Fermilab

NORTHWESTERN
UNIVERSITY

Recent results from MINERvA

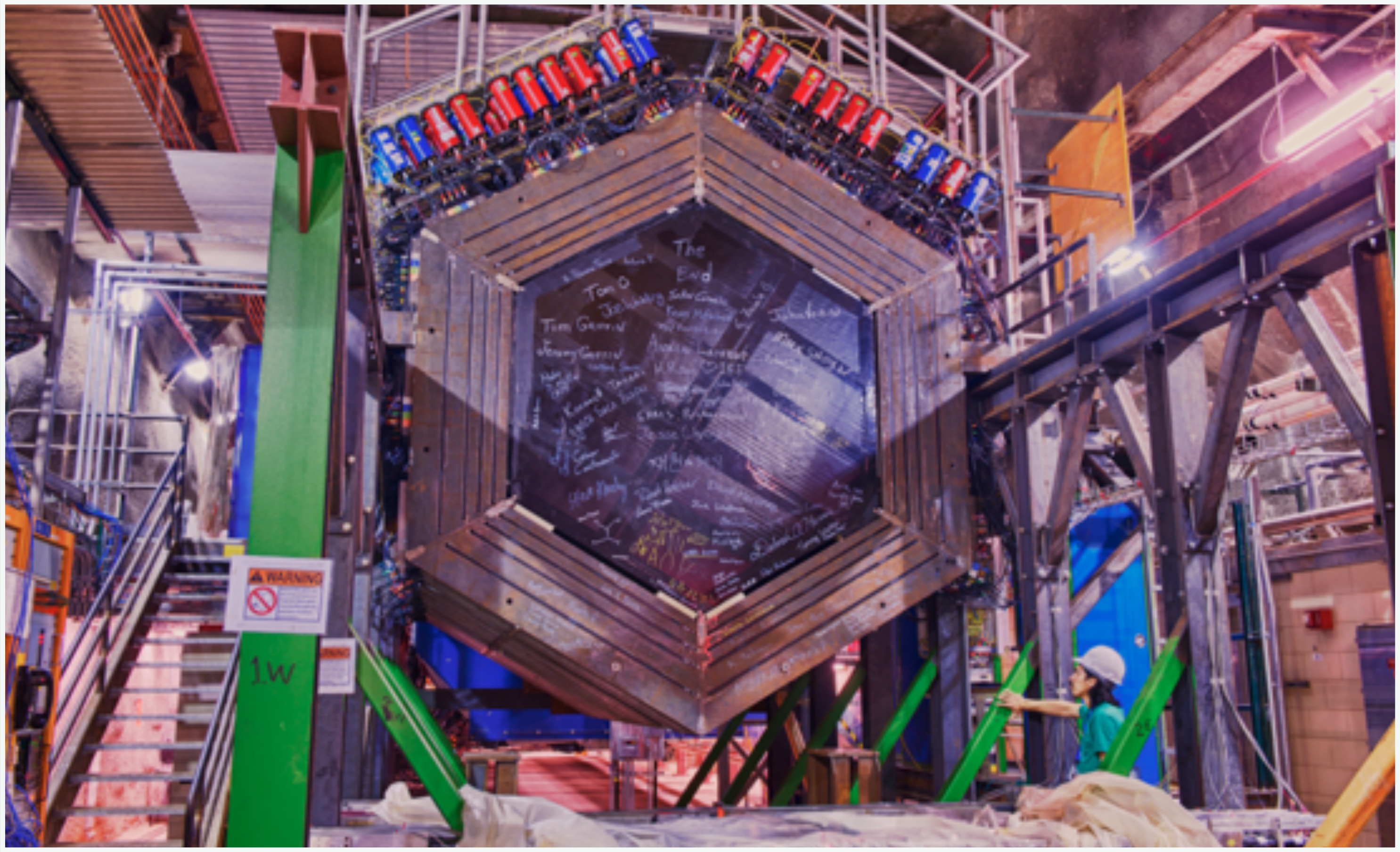
Cheryl Patrick, Northwestern University, USA, for the MINERvA collaboration

Rencontres De Moriond, 14-21 March 2015

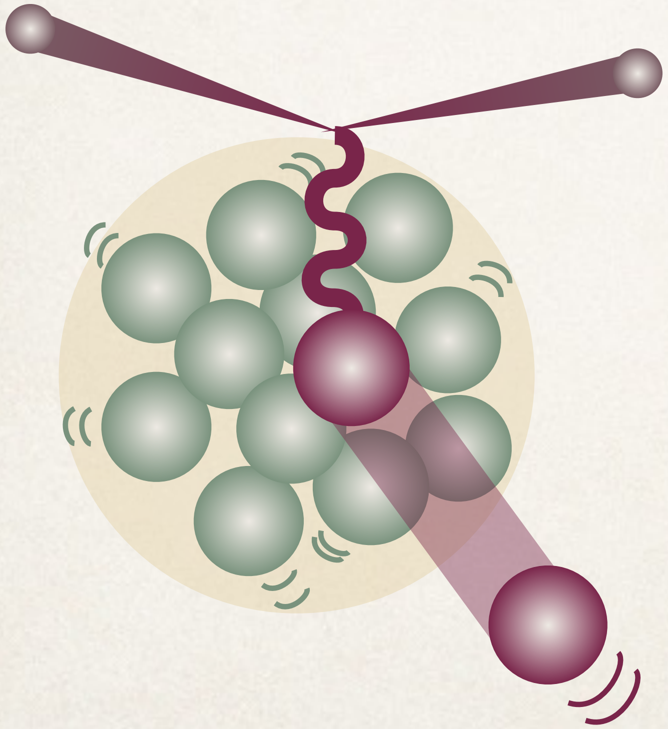
About MINERvA

MINERvA is a dedicated neutrino-nucleus cross-section experiment, situated in Fermilab's NUMI beam along with MINOS and NOvA.

It is able to make high-precision cross-section measurements for many different materials, in the 1-20 GeV range.



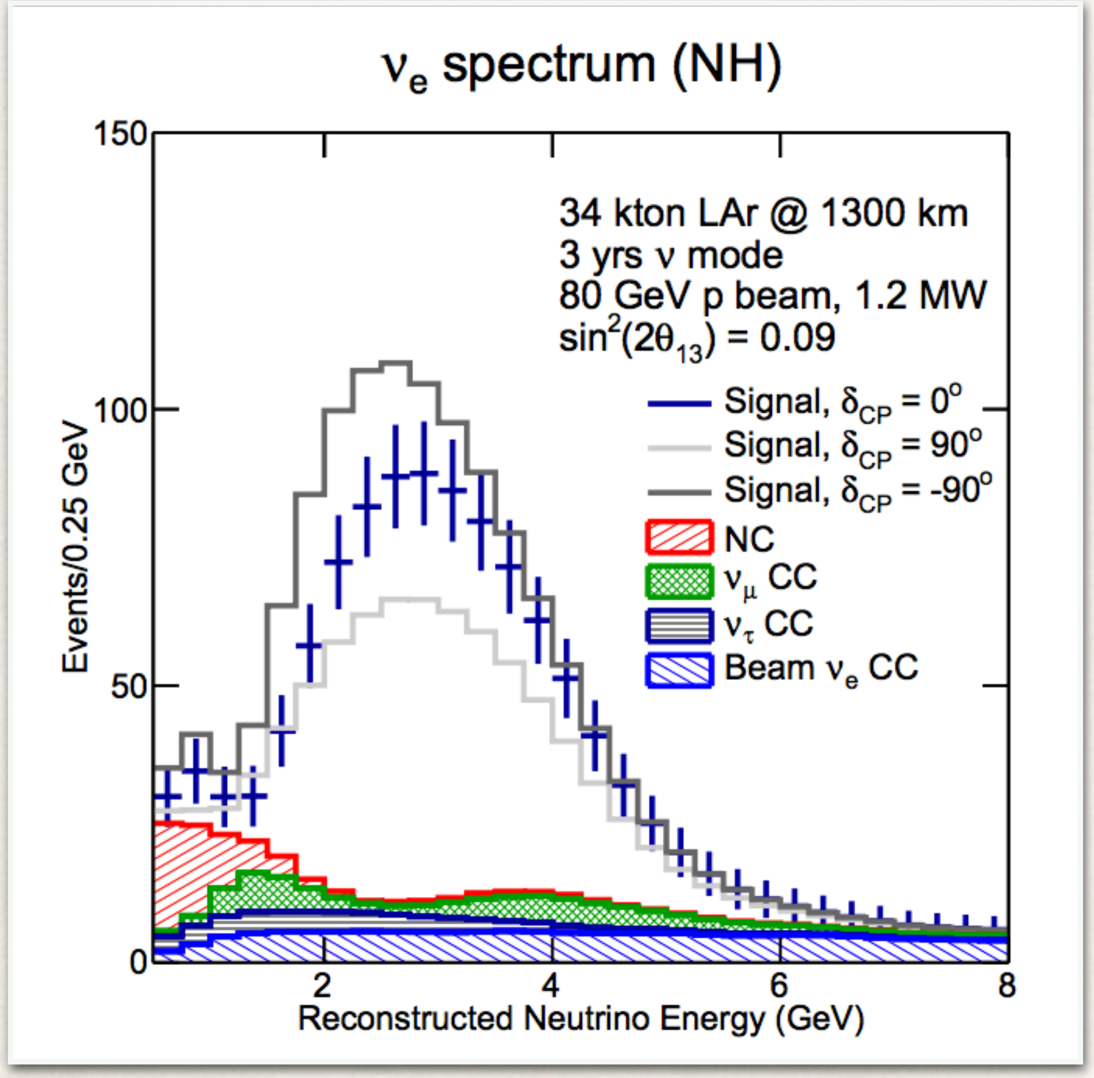
Photograph: Reidar Hahn, Fermilab visual media services



- MINERvA is excellent for probing the **structure of the nucleus**, and its effects on neutrino scattering cross sections
- Its measurements can also provide vital information to **oscillation experiments**

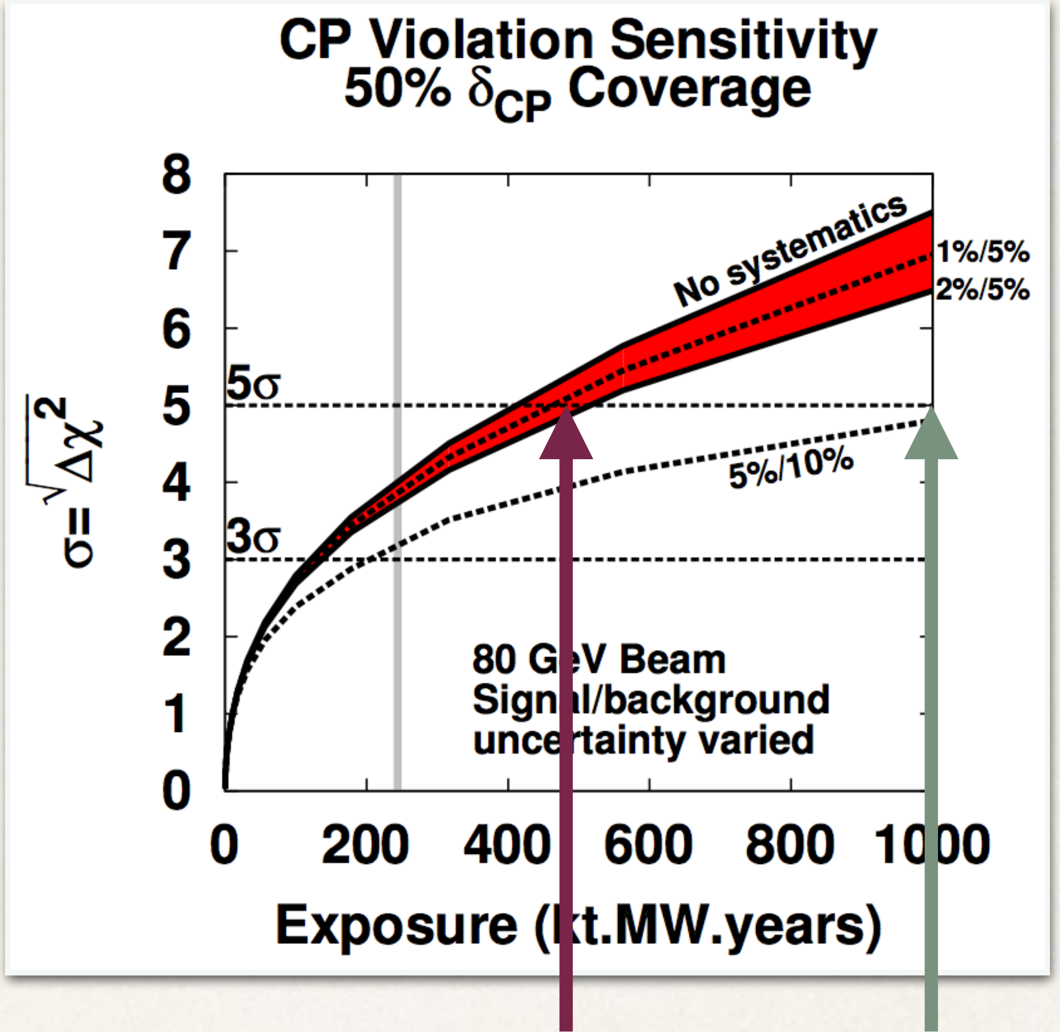
The importance of cross sections

Oscillation experiments compare event rates with predictions to determine parameters such as δ_{CP}.



LBNF signal predictions
arXiv 1307.7335

LBNF Sensitivity to δ_{CP} for different systematic uncertainties



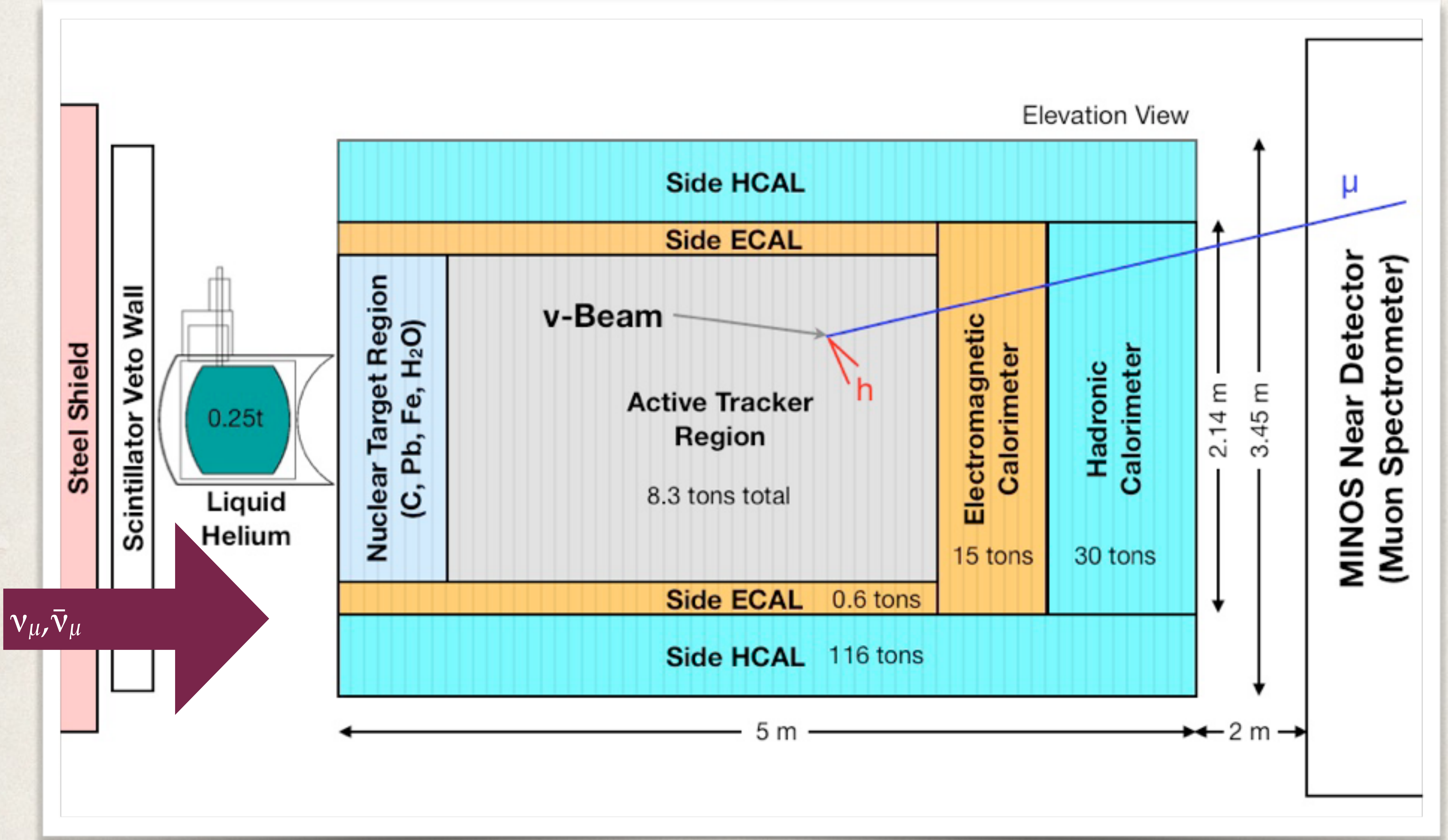
Run for 10 years 25 years

M. Bass, NuInt 2014

To distinguish these parameters, they must reduce systematics. The cross-section model is one of the largest contributors to the uncertainty.

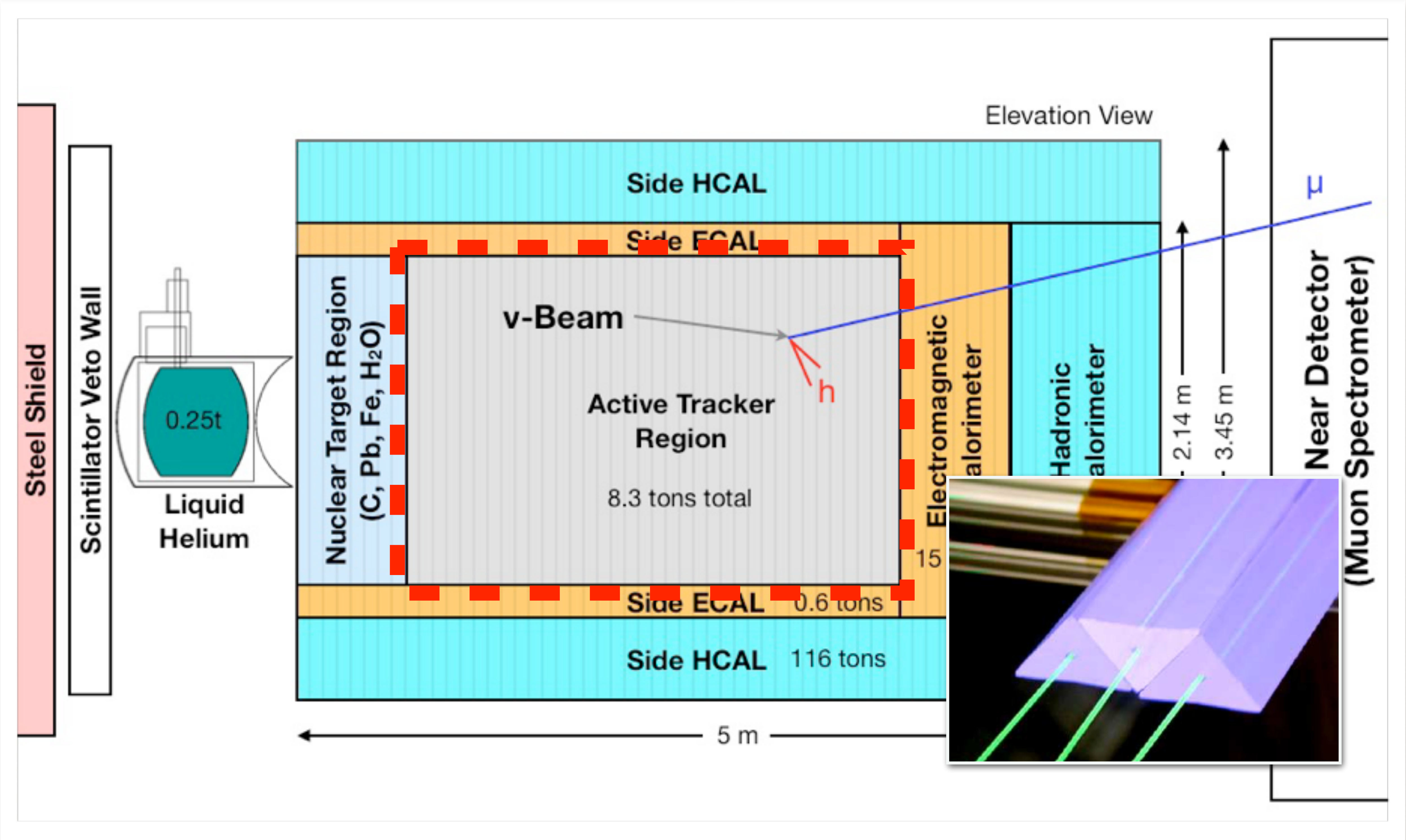
MINERvA can reduce the uncertainties!

MINERvA detector



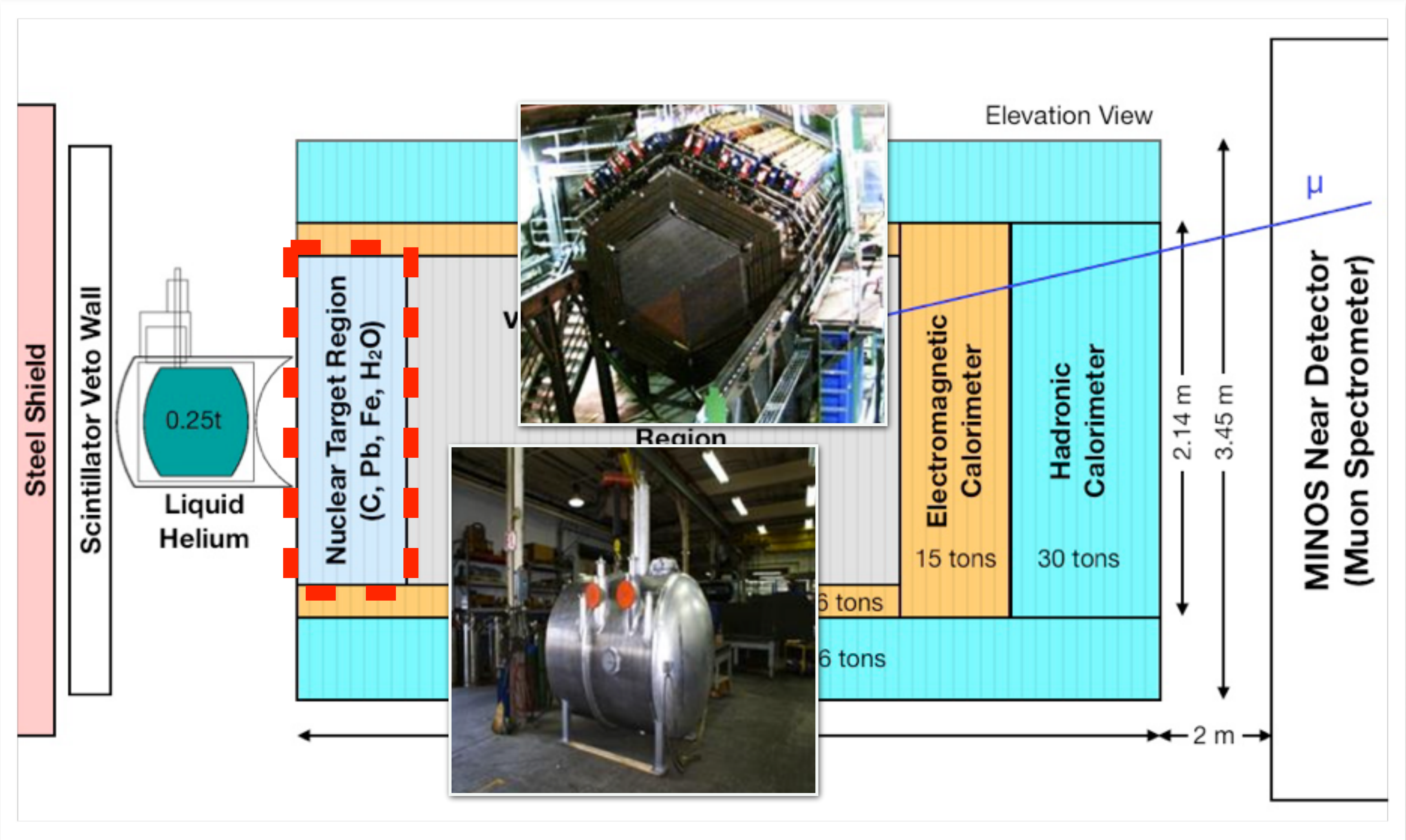
All photographs: Reidar Hahn, Fermilab visual media services

MINERvA detector



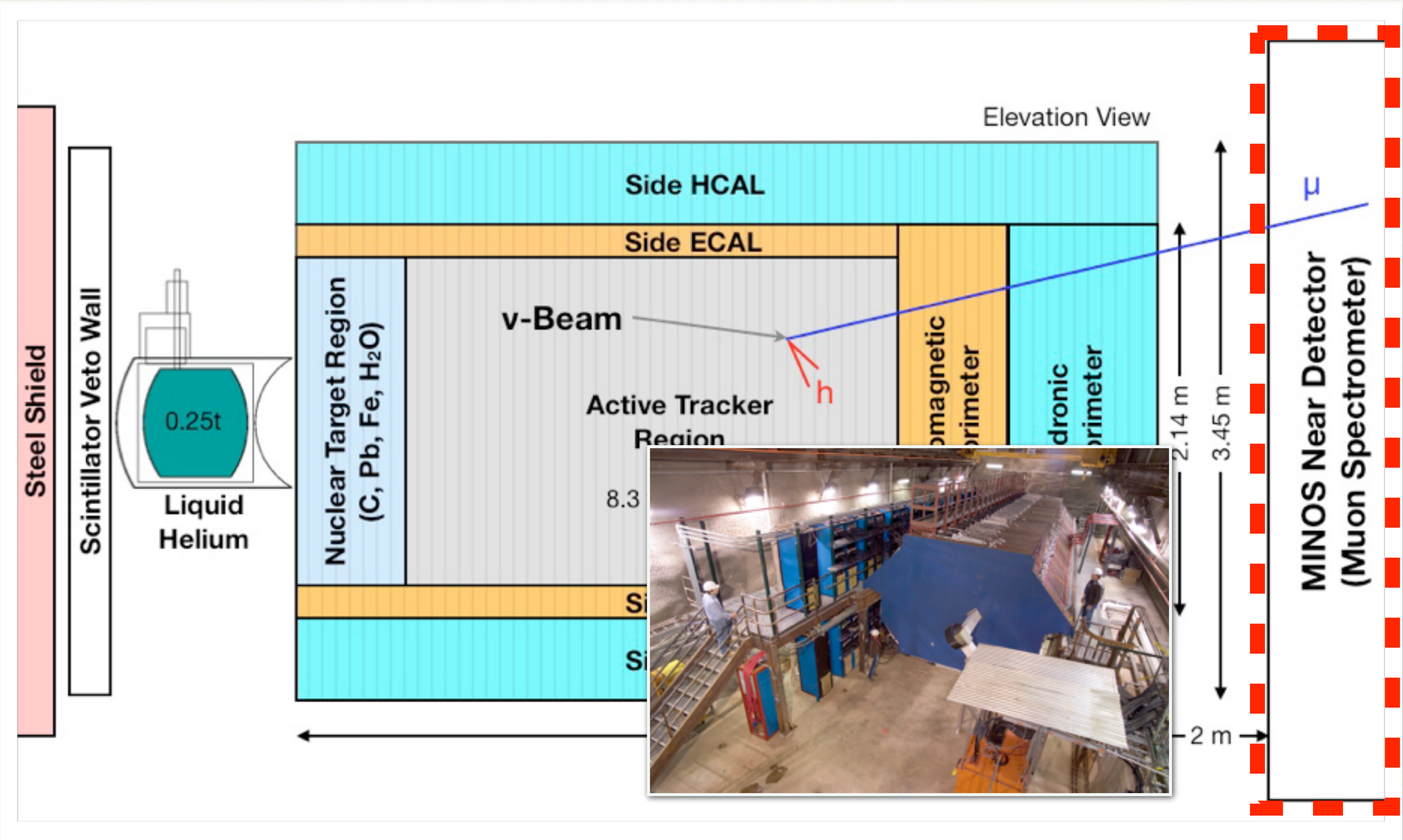
All photographs: Reidar Hahn, Fermilab visual media services

MINERvA detector



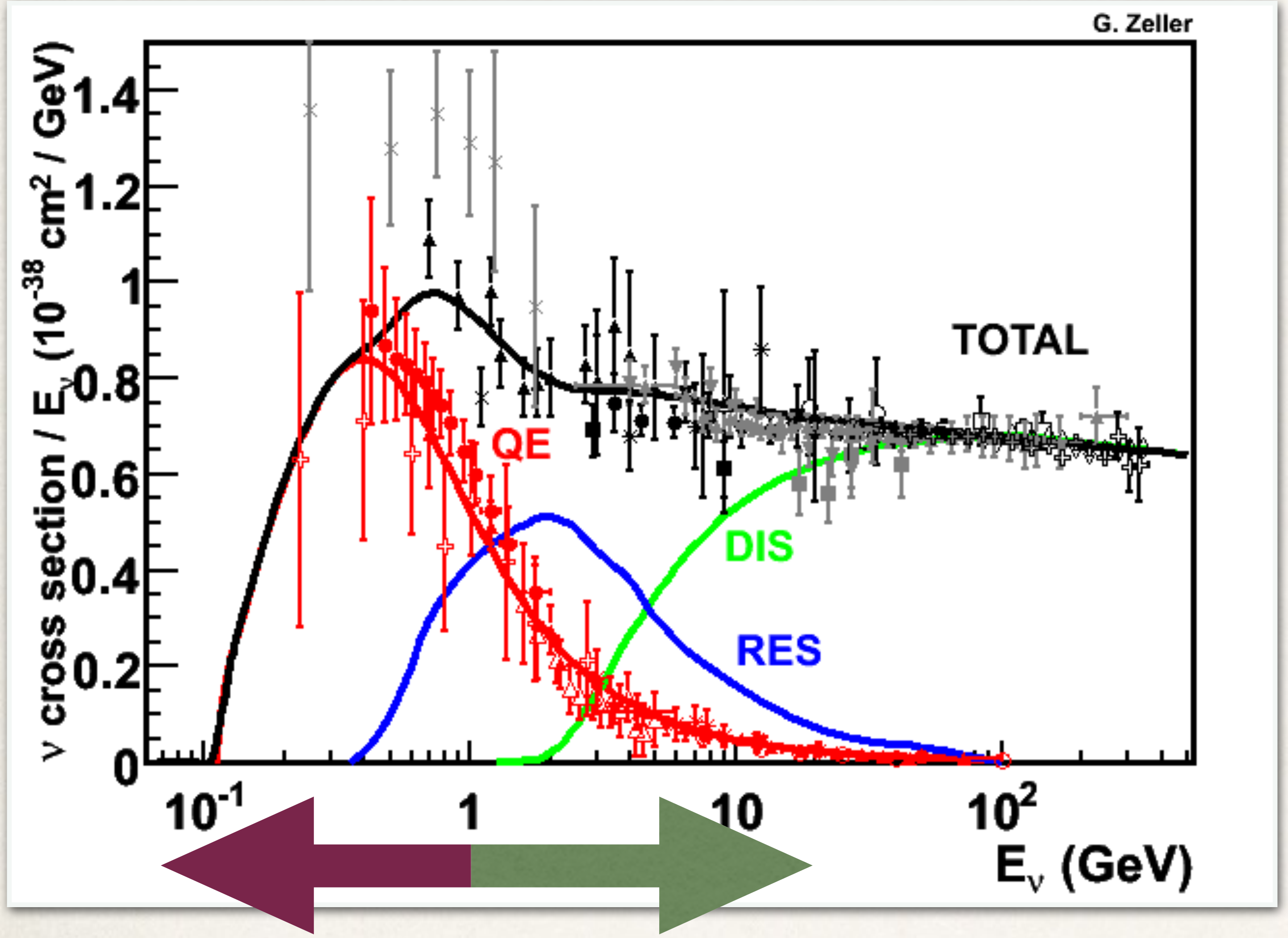
All photographs: Reidar Hahn, Fermilab visual media services

MINERvA detector



All photographs: Reidar Hahn, Fermilab visual media services

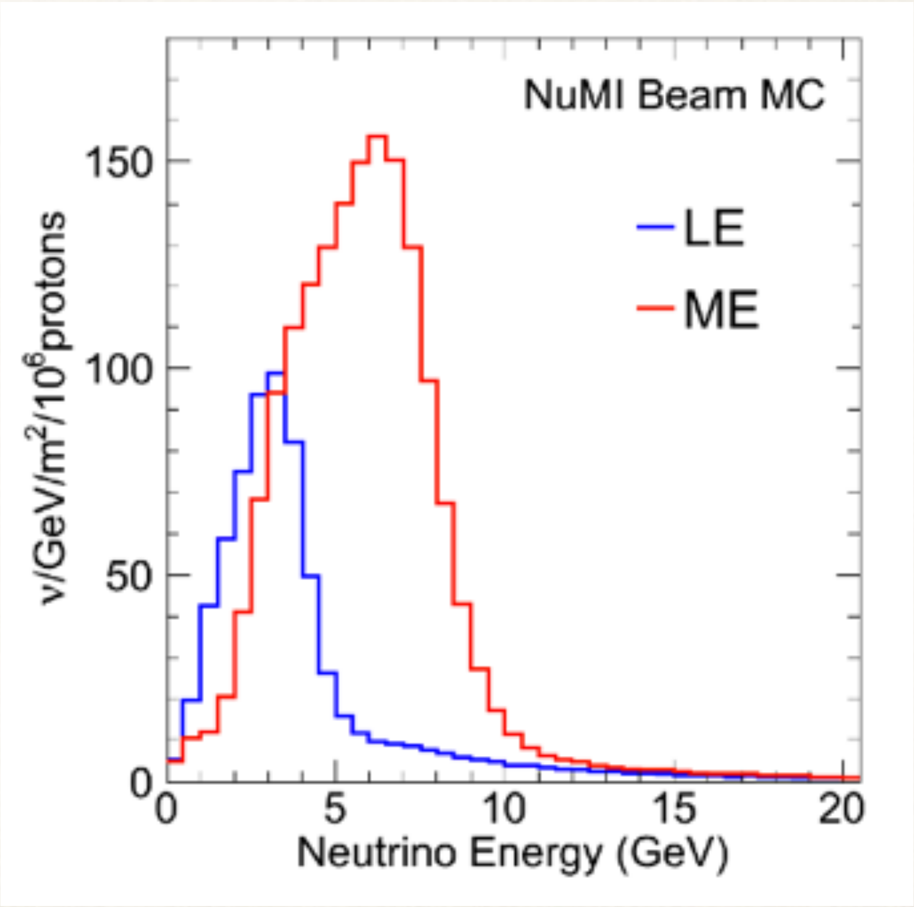
The MINERvA energy range



J.A. Formaggio and G.P. Zeller, Rev. Mod. Phys. 84, 1307-1341, 2012

BooNE experiments, T2K

MINERvA, LBNF, NOvA, MINOS



Low-energy run, 2010-2012

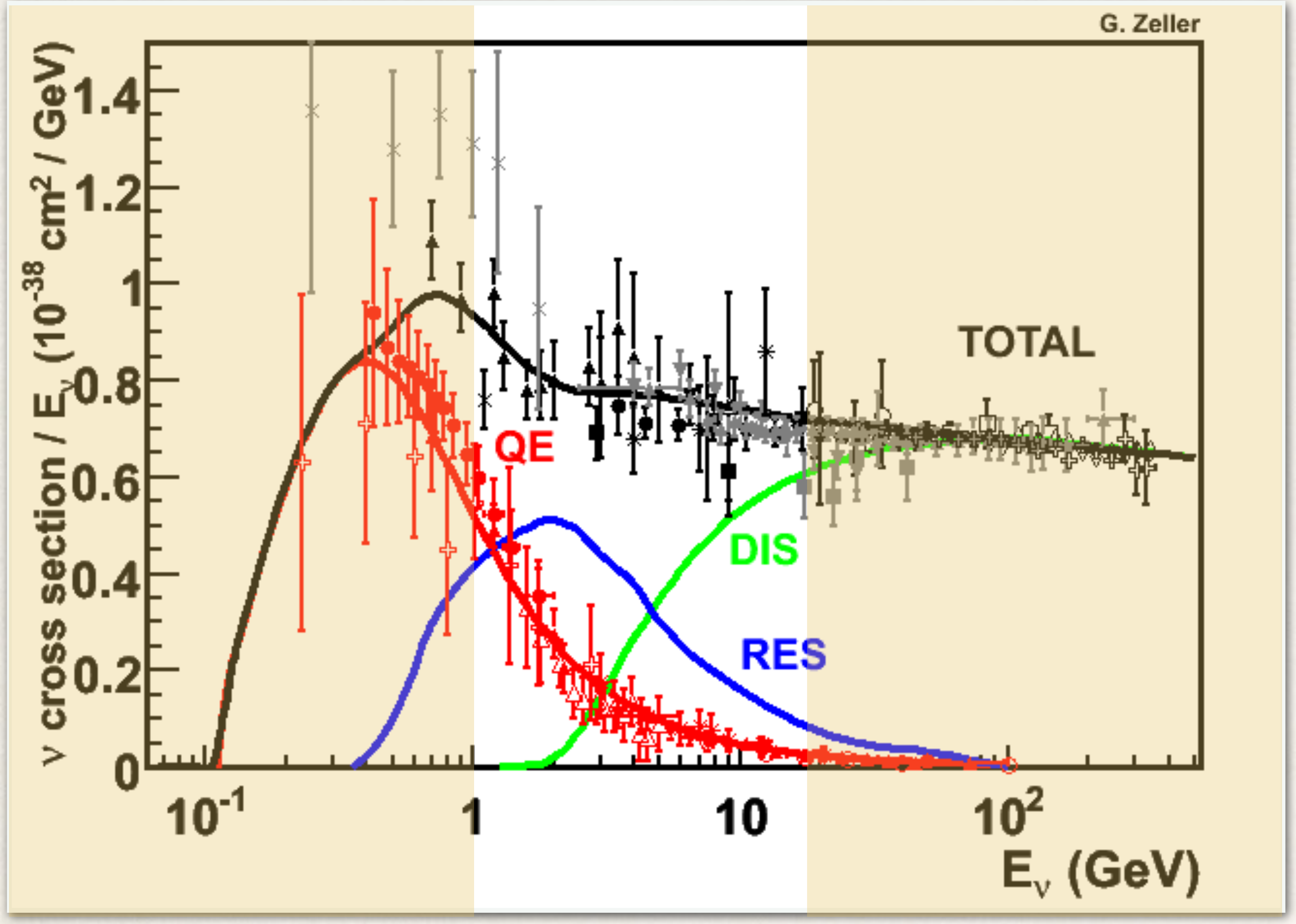
3.98x10^{20} POT (ν)

1.7x10^{20} POT ($\bar{\nu}$)

Medium-energy run, 2013-

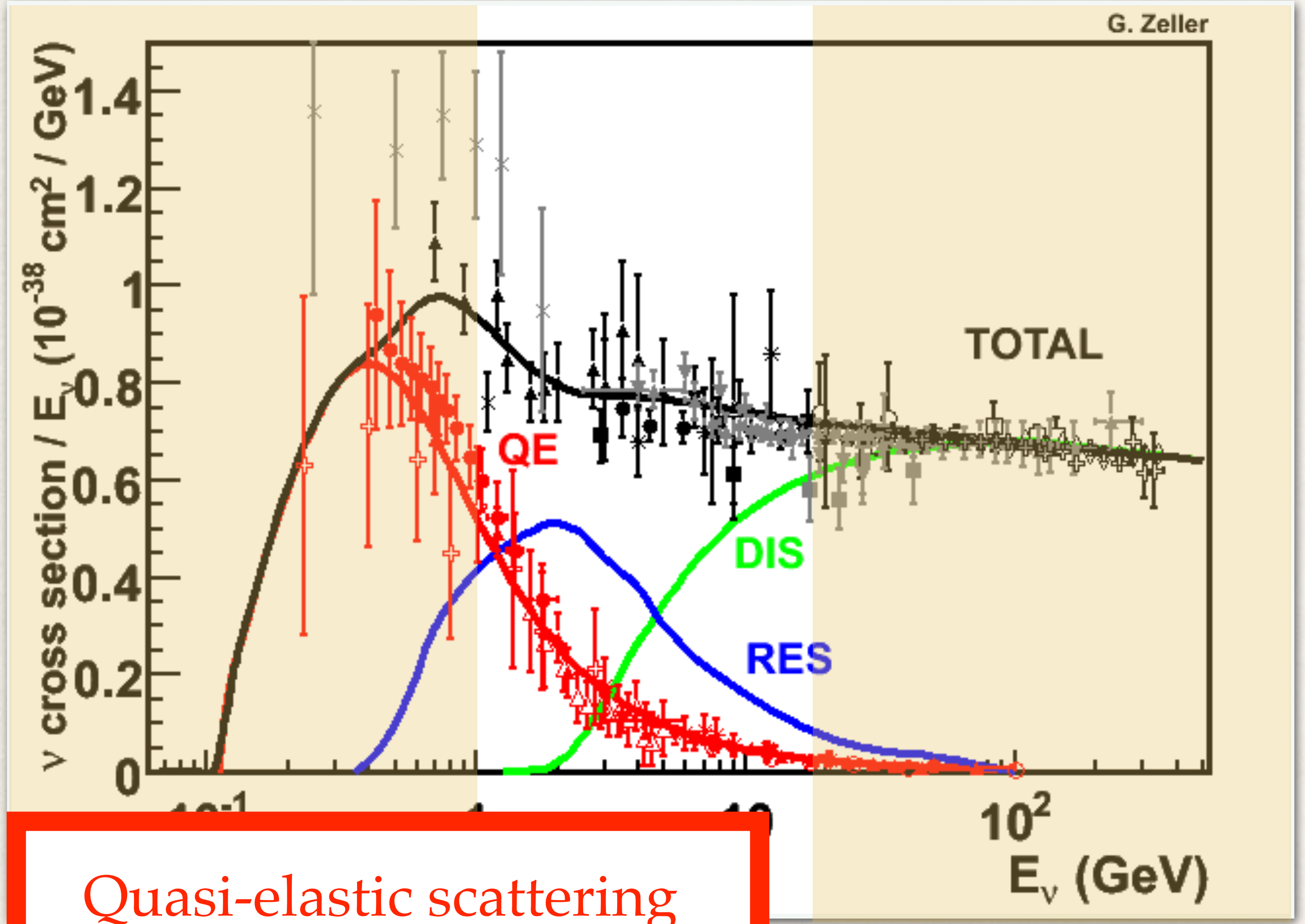
Already exceeded low-energy POT in ν mode

The MINERvA energy range



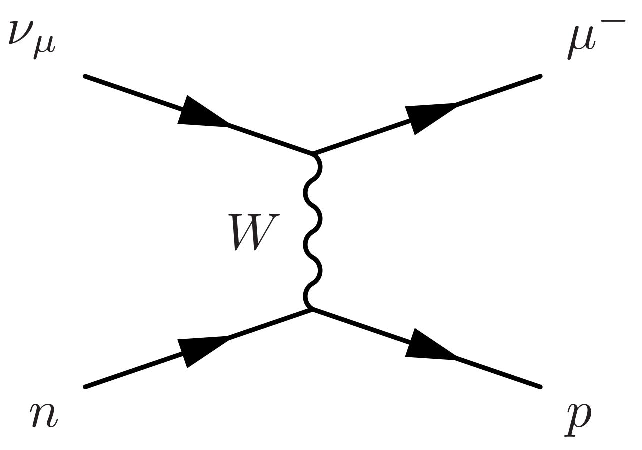
J.A. Formaggio and G.P. Zeller, Rev. Mod. Phys. 84, 1307-1341, 2012

The MINERvA energy range

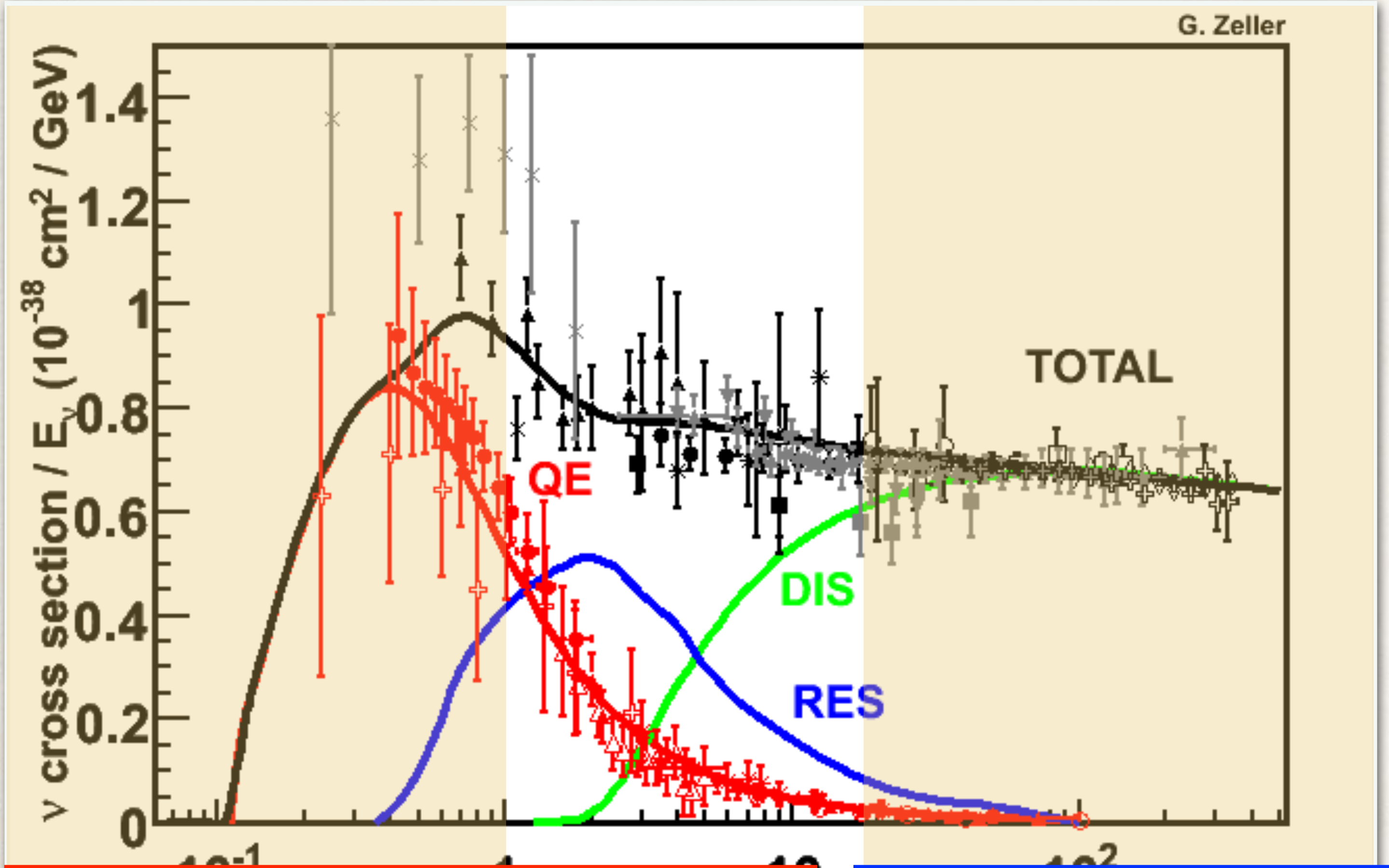


J.A. Formaggio and G.P. Zeller, Rev. Mod. Phys. 84, 1307-1341, 2012

Quasi-elastic scattering

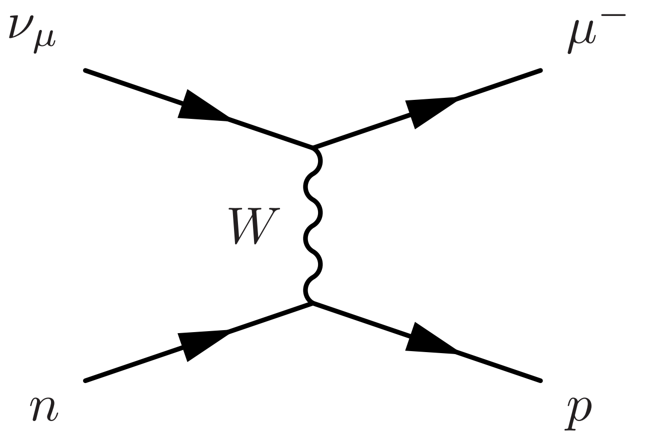


The MINERvA energy range

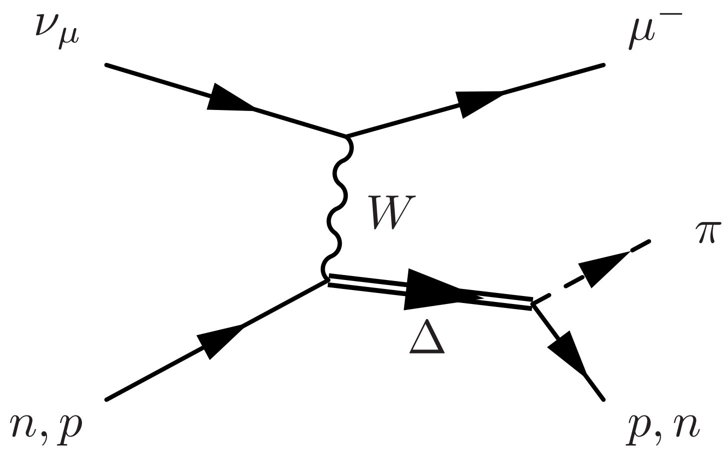


J.A. Formaggio and G.P. Zeller, Rev. Mod. Phys. 84, 1307-1341, 2012

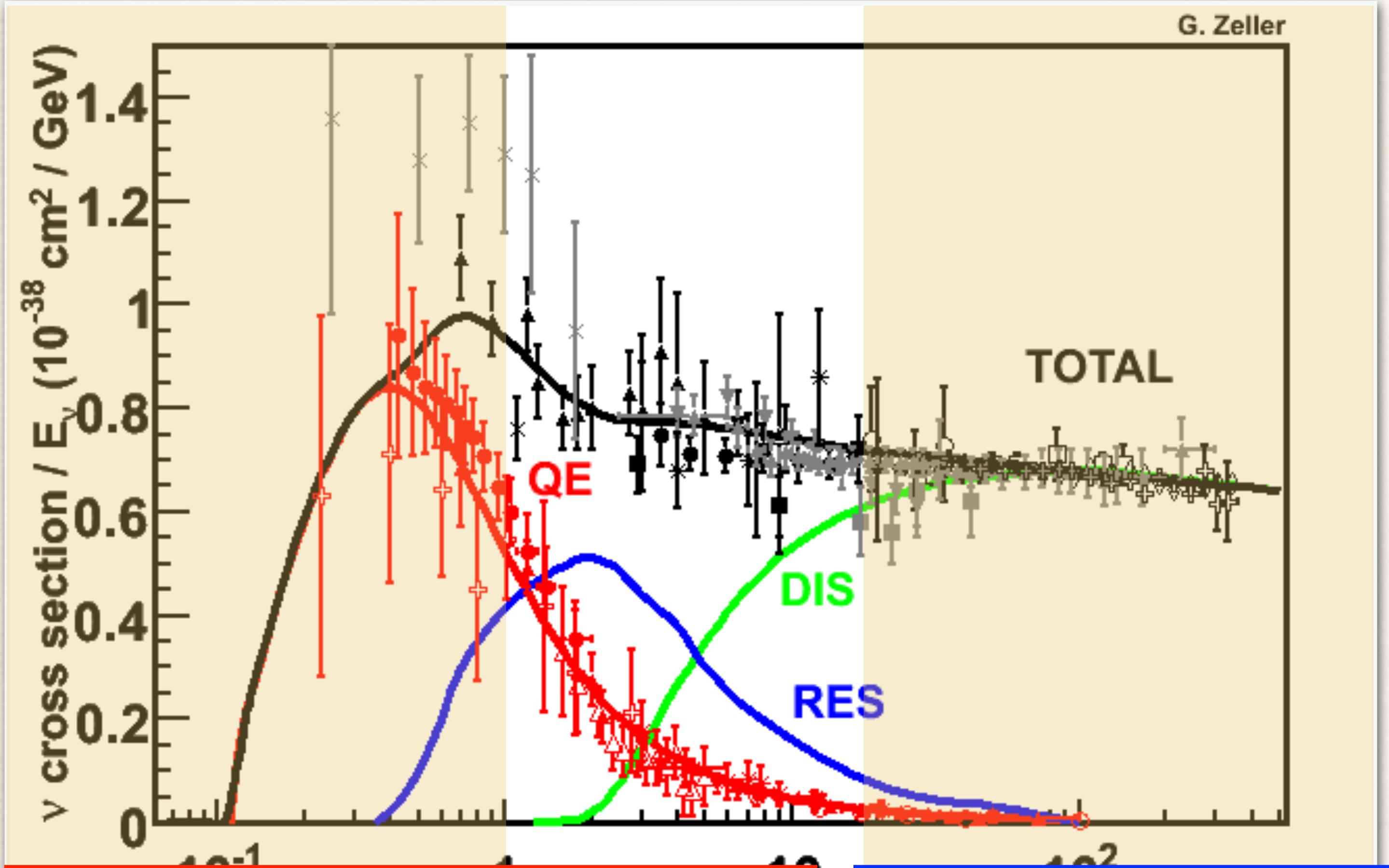
Quasi-elastic scattering



Resonant pion production

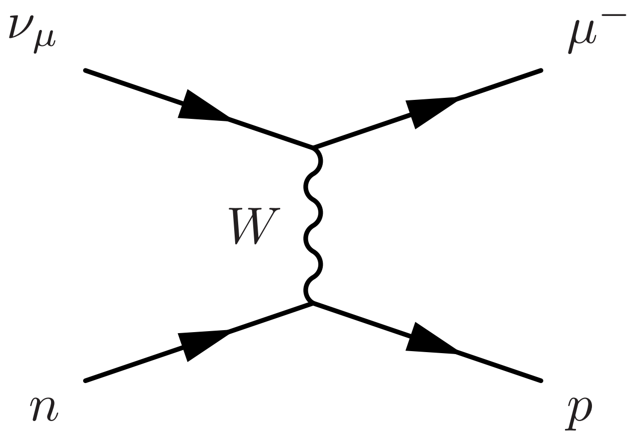


The MINERvA energy range

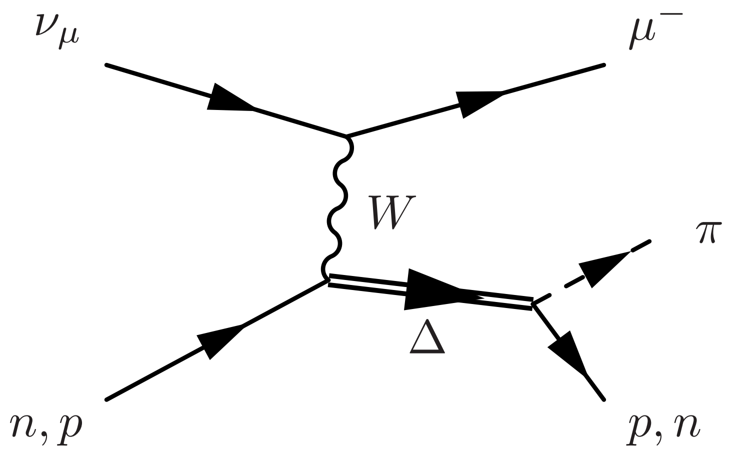


J.A. Formaggio and G.P. Zeller, Rev. Mod. Phys. 84, 1307-1341, 2012

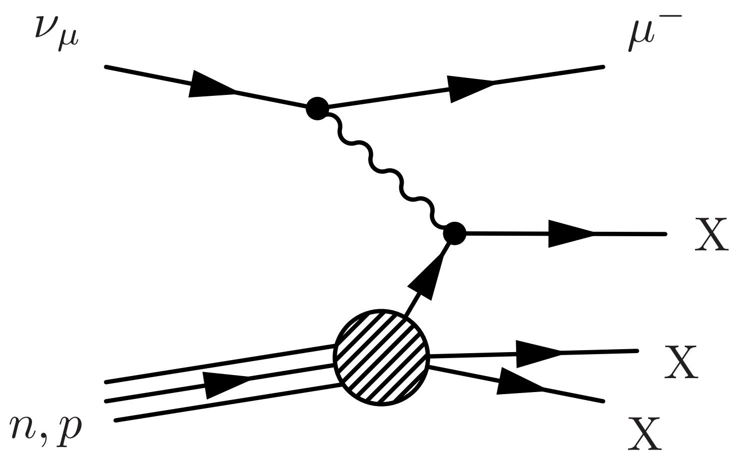
Quasi-elastic scattering



Resonant pion production

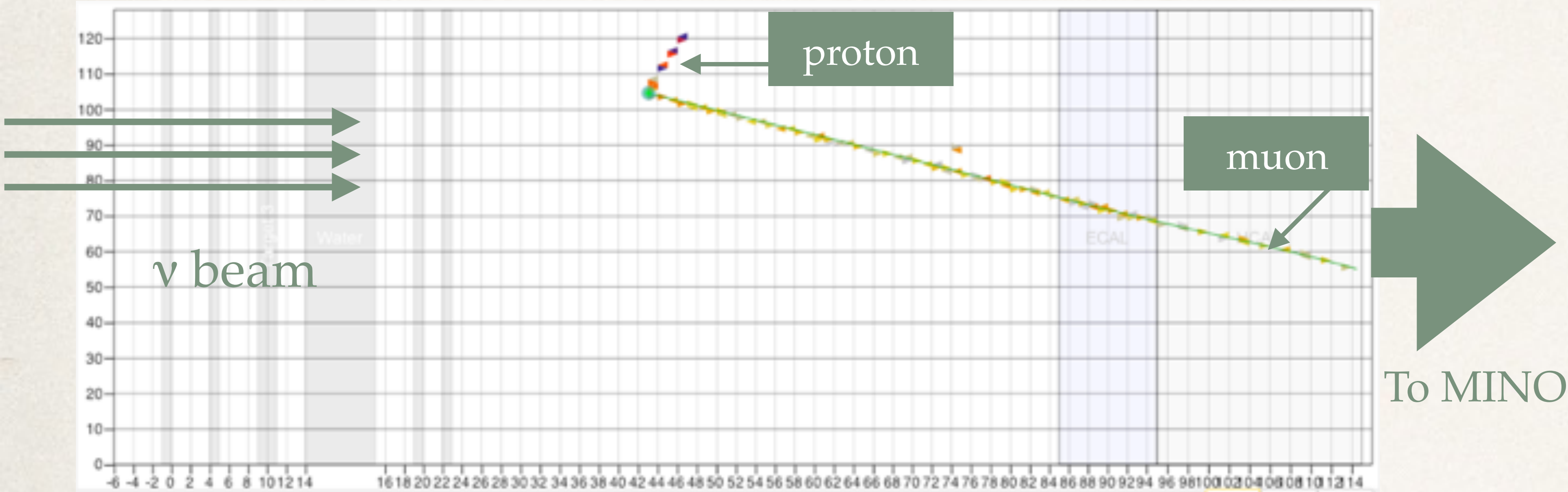


Deep inelastic scattering

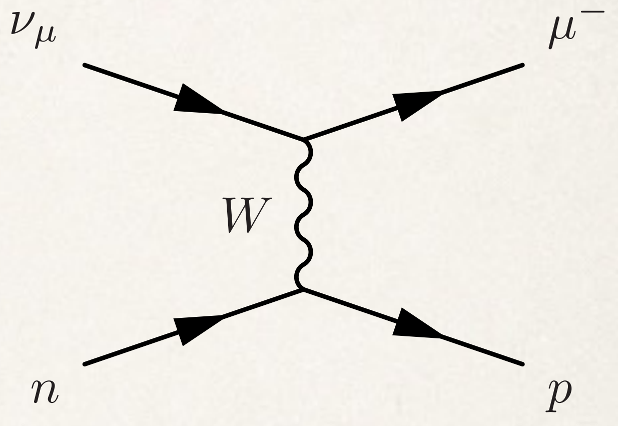


Quasi-elastic events in MINERvA

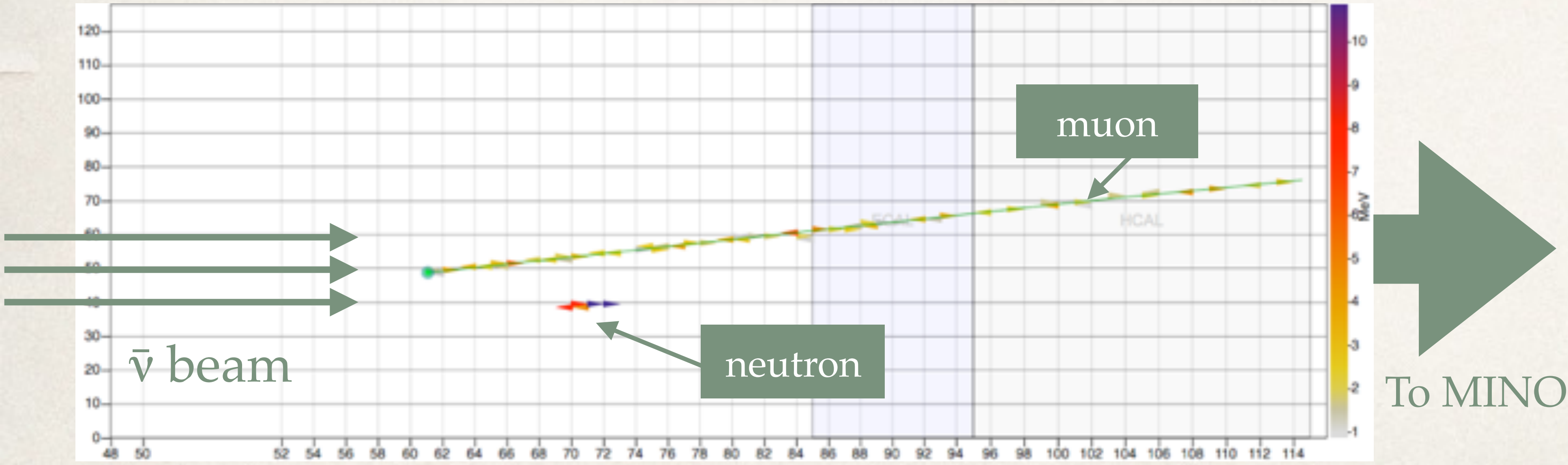
Neutrino mode $\nu_\mu + n \to \mu^- + p$



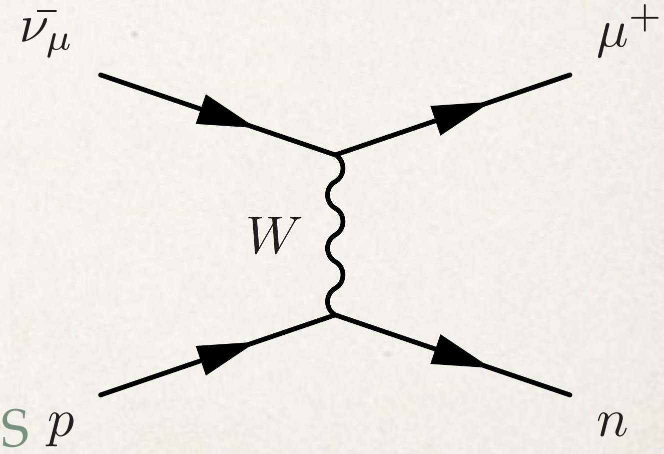
To MINOS



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



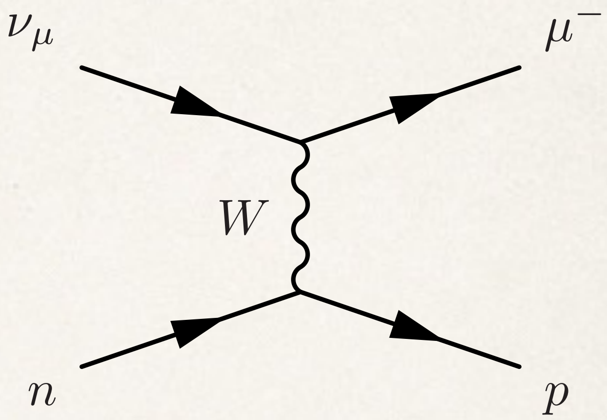
To MINOS

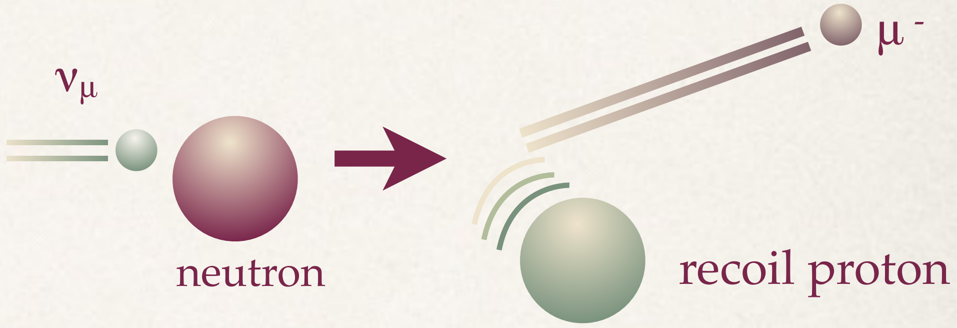


The first analyses I'll show are on data from the scintillator tracker

Quasi-elastic scattering (CCQE)

- There is a **single charged muon** in the final state, plus the **recoil nucleon** (no mesons or other particles)
- We can **reconstruct the neutrino energy and 4-momentum transfer,** Q^2, from just the **muon kinematics**
- But this assumes scattering from a stationary nucleon
- Cross-section model is well-proven on hydrogen/deuterium *C.H. Llewellyn Smith, Phys. Rept. 3C, 261 (1972)*





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

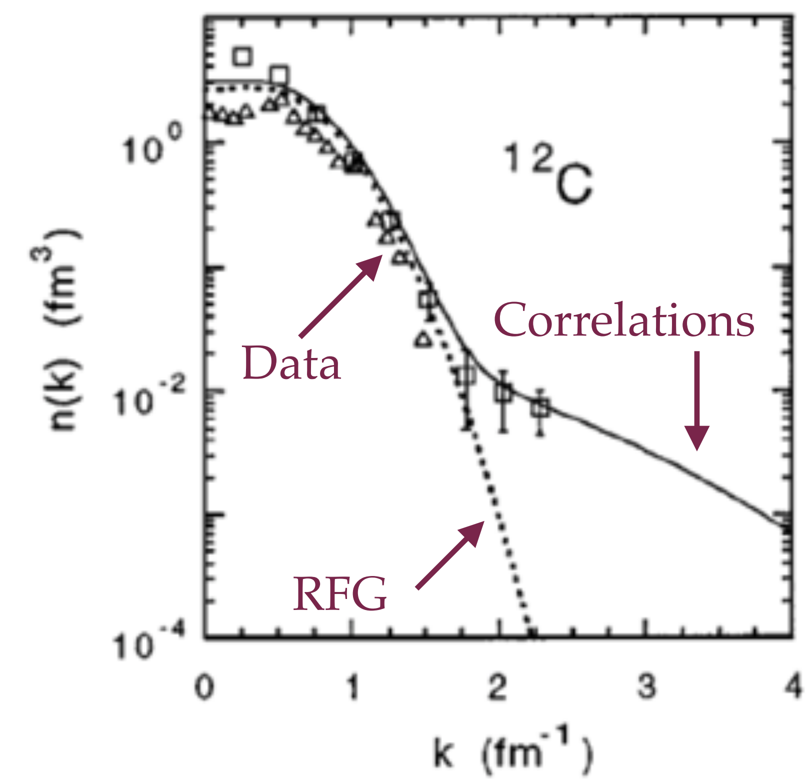
$$E_\nu^{QE} = \frac{m_n^2 - (m_p - E_b)^2 - m_\mu^2 + 2(m_p - E_b)E_\mu}{2(m_p - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

- For **heavier nuclei**, we must model the effects of **interactions between nucleons**
- Nuclear effects affect **energy reconstruction** with the CCQE hypothesis
- When nucleons are correlated, **extra nucleons** may be ejected

Nuclear models

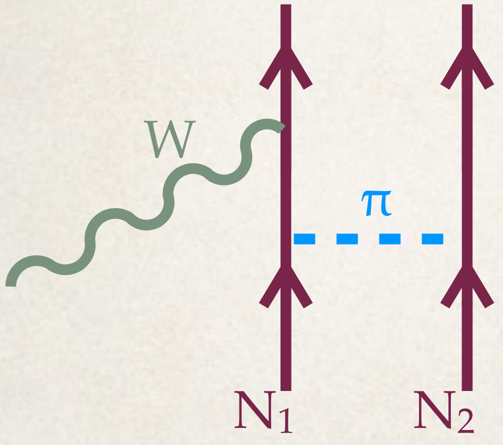
Relativistic Fermi Gas (RFG)

- Popular model is relatively easy to implement, modeling independent particles in a potential generated by the rest of the nucleus *R. Smith and E. Moniz, Nucl.Phys. B43, 605 (1972); Bodek, S. Avvakumov, R. Bradford, and H. S. Budd, J.Phys.Conf.Ser. 110, 082004 (2008);*
- Bodek and Ritchie model short-range correlations to give high-energy tail *A. Bodek, and J. L. Ritchie, Phys. Rev. D23, 1070 (1980), A. Bodek and J. L. Ritchie, Phys. Rev. D24, 1400 (1981)*
- **Local Fermi Gas** (LFG) has a position-dependent momentum distribution *AK. S. Kuzmin, V. V. Lyubushkin, and V. A. Naumov, Eur.Phys.J. C54, 517 (2008)*

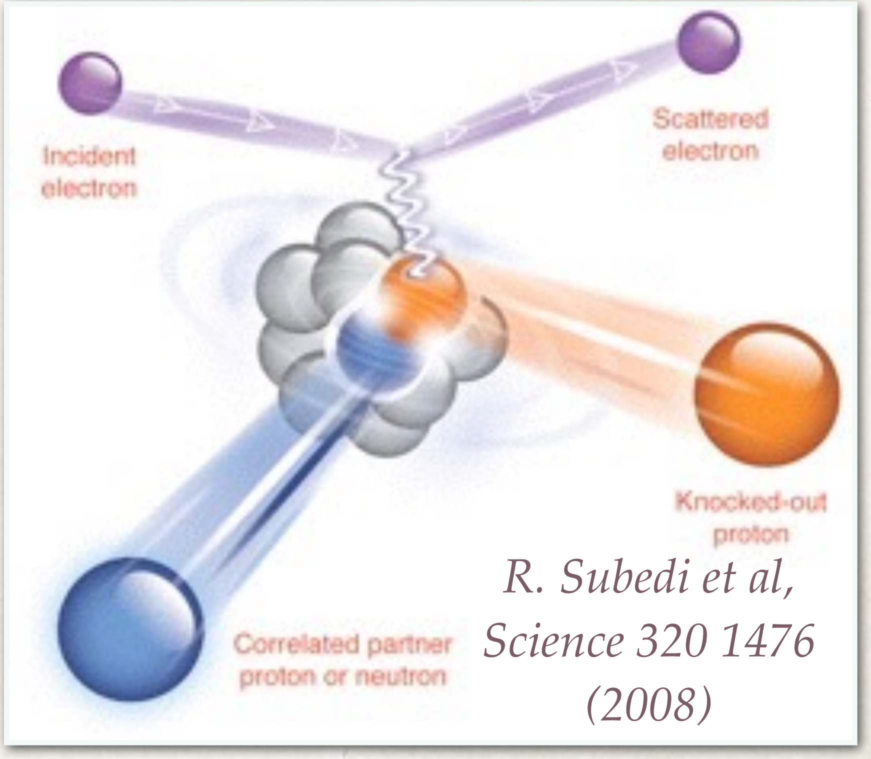


S. Fantoni, V.R. Pandharipande, Nucl. Phys. A 427 (1984) 473 – 492

Meson Exchange Current models (MEC)



Example meson exchange current interaction, from a more detailed list (J Morfín). This illustrates a correlation.



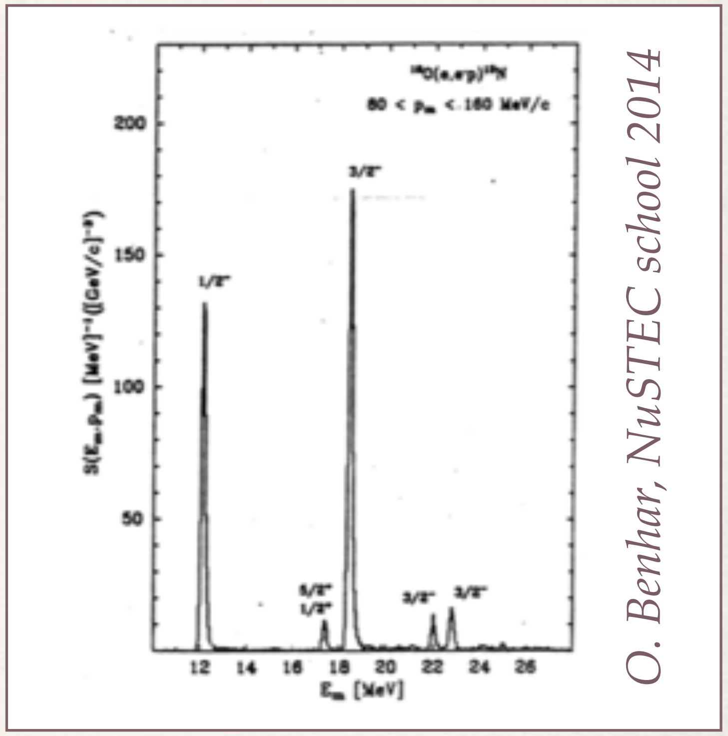
R. Subedi et al, Science 320 1476 (2008)

- Cross sections for meson exchange current diagrams, including correlations, have been calculated *J. Nieves, I. Ruiz Simo and M. J. Vicente Vacas, Phys. Rev. C 83 (2011) 045501*

More nuclear models

Spectral functions (SF)

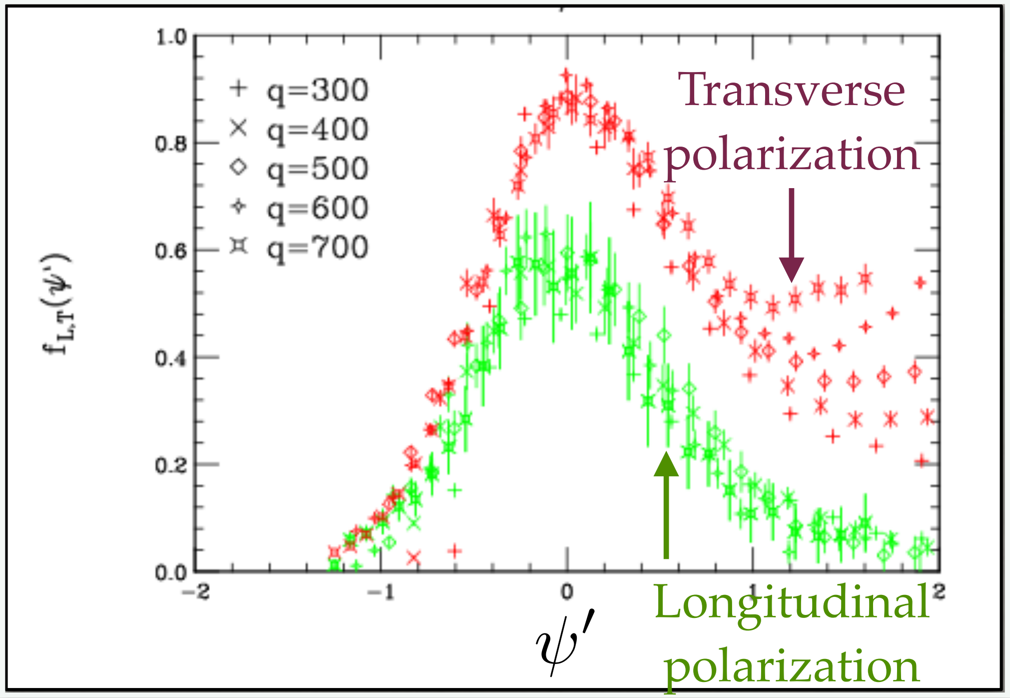
- The shell model of the nucleus gives spectral lines, which can be seen in electron-nucleus scattering experiments
- For a more accurate model of the nucleus, a contribution for correlated pairs is added to the spectral function *O. Benhar, A. Fabrocini, S. Fantoni, and I. Sick, Nucl.Phys. A579, 493 (1994)*



O. Benhar, NuSTEC school 2014

Transverse Enhancement Model (TEM)

- Parameterizes correlation effect seen in electromagnetic electron scattering by modifying nucleon magnetic form factor *A. Bodek, H. Budd, and M. Christy, Eur.Phys.J. C71, 1726 (2011)*
- Note this effect was seen in pure vector scattering - how does it extend to weak interactions with an axial component?



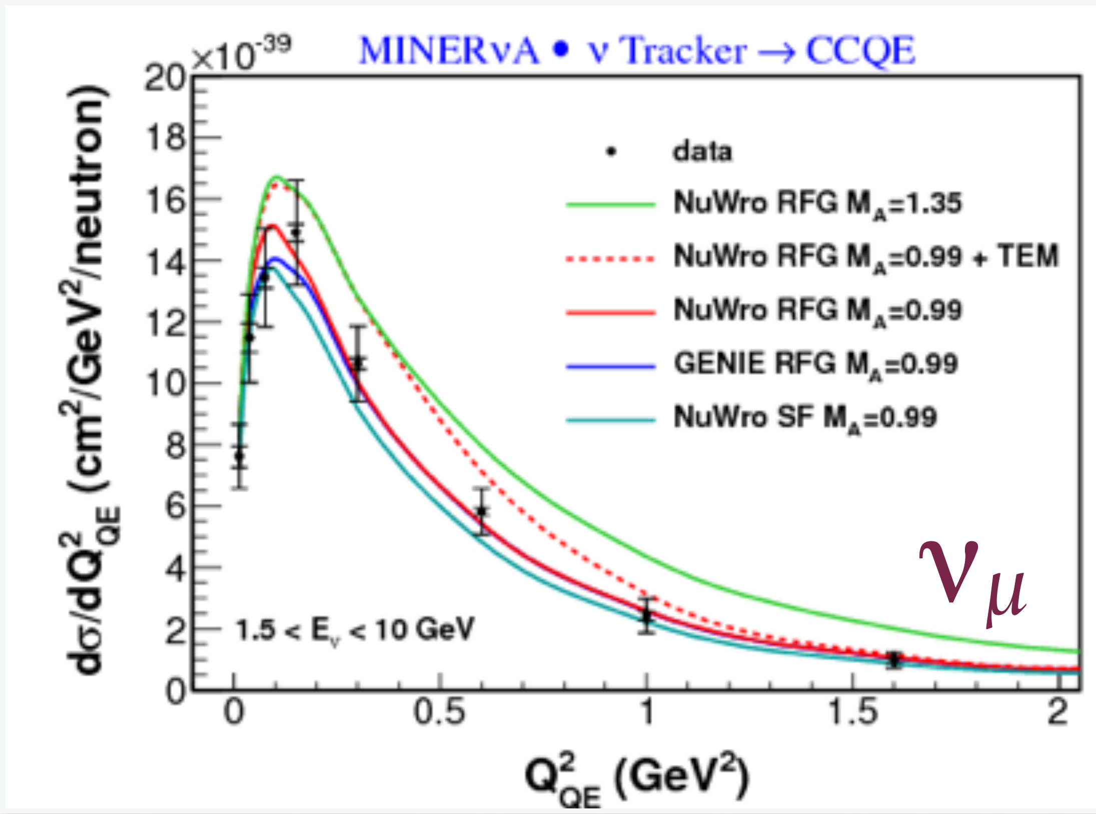
Transverse & longitudinal cross sections
J. Carlson et al, PRC 65, 024002 (2002)

Quasi-elastic results: muon kinematics

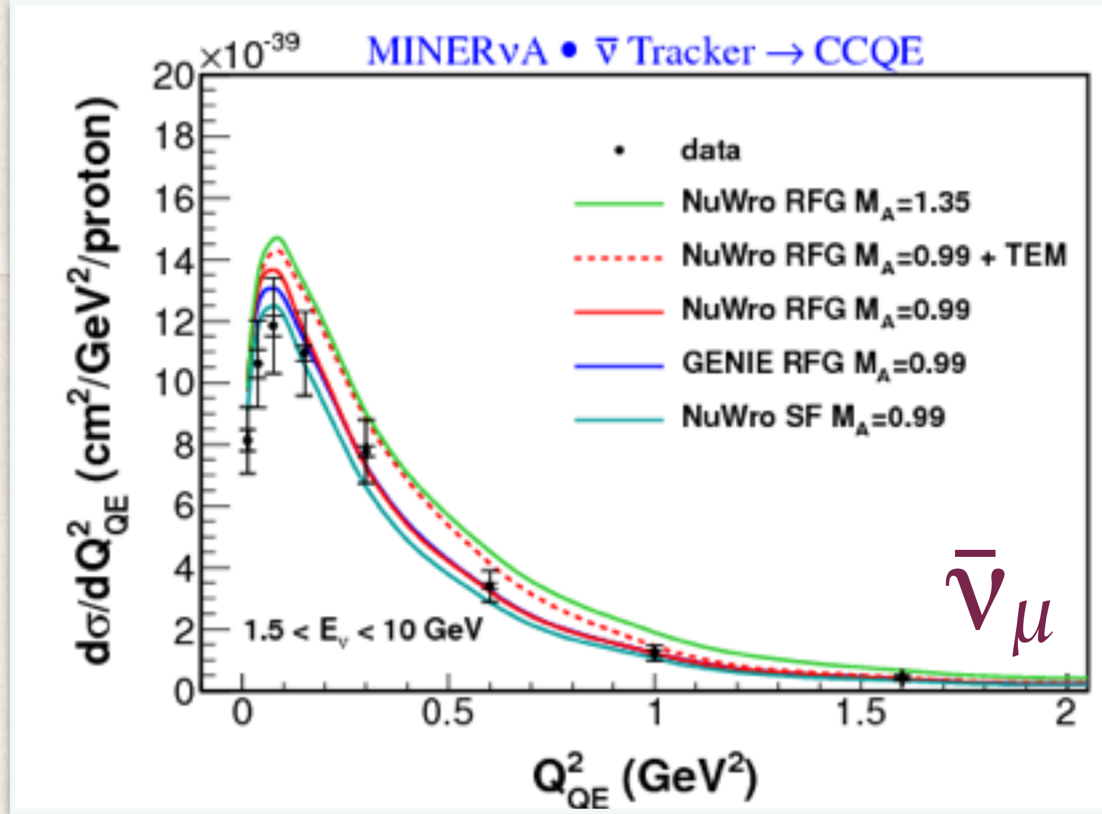
- Compare data to GENIE RFG *C. Andreopoulos, et al., NIM 288A, 614, 87 (2010)* and NuWro *K. M. Graczyk and J. T. Sobczyk, Eur.Phys.J. C31, 177 (2003)* nuclear models

—— GENIE RFG M_A=0.99
—— NuWro RFG M_A=0.99
—— NuWro RFG M_A=1.35

‥‥‥ NuWro RFG+TEM M_A=0.99
—— NuWro SF M_A=0.99



G.A. Fiorentini, D. Schmitz et al, Phys. Rev. Lett. 111, 022502 (2013).

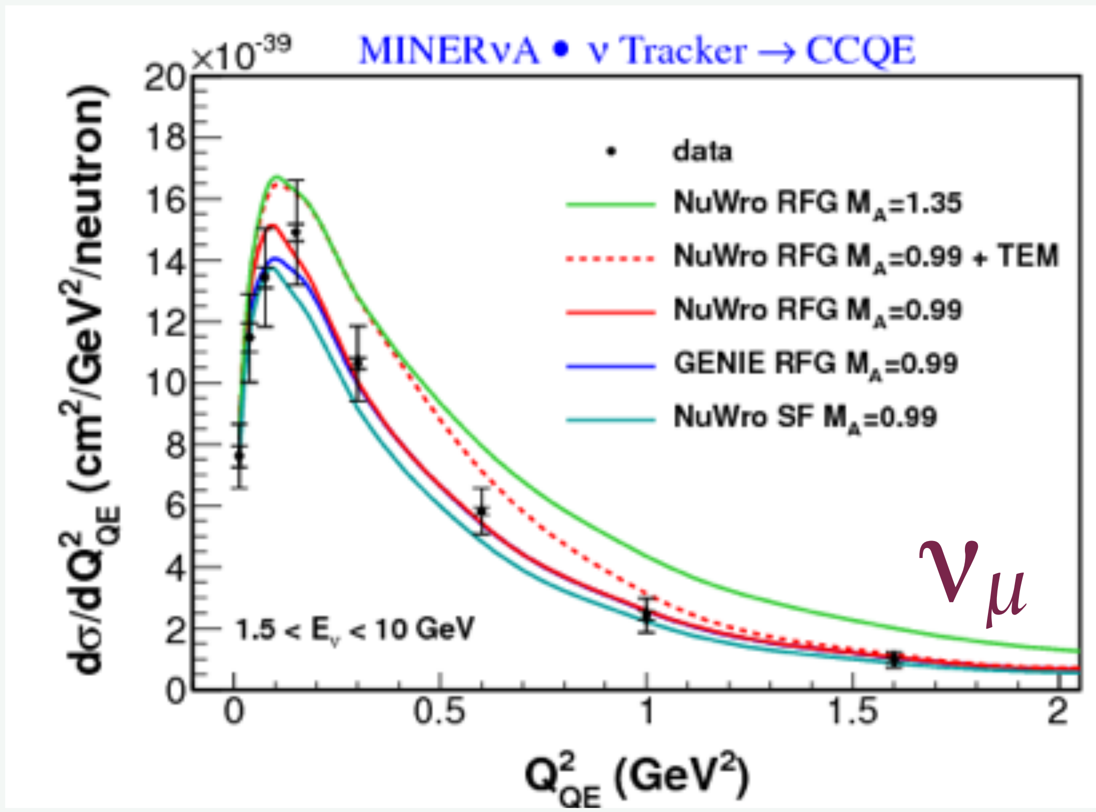


L. Fields, J. Chvojka et al. Phys. Rev. Lett. 111, 022501 (2013)

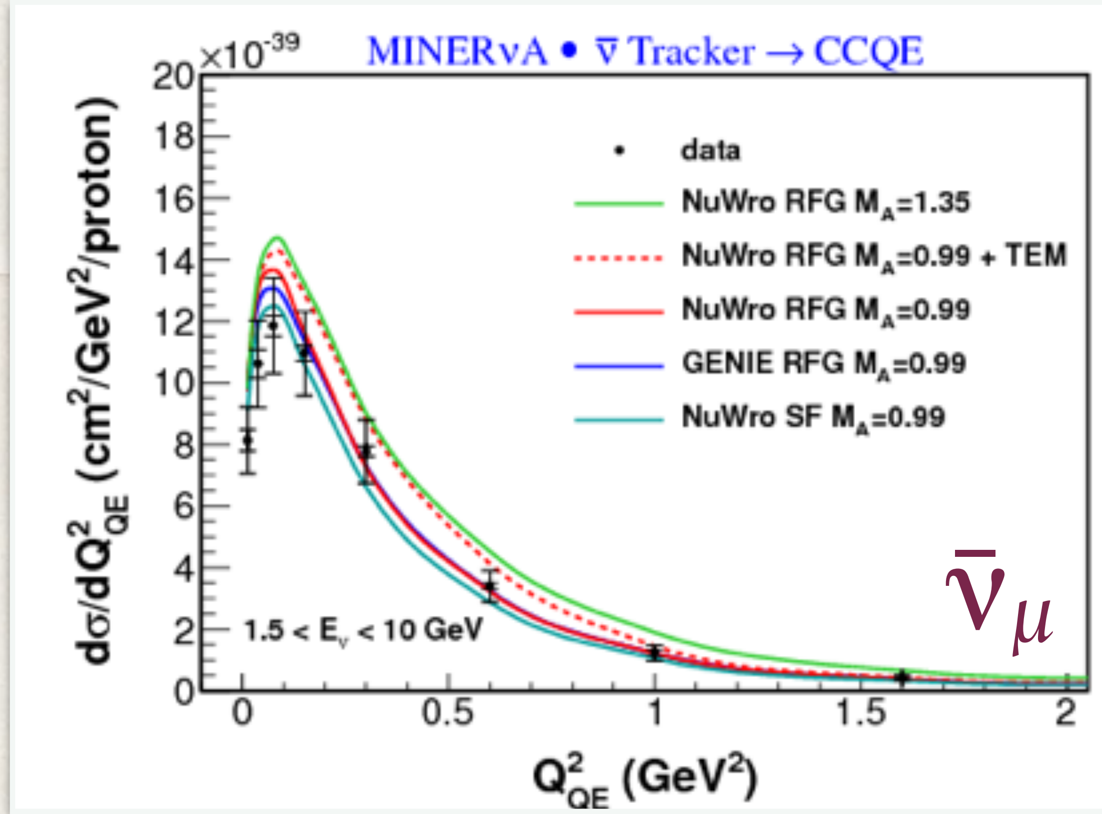
Quasi-elastic results: muon kinematics

- Compare data to GENIE RFG *C. Andreopoulos, et al., NIM 288A, 614, 87 (2010)* and NuWro *K. M. Graczyk and J. T. Sobczyk, Eur.Phys.J. C31, 177 (2003)* nuclear models

🟦	GENIE RFG M_A=0.99	⋯	NuWro RFG+TEM M_A=0.99
🟥	NuWro RFG M_A=0.99		
🟩	NuWro RFG M_A=1.35	—	NuWro SF M_A=0.99



G.A. Fiorentini, D. Schmitz et al, Phys. Rev. Lett. 111, 022502 (2013).

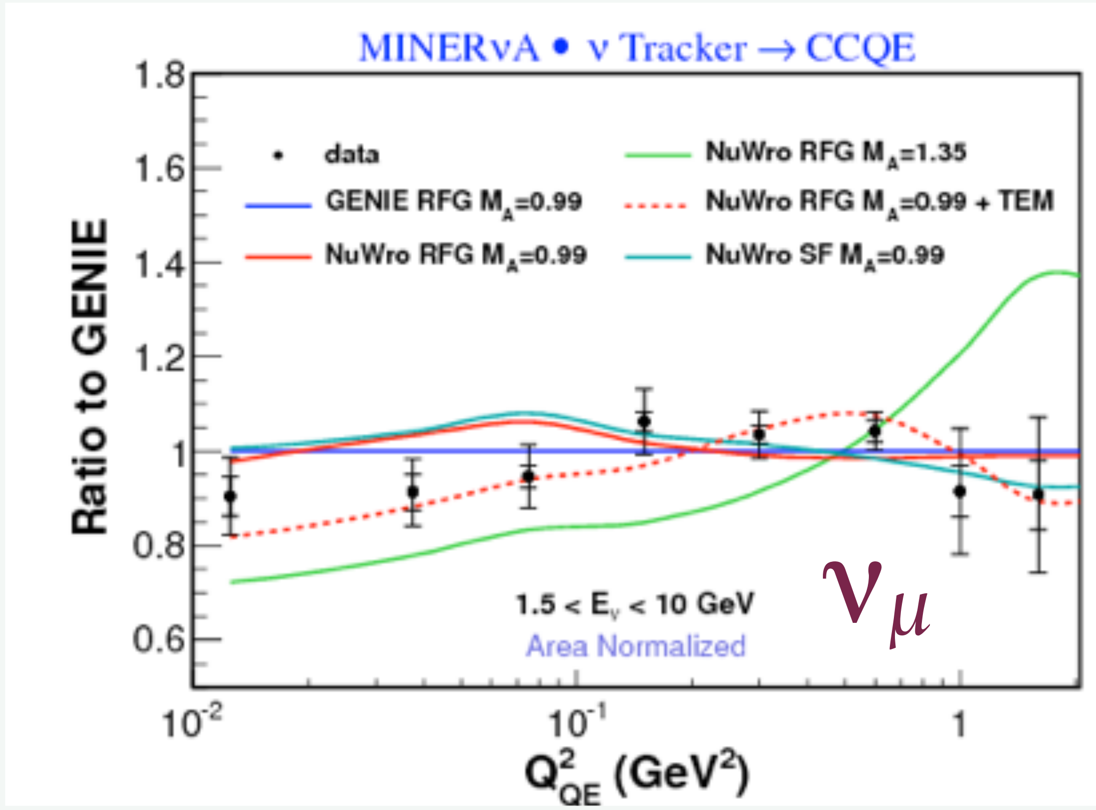


L. Fields, J. Chvojka et al. Phys. Rev. Lett. 111, 022501 (2013)

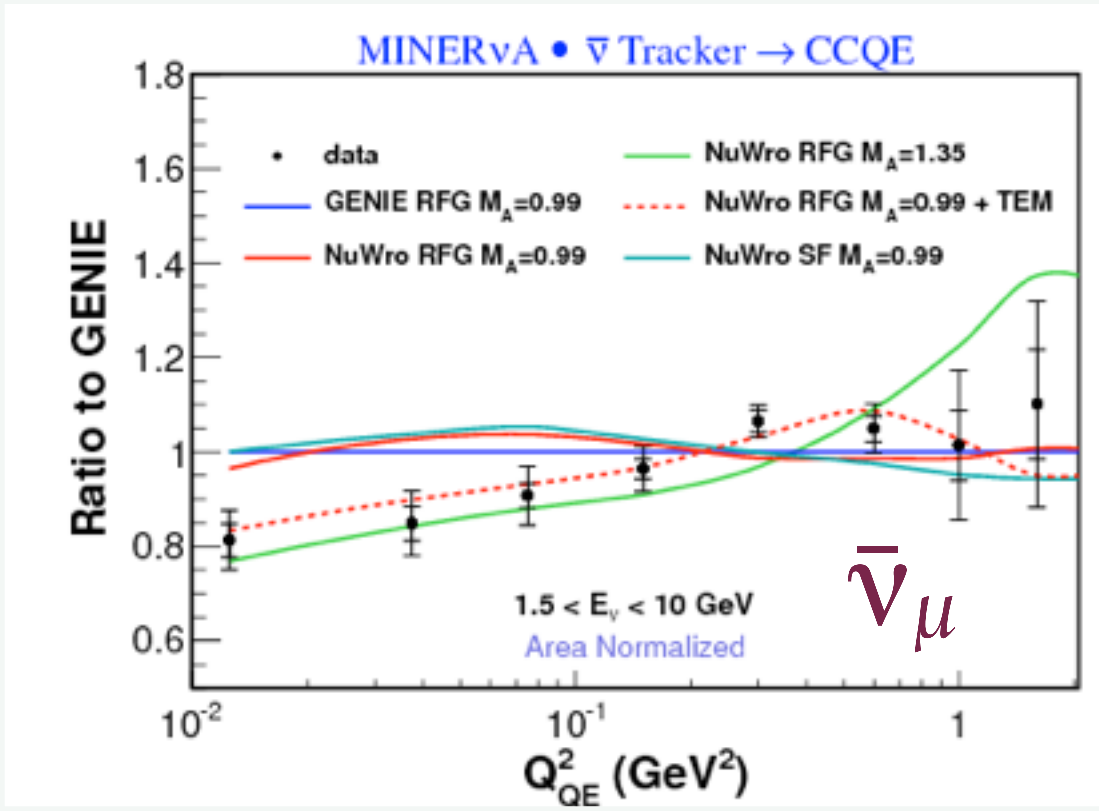
- To make it easier to distinguish:
  - Take **ratios** to GENIE (the MC we used for acceptance correction etc)
  - Use **log scale** to see differences at low Q^2
  - Look at distribution **shapes** to reduce systematic uncertainty, particularly due to flux

Quasi-elastic results: muon kinematics

- — GENIE RFG M_A=0.99
- — NuWro RFG M_A=0.99
- — NuWro RFG M_A=1.35
- ⋯ **NuWro RFG+TEM M_A=0.99**
- — NuWro Spectral functions M_A=0.99



G.A. Fiorentini, D. Schmitz et al, Phys. Rev. Lett. 111, 022502 (2013).

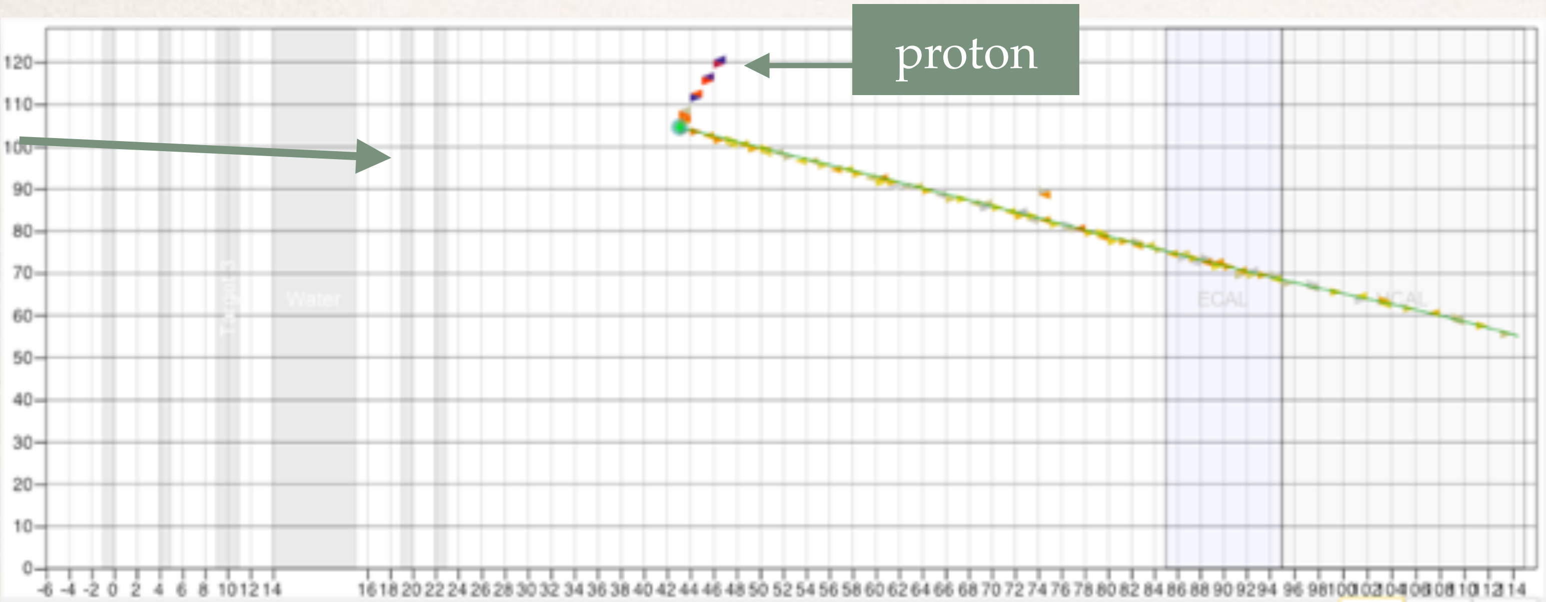


L. Fields, J. Chvojka et al. Phys. Rev. Lett. 111, 022501 (2013)

χ^2 per degree of freedom:

		$\bar{\nu}_\mu$	ν_μ
🟩	RFG (M_A = 1.35):	1.73	2.1
🟥	RFG (M_A=0.99):	2.90	4.1
▥	RFG (M_A=0.99, TEM):	0.66	1.7
🟦	SF (M_A=0.99):	2.99	3.8

Quasi-elastics from proton kinematics

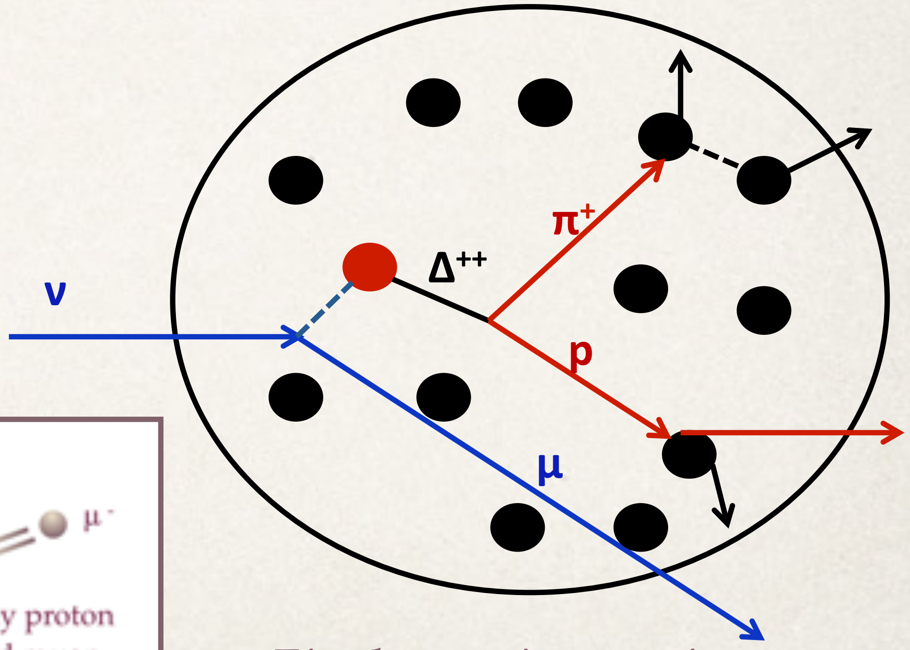


- Instead of using the muon, we can instead reconstruct Q^2 from the kinematics of a **stopping proton**
- Protons can undergo **final-state interactions**, so this is particularly **sensitive to FSI modeling**

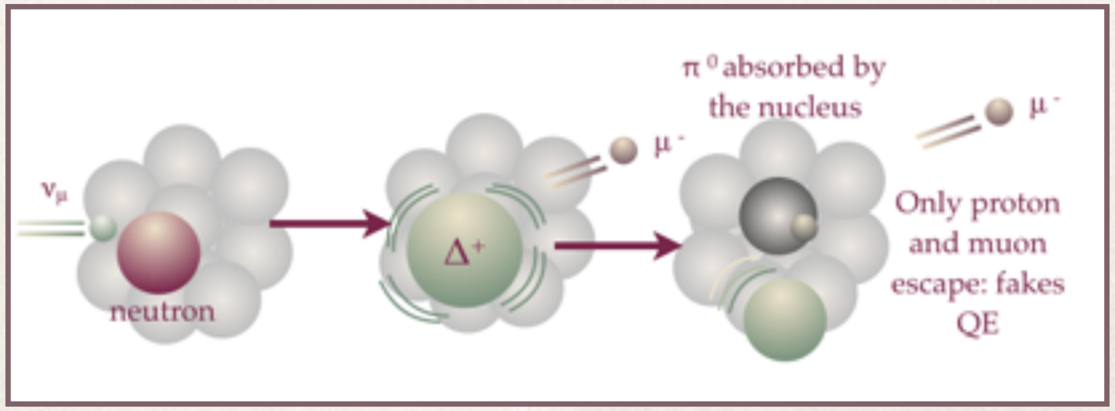
$$Q^2_{QE,p} = (M_n - E_B)^2 - M_p^2 + 2(M_n - E_B)(T_p + M_p - M_n + E_B)$$

$M_{n,p}$ = neutron, proton mass, T_p=proton KE, E_B=binding energy

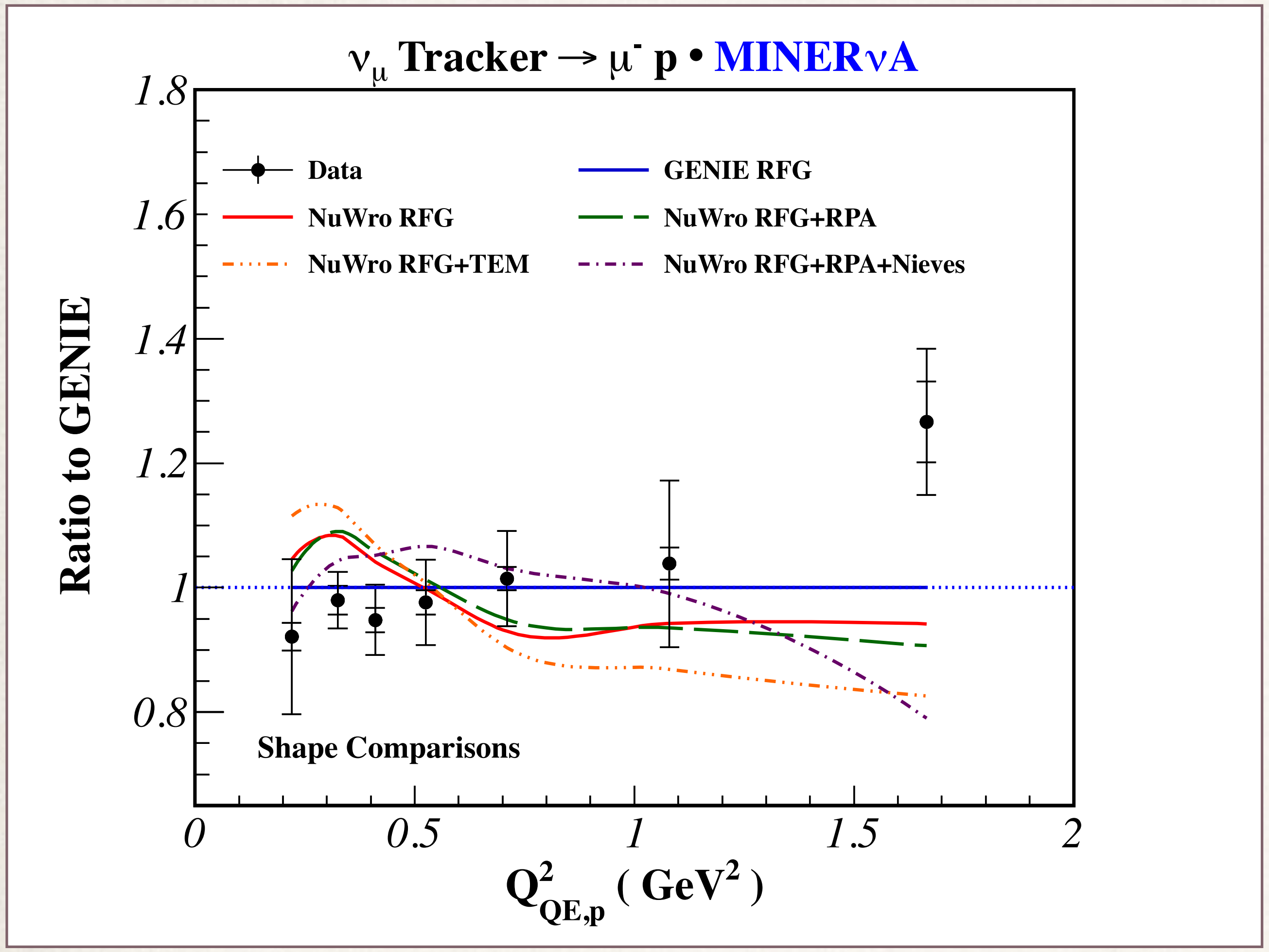
- Hadrons produced in a scattering interaction may re-interact with other nucleons before they escape the nucleus: we call these final-state interactions
- Thus the particles that exit the nucleus may be different, both in type and in energy, from those generated in the initial interaction



Final-state interactions



Quasi-elastics from proton kinematics

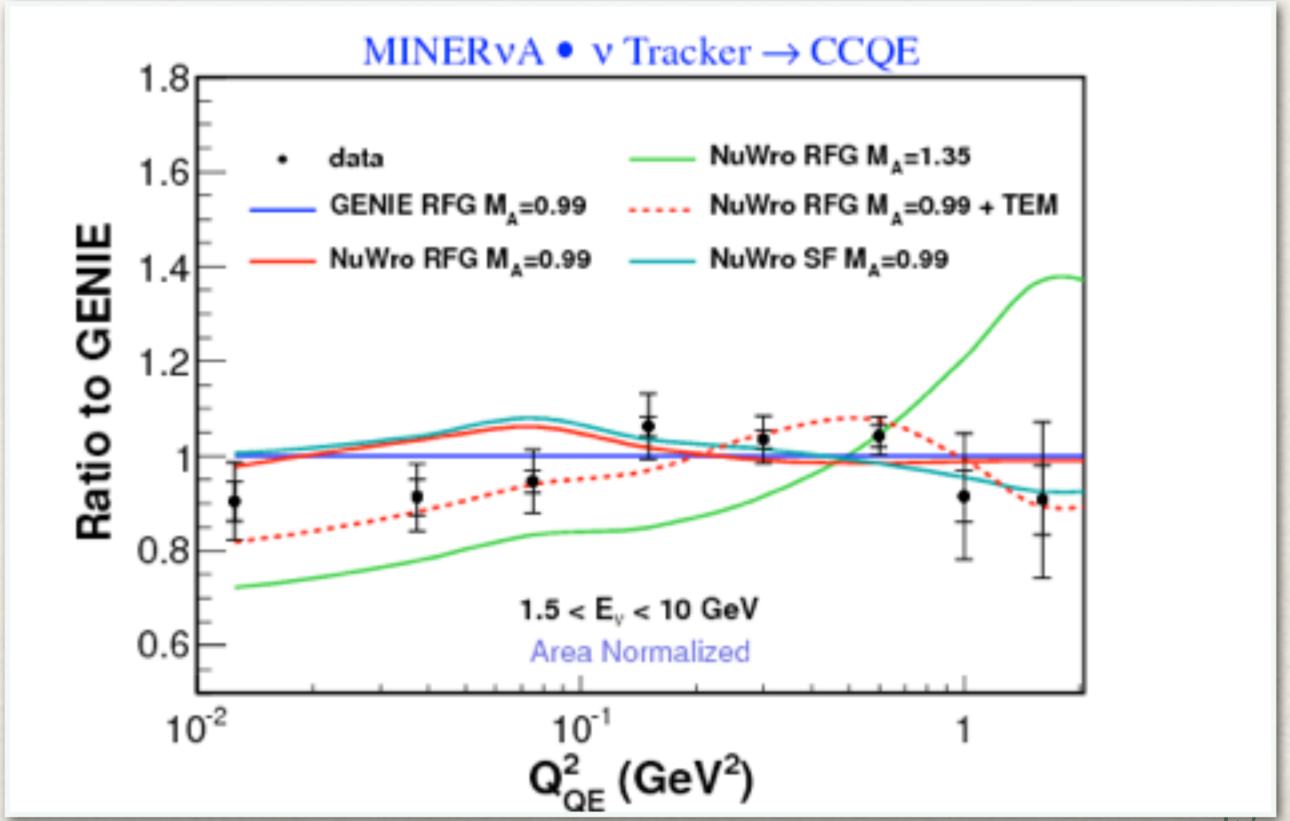


T Walton, arXiv:1409.4497 Accepted by Physical Review D

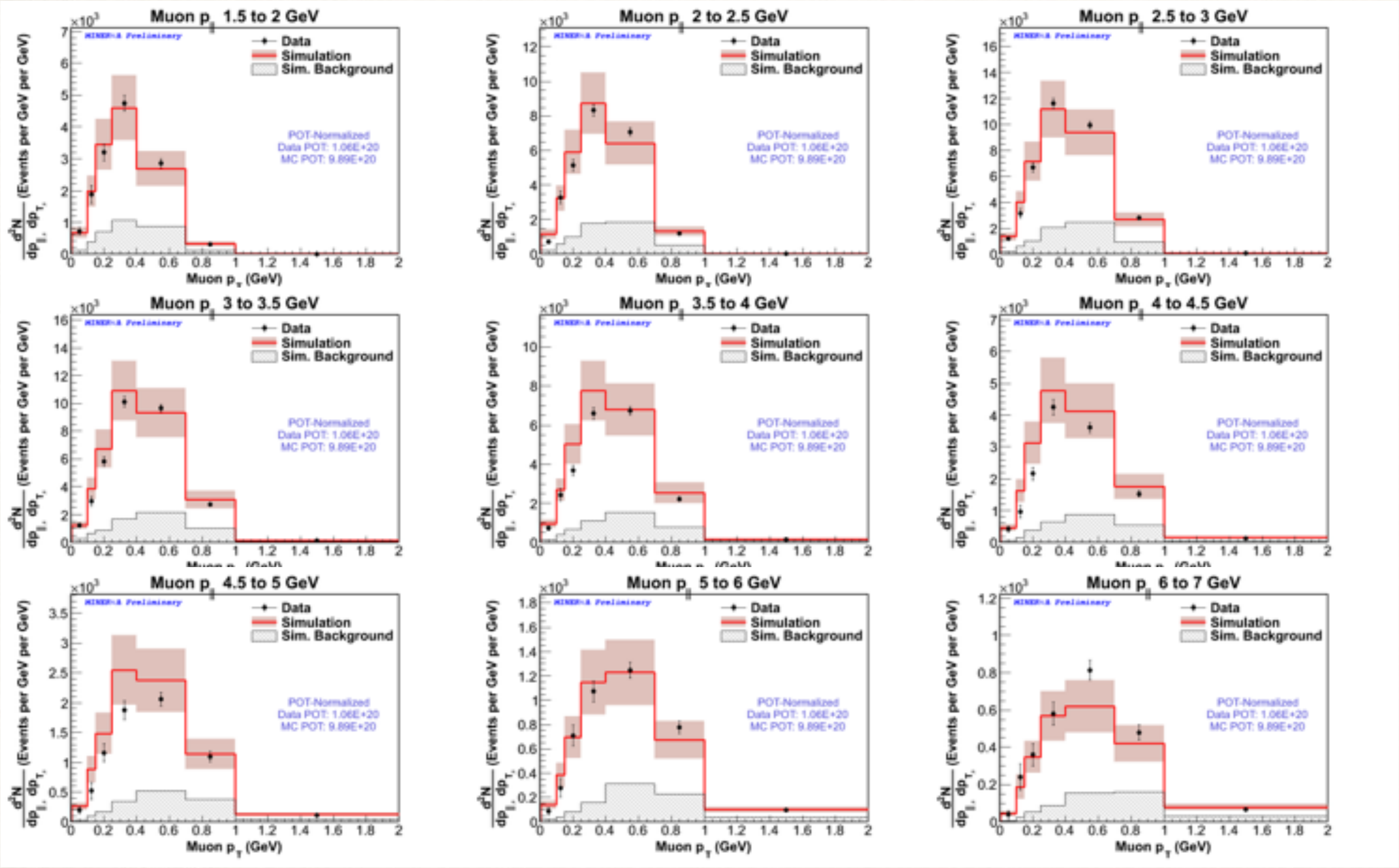
- No one model is able to simulate both our muon- and proton-kinematics data sets

We need a model that gets **everything** right!

- The proton-kinematics study favors GENIE's **Relativistic Fermi Gas model**, with no additional nuclear effects
- Contrast to muon-kinematics study
- Note that the proton-based study has a greater acceptance (no MINOS match)
- However, it is unable to examine the low Q^2 region due to tracking limitations



Double-differential cross sections



Double-differential cross sections in measurable variables will provide extra information to help distinguish between models.

The plots to the left are for the **antineutrino CCQE** sample.

- Plots show data and simulation event distributions vs. transverse muon momentum, in bins of longitudinal muon momentum
- Uncertainties on reconstruction and interaction model are shown on the simulation
- Reducing the uncertainty on the interaction model is a key goal of this study

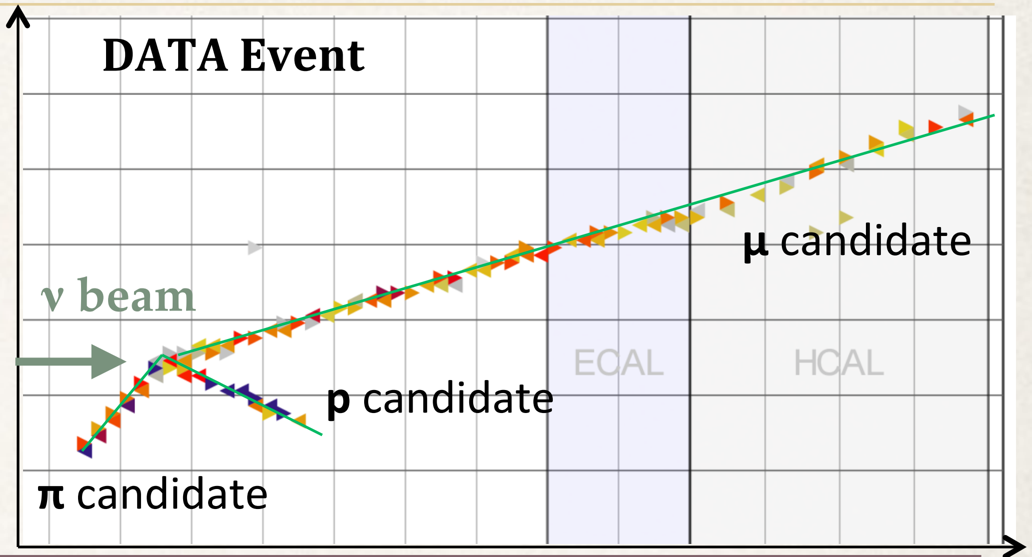
Charged-current $\pi^{\pm}$ production from ν

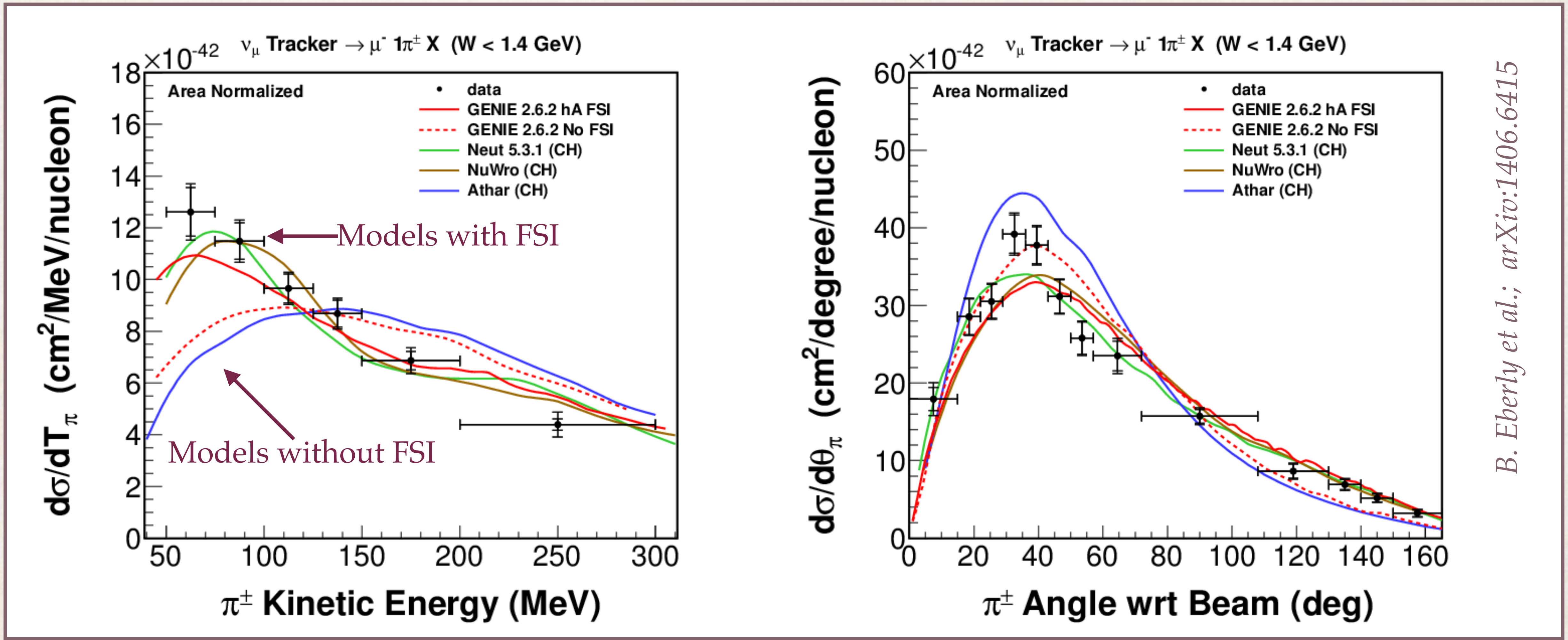
$$\nu_\mu A \to \mu^- \pi^\pm X$$

$$\nu_\mu A \to \mu^- \pi^+ A$$

A is the initial nucleus
X is a recoil nucleus plus any other particles that are not pions

GENIE 2.6.2 and NuWro use Rein-Sehgal model for resonant pion production
Athar, M., Chauhan, S., and Singh, S. K., Eur. Phys. J. A43, 209–227 (2010).
Neut (Rein-Sehgal+FSI): Y. Hayato, Acta Phys.Polon. B40 (2009) 2477-2489





B. Eberly et al.; arXiv:1406.6415

The data constrain primary interaction rate & FSI

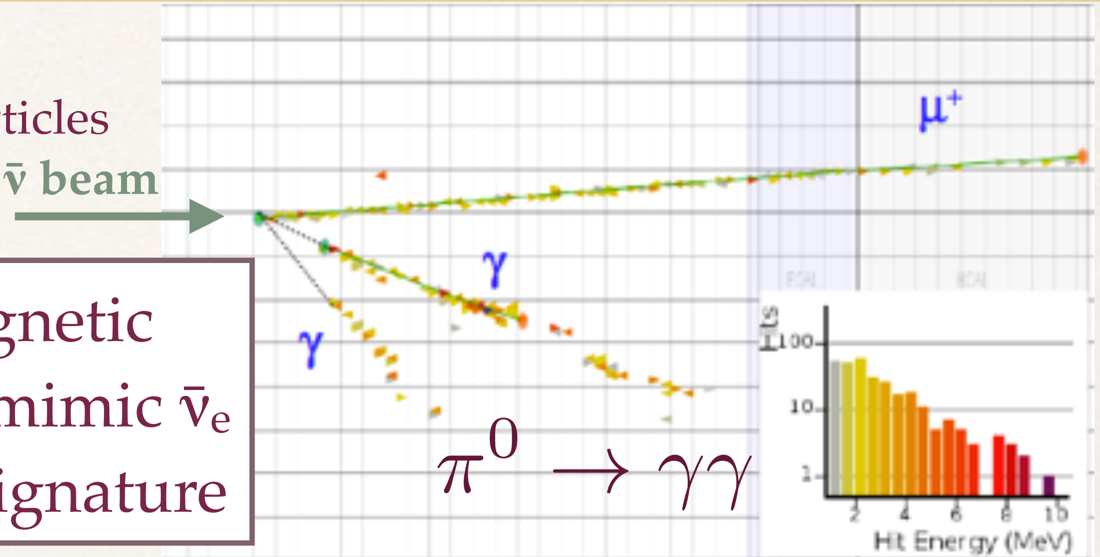
π^0 production from antineutrinos

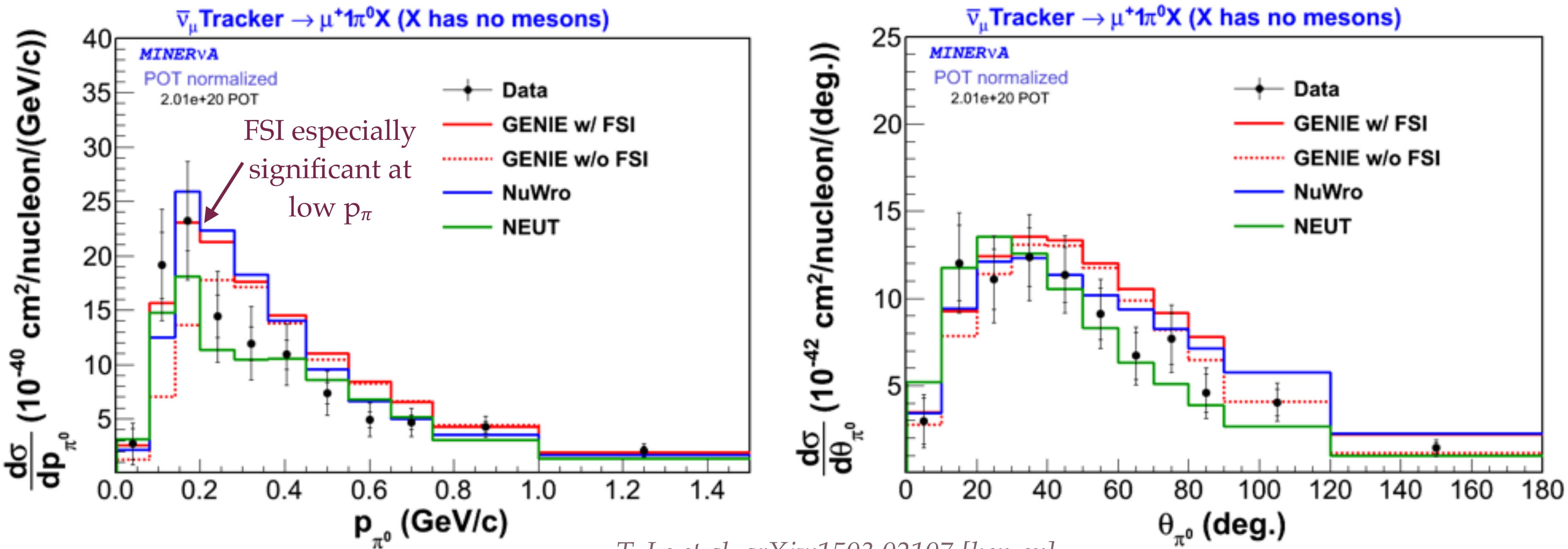
$$\bar{\nu}_\mu A \rightarrow \mu^+ \pi^0 X$$

A is the initial nucleus
X is a recoil nucleus plus any other particles that are not pions

This can help evaluate the approximations made in different generators' FSI models

Electromagnetic showers can mimic $\bar{\nu}_e$ appearance signature

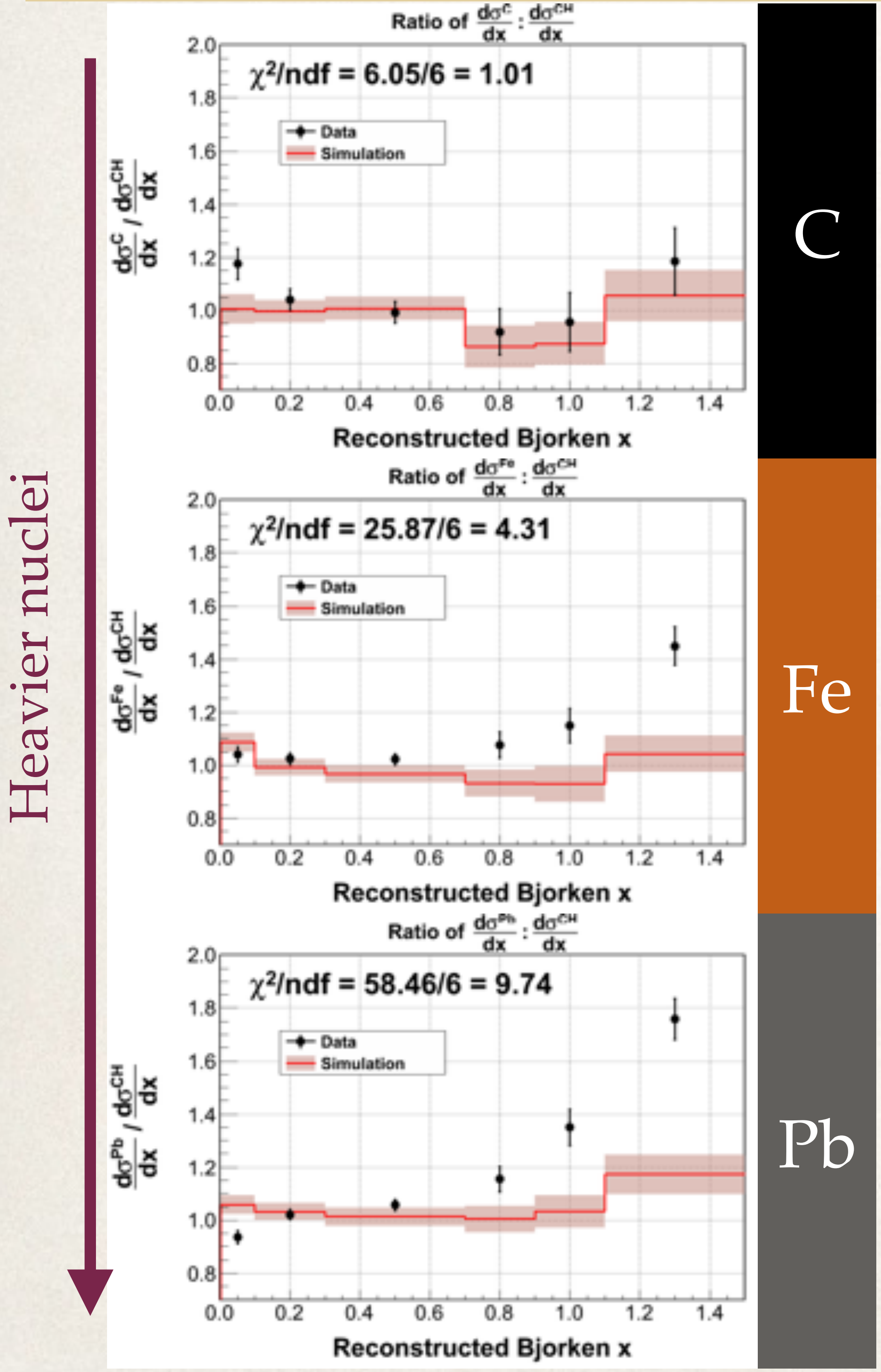




FSI especially significant at low p_π

T. Le et al.,arXiv:1503.02107 [hep-ex]

CC-inclusive cross sections on nuclei



- Compare charged-current inclusive dσ/dx (all channels) on different materials with scintillator (x characterizes type of interaction)

$$x = \frac{Q^2}{2M\nu}$$

- Our simulation
  - **overestimates at low *x*** *(shadowing region)*
  - **underestimates at high *x*** (*more elastic*)
- …with an effect **more pronounced for heavier nuclei**

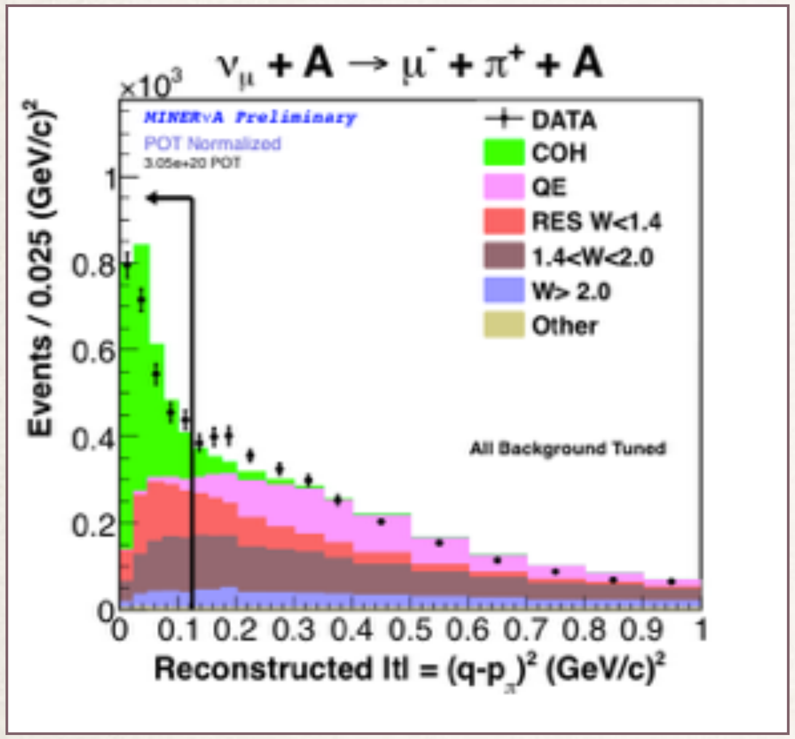
There are no current models that explain these nucleus-dependent behaviors

- But it's vital we understand cross sections on these materials
- MINERvA's **medium-energy dataset** will provide a large, DIS-rich sample to test this further and look at individual interaction channels

B. Tice et al, Phys. Rev. Lett. 112, 231801 (2014).

Other analyses

Coherent pion production

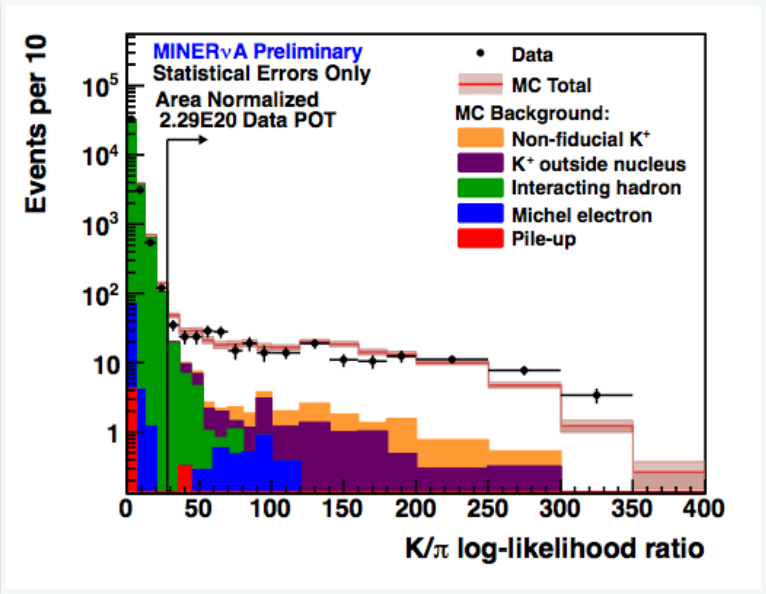


Clear evidence of neutrino scattering that does not break up the nucleus, previously only seen in higher-energy experiments.

A Higuera, A Mislevic et al., Phys. Rev. Lett. 113, 261802 (2014)

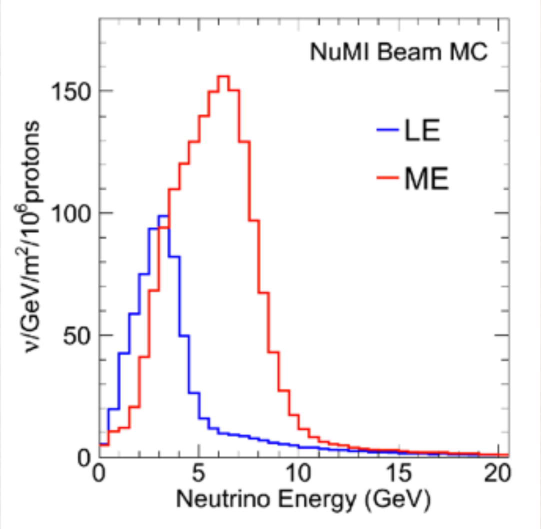
Kaon production

K^+ production from atmospheric neutrinos is a background for proton decay searches.



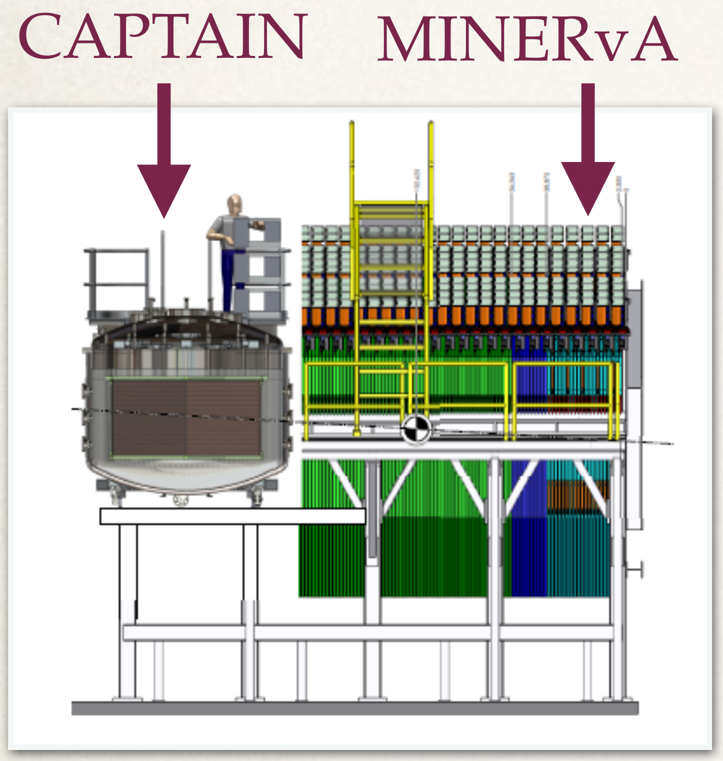
Keep an eye open for a measurement of this cross section, coming soon.

Medium-energy analyses

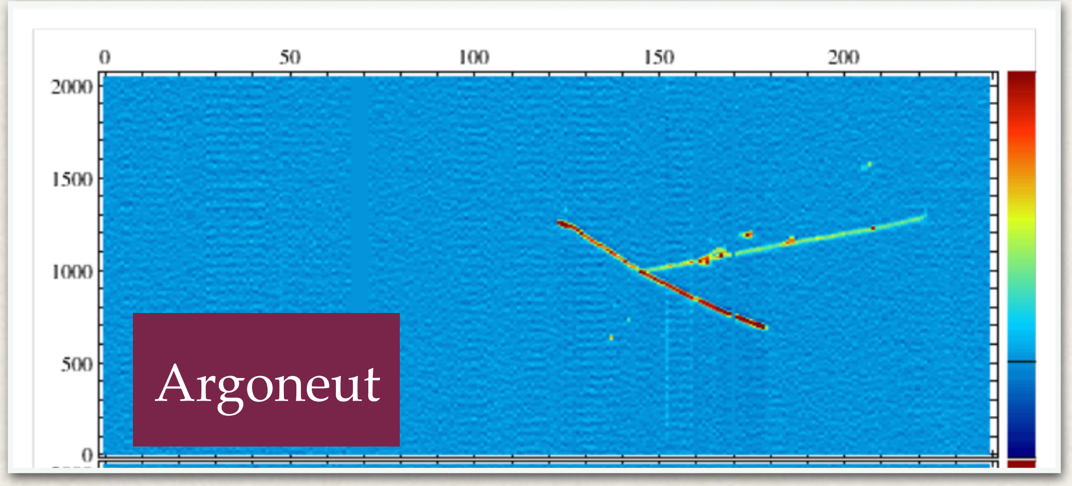


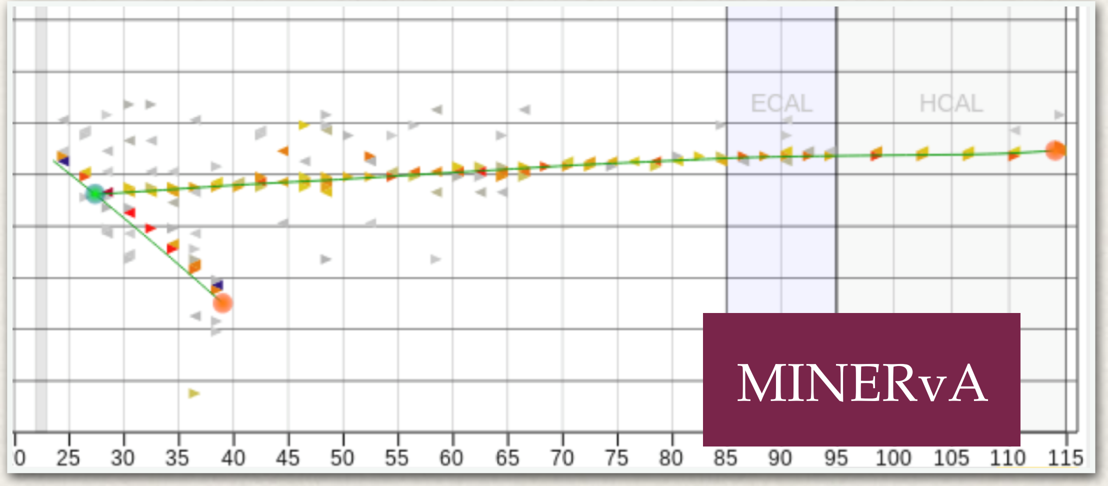
- The analyses we have seen so far used our low-energy data set, but we now have over a year of medium-energy data
- A higher energy range will allow us to probe the DIS region and nucleon structure functions
- Increased statistics will let us study nuclear target ratios for individual interaction types
- Plus higher statistics overall will dramatically reduce uncertainties on all studies

CAPTAIN-MINERvA



- Oscillation experiments (T2K) are already using MINERvA's cross section measurements
- But LBNF will have a liquid argon detector, and we don't have an argon target… how can we help?
- **PROPOSAL:** insert **CAPTAIN detector** upstream of MINERvA!
    - CAPTAIN is a 5-ton liquid argon time-projection chamber
    - Study nuclear effects around the event vertex
    - Complements MicroBooNE's studies by looking at first LBNF oscillation maximum





Comparison of similar event displays in LAr TPC (Argoneut) and MINERvA tracker

Displays show muon plus back-to-back protons

The MINERvA collaboration

- University of California at Irvine
- Centro Brasileiro de Pesquisas Físicas
- University of Chicago
- Fermilab
- Universidad Nacional de Ingeniería
- Northwestern University
- Otterbein University
- Pontificia Universidad Catolica del Peru
- University of Pittsburgh
- University of Rochester
- Rutgers, The State University of New Jersey
- Universidad Técnica Federico Santa María
- Tufts University
- William and Mary
- University of Florida
- Université de Genève
- Universidad de Guanajuato
- Hampton University
- Inst. Nucl. Reas. Moscow
- Massachusetts College of Liberal Arts
- University of Minnesota at Duluth

Thank you for your attention!

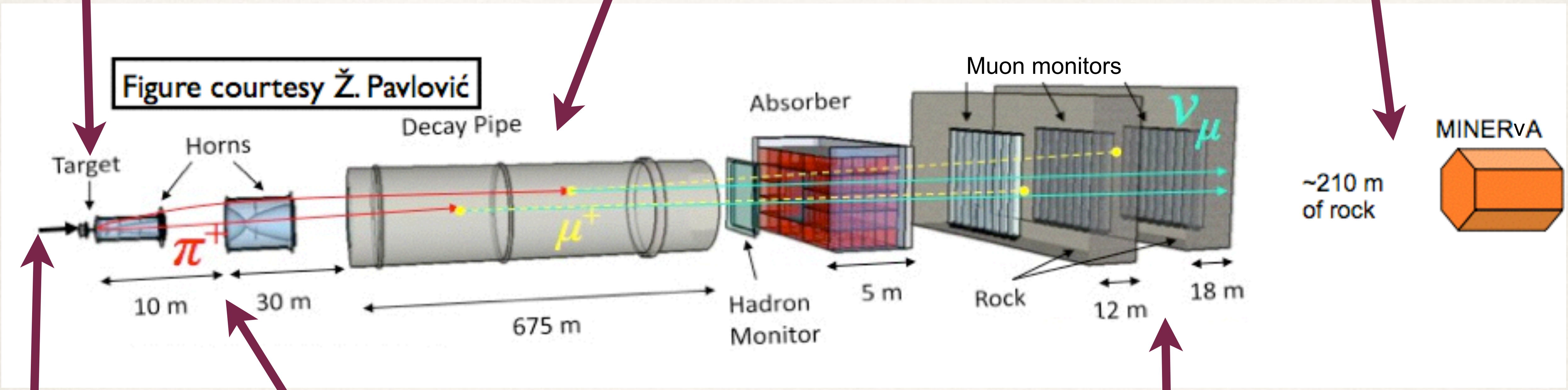
Backup slides

NUMI beamline

Protons hit graphite target, produce mesons (mostly pions, some kaons)

$\pi^+ \rightarrow \mu^+ + \nu_\mu$

Neutrinos!

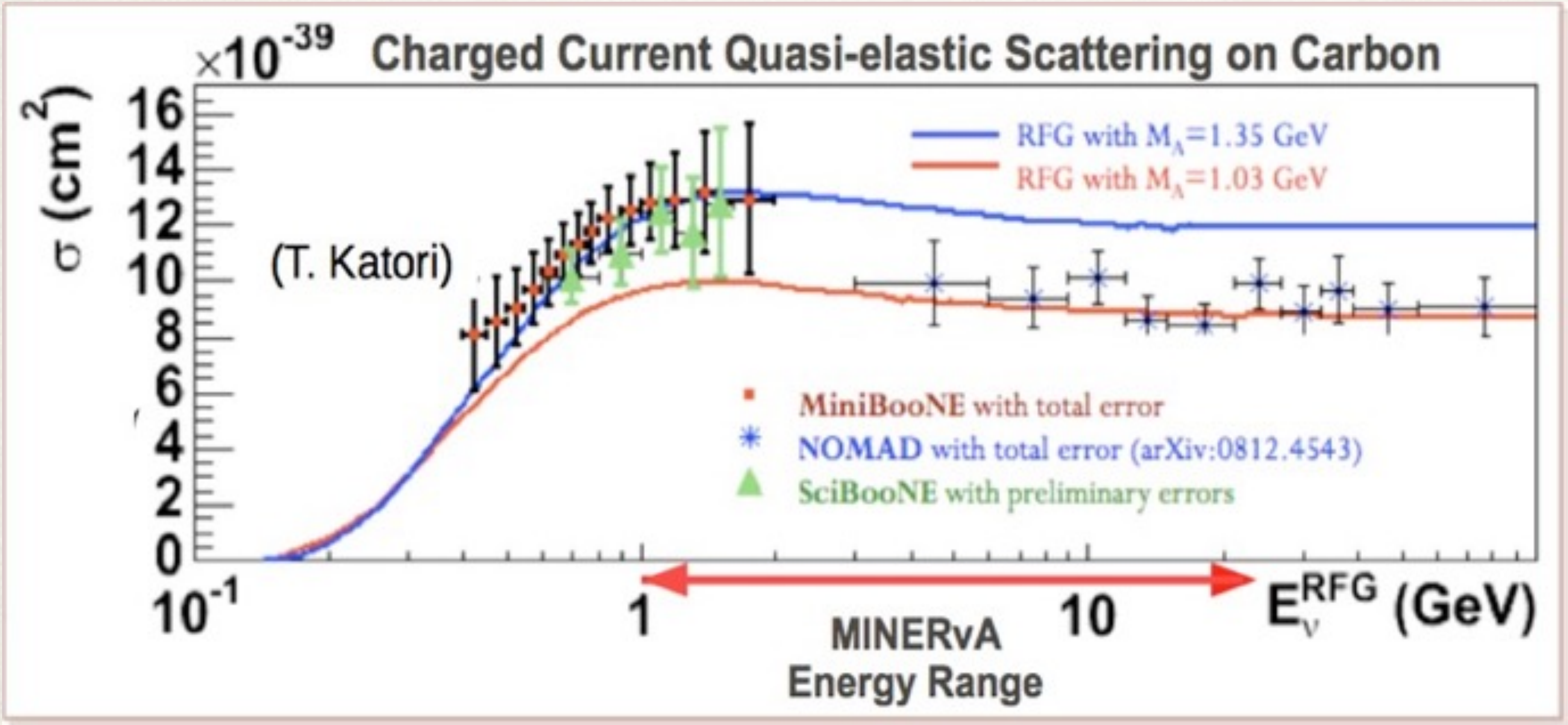


120 GeV protons

Horns focus one charge of meson and defocus the other

Rocks remove muons from beam

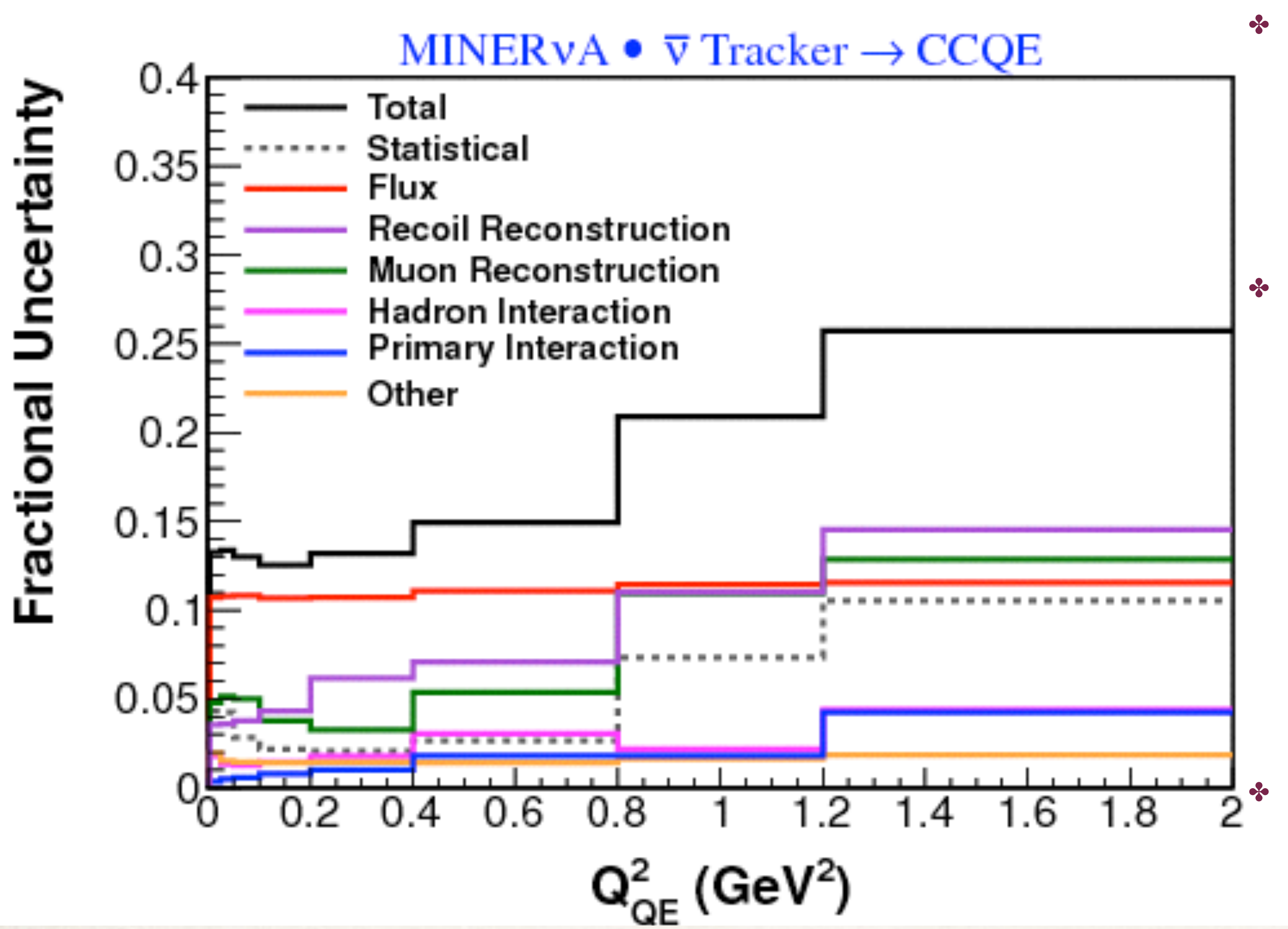
Limitations of RFG model



A.A. Aguilar-Arevalo et al.
[MiniBooNE Collaboration],
Phys. Rev. D 81, 092005 (2010)

- This shows best fits of MiniBooNE, SciBooNE and NOMAD cross-sections to the relativistic Fermi gas model for carbon
- Lower-energy experiments predict M_A=1.35 GeV, NOMAD predicts M_A=1.03 GeV when fitting to the same model
- We could be seeing additional **nuclear effects beyond the RFG model**

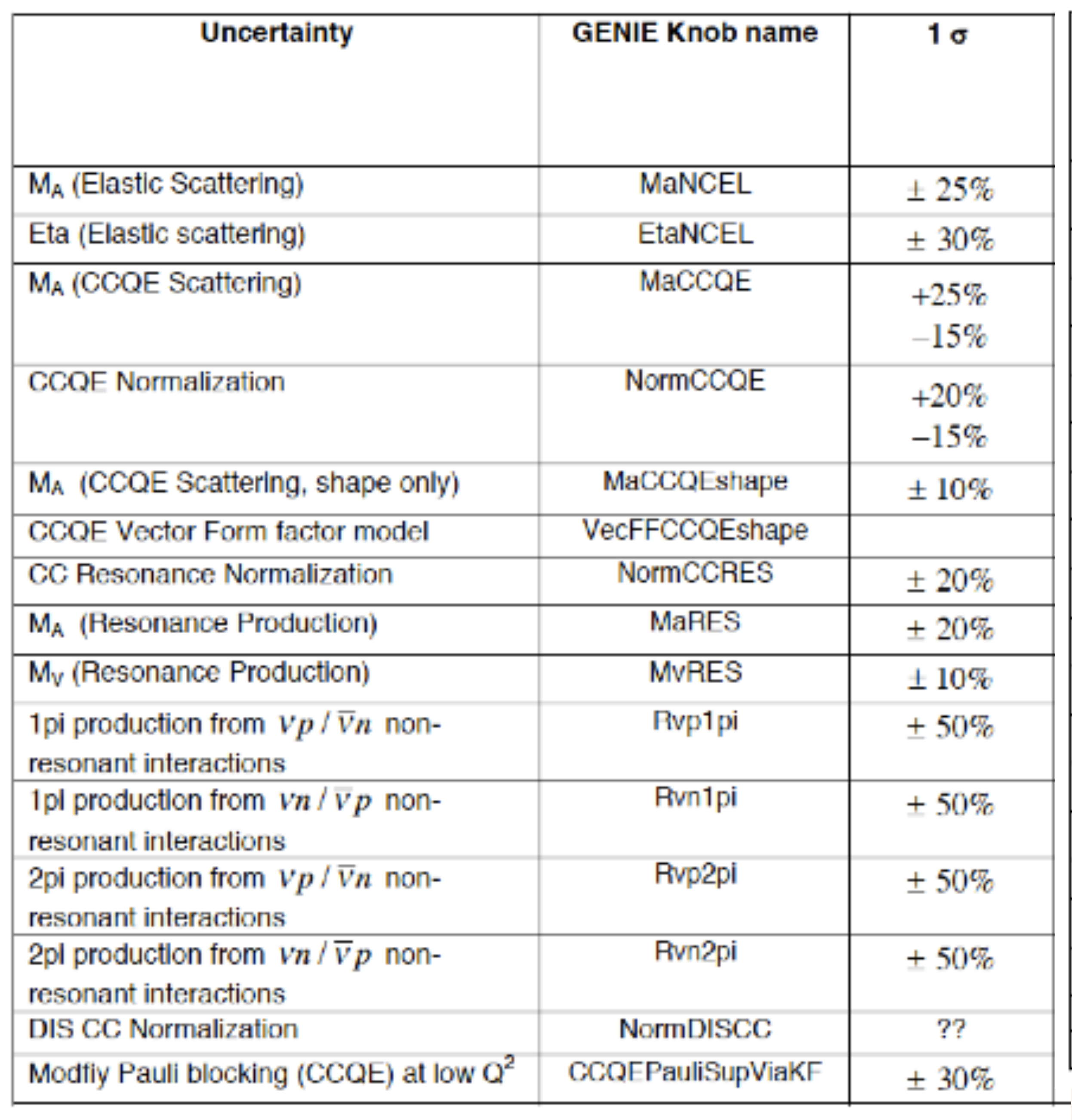
Sources of systematic uncertainty



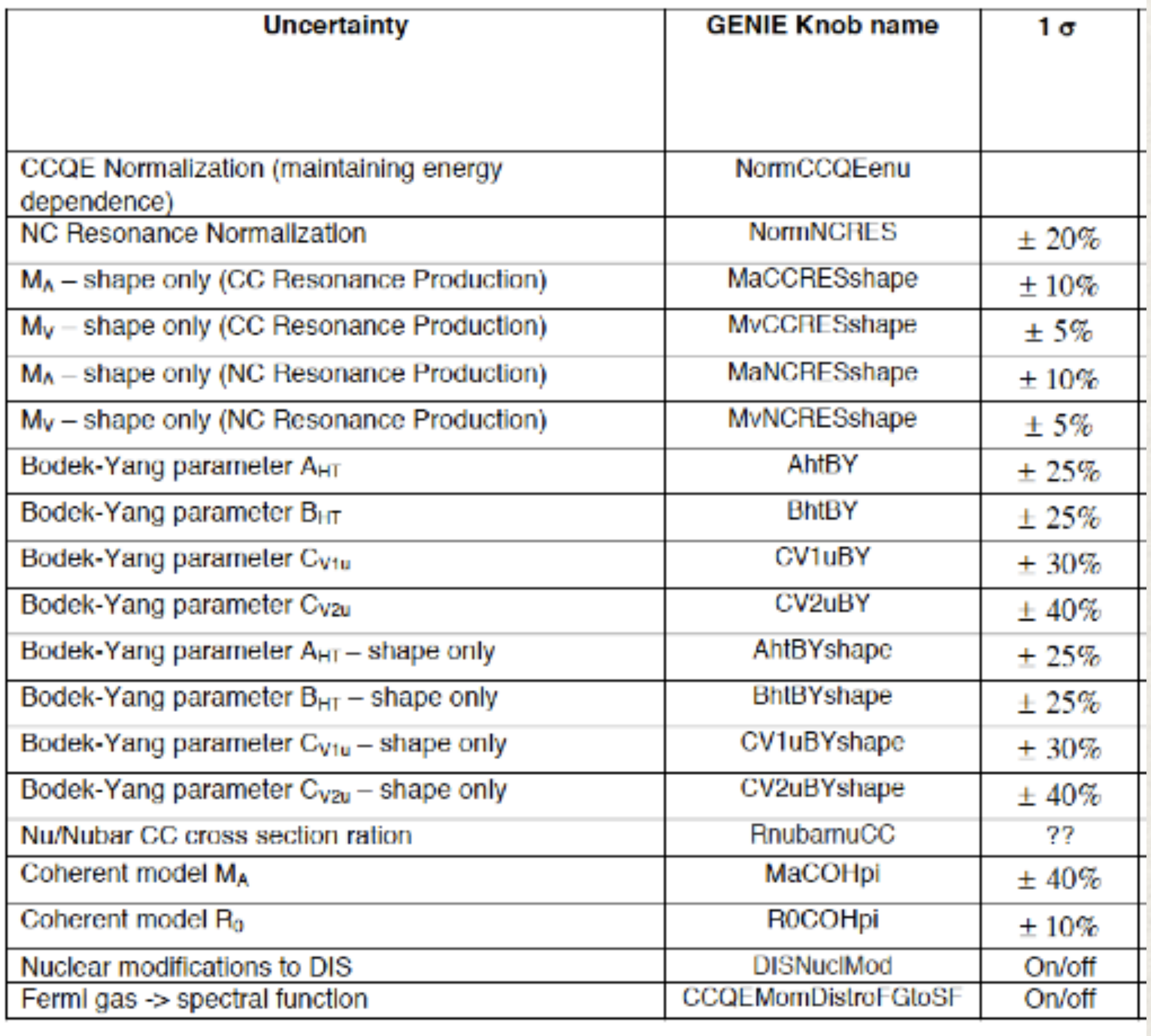
- This indicates systematics evaluated for the CCQE antineutrino analysis
- Different effects are important for different analyses (for example some are especially sensitive to FSI)

- **Recoil**
  - extra track/blob cuts
  - neutron response model
- **Muon reconstruction**
  - energy scale (MINOS range and curvature, MINERvA dE/dx)
  - tracking reconstruction
  - overlapping MINOS tracks
  - vertex resolution
- **Hadron interaction**
  - final state interaction model
- **Primary interaction**
  - quasi-elastic interaction model
  - resonant background model
  - nuclear model
- **Flux**

List of GENIE model uncertainties

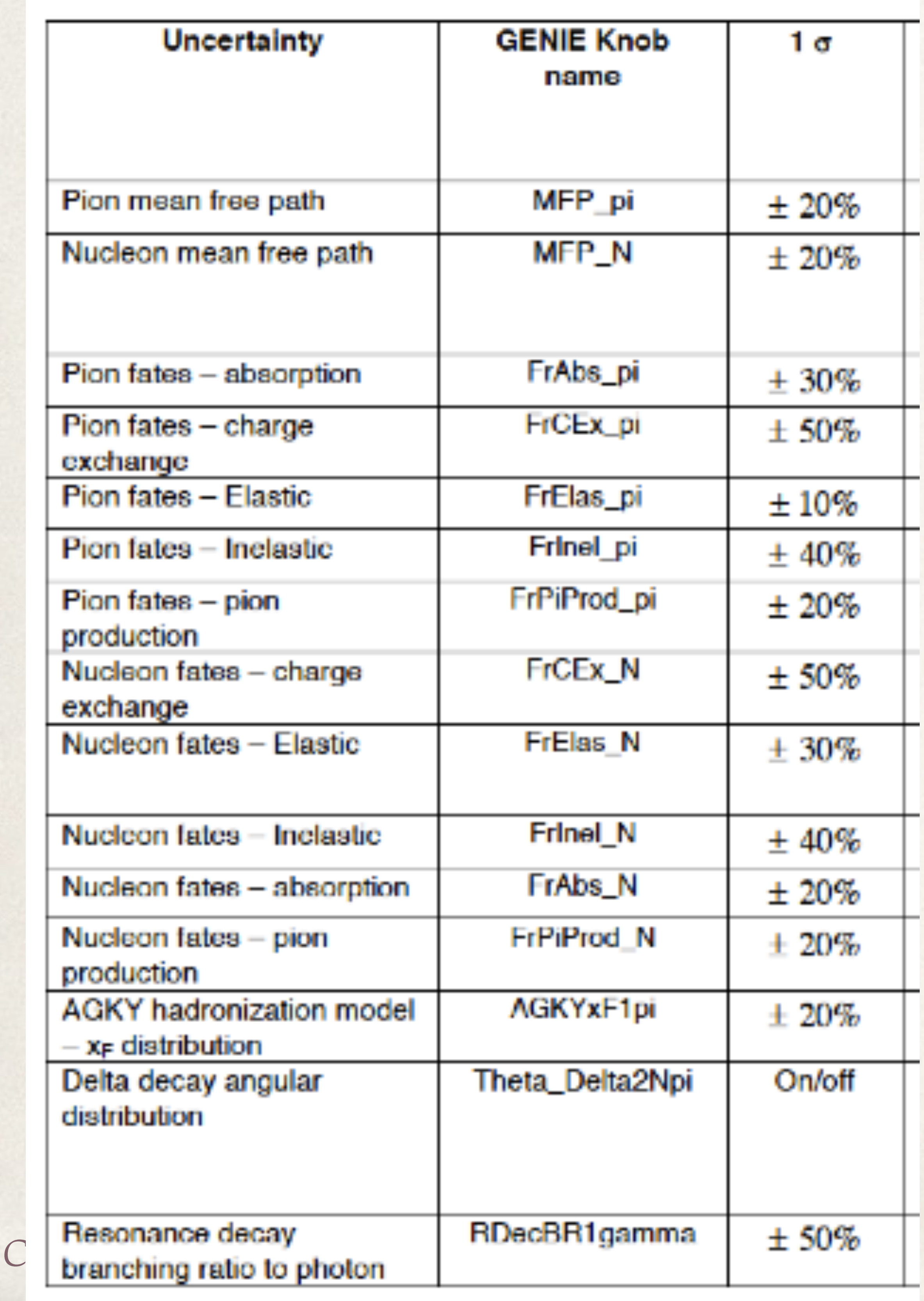


Uncertainty	GENIE Knob name	1 σ
M_A (Elastic Scattering)	MaNCEL	± 25%
Eta (Elastic scattering)	EtaNCEL	± 30%
M_A (CCQE Scattering)	MaCCQE	+25% −15%
CCQE Normalization	NormCCQE	+20% −15%
M_A (CCQE Scattering, shape only)	MaCCQEshape	± 10%
CCQE Vector Form factor model	VecFFCCQEshape	
CC Resonance Normalization	NormCCRES	± 20%
M_A (Resonance Production)	MaRES	± 20%
M_V (Resonance Production)	MvRES	± 10%
1pi production from νp / $\bar{\nu} n$ non-resonant interactions	Rvp1pi	± 50%
1pi production from νn / $\bar{\nu} p$ non-resonant interactions	Rvn1pi	± 50%
2pi production from νp / $\bar{\nu} n$ non-resonant interactions	Rvp2pi	± 50%
2pi production from νn / $\bar{\nu} p$ non-resonant interactions	Rvn2pi	± 50%
DIS CC Normalization	NormDISCC	??
Modfiy Pauli blocking (CCQE) at low Q^2	CCQEPauliSupViaKF	± 30%

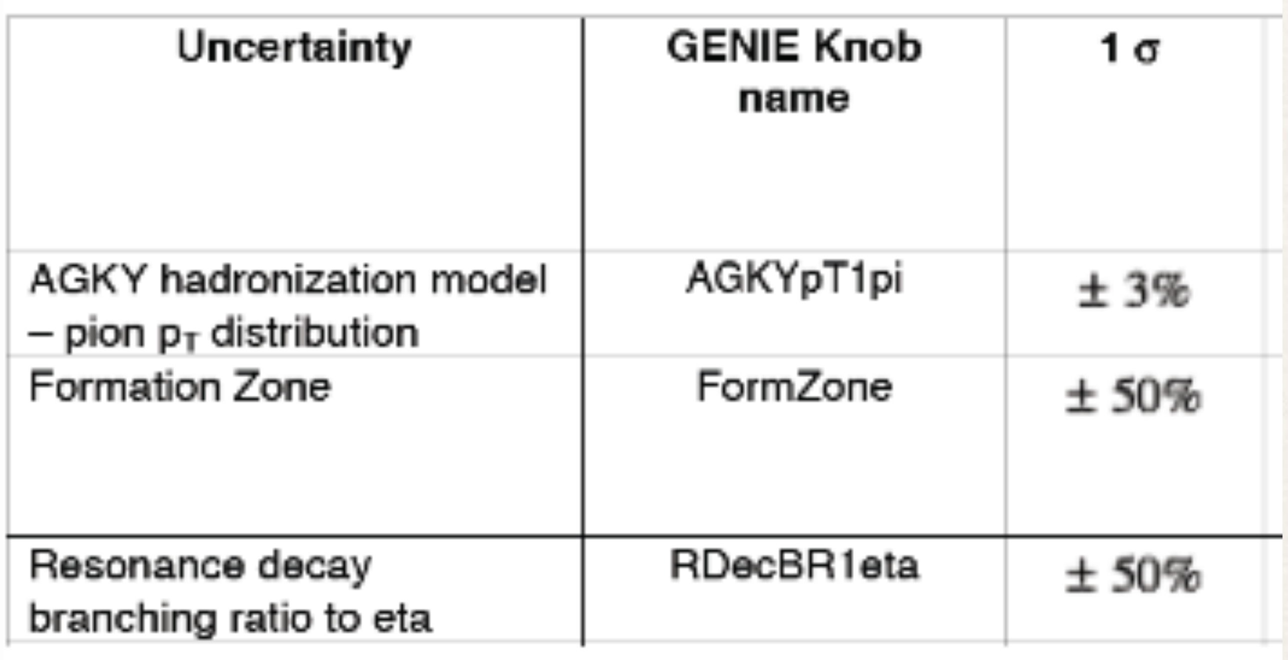


Uncertainty	GENIE Knob name	1 σ
CCQE Normalization (maintaining energy dependence)	NormCCQEenu	
NC Resonance Normalization	NormNCRES	± 20%
M_A – shape only (CC Resonance Production)	MaCCRESshape	± 10%
M_V – shape only (CC Resonance Production)	MvCCRESshape	± 5%
M_A – shape only (NC Resonance Production)	MaNCRESshape	± 10%
M_V – shape only (NC Resonance Production)	MvNCRESshape	± 5%
Bodek-Yang parameter A_{HT}	AhtBY	± 25%
Bodek-Yang parameter B_{HT}	BhtBY	± 25%
Bodek-Yang parameter C_{V1u}	CV1uBY	± 30%
Bodek-Yang parameter C_{V2u}	CV2uBY	± 40%
Bodek-Yang parameter A_{HT} – shape only	AhtBYshape	± 25%
Bodek-Yang parameter B_{HT} – shape only	BhtBYshape	± 25%
Bodek-Yang parameter C_{V1u} – shape only	CV1uBYshape	± 30%
Bodek-Yang parameter C_{V2u} – shape only	CV2uBYshape	± 40%
Nu/Nubar CC cross section ration	RnubarnuCC	??
Coherent model M_A	MaCOHpi	± 40%
Coherent model R_0	R0COHpi	± 10%
Nuclear modifications to DIS	DISNuclMod	On/off
Fermi gas -> spectral function	CCQEMomDistroFGtoSF	On/off

GENIE model uncertainties (cont.)



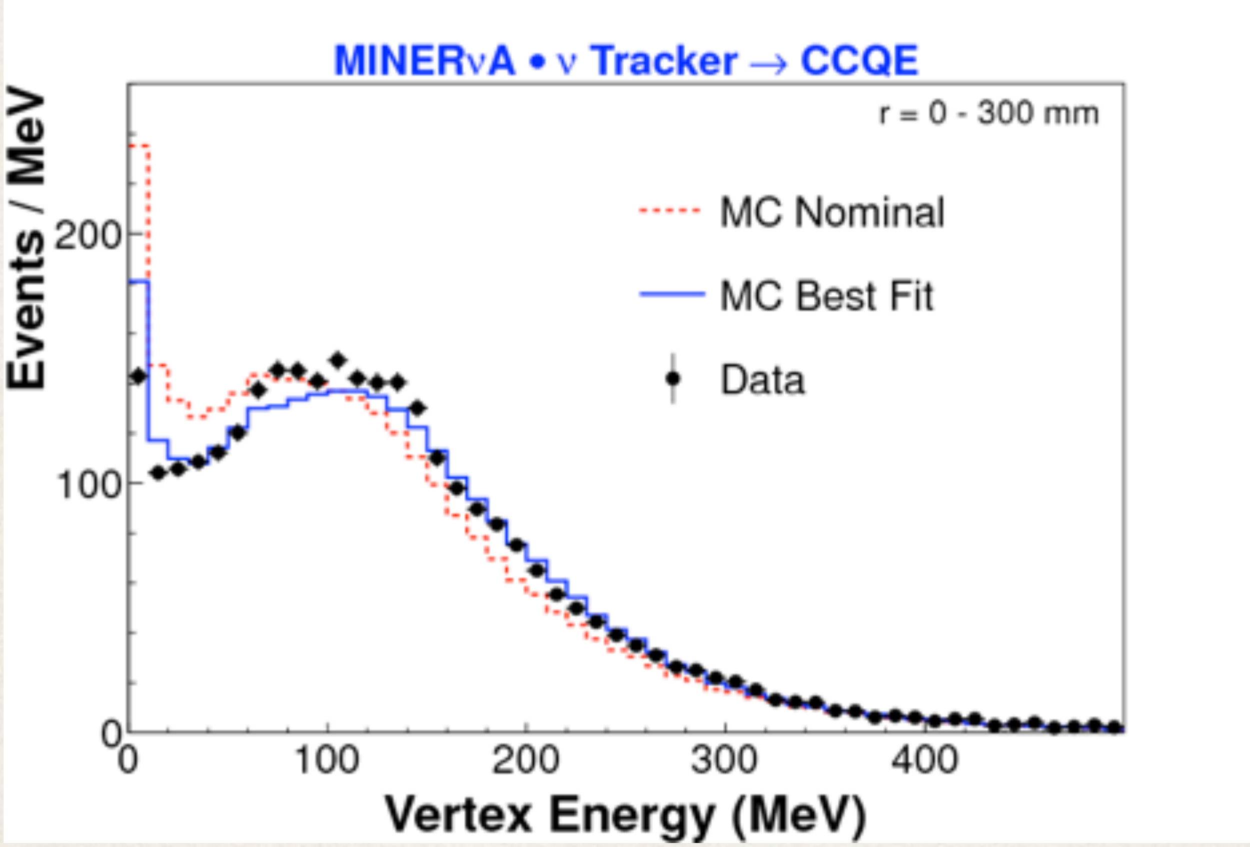
Uncertainty	GENIE Knob name	1 σ
Pion mean free path	MFP_pi	± 20%
Nucleon mean free path	MFP_N	± 20%
Pion fates – absorption	FrAbs_pi	± 30%
Pion fates – charge exchange	FrCEx_pi	± 50%
Pion fates – Elastic	FrElas_pi	± 10%
Pion fates – Inelastic	FrInel_pi	± 40%
Pion fates – pion production	FrPiProd_pi	± 20%
Nucleon fates – charge exchange	FrCEx_N	± 50%
Nucleon fates – Elastic	FrElas_N	± 30%
Nucleon fates – Inelastic	FrInel_N	± 40%
Nucleon fates – absorption	FrAbs_N	± 20%
Nucleon fates – pion production	FrPiProd_N	± 20%
AGKY hadronization model – x_F distribution	AGKYxF1pi	± 20%
Delta decay angular distribution	Theta_Delta2Npi	On/off
Resonance decay branching ratio to photon	RDecBR1gamma	± 50%

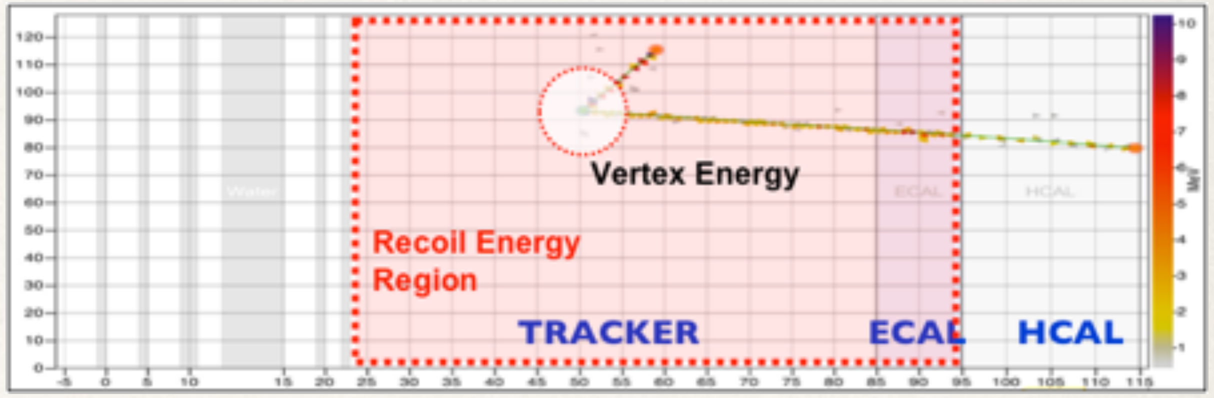


Uncertainty	GENIE Knob name	1 σ
AGKY hadronization model – pion p_T distribution	AGKYpT1pi	± 3%
Formation Zone	FormZone	± 50%
Resonance decay branching ratio to eta	RDecBR1eta	± 50%

Vertex energy - extra protons

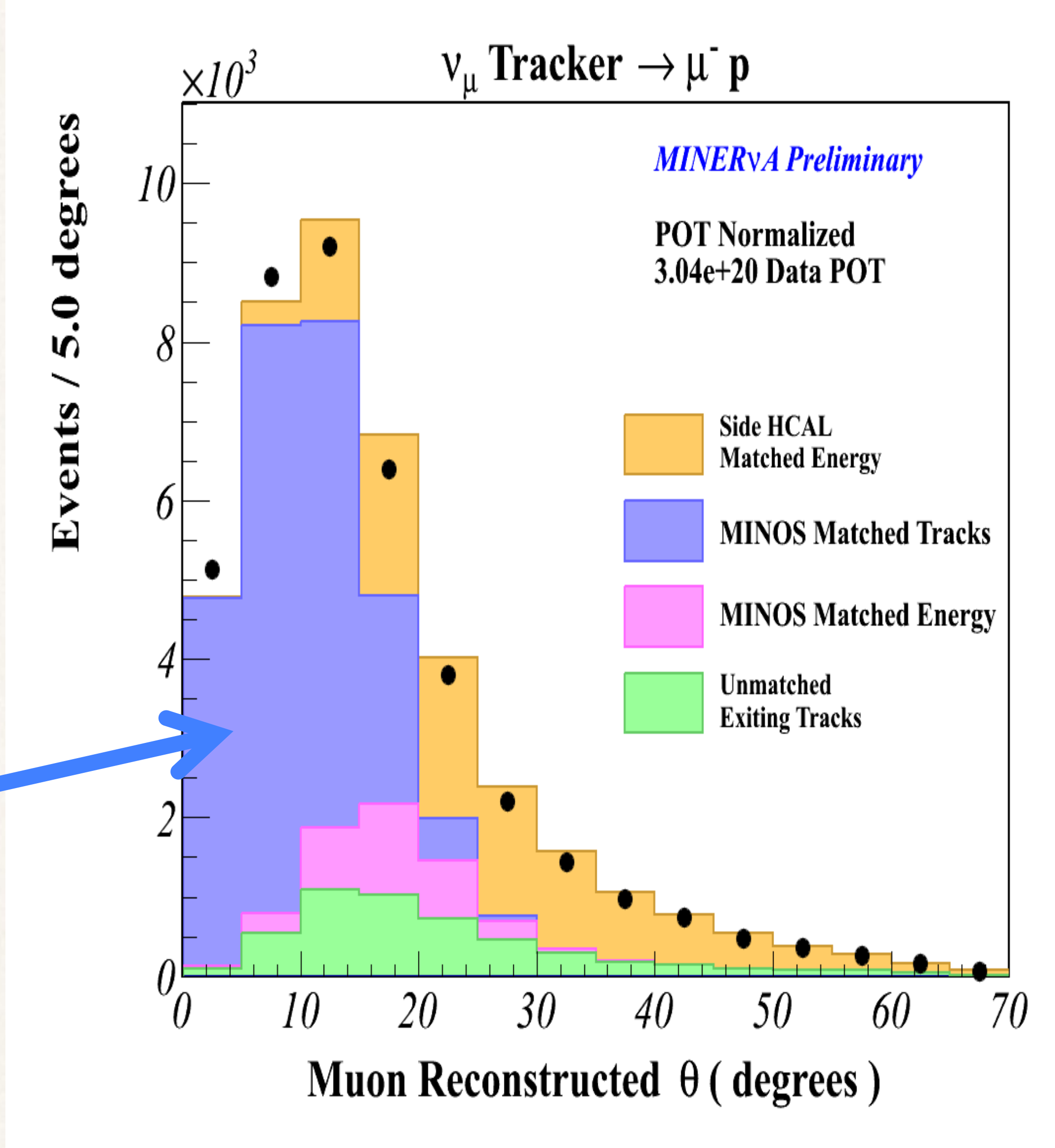
- If a neutrino interacts with a correlated pair the nucleon's,partner may also be ejected
- Recall that we neglected an **area around the vertex** when counting recoil energy
- We now compare the non-track energy deposited within that region to our Monte Carlo, to look for evidence of **additional nucleons**





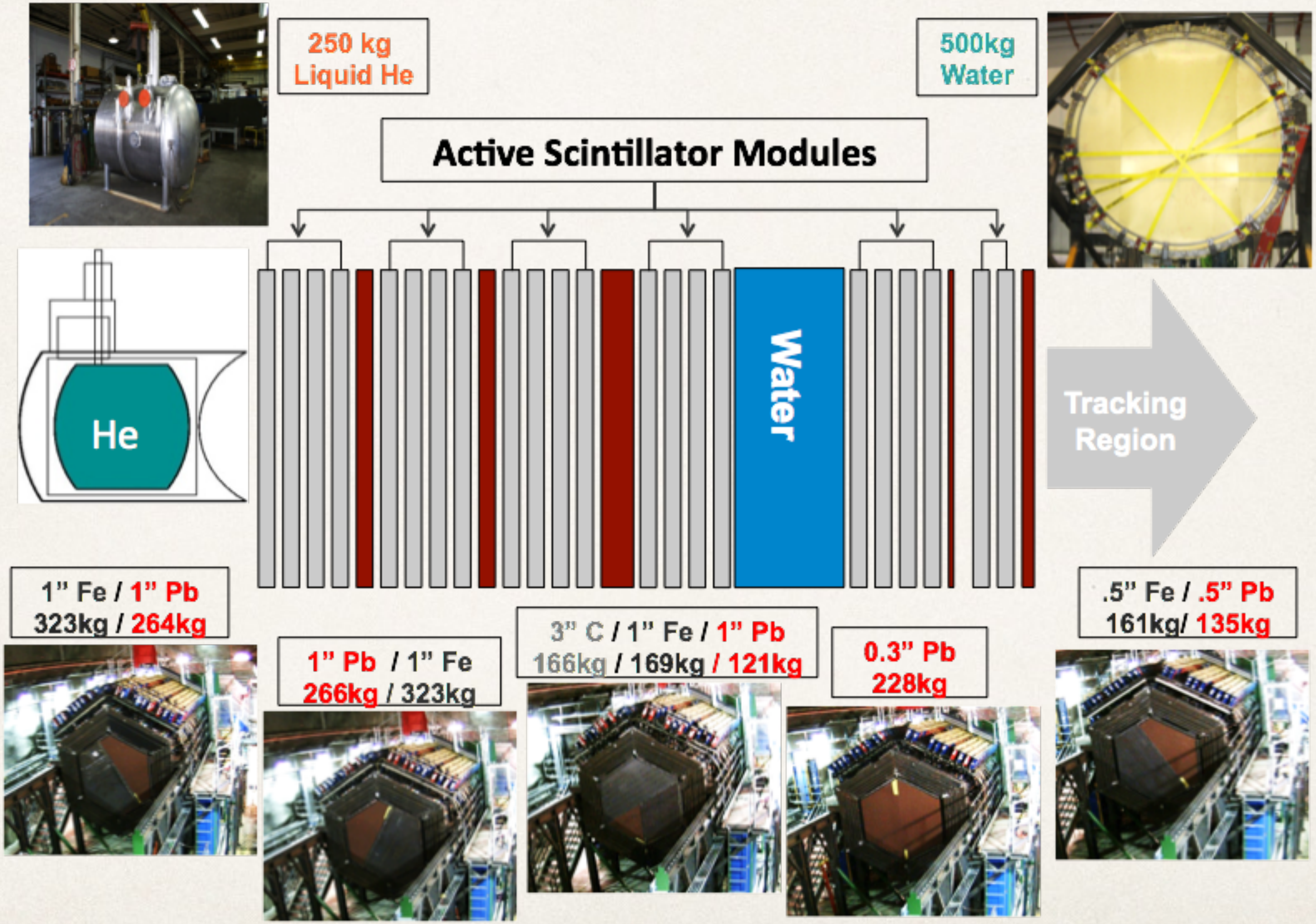
- A **harder neutrino-mode energy spectrum** is seen in data than Monte Carlo
- We simulated extra protons (<225 MeV) to see how this would change the Monte Carlo distribution
- Modeling an **additional proton 25±9%** of the time gave the best fit to the data
- Final state protons suggests initial state **proton-neutron correlations**
- This would explain why no such effect was seen for **antineutrino mode**; we would expect **low-energy neutrons**, to which we have low sensitivity

Acceptance: CCQE from protons



Only blue part is included in muon-kinematics study

MINERvA Nuclear targets



250 kg
Liquid He

500kg
Water

Active Scintillator Modules

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**

C. Patrick, MINERvA Collaboration

Our Monte Carlo: GENIE 2.6.2

Interaction models	**CCQE: axial form-factor**	Dipole with axial mass 0.99 GeV
	CCQE:Vector form-factors	BBBA05
	CCQE: Pseudoscalar form-factors	PCAC/Goldberger-Treiman
	Resonance and coherent	Rein-Seghal
	DIS	GRV94/GRV98 with Bodek-Yang
	DIS and QEL charm	*Kovalenko, Sov.J.Nucl.Phys.52:934 (1990)*
Nuclear effects	**Nuclear model**	RFG, Fermi momentum=225MeV, Pauli blocking, Bodek-Ritchie tail
	FSI modeling	INTRANUKE-hA *(S. Dytman, AIP Conf Proc, 896, pp. 178-184 (2007))*
	Hadronization model	AGKY – transitions between KNO-based and JETSET *T. Yang, AIP Conf. Proc.967:269-275 (2007)*
	Formation zone	SKAT

C. Andreopoulos, et al., NIM 288A, 614, 87 (2010)

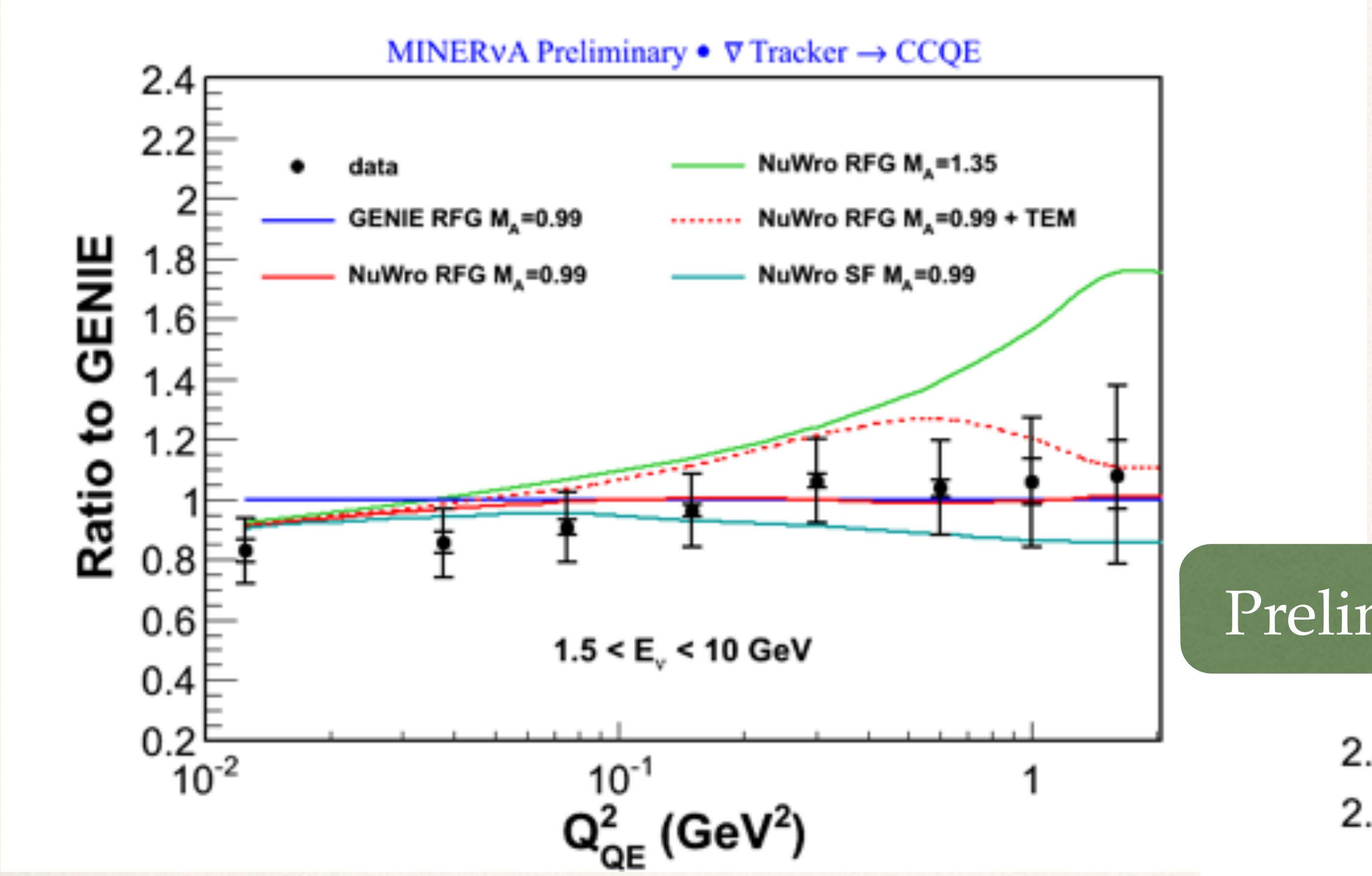
CCQE χ^2 for fits to antineutrino data

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	2.9	2.14
Shape χ^2/d.o.f	2.9	**0.66**	1.73	2.99

CCQE χ^2 for fits to neutrino data

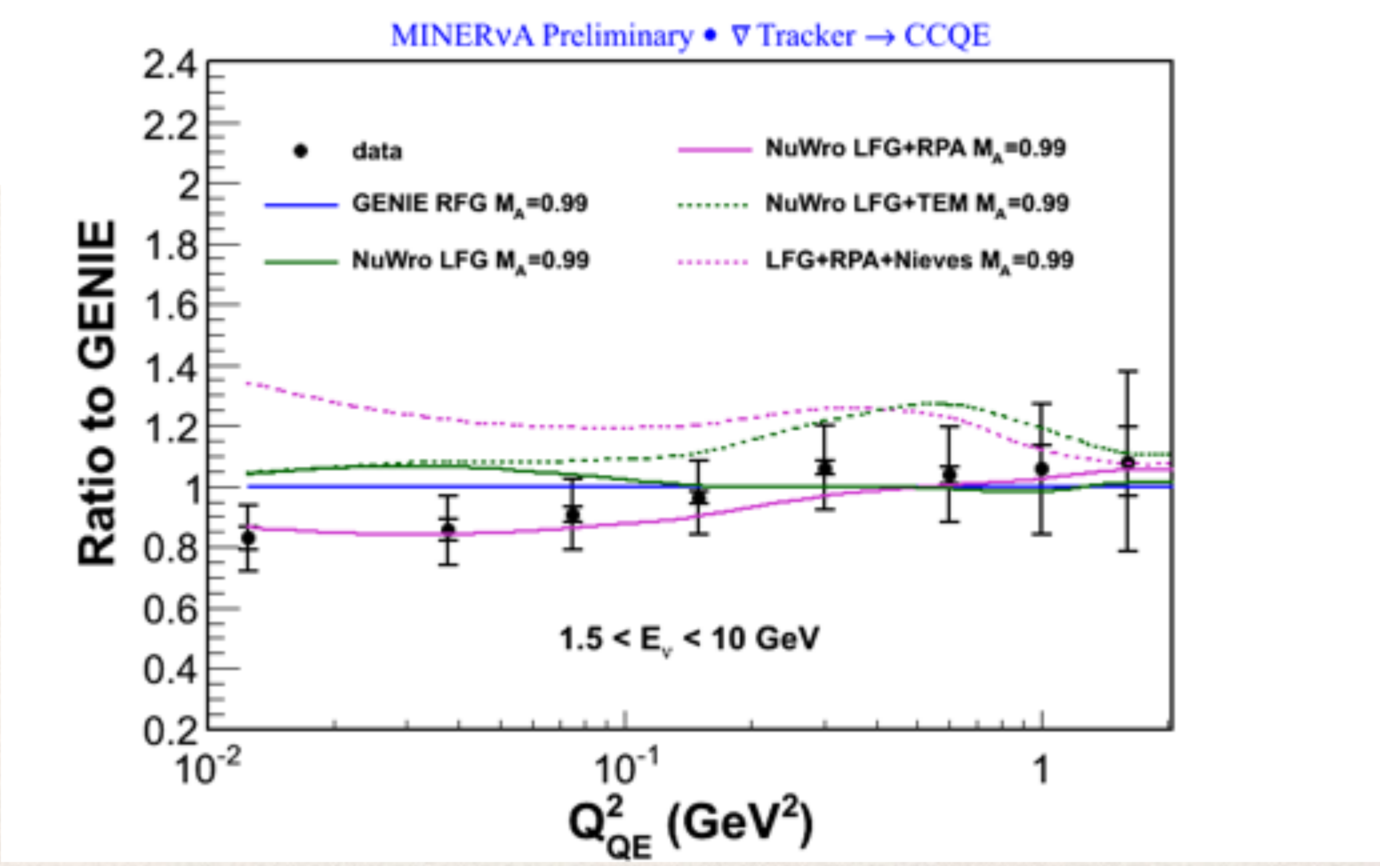
NuWro model	RFG	RFG +TEM	RFG	SF
M_A (GeV)	0.99	0.99	1.35	0.99
Rate χ^2/d.o.f	3.5	2.4	3.7	2.8
Shape χ^2/d.o.f	4.1	**1.7**	2.1	3.8

Rate model comparisons ($\bar{\nu}$)



- A preliminary reprocessing shown at NuInt 2014

Preliminary

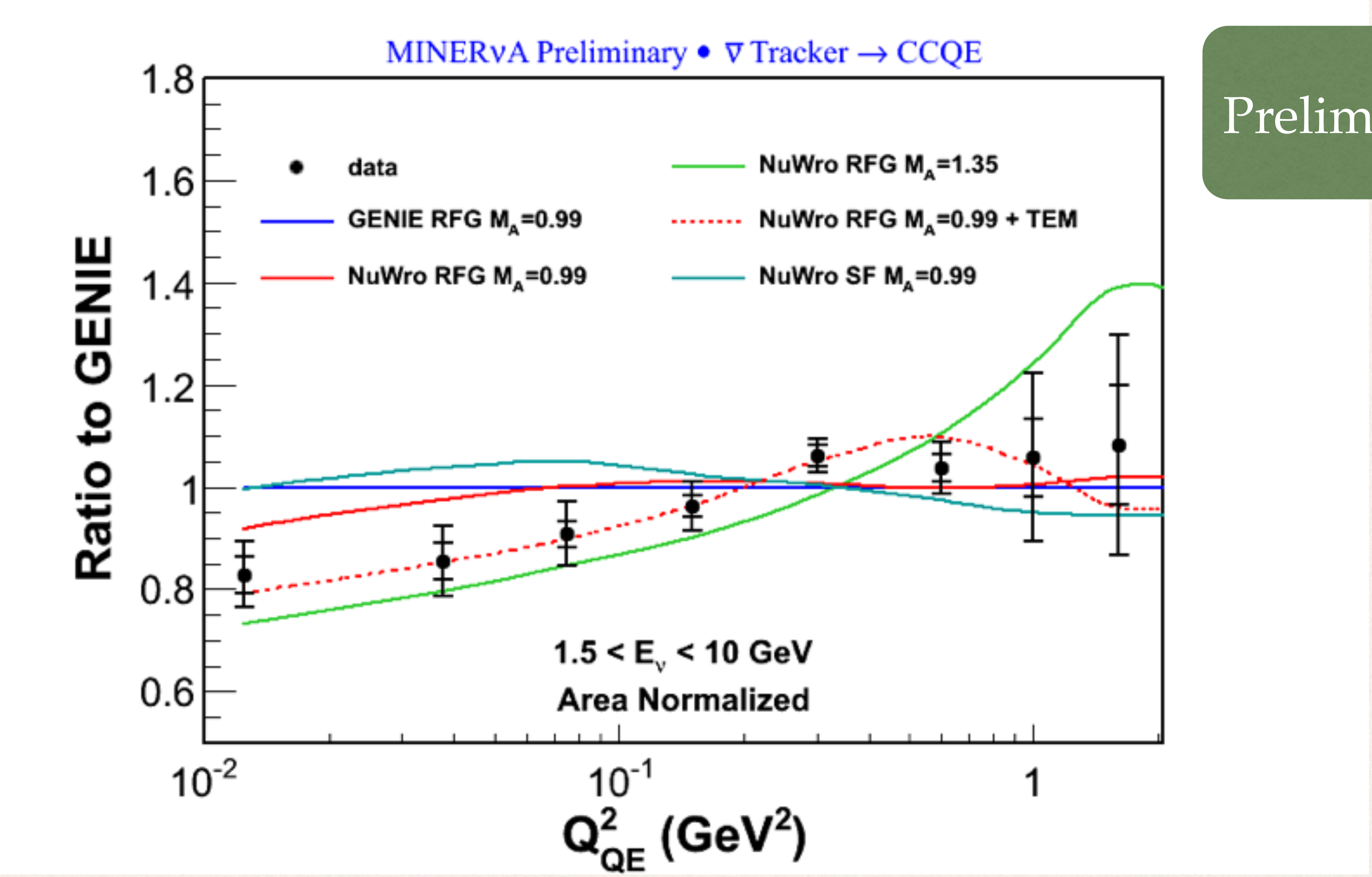


— GENIE RFG M_A=0.99
— NuWro RFG M_A=0.99
— NuWro RFG M_A=1.35
⋯ NuWro RFG M_A=0.99+TEM
— NuWro SF M_A=0.99

— NuWro LFG M_A=0.99
— NuWro LFG+RPA M_A=0.99
⋯ NuWro LFG+TEM M_A=0.99
⋯ NuWro LFG+RPA+Nieves M_A=0.99

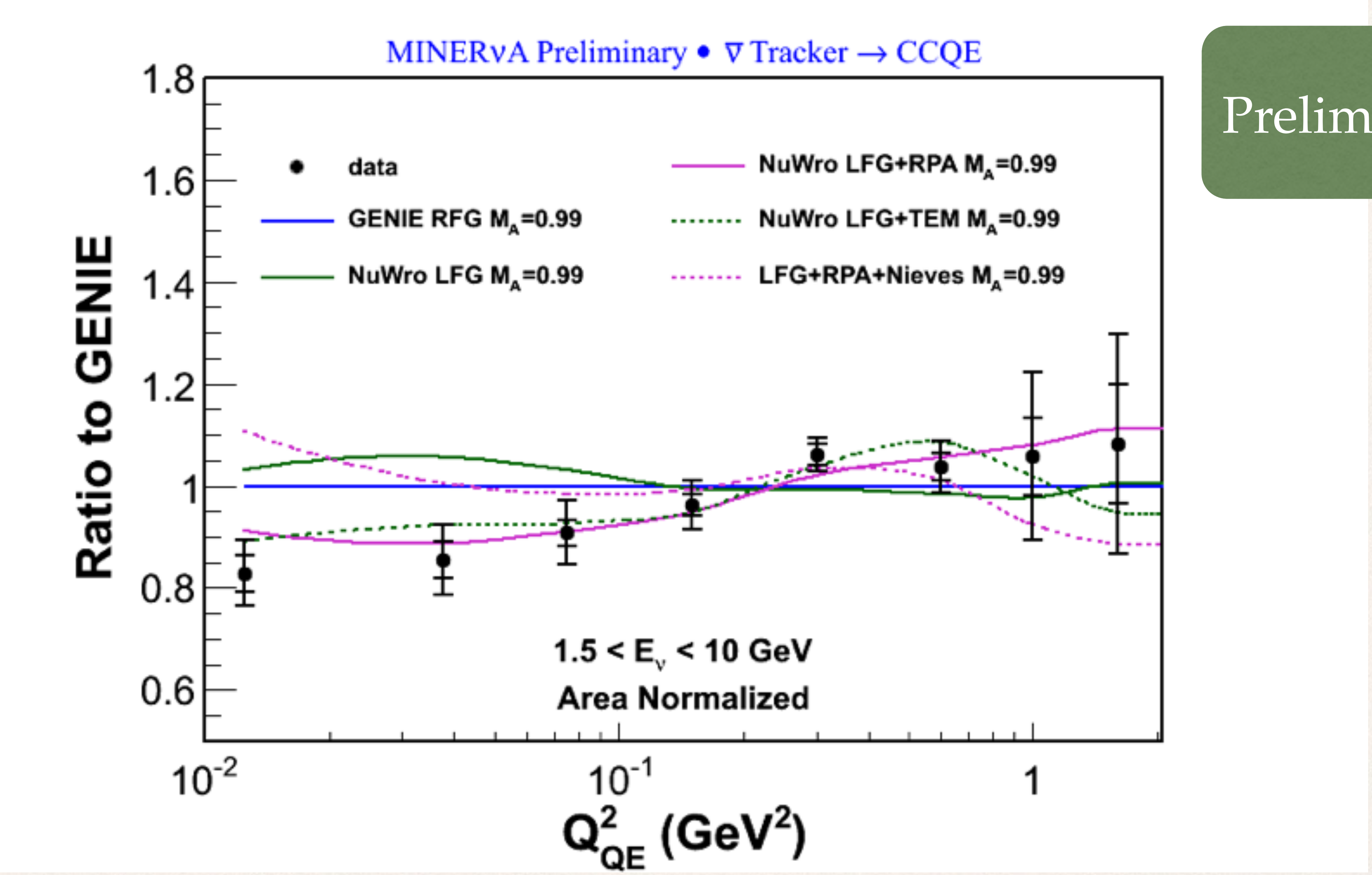
Antineutrino: shape-only ratio (RFG)

Preliminary



- A preliminary reprocessing shown at NuInt 2014

Antineutrino: shape-only ratio (LFG)



Preliminary

- A preliminary reprocessing shown at NuInt 2014

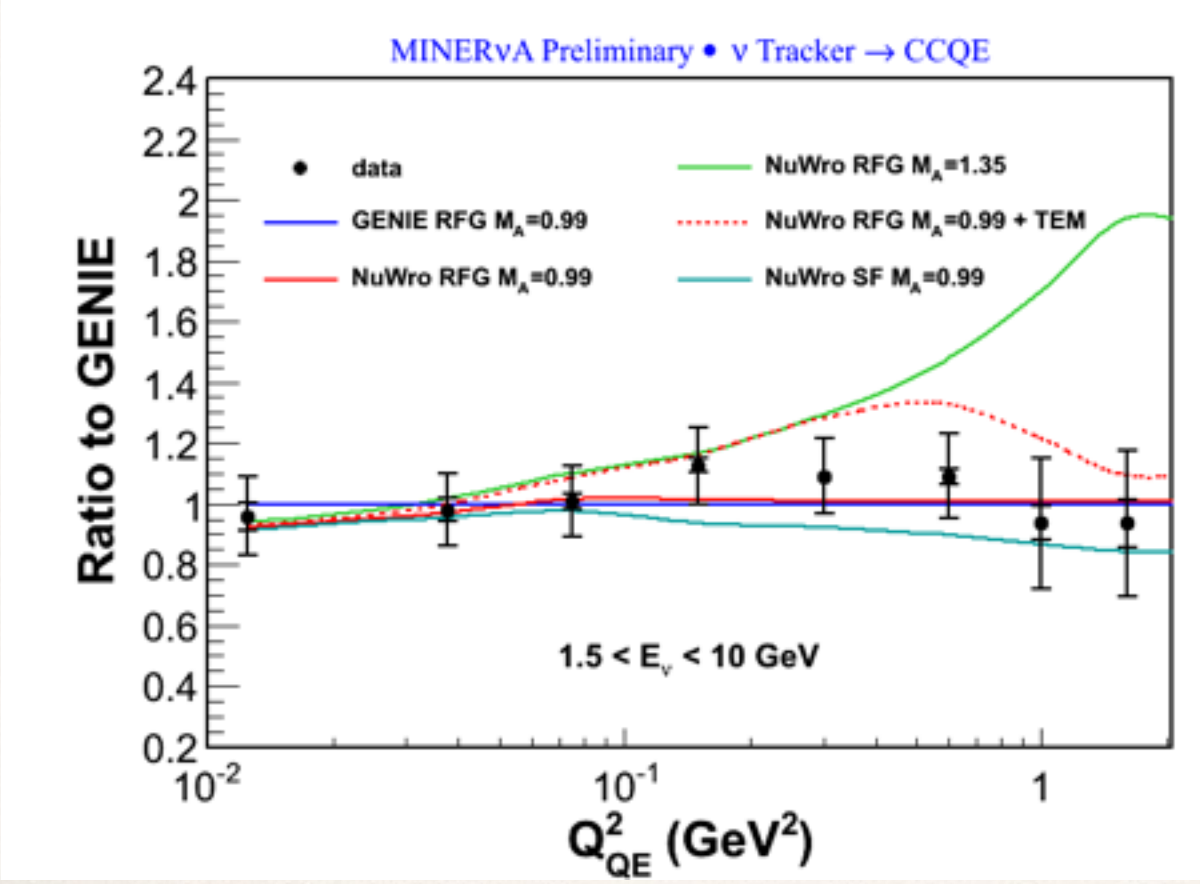
χ^2 for fits to antineutrino data

Preliminary

- A preliminary reprocessing shown at NuInt 2014

	Model	**Rate χ^2/d.o.f (8 degrees of freedom)**	**Shape χ^2/d.o.f (7 degrees of freedom)**
—	GENIE RFG M_A=0.99	2.2	2.44
—	NuWro RFG M_A=0.99	1.19	1.37
—	NuWro RFG M_A=1.35	1.98	1.27
┈	**NuWro RFG M_A=0.99 + TEM**	**0.667**	**0.447**
—	NuWro SF M_A=0.99	1.89	2.61
—	NuWro LFG M_A=0.99	3.61	3.97
—	**NuWro LFG + RPA M_A=0.99**	**0.771**	**0.953**
┈	**NuWro LFG + TEM M_A=0.99**	**1.54**	**1.09**
┈	NuWro LFG + RPA + Nieves M_A=0.99	7.06	4.63

Rate model comparisons (ν)

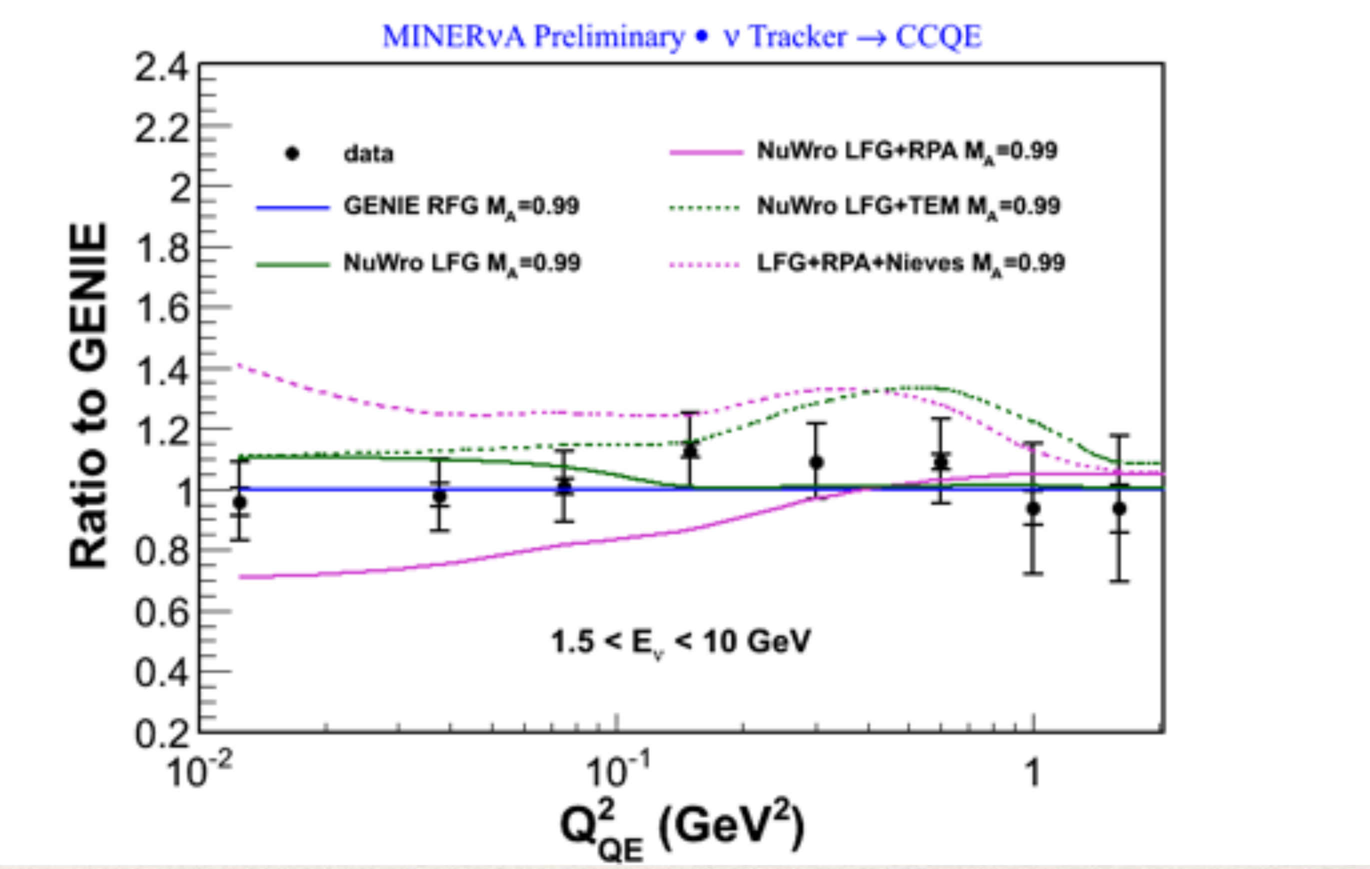


- A preliminary reprocessing shown at NuInt 2014

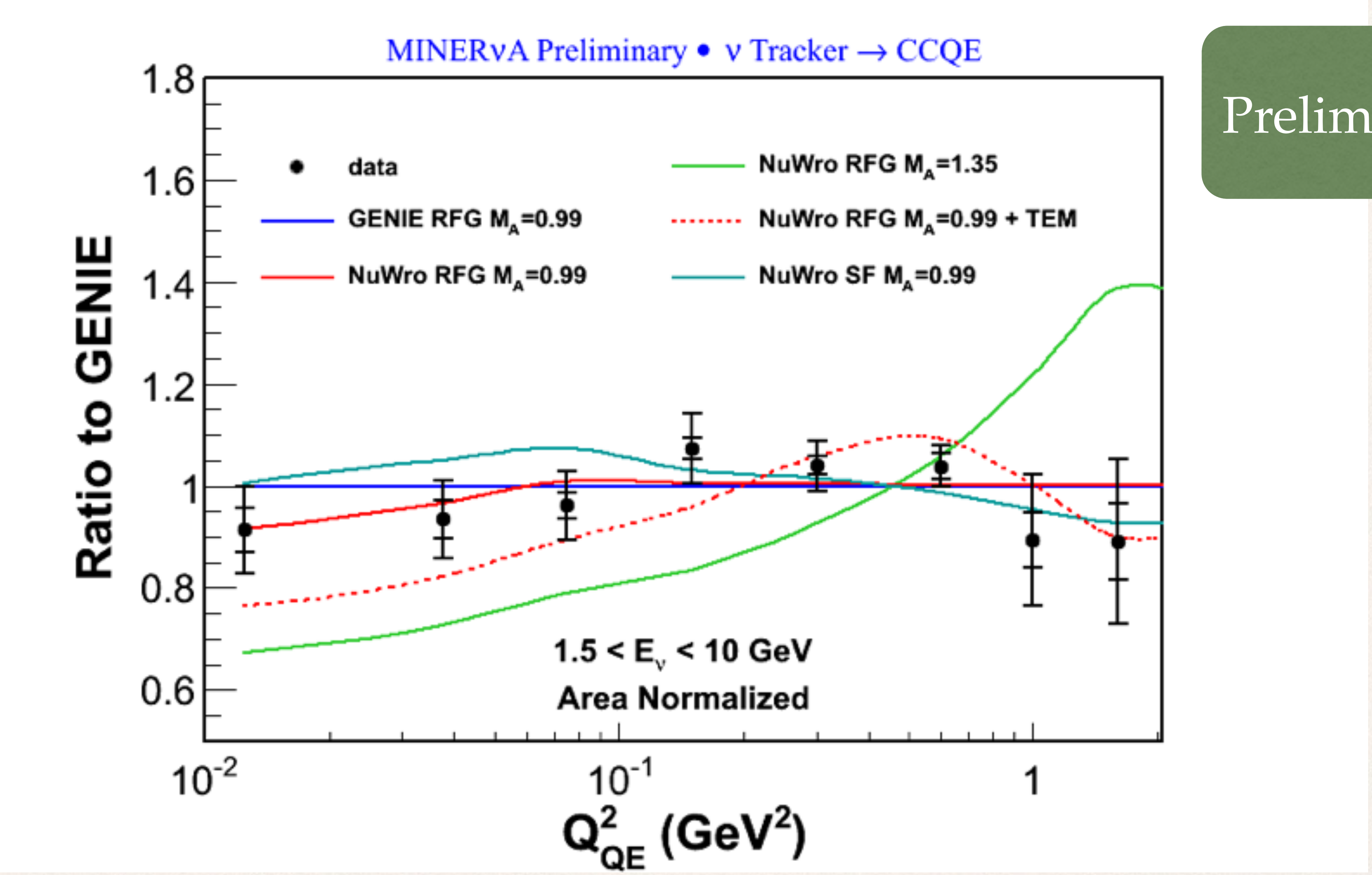
Preliminary

- GENIE RFG M_A=0.99
- NuWro RFG M_A=0.99
- NuWro RFG M_A=1.35
- NuWro RFG M_A=0.99+TEM
- NuWro SF M_A=0.99

- NuWro LFG M_A=0.99
- NuWro LFG+RPA M_A=0.99
- NuWro LFG+TEM M_A=0.99
- NuWro LFG+RPA+Nieves M_A=0.99



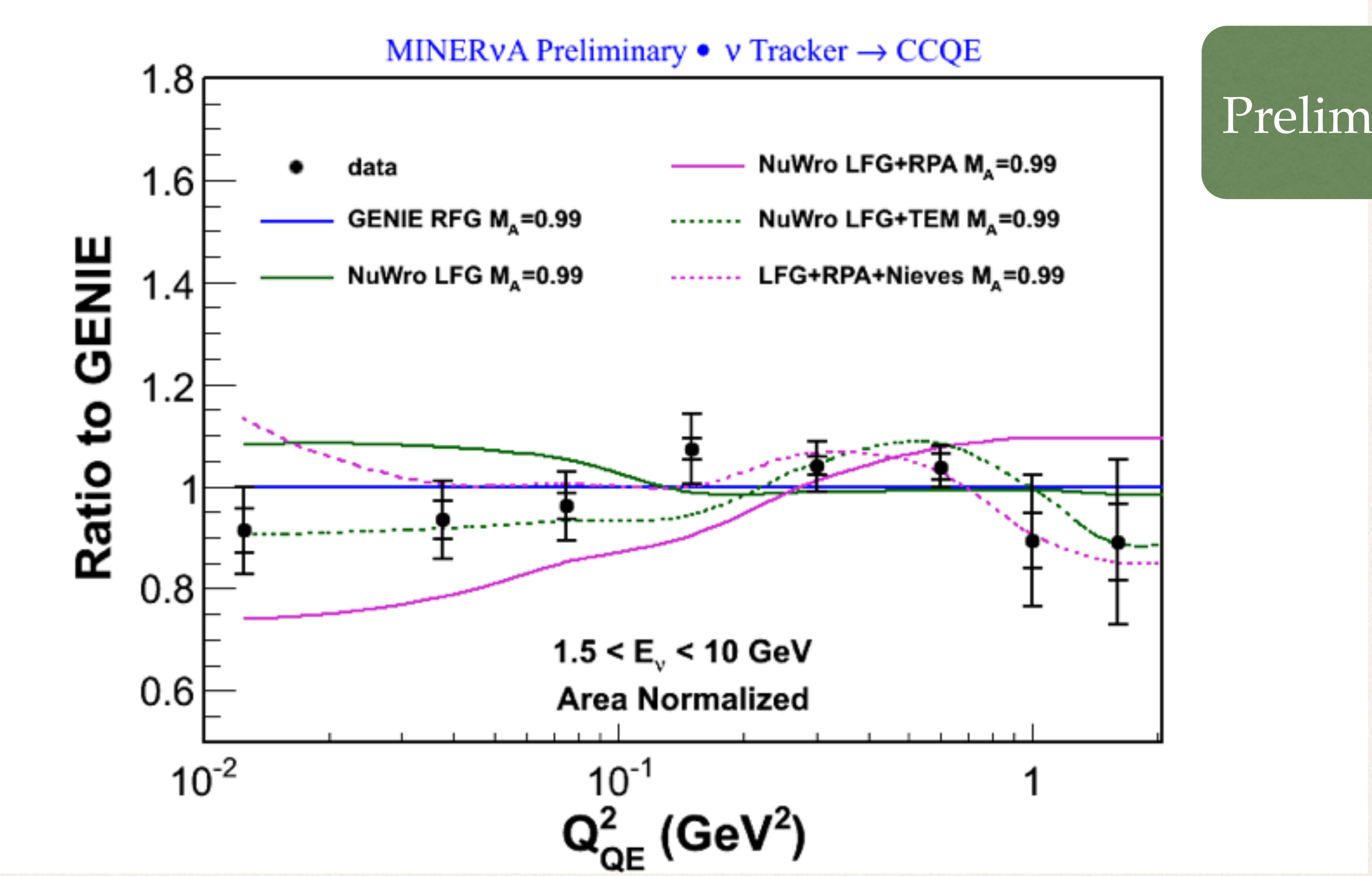
Neutrino: shape-only ratio (RFG)



Preliminary

- A preliminary reprocessing shown at NuInt 2014

Neutrino: shape-only ratio (LFG)



Preliminary

- A preliminary reprocessing shown at NuInt 2014

χ^2 for fits to neutrino data

Preliminary

- A preliminary reprocessing shown at NuInt 2014

	Model	**Rate χ^2/d.o.f (8 degrees of freedom)**	**Shape χ^2/d.o.f (7 degrees of freedom)**
—	GENIE RFG M_A=0.99	1.86	2.06
—	**NuWro RFG M_A=0.99**	**1.47**	**1.66**
—	NuWro RFG M_A=1.35	3.38	1.99
┈	NuWro RFG M_A=0.99 + TEM	2.92	2.26
—	NuWro SF M_A=0.99	2.64	3.43
—	NuWro LFG M_A=0.99	4.77	5.3
—	**NuWro LFG + RPA M_A=0.99**	**1.73**	**1.83**
┈	NuWro LFG + TEM M_A=0.99	3.53	2.75
┈	NuWro LFG + RPA + Nieves M_A=0.99	5.49	4.1

χ^2 for $\bar{\nu}$ and ν rates, combined

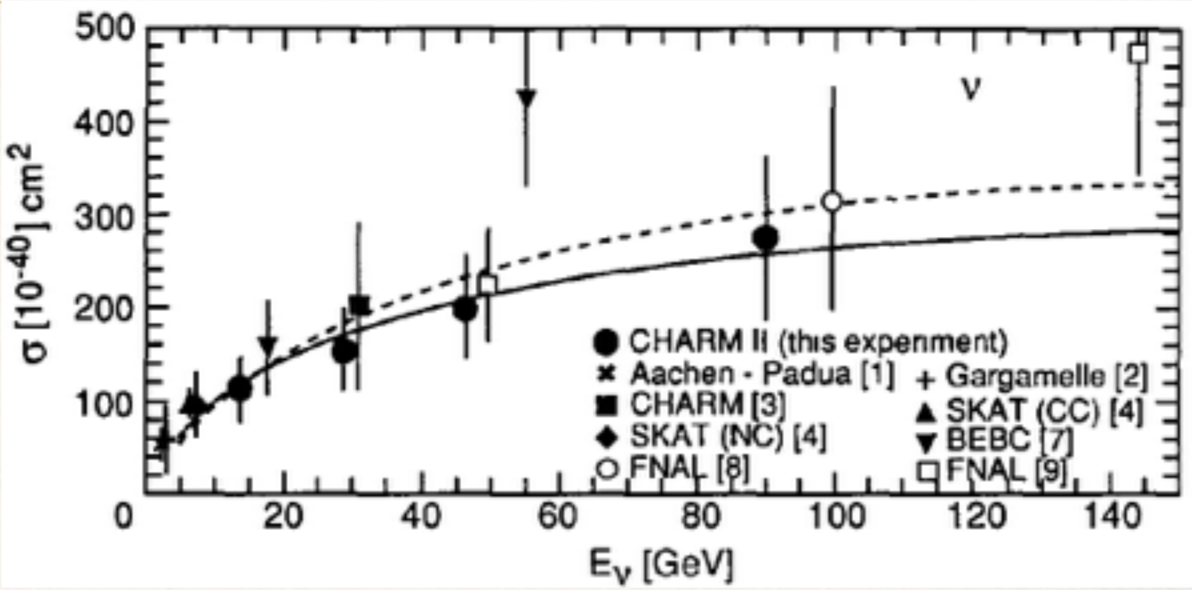
Preliminary

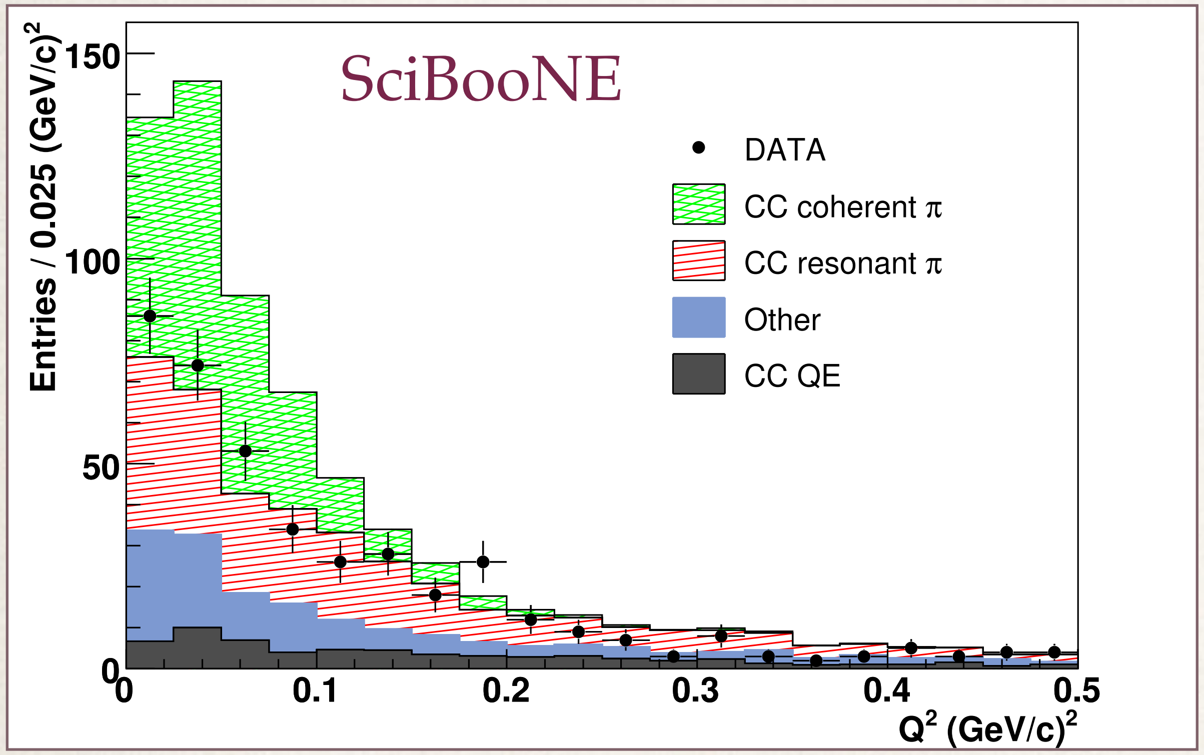
- A preliminary reprocessing shown at NuInt 2014

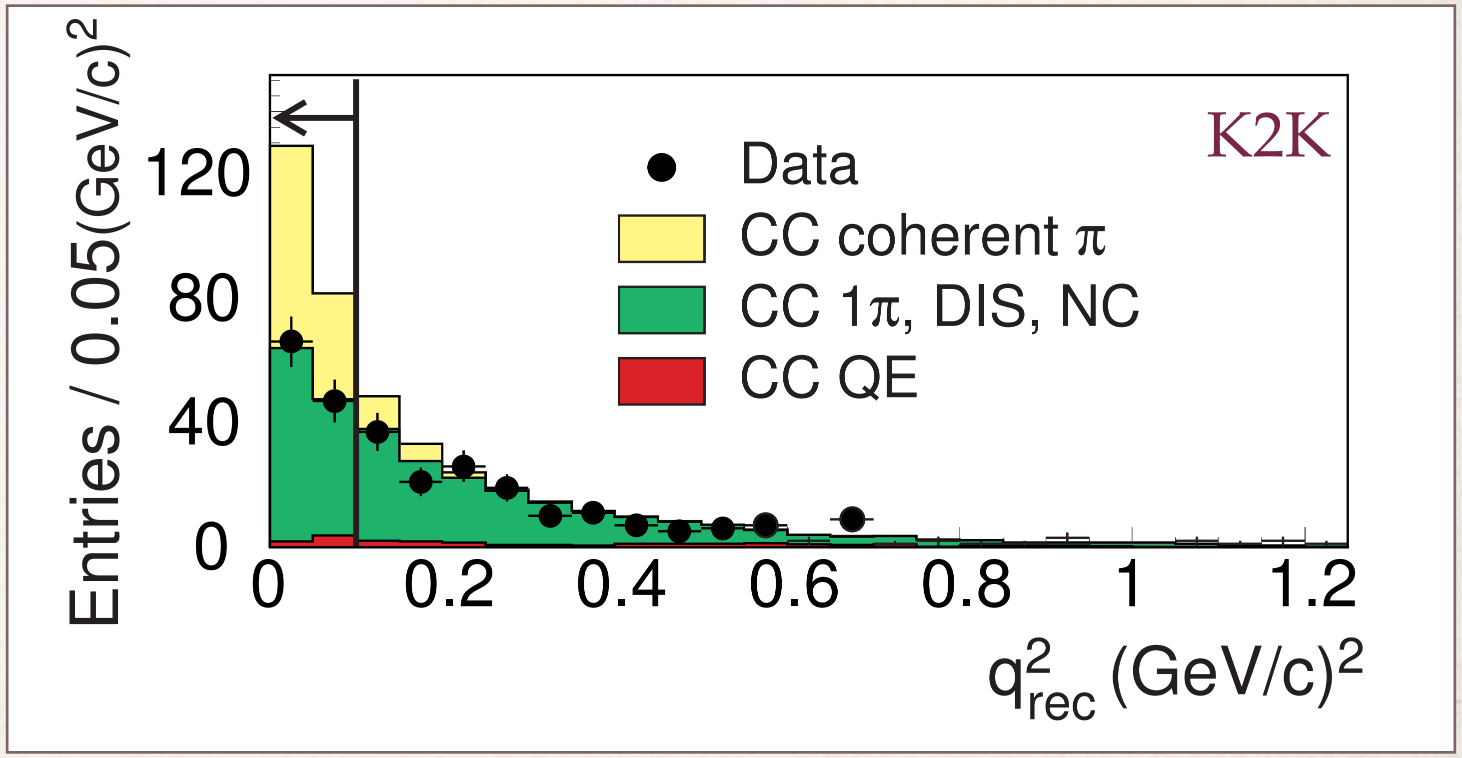
	Model	**Combined rate χ^2/d.o.f (16 degrees of freedom)**
—	GENIE RFG M_A=0.99	2.04
—	**NuWro RFG M_A=0.99**	**1.53**
—	NuWro RFG M_A=1.35	3.14
⋯	**NuWro RFG M_A=0.99 + TEM**	**1.92**
—	NuWro SF M_A=0.99	2.22
—	NuWro LFG M_A=0.99	3.88
—	**NuWro LFG + RPA M_A=0.99**	**1.93**
⋯	NuWro LFG + TEM M_A=0.99	2.59
⋯	NuWro LFG + RPA + Nieves M_A=0.99	5.79

Coherent pion production: I

- Early experiments at high energies see clear evidence of coherent pion production (scattering without breaking up the nucleus)

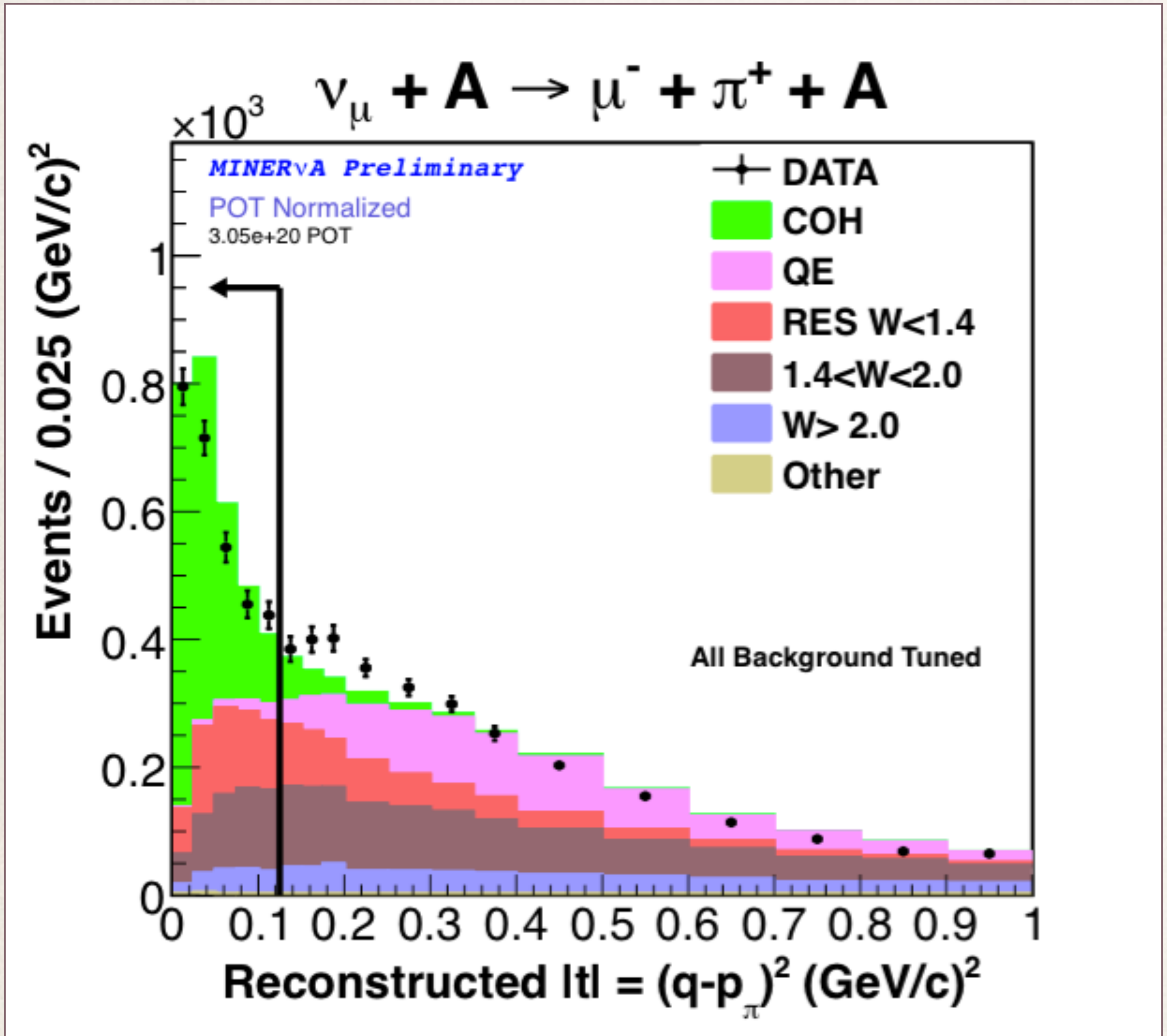






- Lower energy experiments saw results consistent with NEUT's background predictions

Coherent pion production: II



A Higuera, A Mislevic et al., Phys. Rev. Lett. 113, 261802 (2014)

- MINERvA sees clear evidence of coherent scattering in the few-GeV energy region
- Our ability to measure the quality |t| enables us to identify coherent candidates in a model-independent way
- The slope of the |t| distribution is related to the size of the target, so it is easy to distinguish scattering off a nucleus from a nucleon