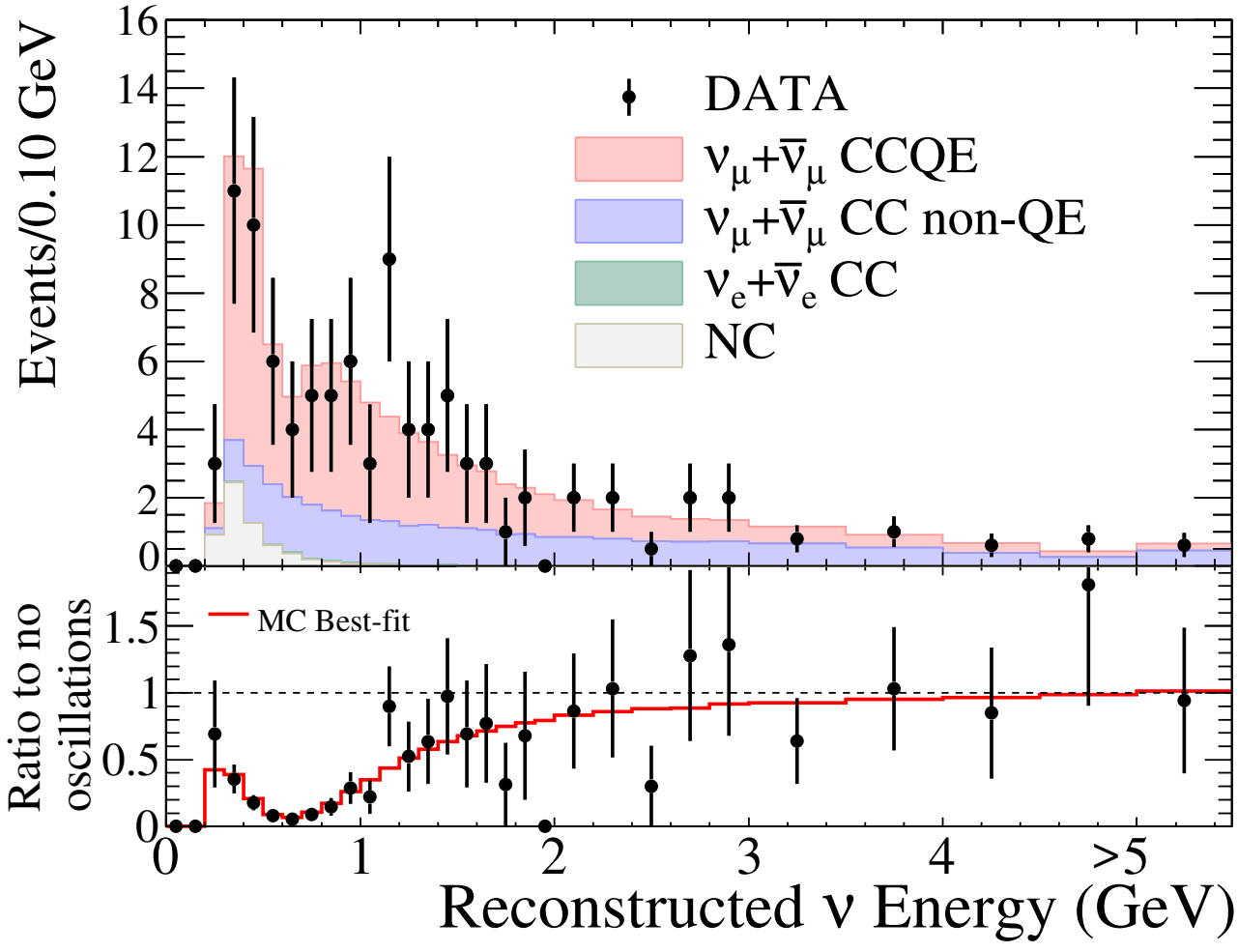
Neutrino-nucleus cross section measurements at MINERνA

Philip Rodrigues

March 12, 2014

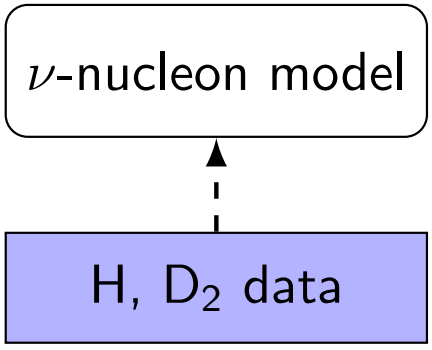
Why understand νA cross sections?

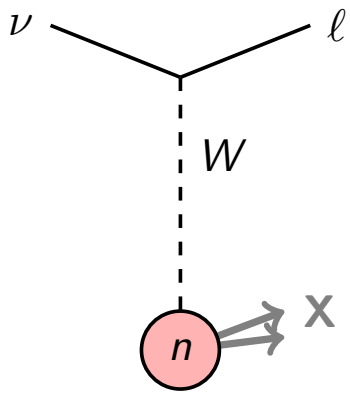
- For ν oscillations, infer $P_{\nu_\alpha \to \nu_\beta}(E_\nu)$ from measured N_{evt}, kinematics
- Eg, T2K ν_μ spectrum at SuperK:



arXiv:1403.1532 and Patrick de Perio's talk

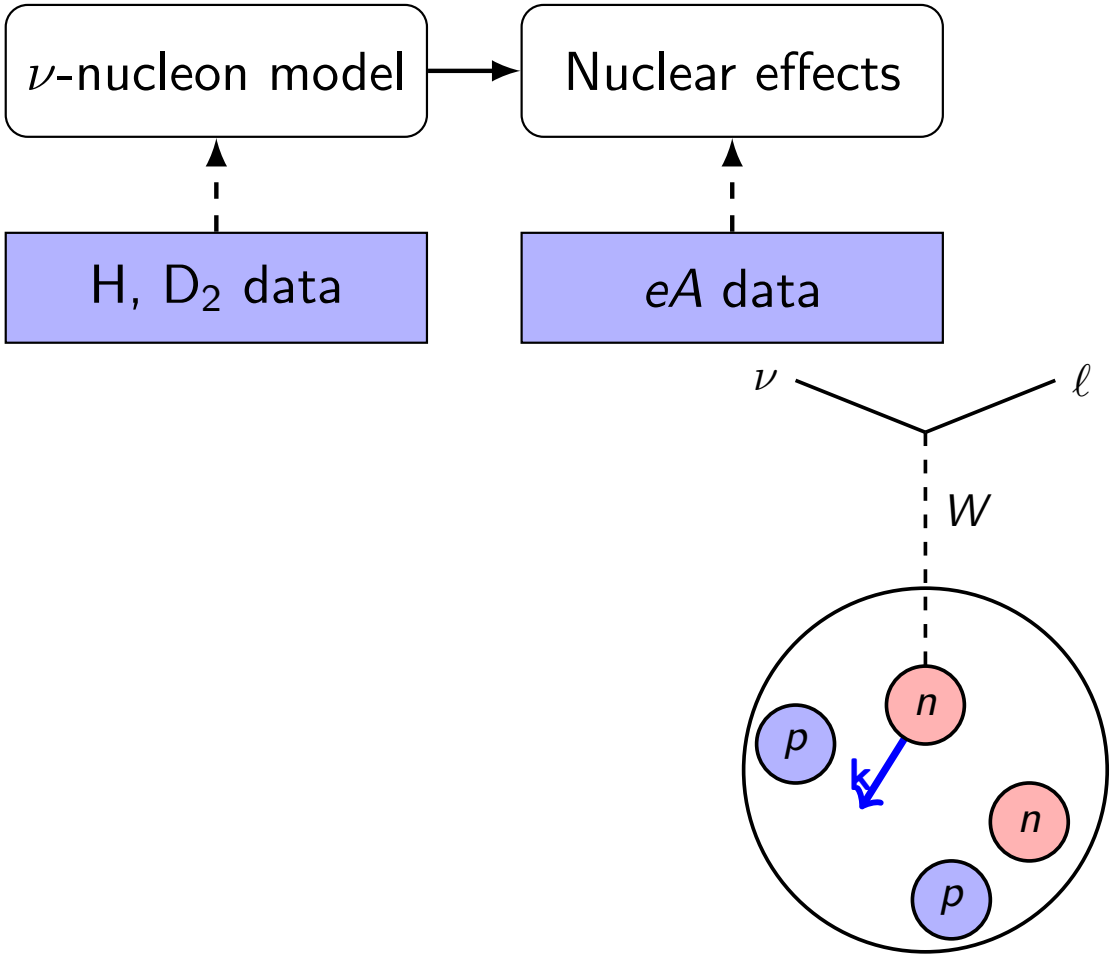
Ingredients to understand νA cross sections





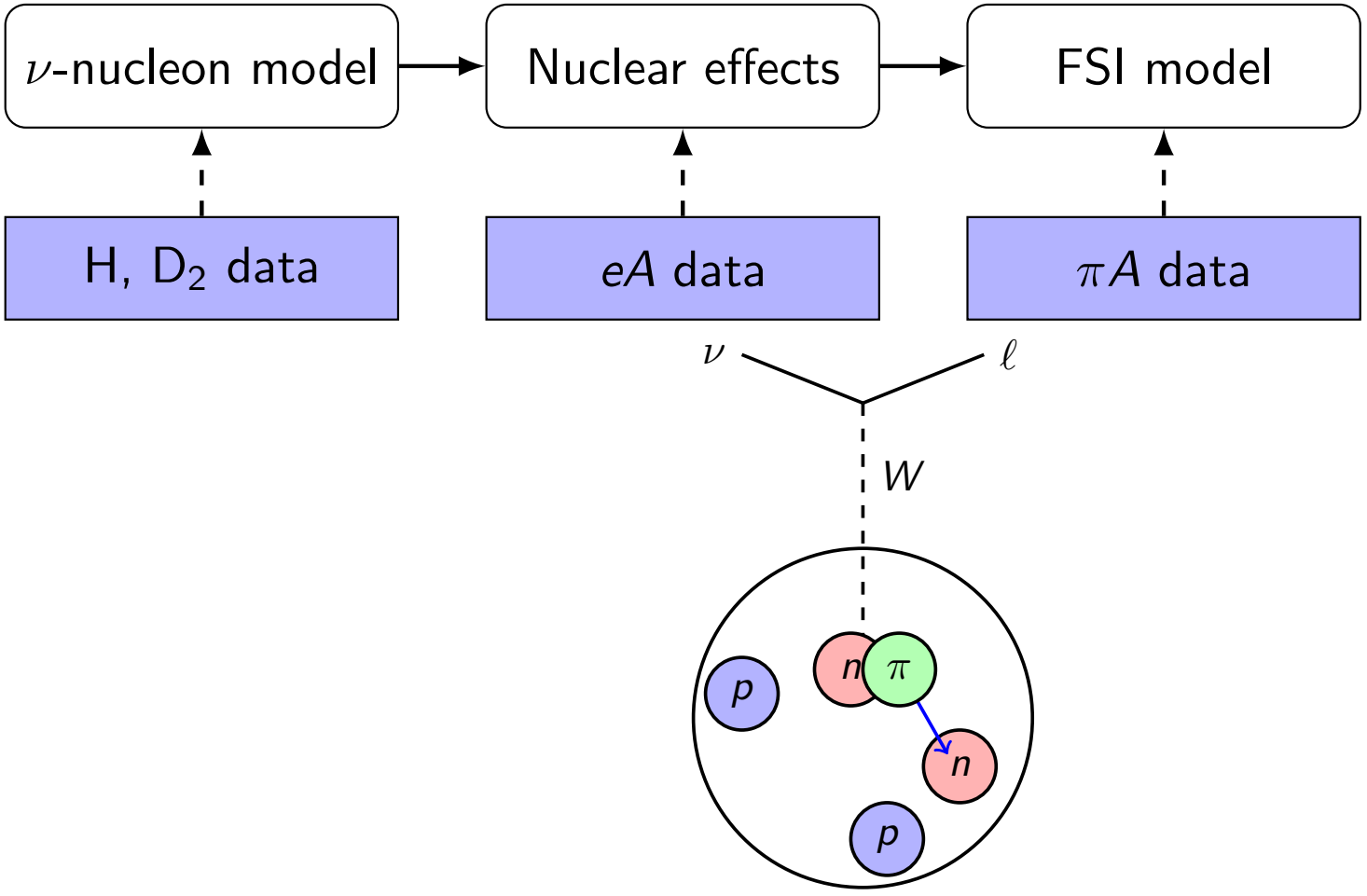
- Model neutrino scattering on free nucleons

Ingredients to understand νA cross sections



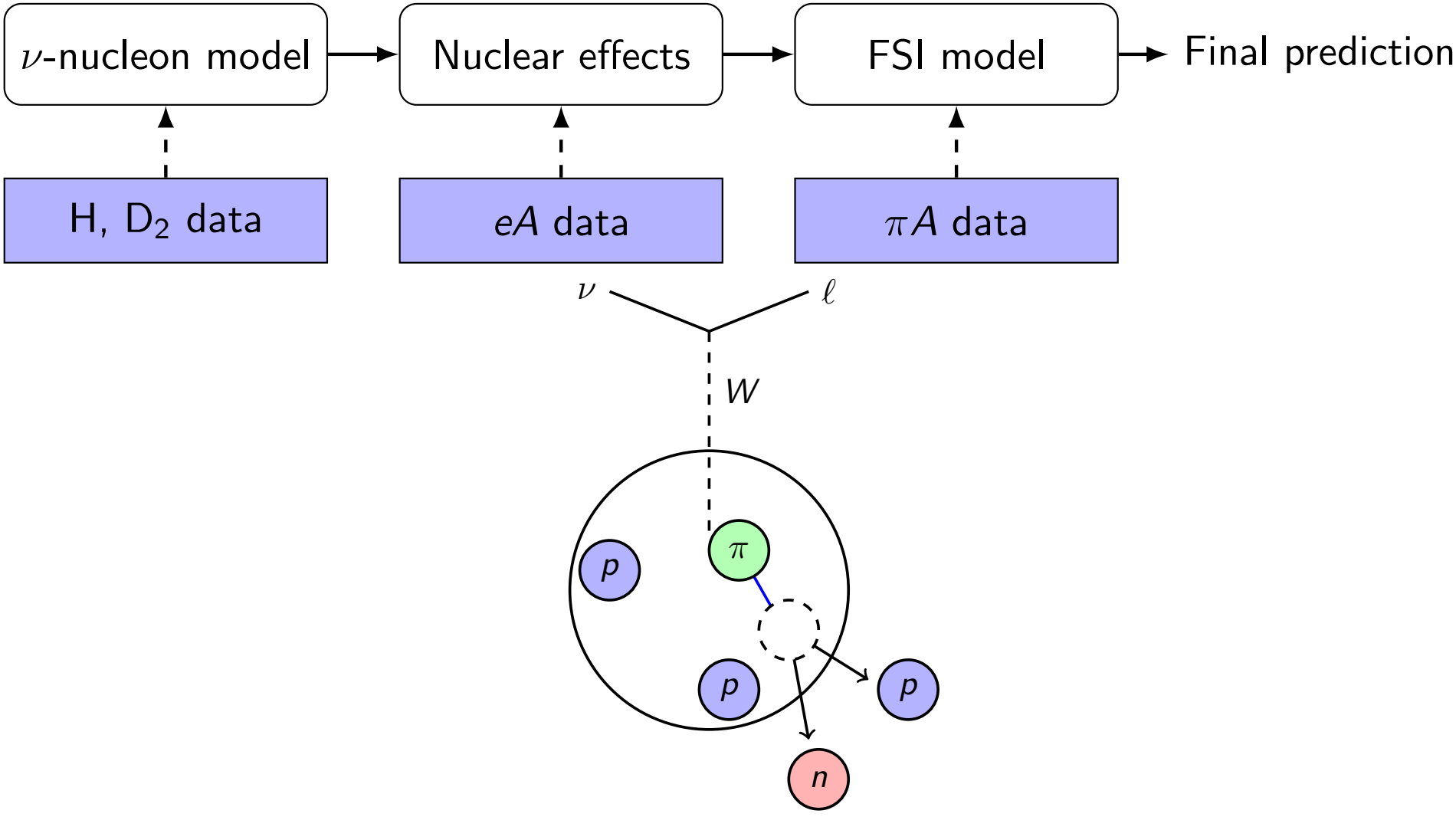
- Add effects due to nucleon bound in nucleus

Ingredients to understand νA cross sections



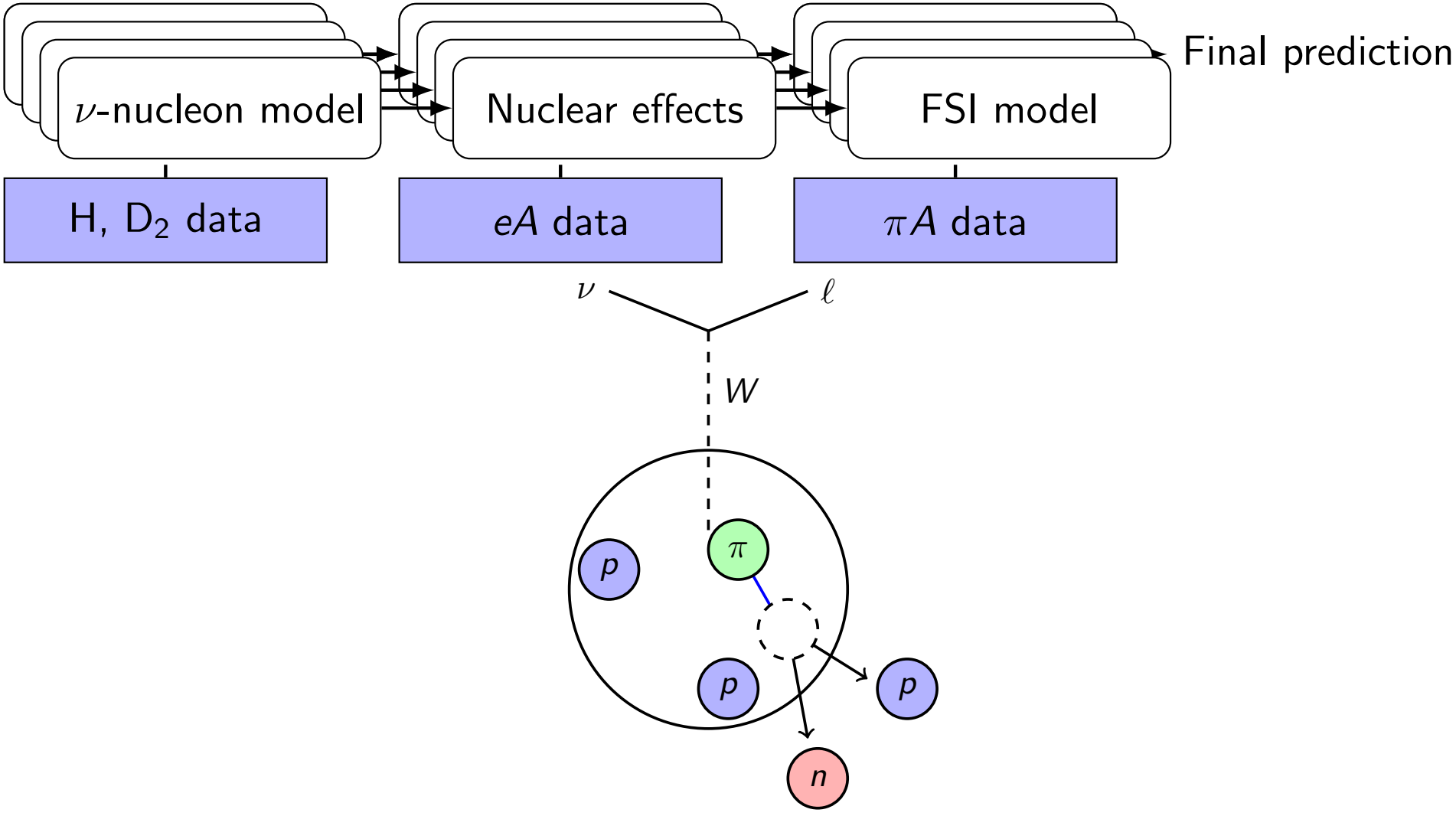
- Model reinteractions of hadrons exiting nucleus

Ingredients to understand νA cross sections



- Model reinteractions of hadrons exiting nucleus

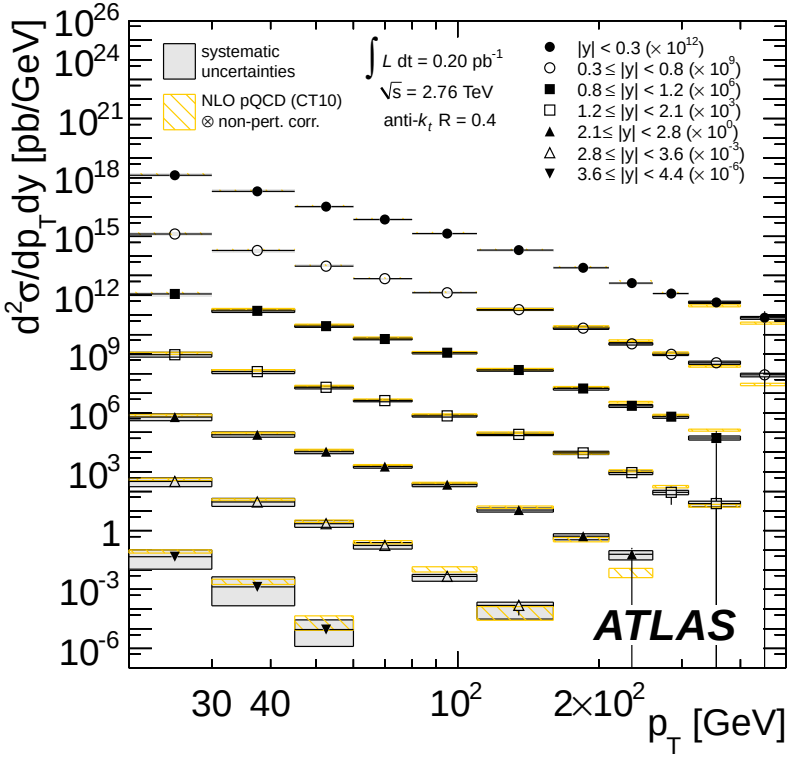
Ingredients to understand νA cross sections



- Repeat for all contributing processes for $E_\nu \sim 1\,\text{GeV}$

Do we understand νA cross sections?

ATLAS inclusive jet cross section

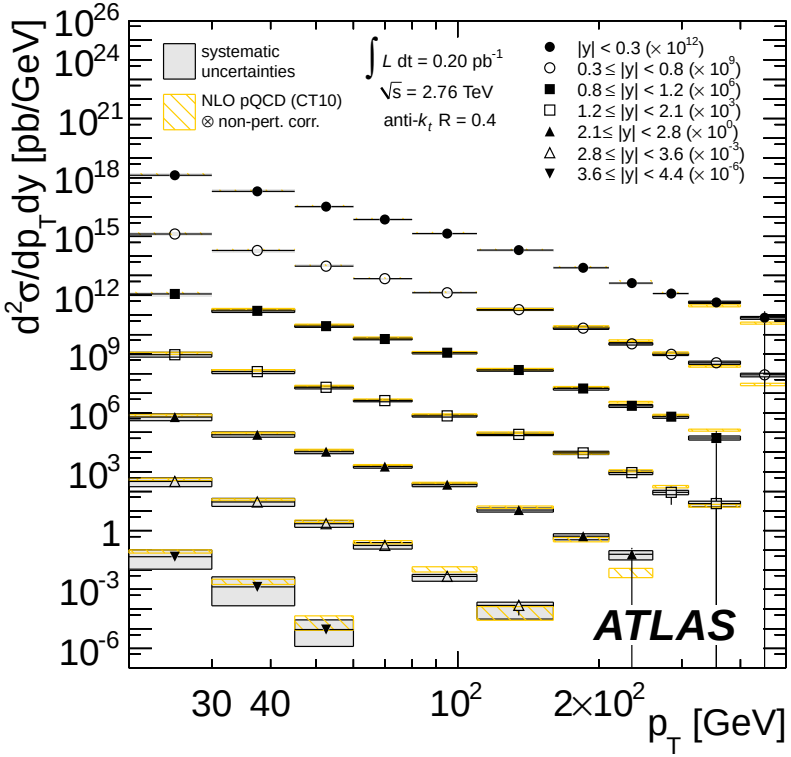


EPJC 73, 2509 (2013)

- Universal model, many orders of magnitude

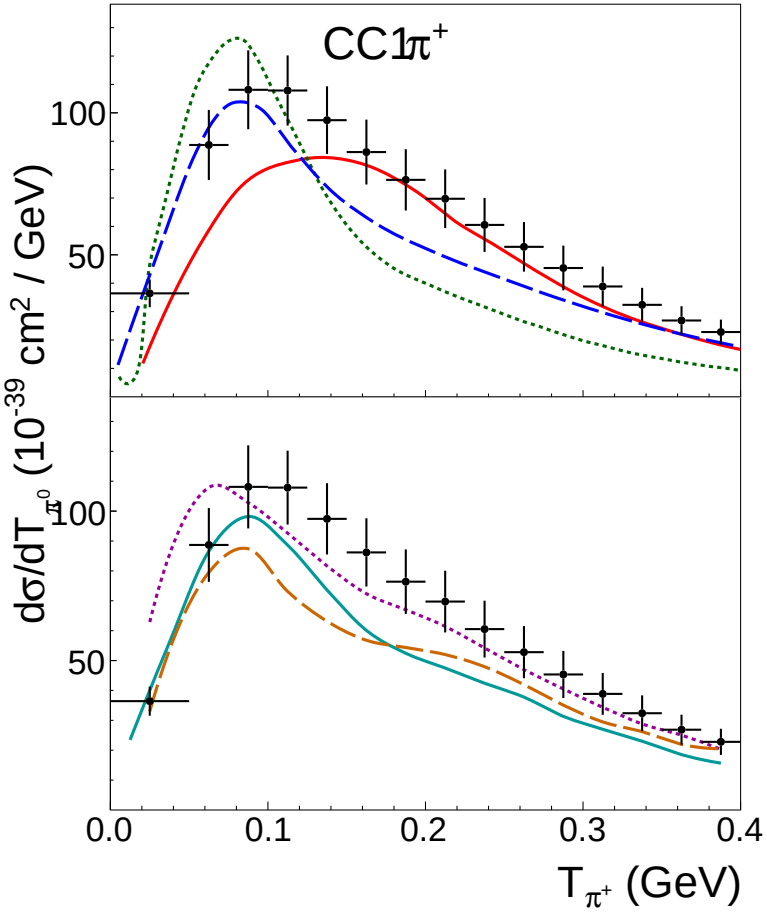
Do we understand νA cross sections?

ATLAS inclusive jet cross section



EPJC 73, 2509 (2013)

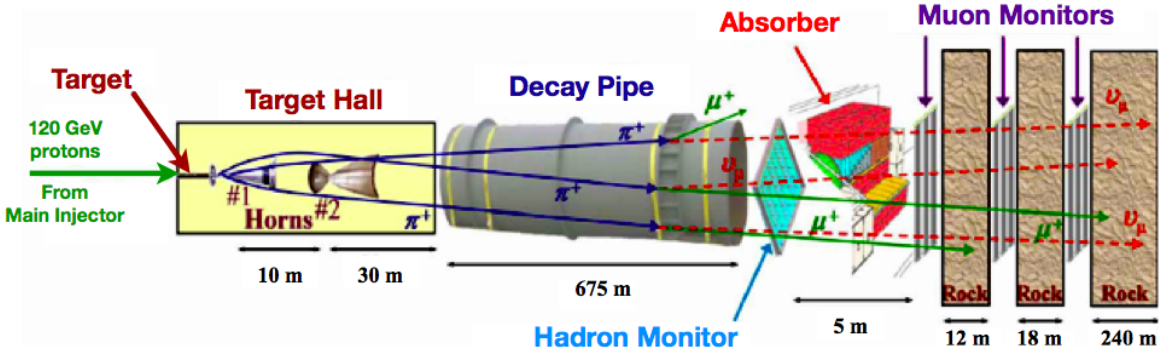
$\nu_\mu\, CH_2 \rightarrow \mu^-\, \pi^+\, X$



P. Rodrigues, arXiv:1402.4709 (NuInt 2012)
Data from PRD 83, 052007 (2011)

- Universal model, many orders of magnitude
- Wide variation in model predictions

Understanding νA cross sections with MINERνA



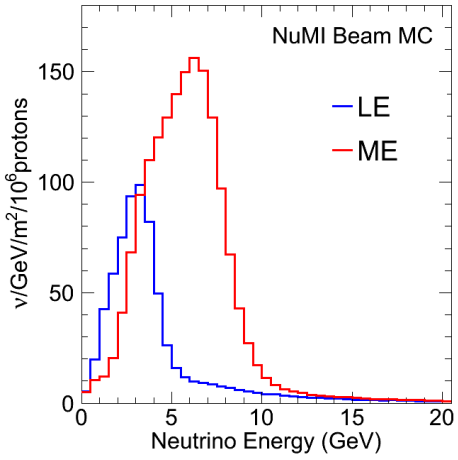
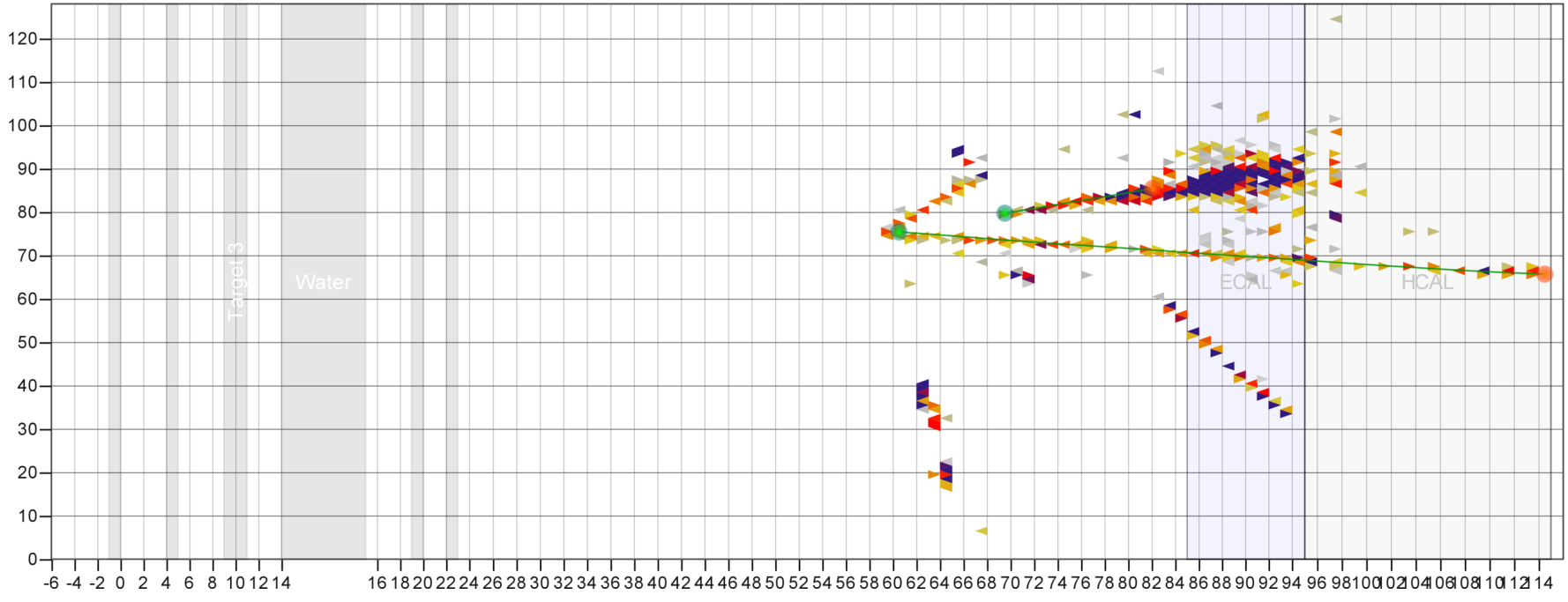
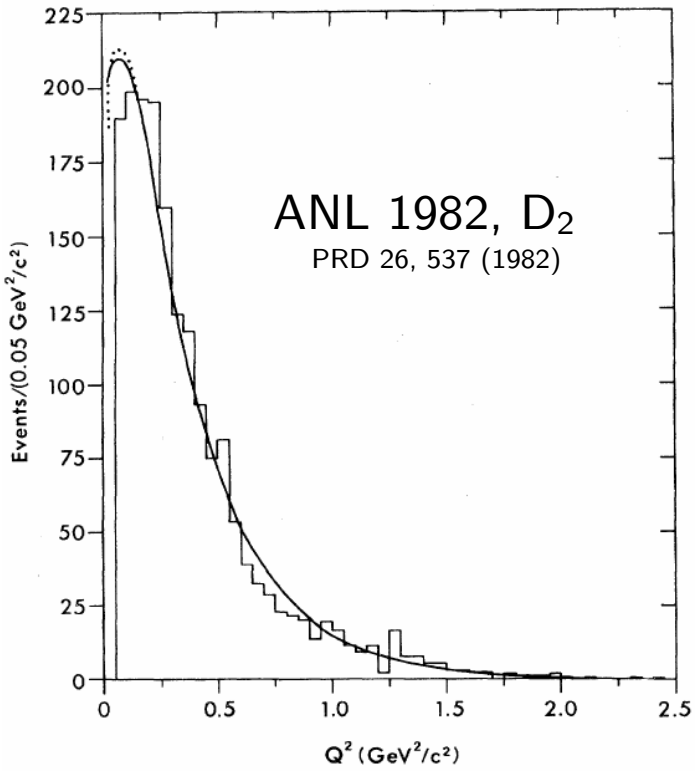


Figure: R. Zwaska



Charged-current quasielastic (CCQE) ν scattering

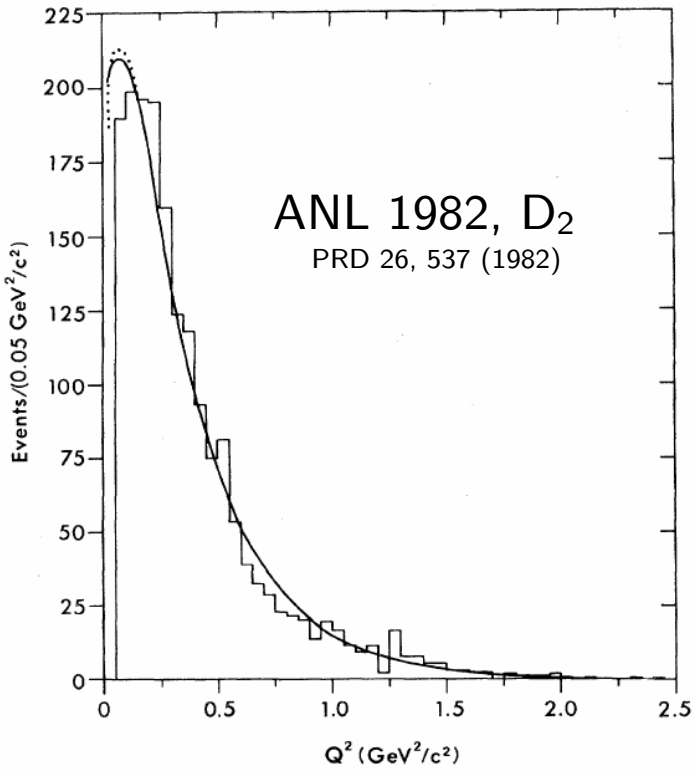
- $\nu_\mu + n \rightarrow \mu^- + p$
- Two-body kinematics $\Rightarrow$ Important signal process for oscillation expts

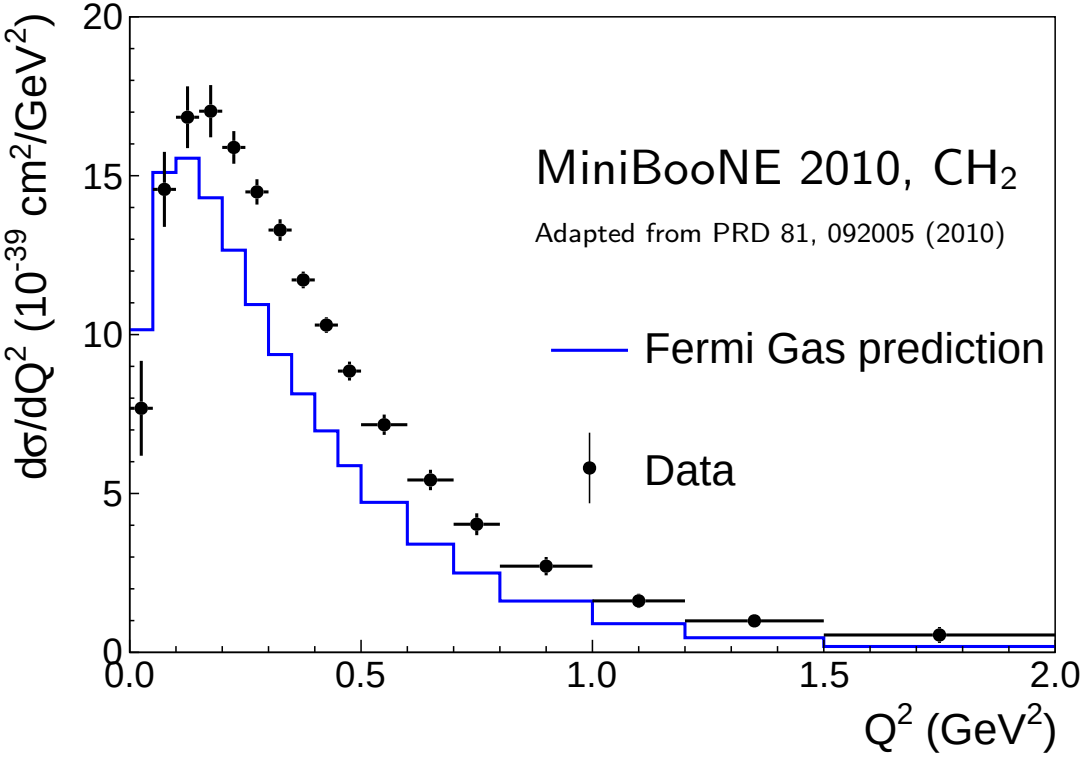


- $d\sigma/dQ^2$ shape understood in neutrino-nucleon scattering

Charged-current quasielastic (CCQE) ν scattering

- $\nu_\mu + n \rightarrow \mu^- + p$
- Two-body kinematics $\Rightarrow$ Important signal process for oscillation expts

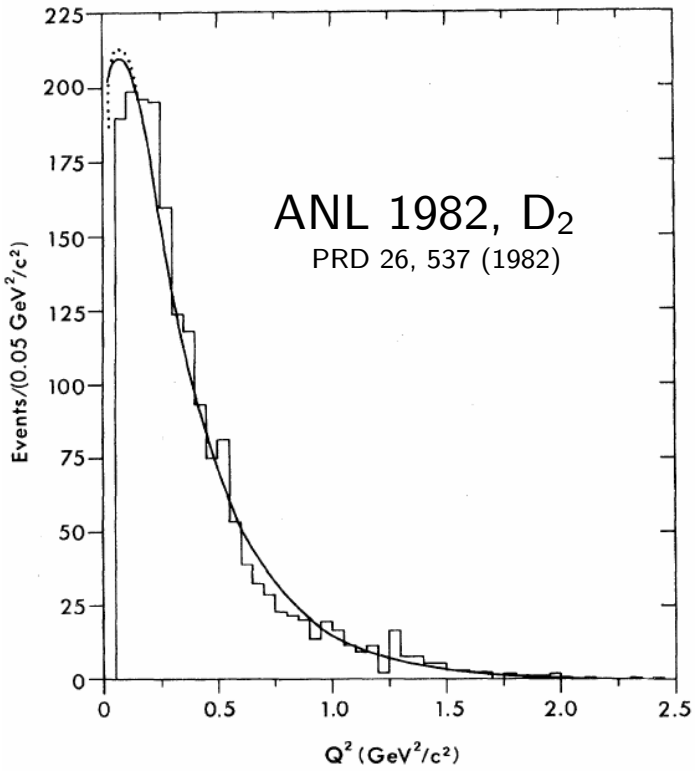


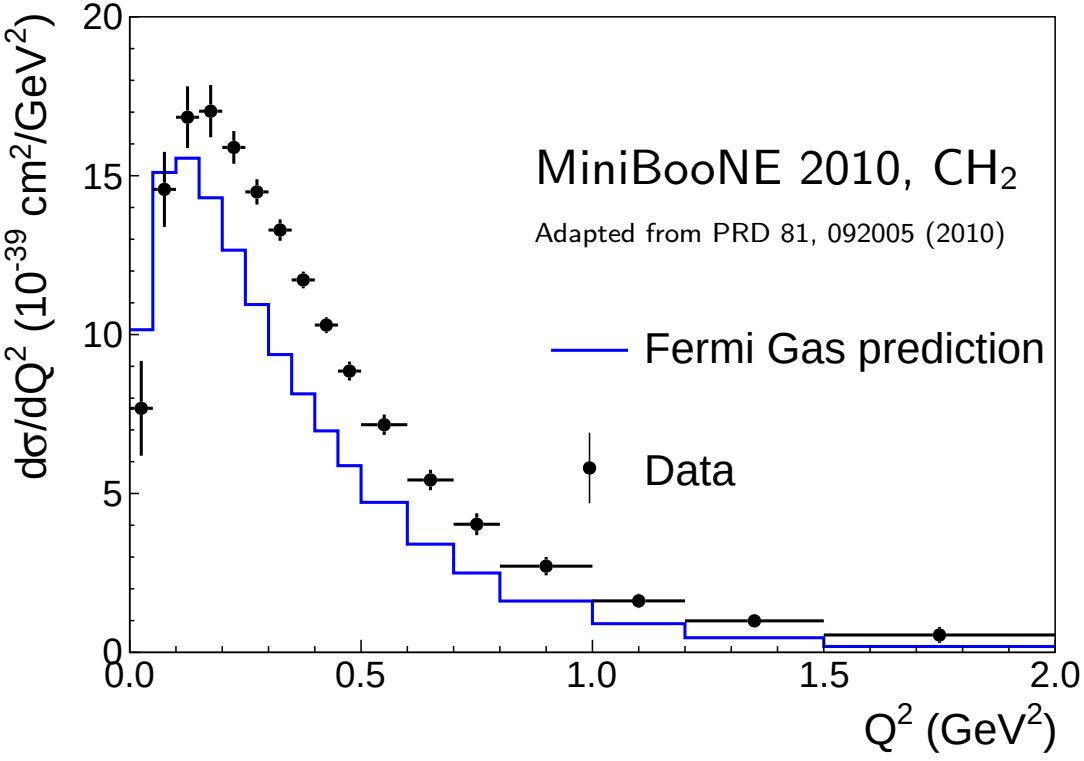


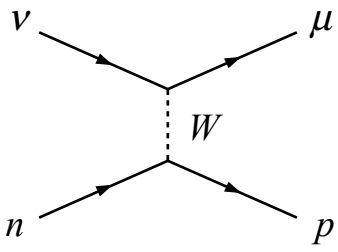
- $d\sigma/dQ^2$ shape understood in neutrino-nucleon scattering
- Nuclear model: independent nucleons in Fermi gas missing something?

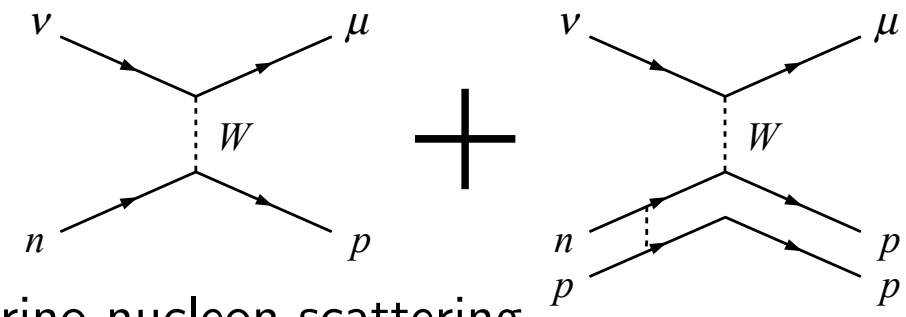
Charged-current quasielastic (CCQE) ν scattering

- $\nu_\mu + n \rightarrow \mu^- + p$
- Two-body kinematics $\Rightarrow$ Important signal process for oscillation expts







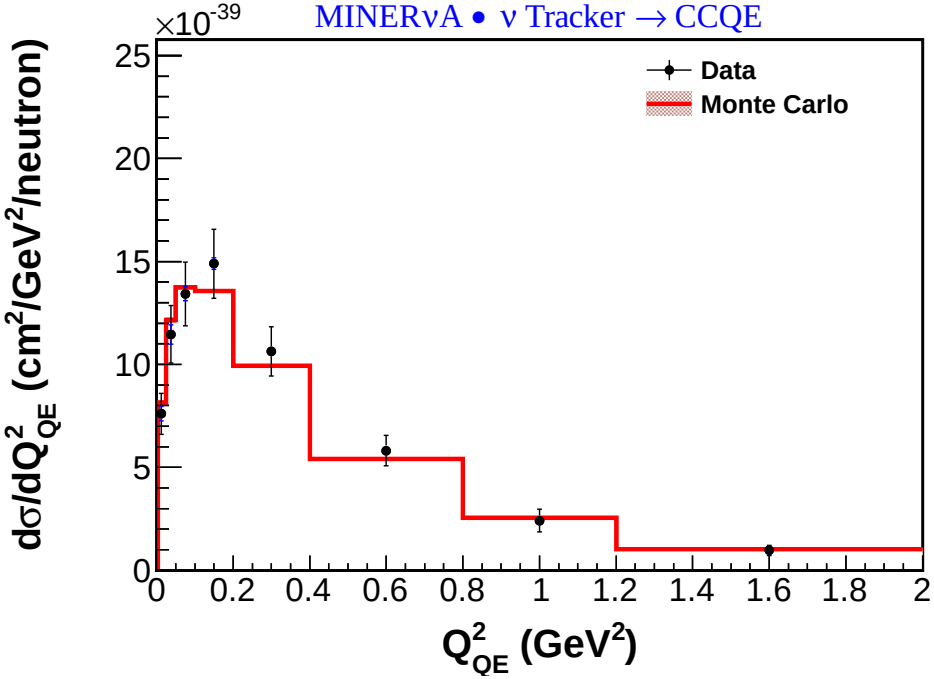


- $\mathrm{d}\sigma/\mathrm{d}Q^2$ shape understood in neutrino-nucleon scattering
- Nuclear model: independent nucleons in Fermi gas missing something?

MINERνA CCQE: Cross sections

- Muon matched to MINOS, few isolated showers, low hadronic recoil energy

Neutrino mode



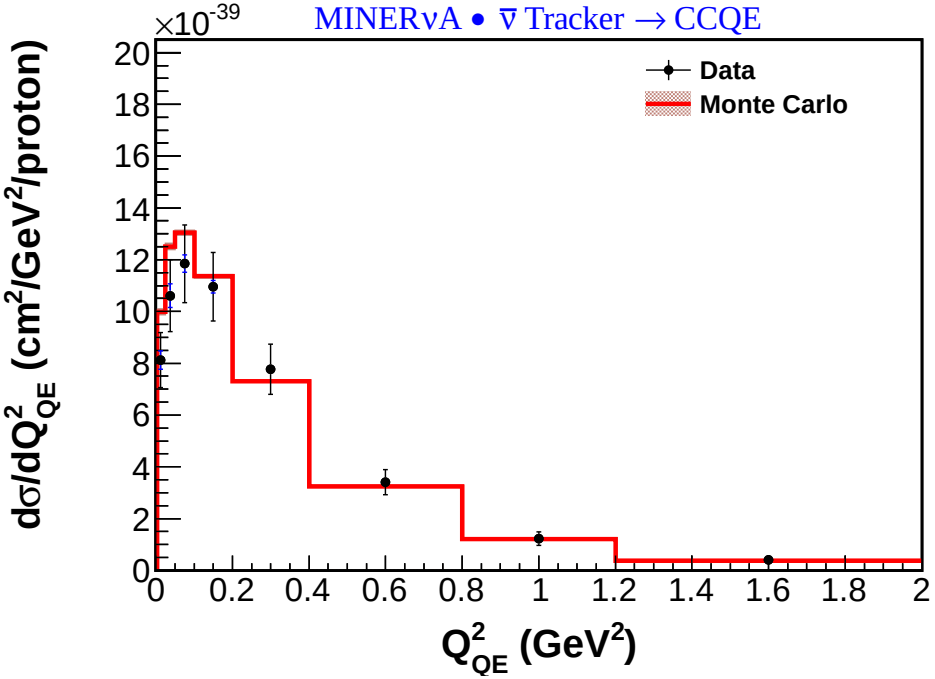
PRL 111, 022502 (2013)

No of events 29,620

Efficiency 47%

Purity 49%

Antineutrino mode



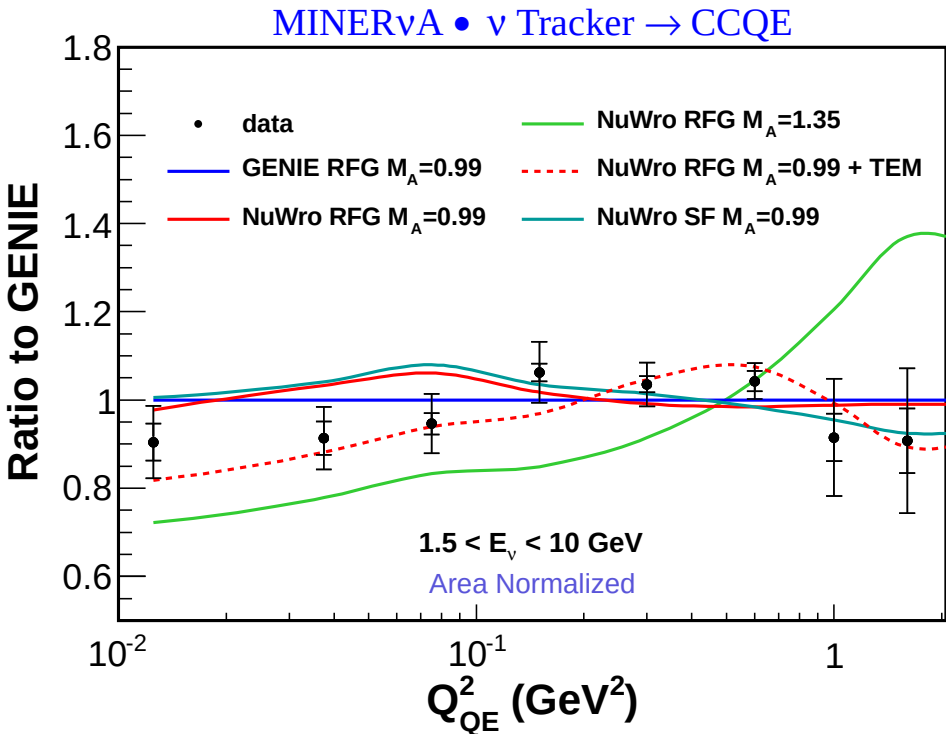
PRL 111, 022501 (2013)

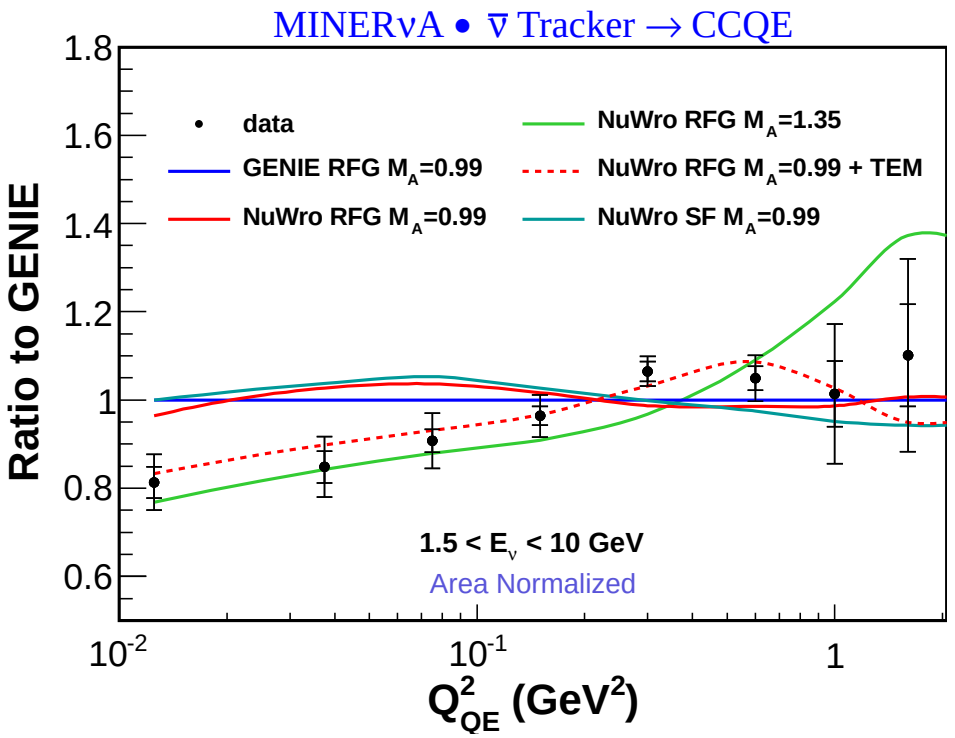
No of events 16,467

Efficiency 54%

Purity 77%

MINERνA CCQE: Model comparisons





- Area normalize, then take ratio to GENIE
- Models:

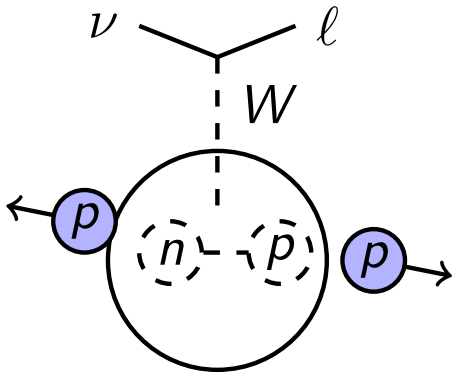
GENIE —— Quasi-independent nucleons in a mean field
NIM A**614**, 87 (2010)

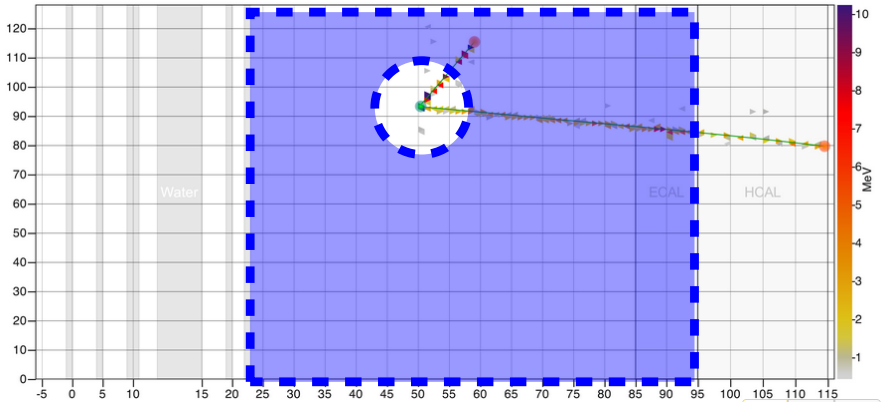
$M_A = 1.35$ —— Modified ν-nucleon cross section Q^2 behaviour
Phys. Rev. D**81**, 092005 (2010)

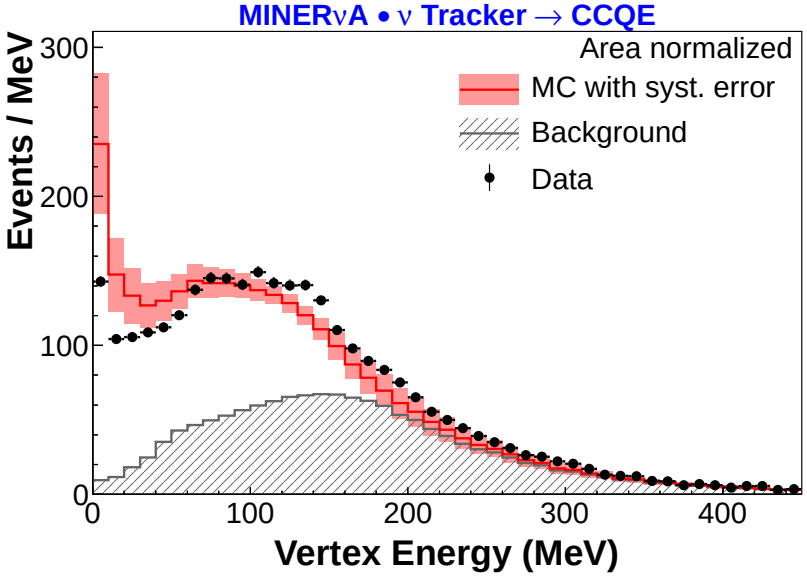
TEM - - - - - Empirical multinucleon effect based on eA data
Eur. Phys. J. C 71:1726 (2011)

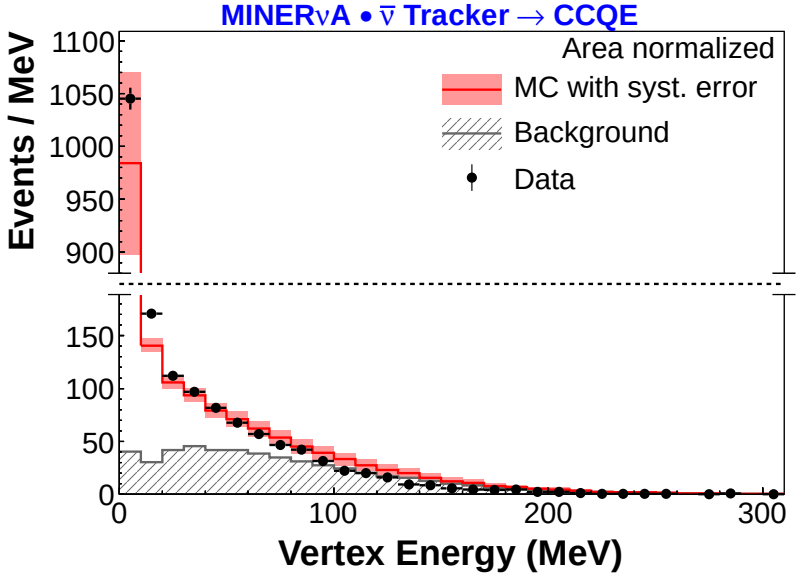
MINERνA CCQE: Vertex energy

- Interactions with NN pairs $\Rightarrow$ excess energy near the vertex









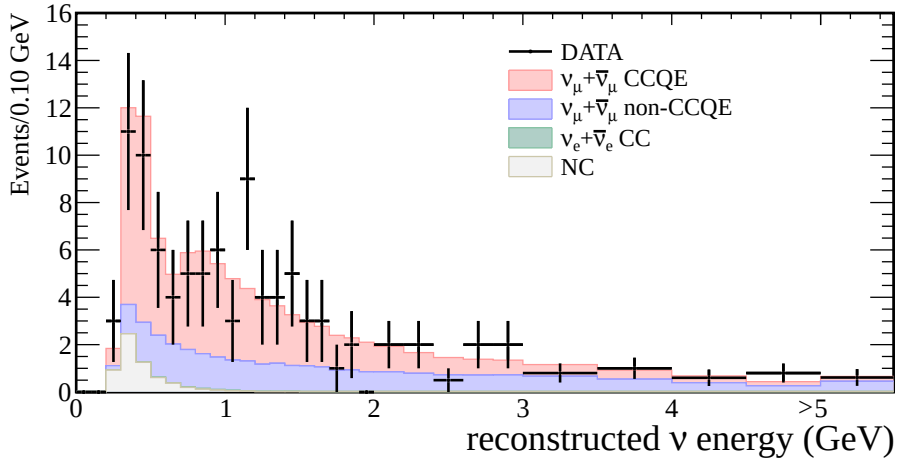
- Harder spectrum in ν_μ mode data than in MC, but not in $\bar{\nu}_\mu$ mode
- Improved agreement with extra proton in $(25 \pm 9)\%$ of events

MINERνA CCQE: Recap

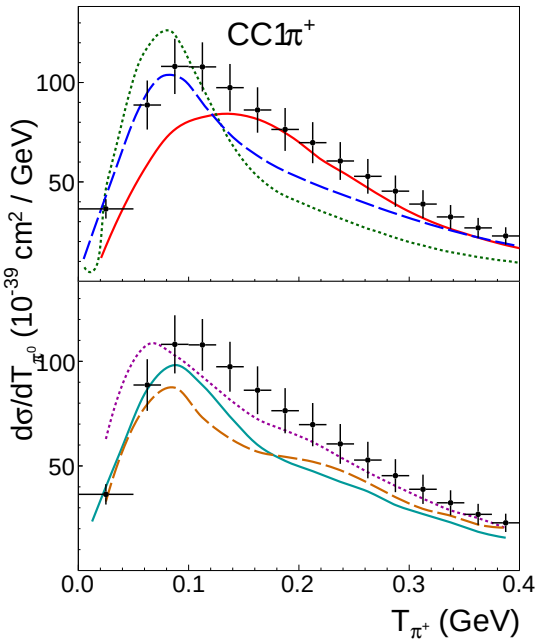
- Further evidence of previously-unmodeled nuclear effects
- Discriminating power between models from $\mathrm{d}\sigma/\mathrm{d}Q^2$
- Vertex energy provides an independent handle

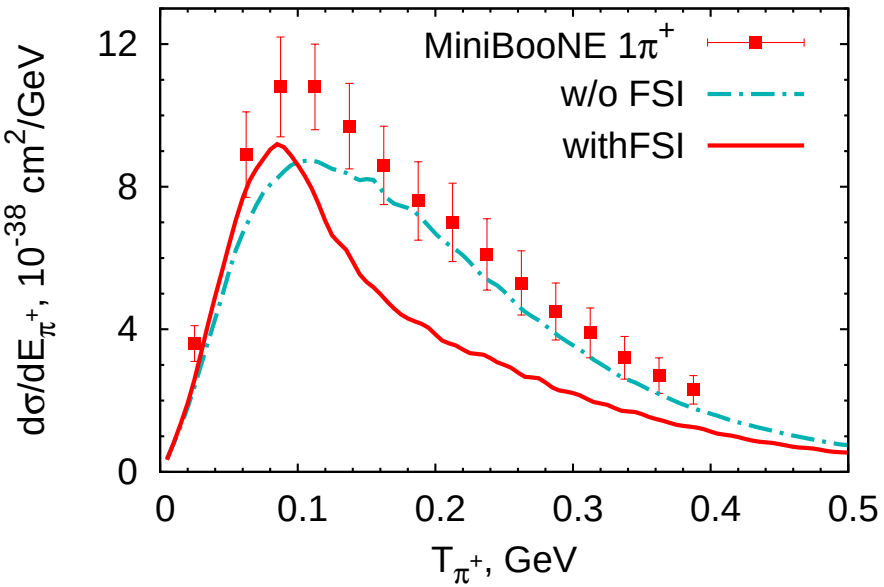
Neutrino-induced charged pion production

- Major background in oscillation experiments (T2K ν_μ again):



- But MiniBooNE data on CH_2 suggest shortcomings in models

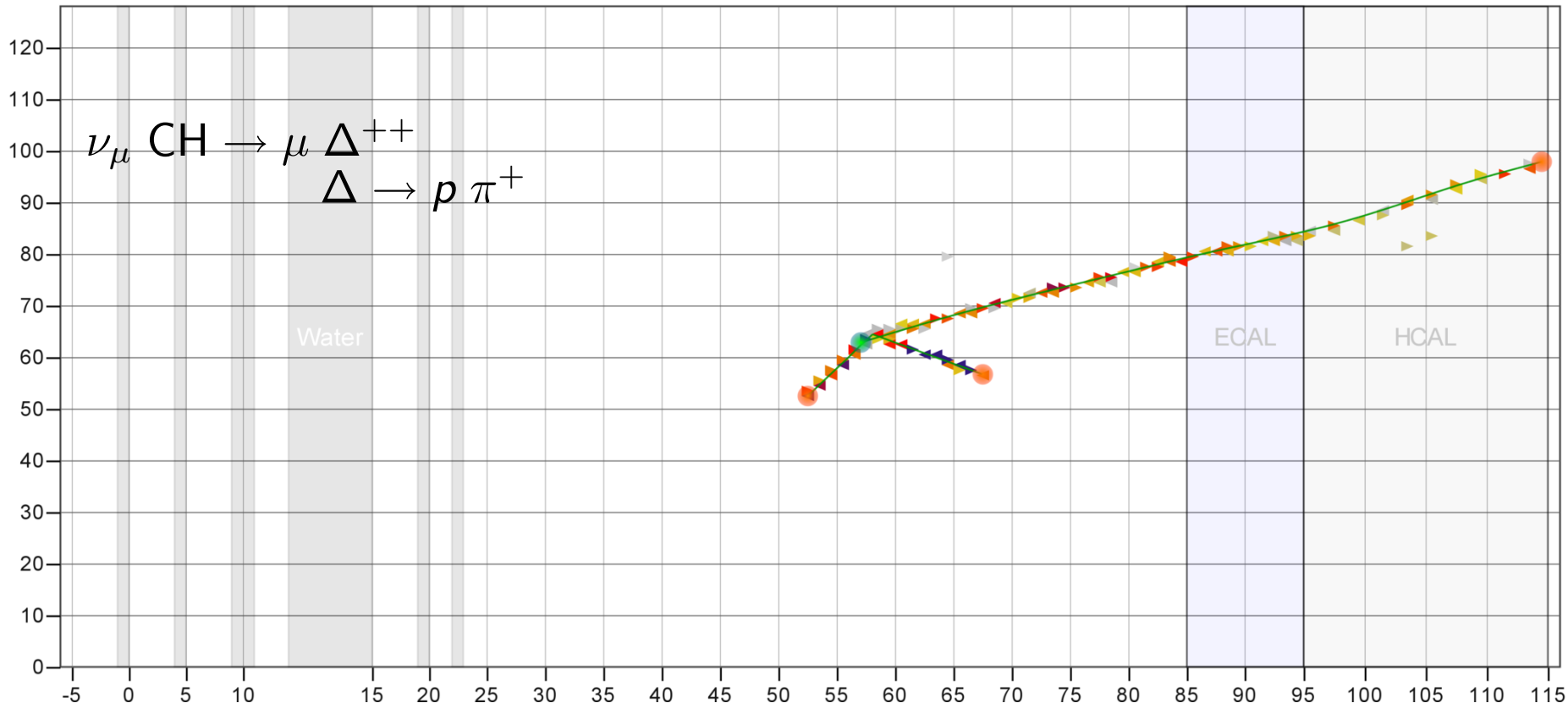




O. Lalakulich *et al.*, arXiv:1107.5947

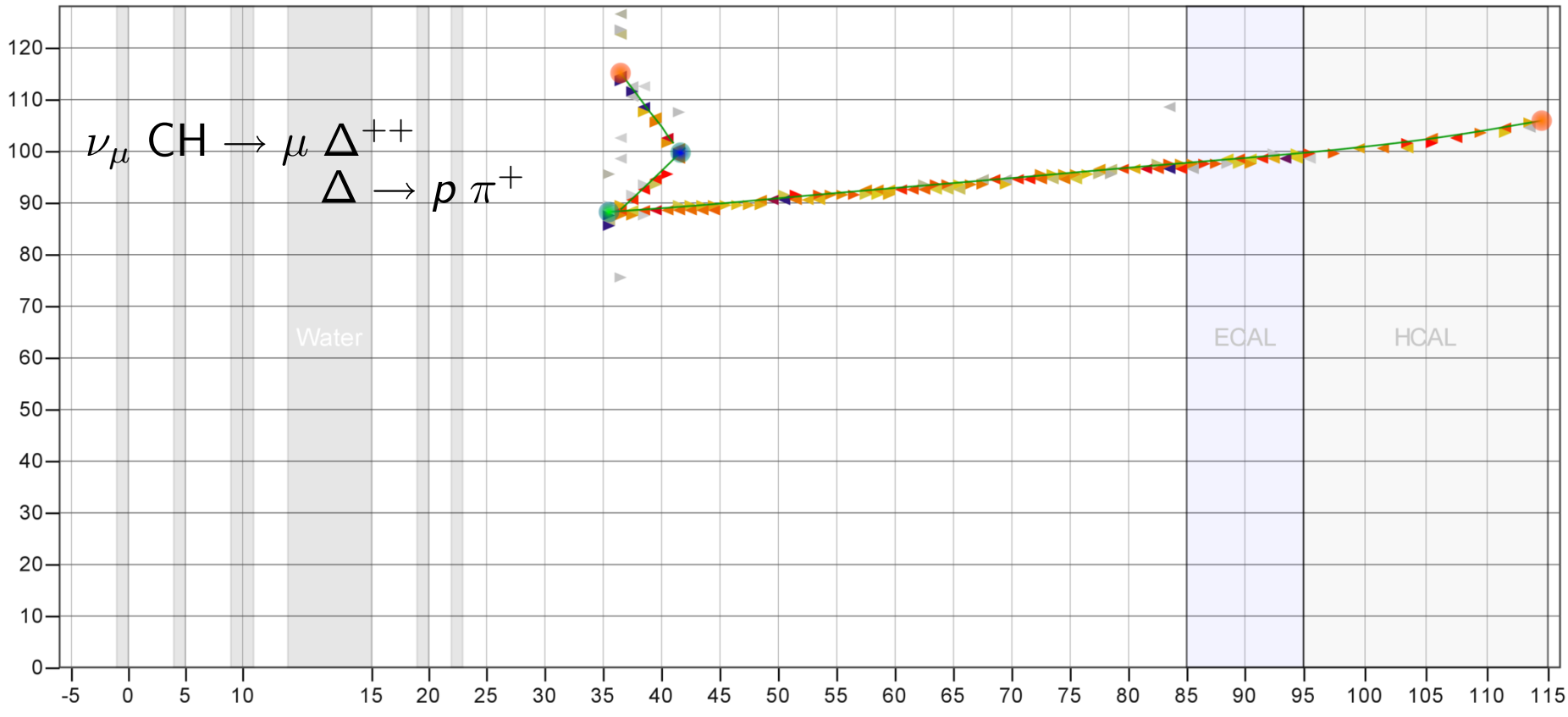
MINERνA charged pion production

- Events with single charged pion exiting nucleus, $W < 1.4\,\mathrm{GeV}$
- Compare pion kinematics with nominal and modified FSI model



MINERνA charged pion production

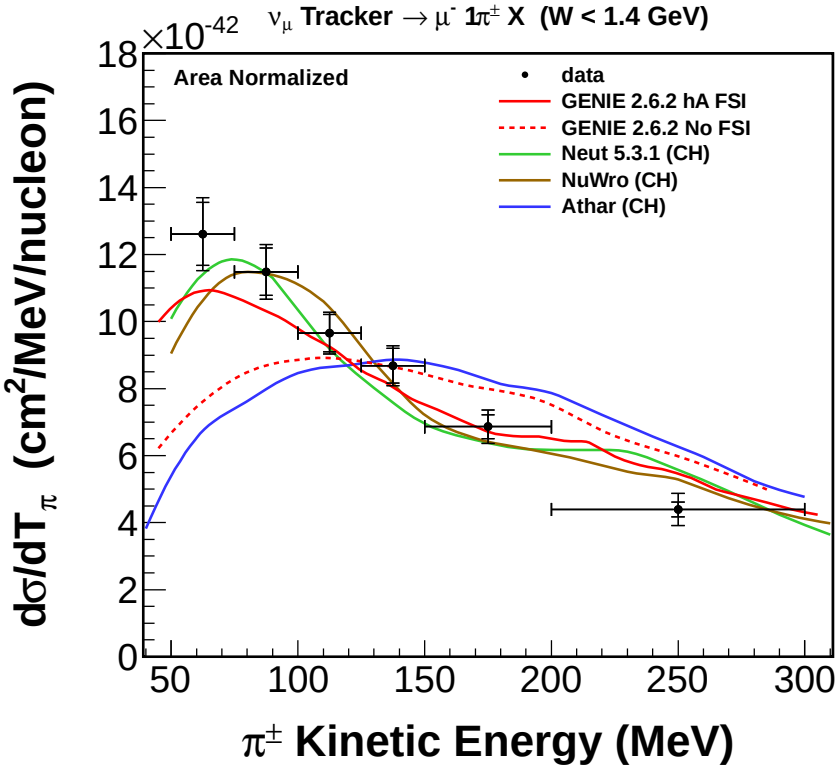
- Events with single charged pion exiting nucleus, $W < 1.4\,\mathrm{GeV}$
- Compare pion kinematics with nominal and modified FSI model

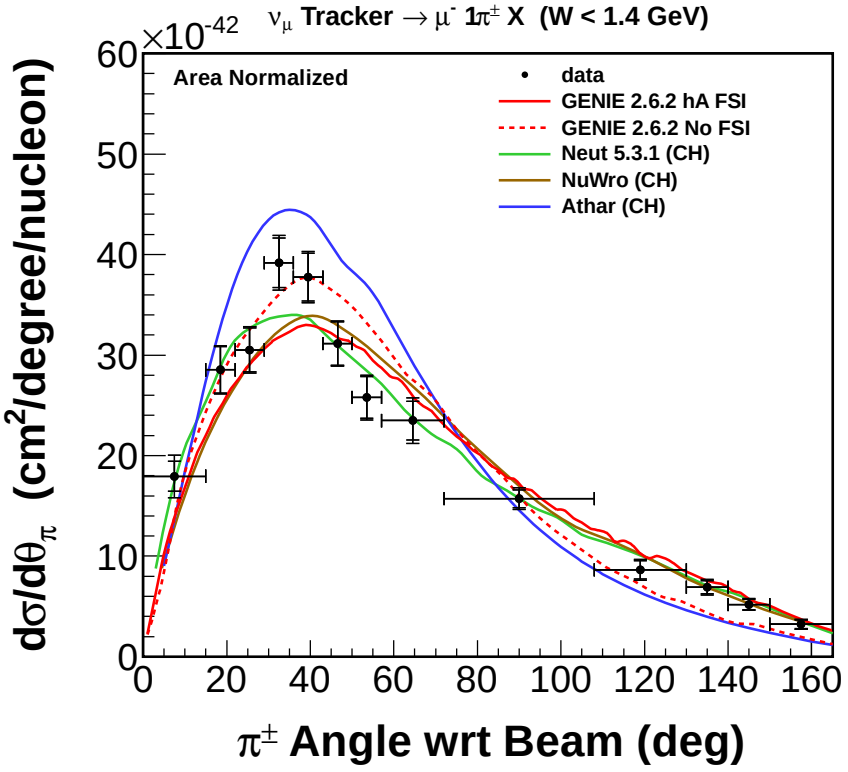


- Select *stopping* pions using $\mathrm{d}E/\mathrm{d}x$ and e from $\pi \rightarrow \mu \rightarrow e$

MINERνA charged pion production: results

- Shape-only comparisons to generator and model predictions





- Shape measurement stats-limited
- Main systematics: hadronic energy response, neutrino interaction models

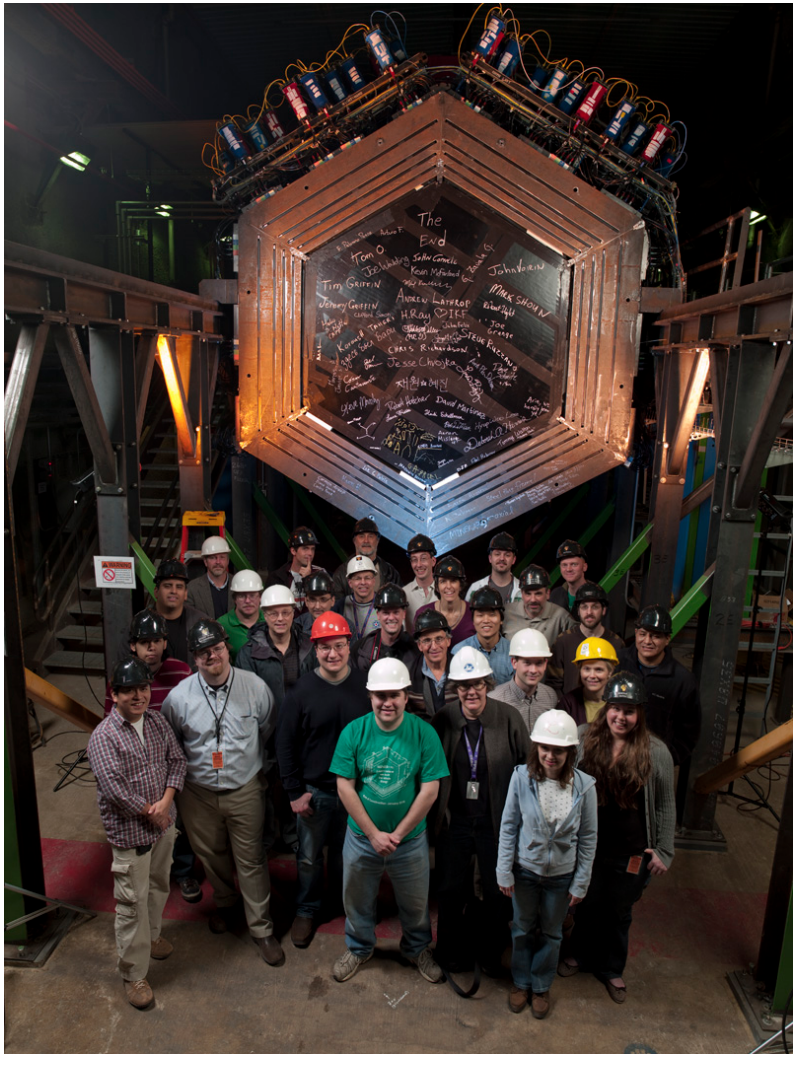
Recap

- MINERνA is constraining cross sections needed for oscillation experiments:

  CCQE evidence for nuclear effects not currently simulated

  CC$\pi^{\pm}$ consistency with current model

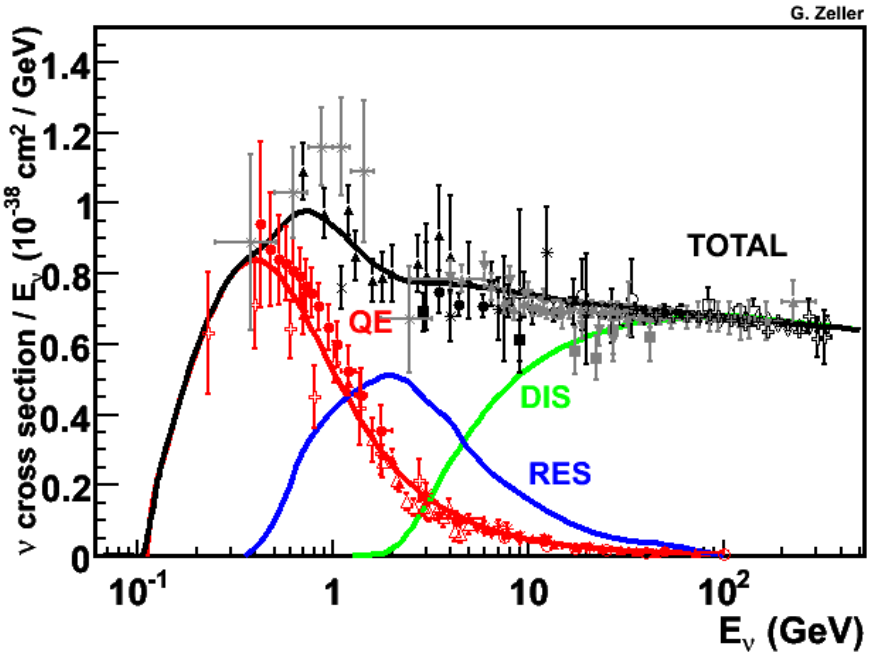
- And more:
  - CC inclusive ratios on different nuclei
    arXiv:1403.2103
  - ν_μ–e scattering
    http://theory.fnal.gov/jetp/talks/WC_talk_J.Park.ppt
  - ν, $\bar{\nu}$ coherent pion production
  - CCQE proton kinematics
  - CC π^0 production
  - ν_e CCQE
  - Kaon production



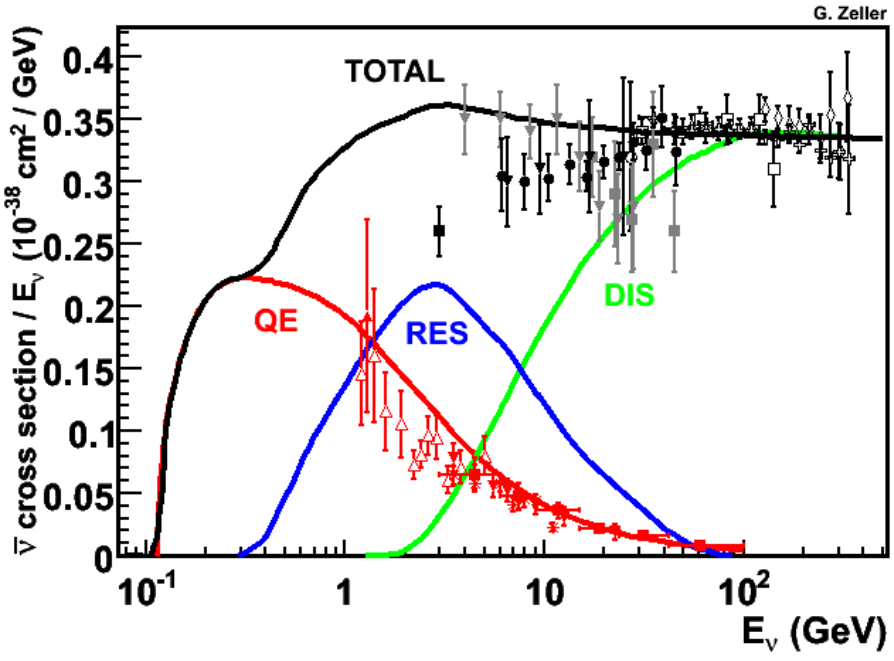
Backup slides

Cross sections: What do we know so far?

ν_μ-nucleon CC cross sections



$\bar{\nu}_\mu$-nucleon CC cross sections

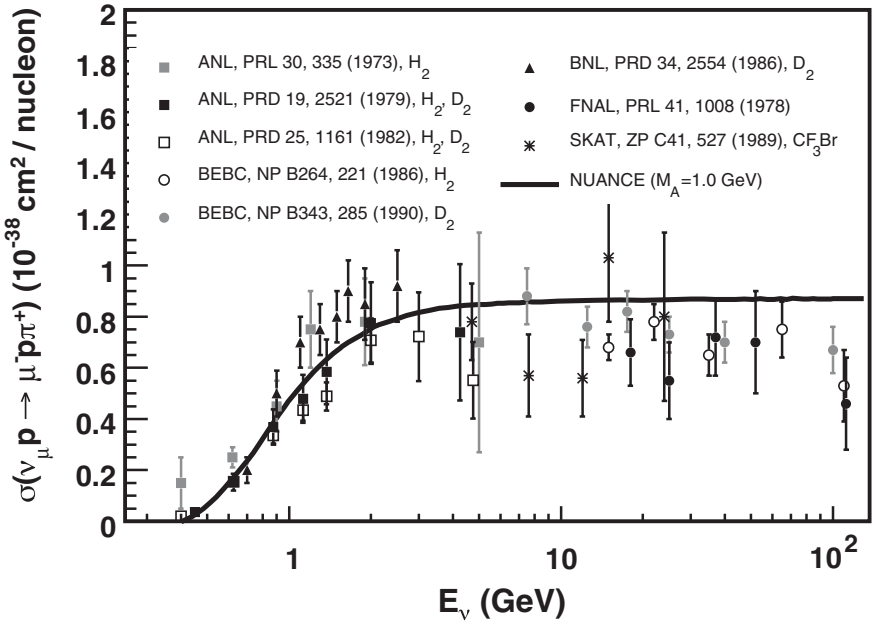


G. Zeller and J. Formaggio, Rev. Mod. Phys. 84, 1307–1341 (2012)

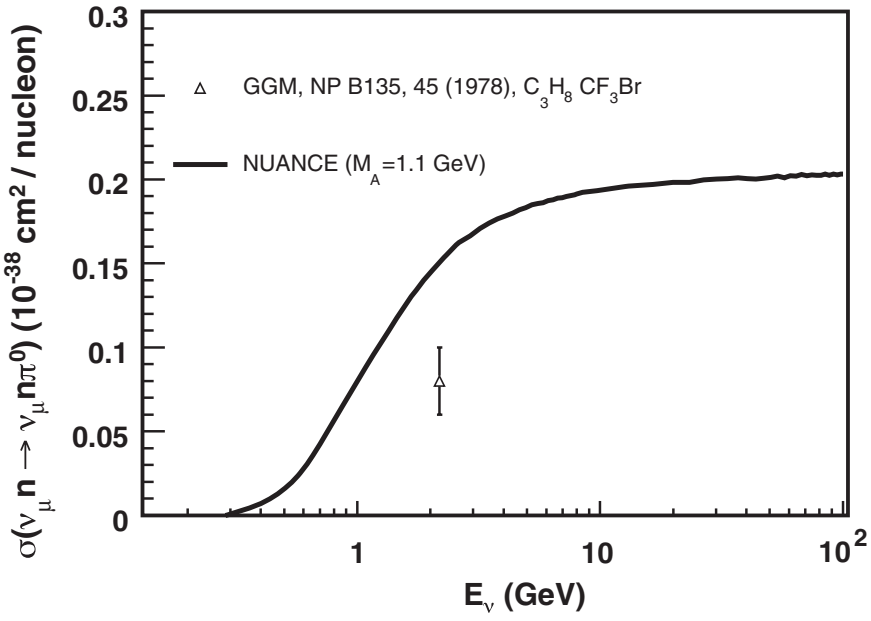
- Not precisely known for $E_\nu \sim 1\,\text{GeV}$
- Multiple contributing processes
- In νA, observe $\sigma_{\nu N} \otimes \sigma_A \otimes \sigma_{\text{FSI}}$

Cross sections: What do we know so far?

$\nu_\mu p \longrightarrow \mu^- p \pi^+$



$\nu_\mu n \longrightarrow \nu_\mu n \pi^0$

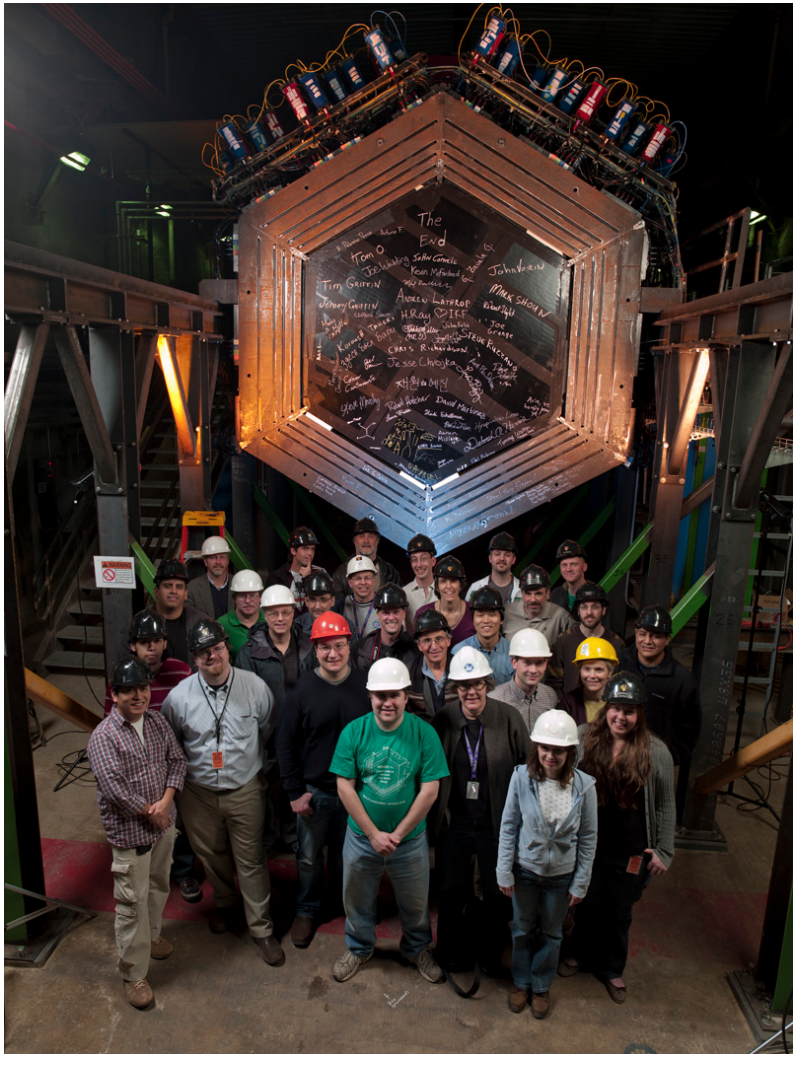


G. Zeller and J. Formaggio, Rev. Mod. Phys. 84, 1307–1341 (2012)

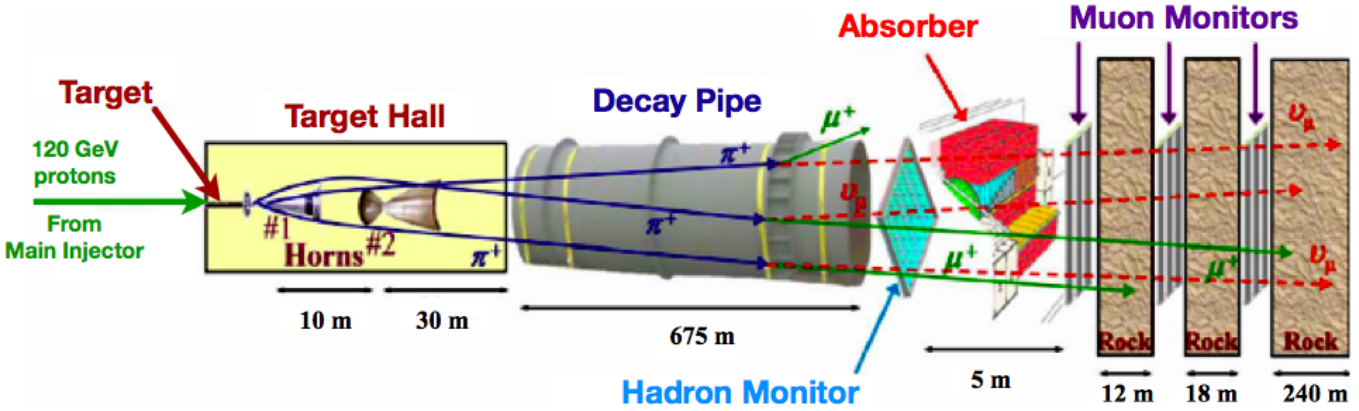
- Not precisely known for $E_\nu \sim 1\,\text{GeV}$
- Multiple contributing processes
- In νA, observe $\sigma_{\nu N} \otimes \sigma_A \otimes \sigma_{\text{FSI}}$

MINERνA: What and why?

- Dedicated neutrino–nucleus scattering experiment in the NuMI beamline
- Measuring exclusive and inclusive ν, $\bar{\nu}$ cross sections on a range of nuclei



The NuMI neutrino beam



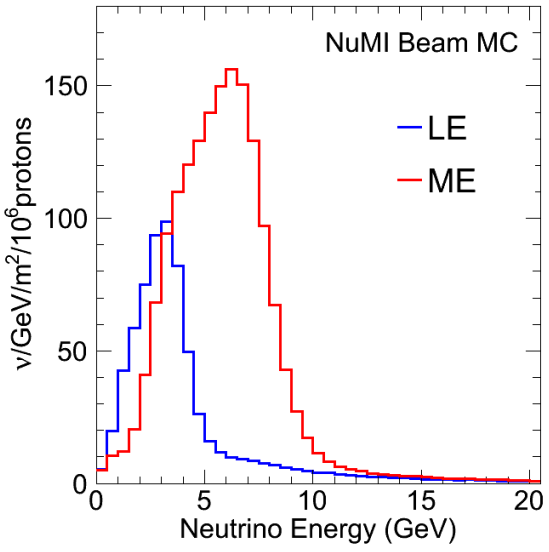
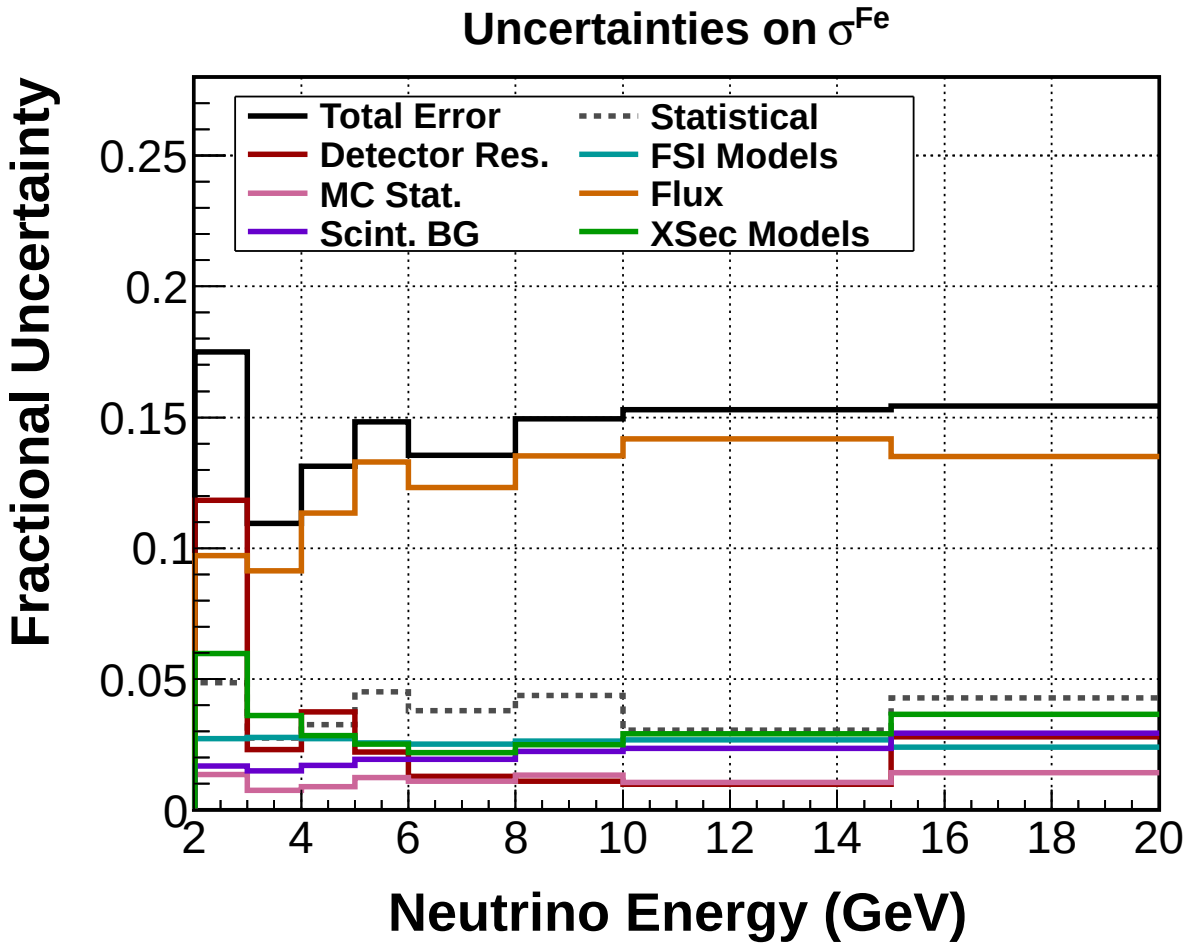


Figure: R. Zwaska

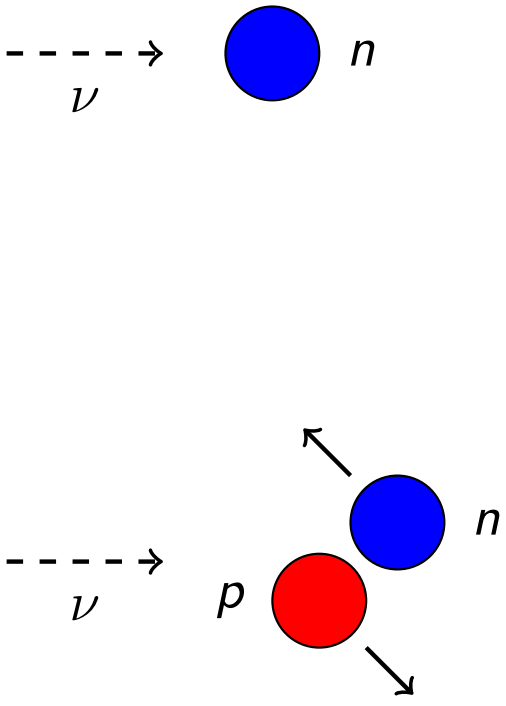
- ν and $\bar{\nu}$ modes
- Tunable energy spectrum
- MINERνA LE run complete:
  - 3.98×10^{20} POT ν mode ($\mathcal{O}(10^6)$ ν_μ CC evts on plastic)
  - 1.7×10^{20} POT $\bar{\nu}$ mode
- Currently running in ME configuration

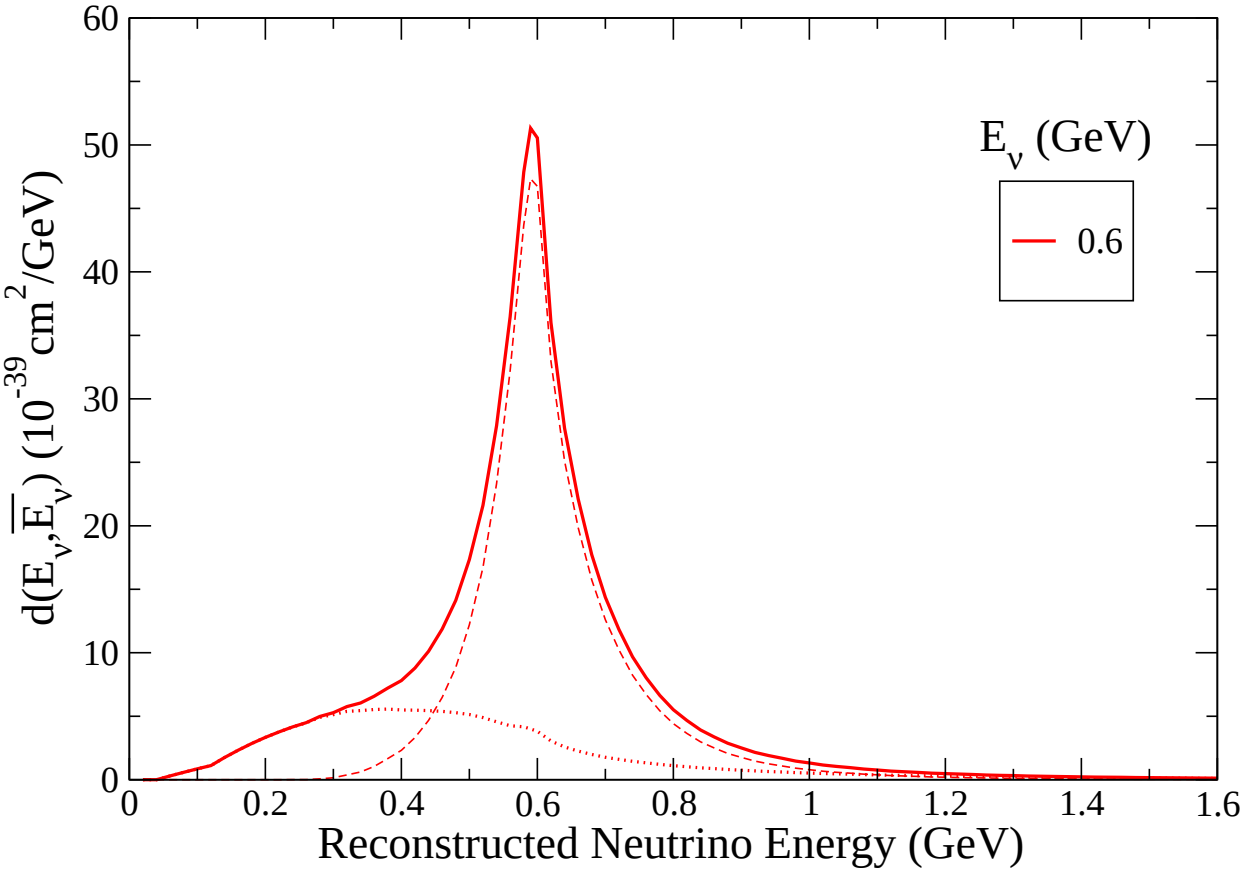
Flux Modelling



- Tune hadron production from NA49 data
- Uncertainties still $\sim 15\%$
- Multi-prong approach planned for $\lesssim 10\%$
  - For now, study distributions weakly dependent on flux

NN correlations





Adapted from Martini *et al.*, arXiv:1211.1523

- Affect lepton kinematics, E_ν reco, hadrons in final state
- Many qualitatively similar calculations available:

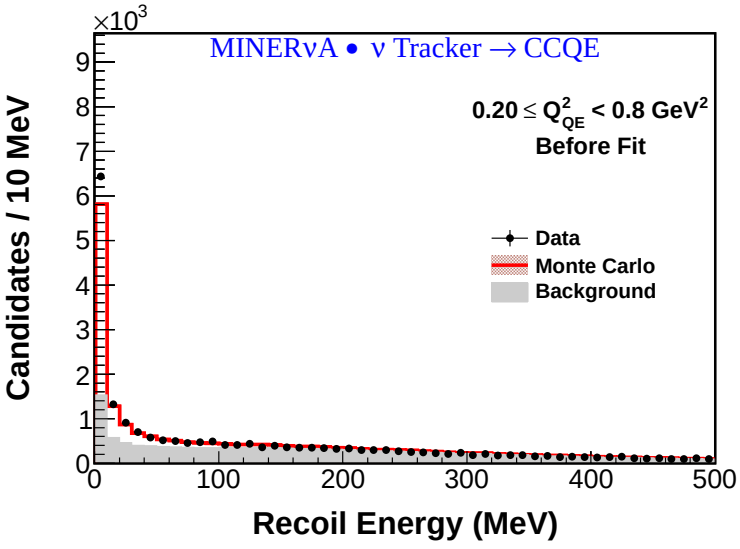
Martini *et al.*, PRC 80, 065001 (2009)
Benhar, arXiv:1012.2032
Nieves *et al.*, PRC 83, 045501 (2011)
Ankowski, Benhar, arXiv:1102.3532
Amaro, *et al.*, arXiv:1104.5446

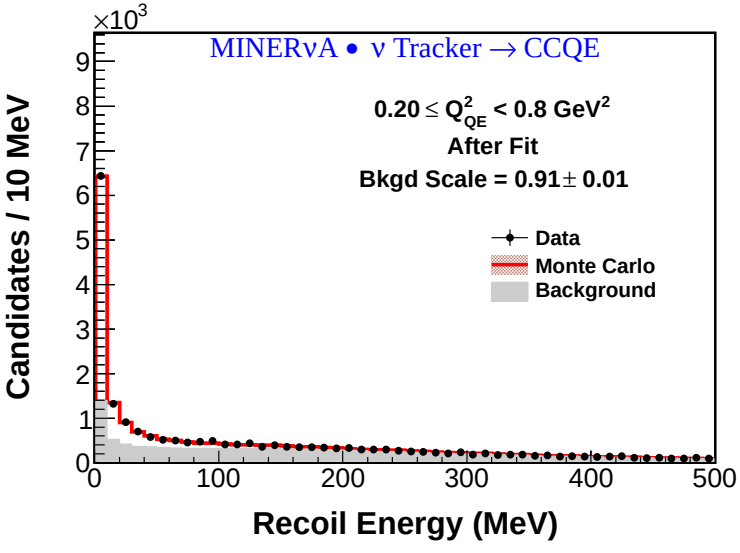
Martini *et al.*, PRC 81, 045502 (2010)
Alvarez-Ruso, arXiv:1012.3871
Fernandez-Martinez, Meloni, PL B697, 477 (2011)
Meucci, *et al.*, arXiv:1103.0636
Antonov *et al.*, arXiv:1104.0125

Amaro *et al.*, PRC 82, 046601 (2010)
Amaro *et al.*, arXiv:1012.4265
Amaro, *et al.*, PL B696, 151 (2011)
Benhar, Veneziano, arXiv:1103.0987

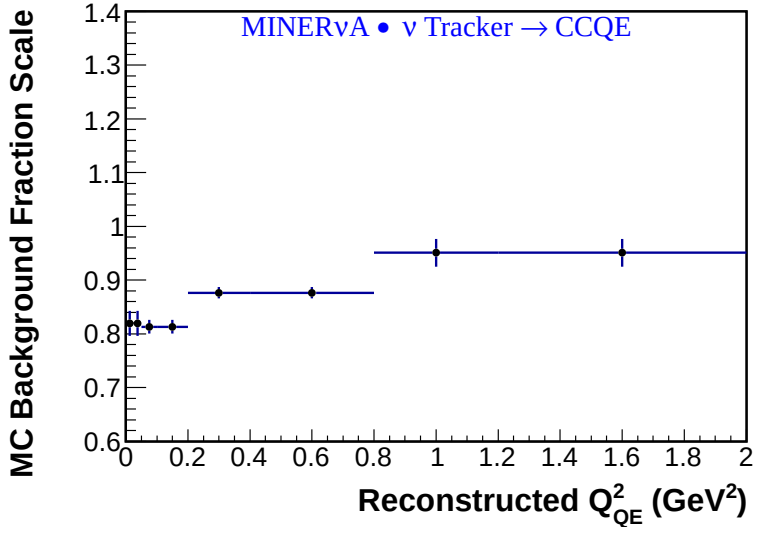
CCQE analysis: Constraining non-QE backgrounds

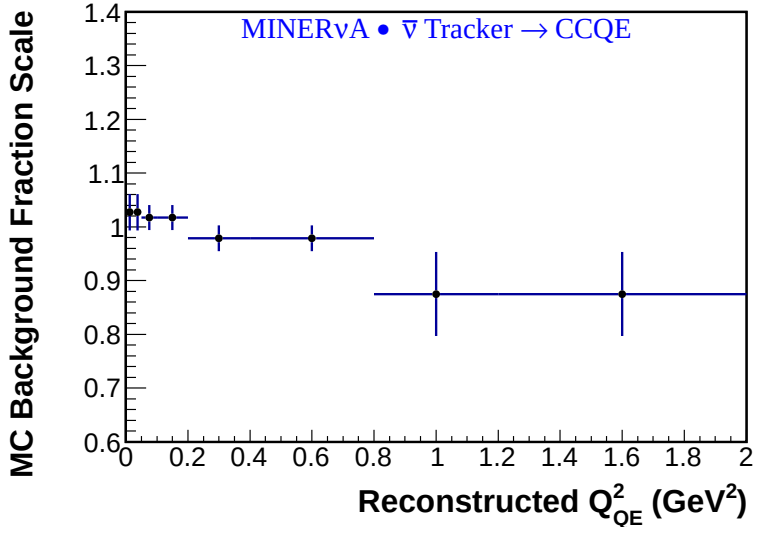
One example bin in Q^2





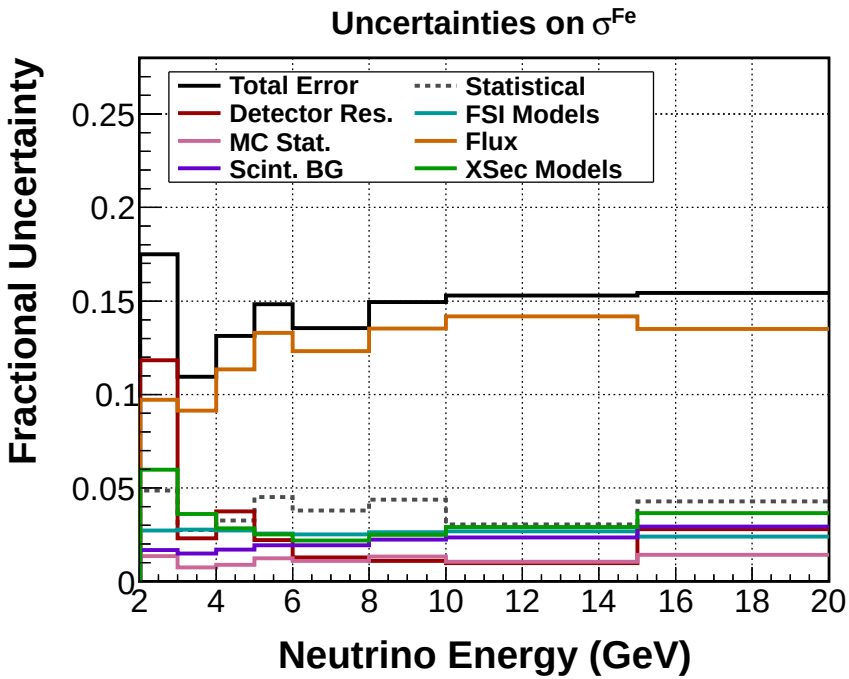
All Q^2 bins





MINERνA CCQE: Systematics

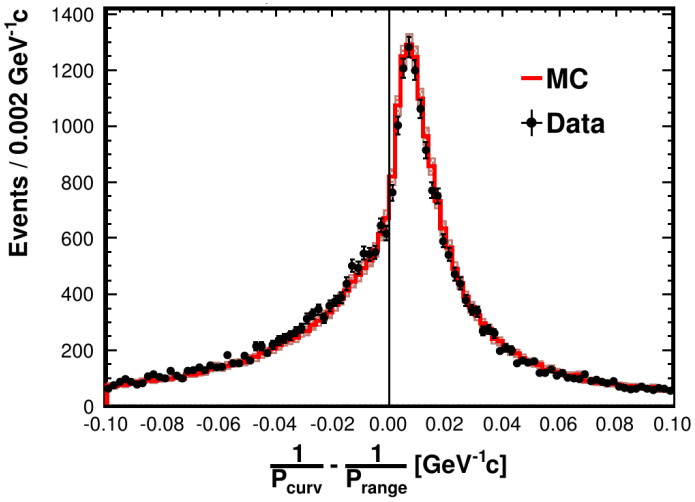
- Flux
  - Tune to NA49 data
  - Remaining 10–15% uncertainties
  - Cancel in shape analysis



MINERνA CCQE: Systematics

- Flux
  - Tune to NA49 data
  - Remaining 10–15% uncertainties
  - Cancel in shape analysis
- Muon energy scale
  - Muon p scale known to 2–3%

p_μ scale



MINOS range

$\pm 2\%$ (all p_μ)

MINOS curvature

$\pm 2.1\%$ ($p_\mu < 1\,\mathrm{GeV/c}$)

$\pm 3.3\%$ ($p_\mu > 1\,\mathrm{GeV/c}$)

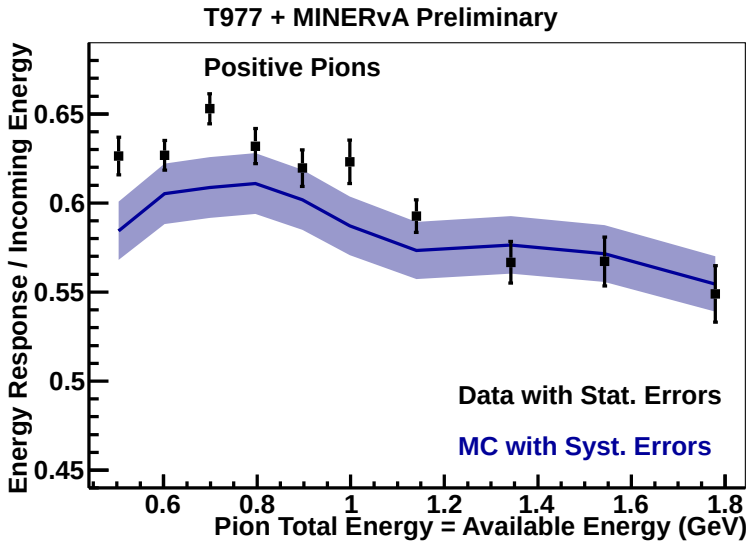
MINERνA

$\pm 11\,\mathrm{MeV}$ (mass model)

$\pm 30\,\mathrm{MeV}$ ($\mathrm{d}E/\mathrm{d}x$)

MINERνA CCQE: Systematics

- Flux
  - Tune to NA49 data
  - Remaining 10–15% uncertainties
  - Cancel in shape analysis
- Muon energy scale
  - Muon p scale known to 2–3%
- Recoil energy reconstruction
  - Hadronic energy scale from testbeam
  - Hadron reinteractions from external data



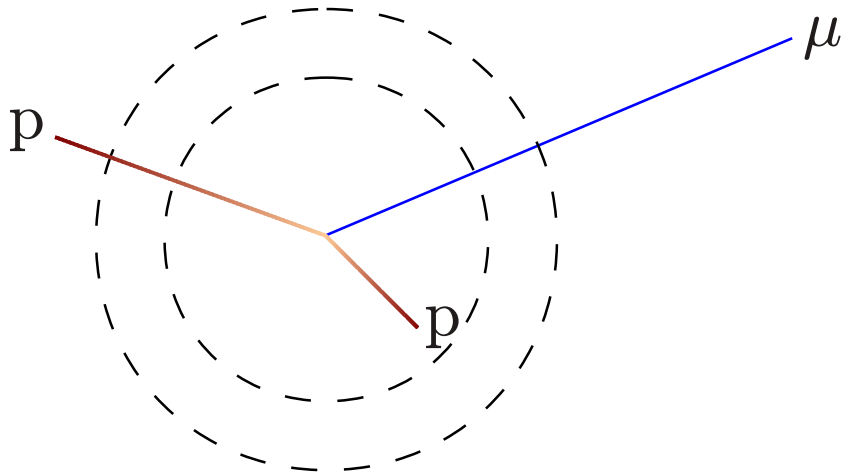
MINERνA CCQE: Systematics

- Flux
  - Tune to NA49 data
  - Remaining 10–15% uncertainties
  - Cancel in shape analysis
- Muon energy scale
  - Muon p scale known to 2–3%
- Recoil energy reconstruction
  - Hadronic energy scale from testbeam
  - Hadron reinteractions from external data
- Interaction modelling
  - 10s of % uncertainties on primary interaction, FSI
  - Enter via efficiency correction, background shape

Model parameter	Uncertainty (%)
CC resonance prod.	20
Δ axial mass M_A^{res}	20
Non-resonant π prod.	50
FSI:	
π, N mean free path	20
π absorption	30

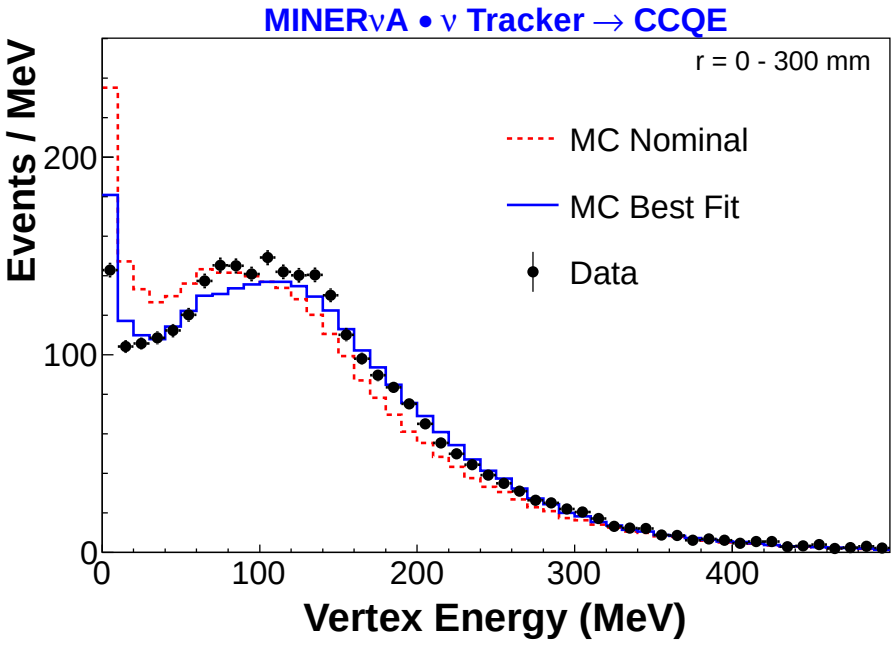
MINERνA CCQE: Vertex energy

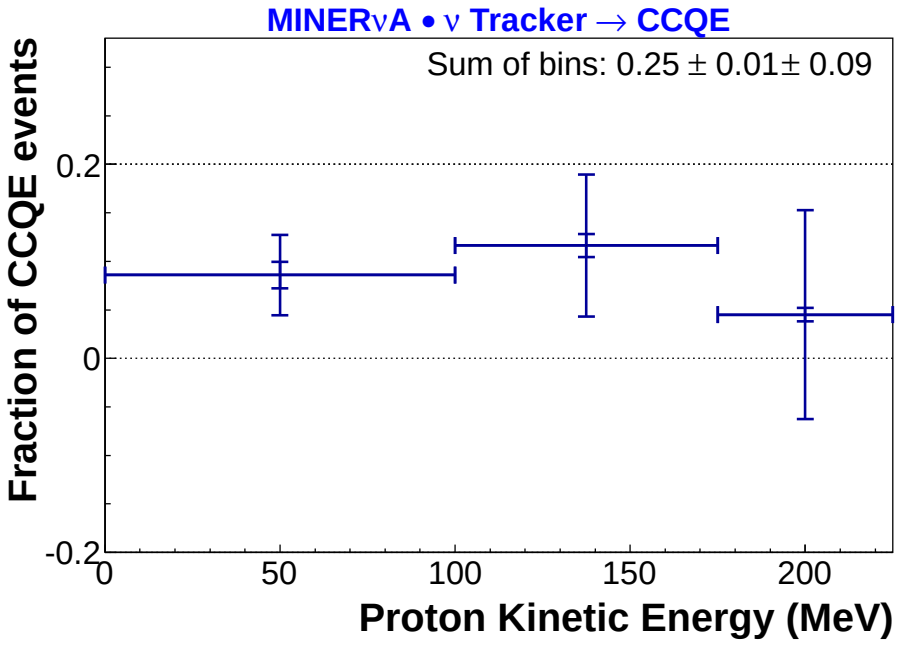
- *Assume* an extra proton
- Use spatial distribution of energy to infer KE distribution of extra proton



MINERνA CCQE: Vertex energy

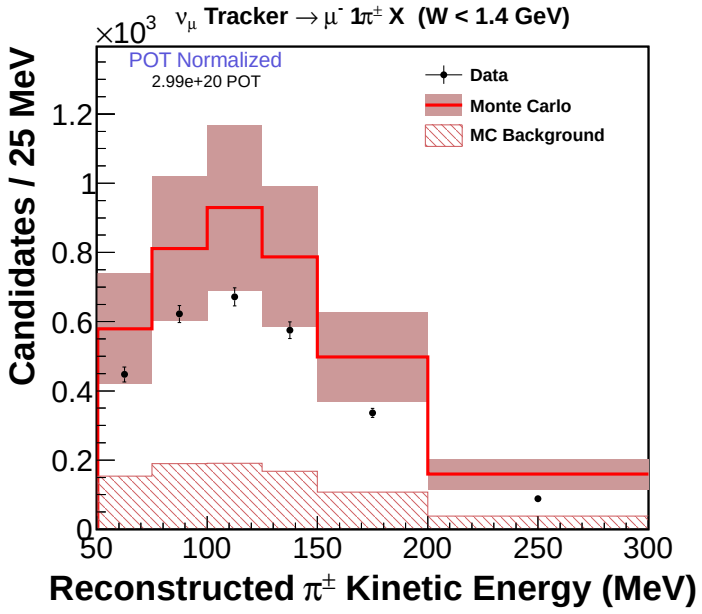
- *Assume* an extra proton
- Use spatial distribution of energy to infer KE distribution of extra proton

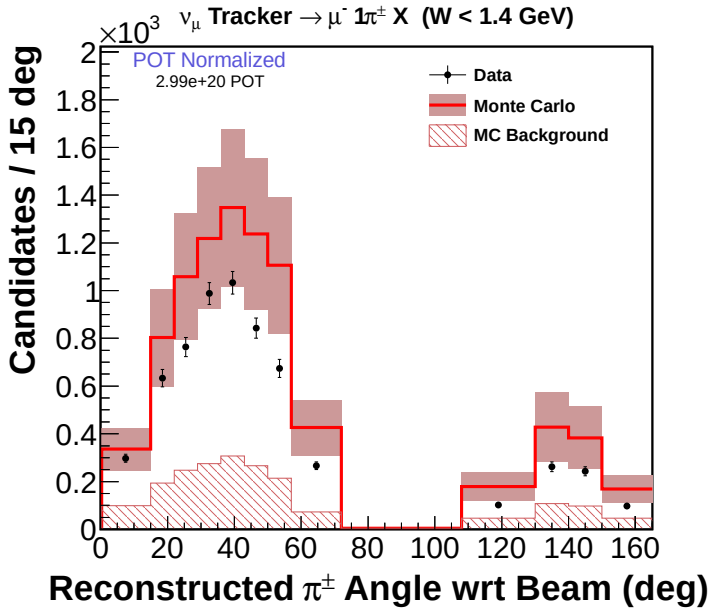


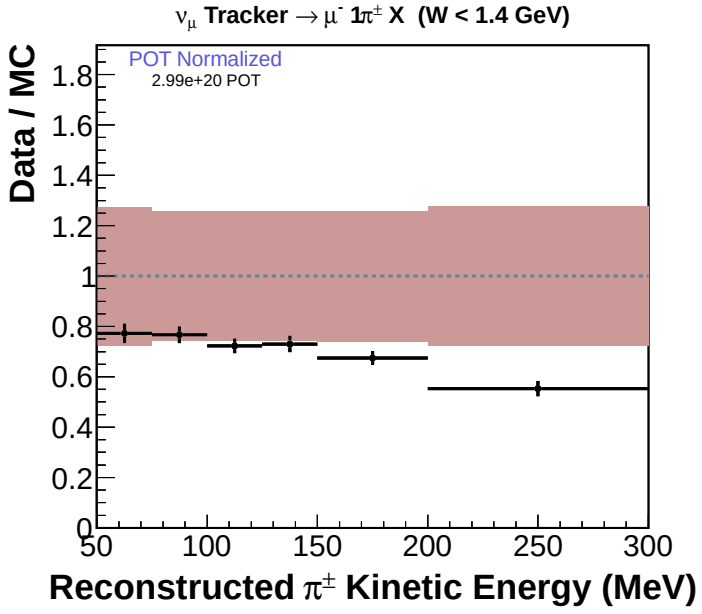


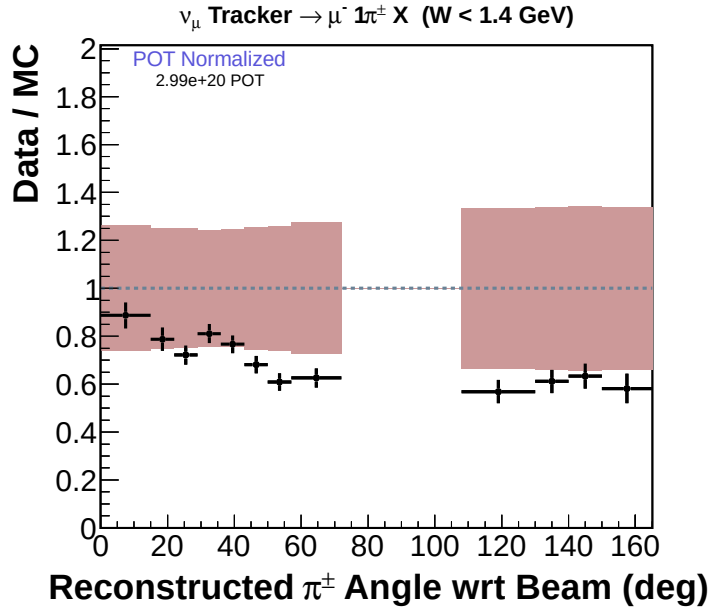
- Extra proton preferred in $(25 \pm 9)\%$ of ν_μ CCQE events
- No increase preferred in $\bar{\nu}_\mu$ mode

MINERνA charged pion production: reco π distributions

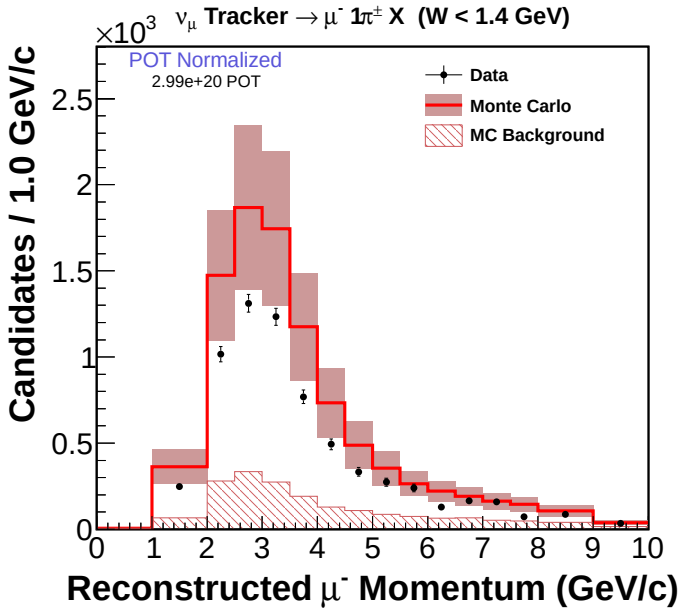


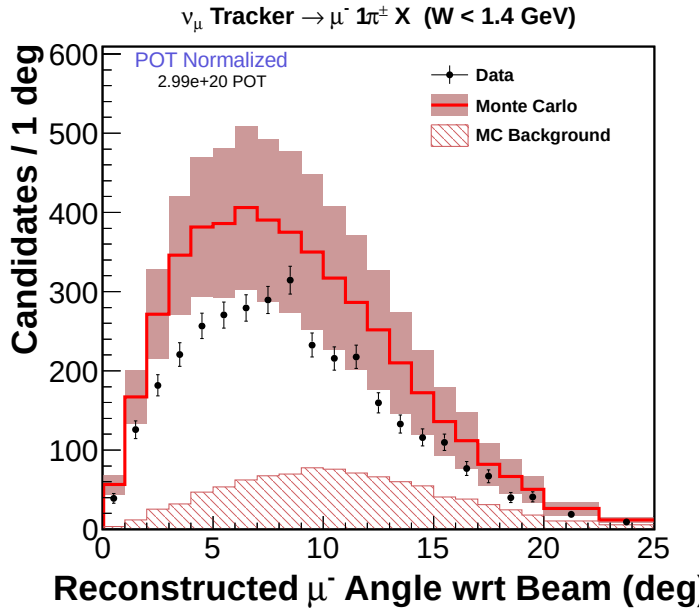


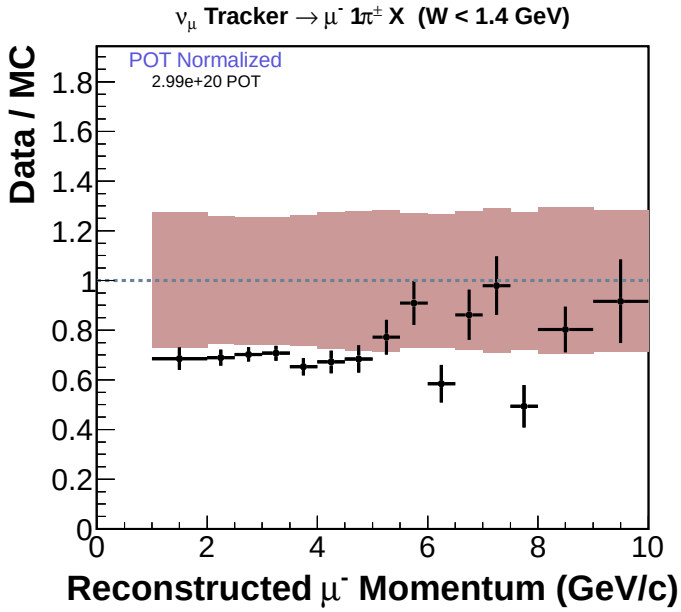


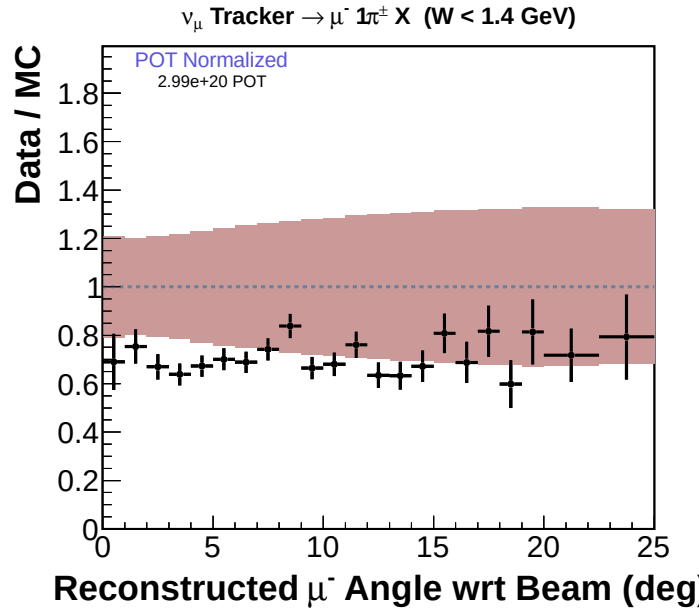


MINERνA charged pion production: reco μ distributions

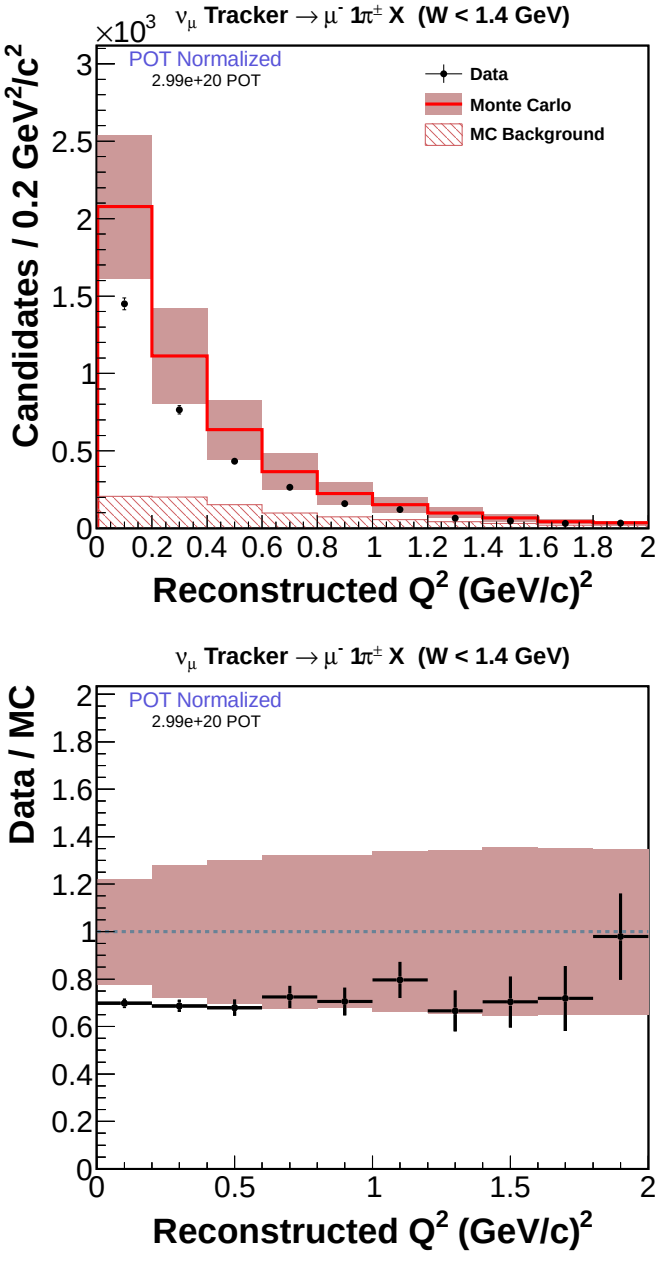






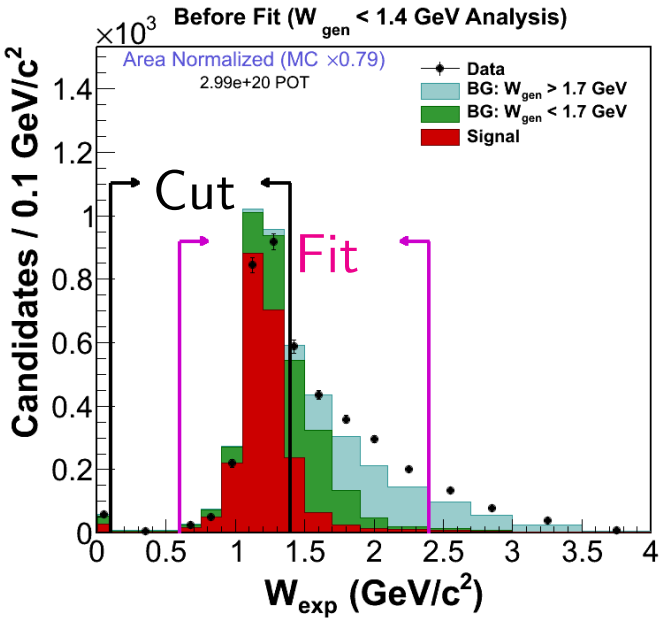


MINERνA charged pion production: reco Q^2 distribution

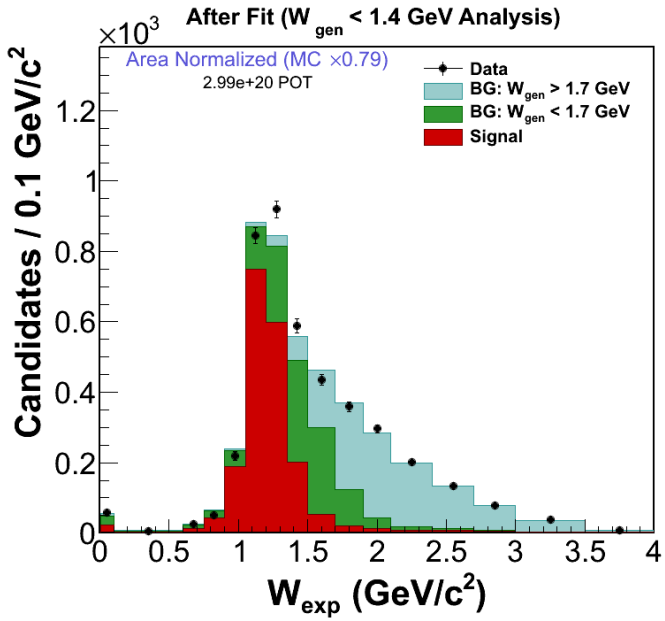


MINERνA charged pion production: BG subtraction

Before fit

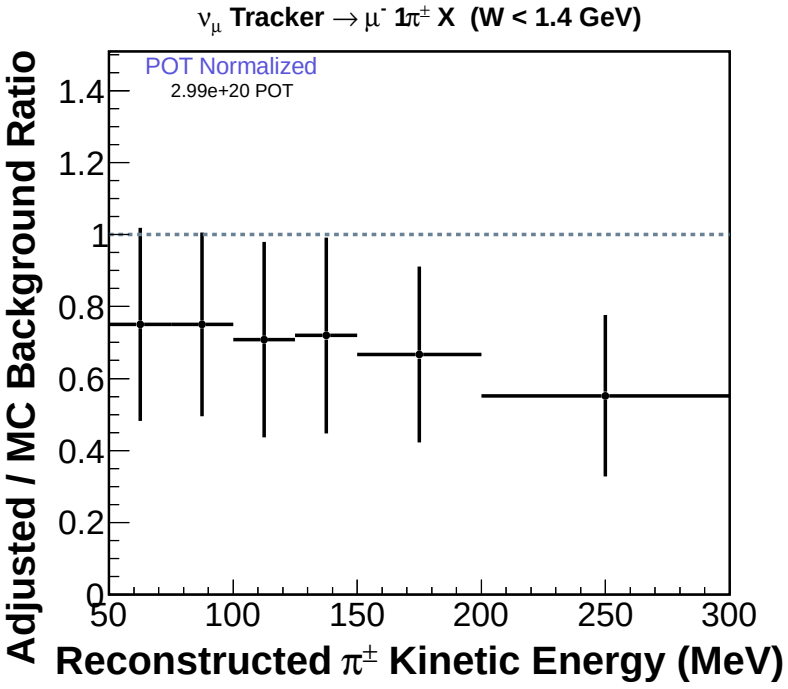


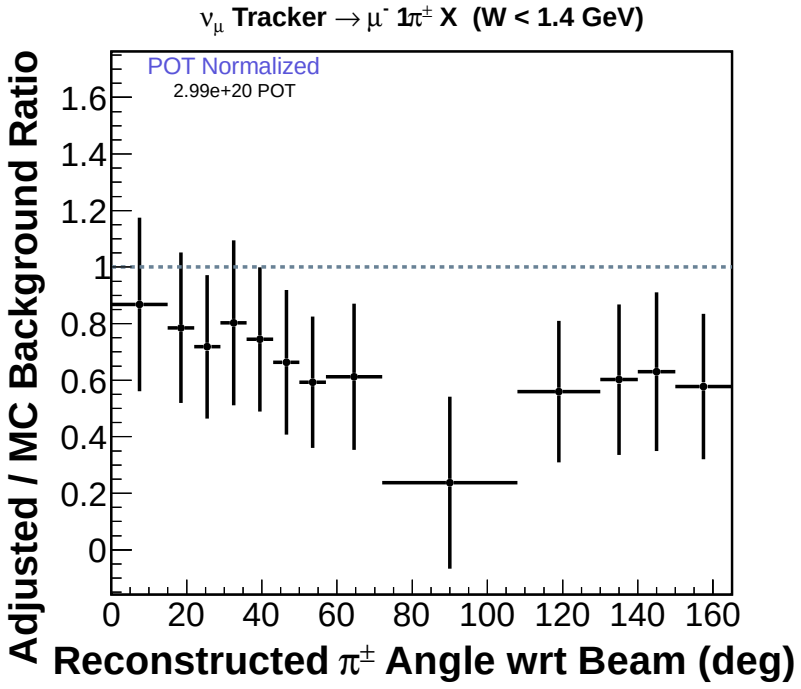
After fit



- Constrain $W > 1.4\,\text{GeV}$ background from sideband fit
- Fit MC templates for relative normalizations

MINERνA charged pion production: BG scales

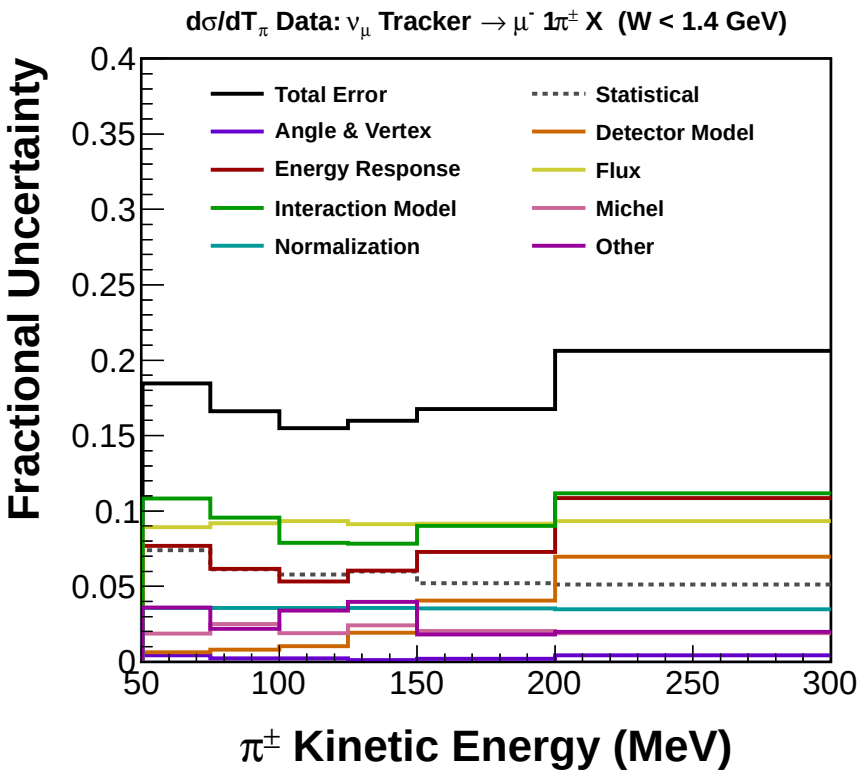


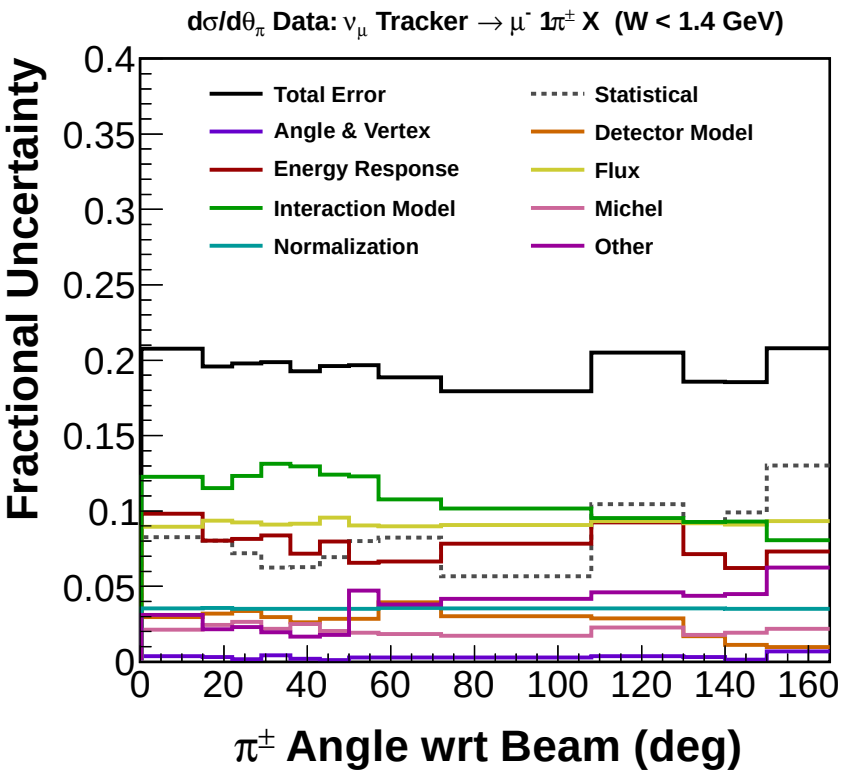


- Errors stat+syst. Dominant uncertainty is detector energy response

MINERνA charged pion production: Systematics

Shape + Normalization





MINERνA charged pion production: Systematics

Shape-only errors