Neutrino-nucleus scattering results from MINERvA

Jeff Nelson
William & Mary

UVA seminar

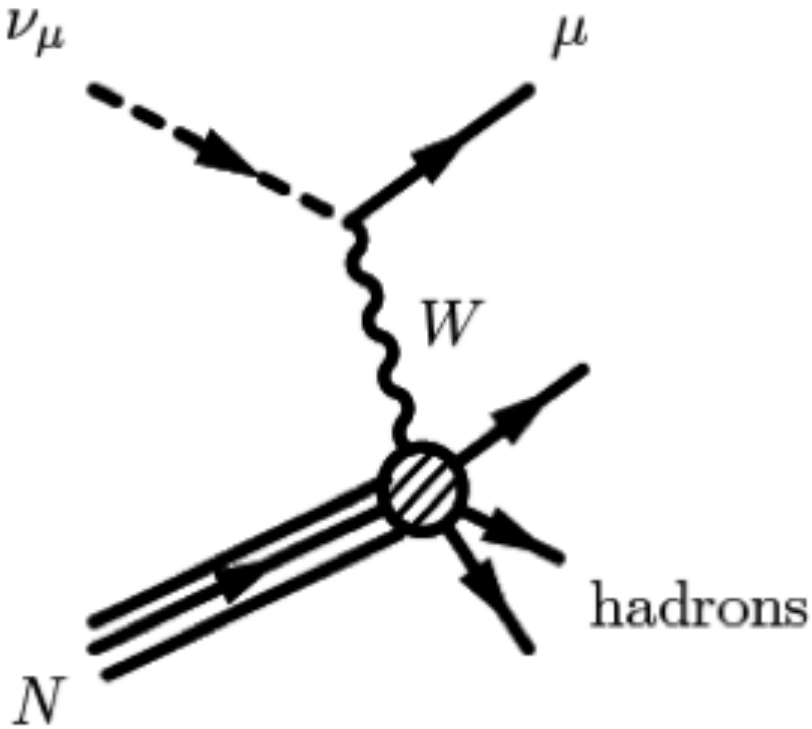
11/11/15

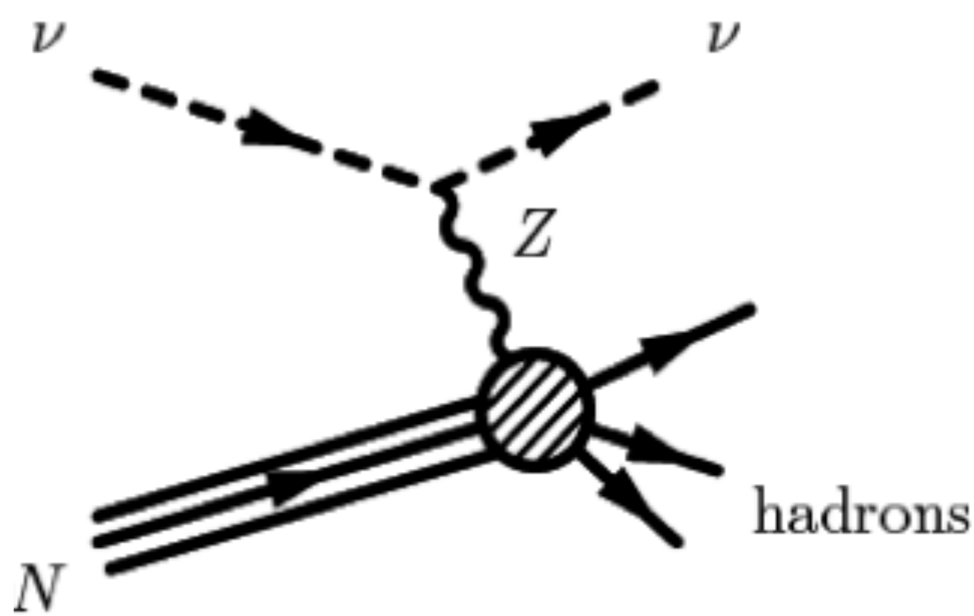
Outline

- Neutrinos Oscillations
  …. and why do we care about neutrino interactions?
- The MINERvA detector
  - Measuring a cross section
  - Need to know your flux
- Step through interaction categories & compare with current models
  - Inclusive scattering
  - Quasi-elastic and QE-like
  - Single charged/neutral pion production
  - Coherent charged pion production
  - Electron neutrino QE
  - Observation of diffractive neutral pion production
  - Inclusive and DIS nuclear effects
- Future plans

Neutrino interactions

- Charged current (CC, W exchange)
  - > Lepton tags neutrino, all energy seen, threshold due to lepton mass
- Neutral current (NC, Z exchange)
  - > Outgoing neutrino – no energy threshold
  - > Missing energy & no flavor information

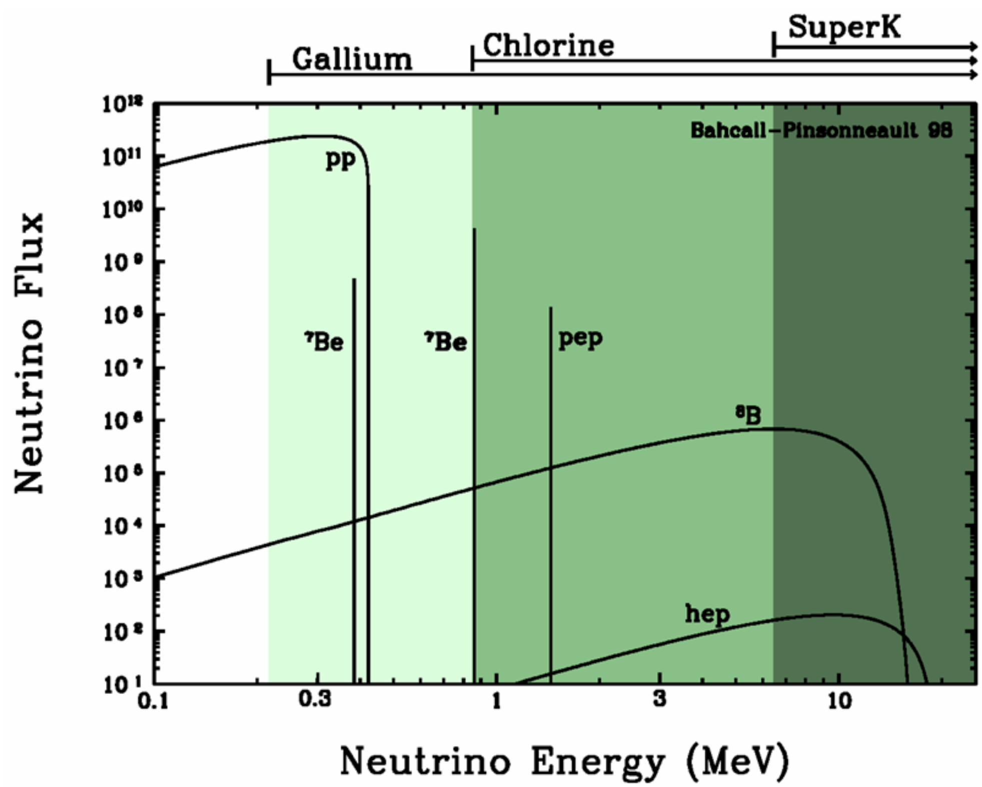




Neutrinos oscillations

Solar neutrinos

- The Sun produces neutrinos as it converts hydrogen to helium
- The neutrino production rate is well known based on the amount of light emitted by the sun

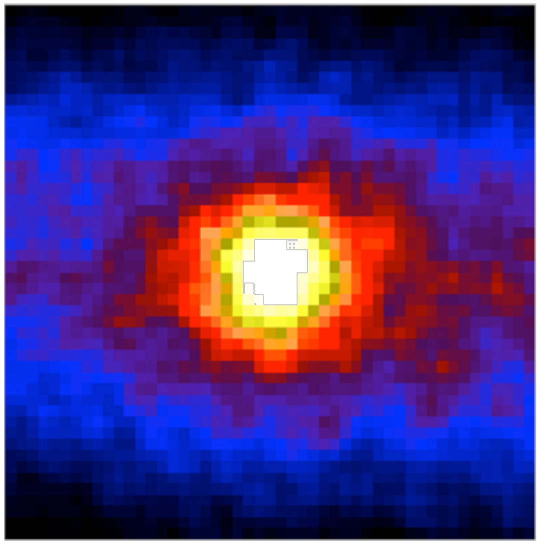


REACTION	TERM. (%)	ν ENERGY (MeV)
$p + p \rightarrow {}^2H + e^+ + \nu_e$	(99.96)	≤ 0.423
or		
$p + e^- + p \rightarrow {}^2H + \nu_e$	(0.44)	1.445
${}^2H + p \rightarrow {}^3He + \gamma$	(100)	
${}^3He + {}^3He \rightarrow \alpha + 2p$	(85)	
or		
${}^3He + {}^4He \rightarrow {}^7Be + \gamma$	(15)	
${}^7Be + e^- \rightarrow {}^7Li + \nu_e$	(15)	0.863 90% 0.385 10%
${}^7Li + p \rightarrow 2\alpha$		
or		
${}^7Be + p \rightarrow {}^8B + \gamma$	(0.02)	
${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$		< 15
${}^8Be^* \rightarrow 2\alpha$		
or		
${}^3He + p \rightarrow {}^4He + e^+ + \nu_e$	(0.00003)	<18.8

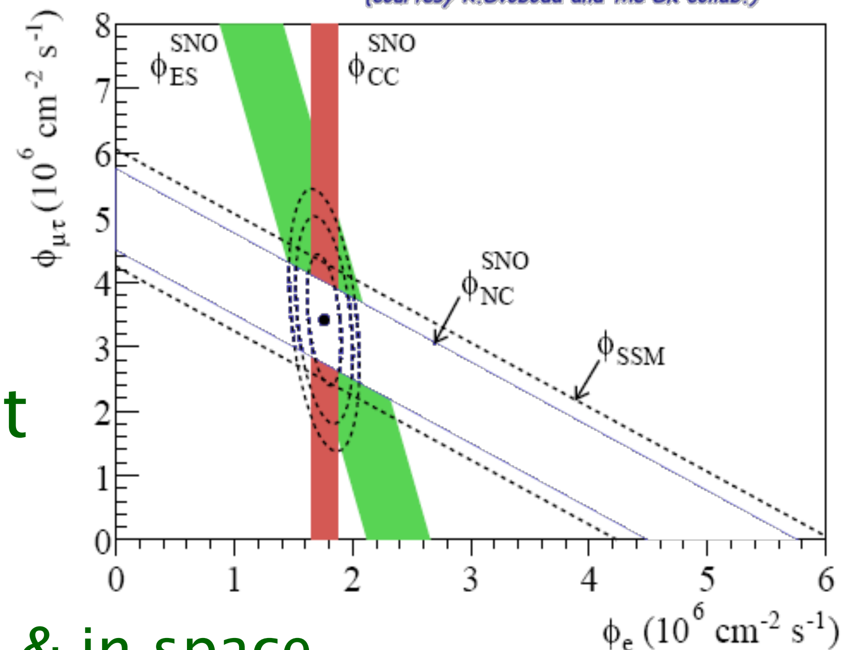
Neutrino terminations from BP2000 solar model.
Neutrino energies include solar corrections:
J. Bahcall, Phys. Rev. C, 56, 3391(1997).

Solar Neutrino Experiments

- Up to 2002 the data was confusing
- Solar electron neutrinos seen by 6 different experiments using 3 techniques
  - > Experiments mostly sensitive to ν_e CC
- Rates and spectrum different than standard solar model
  - > Problem with the neutrinos?
  - > Problem with the solar model?
- Solved by the SNO experiment
  - > Could see all 3 types via NC
  - > It's the neutrinos
  - > They change types inside the Sun & in space



The sun imaged with neutrinos
(courtesy R.Svoboda and the SK collab.)



2-Flavor Oscillation Formalism

- What if there 2 neutrino basis (weak force & mass)?

$$|\nu_l\rangle = \sum U_{li}|\nu_i\rangle$$

- The probability that a neutrino (e.g. ν_μ) will look like another variety (e.g. ν_τ) will be

$$P(\nu_\mu \rightarrow \nu_\tau; t) = |\langle\nu_\tau|\nu_\mu(t)\rangle|^2$$

- 2-component unitary admixture characterized by θ:

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2(2\theta)\,\sin^2(1.27\,\Delta m^2\, L/E)$$

- Experimental parameters

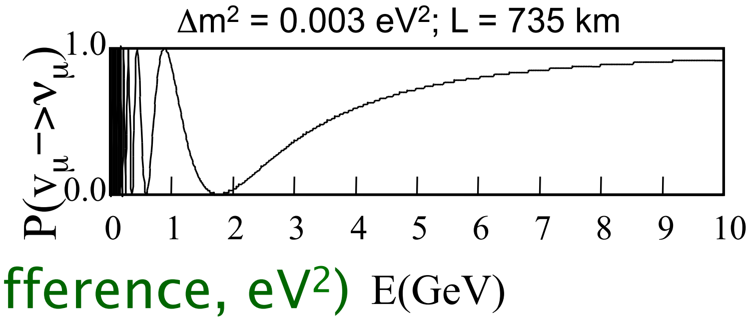
  L (distance from source to detection, km)

  E (particle energy, GeV)

- Oscillation (physics) parameters

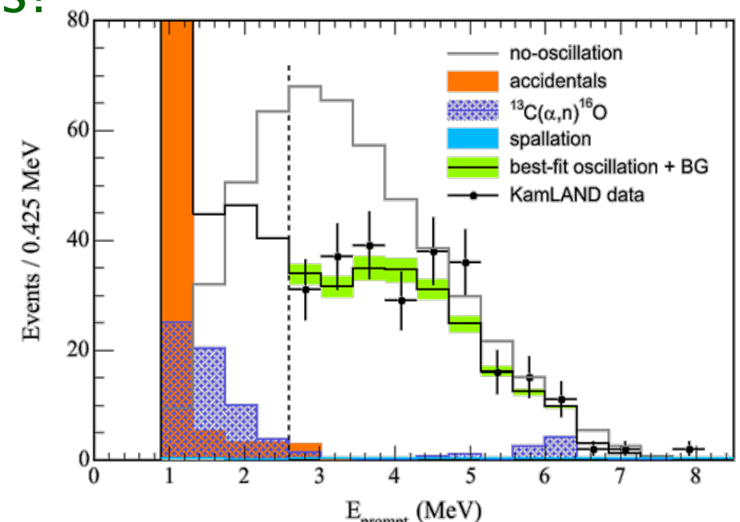
  $\sin^2(2\theta)$ (mixing angle)

  $\Delta m^2 = m_\tau^2 - m_\mu^2$ (mass squared difference, eV^2)

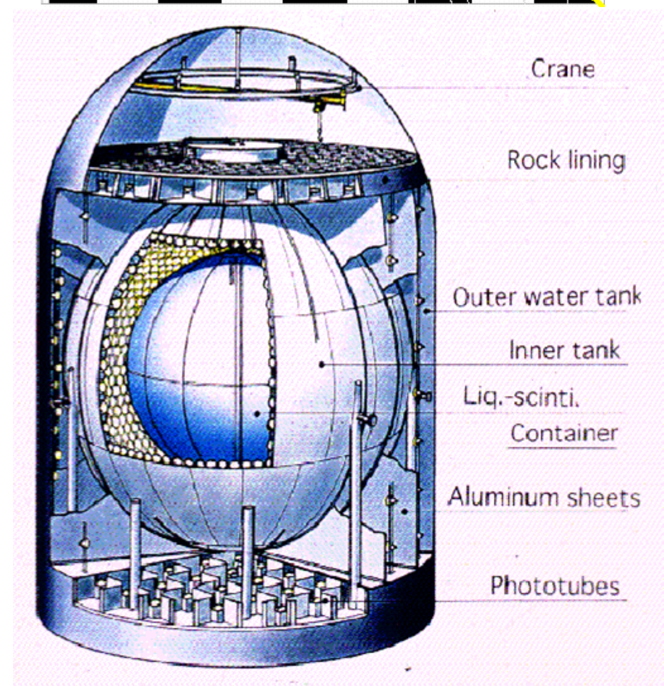


Kamland: Man-Made Neutrino Test

- Reactor experiment with a twist
  - > Go a lonnnnnng long distance to test solar neutrino oscillations with man made neutrinos
  - > 20% of world's nuclear power (was) 100 - 300 km from central Japan
- Neutrinos observed: 1609
- Expectation w/o oscillations: 2450
  - > Spectrum & rates fully consistent with Solar results!
  - > Initial results the same year as SNO

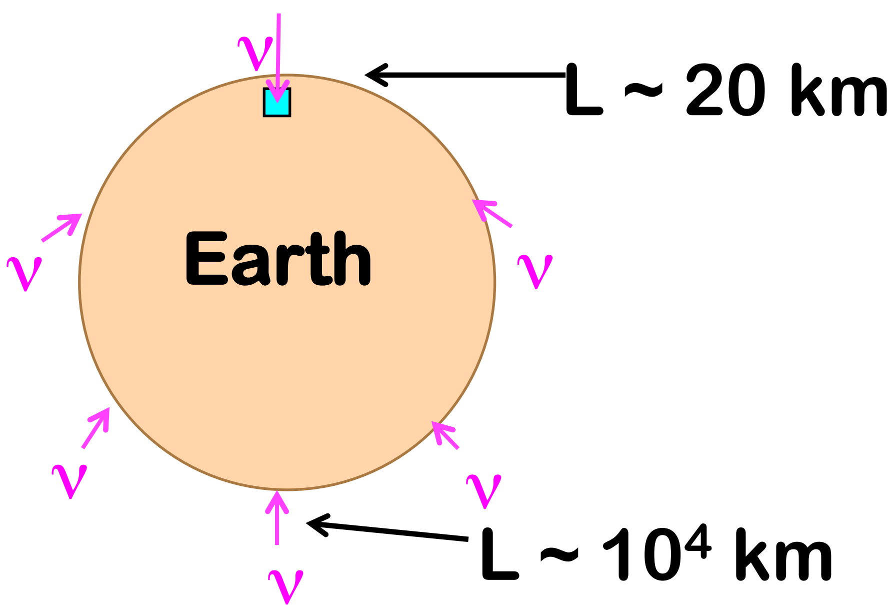


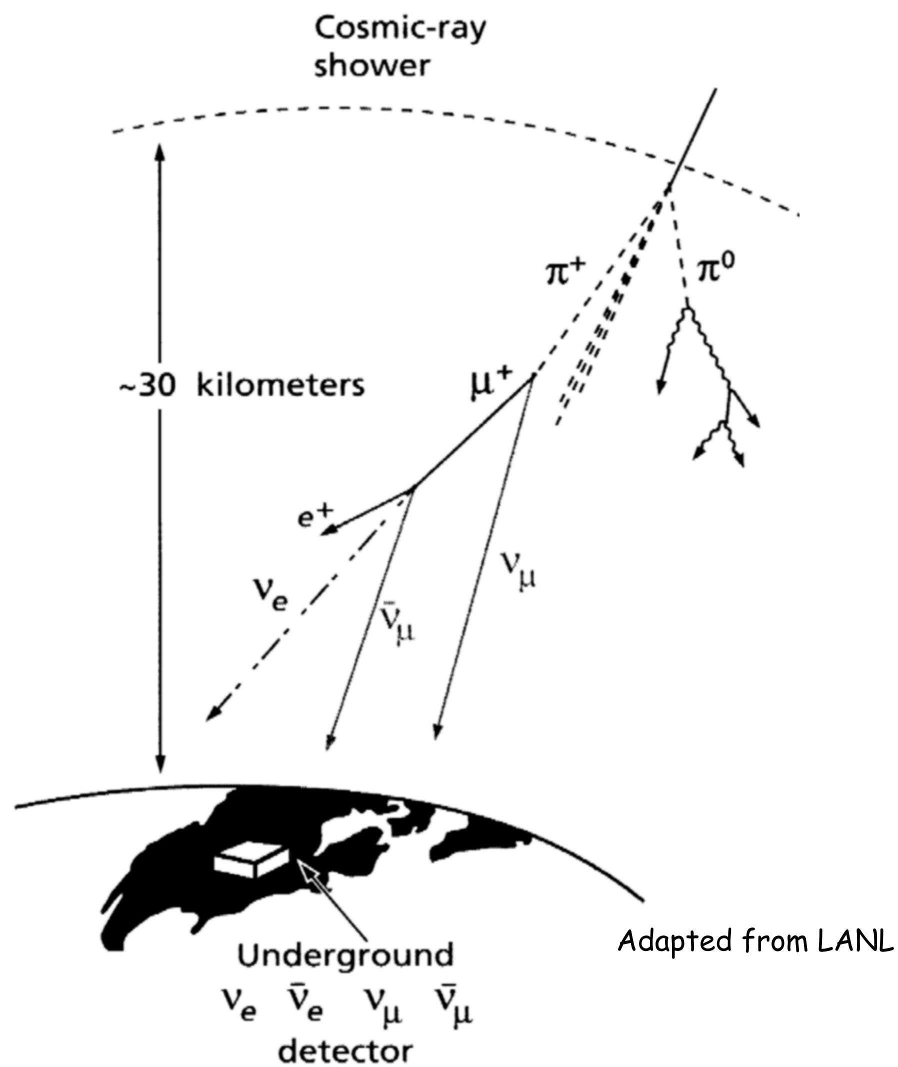
Phys. Rev. Lett. 100, 221803 (2008)



Atmospheric Neutrinos

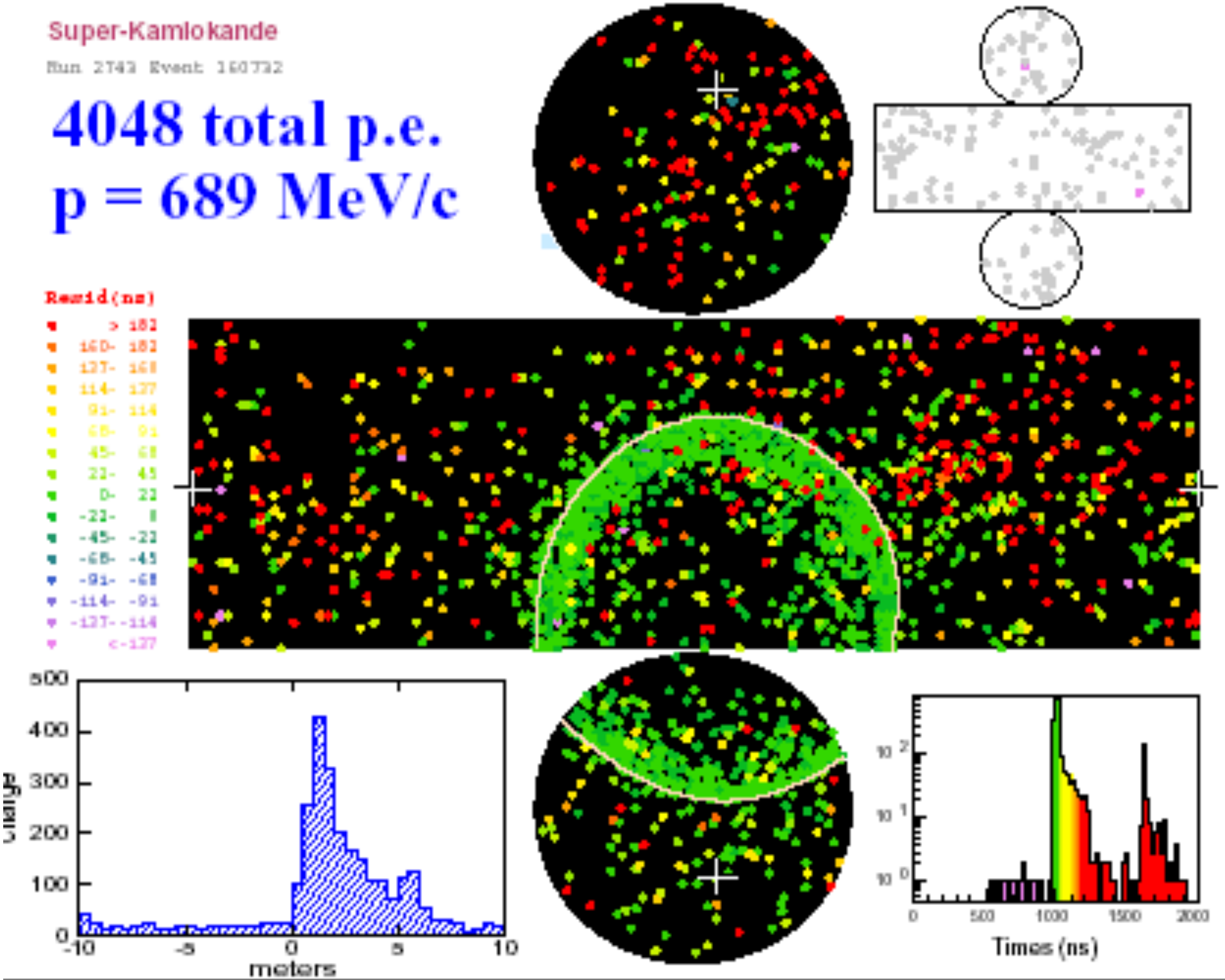
- Primary cosmic rays strike the atmosphere and produce showers of particles including muons
- Long range of distances



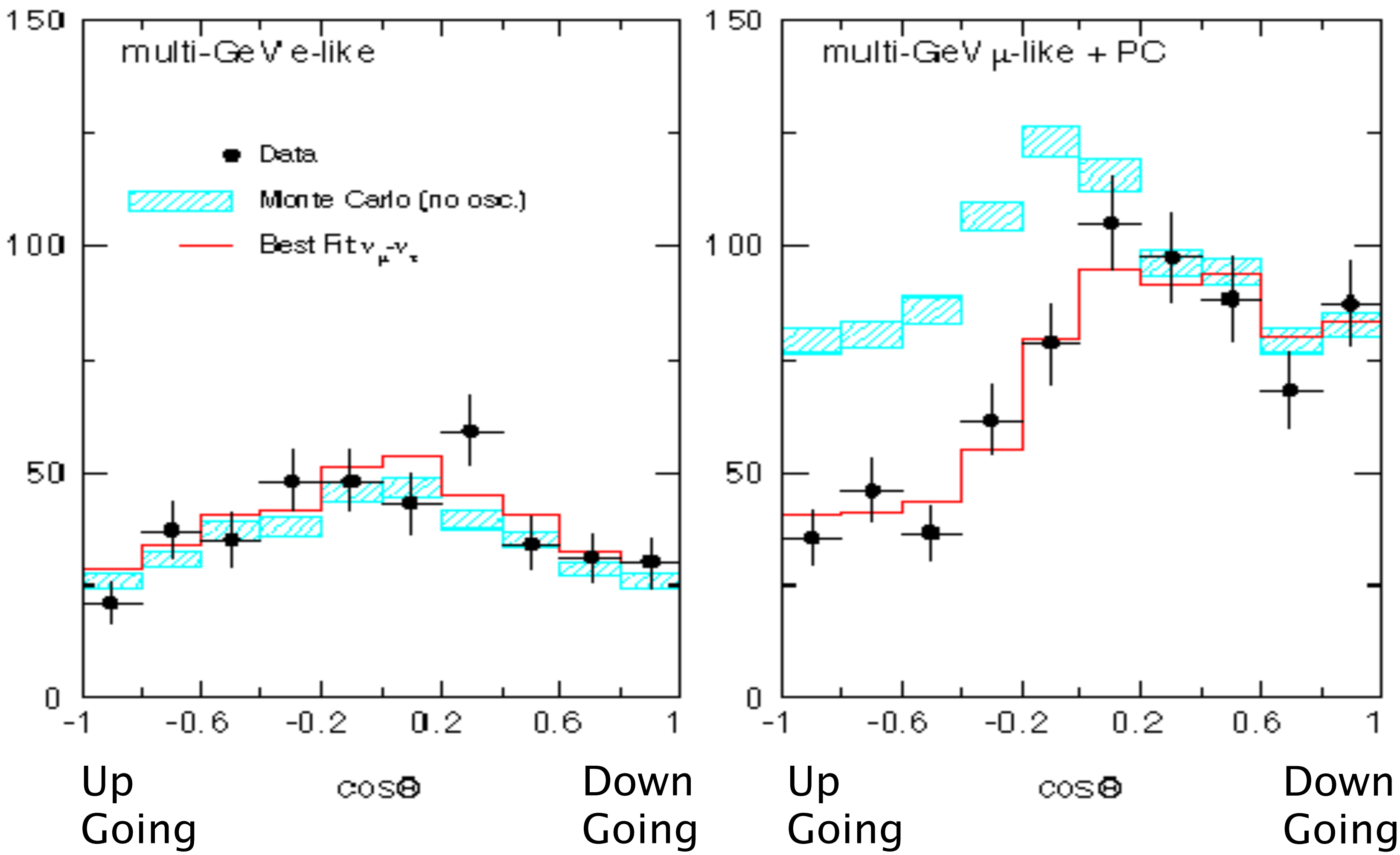


Adapted from LANL

Cerenkov Rings in SuperK

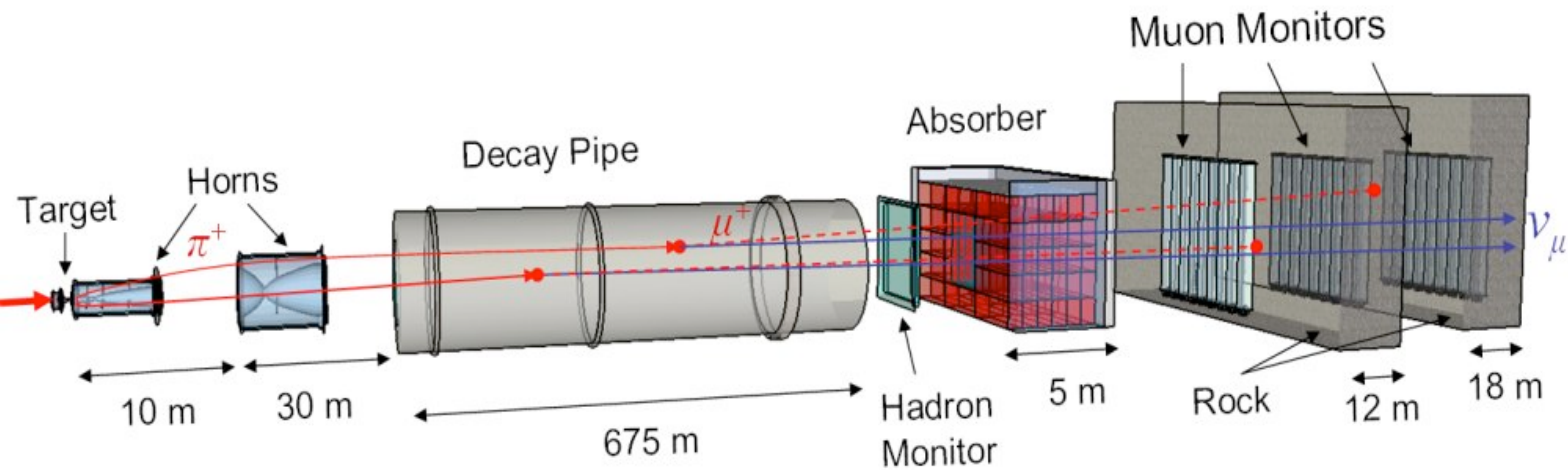


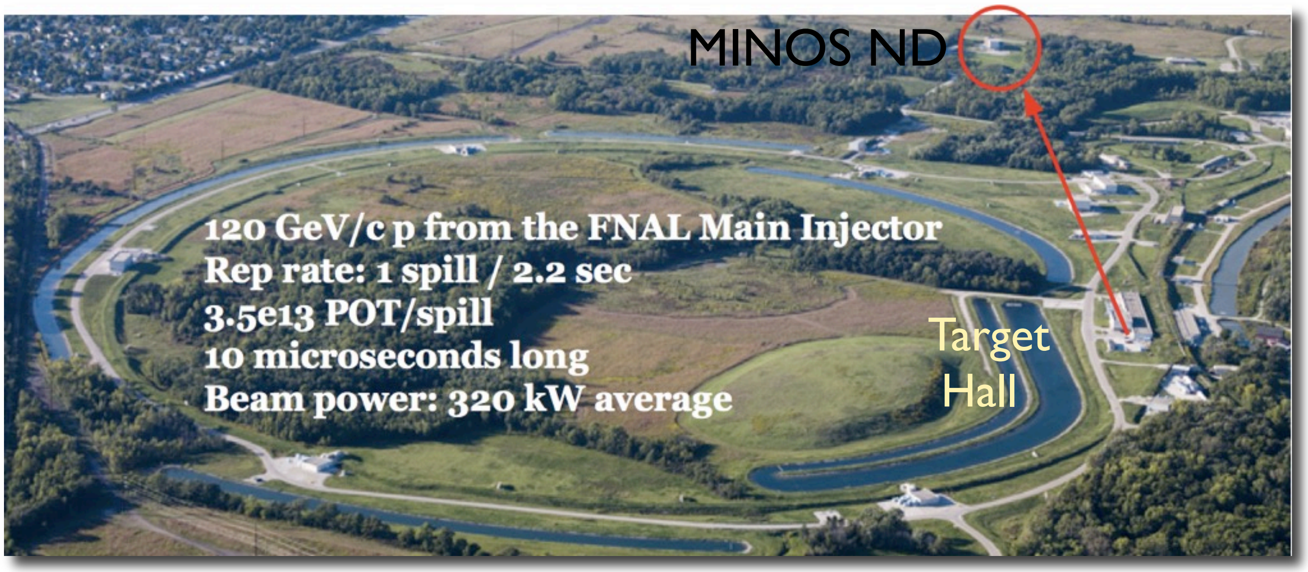
SK neutrino data shows disappearance (1998)

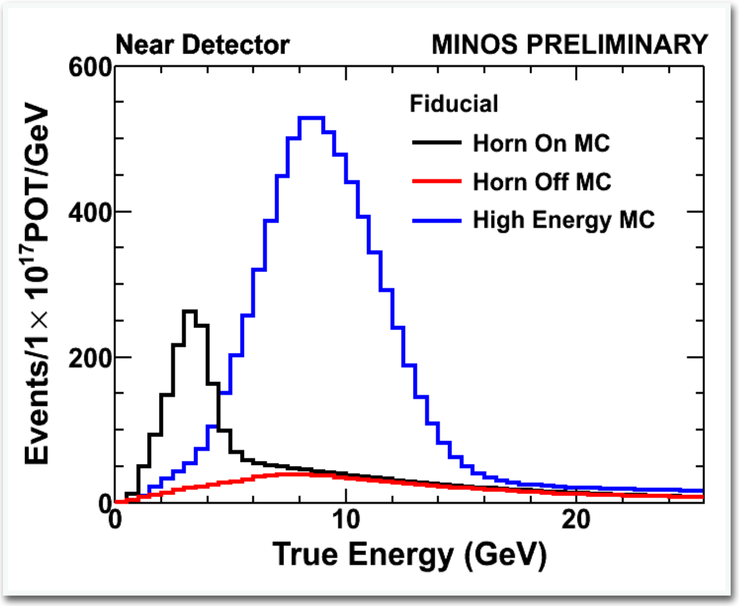


All data (results from 7 experiments) consistent with muon neutrino -> tau neutrino

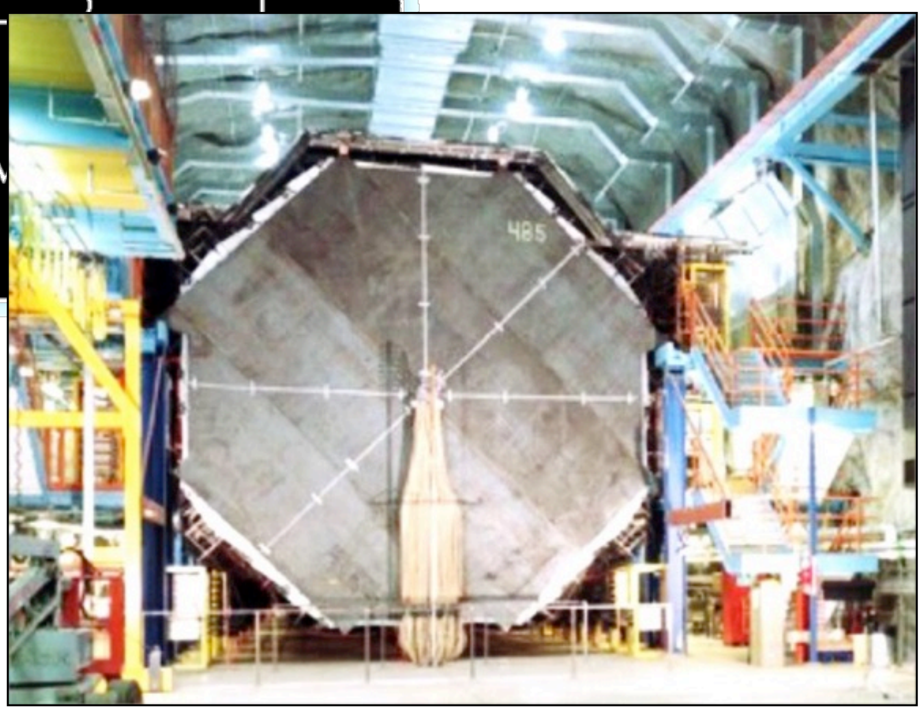
NuMI Neutrino Beam at Fermilab







The MINOS Experiment



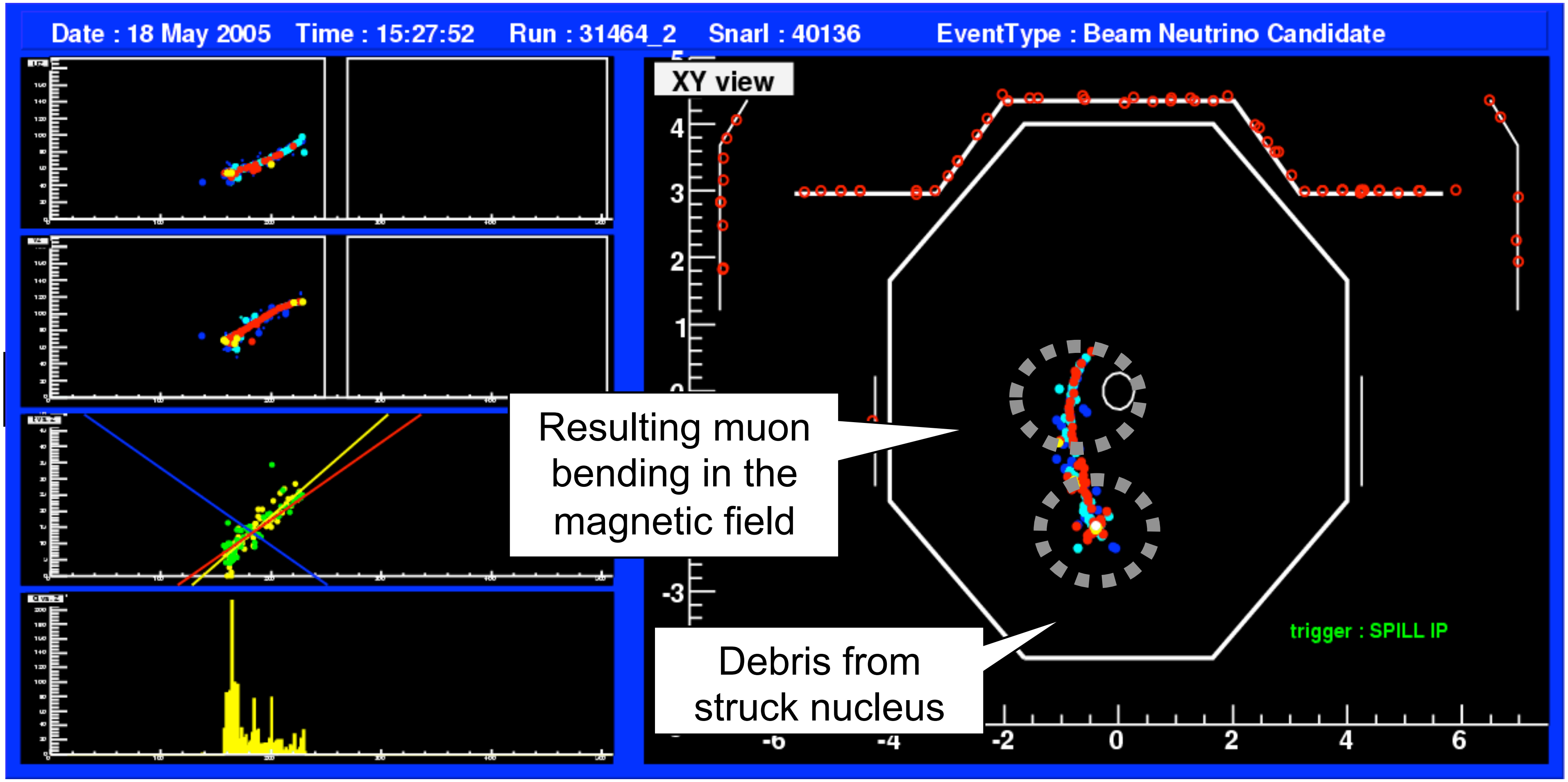
Send neutrinos 735 km
from Fermilab to Soudan

> There's no tunnel — just solid rock
> Their journey takes only 0.0024 sec

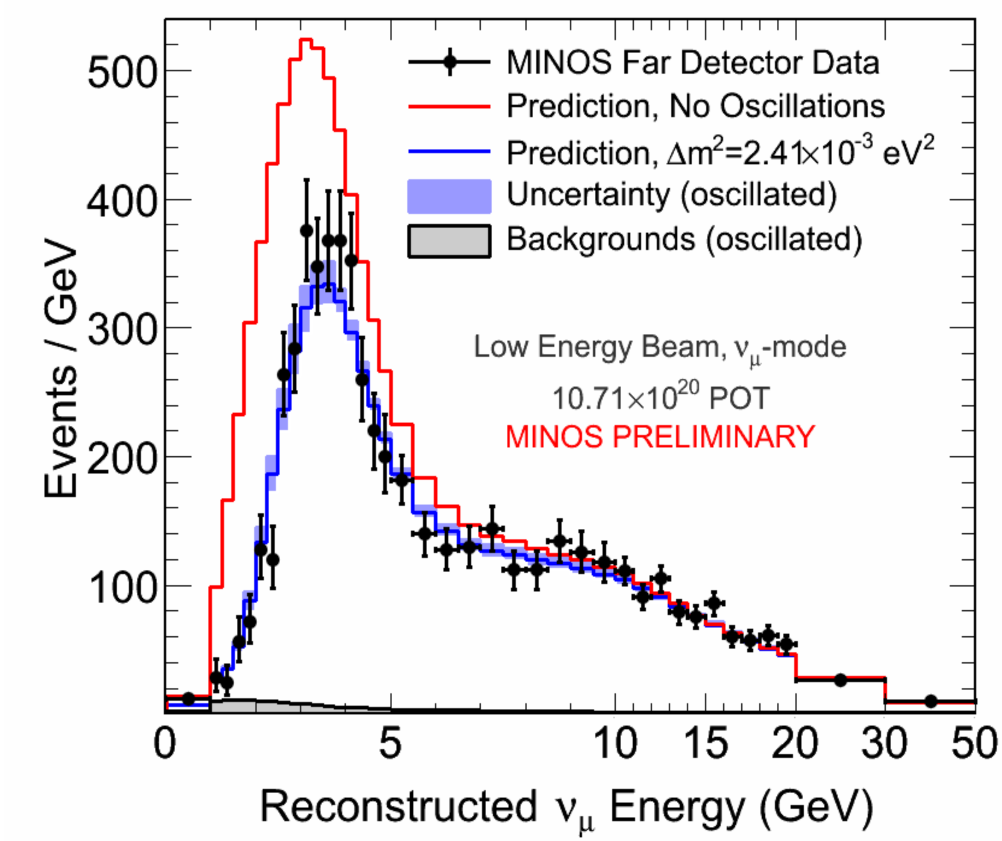
2 neutrino detectors

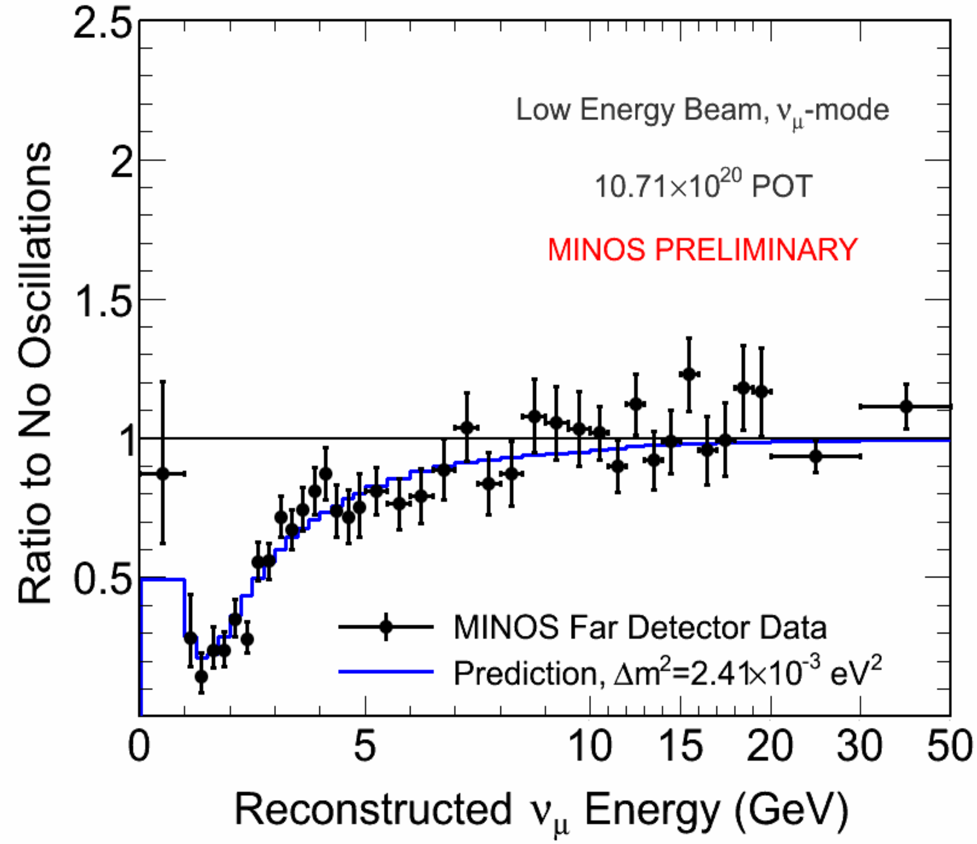
> A small detector at Fermilab ("near detector")
> A large detector at Soudan ("far detector")

A Muon Neutrino Interaction



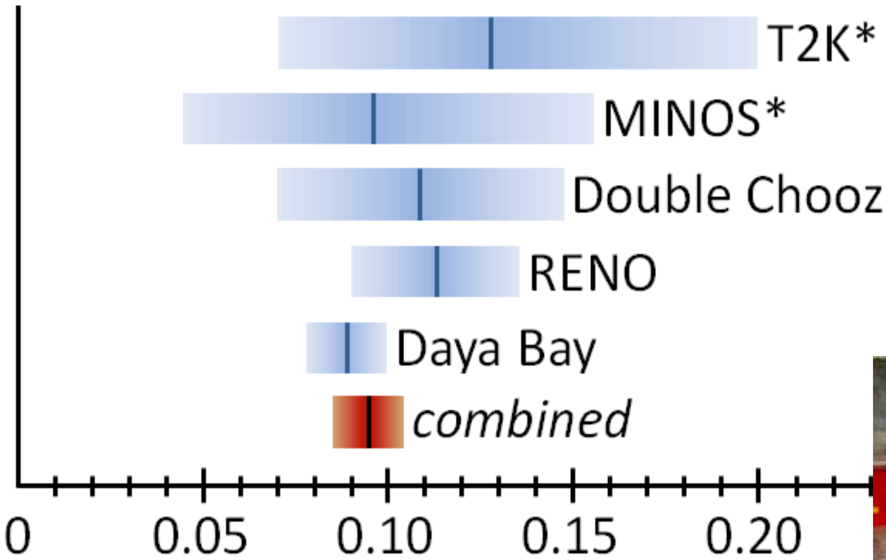
MINOS long-baseline oscillation results (2006) (consistent results w/ K2K, T2K, NOvA)





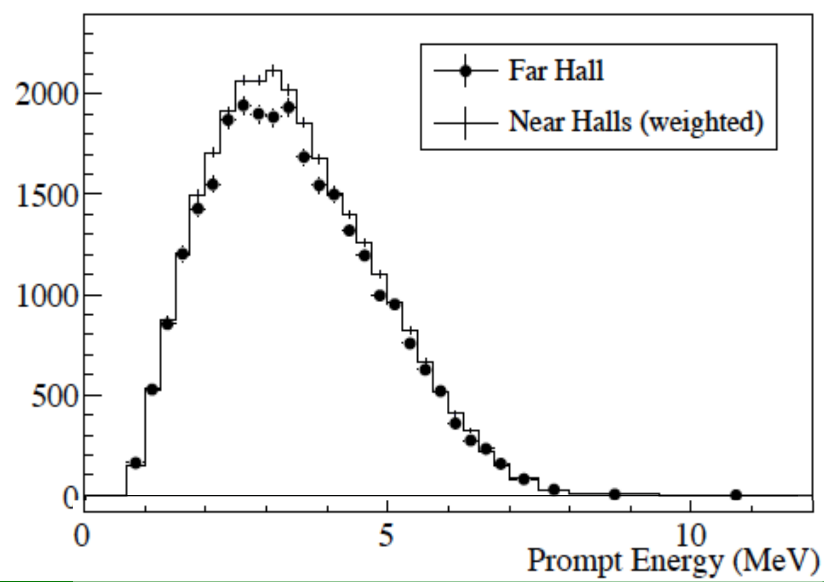
Category	Observed	Predicted (w/o oscillations)
Beam neutrinos	6028	7074
Atmospheric neutrinos	2072	2397

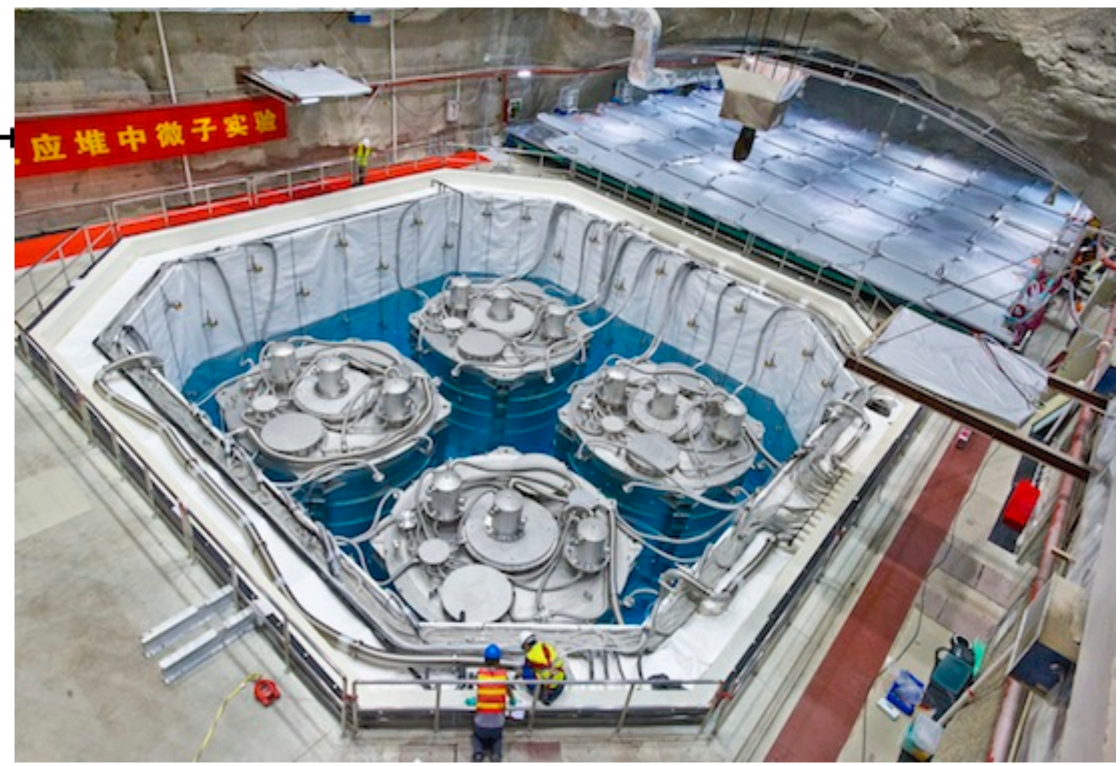
Three-flavor oscillations: the last transition discovered in electron-neutrino disappearance 2012



Consistent results from 3 experiments

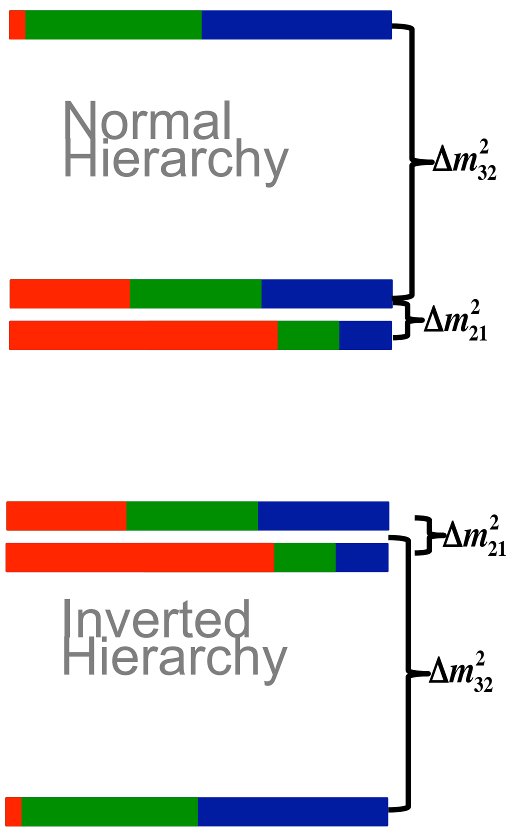
T2K sees equivalent in long-baseline too





The stories told…

- From the atmosphere
  - > Muon neutrino goes to tau neutrino
  - > And only rarely to electron neutrinos
  - > Long baseline beams of neutrinos verify
- From the sun
  - > Electron neutrino goes to something
  - > Long baseline reactor neutrinos verify
- Last transition via precision reactor exp's
  - > Electron neutrino to muon neutrino
  - > Long baseline electron appearance verifies
- What's next?
  - > Hierarchy of neutrino mass spectrum
  - > CP violation in the neutrino sector
  - > Requires precision comparisons of neutrino/antineutrino electron appearance



$\Delta m^2_{32} = m_3^2 - m_2^2$

NOvA – the next generation

2-detector, long-baseline experiment

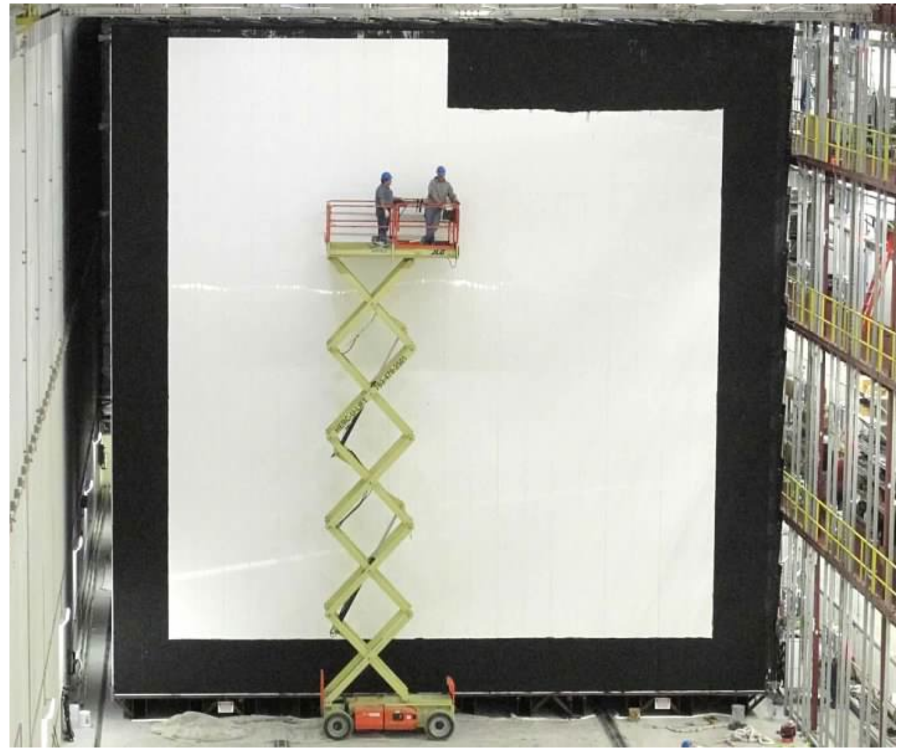
Off-axis neutrinos from NuMI beam

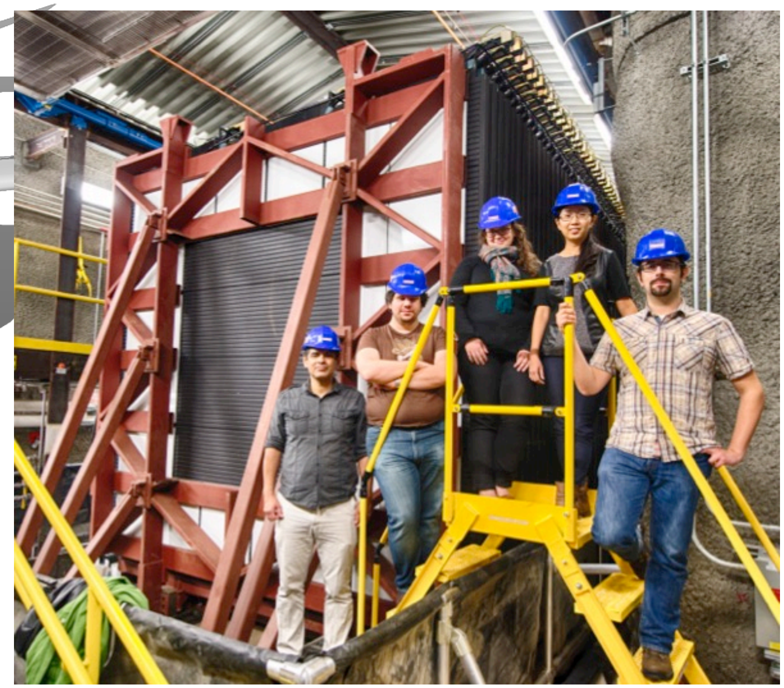
Physics goals:

- Search for electron neutrino appearance (with both neutrinos and antineutrinos)
- Precision studies of muon neutrino disappearance

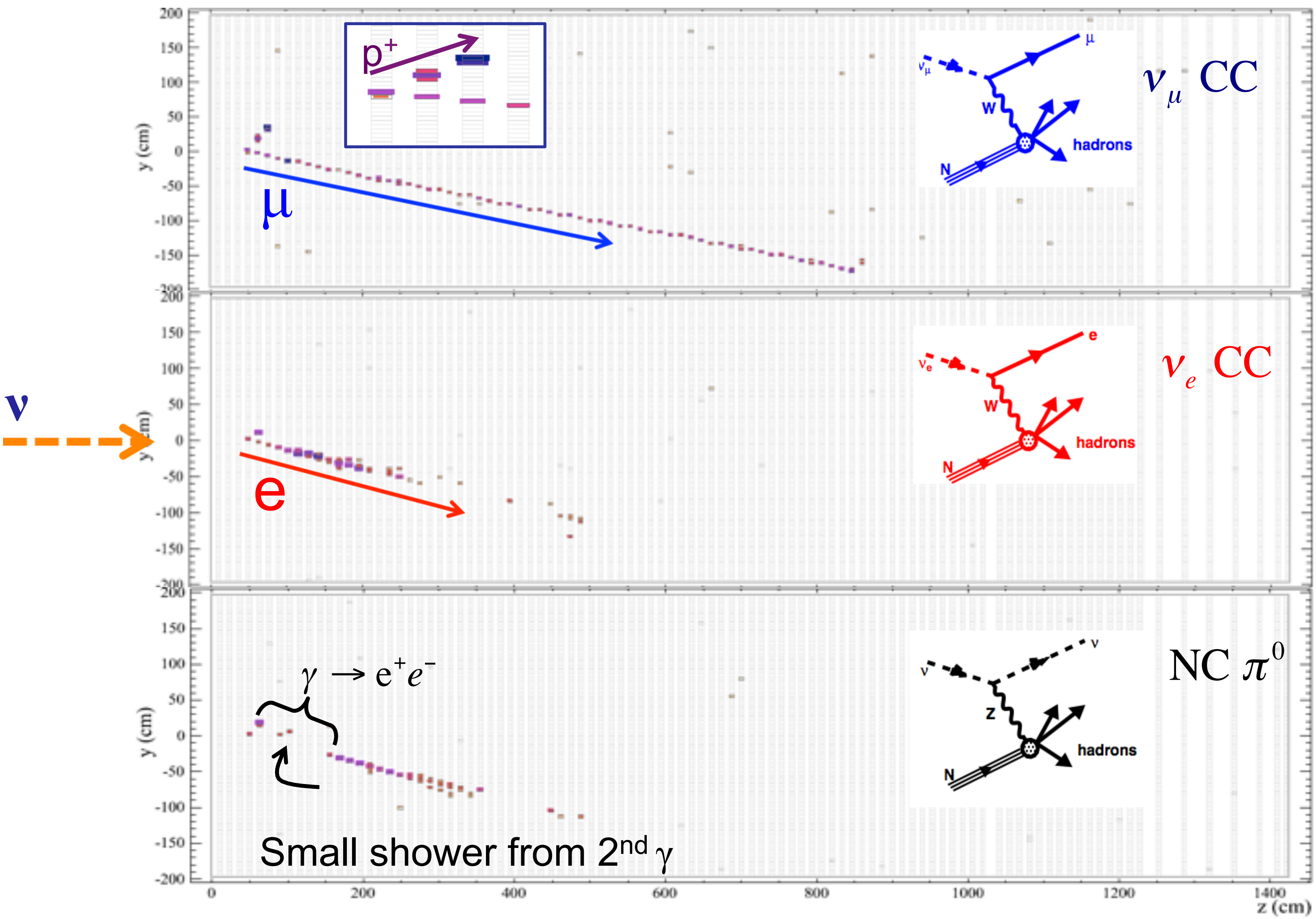
NOνA Detectors

- Designed for electron ID
- Massive, Low-Z, 65% active
- ND: 330 ton, 1 km from source
- FD: 14 kton, 810 km from source

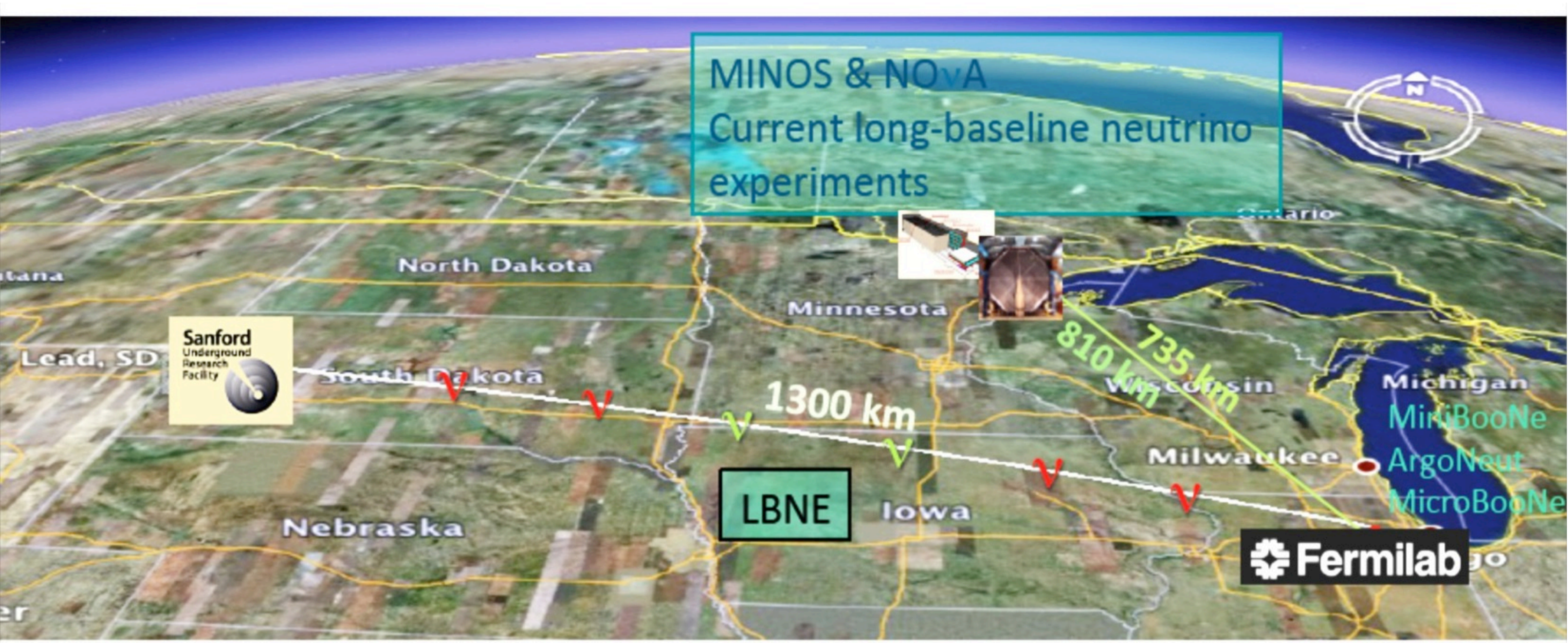




Simulated events in NOvA
(1st results this summer… but that's another seminar)



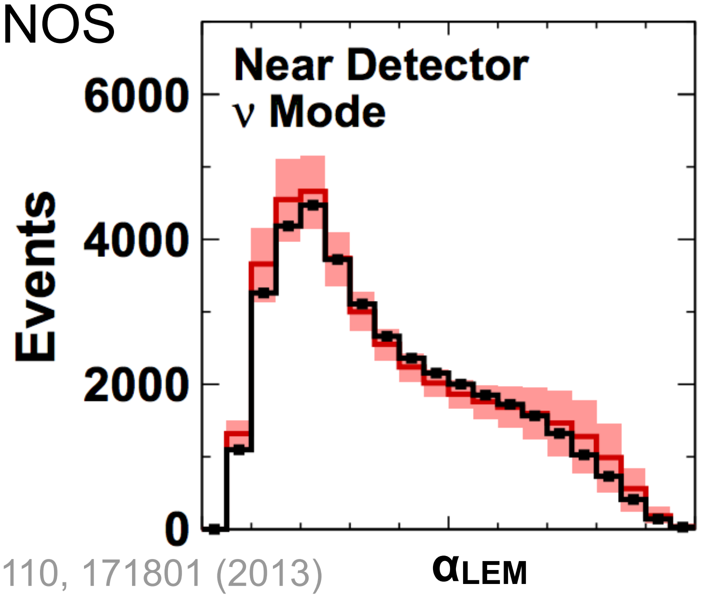
Deep Underground Neutrino Experiment (DUNE) – further future



- Massive Liquid Argon TPC (up to 30 ktons)
- Almost bubble chamber-like event detail
- New beam line with higher power at a longer baseline (LBNF)
- Should start collecting data sometime in the next decade

Uncertainties on signal predictions in ν_e appearance measurements: now & goals

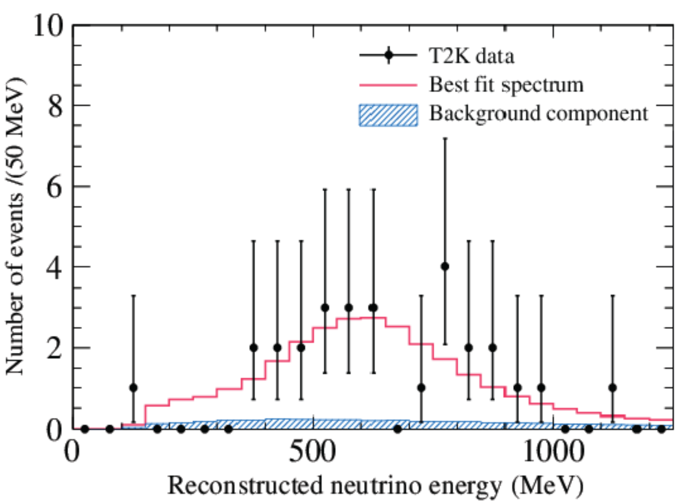
MINOS



PRL 110, 171801 (2013)

5.6% uncertainty on signal prediction

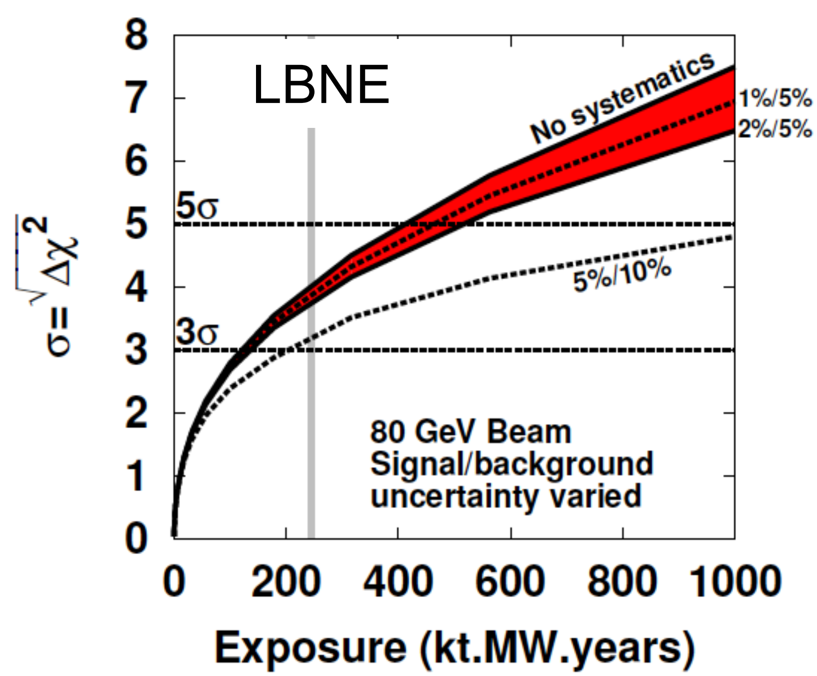
T2K



PRL 112, 061802 (2014)

6.8% uncertainty on signal prediction

CP Violation Sensitivity
50% δ_{CP} Coverage

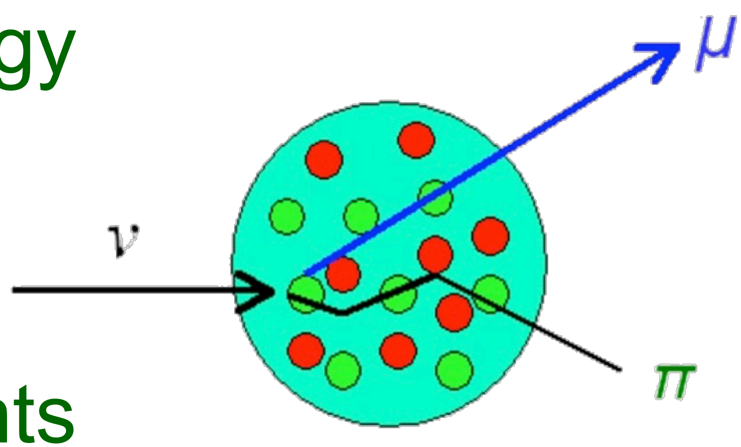


Bass, NuInt2014

- **LBNE's goal is 1%** for total systematic uncertainty on signal prediction
- Sensitivity to CP violation is strongly impacted by uncertainties in signal & background predictions

Neutrino interactions: why care?

- We need to estimate the energy of the incoming neutrino
  > Different from the “visible” energy seen in the detector

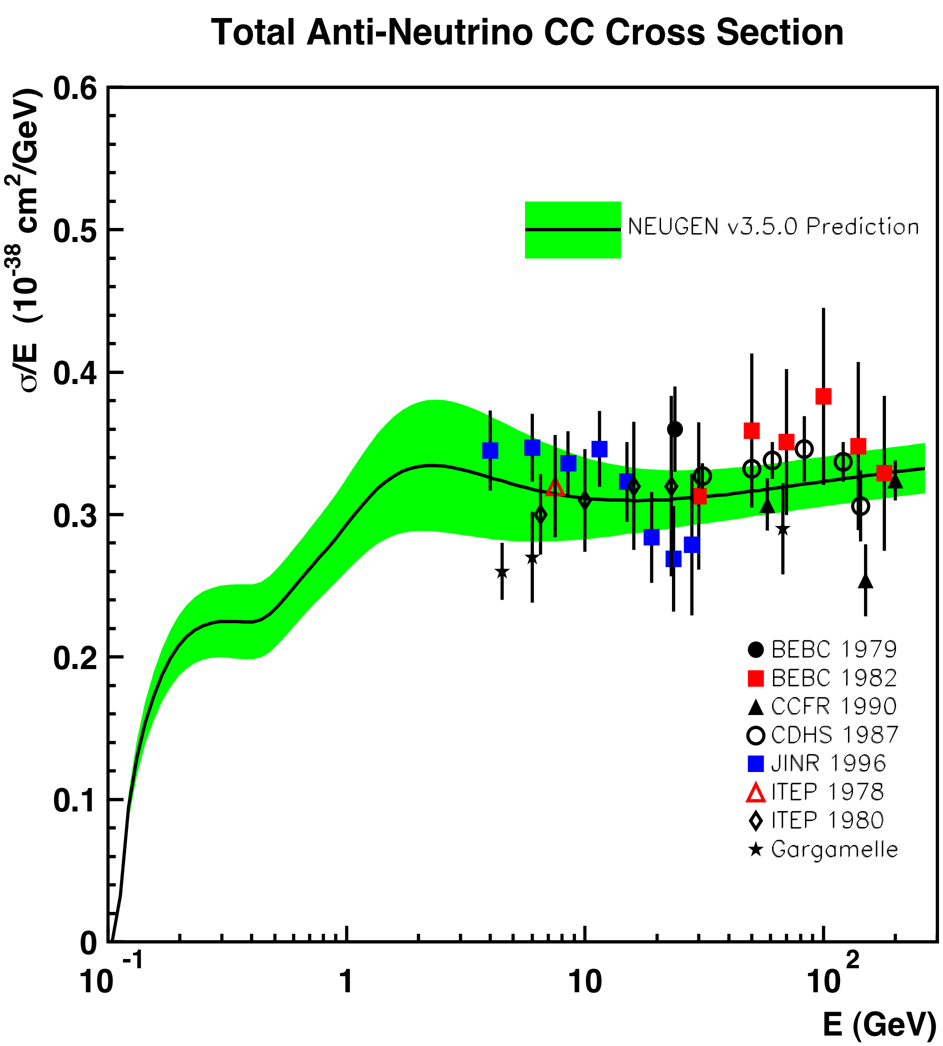


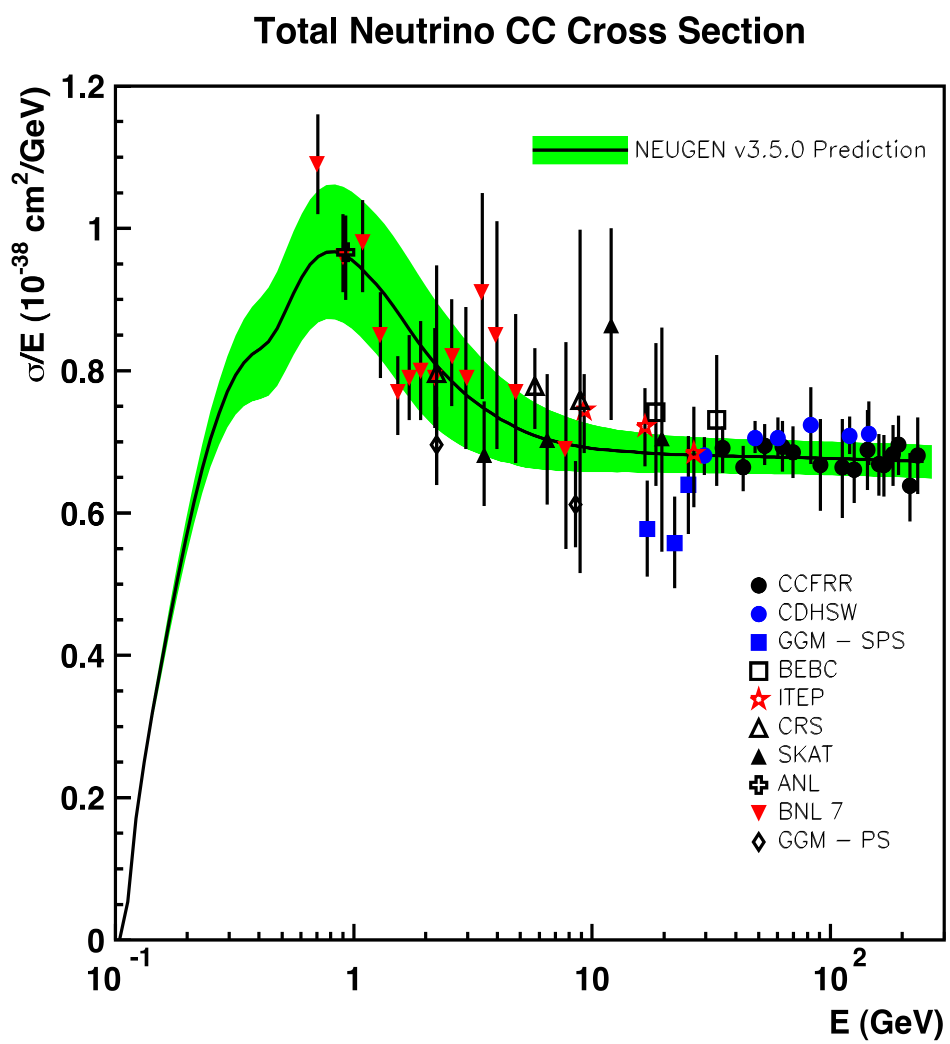
- Neutrino oscillation experiments use nuclei as targets (e.g. O, C, Ar)
  > This affects the visible energy …
  > Motion of struck nucleon within nucleus
  > Number of final state particles
    - We are not sensitive to their rest masses, binding energies
  > Intra-nuclear absorption and scattering
  > Nucleon itself is modified by the nucleus

Neutrino event generators

- Neutrino experiments have are few in situ physics handles
  > MIP/muon, Michel electrons, Neutral Pions
  > Only know the incoming neutrino direction accurately
- We rely heavily on full simulations of neutrino interactions to understand
  > Signal selection
  > Background rejection
  > Energy reconstruction
- In the US program we most often use **GENIE**
  > NIM A, 614, 87 (2010)
- Many others exist
  > Some with fully specified final states
  > Some computed based on physics distributions

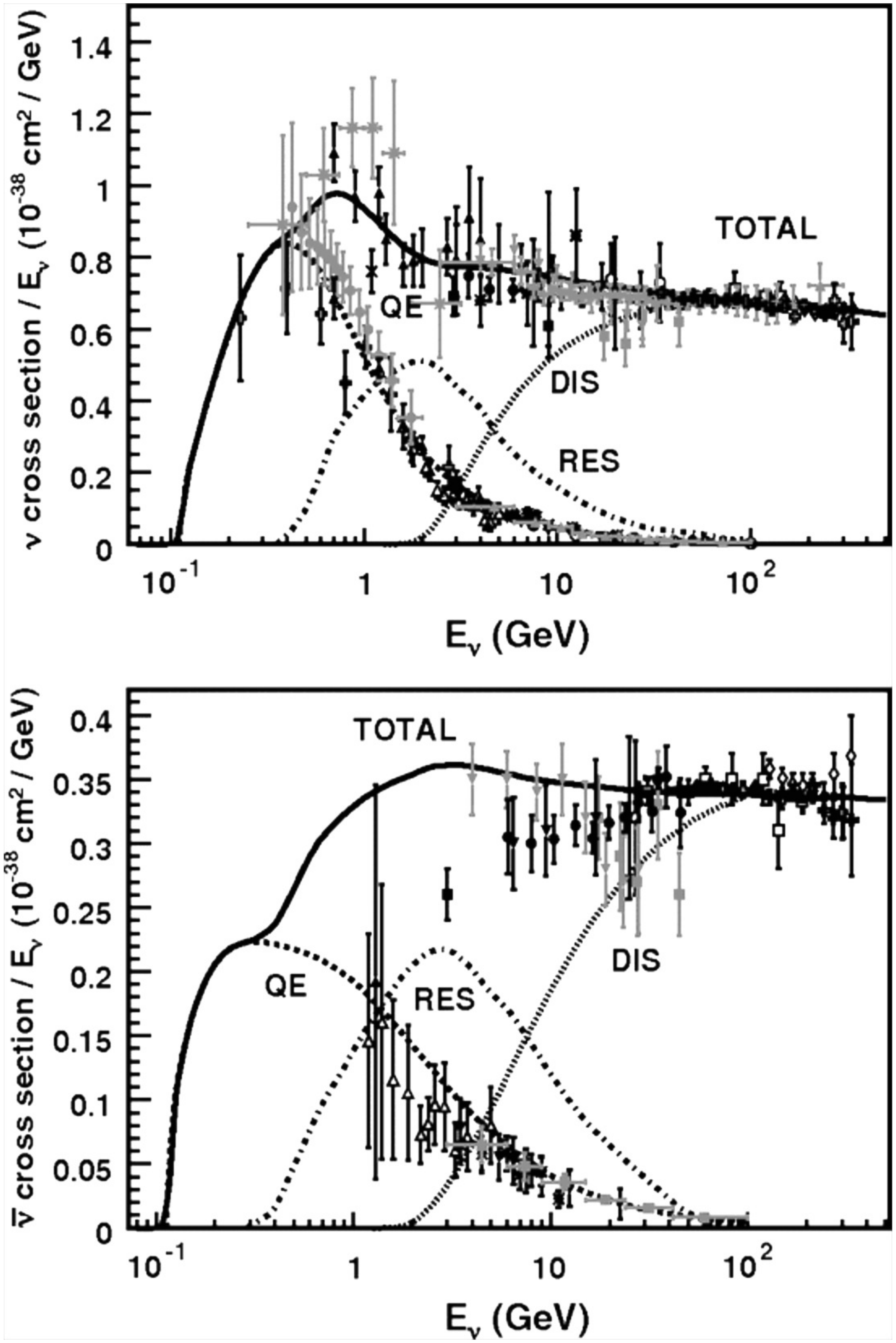
GENIE (nee NEUGEN) model
& world inclusive-scattering data (ca. 2008)





State of scattering (ca. 2011)

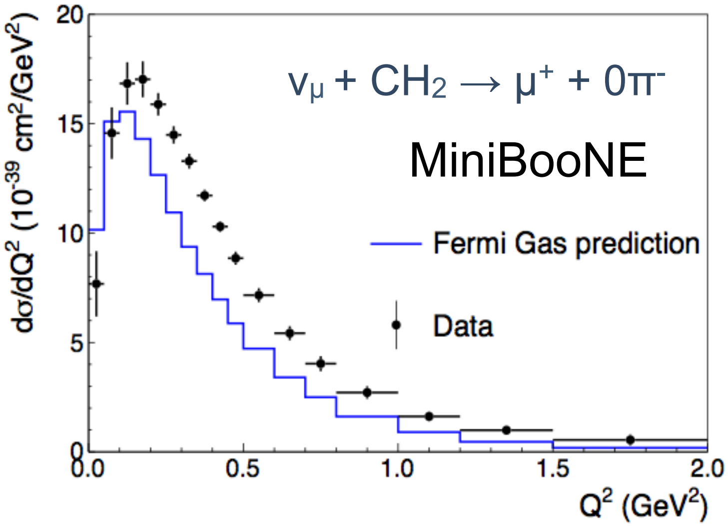
- SPS and TeVatron experimental results
- Getting detailed results from MiniBooNE, K2K ND, and SciBooNE
  - > Dozens of papers
  - > Starting to get the right nuclei
  - > Can't fit it all on one plot anymore… a good thing
  - > Dearth of antineutrino data starting to be addressed
  - > All these are for ~<1 GeV
- Data disagree with models!

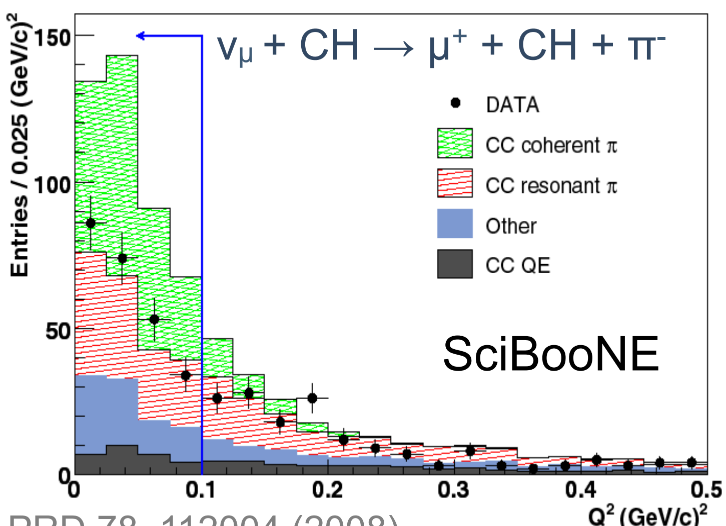


J.A.Formaggio, G.P.Zeller, Rev.Mod.Phys. 84 (2012) 1307

Our generators (models) do not accurately reflect recent cross section data

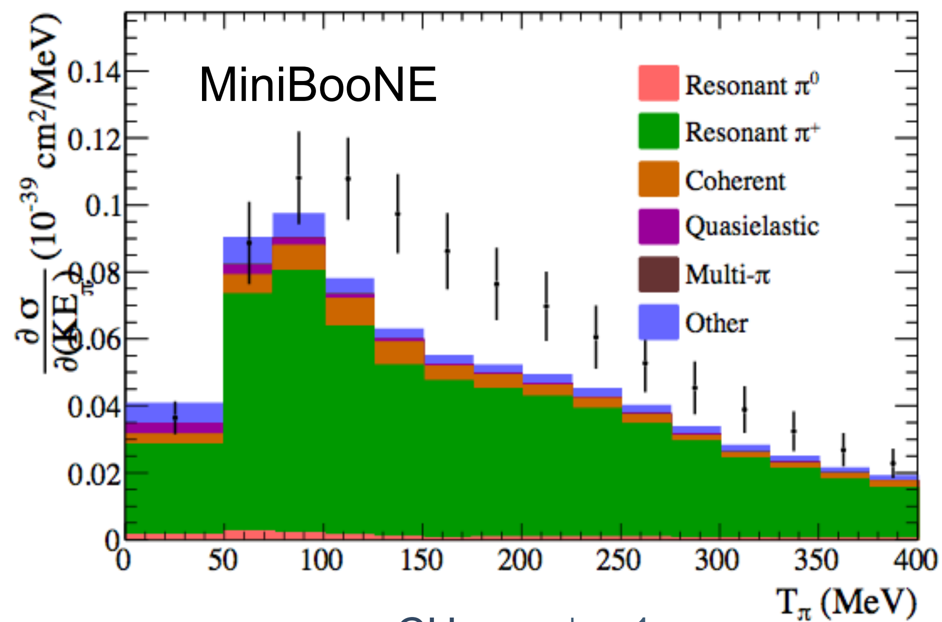
Adapted from PRD 81, 092005 (2010)
by P. Rodrigues





PRD 78, 112004 (2008)

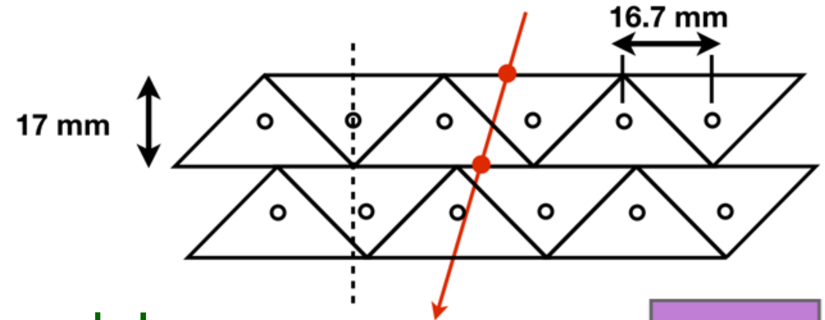
Adapted from PRD 83, 052007 (2011)
by P. Rodrigues

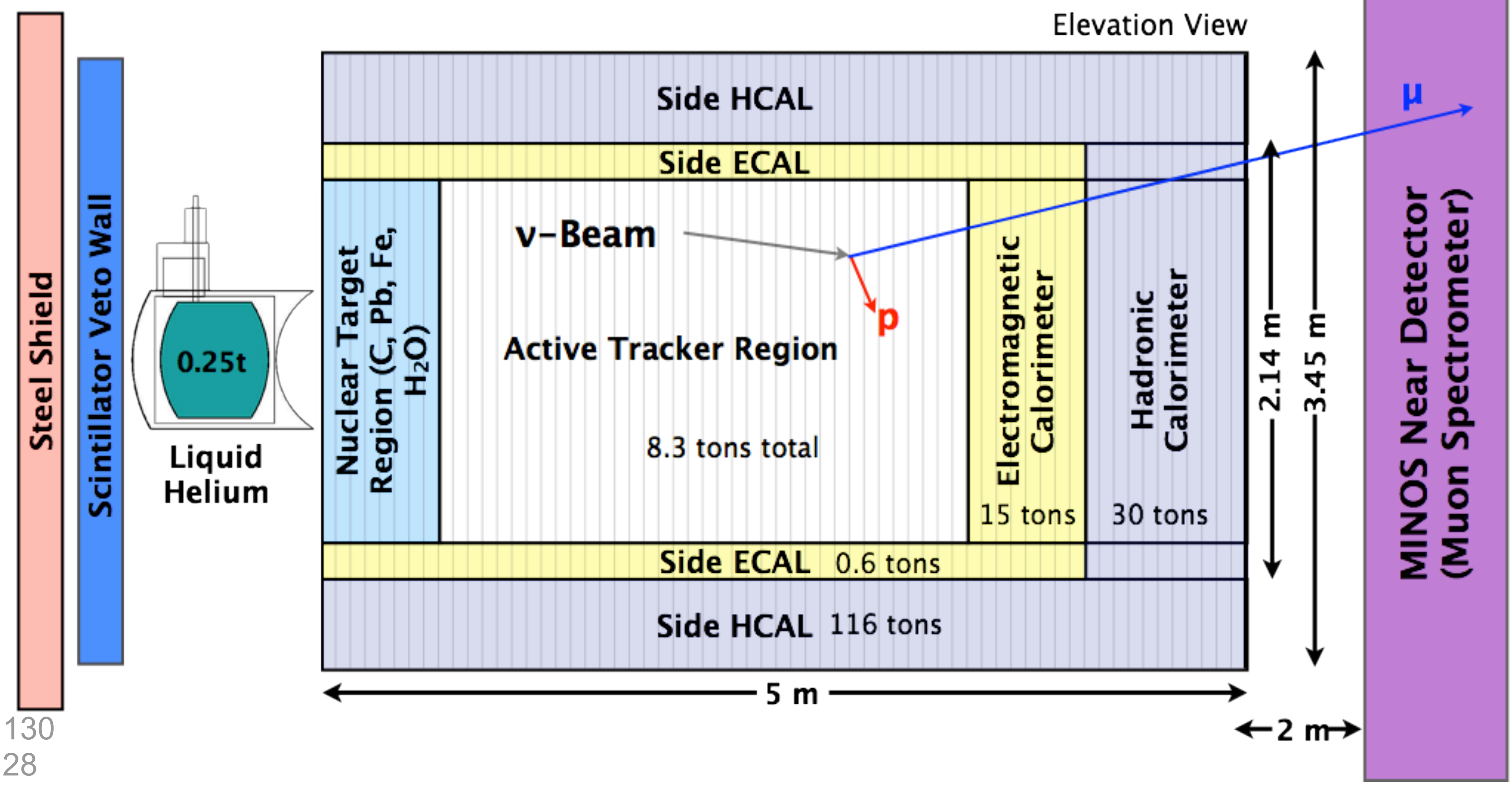


$\nu_\mu + CH_2 \rightarrow \mu^+ + 1\pi^-$

MINERvA

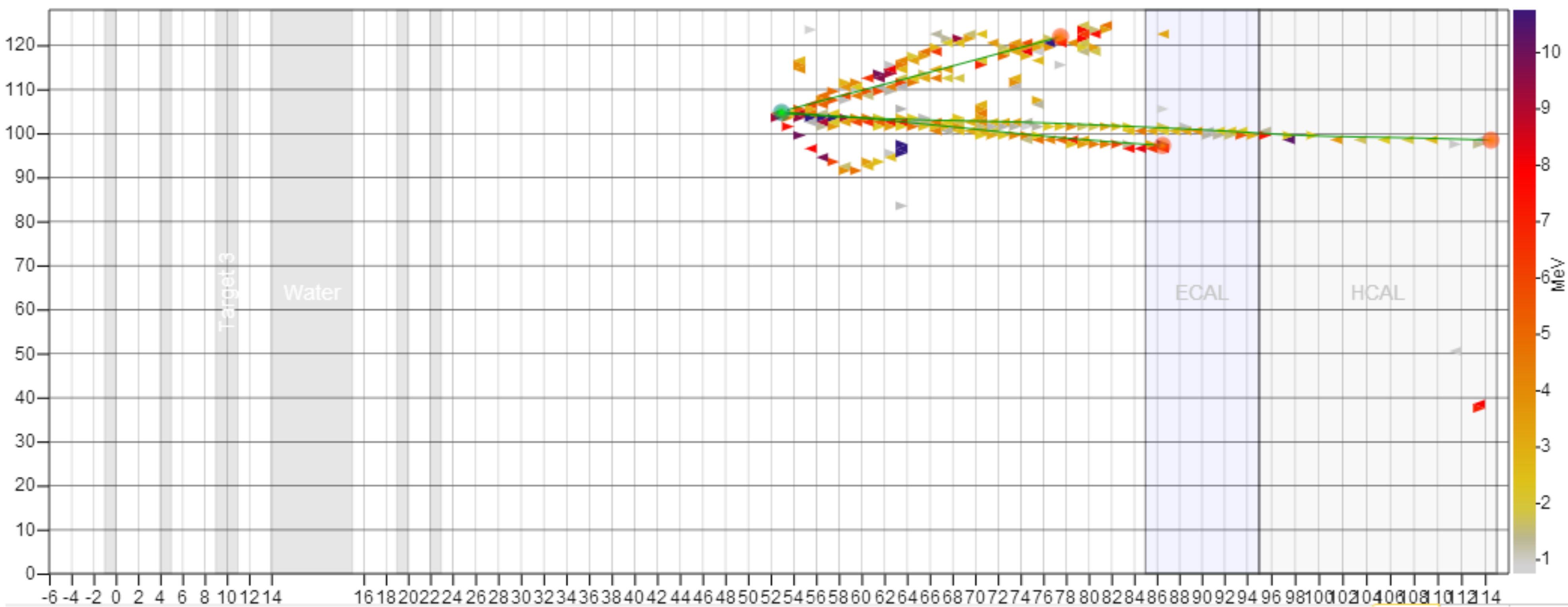
- Finely segmented solid scintillator (CH) detector on axis in NuMI
  - Active tracker is all scintillator
  - Calorimeters are scintillator w/ Fe or Pb
- Targets of Iron, Pb, C, Fe, H_2O & He
- MINOS detector for muon spectrometer
- Test beam program for energy scale/detector model

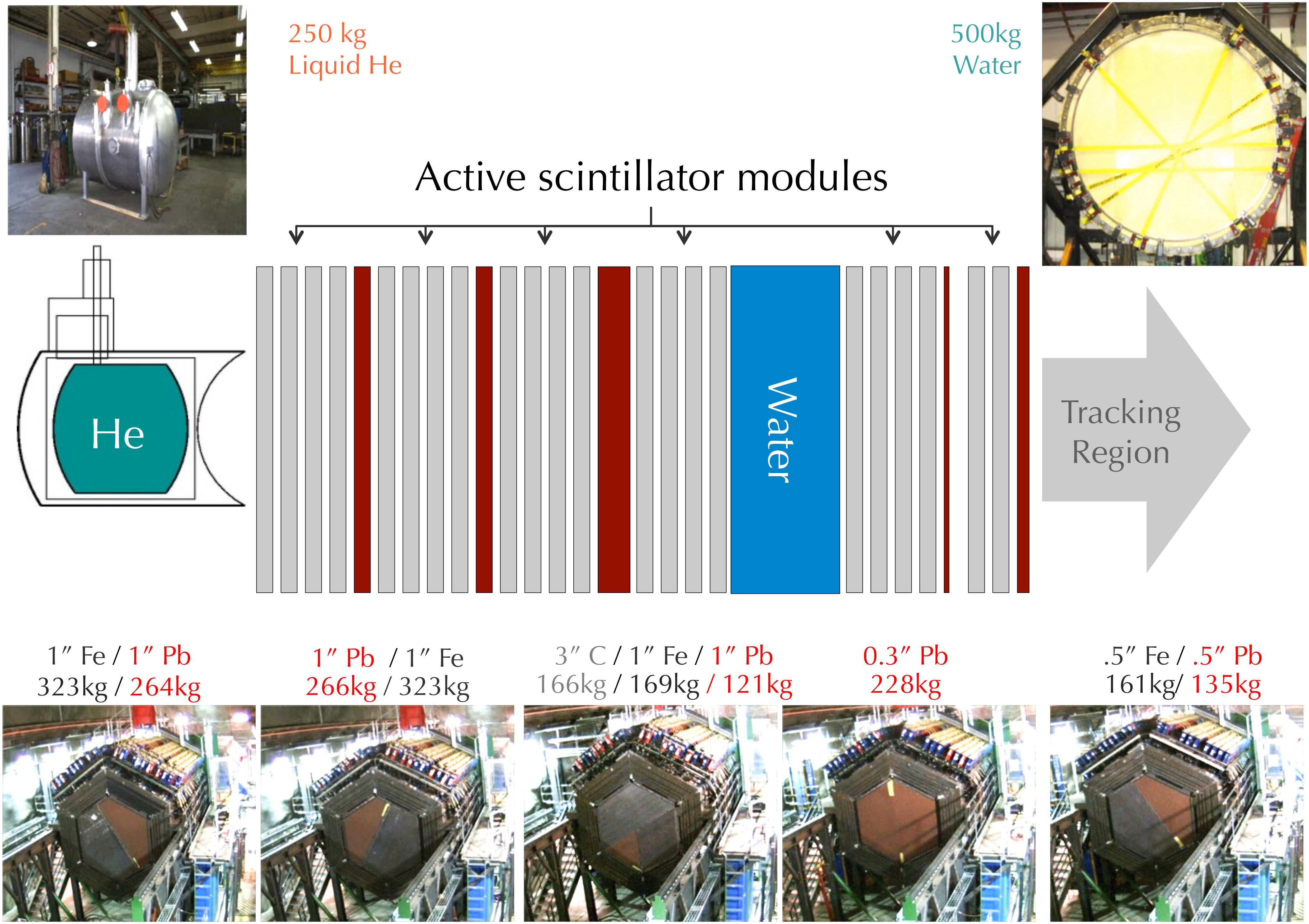




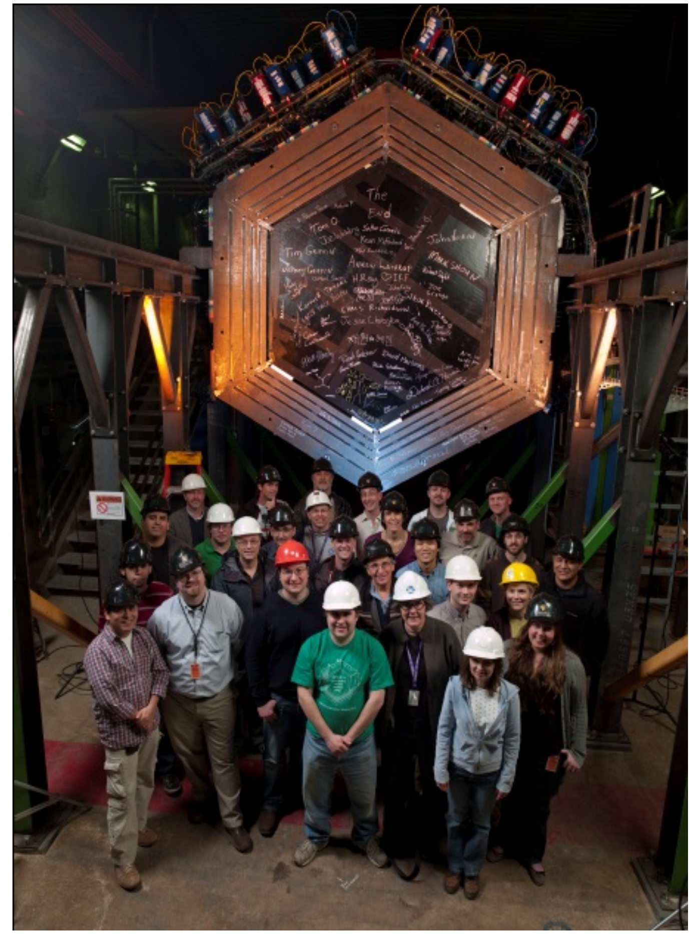
NIM A743 (2014) 130
NIM A789 (2015) 28

A MINERvA event




250 kg
Liquid He
500kg
Water
Active scintillator modules
He
Water
Tracking
Region
1″ Fe / 1″ Pb
323kg / 264kg
1″ Pb / 1″ Fe
266kg / 323kg
3″ C / 1″ Fe / 1″ Pb
166kg / 169kg / 121kg
0.3″ Pb
228kg
.5″ Fe / .5″ Pb
161kg/ 135kg

The MINERvA Collaboration



Measuring a cross section

$$\sigma(E) = \frac{U(D-B)}{\epsilon\Phi T \times \Delta E}$$

- D is data event yield
- B is background estimate
- U( ) an unfolding operation
- Φ is flux
- ε is the acceptance correction
- ΔE is the bin width
- T is the number of target nucleons

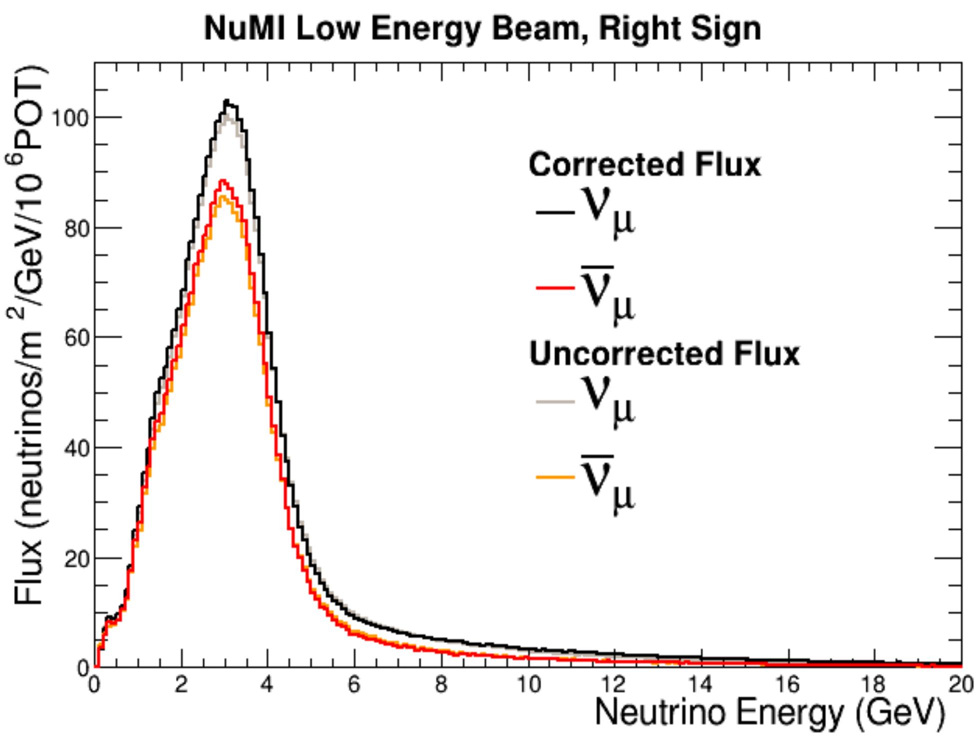
Flux tools: flux critical for any absolute measurement

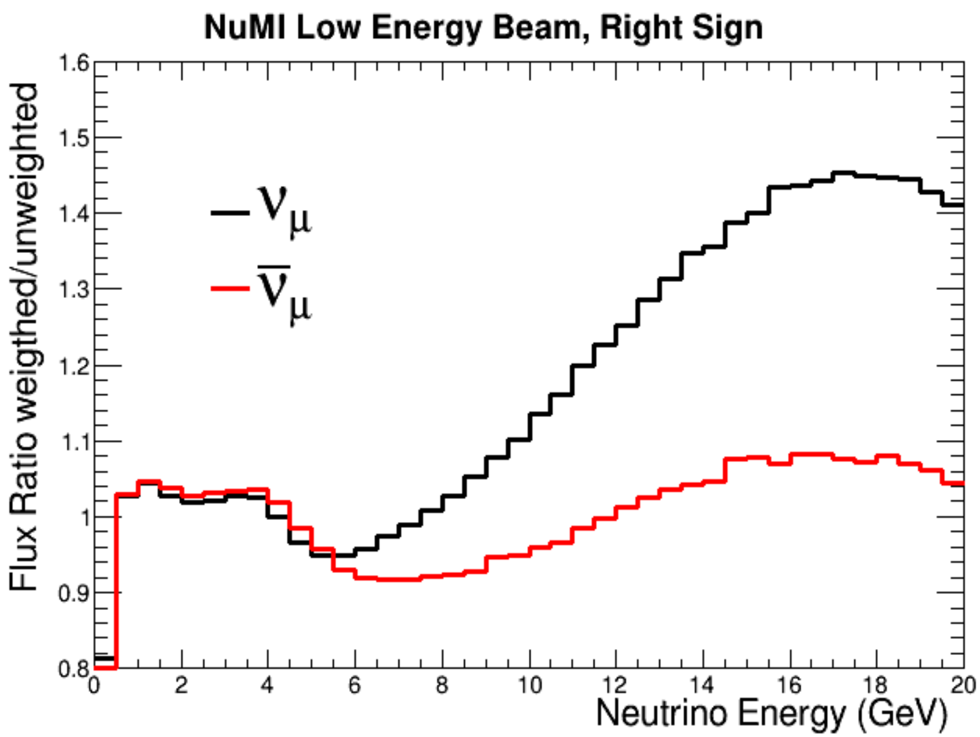
- Hadron production data
  - >External thin & thick target hadron production data Legacy data, NA49, MIPP
  - >Future: US-NA61
- Can also use standard-candle cross sections
  - >Neutrino-electron scattering
  - >Low ν (low recoil) events rates

Final MINERvA constrained flux to be unveiled at 12/17 FNAL seminar
by Leo Aliaga (W&M)

Preview next week at NuInt2015 (<8% errors)

Flux: GEANT4 corrected with external data (preliminary: used for almost all MINERvA results)



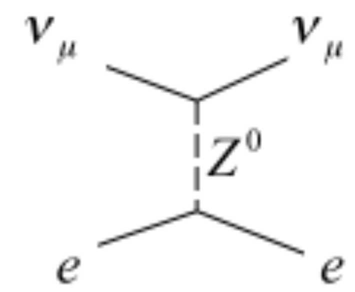


GEANT4 FTFP-based flux turned using NA49 thin-target π/k/p data and MIPP thin-target k/π ratios; corrected for η production

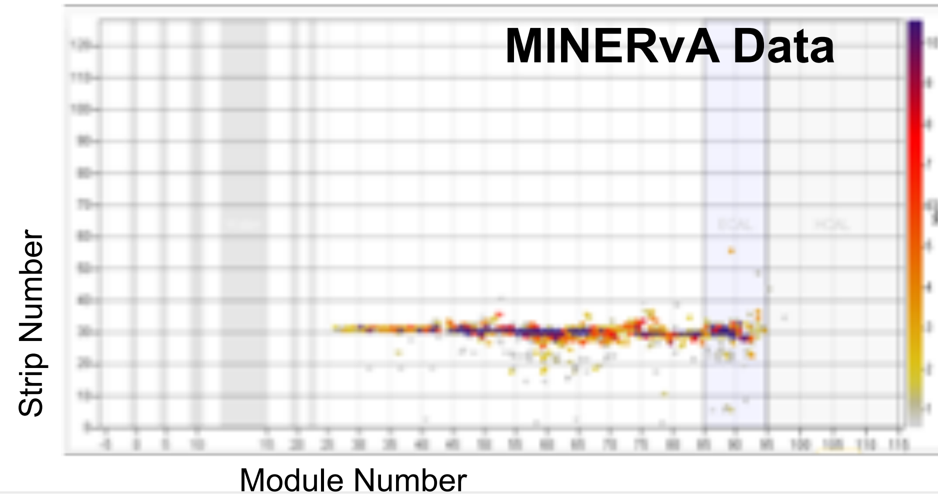
Flux tools: flux critical for any absolute measurement

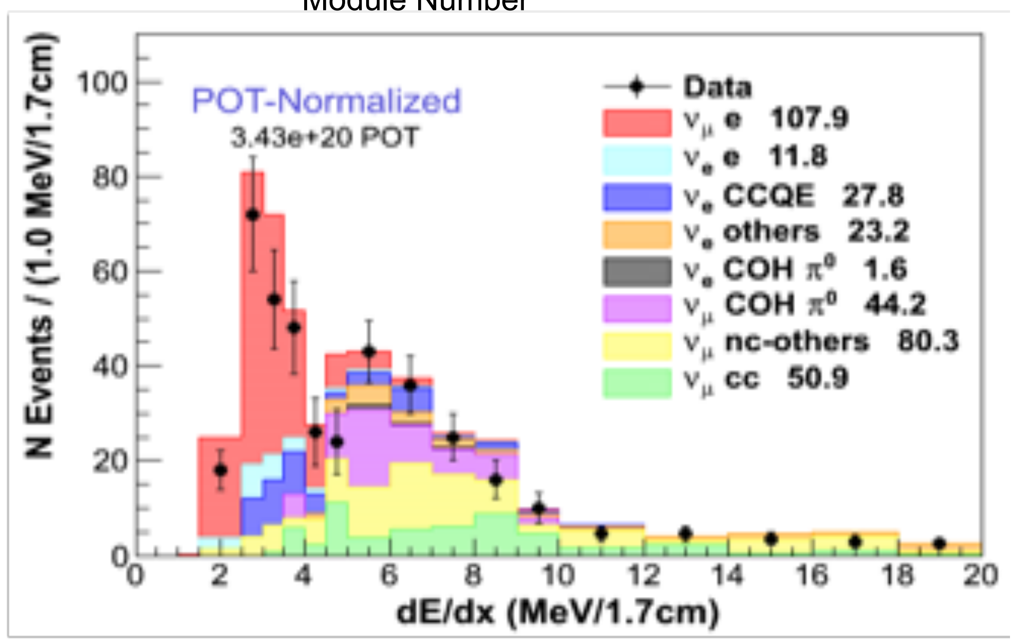
- Hadron production data
  - External thin & thick target hadron production data Legacy data, NA49, MIPP
  - Future: US-NA61
- Can also use standard-candle cross sections
  - Neutrino-electron scattering
  - Low ν (low recoil) events rates

ν-e scattering



- Signal is a single electron moving in beam direction
  - > Purely electro-weak process
  - > Cross section is smaller than nucleus scattering by a factor of 2000
- Improves MINERvA's flux uncertainties
  - > Statistically limited (~8% error)
  - > Results are consistent with new flux calculations
- Important proof of principle for future experiments
  - > Especially for higher energy beams





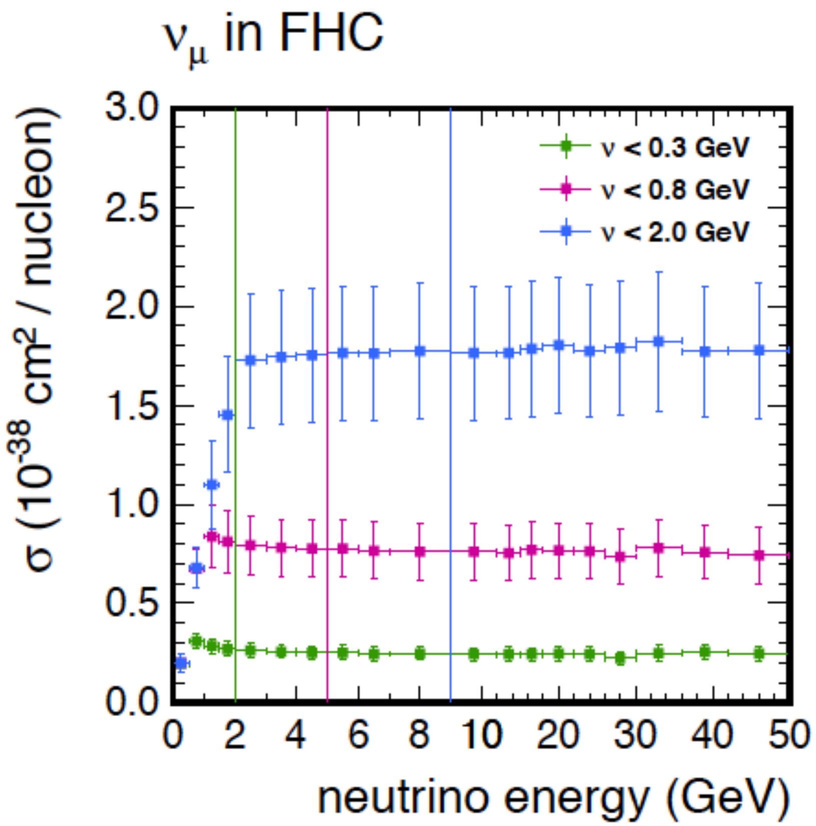
J. Park FNAL JETS, Dec 20, 2013

Flux: low ν

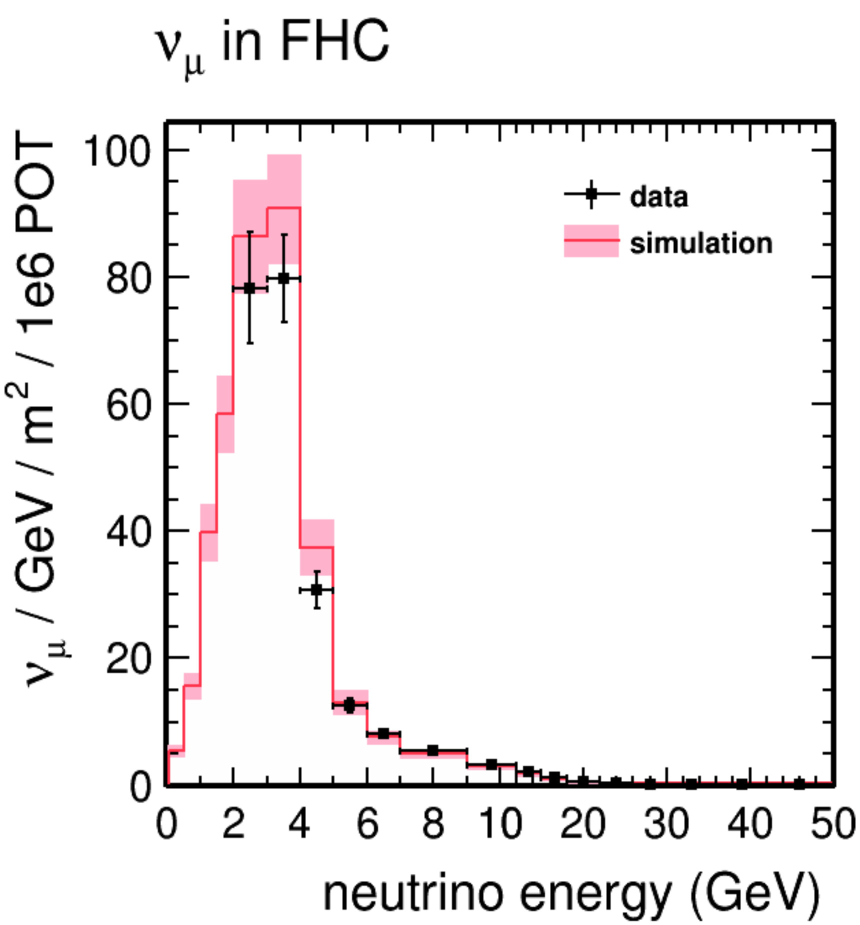
- Charged-current scattering with low hadronic recoil energy (ν) is flat

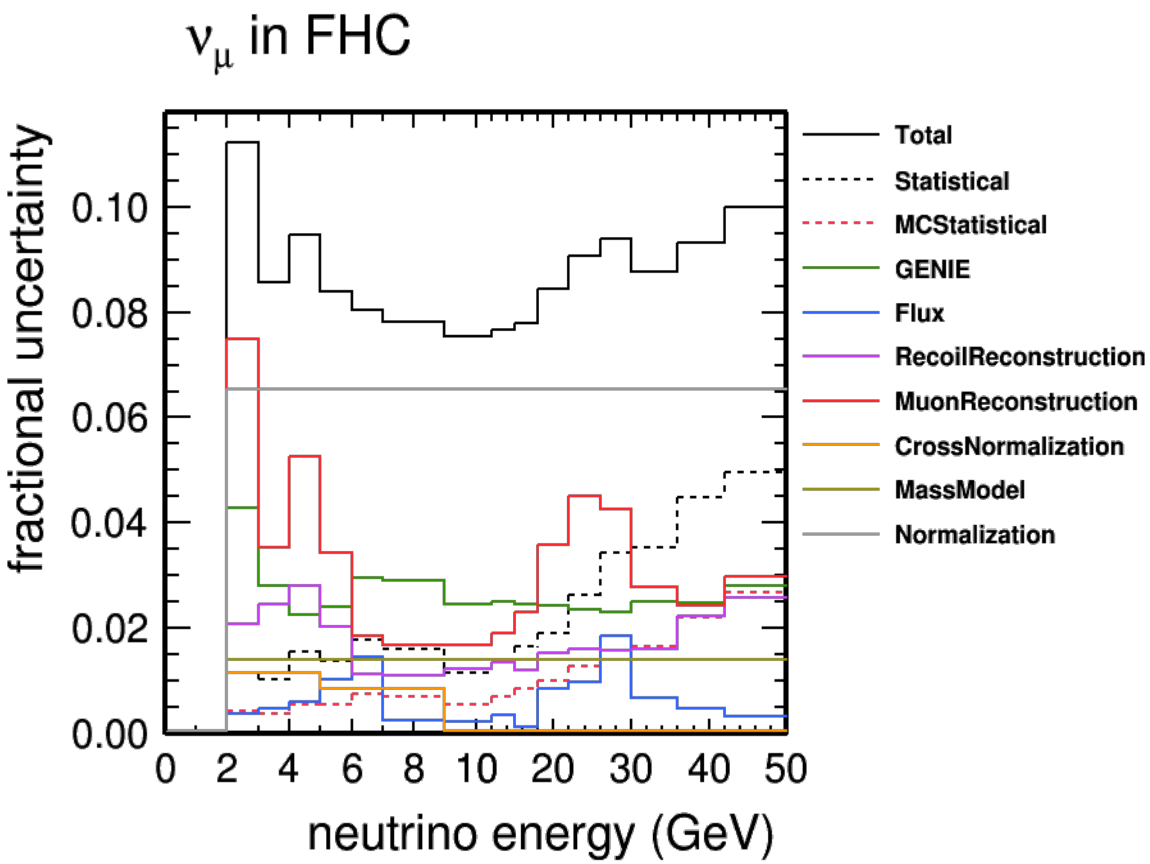
$$\frac{d\sigma}{d\nu} = A\left(1 + \frac{B}{A}\frac{\nu}{E} - \frac{C}{A}\frac{\nu^2}{2E^2}\right)$$

- Gives a measurement of the flux's shape
- Normalization tied to external measurements at high energy



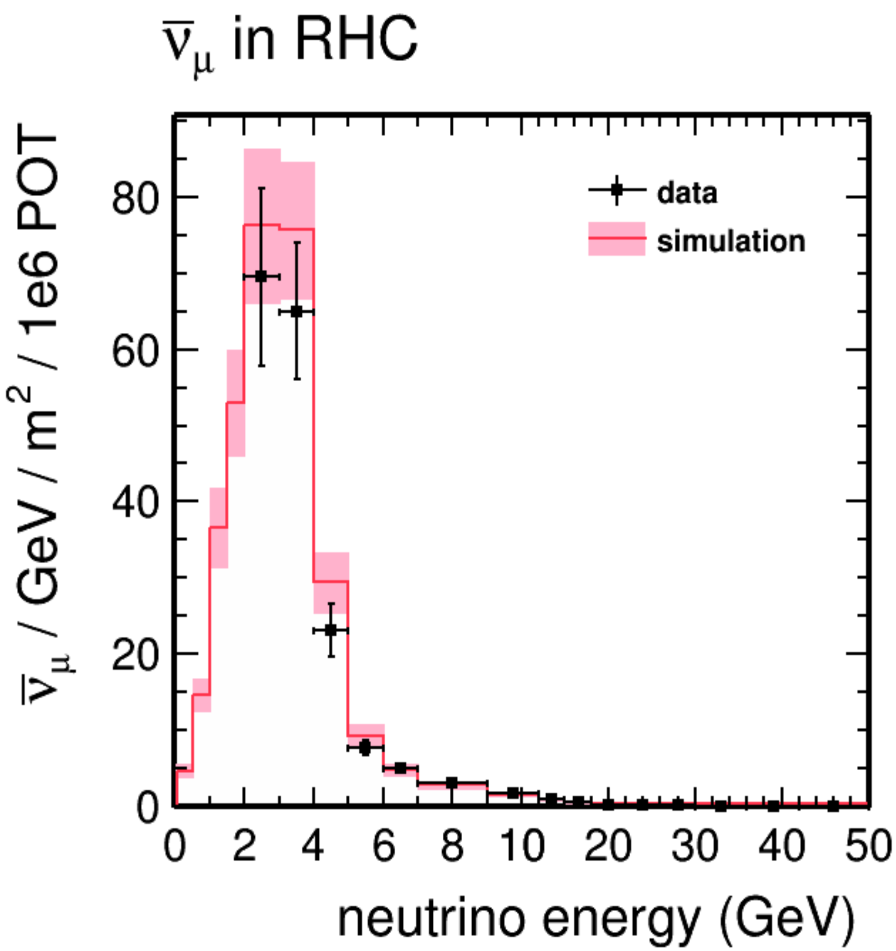
NuMI on-axis neutrino flux from the low-nu method

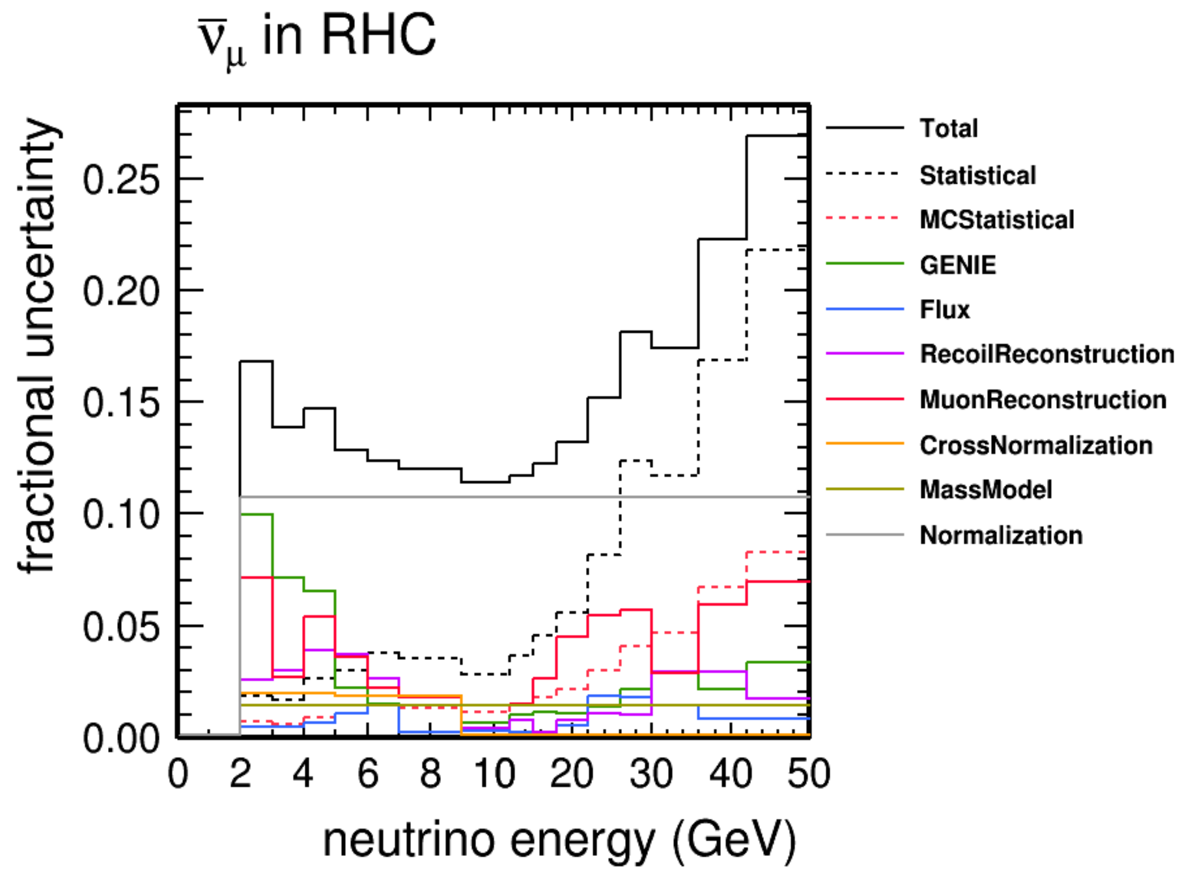




Results are consistent with the neutrino-electron scattering and ex situ fluxes

NuMI on-axis antineutrino flux from the low-nu method



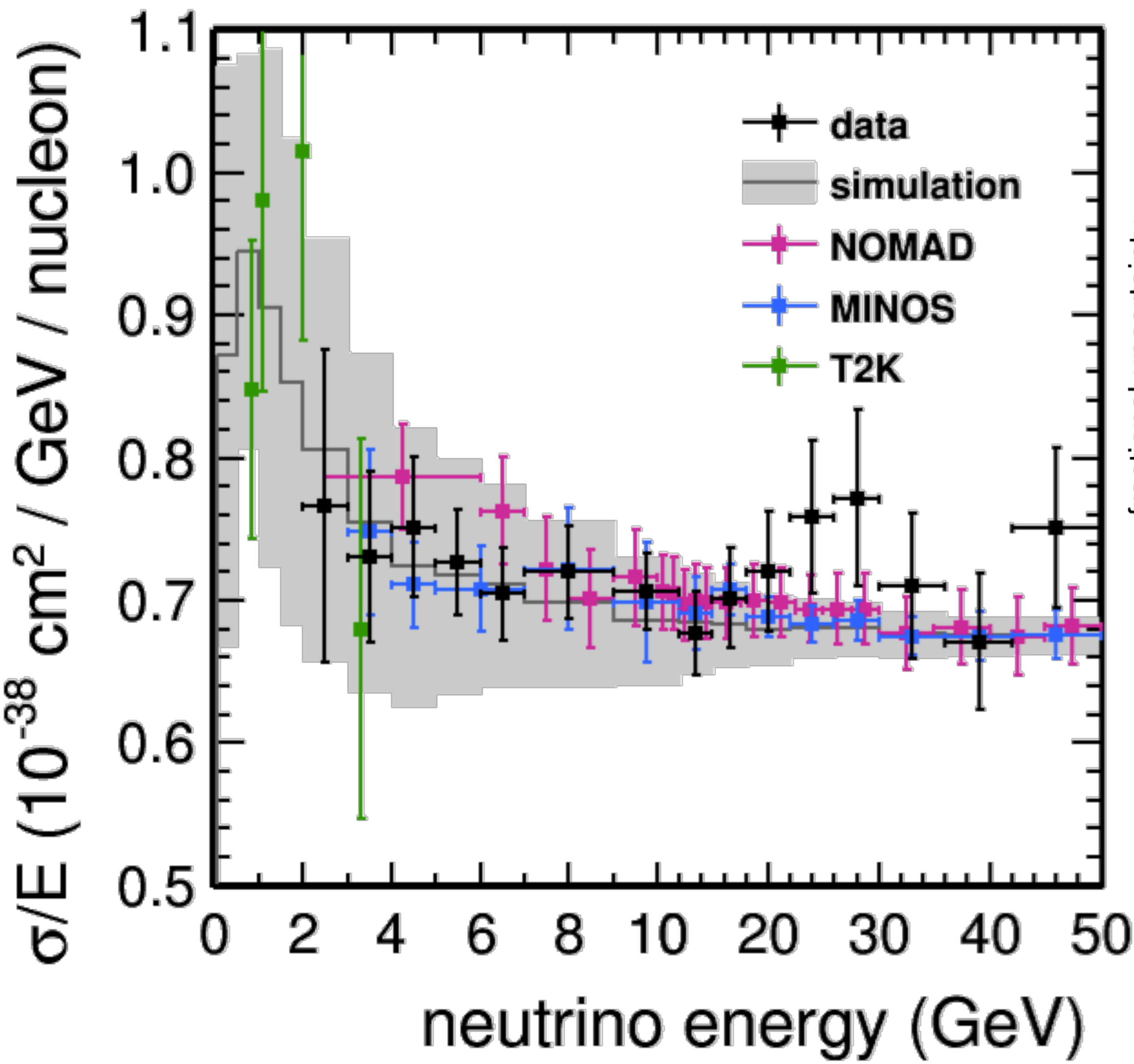


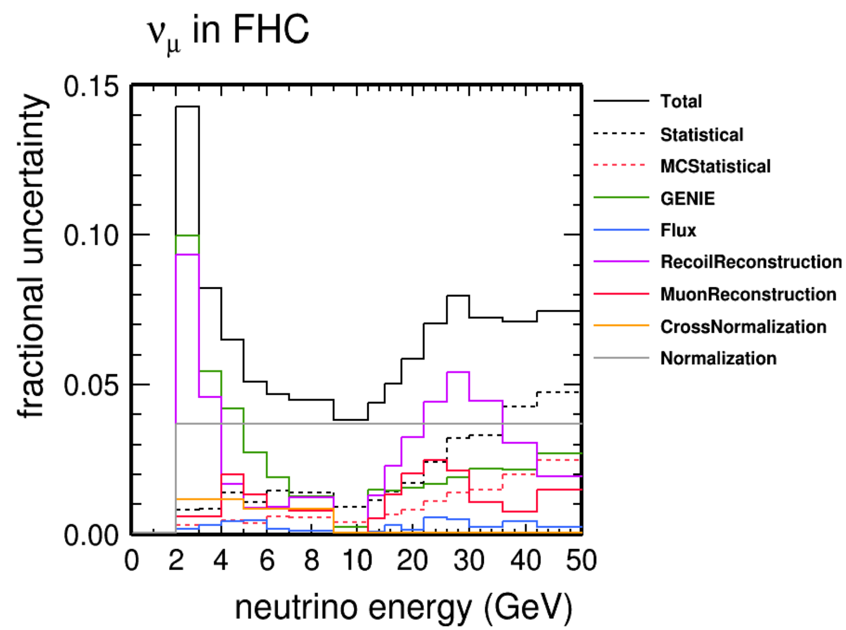
To be unveiled at 1/8/16 FNAL wine & cheese

Simplest thing…
inclusive charged current scattering

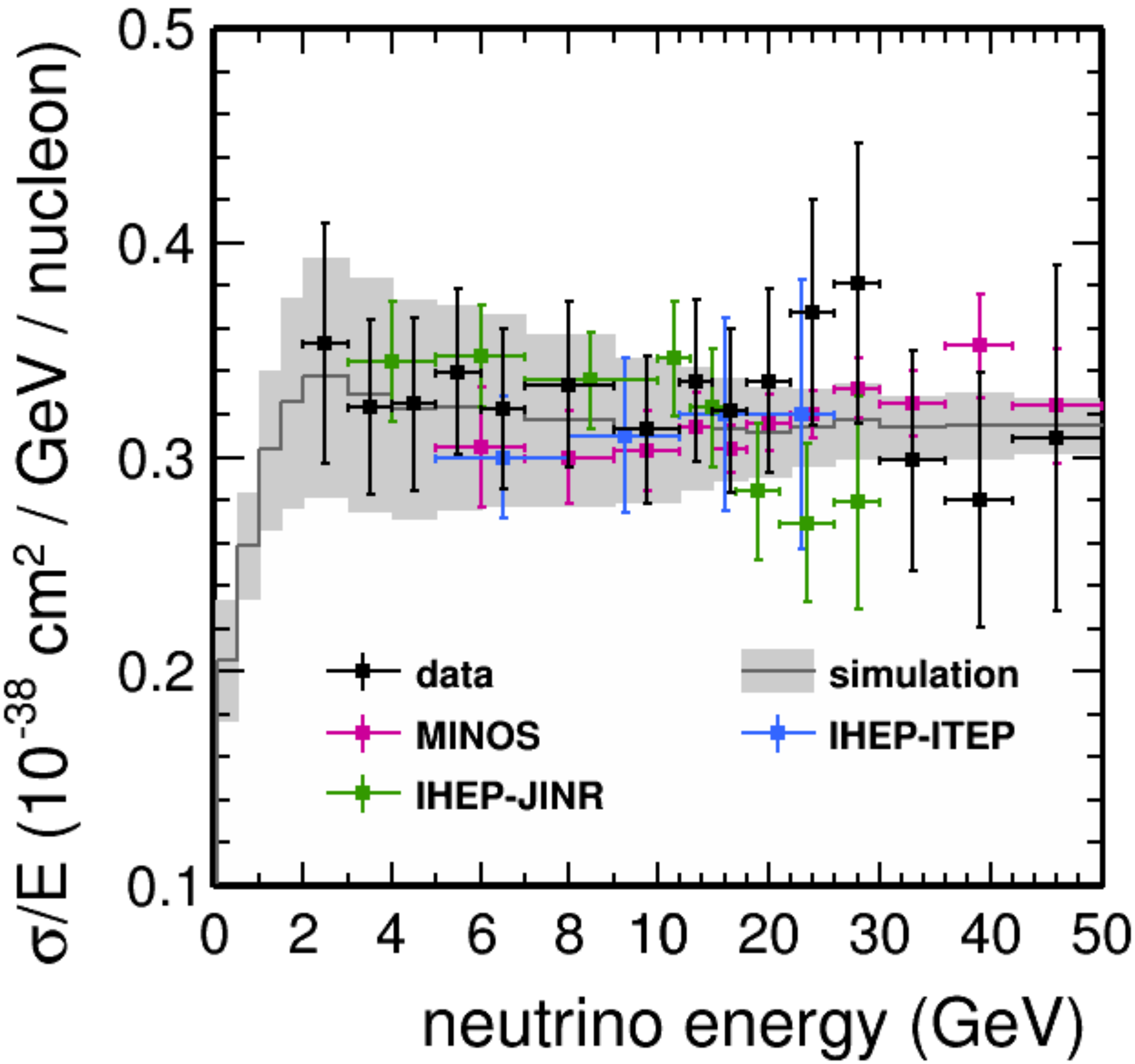
Results use low-nu flux

MINERvA CC inclusive neutrino cross section & world data

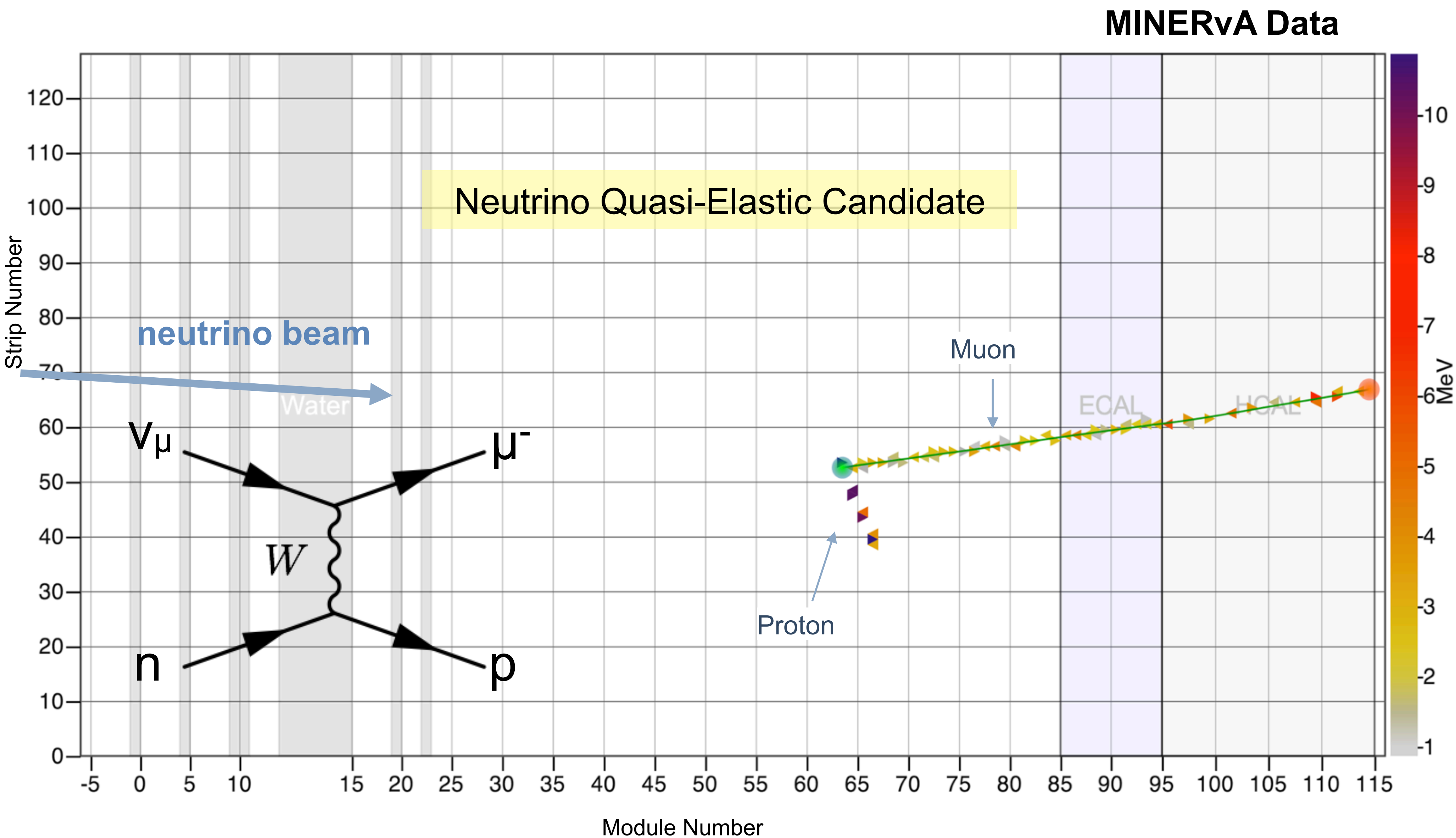




MINERvA CC inclusive antineutrino cross section & world data

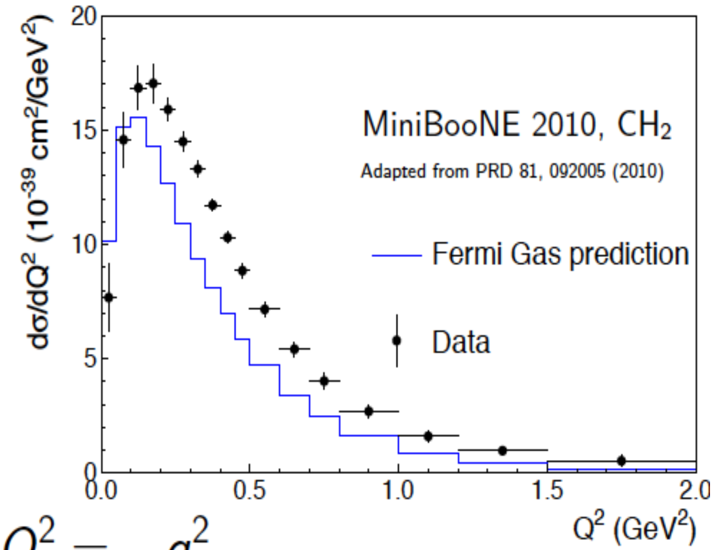


Quasi-elastic scattering



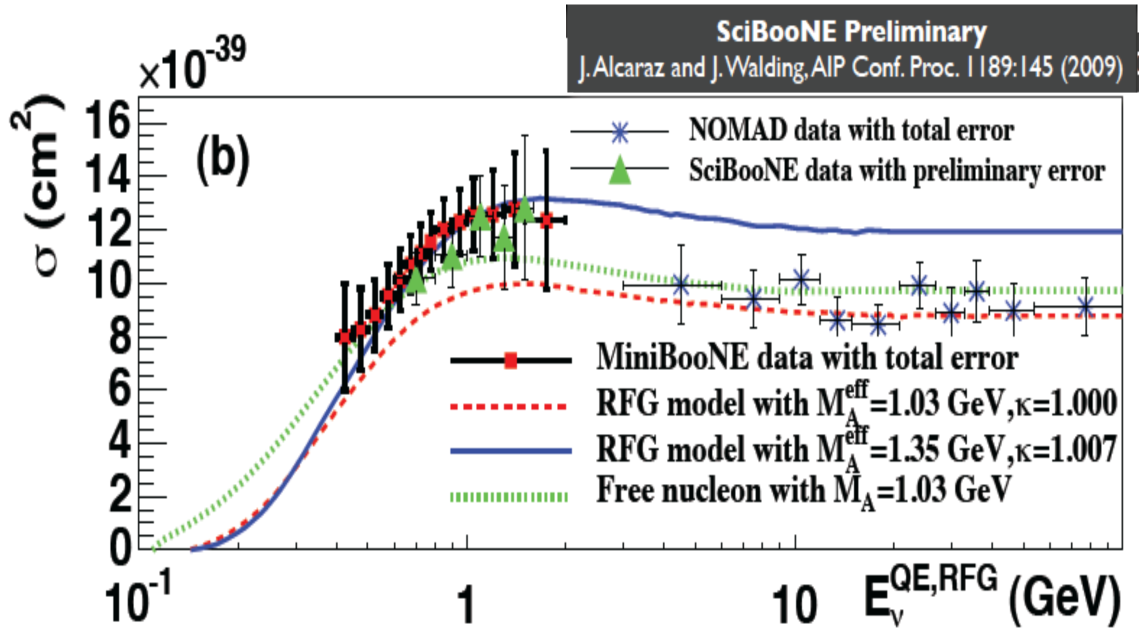
Long-standing problem in ν_μ CCQE

- NOMAD, bubble chambers
  - > Used two-track topology with low thresholds
  - > Consistent with RFG (like GENIE's model) with M_A=1 GeV but prefer a better nuclear model
- K2K, MiniBooNE, MINOS, SciBooNE
  - > Fine-grained scintillator so higher proton tracking threshold
  - > Look for a muon and low recoil; use muon kinematics for energy
  - > See a higher rate and different Q^2 distributions consistent with a higher M_A + low Q^2 suppression



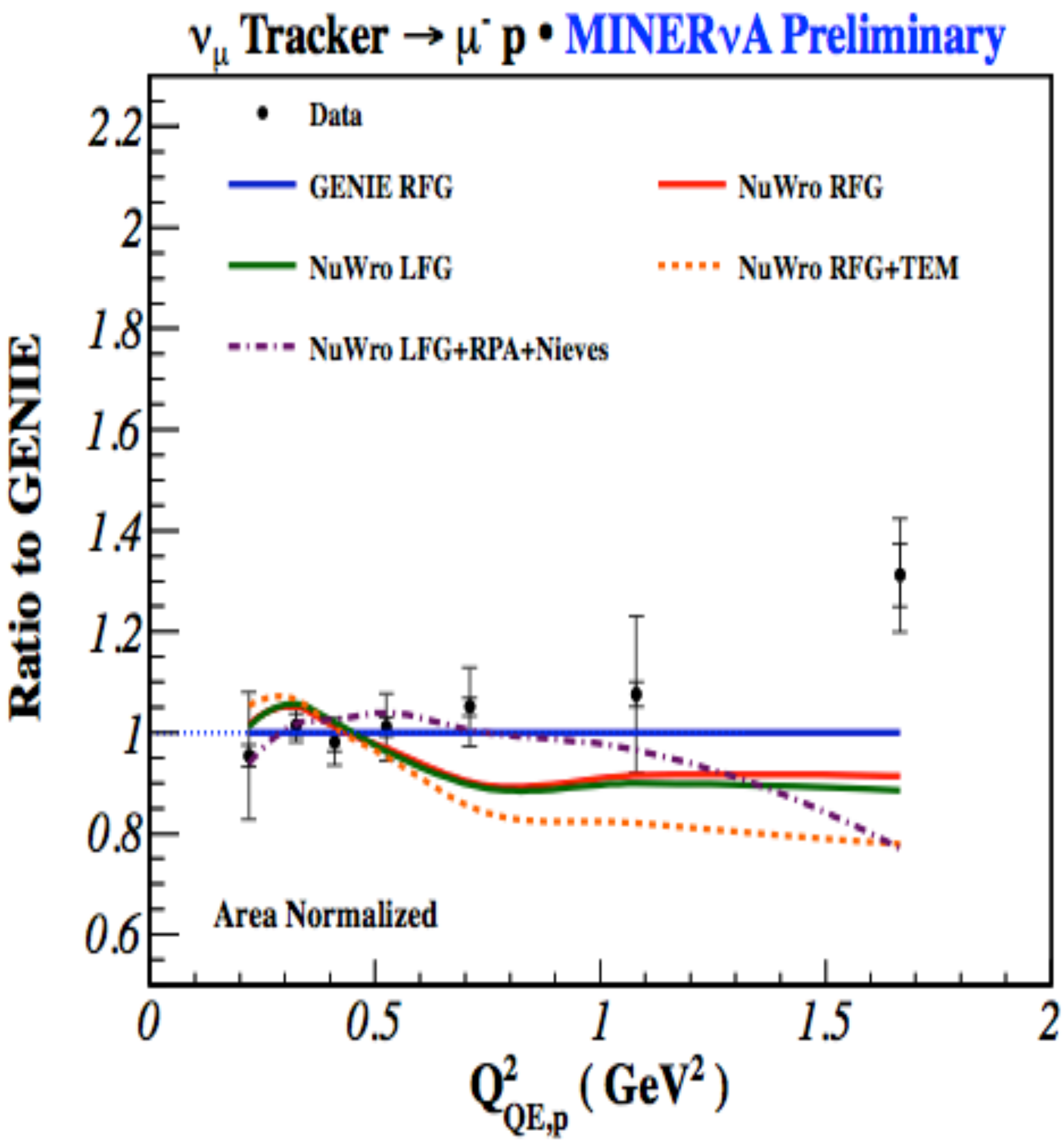
$$Q^2 = -q^2$$

- By 2010: becoming clear that this was probably due to an extra unmodeled process well known in electron scattering
  - > 2 particle, 2 hole (2p2h)
  - > Models include MEC & TE



NOMAD: EPJ C 63, 355 (2009)
MB: PRD 81, 092005 (2010)
K2K: PRD 74, 052002 (2006)
MINOS: PRD 91, 012005 (2015)
SB: J. Walding, IC thesis (2009)

2-track QE, proton-based reconstruction

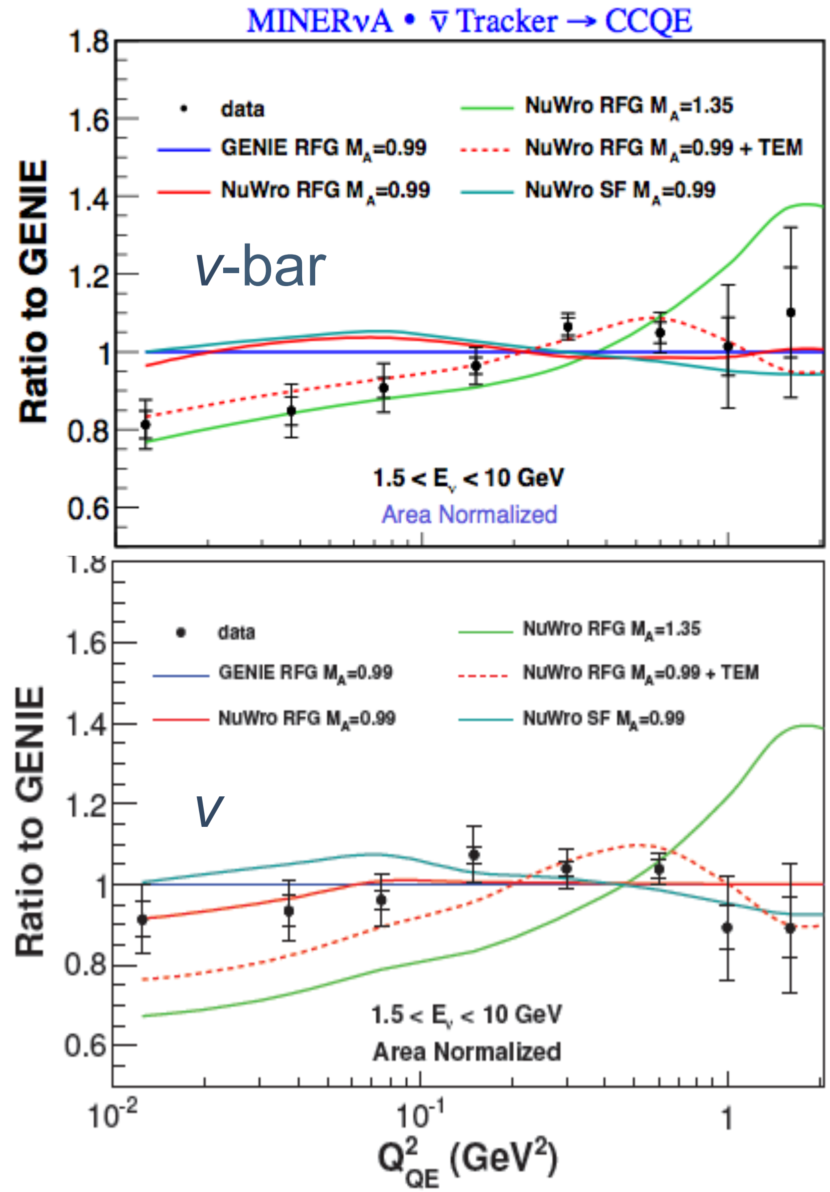


- Select events based on 1 PID'd stopping proton & 1 muon
- Reconstruct kinematics quantities using proton angle and energy
- Very sensitive to final state interactions
- Shape-only comparison
- In proton kinematic variables, see relatively good agreement with Relativistic Fermi Gas (RFA) model for QE scattering
- These 2-track QE make a pretty good standard candle

PRD 91 071301 (2015)

QE-like with lepton-based kinematics

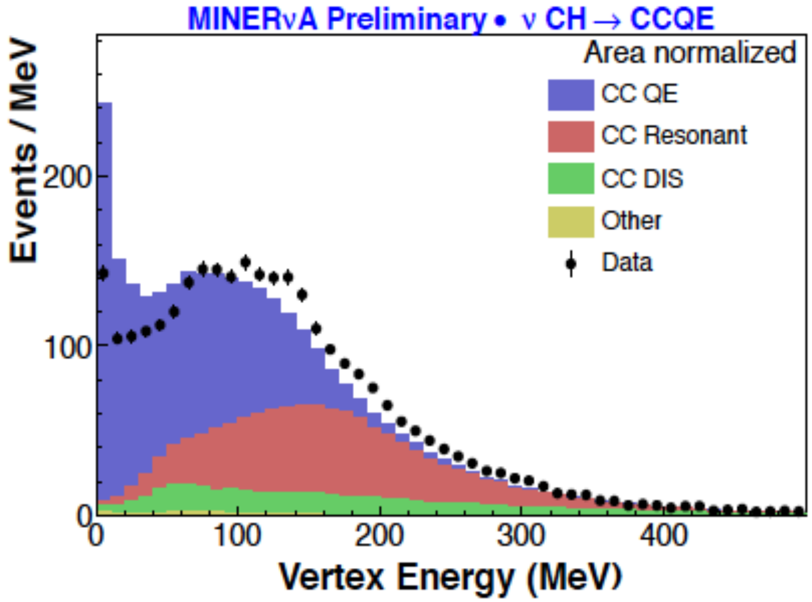
- Reconstruct the muon
  - > Require not too much energy beyond a box around the vertex
- Relatively insensitive to final state interactions (only enter via the background estimate)
- Disagreement with Fermi Gas model seen in total cross section, shape of cross section
  - > Shape alone (right) has model discriminating power
  - > Favors 2p2h contribution
  - > TEM = Transverse Enhancement Model

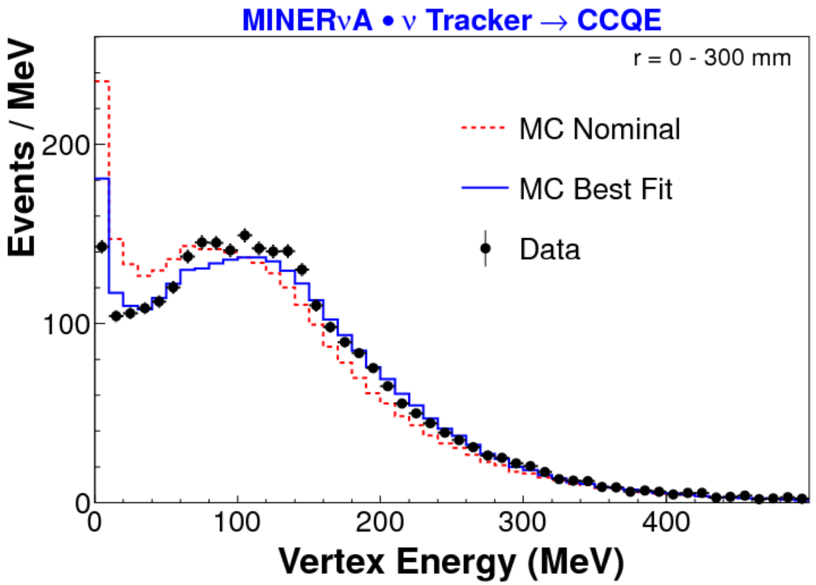


PRL 111, 022502 (2013)
PRL 111, 022501 (2013)

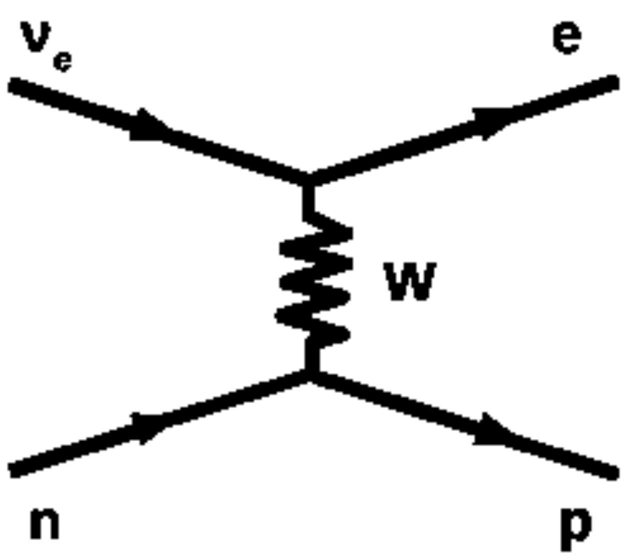
Search region around the vertex for QE-like events for signs of extra particles

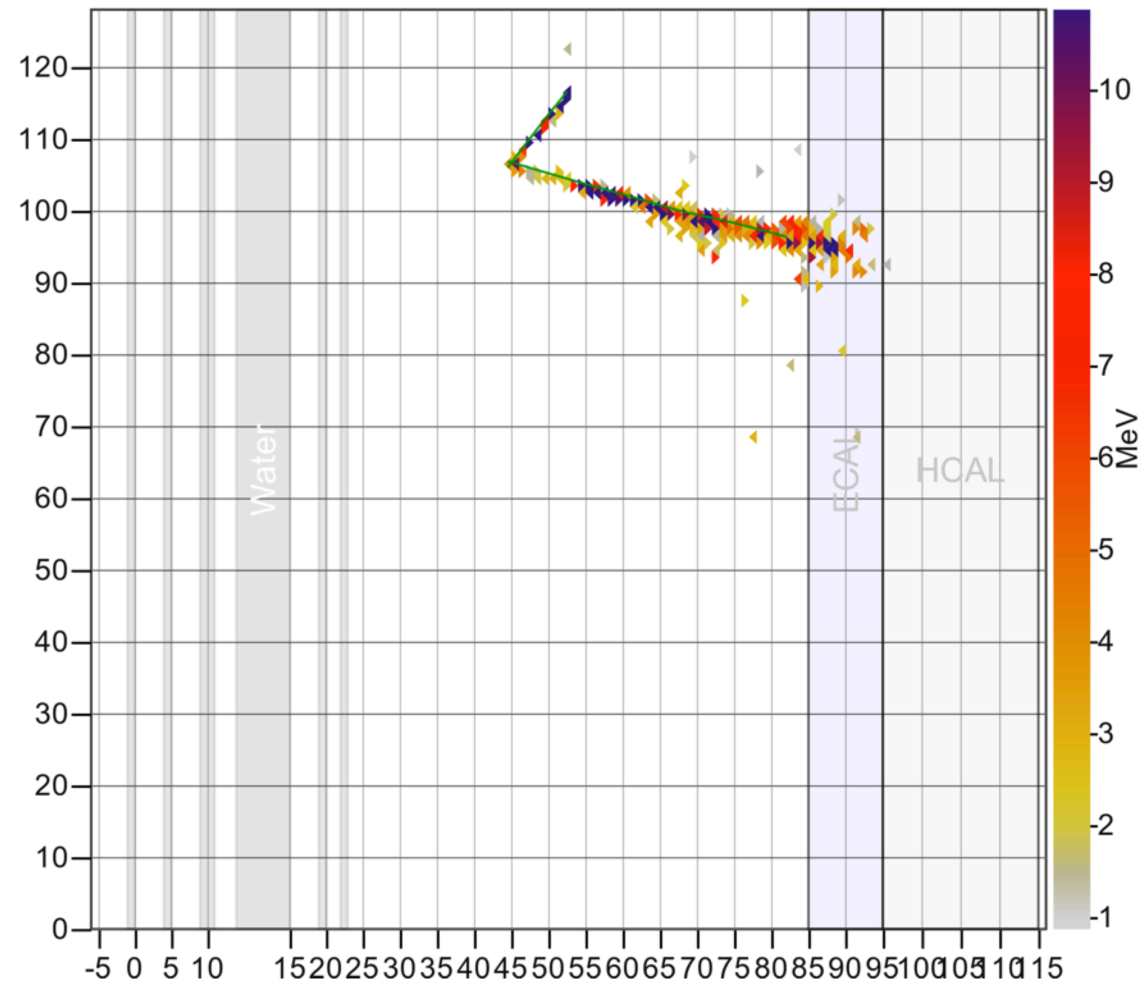
- The model is that a (np) pair are coupled via initial-state pion exchange
  - > Like a deuteron within the nucleus
  - > Neutrino scattering should look like 2 protons in the final state
  - > Antineutrino scattering should look like 2 neutrons in the final state
- Measure distance of extra energy in annuli around the vertex to measure the energy spectrum of the extra particles
  - > Consistent with extra proton production (2p-2h) for (25±9)% of neutrino QE-like events with range up to 250 MeV/c
  - > No excess in antineutrinos QE-like
- GENIE underestimates energy of QE-like hadronic system which will cause biases in neutrino energy reconstruction





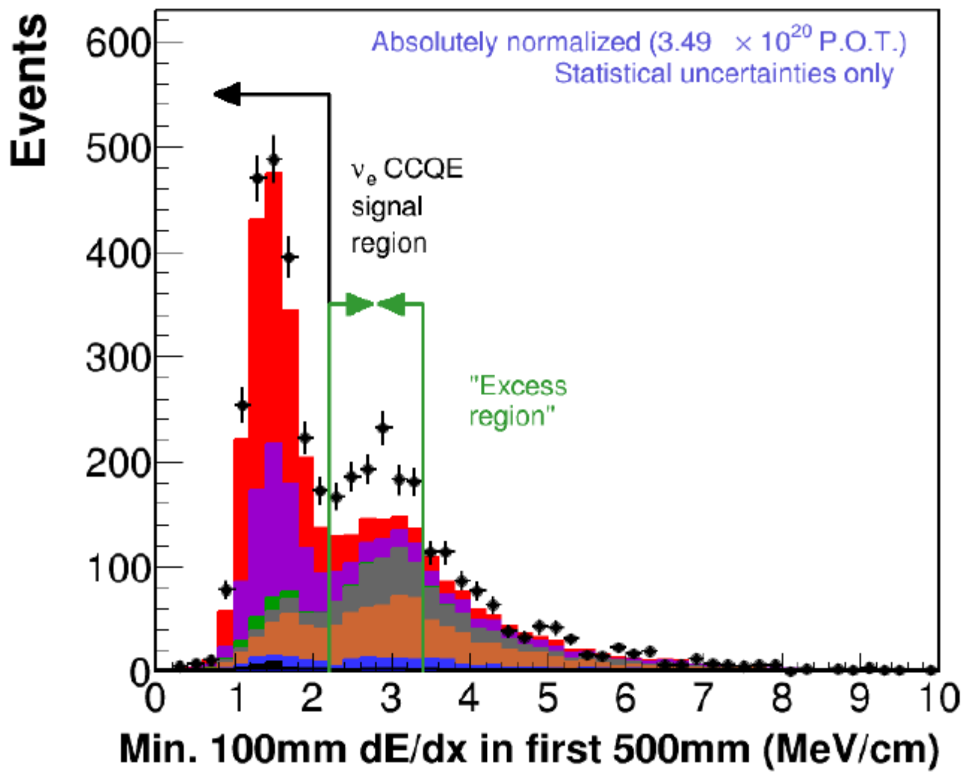
Electron neutrino CC QE: Large signal for electron appearance





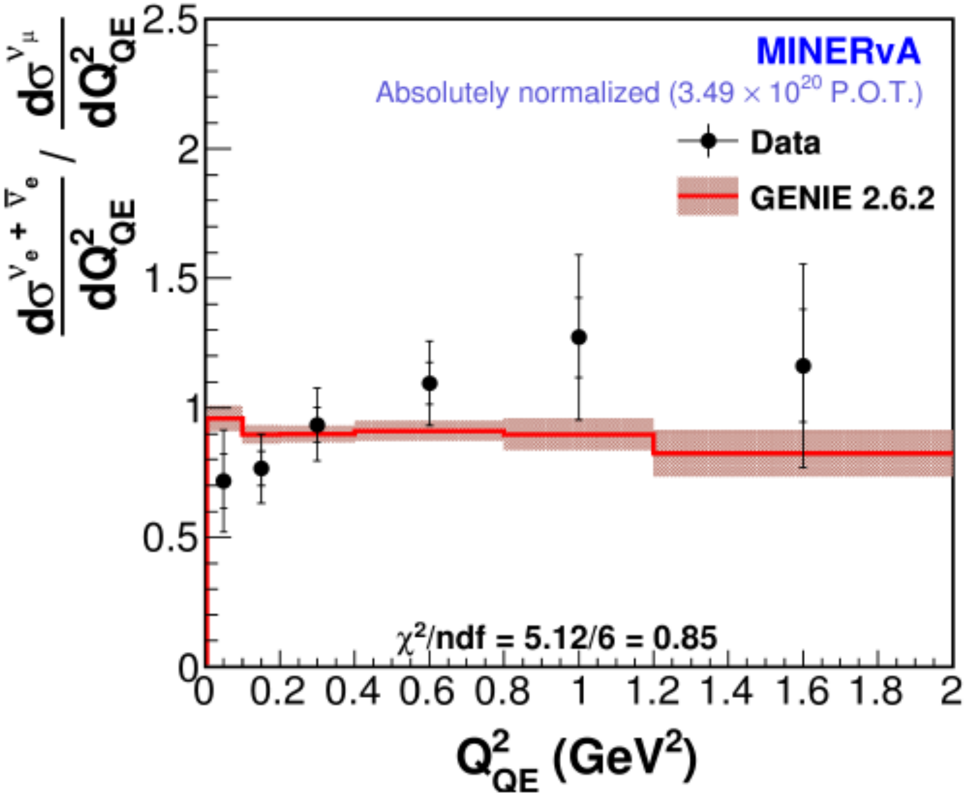
The first time this channel has been measured

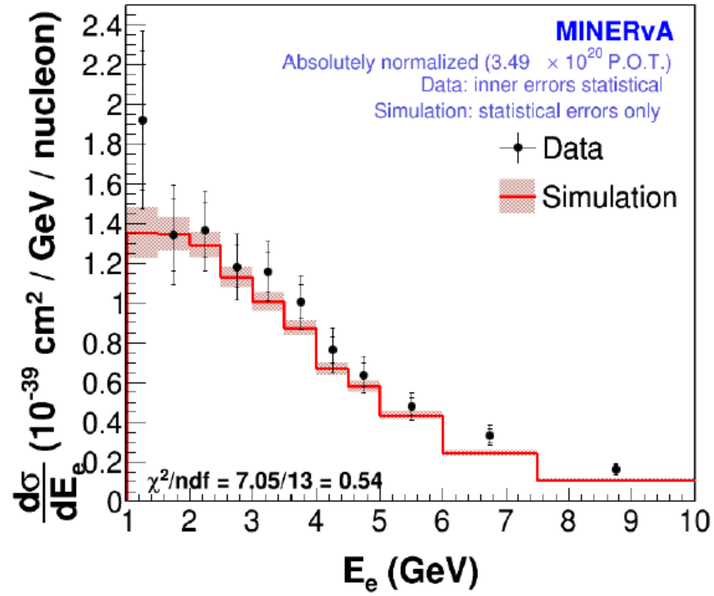
- Isolate the small electron neutrino sample (2% of beam)
- Rely on electrons having one prompt track while neutral pions start their shower with 2 tracks' ionization (e^+e^- pair)

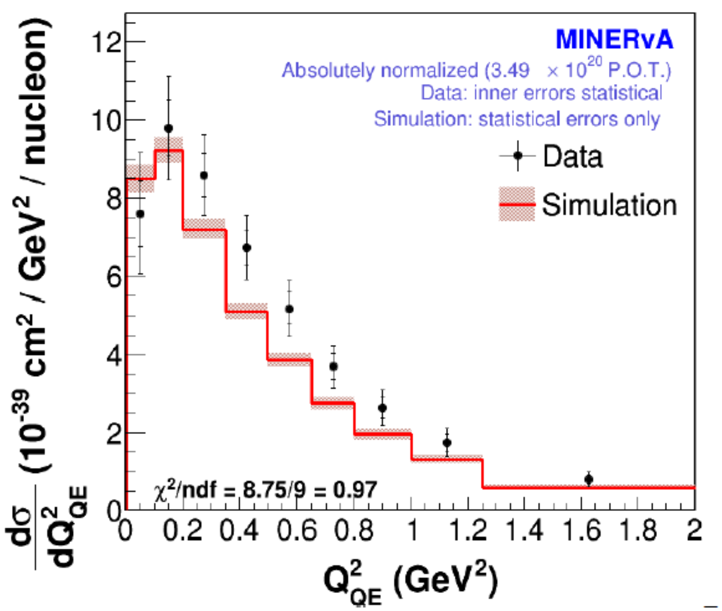


Electron neutrino CC QE is consistent with muon neutrino CC QE

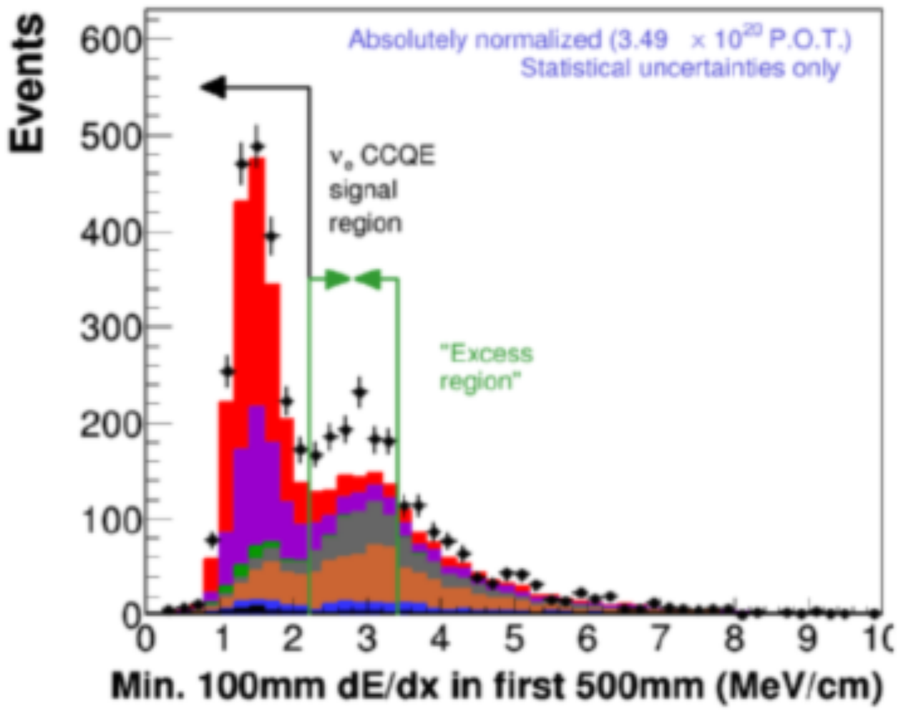
- Constrains differences the between nuclear effects to the 15% level

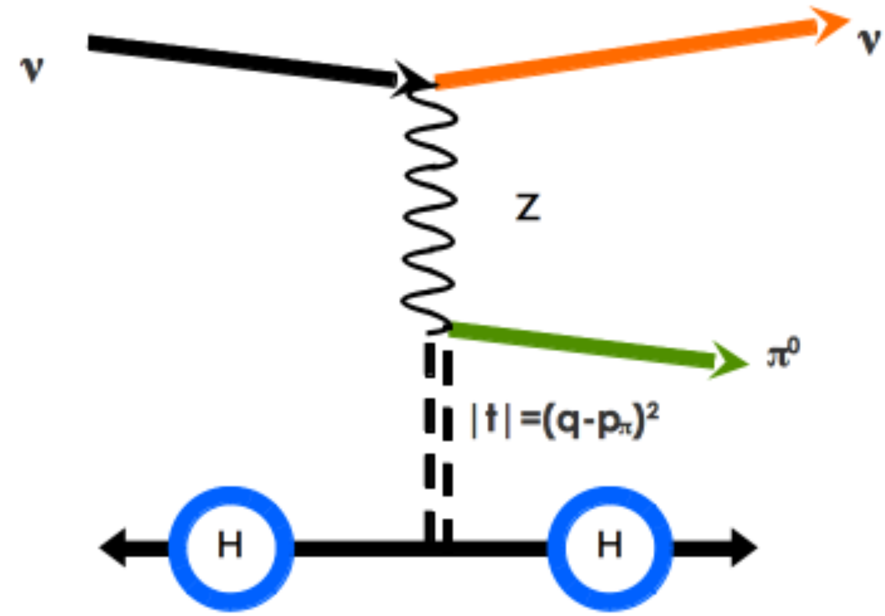






Unmodeled background:
NC diffractive scattering from H





Conceptually similar to NC coherent scattering:

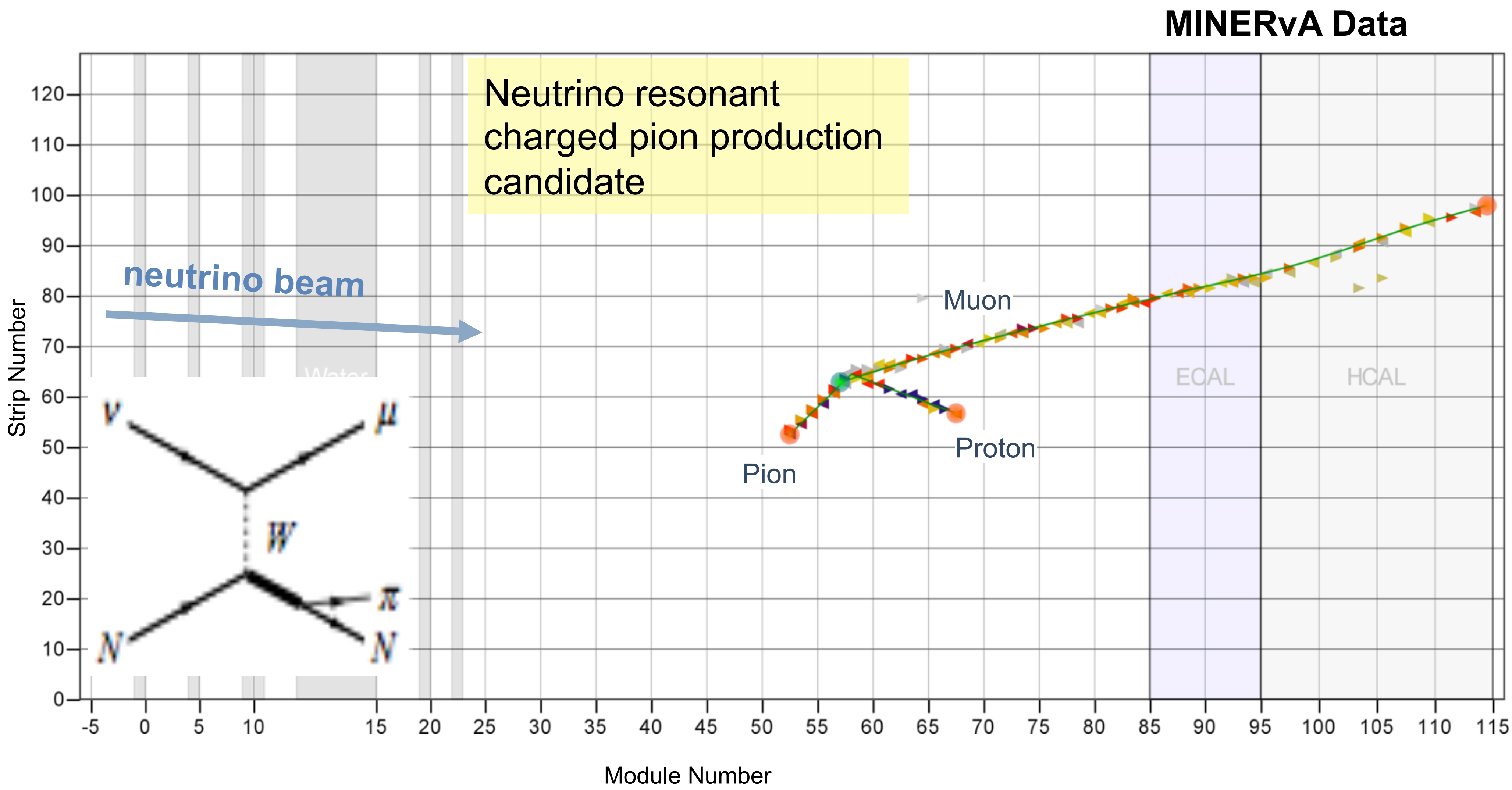
- Little momentum transfer to target
- Vector meson emitted in forward direction

Unique to diffractive scattering from H:

- Recoiling H nucleus (single proton) sometimes visible

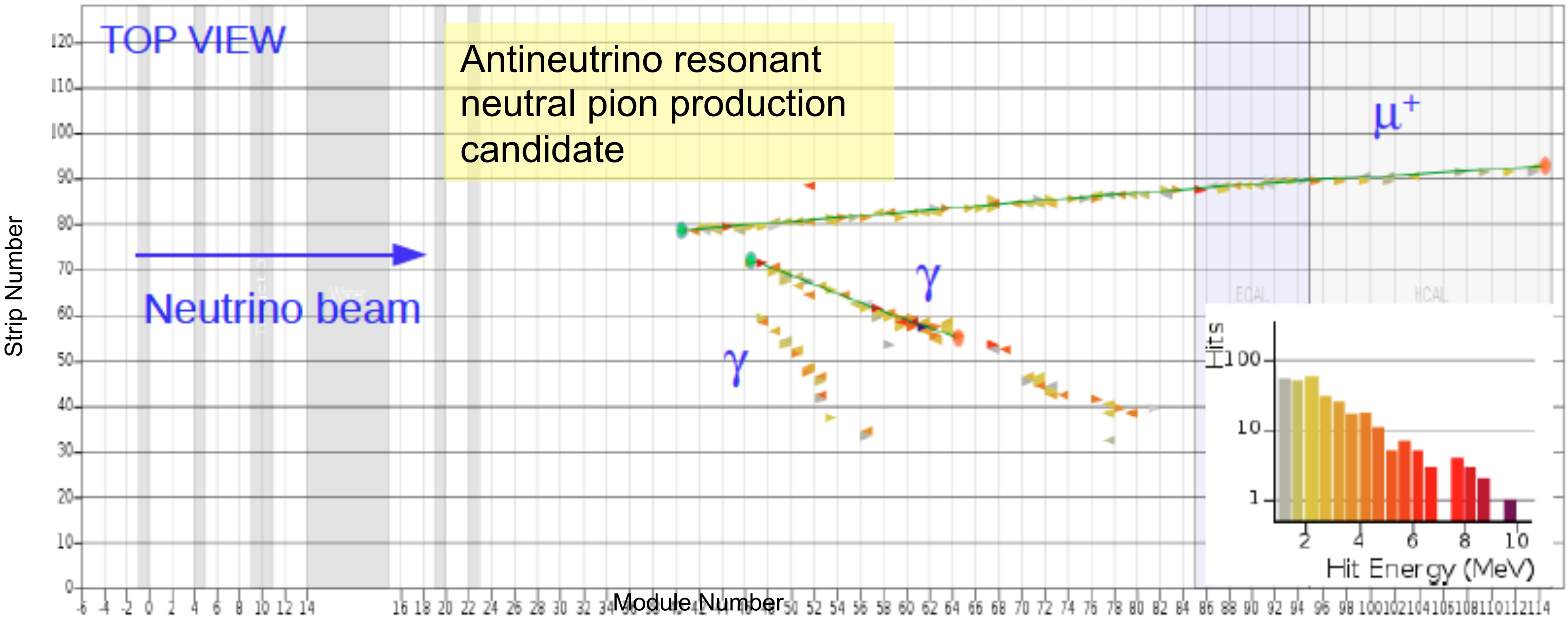
Not in (default) GENIE model

Results: pion production

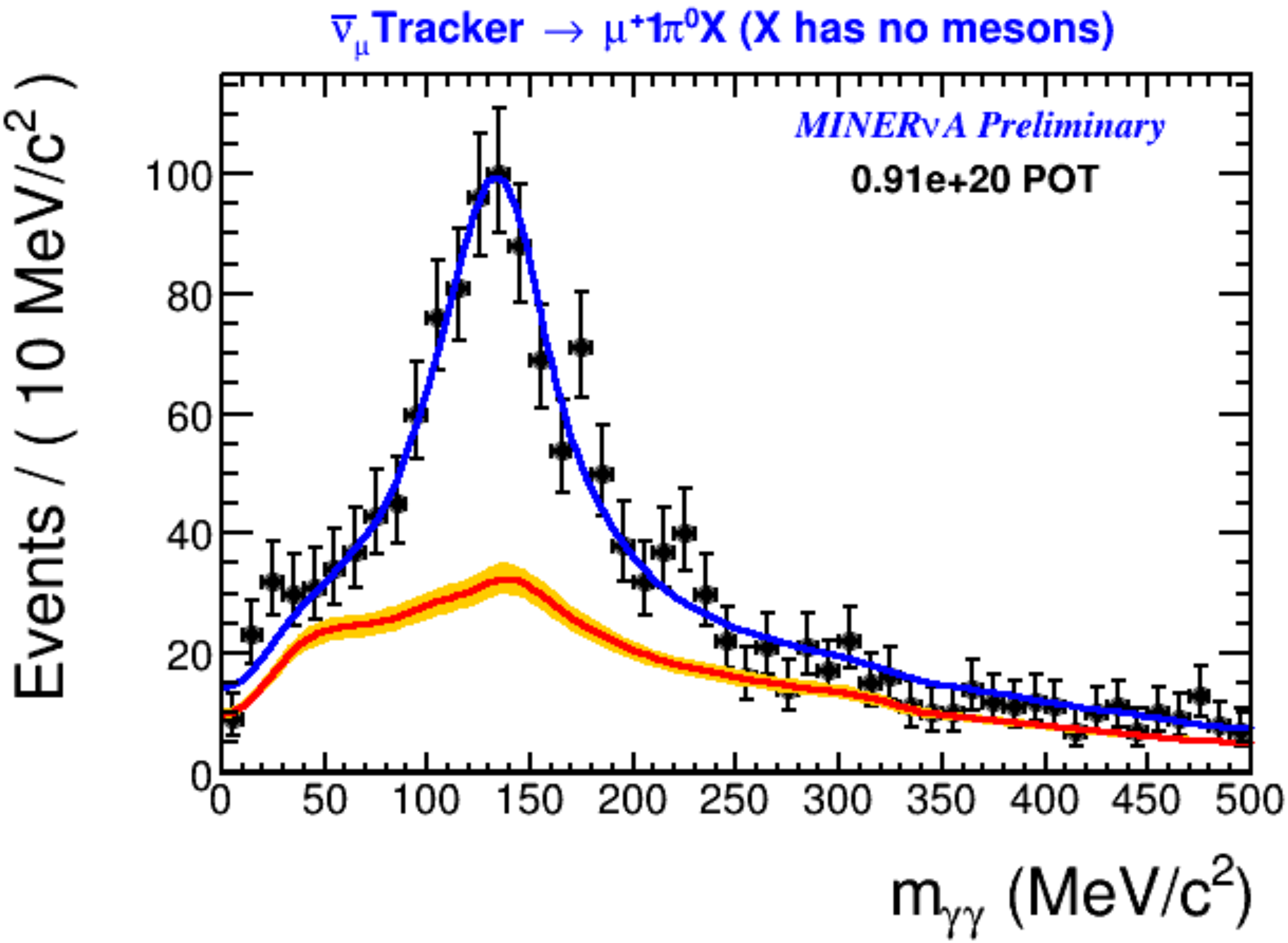


Results: pion production

MINERvA Data

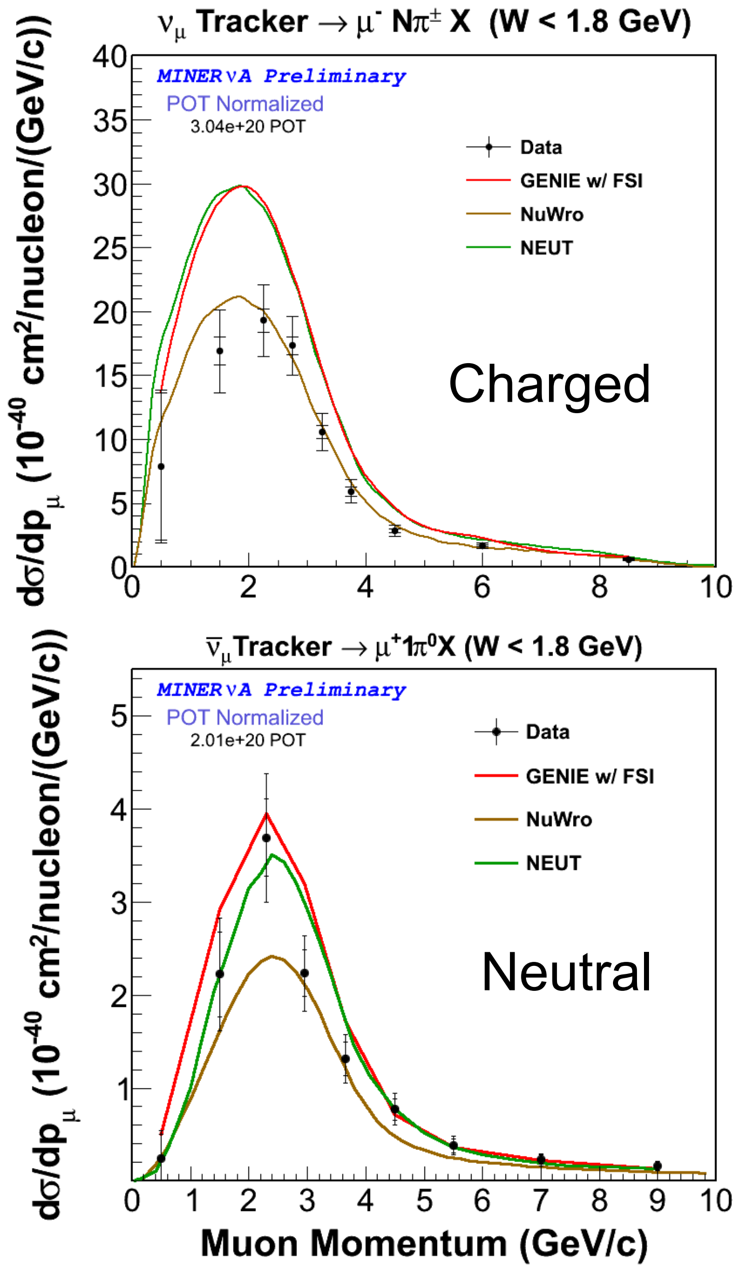


Pizero mass peak after sideband fits



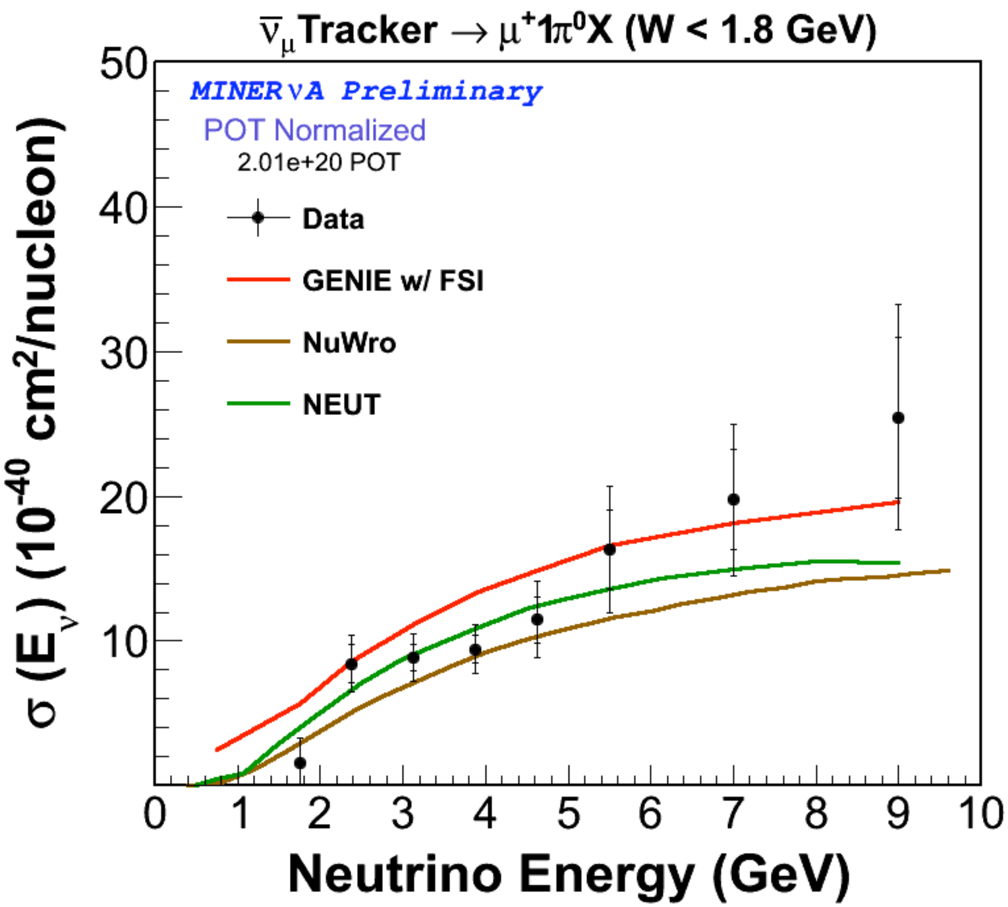
Results: resonant charged pion production

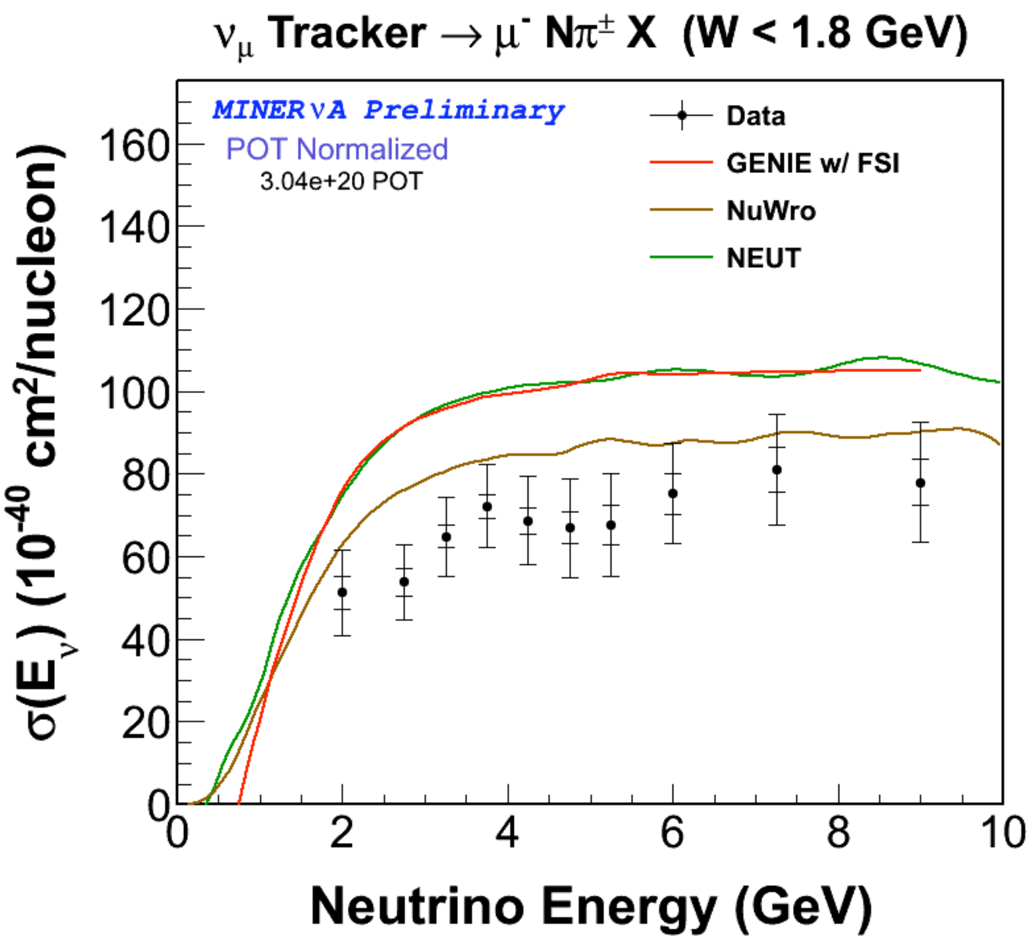
- Differential cross sections with respect to muon kinematics
  - > Muon is not FSI sensitive
  - > Shapes vs both energy and angle are in reasonable agreement with GENIE
- GENIE over-predicts the resonance rate for charged pions by 25%
  - > Charge pion is FSI sensitive
- GENIE mildly over-predicts the rate for neutral pions
  - > Neutral pion is mildly FSI sensitive (Largely through charge exchange)
- The difference in agreement suggests possible FSI deficiency



B. Eberly FNAL JTES, Feb 7 2014
T. Le, FNAL JTES, Jan 9, 2015
C. McGivern, FNAL JTES, June 26, 2015

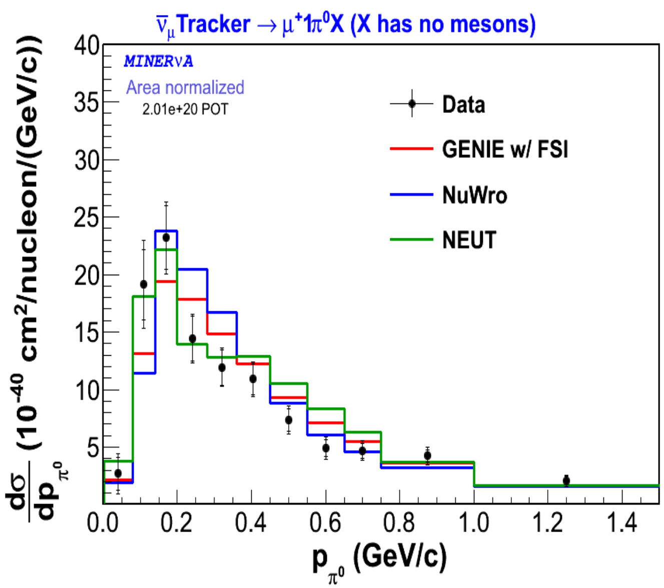
Pion production cross sections vs E_ν

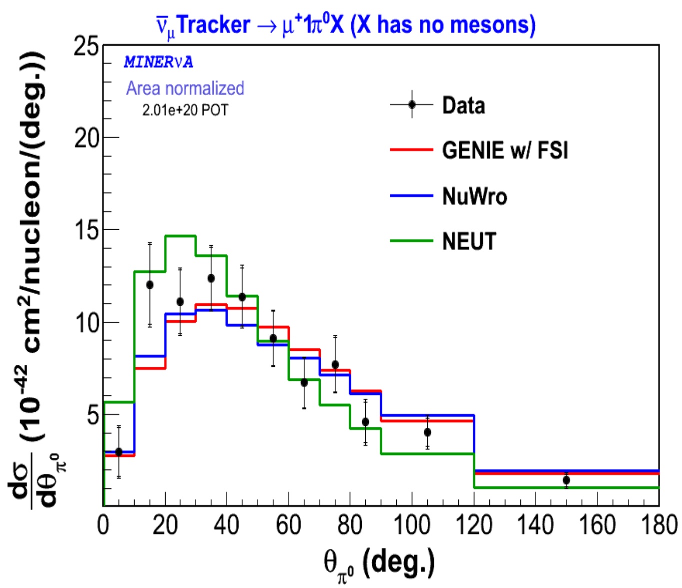




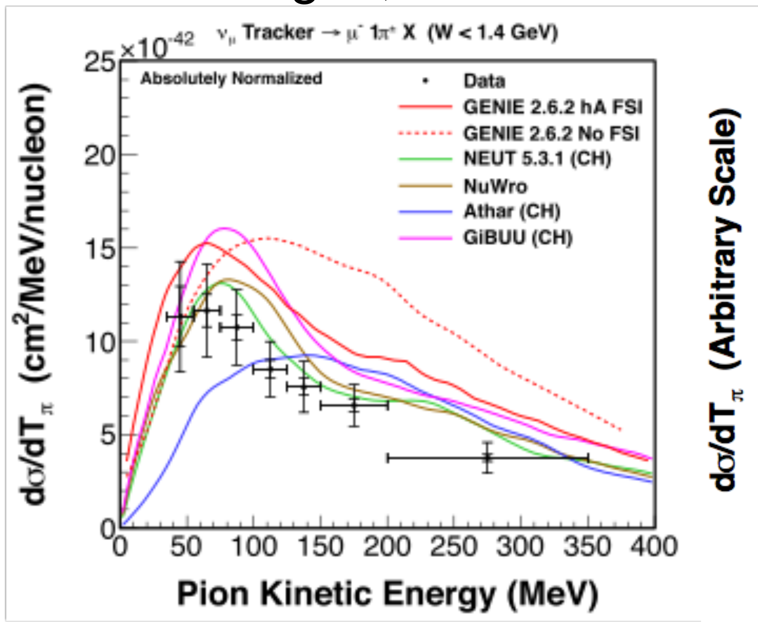
Resonant Pion Production

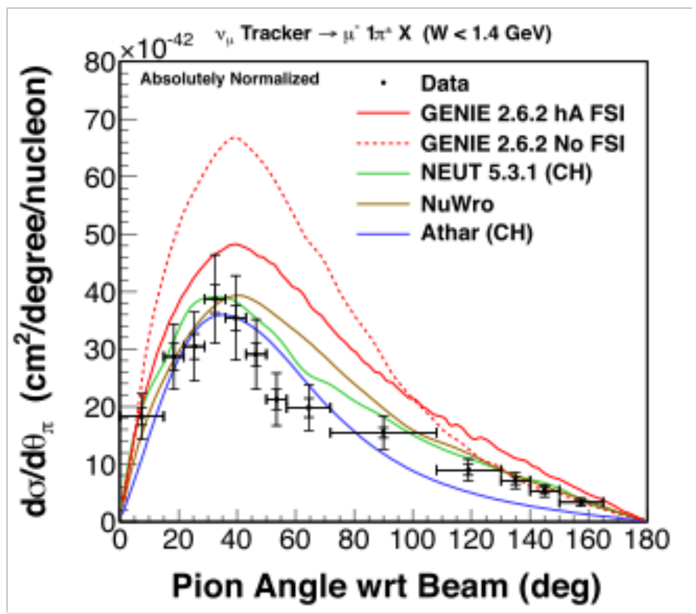
Neutral, absolute



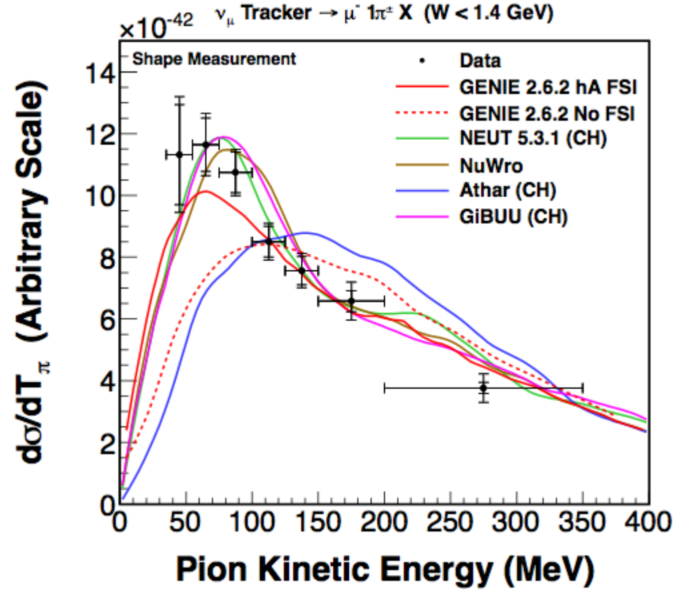


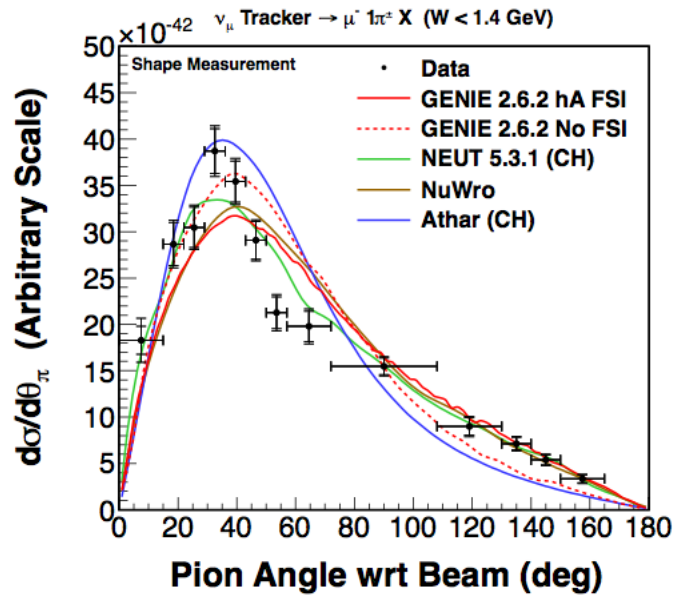
Charged, absolute





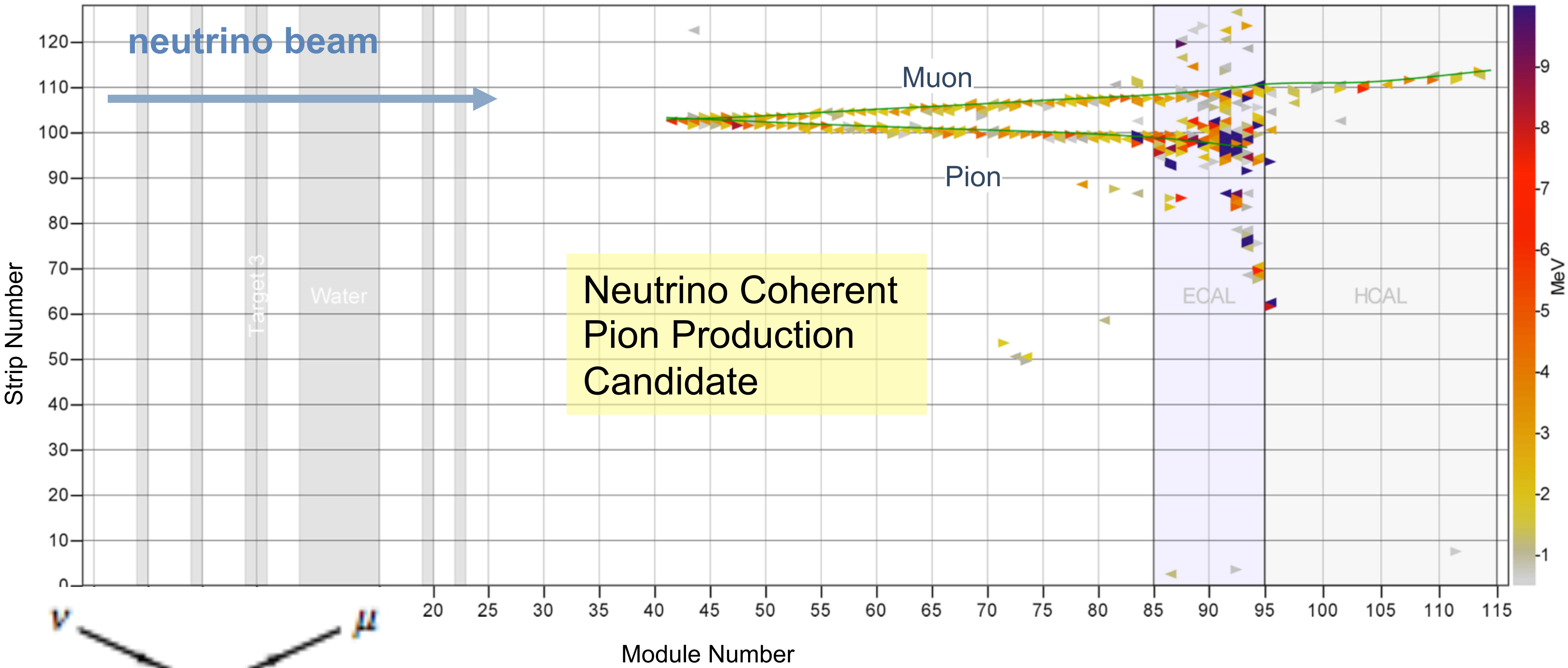
Charged, shape

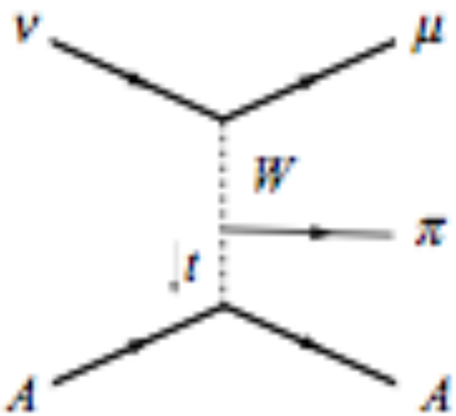




Coherent charged pion production

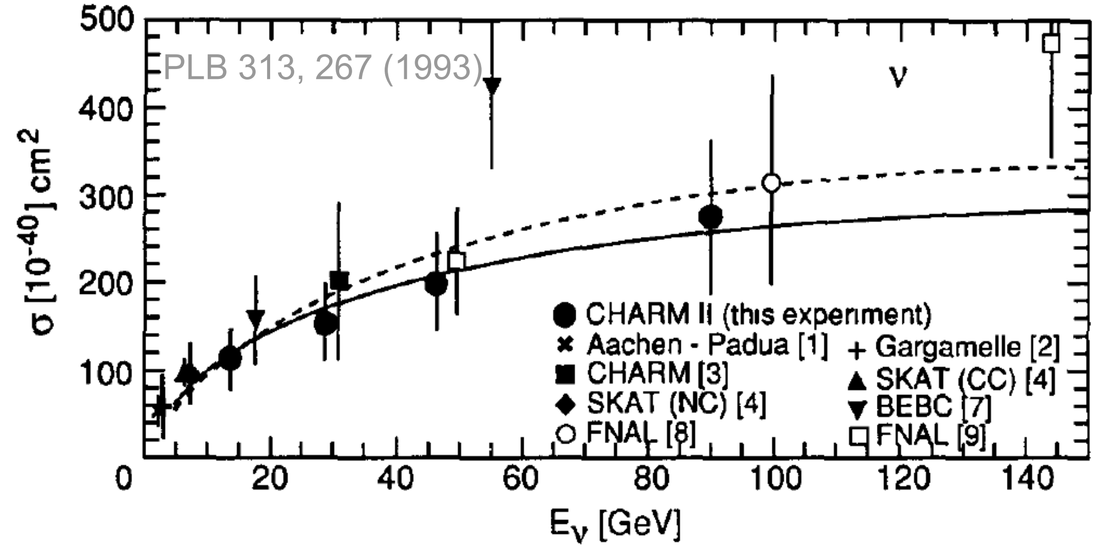
MINERvA Data



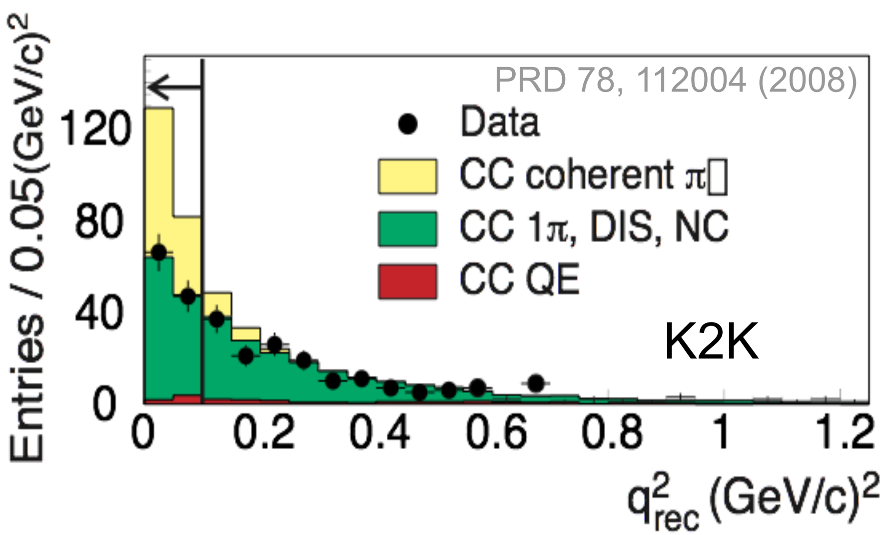


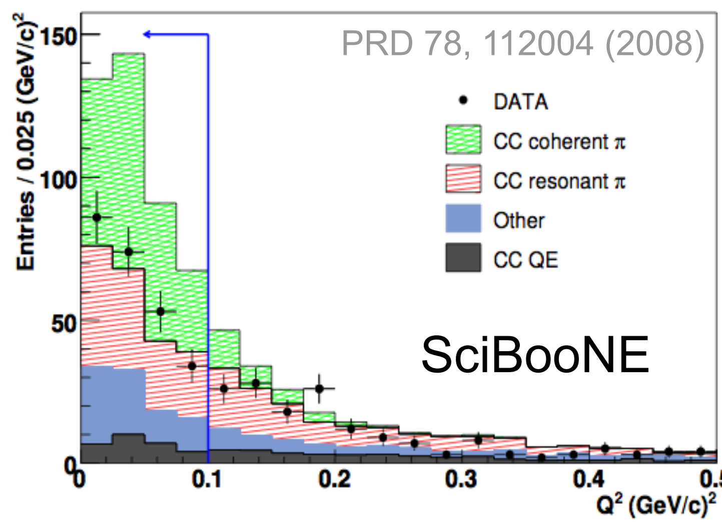
Neutral pion NC analog is a background to electron neutrino appearance measurements

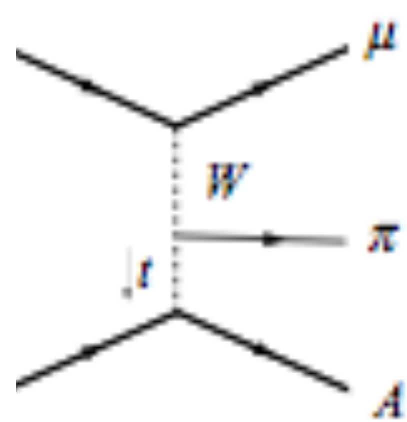
Prior results:
coherent charged pion production results



- Clear signal seen by high energy experiments
- No signals seen in recent low-energy experiments





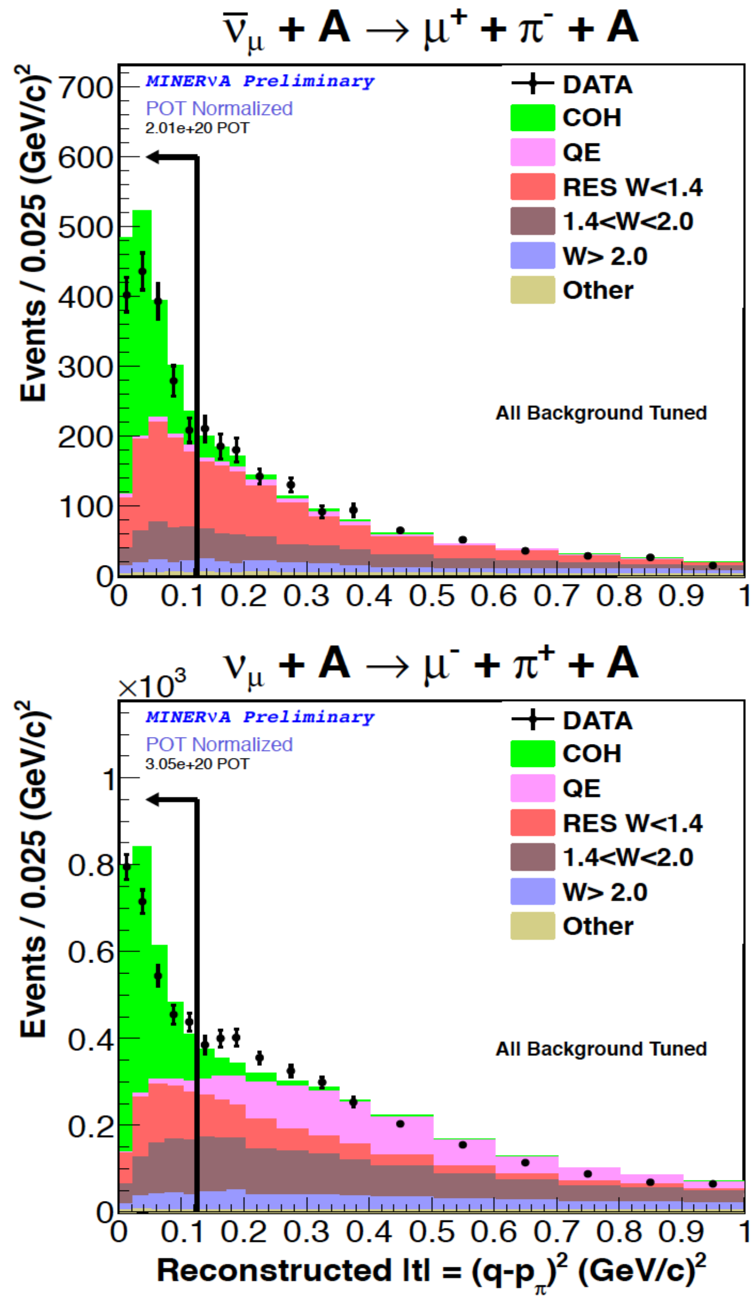


Coherent charged pion production

- MINERvA sees clear signal of neutrino and antineutrino coherent pion production
- Reconstruct |t|
  > The 4-momentum transfer to nucleus (including masses)
  > Minimal model dependence in signal prediction
  > Large background suppression

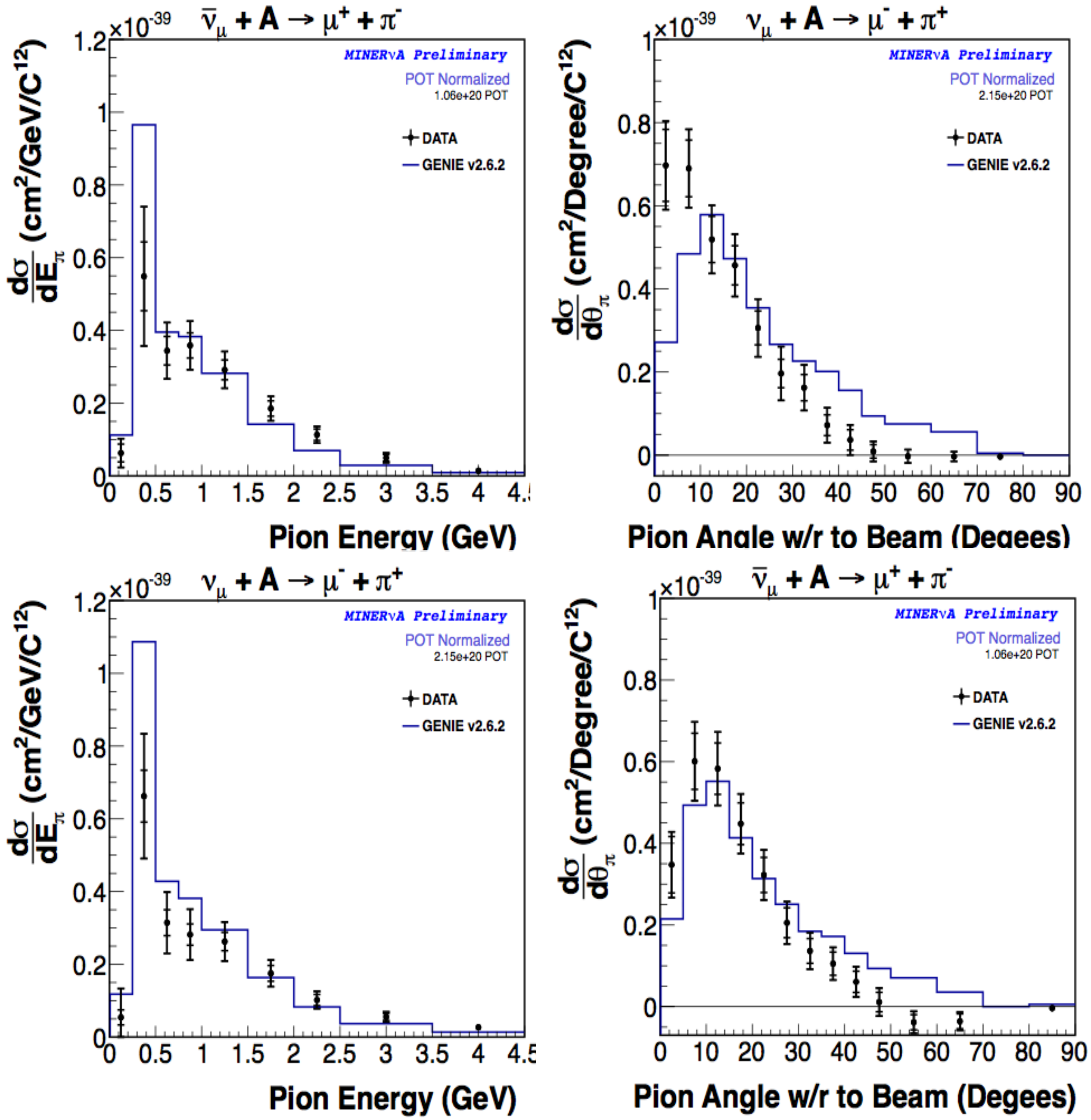
$$Q^2 \geq m_\mu^2[y/(1-y)]$$

$$|t| \geq [(Q^2 + m_\pi^2)/(2yE_\nu)]^2$$



PRL 113, 261802 (2014)

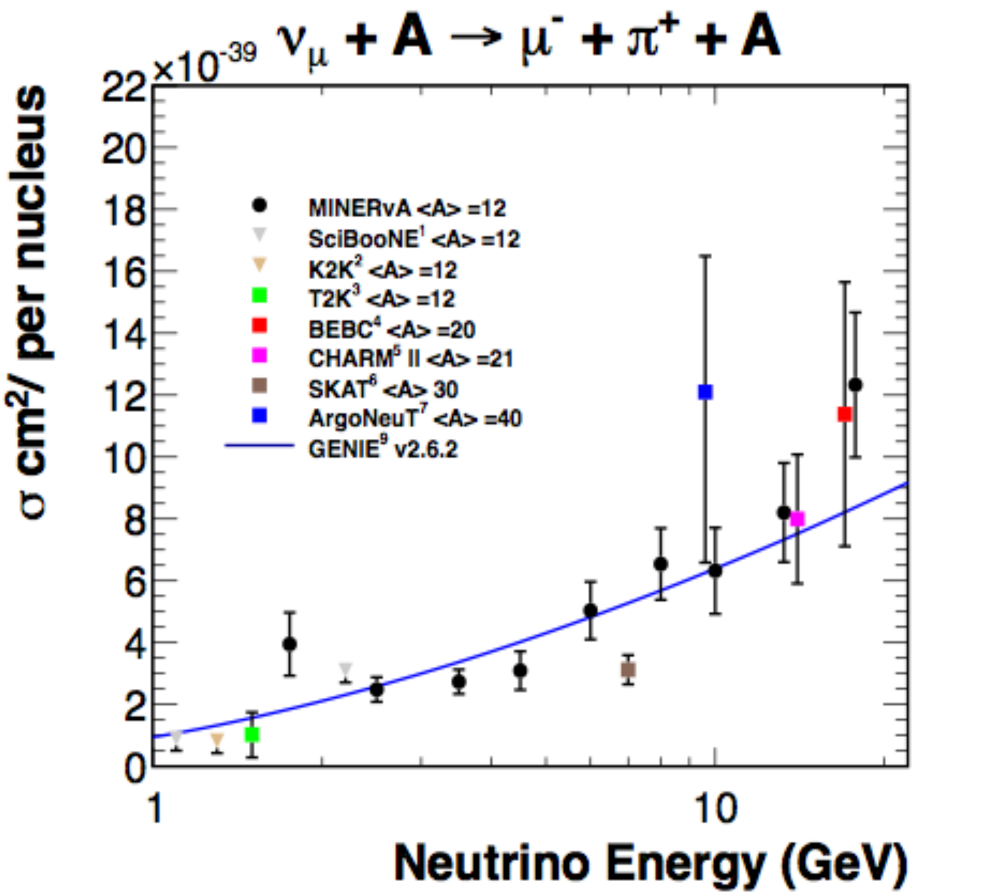
Coherent charged pion production

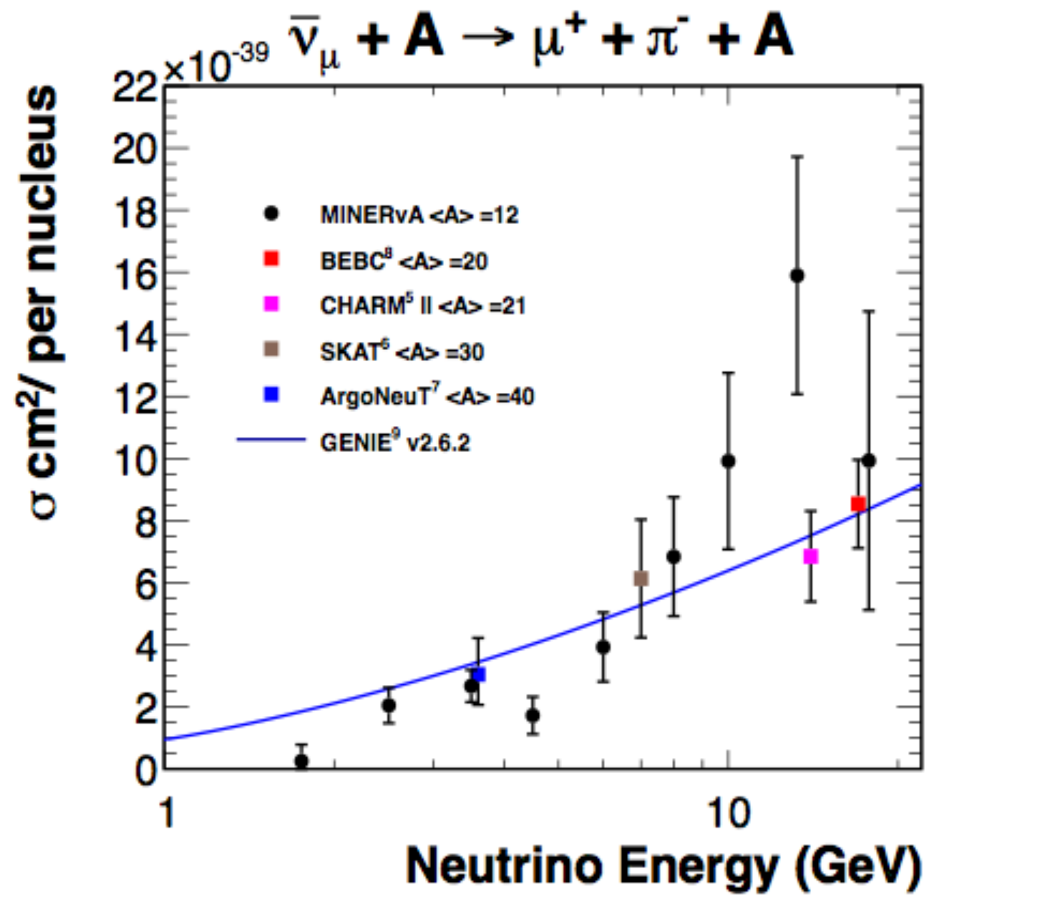


- Data begin to probe kinematic predictions used to model this signal
- See indications that model does not accurately reflect energy or angle of pion
  - > Harder
  - > More forward

PRL 113, 261802 (2014)

Coherent charged pion production



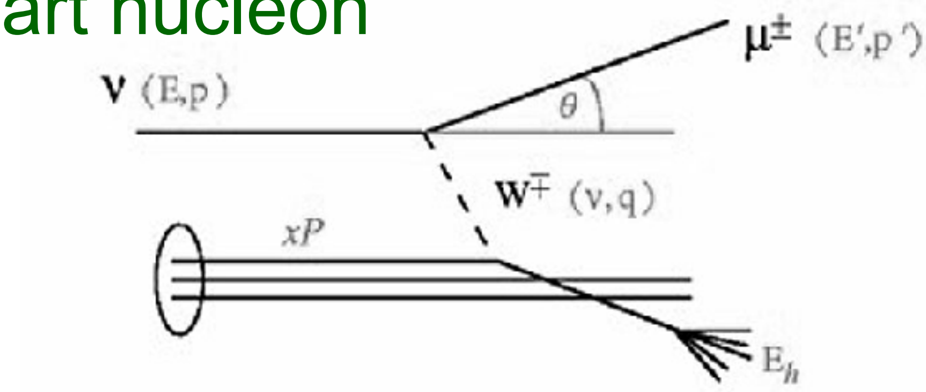


[1] SciBooNE Collaboration (K. Hiraide et al.), Phys. Rev. D 78, 112004 (2008)
[2] K2K Collaboration (M. Hasegawa et al.), Phys. Rev. Lett. 95, 252301 (2005)
[3] T2K Collaboration NuInt 2014 preliminary result
[4] BEBC WA59 Collaboration (P. Marage et al.), Z. Phys. C 31, 191 (1986)
[5] CHARM II Collaboration (P. Vilain et al.), Phys. Lett. B 313, 267 (1993)
[6] SKAT Collaboration (H.J. Grabosh et al.), Z. Phys. C 31, 203 (1986)
[7] ArgoNeuT Collaboration NuInt 2014 preliminary result
[8] BEBC WA59 Collaboration (P. Marage et al.), Z. Phys. C 43, 523 (1989)
[9] GENIE Collaboration (C. Andreopoulos et al.), Nucl. Instrum. Methods A 614, 87 (2010)

PRL 113, 261802 (2014)

Probing Nucleon Structure
Deep Inelastic Scattering (DIS)

- Lepton strikes quark, breaks apart nucleon
- Cross section a function of
  - > Probe (lepton) momentum
  - > Interaction kinematics
  - > Target (quark) momentum



Encoded in **structure functions** – F_1, F_2, F_3

$$\frac{d^2\sigma^{\nu,\bar{\nu}}}{dxdy} = \frac{G_F^2 M_n E_\nu}{\pi(1+Q^2/M_{W,Z}^2)^2}\left[\frac{y^2}{2}2xF_1(x,Q^2) + \left(1 - y - \frac{xyM_n}{2E_\nu}\right)F_2(x,Q^2) \pm y(1-\frac{y}{2})xF_3(x,Q^2)\right]$$

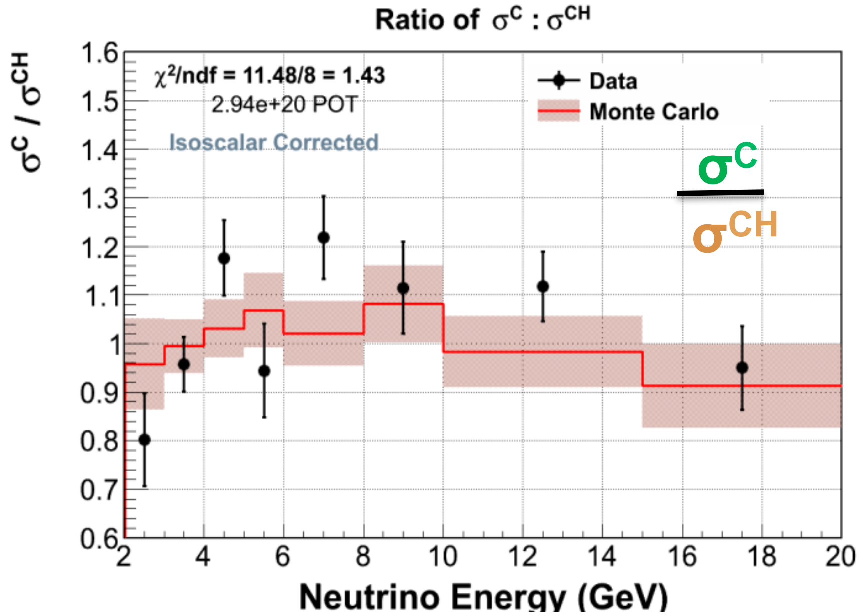
$$\nu = E - E'$$

$$Q^2 = -q^2 = 2E\left(E' - p'cos\left(\theta\right)\right)$$

$$y = E_h/E$$ Inelasticity

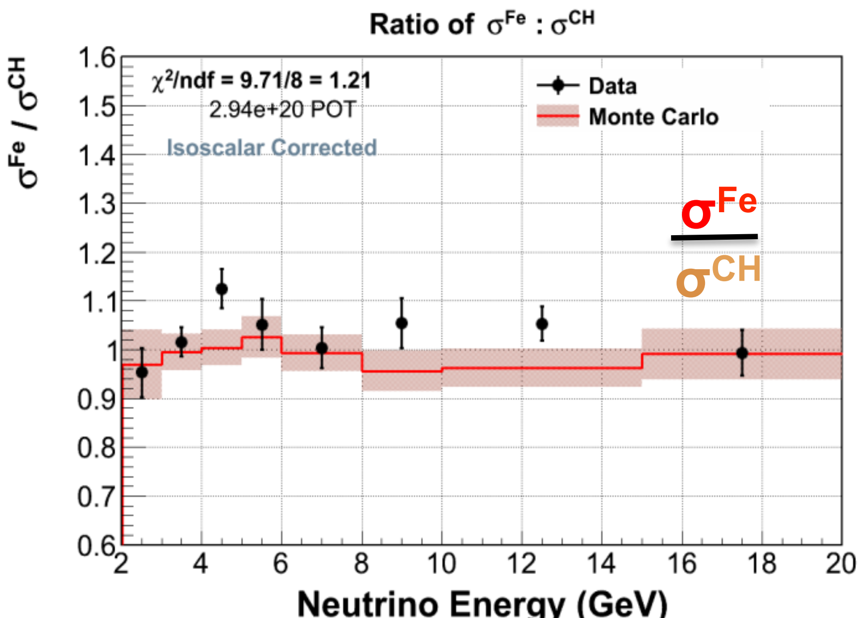
$$x = \frac{Q^2}{2M\nu}$$ Bjorken scaling variable
Fraction of nucleon's momentum carried by the struck quark

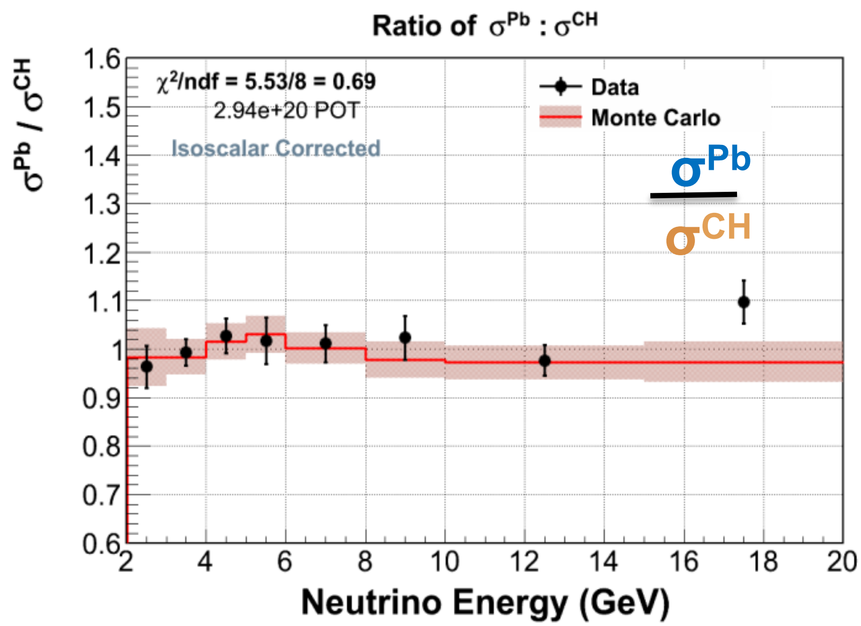
Inclusive cross section ratios on various nuclei



No tension between data and generator vs E_ν

GENIE 2.6.2





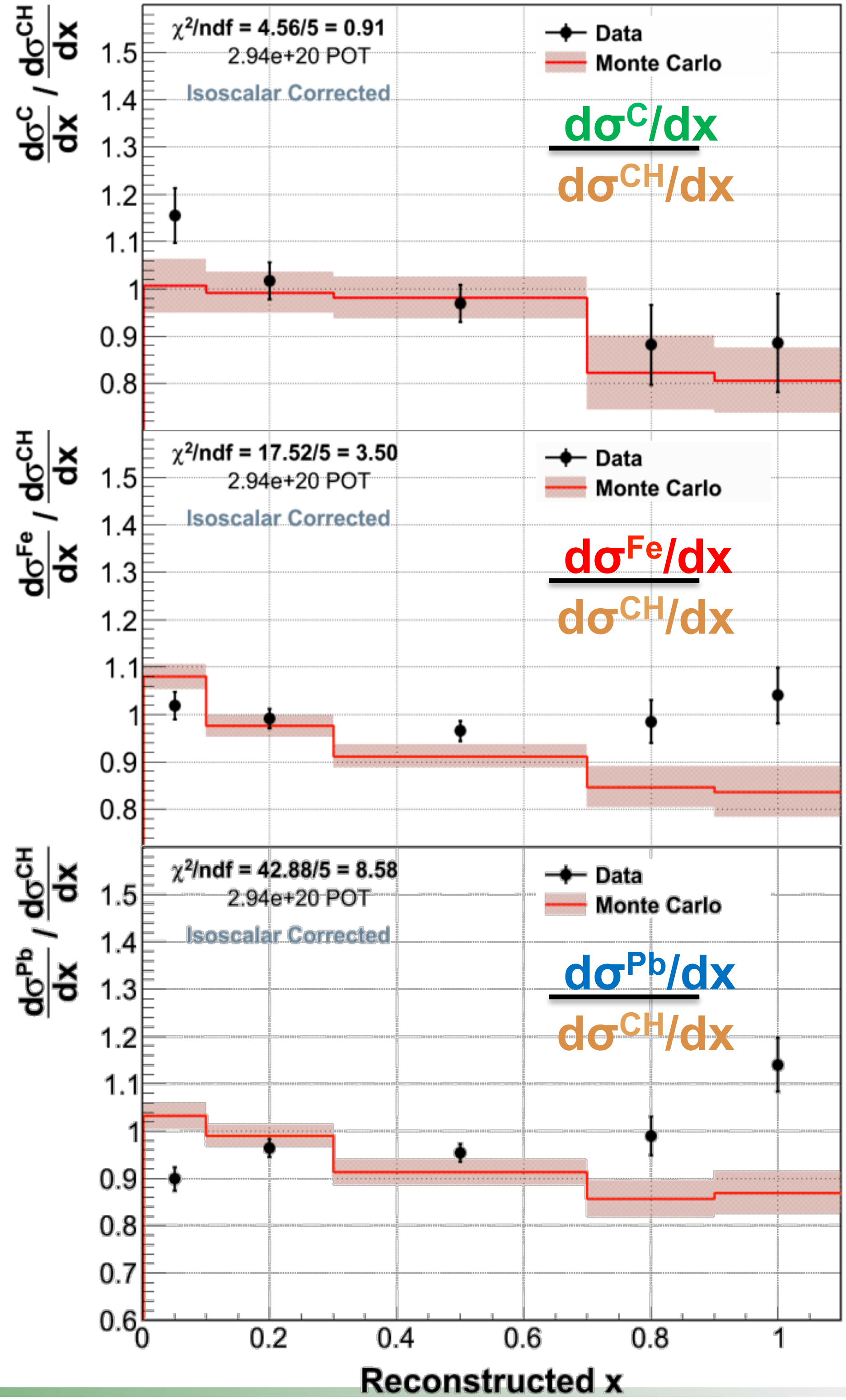
PRL. 112 (2014) 231801

High *x* summary

- At x = [0.7,1.1], observe an **excess** that grows with the size of the nucleus
- This effect is not modeled in simulation

GENIE 2.6.2

PRL. 112 (2014) 231801



Low x summary

- At x = [0.0,0.1], observe a **deficit** that grows with the size of the nucleus
- This effect is not modeled in simulation

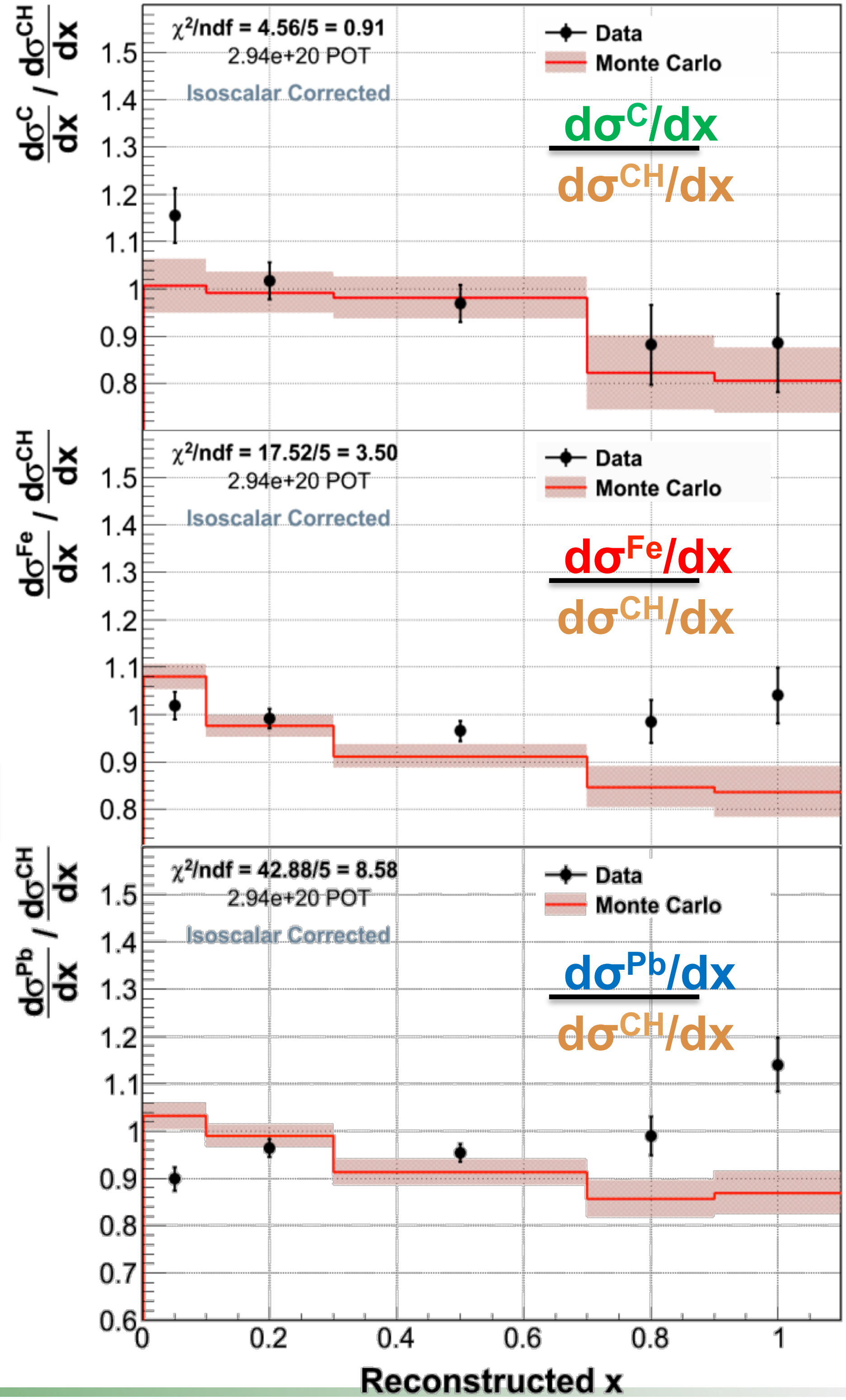
We expected neutrino differences

Neutrinos sensitive to structure function xF_3

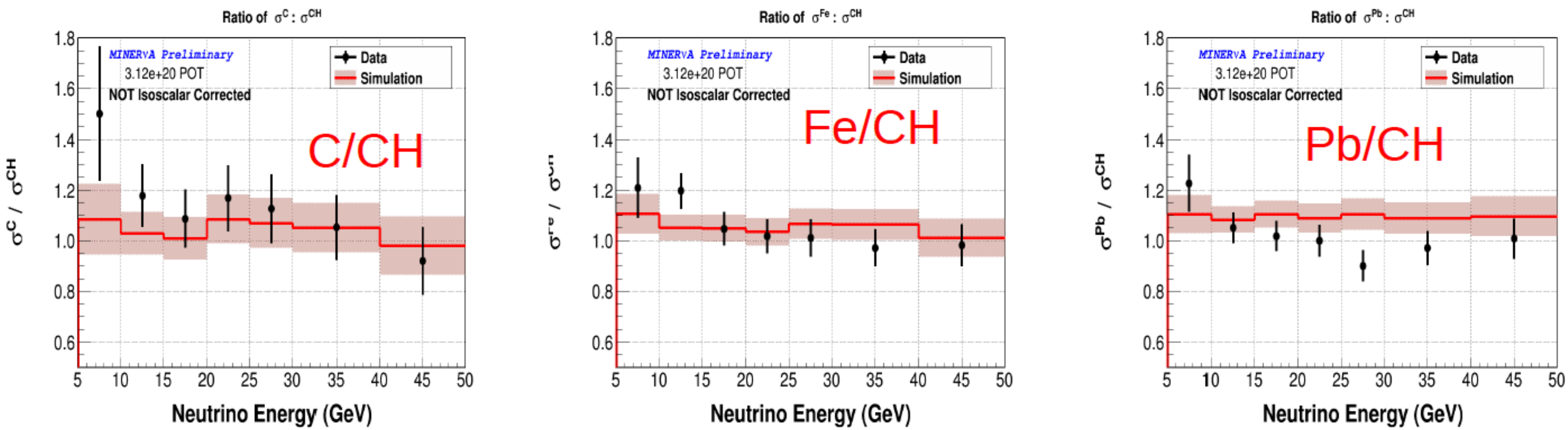
Neutrinos sensitive to axial piece of structure function F_2

GENIE 2.6.2

PRL. 112 (2014) 231801



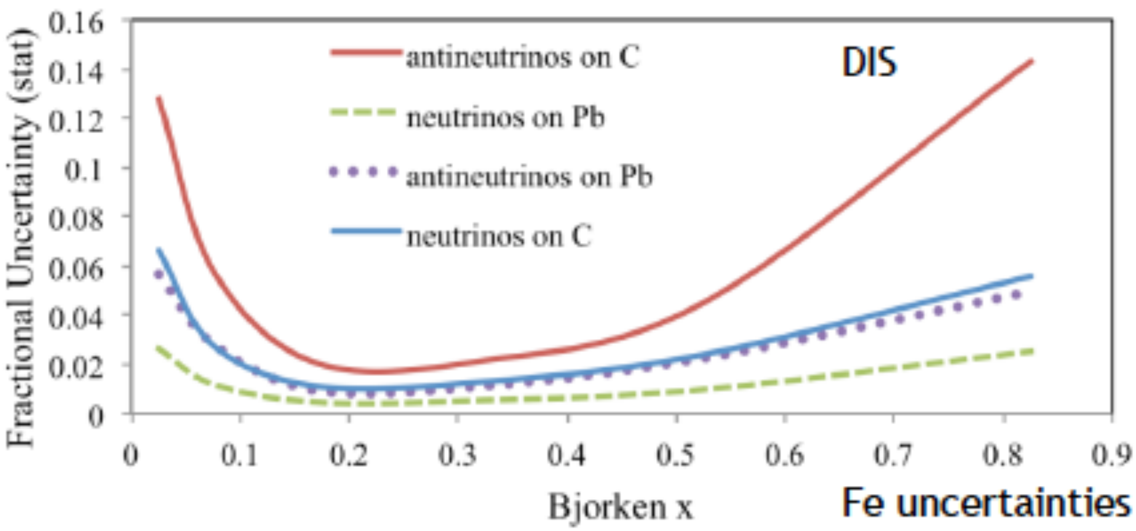
DIS version – might be better than inclusive but stats in LE sample are limited



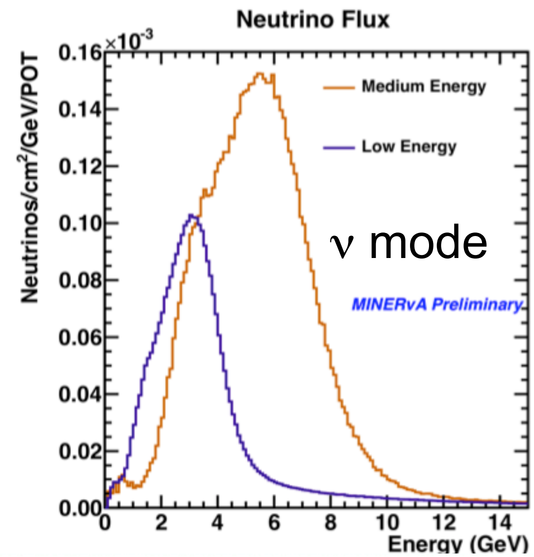
J. Mouseau, JTES 5/15

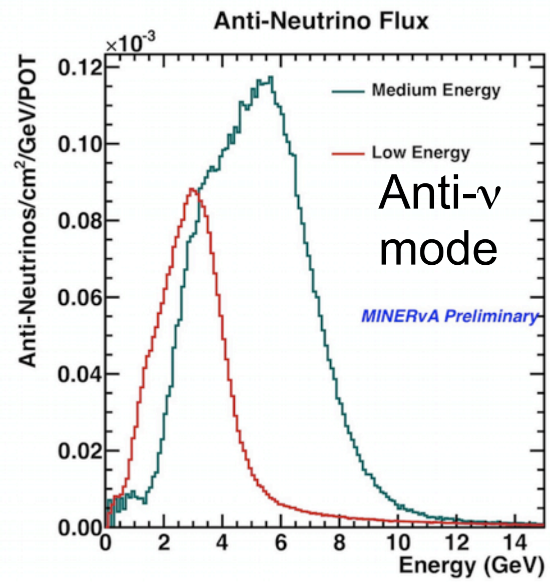
MINERvA ME Program

- 3 times the POT of low-energy sample by FY16 shutdown
- 3.5 times more events/POT
- These statistics will allow study of nuclear effects in exclusive states
- Wider ranges of energies means wider range of kinematics to probe and discriminate between models



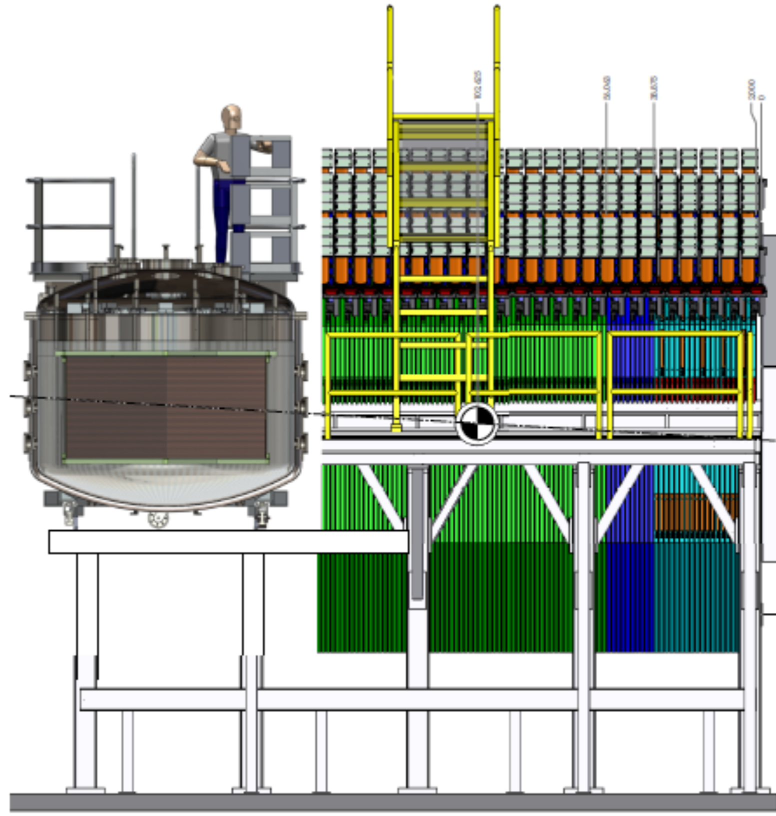
Fe uncertainties are similar to Pb

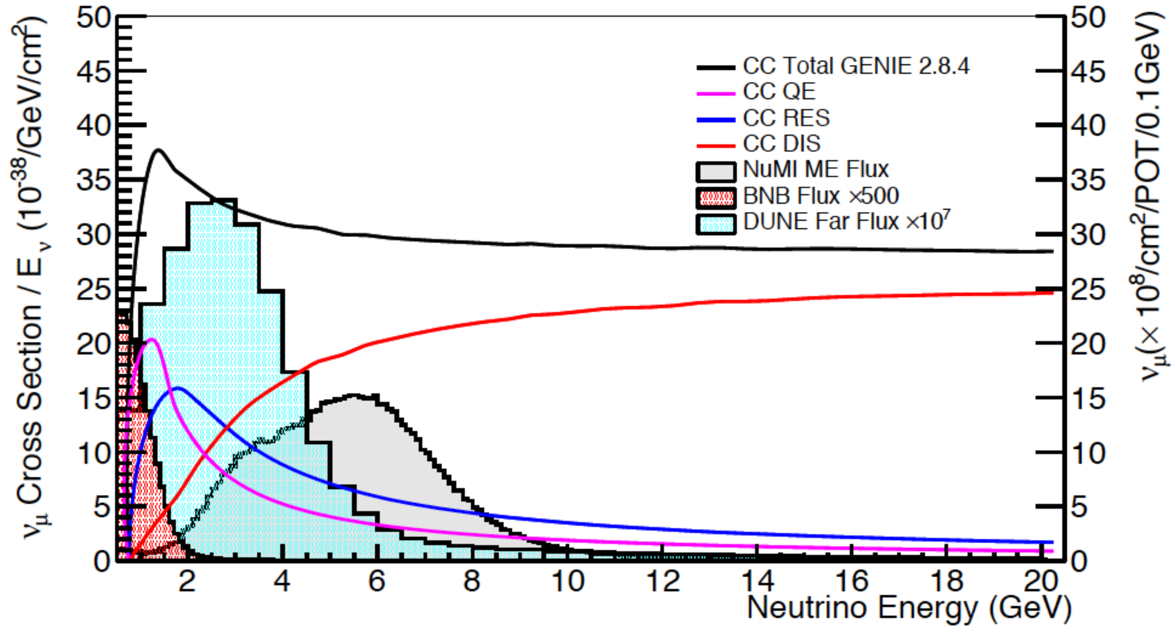




CAPTAIN-MINERvA

- Proposed extension to program (2017-2020)
- Add a LArTPC with MINERvA for downstream containment
- 1st dedicated Ar cross sections in few-GeV region
- Supports the DUNE program





Synopsis

- Future long-baseline neutrino oscillation experiments, including the US-flagships of NOvA and DUNE, need to know cross sections in the few GeV region at unprecedented precision
  - Requires systematics at least a factor of six smaller than the current state of the art
- MINERvA is leading the way in neutrino-nuclear scattering in this energy regime
  - Initial results focus on ν–C
  - A number of new results coming later this month at NuInt2016
  - Near future: evolution of nuclear effects in exclusive channels over a range of nuclei
  - Further future: dedicated liquid argon program
- These results need to be incorporated into models (event generators) for the US neutrino oscillation program to succeed