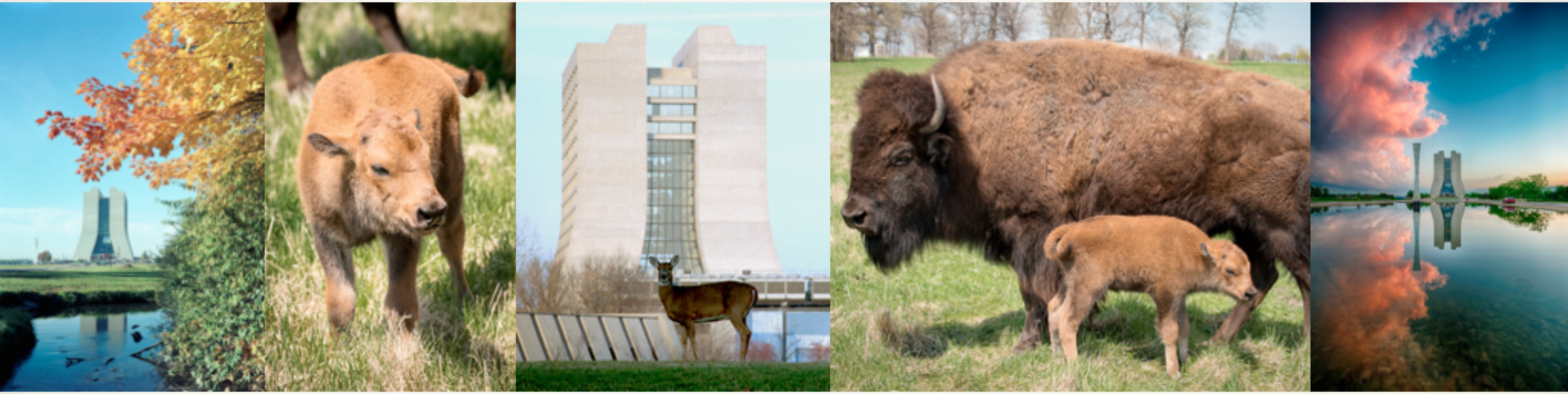


Recent results from MINERvA

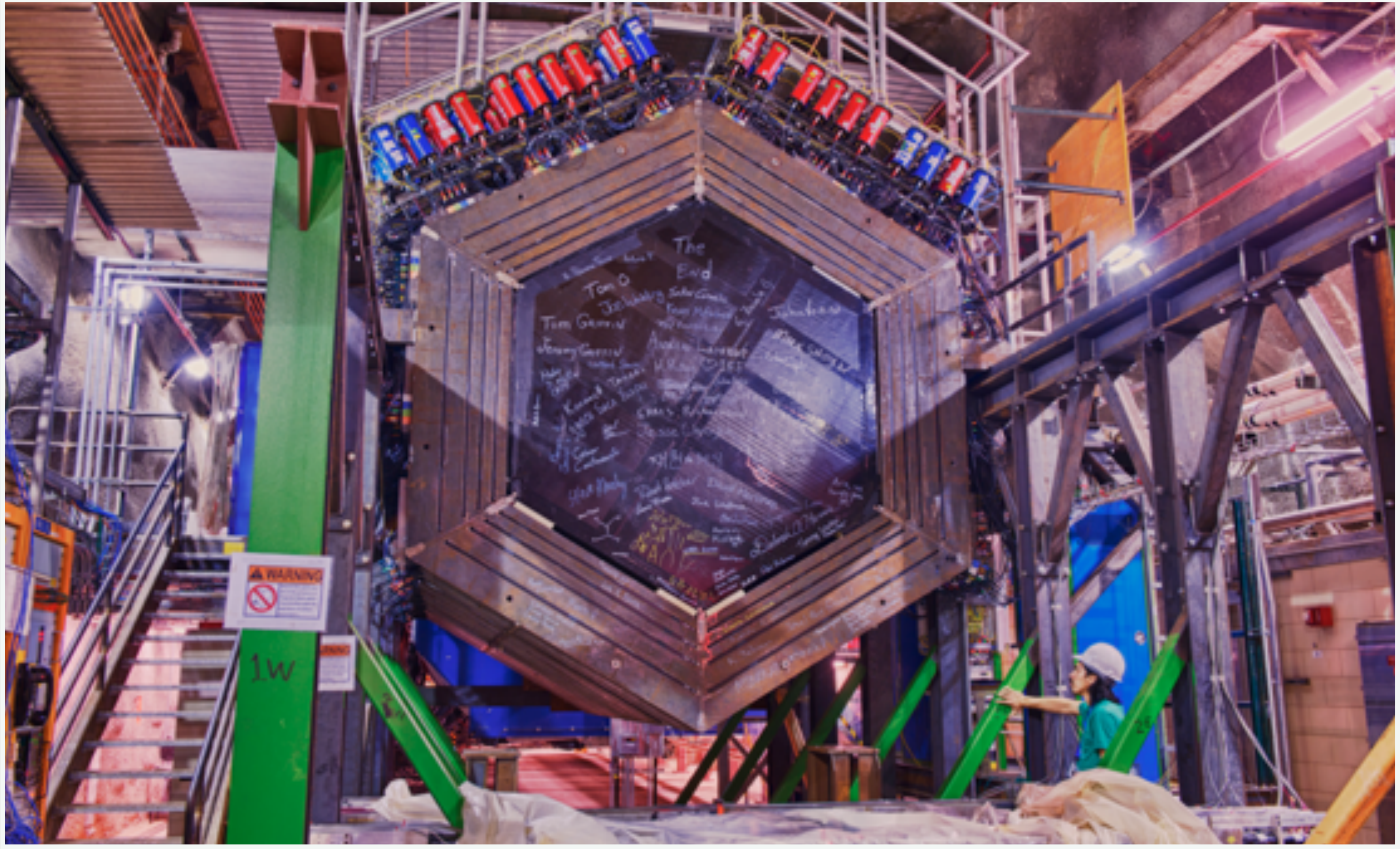
Cheryl Patrick, Northwestern University, USA

I.P.A. 2015, Madison, May 4-6, 2015

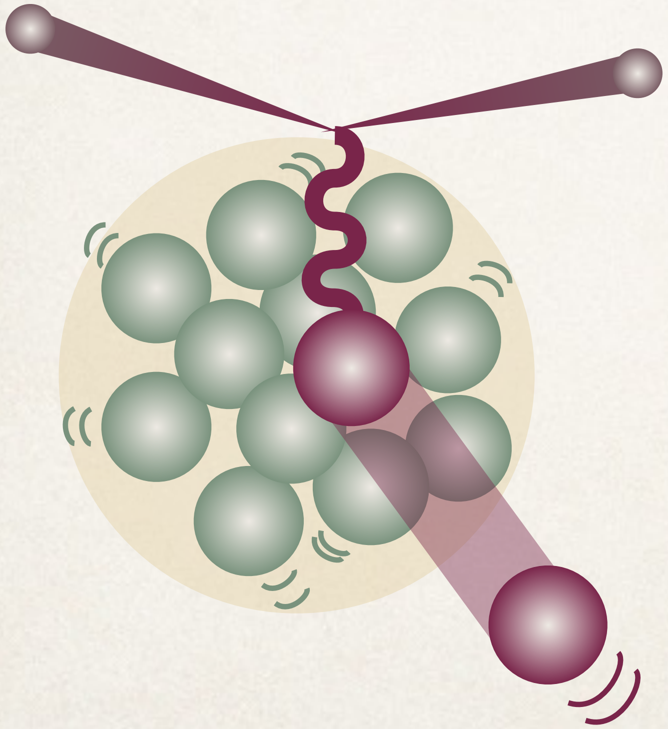
About MINERvA

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



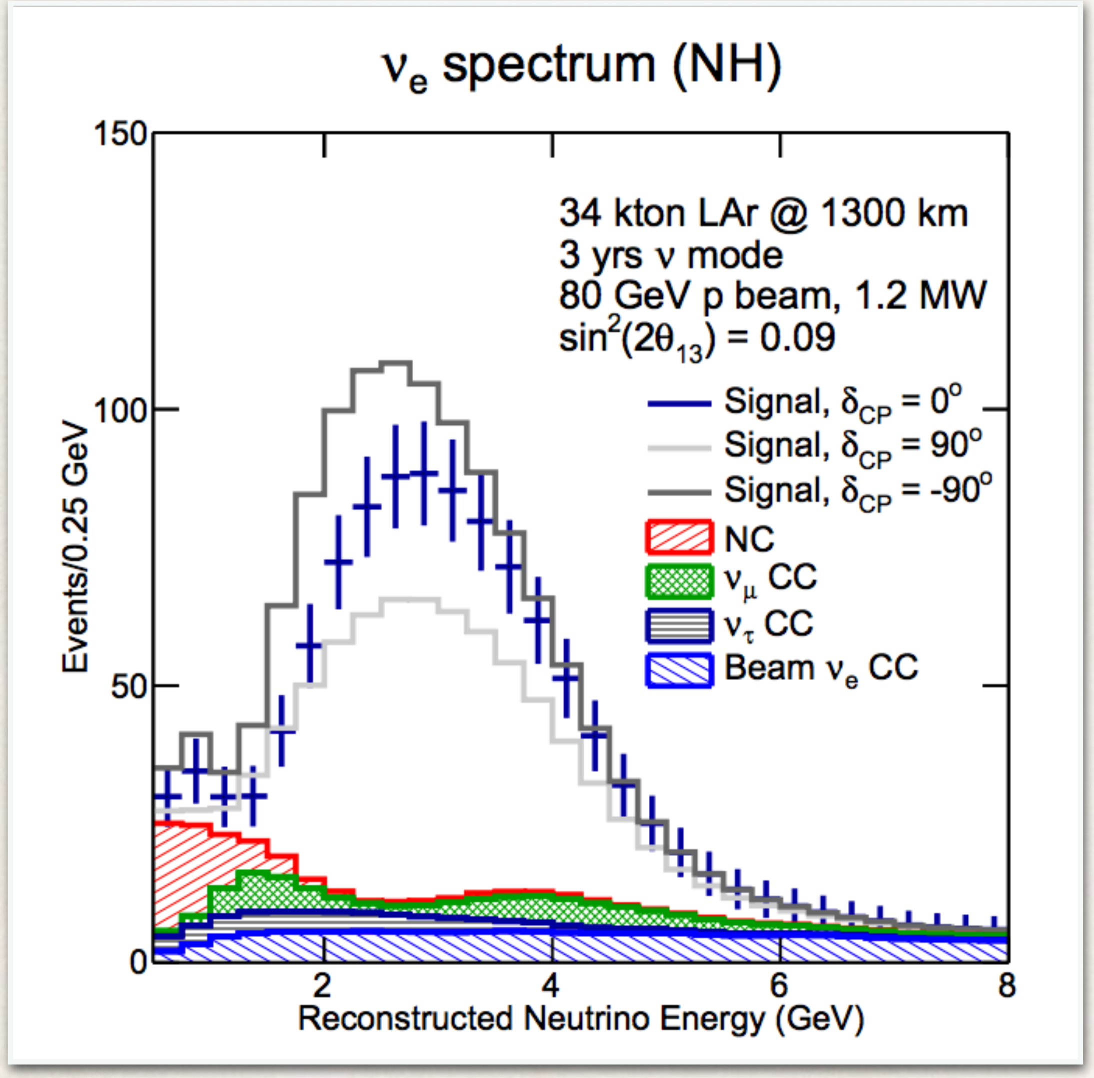
Photograph: Reidar Hahn, Fermilab visual media services



- 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 reduce systematics for **oscillation experiments**

The importance of cross sections

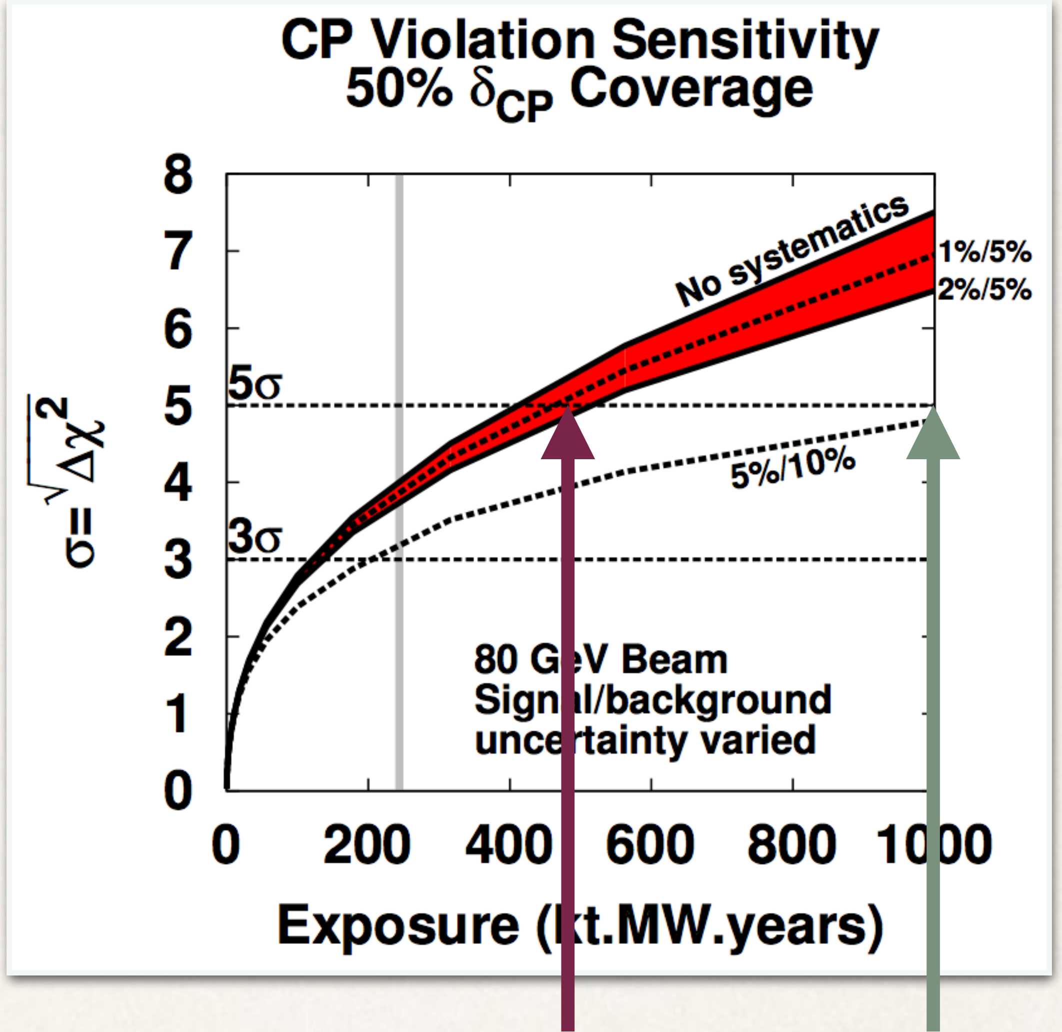
Oscillation experiments compare event rates with predictions to determine parameters such as δ_{CP}



DUNE signal predictions

arXiv 1307.7335

DUNE δ_{CP} sensitivity for different systematic uncertainties



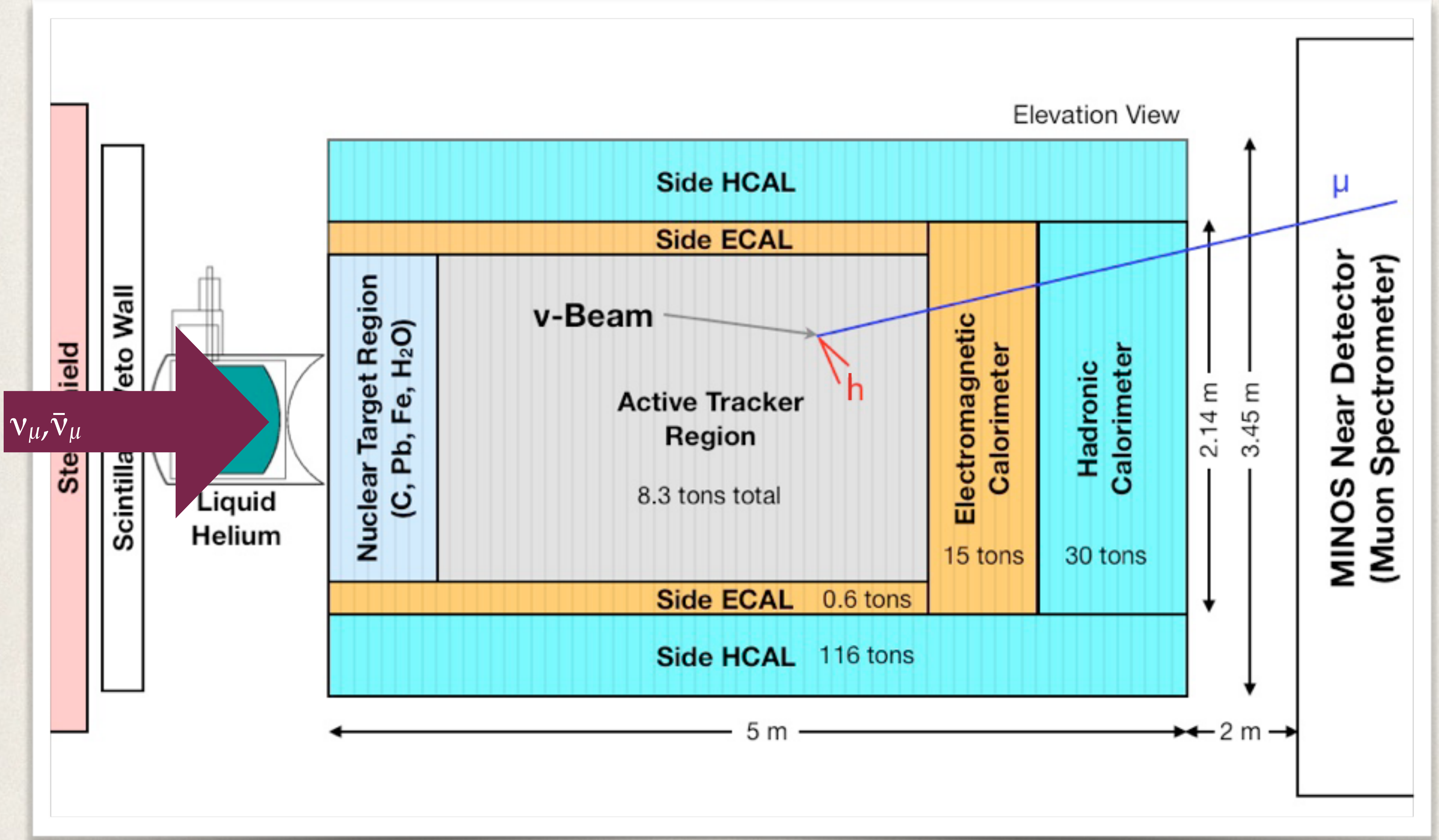
M. Bass, NuInt 2014

Run for 10 years **25 years**

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

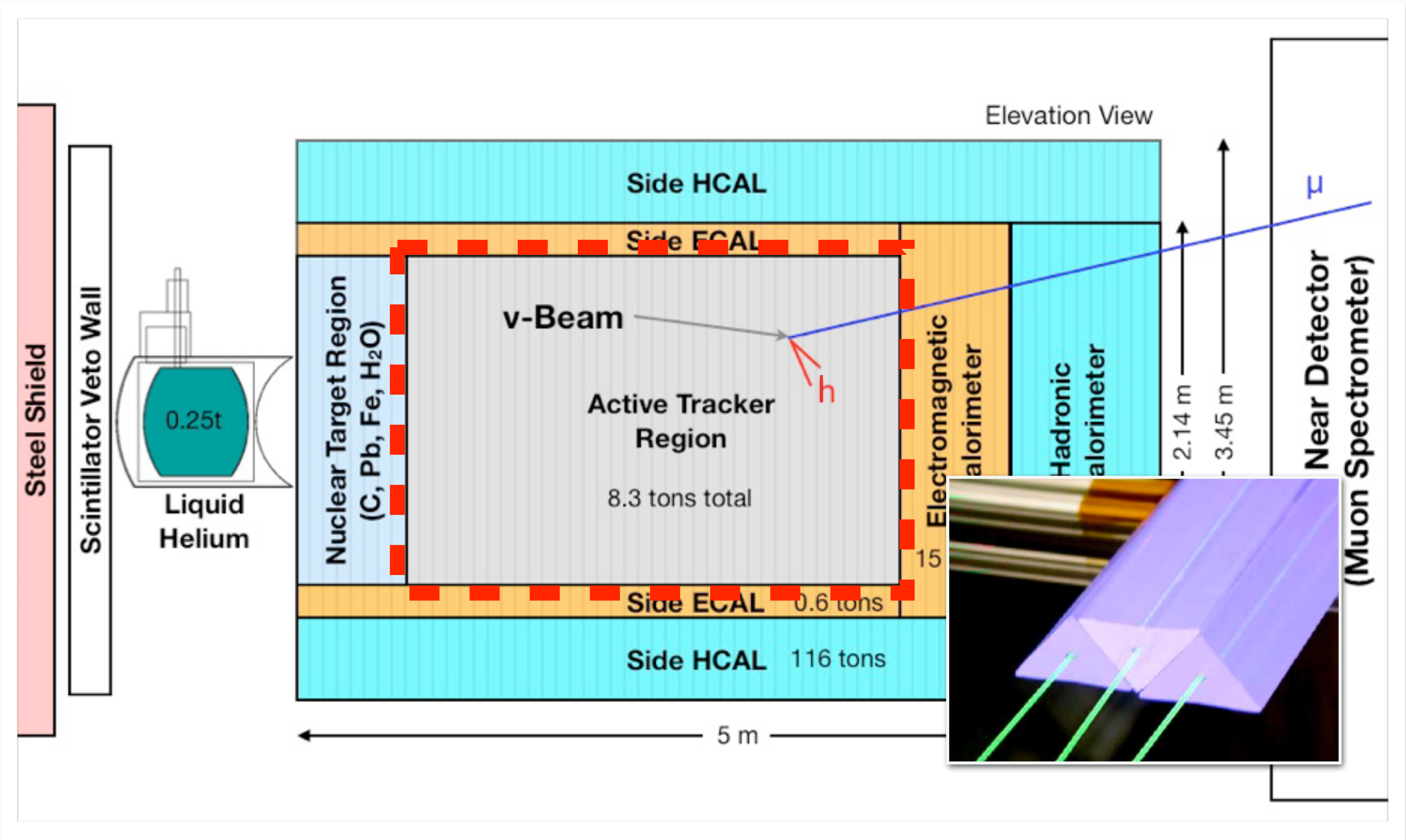
MINERvA can reduce the uncertainties!

MINERvA detector



All photographs: Reidar Hahn, Fermilab visual media services

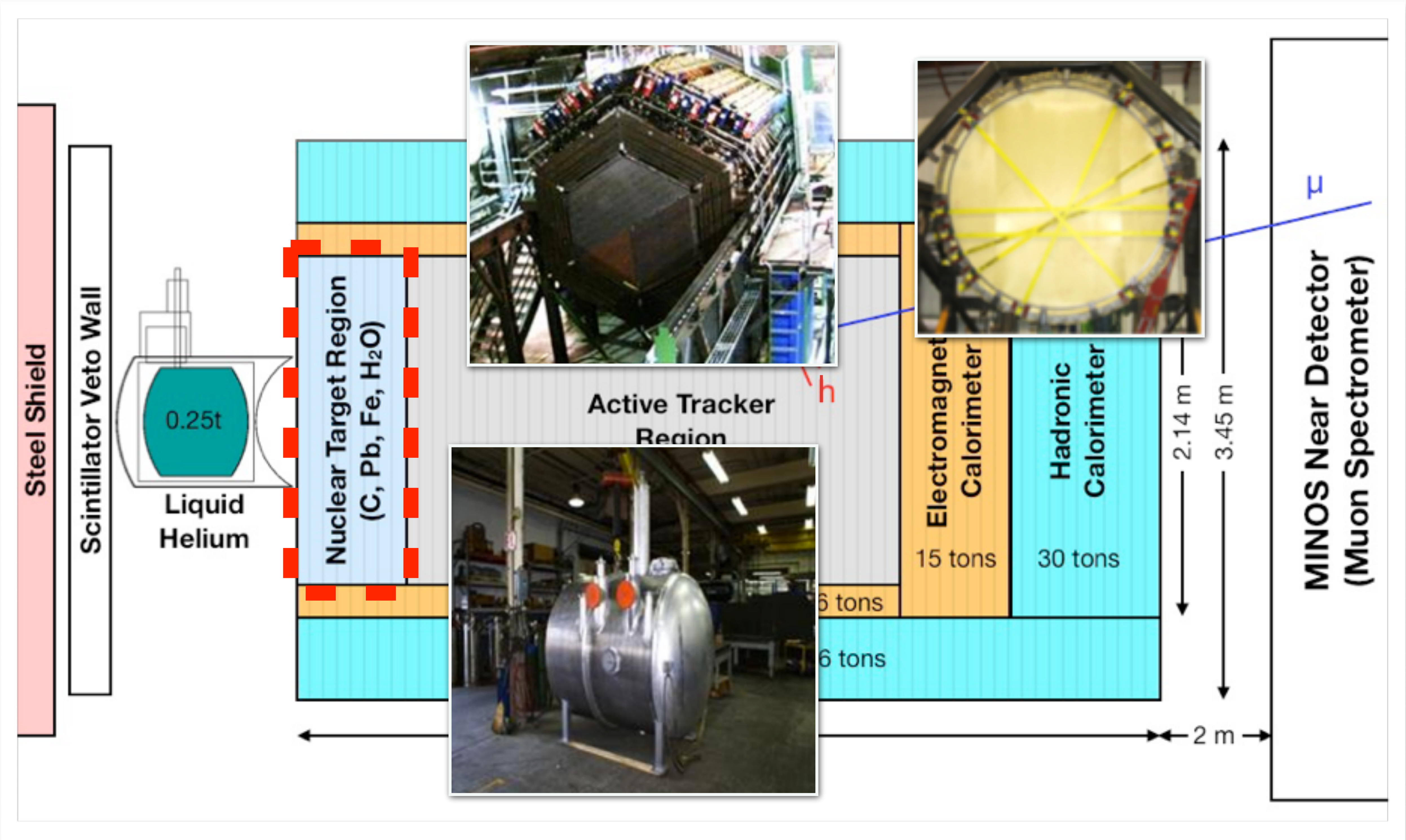
MINERvA detector



All photographs: Reidar Hahn, Fermilab visual media services

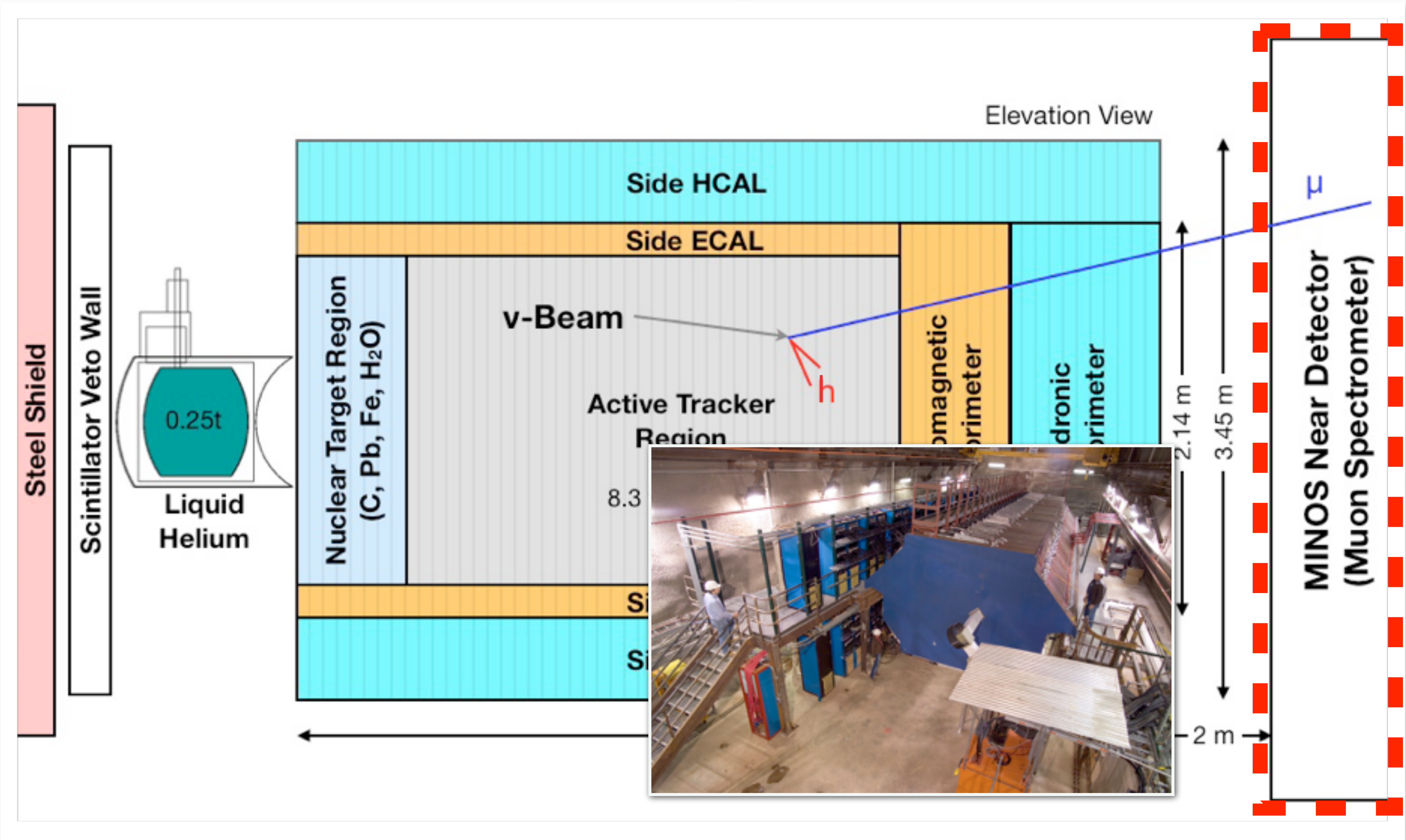
C. Patrick, MINERvA Collaboration

MINERvA detector



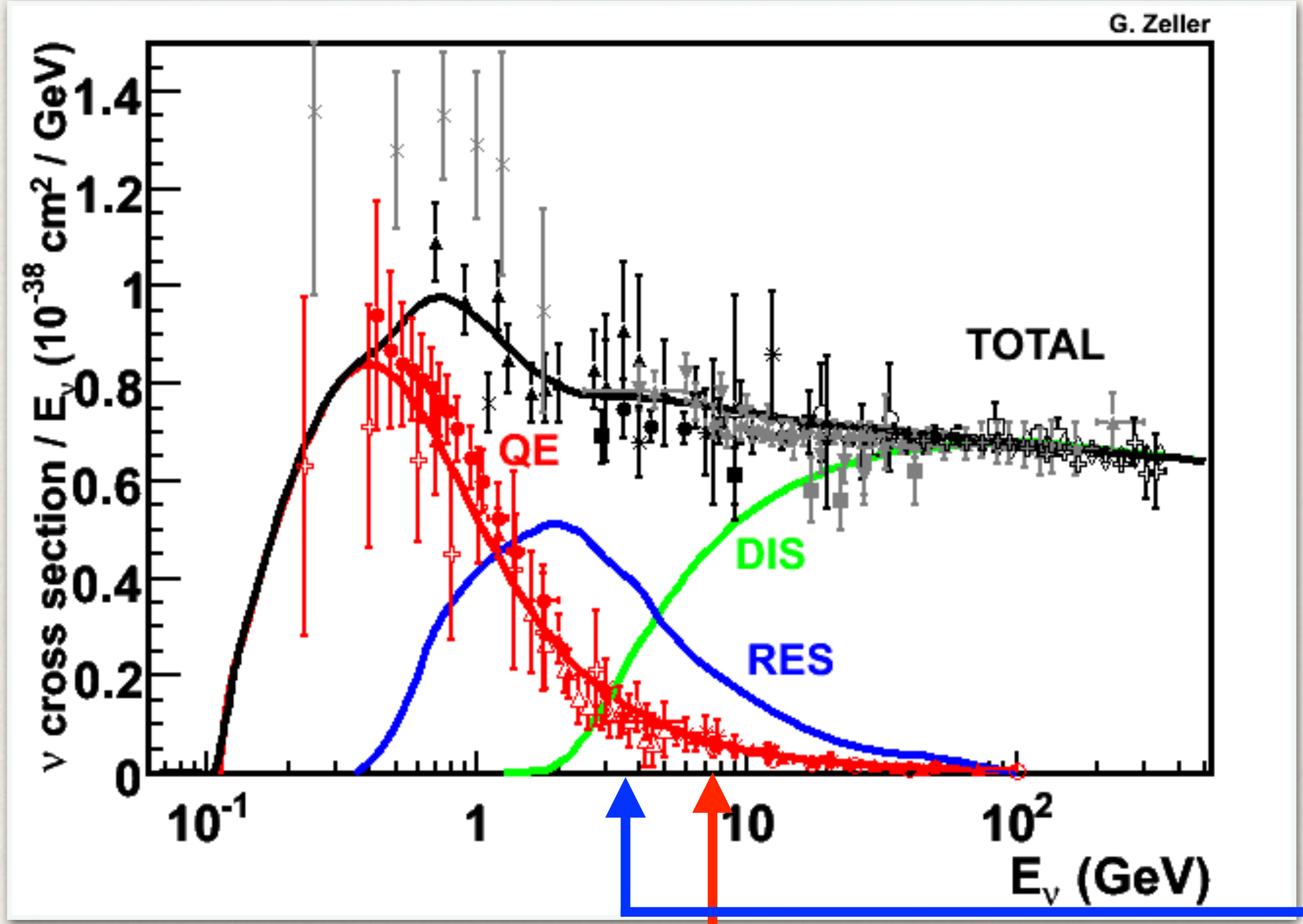
All photographs: Reidar Hahn, Fermilab visual media services

MINERvA detector

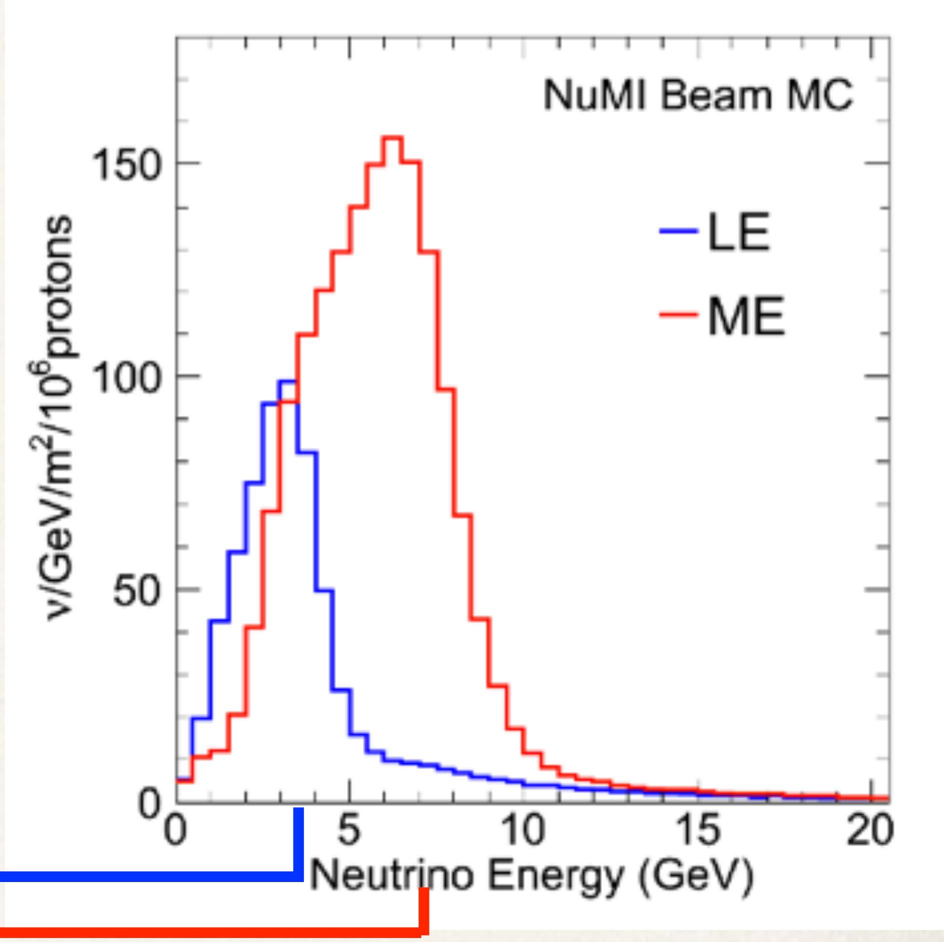


All photographs: Reidar Hahn, Fermilab visual media services

The MINERvA energy range



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

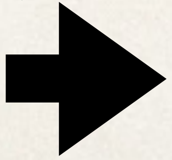


Low-energy run,
2010-2012
3.98x10^{20} POT (ν)
1.7x10^{20} POT ($\bar{\nu}$)

Medium-energy run, 2013-
Already exceeded low-energy
POT in ν mode

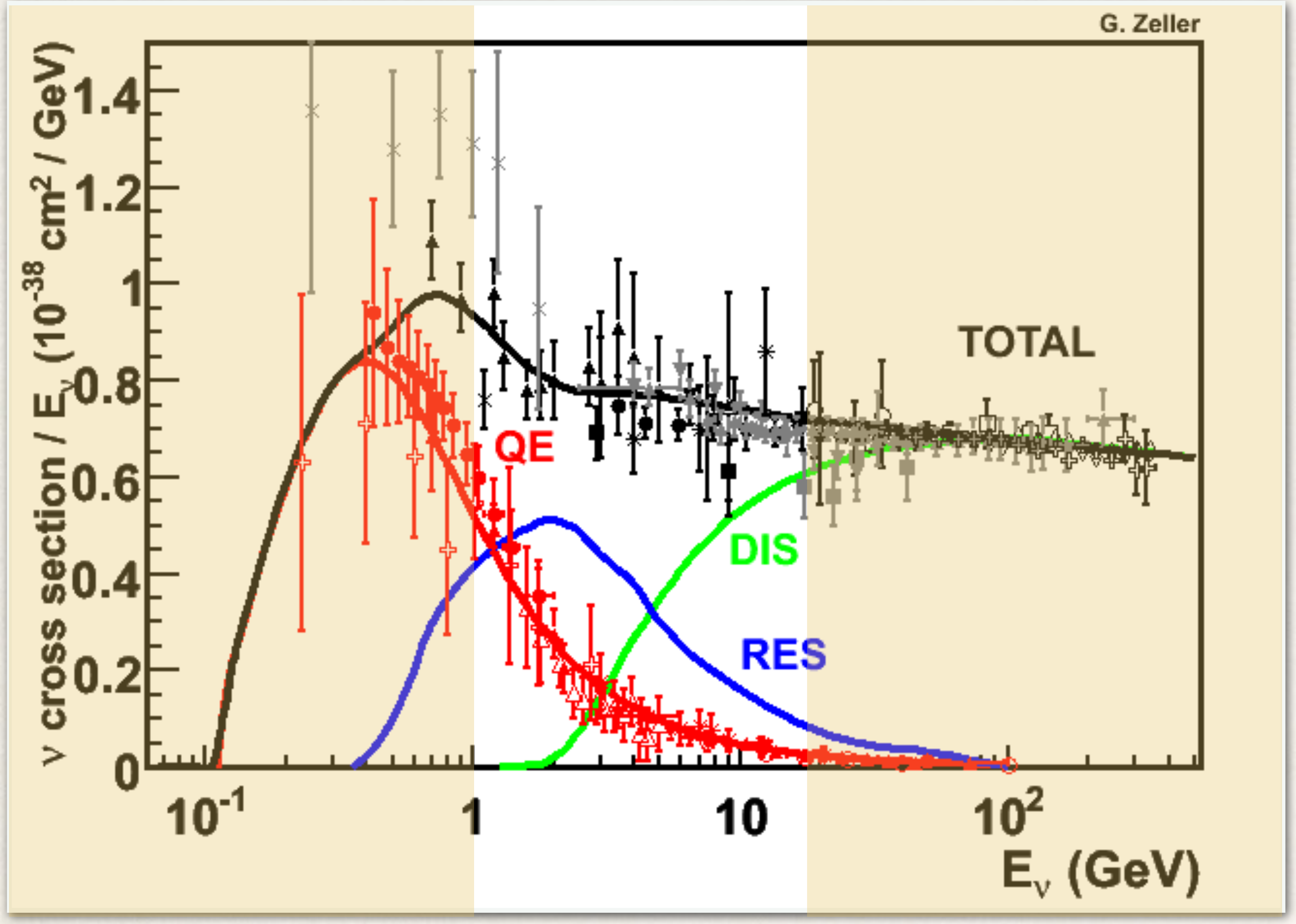
BooNE experiments,
T2K

MINERvA, DUNE,
NOvA, MINOS



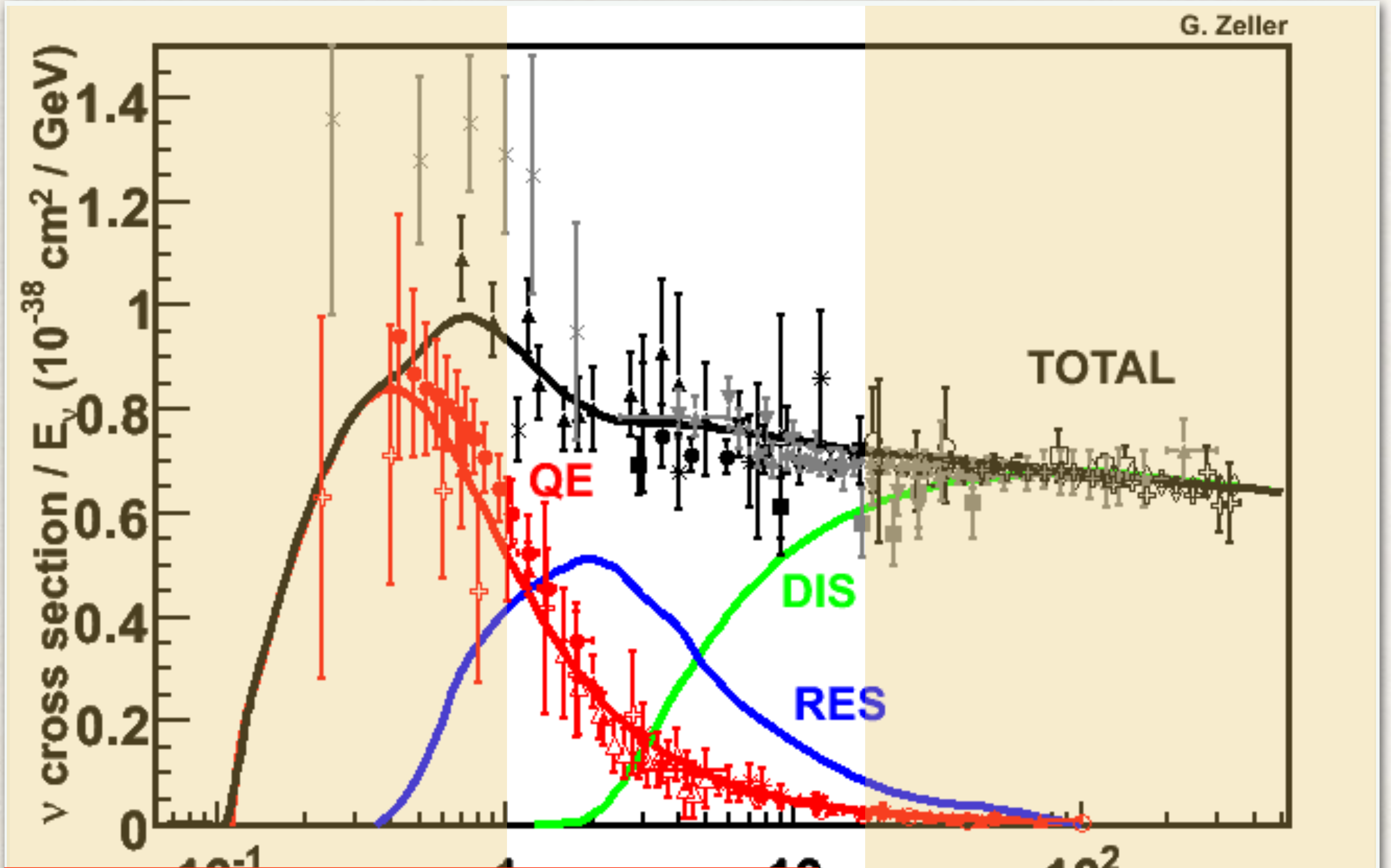
PINGU

The MINERvA energy range



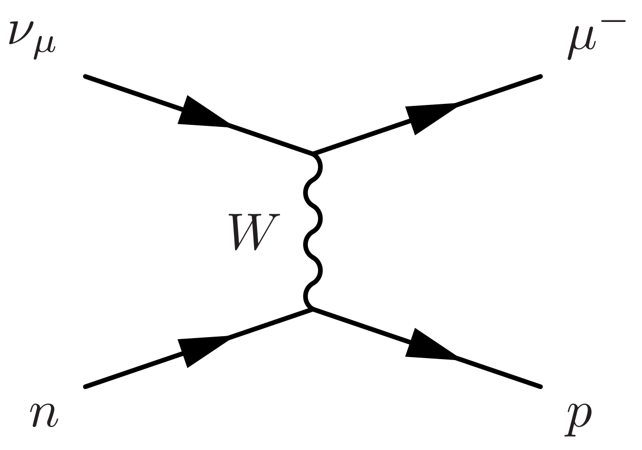
J.A. Formaggio and G.P. Zeller, Rev. Mod. Phys. 84, 1307-1341, 2012

The MINERvA energy range

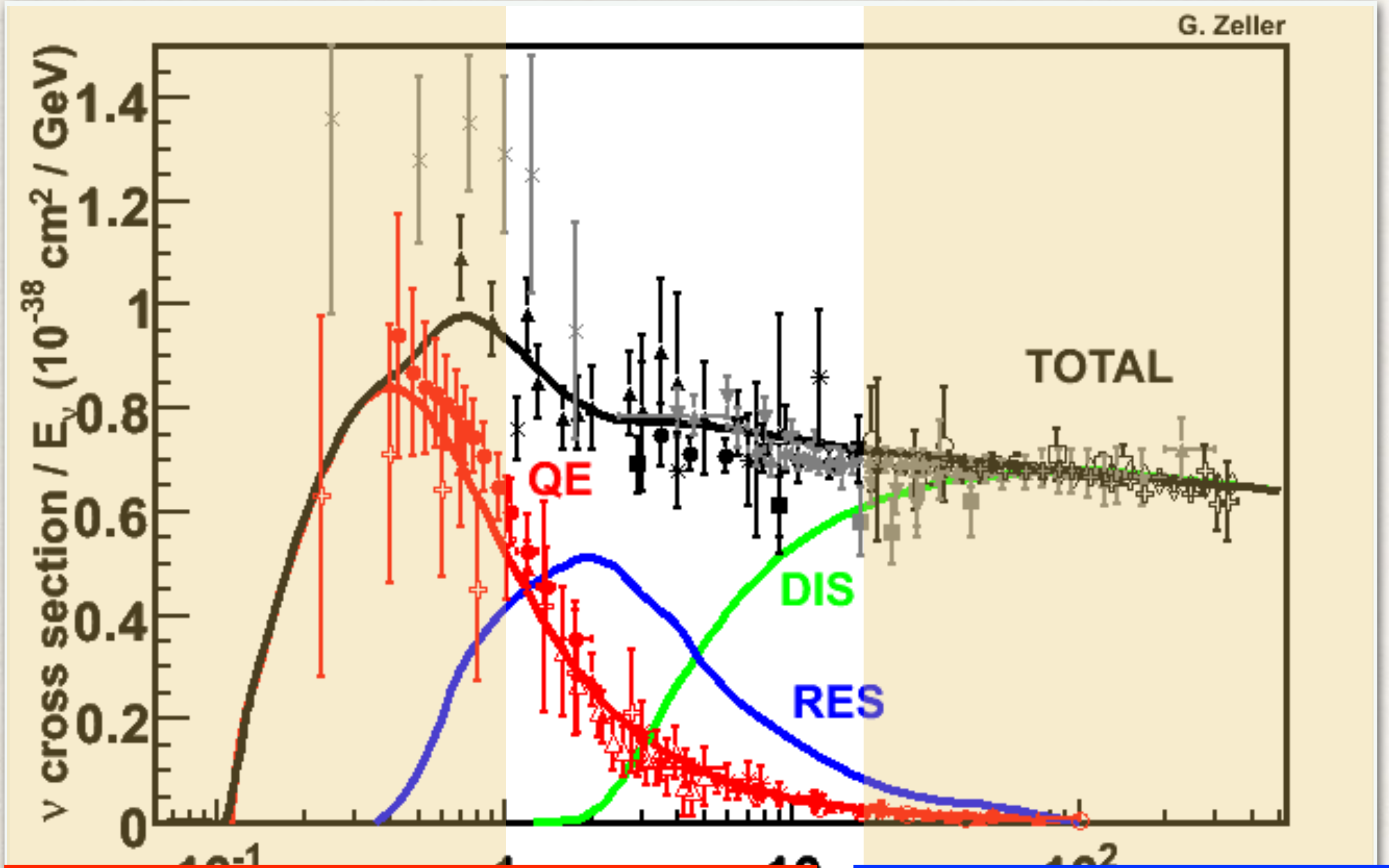


J.A. Formaggio and G.P. Zeller, Rev. Mod. Phys. 84, 1307-1341, 2012

Quasi-elastic scattering



The MINERvA energy range



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

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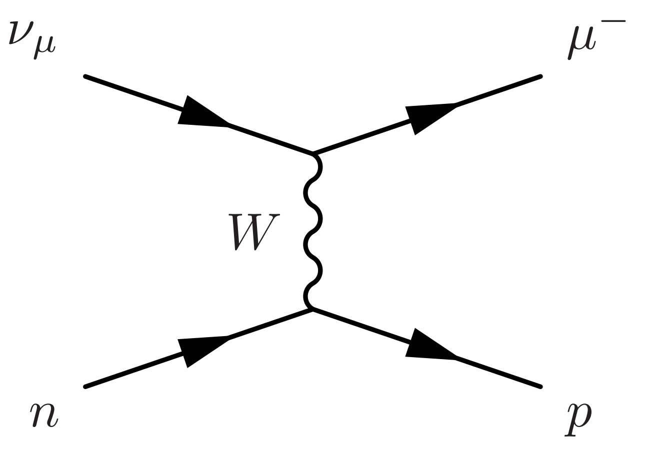
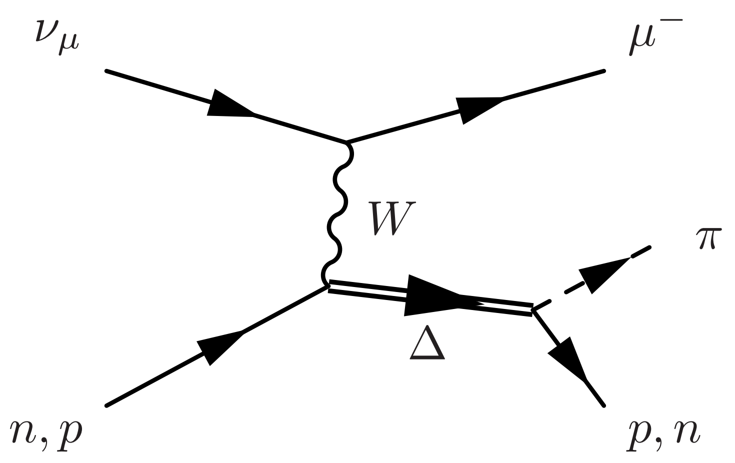
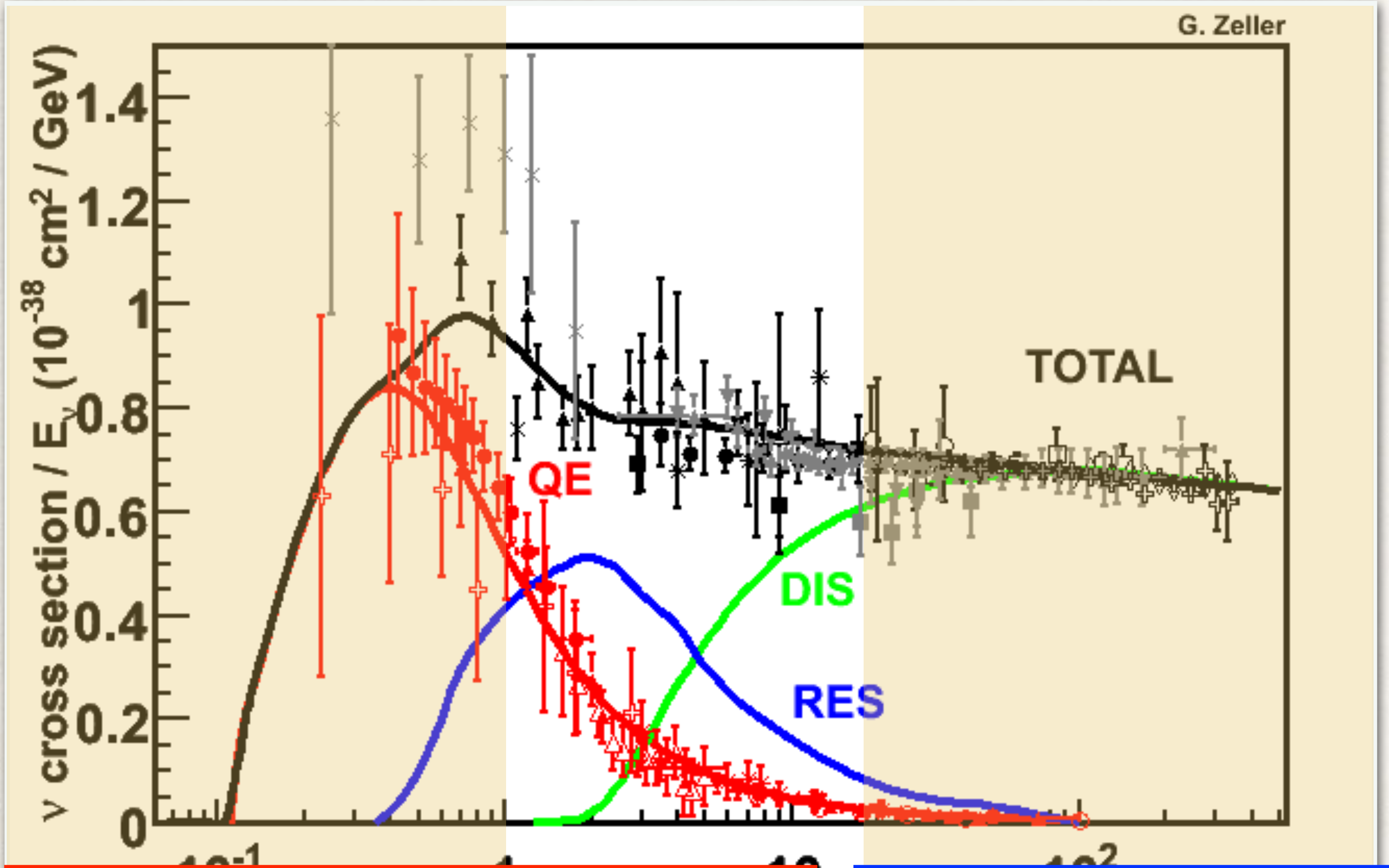


Resonant pion production

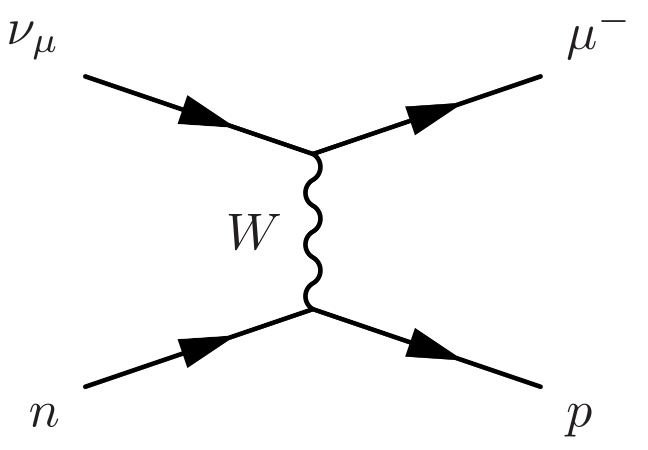


The MINERvA energy range

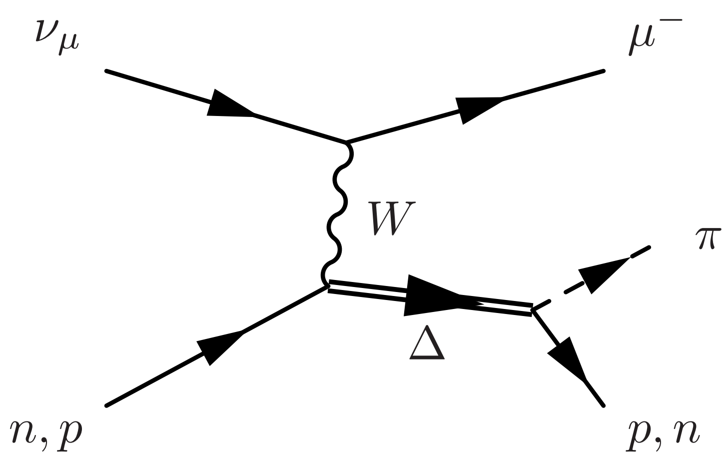


J.A. Formaggio and G.P. Zeller, Rev. Mod. Phys. 84, 1307-1341, 2012

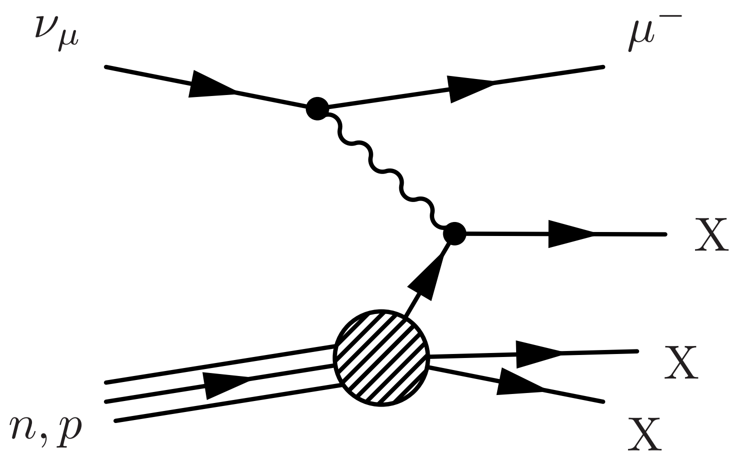
Quasi-elastic scattering



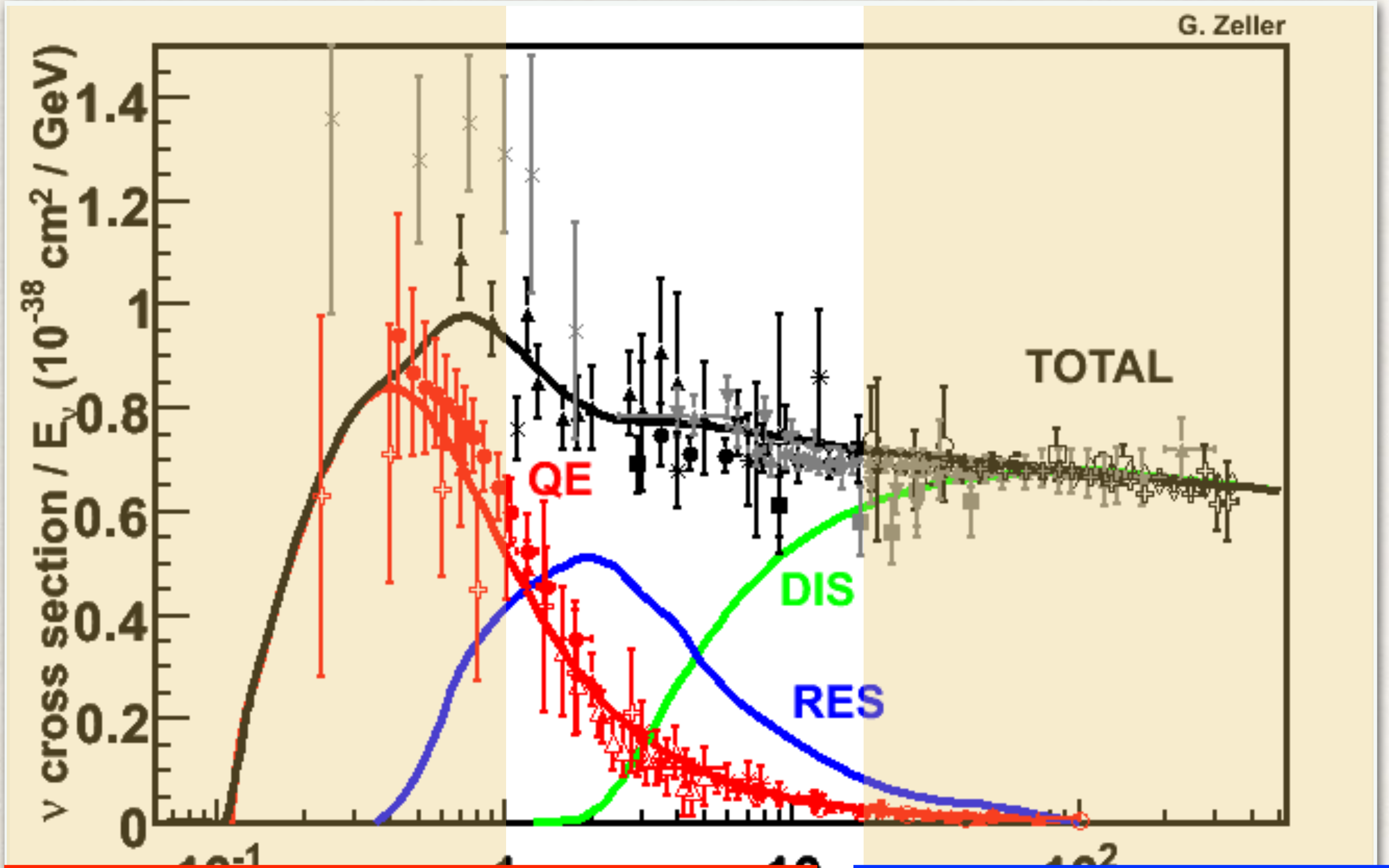
Resonant pion production



Deep inelastic scattering



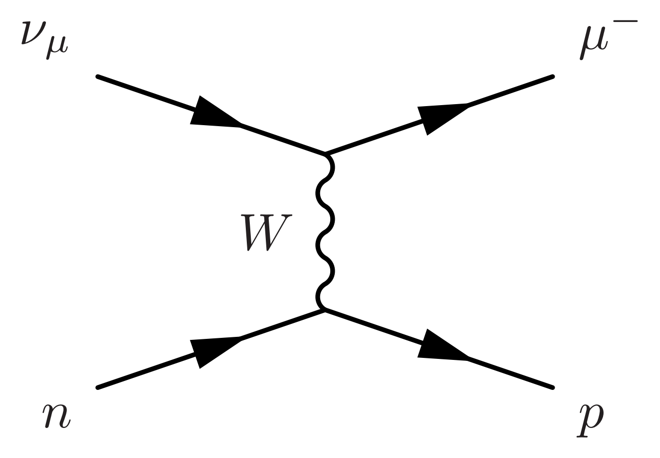
The MINERvA energy range



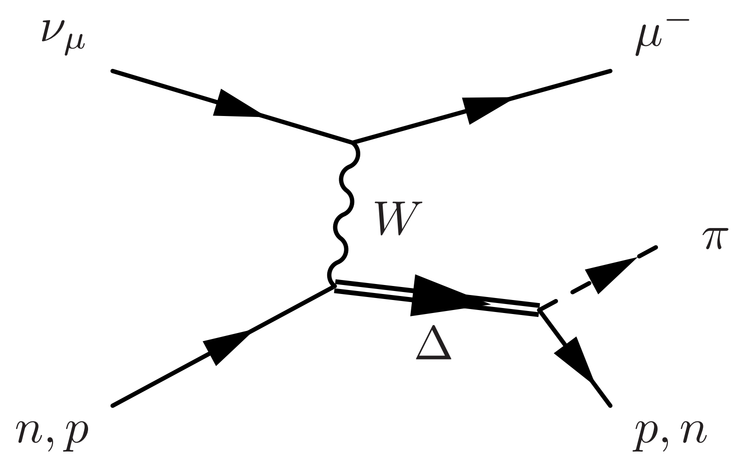
J.A. Formaggio and G.P. Zeller, Rev. Mod. Phys. 84, 1307-1341, 2012

I will be presenting results for all of these interaction types

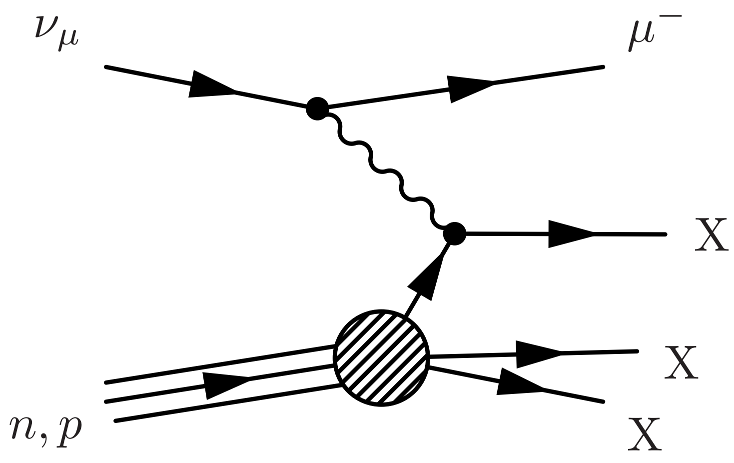
Quasi-elastic scattering



Resonant pion production

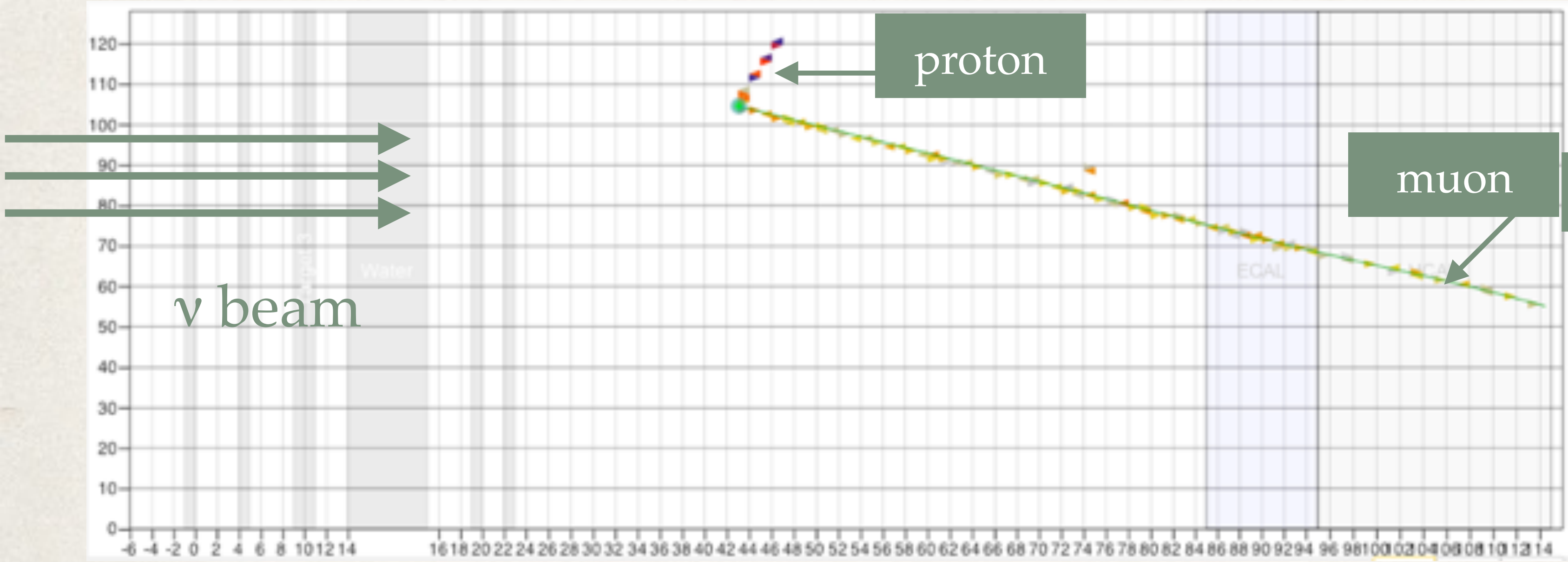


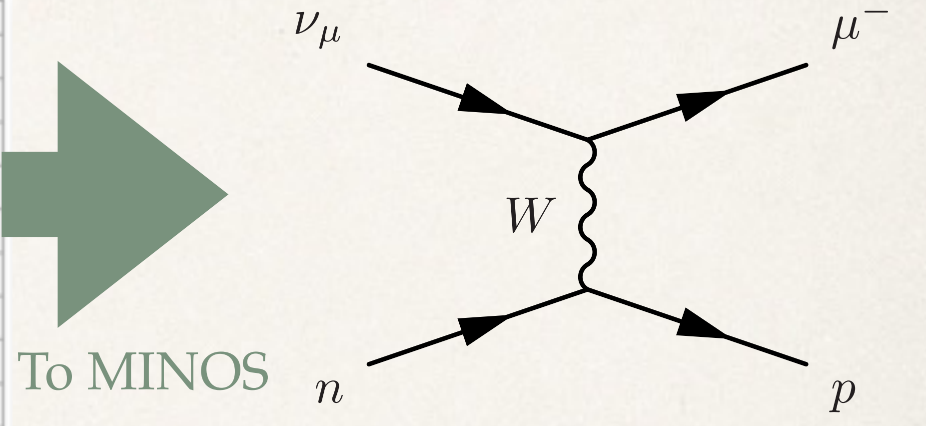
Deep inelastic scattering



Quasi-elastic scattering

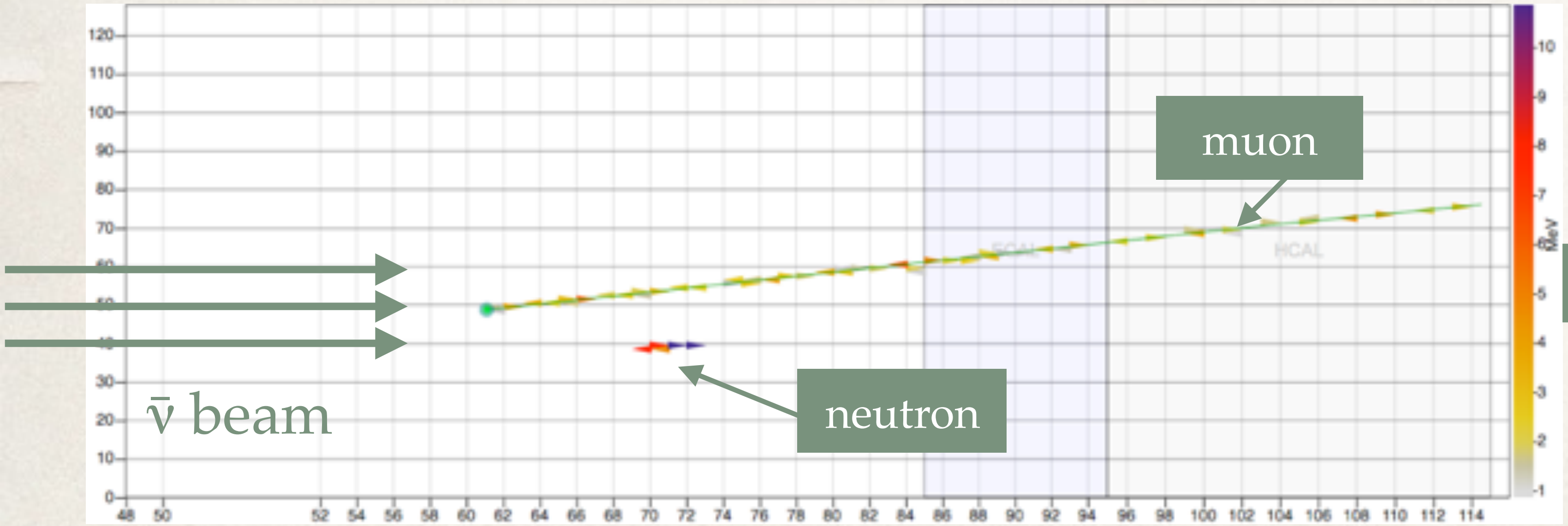
Neutrino mode $\nu_\mu + n \rightarrow \mu^- + p$

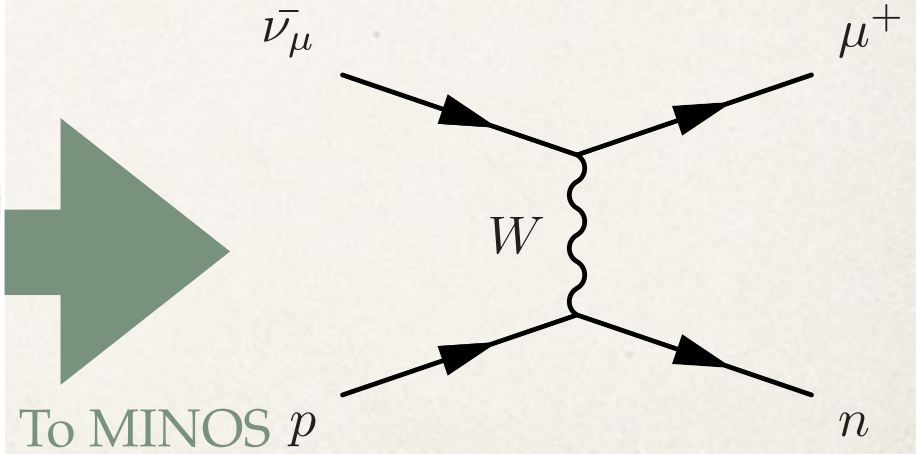




Neutrino energy and four-momentum transfer, Q^2, can be reconstructed from muon kinematics

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

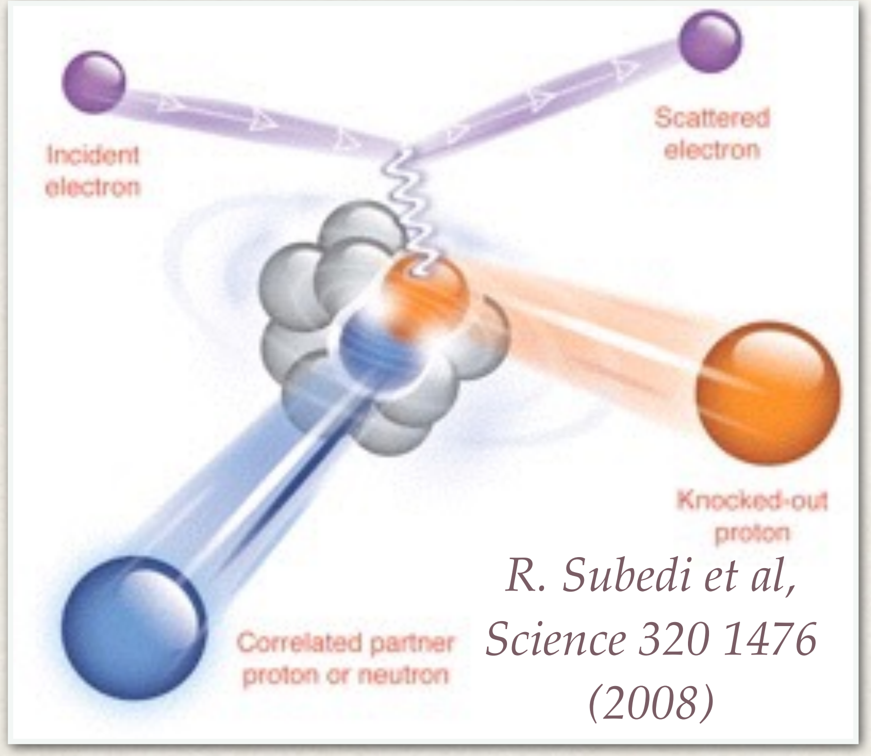




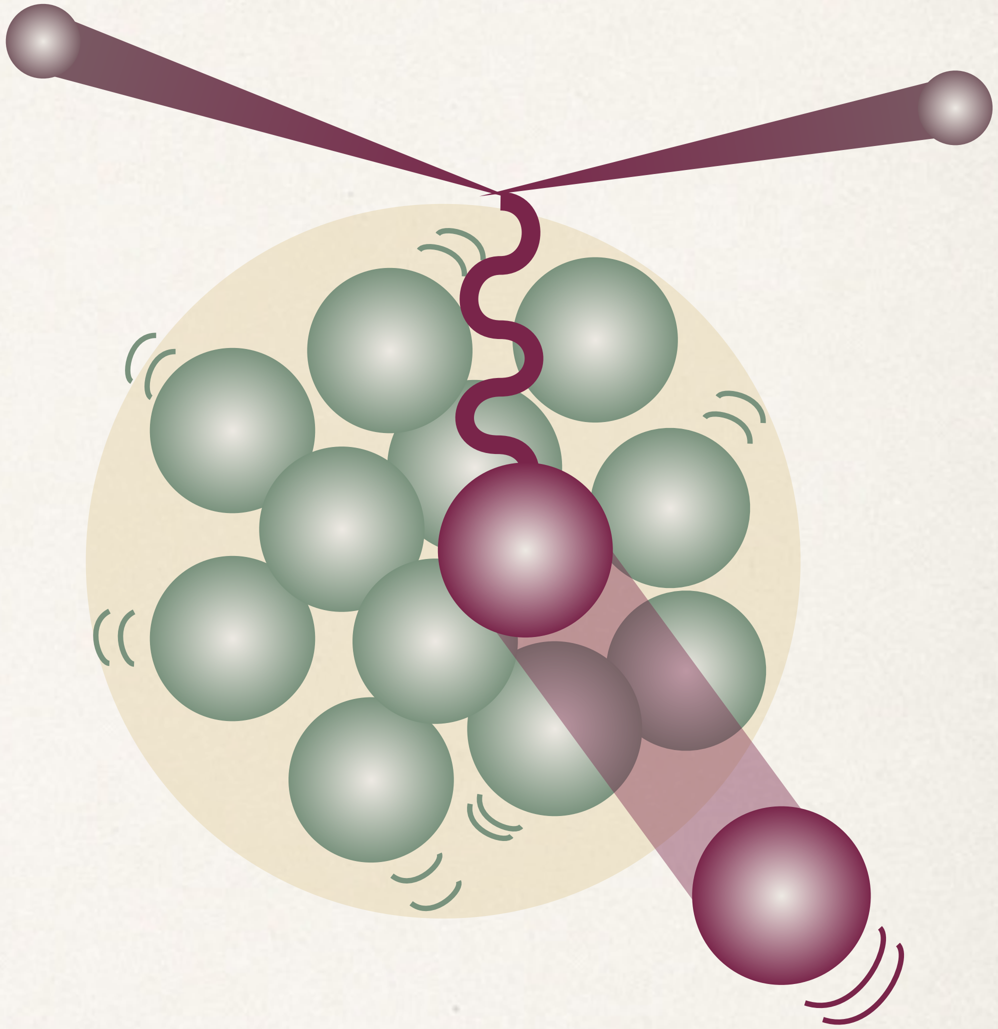
But in the nucleus, it's more complicated

Quasi-elastic scattering in the nucleus

- In a heavy nucleus, nucleons are **not stationary,** and interact with the other nucleons
- A commonly-used simulation of this is the Relativistic Fermi Gas model
- This 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);



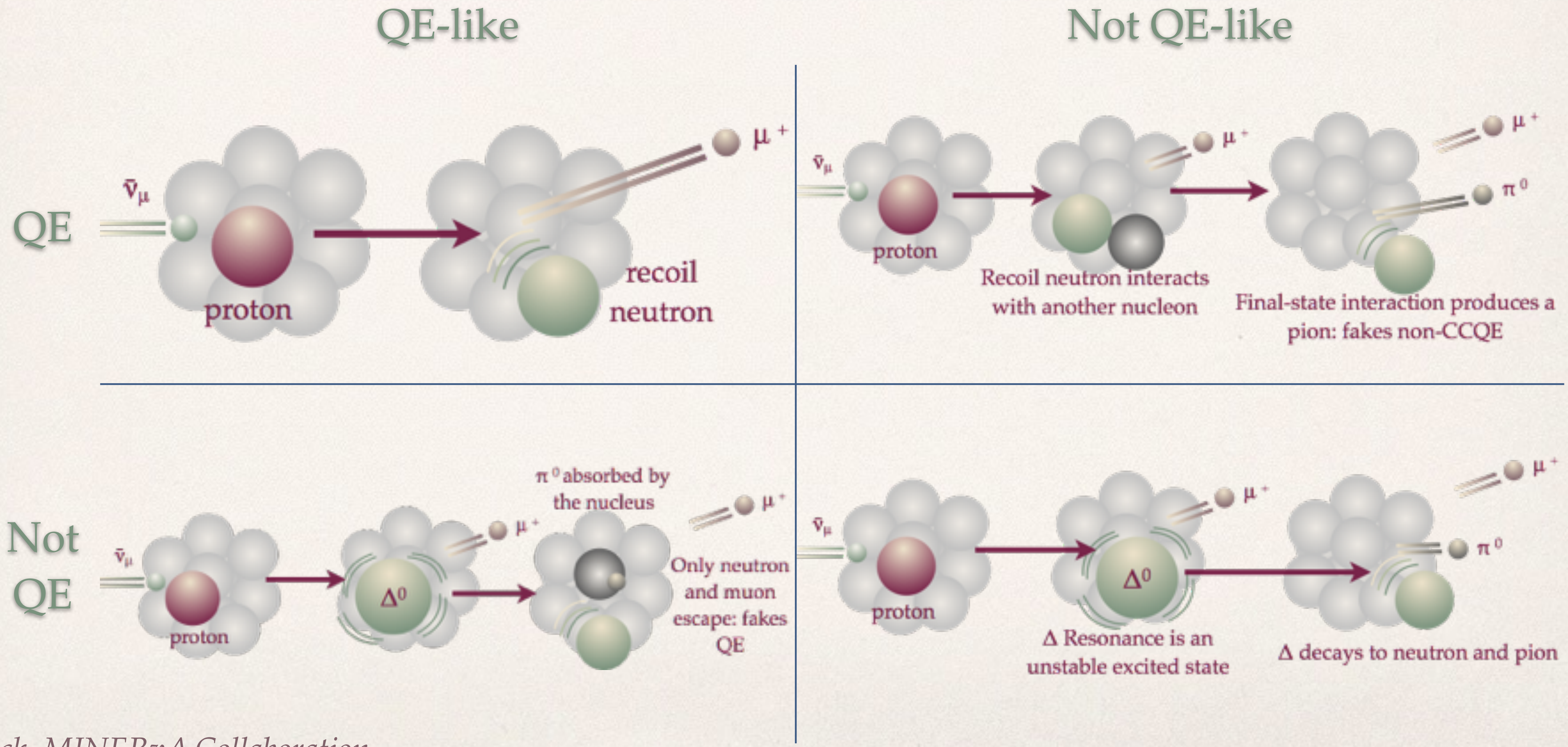
R. Subedi et al, Science 320 1476 (2008)



- Neutrino- and electron-scattering experiments see evidence of further effects including correlations between nucleons
- Nuclear effects affect **energy reconstruction** from final-state kinematics
- When nucleons are correlated, **extra nucleons** may be ejected

Final-state interactions

- 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



Recoil neutron interacts with another nucleon

Final-state interaction produces a pion: fakes non-CCQE

π^0 absorbed by the nucleus

Only neutron and muon escape: fakes QE

Δ Resonance is an unstable excited state

Δ decays to neutron and pion

Final-state interactions

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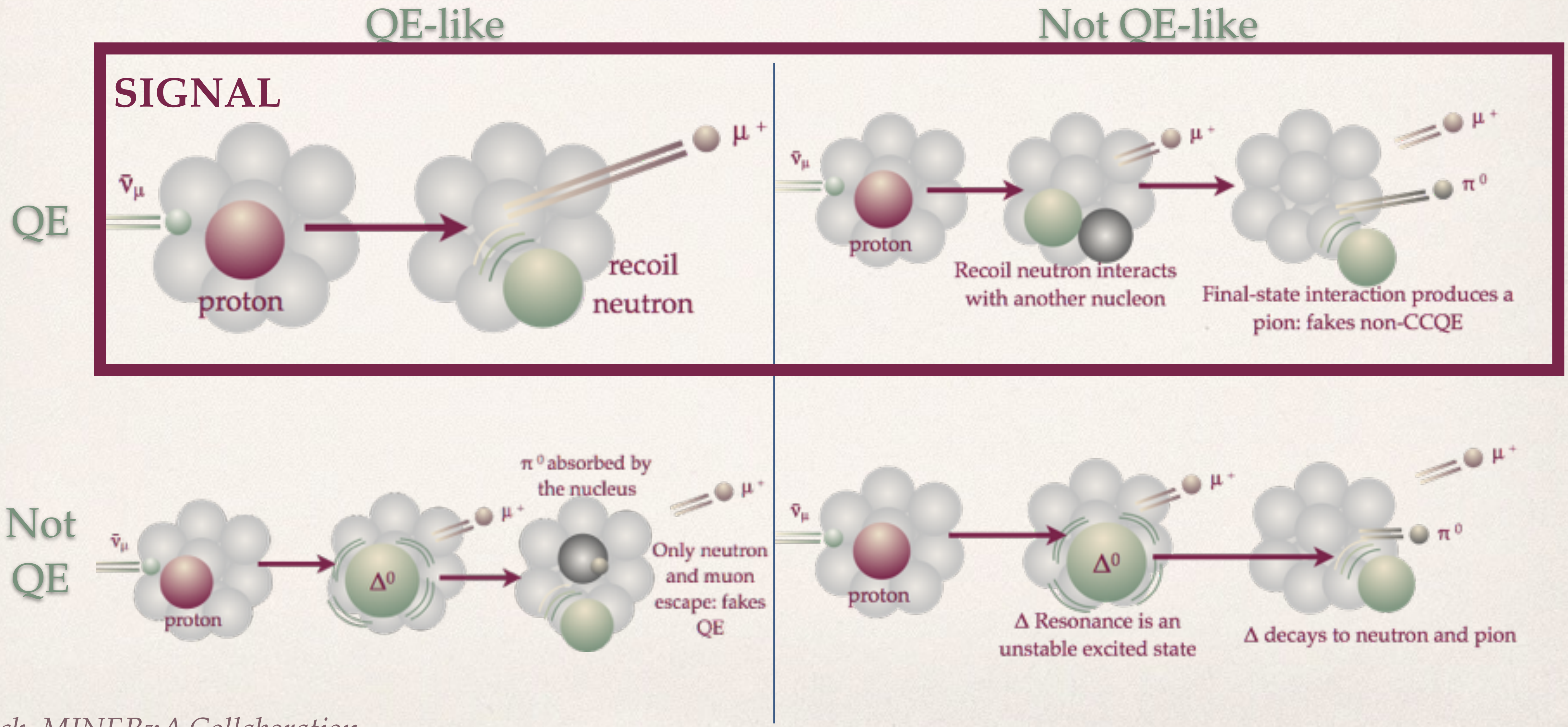

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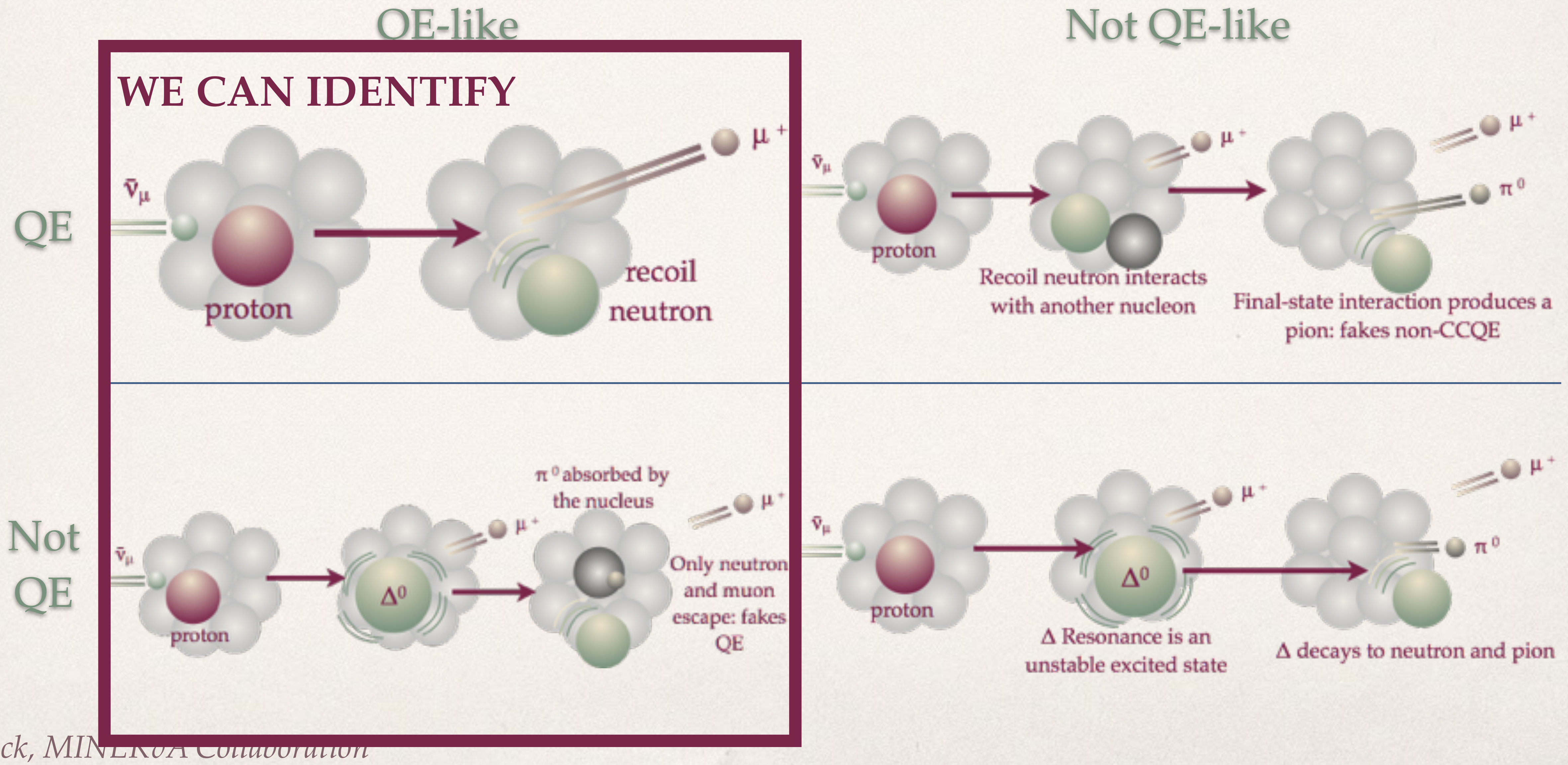
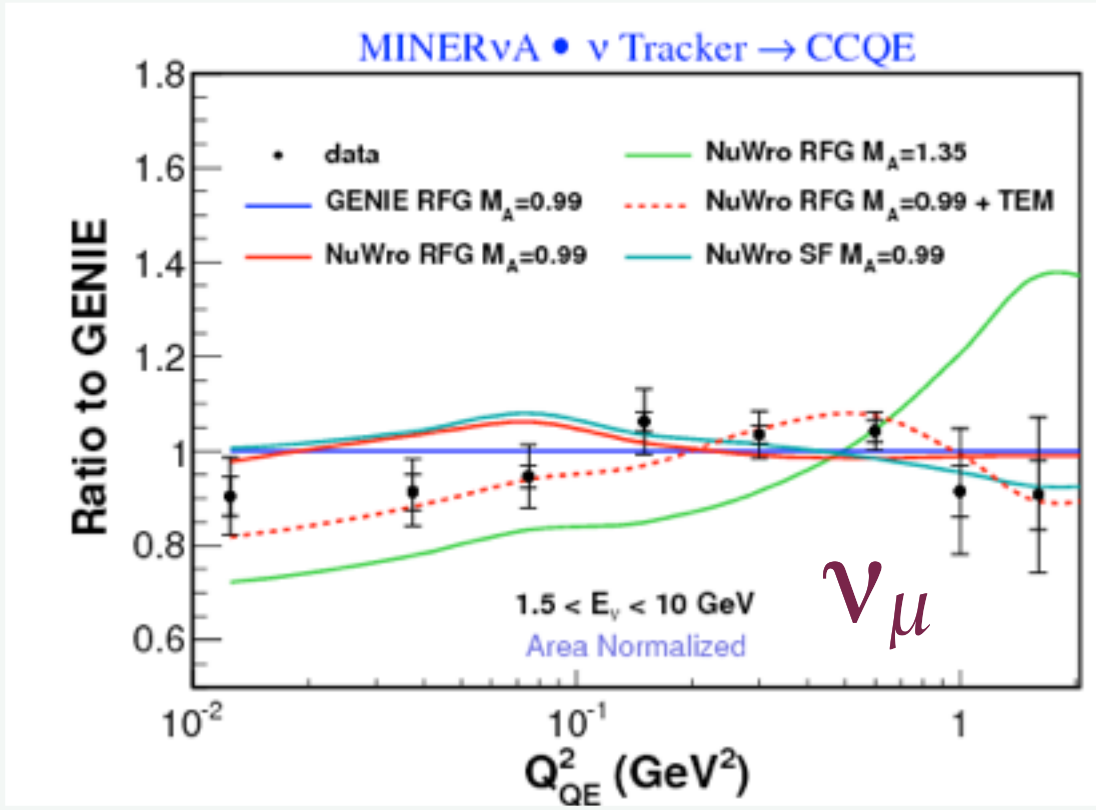


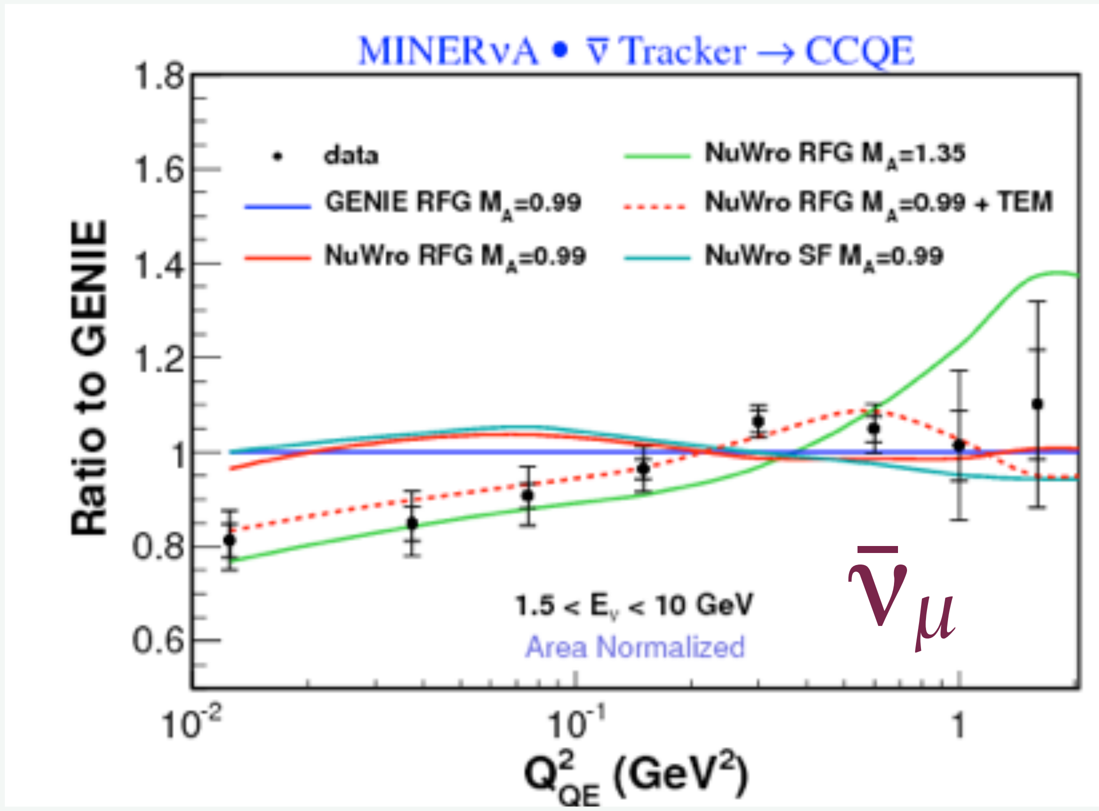
Quasi-elastic results: muon kinematics

- 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

Two models for correlation effects



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:

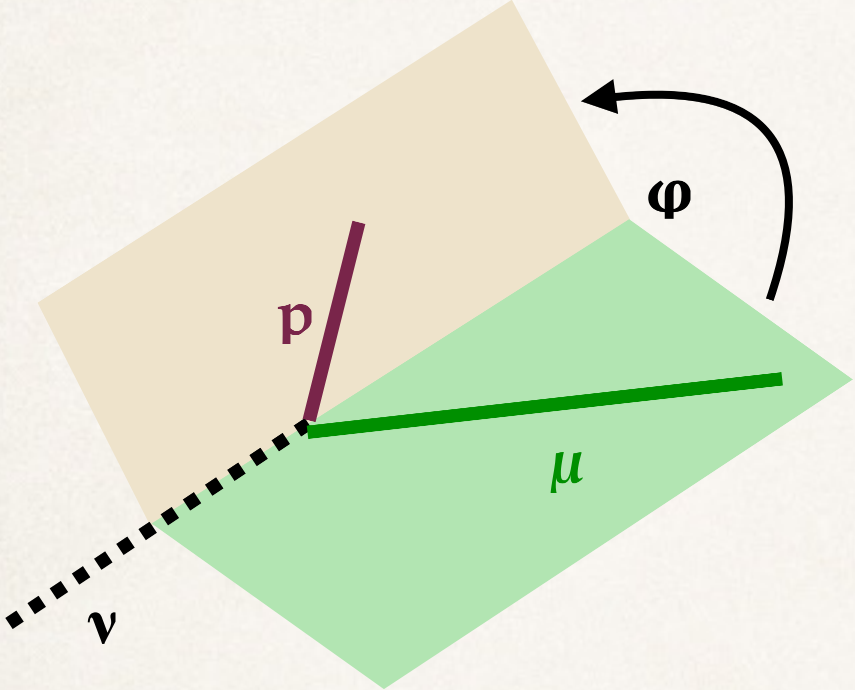
		$\bar{\nu}_\mu$	ν_μ
🟩	RFG (M_A = 1.35):	1.73	2.1
🟥	RFG (M_A=0.99):	2.90	4.1
▥	RFG (M_A=0.99, TEM):	0.66	1.7
🟦	SF (M_A=0.99):	2.99	3.8

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

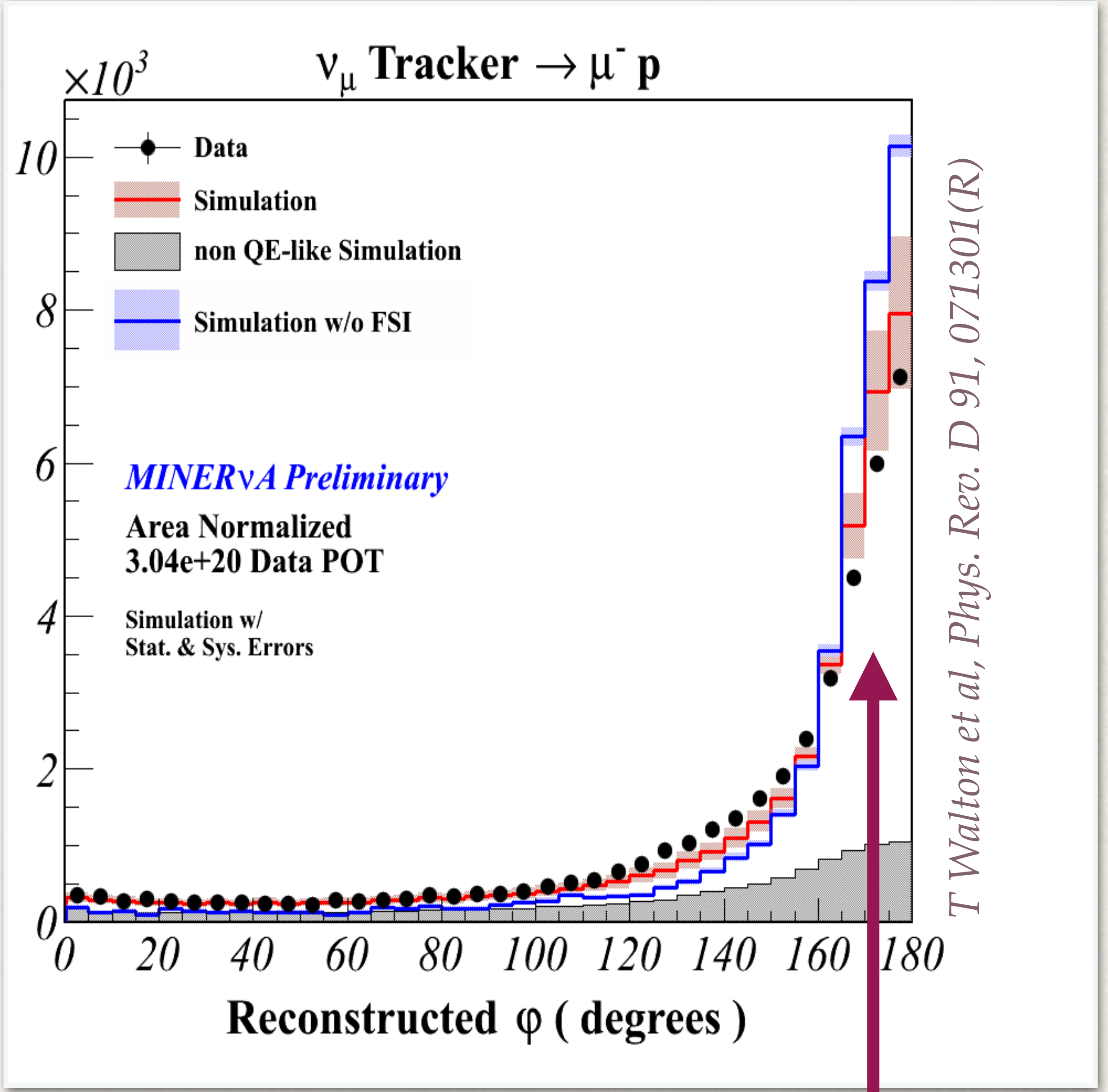
NuWro: *K. M. Graczyk and J. T. Sobczyk, Eur.Phys.J. C31, 177 (2003)*

Quasi-elastics with a proton track

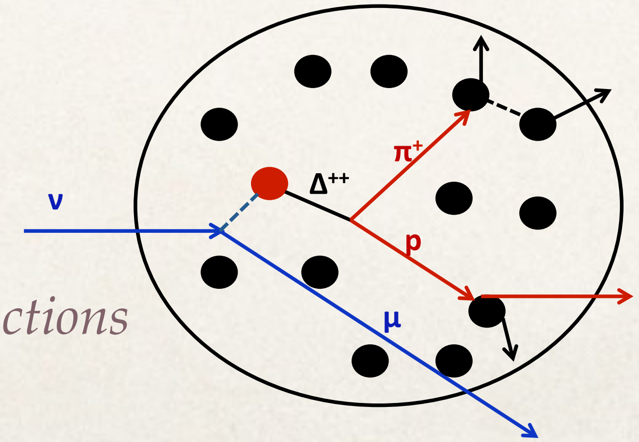
Study the angle between the ν-μ and ν-p planes:



- For QE scattering from a stationary neutron, φ should be 180 °
- Fermi motion, FSI and quasi-elastic-like resonant events cause the spread in the distribution



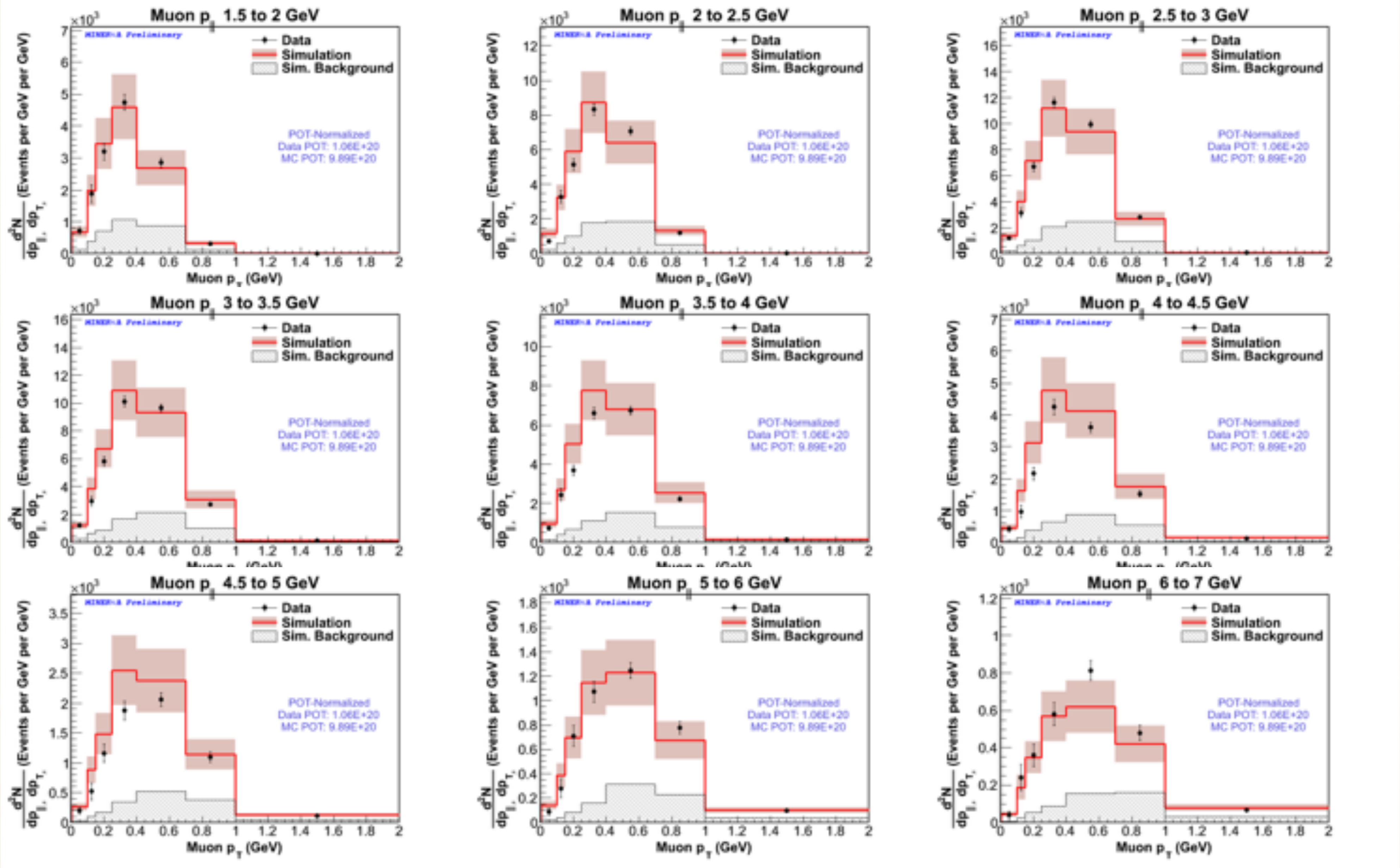
T Walton et al, Phys. Rev. D 91, 071301(R)



Final-state interactions

Data event distribution tends to lower coplanarity angle - due to unmodeled FSI, or nuclear correlation effects?

Double-differential QE cross sections

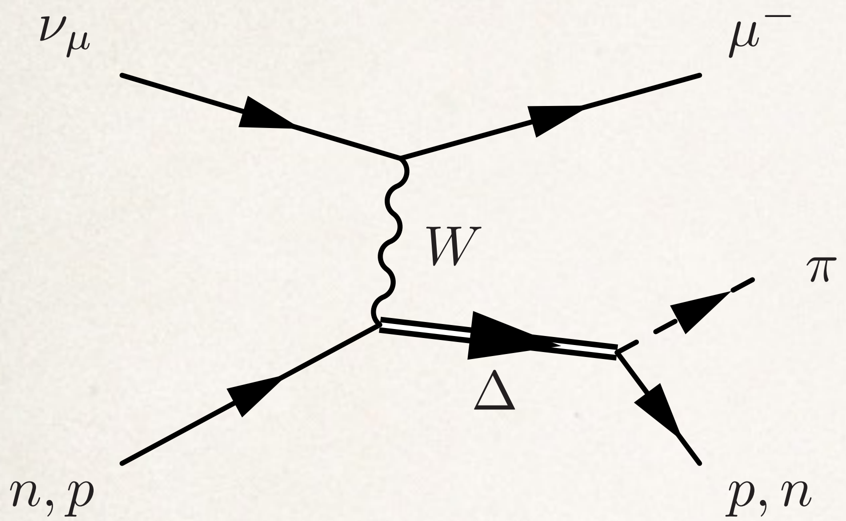


Cross sections vs muon transverse and longitudinal momentum should help distinguish between models

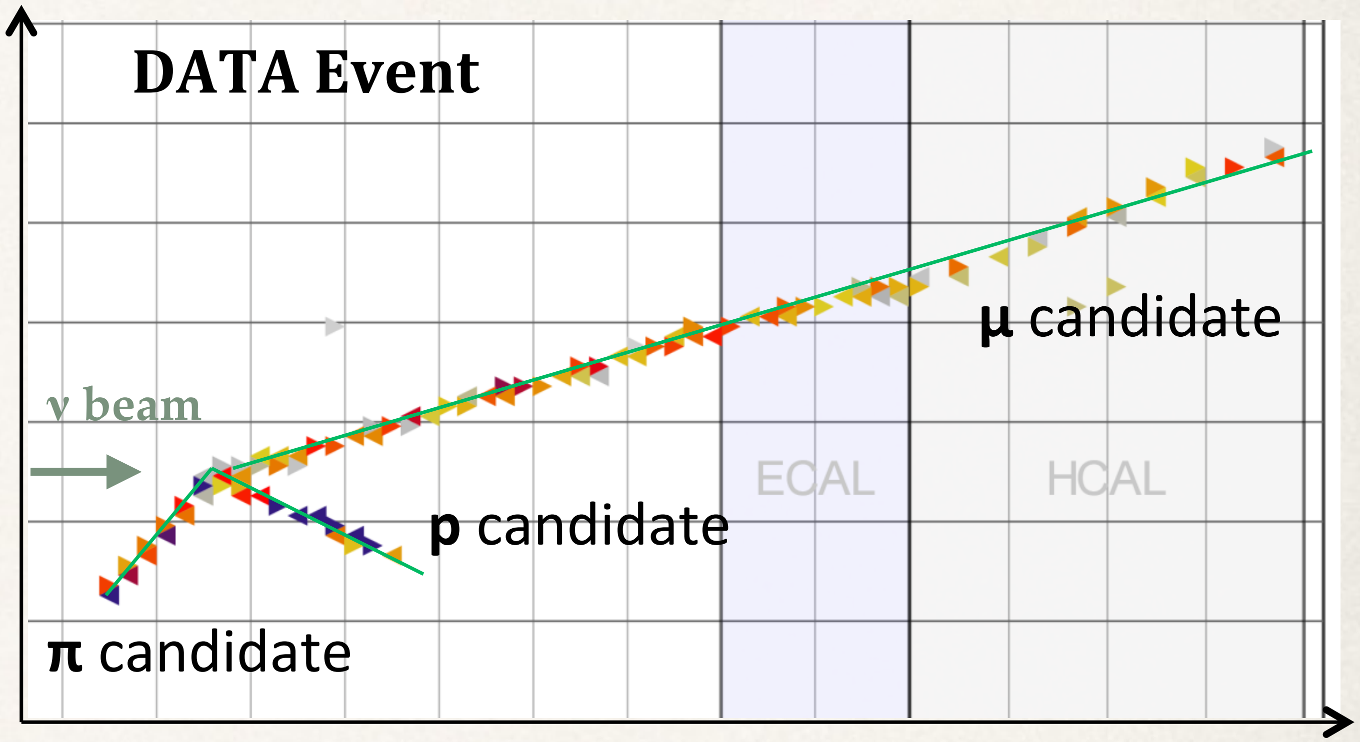
Neutrino and antineutrino results coming soon!

- Uncertainties on reconstruction and interaction model are shown on the simulation
- The GENIE model carries the largest uncertainty in many bins
- Reducing the uncertainty on the interaction model is a key goal of this analysis

Single pion production

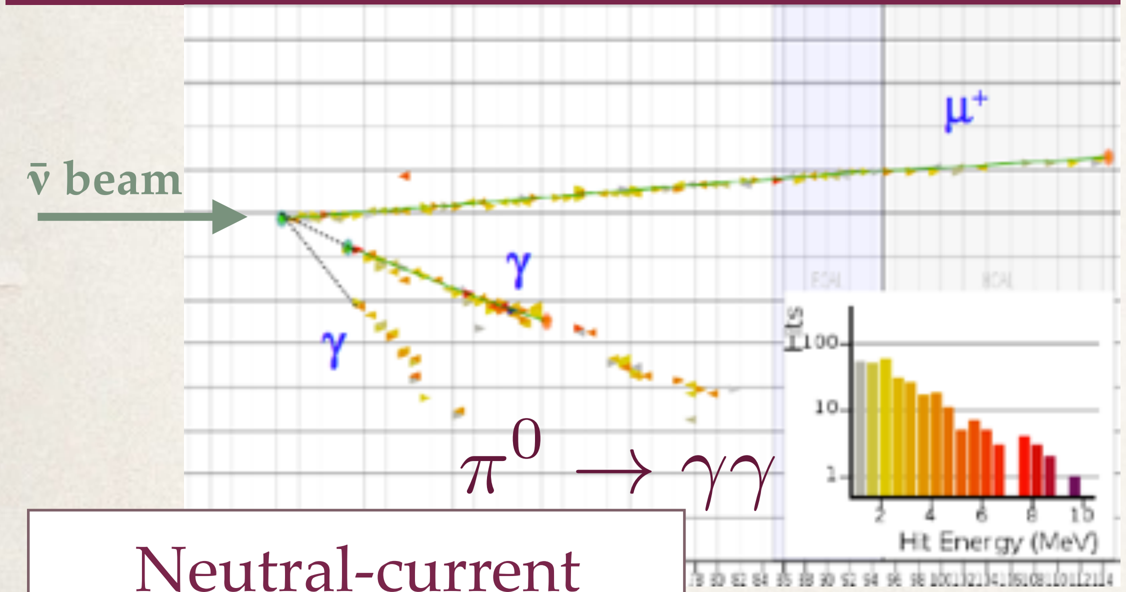


Charged pion production from ν



B. Eberly et al.; arXiv:1406.6415

Neutral pion production from ν̄

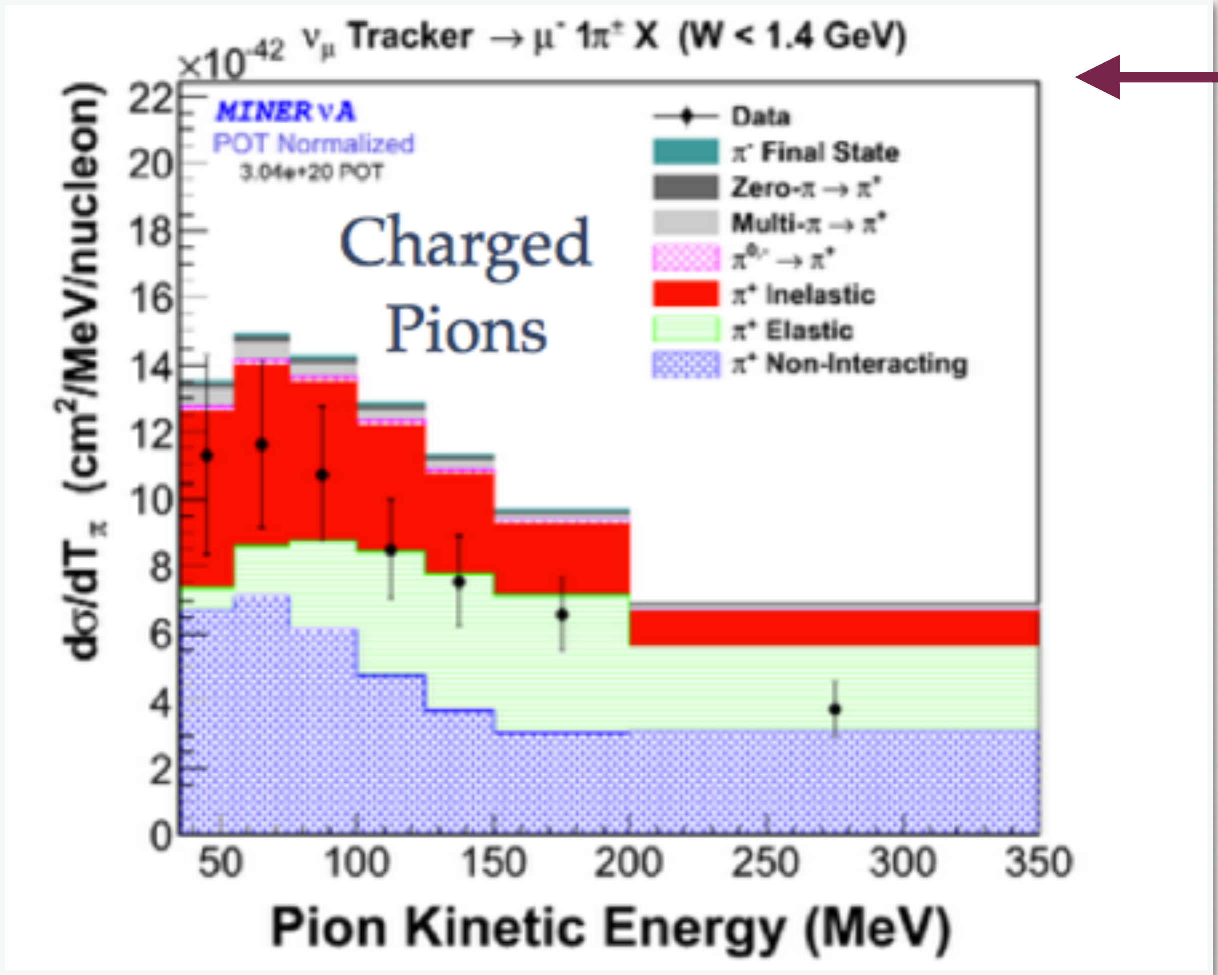


Neutral-current analogue can mimic $\bar{\nu}_e$ appearance signature

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

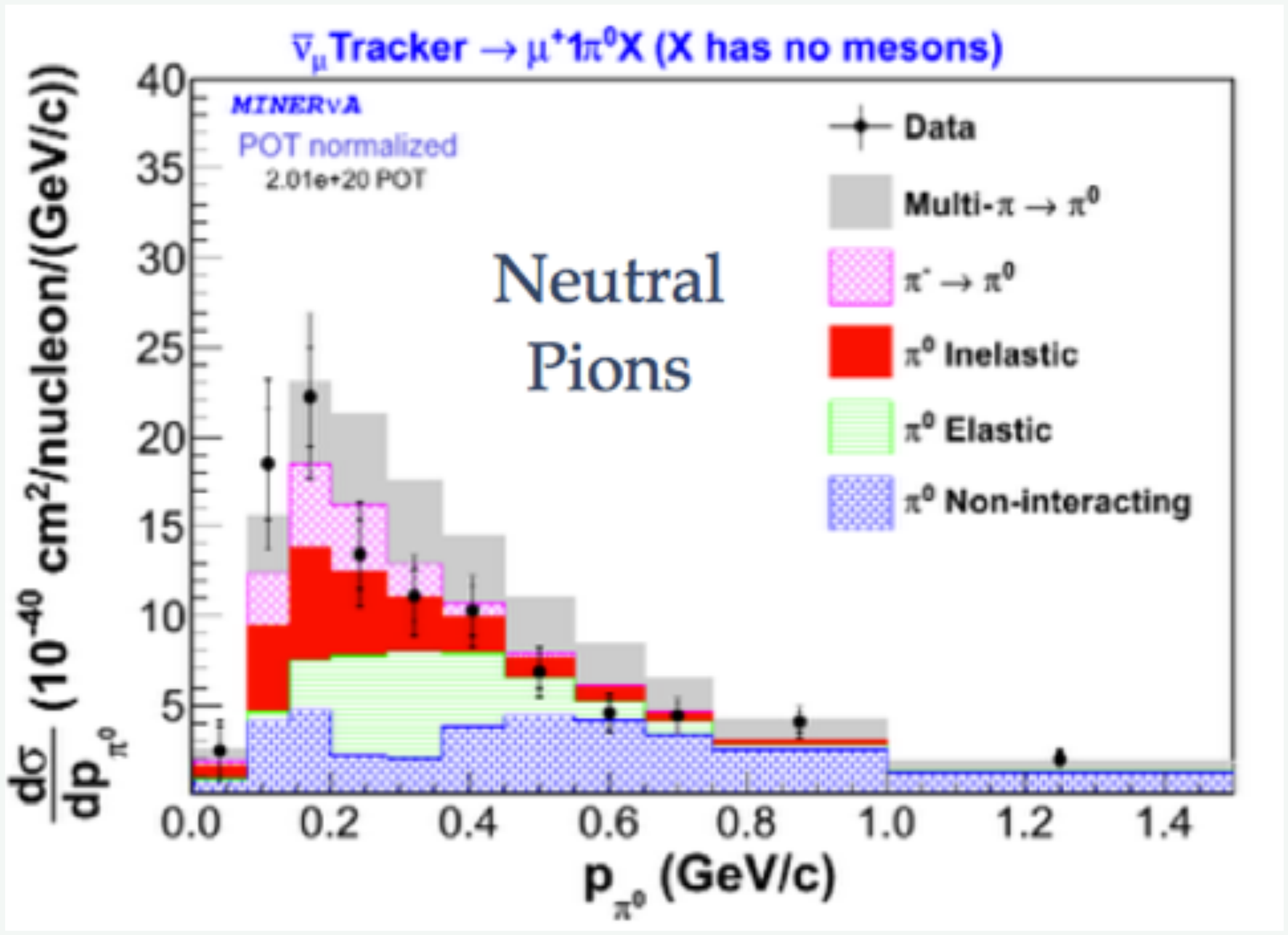
- Two different measurements of 1-pion production (mostly from resonant events)
- The cross section is higher for $\pi^\pm$ than for π^0 production
- Compare data with GENIE simulation of which FSI processes lead to these final states

Single-pion production -FSI processes



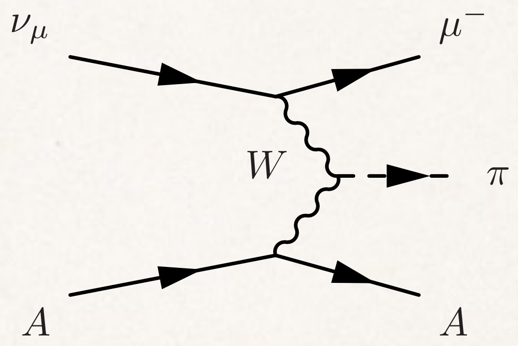
- Around half of these charged pions underwent some kind of FSI
- Data shape agrees well with Monte Carlo, but simulation over-predicts the rate

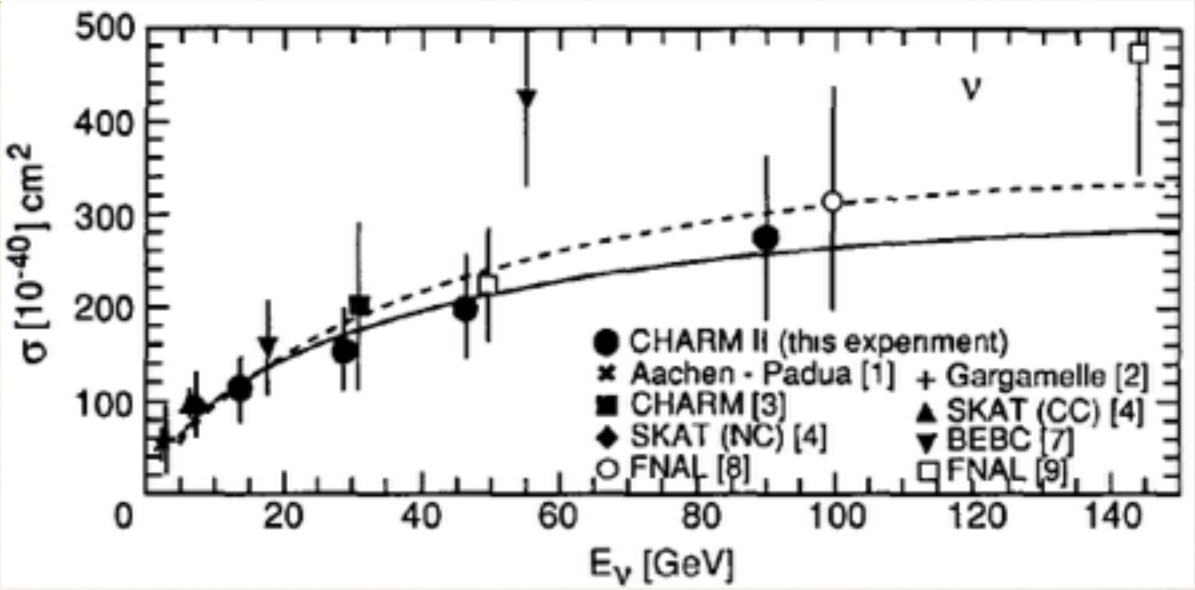
- π^0 production data and simulation have poor shape agreement
- The majority of events experience FSI
- Large contribution from $\pi^\pm$ undergoing FSI (remember $\pi^\pm$ cross section higher than π^0)



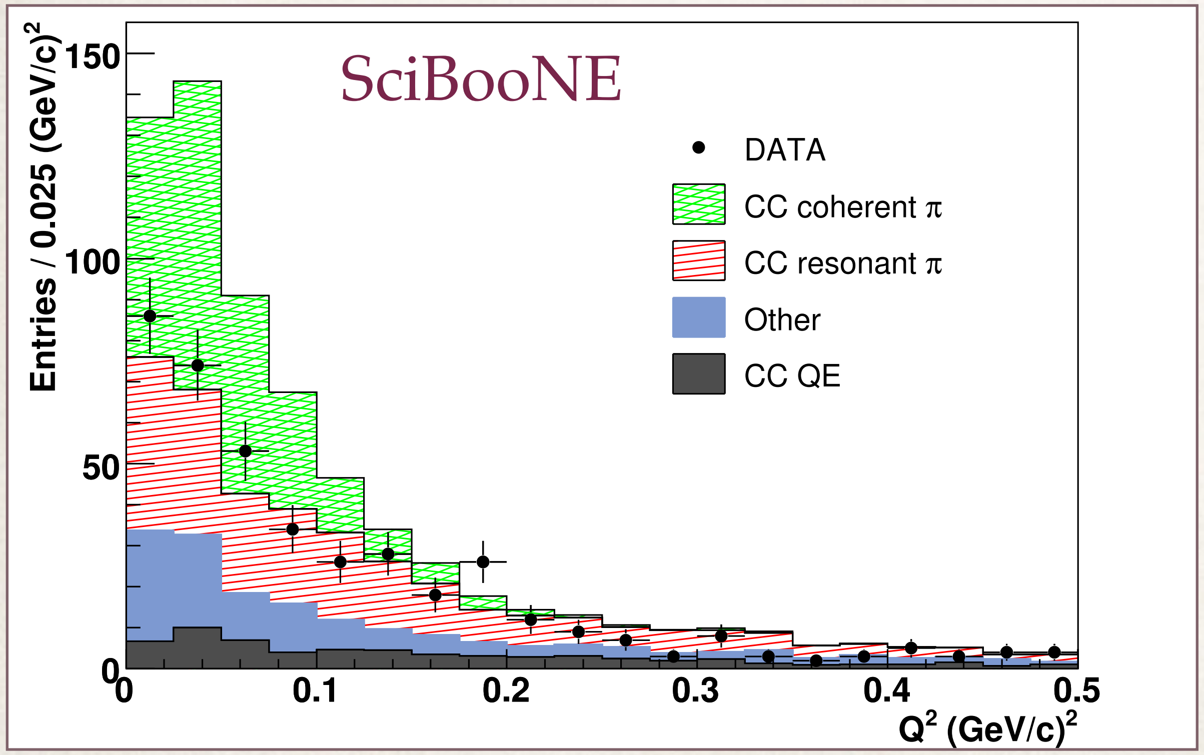
Coherent pion production: I

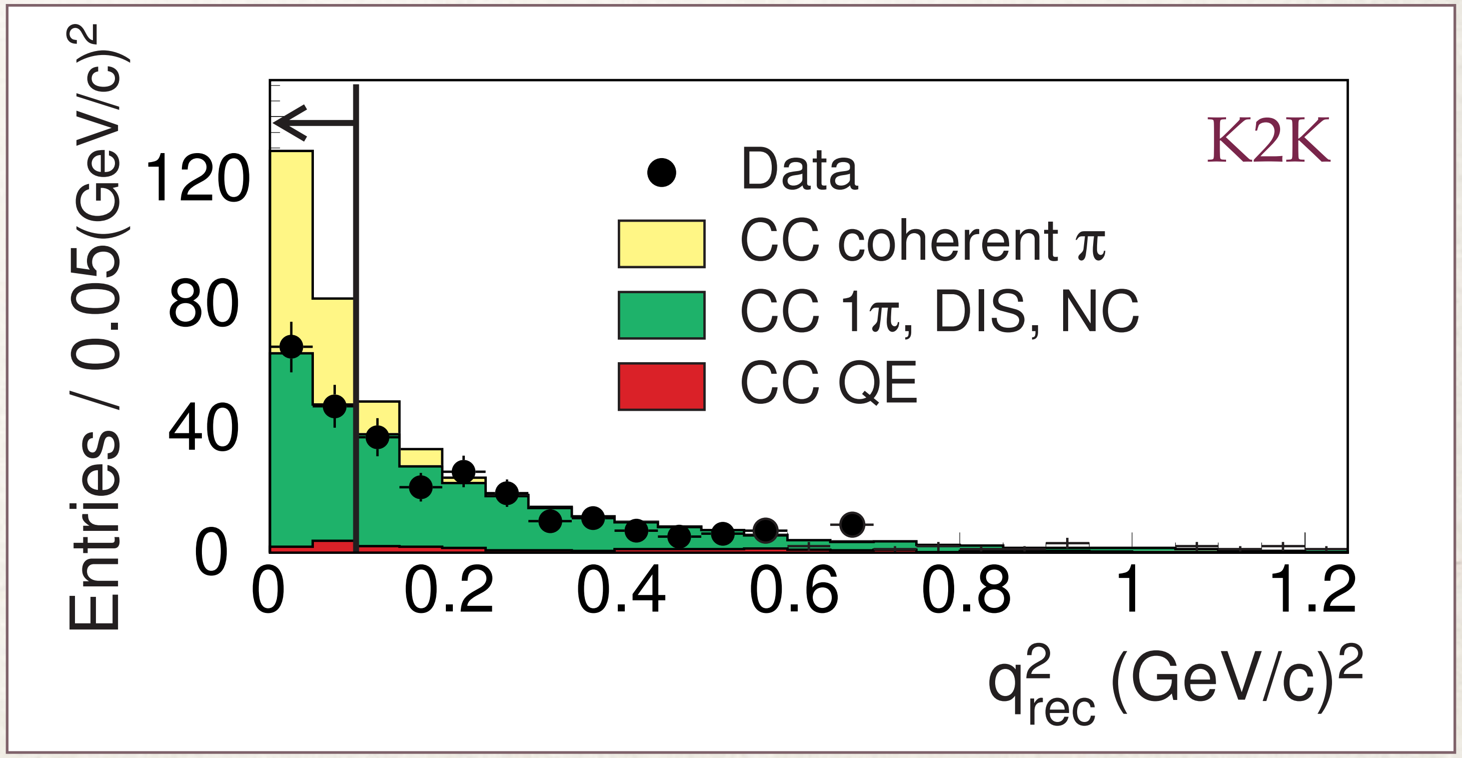
- Early experiments at high energies see clear evidence of coherent pion production (scattering without breaking up the nucleus)



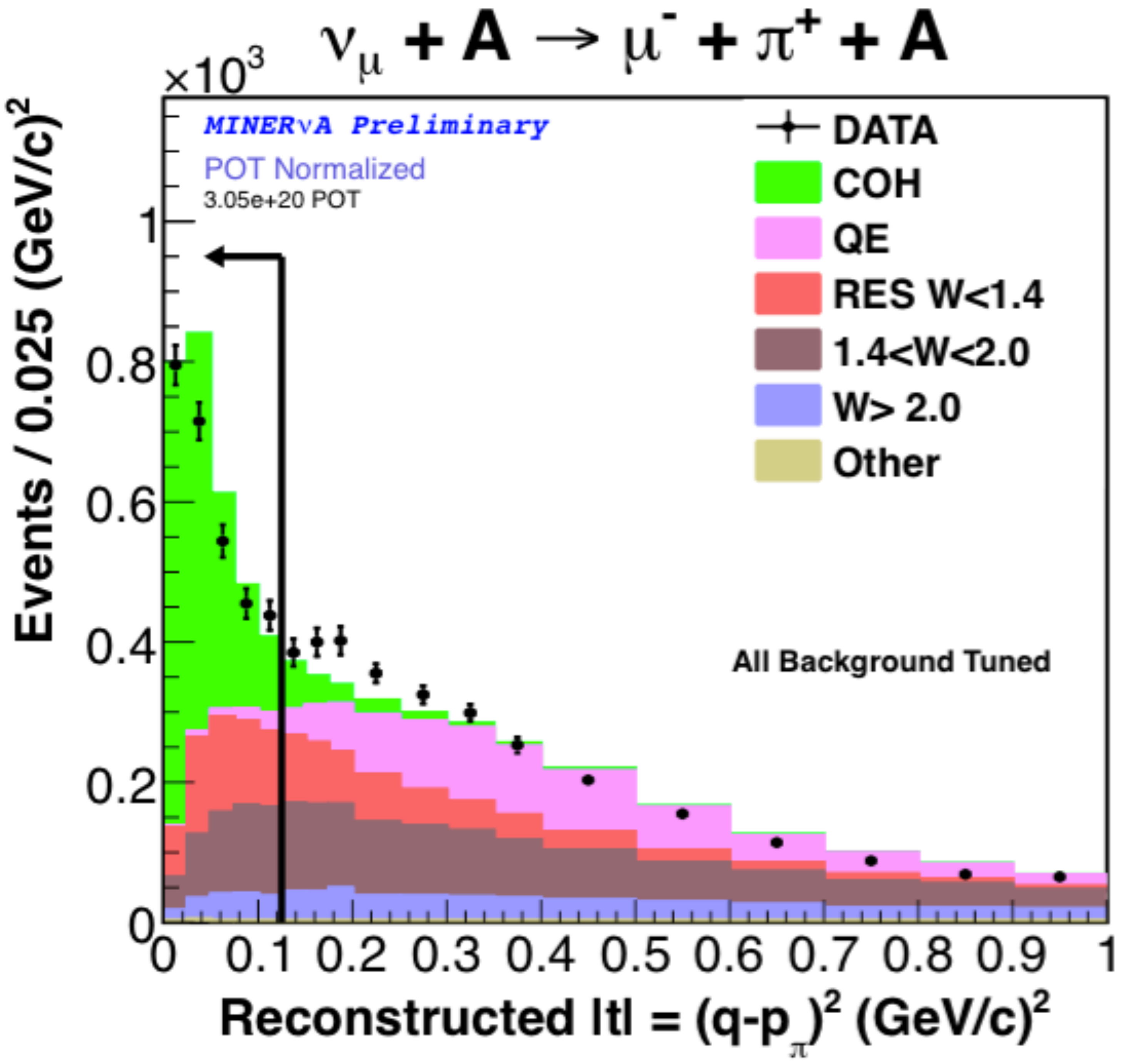


- Lower energy experiments saw results consistent with NEUT's background predictions





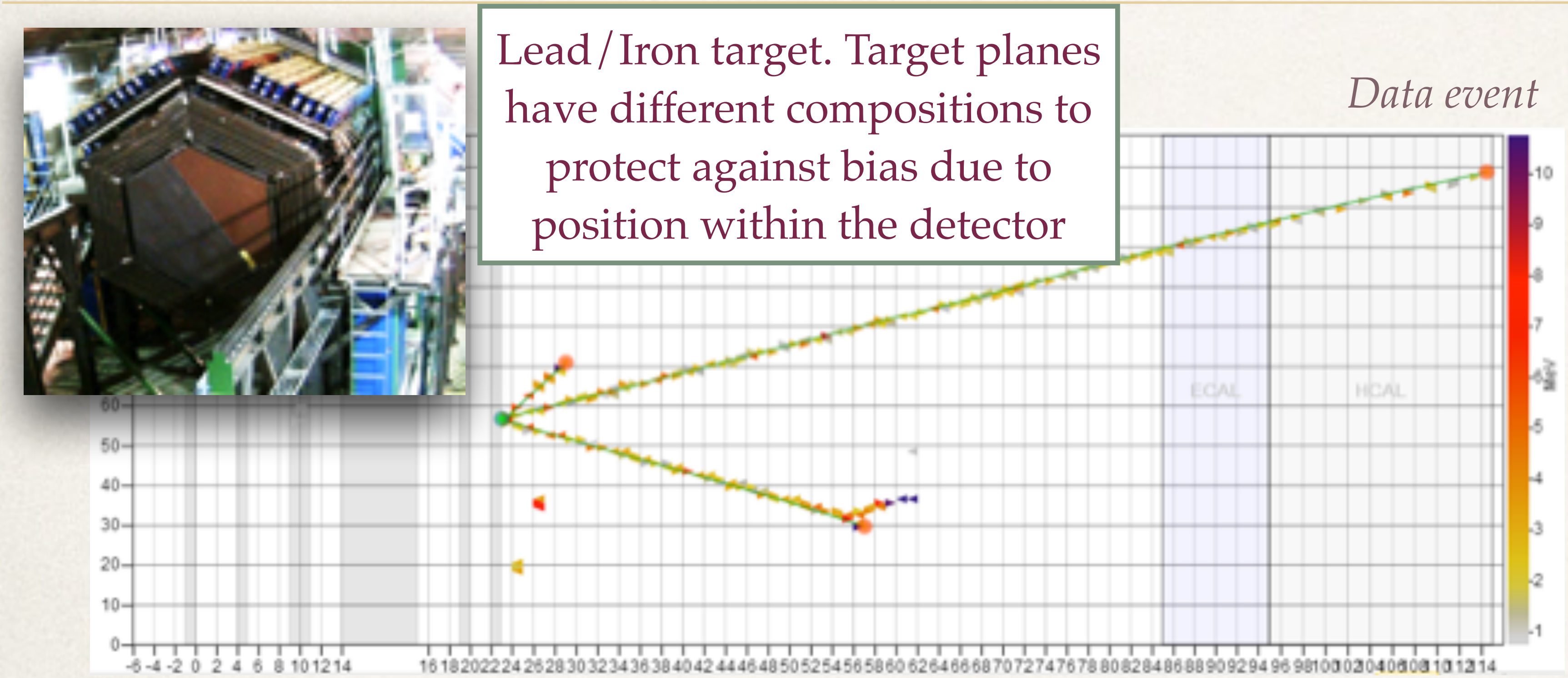
Coherent pion production: II



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 quantity |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

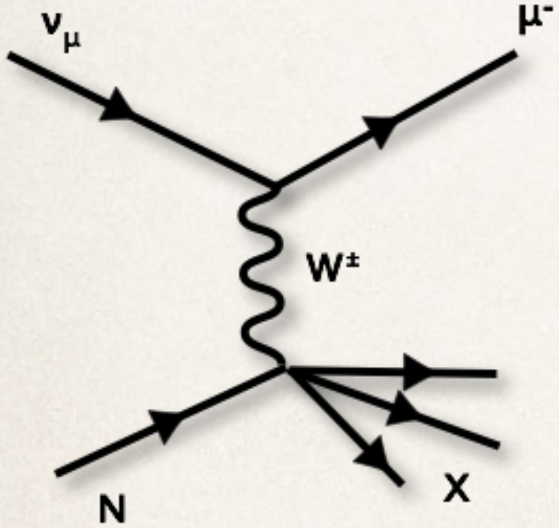
Events in the nuclear targets



Lead/Iron target. Target planes have different compositions to protect against bias due to position within the detector

Data event

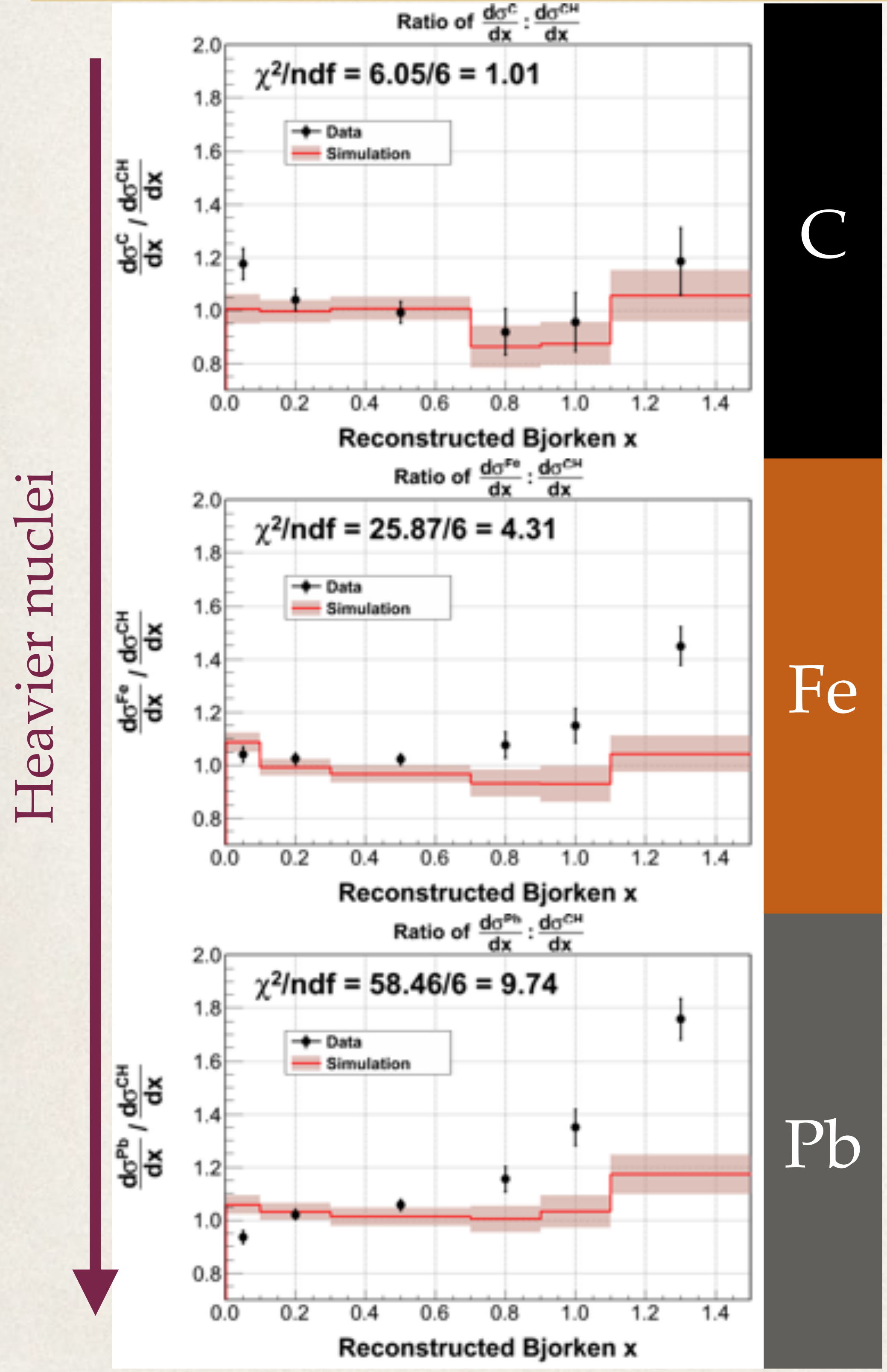
MINERvA's nuclear target region allows us to look at scattering on different materials, to see how the the composition of the nucleus affects cross section



We look at the **charged-current inclusive** cross sections: **all** interactions that produce a negative muon.

Oscillation experiments need to understand cross sections on the materials their detectors are made of, especially if they can't take near/far detector ratios

CC-inclusive cross sections on nuclei



- Bjorken x characterizes the type of interaction

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

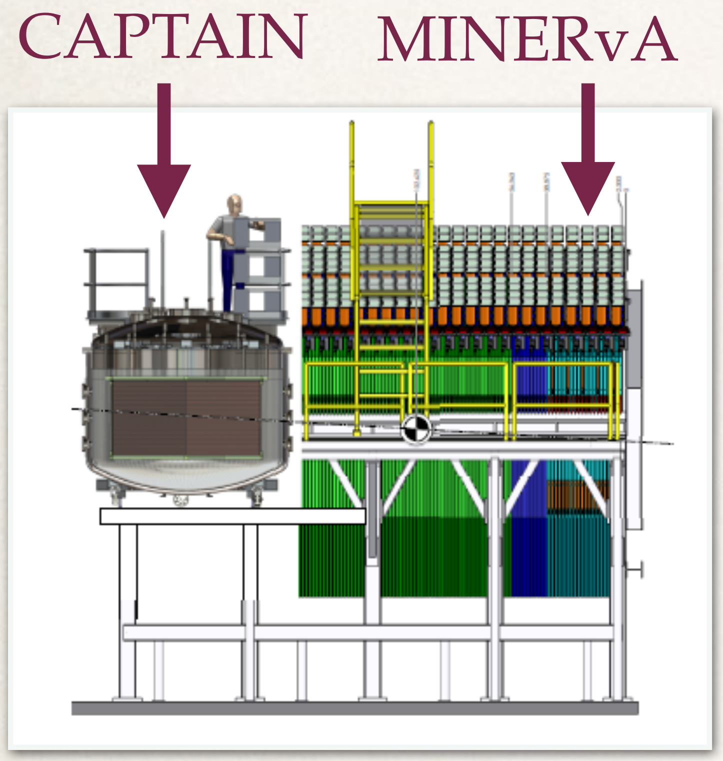
- Our simulation
  - **overestimates at low x** *(shadowing region)*
  - **underestimates at high x** (*more elastic*)
- …with an effect **more pronounced for heavier nuclei**

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

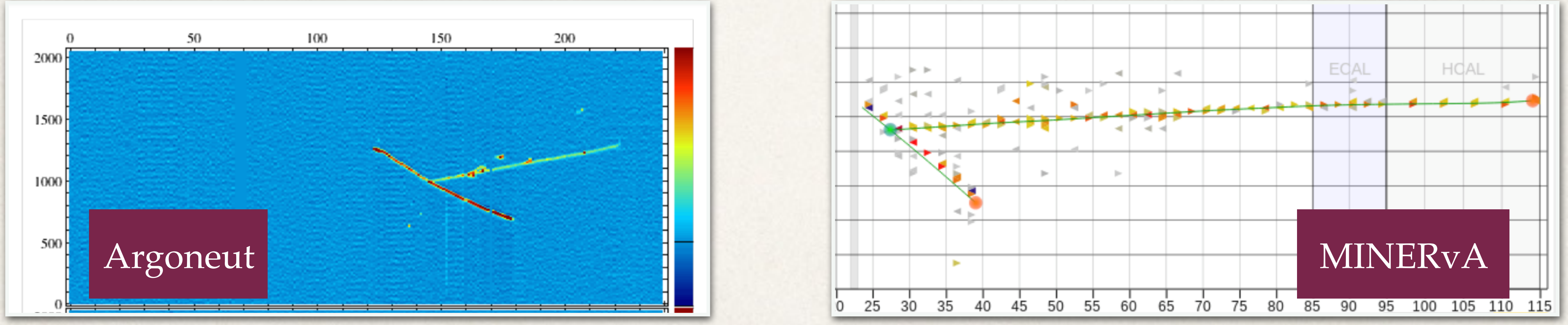
- But it's vital we understand cross sections on these materials
- MINERvA's **medium-energy dataset** will provide a large, DIS-rich sample to test this further and look at individual interaction channels

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

CAPTAIN-MINERvA



- Oscillation experiments (T2K) are already using MINERvA's cross section measurements
- But DUNE 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 DUNE oscillation maximum

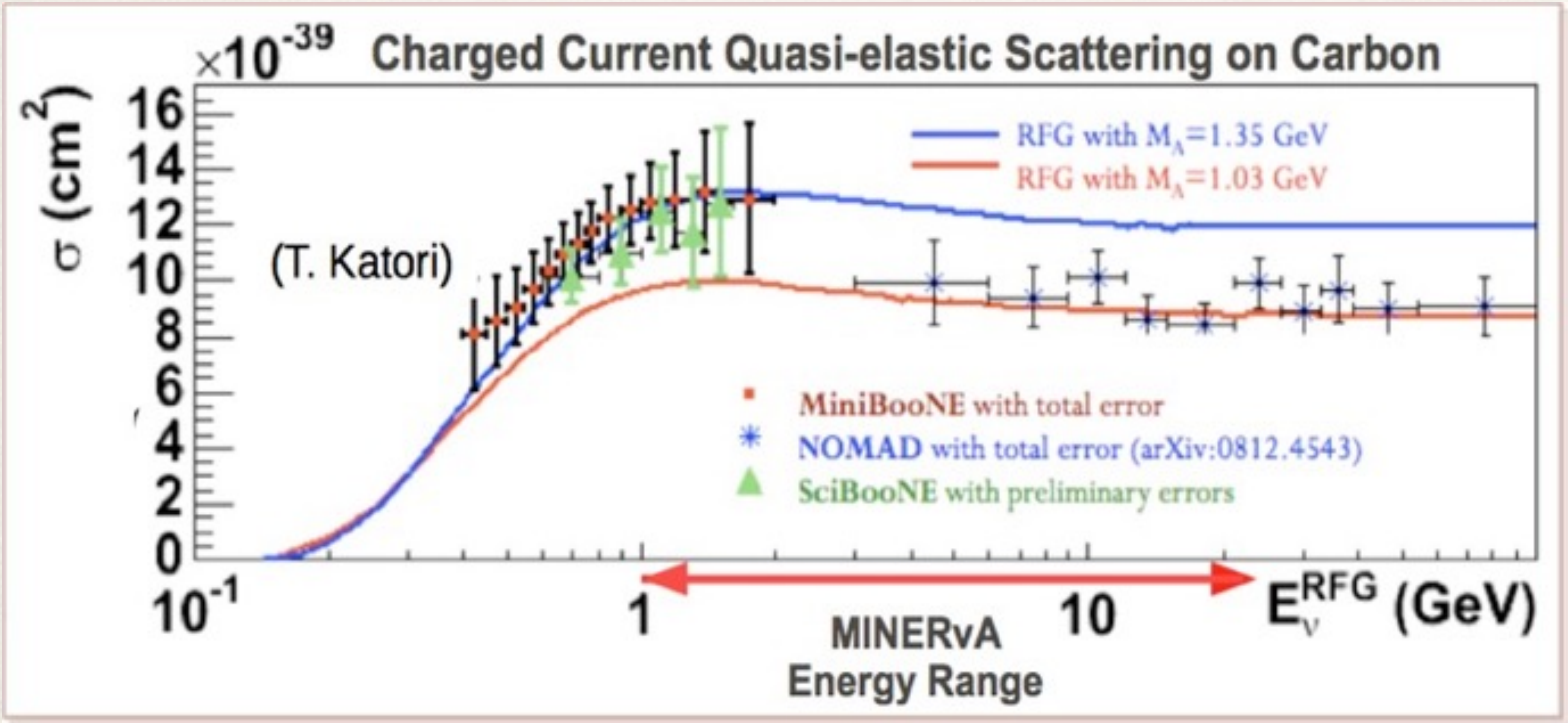


Comparison of similar event displays in LAr TPC (Argoneut) and MINERvA tracker

Thanks for your attention!

Backup slides

Limitations of RFG model

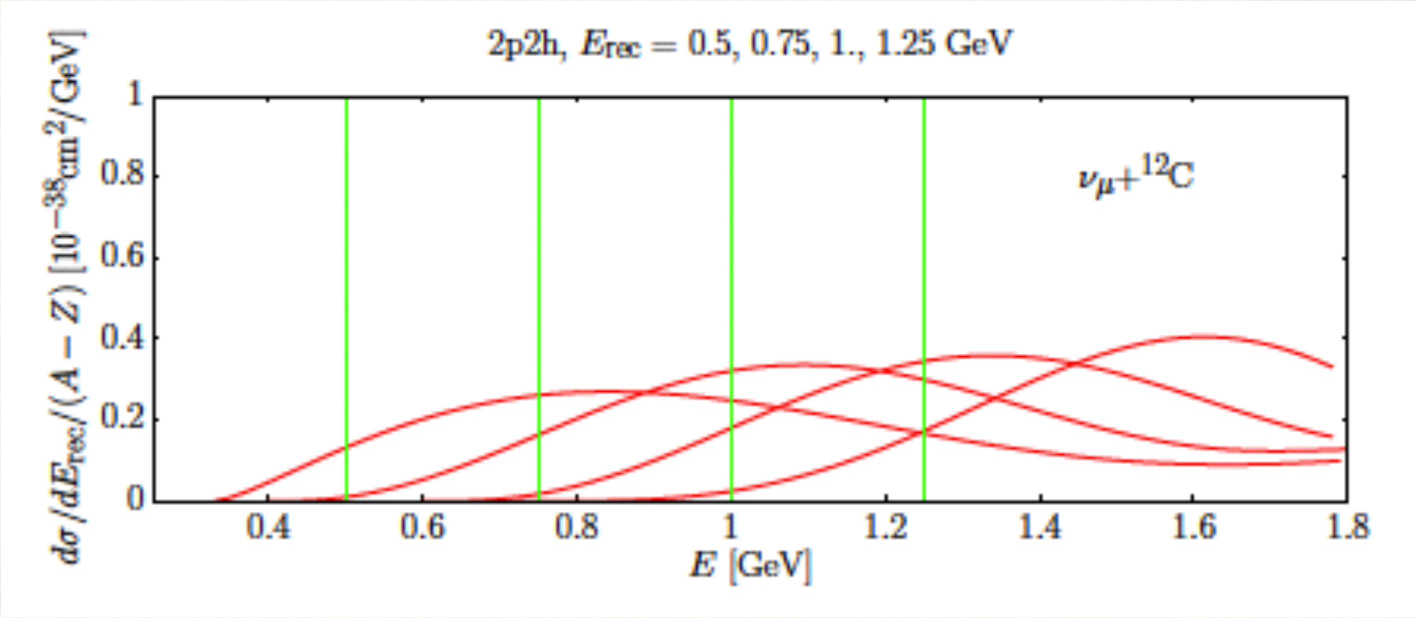


Best fits of MiniBooNE, SciBooNE and NOMAD cross-sections to RFG

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

Lower-energy experiments predict M_A=1.35 GeV, NOMAD predicts M_A=1.03 GeV

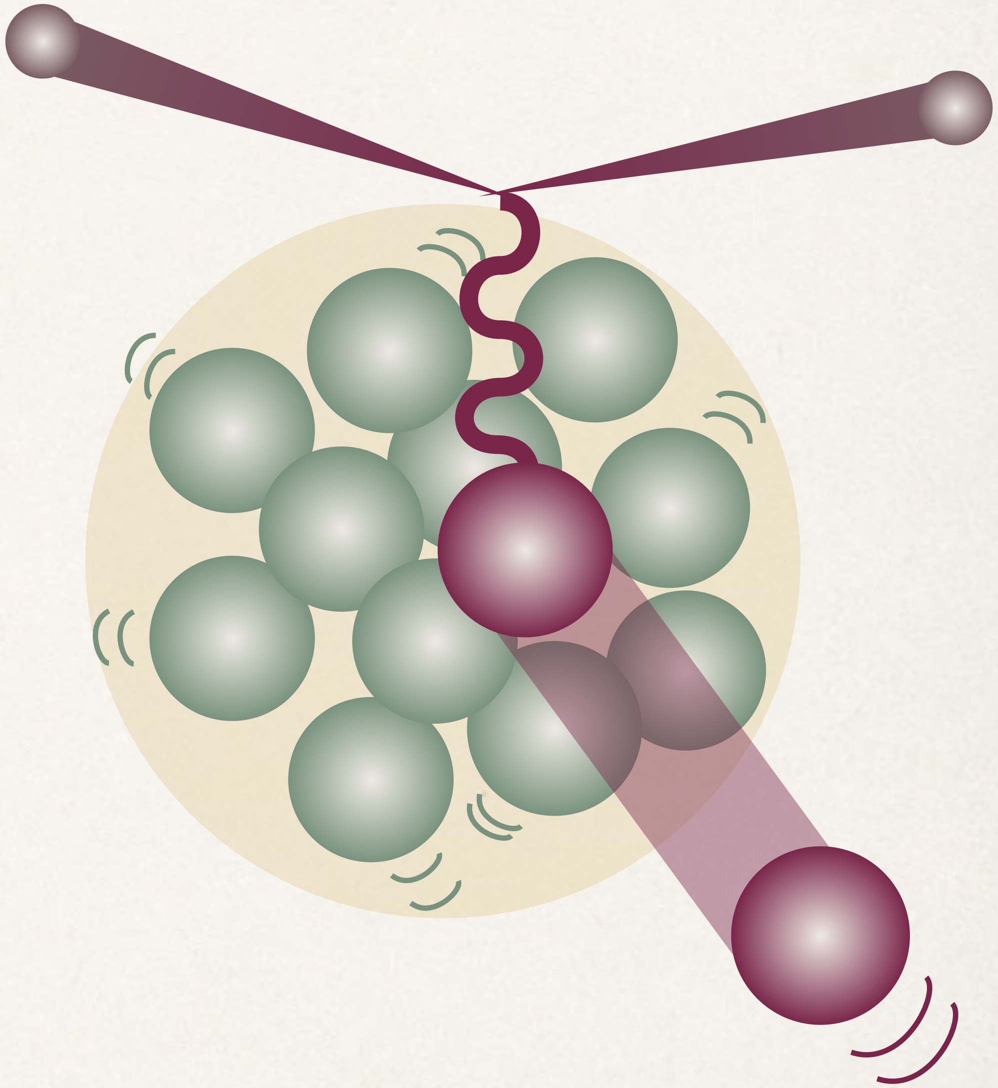
- We could be seeing additional **nuclear effects beyond the RFG model**
- **Correlated nucleon pairs** have been observed in electron scattering (JLab)
- These can affect **energy reconstruction**, and can cause **extra nucleons** to be emitted



Energy resolution with correlated pairs

Nucleons in the nucleus

- In a heavy nucleus, nucleons are **not stationary**
- They interact with the other nucleons
- A commonly-used simulation of this is the Relativistic Fermi Gas model
  - Treat nucleons as independent particles, but in a **mean field** generated by the rest of the nucleus
  - Initial-state momenta are **Fermi distributed**
  - Pauli blocking
- Cross-sections can be modeled by a multiplier to the Llewellyn Smith cross-section

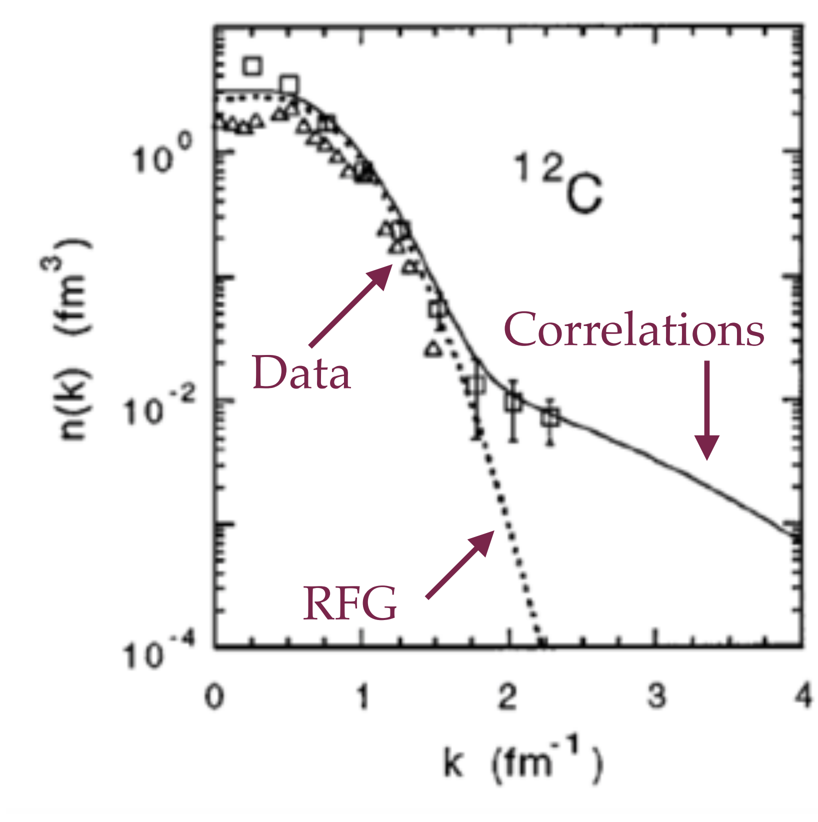


R. Smith and E. Moniz, Nucl.Phys. B43, 605 (1972); Bodek, S. Avvakumov, R. Bradford, and H. S. Budd, J.Phys.Conf.Ser. 110, 082004 (2008);

Modeling nuclear effects

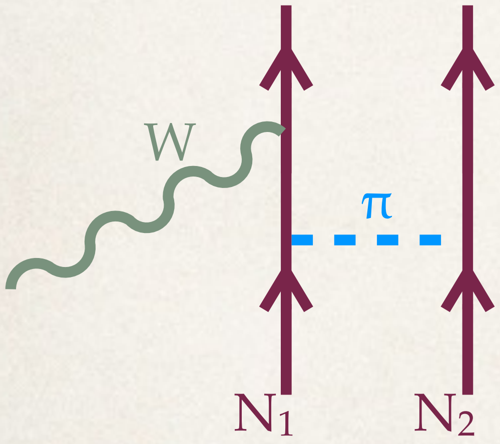
Relativistic Fermi Gas (RFG) extensions

- 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)



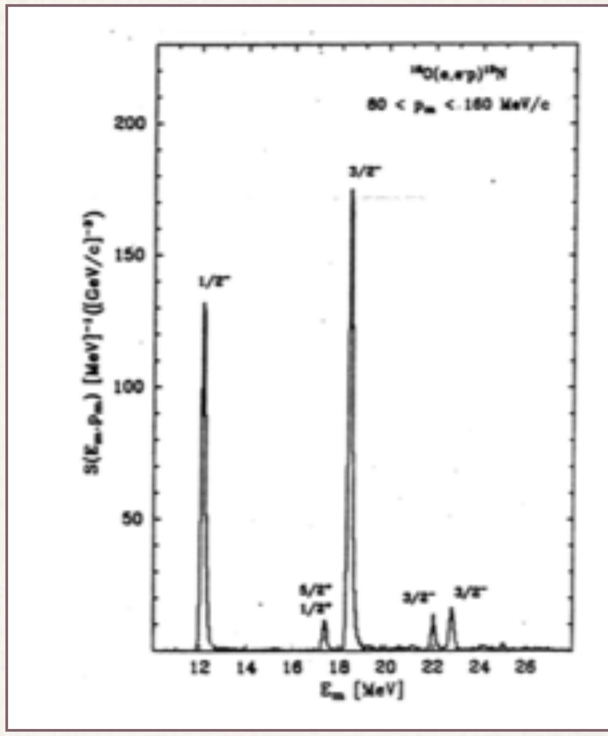
Example meson exchange current interaction, from a more detailed list (J Morfín). This illustrates a correlation.

- 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*
- These can address both short- and medium-range correlations and interactions between nucleons

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)*

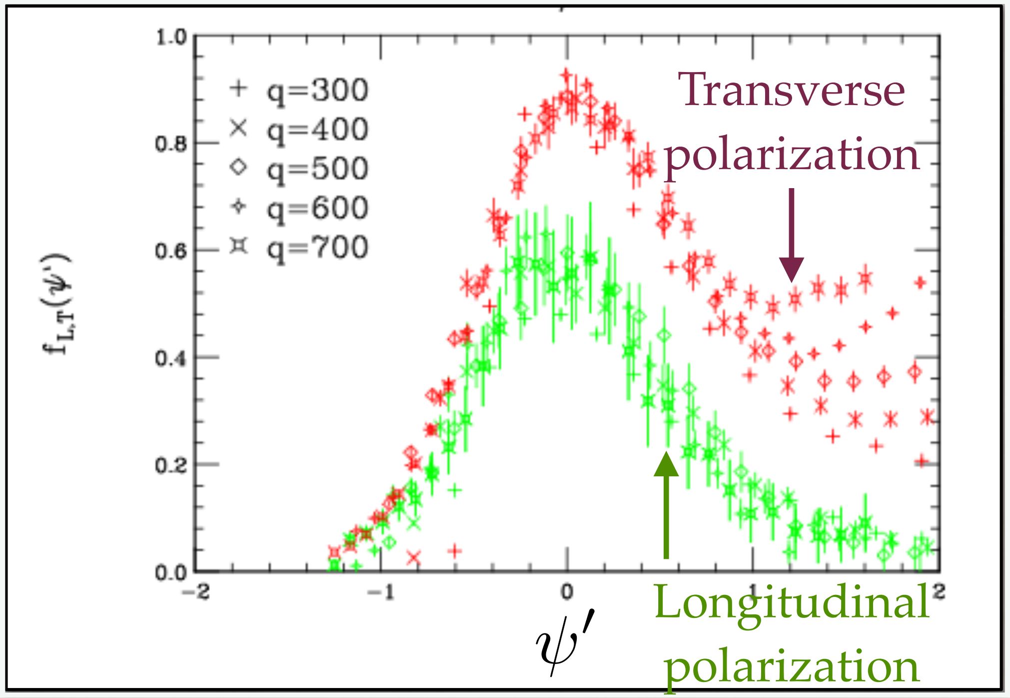


O. Benhar, NuSTEC school 2014

Transverse Enhancement Model (TEM)

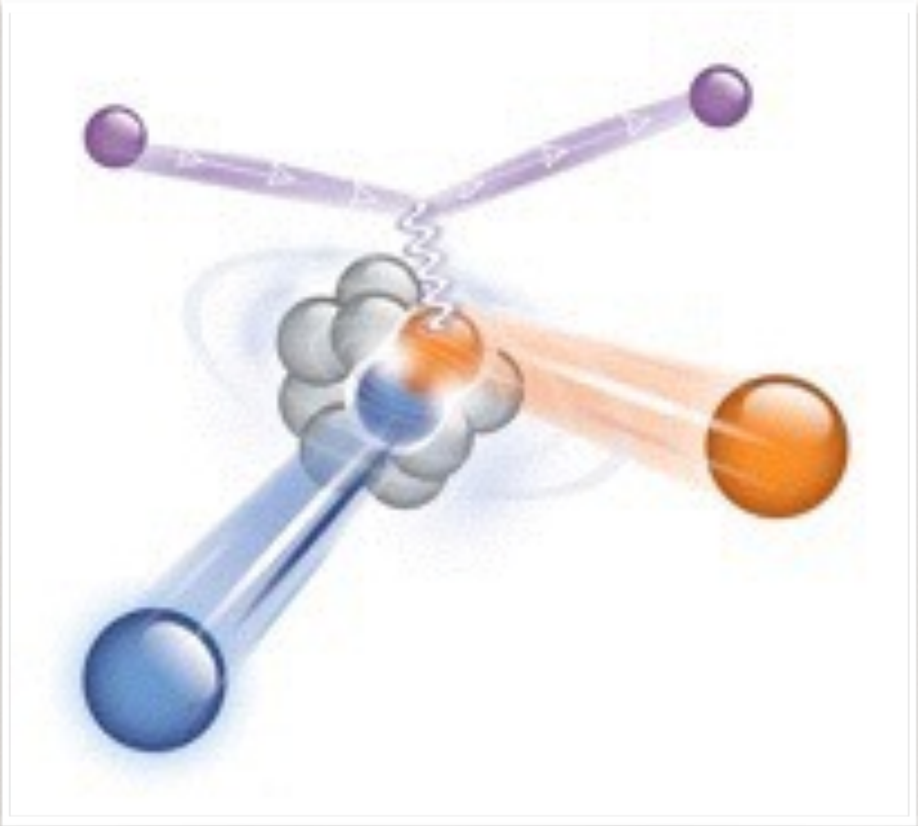
$$F_1(Q^2) = \frac{G_E + \tau G_M}{1+\tau} \qquad \xi F_2(Q^2) = \frac{G_M - G_E}{1+\tau}$$

- 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)*
- This was seen in pure vector scattering - how does it extend to weak (V-A) interactions?



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

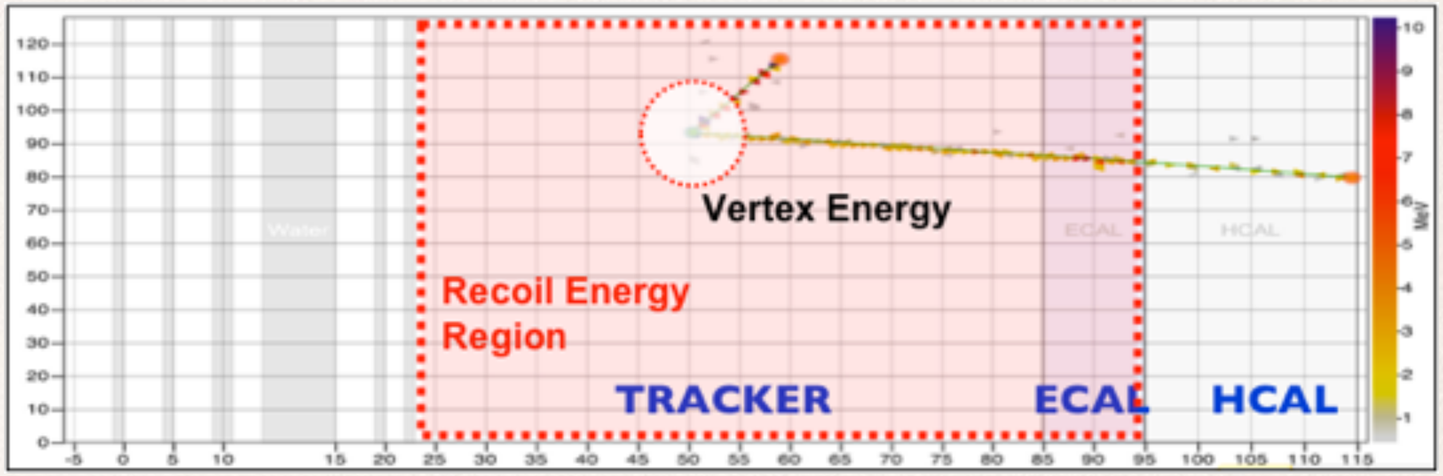
Energy around the vertex



R. Subedi et al.2008 Science 320 1476

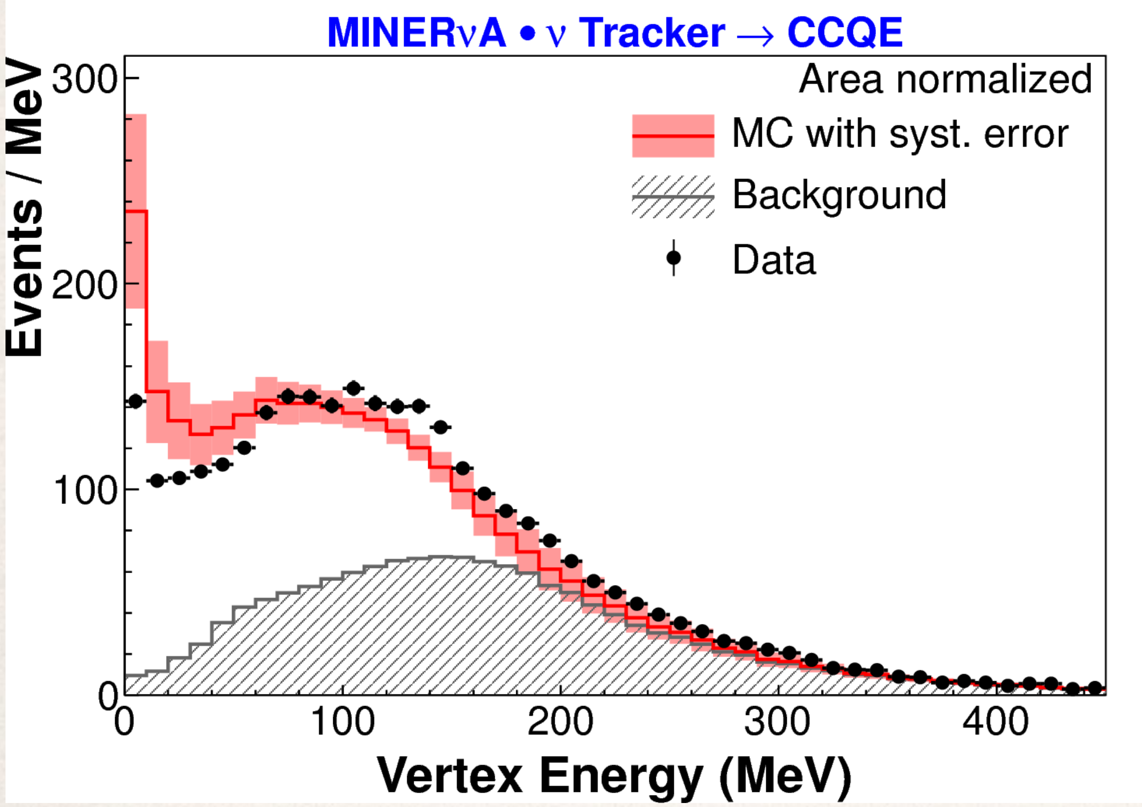
Transverse enhancement parameterizes a model with **correlated pairs** of nucleons

If a neutrino interacts with a paired nucleon, its partner may also be ejected



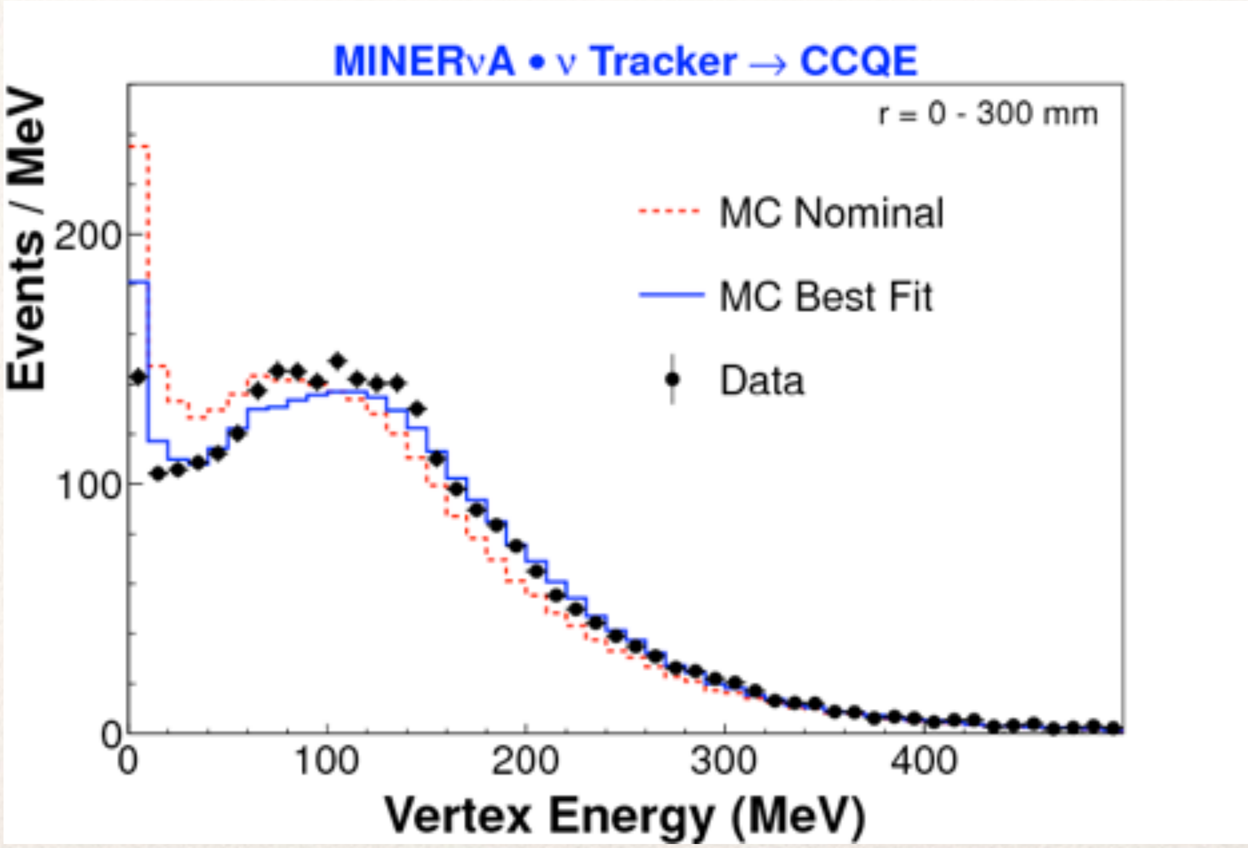
- Recall that we neglected an **area around the vertex** when we counted the total recoil energy
- We now compare the non-track energy deposited within that region to our Monte Carlo, to look for evidence of **additional nucleons**
- Our "vertex region" would contain nucleons with an energy up to 225 MeV (neutrino mode) or 120 MeV (antineutrino mode)

Vertex energy - extra protons

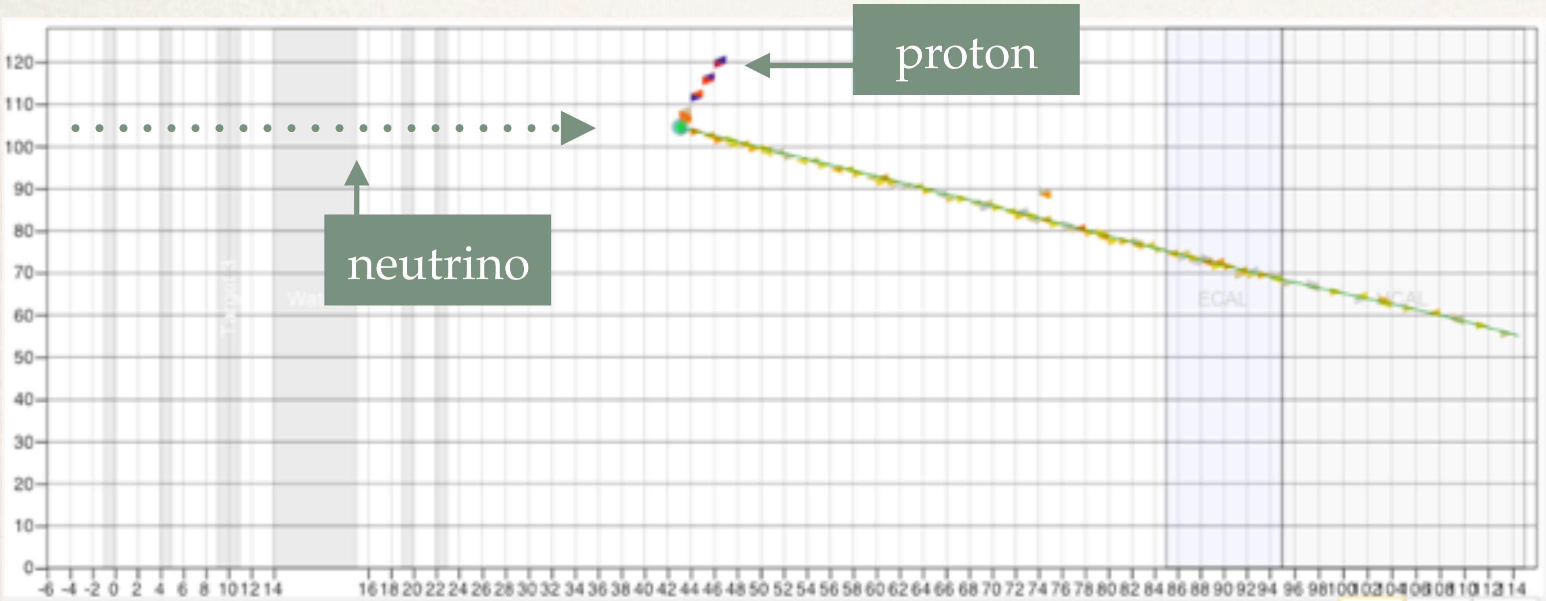


- A **harder neutrino-mode energy spectrum** is seen in data than Monte Carlo
- It is not seen in antineutrino mode
- We simulated extra protons with kinetic energies up to 225 MeV to see how this would change the Monte Carlo distribution

- 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



Quasi-elastics from proton kinematics

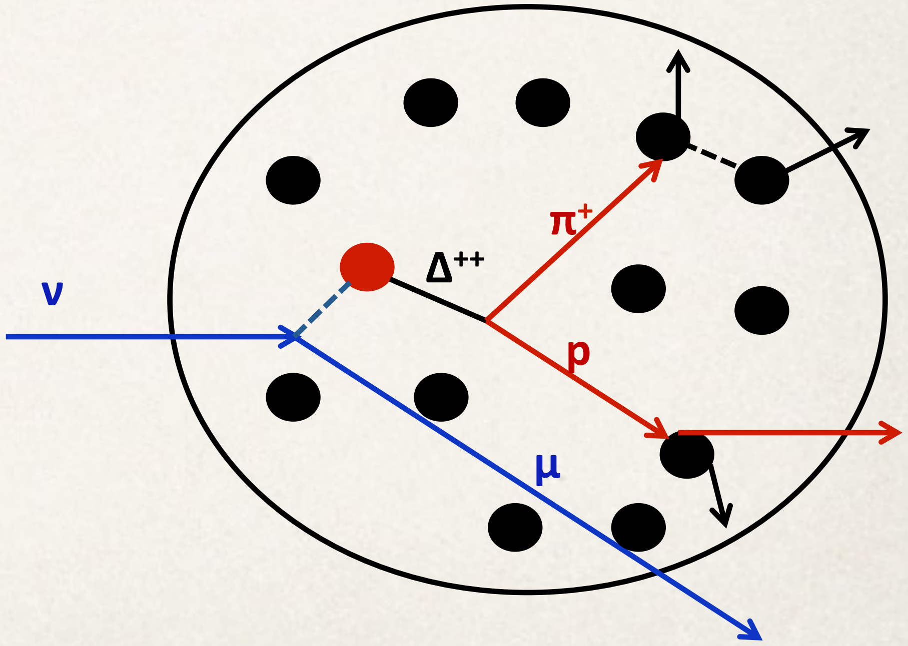


- Instead of using the muon, we can instead reconstruct Q^2 from the kinematics of a **stopping proton**
- Protons can undergo **final-state interactions**, so this is particularly **sensitive to FSI modeling**

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

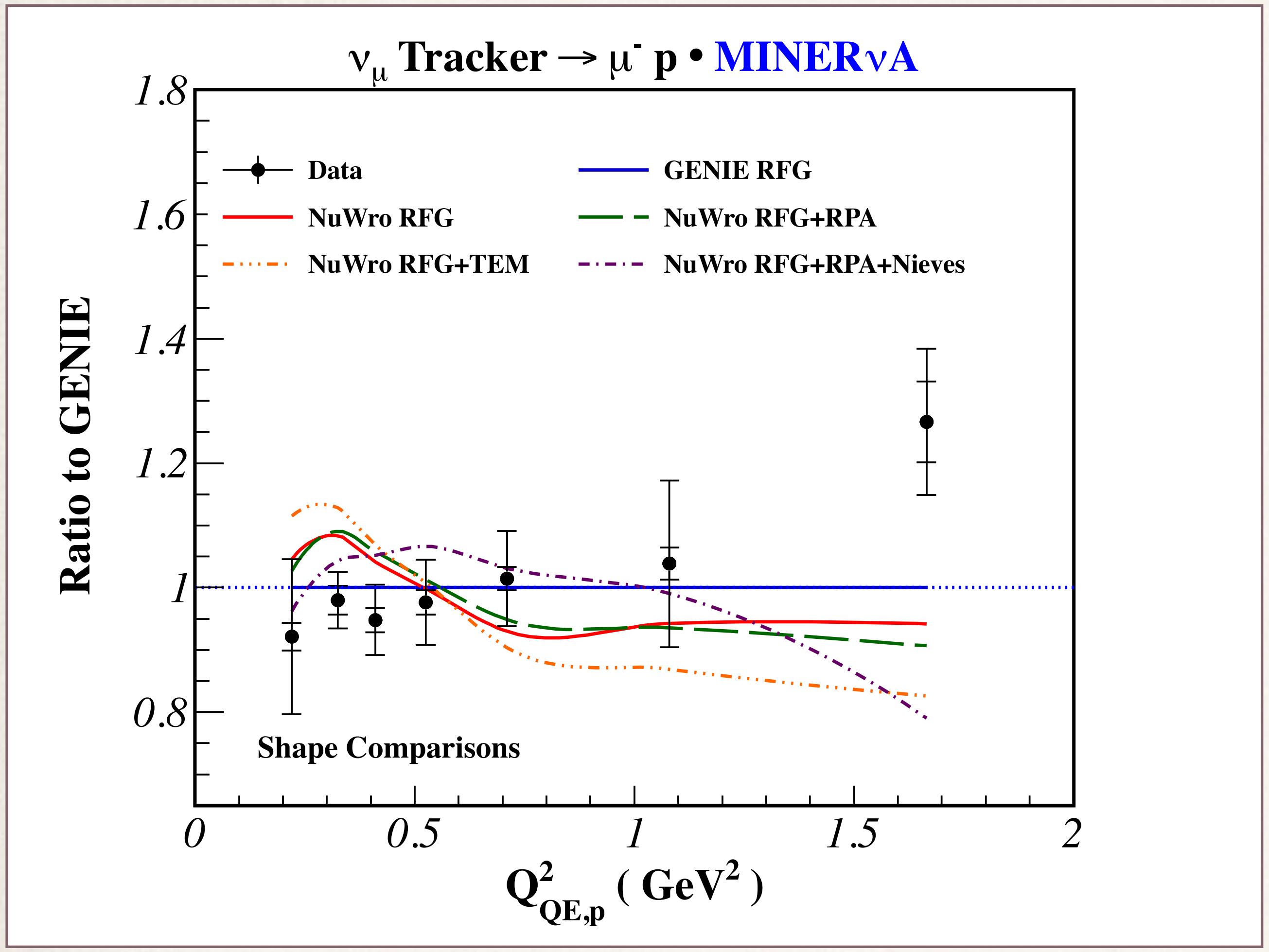
$M_{n,p}$ = neutron, proton mass, T_p=proton KE, E_B=binding energy

- In this study, our signal definition is QE-like, based on final-state particles
- Thus our signal includes some resonant and DIS interactions



Final-state interactions

Quasi-elastics from proton kinematics

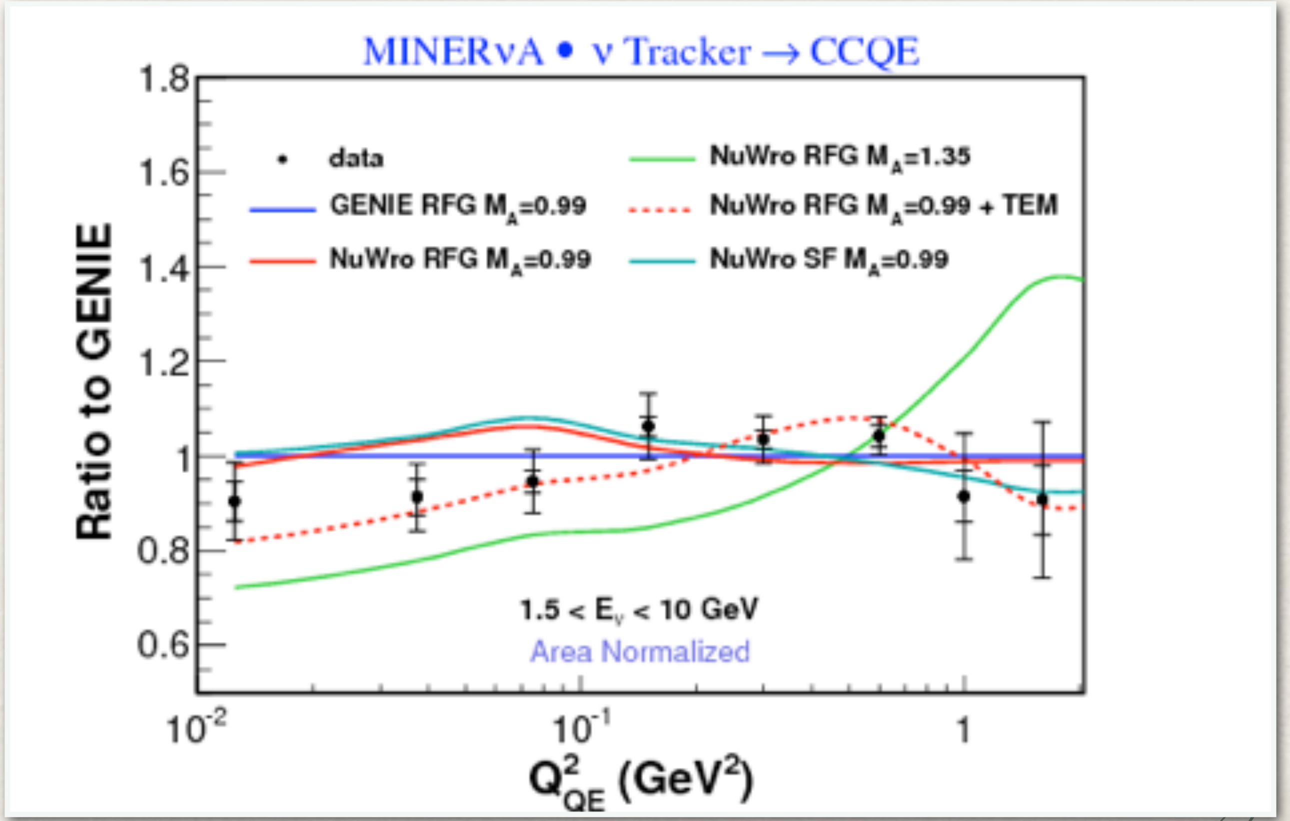


T Walton et al, Phys. Rev. D 91, 071301(R)

- 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

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

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



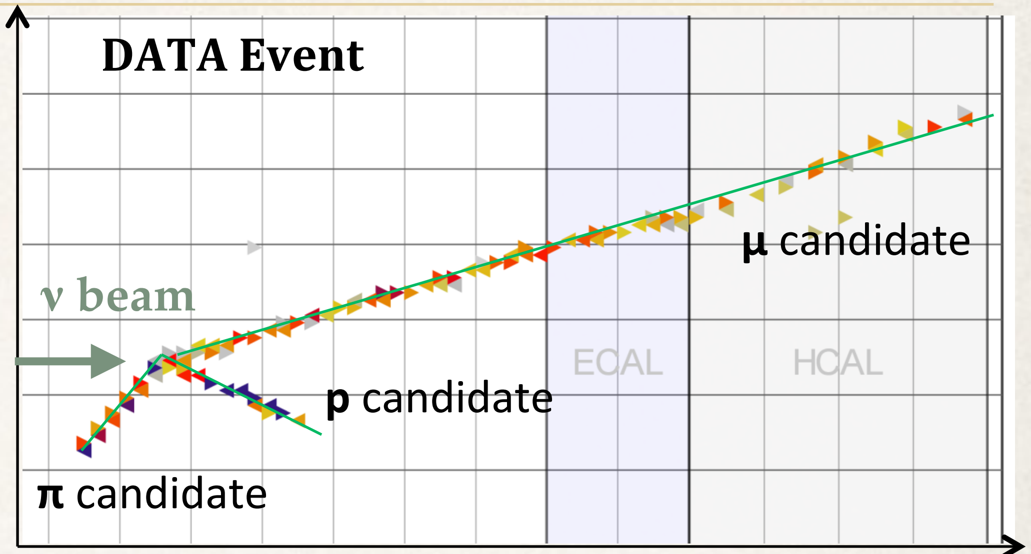
Charged-current $\pi^\pm$ production from ν

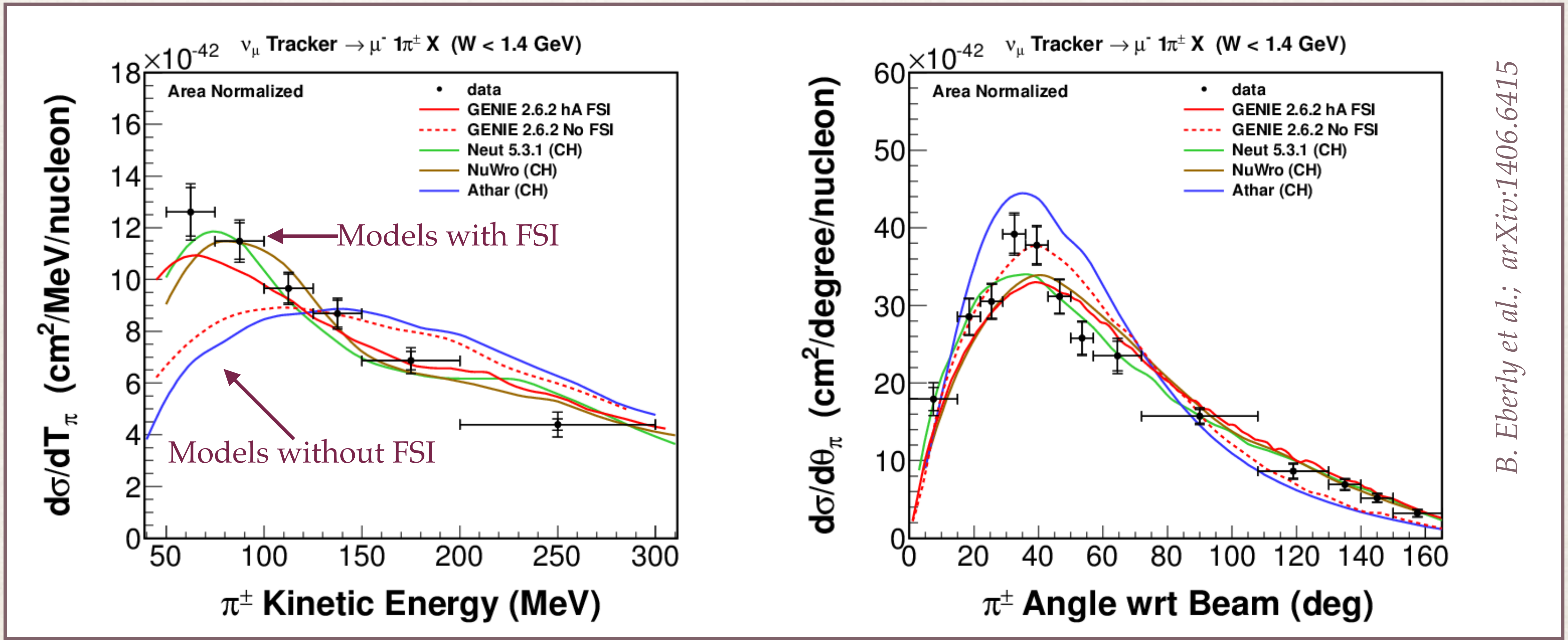
$$\nu_\mu A \to \mu^- \pi^\pm X$$

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

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

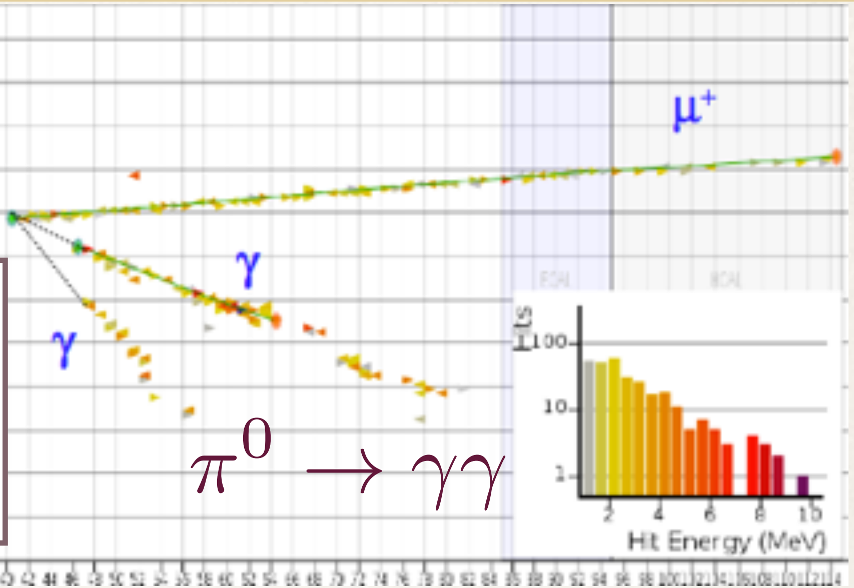
$$\bar{\nu}_\mu A \rightarrow \mu^+ \pi^0 X$$

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

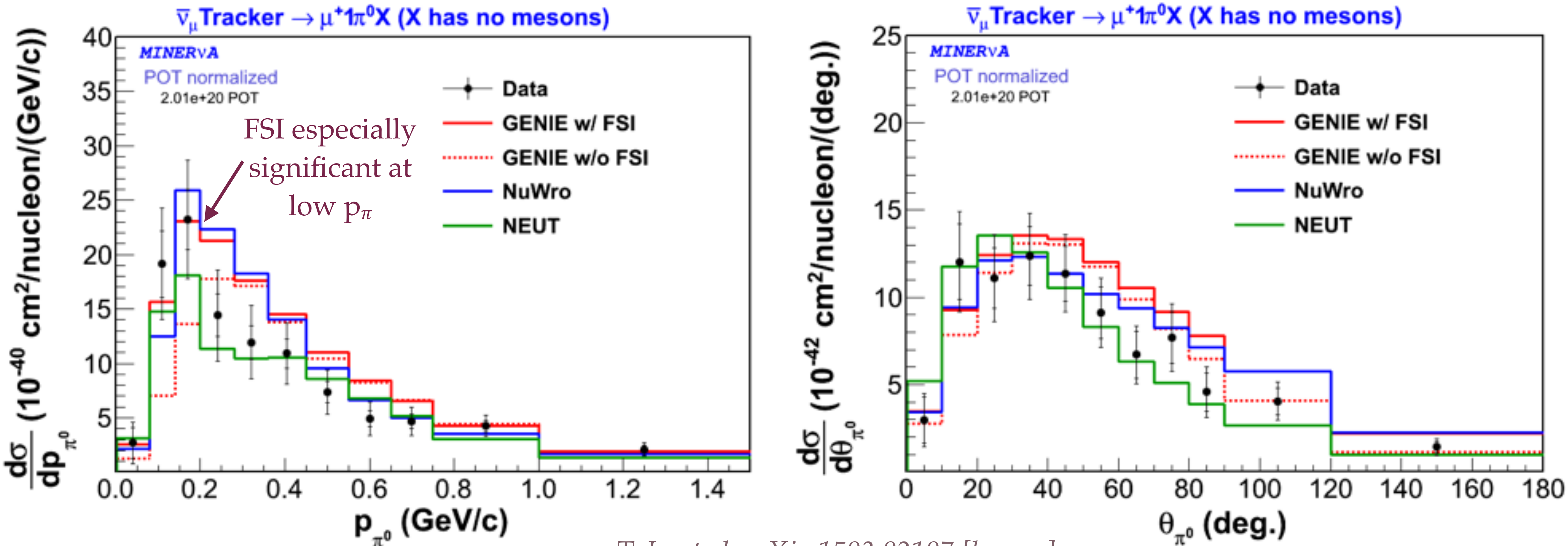
This can help evaluate the approximations made in different generators' FSI models

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

$\bar{\nu}$ beam



$\pi^0 \rightarrow \gamma\gamma$



FSI especially significant at low p_π

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

NUMI beamline

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

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

Neutrinos!

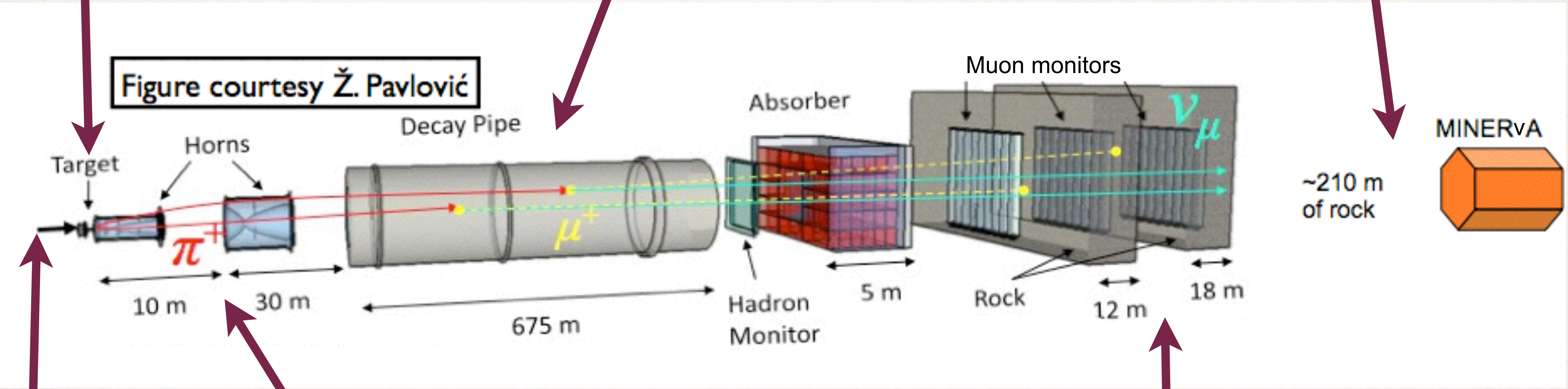


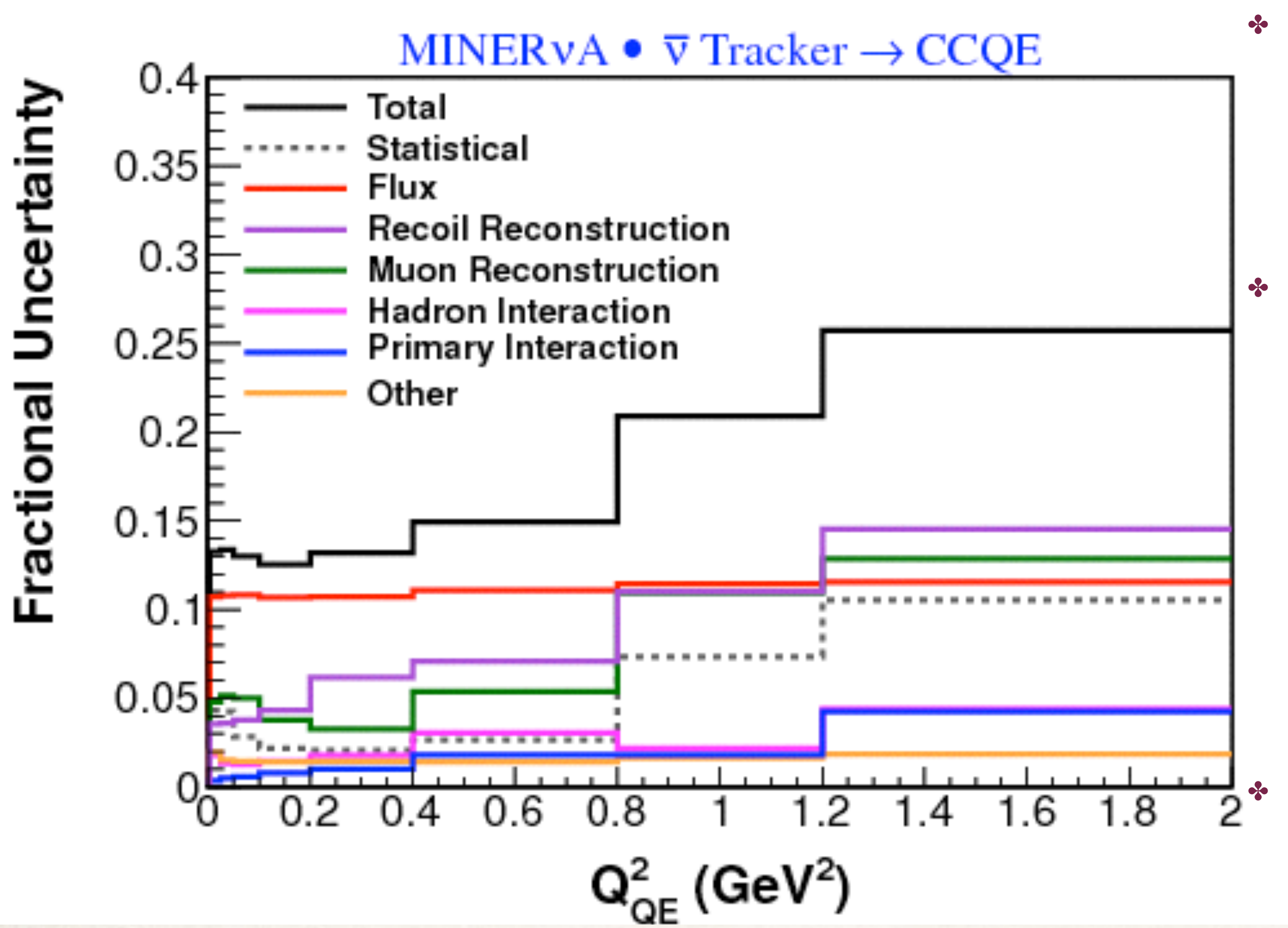
Figure courtesy Ž. Pavlović

120 GeV protons

Horns focus one charge of meson and defocus the other, leading to neutrinos or antineutrinos

Rocks remove muons from beam

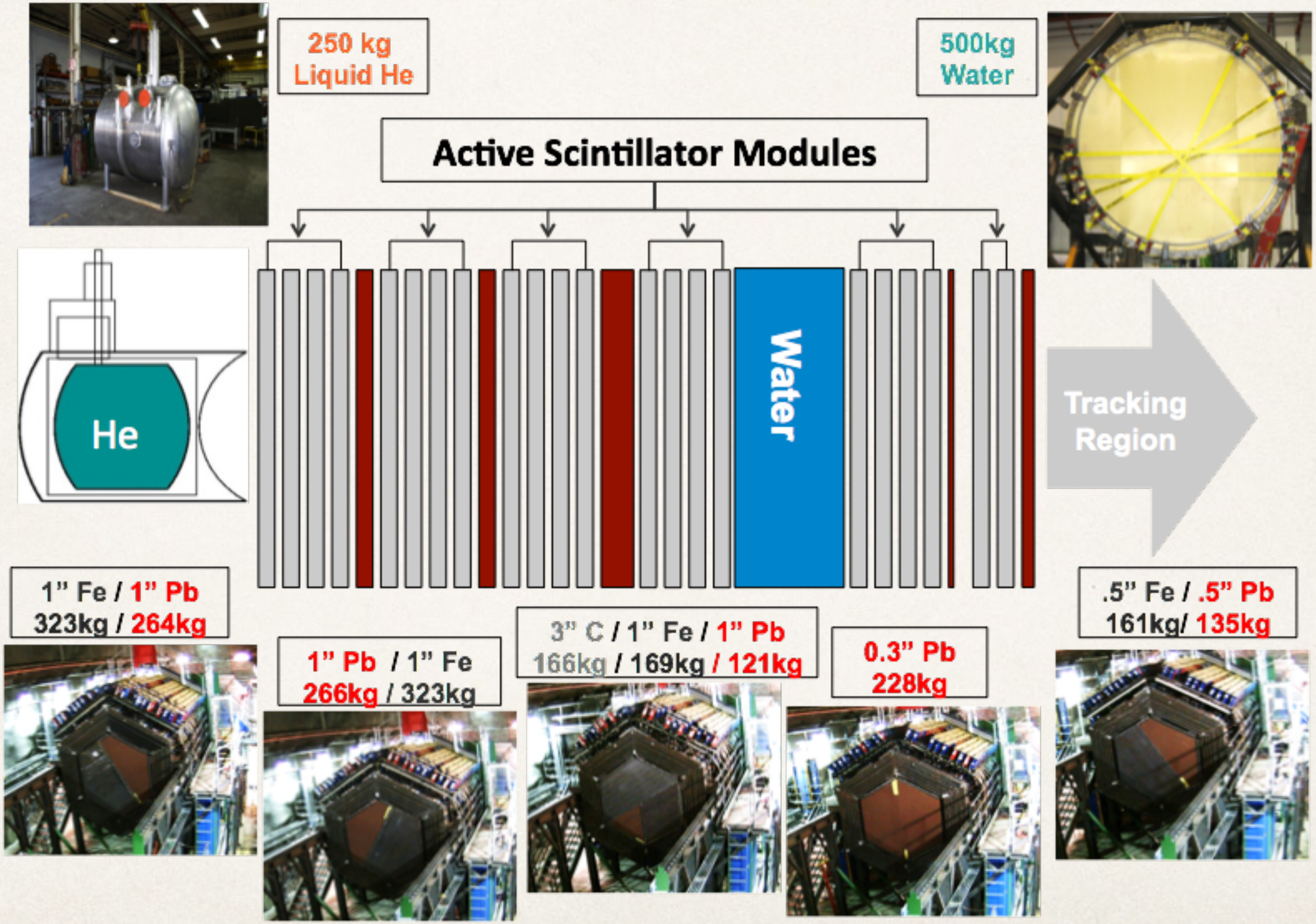
Sources of systematic uncertainty



- 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**
  - recoil energy due to particle
  - 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**

Interactions on nuclear targets



250 kg
Liquid He

500kg
Water

Active Scintillator Modules

He

Water

Tracking
Region

1" Fe / 1" Pb
323kg / 264kg

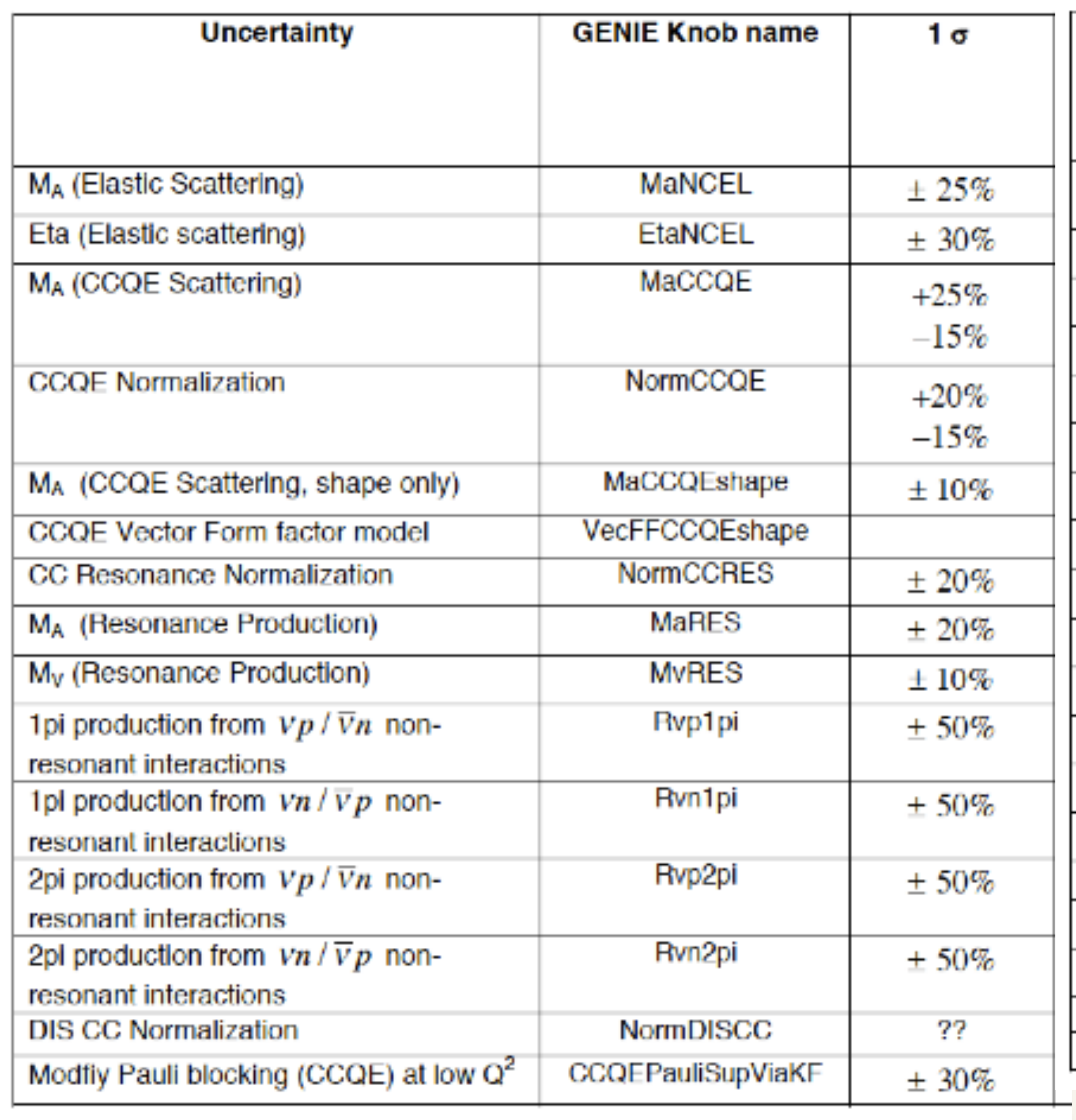
1" Pb / 1" Fe
266kg / 323kg

3" C / 1" Fe / 1" Pb
166kg / 169kg / 121kg

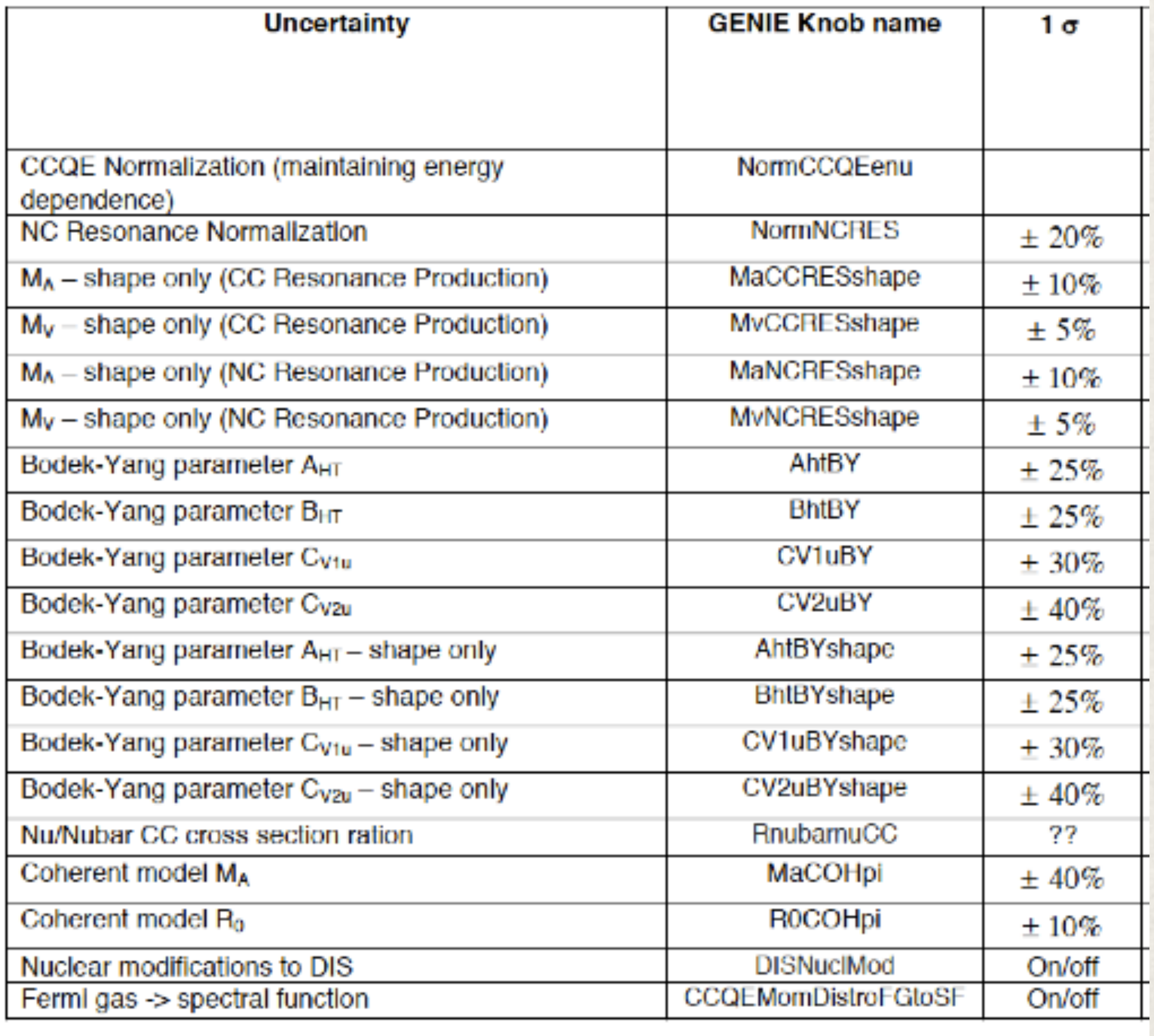
0.3" Pb
228kg

.5" Fe / .5" Pb
161kg/ 135kg

List of GENIE model uncertainties

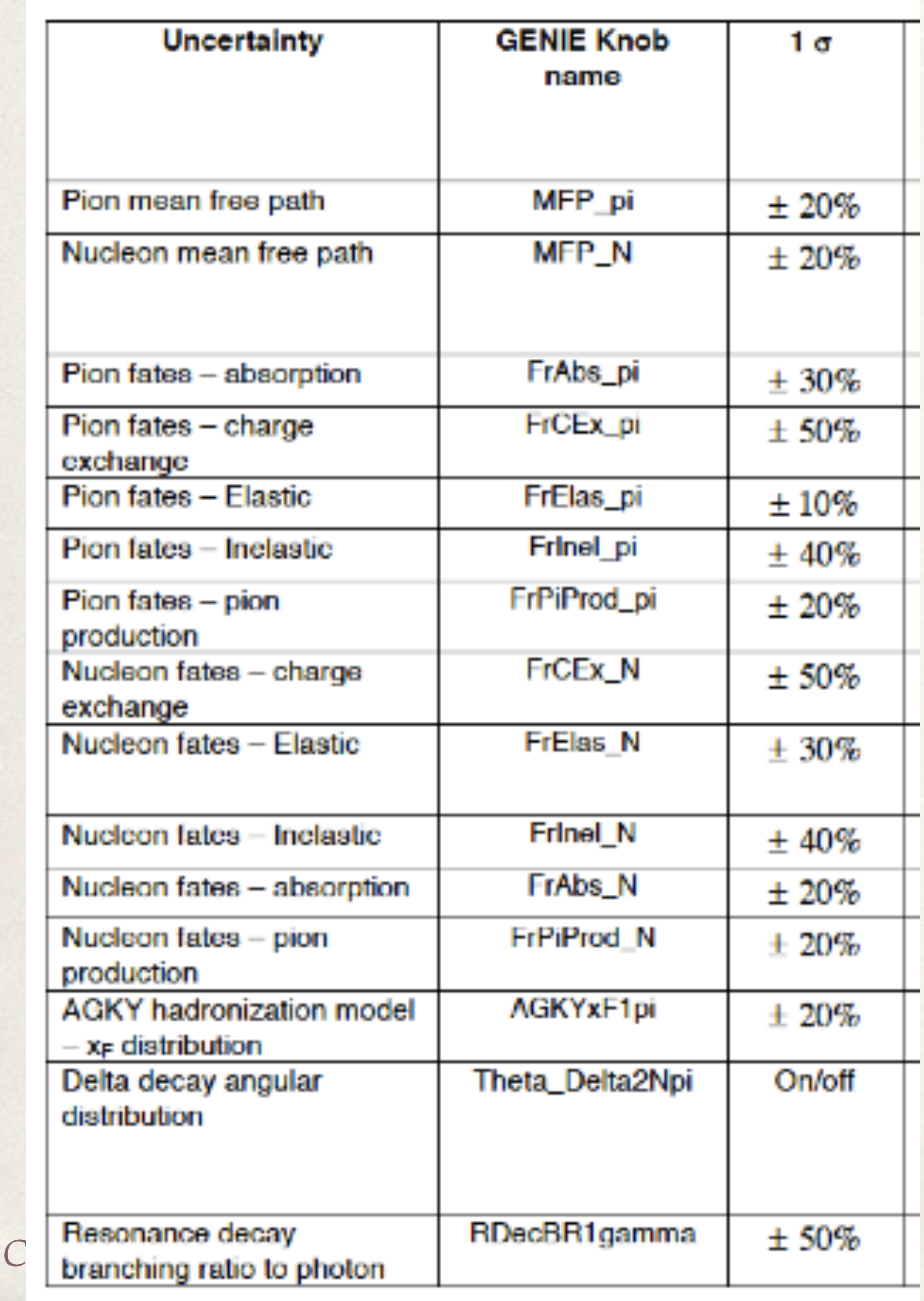


Uncertainty	GENIE Knob name	1 σ
M_A (Elastic Scattering)	MaNCEL	± 25%
Eta (Elastic scattering)	EtaNCEL	± 30%
M_A (CCQE Scattering)	MaCCQE	+25% −15%
CCQE Normalization	NormCCQE	+20% −15%
M_A (CCQE Scattering, shape only)	MaCCQEshape	± 10%
CCQE Vector Form factor model	VecFFCCQEshape	
CC Resonance Normalization	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%

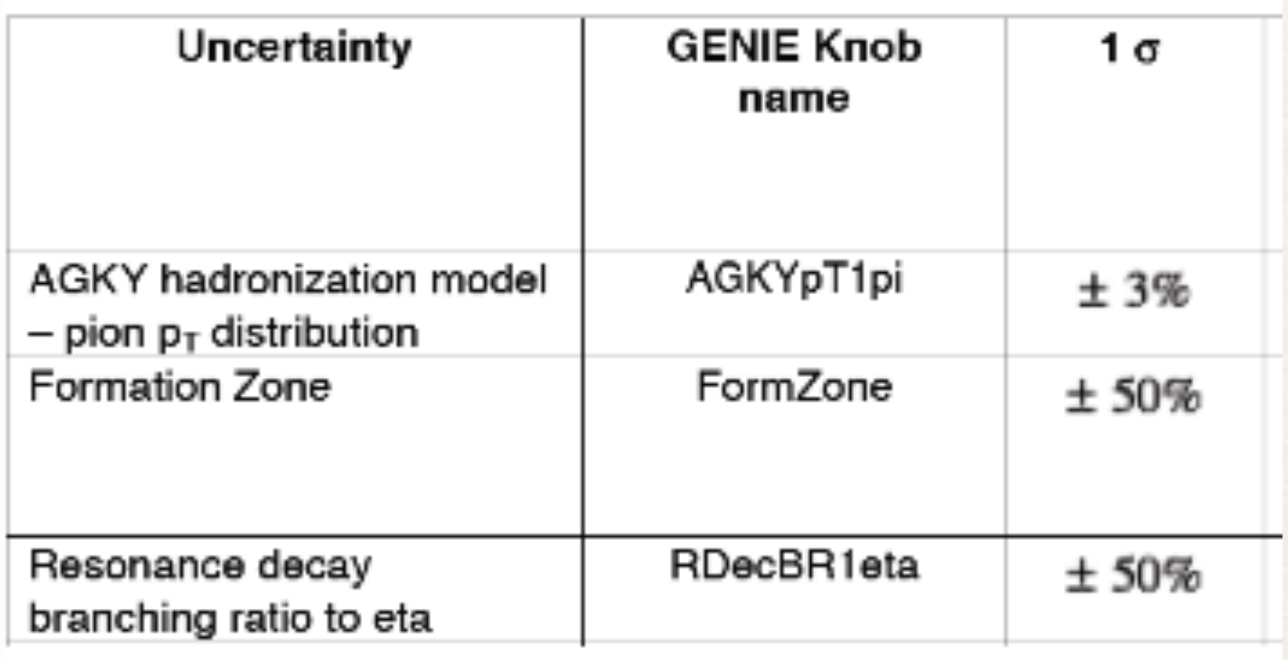


Uncertainty	GENIE Knob name	1 σ
CCQE Normalization (maintaining energy dependence)	NormCCQEenu	
NC Resonance Normalization	NormNCRES	± 20%
M_A – shape only (CC Resonance Production)	MaCCRESshape	± 10%
M_V – shape only (CC Resonance Production)	MvCCRESshape	± 5%
M_A – shape only (NC Resonance Production)	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%

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)