Neutrino-nucleus cross section measurements at MINERνA

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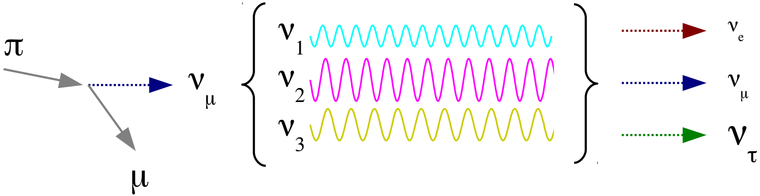
April 18, 2014

Outline

Why neutrino oscillation measurements need precise understanding of neutrino-nucleus interactions, and how MINERνA is contributing

Oscillations and cross sections

Neutrino oscillation experiments need precise cross sections



- Oscillation probability:

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{E_\nu}\right)$$

(Nature, Experimental)

Known knowns and known unknowns

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \qquad \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Known knowns and known unknowns

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- $s_{ij} = \sin\theta_{ij}$, $c_{ij} = \cos\theta_{ij}$
- Measured, Unmeasured

Known knowns and known unknowns

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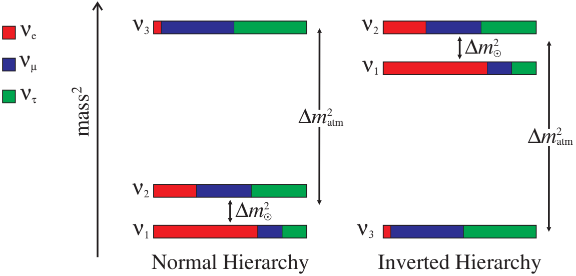
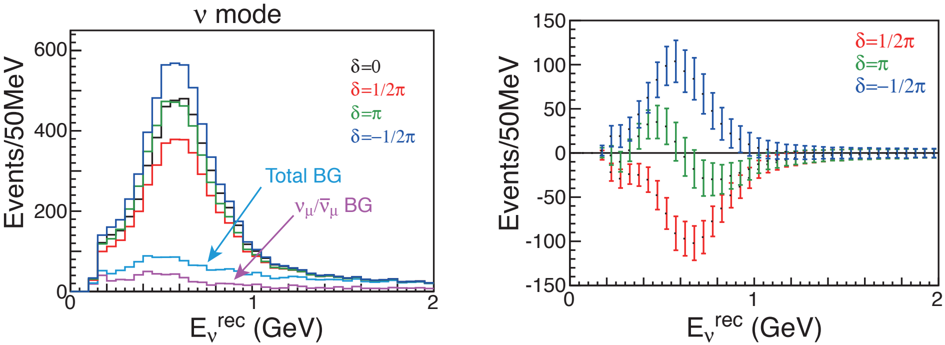


Measuring δ, hierarchy

- $P(\nu_\mu \to \nu_e)$, $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ depend on δ, hierarchy

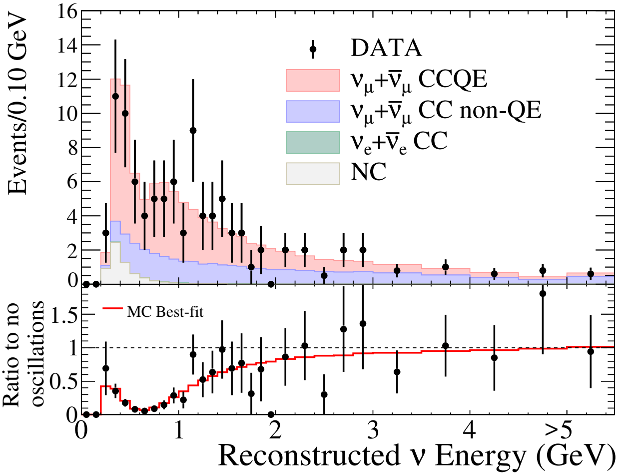


Source: HyperK LOI, arXiv:1109.3262. NH. $\sin^2 2\theta_{13} = 0.1$

- Need precise signal and background predictions
- Infer E_ν from final state particles

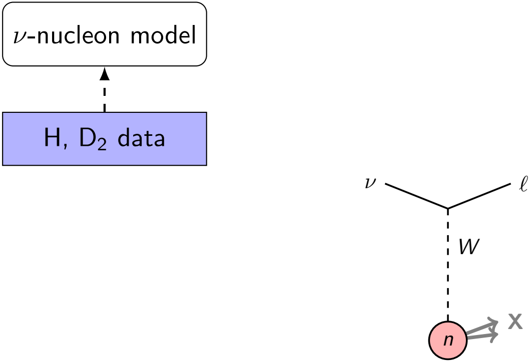
Knowing the known knowns better

- $P(\nu_\mu \to \nu_\mu)$ depends on θ_{23}, Δm^2_{32}
- Eg, T2K ν_μ spectrum at SuperK:



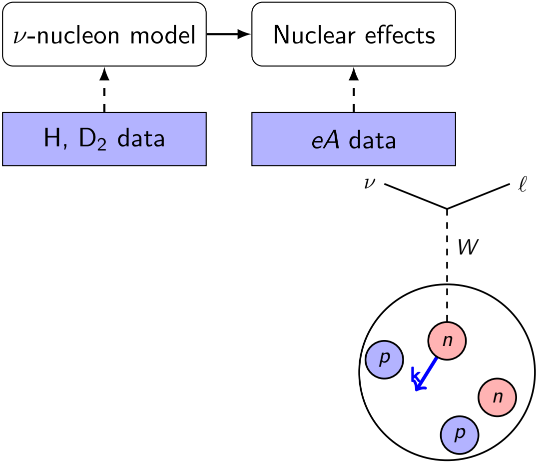
arXiv:1403.1532

Many ingredients needed to model νA cross sections



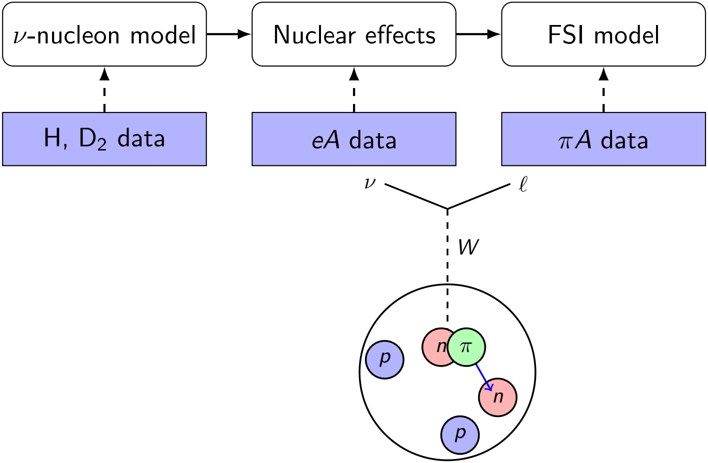
- Model neutrino scattering on free nucleons

Many ingredients needed to model νA cross sections



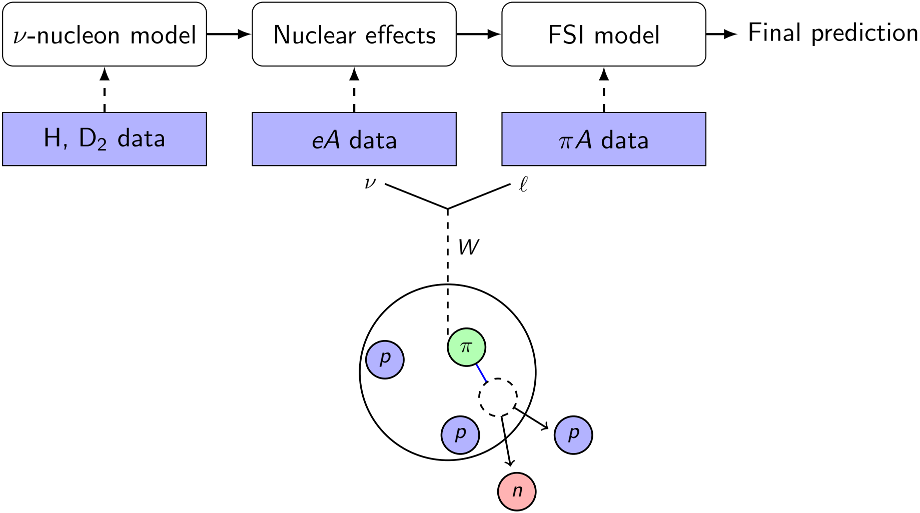
- Add effects due to nucleon bound in nucleus

Many ingredients needed to model νA cross sections



- Model reinteractions of hadrons exiting nucleus

Many ingredients needed to model νA cross sections



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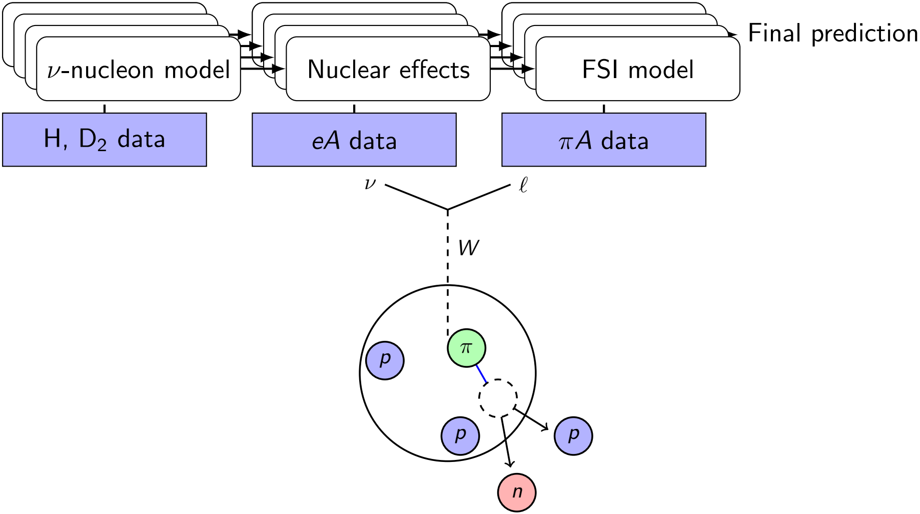
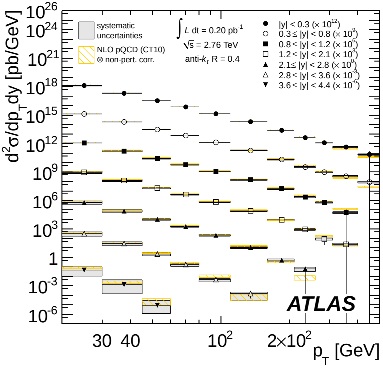


- Repeat for all contributing processes for $E_\nu \sim 1\,\text{GeV}$

Do we understand νA cross sections?

ATLAS inclusive jet cross section



EPJC 73, 2509 (2013)

- Universal model, many orders of magnitude

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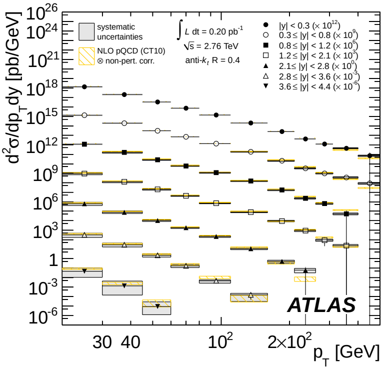
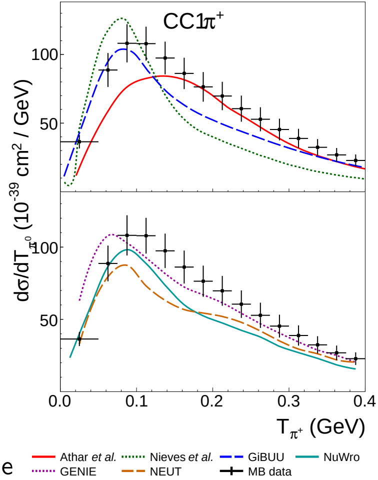


EPJC 73, 2509 (2013)

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



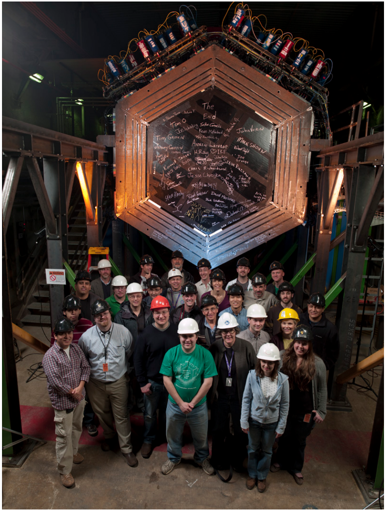
P. Rodrigues, arXiv:1402.4709 (NuInt 2012)
Data from PRD 83, 052007 (2011)

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

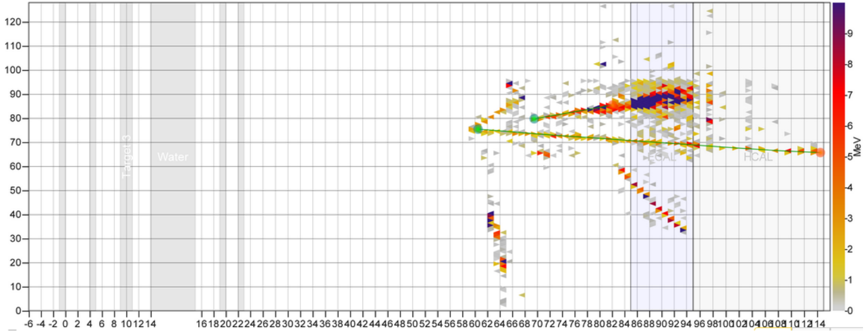
The MINERνA experiment

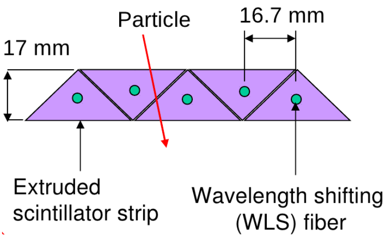
MINERνA: What and why?

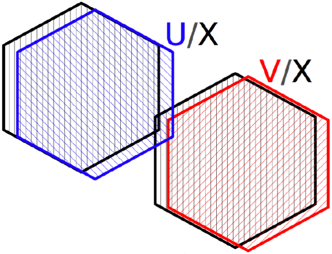
- Dedicated neutrino–nucleus scattering experiment in the NuMI beamline
- Measuring exclusive and inclusive ν, $\bar{\nu}$ cross sections on a range of nuclei



MINERνA detector







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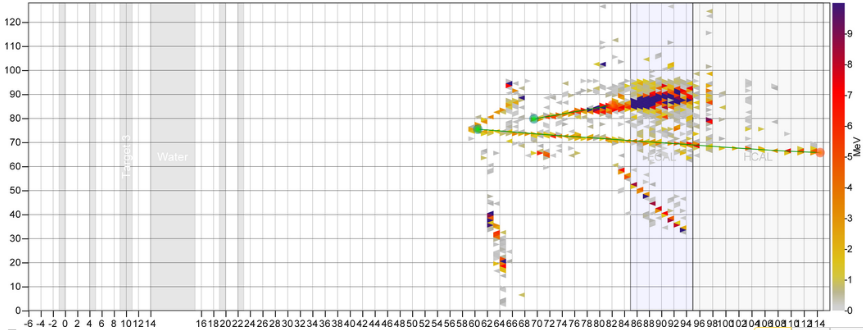
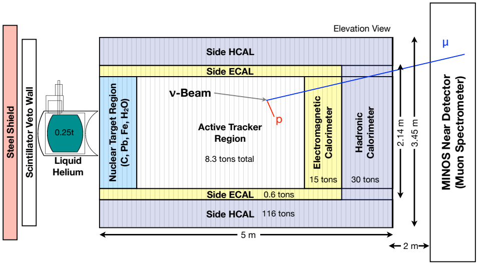
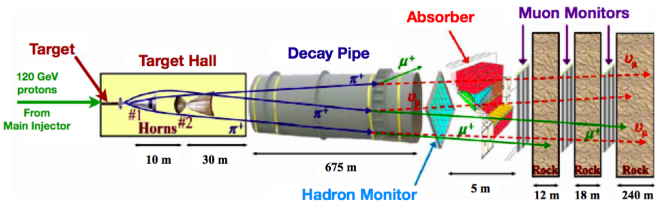




The NuMI neutrino beam



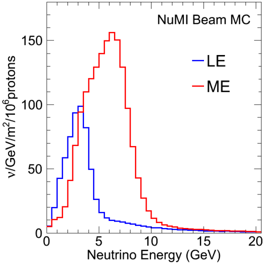
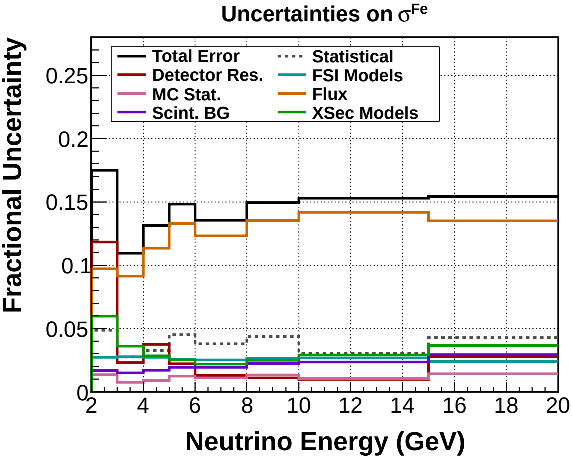


Figure: R. Zwaska

- 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

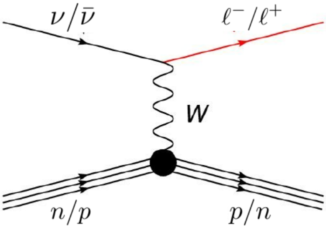
Flux Modelling

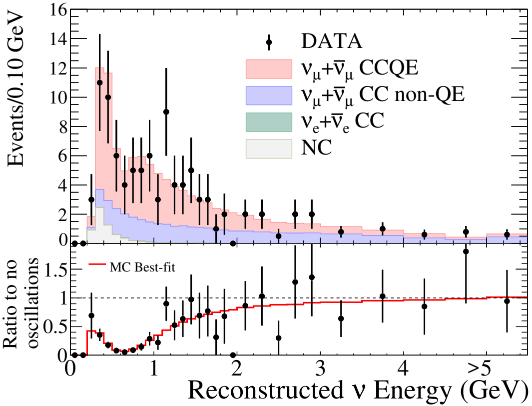


- Tune hadron production from NA49 data
- Uncertainties still $\sim 15\%$
- Multi-prong approach planned for $\lesssim 10\%$
  - For now, study distributions weakly dependent on flux

Charged-current quasielastic scattering in MINERνA

Charged-current quasielastic scattering

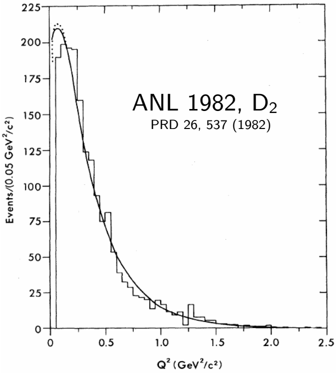




- Simplest CC νN process; Two-body kinematics allow E_ν reco from $\ell^\pm$

Charged-current quasielastic measurements

- Expressed in terms of $Q^2 = -(\text{4-momentum transferred to nucleon})^2$:



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

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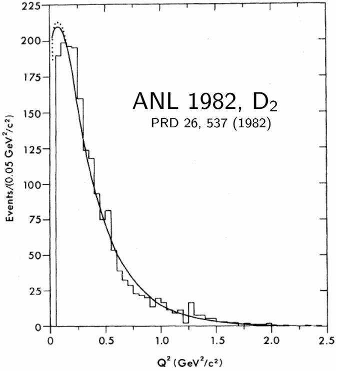

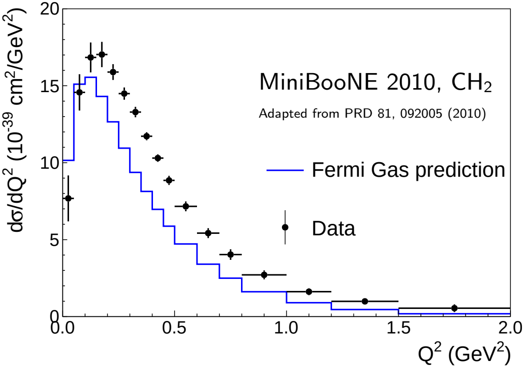

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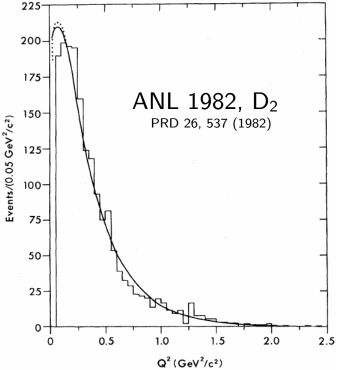

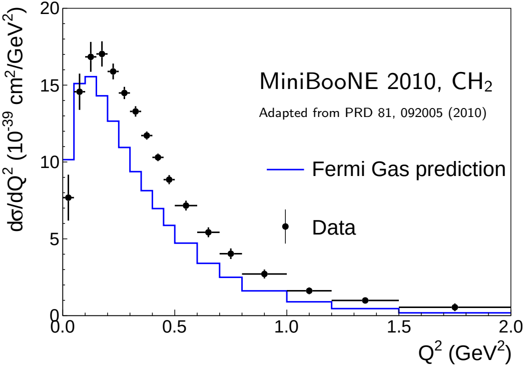

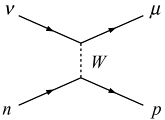

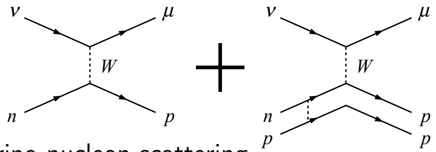

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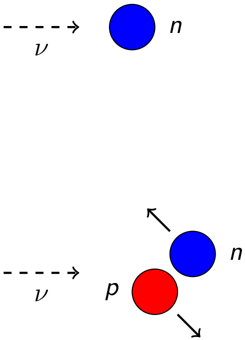
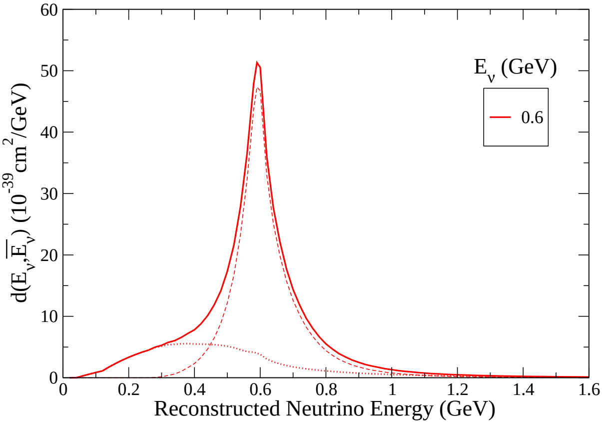
Implication for oscillation experiments





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

- Affect lepton kinematics, E_ν reco, hadrons in final state

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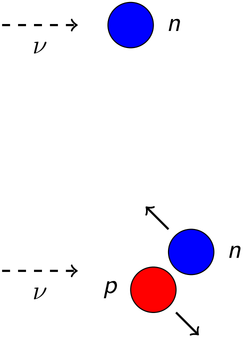
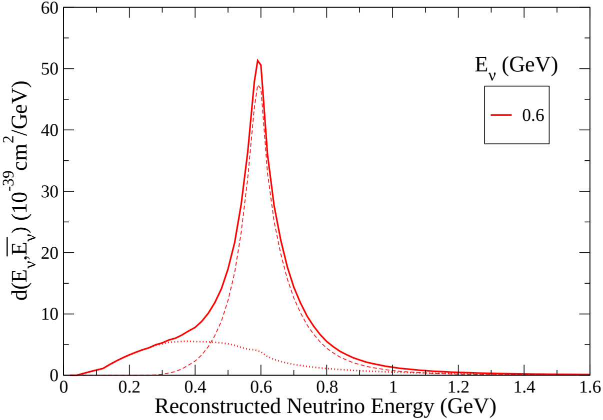




Adapted from Martini *et al.*, arXiv:1211.1523

- 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

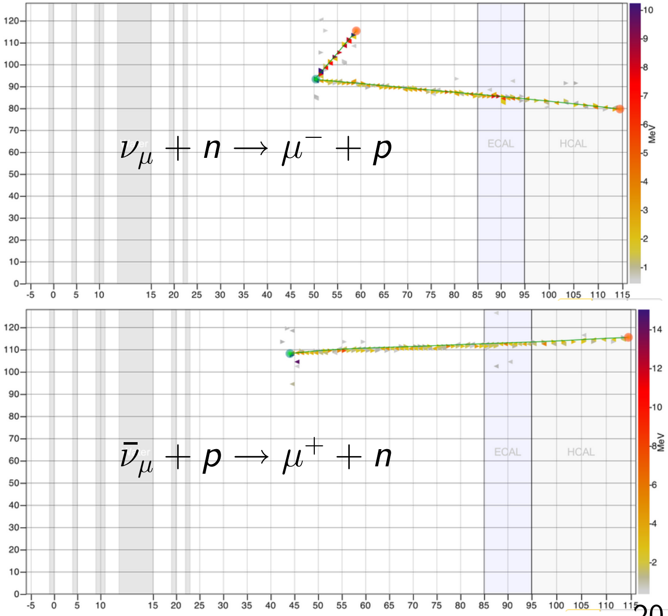
Martini *et al.*, PRC 81, 045502 (2010)
Alvarez-Ruso, arXiv:1012.3871
Fernandez-Martinez, Meloni, PL B697, 477 (2011)
Meucci, *et al.*, arXiv:1103.0636
Antonov *et al.*, arXiv:1104.0125

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

MINERνA CCQE analysis

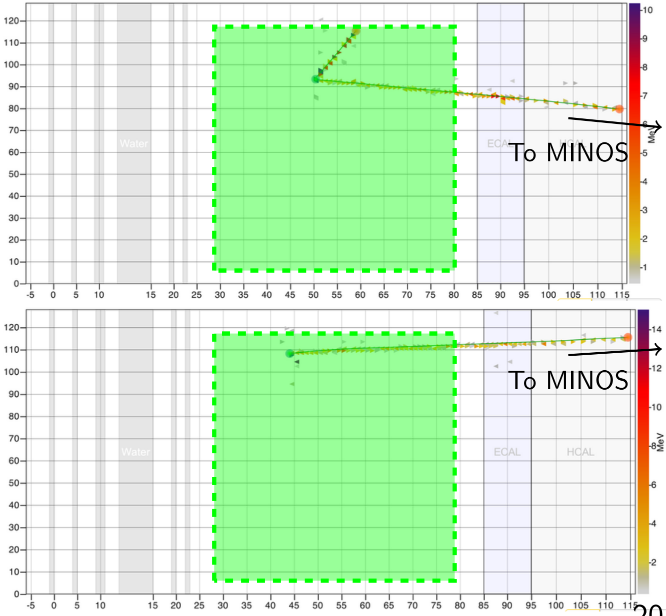
- Aims:
  1. Make shape-only comparisons of $\frac{d\sigma}{dQ^2}$ to nominal model and models with multinucleon effects
  2. Look at energy near the interaction vertex for evidence of multinucleon emission
- In both ν and $\bar{\nu}$ data

CCQE selection

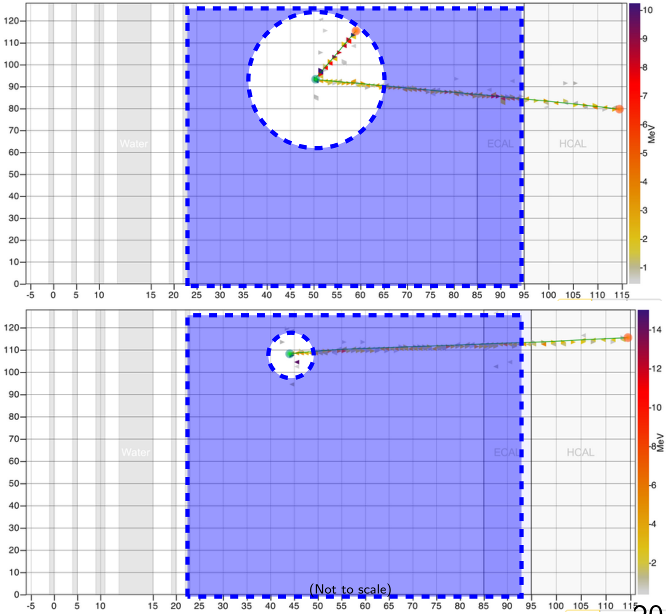


CCQE selection

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



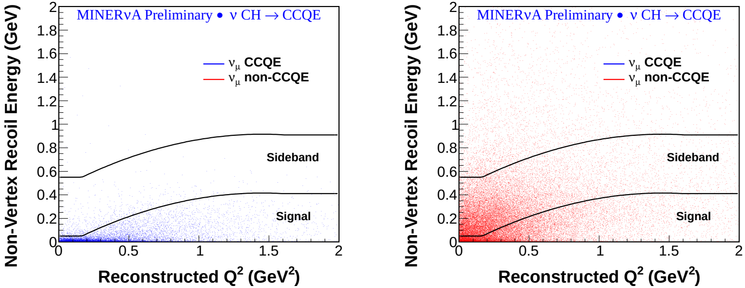
CCQE selection



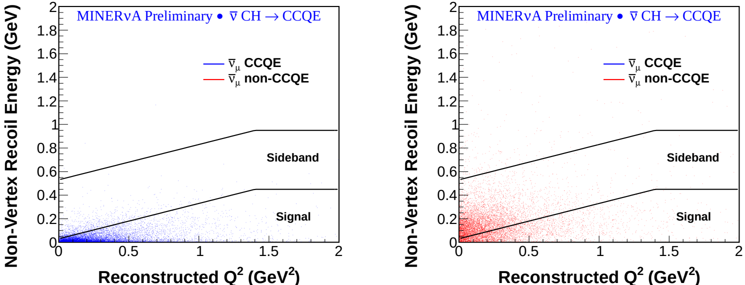
- Require low non-vertex recoil energy
- ν: $r < 300\,\mathrm{mm}$
- $\bar{\nu}$: $r < 100\,\mathrm{mm}$

Recoil energy cut

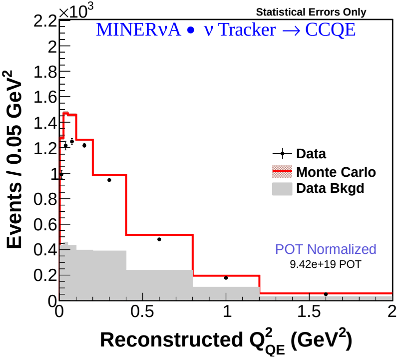
Neutrino mode

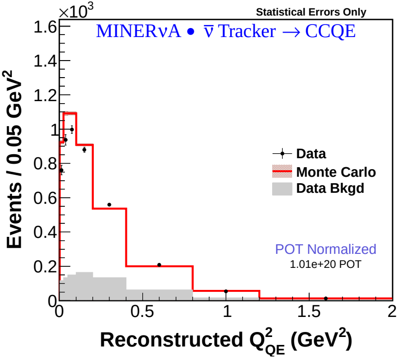


Antineutrino mode



Final event selections



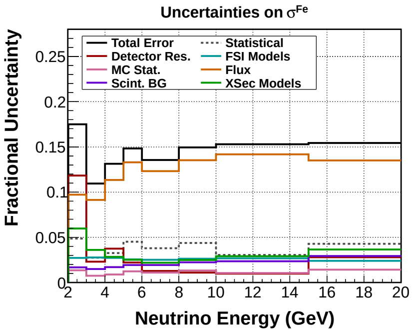


	ν	ν̄
No of events	29,620	16,467
Efficiency	47%	54%
Purity	49%	77%

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

Systematics

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



Systematics

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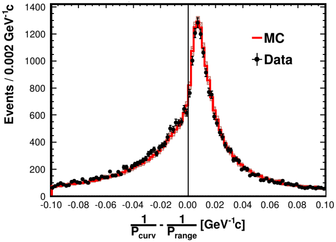
- Muon energy scale
  - Muon p scale known to 2–3%

p_μ scale



MINOS range

$\pm 2\%$ (all p_μ)

MINOS curvature

$\pm 2.1\%$ ($p_\mu < 1$ GeV/c)

$\pm 3.3\%$ ($p_\mu > 1$ GeV/c)

MINERνA

± 11 MeV (mass model)

± 30 MeV (dE/dx)

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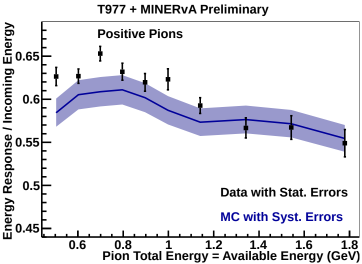
- Recoil energy reconstruction
  - Hadronic energy scale from testbeam
  - Hadron reinteractions from external data



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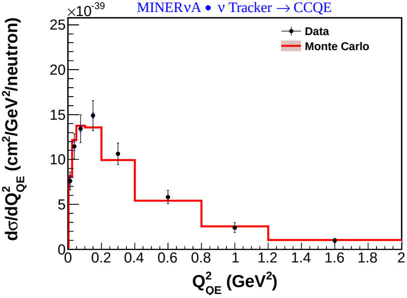
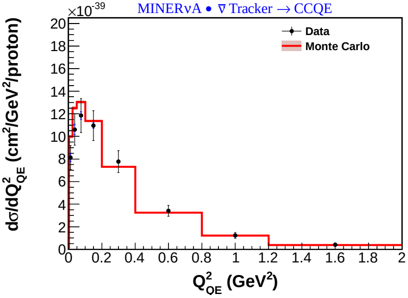
  - Hadron reinteractions from external data
- Interaction modelling
  - 10s of % uncertainties on primary interaction, FSI
  - Enter via efficiency correction, background shape

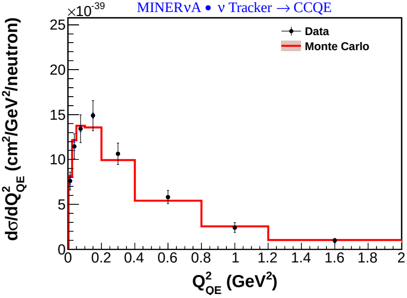
Model parameter	Uncertainty (%)
CC resonance prod.	20
Δ axial mass M_A^{res}	20
Non-resonant π prod.	50
FSI:	
π, N mean free path	20
π absorption	30

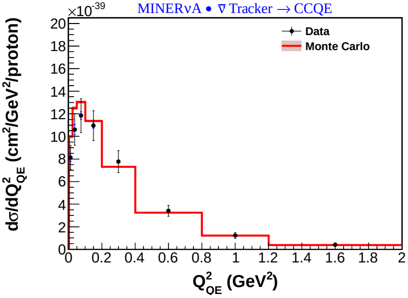
Differential cross section

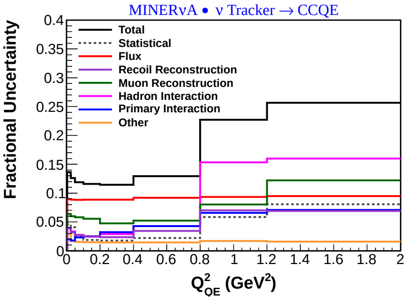


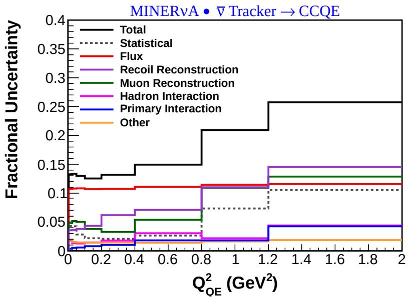


Differential cross section

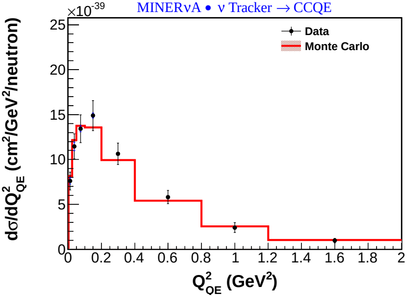


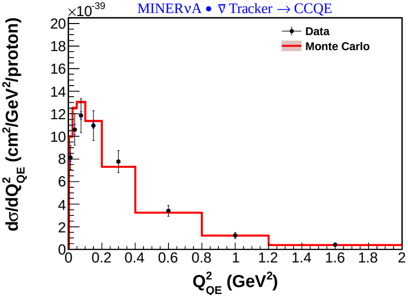


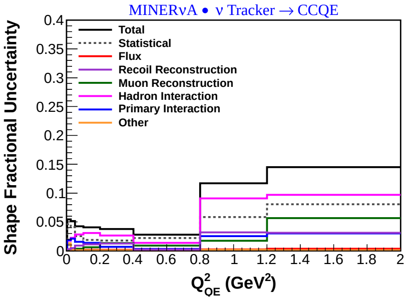


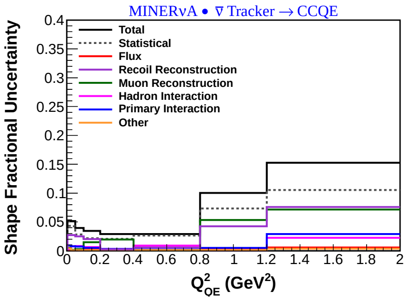


Differential cross section

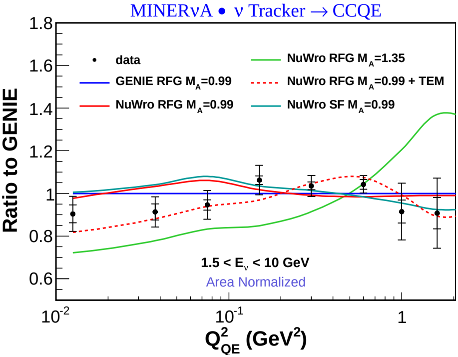


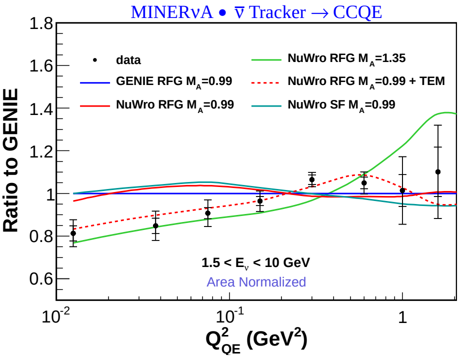






Model comparisons





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

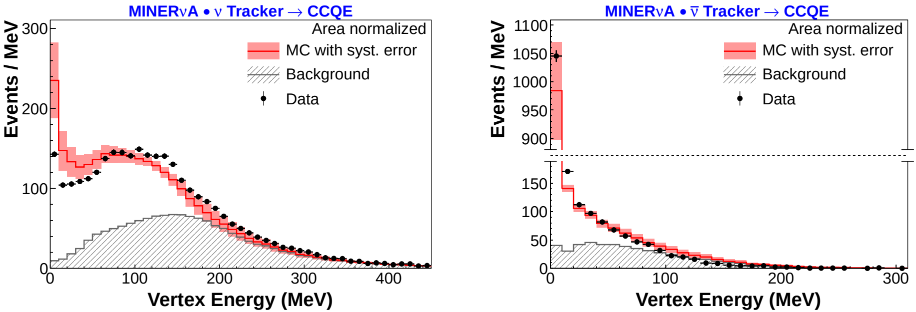
GENIE — Quasi-independent nucleons in a mean field
NIM A**614**, 87 (2010)

$M_A = 1.35$ — Modified nucleon form factor from MiniBooNE data
Phys. Rev. D**81**, 092005 (2010)

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

Vertex energy

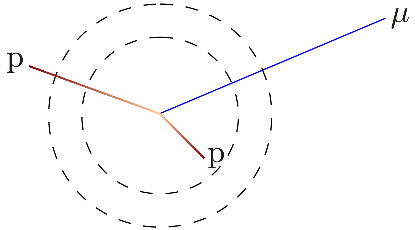
- Multinucleon emission expected in interactions with correlated nucleons
  - Look for excess energy in the vertex region excluded from recoil cut



- Harder spectrum in ν_μ mode data than in MC, but not in $\bar{\nu}_\mu$ mode

Vertex energy

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



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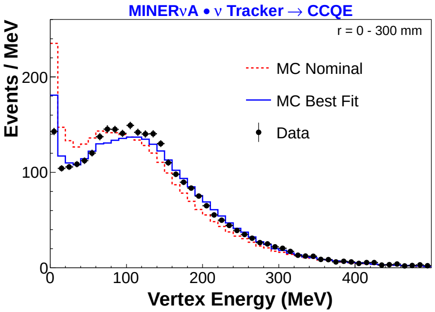
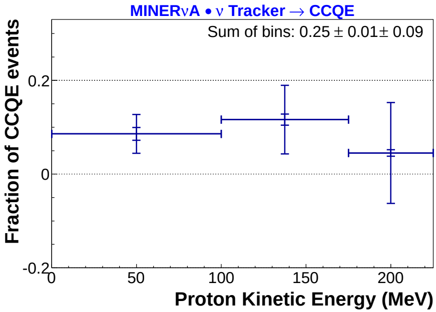




- Extra proton preferred in $(25 \pm 9)\%$ of ν_μ CCQE events
- No increase preferred in $\bar{\nu}_\mu$ mode

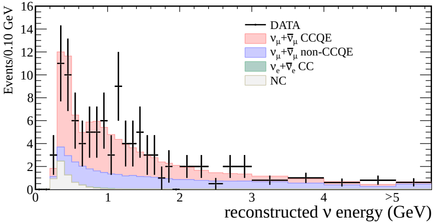
CCQE conclusions

- Shape-only comparison of $\frac{d\sigma}{dQ^2}$ in CCQE $\nu_\mu/\bar{\nu}_\mu$ scattering
- Disagreement with model used in generators (and thus osc expts)
  - Better agreement with TEM model
- Disagreement in vertex energy in ν mode.
  - Consistent with *np* initial state correlated pairs
- Next steps:
  - Increased statistics
  - Michel veto
  - $\frac{d^2\sigma}{dp_\mu \, d\cos\theta_\mu}$

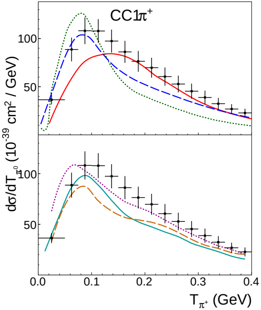
Charged-current $\pi^{\pm}$ production

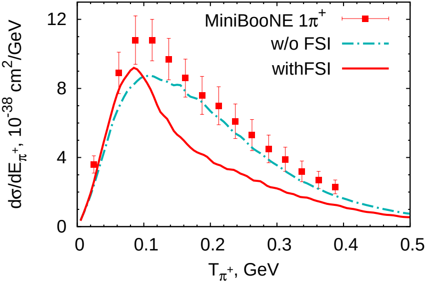
Neutrino-induced charged pion production

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



- But MiniBooNE data on CH_2 suggest shortcomings in models

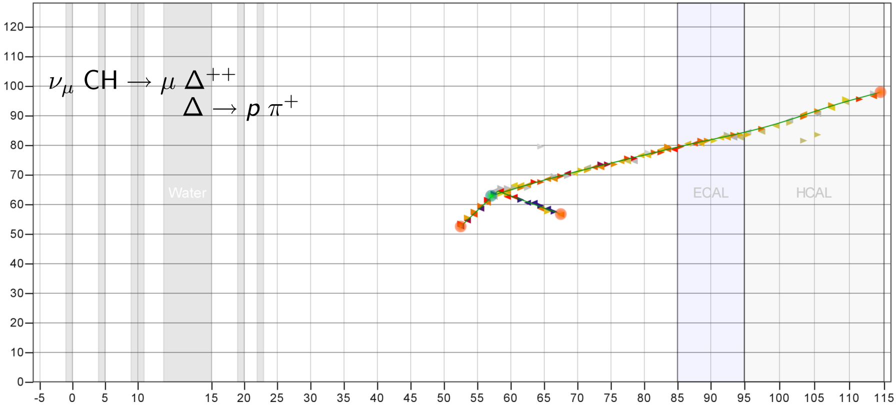




O. Lalakulich *et al.*, arXiv:1107.5947

MINERνA charged pion production

- Events with single charged pion exiting nucleus, $W < 1.4$ GeV
- Compare pion kinematics with available models



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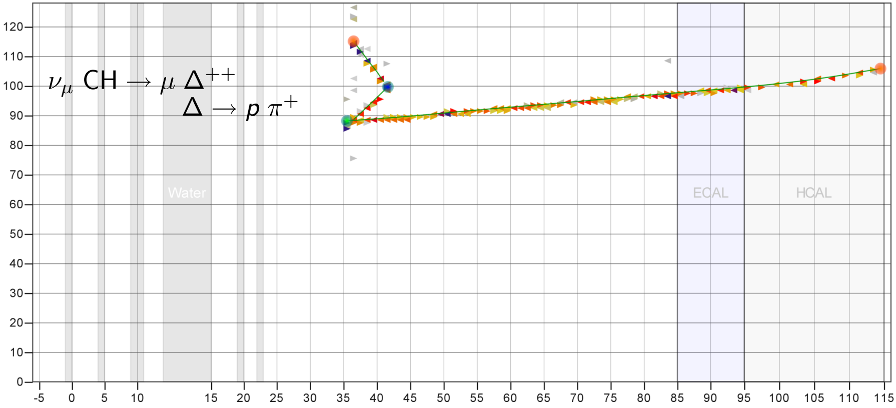
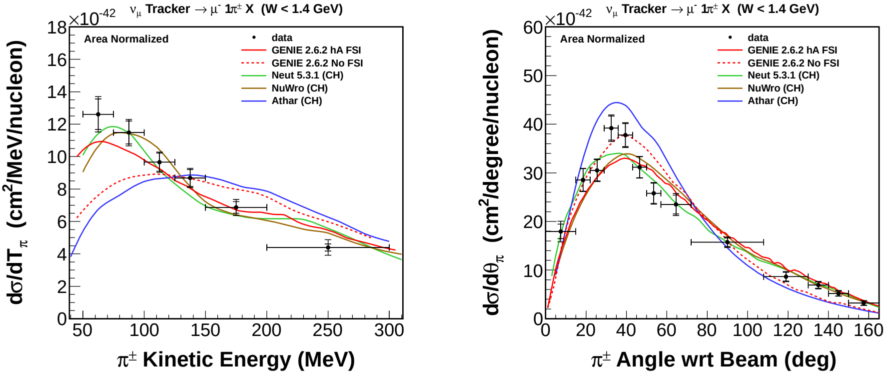


- Select *stopping* pions using dE/dx and e from $\pi \rightarrow \mu \rightarrow e$

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

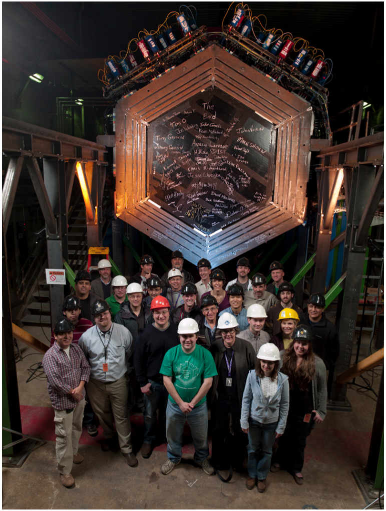
Recap

- 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

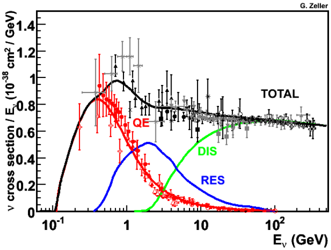


Backup slides

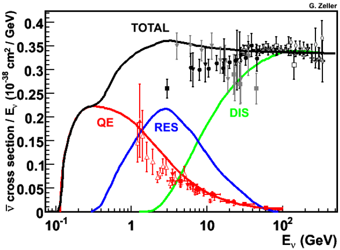
Because it's there

- "Because it's there!"
- Not well-known at $E_\nu \sim 1\,\mathrm{GeV}$
  - Few measurements with few events
  - Large syst uncertainties, esp flux
- Weak-only probe of nucleon, nuclear dynamics
  - Understand strongly-coupled systems

ν-nucleon cross sections

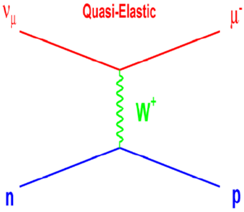


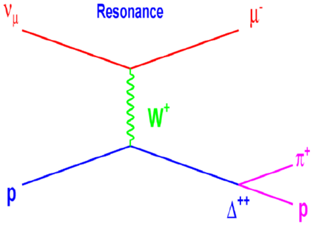
$\bar{\nu}$-nucleon cross sections

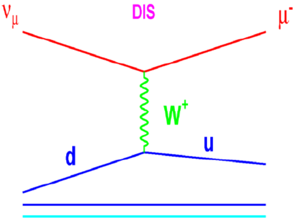


G. Zeller and J. Formaggio, Rev. Mod. Phys. 84, 1307–1341 (2012)

ν cross sections around 1 GeV



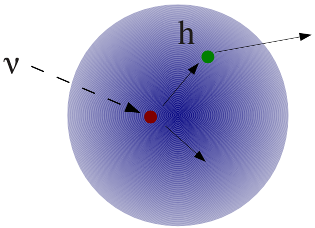


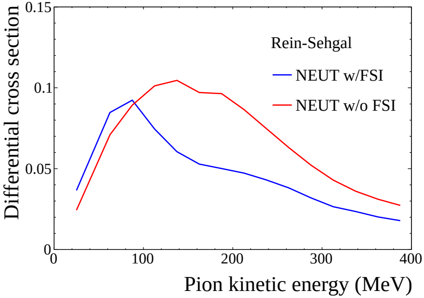


Higher E_ν, Q^2 $\longrightarrow$

- Charged- and neutral-current processes (CC, NC)
- Interaction with nucleon most significant
- $Q^2 = (\text{4-momentum transferred to nucleon})^2$

ν cross sections around 1 GeV

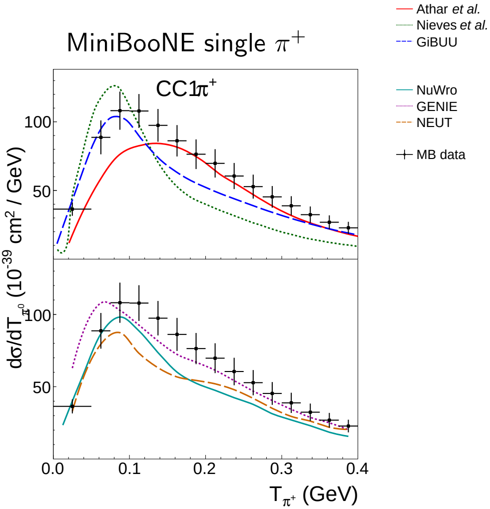




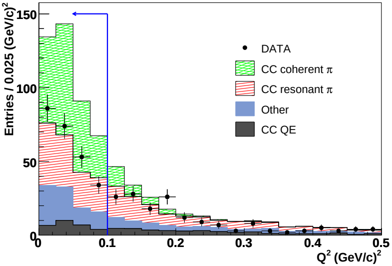
- Charged- and neutral-current processes (CC, NC)
- Interaction with nucleon most significant
- $Q^2 = (\text{4-momentum transferred to nucleon})^2$
- Nucleon bound inside nucleus
  - "Initial state interactions": Binding energy, Pauli blocking, Initial momentum
  - Final state interactions (FSI) change hadron types and momenta

Puzzles

MiniBooNE single π^+



SciBooNE coherent π^+ search



Phys. Rev. D78:112004 (2008).
See also: Phys. Rev. Lett. 95:252301 (2005).

Neutrino mixing unknowns

- Neutrino oscillation knowns:
  - Three mixing angles θ_{12}, θ_{23}, θ_{13}
  - Mass splittings Δm^2_{12}, $|\Delta m^2_{23}|$

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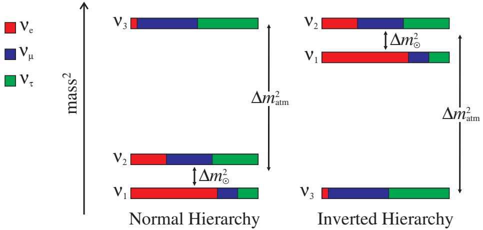
- Neutrino oscillation knowns:
  - Three mixing angles θ_{12}, θ_{23}, θ_{13}
  - Mass splittings Δm^2_{12}, $|\Delta m^2_{23}|$
- Unknowns:
  - CP-violating phase δ
  - Sign of Δm^2_{23}

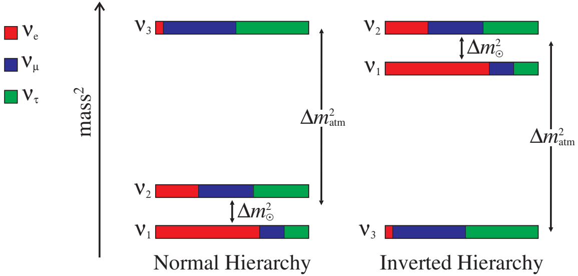


Neutrino mixing unknowns

- PMNS matrix relates mass and flavour eigenstates:

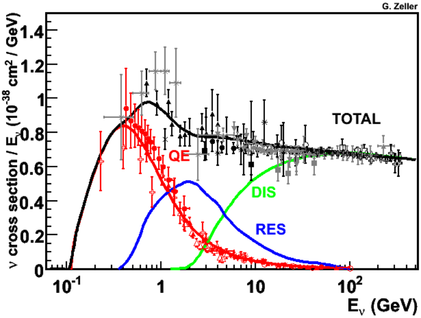
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}\exp(-i\delta) \\ 0 & 1 & 0 \\ -s_{13}\exp(i\delta) & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- $s_{ij} = \sin\theta_{ij}$, $c_{ij} = \cos\theta_{ij}$
- Measured, Unmeasured
- Also unknown: ordering of mass eigenstates:

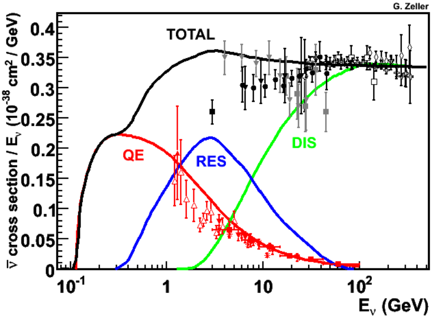


Cross sections: What do we know so far?

ν_μ-nucleon CC cross sections



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

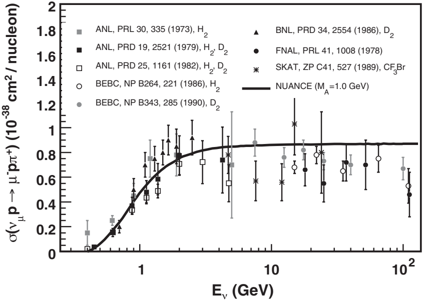


G. Zeller and J. Formaggio, Rev. Mod. Phys. 84, 1307–1341 (2012)

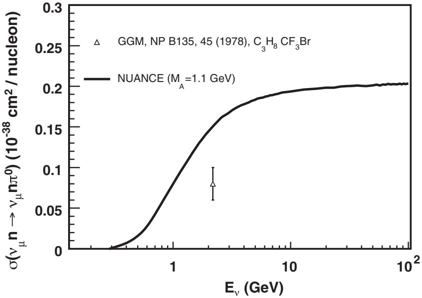
- Not precisely known for $E_\nu \sim 1\,\mathrm{GeV}$
- Multiple contributing processes

Cross sections: What do we know so far?

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



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



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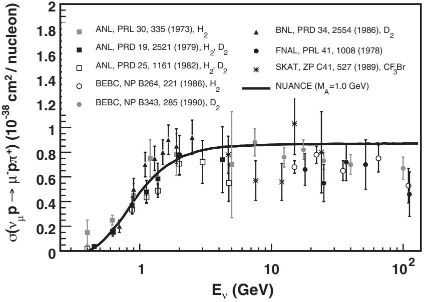

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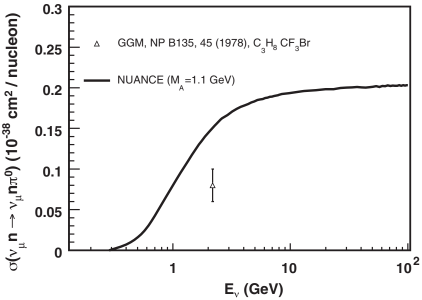


G. Zeller and J. Formaggio, Rev. Mod. Phys. 84, 1307–1341 (2012)

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

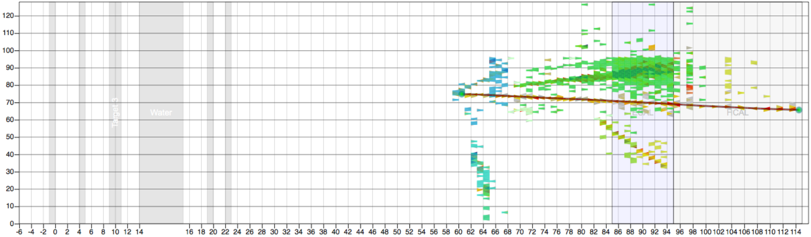
Where do cross sections come in?

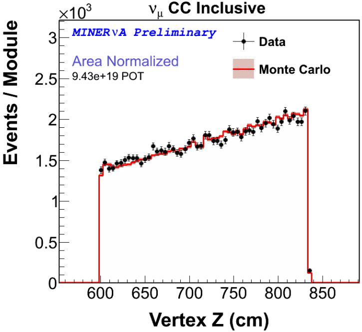
$$N_{\text{FD}} = \Phi_{\nu_\alpha} \times P_{\nu_\alpha \to \nu_\beta}(E_\nu) \times \sigma_{\nu_\beta}(E_\nu) \times \mathbf{R}(E_\nu, E_{\text{visible}}) + N_{\text{bg}}$$

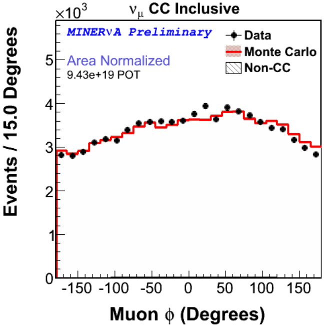
- ν_e σ unmeasured. σ_{ν_e}, σ_{ν_μ} differences
  M. Day and K. S. McFarland, Phys. Rev. D 86, 053003 (2012)
- $E_\nu \leftrightarrow E_{\text{visible}}$ from cross section MC
  - Čerenkov: Lepton kinematics + CCQE hypothesis (T2K, MiniBooNE)
  - Sampling calorimeters: $E_{\text{lepton}} + E_{\text{had}}$ (MINOS, Noνa)
- And all the same issues for backgrounds
- Near detectors partially cancel some of these effects, but still:

Precision ν oscillation experiments need precision ν-nucleus cross sections

MINERνA reconstruction

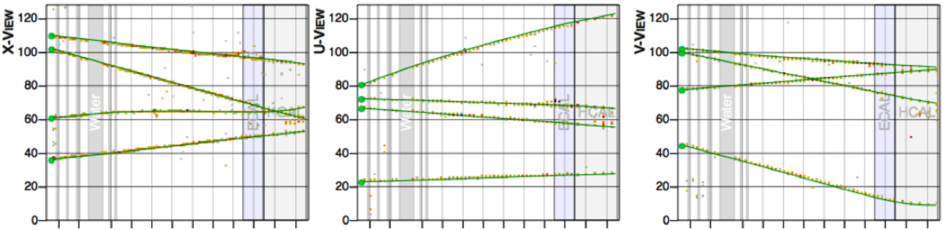






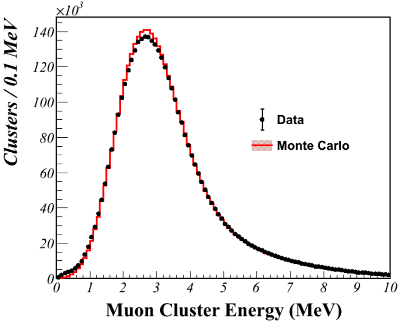
- Today's analyses require μ track matched to MINOS

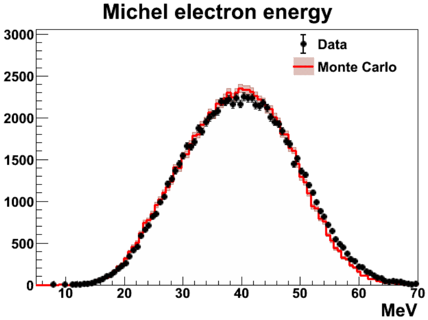
Calibration



- Plentiful supply of μ from ν interactions in rock

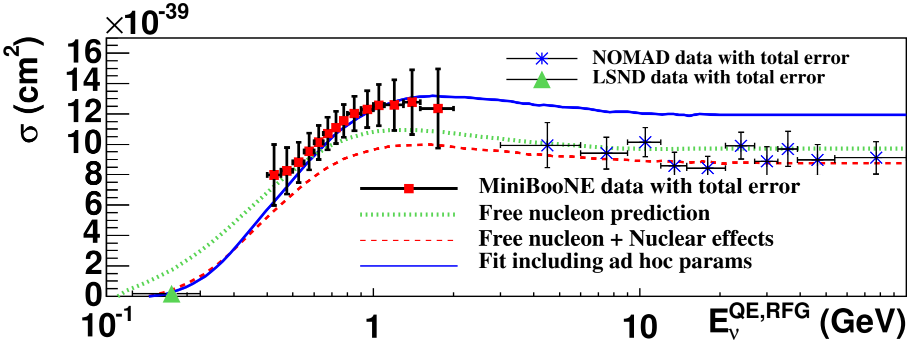
Calibration





- Plentiful supply of μ from ν interactions in rock
- Set energy scale. Cross check with Michel electrons ($\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$)
- Also used to measure pixel-to-pixel PMT crosstalk

Charged-current quasielastic scattering on nuclei

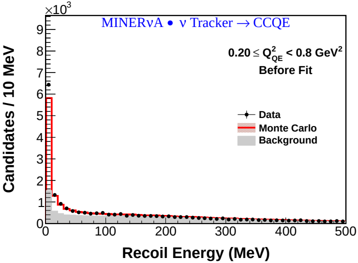


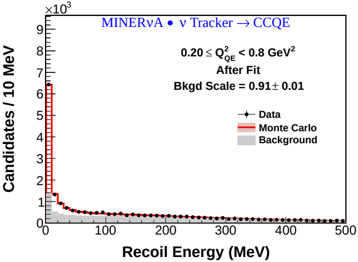
Phys. Rev. D81:092005 (2010), my legend

- Free nucleon prediction based on H, D_2 data
- Model nucleus as independent nucleons in a Fermi gas
- Something must be missing...

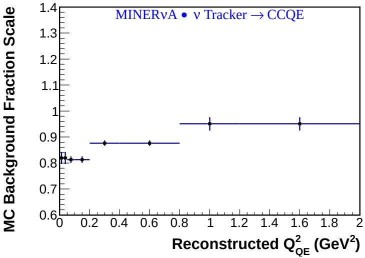
CCQE analysis: Constraining non-QE backgrounds

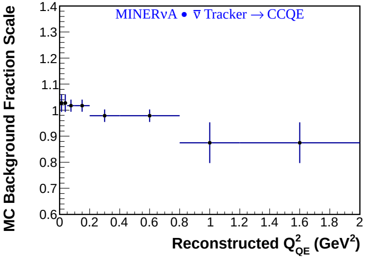
One example bin in Q^2





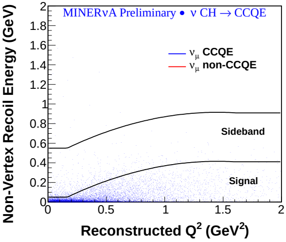
All Q^2 bins

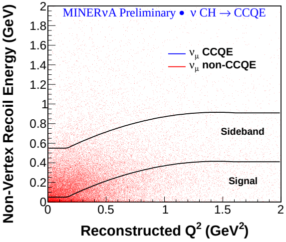




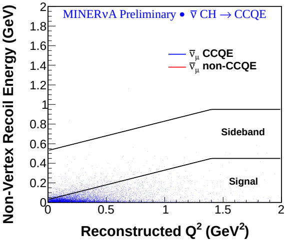
CCQE analysis: Recoil energy cut

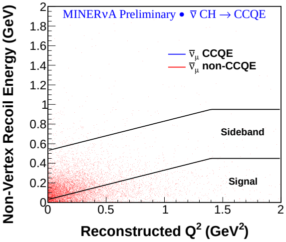
Neutrino mode



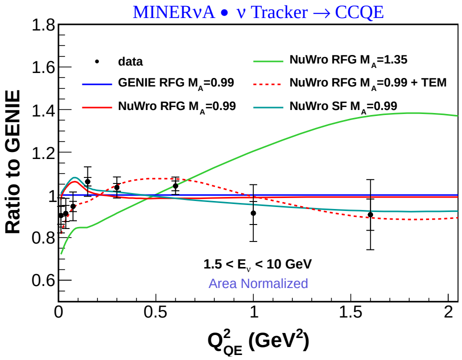


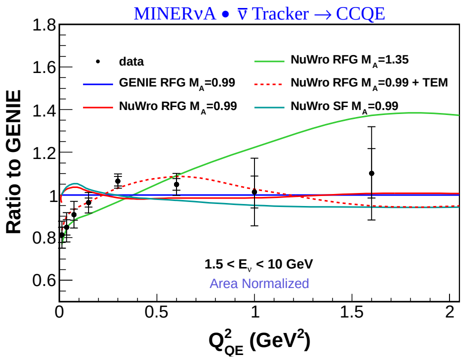
Antineutrino mode





Model comparisons, linear abscissa





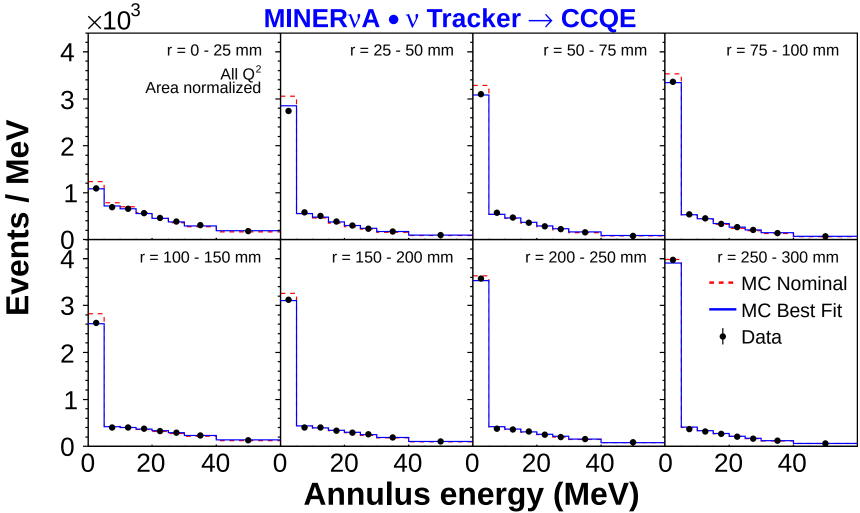
- Area normalize, then take ratio to GENIE
- Models:

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

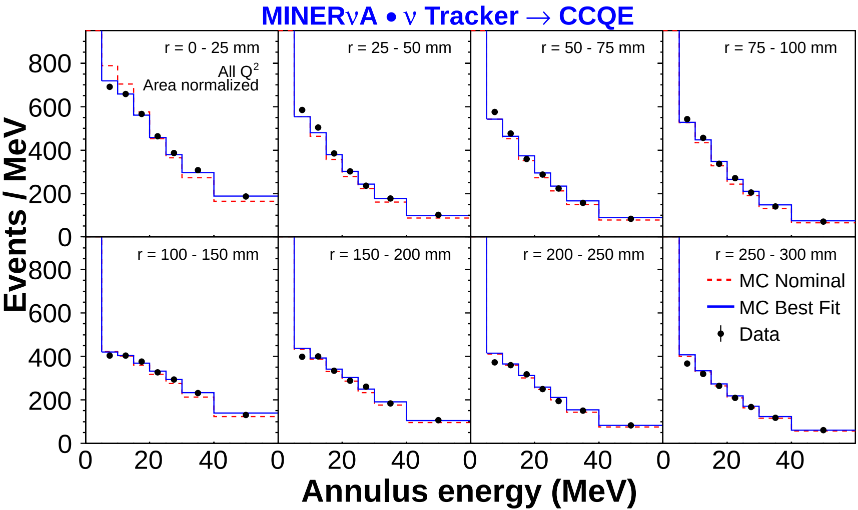
$M_A = 1.35$ —— Modified nucleon form factor from MiniBooNE data
Phys. Rev. D**81**, 092005 (2010)

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

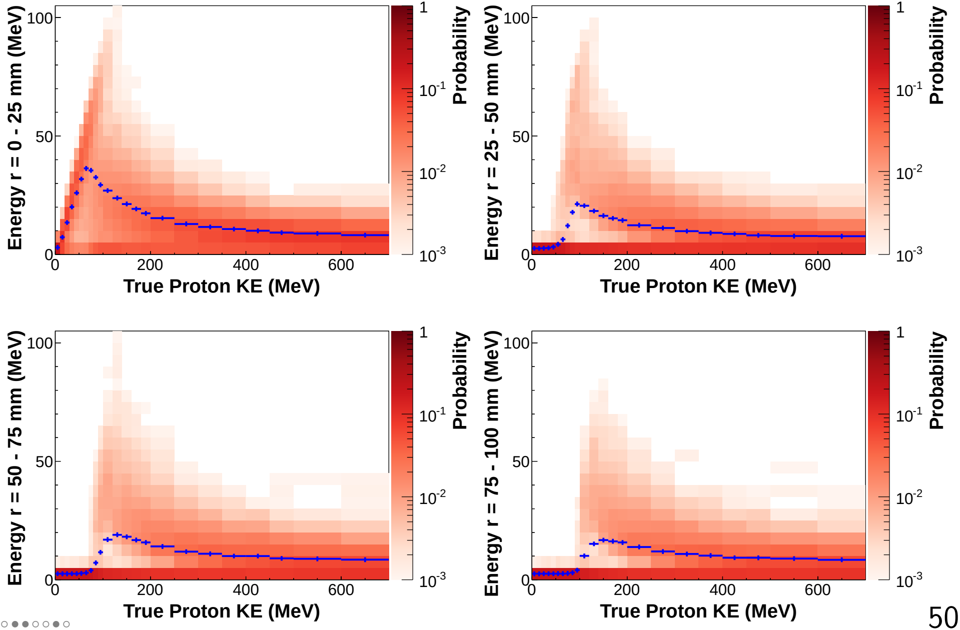
Vertex energy fit distributions



Vertex energy fit distributions, zoomed y

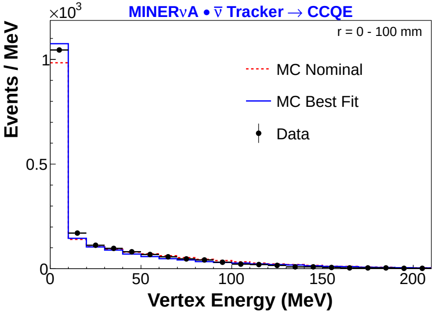


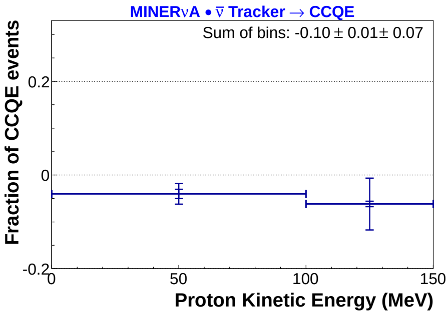
Annulus energy *vs* proton KE



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

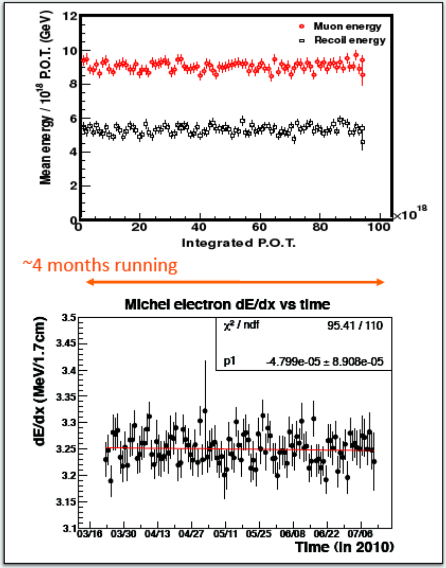
- *Assume* an extra proton
- Use spatial distribution of energy to infer KE distribution of extra proton





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

3. Recoil Energy Scale



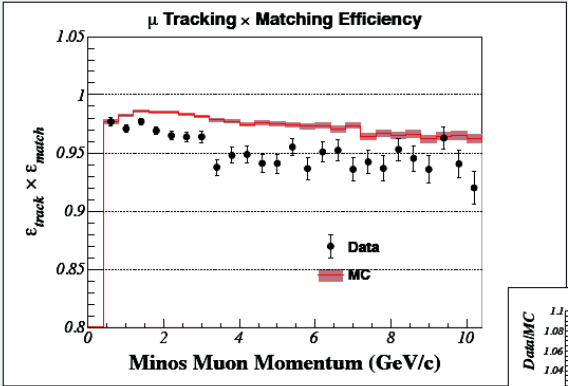
Muons

Recoil

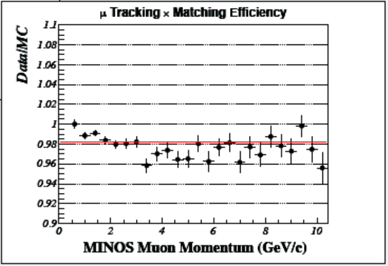
Calibrated detector
very stable
at high and low
energy scales

Electron dE/dx

Muon Tracking Efficiency



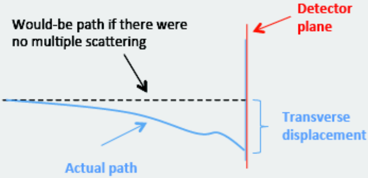
MINERvA muon tracking efficiency



Momentum provided by MINOS ND

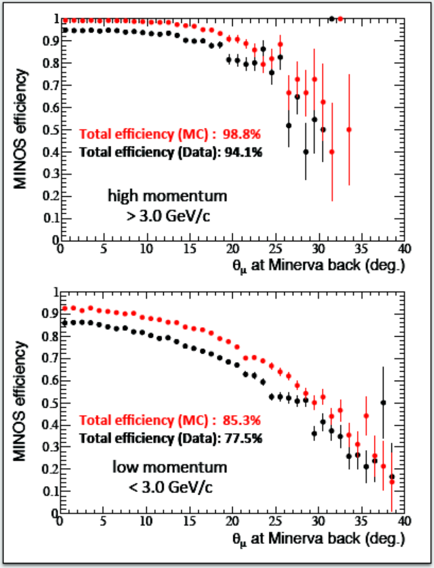
Muon Tracking Efficiency

MINOS muon tracking efficiency

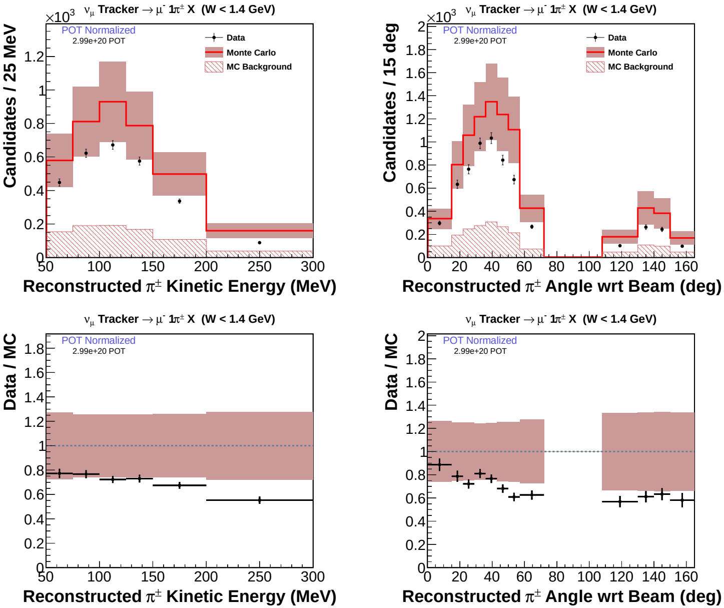


use scattering in MINERvA ECAL+HCAL to split into **high** and **low** momentum samples

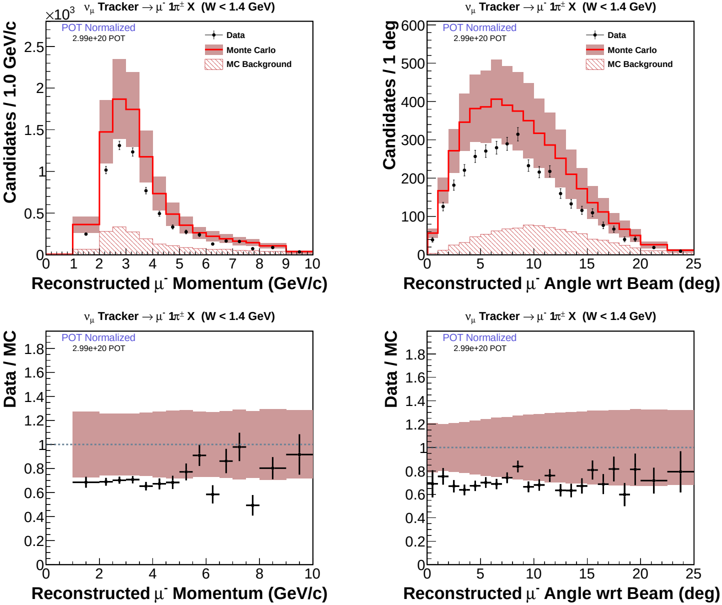
Total Corrections	neutrinos	antineutrinos
$p_\mu < 3.0$ GeV/c	(-10.1 ± 4.7) %	(-7.8 ± 3.4) %
$p_\mu > 3.0$ GeV/c	(-6.7 ± 2.6) %	(-4.5 ± 1.9) %



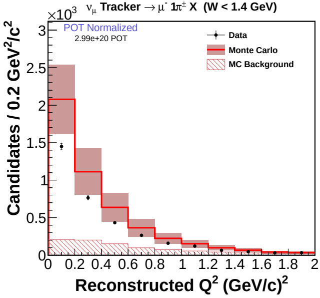
MINERνA charged pion production: reco π distributions

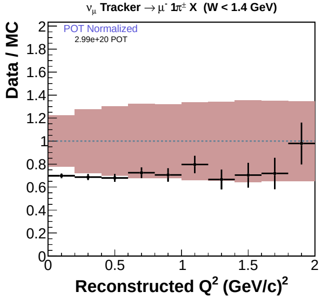


MINERνA charged pion production: reco μ distributions



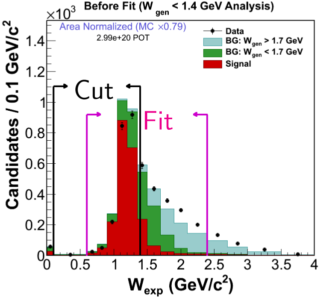
MINERνA charged pion production: reco Q^2 distribution



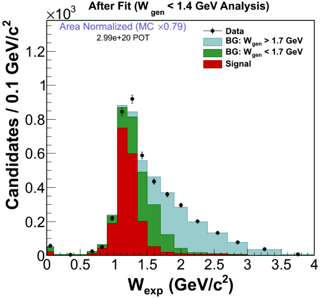


MINERνA charged pion production: BG subtraction

Before fit

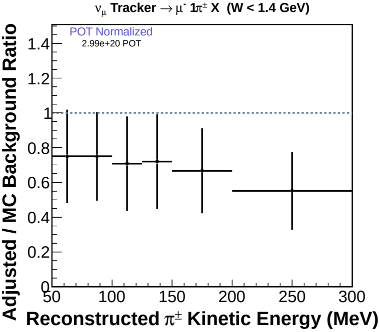


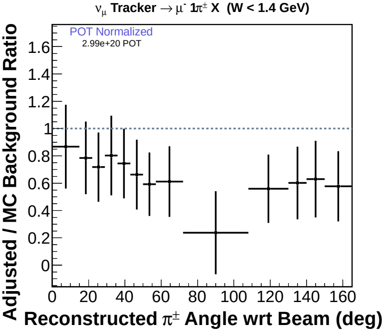
After fit



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

MINERνA charged pion production: BG scales

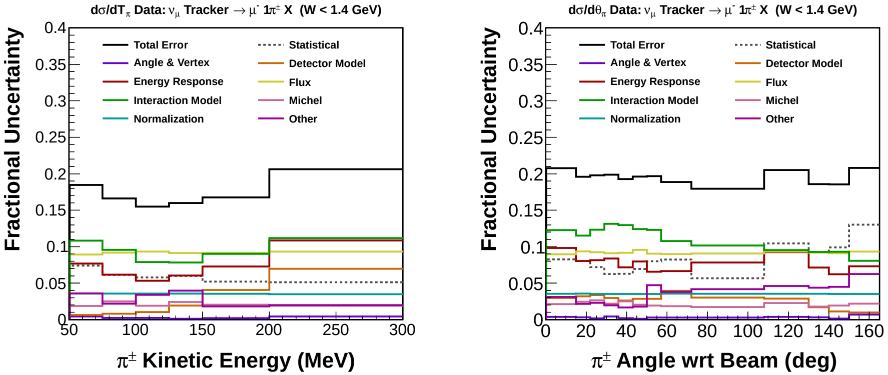




- Errors stat+syst. Dominant uncertainty is detector energy response

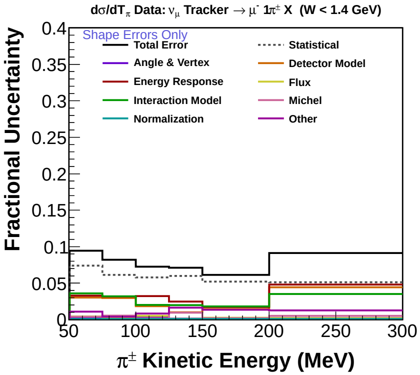
MINERνA charged pion production: Systematics

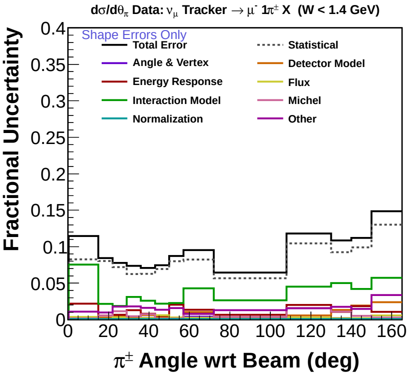
Shape + Normalization



MINERνA charged pion production: Systematics

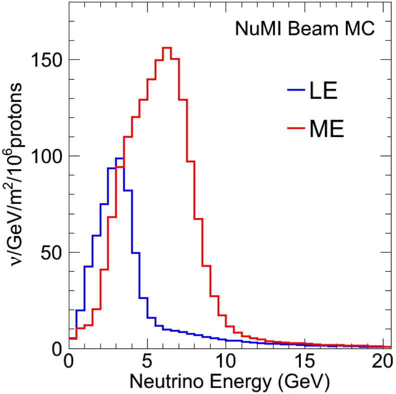
Shape-only errors

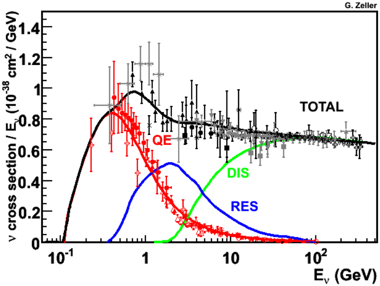




CC inclusive nuclear target ratios

CC inclusive ratios





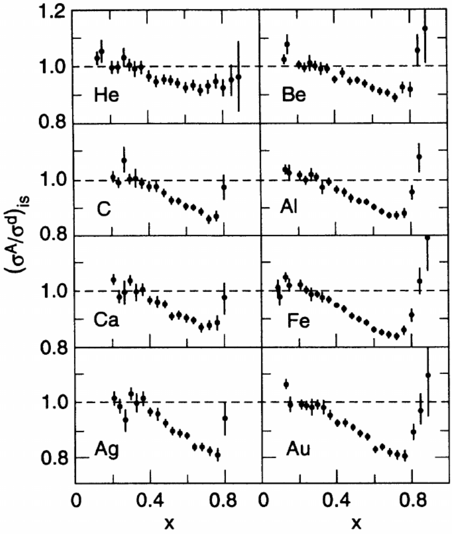
G. Zeller and J. Formaggio,Rev. Mod. Phys. 84, 1307–1341 (2012)

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

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 MINERνA

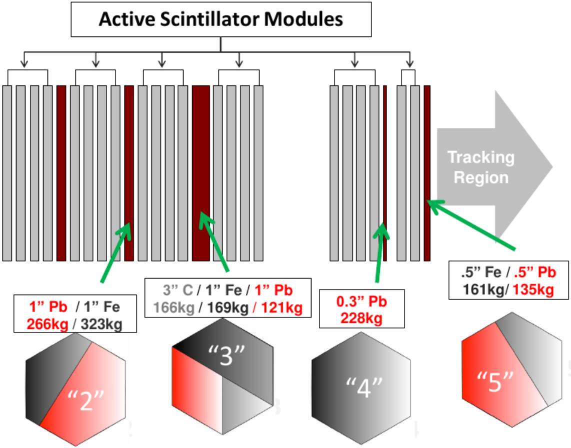
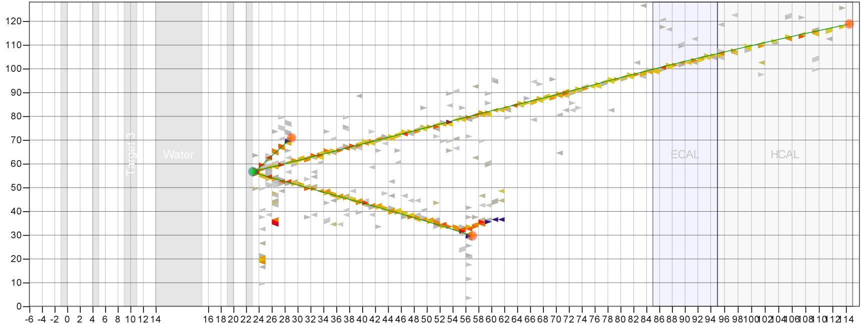


Figure: B. Tice

- We have nuclear targets. But not D_2...
- Strategy:
  1. Select CC ν_μ events in nuclear targets and scintillator (CH)
  2. Construct ratios $\langle nucleus \rangle$/CH in E_ν and x

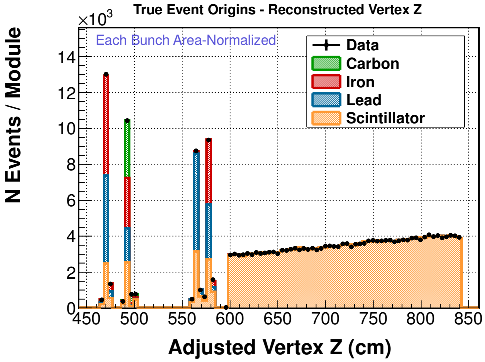
Selection



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

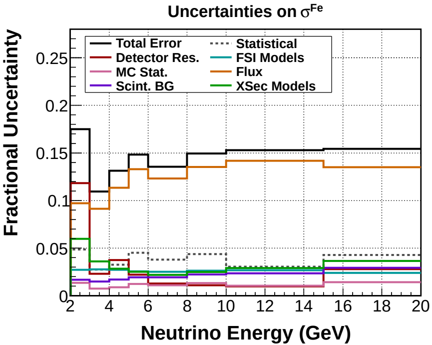
- Only significant background: events on plastic
- Reconstruct E_μ, θ_μ, E_{had} to calculate E_ν, Q^2, x

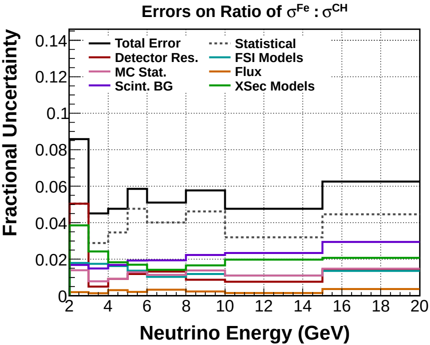
Plastic background subtraction



- ▸ Use data CC ν_μ events in scintillator to predict background
- + Geometric acceptance correction from muon gun
- + Efficiency correction as fn of E_{had} from simulation

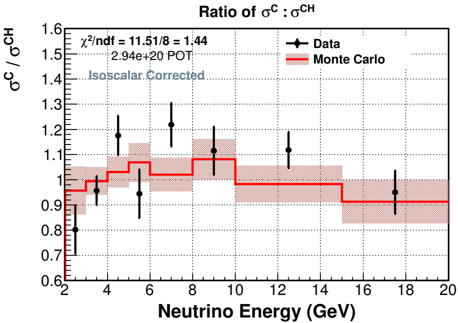
Systematics

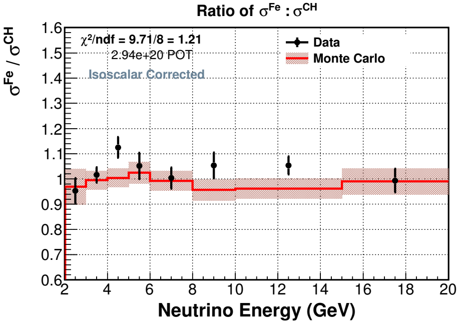


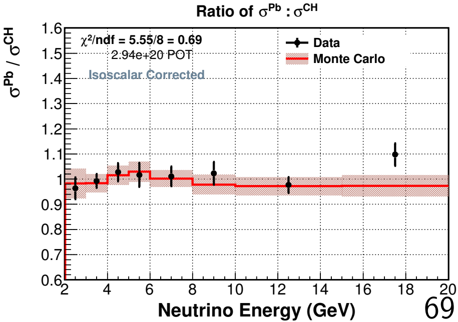


- Evaluated in similar way to CCQE analysis
- Most significant new one is plastic background

Results in E_ν

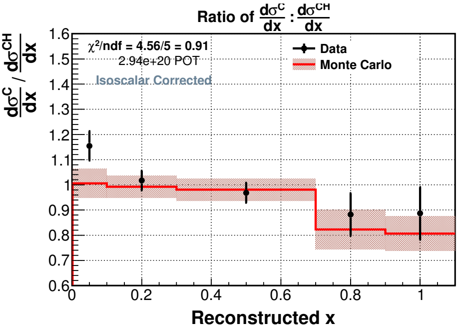


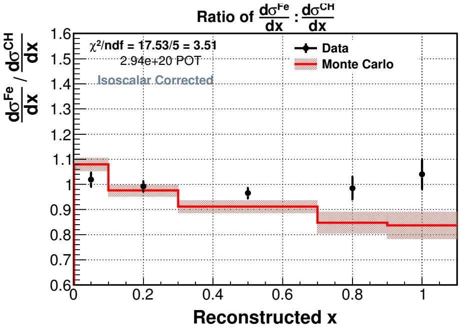


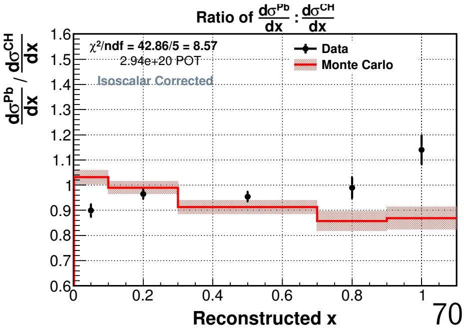


- Unfolded to true E_ν
- No evidence of systematic discrepancy with generator

Results in x







- Deficit at low x_{reco}, excess at high x_{reco}
- Both increase with size of nucleus

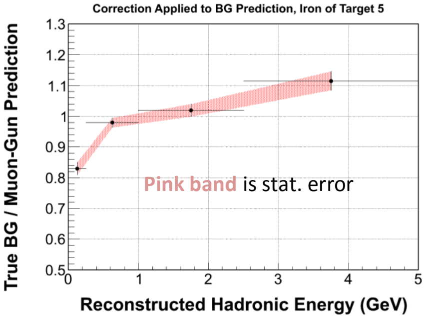
Conclusions and next steps

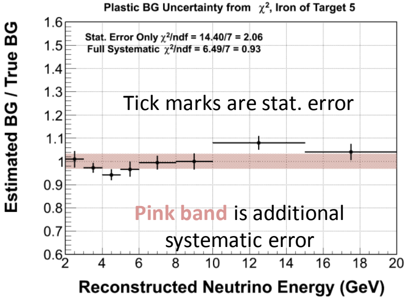
- Suggestions of unmodelled nuclear effects in x but not E_ν
- Analysis with future data
  - $10\times$ more stats
  - Higher $E_\nu \Rightarrow$ More DIS
  - Reach to lower x

Predict spectrum of background using:

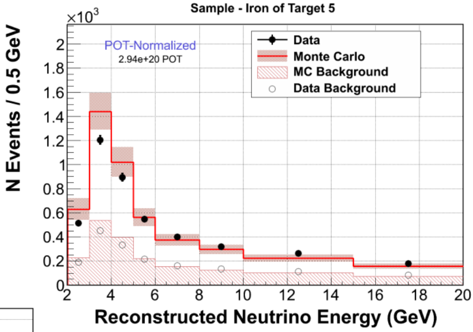
Reconstruction Efficiency

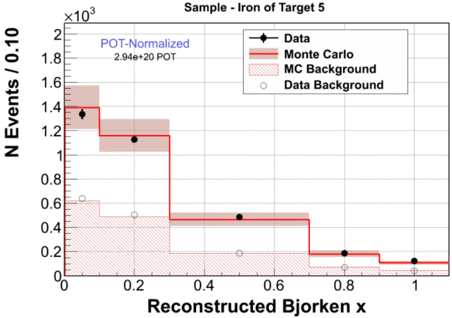
- Unique correction for each nuclear target
- Errors are MC stat. and an additional correlated error
  - Additional uncertainty scale determined by adding uncorrelated uncertainty on top of stat. until $\chi^2/dof = 1$
  - Additional uncertainty applied as correlated event-to-event and target-to-target





$$\left(\frac{d\sigma}{dx}\right)_i = \frac{\sum_j U_{ij}(d_j - b_j)}{\epsilon_i(\Phi T)\Delta x_i}$$





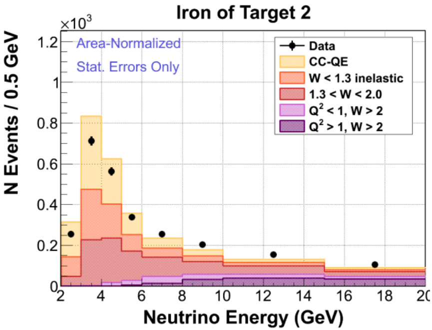
A separate estimated background for **data** and **MC**

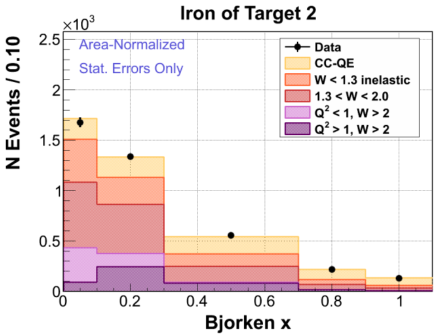
Kinematic Content

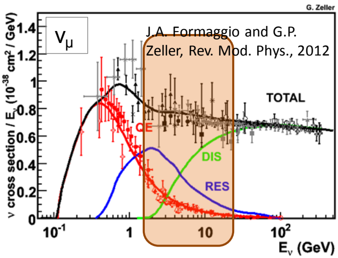
Signal Kinematics
2 < Neutrino Energy < 20 GeV
0 < Muon Angle < 17 deg

Invariant hadronic mass

$$W = \sqrt{M^2 + 2M\nu - Q^2}$$



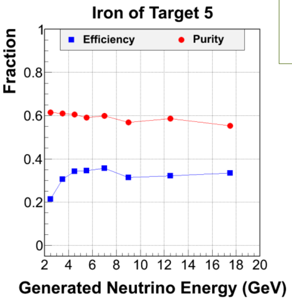




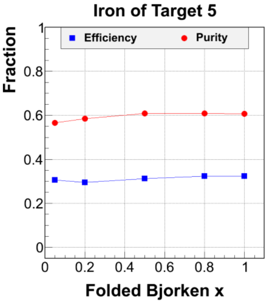
Reconstruction Efficiency

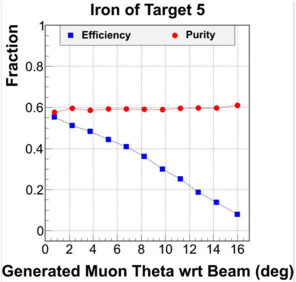
$$\left(\frac{d\sigma}{dx}\right)_i = \frac{\sum_j U_{ij}(d_j - b_j)}{\epsilon_i(\Phi T)\Delta x_i}$$

Signal Kinematics
2 < Neutrino Energy < 20 GeV
0 < Muon Angle < 17 deg

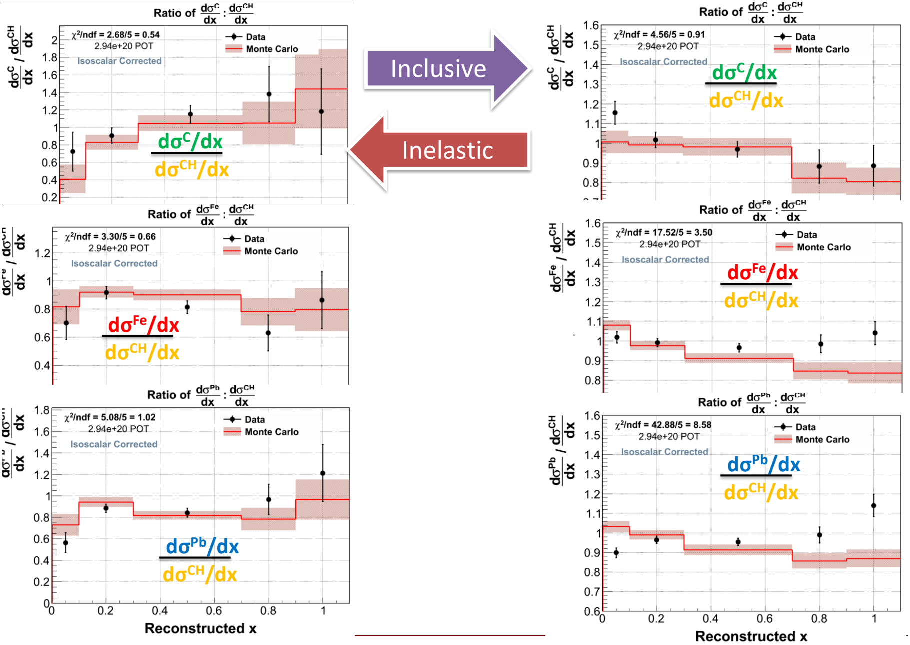


MINOS-match requirement
Muon momentum threshold ~ 2 GeV





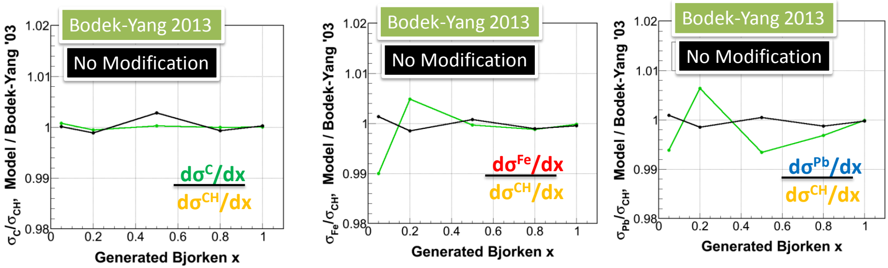
MINOS-match requirement
Geometric acceptance primary driver for efficiency loss
Angular threshold ~ 17 deg


Inclusive
Inelastic
Ratio of dσ^C/dx : dσ^CH/dx
χ²/ndf = 2.68/5 = 0.54
2.94e+20 POT
Isoscalar Corrected
Data
Monte Carlo
dσ^C/dx / dσ^CH/dx
Ratio of dσ^C/dx : dσ^CH/dx
χ²/ndf = 4.56/5 = 0.91
2.94e+20 POT
Isoscalar Corrected
Data
Monte Carlo
dσ^C/dx / dσ^CH/dx
Ratio of dσ^Fe/dx : dσ^CH/dx
χ²/ndf = 3.30/5 = 0.66
2.94e+20 POT
Isoscalar Corrected
Data
Monte Carlo
dσ^Fe/dx / dσ^CH/dx
Ratio of dσ^Fe/dx : dσ^CH/dx
χ²/ndf = 17.52/5 = 3.50
2.94e+20 POT
Isoscalar Corrected
Data
Monte Carlo
dσ^Fe/dx / dσ^CH/dx
Ratio of dσ^Pb/dx : dσ^CH/dx
χ²/ndf = 5.08/5 = 1.02
2.94e+20 POT
Isoscalar Corrected
Data
Monte Carlo
dσ^Pb/dx / dσ^CH/dx
Reconstructed x
Ratio of dσ^Pb/dx : dσ^CH/dx
χ²/ndf = 42.88/5 = 8.58
2.94e+20 POT
Isoscalar Corrected
Data
Monte Carlo
dσ^Pb/dx / dσ^CH/dx
Reconstructed x

Do our data prefer a model?

Using MINERvA bins and acceptance

Comparison of predicted for cross section **ratio**



- Charged lepton data suggest we should see < 1% effect

Recoil Energy Resolution