Results from the MINERνA experiment

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for the MINERνA collaboration

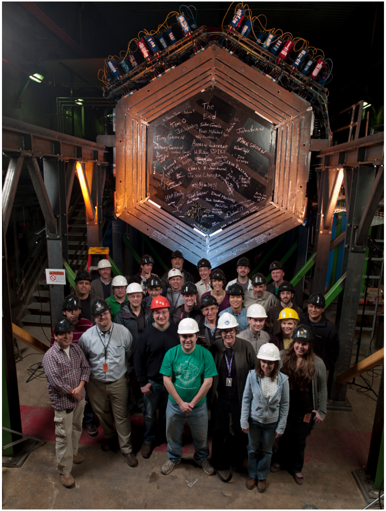
June 12, 2013

Introduction

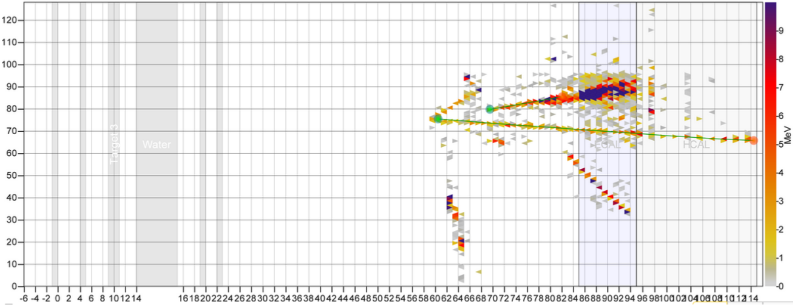
- The MINERνA experiment
- Data taking, preparing for the future
- Recent results: ν_μ and $\bar{\nu}_\mu$ CCQE scattering

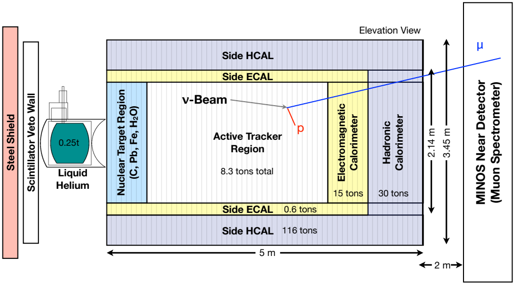
MINERνA: What and why?

- Dedicated neutrino–nucleus scattering experiment in the NuMI beamline
- Measuring exclusive and inclusive ν cross sections on a range of nuclei
- Motivations:
  - Nuclear modelling
  - Oscillation experiments

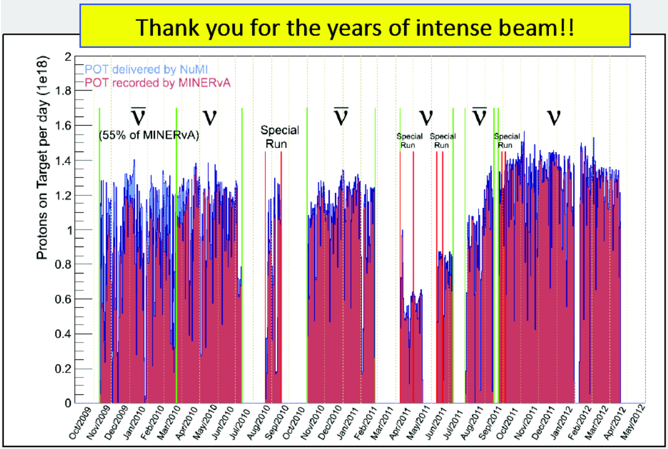


MINERνA detector



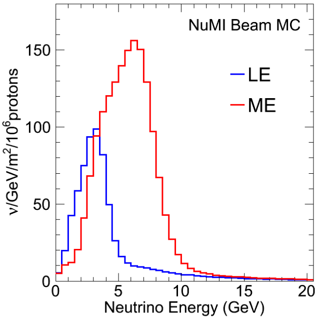


Data taken

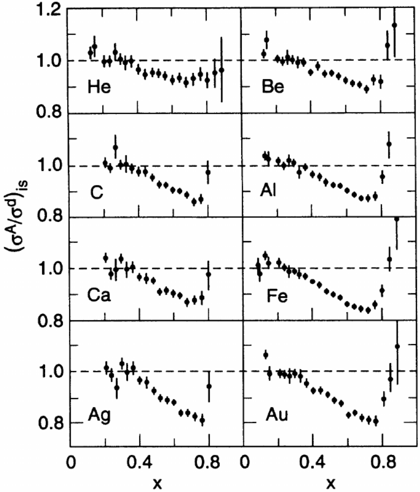


- 3.98×10^{20} POT ν_μ LE; 1.7×10^{20} POT $\bar{\nu}_\mu$ LE
- Livetime: 97.1% MINERνA, 93.3% MINOS ND
- Thank you to accelerator and NuMI beam groups
- Thank you to MINOS for sharing their Near Detector data

Physics goals in the NOνA era



EMC effect in electron scattering



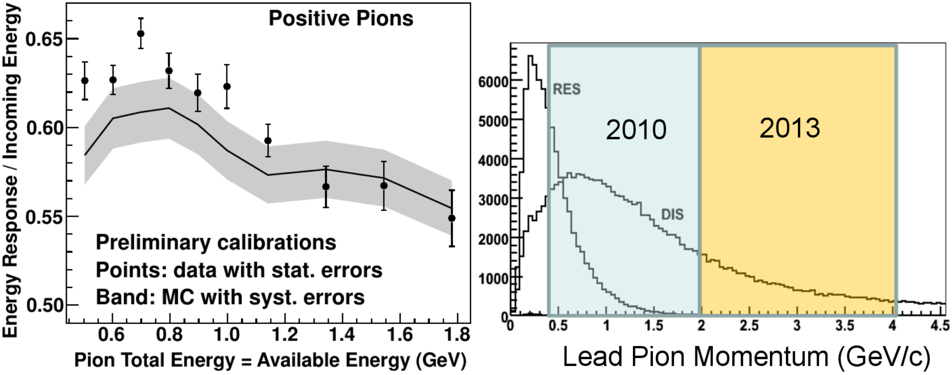
SLAC E139: PRD **49** 4348 (1994)

- Higher E_ν, higher event rates
- Exclusive processes at higher E_ν
- ν, $\bar{\nu}$ DIS and the EMC effect
- Proposal for D_2 in cryotarget

Preparing for the NOνA era: DAQ upgrade

- Higher ν event rate:
  - Required $\sim 5\times$ increase in readout electronics speed
- FNAL EE and MINERνA collaborators designed and implemented new VME modules in < 6 months: $10\times$ faster

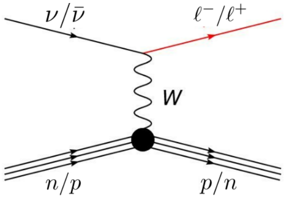
Testbeam detector



- Ran in MTest facility from June–July 2010
- Constrains π, p response: essential for analysis
- Currently E_π from 0.5 GeV to 1.8 GeV
- Higher pion energies in ME beam: need photosensors, beam time scheduling

Recent results: ν_μ and $\bar{\nu}_\mu$ CCQE scattering

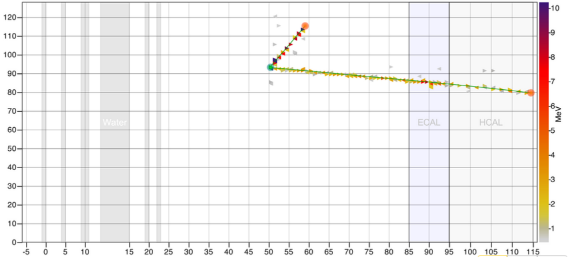
Charged current quasielastic scattering



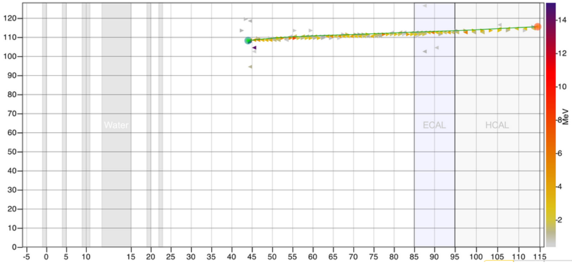
- Measured on *n*, *p* in bubble chambers
- +Fermi Gas model ⇒ standard candle in ν-nucleus scattering?
- More recently: hints of more complex nuclear effects
  - Scatter off correlated nucleons
  - Modifies total σ, $\ell^\pm$ kinematics, FS hadrons

CCQE events in the MINERνA detector

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

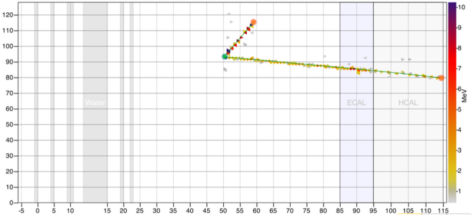


$$\bar{\nu}_\mu + p \to \mu^+ + n$$

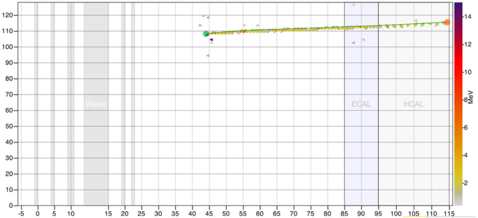


CCQE event selection

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



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



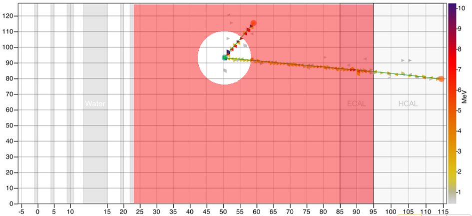
1. Muon matched to MINOS with appropriate charge
2. Few isolated showers
3. Low non-muon "recoil" energy
   - Excluding a region near the vertex: limit sensitivity to low energy hadrons

- Constrain non-QE backgrounds with fit to recoil distribution
- These results: $\sim 1/3\ \nu_\mu$ data, $\sim 2/3\ \bar{\nu}_\mu$ data

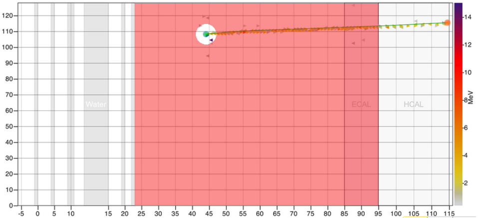
	ν mode	$\bar{\nu}$ mode
Vertex region	30 cm	10 cm
Contains protons...	KE $<$ 225 MeV	KE $<$ 120 MeV
Isolated showers	≤ 2	≤ 1

CCQE event selection

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



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



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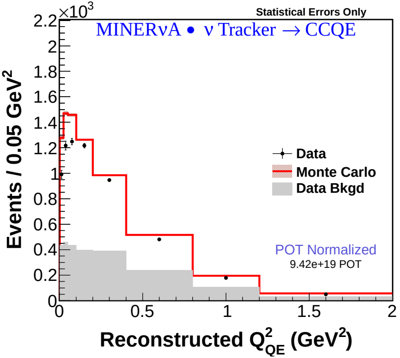
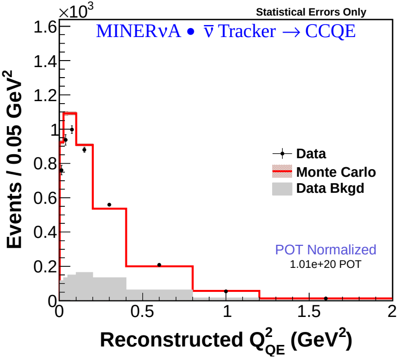
Final event selections





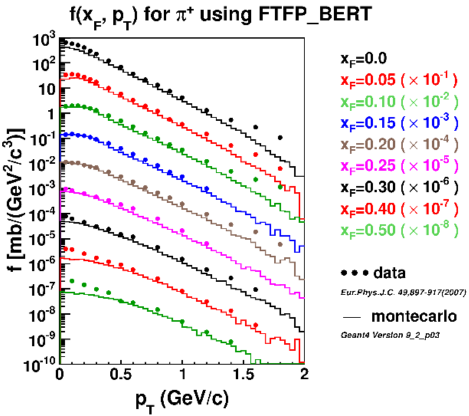
No of events	29,620
Efficiency	47%
Purity	49%

No of events	16,467
Efficiency	54%
Purity	77%

- Next steps: subtract backgrounds and unfold to true Q^2_{QE} to get a cross section
- But first, systematics...

Systematics

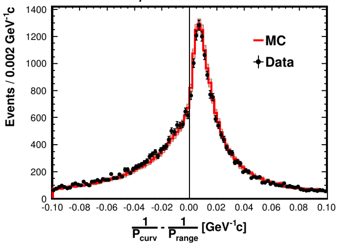
- Flux
  - Tune to NA49 data
  - Remaining 10–15% uncertainties



Systematics

- Flux
  - Tune to NA49 data
  - Remaining 10–15% uncertainties
- Energy scale
  - Muon p scale known to 2–3%
  - Hadronic energy scale from testbeam
  - Hadron reinteractions from external data

p_μ scale



Systematics

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  - Tune to NA49 data
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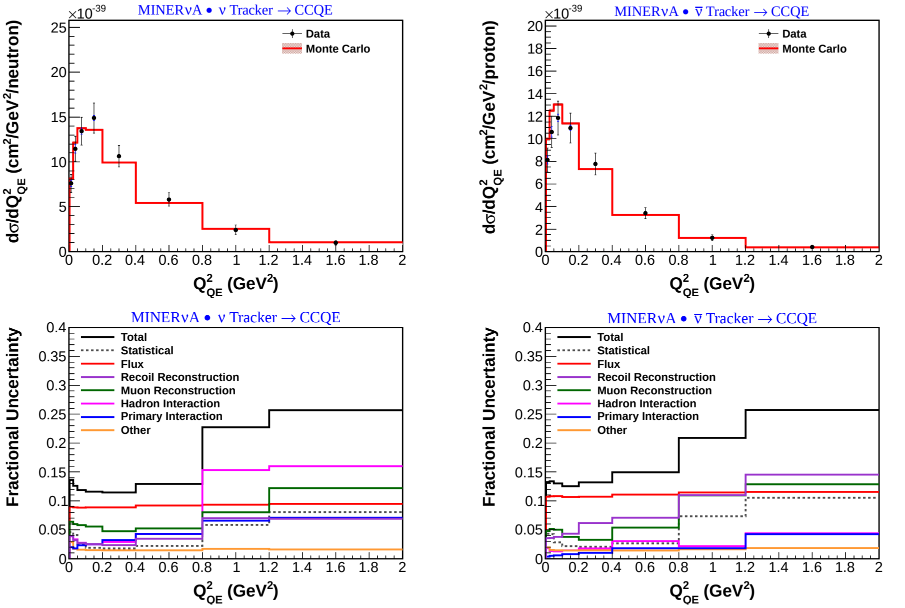
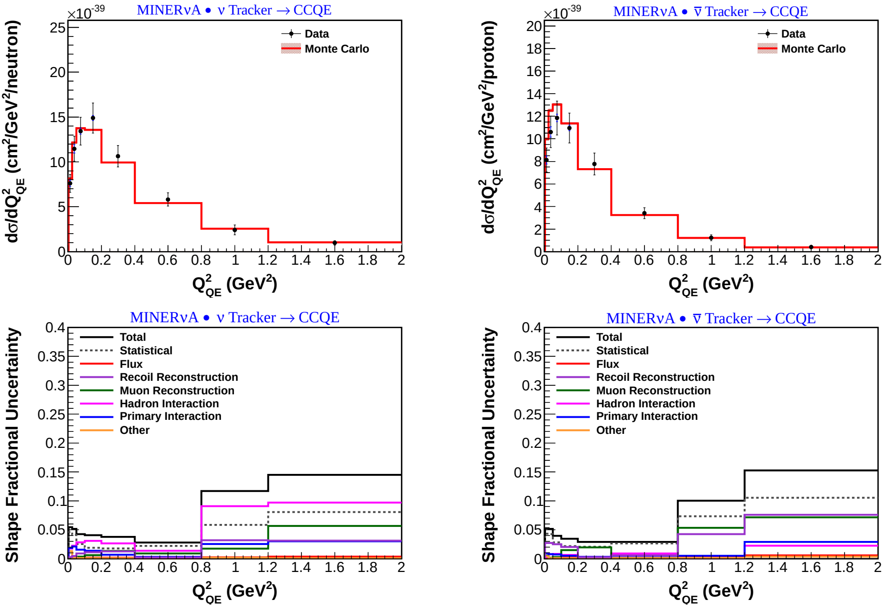
- Energy scale
  - Muon p scale known to 2–3%
  - Hadronic energy scale from testbeam
  - Hadron reinteractions from external data
- Interaction modelling
  - 10s of % uncertainties on primary interaction, FSI

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

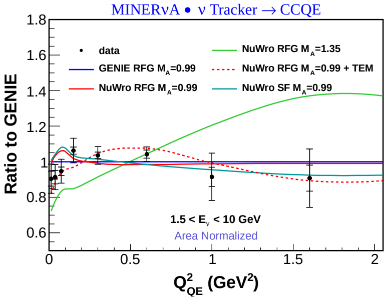
Differential cross section

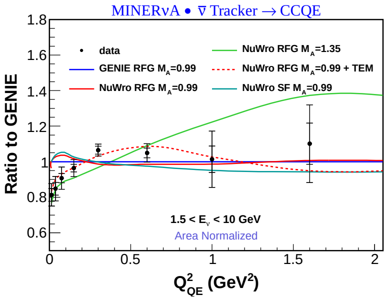


Differential cross section



Model comparisons





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

GENIE —— Nucleons in a mean field

$M_A = 1.35$ —— Modified nucleon form factor from MiniBooNE data

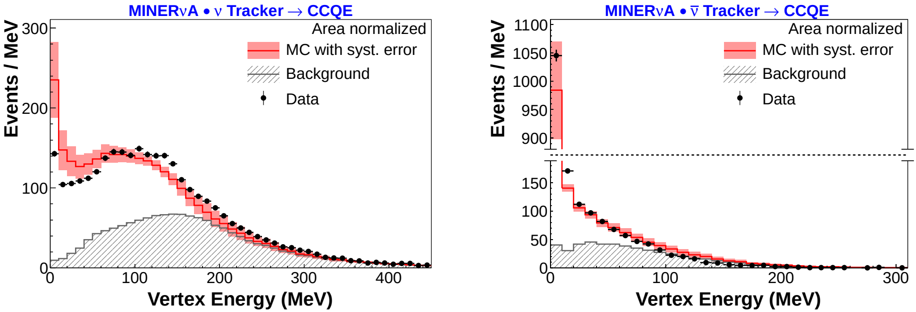
Phys. Rev. D**81**, 092005 (2010)

TEM - - - - Empirical multinucleon effect based on *e* scattering data

(Eur. Phys. J. C 71:1726 (2011))

Vertex energy

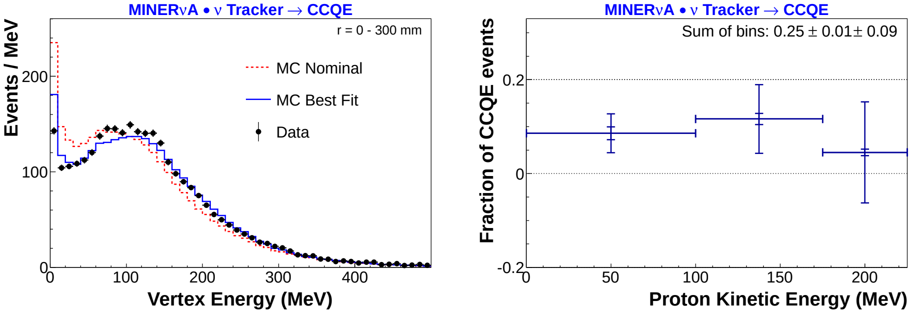
- Multinucleon emission expected in interactions with correlated nucleons
  - Look for excess energy in the vertex region excluded from recoil cut



- 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



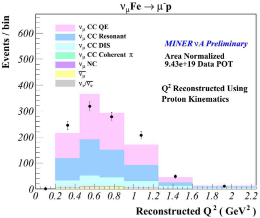
- Extra proton preferred in $(25 \pm 9)\%$ of ν_μ CCQE events
- No increase preferred in $\bar{\nu}_\mu$ mode

Conclusions

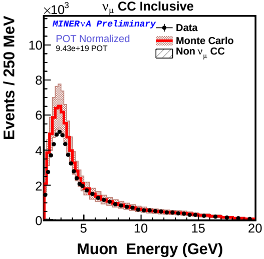
- MINERνA has successfully completed the LE run
- Preparing for an exciting physics programme with ME beam
- Measurements of ν_μ and $\bar{\nu}_\mu$ CCQE point leading the way to improved models
- Many more results soon: poster session and New Perspectives

Analyses with existing data

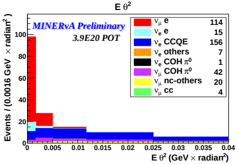
CCQE two-track



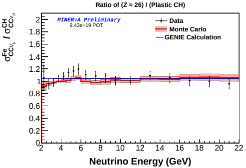
ν_μ CC inclusive on CH



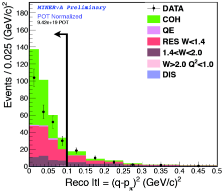
ν_μ — e scattering



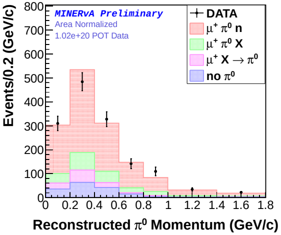
ν_μ CC inclusive nuclear targets



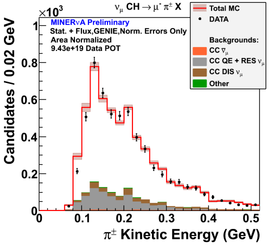
ν_μ CC coherent scattering



$\bar{\nu}_\mu$ CC1π^0



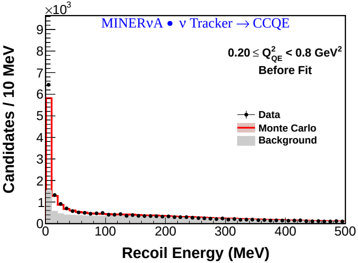
ν_μ CC1$\pi^\pm$

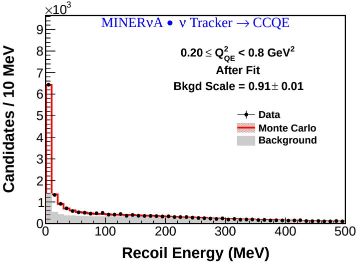


Backup slides

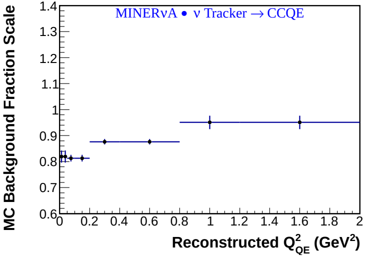
Constraining non-QE backgrounds

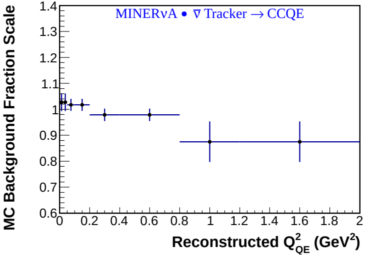
One example bin in Q^2



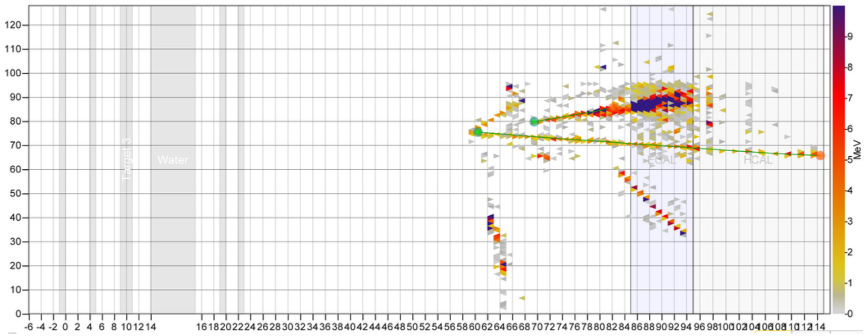


All Q^2 bins





MINERνA detector



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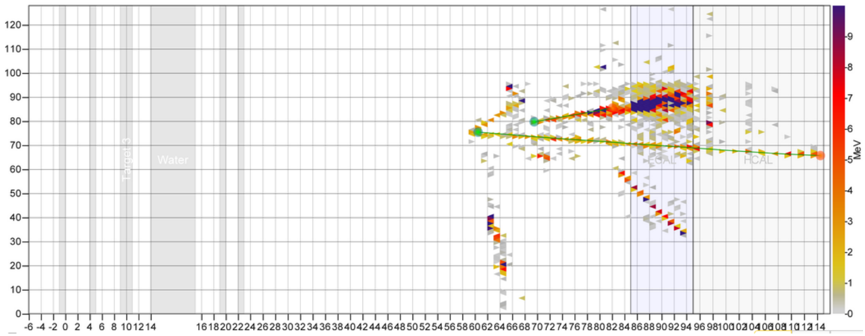

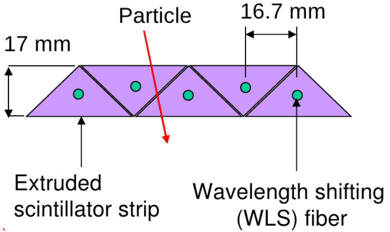

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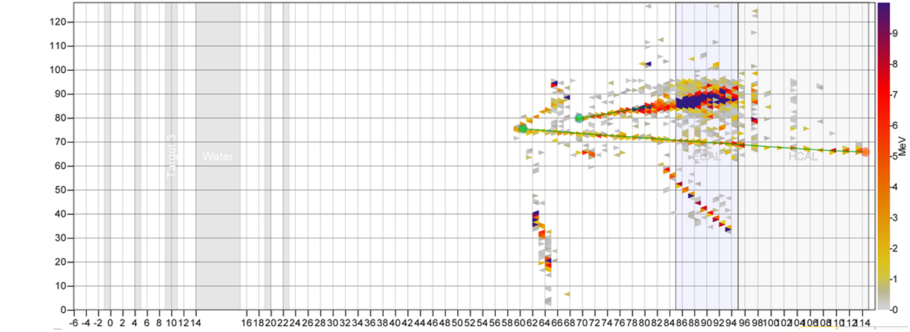
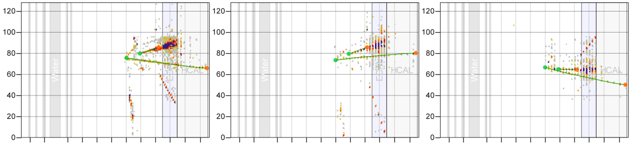
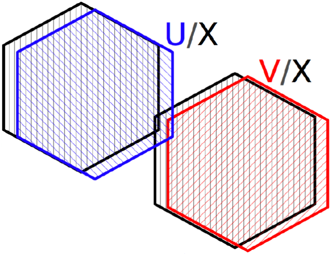
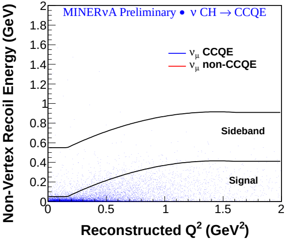


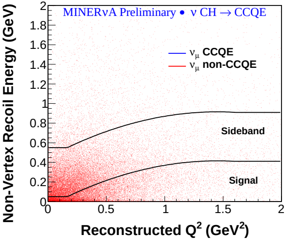




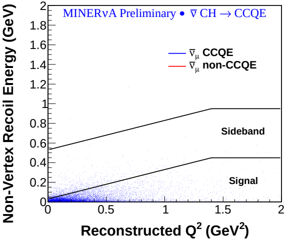
Recoil energy cut

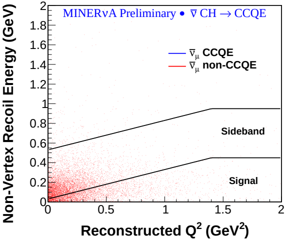
Neutrino mode



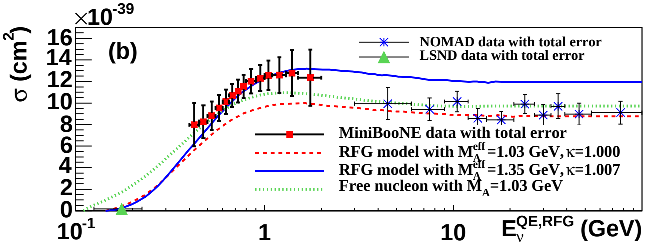


Antineutrino mode

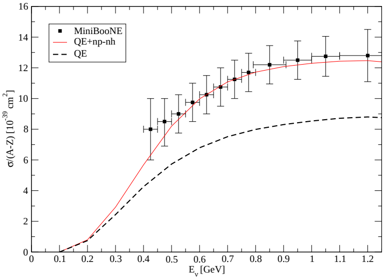




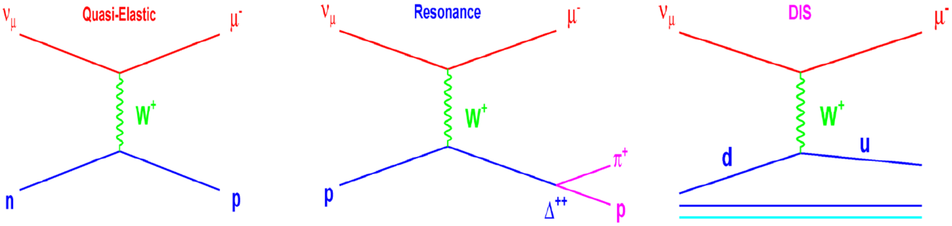
Charged current quasielastic scattering



- $\nu_\mu + n \to \mu^- + p$
- $\bar{\nu}_\mu + p \to \mu^+ + n$
- No pions in final state
- Tension between recent results and bubble chamber data
  - Multinucleon correlations?
  - Affect $\ell^\pm$ kinematics and FS hadrons



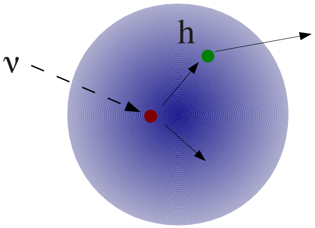
ν cross sections around 1 GeV

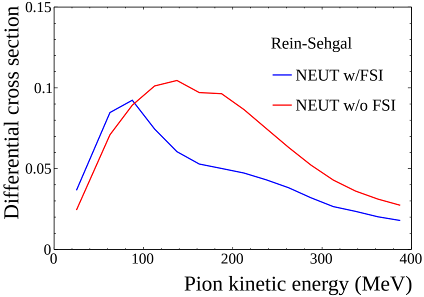


Higher E_ν, Q^2 $\longrightarrow$

- 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



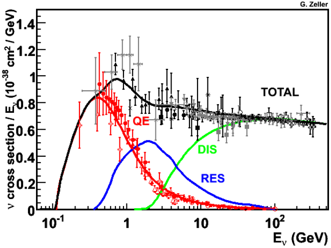


- Charged- and neutral-current processes (CC, NC)
- Interaction with nucleon most significant
- $Q^2 = (\text{4-momentum transferred to nucleon})^2$
- Nucleon bound inside nucleus
  - "Initial state interactions": Binding energy, Pauli blocking, Initial momentum
  - Final state interactions (FSI) change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

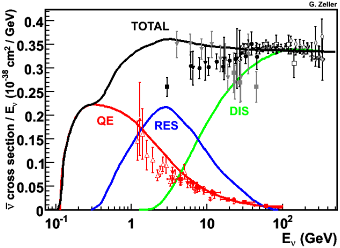
Why measure ν cross sections?

- "Because it's there!"
- Not well-known at $E_\nu \sim 1\,\text{GeV}$
  - 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



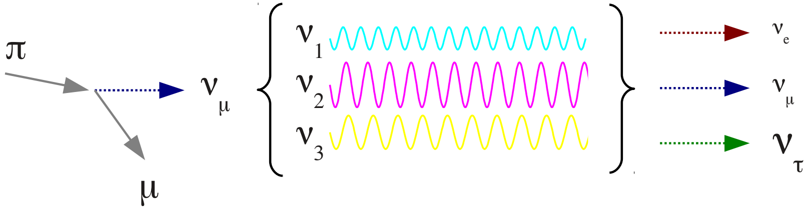
$\bar{\nu}$-nucleon cross sections



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

Why measure ν cross sections? Oscillations

- Neutrino oscillation experiments need precise cross sections



- A reminder:
  - Flavour eigenstates $(\nu_e, \nu_\mu, \nu_\tau) \neq$ mass eigenstates (ν_1, ν_2, ν_3):
  - Propagation by mass eigenstate with frequency $\propto m_i$
  - Different flavour eigenstates at production and detection
  - Oscillation probability depends on flavour–mass mixing matrix (*à la* CKM) and Δm^2s

Neutrino mixing unknowns

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

Neutrino mixing unknowns

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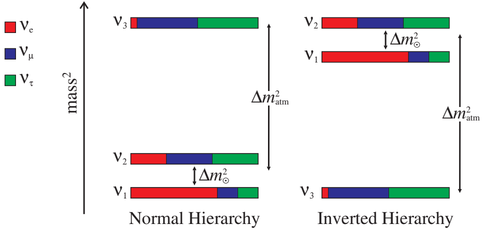
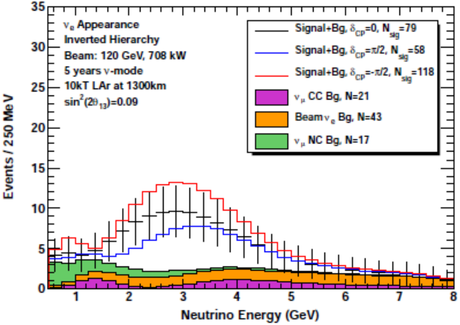
  - Three mixing angles θ_{12}, θ_{23}, θ_{13}
  - Mass splittings Δm^2_{12}, $|\Delta m^2_{23}|$
- Unknowns:
  - CP-violating phase δ
  - Sign of Δm^2_{23}



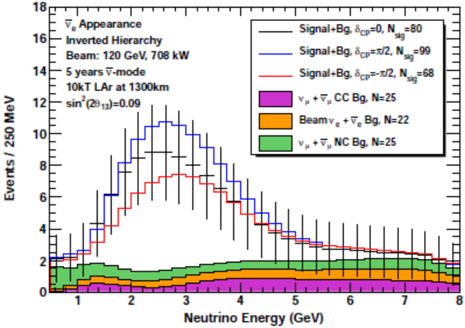
Measuring δ, hierarchy

- Look for small effects in $P(\nu_\mu \to \nu_e)$ vs $P(\bar{\nu}_\mu \to \bar{\nu}_e)$

$\nu_\mu \to \nu_e$



$\bar{\nu}_\mu \to \bar{\nu}_e$



Source: LBNE CDR

- Largest possible δ effect shown! (IH)
- Need precise signal and background predictions

Where do cross sections come in?

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

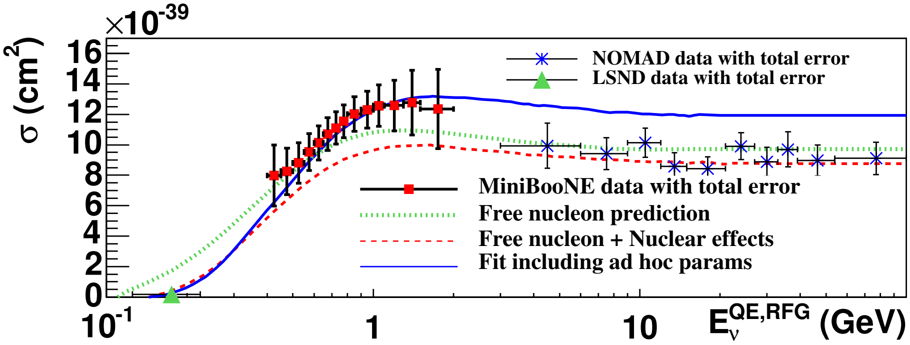
- ν_e σ unmeasured. σ_{ν_e}, σ_{ν_μ} differences[1]
- $E_\nu \leftrightarrow E_{\mathrm{visible}}$ from cross section MC
  - Čerenkov: Lepton kinematics + CCQE hypothesis (T2K, MiniBooNE)
  - Sampling calorimeters: $E_{\mathrm{lepton}} + E_{\mathrm{had}}$ (MINOS, Noνa)
- And all the same issues for backgrounds
- Near detectors partially cancel some of these effects, but still:

Precision ν oscillation experiments need precision ν-nucleus cross sections

[1] M. Day and K. S. McFarland, Phys. Rev. D 86, 053003 (2012)

Why else? Puzzles!

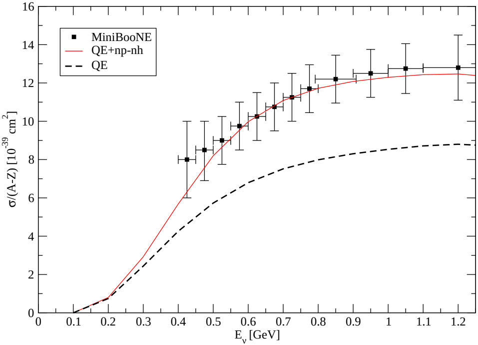
- In CCQE:

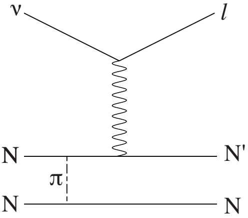


Phys. Rev. D81:092005 (2010), my legend

- Simplest CC topology. Hoped for a standard candle...
- How to reconcile MiniBooNE, NOMAD, bubble chamber CCQE measurements?

A possible solution



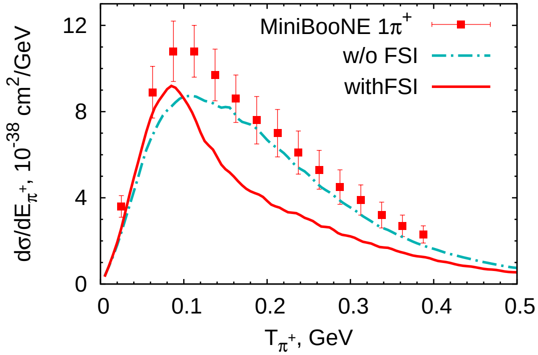


Martini *et al.*, Phys. Rev. C 80:065501 (2009)

- Scatter off correlated pairs of nucleons
- Known effect in *eA* scattering
- Several models on the market:
  - No final state nucleon predictions
  - Not all valid at all energies

Why else? Puzzles!

- In CC π^+ production:

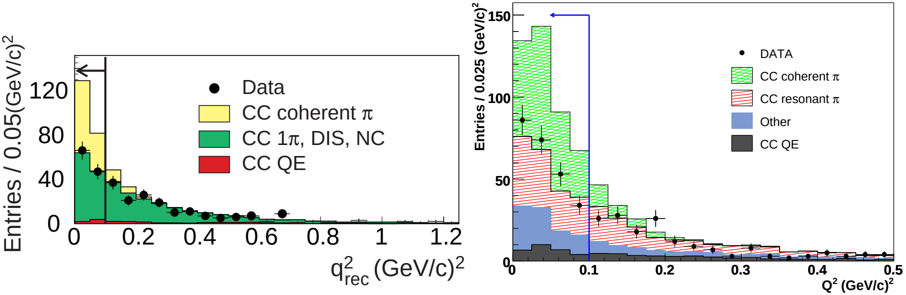


Data: Phys. Rev. D83, 052007 (2011), GiBUU, arXiv:1210.4717

- GiBUU, a well-validated, sophisticated nuclear transport code
- Agrees better with MiniBooNE data without FSI!
- A potential background for CCQE measurements

Why else? Puzzles!

- In coherent π^+ production:



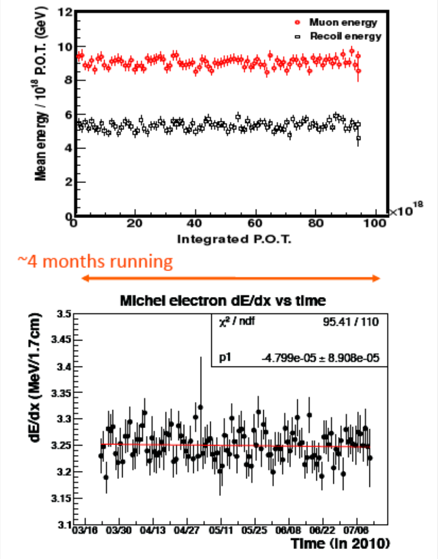
Phys. Rev. Lett. 95:252301 (2005). Phys. Rev. D78:112004 (2008)

- K2K and SciBooNE find no evidence for coherent π^+ production for $E_\nu \approx 1 - 2\,\mathrm{GeV}$
- Process seen at higher energies

Measuring ν cross sections: why it's hard

- Cross section is *tiny*
  - Need large detectors for appreciable event rate
  - Need fine granularity identify interaction type
  - $\Rightarrow$ Many readout channels, high cost
- Flux is not precisely known
  - Depends on hadronic physics
- Beam has wide energy spread
- Observe (Nucleon-level σ) $\otimes$ (Nuclear effects) $\otimes$ (FSI)

3. Recoil Energy Scale



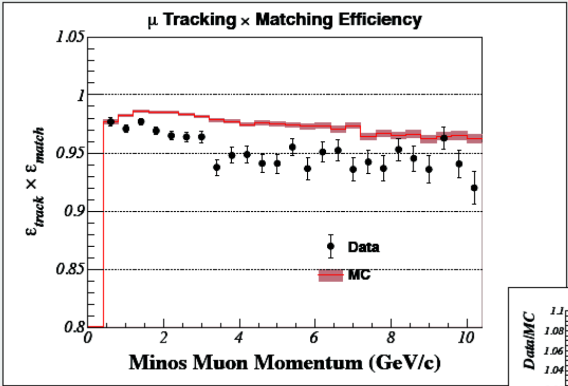
Muons

Recoil

Calibrated detector
very stable
at high and low
energy scales

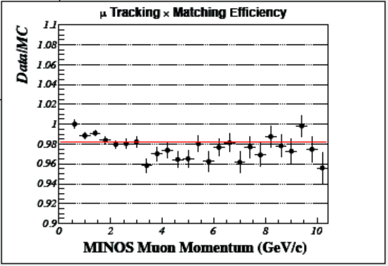
Electron dE/dx

Muon Tracking Efficiency



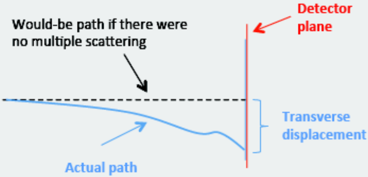
MINERvA muon tracking efficiency

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) %