MINERvA - Neutrino-nucleus cross sections are important!

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FUNFACT, JLab
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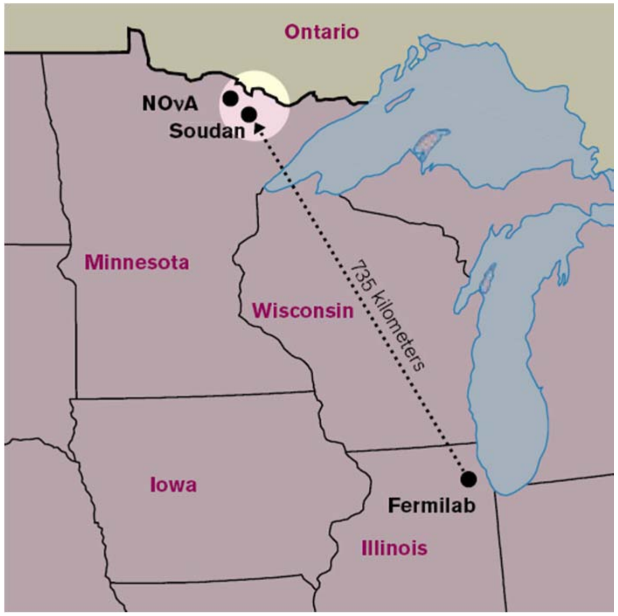
- ν oscillations → νA cross sections
- MINERvA
  - CC quasielastic results
  - CC pion production results

Big Picture

- Neutrino physics seeks oscillation results
  - Δm^2, mixing angles all known with moderate accuracy
  - CP violation is major goal for future (DUNE) need $\nu_\mu \rightarrow \nu_e, \overline{\nu}_\mu \rightarrow \overline{\nu}_e$
  - There are 3 generations of ν (just like quarks), sterile ν? (MicroBooNE)
- E.g. Fermilab, home to many ν experiments, e.g. NOvA which has 213 scientists from 39 institutions.



Experiments are hard, e.g. NuMI at FNAL (MINERvA, MINOS, NOvA)

- Think of neutrons or photons, but worse
  - Need tertiary beam, no tagging, no simple monitoring
  - Need very large, monolithic detector, e.g. 15 kT liquid scintillator

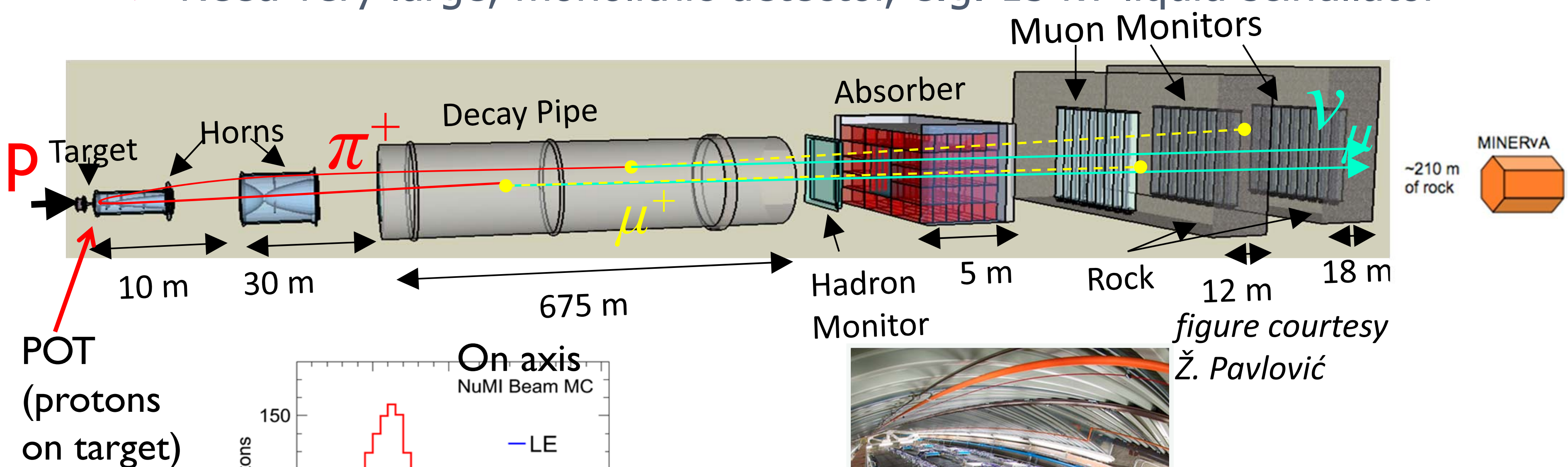
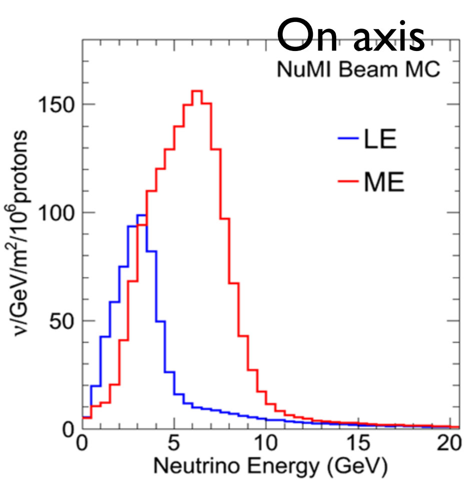
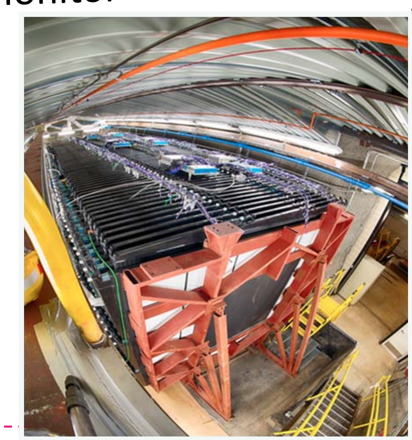


figure courtesy Ž. Pavlović





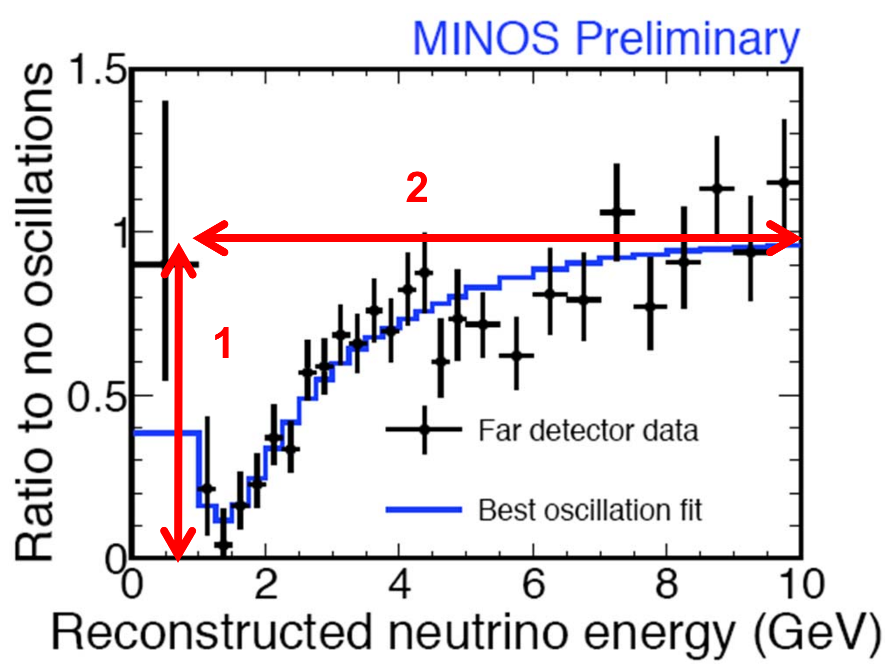
NOvA - liquid scintillator

Primer on neutrino experiments

- Beams are wide-band (width~GeV) to see wide range of E at a given L. (e.g. ν_μ disappearance)

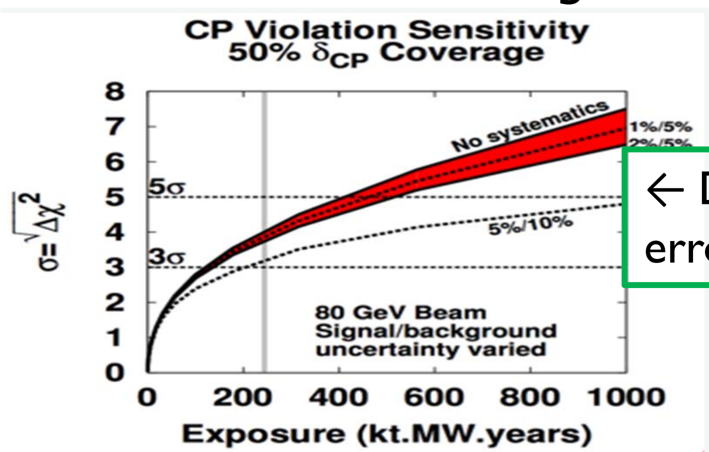
$$P(\nu_\mu \to \nu_\mu) = 1 - \underbrace{\boxed{\sin^2 2\theta}}_{1} \sin^2(1.267 \underbrace{\boxed{\Delta m^2}}_{2} L/E)$$

- Beams are low intensity, detectors massive, runs long.
- Beams are poorly monitored, must calculate flux from POT
- Detect ν through interaction
- Must calculate ν energy for each event from final state
- Target is detector, acceptance very large
- No trigger



Need high quality interaction models

- All modern target/detectors are 'heavy' nuclei- C, O, Ar
- Detectors (MINOS, DUNE) determine ν energy by measuring energy of all final state particles
  - But need models for undetected particles (neutrals)
- Detectors (T2K, MiniBooNE, MINERvA) determine ν energy by finding specific topology for simple reactions
  - But must account for systematic errors, esp. nuclear model
- Experiments must often work with MC that doesn't agree with data!



← DUNE error plot

T2K error budget→

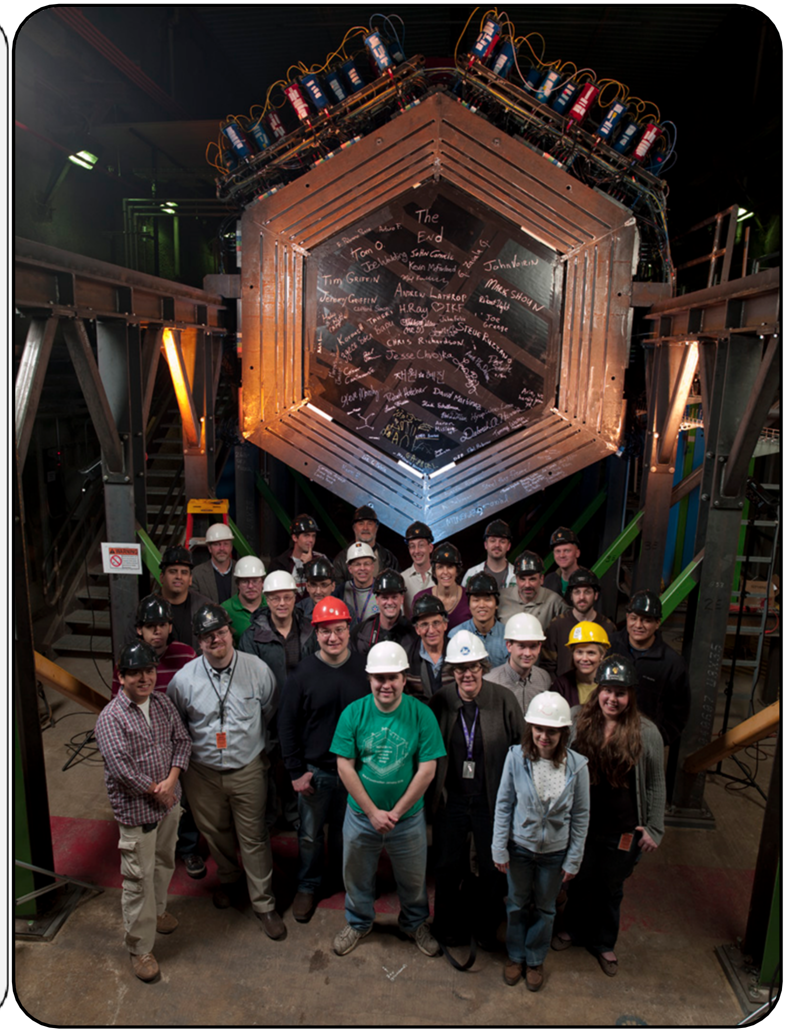
Source of Uncertainty	Est. stan. dev.
Cross section (MC)	**4.9%**
Cross section (ND280), Flux	2.7%
Far Det, FSI	**5.6%**
Oscillation parameters	0.2%
TOTAL	8.1%

MINERvA Collaboration

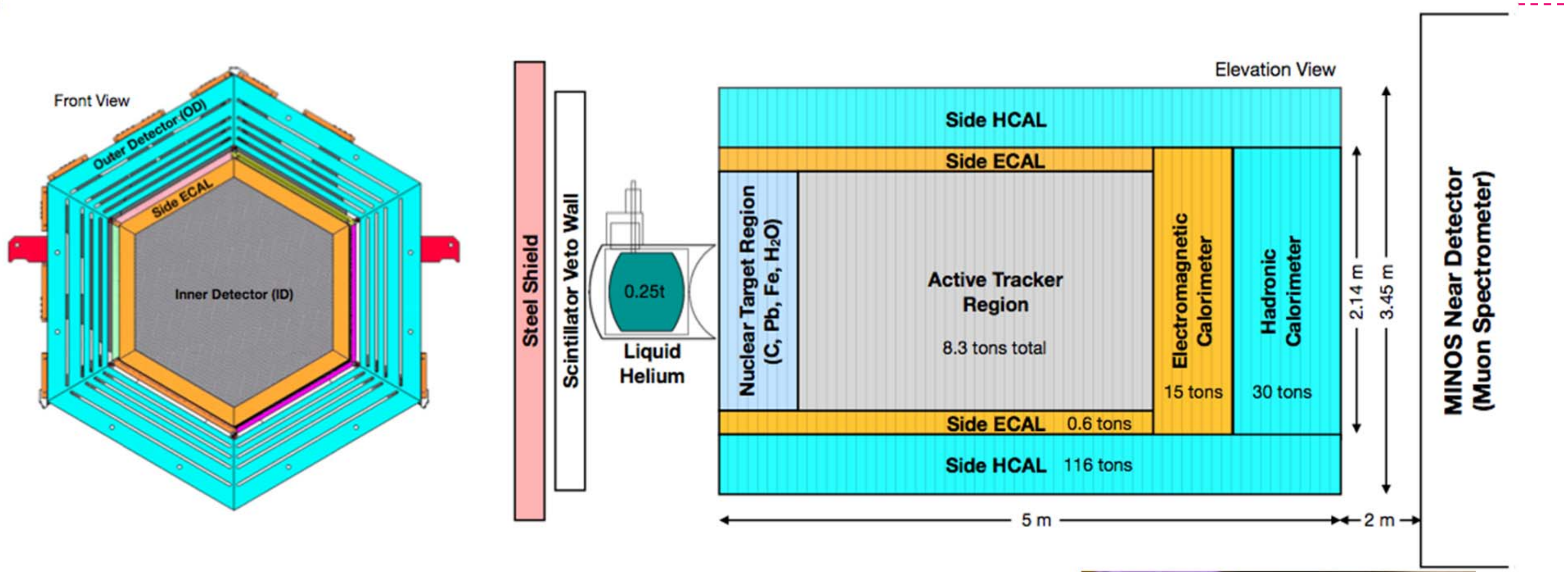
~60 collaborators from particle and nuclear physics

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

Otterbein University
Pontificia Universidad Catolica del Peru
University of Pittsburgh
University of Rochester
Rutgers University
Tufts University
University of California at Irvine
University of Minnesota at Duluth
Universidad Nacional de Ingeniería
Universidad Técnica Federico Santa María
College of William and Mary

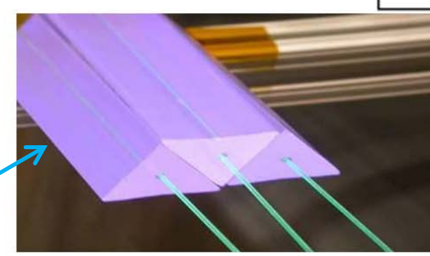


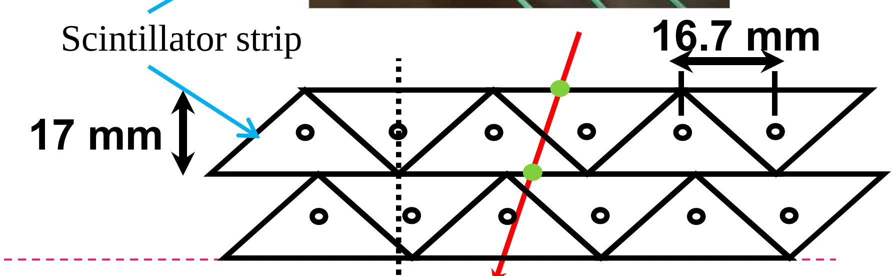
MINERvA detector



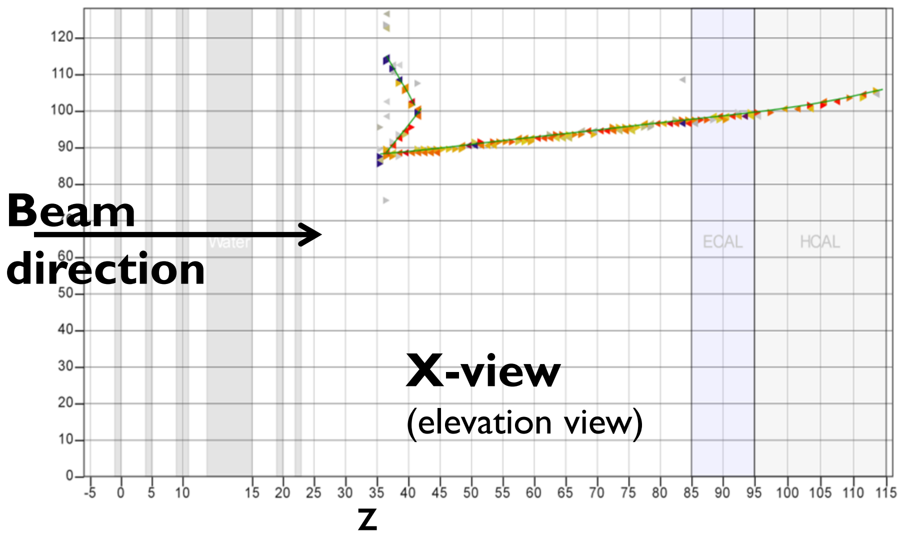
Central region is **finely segmented scintillator tracker**

~32k plastic scintillator strip channels total



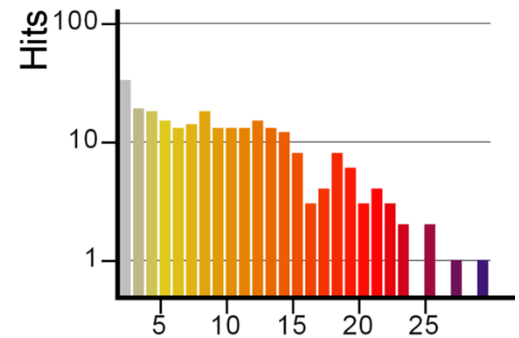


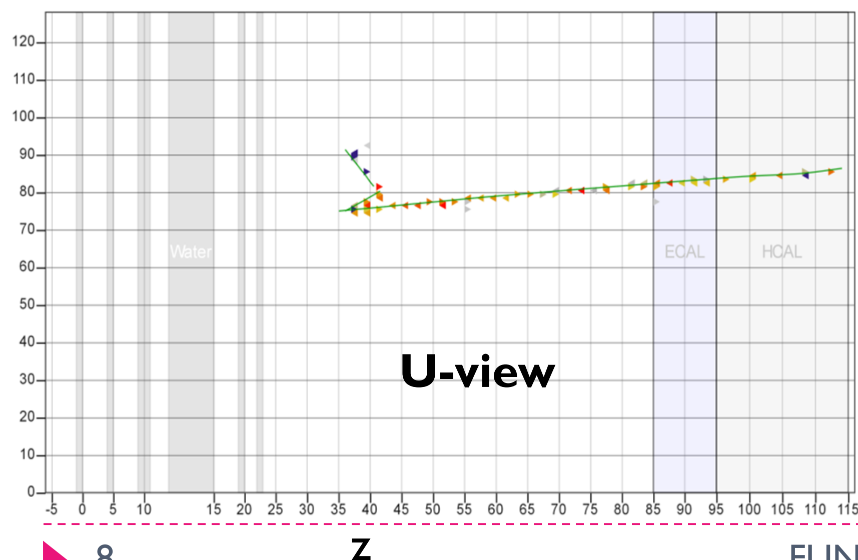
Sample event (3 views for 3-d track)

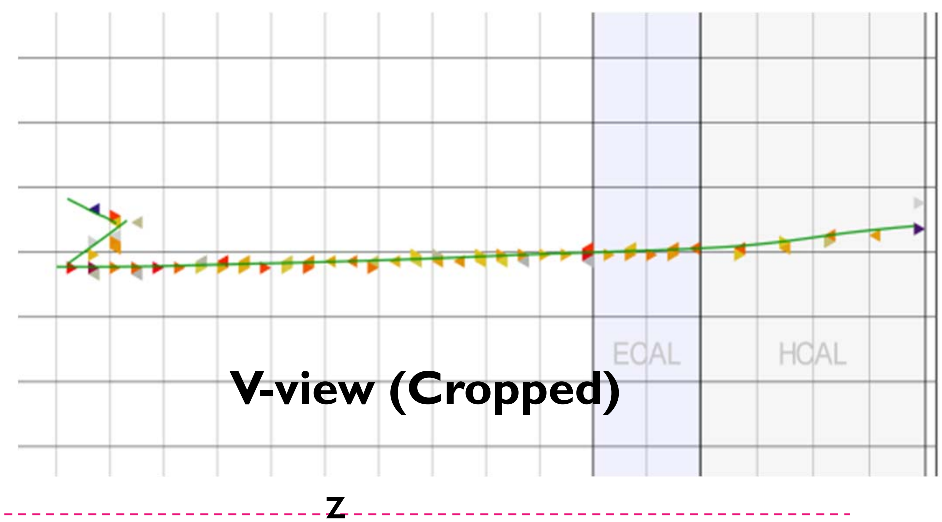


Data Candidate: Scattering π^+

Look for vs. z
1. No energy deposit
2. Vertex
3. Significant deposit



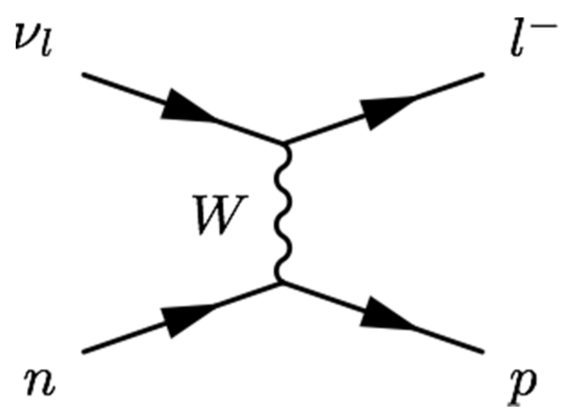




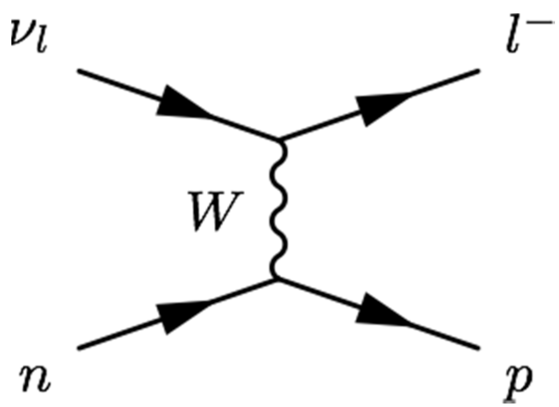
MINERvA publications (~all CC=Charged Current, i.e. $W^{\pm}$ exchange)

- "neutrino communications"- MPLA - 0.1 Hz, 1% bit error rate
  - One of top 10 physics results – Physics World - 2012
- ν_μ QE-like in CH - PRL 111, 022502 (2013)
- $\bar{\nu}_\mu$ QE-like in CH - PRL 111, 022501 (2013)
- Detector – NIM A473, 130 (2014)
- ν_μ inclusive ratios (Fe:C, Pb:C) PRL 112, 231801 (2014)
- CC Coherent charged pion – ν and $\bar{\nu}$ CH PRL 113, 261802 (2014)
- 2-track QE ν_μ CH (μ and Np) PRD 91, 071301 (2015)
- Many more on the way…
  - ν_μ Single charged pion in CH (submitted to PL)
  - π^0 production – $\bar{\nu}$ CH (submitted to PL)
  - ν-e scattering yield as beam flux calibrator (CH)
  - ν_μ DIS in CH, Fe, Pb

CC Quasielastic Scattering



Charged-Current QuasiElastic scattering



- Key signal channel for oscillation experiments
- 'Simple' process, signature should be easy to identify
- Heavy nuclei complicate the picture

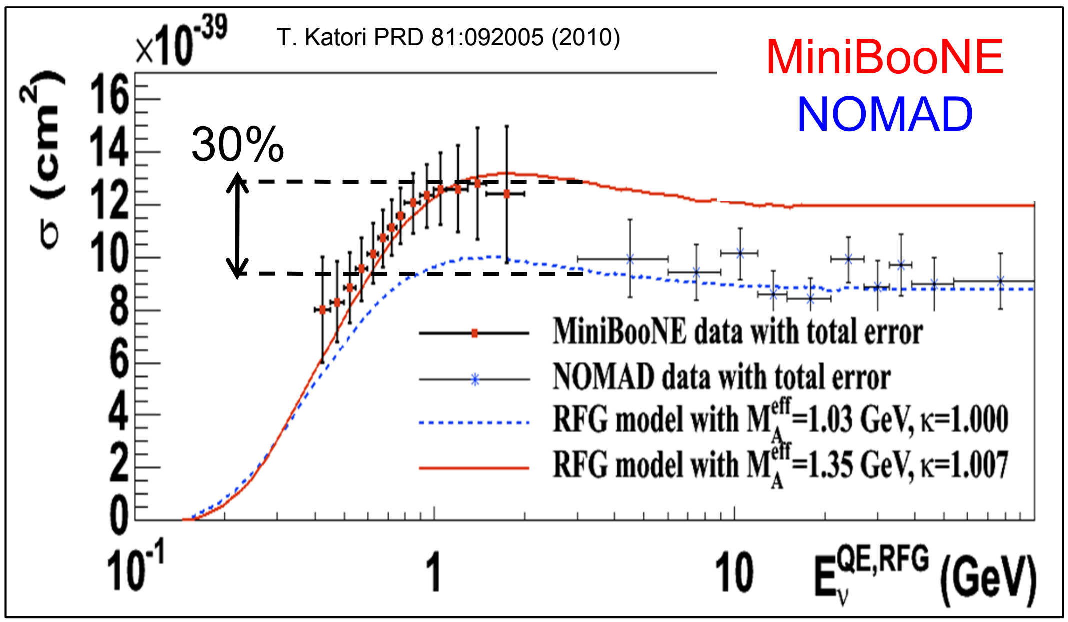
- We can reconstruct the neutrino energy and 4- momentum transfer Q^2 from only muon variables, assuming a stationary initial state nucleon and QE kinematics.

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

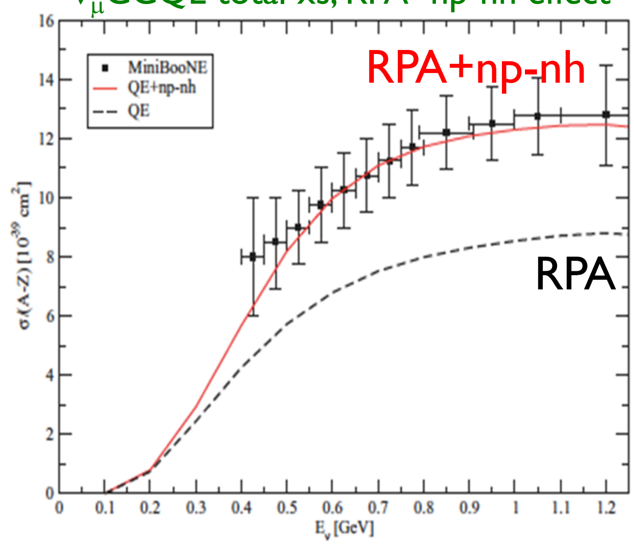
$$Q^2_{QE} = 2\underline{E_\nu^{QE}}(\underline{E_\mu} - \underline{p_\mu \cos\theta_\mu}) - m_\mu^2$$

Recent confusion in CCQE interpretation

- MiniBooNE (E_ν~1 GeV) seems incompatible with NOMAD (E_ν~10 GeV) and many models.
- What are degrees of freedom sampled, how to describe them?
- Experimenter's soln: change axial form factor (nucleon in medium)
- Theorist's soln: add interaction with correlated nucleon pairs [well-understood in (e,e'), called MEC or np-nh]



ν_μCCQE total xs, RPA+np-nh effect

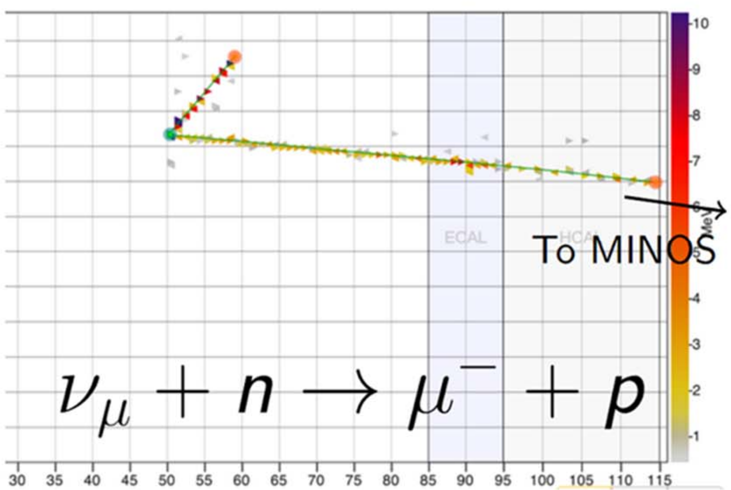


Martini, et al. PRC 81: 045502 (2010)

CCQE lepton only event selection

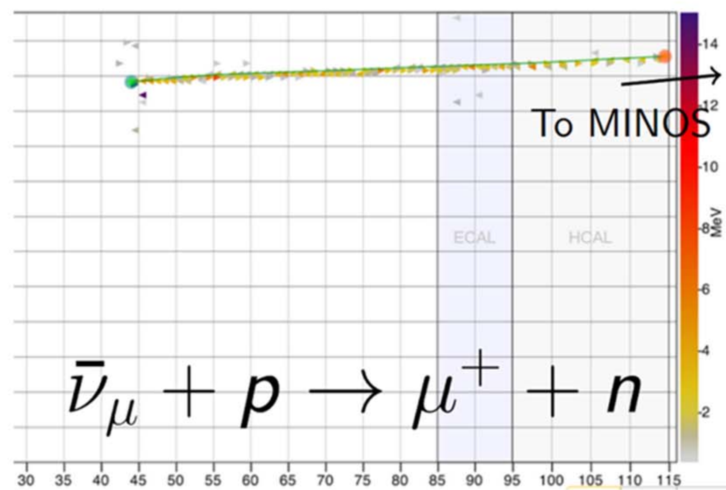
Neutrino mode:

- Muon track charge matched in MINOS as a **μ^-**
- No requirement on the number of additional tracks from the vertex outside nearby region
- Background subtracted with sidebands, 47% eff., 49% purity



Antineutrino mode:

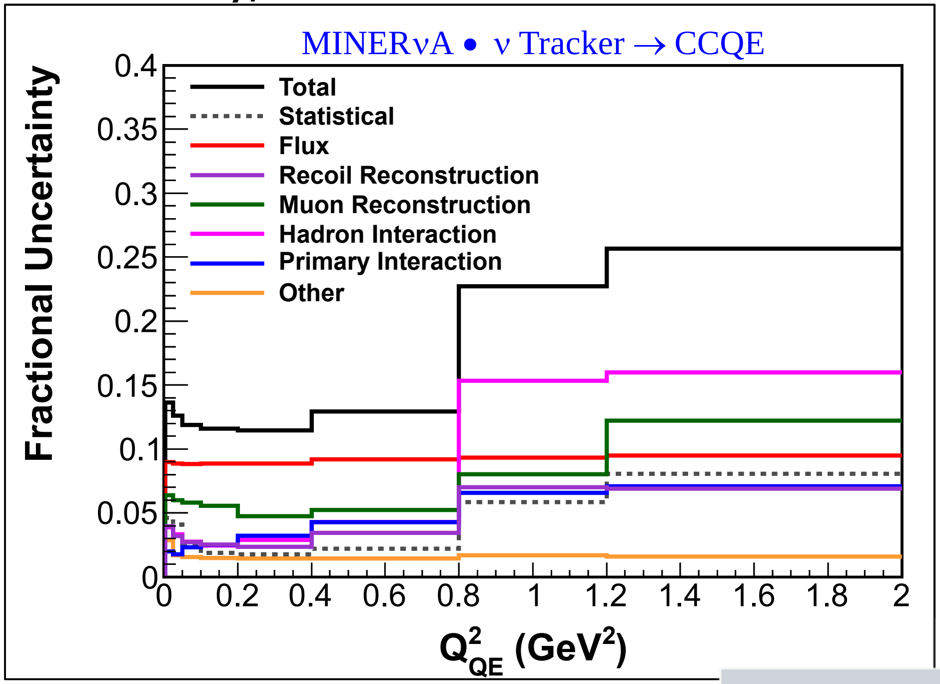
- Muon track charge matched in MINOS as a μ+
- No additional tracks from the vertex
- The ejected neutron may scatter, leaving an energy deposit, but it does not make a track from the vertex

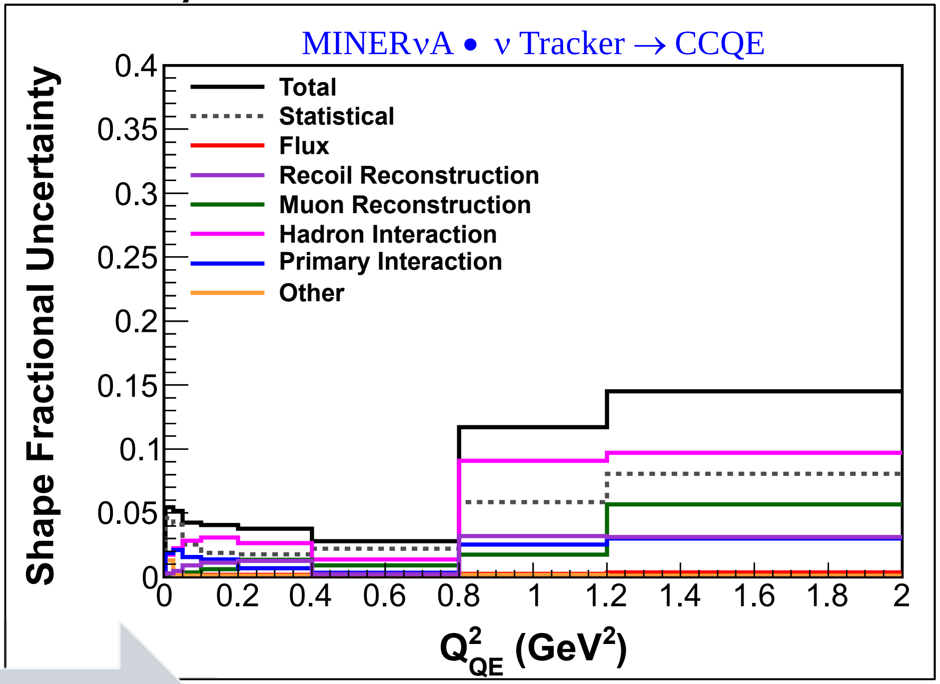


Measurement of anti-ν_μ Quasi-Elastic Scattering on a Hydrocarbon Target at E_ν~3.5 GeV, Phys. Rev. Lett. 111, 022501 (2013)
Measurement of ν_μ Quasi-Elastic Scattering on a Hydrocarbon Target at E_ν~3.5 GeV, Phys. Rev. Lett. 111, 022502 (2013)

Systematic errors – absolute vs. shape

- Very detailed analysis of systematic errors through reweighting
- Due to problems with flux, early data is presented as ratios or shape analyses to get more info
- Usually, flux becomes small contribution to systematics

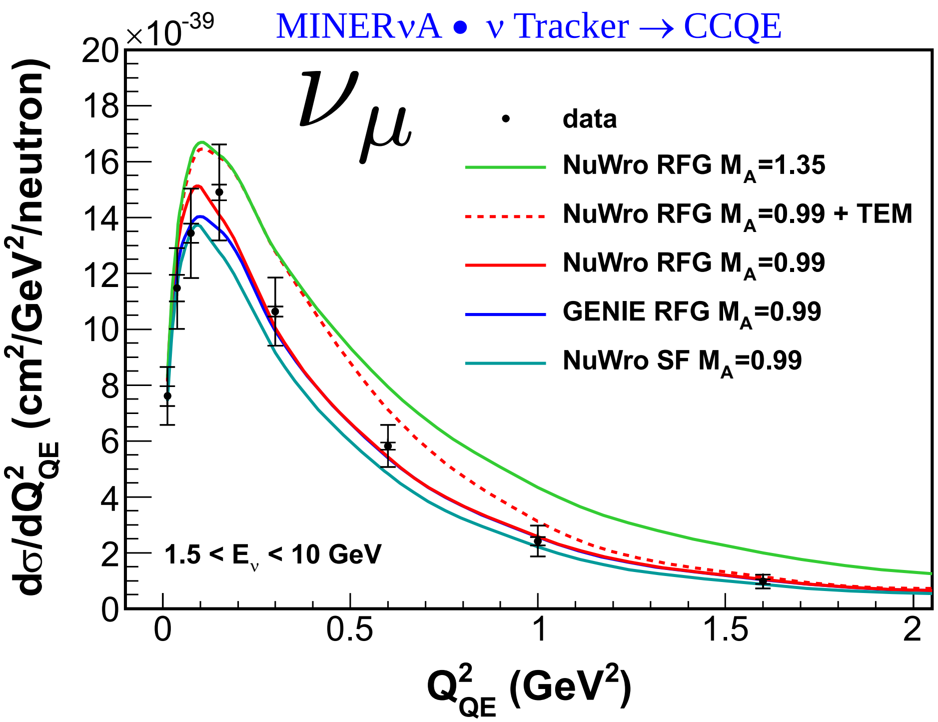


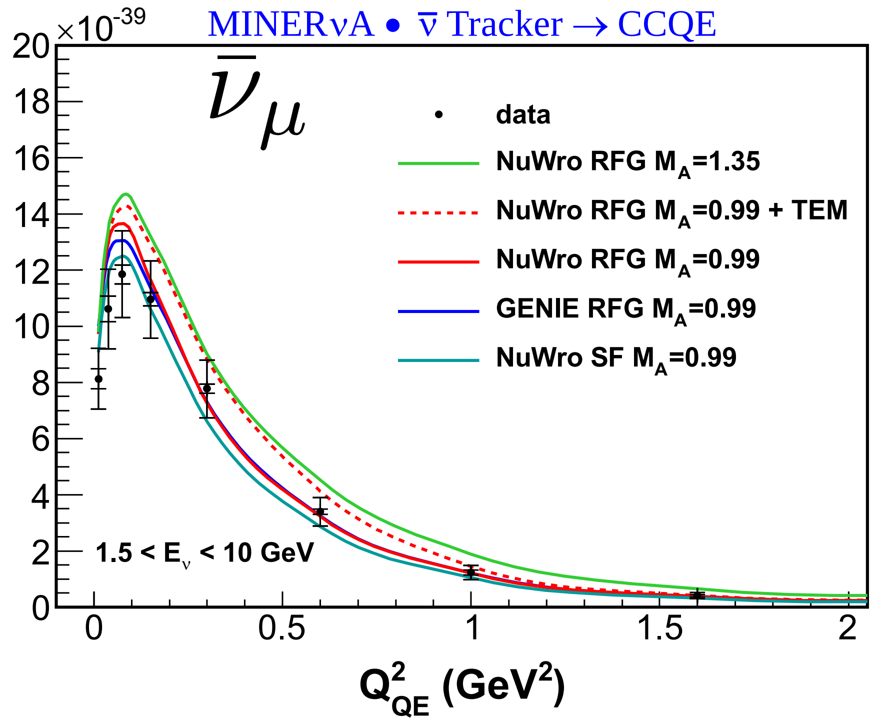


Shape only

CCQE-like Absolute cross sections

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



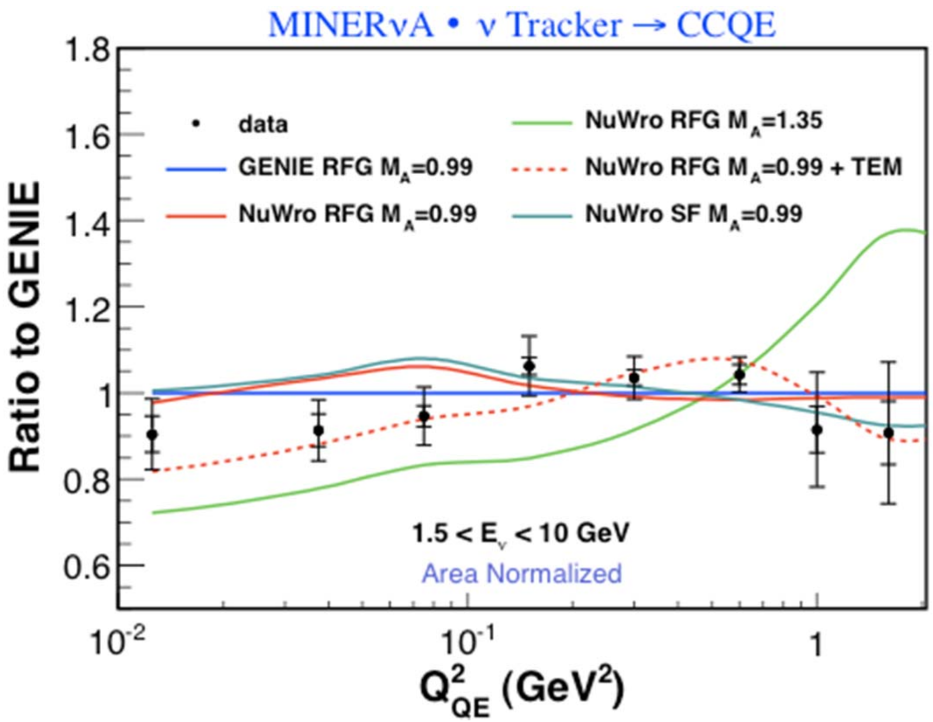


- Here, only M_A=1.35 GeV (axial response changes in nucleus?) is disfavored. N.B. This is model used by MiniBooNE in its low energy oscillation analysis
- Move to shape analysis

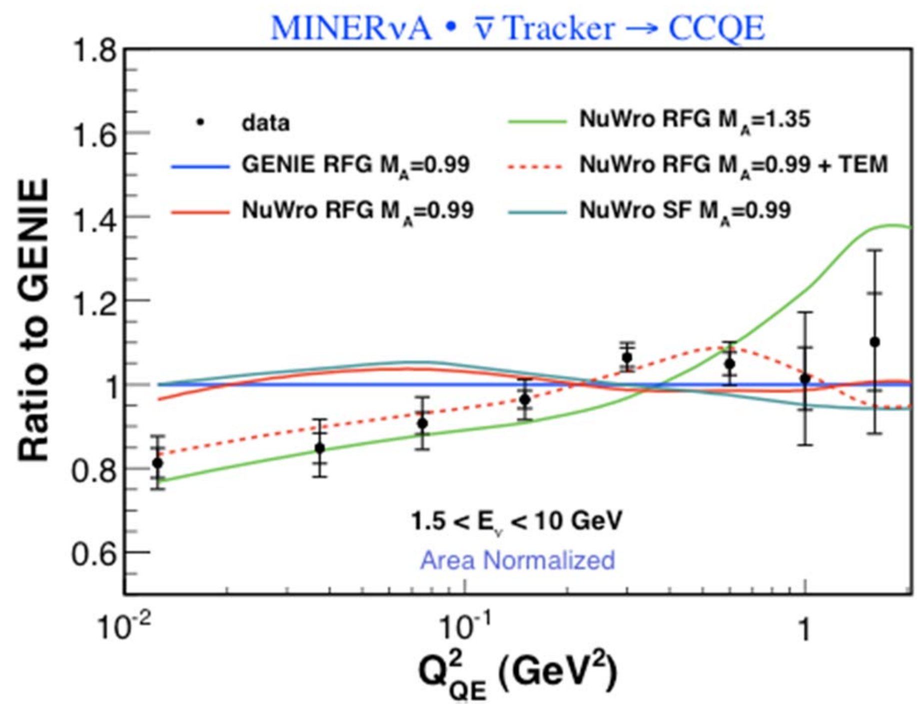
dσ/dQ² Shape

show ratio of each with GENIE event generator

ν_μ CCQE



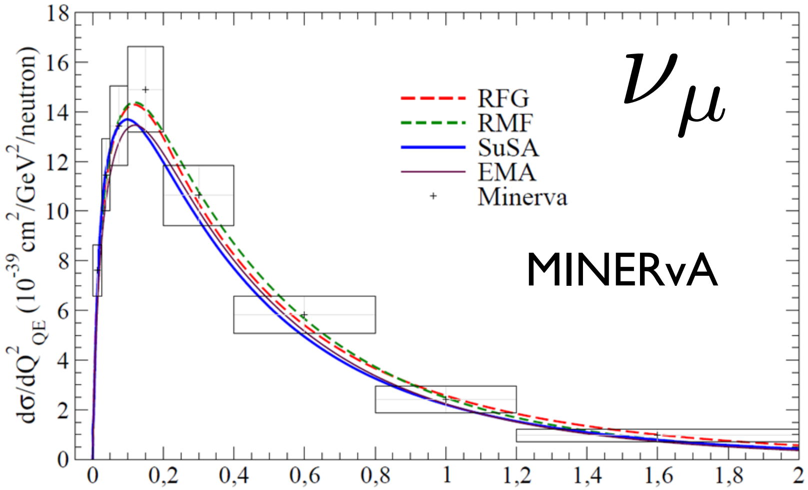
$\bar{\nu}_\mu$ CCQE

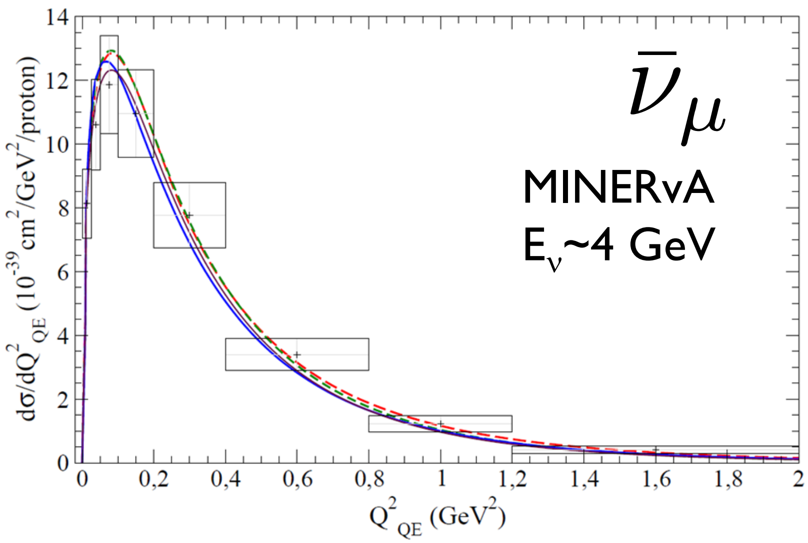


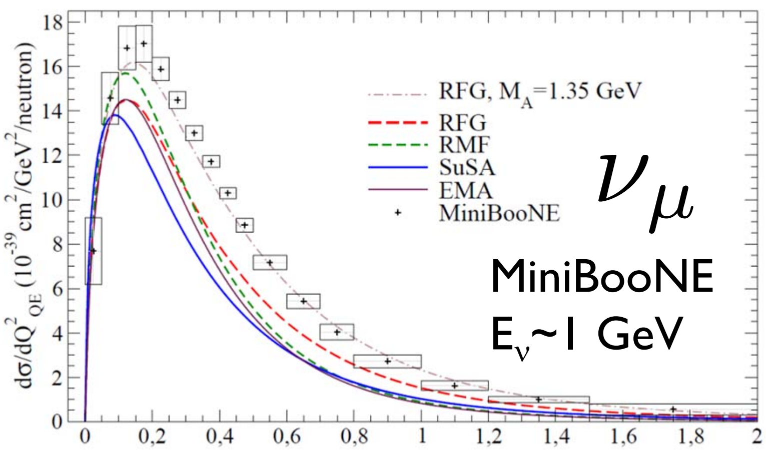
- Best fit prefers data-driven multi-nucleon model (red dot)
  TEM:Bodek, Budd, Christy, Eur. Phys. J. C71, 1726 (2011)

Recent theoretical work
Megias, et al. – PRD 91 (2015) 073004

- SUSA model
  - Phenomenological match to wide range of (e,e') data
  - Take advantage of ~Nachtman and nucleus scaling.
  - Must add MEC by hand
- RMF (relativistic mean field)
  - More microscopic (N off-shell)
  - No need for MEC

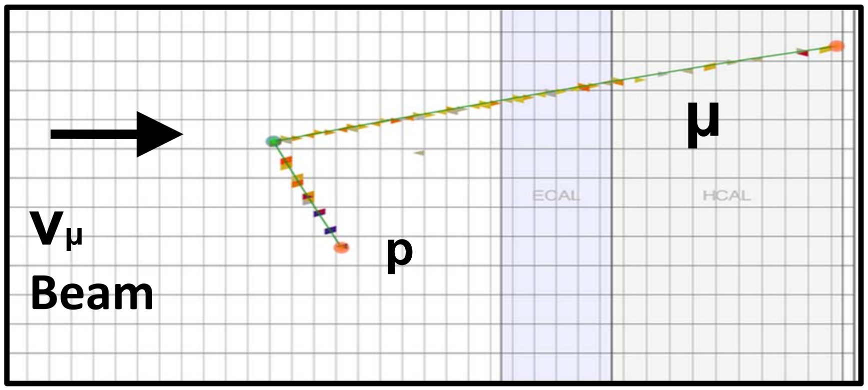






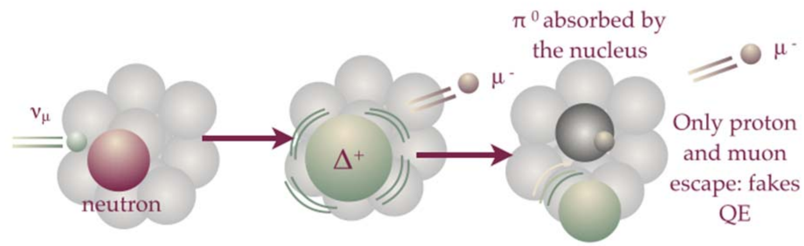
CCQE with Muon + N protons

MINERvA Tracker Region:



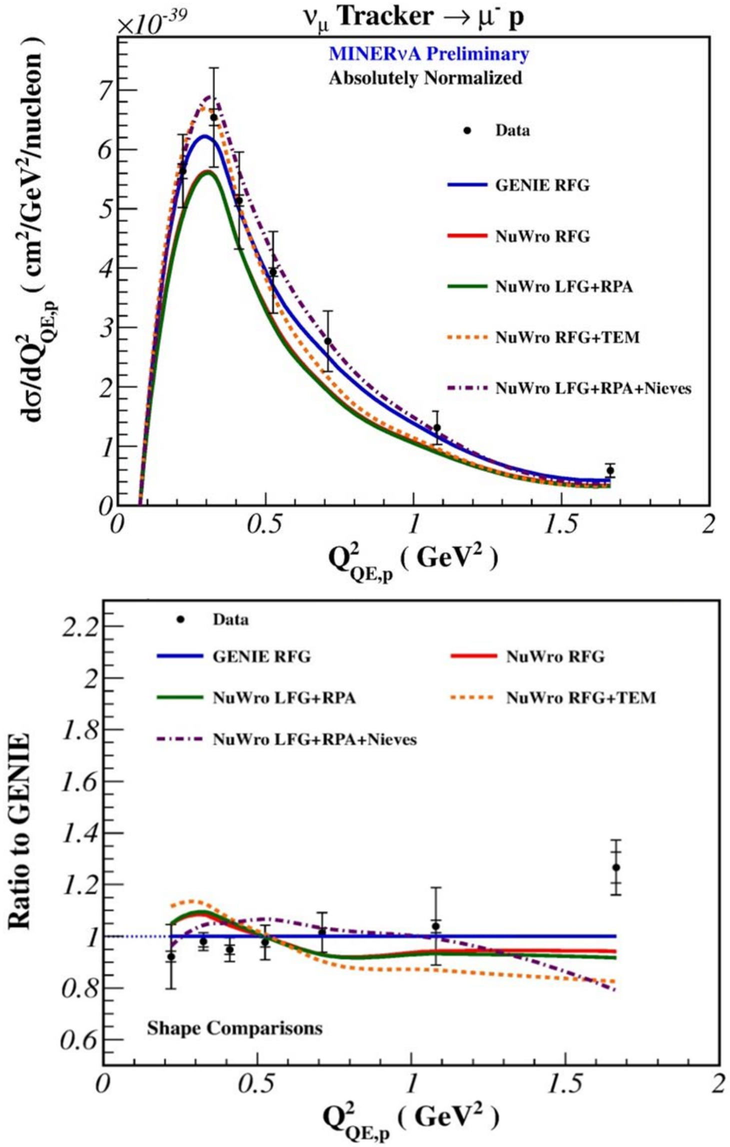
$$Q^2_{QE,p} = (M')^2 - M_p^2 + 2M'(T_p + M_p - M')$$

M' = Mn - Ebind
Ebind = binding energy
Tp = proton kinetic energy
Mn = mass of neutron
Mp = mass of proton



- Neutrino-neutron CCQE scattering produces a proton. Instead of using muon kinematics to reconstruct Q^2, we can use proton kinematics
- We require a muon and at least one proton in the final state, but no pions or other mesons. Proton must have KE>110 MeV to be tracked.
- Main background is resonant or DIS events that after FSI have no pions
- Quasi-elastics could produce more than one proton through FSI or MEC

Muon + N Protons: Results

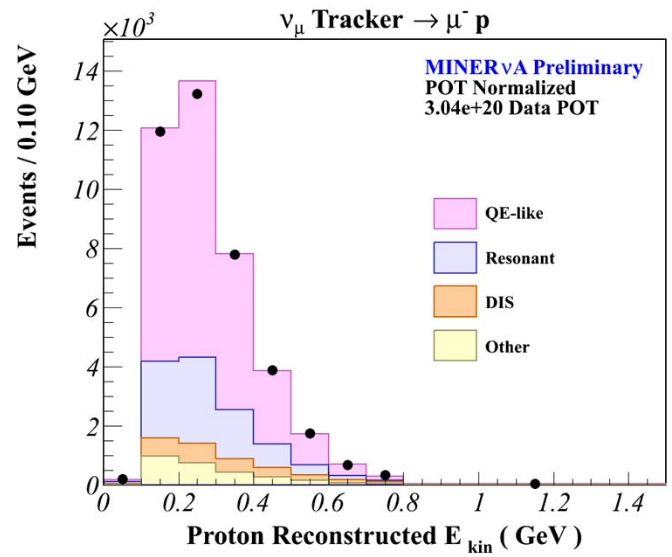


- Using proton kinematics, data favors standard Relativistic Fermi Gas (RFG), different from previous QE results
- As a check, muon kinematics were used for same events. New data favored RFG + TEM, similar to first QE results
- Models used by neutrino oscillation experiments must reproduce hadronic and leptonic kinematics, since both affect neutrino energy reconstruction

Measurement of μ plus p final states in ν_μ Interactions on Hydrocarbon at average E_ν of 4.2 GeV
PRD 91, 071301 (2015)

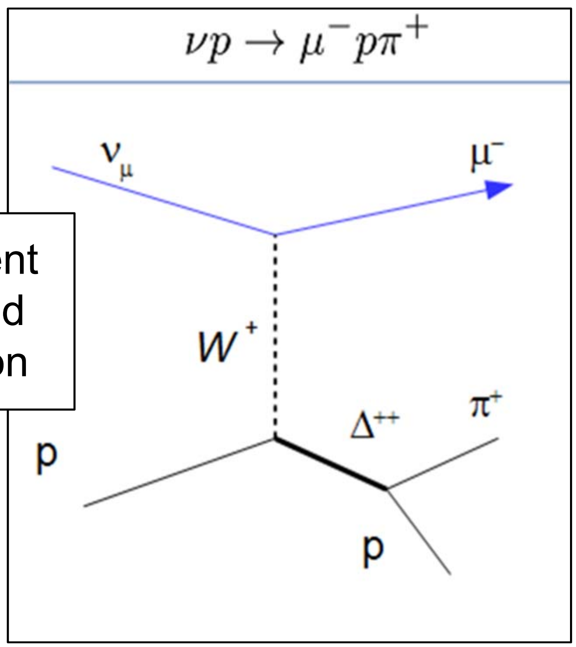
Discussion

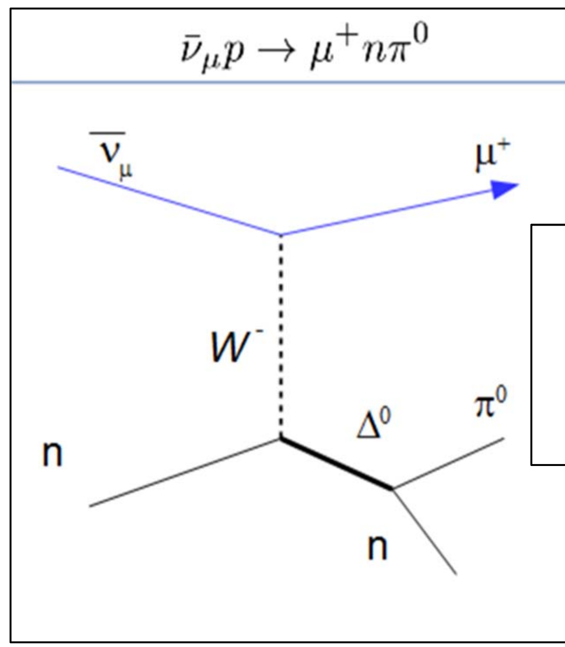
- Evolution is interesting
  - Axial form factor vs. normalization vs. nuclear physics (MEC)
  - Many theory papers with MEC match MiniBooNE data well
  - Recent theory papers call this into question
  - If MEC, should see evidence in low energy nucleon 'tracks' close to vertex (e.g. in 30 cm volume around vertex)
- MINERvA studied vertex energy
  - Proton distribution from μ+Np expt.
  - Incl expt measured vertex energy, consistent with extra proton for ν, but matches $\bar{\nu}_\mu$ (consistent with MEC)
  - protons give response in scintillator, evidence for MEC?
  - Interesting future possibility (under study)



CC Single Pion Production

Charged-Current
Single Charged
Pion Production

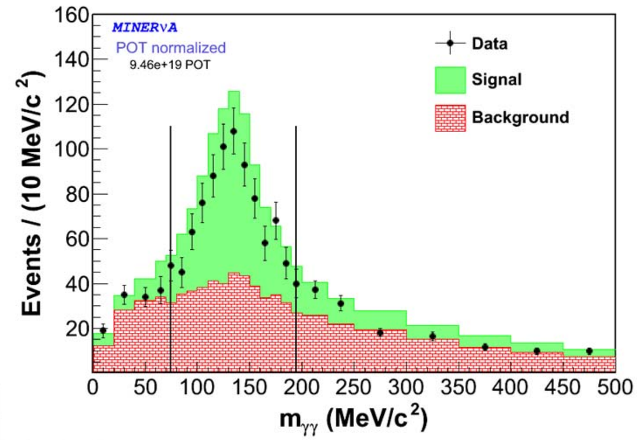




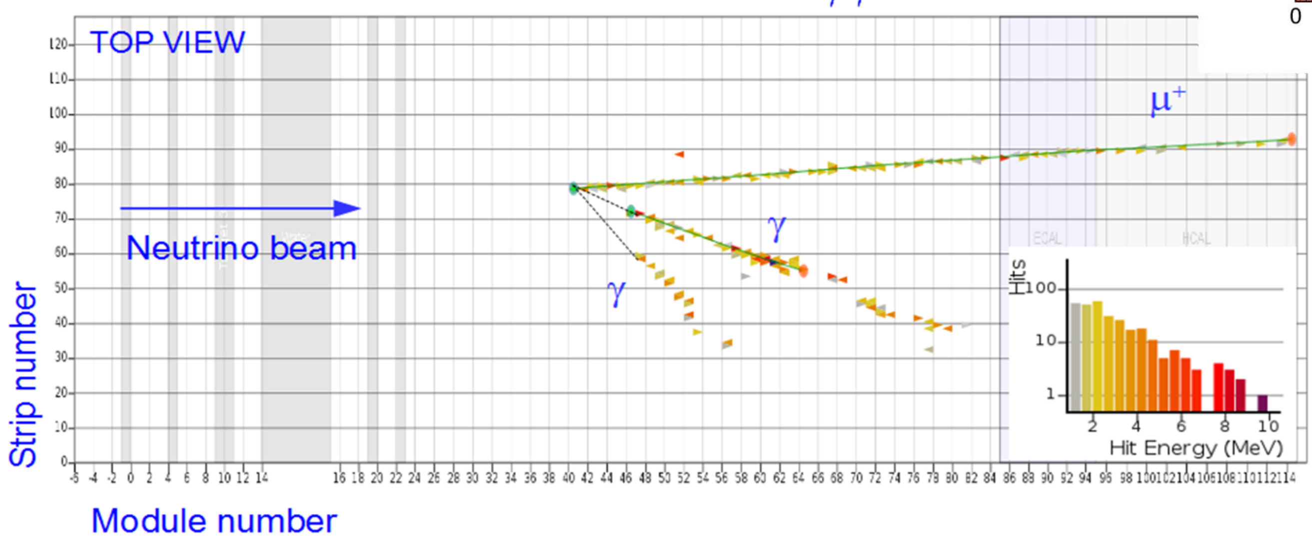
Charged-Current
Single Neutral
Pion Production
by nubar

Charged-Current Single Neutral Pion Production by $\bar{\nu}_\mu$

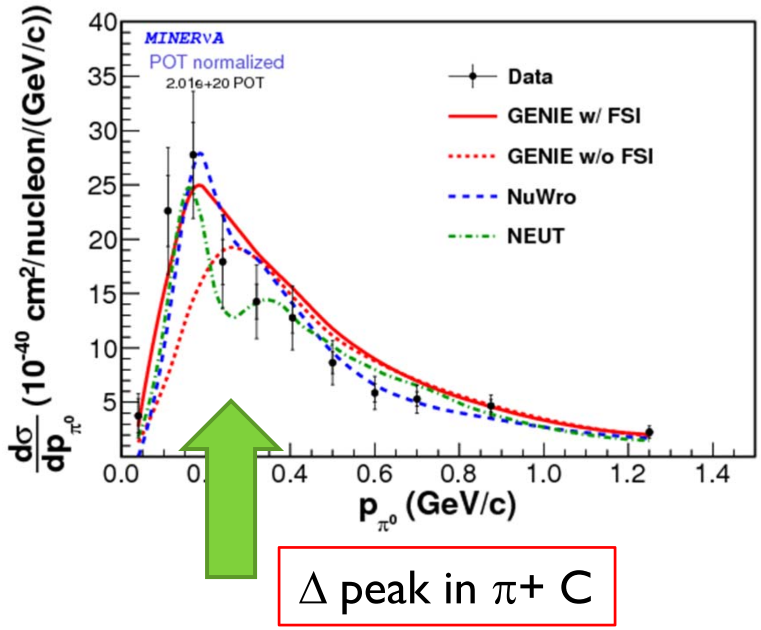
- Importance as background for oscillation expts
  - ❑ can mimic electron neutrino signal
  - ❑ π^0 decays to 2 photons and easy to miss 1 of them
- Only 1 low statistics data point before

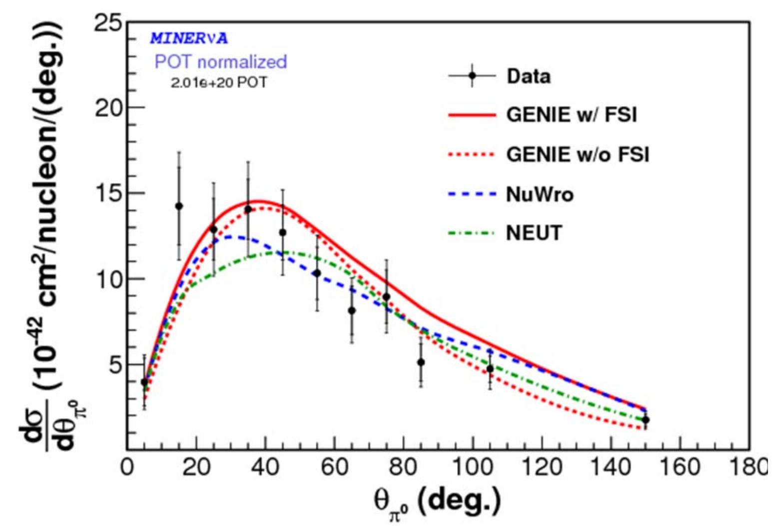


$$\bar{\nu}_\mu + \mathrm{CH} \to \mu^+ \pi^0 X$$
$$\hookrightarrow \gamma\gamma$$



Single Neutral Pion Production Results





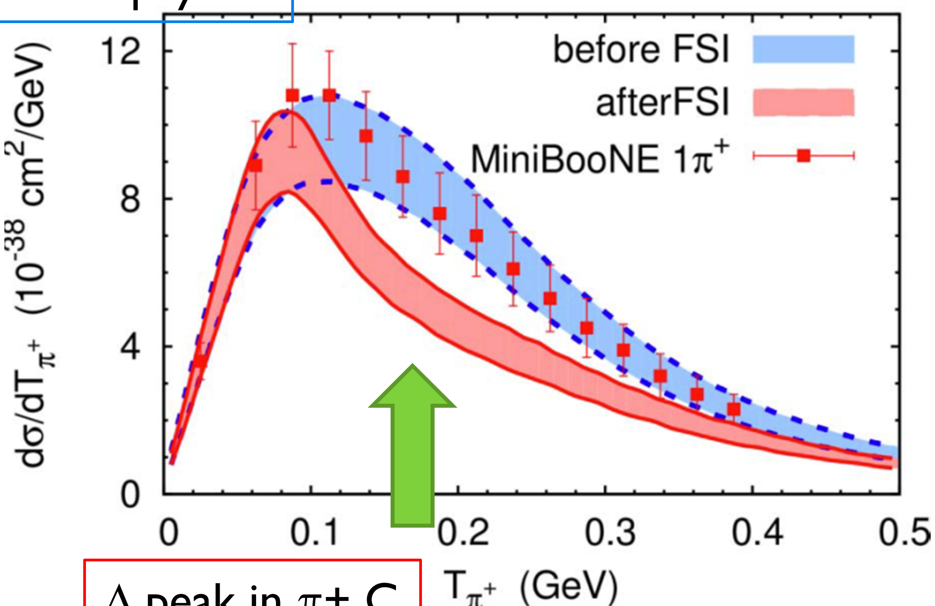
- Data are in better agreement when final state interactions are included
- First measurement of the differential cross sections vs π^0 kinematics for this pion production channel (hard to simulate).
- These cross sections can be used as benchmark to evaluate neutrino generator performance in π^0 production by anti-neutrinos for current and future oscillation experiments

Data relevant to CCQE-like oscillation signal
(How often does pion disappear in FSI?)

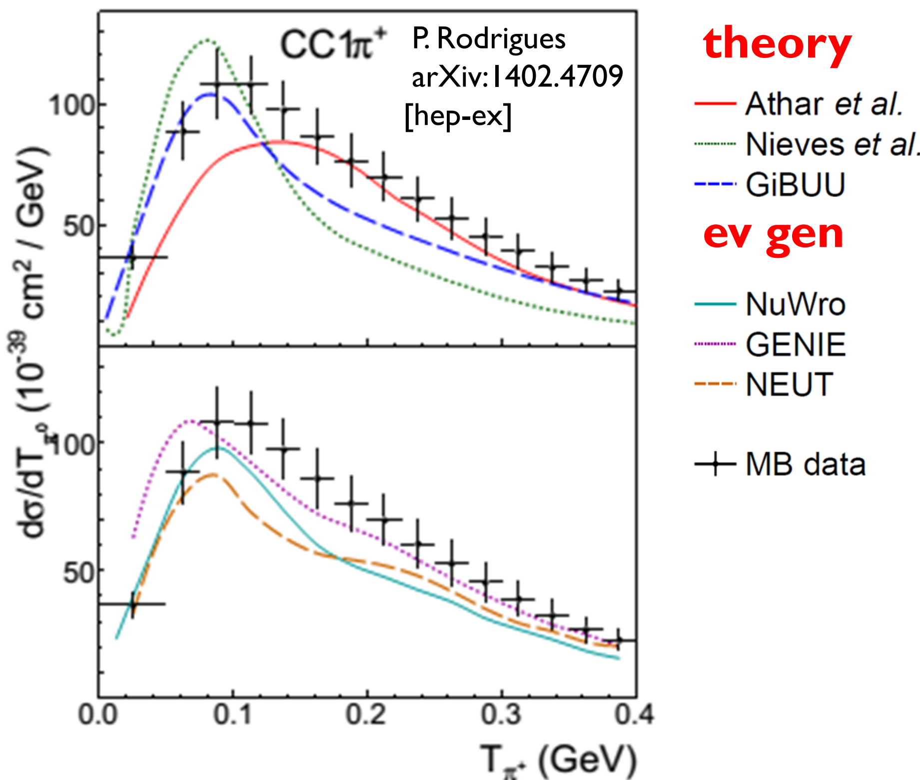
- MiniBooNE data hard to reproduce, questions FSI models?
- Surprising result, needs more data (different detector, E_ν)

GiBUU: Best nuclear physics

Data at E_ν~1 GeV

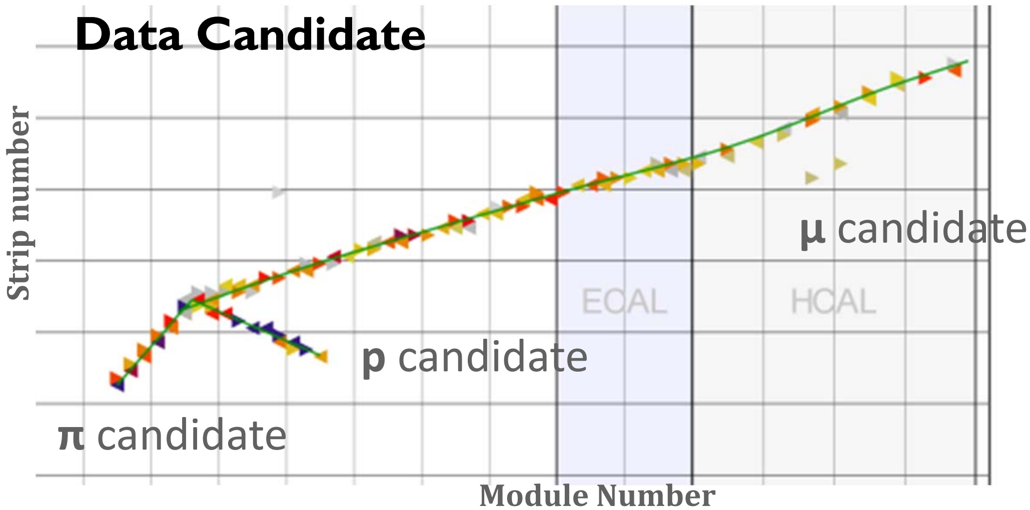


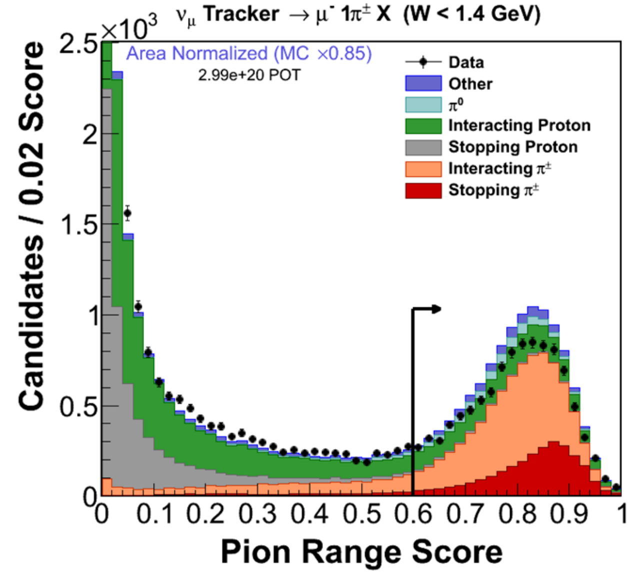
Δ peak in π+ C



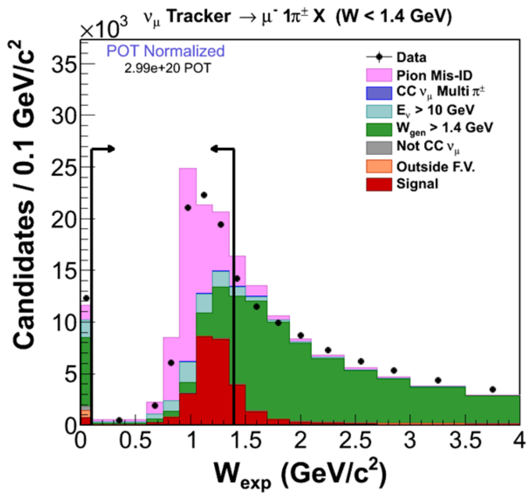
GiBUU: O. Lalakulich and U. Mosel, PRC 87, 014602 (2013)
NuWro: T. Golan, C. Juszczak, J. Sobczyk Phys Rev C80, 15505 (2012)
Nieves: E. Hernanadez, J. Nieves, M.Vicente Vacas, Phys Rev D87, 113009 (2013)

Need to detect a pion+muon in plastic





Main bkgd from true events at W>1.4 GeV Subtract feeddown events with MC.



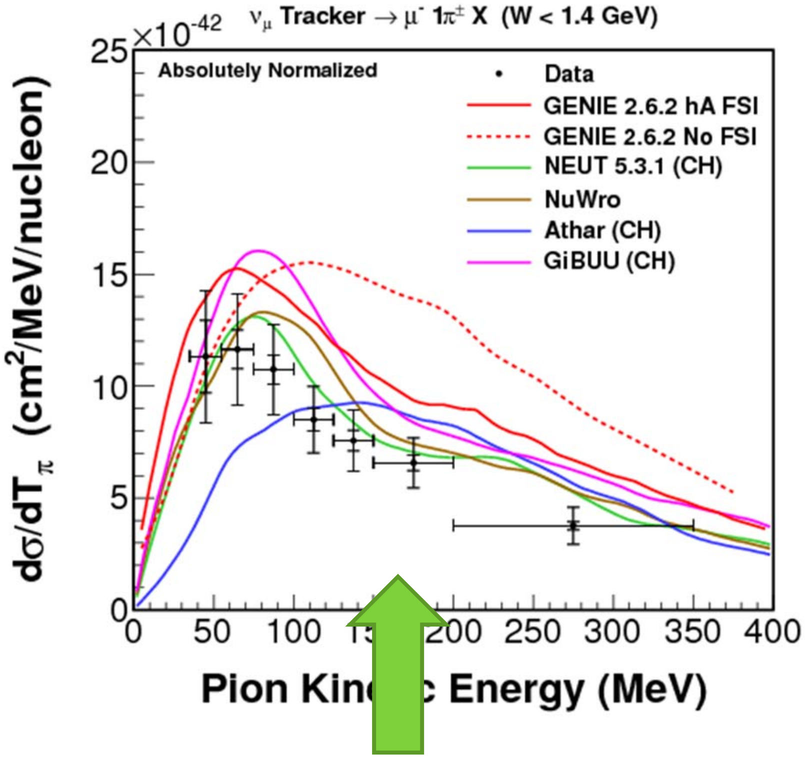
π PID from range formula, Michel tag (purity~90%)

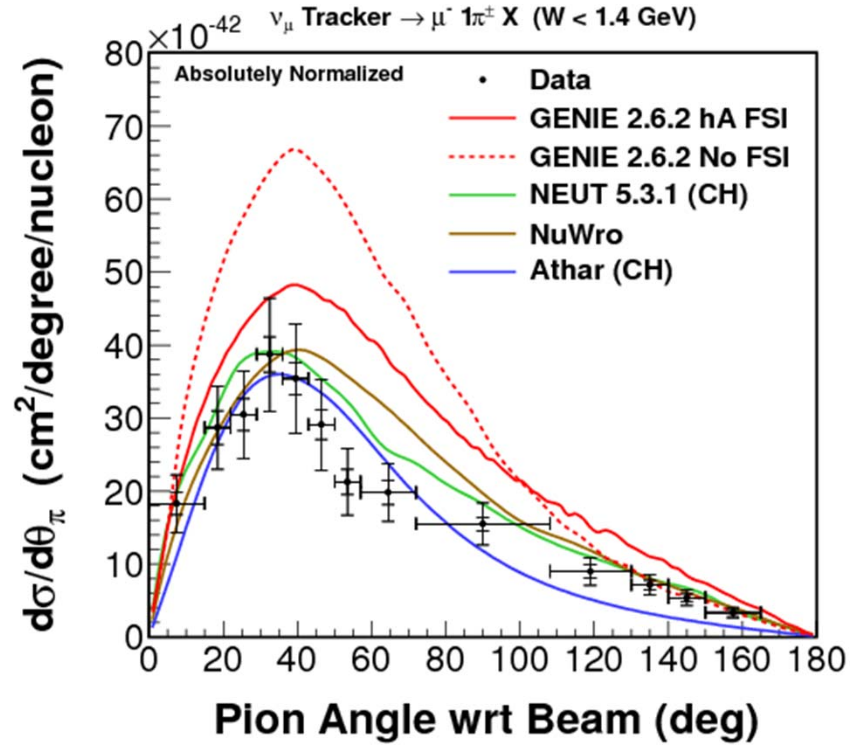
$E_\nu = E_\mu + E_H$

$Q^2 = 2E_\nu(E_\mu - p_\mu\cos\theta_{\mu\nu}) - m_\mu^2$

$W_{exp}^{\ 2} = -Q^2 + m_n^{\ 2} + 2m_n E_H$

Absolute cross section- model comparisons

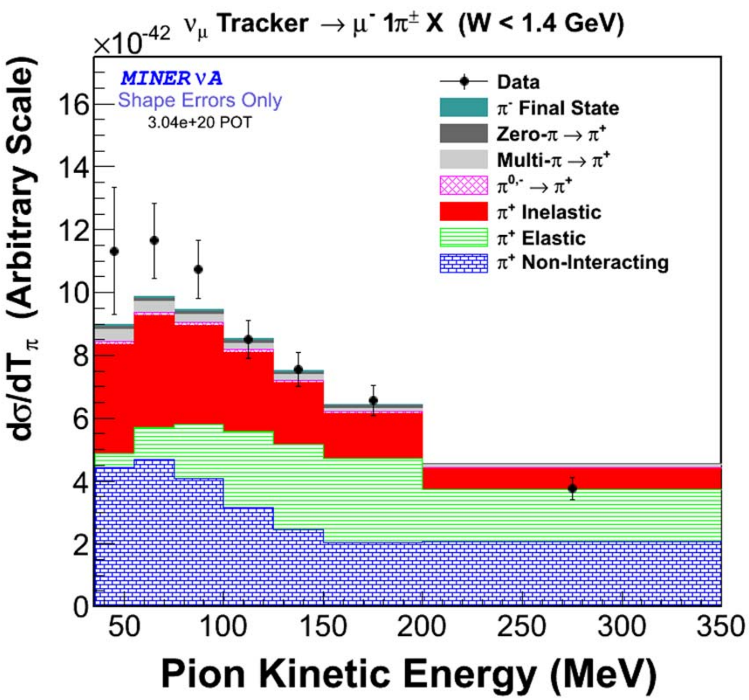


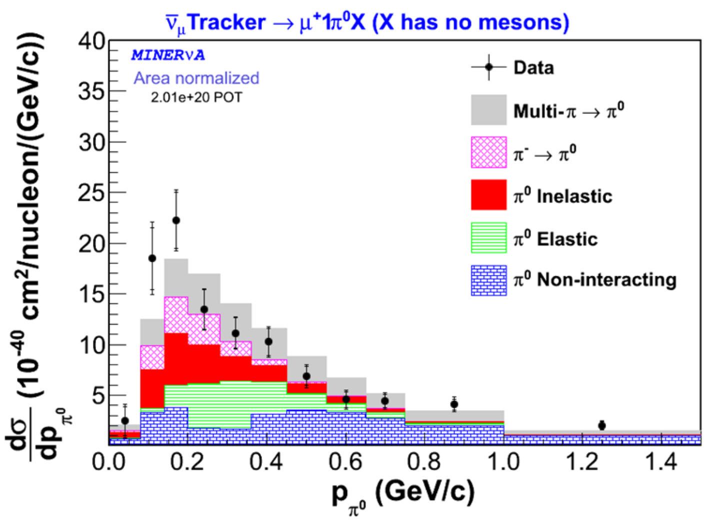


- NEUT and NuWro normalization agree the best with data.
- GiBUU, GENIE normalizations disfavored by a couple σ
- Shape equally described by all calcs with modern FSI (π scattering)
- Important to characterize FSI effects for better understanding

Dig deeper into FSI

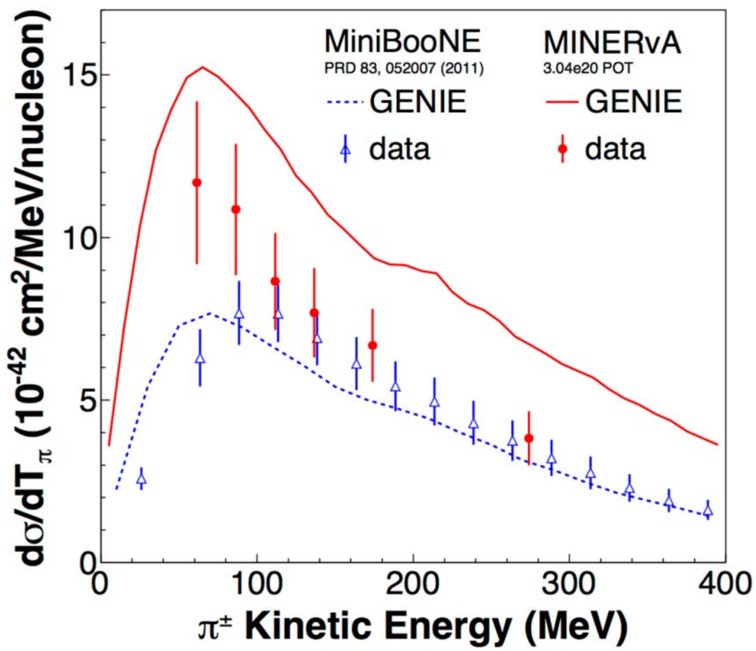
- Data are sensitive to pion prod xs, medium effects; however, FSI is largest effect.
- Data for π^+ dominated by Δ, less so for π^0.



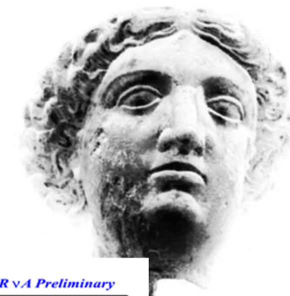


discussion

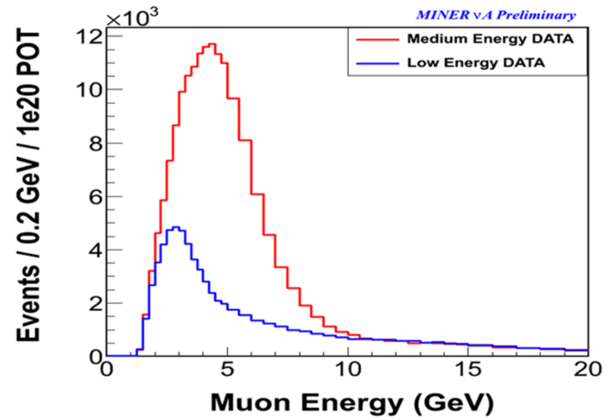
- Tension with models is shifted
- MiniBooNE - <E_ν>~1 GeV
  - Best models (GiBUU, Valencia) strongly disagree in shape
  - Event generators have shape right, but problems in detail
- MINERvA - <E_ν>=4 GeV
  - Dominantly Δ resonance formation, decay in nucleus, very similar to MiniBooNE
  - Event generators have shape, magnitude
  - GiBUU has shape right, but wrong magnitude
- No calculation describes both data sets well
  - Theory based calculations have better physics (nuclear corrections), but don't describe data better than simpler event generator codes.
  - Energy dependence difficult for all calcs.

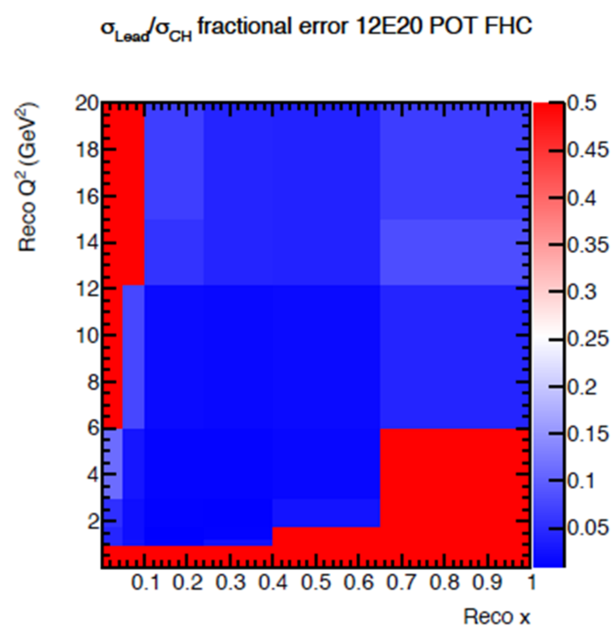


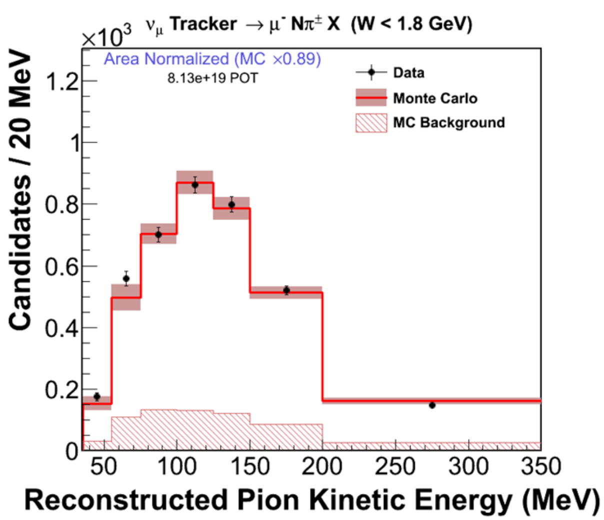
MINERvA Medium Energy Data



- Run started in 2013
  - Already more POT than LE data taking
- New possibilities
  - Higher ν energy allows study of DIS region and nucleon structure functions
  - Increased statistics gives nuclear target ratios for all interactions

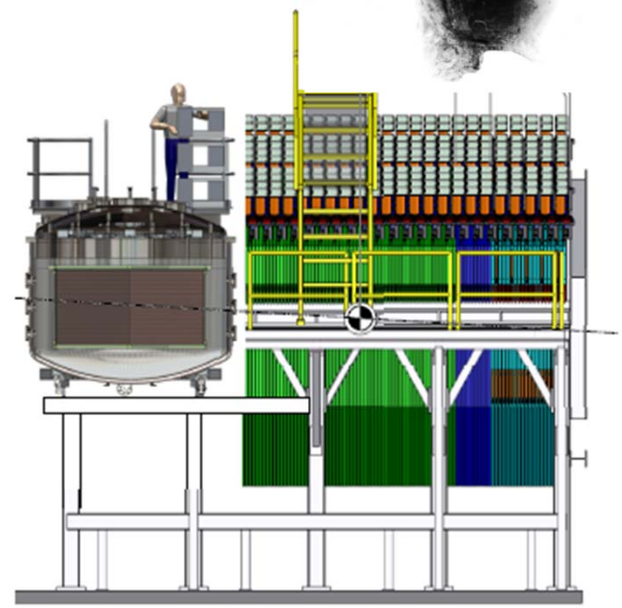




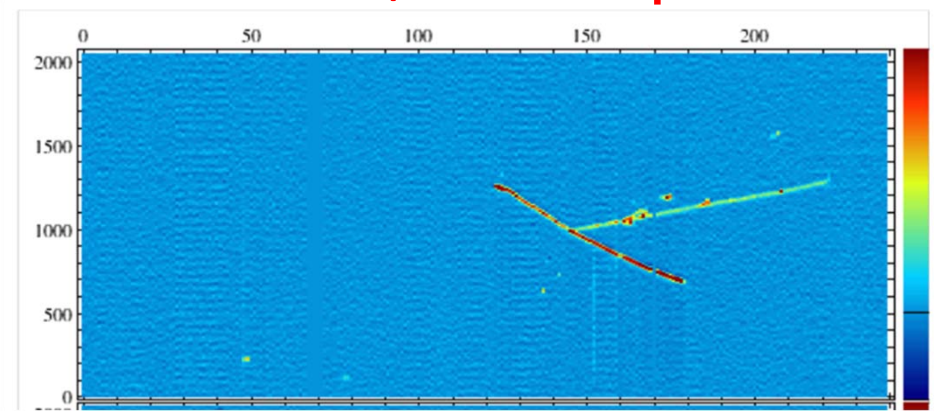


CAPTAIN-MINERvA

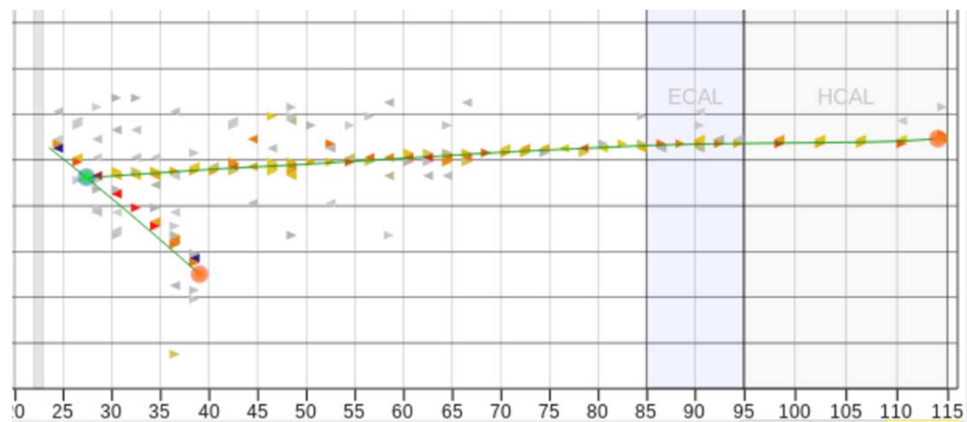
- Extend the physics reach of MINERvA by putting active LAr target upstream of scintillator
- High statistics data for Ar/CH ratios possible
- Direct probe of nuclear effects
- These will be used by DUNE just like T2K is already making use of MINERvA data, ν energy very similar.



Back to back protons + μ candidate events:



ArgoNeuT event



MINERvA event

CAPTAIN-MINERvA letter of intent: http://minerva.fnal.gov

Conclusions

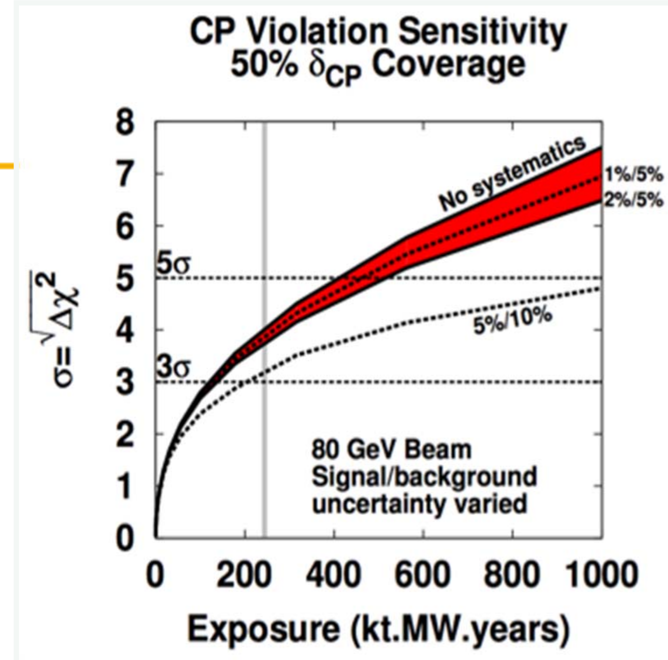
- ν oscillation expts depend on MC, cross section results
  - Daya Bay, MiniBooNE, and T2K have great results at low $E\nu$.
  - NOvA (taking data now) and DUNE are future at higher $E\nu$.
- MINERvA cross section results are taking a lead role.
  - Provide detailed data at ν energy close to NOvA, DUNE
  - Emphasize shape and ratios in first publications (flux work important)
  - Comparisons to MiniBooNE at lower energy come first.
- clarify problems of today, produce new detail for future.
  - Provide data for understanding systematic errors (links to MC)
  - CCQE data most consistent with model with MEC
  - CC1π data has shape similar to MiniBooNE, disagreement with models less dramatic but no model agrees with both data sets

backup

- Some info on flux - what is latest?
- Details on tracking, vertexing?
- Details on models?

Oscillations-cross section interface

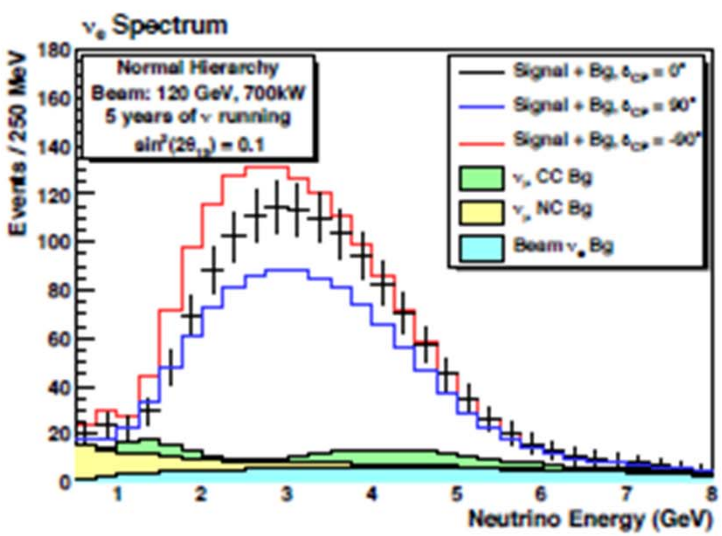
- Cross section experiments provide
  - Cross sections for many processes, energy and A dependence
  - Tests of E_ν methods
  - Ways to reduce systematic errors coming from model dependence
- Event generators
  - Provide MC models for all processes for all E_ν, nuclei
  - Interpolate between experiments

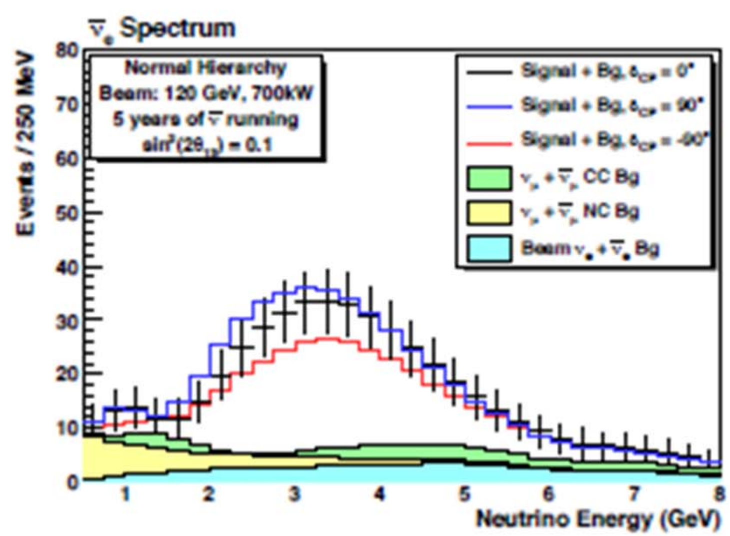


Source of Uncertainty	Est. stan. dev.
Cross section (MC)	**4.9%**
Cross section (ND280), Flux	2.7%
Far Det, FSI	**5.6%**
Oscillation parameters	0.2%
TOTAL	8.1%

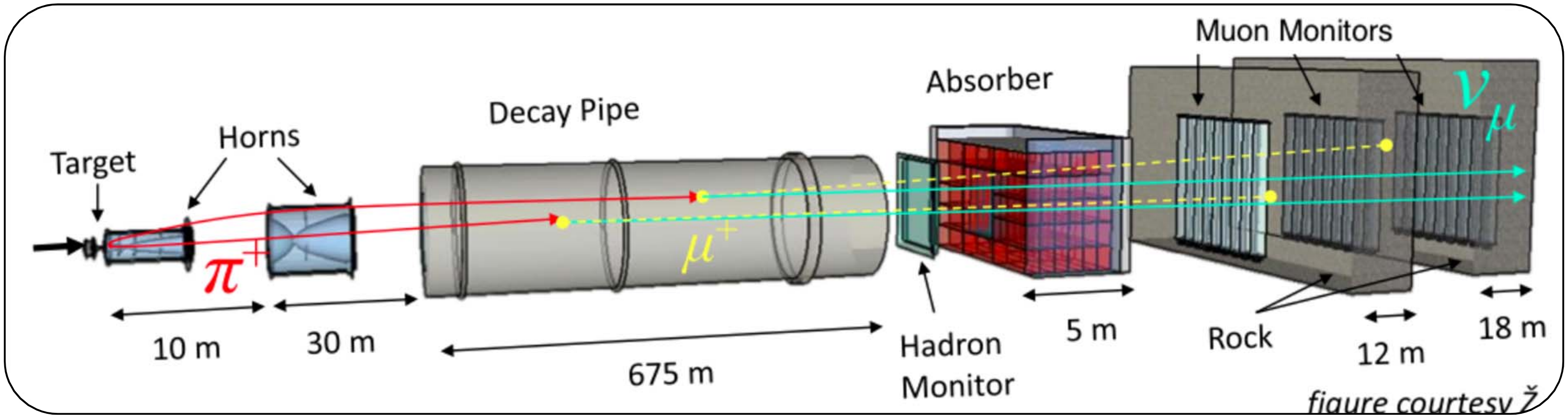
Future Oscillations - LBNE

- Maximum CP effect is range of red-blue curve
- E_ν Spectrum information is convolution of flux, cross section, and oscillation effects
- Backgrounds are significant, vary with energy and are different between neutrino and anti-neutrino beams
  - Feed-down from higher energy makes 2nd maximum difficult



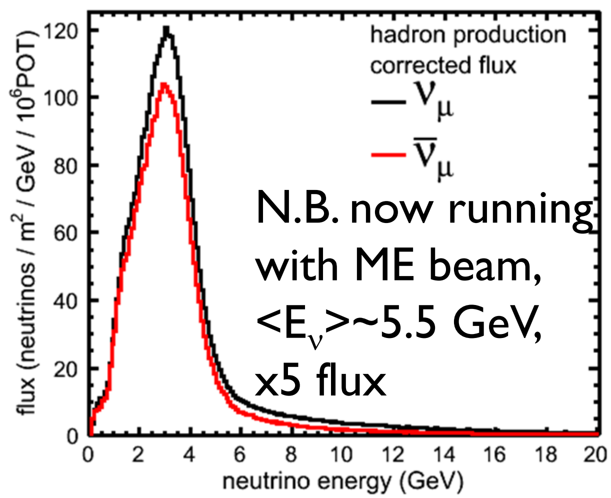


NuMI Beam (~same for MINOS, NOvA)



- NuMI is a "conventional" neutrino beam, neutrinos from focused pions
- For MINERvA, flux must be calculated, use hadron prod data.
- **protons on target (POT) to MINERvA**
  - neutrino (LE): 3.9E20 POT
  - anti-neutrino (LE): 1.0E20 POT

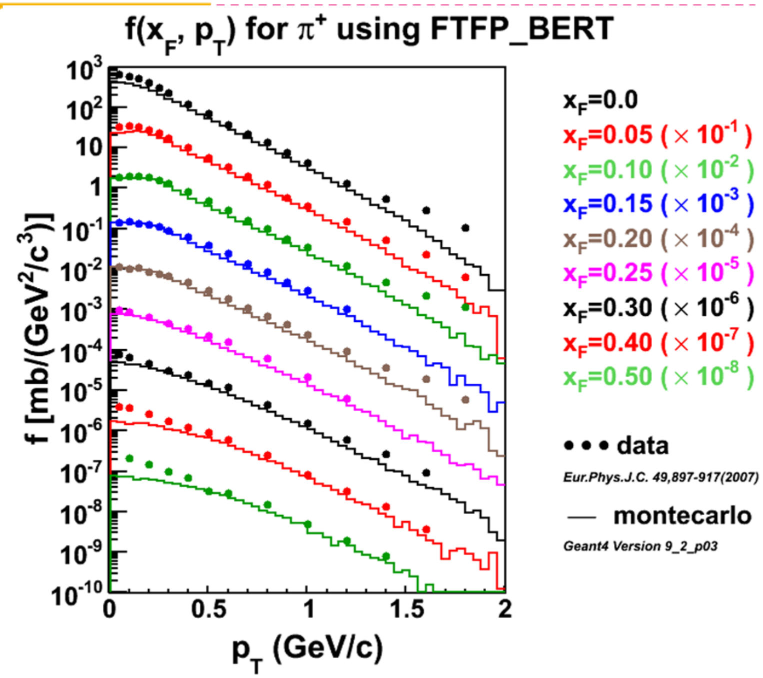
NuMI Low Energy Beam Flux

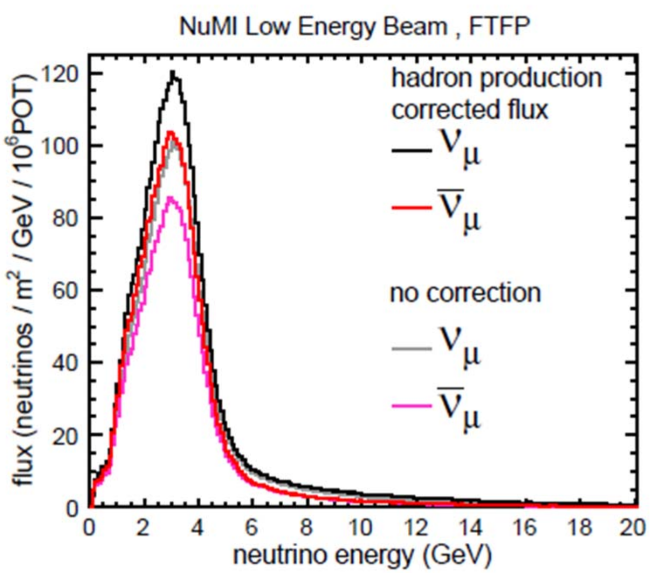


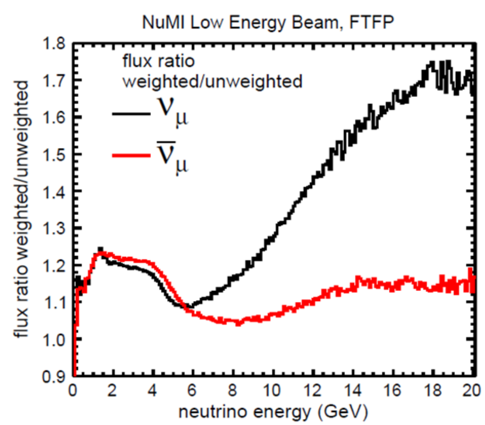
NuMI Flux Measurement

•Flux measurements are hard!

•MINERvA flux is simulated by GEANT4 and reweighted to match hadron production data from NA49. Recent MIPP publication will help a lot.







Differential Cross Section

Differential cross-section vs. ***4-momentum transfer squared***

not to "generator Q^2"

Q^2_{QE} reco μ kinematics $\rightarrow$ Q^2_{QE} true μ kinematics

backgrounds constrained by data

$$\left(\frac{d\sigma}{dQ^2_{QE}}\right)_i = \frac{1}{\Phi T}\frac{1}{\Delta Q^2_{QE}}\frac{\sum_j U_{ij}\left(N_{data,j} - N_{bg,j}\right)}{\varepsilon_i}$$

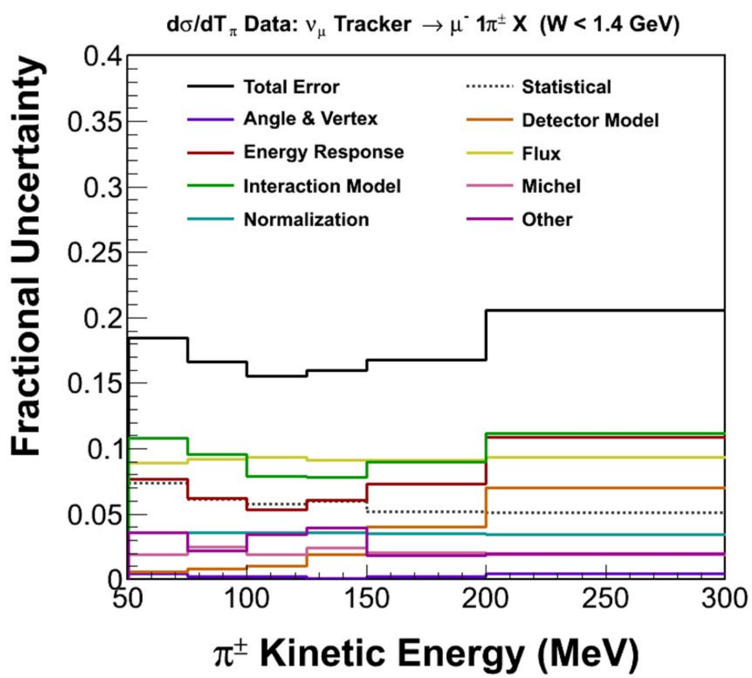
flux, targets

bin size

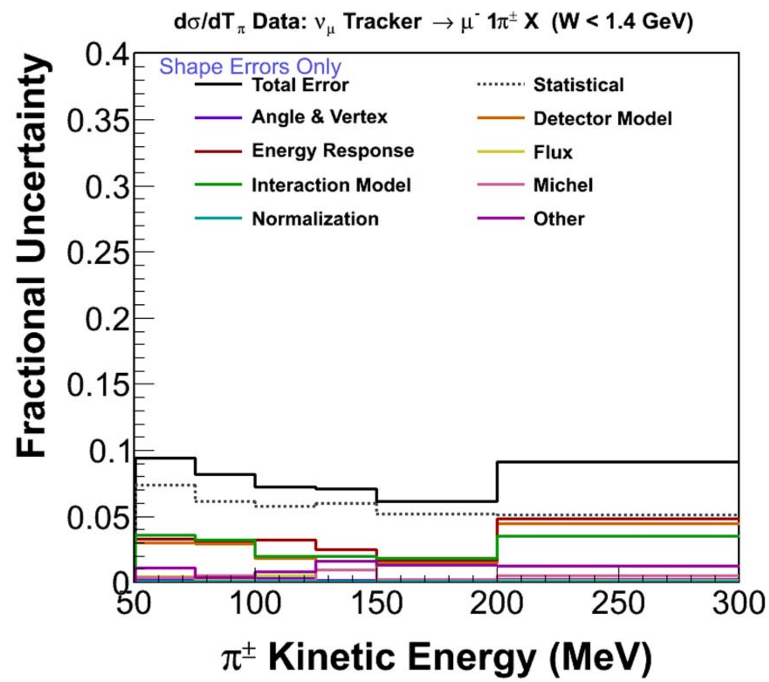
muon eff constrained with data;

recoil eff uses MC away from vertex

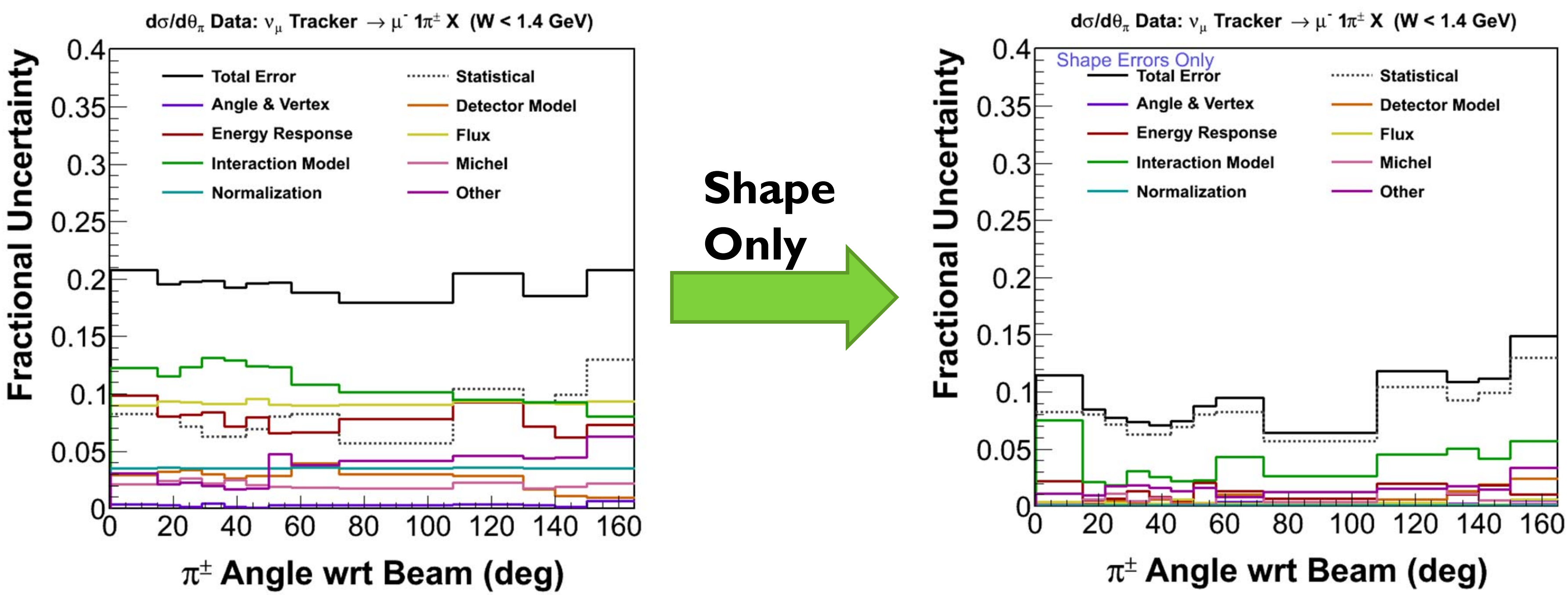
T_π Error Summary



Shape Only

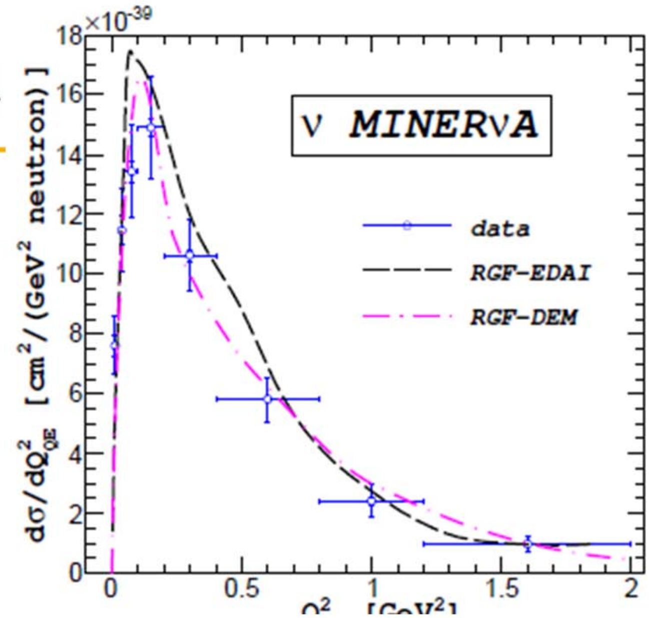


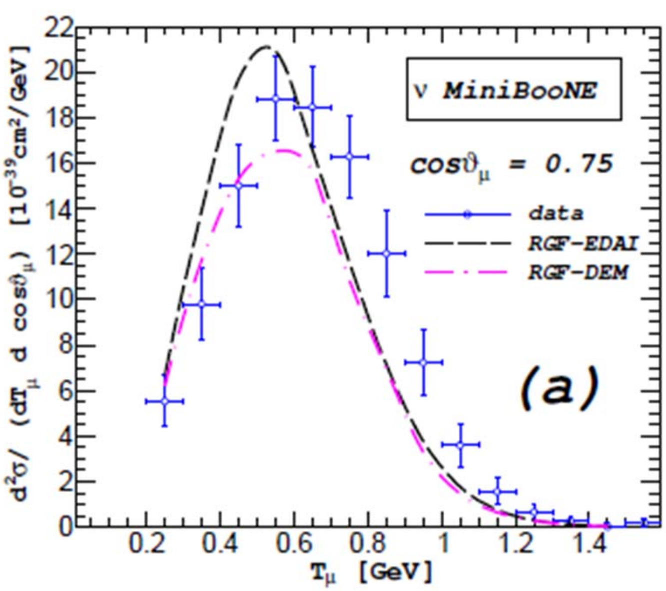
θ_π Error Summary

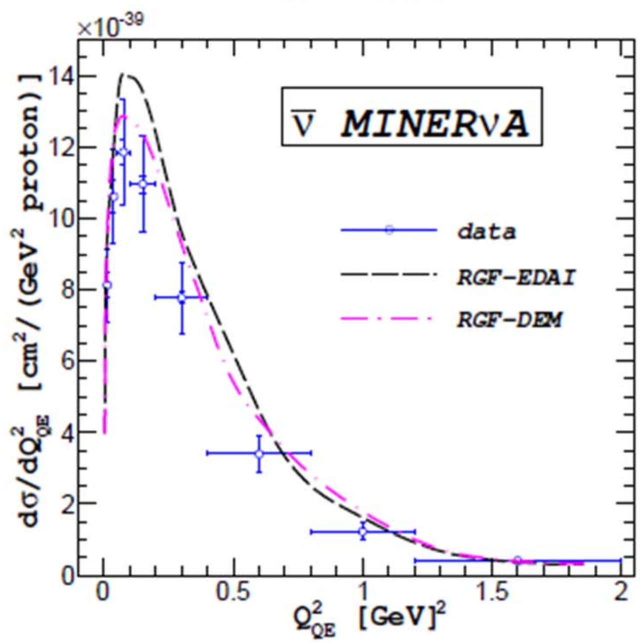


Recent theoretical work Meucci, Giusti arXiv:1404.3554

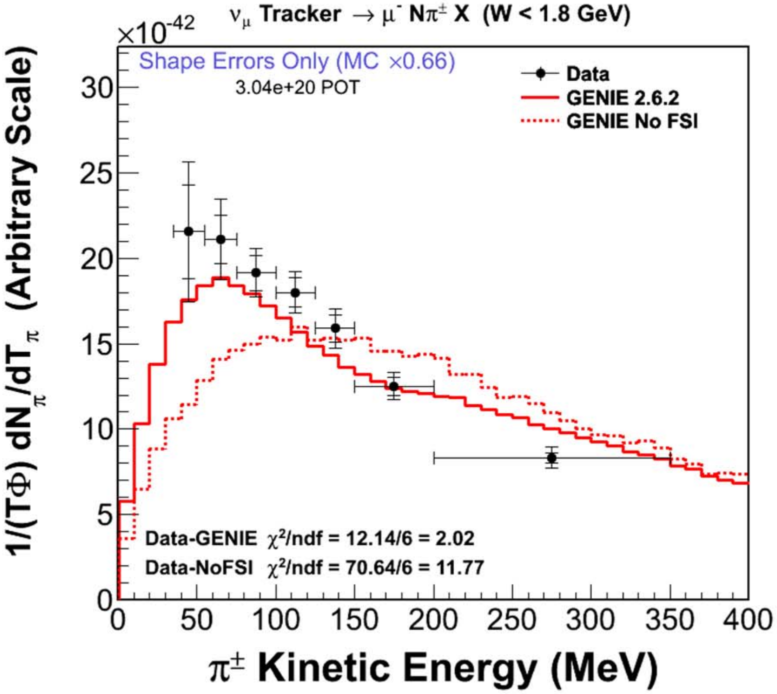
- Relativistic Greens' Function model
- Full correlations in initial state
- Key concept is nucleon FSI (EDAI, DEM are 2 versions)
- No MEC needed!

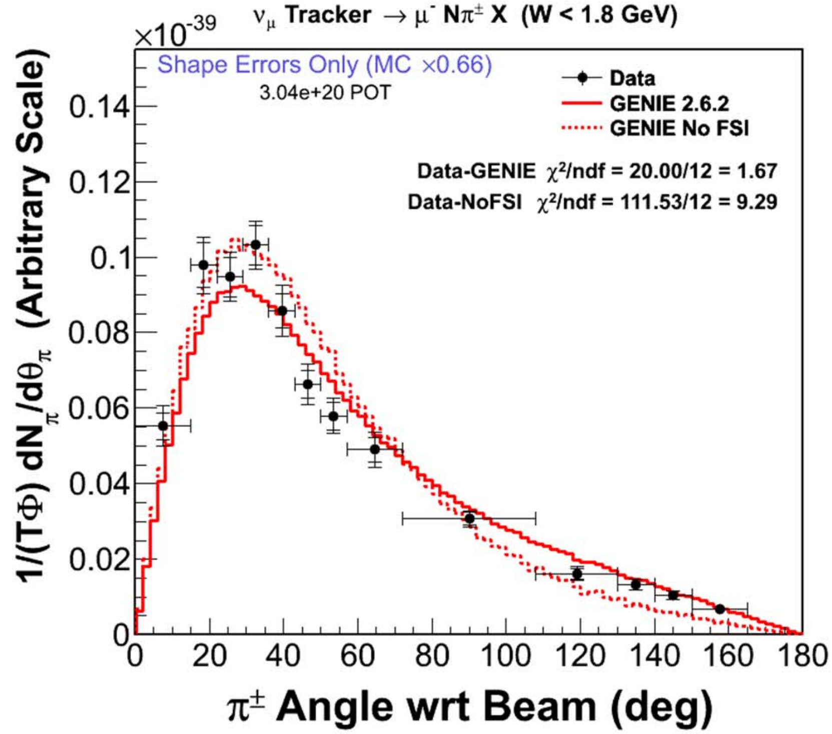






Shape results (W<1.8 GeV)

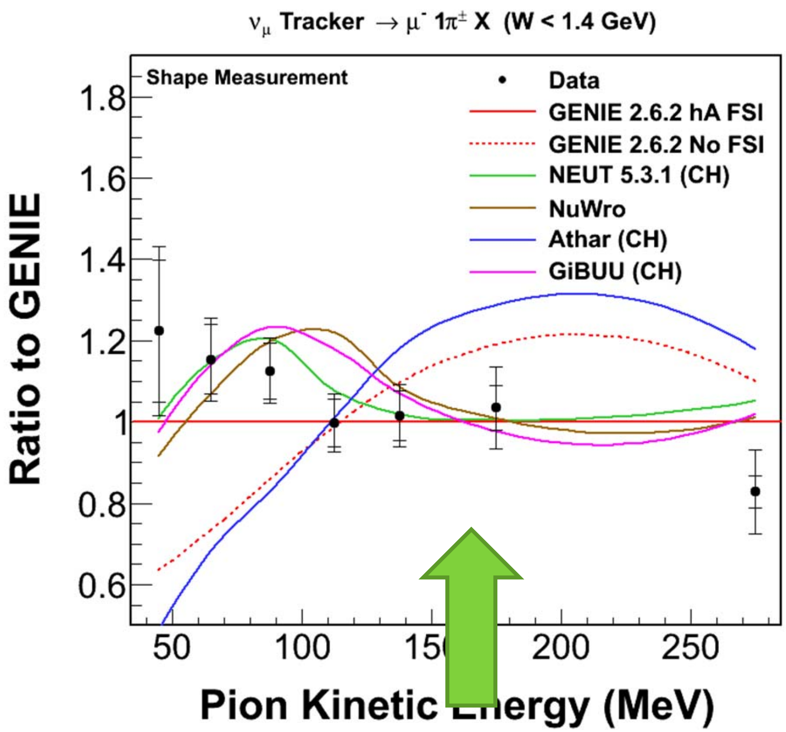


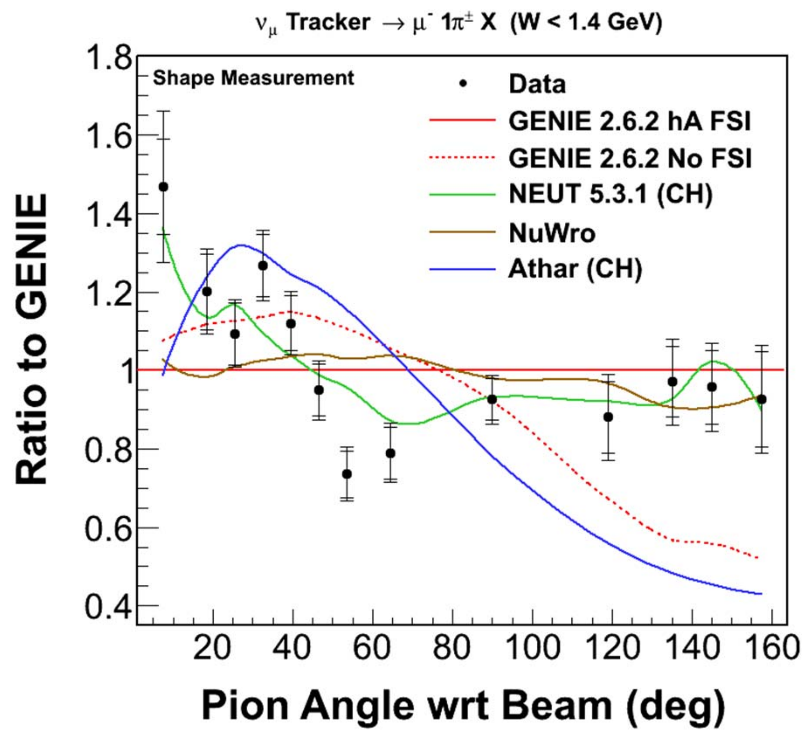


- Another version of the analysis, allowing for multiple pions in the final state and higher order resonances: W < 1.8 GeV
- Consistency with W < 1.4 provides some reassurance that the analysis is robust against choice of W cut, multi-nucleon correlations

Shape results – model comparisons

- Each calc normalized to data, show ratio to GENIE w/FSI

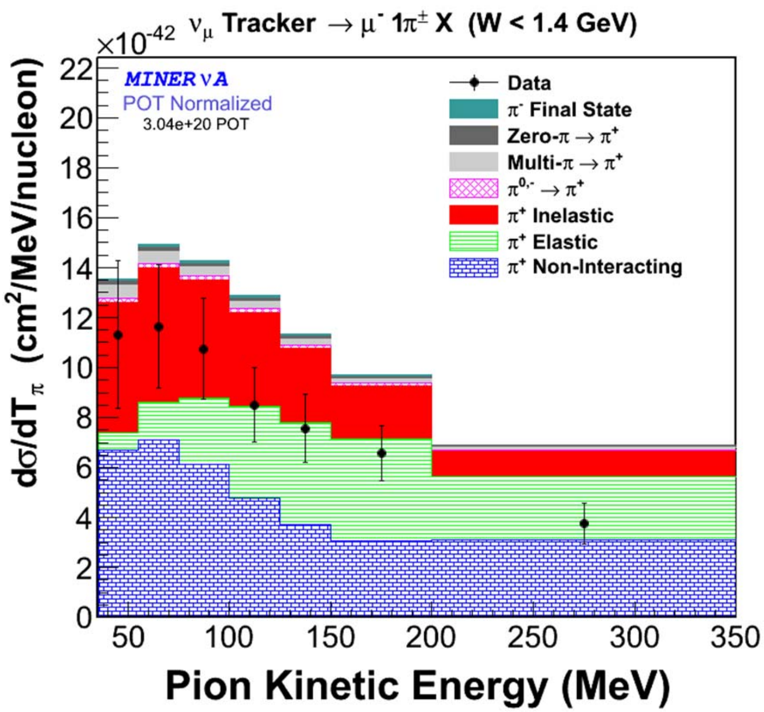


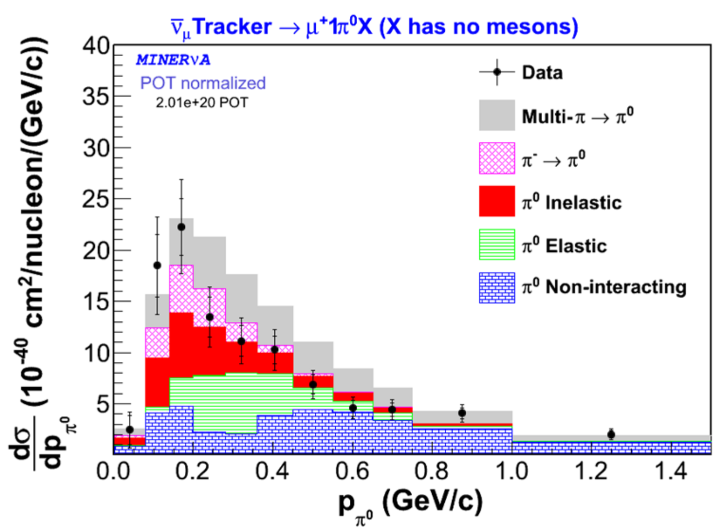


- GiBUU, NuWro, NEUT and GENIE all predict the data shape well
- Data sensitive to the details in pion interaction models
- Athar does not agree with data. Likely due to an insufficient FSI model

Dig deeper into FSI

- Data are sensitive to pion prod xs, medium effects; however, FSI is largest effect.
- Data for π^+ dominated by Δ, less so for π^0.





MINERvA Next Results

- MINERvA has lots of Low Energy Data for analysis

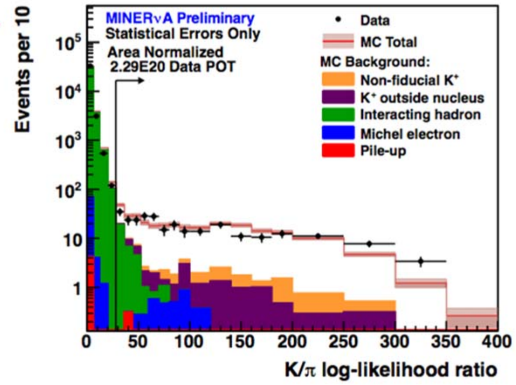
- Electron Neutrino CCQE
  - o Important test of whether assumptions based on ν_μ scattering hold

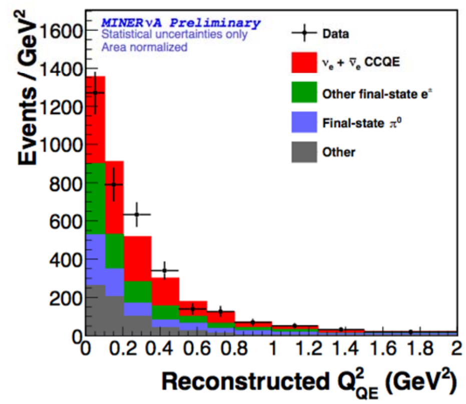
- Kaon Production
  - o Kaons can mimic proton decay signal

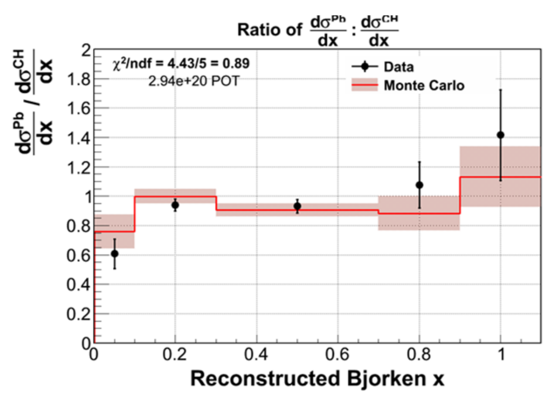
- Exclusive Nuclear Target ratios

- Double Differential CCQE Cross Section

… and more!







Model details

- Theory-based models use best (e,e') models
  - Good nuclear models (e.g. Spectral Function, RMF)
  - Nuclear medium corrections to production vertex
  - Higher order mechanisms, e.g. MEC
  - Theory-based nonresonant pion production
- Event generators (MC) have simpler models
  - Fermi Gas nuclear model (SF recently added)
  - No nuclear medium effects
  - No higher order mechanisms (recently added)
  - Phenomenological nonresonant pion production
  - Recent additions not reflected in results shown here