# Measuring neutrino-nucleus interactions with MINER$\nu$A

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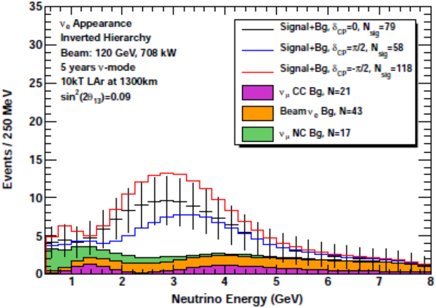
June 2, 2014

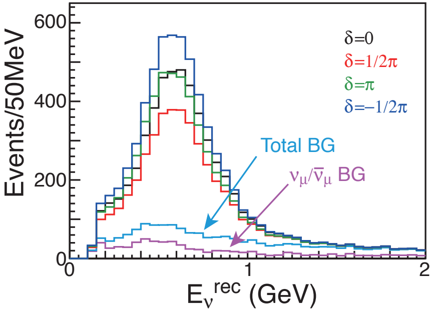
# Understanding few-GeV neutrino interactions with nuclei is vital for precision oscillation measurements

LBNE



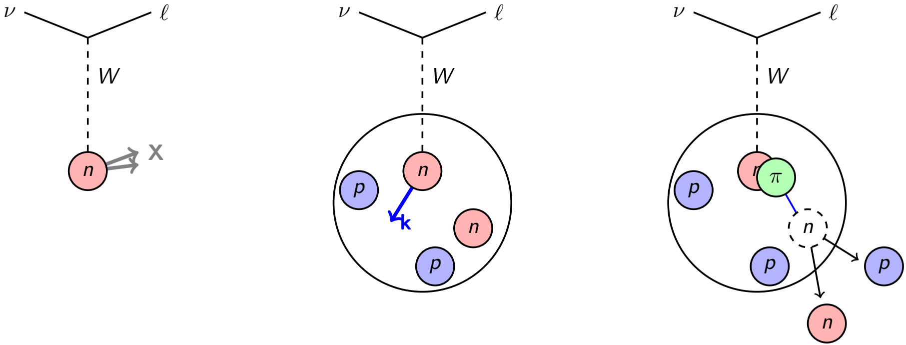

LBNE CDR, arXiv:1307.7335

HyperK



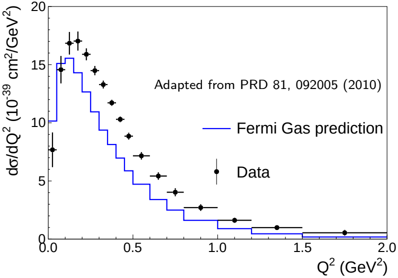

HyperK LOI, arXiv:1109.3262. NH. $\sin^2 2\theta_{13} = 0.1$

# Understanding neutrino interactions requires understanding complex strongly-bound systems

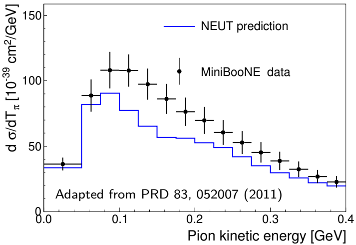


# Models currently used by experiments do not agree with recent data

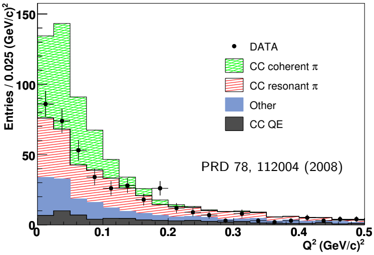
MiniBooNE $\nu_\mu + CH_2 \to \mu^- + 0\pi$



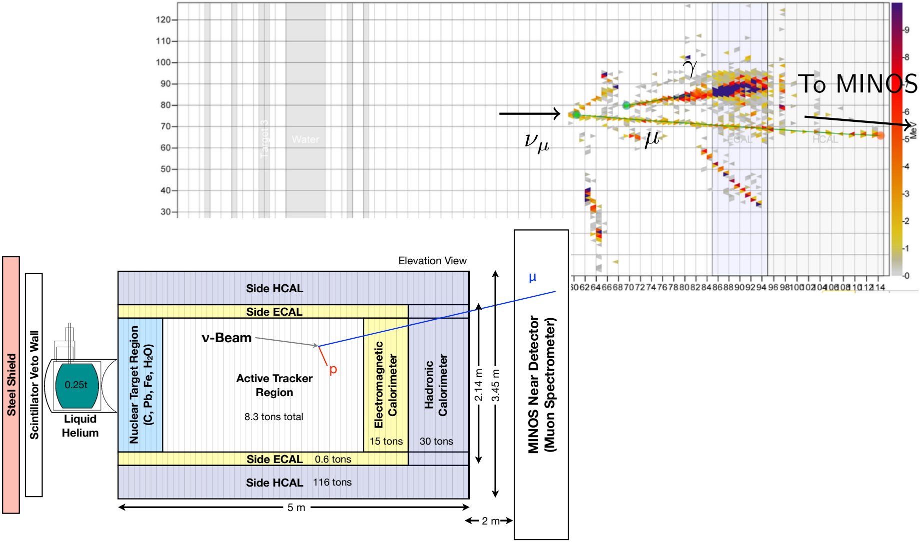

MiniBooNE $\nu_\mu + CH_2 \to \mu^- + 1\pi^+$




SciBooNE $\nu_\mu + CH \to \mu^- + CH + \pi^+$



# The MINER$\nu$A detector provides a fine-grained view of neutrino-nucleus interactions



## How to measure a cross section

$$\sigma_i = \frac{U_{ij}(N_j - B_j)}{\Phi_i T \varepsilon_i}$$

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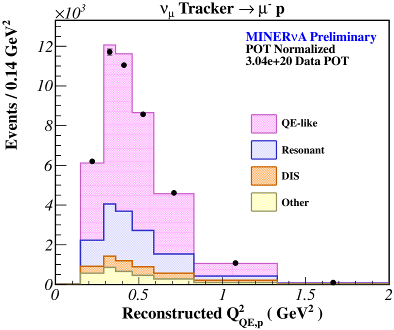
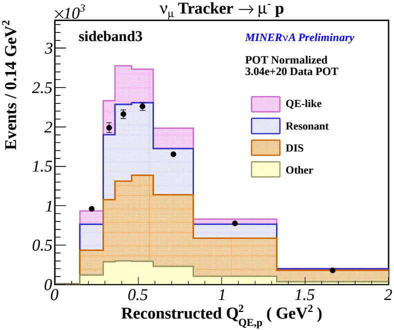
CCQE $\mu + p$ signal

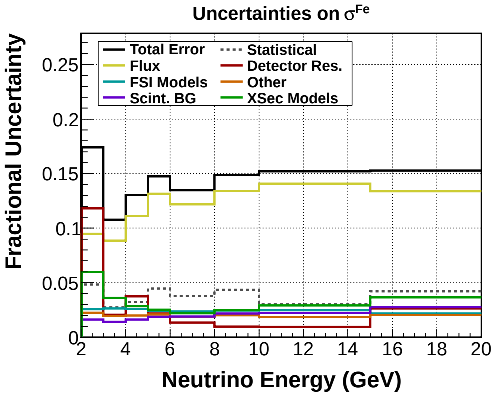



CCQE $\mu + p$ sideband



# How to measure a cross section

$$\sigma_i = \frac{U_{ij}(N_j - B_j)}{\Phi_i T \varepsilon_i}$$



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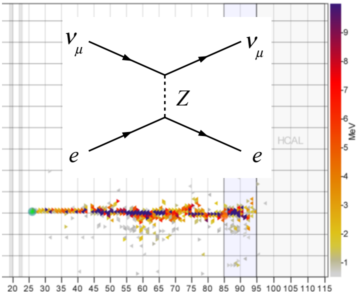
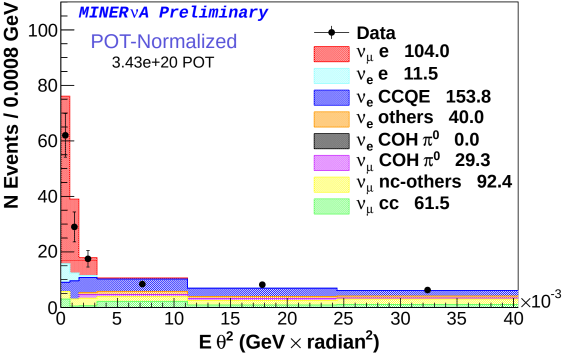
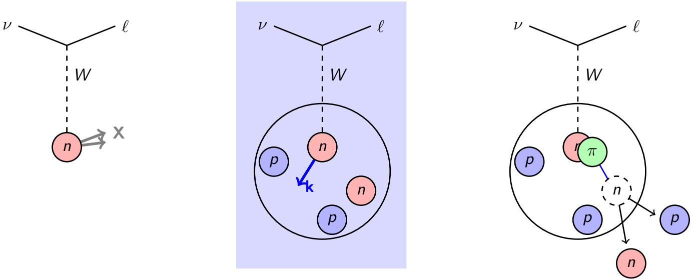


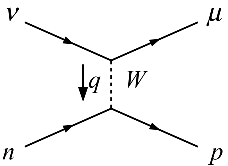




Poster 49: J. Park and 33: L. Ren

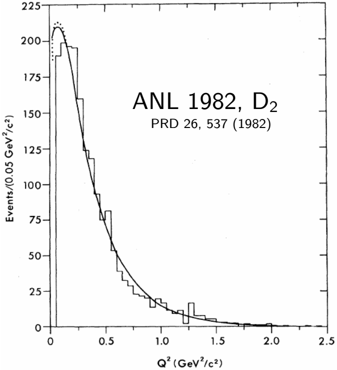
# Probing the nuclear model with charged-current quasielastic scattering



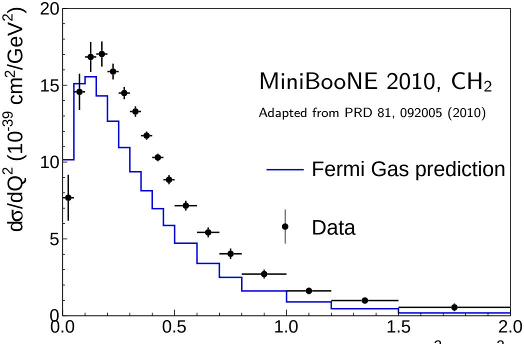
# Charged-current quasielastic scattering on nuclear targets is not well described by a simple nuclear model




On nucleons

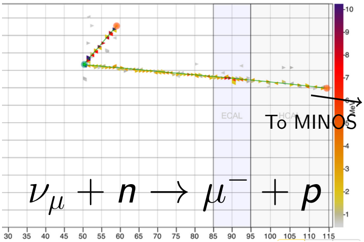


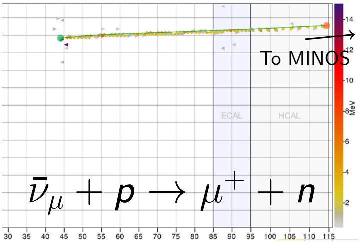

On carbon

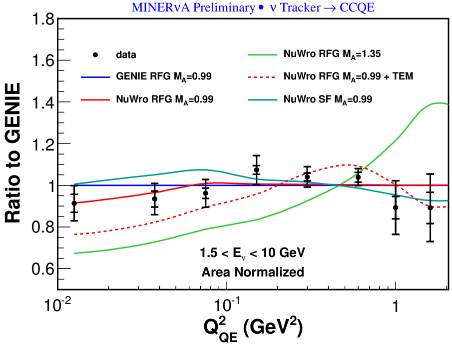


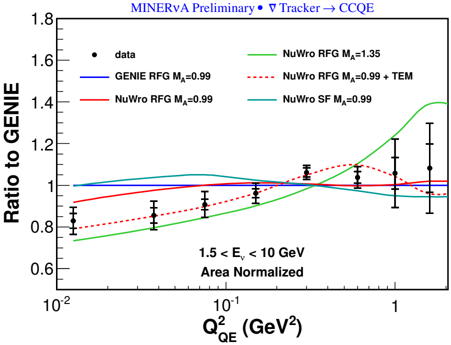

$$Q^2 = -q^2$$

# MINER$\nu$A discriminates between nuclear models via lepton kinematics

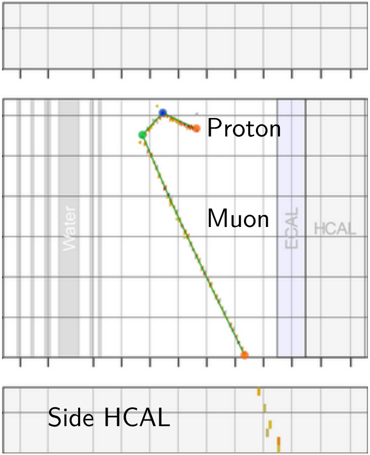


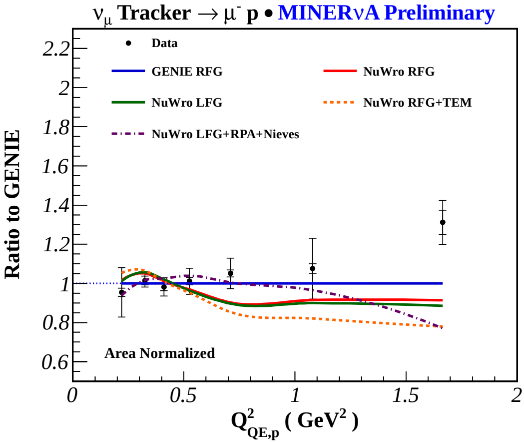



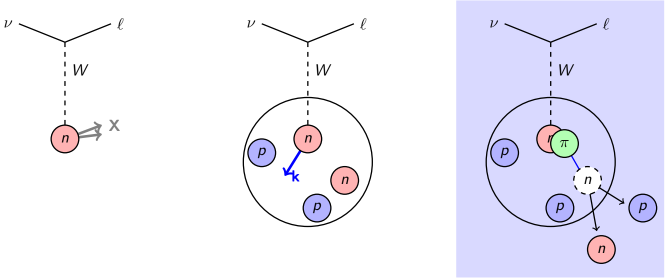



# A $\mu + p$ CCQE sample probes the hadronic side of the interaction



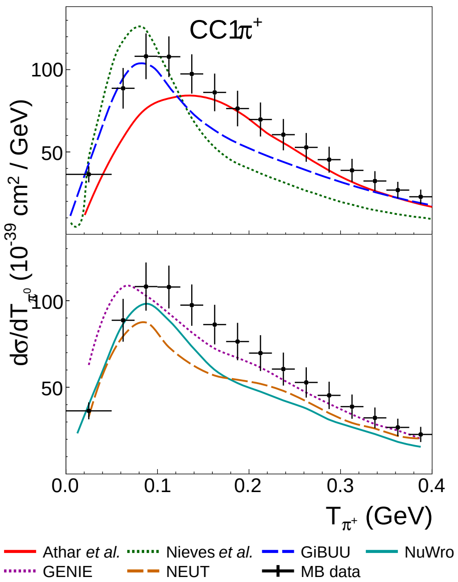



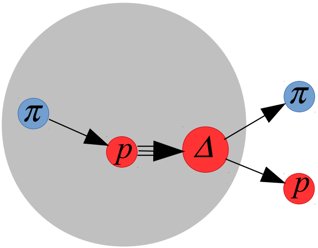
# Validating final state effects in single pion production



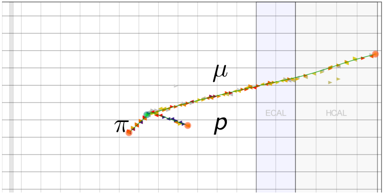
# Previous single pion production data show tension with models

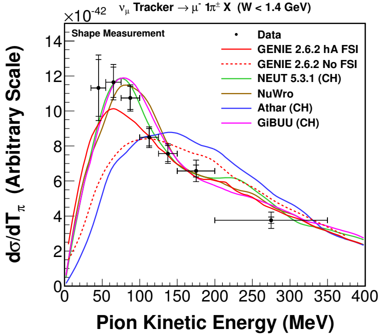
MiniBooNE data on $CH_2$

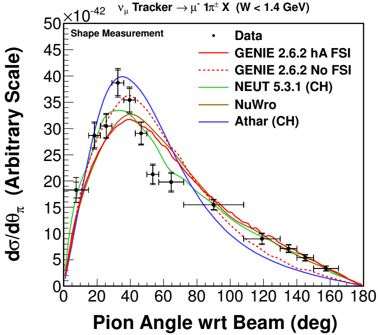


# In CC single $\pi^+$ production, MINER$\nu$A pion kinematics show broad agreement with models

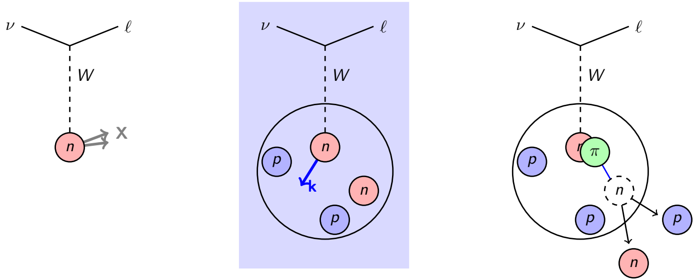


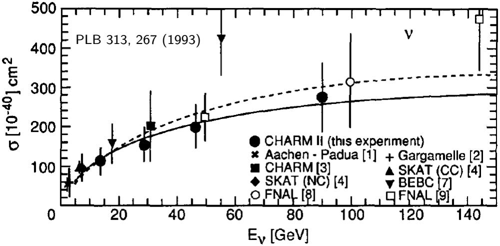



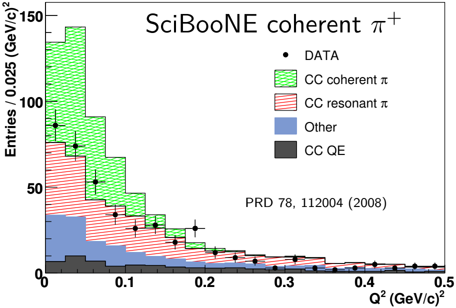

Poster 31: L. Rakotondravohitra

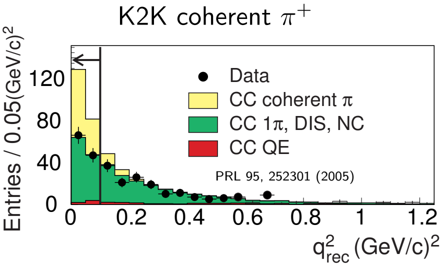
# Interacting with the whole nucleus: coherent pion production



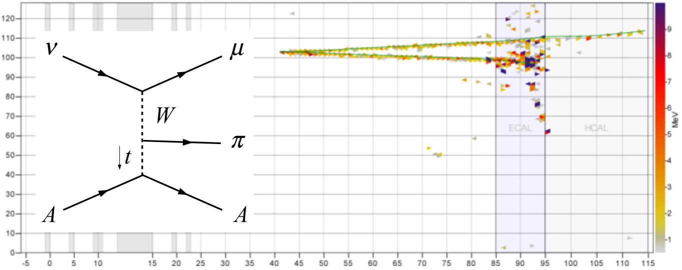
## Recent experiments find no evidence for coherent $\pi^+$ production at $E_\nu \sim 1\,\text{GeV}$

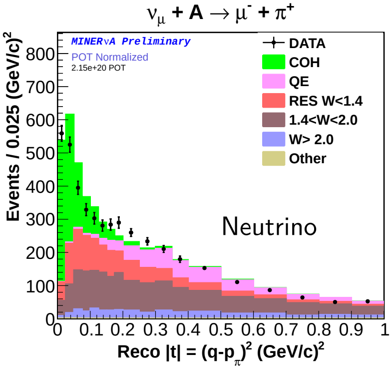


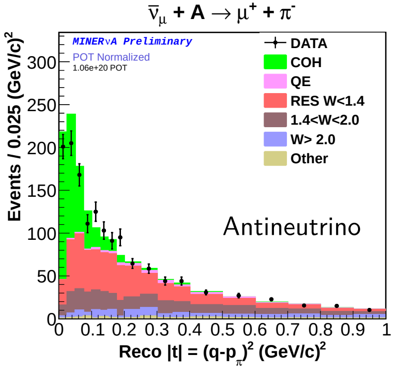



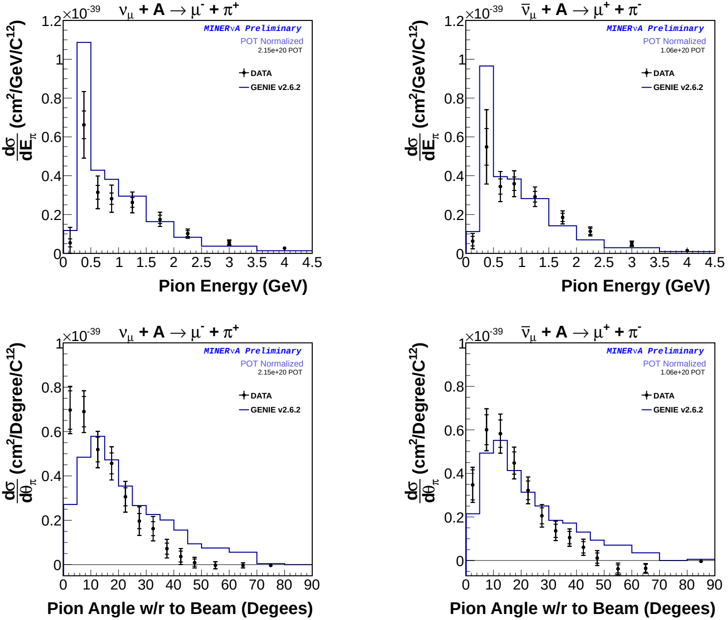
# MINERνA sees clear evidence of coherent pion production



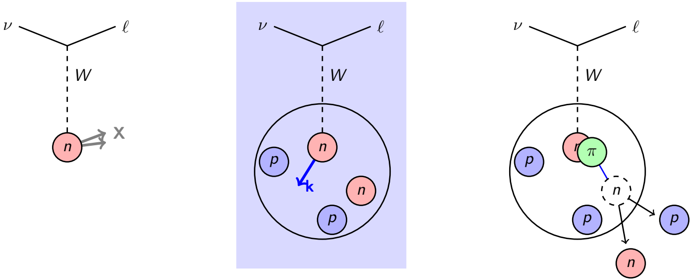



# MINER$\nu$A coherent pion kinematics disfavour current model




Poster 111: A. Mislivec

# Beyond carbon: inclusive charged-current scattering on different nuclei



# Ratios of cross sections on MINER$\nu$A's passive targets probe nuclear effect variations with $A$

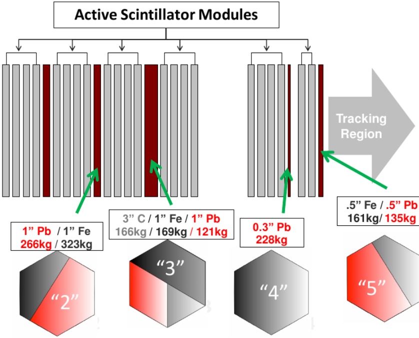
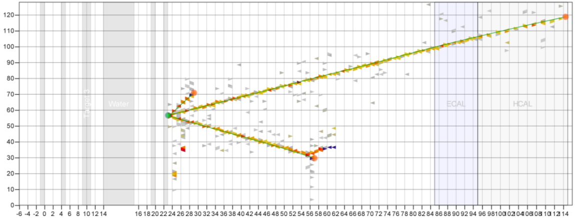
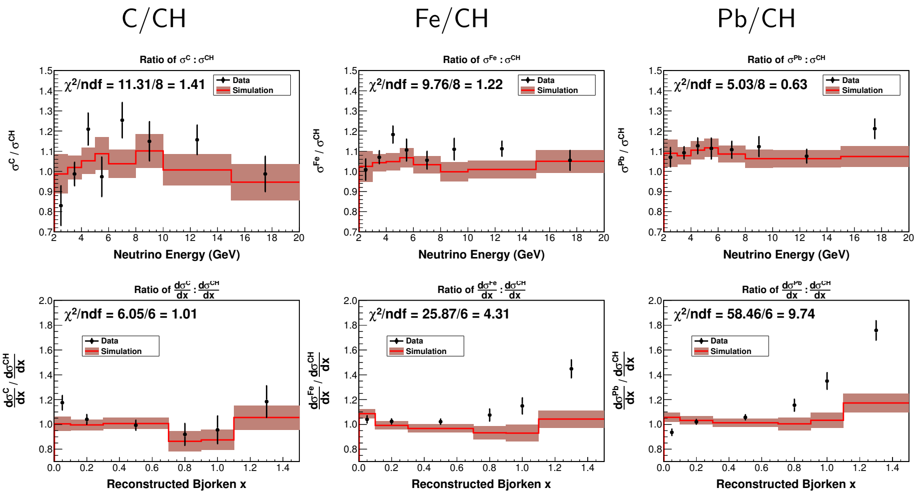



Figure: B. Tice



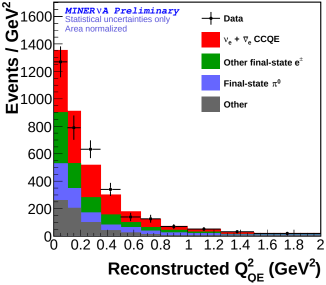
# MINERνA passive target data shows consistency with model in $E_\nu$ but not $x$



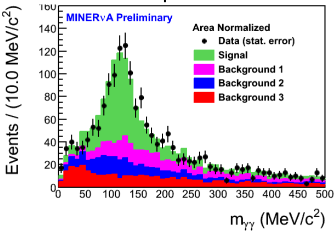

Increasing $A \longrightarrow$

# What's next: CC1$\pi^0$, kaon production, $\nu_e$ CCQE, and higher $E_\nu$

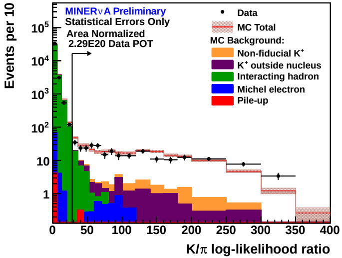
## $\nu_e$ CCQE




## CC $\pi^0$ production

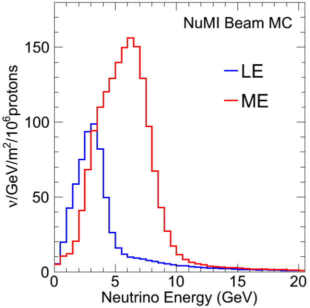



## $K/\pi$ separation

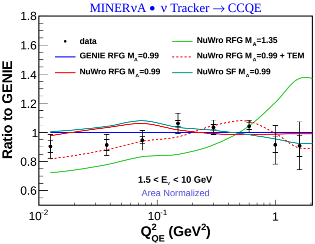


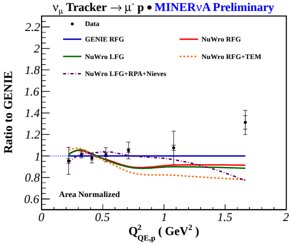

Poster 32: C. Marshall

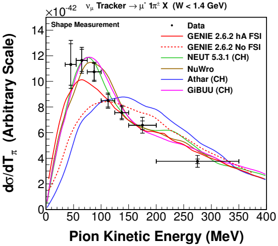
## Higher $E_\nu$

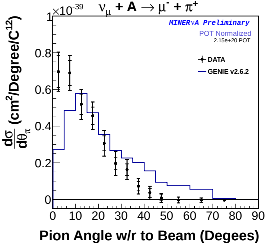


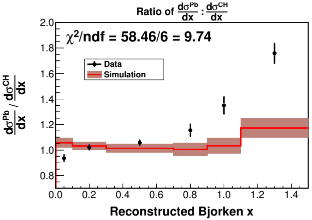
# Recap: MINER$\nu$A data is pointing the way for generators and models



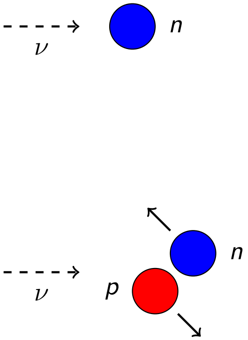



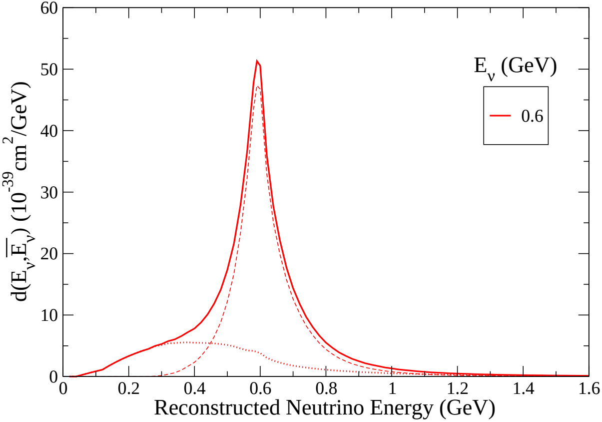



# Backup slides

# Implication for oscillation experiments

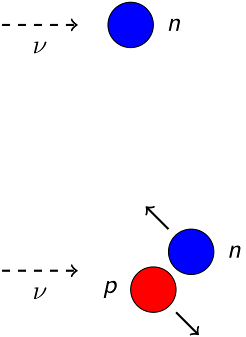


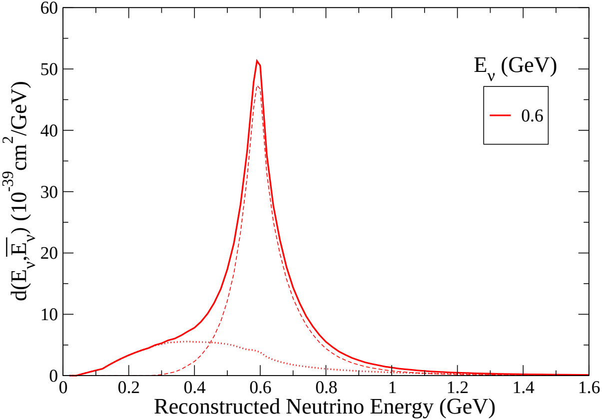




Adapted from Martini *et al.*, arXiv:1211.1523

- Affect lepton kinematics, $E_\nu$ reco, hadrons in final state

# Implication for oscillation experiments




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

- Affect lepton kinematics, $E_\nu$ 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

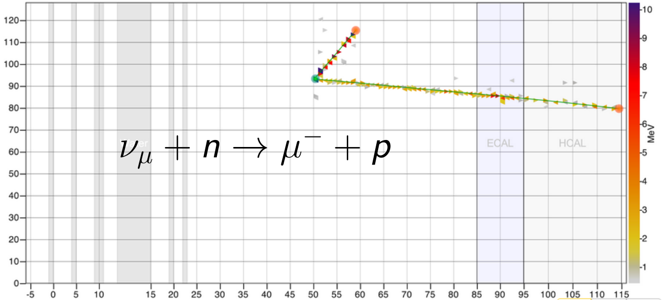
Martini *et al.*, PRC 81, 045502 (2010)
Alvarez-Ruso, arXiv:1012.3871
Fernandez-Martinez, Meloni, PL B697, 477 (2011)
Meucci, *et al.*, arXiv:1103.0636
Antonov *et al.*, arXiv:1104.0125

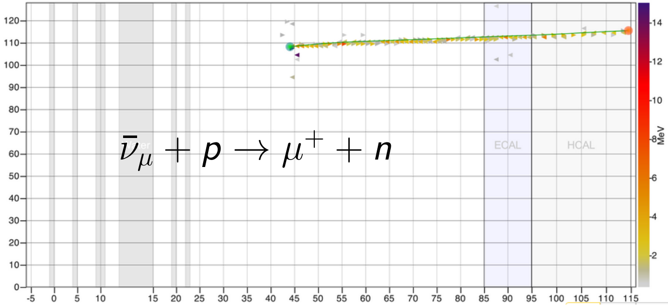
Amaro *et al.*, PRC 82, 046601 (2010)
Amaro *et al.*, arXiv:1012.4265
Amaro, *et al.*, PL B696, 151 (2011)
Benhar, Veneziano, arXiv:1103.0987

# MINER$\nu$A CCQE analysis

- Aims:
  1. Make shape-only comparisons of $\frac{\mathrm{d}\sigma}{\mathrm{d}Q^2}$ to nominal model and models with multinucleon effects
  2. Look at energy near the interaction vertex for evidence of multinucleon emission
- In both $\nu$ and $\bar{\nu}$ data

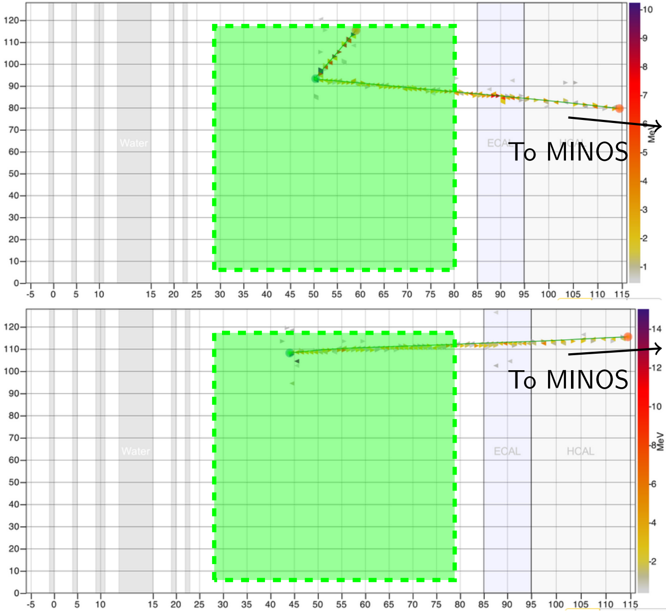
# CCQE selection



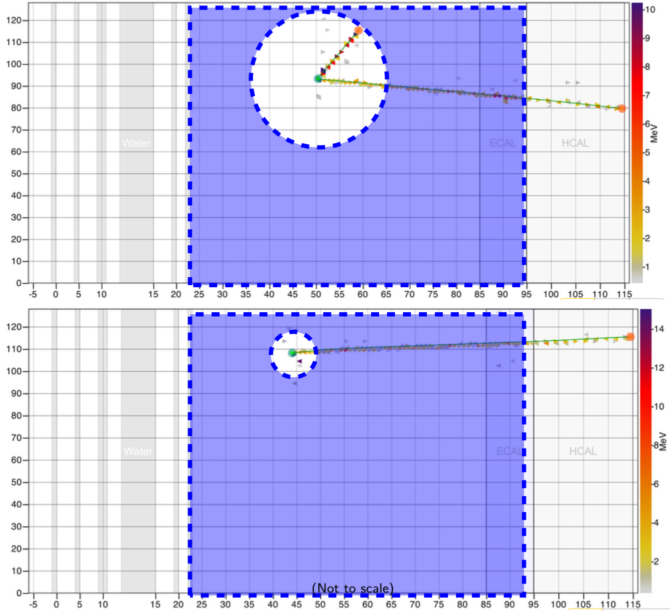



# CCQE selection

- Fiducial volume
- MINOS matched track
- $\nu$: $\leq 2$ isolated showers
- $\bar{\nu}$: $\leq 1$ isolated showers



# CCQE selection

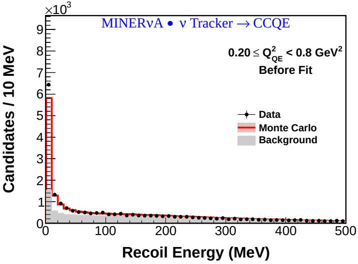


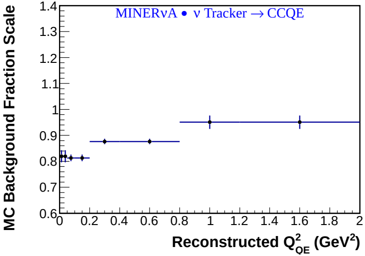

- Require low non-vertex recoil energy
- $\nu$: $r < 300\,\mathrm{mm}$
- $\bar{\nu}$: $r < 100\,\mathrm{mm}$

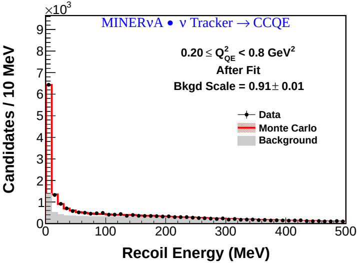
# CCQE analysis: Constraining non-QE backgrounds

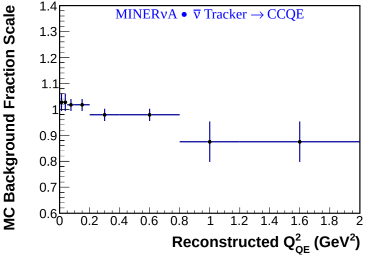
One example bin in $Q^2$

All $Q^2$ bins



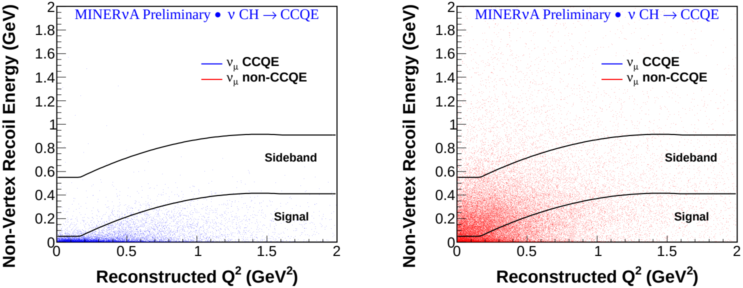



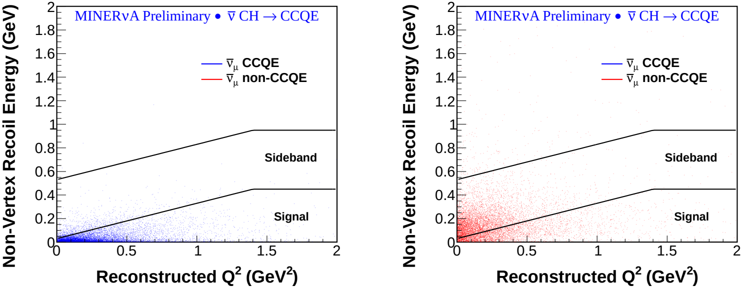



# CCQE Recoil energy cut

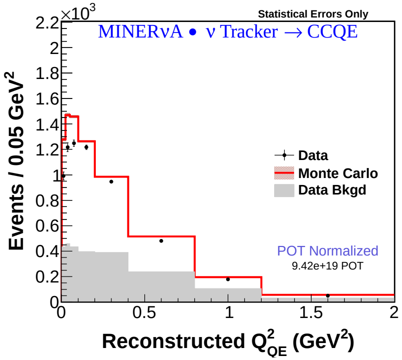
## Neutrino mode

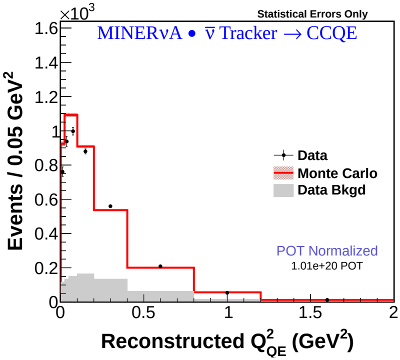



## Antineutrino mode



# CCQE Final event selections



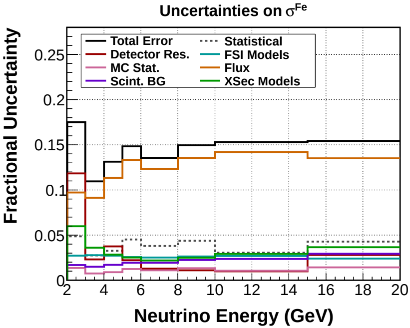




| | ν | $\bar{\nu}$ |
|---|---|---|
| No of events | 29,620 | 16,467 |
| Efficiency | 47% | 54% |
| Purity | 49% | 77% |

- Constrained background using fit to $E_{\mathrm{recoil}}$ distribution
- Then subtract BG, unfold, efficiency correct to get $\sigma$
- But first, systematics...

# CCQE Systematics

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



# CCQE Systematics

- Flux
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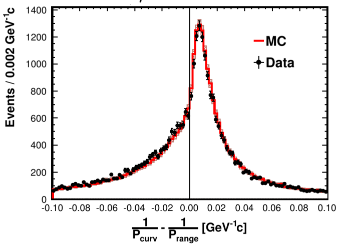
- Muon energy scale
  - Muon $p$ scale known to 2–3%

$p_\mu$ scale




MINOS range

$\pm 2\%$ (all $p_\mu$)

MINOS curvature

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

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

MINER$\nu$A

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

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

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- Flux
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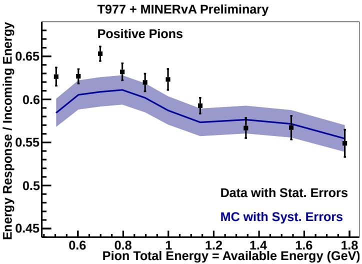
- Muon energy scale
  - Muon $p$ scale known to 2–3%
- Recoil energy reconstruction
  - Hadronic energy scale from testbeam
  - Hadron reinteractions from external data

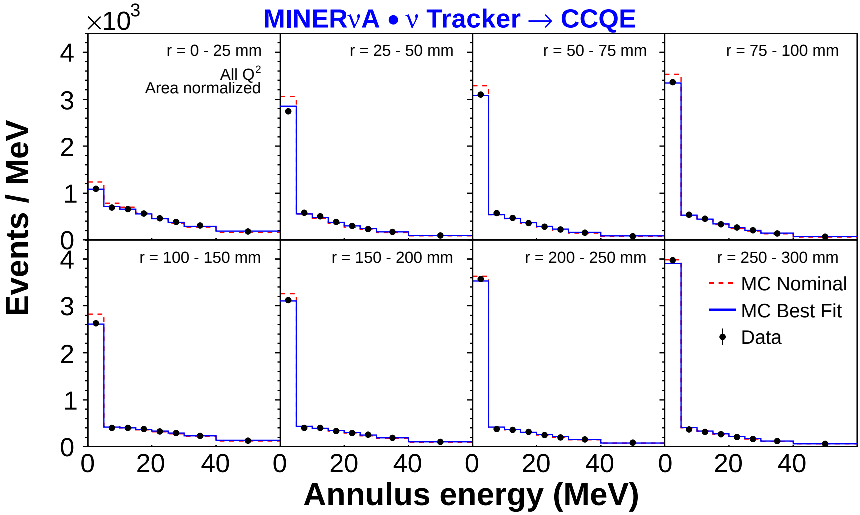


# CCQE Systematics

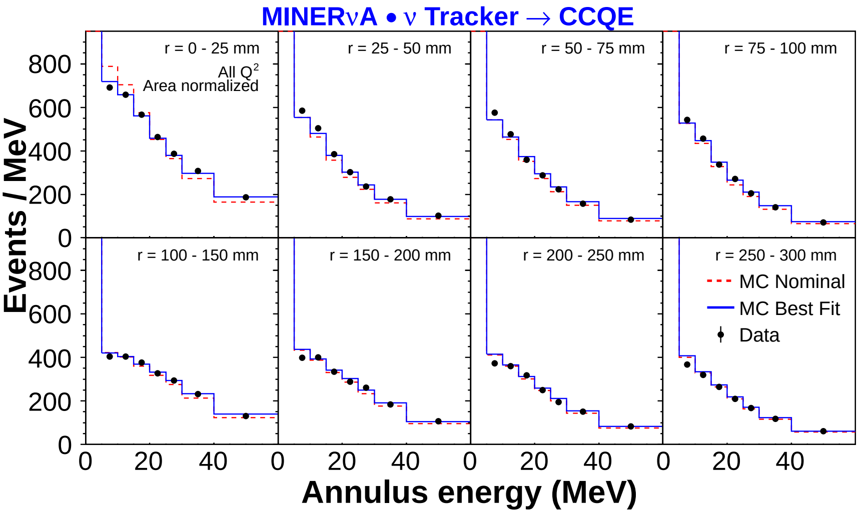
- Flux
  - Tune to NA49 data
  - Remaining 10–15% uncertainties
  - Cancel in shape analysis
- Muon energy scale
  - Muon $p$ scale known to 2–3%
- Recoil energy reconstruction
  - Hadronic energy scale from testbeam
  - Hadron reinteractions from external data
- Interaction modelling
  - 10s of % uncertainties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

| Model parameter | Uncertainty (%) |
|---|---|
| CC resonance prod. | 20 |
| $\Delta$ axial mass $M_A^{\text{res}}$ | 20 |
| Non-resonant $\pi$ prod. | 50 |
| FSI: | |
| $\pi$, $N$ mean free path | 20 |
| $\pi$ absorption | 30 |

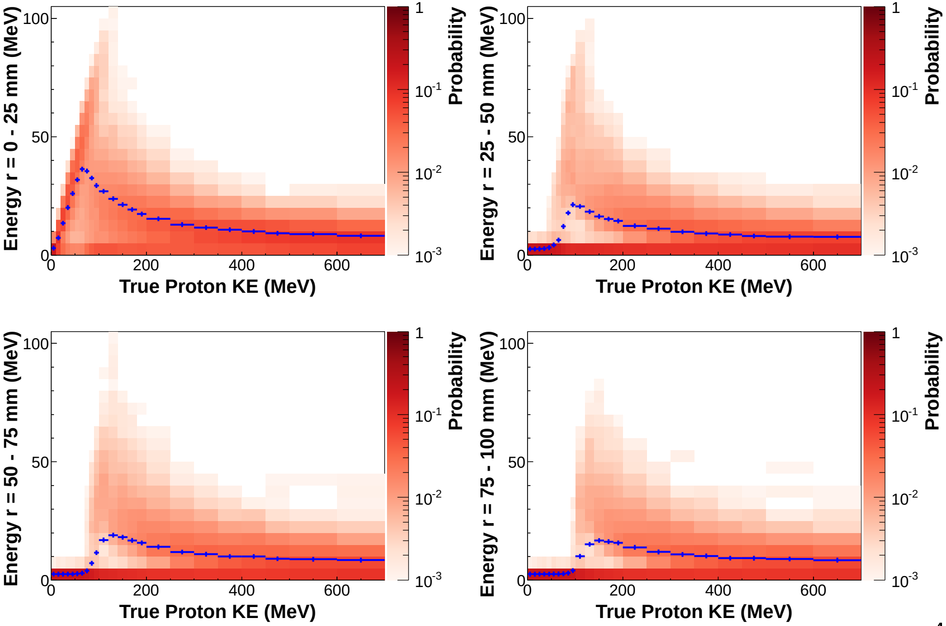
# Vertex energy fit distributions



# Vertex energy fit distributions, zoomed $y$

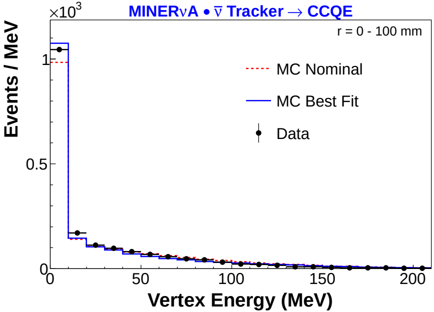


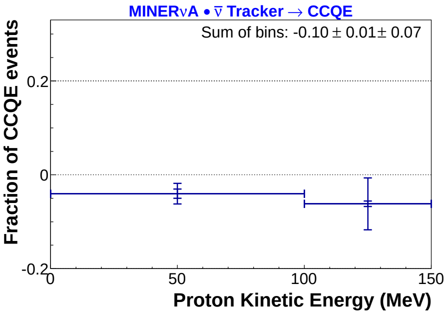
# Annulus energy *vs* proton KE



# Vertex energy, $\bar{\nu}$ mode

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



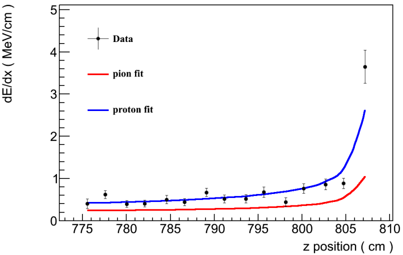

- No increase preferred in $\bar{\nu}_\mu$ mode

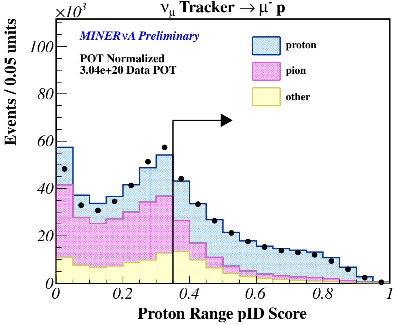
# CCQE $\mu + p$ sample

- Select events with two or more tracks: $1\mu$ and the rest protons
- Signal defined by final state: one $\mu$, at least one proton with momentum above 450 MeV/$c$, no pions

# CCQE $\mu + p$ sample: identifying protons

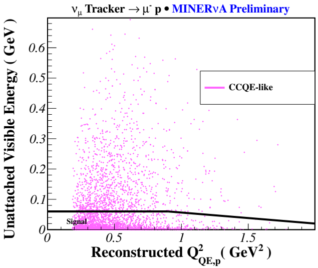
- Proton d$E$/d$x$ profile does PID and momentum reco

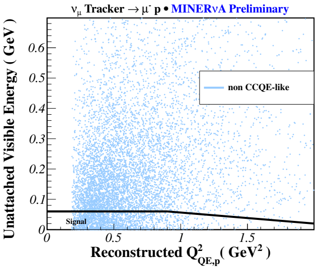


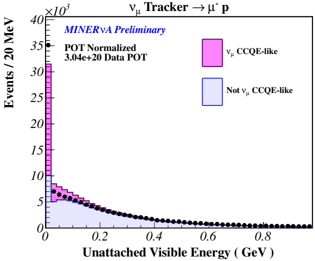



# CCQE $\mu + p$ sample: removing non-CCQE events

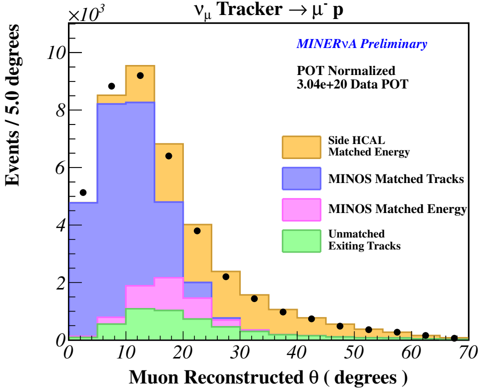
- Cut on "unattached visible energy" as a function of $Q^2$ and require no Michel electron



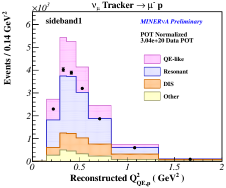



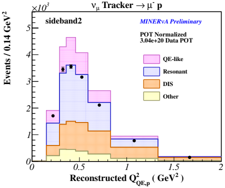



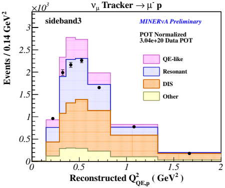
# CCQE $\mu + p$ sample: where do the muons go?

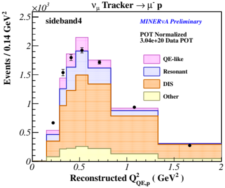


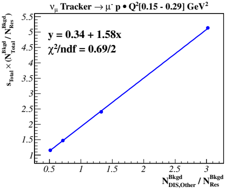
# CCQE $\mu + p$ sample: background tuning method

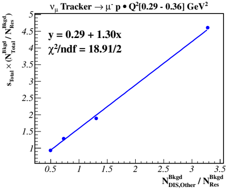


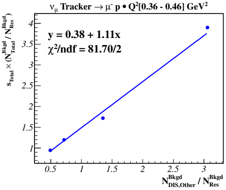

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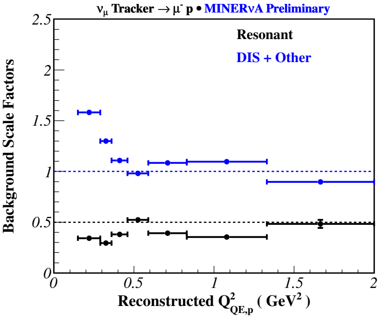
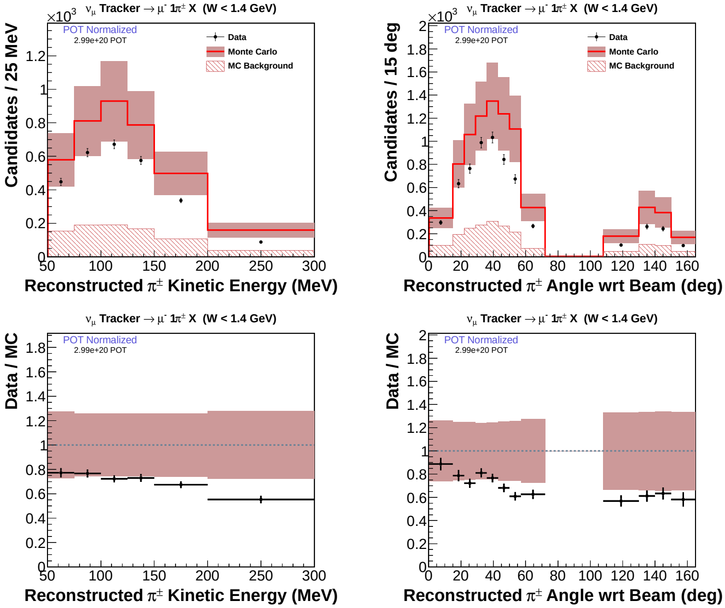
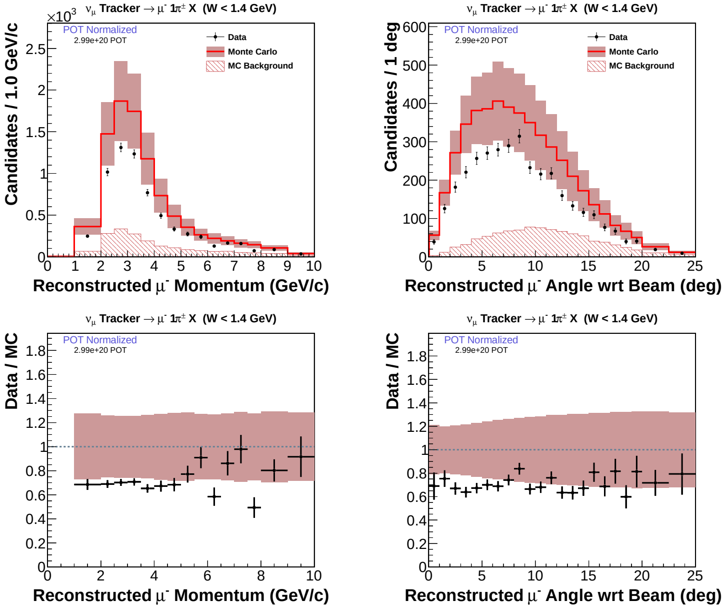
# CCQE $\mu + p$ sample: background tuning result



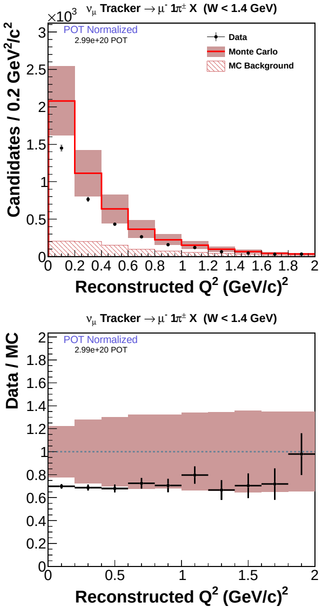
# MINER$\nu$A charged pion production: reco $\pi$ distributions



# MINER$\nu$A charged pion production: reco $\mu$ distributions

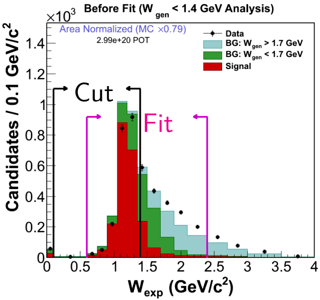


# MINER$\nu$A charged pion production: reco $Q^2$ distribution

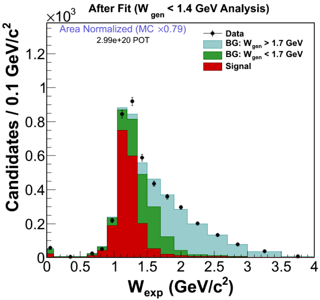


# MINER$\nu$A charged pion production: BG subtraction

Before fit

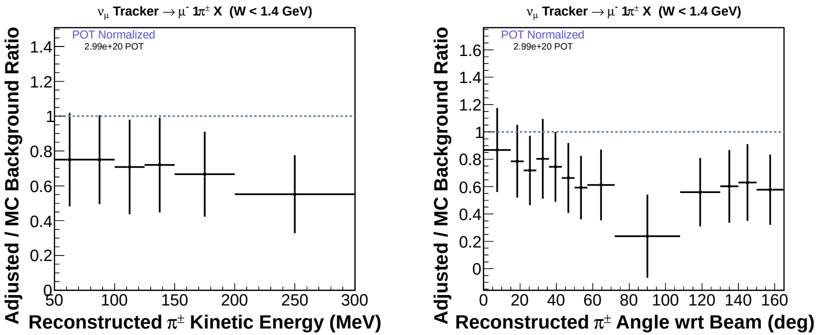



After fit



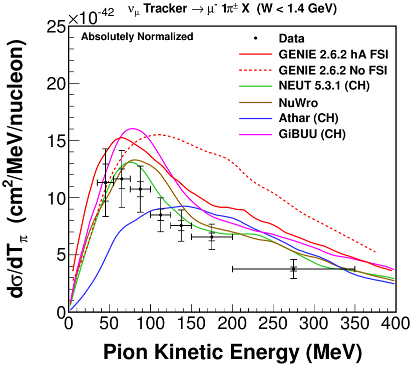

- Constrain $W > 1.4\,\text{GeV}$ background from sideband fit
- Fit MC templates for relative normalizations

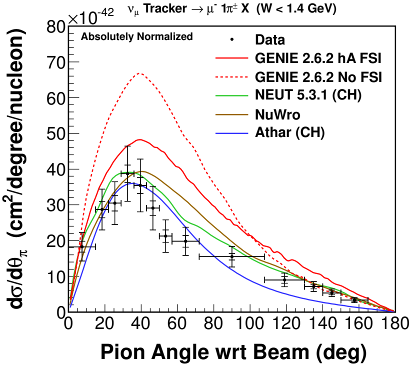
# MINER$\nu$A charged pion production: BG scales




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

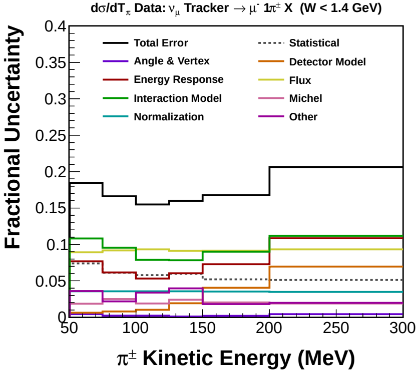
# MINERνA charged pion production: absolutely-normalized results

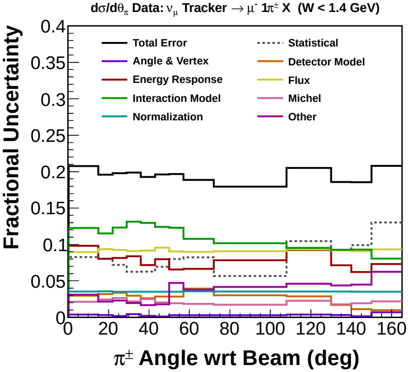


# MINER$\nu$A charged pion production: Systematics

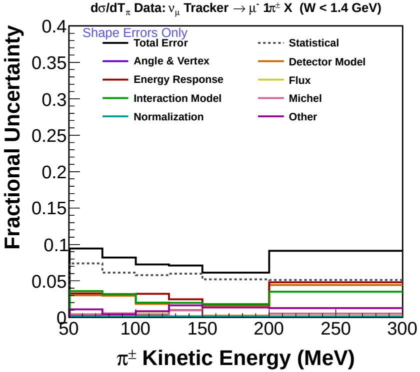
Shape + Normalization

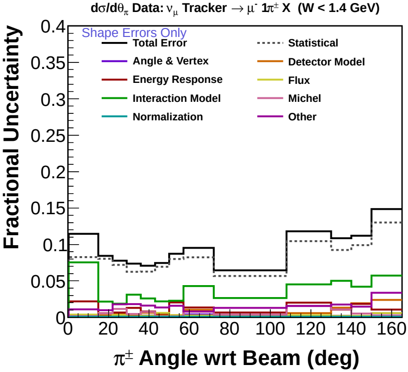


# MINER$\nu$A charged pion production: Systematics

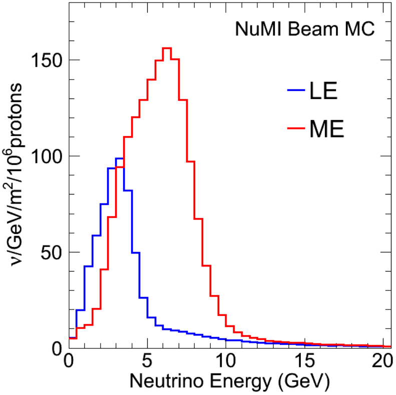
Shape-only errors

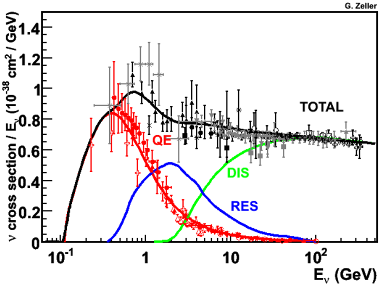


# CC inclusive nuclear target ratios

# CC inclusive ratios



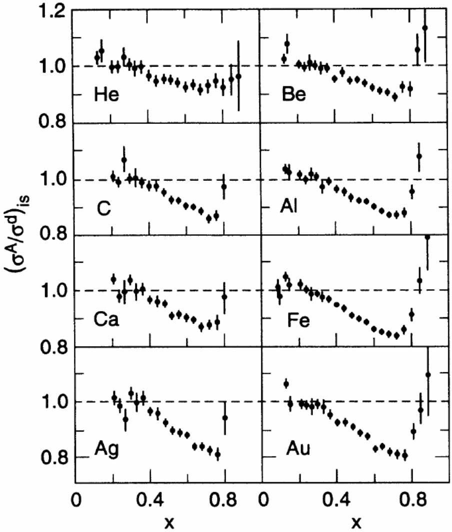

G. Zeller and J. Formaggio,Rev. Mod. Phys. 84, 1307–1341 (2012)

$$Q^2 = 2E_\nu(E_\mu - p_\mu \cos\theta_\mu) \qquad \nu = E_\nu - E_\mu \qquad x = \frac{Q^2}{2M\nu}$$

# CC inclusive ratios

- "EMC effect" well-studied but not well-understood
- What can neutrino data say?
  - Sensitive to a different combination of structure functions $F_1$, $F_2$, $xF_3$

EMC effect in electron scattering




SLAC E139: PRD **49** 4348 (1994)

# CC inclusive ratios in MINER$\nu$A

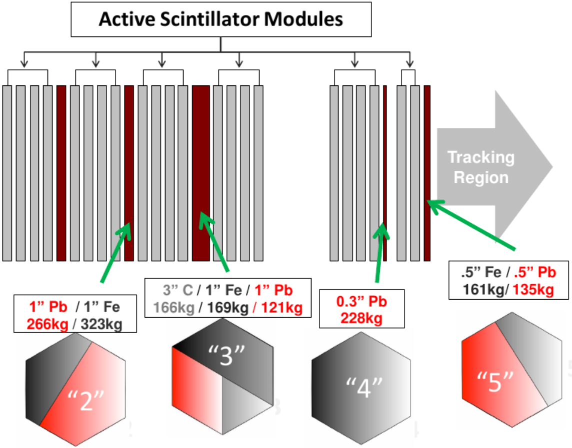
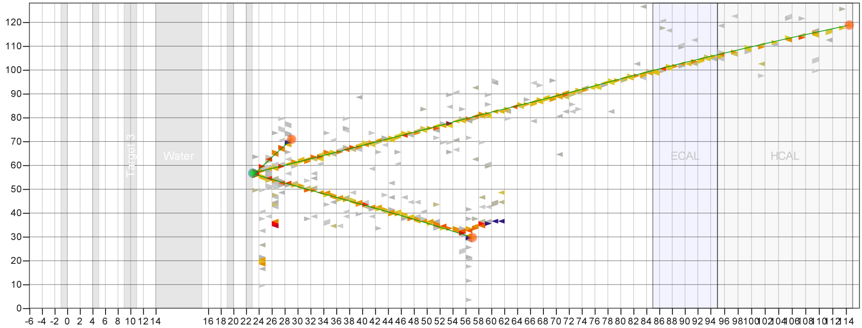



Figure: B. Tice

- We have nuclear targets. But not $D_2$...
- Strategy:
  1. Select CC $\nu_\mu$ events in nuclear targets and scintillator (CH)
  2. Construct ratios $\langle \textit{nucleus} \rangle / \mathrm{CH}$ in $E_\nu$ and $x$

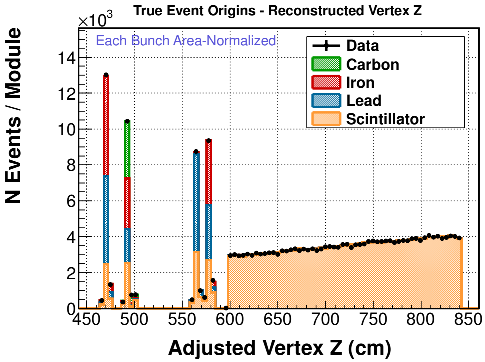
# Selection




1. MINOS-matched track
2. Vertex in nuclear target or scintillator plane immediately downstream

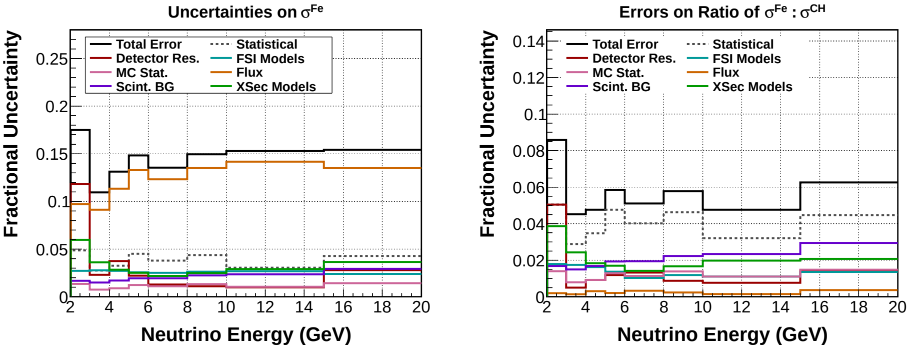
- Only significant background: events on plastic
- Reconstruct $E_\mu$, $\theta_\mu$, $E_{\text{had}}$ to calculate $E_\nu$, $Q^2$, $x$

# Plastic background subtraction




- Use data CC $\nu_\mu$ events in scintillator to predict background
- \+ Geometric acceptance correction from muon gun
- \+ Efficiency correction as fn of $E_{\text{had}}$ from simulation

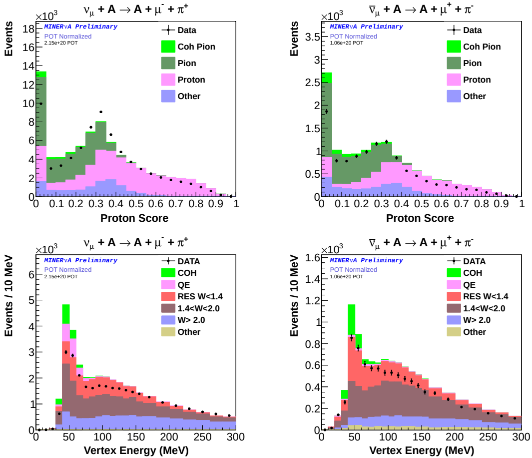
# Systematics




- Evaluated in similar way to CCQE analysis
- Most significant new one is plastic background

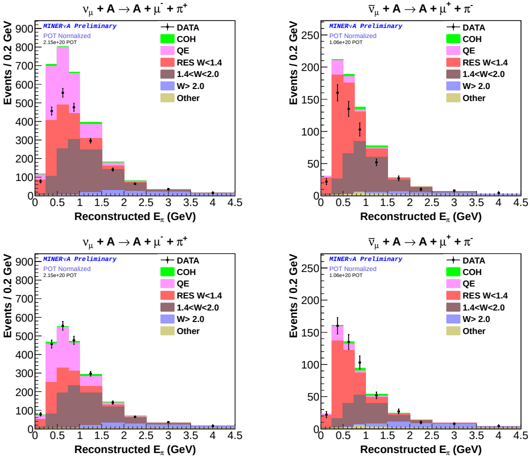
# CC coherent pion production: Selection

- Exactly two tracks, one of which is MINOS-matched $\mu$
- d$E$/dx profile consistent with pion (proton score $< 0.35$
- Energy near the vertex between 30 and 70 MeV
- Small reconstructed $|t| = |(q - p_\pi)^2|$: $|t| < 0.125\,\mathrm{GeV}$



# CC coherent pion production: Background tuning

- Fit resonant, low $W$, high $W$ components to $E_\pi$ distribution in $0.2 < |t| < 0.6$ sideband.




| BG Component | Scale $\nu$ | Scale $\bar{\nu}$ |
|---|---|---|
| QE | $0.7 \pm 0.3$ | 1.0 (fixed) |
| $W < 1.4$ | $0.6 \pm 0.3$ | $0.7 \pm 0.1$ |
| $1.4 < W < 2.0$ | $0.7 \pm 0.1$ | $0.6 \pm 0.1$ |
| $W > 2.0$ | $1.1 \pm 0.1$ | $1.9 \pm 0.3$ |