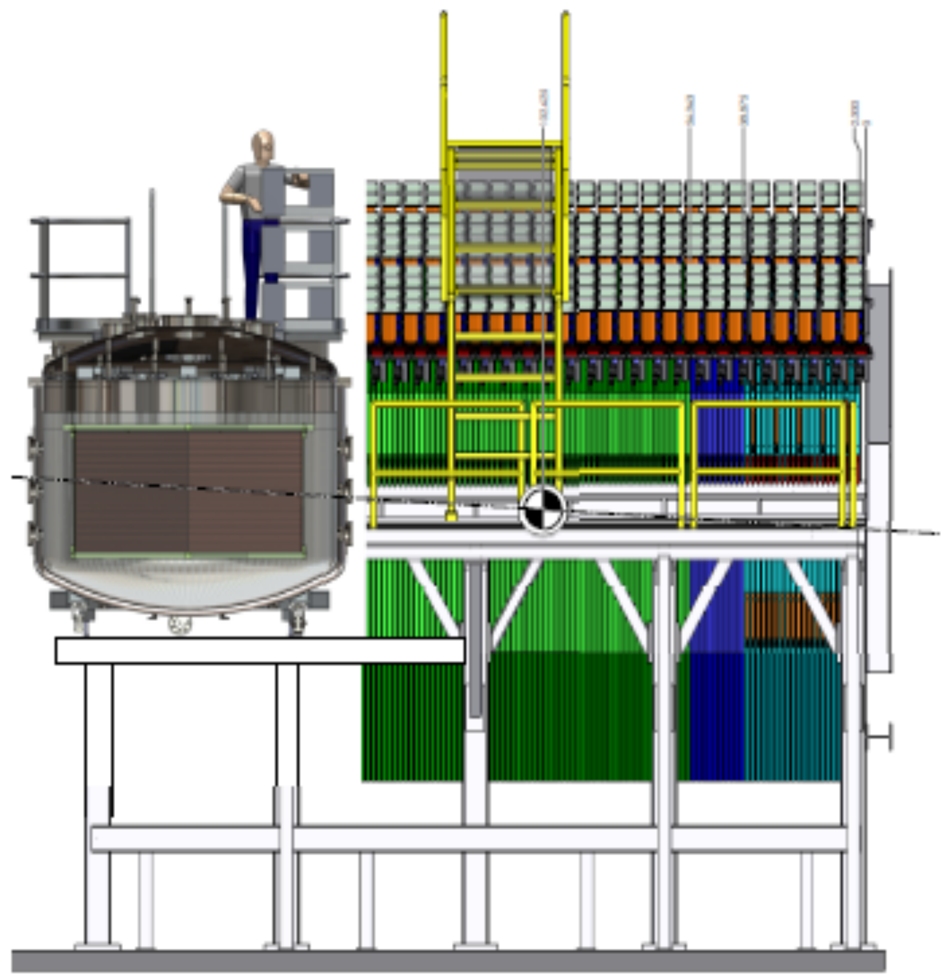
CAPTAIN-MINERνA Proposal

- We are proposing to install the CAPTAIN **LAr TPC** detector upstream of (or within) MINERνA to study neutrino-argon interactions in the medium-energy NuMI beam.
- CAPTAIN would serve as the vertex detector, and outgoing particles could be tracked in MINERνA.
- The MINERνA detector can also be used to measure ratios of interactions on argon to other nuclei (CH)
- The MINOS Near Detector would continue to be used as the downstream muon spectrometer.
- **We will study cross-sections, particle ID and event reconstruction important for DUNE**

CAPTAIN-MINERνA

Install CAPTAIN Upstream of MINERνA

- Liquid argon TPC detector:
  - Portable and evacuable cryostat
  - **5-ton instrumented liquid argon**
- TPC:
  - Hexagonal prism, vertical upward drift (E = 500 V/cm, v_d = 1.6 mm/μs)
  - 2001 channels (667/plane)
  - 3 mm pitch and wire spacing
- Laser calibration system
- Photon detection system
- MicroBooNE cold electronics
- Purification system design based on MicroBooNE and LAPD



CAPTAIN-MINERνA Physics

- Neutrino-argon data can be used to test the extrapolations of the models which are mostly based on other nuclear targets.
- **Importantly for DUNE, we want to minimize the need for extrapolations by having a large sample of neutrino-argon data to tune the models**
  - Can provide constraints that are independent from DUNE's near detector measurements (and in a different flux)

Event rates

$6\text{x}10^{20}$ POT Neutrino mode	Events w/ reco μ	Events w/ reco μ and charge
CCQE-like	916k	784k
$CC1\pi^{\pm}$	1953k	966k
$CC1\pi^{0}$	1553k	597k

These statistics are adequate for the physics goals; the downstream position would yield higher statistics.

Results presented here show only neutrino mode; we hope to run for 2 years and acquire $6\text{x}10^{20}$ POT in neutrino mode plus $6\text{x}10^{20}$ POT in antineutrino mode.

CAPTAIN-MINERνA: 128 Collaborators, 30 Institutions

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S. Fernandes, I. Stancu

Argonne National Laboratory
Z. Djurcic

Brookhaven National Laboratory
H. Chen, V. Radeka, C. Thorn

University of California, Davis
H. Berns, K. Bilton, D. Danielson, S. Gardiner, C. Grant, E. Pantic, R. Svoboda, N. Walsh

University of California, Irvine
C. Pitcher, M. Smy

University of California, LA
D. Cline, K. Hickerson, K. Lee, E. Martin, J. Shin, A. Teymourian, H. Wang

Centro Brasileiro de Pesquisas Físicas
M.F. Carneiro, H. da Motta, A. Ghosh

Fermilab
L. Bagby, M. Betancourt, L. Fields, D.A. Harris, J. Kilmer, M. Kiveni, J.G. Morfin, J. Osta, G.N. Perdue, L. Rakotondravohitra, E.L. Snider, J.T. Sobczyk

University of Florida
J. Mousseau, H. Ray, D. Rimal, M. Wospakrik

Universidad de Guanajuato
V.M. Castillo-Vallejo, J. Felix, M.A. Ramirez, E. Valencia, G. Zavala

Hampton University
M.E. Christy

University of Hawaii
J. Maricic, M. Rosen, Y. Sun

University of Houston
B. Bhandari, A. Higuera, L. Whitehead

Lawrence Berkeley National Laboratory
V. Gehman, C. Tull

Los Alamos National Laboratory
J. Danielson, S. Elliot, G. Garvey, E. Guardincerri, T. Haines, W. Ketchum, D. Lee, Q. Liu, W. Louis, C. Mauger, G. Mills, J. Mirabal-Martinez, J. Ramsey, K. Rielage, C. Sinnis, W. Sondheim, C. Sterbenz, C. Taylor, R. Van de Water, A. Yarritu

Louisiana State University
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E. Maher

Massachusetts Institute of Technology
L. Winslow

University of Minnesota
J. Bian, M. Marshak

University of Minnesota at Duluth
R. Gran

University of New Mexico
F. Giuliani, M. Gold

Oregon State University
H. Schellman

University of Pittsburgh
S. Dytman, C.L. McGivern, B. Messerly, D. Naples, V. Paolone, L. Ren

Pontificia Universidad Catolica del Peru
E. Endress, A.M. Gago, S.F. Sanchez, J.P. Velasquez

University of Rochester
A. Bercellie, A. Bodek, H. Budd, G.A. Diaz, R. Fine, T. Golan, J. Kleykamp, S. Manly, C.M. Marshall, K.S. McFarland, A.M. McGowan, A. Mislivec, P.A. Rodrigues, D. Ruterbories, J. Wolcott

Stony Brook University
C. McGrew

Tufts University
O. Altinok, H. Gallagher, W.A. Mann

Universidad Nacional de Ingenieria
G. Salazar, C.J. Solano Salinas, A. Zegarra

Universidad Tecnica Federico Santa Maria
W.K. Brooks, J. Miller

College of William and Mary
L. Aliaga, M. Kordosky, J.K. Nelson, A. Norrick, D. Zhang

CAPTAIN-MINERνA

- CAPTAIN-MINERvA would study neutrino-argon interactions in the medium-energy NuMI beam
  - Ideally 6×10^{20} POT in both neutrino and antineutrino mode
- The proposal is signed by members of both collaborations
- Unique and complementary to existing LAr R&D
- **We welcome additional Brazilian collaborators desiring to understand ν LAr interactions in advance of the DUNE experiment**

Further Coordinated Collaboration of NP-HEP Theory and Experiment

Nuclear Physics Meets Particle Physics

Theorists and Experimentalists

LATIN AMERICAN COLLABORATION IN FERMILAB NEUTRINO EXPERIMENTS

The MINERνA Model: Latin American collaboration at FNAL

- Students studying for their Masters Degree 27 students (so far)
  - Visiting Scientist Invitation
  - J-1 visa Trainee Program: On-site Mentor
  - 1-year residency at Fermilab working on experiment
  - As long as funding permits: Fermilab covers housing costs and adds to perDiem
- Students receiving or currently studying for their Doctorate 11 students
  - Visiting Scientist Invitation and Scholar Visa
  - Multi-year residency at Fermilab working on experiment
  - As long as funding permits: Fermilab covers housing costs and minimal add to perDiem
- Post Doctoral Associates 5
- Visiting Scientist and scholar visa
  - Multi-year residency at Fermilab working on experiment
  - As long as funding permits: Fermilab covers housing costs and minimal add to perDiem
- Professors
  - Multiple 2-4 week visits and one 1-year Sabbatical 25 visits 1 Sabbatical
  - As long as funding permits: Fermilab covers housing costs

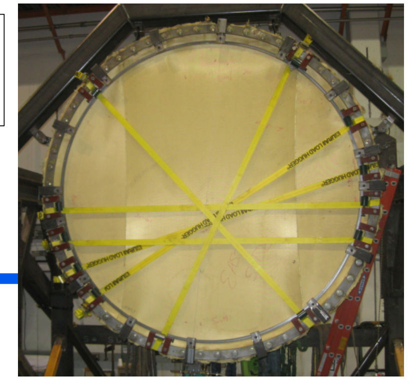
Conclusions

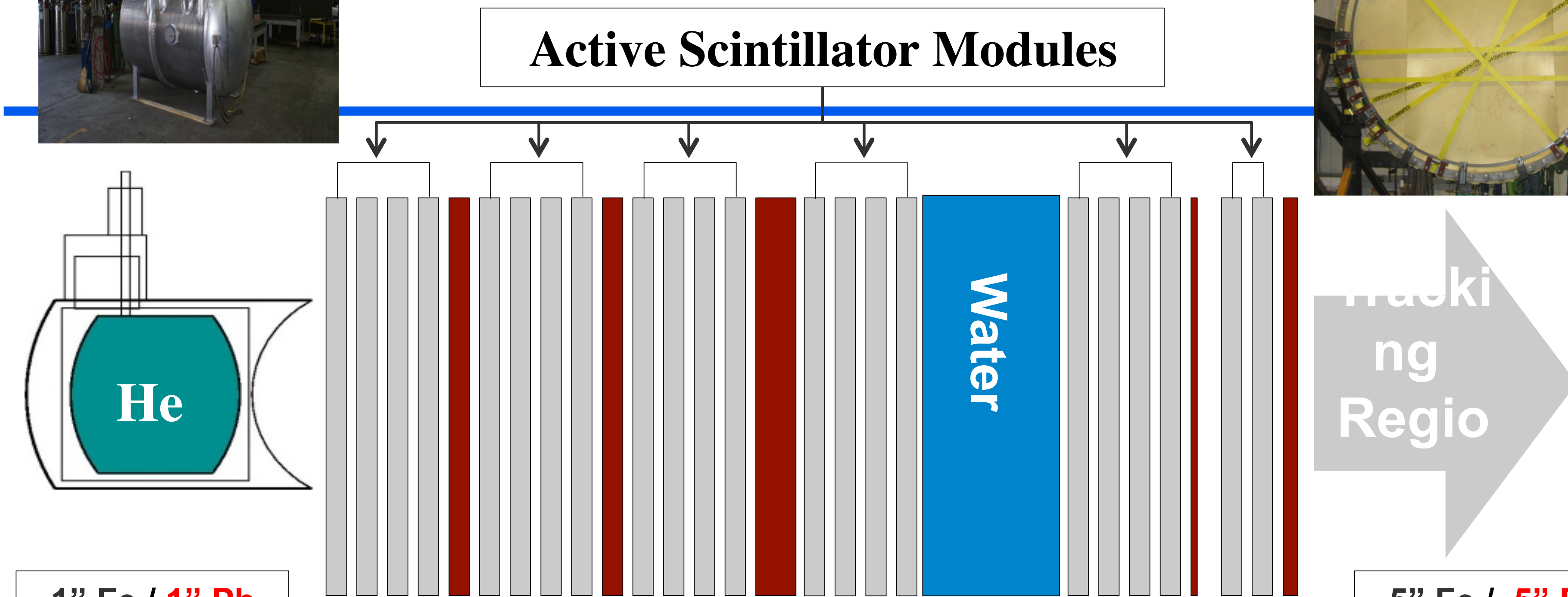
- **Fermilab offers current and near-future experimental approaches to studying the nature of the neutrino and how it interacts with matter.**
- **Current and near-future scattering experiments are welcoming new groups.**
- **Already a strong Latin American – Brazil, Chile, Mexico and Peru – presence in MINERνA.**
- **Both MINERνA and CAPTAIN-MINERνA would welcome (additional) collaborators from Brazil!**
- **There is at least one working model of how Brazilian physicists can collaborate at Fermilab in neutrino research.**

Backup Slides

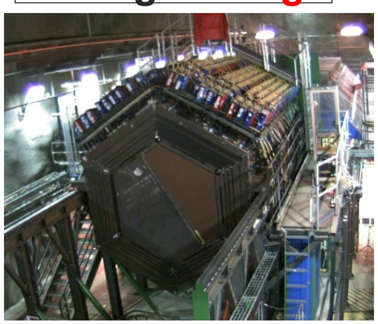
250 kg
Liquid He

452kg
Water



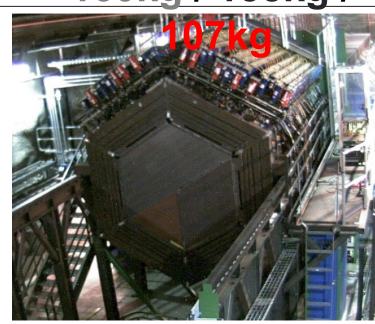


1” Fe / 1” Pb
322kg / 263kg

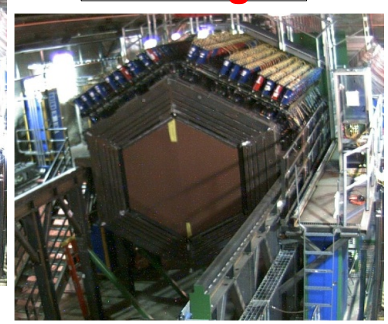


1” Pb / 1” Fe
263kg / 321kg

3” C / 1” Fe / 1” Pb
160kg / 158kg / 107kg

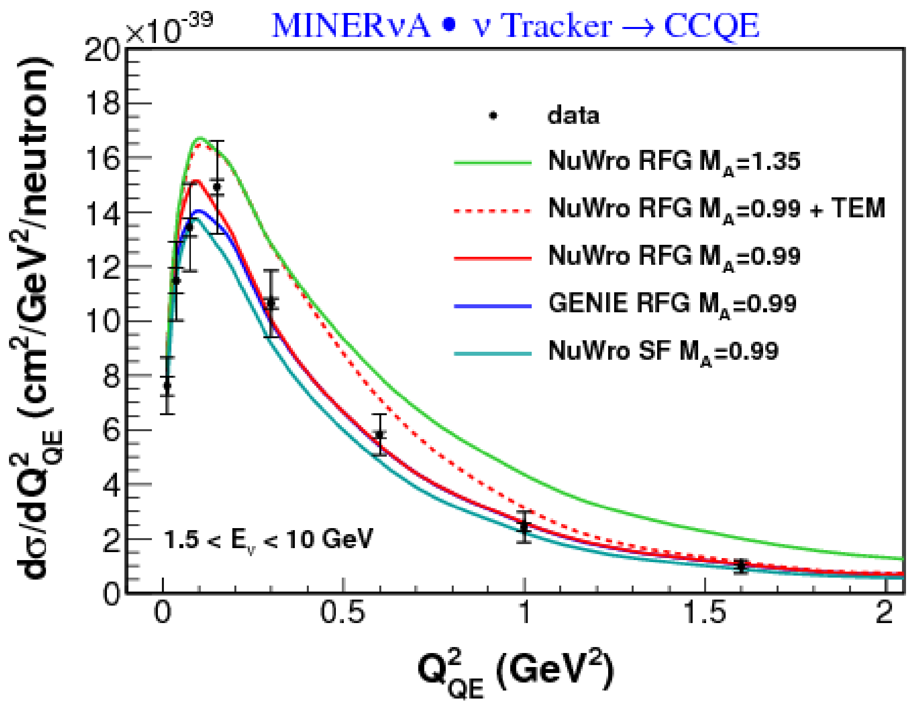


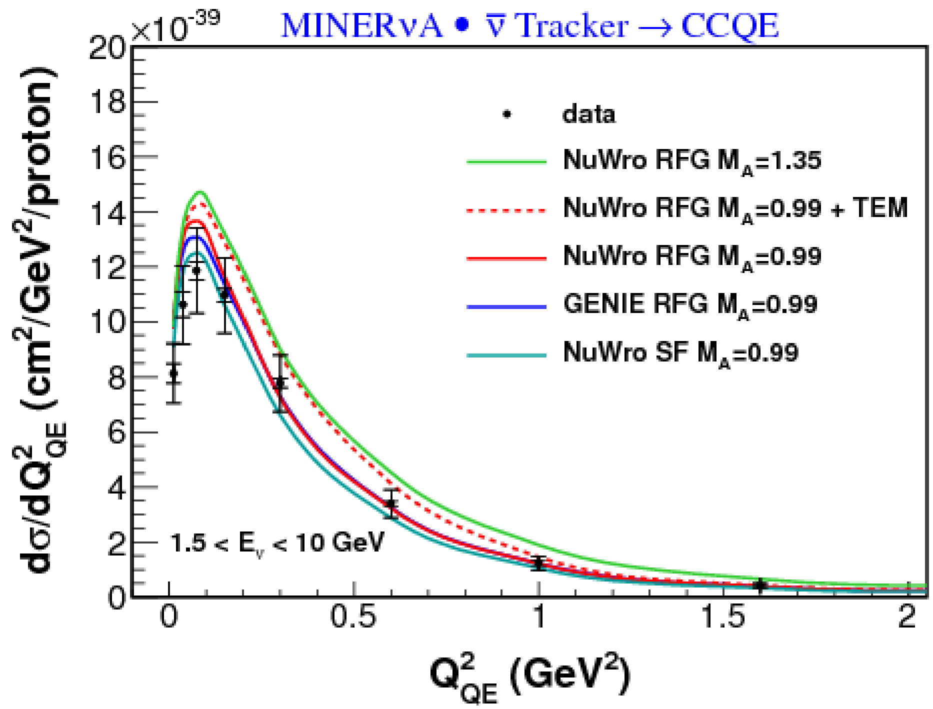
0.3” Pb
225kg



.5” Fe / .5” Pb
162kg/ 134kg

Absolute Cross Section - $\frac{d\sigma}{dQ^2_{QE}}$





$M_A = 1.35$ best fit to MiniBooNE data

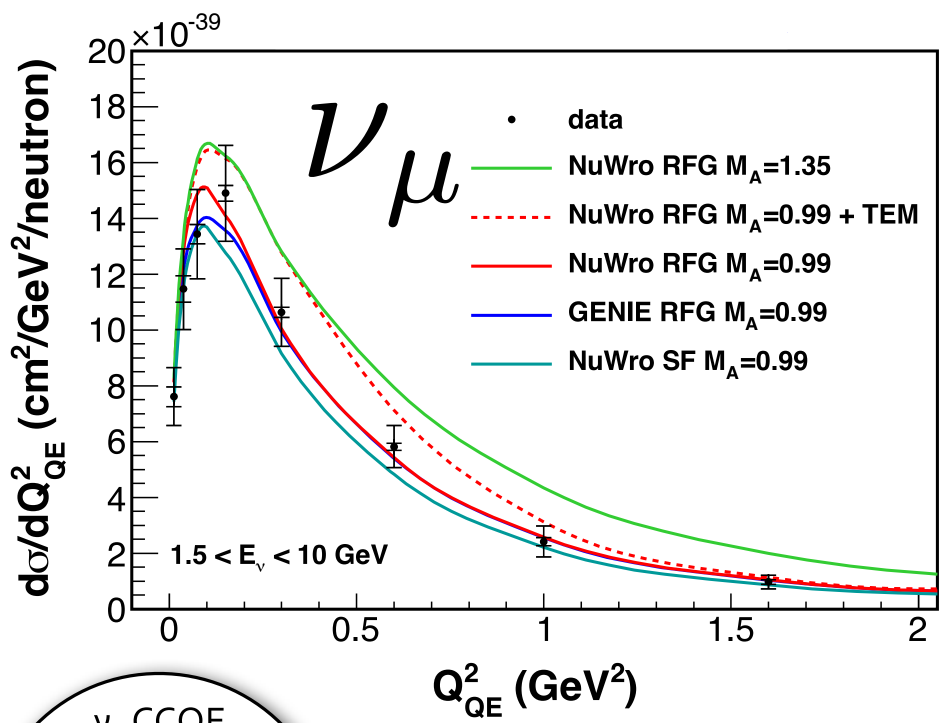
TEM empirical model based on electron scattering data

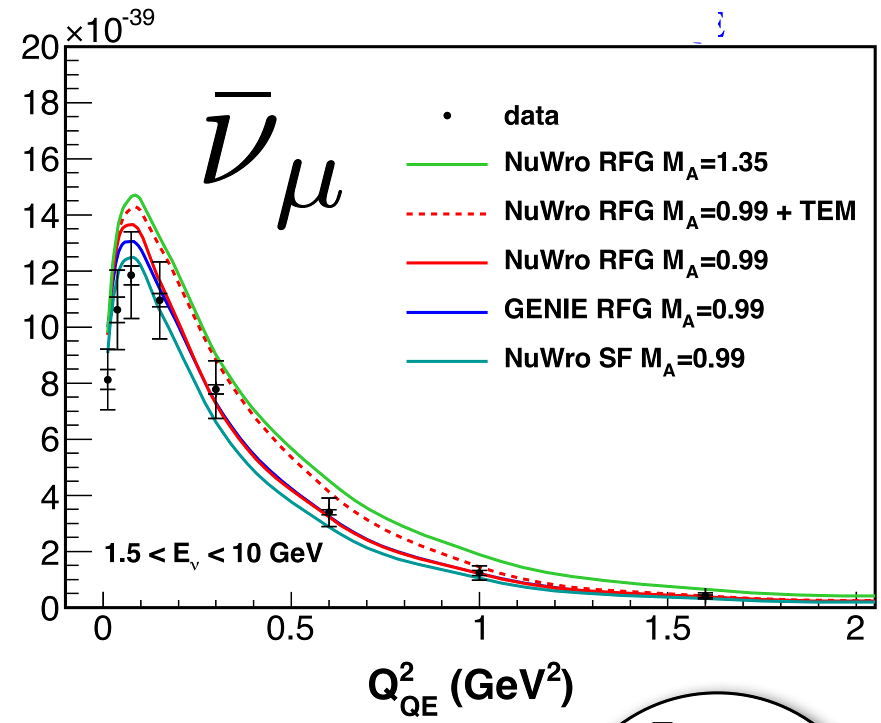
GENIE independent nucleons in mean field

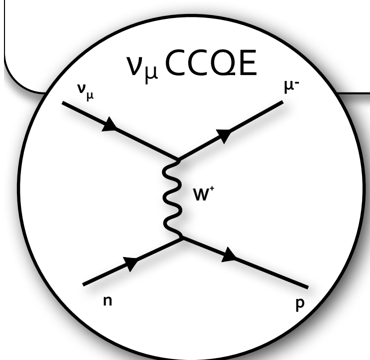
SF more realistic nucleon momentum-energy relation

MINERvA QE Scattering Results

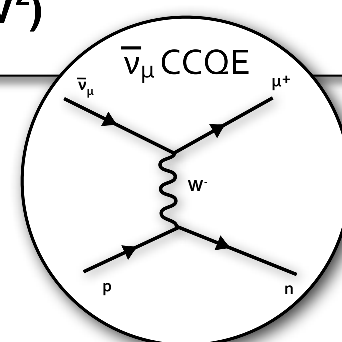
$$\frac{d\sigma}{dQ^2_{QE}}$$



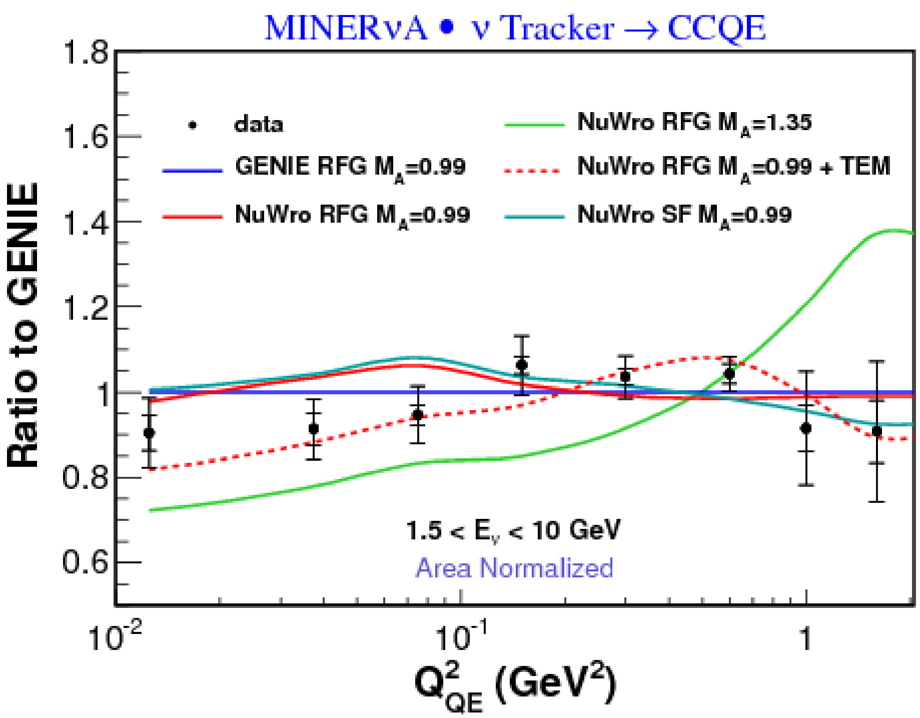


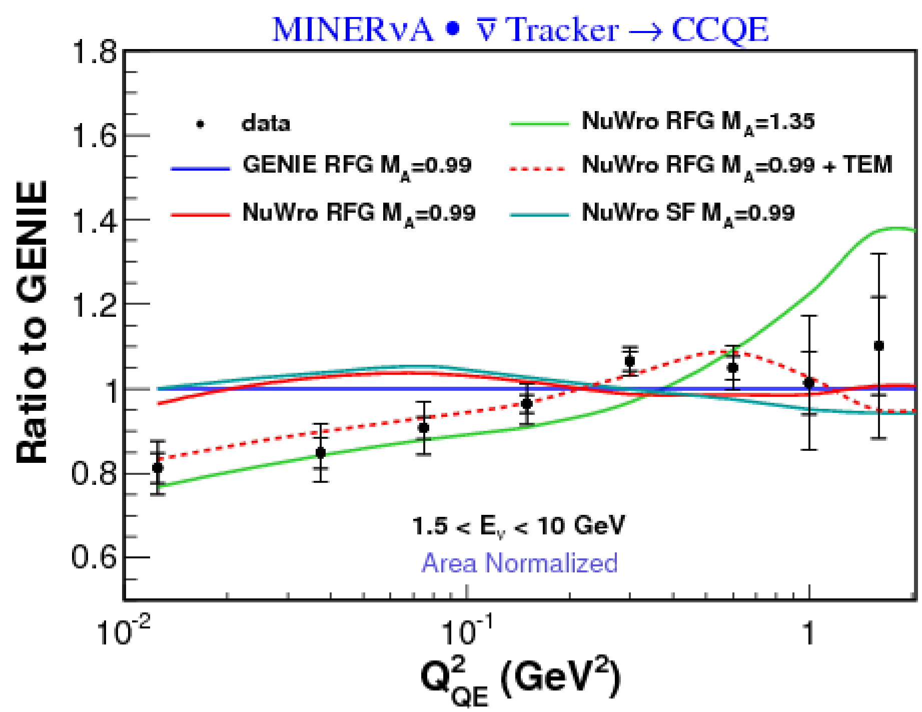


	Events	Efficiency	Purity
Neutrinos	29,620	47%	49%
Antineutrinos	16,467	54%	77%



Cross Section Shape - $\frac{d\sigma}{dQ^2_{QE}}$





$M_A = 1.35$ Phys.Rev.Lett. 100, 032301 (2008)

TEM Eur. Phys. J. C 71, 1726 (2011)

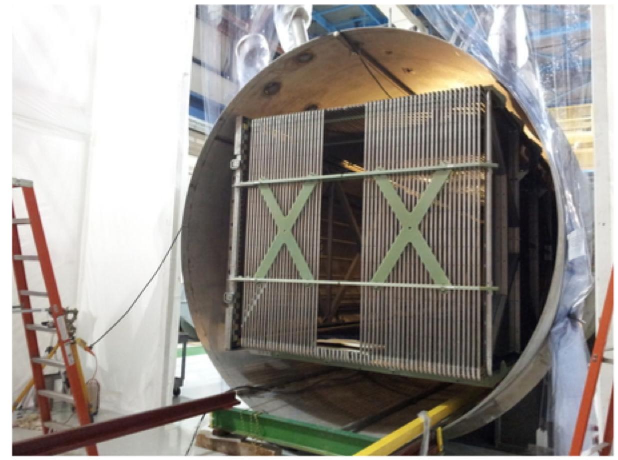
GENIE Nucl.Instrum.Meth. A 614:87-104 (2010)

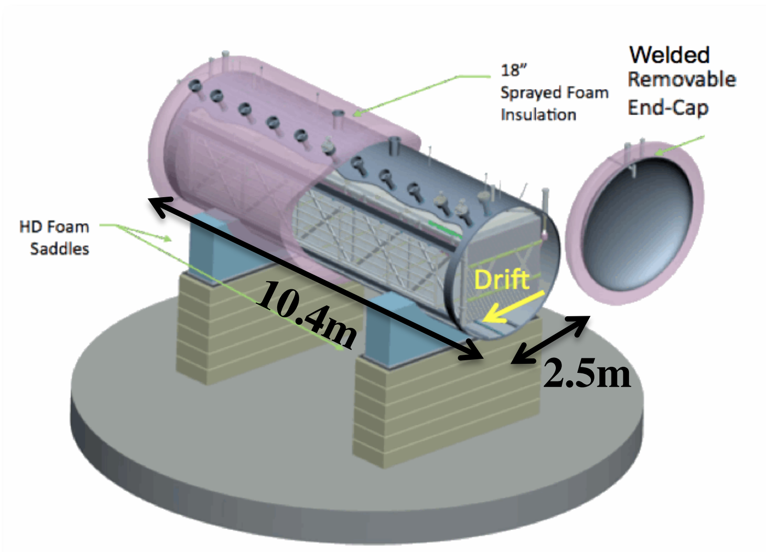
SF Nucl.Phys. A579, 493 (1994)

MicroBooNE (170 ton LAr TPC)

Will start taking data early 2014 - 116 collaborators from 20 institutions

TPC is size of a school bus

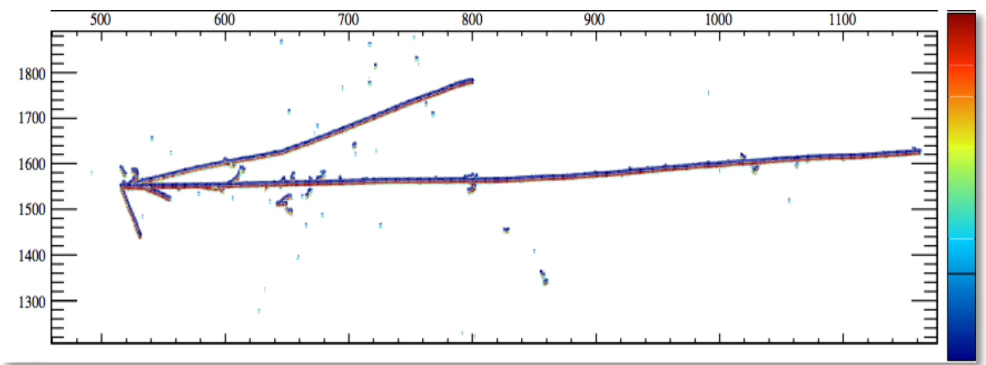




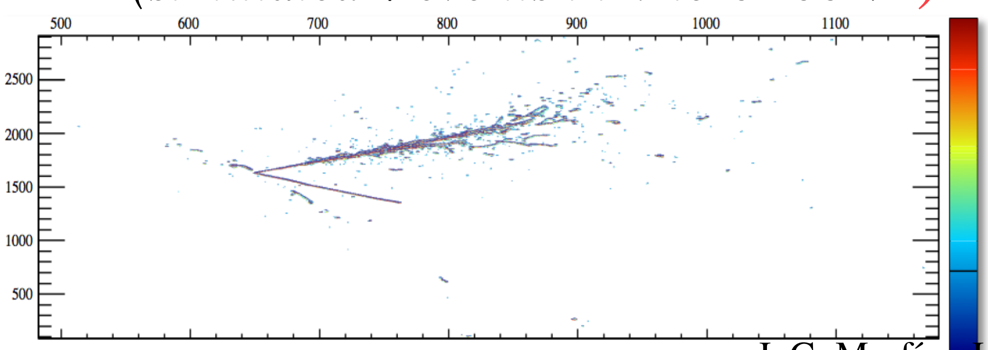
- **170 ton LAr TPC**
  - *same beam & location as MiniBooNE*
  - *new detector technology*
- **Goals:**
  - *investigate MiniBooNE low energy excess*
  - *measure neutrino interactions in argon*
  - *R&D for future LAr TPCs*

MicroBooNE: Cross Sections

- will more precisely examine final states produced in ν interactions by exploiting LAr TPC capabilities and building off of what we've learned in MiniBooNE*)* & ArgoNeuT*)*



(simulated ν events in MicroBooNE)



	BNB	NuMI
Total Events	145k	60k
ν_μ CCQE	68k	25k
NC π^0	8k	3k
ν_e CCQE	0.4k	1.2k
POT	6×10^{20}	8×10^{20}

Projected Event Rates for MicroBooNE in 2-3 years.

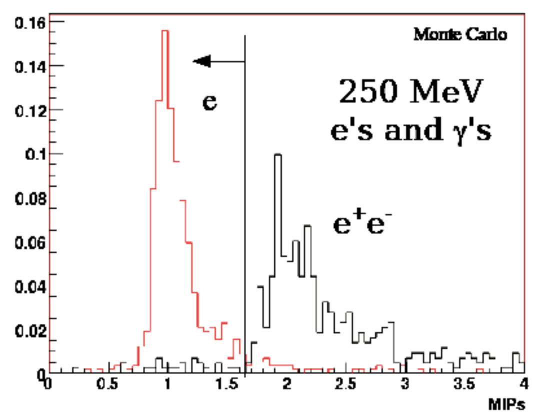
- MicroBooNE will make first σ_ν measurements in argon at low neutrino energies (~1 GeV)

- these analyses will benefit from well-known Booster neutrino flux

Aguilar-Arevalo et al., PRD 79, 072002 (2009)

MicroBooNE: Excellent e/γ separation

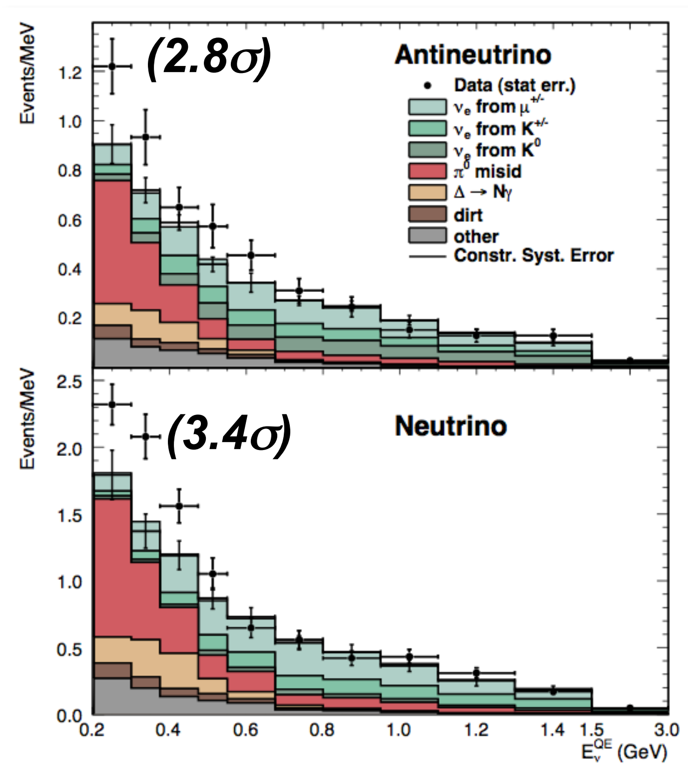
- LAr TPC images events and collects charge - do e/γ separation via dE/dx.
- Look at MIP deposition in first 2.4 cm of track before shower starts
  - GEANT4 MC: 90% electron efficiency with 6.5% gamma background
- e/γ separation removes single γ backgrounds



- Electron Neutrino efficiency 2x better than MiniBooNE
- Sensitivity down to 10's of MeV compared to MiniBoNE 200 MeV

Motivation: MiniBooNE Excess

- **MiniBooNE has published final results for entire ~10 year data set**
  (Aguilar-Arevalo et al., Phys. Rev, Lett. 110, 161801 (2013))



- **observe an excess of low energy events in both running modes**

- **source of the excess is unknown (MicroBooNE!)** < γ **(background)** / e⁻ (signal)

- **both outcomes are interesting**

MicroBooNE R&D

- **MicroBooNE detector is not a pure prototype for LBNE; however, it incorporates several major advances over the (larger, 1st generation) ICARUS detector, which are important "proofs of principle" for next generation large detectors:**

  - non-evacuated cryostat
  - cold (in liquid) electronics
  - 2.5 meter drift

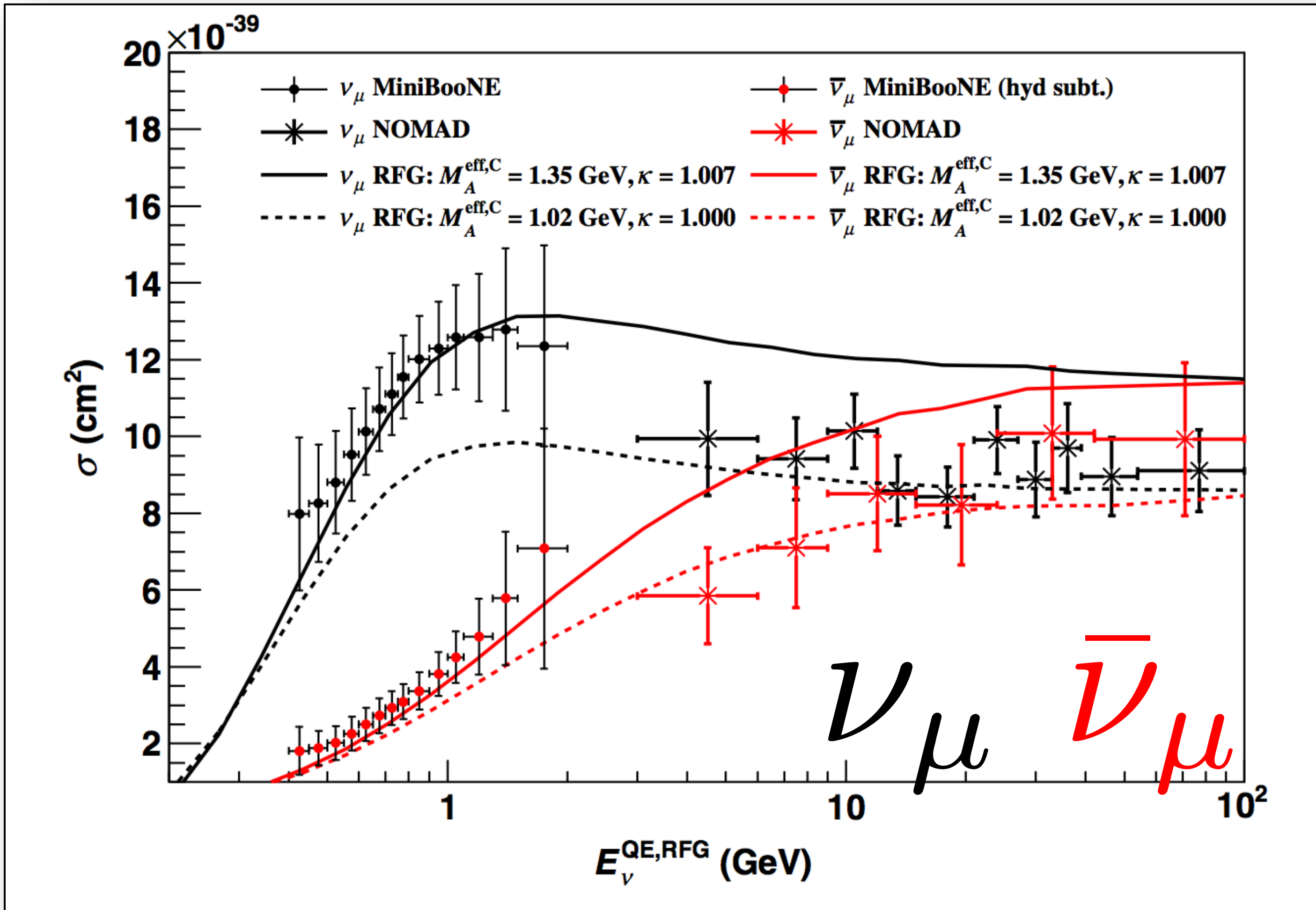
Cryosta vessel

- **additionally, MicroBooNE will collect a large data set of ν events which will be used to develop fully automated event reconstruction**

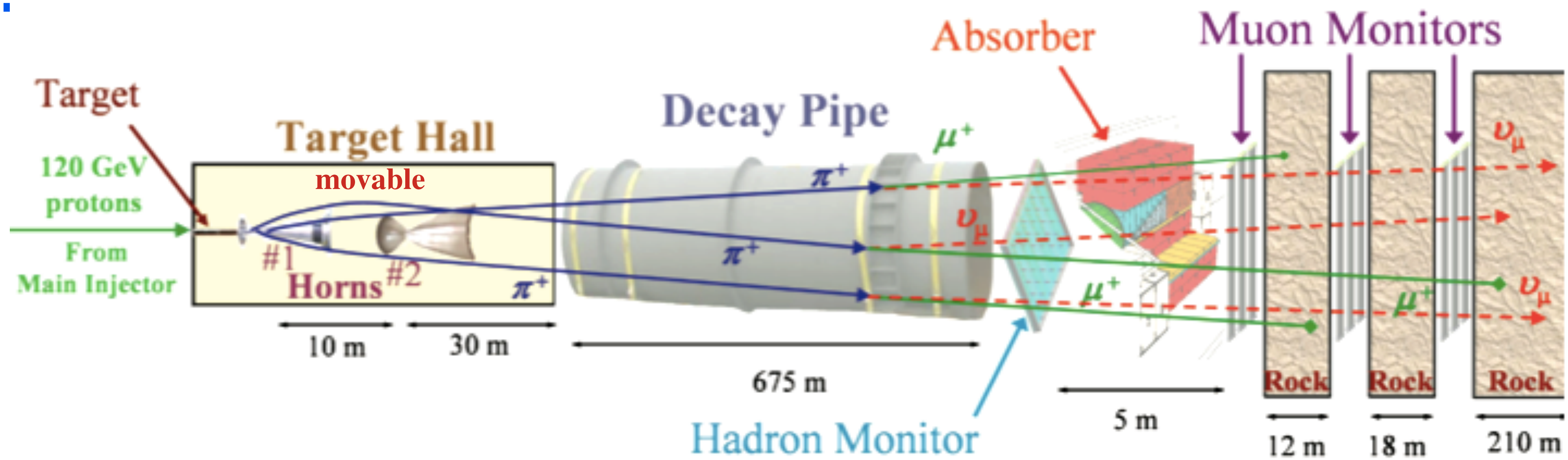
- **being near the surface, MicroBooNE will also measure non-beam backgrounds which are relevant to determining the reach of add'l physics which can or cannot be done with a surface detector**

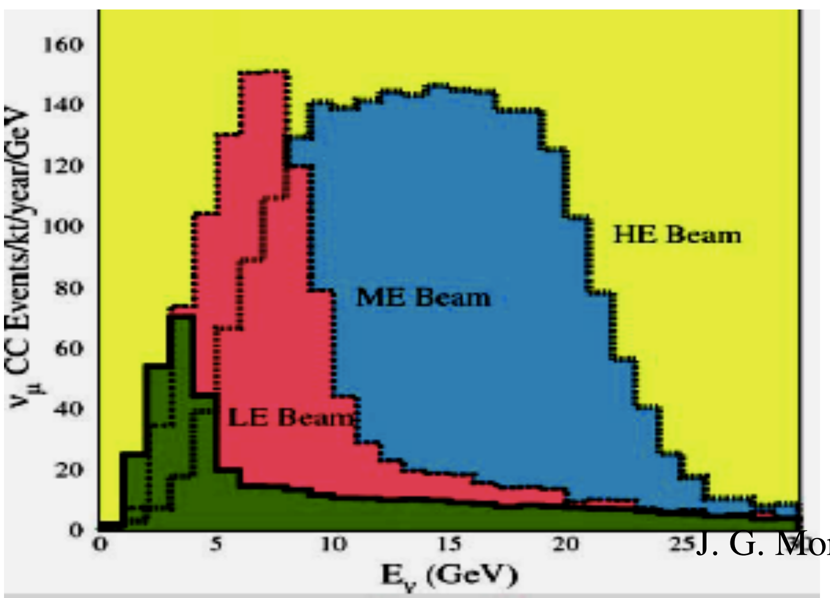
Pre-MINERvA: Conflicting Results for QE Scattering:

MiniBooNE gets higher M_A



How do we **Measure** Oscillation Parameters?
The NuMI (**N**eutrinos from the **M**ain **I**njector) Beam



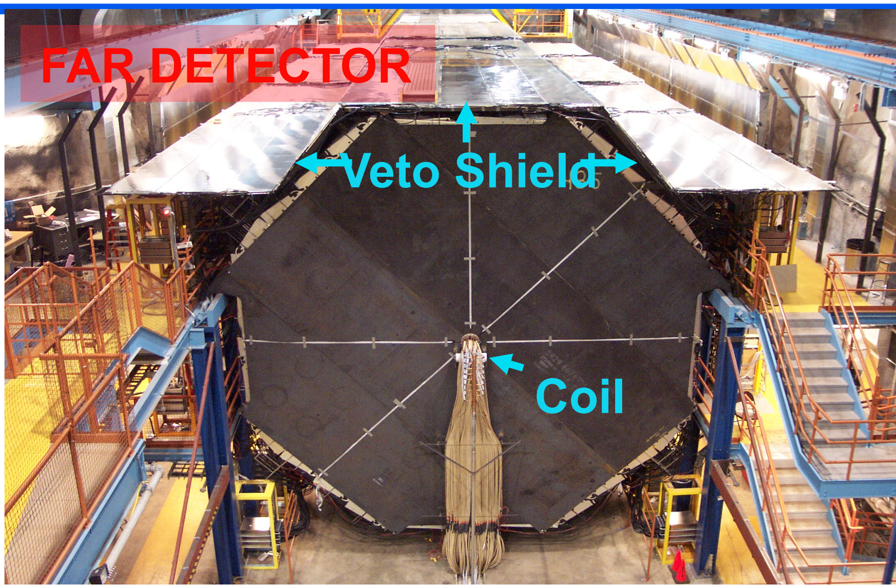


Beam	Target z position-cm	FD(735 km) Events per 1e20 pot
LE-10	-10	390
ME	-100	1500
HE	-350	3410

How do we **Measure** these Oscillation Parameters?

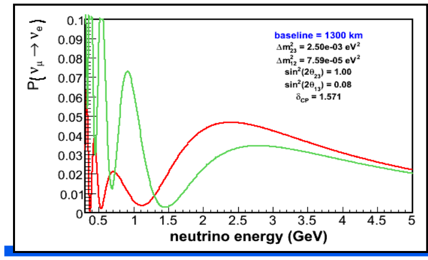
Taking Control of L / E: The MINOS Experiment (Collaborators from Brazil):

Two Neutrino Detectors 735 km apart



2.54 cm thick magnetized (1.2T) steel plates in between
4.1 x 1cm scintillator strips: orthogonal U,V planes

	Far Det	Near Det
Mass(kt)	5.4	1
Size(m^3)	8x8x3	3.8x4.8x1
Steel/Scint. Planes	484/484	282/152



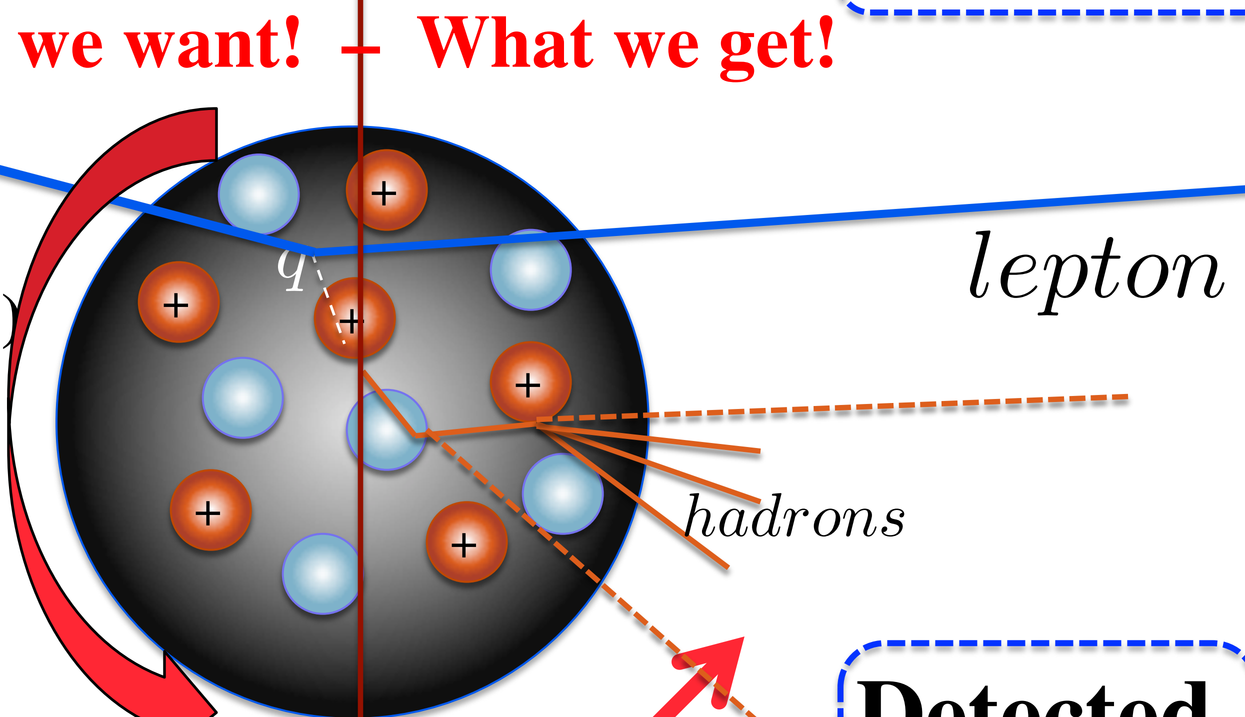
Physics of GeV ν-nucleus Interactions
How do we improve the nuclear model

E_ν^{Incoming}

E^{Detected}

What we want! – What we get!

Initial Nucleon State (RFG, SF, MEC, SRC..)



Cross Sections

Produced Channel

Formation Lengths, Final-State Interaction

Detected Topology

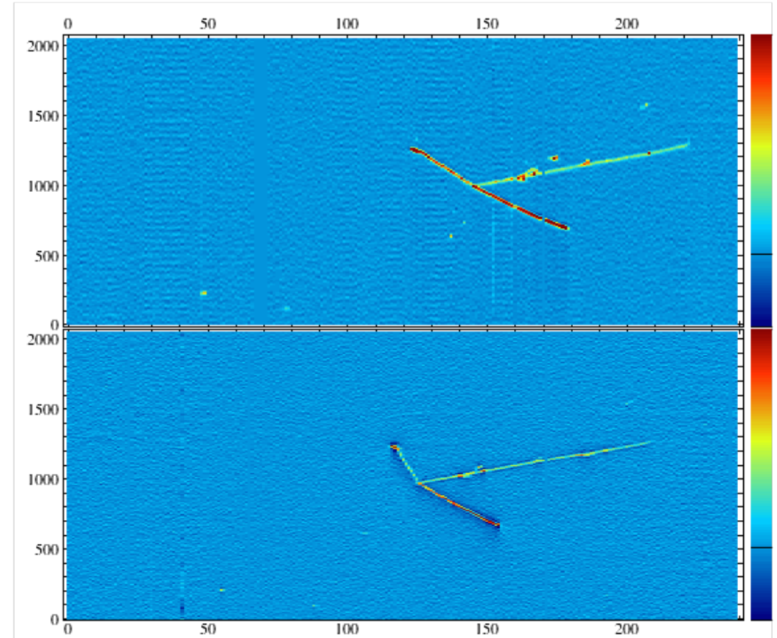
MINERνA ν Scattering Physics Program

In red → studied in LE Beam * → Latin American Participation

- *Quasi-elastic – (Brasil), (Guatemala/Mexico)
- *Resonance Production - 1pi – (Mexico)
- Resonance/transition Region - npi resonance to DIS
- *Inclusive (Brasil, Peru)/ Deep-Inelastic Scattering (better in ME beam)
- *Coherent Pion Production (Mexico)
- Strange and Charm Particle Production (better in ME beam)
- *σ_T (Brasil, Peru), Structure Functions and PDFs (ME beam better)
  - s(x) and c(x)
  - High-x parton distribution functions
- *Nuclear Effects (He, C, H_2O, Fe and Pb) (Peru)
- Generalized Parton Distributions
- *Test Beam Effort (Brasil, Mexico, Peru)

How is this program unique?

- Compared to ArgoNEUT
  - Took data in NuMI low-energy configuration (peak energy ~3 GeV)
  - With 20x the fiducial mass and roughly 10x more POT in neutrinos in one year, CAPTAIN will have more statistics and better containment
- Compared to MicroBooNE
  - BNB with neutrino energy ~1 GeV, consistent with 2nd oscillation maximum at 1300 km; will be complementary to CAPTAIN-MINERvA's measurements at 1st oscillation maximum
  - MicroBooNE interactions will mostly be quasi-elastic (~60%); approximately 68% of interactions in CAPTAIN-MINERvA will have a pion in the final state – gives us a unique opportunity to study events with large particle multiplicities



O. Palamara, NuInt 14

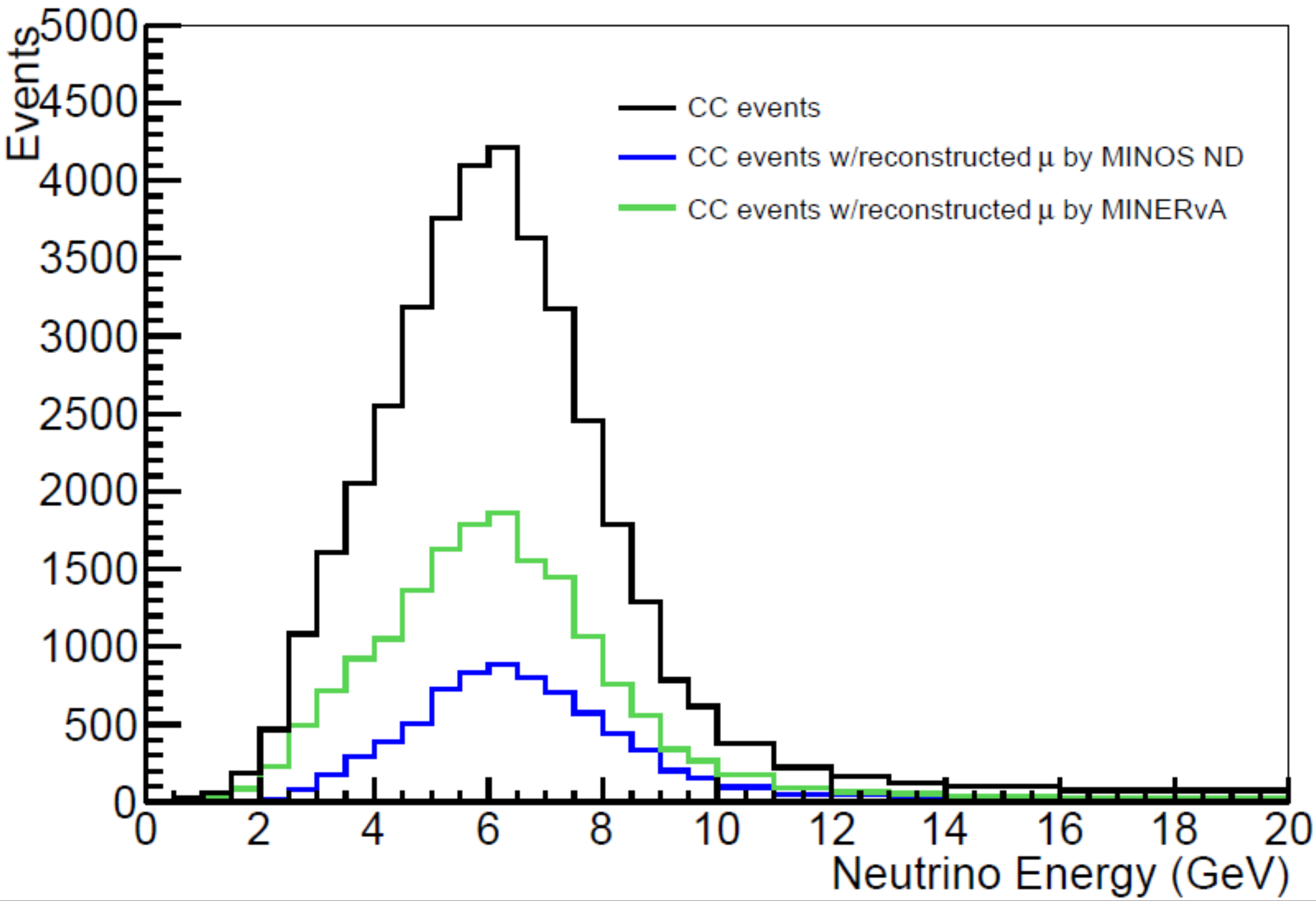
Real neutrino event in ArgoNEUT (back-to-back proton + muon candidate).

We expect similarly excellent resolution in CAPTAIN.

How is this program unique?

- **Only experiment making high-statistics measurements of neutrino interactions on argon in the medium energy range before DUNE**
- **CAPTAIN-MINERvA can measure cross section ratios (i.e., argon to carbon)**
  - **Study how processes vary on different nuclei (Models used in neutrino event generators depend on data from a variety of nuclei)**
  - **More stringent tests of the models can be performed with ratios due to cancellation of large systematic uncertainties such as the neutrino flux**
- **CAPTAIN-MINERvA can constrain the essentially unknown nuclear model of argon by measuring the energy dependence of nuclear effects convolved with cross section.**
  - **The incoming neutrino energy distribution is different in the far detector compared to the near detector → different energy-dependent nuclear effects in the two detectors**
- **CAPTAIN-MINERvA could serve as a model for the DUNE near detector system**
  - **DUNE near detector reference design is a fine-grained tracker; a possible enhancement being considered is the addition of an upstream LAr TPC**

Neutrino Energy Spectrum

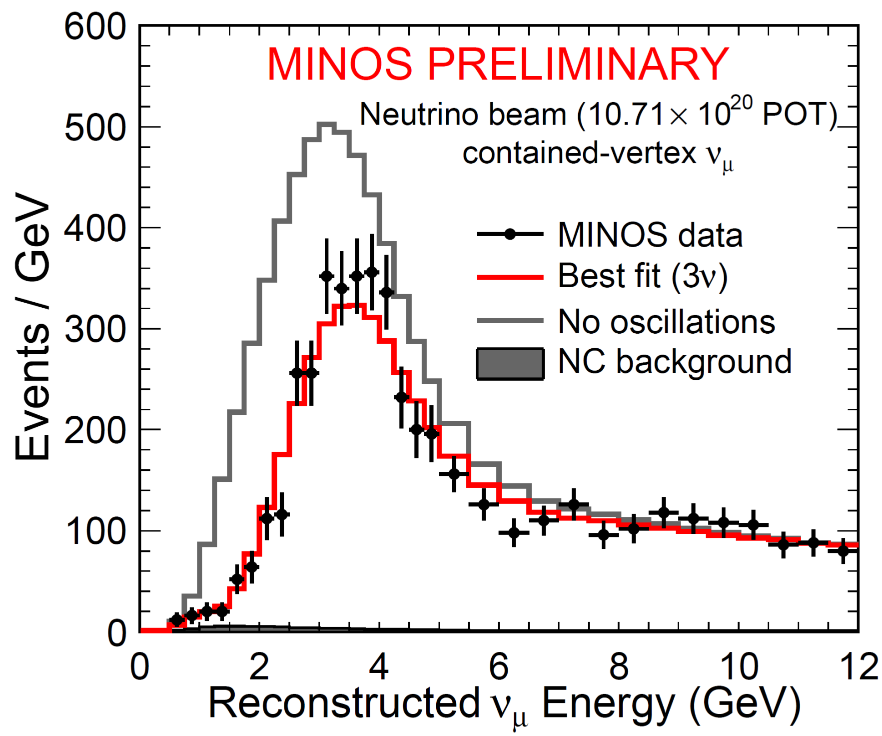


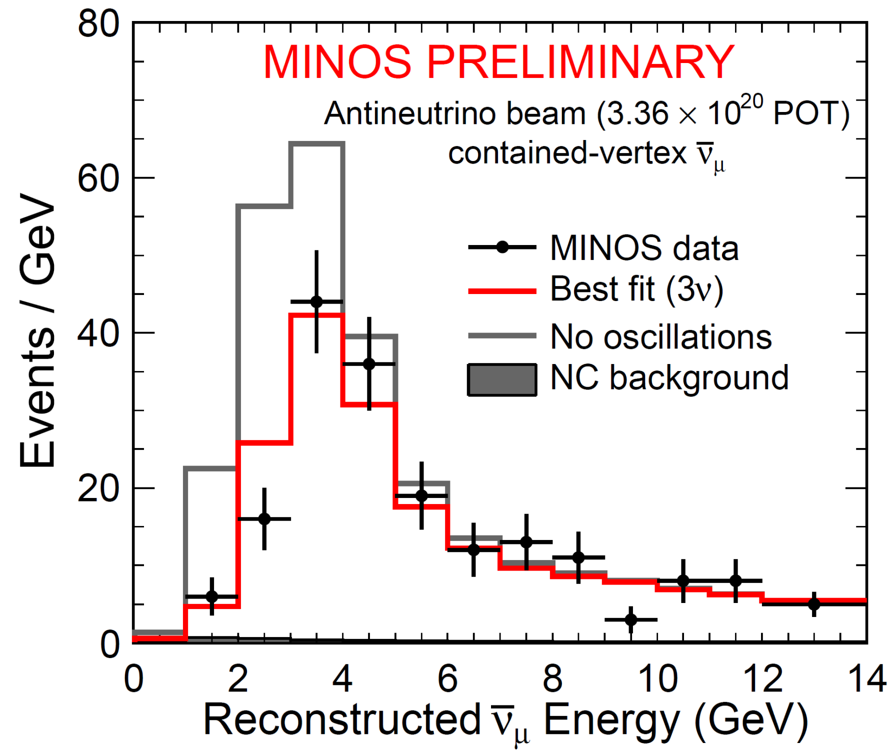
CAPTAIN-MINERvA Schedule

Important factors:

- Availability of the CAPTAIN detector – earliest date CAPTAIN could be moved to Fermilab is Fall 2016
- Availability of NuMI and BNB beams – we expect both to be available through at least 2021
- Availability of MINERvA detector and collaboration
  - MINERvA's default plan is to stop collecting data when they have 12e20 POT of antineutrino data. Depends on beamline performance and choice of NuMI running mode, but could be as early as 2018.
  - CAPTAIN-MINERvA data collection should begin by 2018 at the latest to ensure the participation of MINERvA collaborators. A significant time gap between the end of MINERvA's data collection and the beginning of CAPTAIN-MINERvA's run will make it difficult for interested MINERvA collaborators to participate.
- Installation of necessary infrastructure at Fermilab (see technically-driven schedule)
- Operating both CAPTAIN-MINERvA and CAPTAIN-BNB on a timescale such that they can both provide useful information for DUNE

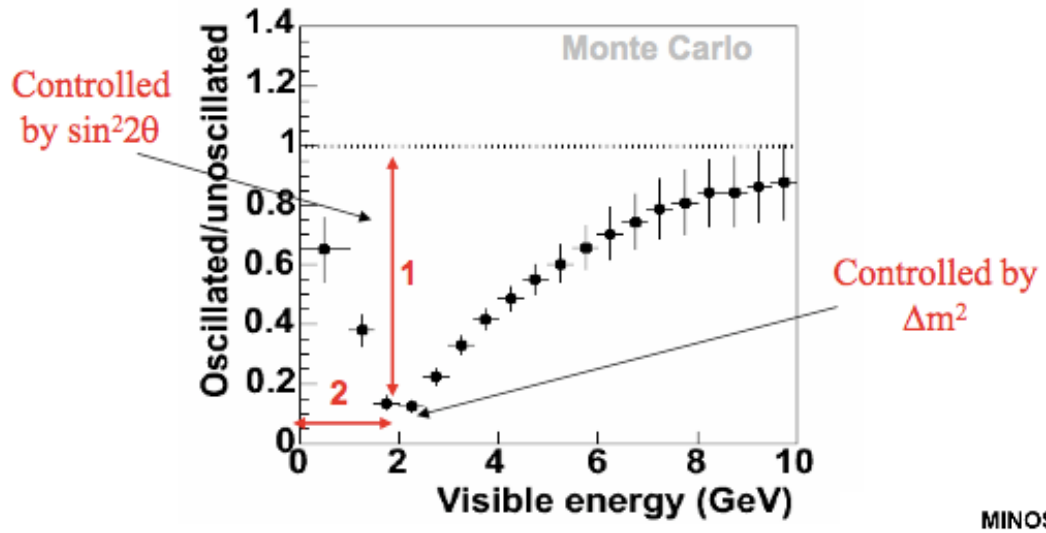
How do we **Measure** Oscillation Parameters?
Example MINOS – disappearance measurement

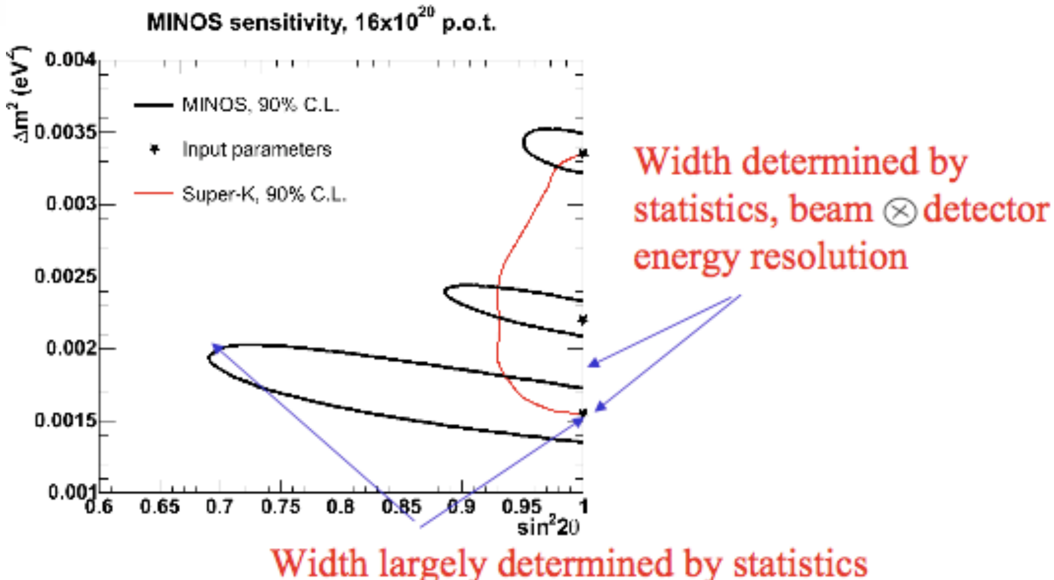




How do we **Measure** these Oscillation Parameters?

Totally dependent on detected energy



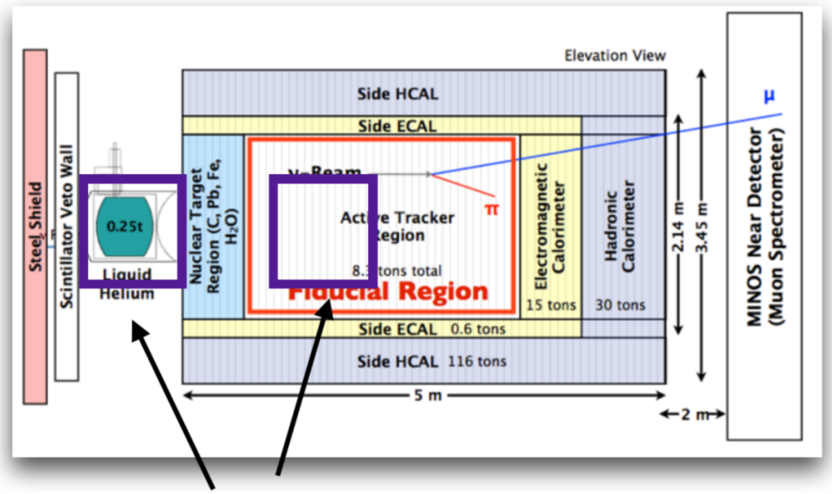


Pulling out extra MINERνA modules

- **In order to remove MINERνA's helium target and install CAPTAIN, we estimate 1.5 months of downtime when MINERνA cannot take data.**
- **In order to remove enough modules to remove the nuclear target region and half the tracker region, it would take another 3 months.**
- **For a 1-year run or longer it makes sense to take the extra time, if MINERνA has already received its 12E20POT in antineutrino running**

MINOS/MINERvA Hall

unscaled

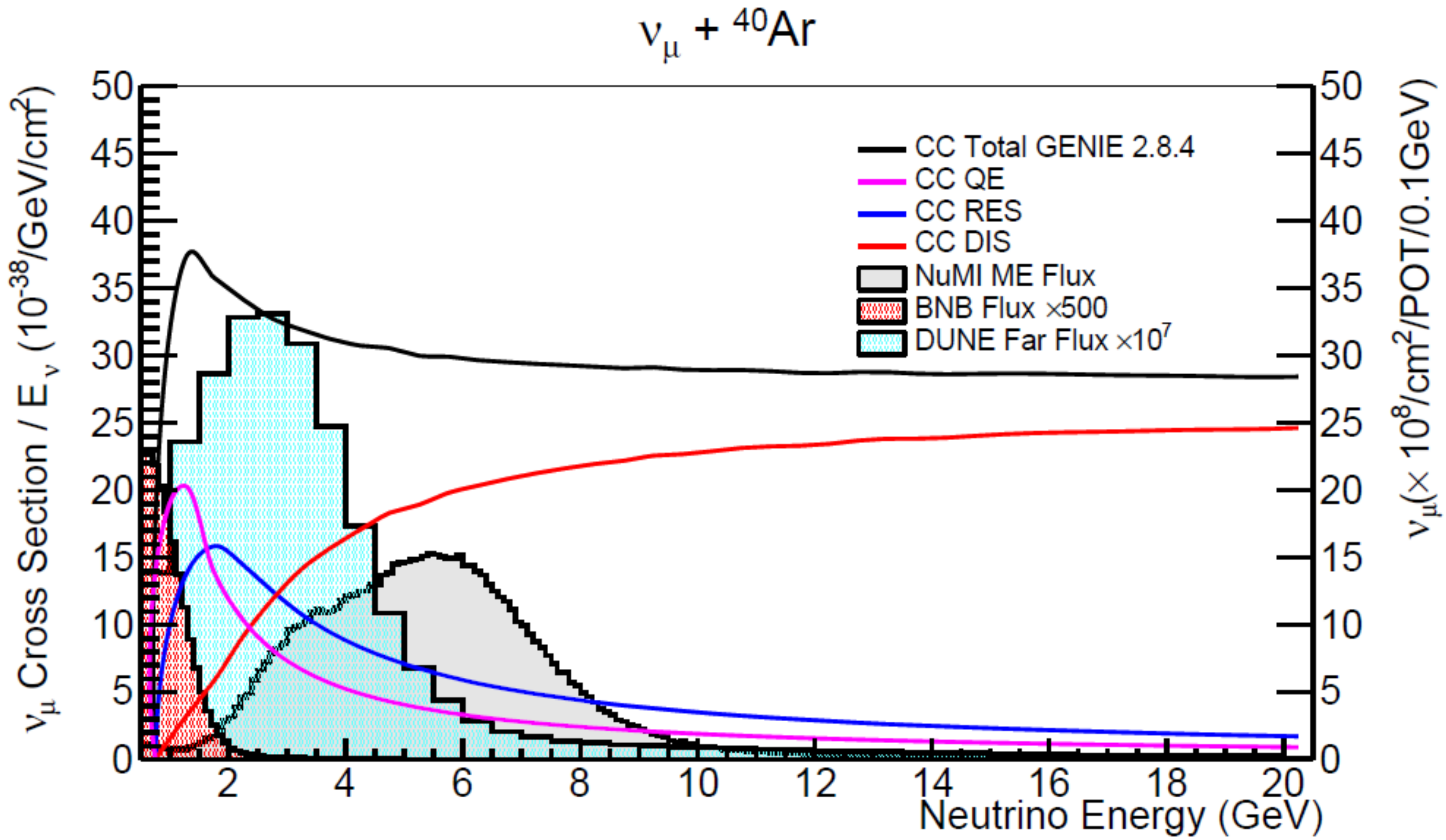


Two posible locations

a) at the position of the He target
b) at the module 30 (removing half of the tracker)

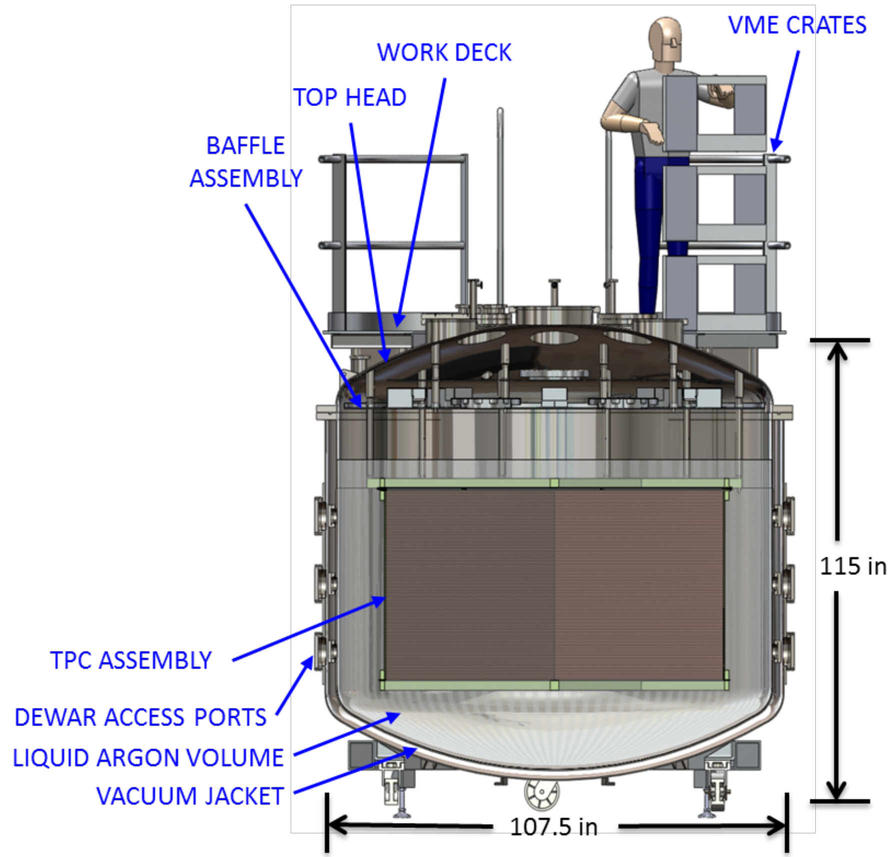
Channel	ratio
CCQE-like	1.33
CC 1 π^+	1.51
CC 1 π^0	1.58

How is this program unique?



CAPTAIN LAr TPC

- Liquid argon TPC detector:
  - Portable and evacuable cryostat
  - 5-ton instrumented liquid argon
- TPC:
  - Hexagonal prism, vertical upward drift (E = 500 V/cm, v_d = 1.6 mm/μs)
  - 2001 channels (667/plane)
  - 3 mm pitch and wire spacing
- Laser calibration system
- Photon detection system
- MicroBooNE cold electronics
- Purification system design based on MicroBooNE and LAPD



ν-Nucleus Scattering

What do we observe in our detectors?

Significant implications for Oscillation Experiments

- The events we observe in our detectors are convolutions of:

$$Y_{c\text{-like}}(E) \propto \phi(E' \geq E) \otimes \sigma_{c,d,e..}(E' \geq E) \otimes Nuc_{c,d,e..\rightarrow c}(E' \geq E)$$

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  effective $\sigma_c^A(E)$

- Experimentally, the convolution of initial cross section and nuclear effects are combined into an effective cross section $\sigma_c^A(E)$ that **depends on incoming neutrino energy spectrum and nuclear effects that populate the yield $Y_c^A(E)$.**
- This implies, for example, effective $\sigma_{\pi+}^C$ (1 GeV) measured in the Booster beam **will be different** than the same effective $\sigma_{\pi+}^C$ (1 GeV) observed in the higher energy NuMI beam due to, for example, more feed down from multi-pi events. **Can not simply plug in effective $\sigma_{\pi+}^A$ from experiments in a different beam.**
- In a two-detector LBL oscillation experiment, neutrino flux entering the FD is different than the neutrino flux at the ND due to geometry and oscillations. The σ_c^A (E) effective that should be applied to expectations (Monte Carlo) at FD is NOT the same as that which we would measure at the ND. **However, the ND results give us an excellent starting point for calculating the difference.**