Quasi-Elastic Cross Sections
Pittsburgh Neutrino Flux Workshop

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Northwestern University

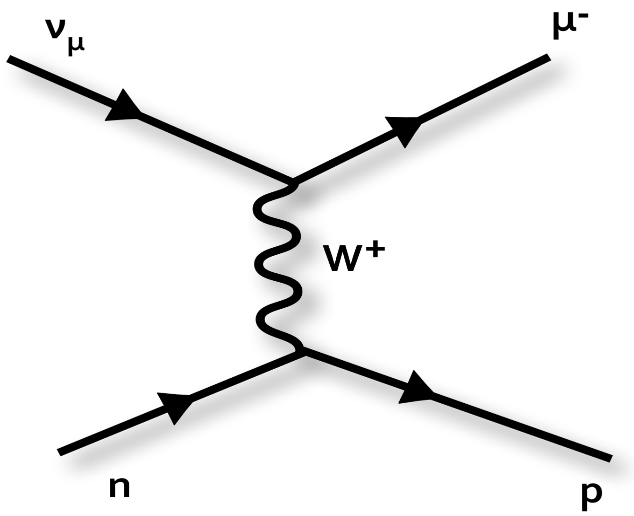
2012-12-07

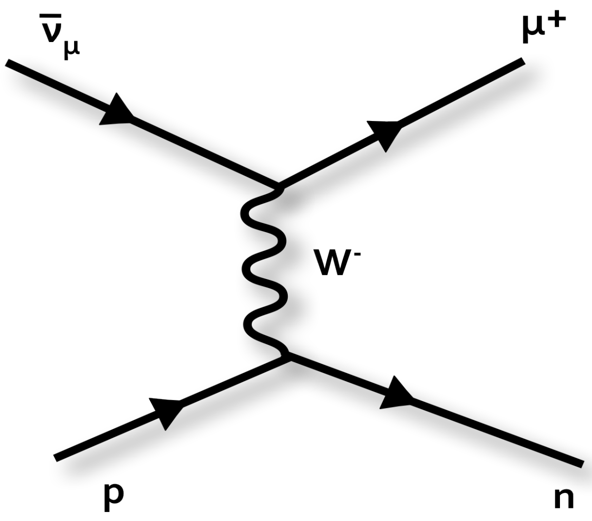
Outline

- Introduction
  - Overview of quasi-elastic interactions
- Recent quasi-elastic measurements and prospects:
  - MiniBooNE
  - MINERvA
  - T2K
  - ArgoNeuT (topological 1μ + Np)
  - NOMAD
- Conclusions/outlook

Introduction

- Charged-current quasi-elastic scattering:





- Has been used as a "standard candle" for flux measurements
- Clean experimental signature
- Easily reconstructible kinematics if you assume a nucleon at rest:

$$E_\nu = \frac{m_\mu^2 - (m_p - E_b)^2 - m_\mu^2 + 2(m_p - E_b)E_\mu}{2(m_p - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

$$Q^2 = 2E_\nu(E_\mu - p_\mu \cos\theta_\mu) - m_\mu^2$$

Q = 4-momentum transferred from neutrino to proton

Introduction

- Charged-current quasi-elastic scattering on free nucleons:

Phys. Rep. 3, 261 (1972)

$$\frac{d\sigma}{dQ^2}_{QE} = \frac{M^2 G_F^2 \cos^2\theta_C}{8\pi E_\nu^2}\{A(Q^2) \pm B(Q^2)\frac{s-u}{M^2} + C(Q^2)\frac{(s-u)^2}{M^4}\}$$

  - Sign on B term is minus for neutrinos, plus for antineutrinos
  - G_F is the Fermi constant, 1.17 x 10^{-5} GeV^{-2}
  - M is the average nucleon mass, 938.92 MeV
  - θ_C is the Cabbibo angle; cos θ_C = 0.9742
  - E is the neutrino energy
  - s and u are Mandelstam variables

Introduction

- Charged-current quasi-elastic scattering on free nucleons:

$$A(Q^2) = \frac{m_\mu^2 + Q^2}{M^2}\left\{(1+\frac{Q^2}{4M^2})F_A^2 - (1-\frac{Q^2}{4M^2})F_1^2 + \frac{Q^2}{4M^2}(1-\frac{Q^2}{4M^2})(\xi F_2)^2 + \frac{Q^2}{M^2}Re(F_1^*\xi F_2) - \frac{Q^2}{M^2}(1+\frac{Q^2}{4M^2})(F_A^3)^2 - \frac{m_\mu^2}{4M^2}\left[|F_1+\xi F_2|^2 + |F_A + 2F_P|^2 - 4(1+\frac{Q^2}{4M^2})((F_V^3)^2 + F_P^2)\right]\right\}$$

$$B(Q^2) = \frac{Q^2}{M^2}Re\left[F_A^*(F_1+\xi F_2)\right] - \frac{m_\mu^2}{M^2}Re\left[(F_1 - \tau\xi F_2)F_V^{3*} - (F_A^* - \frac{Q^2}{2M^2}F_P)F_A^3\right]$$

$$C(Q^2) = \frac{1}{4}\left\{F_A^2 + F_1^2 + \tau(\xi F_2)^2 + \frac{Q^2}{M^2}(F_A^3)^2\right\}$$

- Definitely not simple!
  - But if you look closely, there are just 6 form factors involved
  - Form factors are used to parameterize our ignorance of the hadronic component of the cross-section and must be taken from experiment

Introduction

- Charged-current quasi-elastic scattering on free nucleons:
  - Most of the form factors are known:
    - F_V^3 and F_A^3 are negligibly small
    - The vector form factors are related to the Sachs electric and magnetic form factors (G_E and G_M), which are known:

$$F_1(Q^2) = \frac{G_E + \tau G_M}{1+\tau} \qquad \xi F_2(Q^2) = \frac{G_M - G_E}{1+\tau} \qquad \tau = \frac{Q^2}{4M^2}$$

    - The pseudoscalar form factor is proportional to the axial form factor:

$$F_P(q^2) \approx \frac{2M^2}{m_\pi^2 - q^2} F_A(q^2)$$

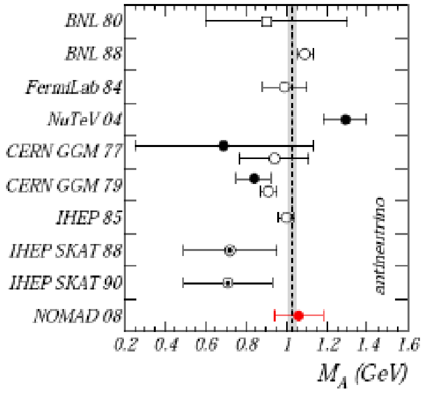
Introduction

- Charged-current quasi-elastic scattering on free nucleons:
  - Which leaves us with just one unknown form factor, the axial form factor, usually parameterized as a dipole:

$$F_A^{dipole}(Q^2) = \frac{F_A(0)}{(1 - \frac{q^2}{M_A^2})^2}$$

$F_A(0)$ is known from beta decay

So, we are left with just one significant unknown parameter: The "axial mass" M_A

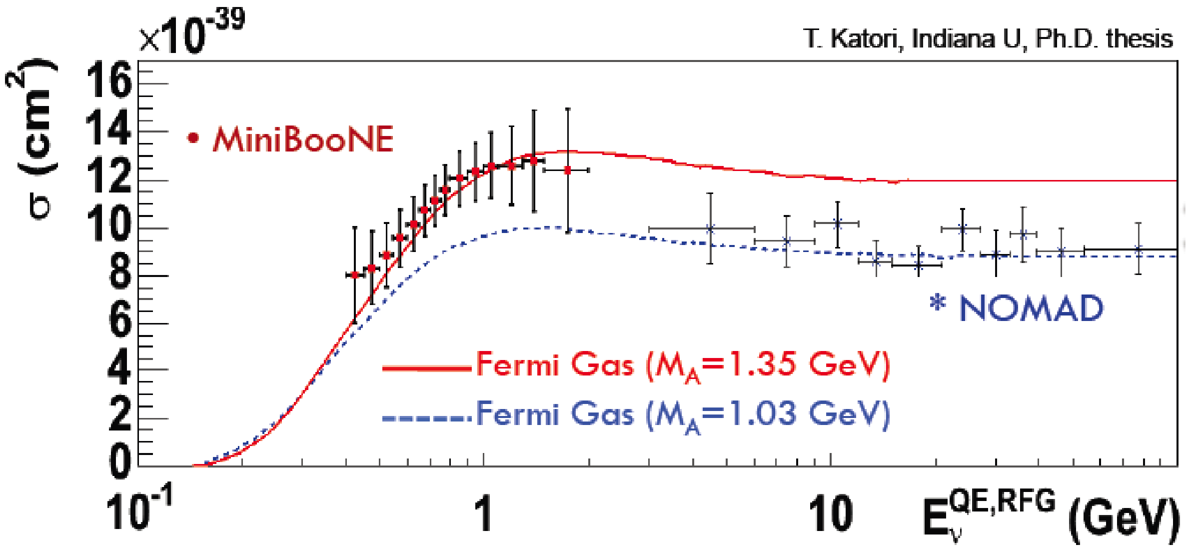


from Lyubushkin, etal [NOMAD collab] Eur.Phys.J.C63:355-381,2009

M_A has been measured a lot, mainly by older bubble chambers (many deuterium-filled). World average as of 2002 was $M_A = 1.026 \pm 0.021$, and measurements agreed fairly well.

Introduction

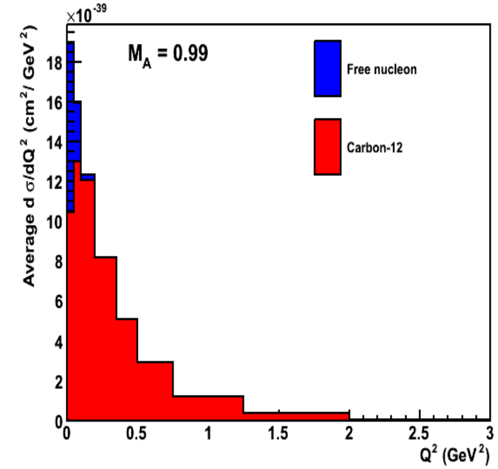
- Charged-current quasi-elastic scattering:
  - But then MiniBooNE turned this view that quasi-elastics are well understood upside down:



  - MiniBooNE prefers a much larger axial mass than older experiments; this preference is supported by SciBooNE, K2K & MINOS

Introduction

- Charged-current quasi-elastic scattering:
  - So, what gives?
    - One issue: everything I've told you so far applies to free nucleons.
    - But modern neutrino detectors are made of materials with heavy nucleii (to get high event rates)
    - The nucleons in modern experiments are not free!



C. Patrick

How the nucleus changes the cross-section:

Initial state nucleons have fermi momentum → smears final state kinematics

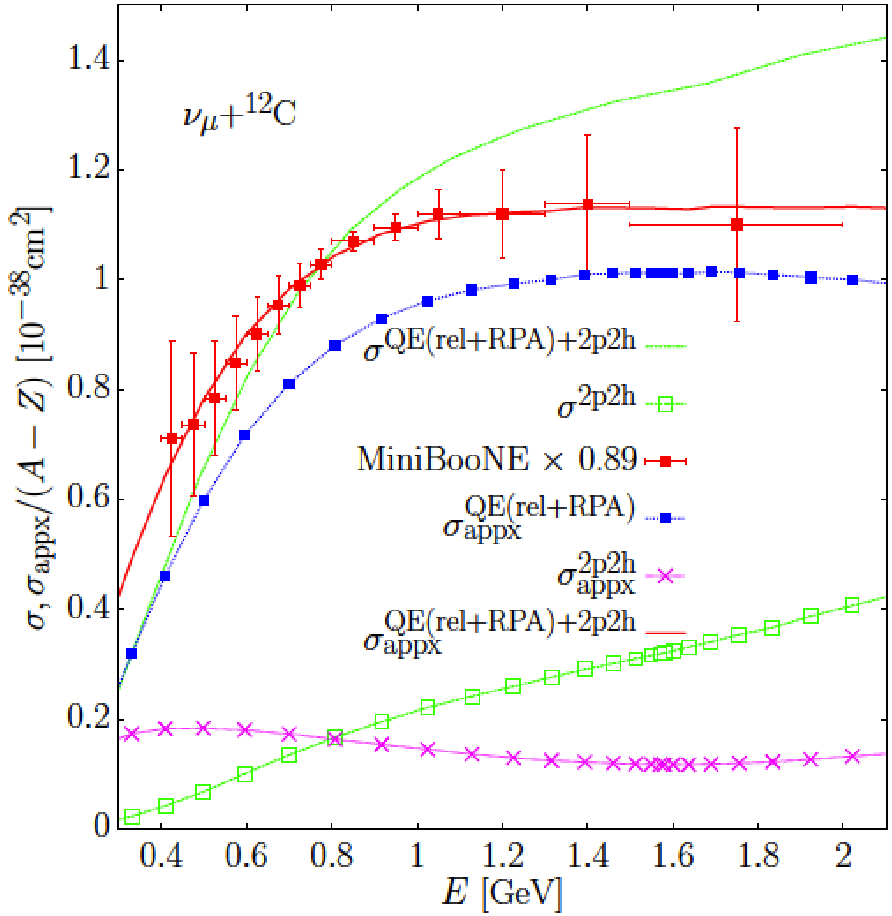
Final state nucleons undergo FSI

The cross-section is lower than for free nucleons, especially for low values of momentum transfer (pauli blocking and other effects)

Neutrinos can interact with multi-nucleon bound states (sometimes called meson exchange currents or MEC); not yet experimentally confirmed (although there are hints)

Introduction

- Charged-current quasi-elastic scattering:
  - The MiniBooNE results hint at the presence of MEC:



Traditional + MEC QE cross-section

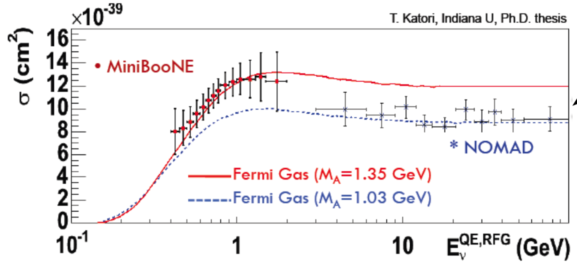
Traditional + MEC QE cross-section
If you use traditional energy reconstruction
(which MiniBooNE did)

Traditional QE cross-section

J. Nieves, NuInt 2012

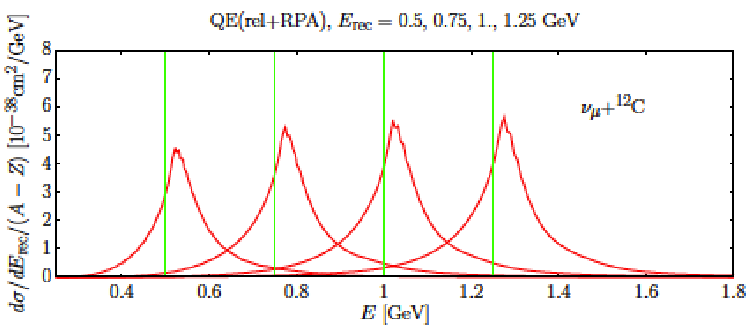
The model that includes MEC fits shape of MiniBooNE data well

MiniBooNE data would include MEC events
NOMAD data would exclude most MEC, which could explain NOMAD/MiniBooNE discrepancy

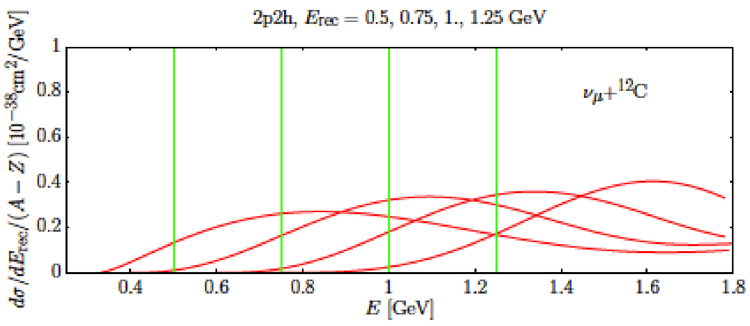


Introduction

- Charged-current quasi-elastic scattering:
  - More on "meson exchange currents"



Energy resolution in traditional quasi-elastic scattering



Energy resolution for meson exchange current portion of QE-like cross-section

J. Nieves, NuInt 2012

Energy reconstruction using quasi-elastic kinematics does not work for MEC!

This has potentially big implications for flux & oscillation measurements

We don't know what component of the QE "signal" is from MEC

Introduction

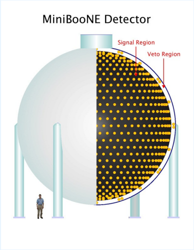
- Summarizing the current situation for quasi-elastic scattering:
  - Experiments have produced contradictory QE measurements
  - Theorists have postulated QE-like processes that could have significant implications for flux and oscillation measurements, but have not yet been experimentally confirmed

Several experiments are currently trying to change this situation and significantly reduce current CCQE cross section uncertainties

The rest of the talk is a summary of those efforts by MiniBooNE, T2K, MINERνA, NOMAD and Liquid Argon detectors

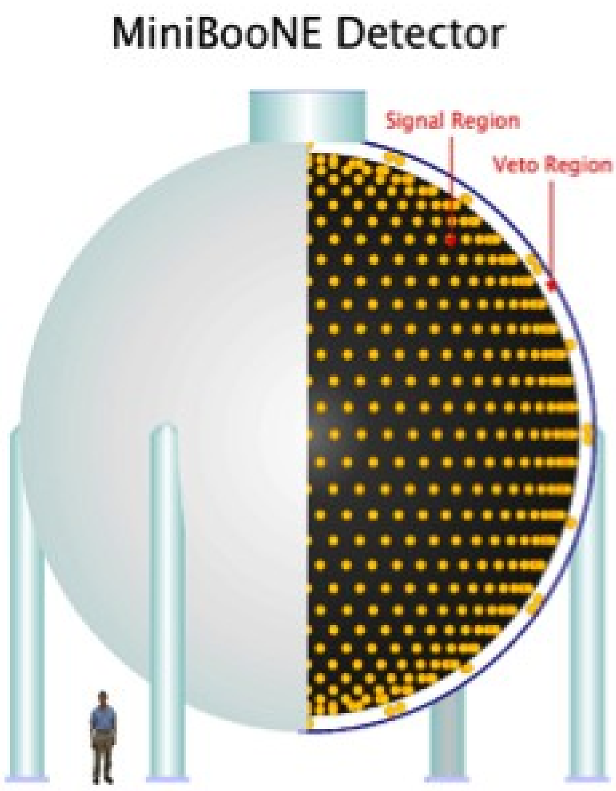
(With apologies to experiments I don't have time to review, such as MINOS, & SciBooNE)

MiniBooNE

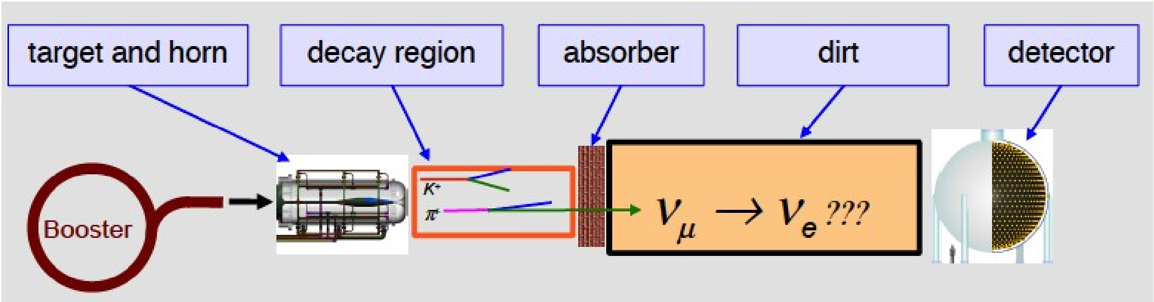


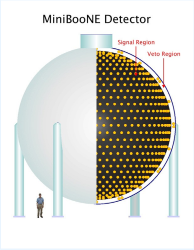
MiniBooNE

- MiniBooNE:



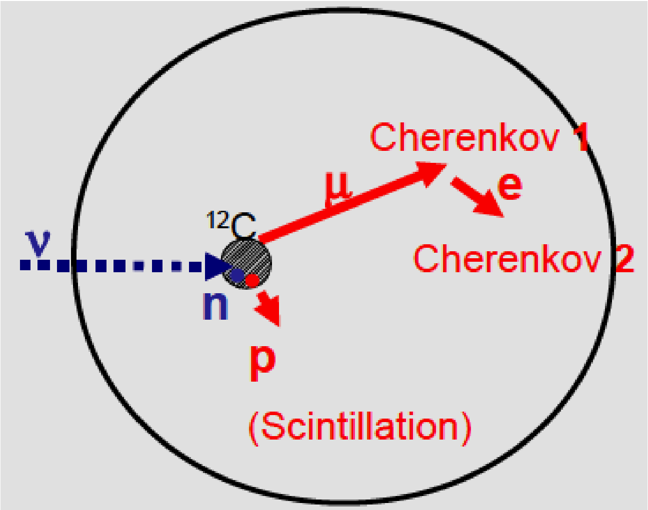
- Cherenkov detector; 12.2 meter diameter sphere of mineral oil; in Booster beam at Fermilab
- Famous as short-baseline oscillation experiment, but a prolific source of cross-section measurements
- Relatively low energy
  - <Eν> ~ 700 MeV
  - CCQE measured over 0.4-2 GeV

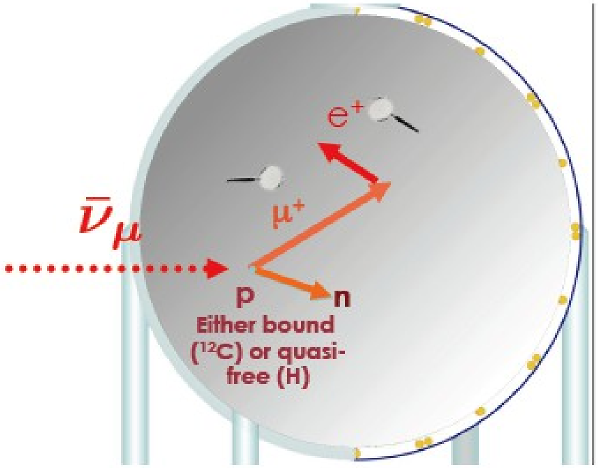




MiniBooNE

- MiniBooNE's ν and $\bar{\nu}$ CCQE measurements:





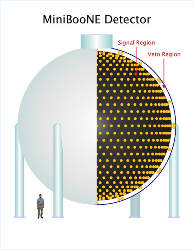
Selection Criteria

One stopping muon + one e decay (two subevents)

No selection of secondary nucleon

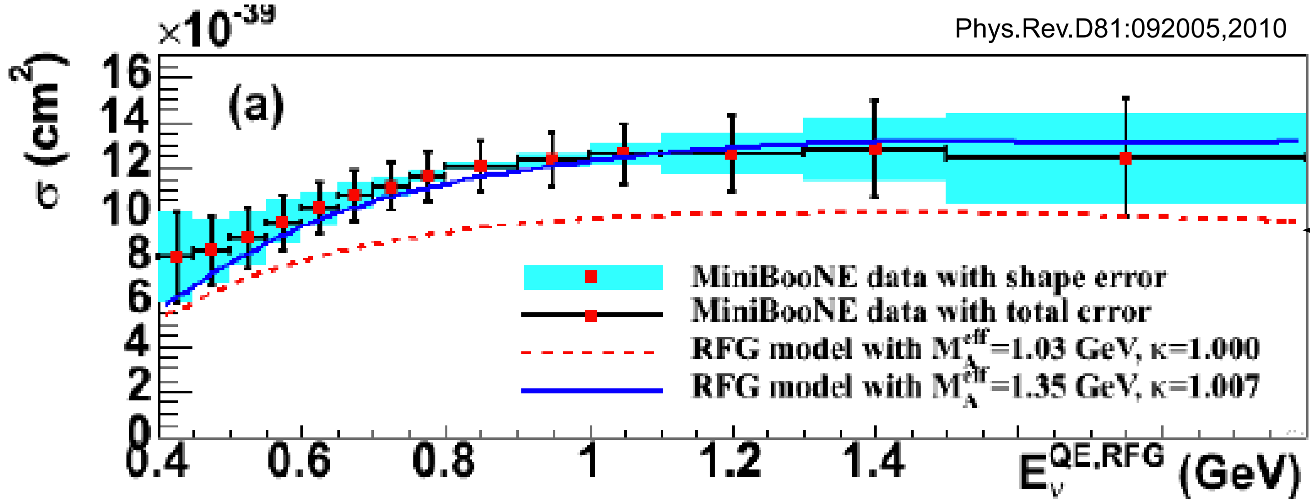
Veto events with second e decay (three subevents) for ν-mode (lowers pion backgrounds)

μ/e separation PID (single -π backgrounds are more e-like)



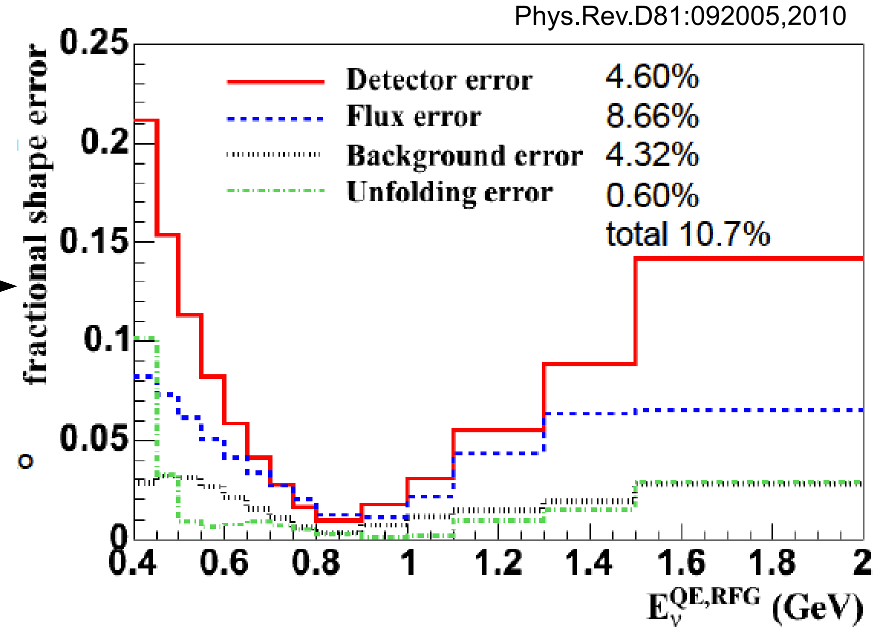
MiniBooNE

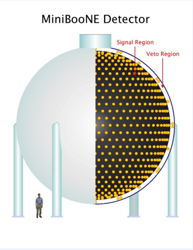
- MiniBooNE's ν CCQE measurement:



A zoomed-in version of the plot you saw earlier in this talk

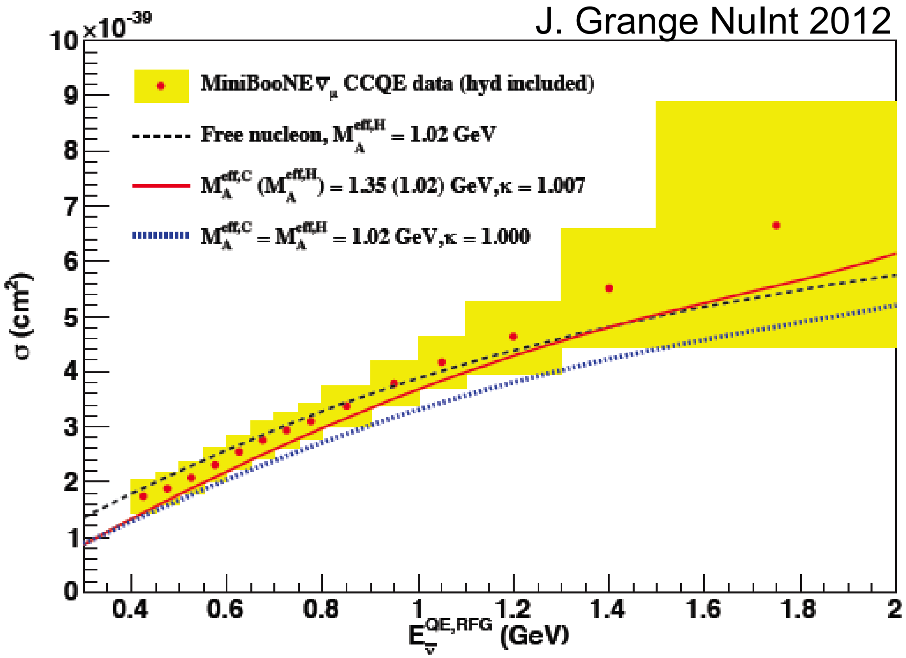
Shape uncertainty
Total (shape+norm) uncertainties vary from 10-20%





MiniBooNE

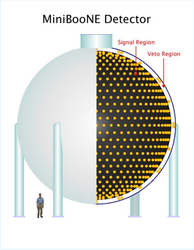
▶ MiniBooNE's $\bar{\nu}$ CCQE measurement:



Anti-neutrino data also prefers a higher normalization than standard $M_A \approx 1$

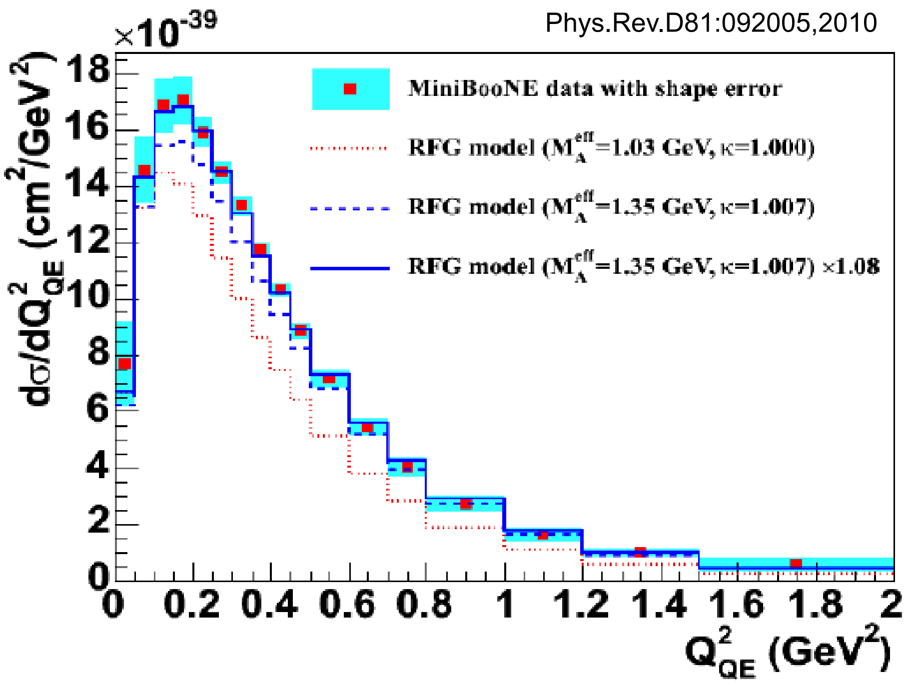
Uncertainties vary from 11% to 35%

Error source	Normalization uncertainty (%)
anti-ν flux	9
Backgrounds	9
Detector	5
Unfolding	2
Total (includes correlations)	**14**

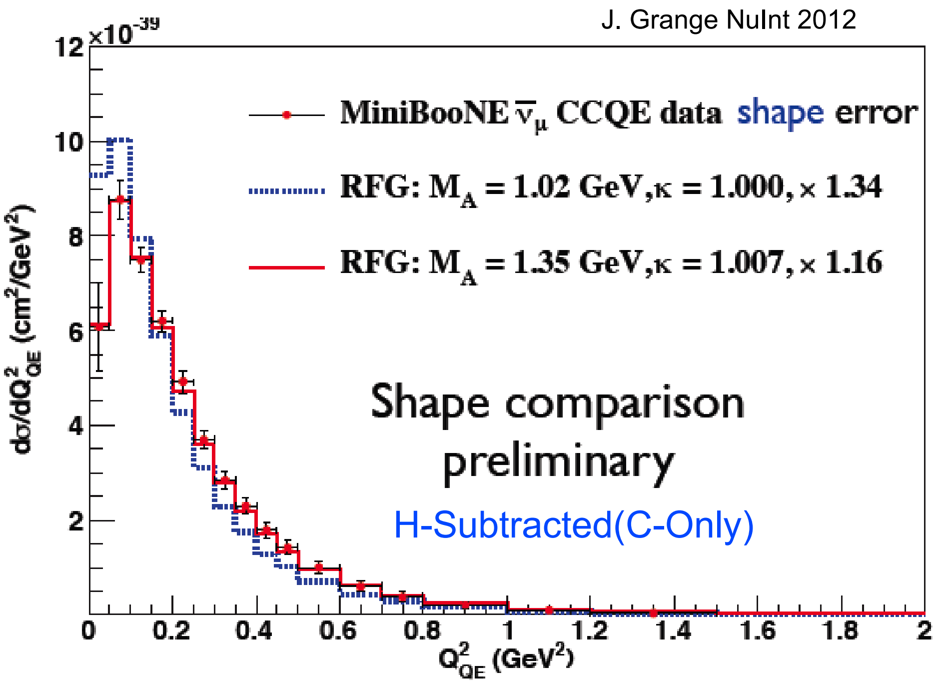


MiniBooNE

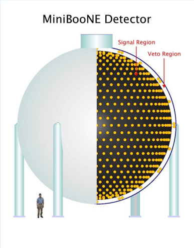
- M_A behavior can also be seen in Q2 distributions:



Neutrino



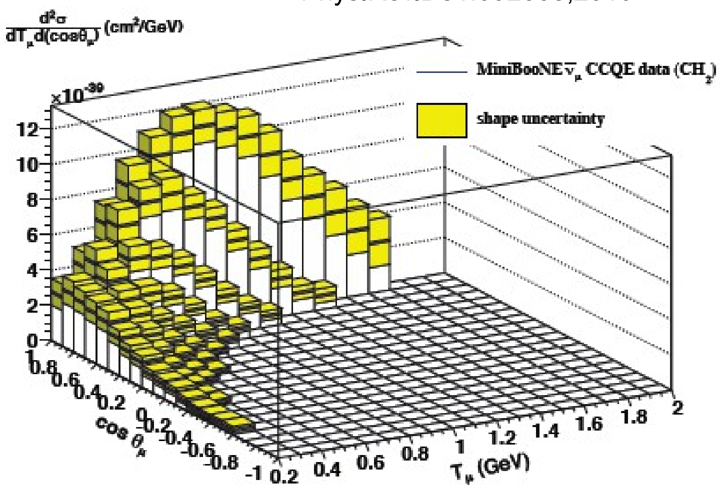
Anti-Neutrino



MiniBooNE

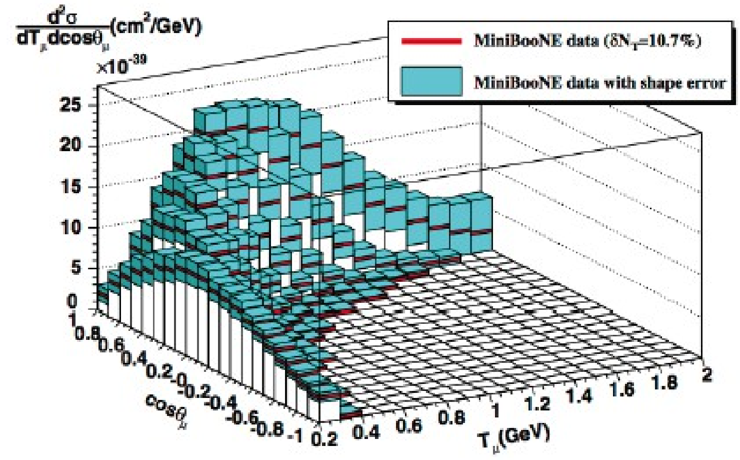
- Double differentials are also available for both modes:

Phys.Rev.D81:092005,2010



$\bar{\nu}_\mu$ CCQE

J. Grange NuInt 2012



ν_μ CCQE

MiniBooNE Summary/Outlook

Final data samples have been analyzed

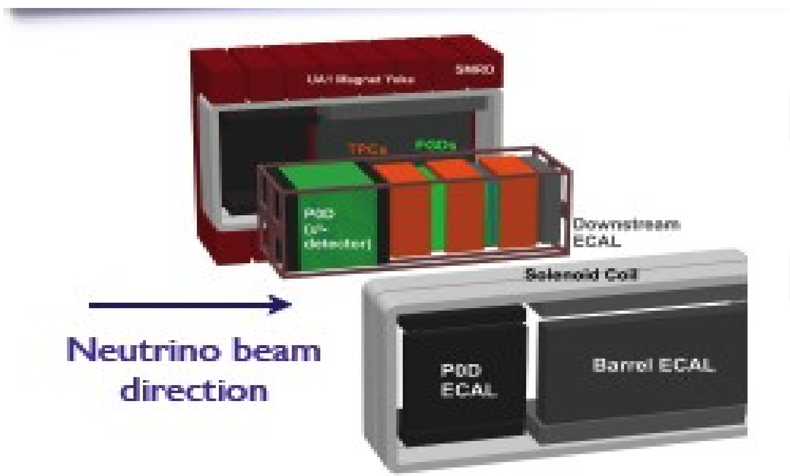
Analyses may be revisited in light of new knowledge of nuclear effects, but large changes in uncertainties are not expected

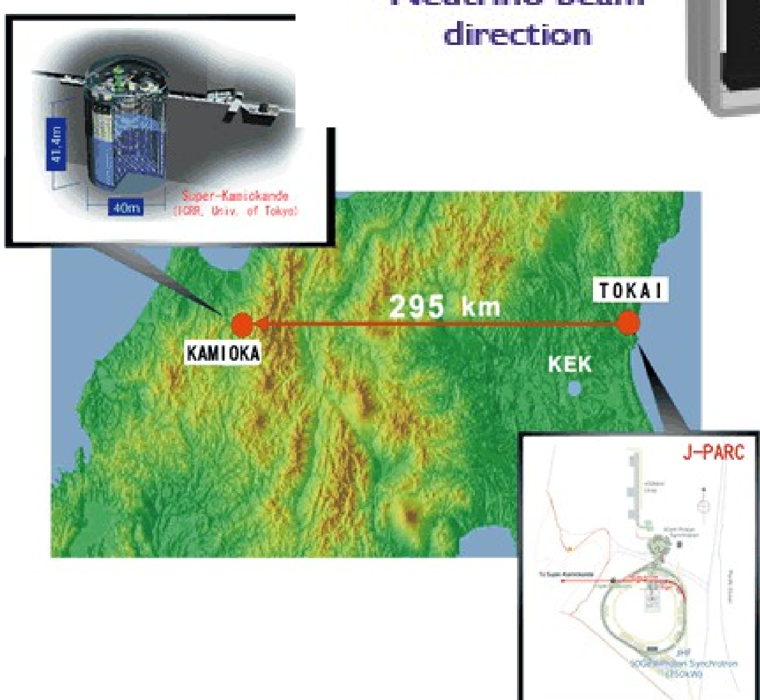
An analysis with proton reconstruction may also be attempted

T2K

T2K Near Detector (ND280)

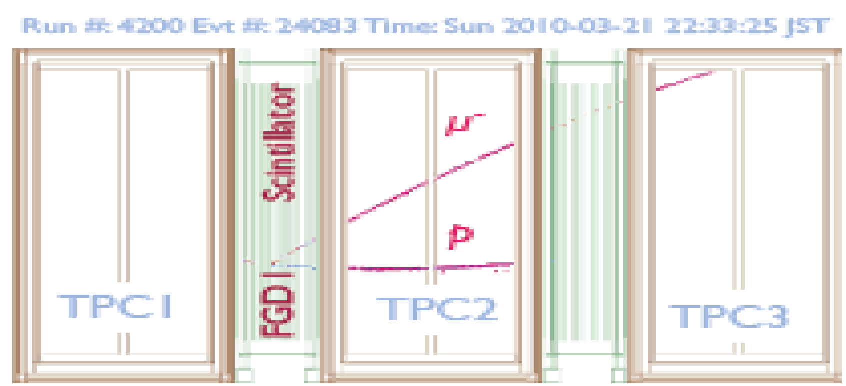
- T2K Near Detector:





- Suite of detectors that serves as off-axis near companion to Super-K for long-baseline studies
- Will measure cross-sections and other inputs to oscillation results
- Similar energy range to MiniBooNE
  - $\langle E_\nu \rangle \sim 850$ MeV

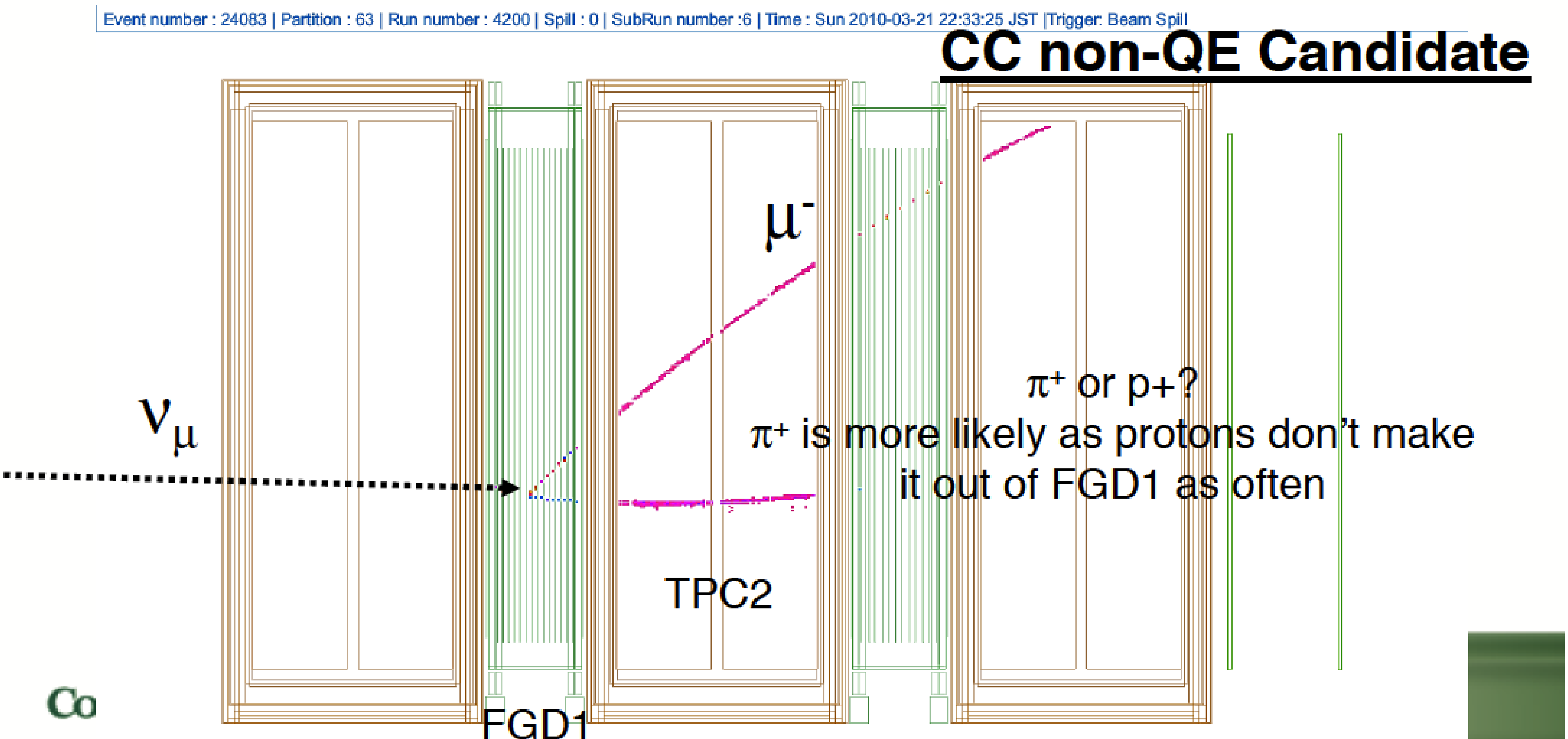
    (peak @ 600 MeV w/ long tail)
- B = 0.2 T Magnetic field



T2K Near Detector (ND280)

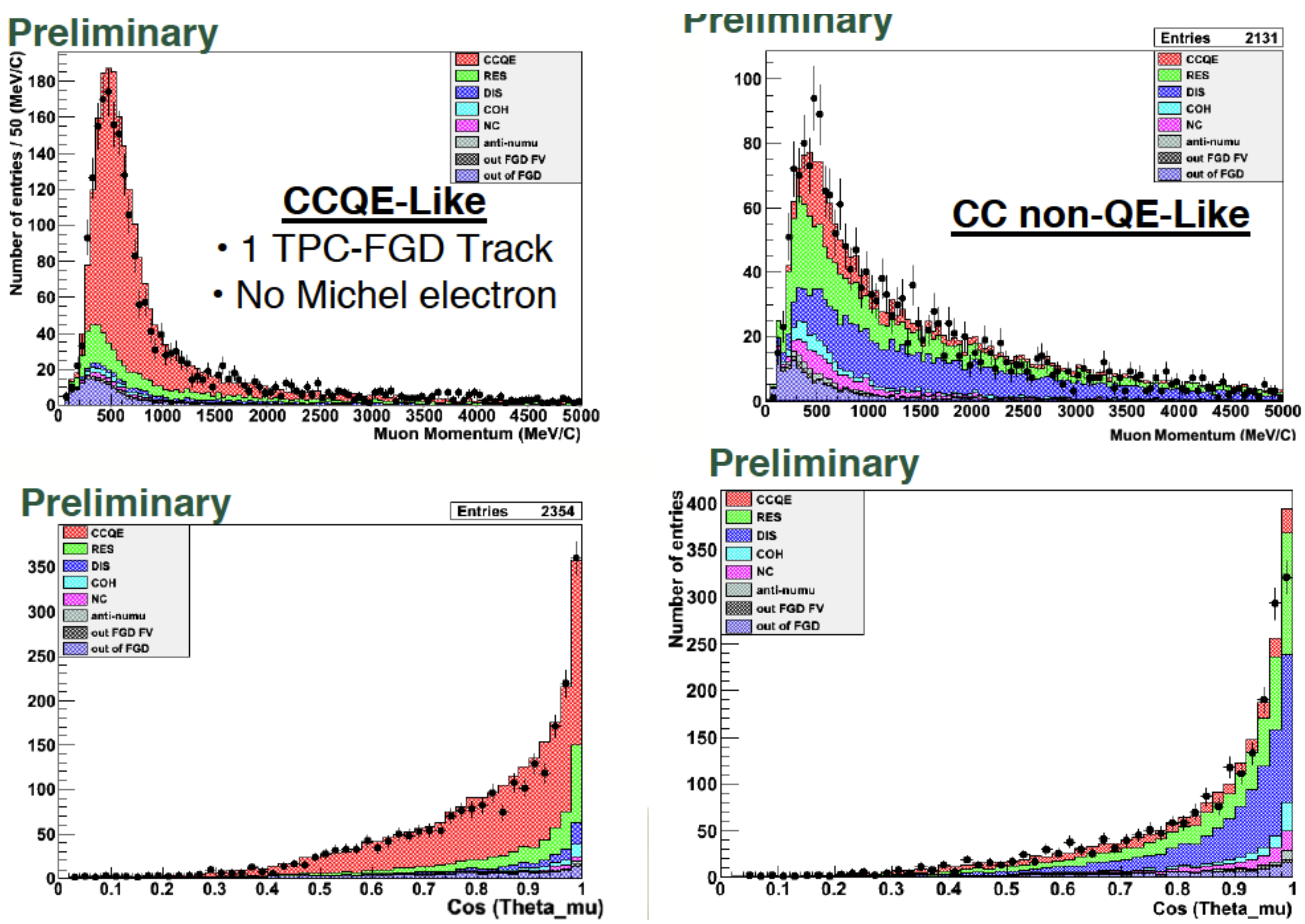
- CCQE selection
  - No second track in TPC2
  - No Michel electron in FGD1
- CC non-QE selection
  - Any extra tracks in TPC2
  - Any Michel electrons in FGD1

D. Ruterbories, NuInt 2012



T2K Near Detector (ND280)

D. Ruterbories, NuInt 2012



These samples are currently used to constrain far detector rates for oscillation measurements. The constraint uses fits to various cross-section and flux parameters.

T2K Near Detector (ND280)

D. Ruterbories, NuInt 2012

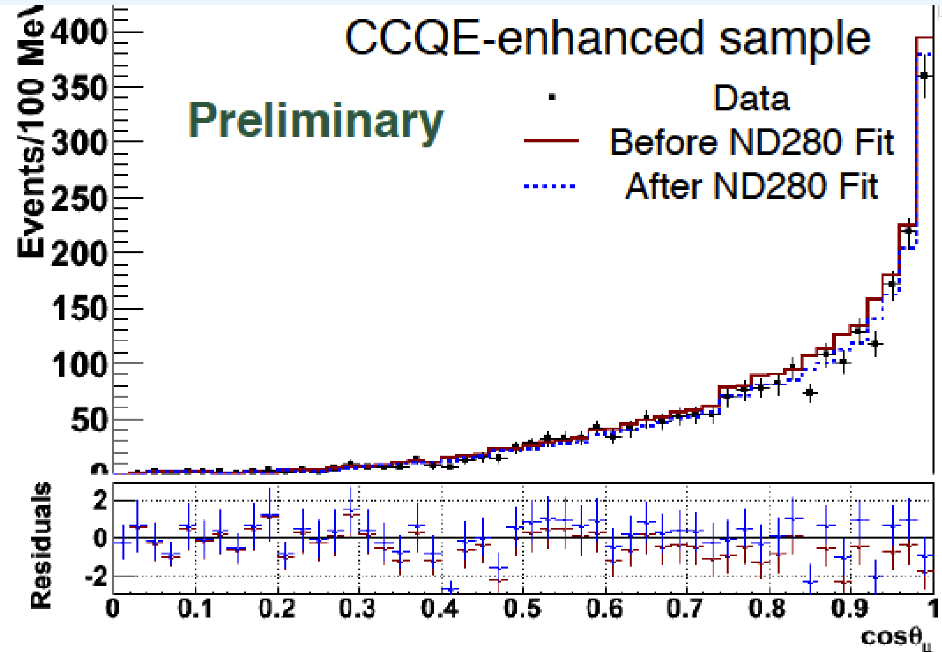
Fitter Results

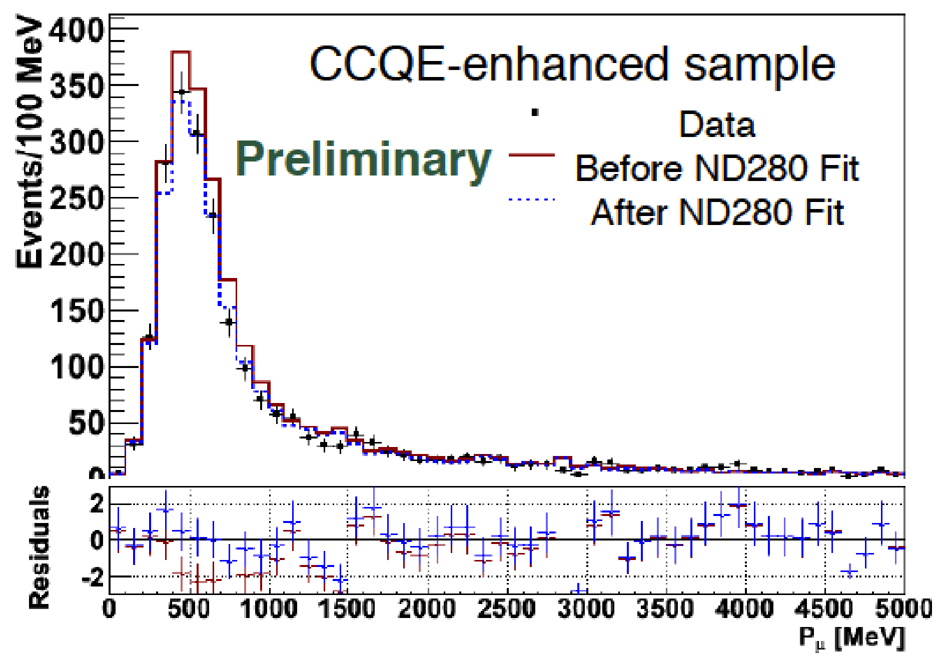
	Prior Value and Uncertainty	Fitted Value and Uncertainty
M_A^{QE} (GeV)	1.21 ± 0.45	1.19 ± 0.19
CCQE Norm. 0-1.5 GeV	1.000 ± 0.110	0.941 ± 0.087
CCQE Norm. 1.5-3.5 GeV	1.00 ± 0.30	0.92 ± 0.23
CCQE Norm. >3.5 GeV	1.00 ± 0.30	1.18 ± 0.25

Fitted value and uncertainty are propagated to the SK ν_e appearance fit

- Reduction in all uncertainties
  - 0.45 –> 0.19 for M_aQE
- Lower the normalization in two lower energy regions
  - 0->1.5 GeV ~6% reduction
  - 1.5->3.5 GeV ~8% reduction

Colorado State University





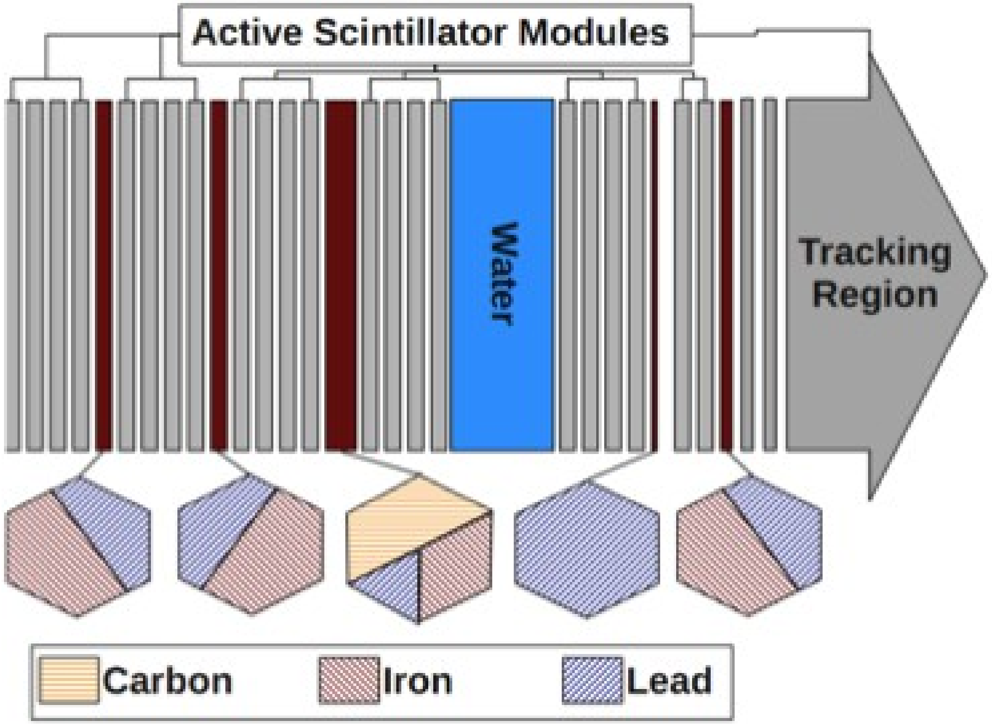
T2K Near Detector (ND280)

- T2K Future Plans:
  - Use this sample to directly extract M_A and cross-sections
  - Add a selection that includes two tracks (muon + proton)
  - Select CC pion samples to help understand pion backgrounds
  - Expect to take 25 times more POT
  - Eventual cross-section uncertainties are unclear
    - Flux uncertainties are likely to be among largest systematics:
      - Currently 14%, eventual goal is 5-10%

MINERνA

MINERvA

- MINERvA: A dedicated neutrino cross-section experiment



- Large volume of plastic scintillator (CH) interspersed with nuclear targets
- Sits in NuMI beamline at Fermilab directly upstream of MINOS near detector, which is used as a muon spectrometer

Nuclear targets made of carbon, iron, lead, water and helium will help unravel nuclear component of cross-sections

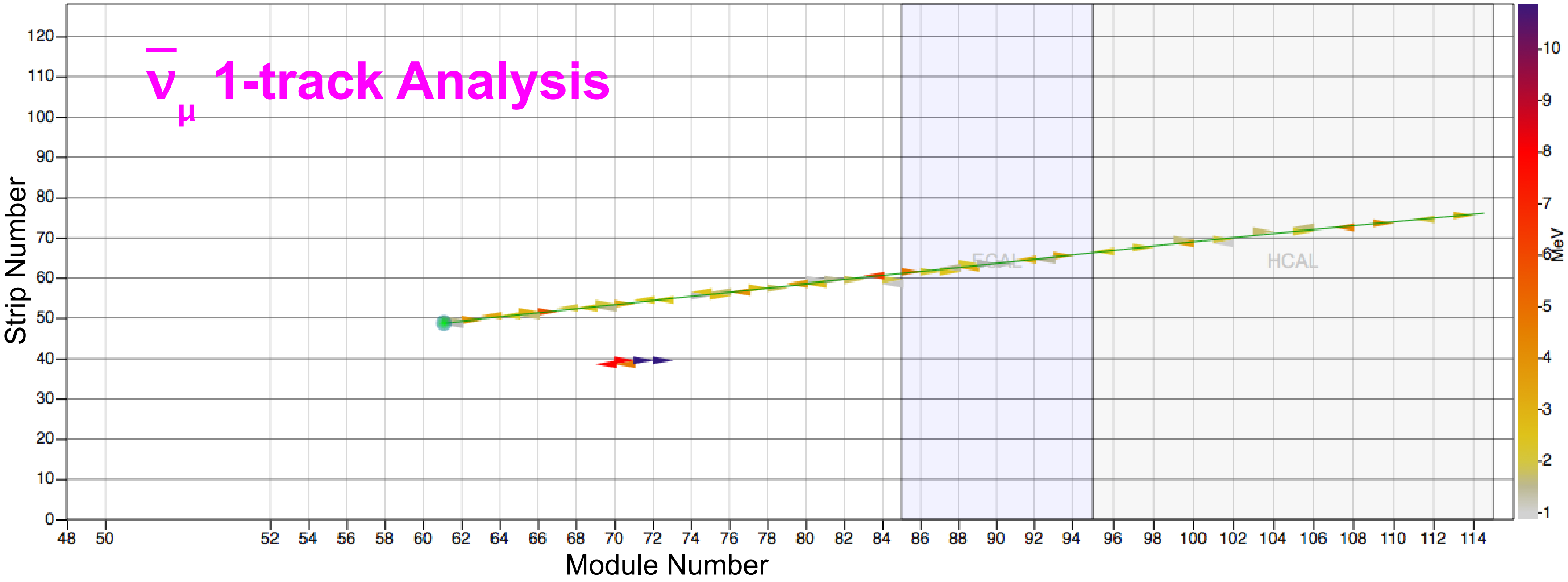
MINERνA

- Multiple reconstruction methods, beam configurations, target nuclei → Many dozens of potential analyses
- MINERνA have presented results from three QE analyses

Beam	Target	Muon Rec	Number of Tracks	Background Supression
LE anti-nu	Scintillator	MINERvA + MINOS	1	Calorimetric Recoil
LE nu	Scintillator	MINERvA + MINOS	1	Calorimetric Recoil
LE nu	Fe, Pb, C	All	2	Recoil + Kinematics

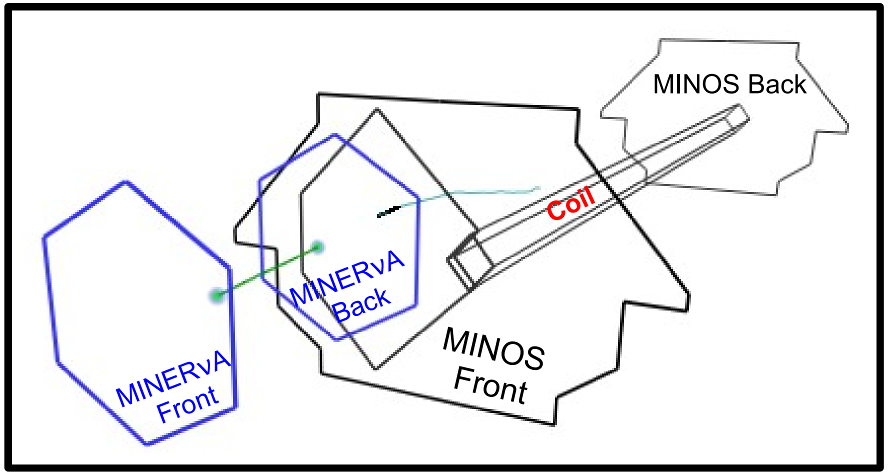
Neutrino mode analyses use ~1/4 of total Low Energy run POT
Anti-Nu mode analysis uses ~1/3

MINERvA



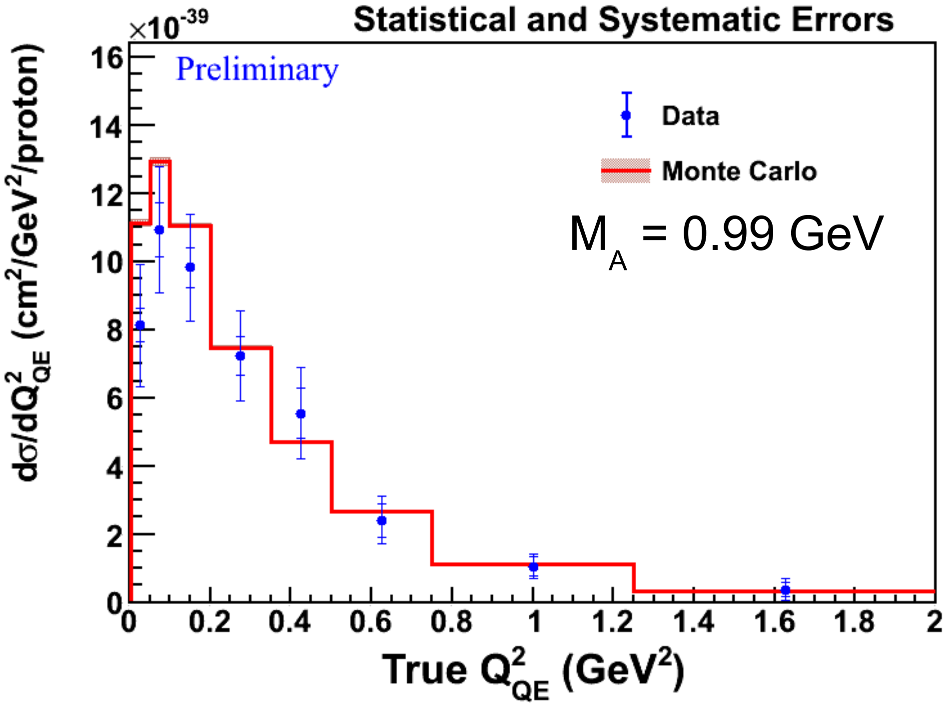
Start by reconstructing a track in MINERvA

Must be matched to a track in MINOS with positive charge, no additional tracks, no more than one large energy deposition, small amounts total recoil energy

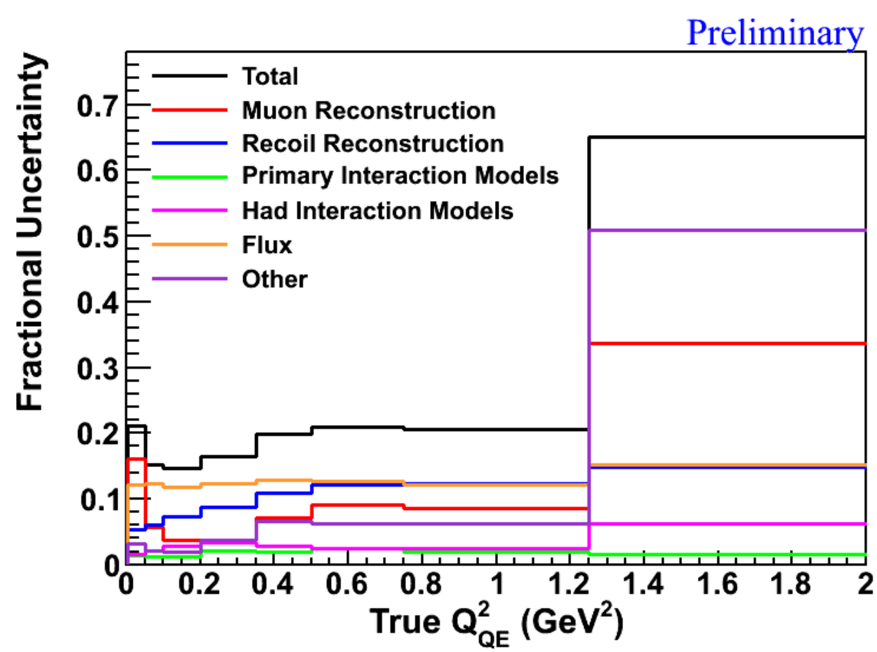


MINERνA

▶ Differential Cross-section Systematic Uncertainties:



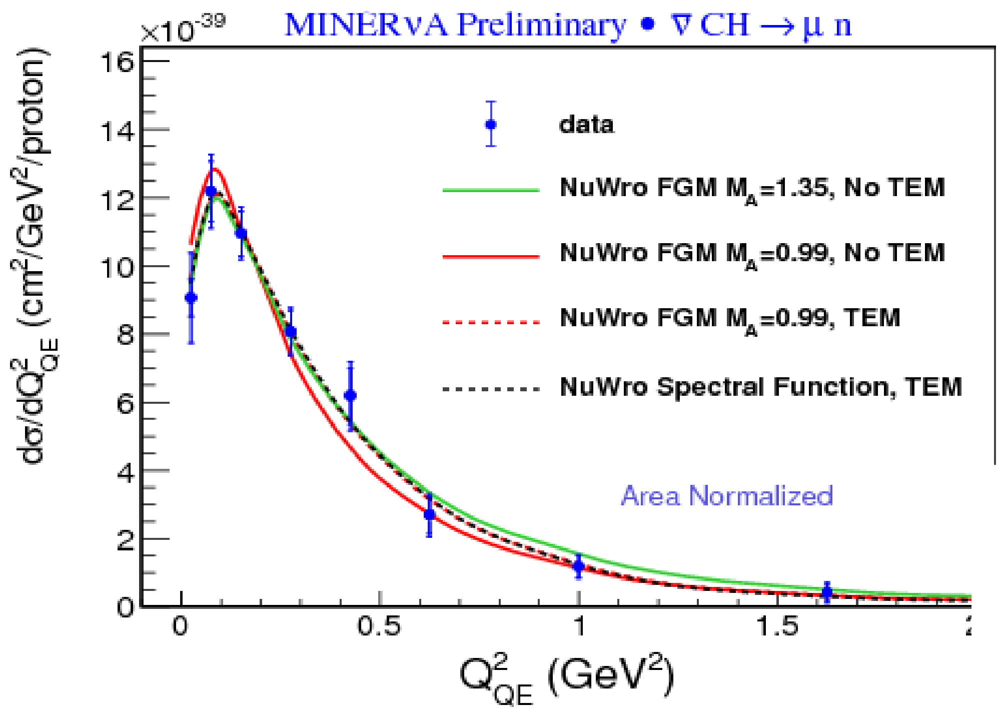
Total flux integrated (over 1.5-12 GeV) cross section uncertainties vary between 18 and 80% over Q^2



J. Osta, CIPAN 2012

Both statistical and systematic uncertainties are expected to be significantly lower in the future;

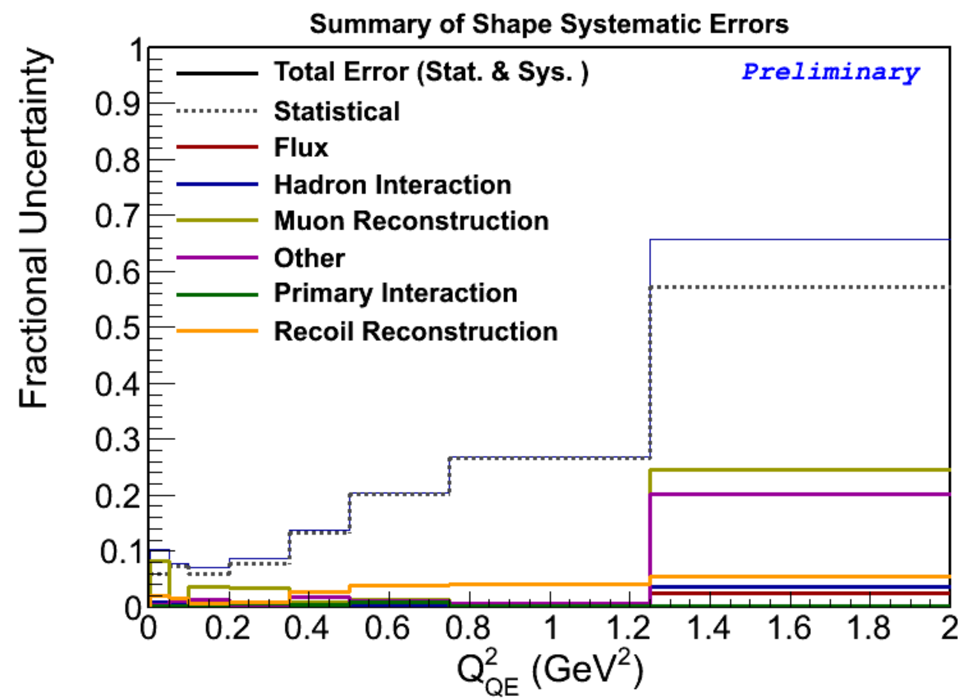
MINERνA



Comparison with Models

NuWro: Golal, Jusczak, Sobczyk
arXiv:1202.4197

TEM model: Bodek, Budd, Christy
Eur. Phys. J. C(2011) 71:1726



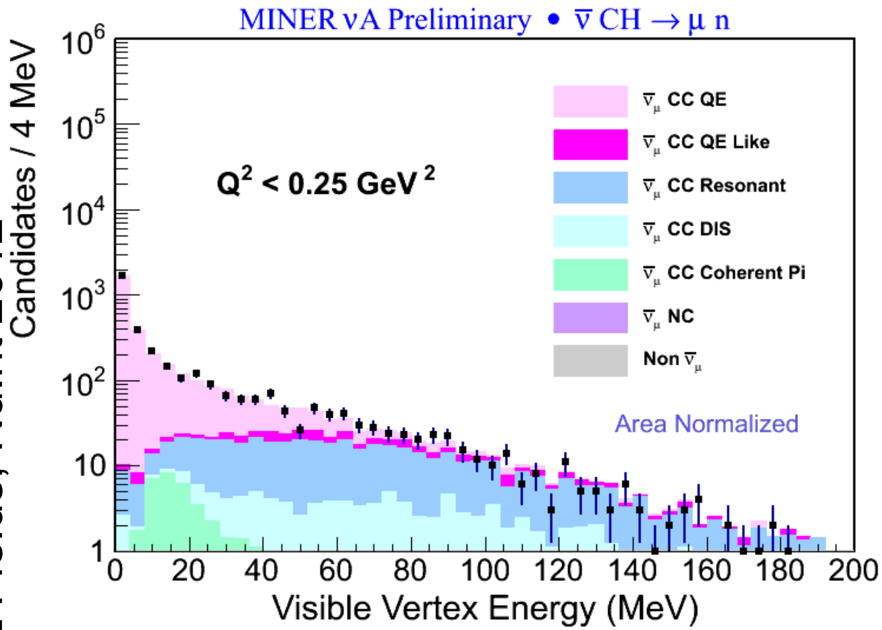
L Fields, NuInt 2012

Comparison of our results with various models. The models with "TEM" include a MEC-like modification to the cross-section

MINERνA

- One last tidbit from this analysis:

L Fields, NuInt 2012

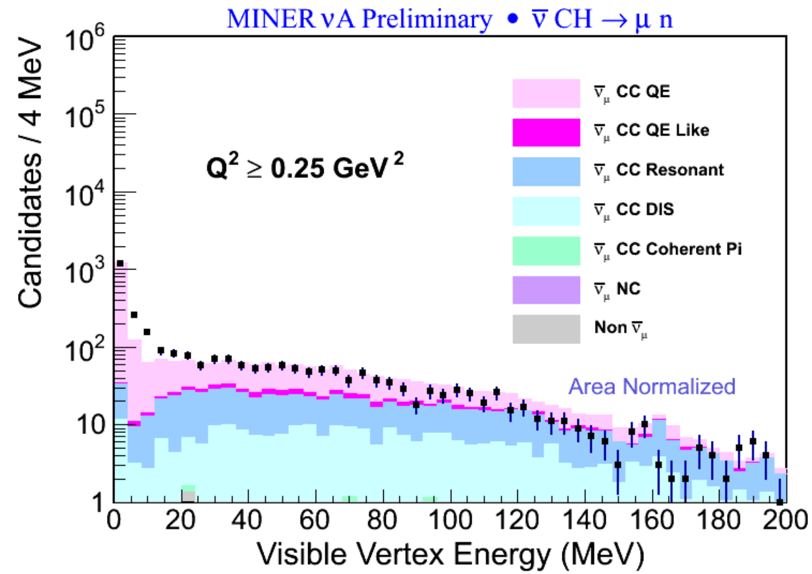


A first peak inside "the vertex box"

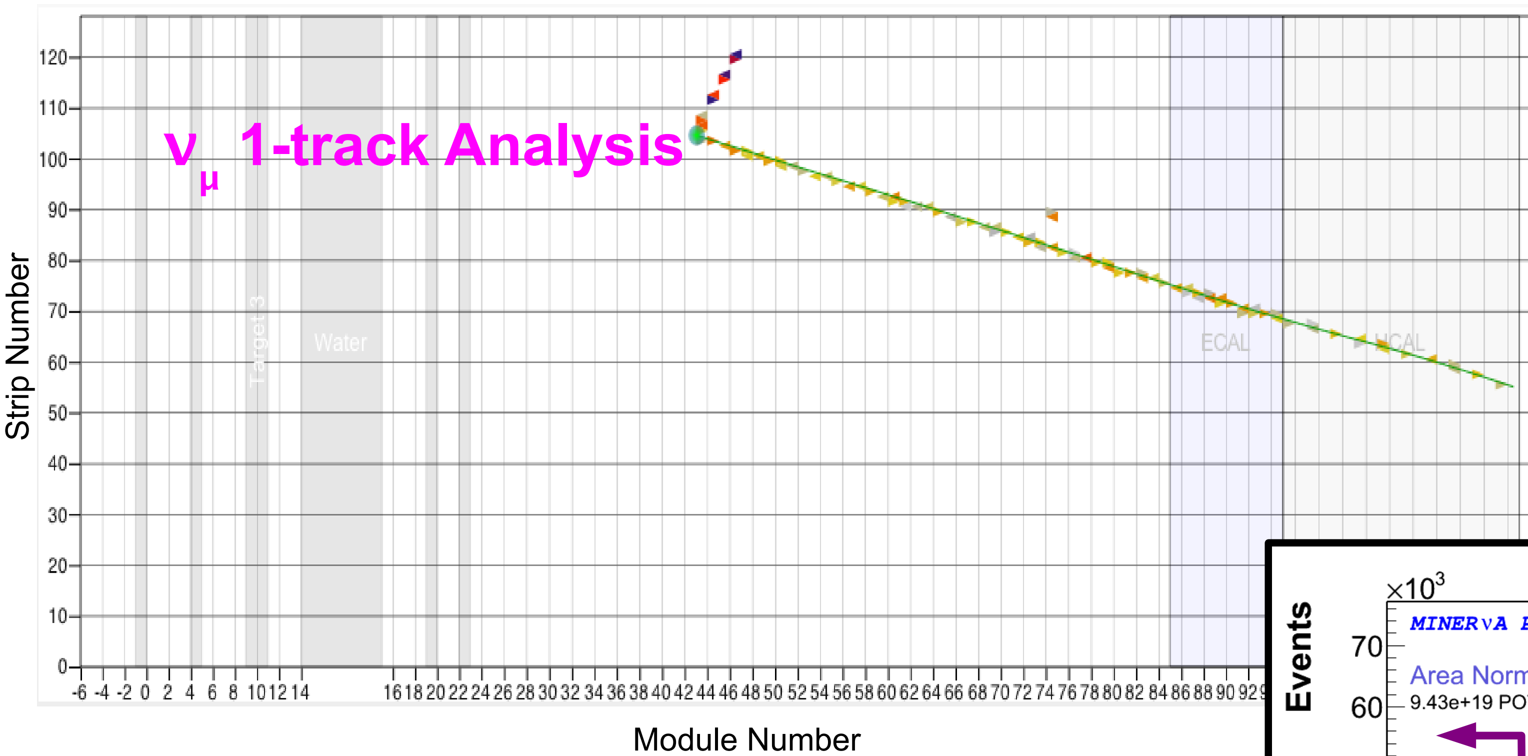
Measurements of **visible** energy in a 10mm radius around the vertex

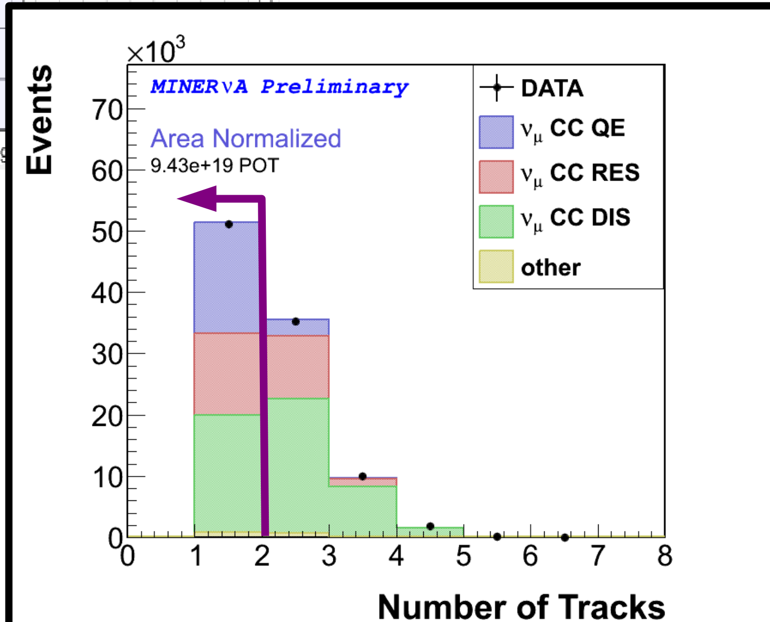
This energy is **excluded** from our standard recoil energy definition

Data agrees well with GENIE at low Q^2, but has excess in 0-20 GeV region at high Q^2



MINERνA



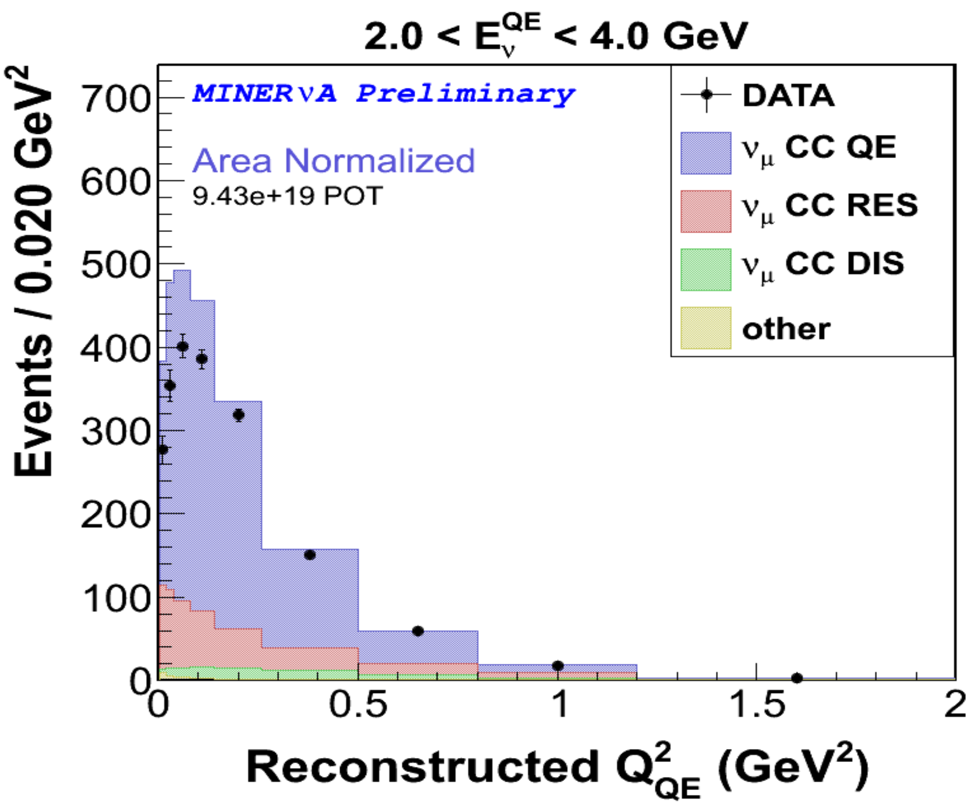


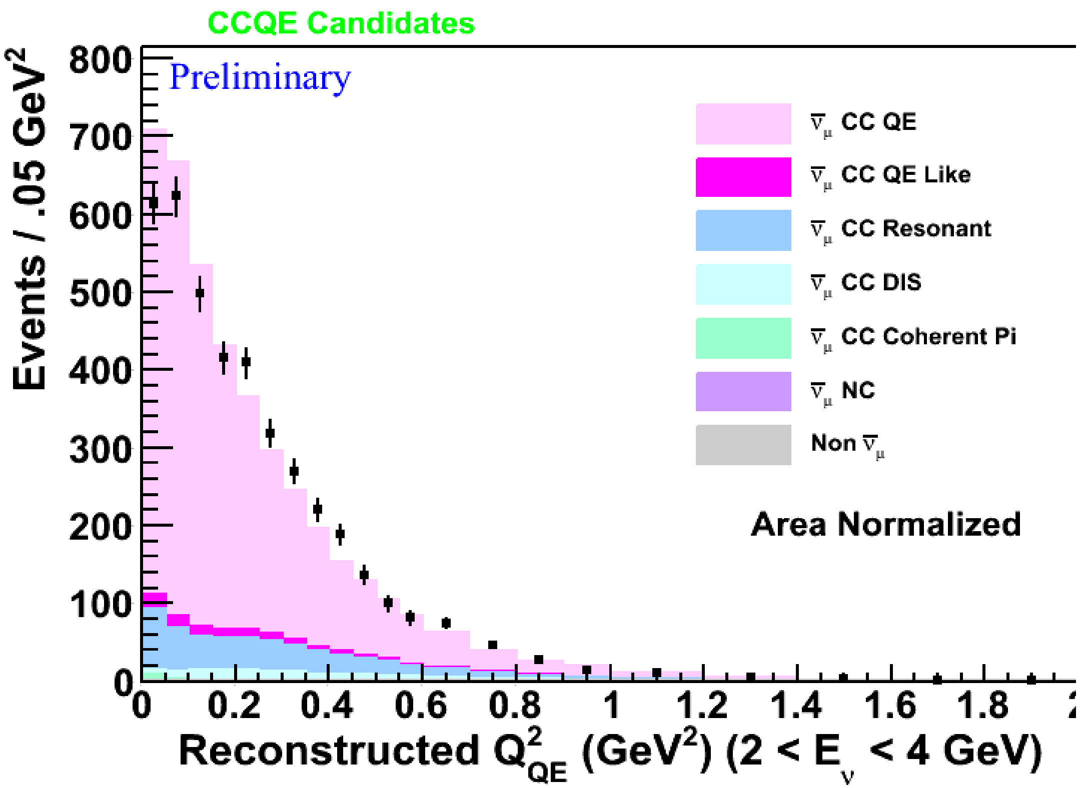
Sample selection very similar to anti-nu analysis

Requires MINOS-matched track, no extra tracks, less than two isolated blobs and little recoil energy (with vertex energy excluded)

MINERvA

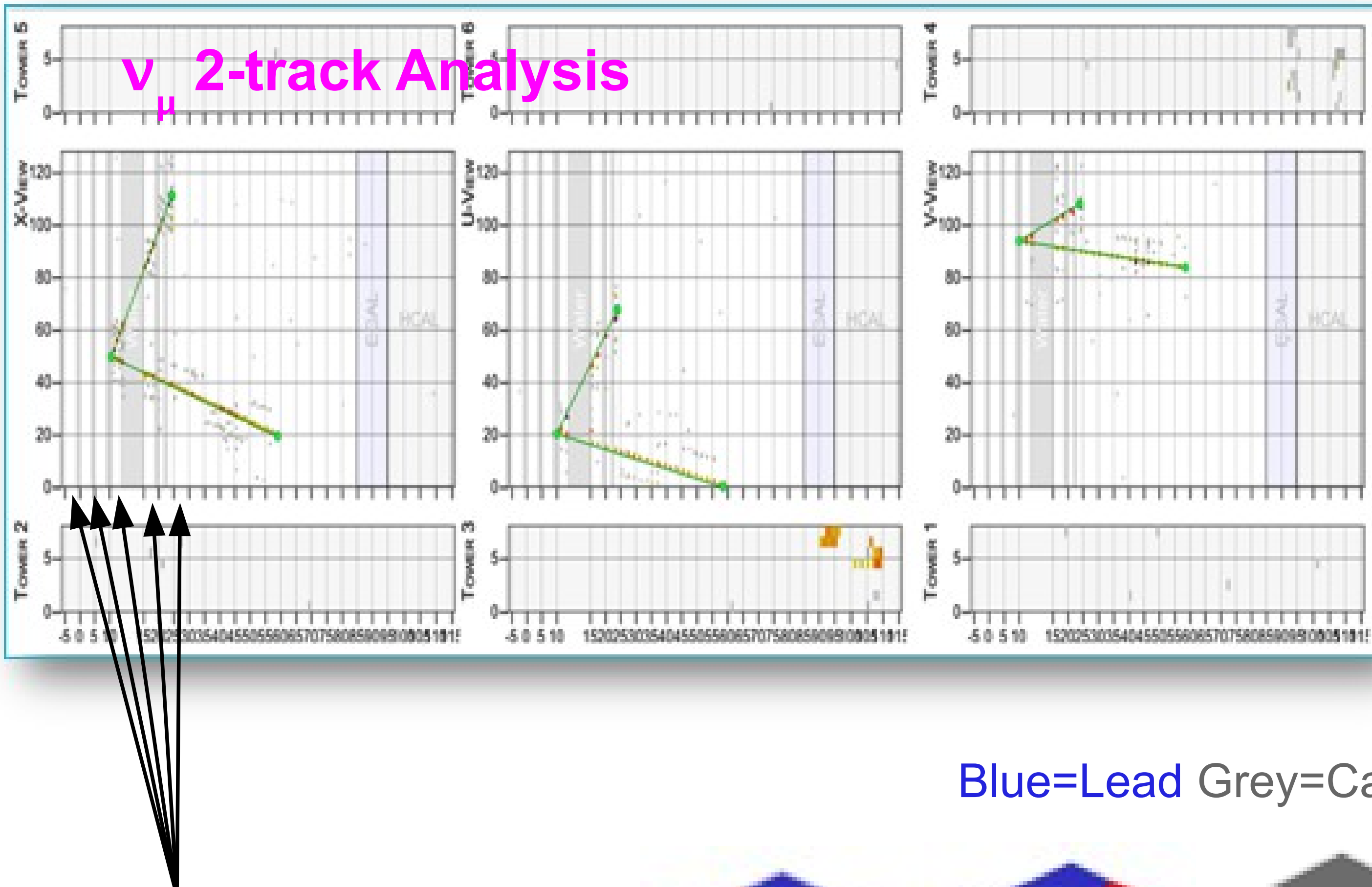
- Comparing the neutrino and anti-neutrino 1-track QE samples:





NuInt 2012

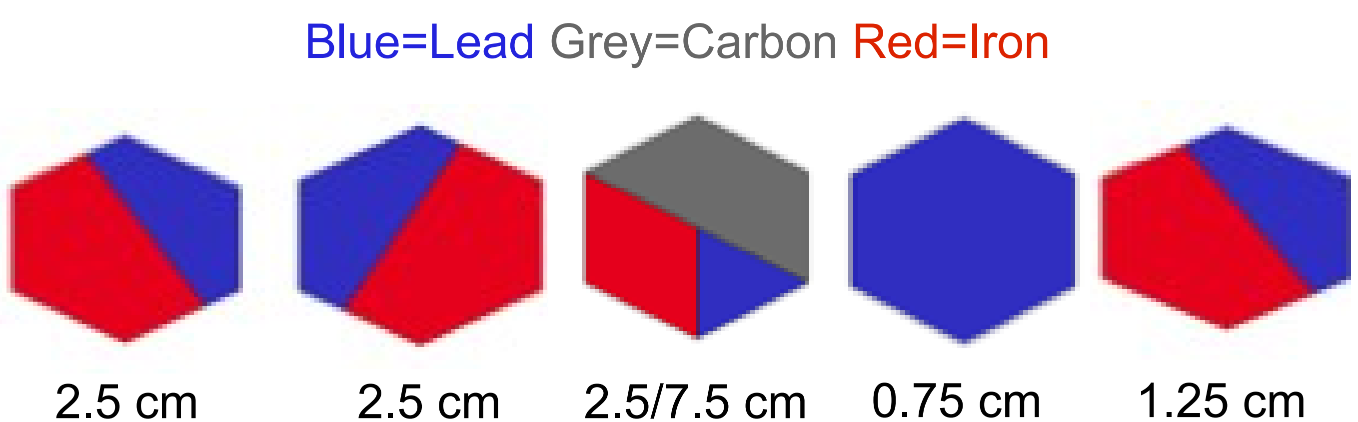
MINERνA



This is the first analysis to use non-MINOS matched muons

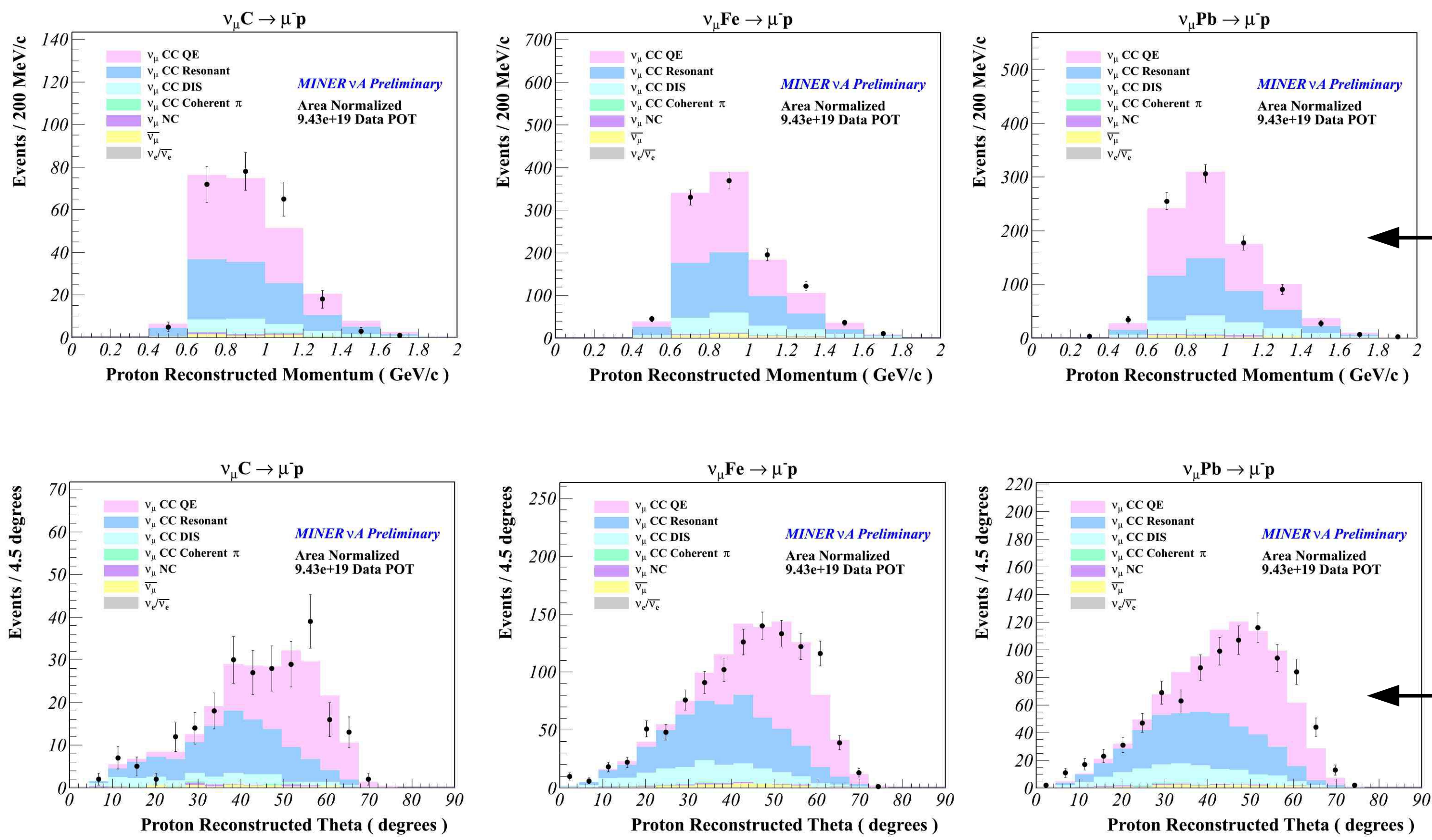
In most cases, only a lower limit on the muon momentum is known, and the muon charge is unknown

This analysis reconstructs 2-track QE candidates in targets 1,2,3,4 and 5
He & H20 targets were not yet filled for this data set.



MINERνA

- Proton distributions for candidates passing all cuts:



Proton momentum

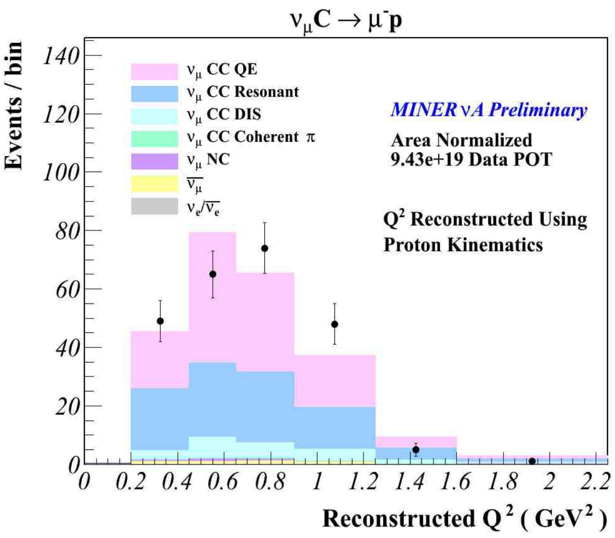
Proton angle (wrt beam)

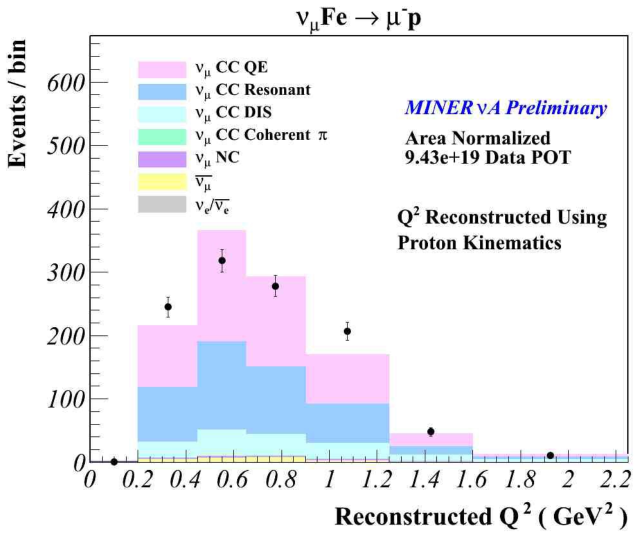
NuInt 2012

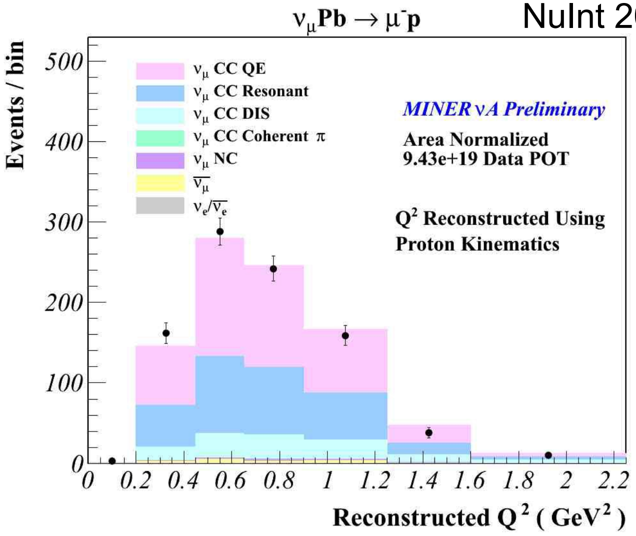
MINERνA

- Q^2 distributions for candidates passing all cuts:

NuInt 2012







Q^2 shapes match GENIE relatively well at this level of statistics.

Coming soon: background subtraction, target ratios.

MINERνA

- MINERνA Future Plans:
  - 1st paper in the next year:
    - $d\sigma/dQ^2$ in the 1-track analyses, with emphasis on shape
  - Initial analyses using 2-track reconstruction and candidates in nuclear targets will follow soon
  - When flux uncertainties are reduced:
    - Cross-sections versus energy, double differentials
    - Goal is uncertainties of 5-10% in focusing peak (~2-5 GeV)
      - NOvA era running will enable higher energy measurements

ArgoNeuT

ArgoNeuT (Argon Neutrino Test)

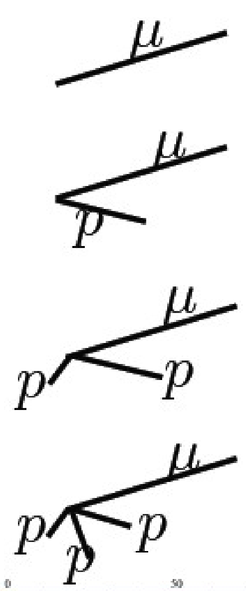
- ArgoNeuT:
  - 170 Liter Liquid Argon TPC in NuMI beamline at Fermilab
  - First LAr detector to sit in a low-energy neutrino beam
  - Important step in development of kiloton scale LAr detectors

- Pixel size of 4 mm x 0.3 mm
- Very low detection thresholds (21 MeV KE for protons)

Bubble-chamber precision → Excellent probe of nuclear effects near vertex

ArgoNeuT (Argon Neutrino Test)

- 1μ+Np topologies:

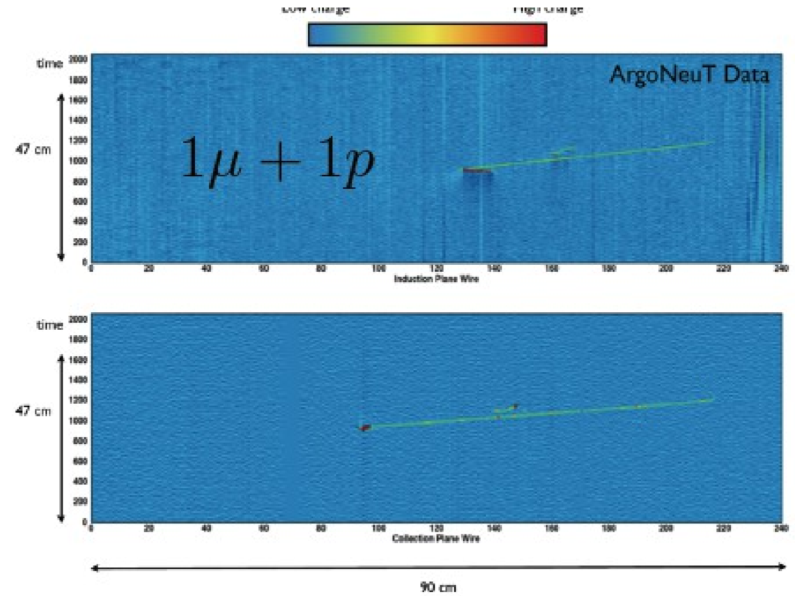


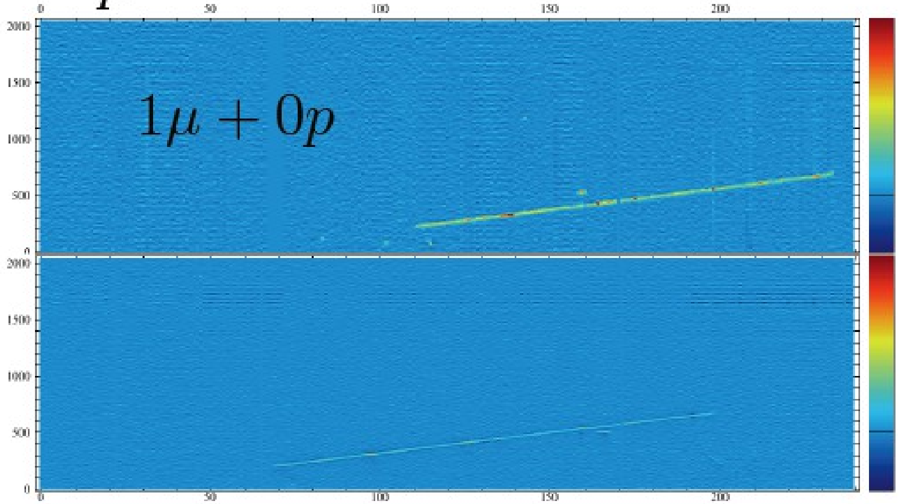
$1\mu + 0p$

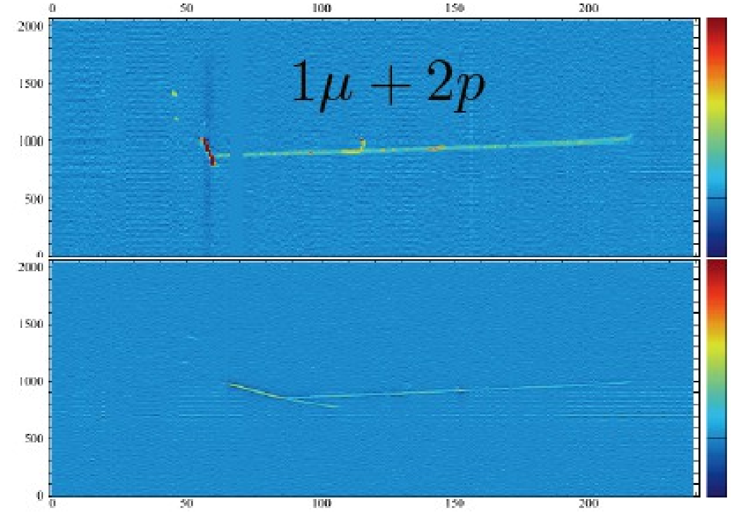
$1\mu + 1p$

$1\mu + 2p$

$1\mu + 3p$

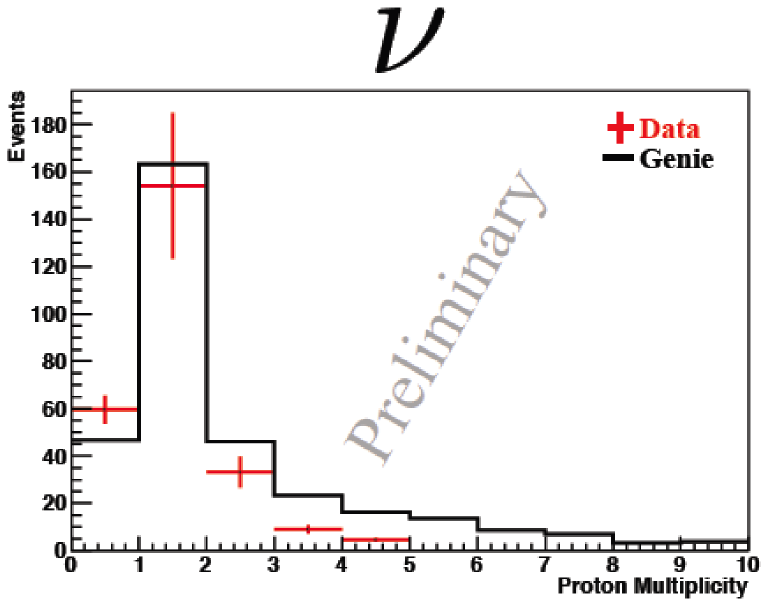


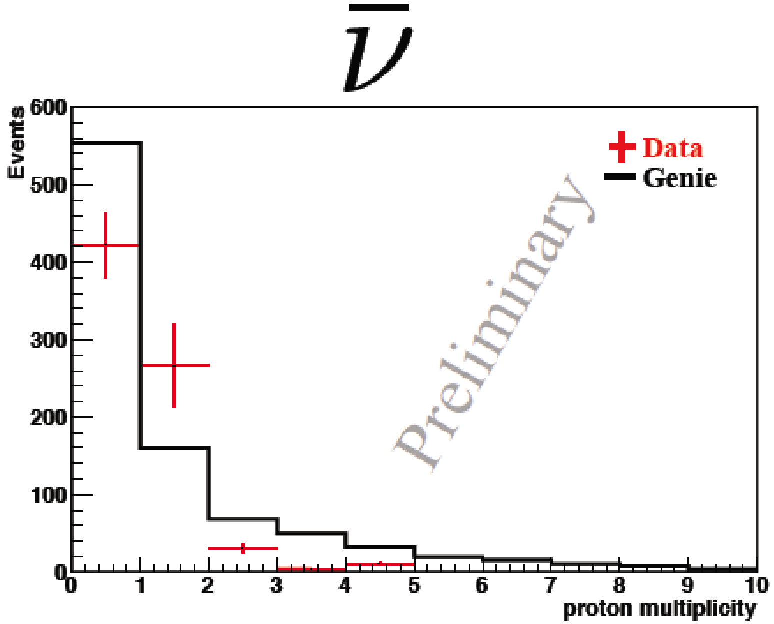




ArgoNeuT (Argon Neutrino Test)

- Proton multiplicities (in $\bar{\nu}$-mode data):





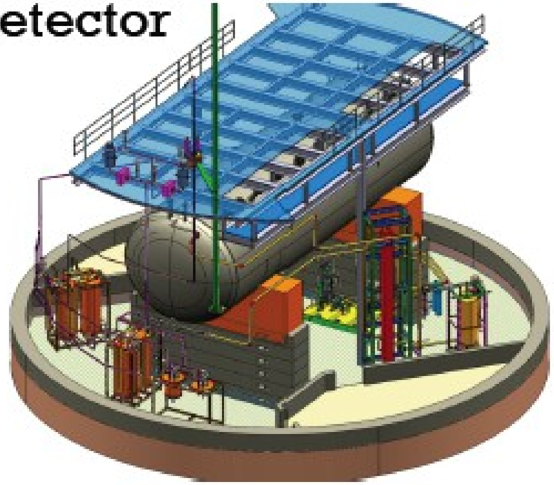
K Partyka, NuInt 2012

Results are preliminary – reconstrution currently geared towards lower multiplicities (<5 protons)

This is the first of lots of new information that Liquid Argon detectors will provide about vertex activity

MicroBooNE

- Longer-term prospects for Liquid Argon CCQE measurements:



- 60 Ton LAr TPC
- Located in Booster beam at FNAL
- Will also see off-axis NuMI beam

Lower event rates than MiniBoone, with likely similar flux uncertainties

But much improved ability to separate final states by multiplicity – will take an ArgoNeuT like approach to event classification

Expected event rate for BNB 6.6 x 10^{20} POT
60 ton fiducial volume

production mode	# events
CC QE ($\nu_\mu n \rightarrow \mu^- p$)	60,161

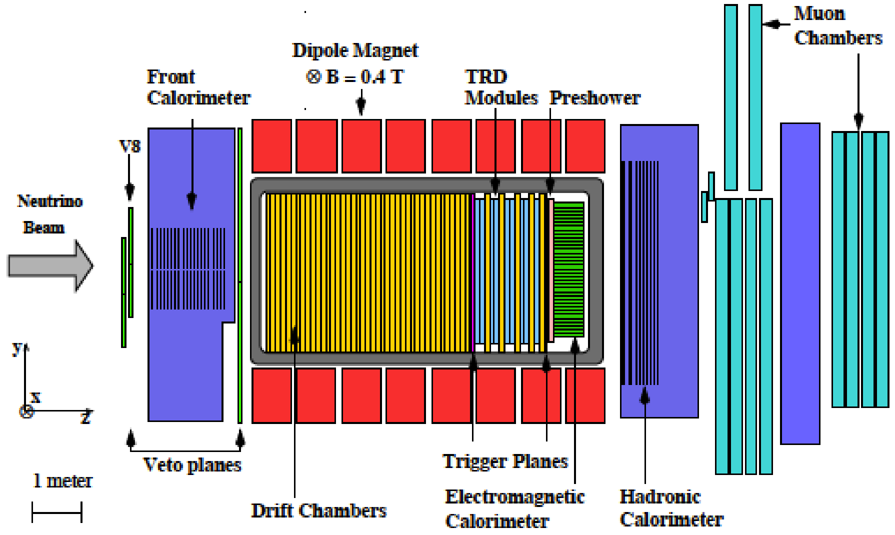
Also: 40,000 NuMI events

ICARUS (600 ton Lar detector at LNGS) is planned to move to CERN, and may also make ν-LAr cross-section measurements

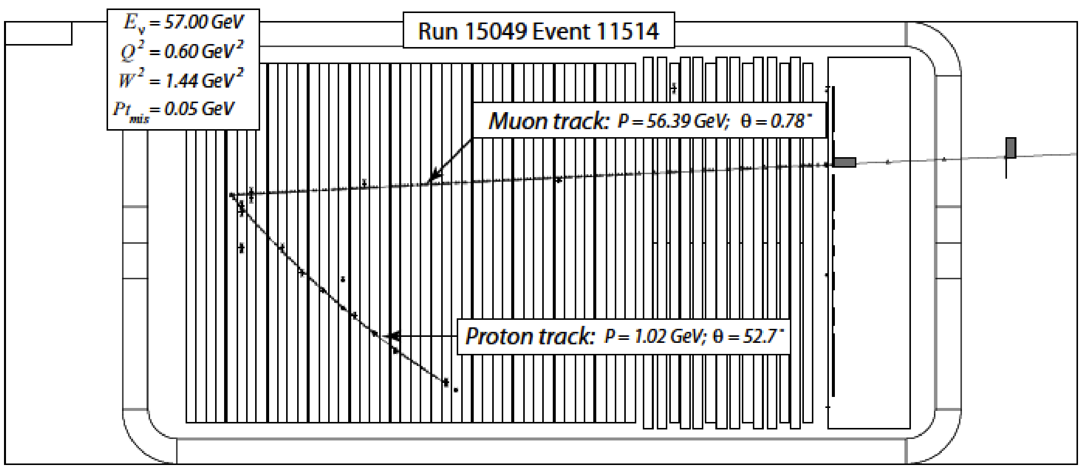
NOMAD

NOMAD

- NOMAD: An older, higher energy experiment



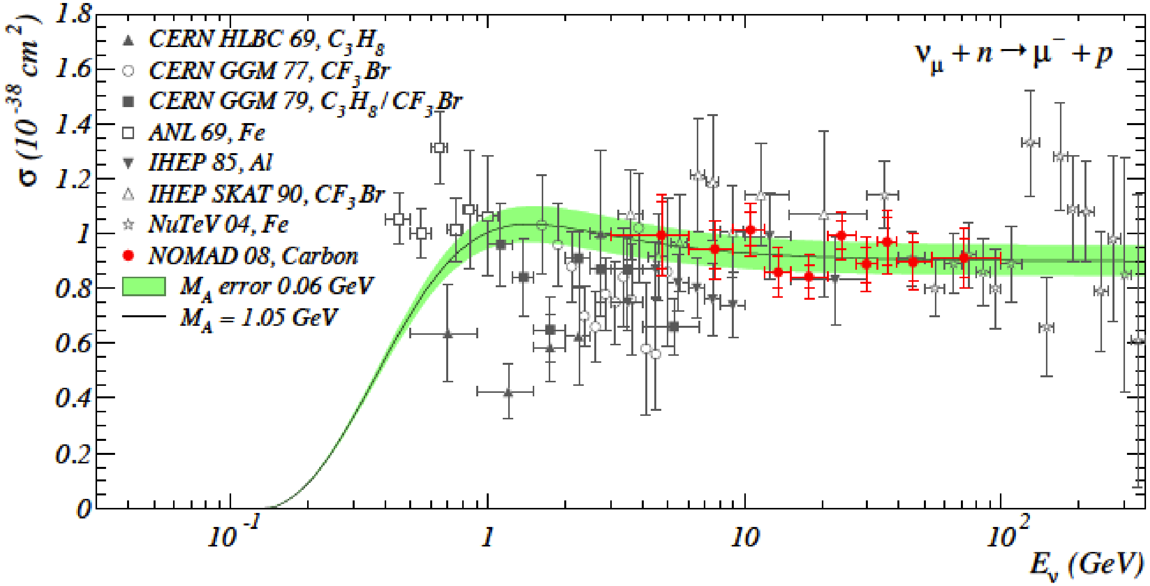
- 2.7 ton active target drift chambers, made primarily of carbon, combined with TRD's, electronic and hadronic calorimeters and muon chambers
- Wide band beam; measured CCQE from 3-100 GeV



Used two reconstructed samples – 1 and 2 tracks (explicitly excludes more than 2 tracks)

NOMAD

- NOMAD: An older, higher energy experiment

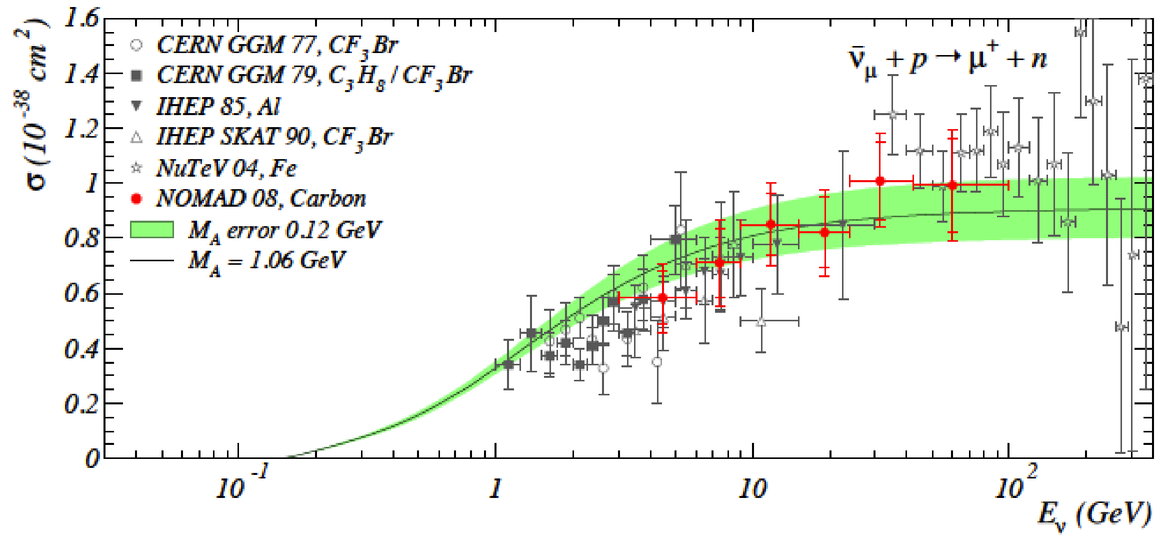


Neutrino

Uncertainties of 7-15% over 3-100 GeV

Anti-Neutrino

Uncertainties of 13-17% over 3-100 GeV



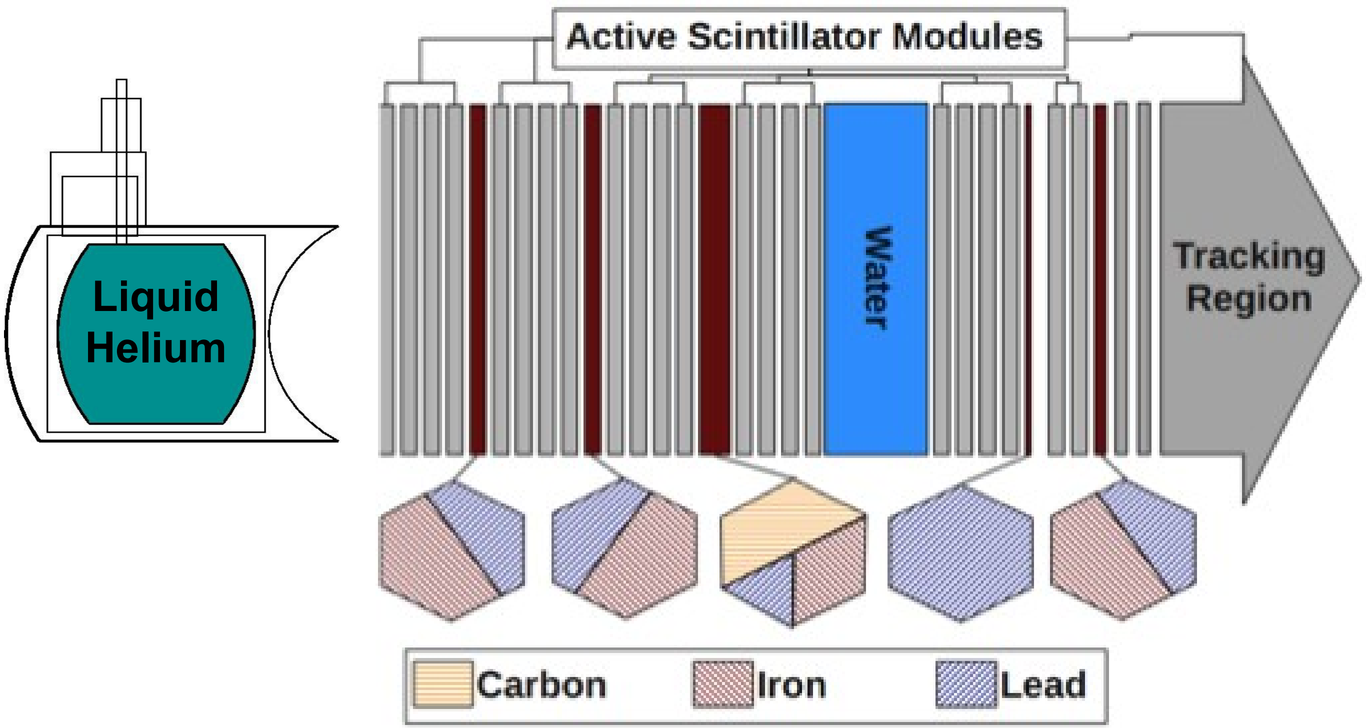
Conclusion/Outlook

- The best current measurements of cross-sections are from MiniBooNE and NOMAD
  - There is tension between the experiments that may be explained by QE-like processes
  - Uncertainties are large in some regions, and there is a small gap between their energy ranges
- Several current (MINERνA, T2K, ArgoNeuT) and future (MicroBooNE, NOνA, ICARUS) experiments hope to:
  - Fill in gap region
  - Reduce uncertainties to 5-10%
  - Understand origin of tension

Thank You!

Backup Slides

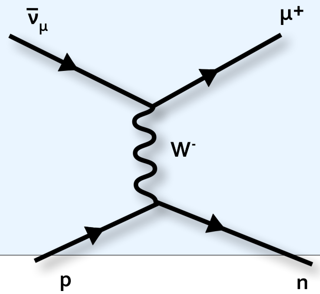
MINERνA



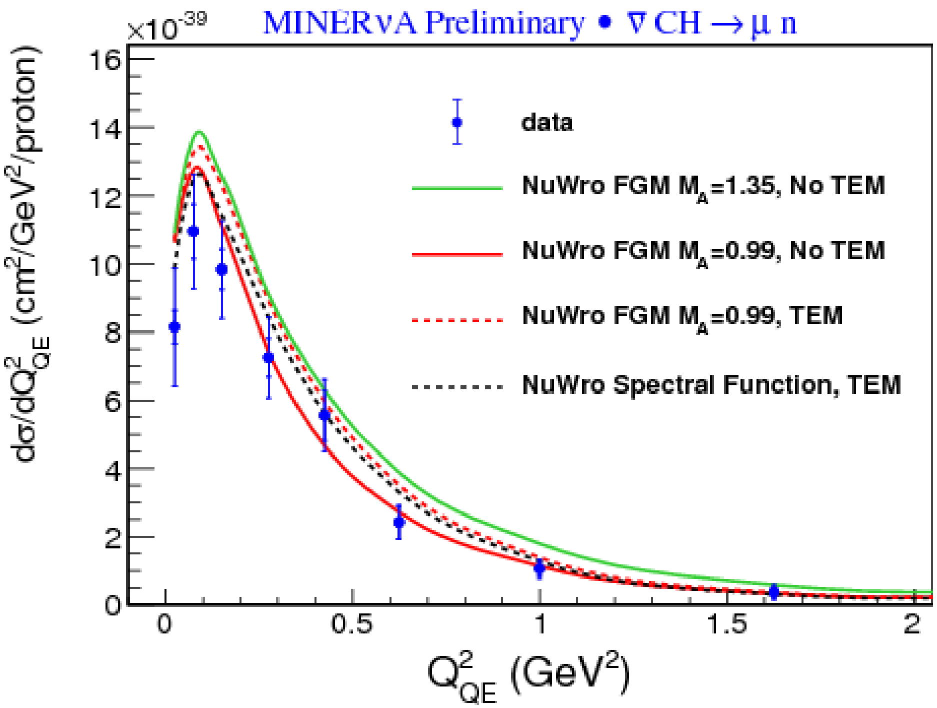
Addition of nuclear targets adds possibility of CCQE measurements in six different materials

Estimated event rates for complete LE neutrino run

Material	Mass (kg)	QE Events (Before Acceptance)
Plastic Scintillator	5470	200,222
Fe	951	40838
Pb	971	48114
C	163	6340



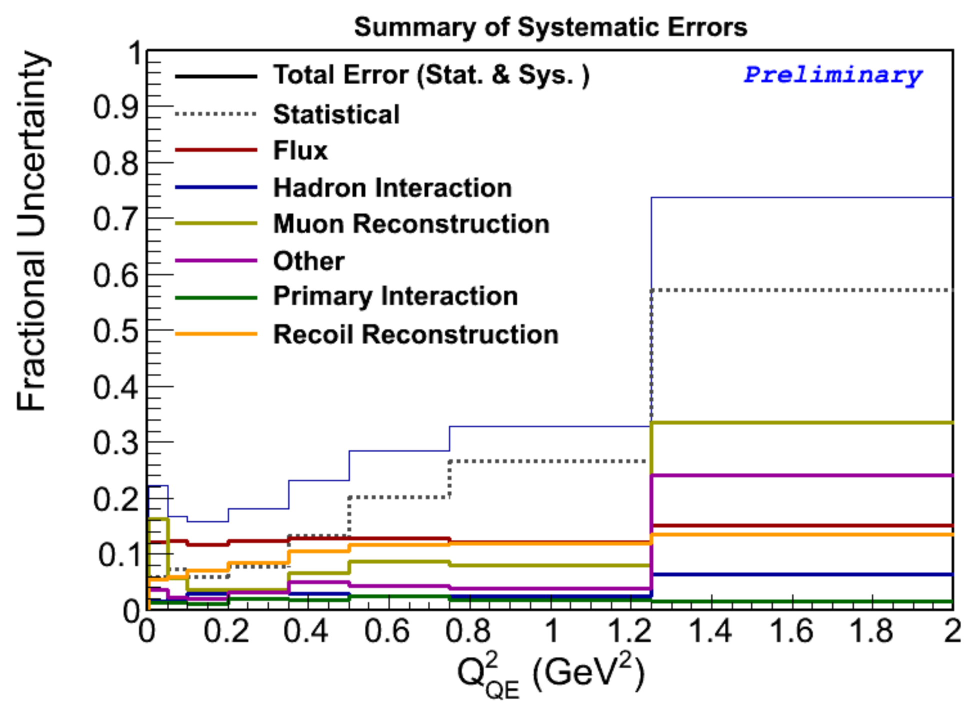
MINERνA



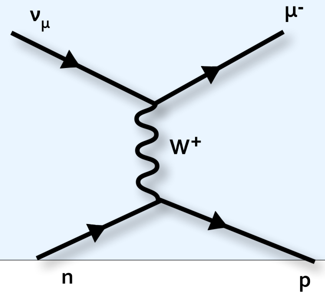
Comparison with Models

NuWro: Golal, Jusczak, Sobczyk
arXiv:1202.4197

MEC model: Bodek, Budd, Christy
Eur. Phys. J. C(2011) 71:1726

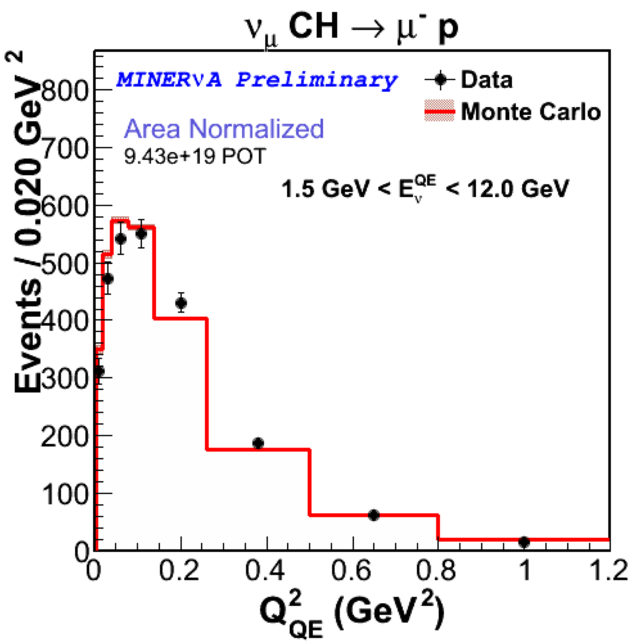


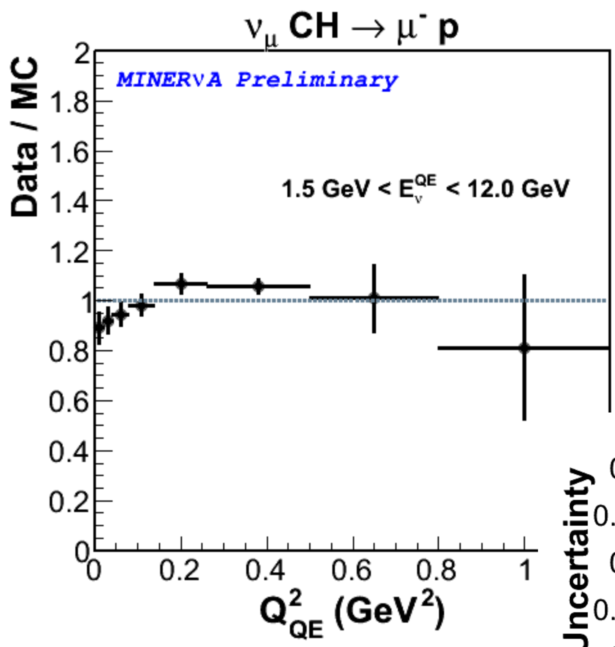
Comparison of our results with various models. The models with "TEM" include a MEC-like modification to the cross-section



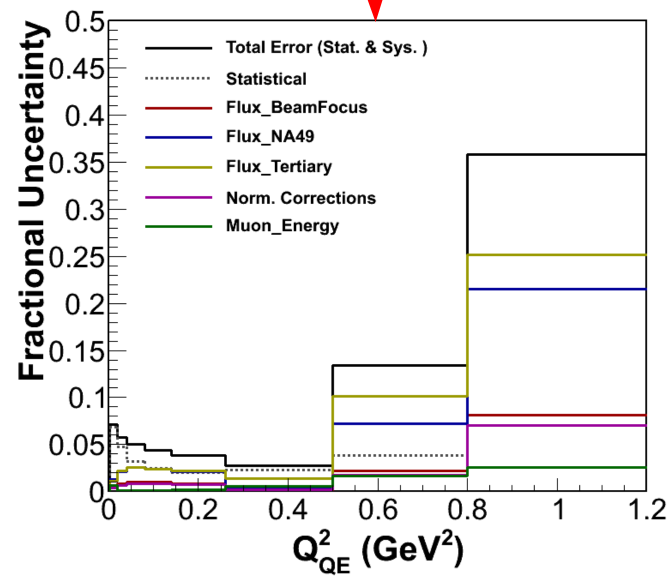
MINERνA

Where the analysis stands now:





Error bars include partial systematic uncertainties, summarized here



Shape appears consistent with Genie (M_A = 0.99, RFGM) currently.

Improved uncertainties and full efficiency corrected cross-sections coming soon!