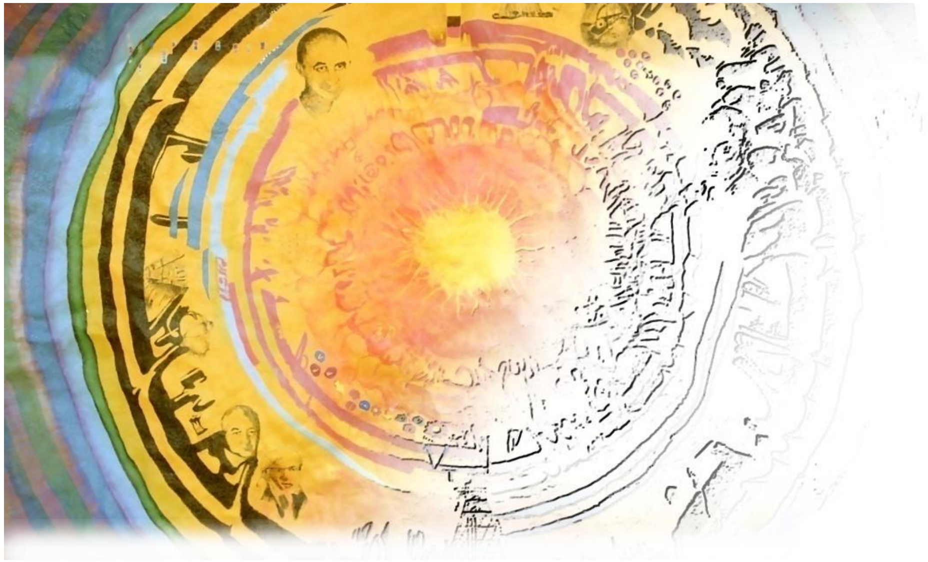
Preliminary Results for CCQE Scattering with the MINOS Near Detector

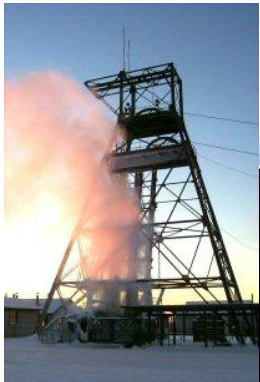


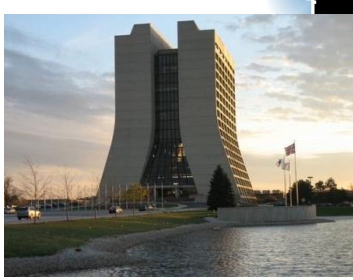
Mark Dorman, UCL

Overview

- Introduction to the MINOS experiment and NuMI beam
- ν_μ-CC QE scattering theory and the axial-vector mass
- Event selection and data analysis methodology
- Axial-vector mass results and systematic errors
- Summary and outlook for the analysis

The MINOS Experiment



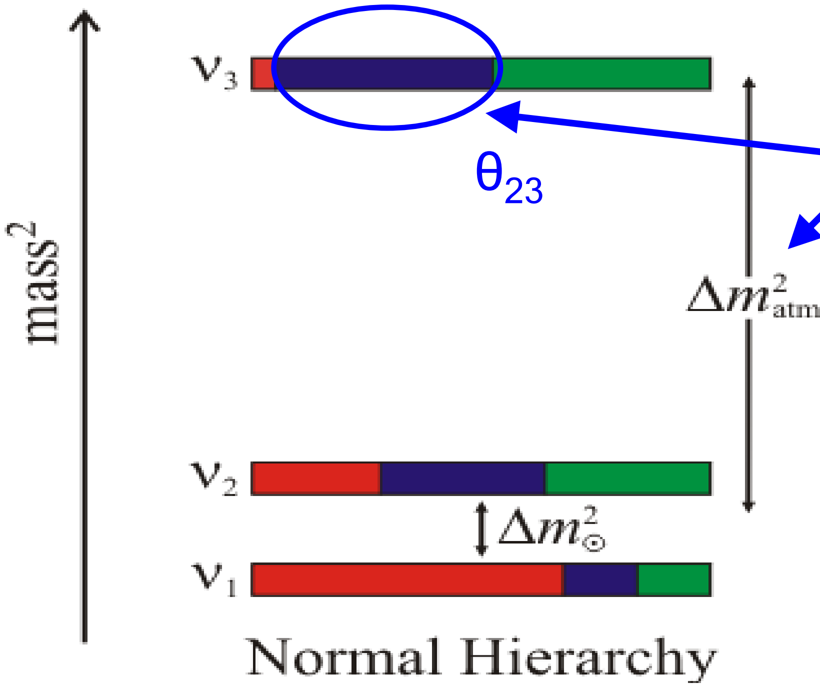


- The Main Injector Neutrino Oscillation Search.
- Neutrino beam is produced using the Neutrinos at the Main Injector (NuMI) facility at FNAL.
- The beam passes through the Near Detector (ND) on-site at FNAL and the Far Detector (FD), 735km away in the Soudan Underground Mine.
- Interesting things happen between the two!

The MINOS Collaboration

The collaboration comprises ~150 physicists from ~30 institutions.

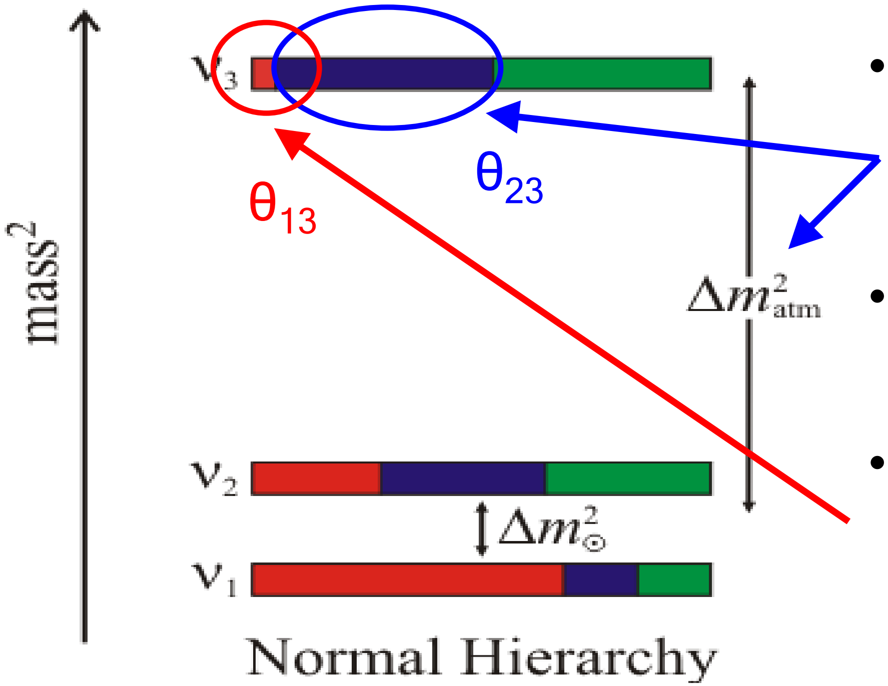
MINOS Physics Goals



(electron, muon, tau flavours)

- Make precision measurements of the oscillation parameters Δm^2 and $\sin^2(2\theta)$ [$\nu_\mu \rightarrow \nu_\tau$].
- Rule out exotic models such as neutrino de-coherence or decay.

MINOS Physics Goals



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- Make precision measurements of the oscillation parameters Δm^2 and $\sin^2(2\theta)$ [$\nu_\mu \rightarrow \nu_\tau$].
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- Search for sub-dominant oscillations at Δm^2_{atm} [$\nu_\mu \rightarrow \nu_e$].

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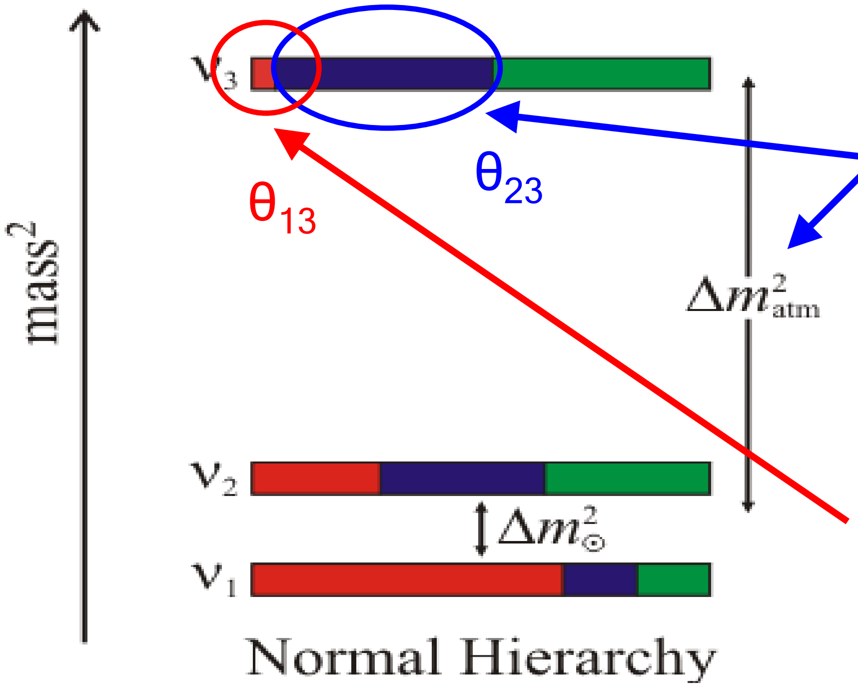
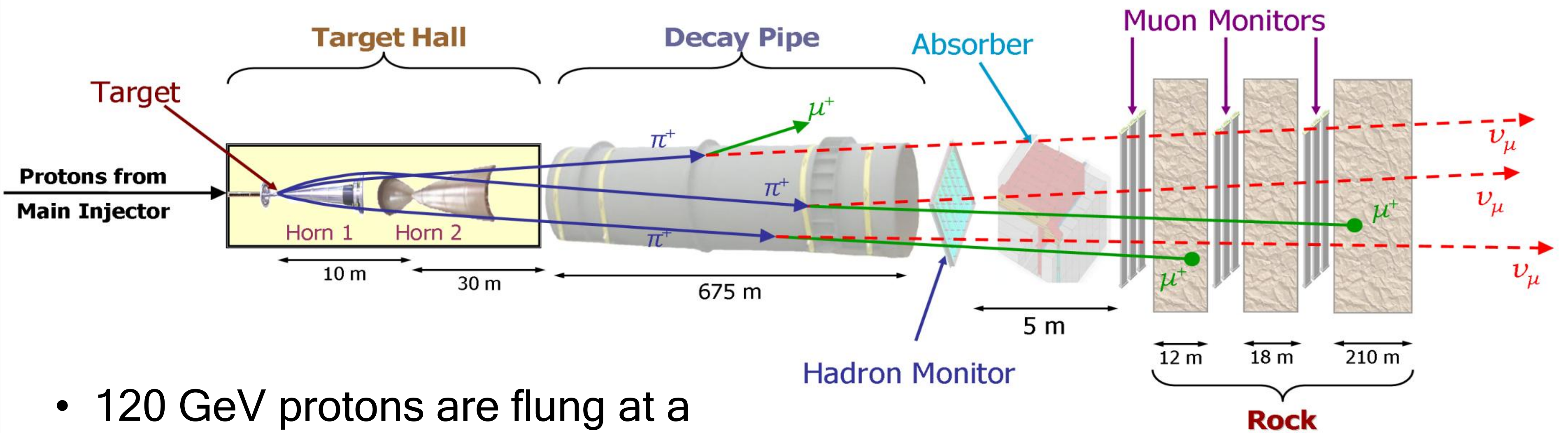


(electron, muon, tau flavours)

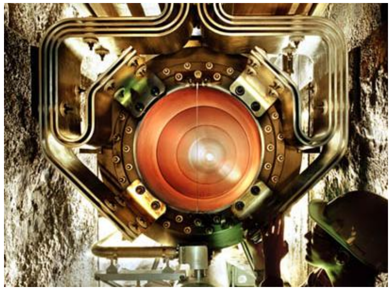
- ND-only measurements of neutrino interaction physics.

- Make precision measurements of the oscillation parameters Δm^2 and sin^2(2θ) [$\nu_\mu \rightarrow \nu_\tau$].
- Rule out exotic models such as neutrino de-coherence or decay.
- Search for sub-dominant oscillations at Δm$^2_{atm}$ [$\nu_\mu \rightarrow \nu_e$].
- Search for possible mixing to sterile neutrinos [$\nu_\mu \rightarrow \nu_s$].
- Investigate anti-neutrino oscillations (CPT test) [$\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau$].

The NuMI Beam



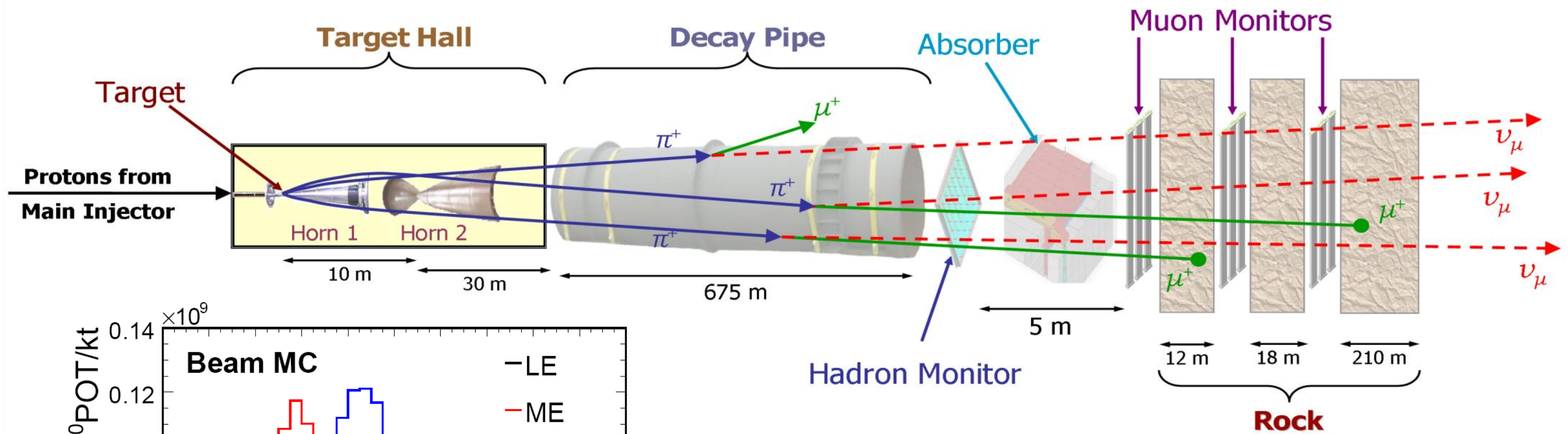
- 120 GeV protons are flung at a graphite target and the resultant spray of secondary hadrons are focused by magnetic "horns" and subsequently decay to neutrinos.

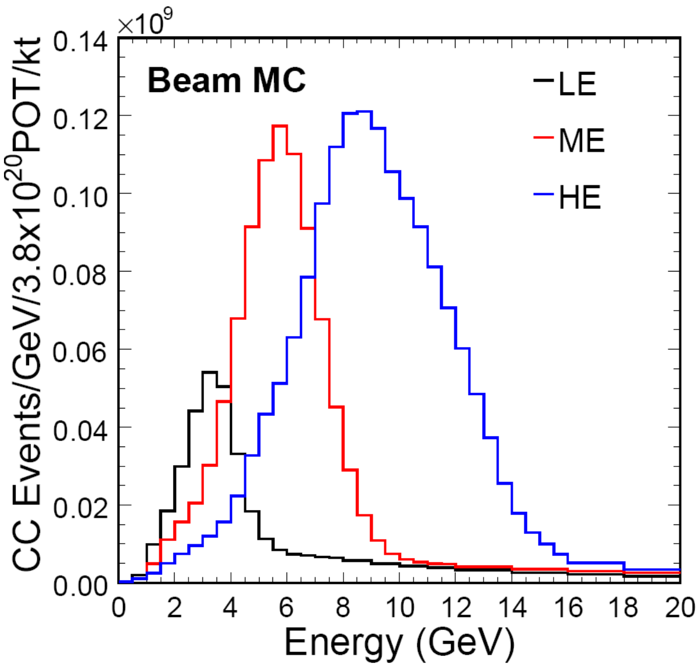


End view of horn.

- In the nominal low energy beam configuration the beam comprises $92.9\%\ \nu_\mu,\ 5.8\%\ \bar{\nu}_\mu,\ 1.3\%\ \nu_e + \bar{\nu}_e$

Variable Beam Energy

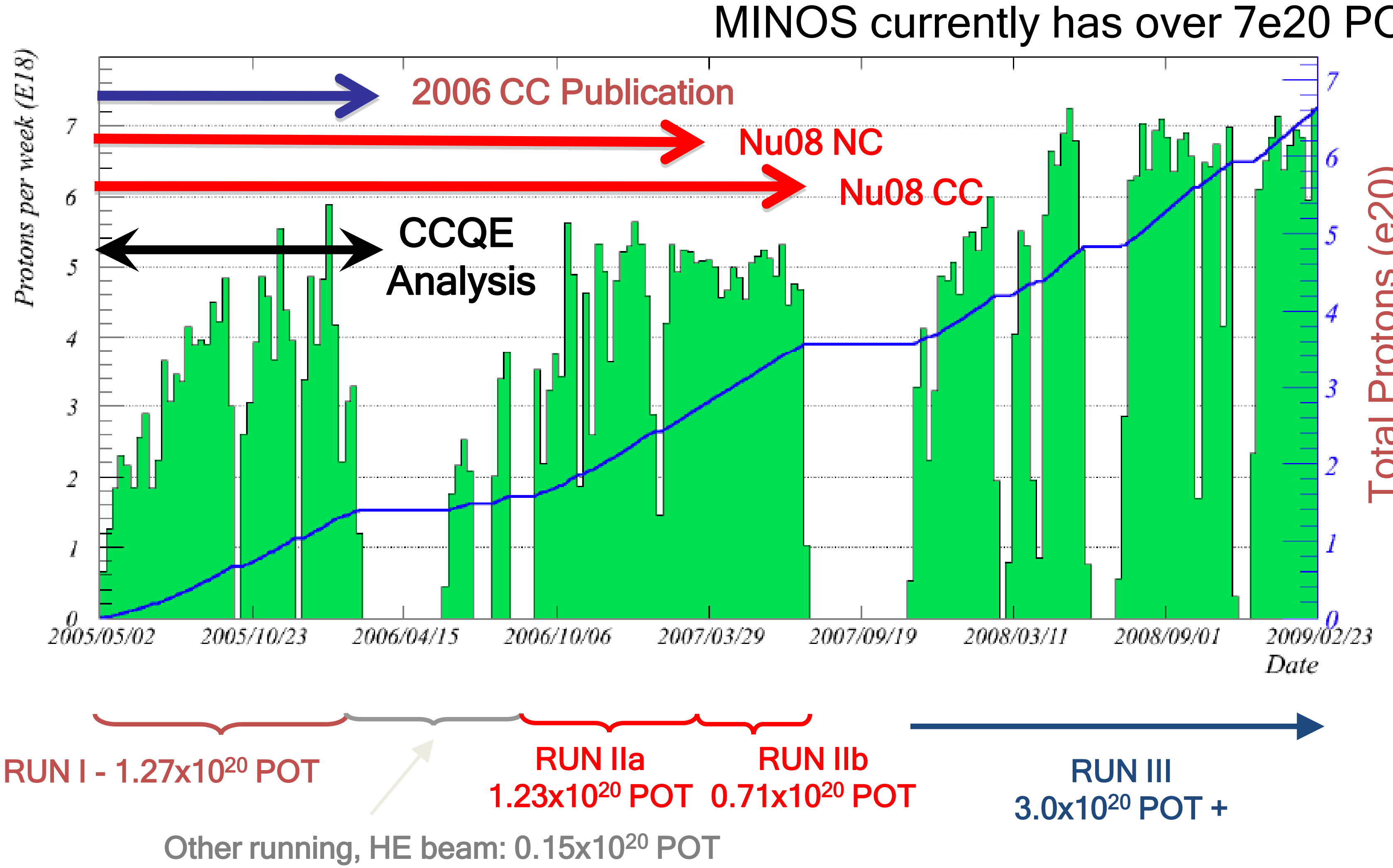




- The distance between the target and first horn can be changed to give a variable beam energy.
- We can also vary the current passing through the horns to further tweak the energy spectrum or sign-select.

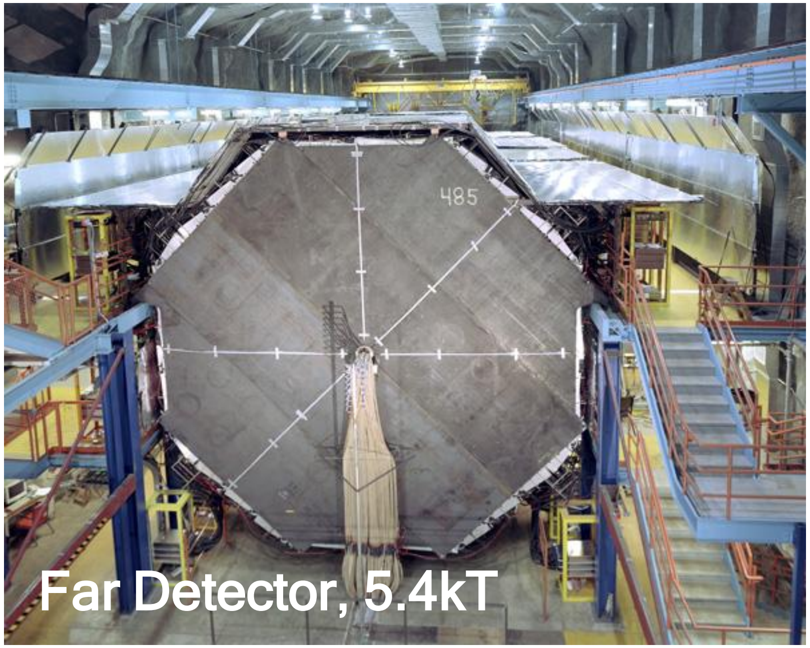
NuMI Beam Performance

MINOS currently has over 7e20 POT!



The MINOS Detectors

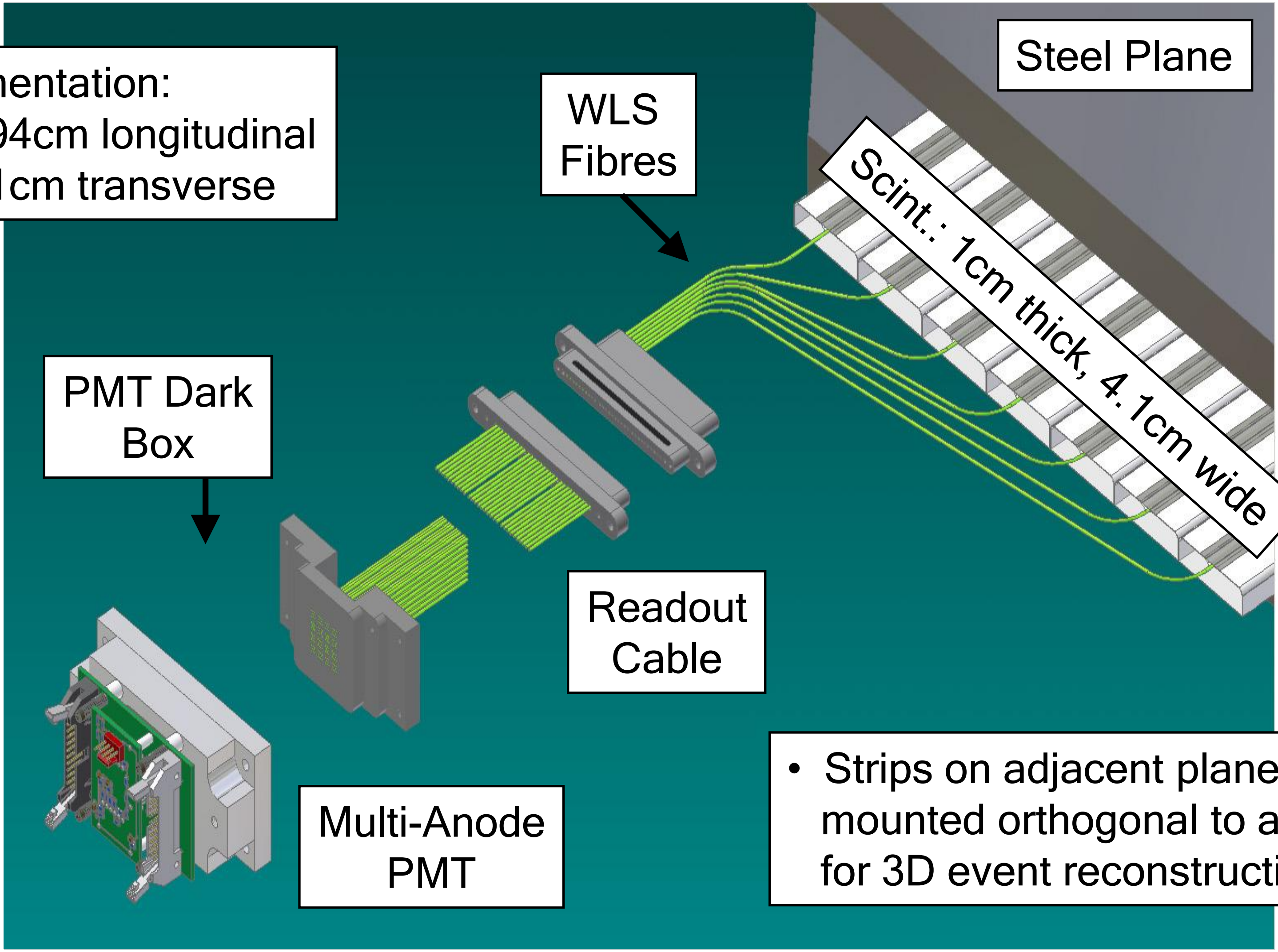
- Detectors are massive steel-scintillator tracking/sampling calorimeters.
- Both detectors are magnetised to 1.3T which allows us to sign-select particles.



- The detectors are designed to be as functionally similar as possible in order to “cancel” many systematic errors in oscillation measurements.
- The ND sees a much larger rate of neutrino interactions though.

Detector Technology

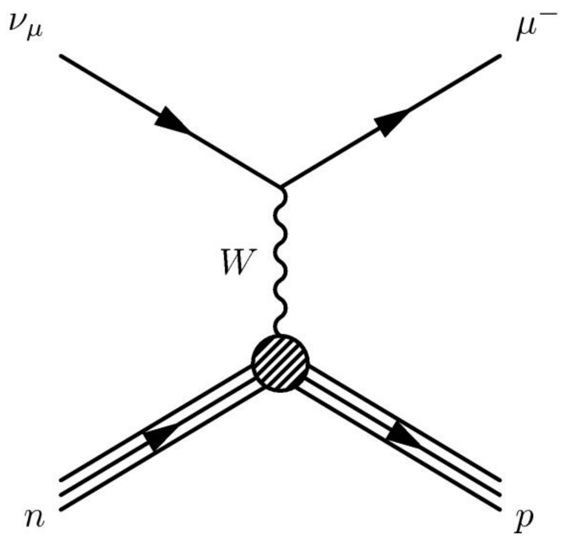
- Segmentation:
  5.94cm longitudinal
  4.1cm transverse



- Strips on adjacent planes are mounted orthogonal to allow for 3D event reconstruction.

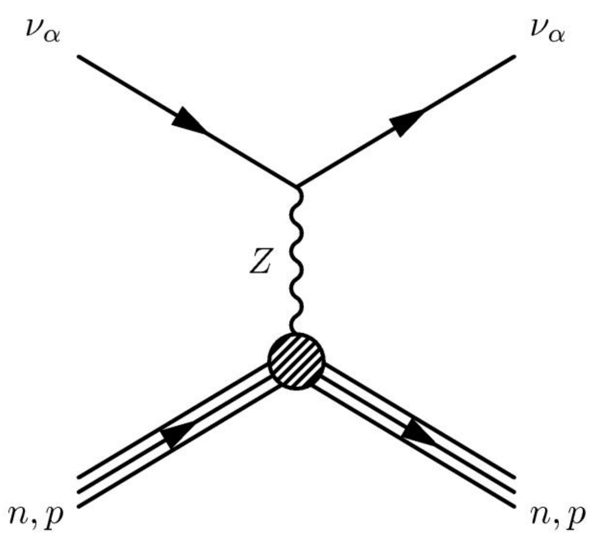
Events in the MINOS Detectors

ν_μ CC Event



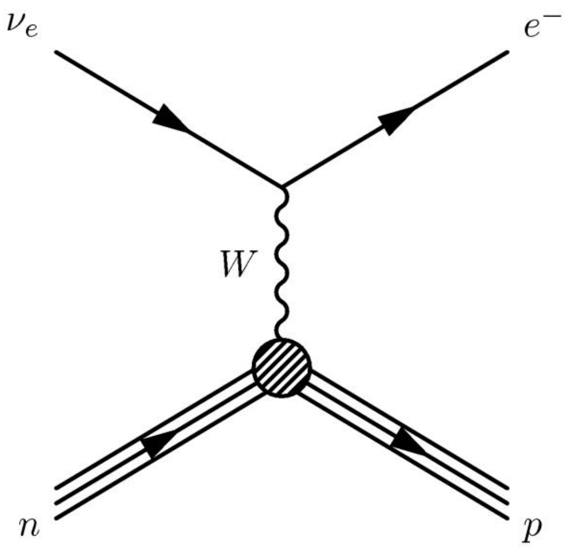
What we look for in the muon neutrino / anti-neutrino analyses.

NC Event



What we use for the sterile neutrino analysis.

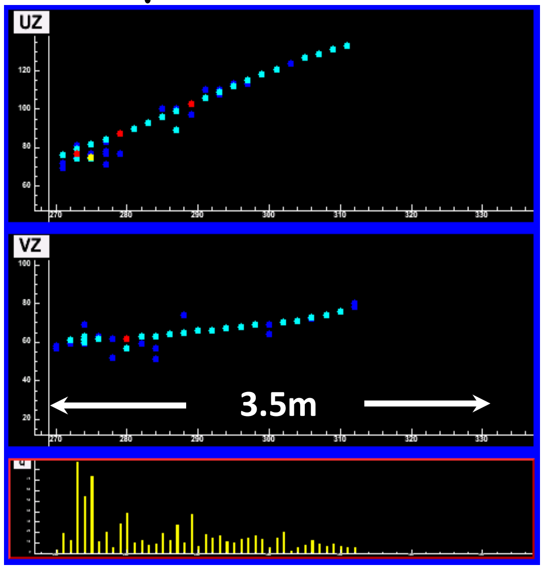
ν_e CC Event



What we look for in the electron neutrino analysis.

Events in the MINOS Detectors

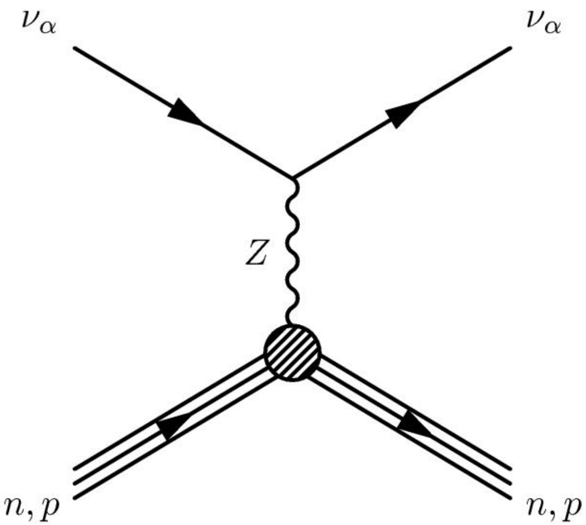
ν_μ CC Event



Long muon track with hadronic activity at the vertex.

What we look for in the muon neutrino / anti-neutrino analyses.

NC Event



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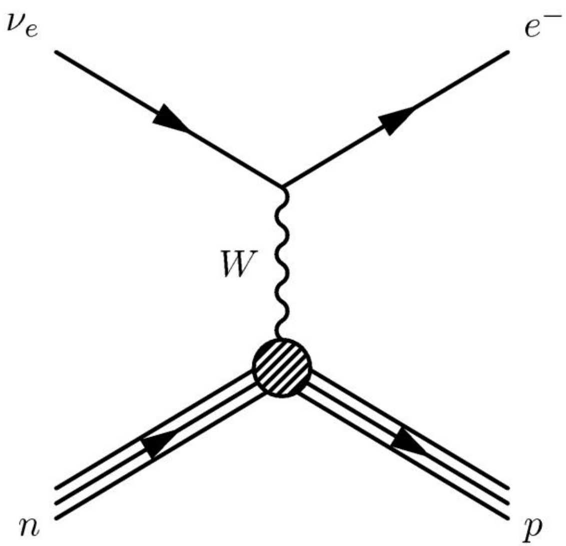
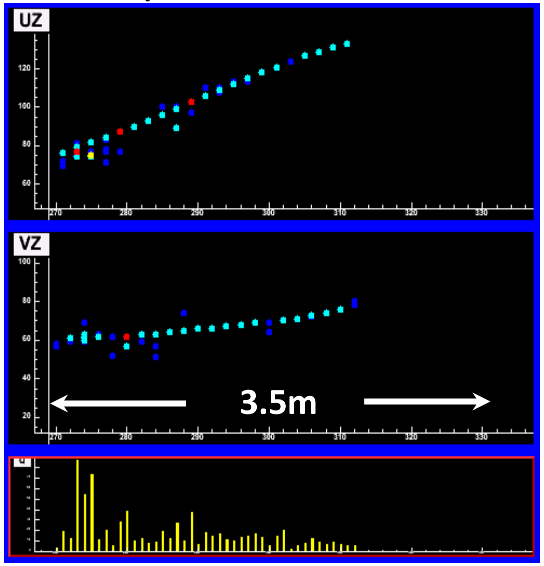


What we look for in the electron neutrino analysis.

Events in the MINOS Detectors

ν_μ CC Event



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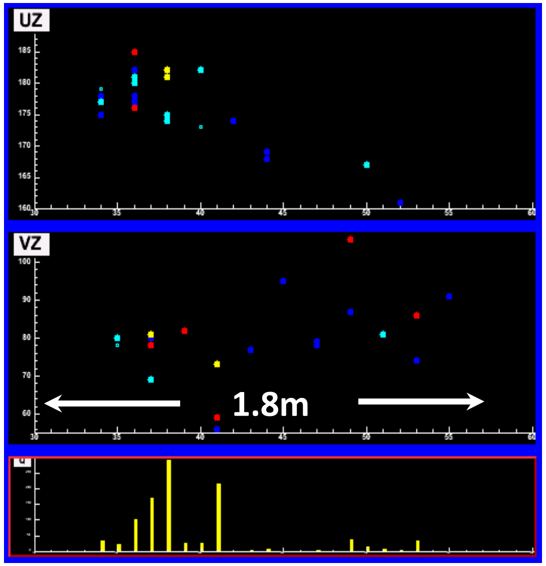
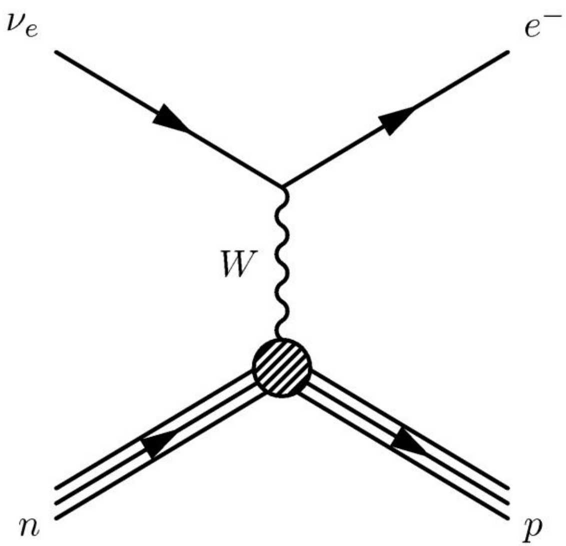


Short event often with a diffuse shower.

What we use for the sterile neutrino analysis.

ν_e CC Event



What we look for in the electron neutrino analysis.

Events in the MINOS Detectors

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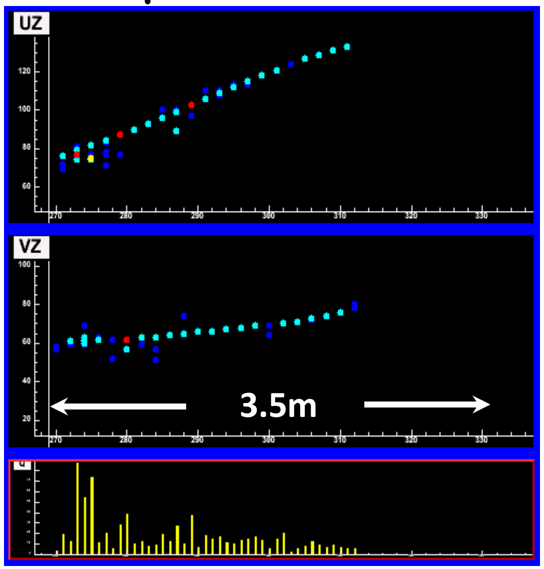

Long muon track with hadronic activity at the vertex.

What we look for in the muon neutrino / anti-neutrino analyses.

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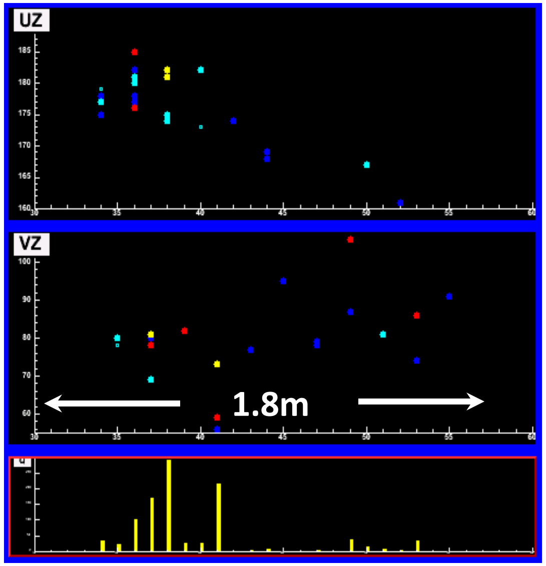

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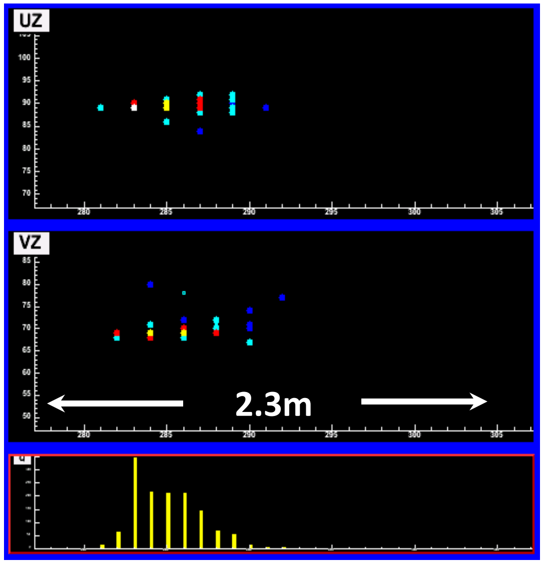
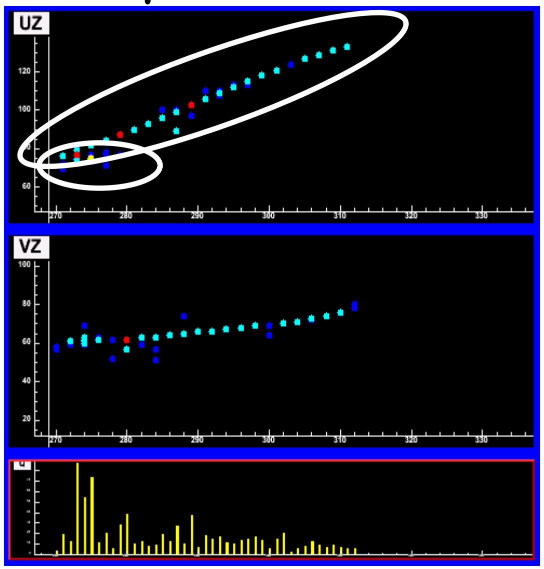


Short event with a compact, EM-like shower profile.

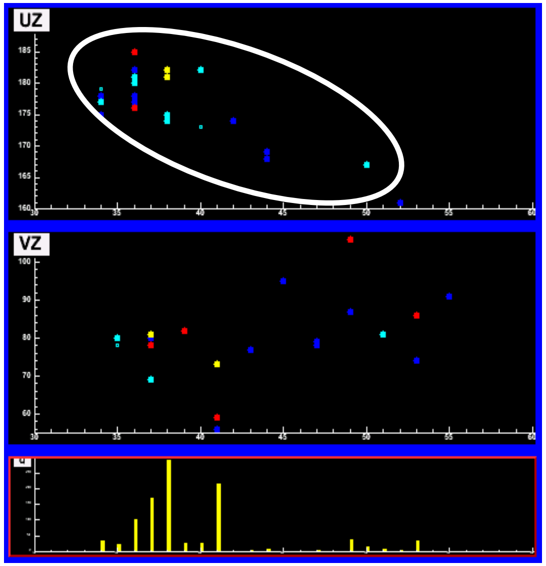
What we look for in the electron neutrino analysis.

Events in the MINOS Detectors

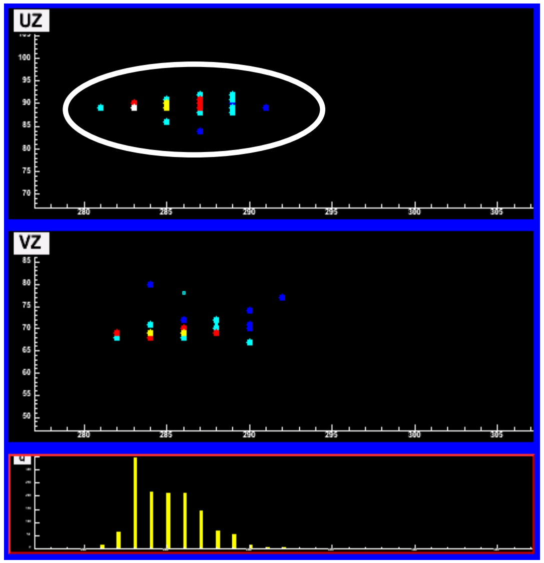
ν_μ CC Event



NC Event



ν_e CC Event



$$E_\nu = E_\mu + E_{shw}$$

Muon energy resolution:

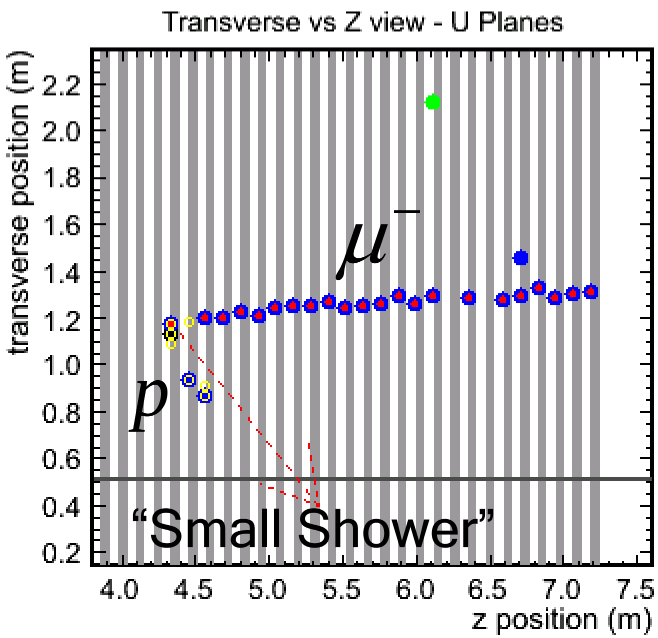
6% from range in the detector
13% from curvature in the magnetic field

Shower energy resolution:

$$\approx 56\% / \sqrt{E}$$

Candidate CCQE Scattering Event

- There are various types of ν_μ-CC scattering that occur in experiments like MINOS, the dominant three are:



Quasi-Elastic Scattering:
(target is modified but does not break up)

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

Resonance Production:

$$\nu_\mu + n \rightarrow \mu^- + \Delta^+ \rightarrow \pi^0 + p$$

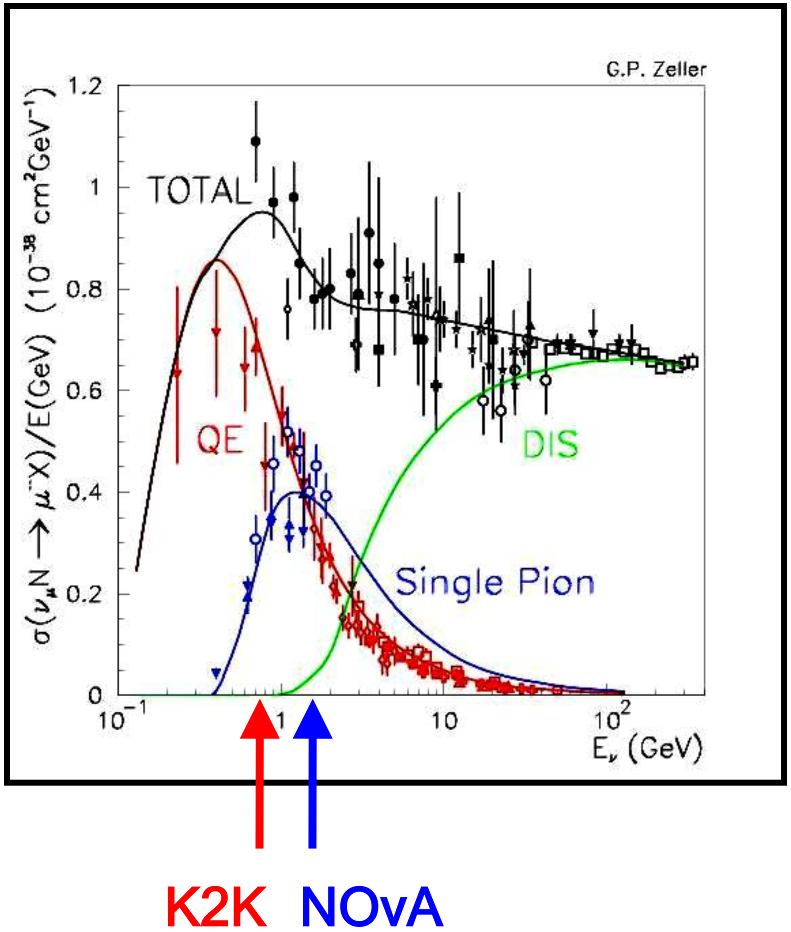
Deep Inelastic Scattering:
(target does break up)

$$\nu_\mu + N \rightarrow \mu^- + X$$

Increasing invariant mass.

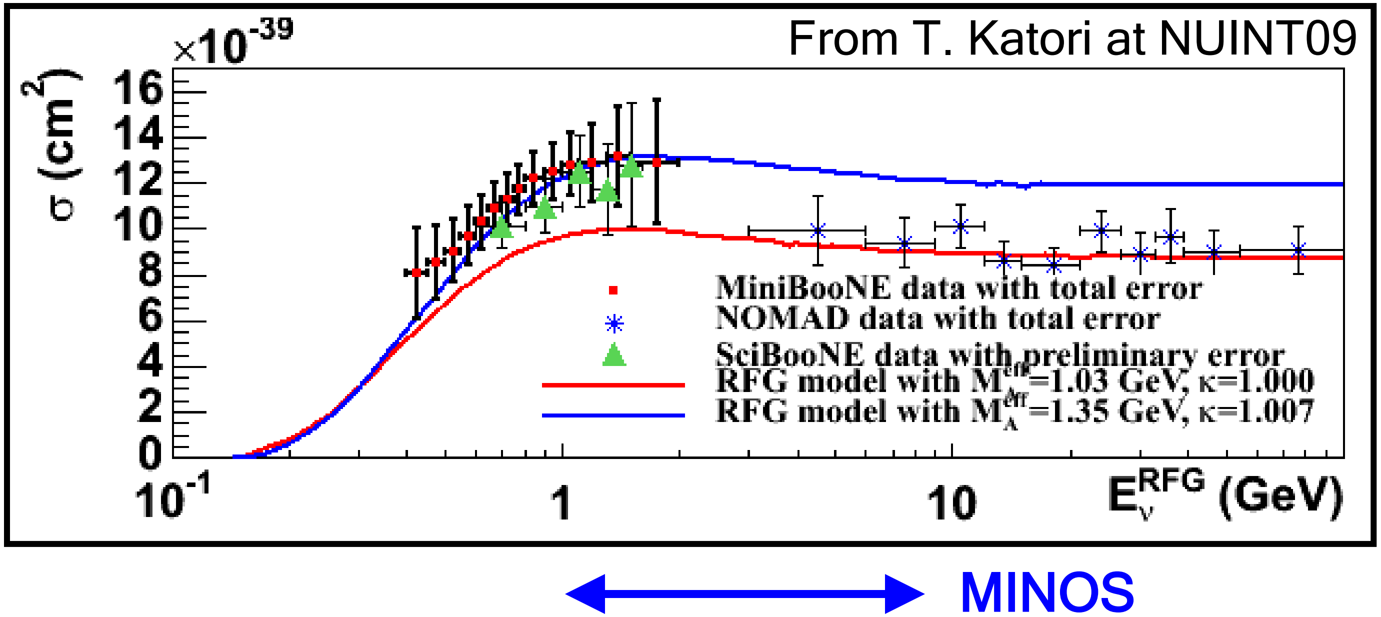
Why do we care about CCQE?

- Dominant interaction mode at low energy where future experiments will operate (e.g. T2K, NOvA).
- Could be an important systematic for θ_{13} measurements but is also hugely interesting in its own right:
  - Fundamental process
  - Probe axial nature of nucleon
  - Window onto nuclear effects
  - …
- CCQE cross section measurements have been being made for 40 years but the devil is in the details…



Why do we care about CCQE?

- Cross section is not well understood, for example see recent results from the MiniBooNE and NOMAD experiments:



- Before I talk more about the current status of CCQE cross section measurements I think we need to take a quick theory diversion…

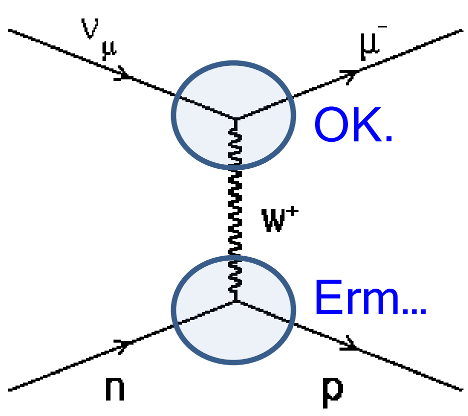
Towards the CCQE Cross Section

- Incorporation of parity violation in the weak interaction leads to the V-A form of the weak current:

$$\boxed{\bar{u}_{e^-}\gamma_\mu u_\nu} \longrightarrow \boxed{\bar{u}_{e^-}\gamma_\mu(1-\gamma_5)u_\nu}$$

Fermi's original 4-vector current ⟶ *V-A weak current*

- This is valid for lepton-lepton and quark-quark vertices but how about a vertex involving nucleons:



CCQE Scattering

- Additional strong interaction effects must be taken into account.
- We know that such effects conserve the net electric charge (proton always has charge +1).
- There is no reason to believe the same is true in the weak interaction.

Nucleon Form Factors

- Describe hadronic vertex in terms of nucleon form factors which define how much of each type of possible weak current contributes to a scatter:

$$\bar{u}_p(P')\Gamma^{\mu}_{CC}(q^2)u_n(P) \quad \text{where} \quad \Gamma^{\mu}_{CC} = \boxed{\gamma^{\mu}F_V(q^2) + \frac{i\sigma^{\mu\nu}q^{\nu}}{2M}F_M(q^2) + \frac{q_{\mu}}{M}F_S(q^2)} + \boxed{\left(\gamma^{\mu}F_A(q^2) + \frac{i\sigma^{\mu\nu}q^{\nu}}{2M}F_T(q^2) + \frac{q_{\mu}}{M}F_P(q^2)\right)\gamma_5}$$

(V-type and A-type currents)

- These form factors are functions of the probe strength, Q^2.

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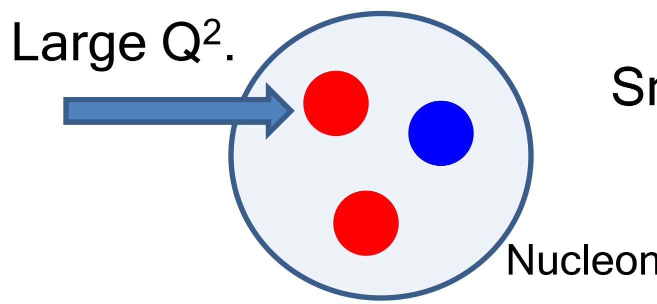
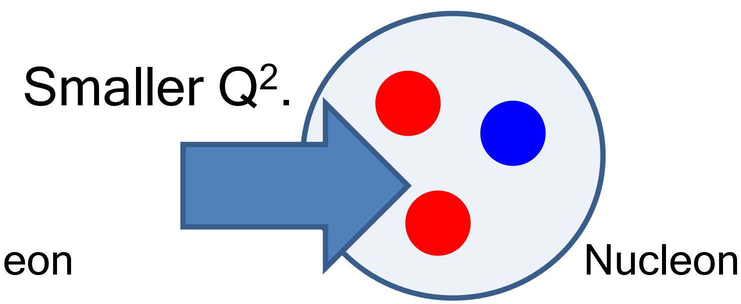
- These form factors are functions of the probe strength, Q^2.

(V-type and A-type currents)

$$\lambda \propto \frac{1}{p}$$

de Broglie Relation





Probe sees different levels of nucleon structure depending upon it's momentum.

Nucleon Form Factors

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$$+ \boxed{\left(\gamma^{\mu}F_A(q^2) + \frac{i\sigma^{\mu\nu}q^{\nu}}{2M}F_T(q^2) + \frac{q_{\mu}}{M}F_P(q^2)\right)\gamma_5}$$

(V-type and A-type currents)

- These form factors are functions of the probe strength, Q^2.

Multiplied by lepton mass in cross section so neglected for our muons.

- In practice, only 3 of the form factors are non-zero:

$$\Gamma^{\mu}_{CC} = \gamma^{\mu}\left[F_V^1(q^2) - \gamma_5 F_A(q^2)\right] + \frac{i\sigma^{\mu\nu}q^{\nu}}{2M}\xi F_V^2(q^2)$$

Well measured through electron scattering experiments.

Not well measured and <u>only neutrino scattering experiments can extract $F_A(Q^2)$.</u>

σ_{CCQE} and the Axial-Vector Form Factor

$$\frac{d\sigma}{d|q^2|} = \frac{M^2 G_F^2 cos^2(\theta_c)}{8\pi E_\nu^2}\left[A(q^2) - B(q^2)\frac{s-u}{M^2} + C(q^2)\frac{(s-u)^2}{M^4}\right]$$

CCQE Differential Cross Section

- *A*, *B* and *C* are functions of the form factors and, in particular, depend on:

$$F_A(q^2) = \underbrace{\frac{F_A(0)}{(1-\frac{q^2}{M_A^2})^2}}_{\text{“Dipole Form”}}$$

Well known from neutron β-decay experiments.

The axial-vector mass for CCQE scattering.

σ_{CCQE} and the Axial-Vector Form Factor

$$\frac{d\sigma}{d|q^2|} = \frac{M^2 G_F^2 cos^2(\theta_c)}{8\pi E_\nu^2}\left[A(q^2) - B(q^2)\frac{s-u}{M^2} + C(q^2)\frac{(s-u)^2}{M^4}\right]$$

CCQE Differential Cross Section

- *A*, *B* and *C* are functions of the form factors and, in particular, depend on:

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

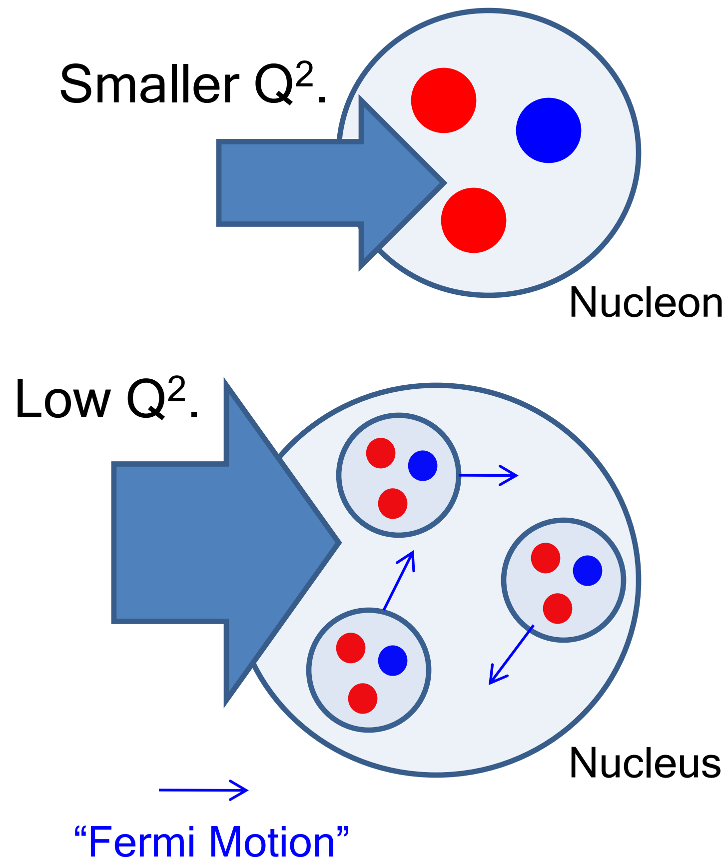
Dipole form looks a bit like a propagator.

Could think of M_A as the mass of the exchanged boson corresponding to the axial-vector part of the weak interaction.

- So we know the vector form factors and $F_A(0)$ => the uncertainty in this cross section is dominated by the uncertainty on the value of the axial mass.

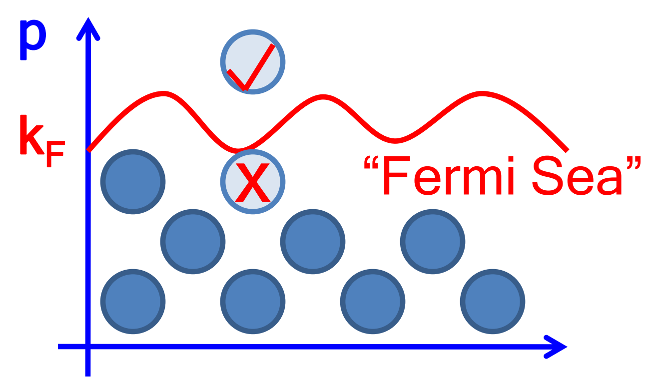
Nuclear Effects

- Of course in experiments we are not scattering off quarks, or even nucleons, but from nuclei.
- Nuclear effects become important at very low Q^2 (where we are interacting with a number of nucleons bound in a nucleus).
- Nuclear effects modify the cross section.
- Most neutrino event generators model their nuclei and the associated effects using the relativistic Fermi gas model.
- In MINOS the neutrinos are scattering off iron nuclei - heavy!



The Fermi Gas Model and Pauli-Blocking

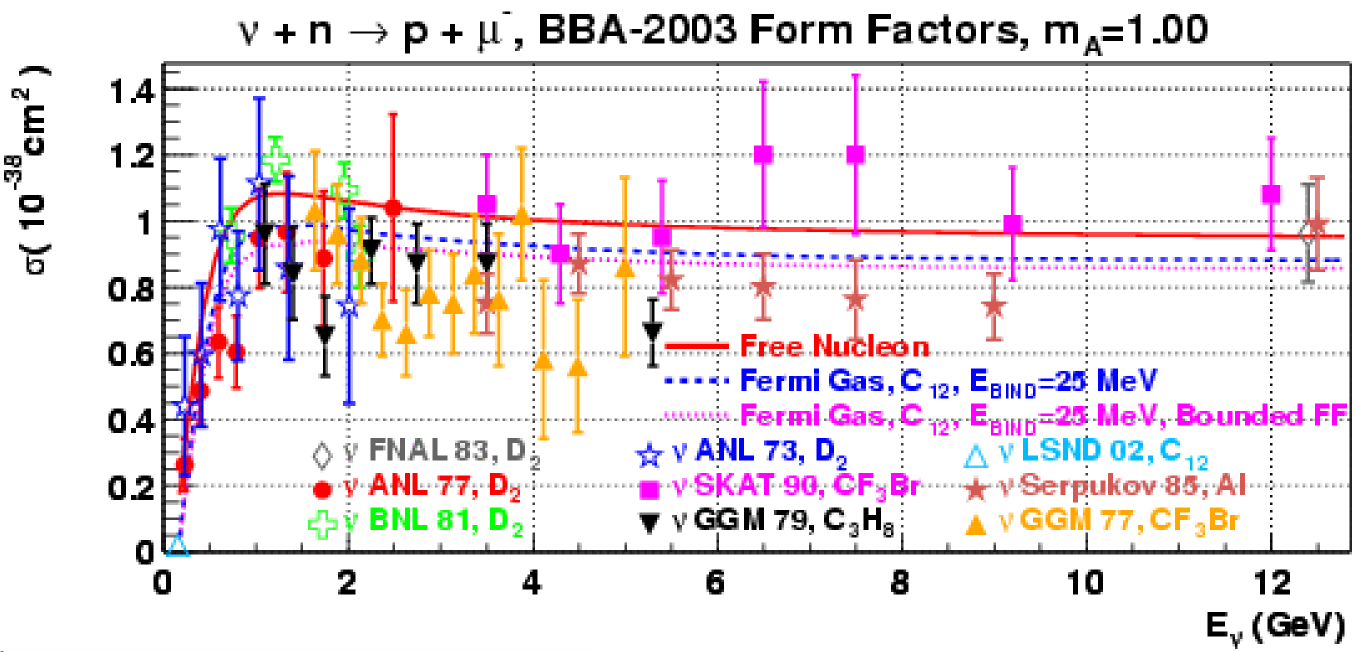
- All momentum levels below the Fermi momentum, k_F, are filled.
- Apply Pauli-exclusion principle to the nucleons: identical fermions can't occupy the same quantum state.

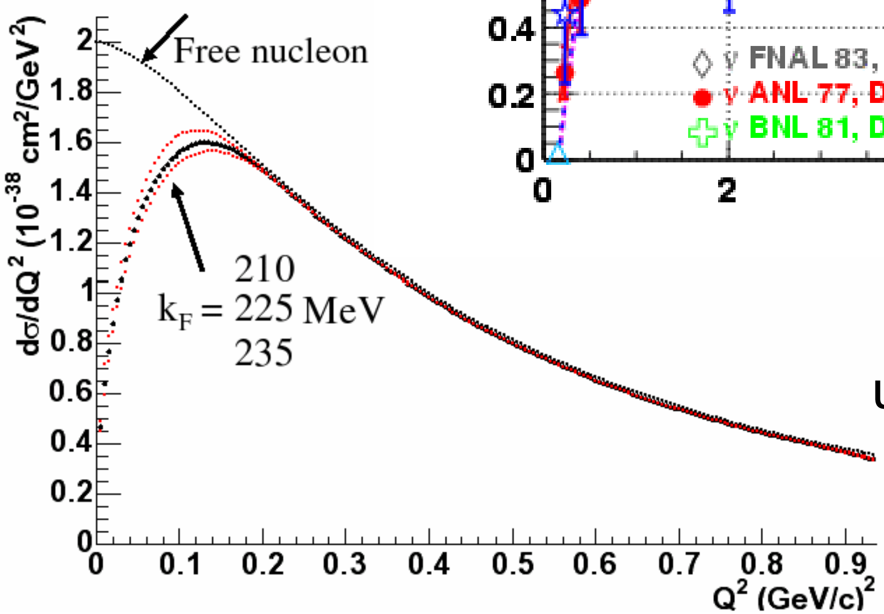


- So any CCQE interaction which leaves the final state nucleon with momentum below k_F is considered to be "Pauli-blocked" (in the event generators this is essentially a Heaviside function).
- Fermi gas model takes care of other nuclear effects too, things like the Fermi motion of nucleons etc. Final state interactions in the nuclear medium are treated separately (will come back to this later).

Impact of Pauli-Blocking

Significant effect on cross section!





Nuclear effects result in a somewhat uniform decrease in the cross section as a function of energy but are limited to the low Q^2 region.

A Generic Axial Mass Measurement

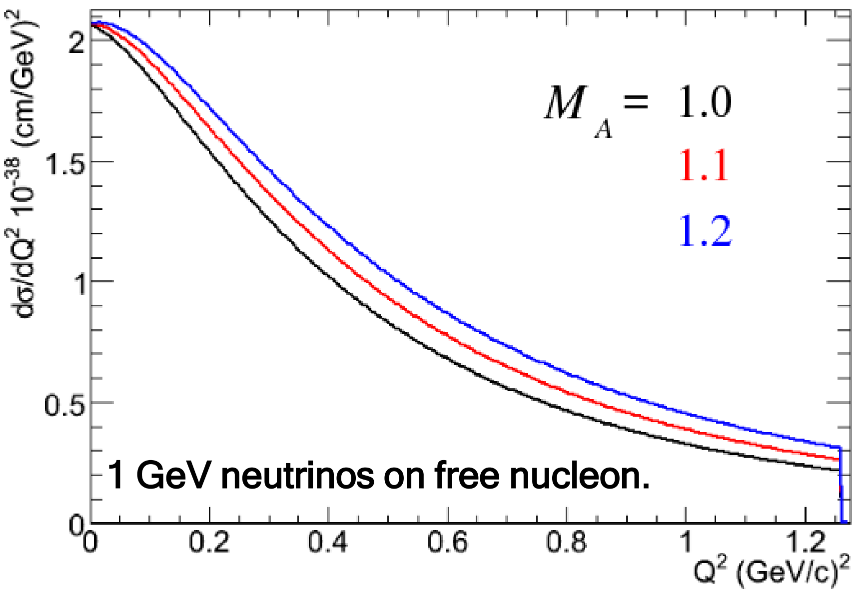
- The CCQE differential cross section with respect to Q^2 depends upon M_A…

… can measure M_A by looking at the Q^2 distribution for CCQE scattering events.

- Changes in the value of M_A affect both the shape and rate of the cross section - it is these effects that give sensitivity.

- Possible analysis choices:

If you don't have a good flux measurement you can use a shape-only fit for M_A.



Fermi gas is too simplistic - can either ignore the low Q^2 region in fits or try to modify the CCQE sample at low Q^2 with another parameter.

Current Status of Axial Mass Results

Experiment	Target	Events	Method	M_A, GeV	Ref.
ANL 69	*Steel*		$d\sigma/dQ^2$	1.05 ± 0.20	[1]
			σ	0.97 ± 0.16	
ANL 73	*Deuterium*	166	$d\sigma/dQ^2$	0.94 ± 0.18	[2]
			$\sigma \otimes d\sigma/dQ^2$	0.95 ± 0.12	
			σ	$0.75^{+0.13}_{-0.11}$	
ANL 77	*Deuterium*	~ 600	$d\sigma/dQ^2$	1.01 ± 0.09	[3]
			$\sigma \otimes d\sigma/dQ^2$	0.95 ± 0.09	
			σ	0.74 ± 0.12	
ANL 82	*Deuterium*	1737	$d\sigma/dQ^2$	1.05 ± 0.05	[4]
			$\sigma \otimes d\sigma/dQ^2$	1.03 ± 0.05	
BNL 81	*Deuterium*	1138	$d\sigma/dQ^2$	1.07 ± 0.06	[6]
BNL 90	*Deuterium*	2538	$d\sigma/dQ^2$	$1.070^{+0.040}_{-0.045}$	[8]
FermiLab 83	*Deuterium*	362	$d\sigma/dQ^2$	$1.05^{+0.12}_{-0.16}$	[9]
NuTeV 04	*Steel*	21614	σ	1.11 ± 0.08	[23]
MiniBooNE 07	*Mineral oil*	193709	$d\sigma/dQ^2$	1.23 ± 0.20	[26]
CERN HLBC 64	*Freon*	236	$d\sigma/dQ^2$	$1.00^{+0.35}_{-0.20}$	[11]
CERN HLBC 67	*Freon*	90	$\sigma \otimes d\sigma/dQ^2$	$0.75^{+0.24}_{-0.20}$	[12]
CERN SC 68	*Steel*	236	$d\sigma/dQ^2$	$0.65^{+0.45}_{-0.40}$	[13]
CERN HLBC 69	*Propane*	130	$\sigma \otimes d\sigma/dQ^2$	0.70 ± 0.20	[14]
			σ	0.88 ± 0.19	
CERN GGM 77	*Freon*	687	$d\sigma/dQ^2$	0.96 ± 0.16	[15]
			σ	0.87 ± 0.18	
CERN GGM 79	*Propane/Freon*	556	$d\sigma/dQ^2$	0.99 ± 0.12	[17]
			σ	0.94 ± 0.07	
CERN BEBC 90	*Deuterium*	552	$d\sigma/dQ^2$	1.08 ± 0.08	[18]
IHEP 82	*Aluminium*	898	$d\sigma/dQ^2$	1.00 ± 0.07	[19]
IHEP 85	*Aluminium*	1753	$d\sigma_{\nu+\bar{\nu}}/dQ^2$	1.00 ± 0.04	[20]
IHEP SCAT 88	*Freon*	464	$\sigma \otimes d\sigma/dQ^2$	0.96 ± 0.15	[21]
			σ	1.08 ± 0.07	
IHEP SCAT 90	*Freon*		$d\sigma/dQ^2$	1.05 ± 0.07	[22]
			$\sigma \otimes d\sigma/dQ^2$	1.06 ± 0.05	
K2K 06, SciFi	*Water*	~ 12000	$d\sigma/dQ^2$	1.20 ± 0.12	[24]
K2K 08, SciBar	*Carbon*		$d\sigma/dQ^2$	1.144 ± 0.077	[25]

← Lyubushkin *et al*. arXiv:0812.4543

- Also:
  MiniBooNE: 1.35+-0.17 (NUINT09)
  NOMAD: 1.05+-0.07 (above paper)
- World average (circa 2002):
  1.026 +- 0.021 GeV
- Complications:
  Target nucleus
  Energy range
  Kinematic resolution
  Shape v.s. rate
  Input vector form factors
  Number of CCQE events

=>M_A is effective parameter?

MINOS CCQE Analysis Overview

- MINOS has been going flowchart crazy recently so here it is…

Take Data! → Select ν_μ-CC events. → Select CCQE sub-sample.

Select ν_μ-CC events. ↓ Tune flux model.

Select CCQE sub-sample. ↓ Shape-only fits for M_A^{QE}. ↓ Estimate systematic errors.

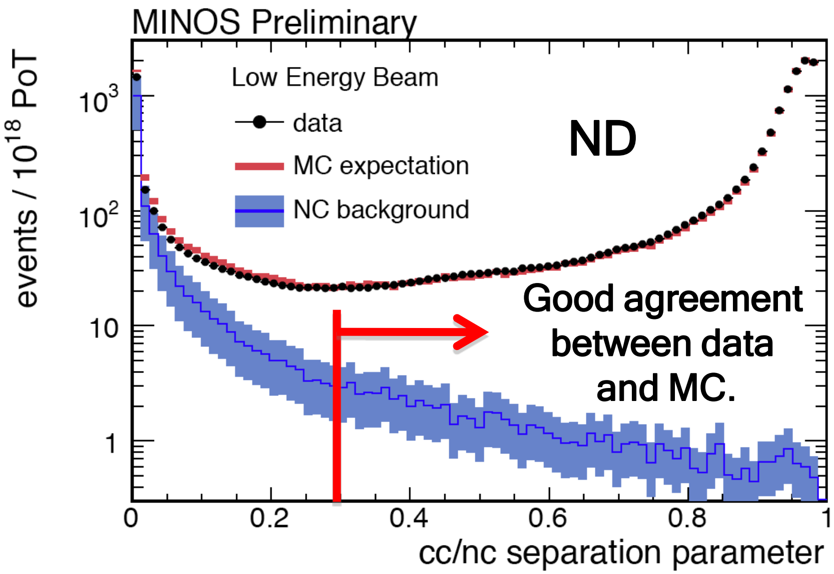
- Measurements of the absolute flux at the MINOS ND down to the lowest energies are currently being performed.

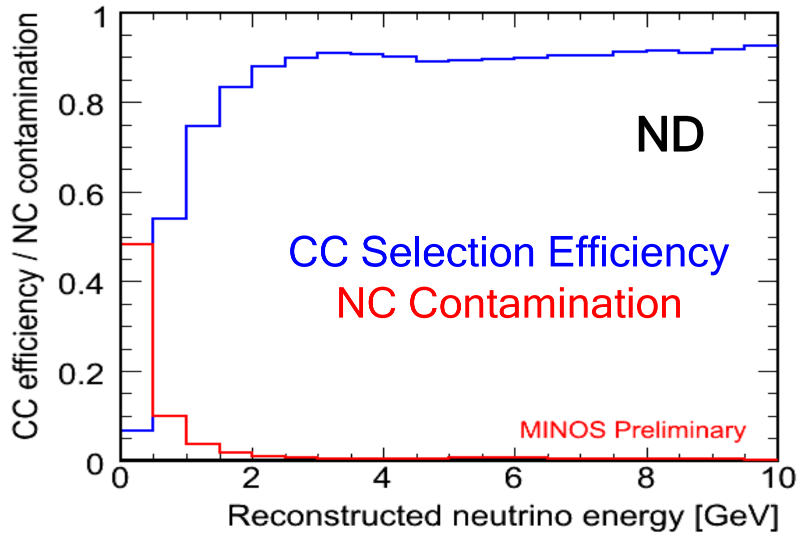
  (>3 GeV recently published for neutrinos, >5 for anti-neutrinos)

- As such we have performed a shape based measurement of M_A^{QE}.

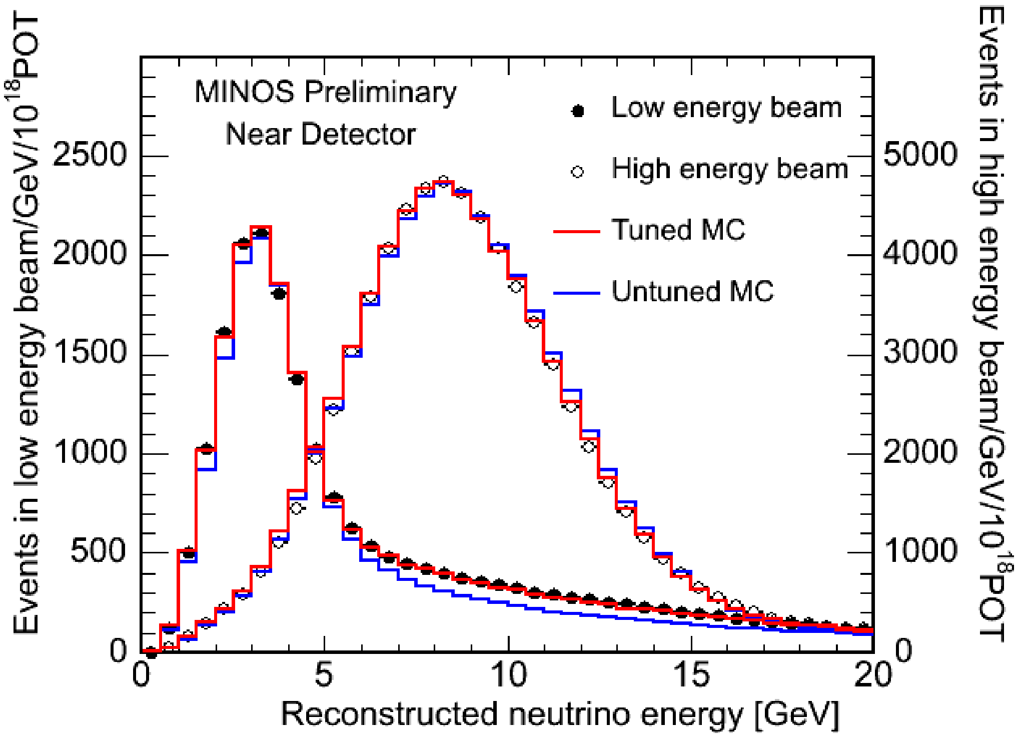
Selecting ν_μ-CC Events

- We first remove the majority of NC events by requiring a reconstructed track and then further enrich the sample using a nearest neighbour technique (kNN).
- The kNN combines variables that differentiate between muon tracks and the pion or proton tracks that can be reconstructed in NC events.





Flux Model Tuning

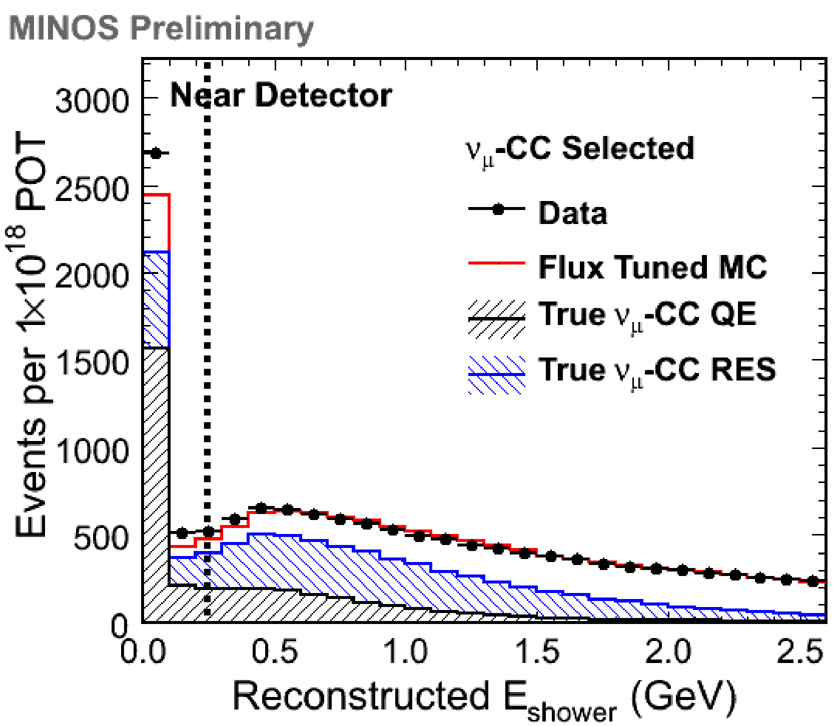


- Different beam configurations sample different regions in parent hadron x_f and p_T.
- We fit the data and tune our FLUKA hadron production model.
- The fits also include nuisance parameters for beam optics effects, cross sections and ND energy scales.

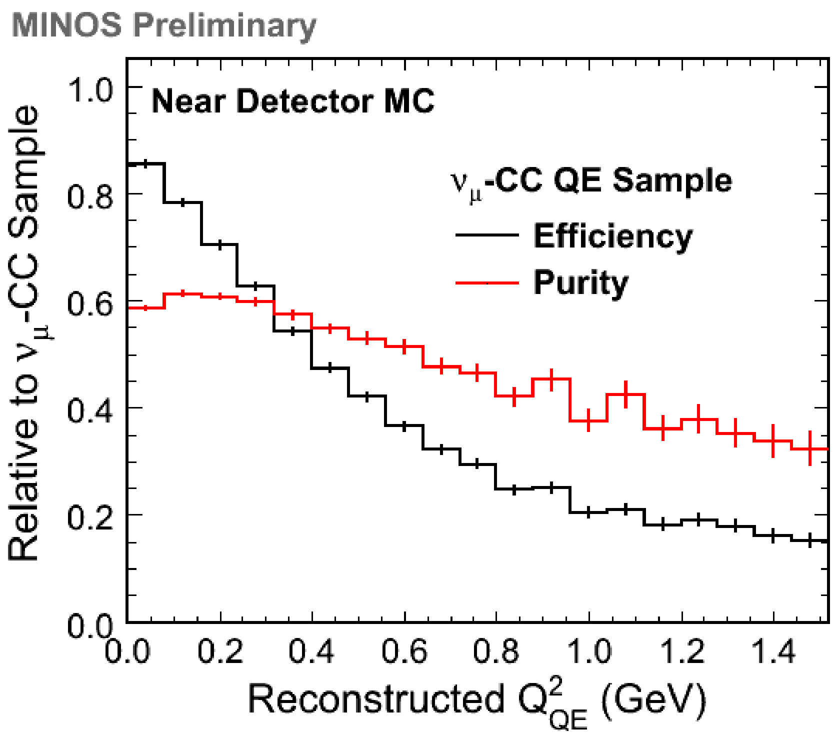
- This flux-tuning procedure has been very successful and all of the MC distributions shown in my talk will use the tuned hadron production model.

Selecting ν_μ-CC QE Events

- We select a QE-enriched sample using a simple cut on the hadronic shower energy and only consider events with muons that stop in the ND:

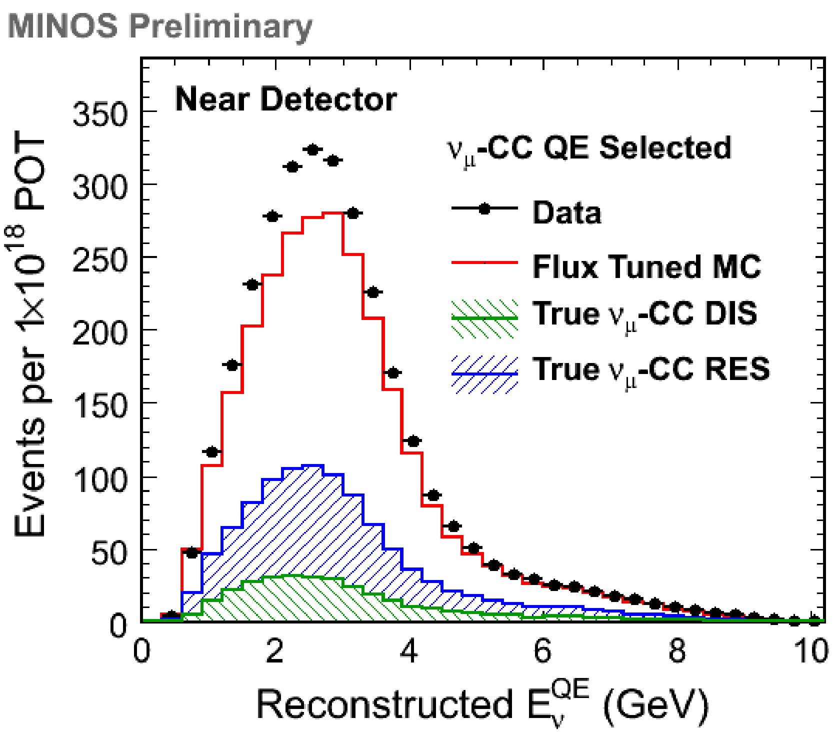


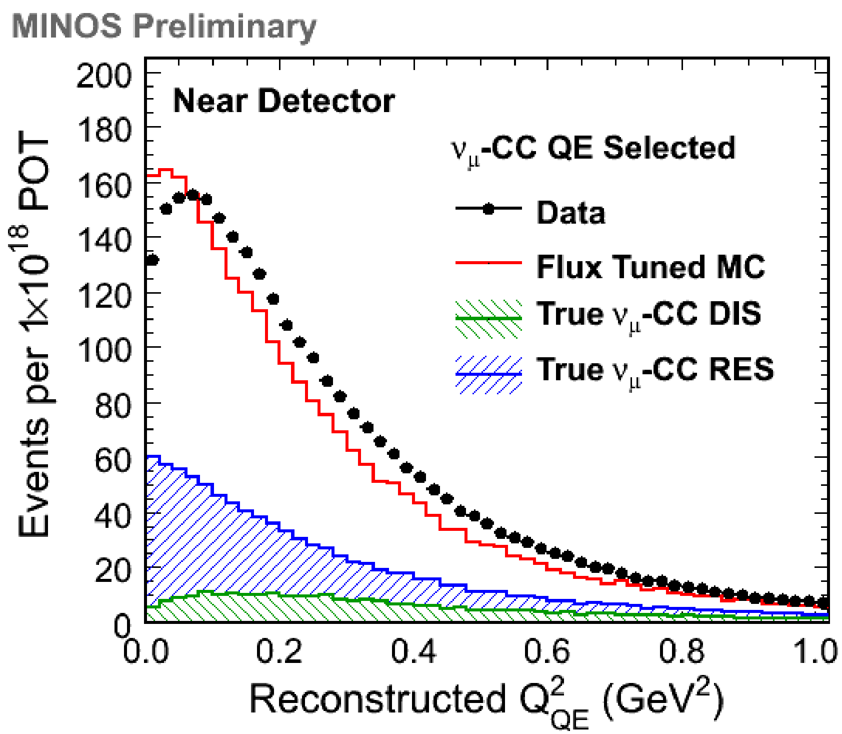
E_{had} < 250 MeV for QE sample



Efficiency: 53%, Purity: 61%

Data/MC Comparison for CCQE Sample



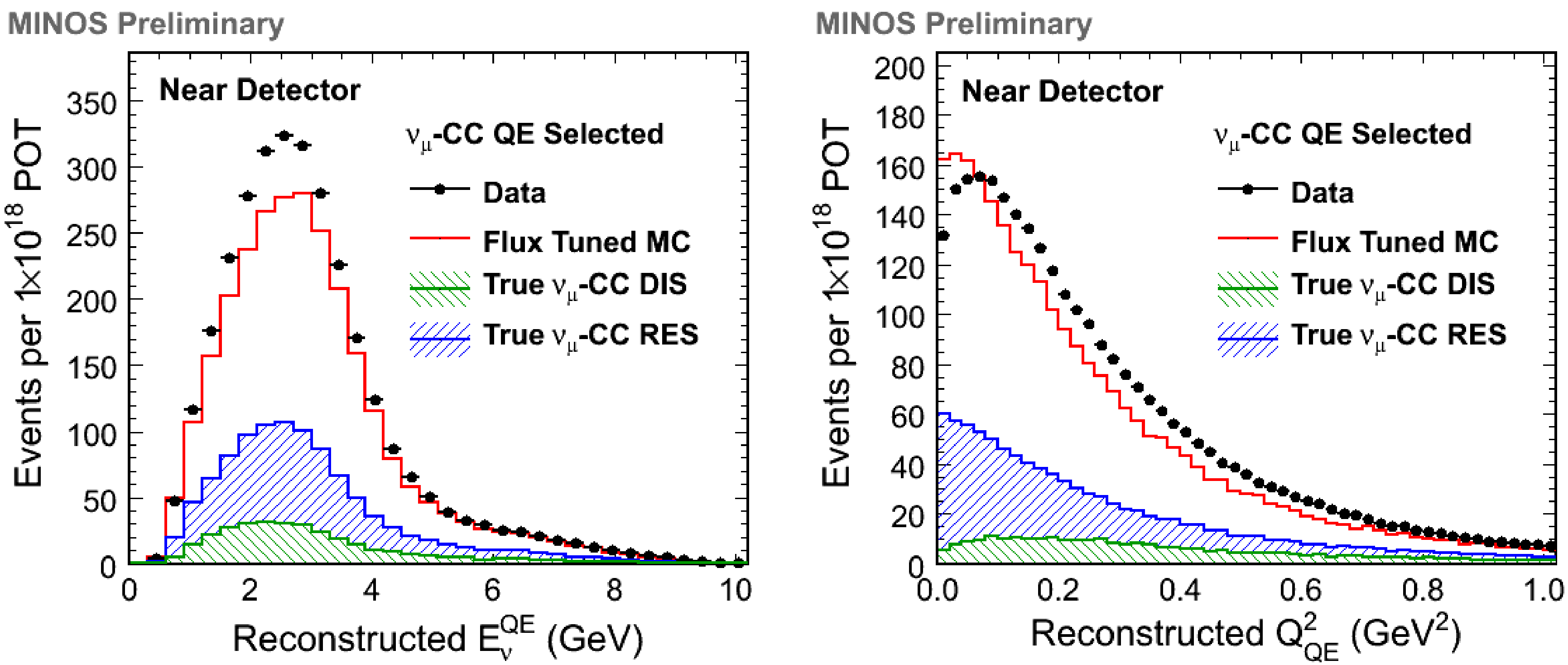


$$E_\nu^{QE} = \frac{(m_N + \varepsilon_B)E_\mu - 2(m_N\varepsilon_B + \varepsilon_B^2 + m_\mu^2/2)}{m_N + \varepsilon_B - E_\mu + p_\mu \cos(\theta_\mu)}$$

$$Q^2_{QE} = -2E_\nu^{QE}[E_\mu - p_\mu \cos(\theta_\mu)] + m_\mu^2$$

"QE-assumed kinematics."

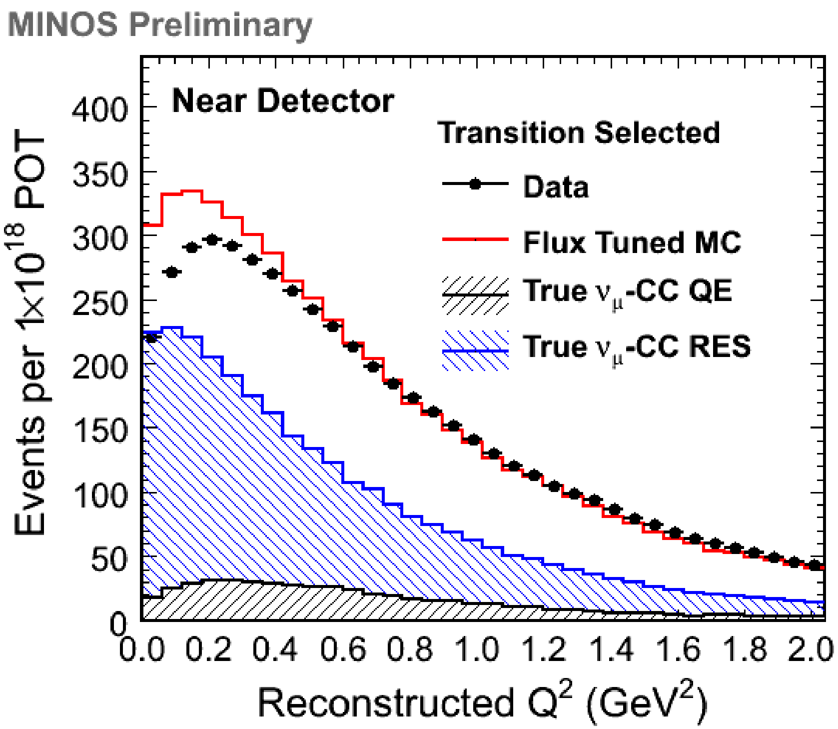
Data/MC Comparison for CCQE Sample



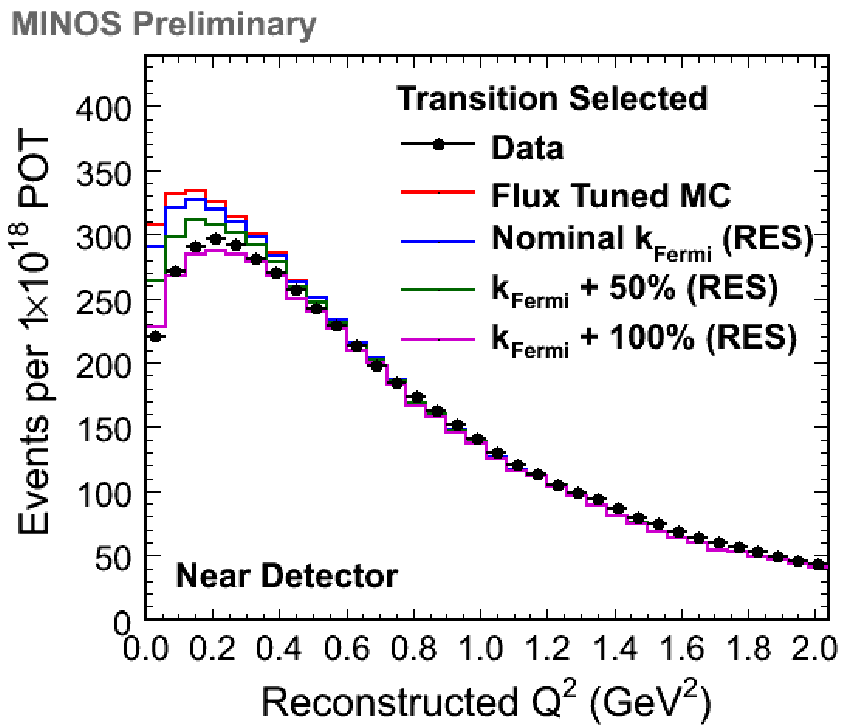
Total # of events selected:
Data: 344,736
MC: 292,501

Data wants more low Q^2 suppression and a flatter spectrum at higher Q^2.

Understanding the Resonances



We can select a resonance enhanced sample using W cuts and see large differences between data and MC in the low Q^2 (nuclear effect) region.



Suggests a mis-modeling of nuclear effects for resonance interactions. No Pauli-blocking of resonance events in the default MC -> turn on for CCQE analysis.

Fitting for an Effective M_A^{QE}

- Use MINUIT to minimize:

Fit parameters

observed events in bin i

expected events in bin i

Shift in systematic parameter j from nominal

$$\chi^2 = \sum_{i=1}^{\#bins} \frac{[o_i - e_i(\alpha_1,\ldots,\alpha_N)]^2}{o_i + Se_i(\alpha_1,\ldots,\alpha_N)} + \sum_{j=2}^{N} \frac{\Delta\alpha_j^2}{\sigma_{\alpha_j}^2}$$

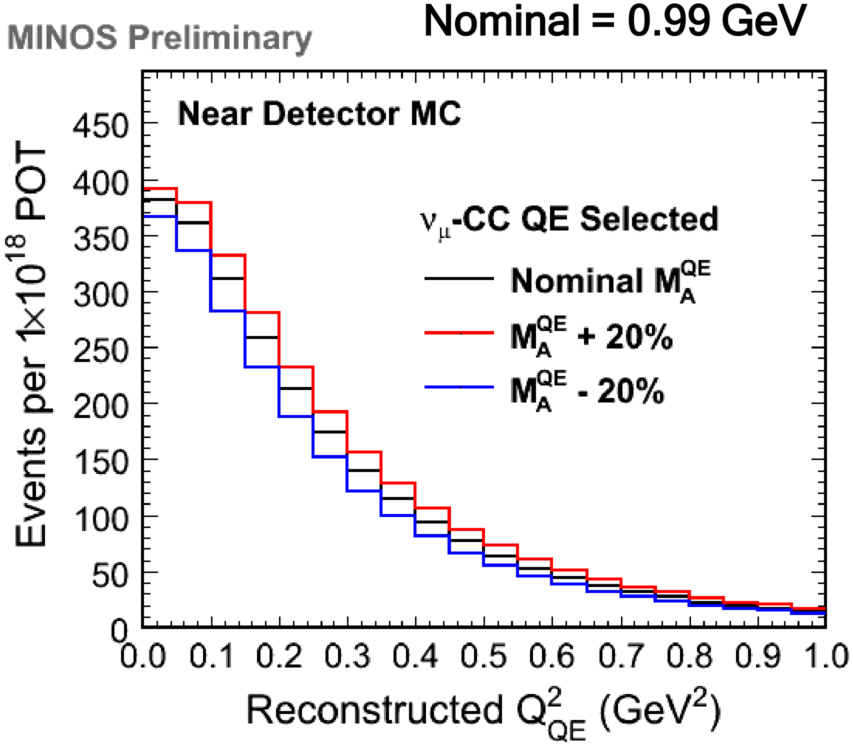
1σ error for systematic parameter j

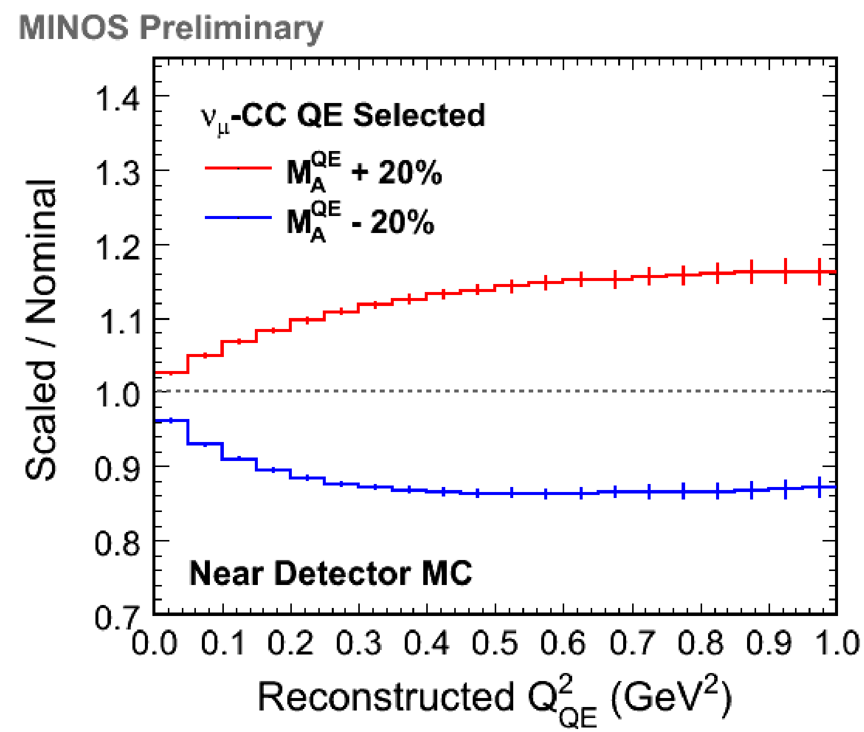
MC normalization

- Will show results from 2 shape-only fits to Q^2_{QE} (>0.3 and >0.0 GeV^2).
- The most important systematic effects are considered directly in the fits whilst other uncertainties are studied via their impact on the fit results.
- Based on observations of the resonance sample we apply Pauli-blocking to the resonance interactions. We also apply a correction for the Coulomb interaction between the nucleus and outgoing lepton.

Fit Parameter: M_A^{QE}-Scale

Nominal = 0.99 GeV

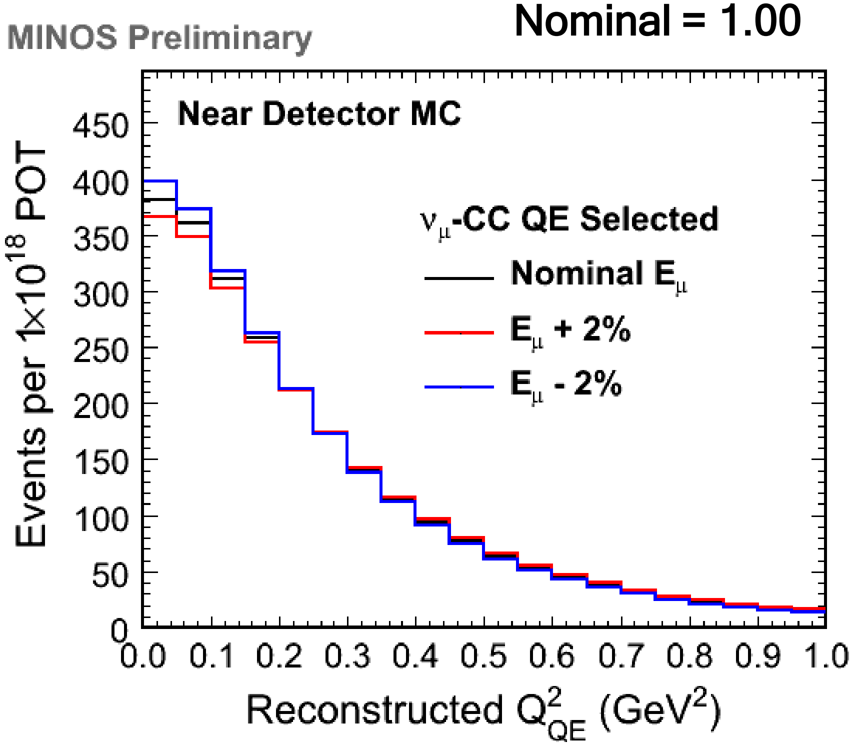


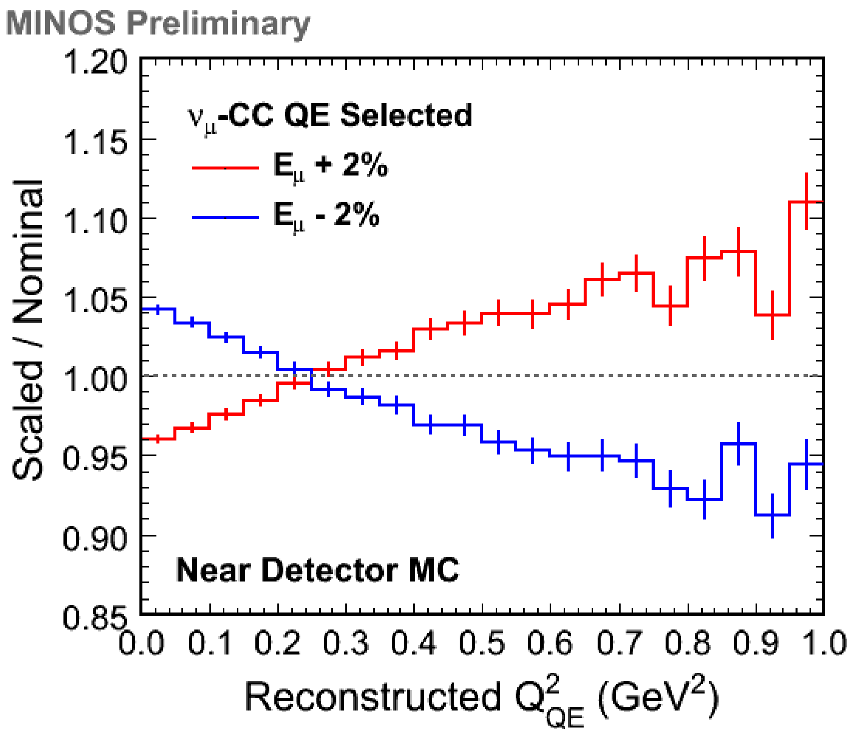


- Treated as a free parameter in the fits. The effect on the QE sample is asymmetric due to the non-QE background. Note that these figures are absolutely normalized although the fits only consider the Q^2 shape.

Fit Parameter: Muon Energy Scale

Nominal = 1.00

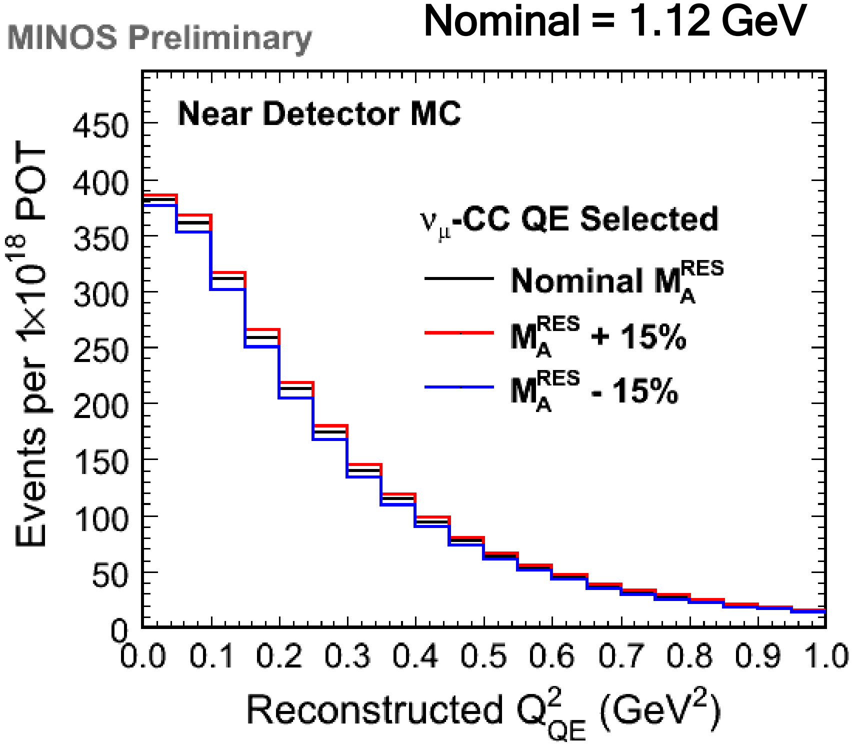


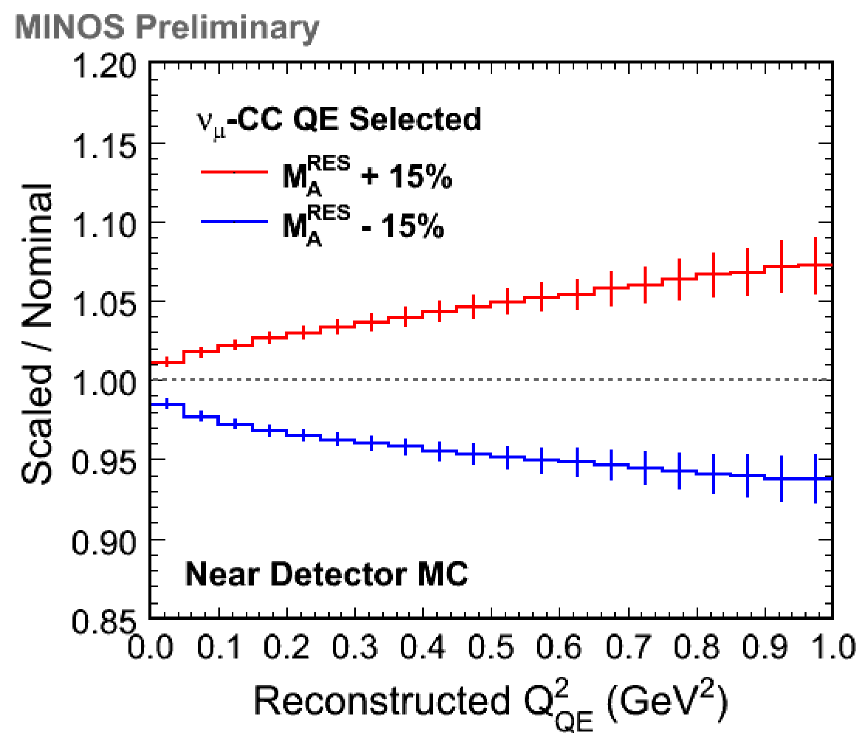


- We take a 1σ error of 2% for use in the penalty term (this is the published MINOS uncertainty for stopping muons). This parameter changes Q^2 via the muon-only kinematic reconstruction.

Fit Parameter: M_A^{RES}-Scale

Nominal = 1.12 GeV

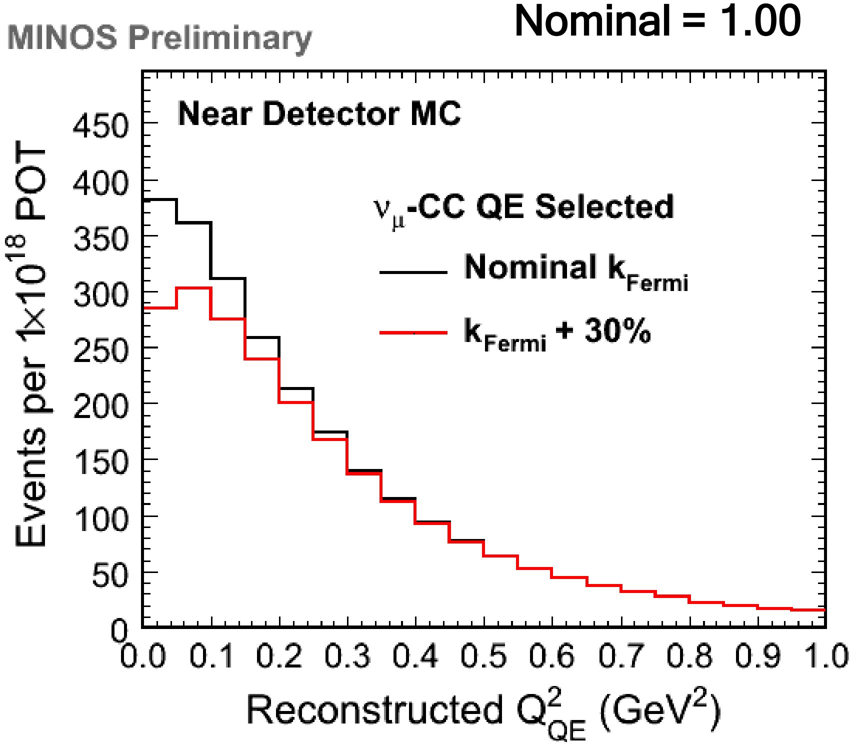


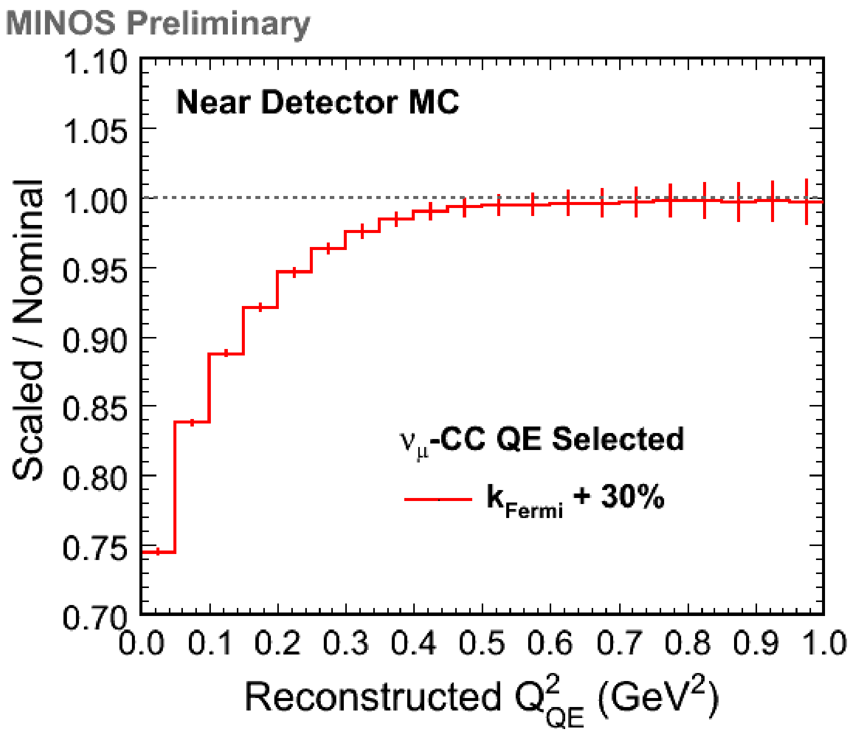


- We take a 1σ error of 15% for use in the penalty term (again, this is the published MINOS uncertainty). This parameter can change both the shape and rate of the resonance background in the QE sample.

Fit Parameter: Low Q^2 Suppression

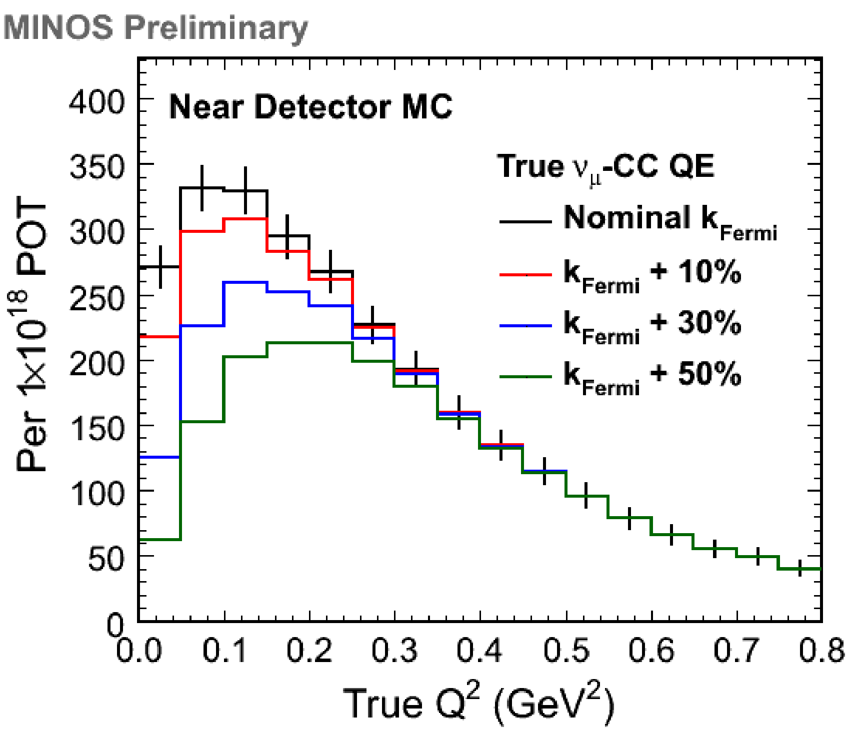
Nominal = 1.00

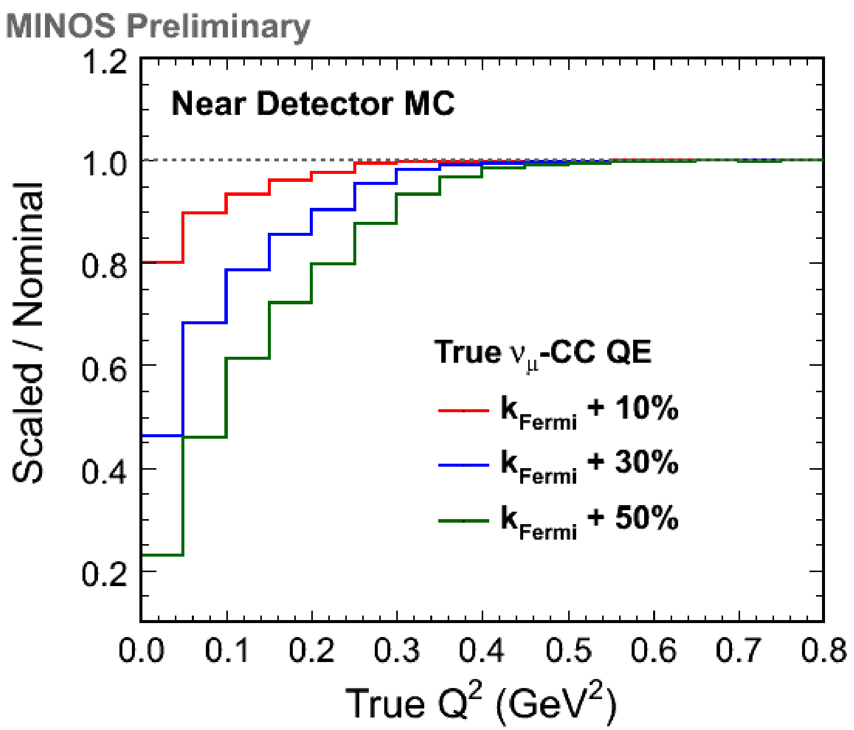




- We fit a scaling of the Fermi momentum used to Pauli-block QE events. This is an effective parameter to account for mis-modeled nuclear effects and is only used when we fit for M_A^{QE} below Q^2=0.3 GeV^2.

More on Effective Low Q^2 Suppression

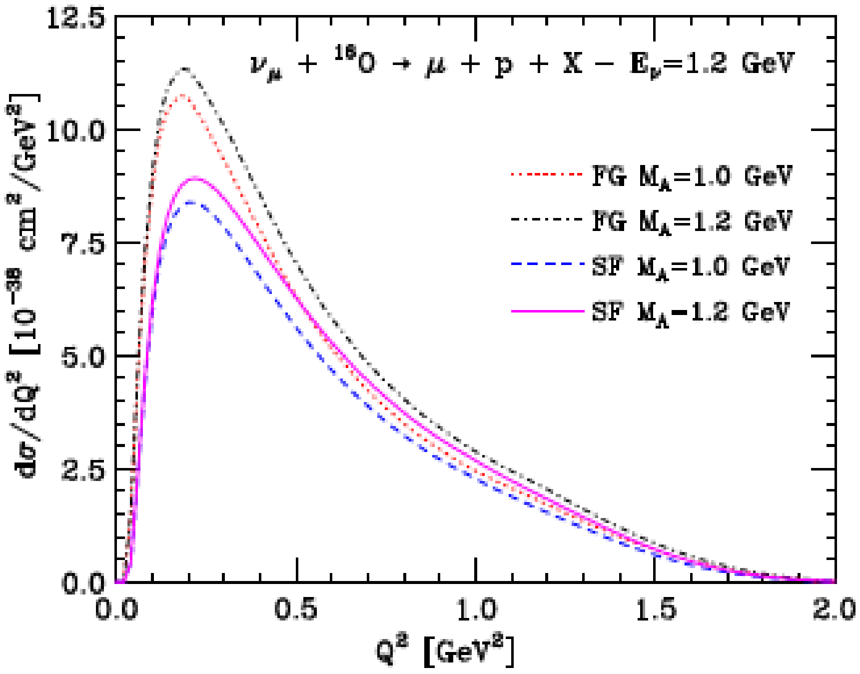




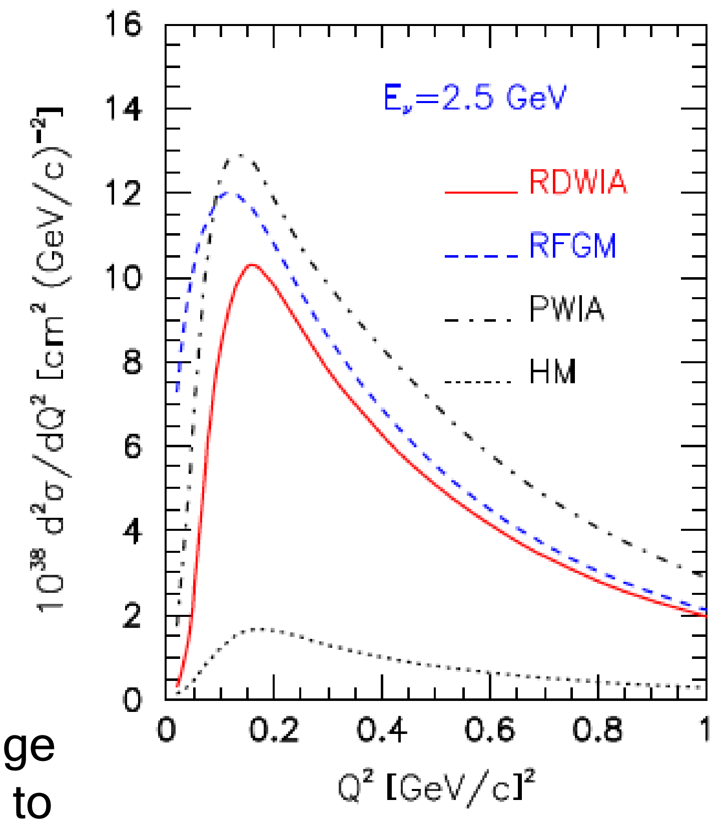
- Now looking at true Q^2 for true ν_μ-CC QE events. We take an assumed 1σ error of 30% on this parameter which corresponds to removing about 50% of the lowest Q^2 events. There are limitations for this parameter…

Examples of Nuclear Model Spread

Benhar and Meloni 2009, 0903.2329[hep-ph]



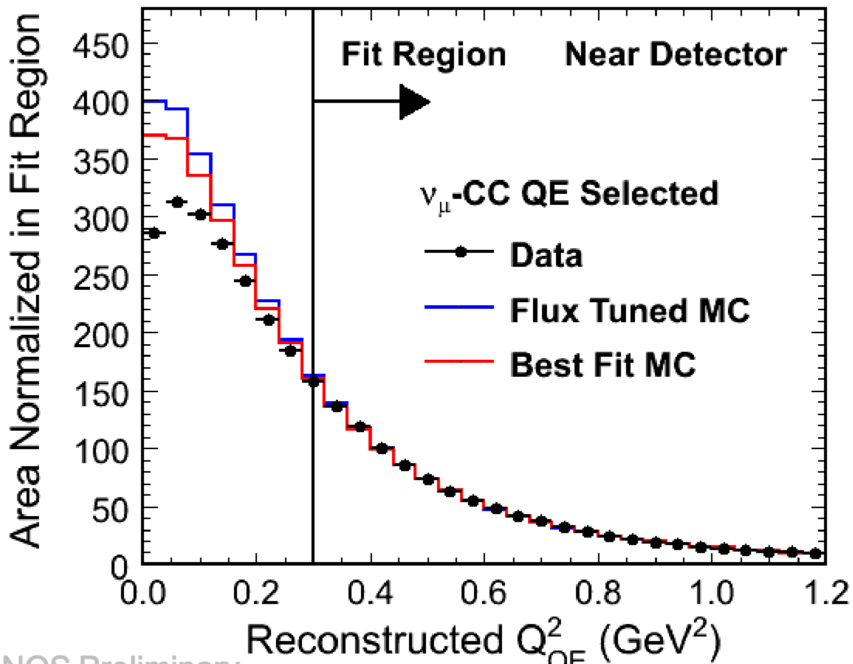
Butkevich 2008, Phys.Rev.C 78 (015501)

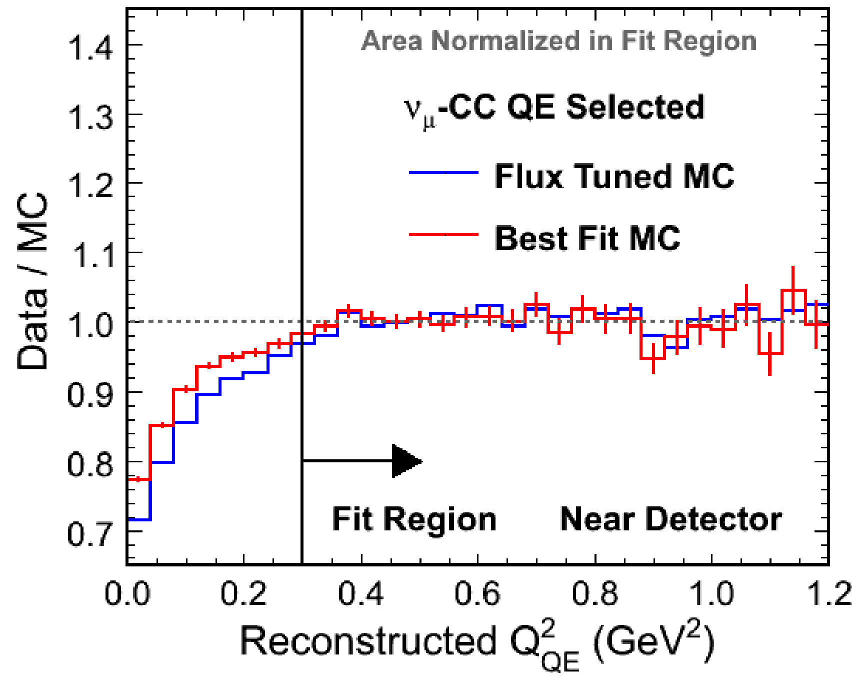


Comparing FG to SF there is a Q^2 shape change persisting out to 0.6 GeV^2. Comparing RFGM to RDWIA there is only a Q^2 shape change out to 0.2 GeV^2.

"Beyond-the-Fermi-gas" nuclear models.

Results for >0.3 GeV² Fit



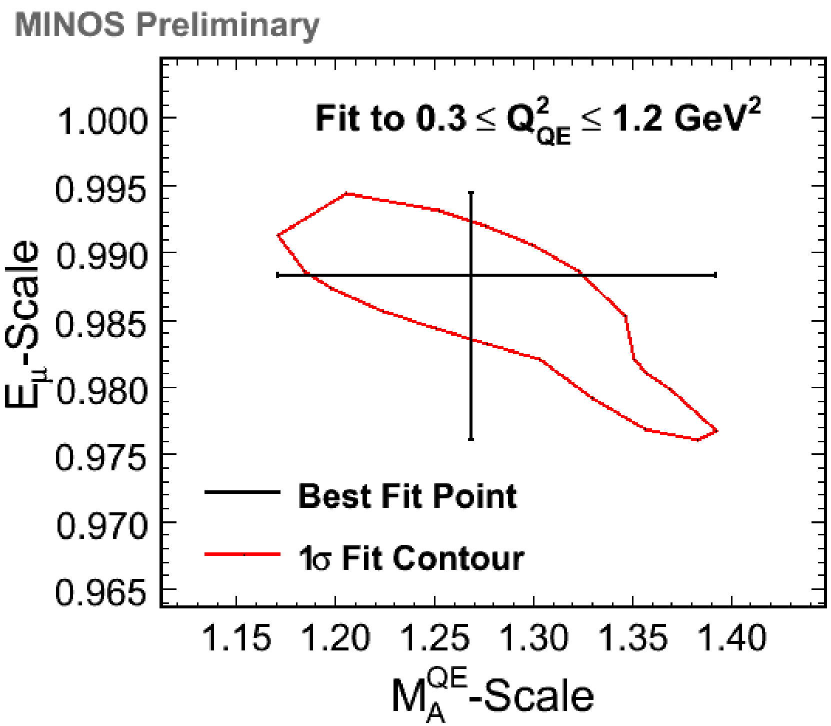


MINOS Preliminary

Parameter	M_A^{QE} (GeV)	E_μ-Scale	M_A^{RES} (GeV)
Best Fit	1.256	0.988	1.065

- Reduced χ^2: 1.545 -> 0.836
- MC Scale Factor: 1.311 -> 1.103

>0.3 GeV² Fit Contour and Correlations



Fit Parameter	M_A^{QE} Scale	E_μ Scale	M_A^{RES} Scale
M_A^{QE} Scale	1.00	-0.62	-0.55
E_μ Scale	-0.62	1.00	-0.12
M_A^{RES} Scale	-0.55	-0.12	1.00

MINOS Preliminary

- Contour drawn from MINUIT and minimized at every point with respect to the other fit parameter; the M_A^{RES}-scale. There is a relatively strong anti-correlation between these two fit parameters.

Systematic Errors and >0.3 GeV^2 Result

Change in both data and MC -> sanity check.

Re-weight the MC for changes to the normalization of low multiplicity channels.

Vary flux tuning using errors from beam fits (and from not using them at all).

Systematic Source	Positive Shift (GeV)	Negative Shift (GeV)
QE Selection Cut	0.018	0.033
Hadronic Energy Offset	0.045	0.047
Final State Interactions	0.042	0.042
DIS Cross Section	0.033	0.035
Flux Tuning	0.025	0.025
QE Nuclear Effects	0.000	0.077
RES Nuclear Effects	0.000	0.021
Quadrature Sum	0.076	0.115

MINOS Preliminary

$$\text{Effective } M_A^{QE} = 1.26\ ^{+0.12}_{-0.10}\,(\text{fit})\ ^{+0.08}_{-0.12}\,(\text{syst})\ \text{GeV}$$

MINOS Preliminary

Systematic Errors and >0.3 GeV^2 Result

Includes effects such as mis-calibration and mis-reconstruction.

Changes to intra-nuclear re-scattering parameters such as pion elastic or in-elastic scattering, charge exchange, secondary pion production, the formation time and nucleon absorption.

Investigated via changes to the value of the Fermi momentum used to apply Pauli-blocking.

Systematic Source	Positive Shift (GeV)	Negative Shift (GeV)
QE Selection Cut	0.018	0.033
Hadronic Energy Offset	0.045	0.047
Final State Interactions	0.042	0.042
DIS Cross Section	0.033	0.035
Flux Tuning	0.025	0.025
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MINOS Preliminary

$$\text{Effective } M_A^{QE} = 1.26\ ^{+0.12}_{-0.10}\,(\text{fit})\ ^{+0.08}_{-0.12}\,(\text{syst})\ \text{GeV}$$

MINOS Preliminary

Intra-Nuclear Re-Scattering (FSI)

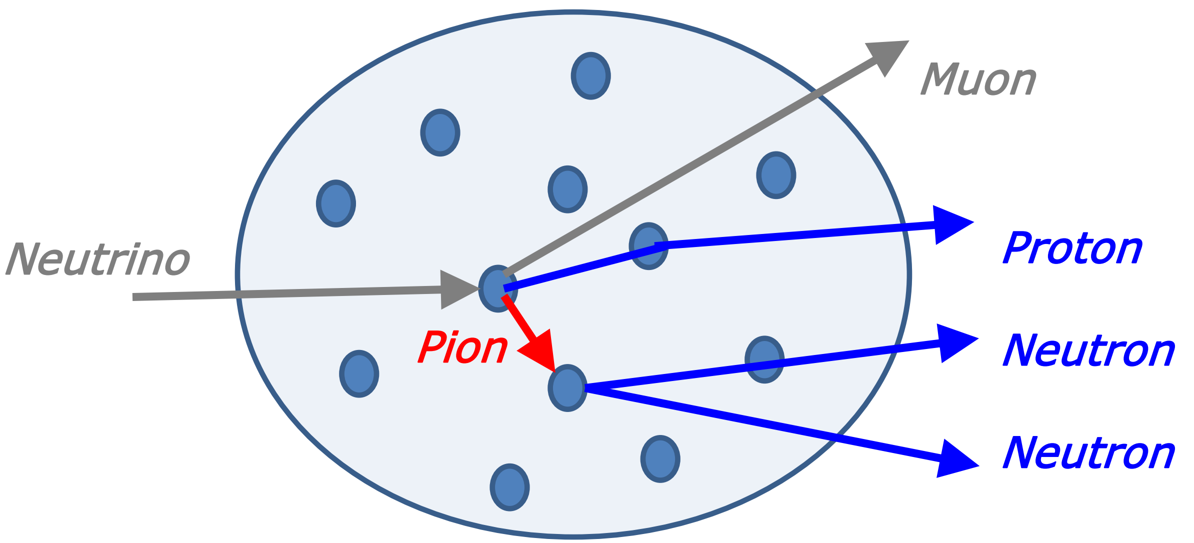
- Hadron mean free path is of order fm.
- Many possibilities to mask the primary interaction (approximately 40% in Iron).
- FSI change both the final hadronic state multiplicities and observable kinematics.

$$\nu_\mu Fe \to \mu^- p$$ or

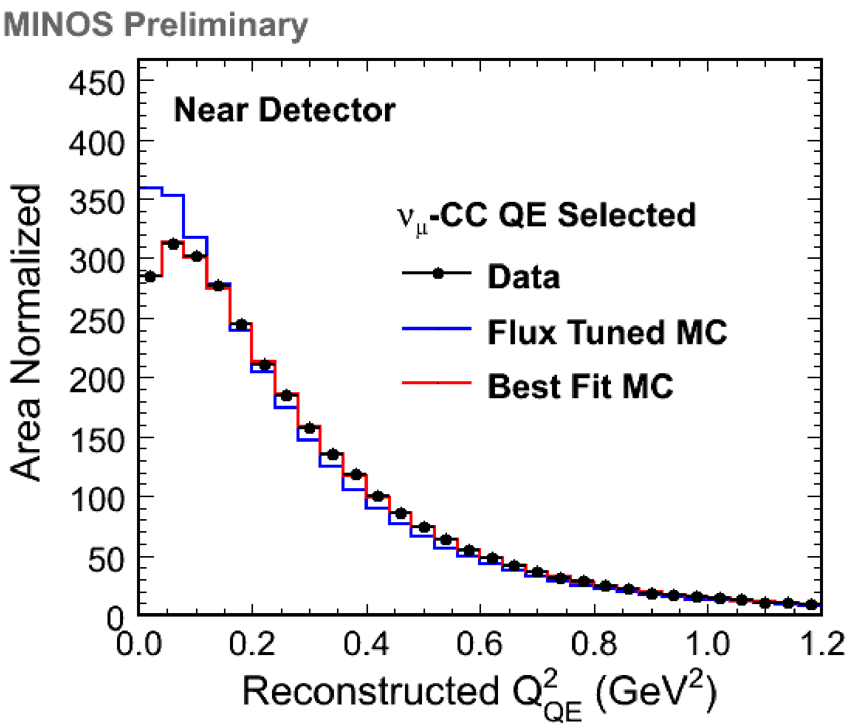
$$\nu_\mu Fe \to \mu^- ppn$$ or

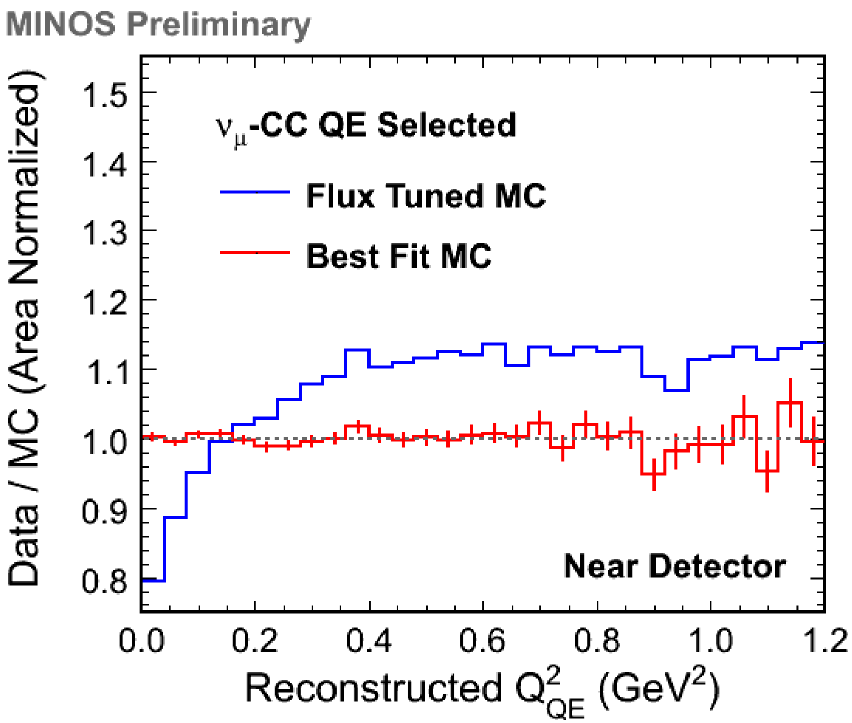
$$\nu_\mu Fe \to \mu^- ppppnnnnn$$

or...



Results for >0.0 GeV² Fit



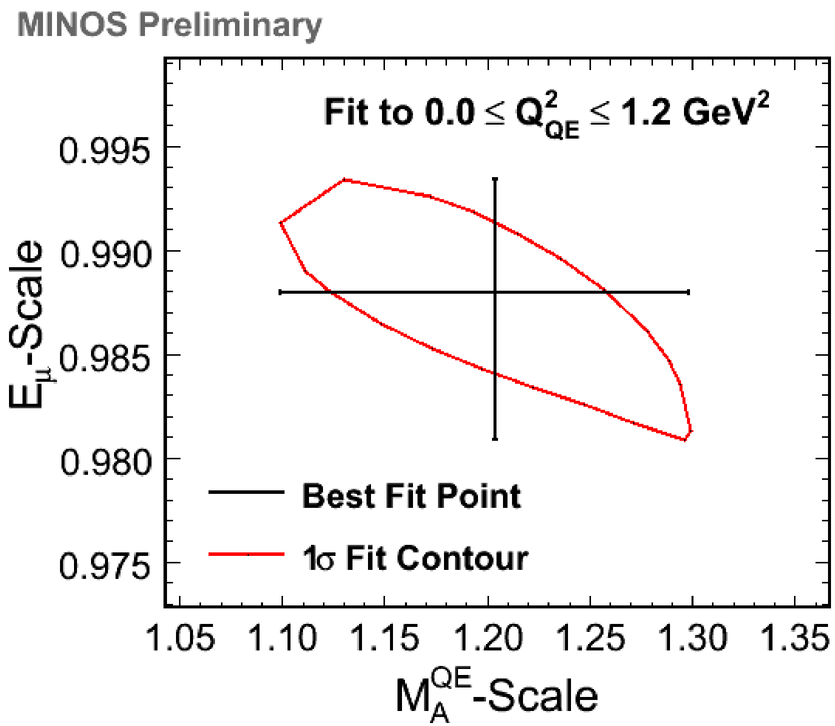


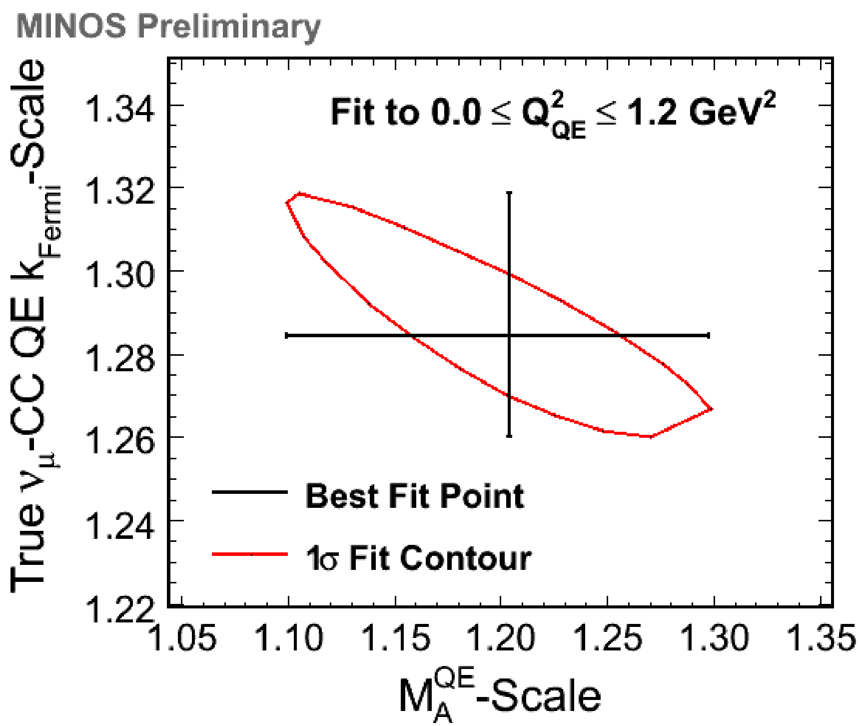
MINOS Preliminary

Parameter	M_A^{QE} (GeV)	E_μ-Scale	M_A^{RES} (GeV)	k_{Fermi}-Scale
Best Fit	1.192	0.988	1.112	1.284

- Reduced χ^2: 216.5 -> 1.023
- MC Scale Factor: 1.180 -> 1.140

>0.0 GeV^2 Fit Contours





- Contours are drawn from MINUIT and minimized at every point with respect to the other fit parameters; the M_A^{RES}-scale and either the QE Fermi momentum scale or stopping muon energy scale.

Systematic Errors and >0.0 GeV^2 Result

The results and uncertainties from the two fit configurations are very consistent!

Systematic Source	Positive Shift (GeV)	Negative Shift (GeV)
QE Selection Cut	0.027	0.066
Hadronic Energy Offset	0.065	0.075
Final State Interactions	0.079	0.079
DIS Cross Section	0.026	0.025
Flux Tuning	0.044	0.044
RES Nuclear Effects	0.023	0.000
Quadrature Sum	0.120	0.137

MINOS Preliminary

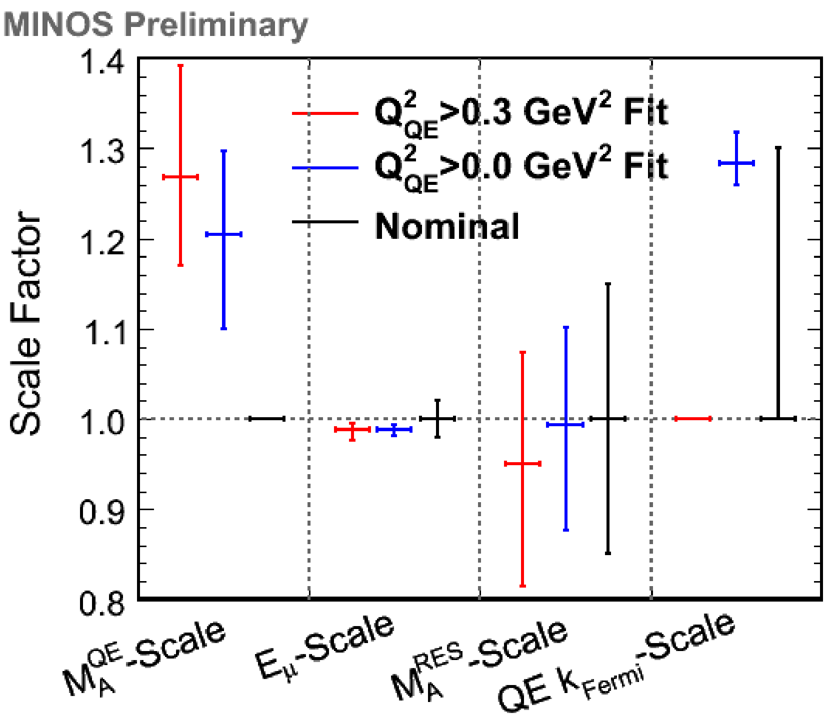
$$\text{Effective } M_A^{QE} = 1.19\ ^{+0.09}_{-0.10}\ (\text{fit})\ ^{+0.12}_{-0.14}\ (\text{syst})\ \text{GeV}$$

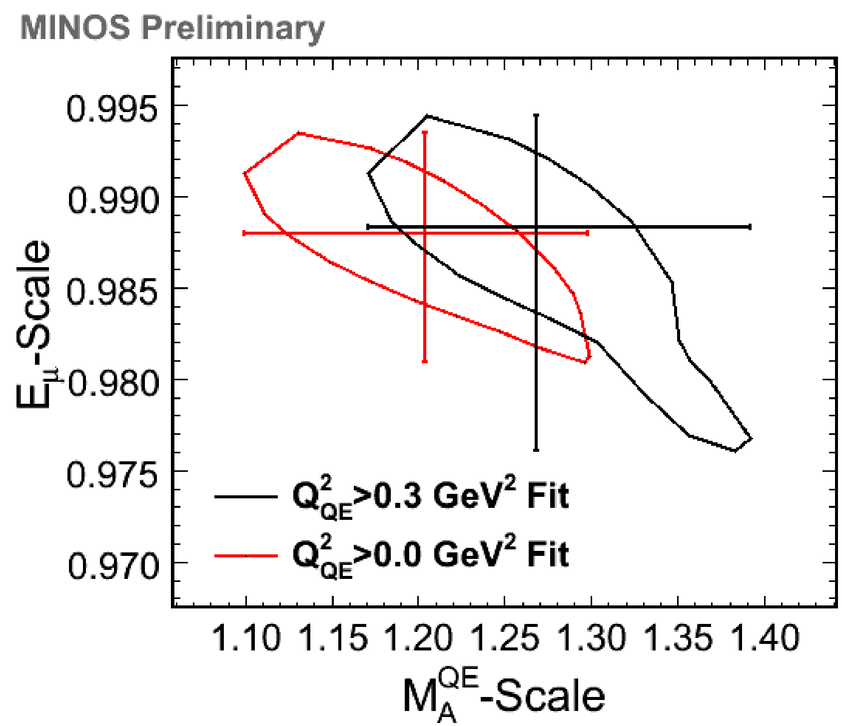
MINOS Preliminary

Fit errors are reduced because of the extra statistics from the low Q^2 region.

Additional systematic error is increased due to inclusion of low Q^2 region.

Comparison of Fit Results





- Left figure shows the two sets of fit results along with the errors returned by the fits and points showing the nominal parameter values and input 1σ errors. Right figure shows an overlay of 1σ contours from the fits.

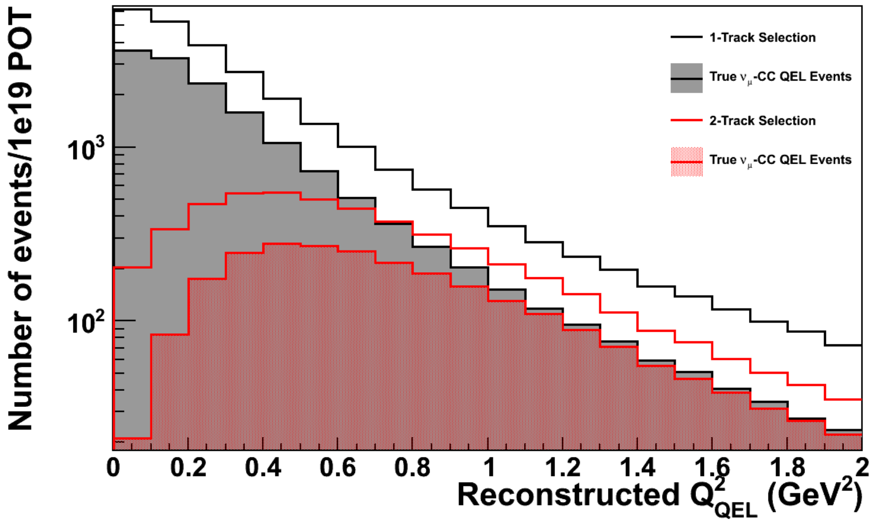
Summary

- From a fit above the region where we might expect serious nuclear effect mis-modeling we find a best fit effective $M_A^{QE} = 1.26\ ^{+0.12}_{-0.10}\ ^{+0.08}_{-0.12}$ GeV best represents our data.
- From a fit above Q^2=0.0 GeV^2 we find that a best fit effective $M_A^{QE} = 1.19\ ^{+0.09}_{-0.10}\ ^{+0.12}_{-0.14}$ GeV, along with an effective low Q^2 suppression given by taking a Fermi momentum scaling of 1.28 higher than nominal, best represents our data.
- The MINOS preliminary results, on Iron and at higher energy than K2K and MiniBooNE (2.5 GeV peak with most data from 1-6 GeV), show the same trends as these experiments.
- Our data wants more low Q^2 suppression, consistent with a ‘beyond the Fermi Gas’ nuclear model. The shape of the Q^2 spectrum requires an increase in the relative number of high Q^2 events, which we accomplish in our model by increasing M_A^{QE}.

Analysis Outlook Part 1

- There are a number of routes for extending and improving this analysis:
  - use of additional data (we have over 5 times the amount of low energy running as well as data from alternate beam configurations)
  - potential measurement with anti-neutrino QE events using the 6% contribution of anti-neutrinos to our beam
  - investigation of absolute rate and absolute cross section
  - improved QE selection:

We are developing an entirely complimentary QE selection procedure that looks for proton tracks. In particular, this sample has a higher Q^2 reach.

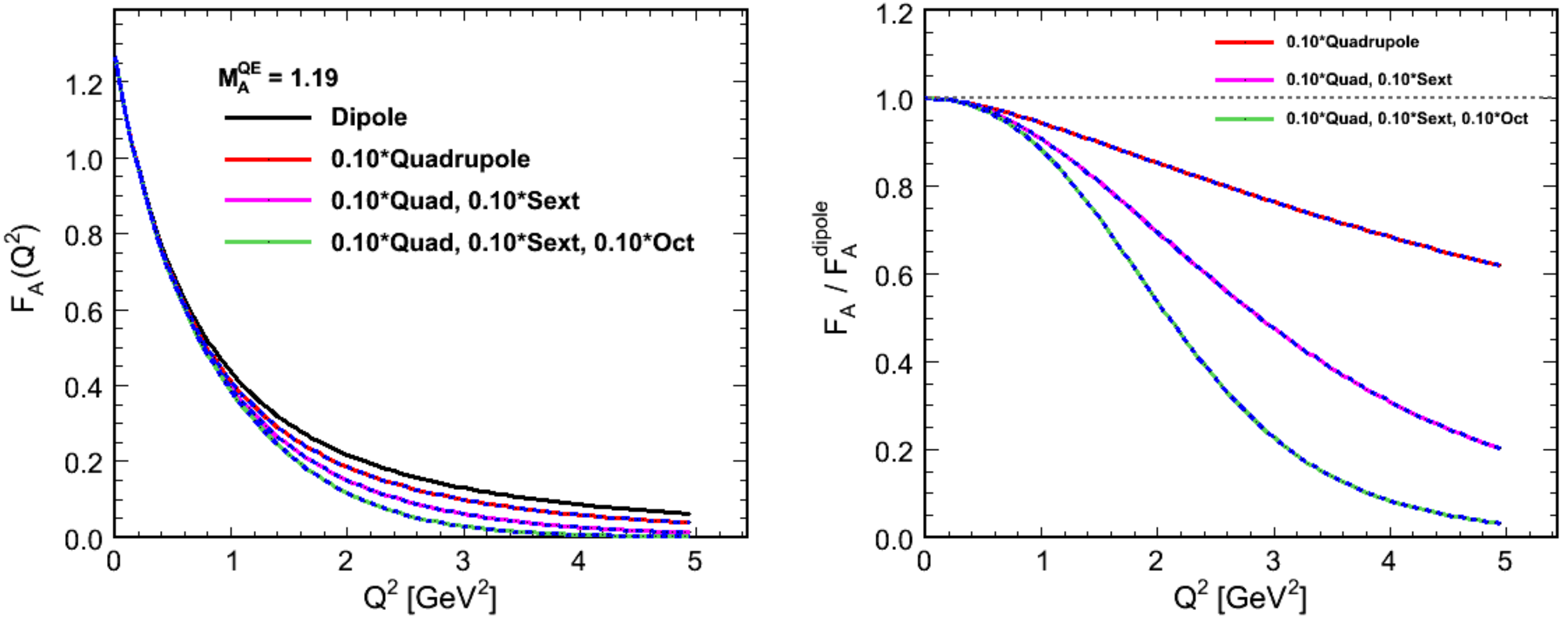


Analysis Outlook Part 2

- Currently putting together a paper in which we hope to include some statement about deviations from the dipole form for F_A:

$$F_A^{dipole} = \frac{F_A(Q^2=0)}{\left[1+\frac{Q^2}{M_A^2}\right]^2} \rightarrow F_A^{multipole} = \frac{F_A(Q^2=0)}{\left[\sum_{i=0}^{n}\frac{c_i(Q^2)^i}{(M_A^2)^i}\right]^2}$$

Where the c_i are the "pole coefficients".

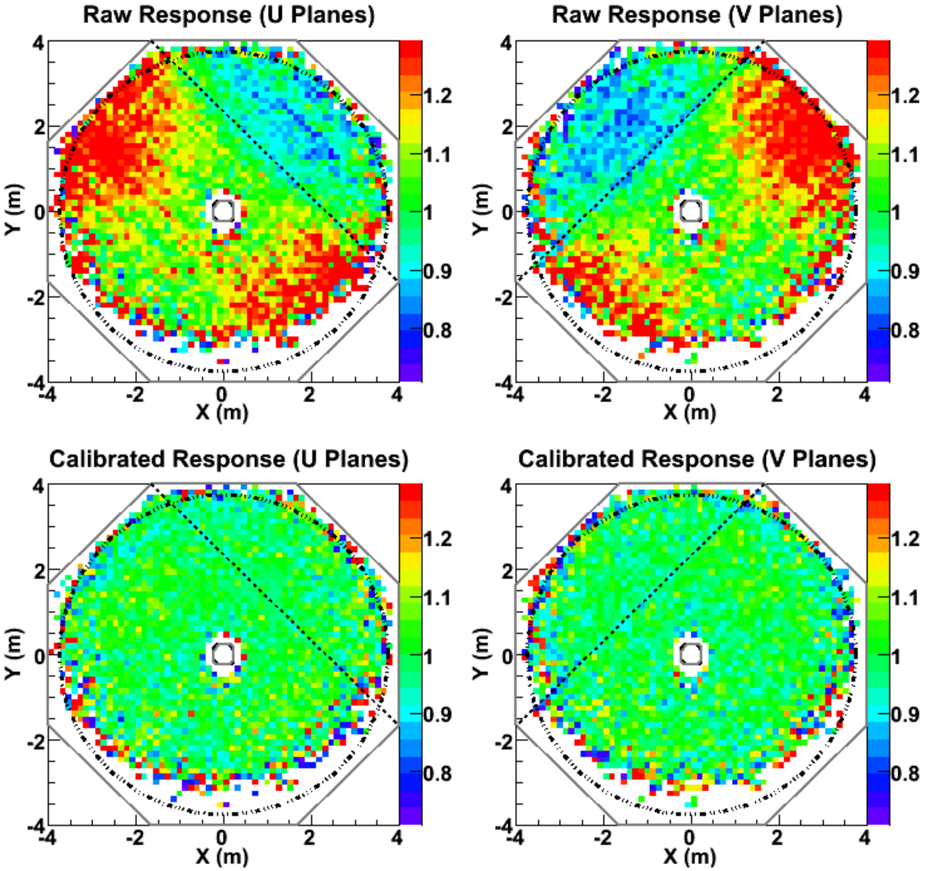


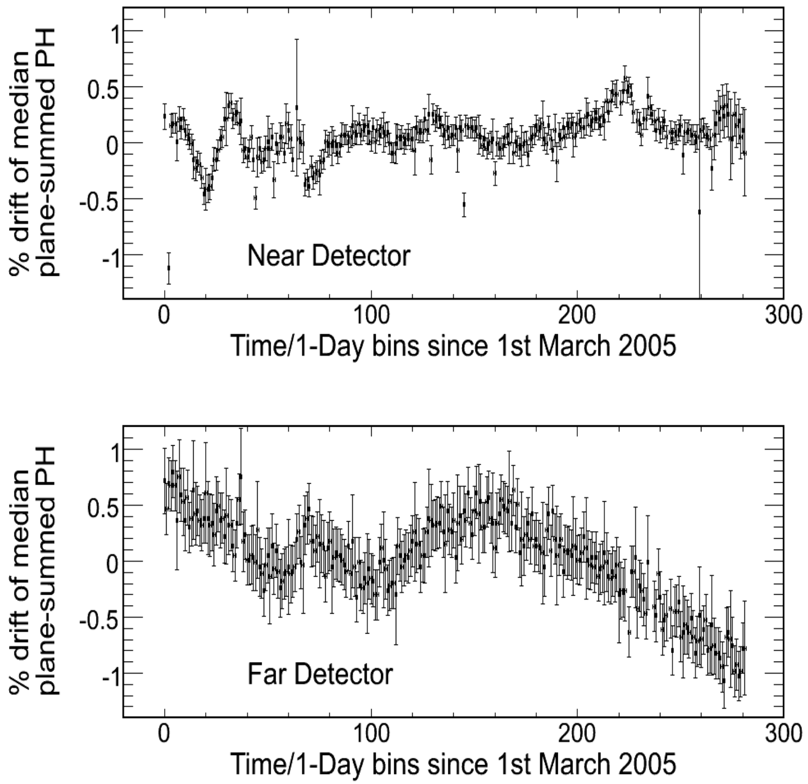
Final Remarks

- Accurate knowledge of the CCQE cross section is both important for current and future neutrino oscillation measurements but is also very interesting in it's own right.
- Understanding CCQE events involves nuclear and particle physics theory as well as knowledge from a wide variety of experimental results – complicated but interesting!
- The CCQE cross section really is a hot topic in neutrino physics at the moment – can look forward to lots of new input from experiments like T2K and, in particular, the Minerva experiment at Fermilab over the coming years.
- Any questions?

Backup Slides

Detector Calibration

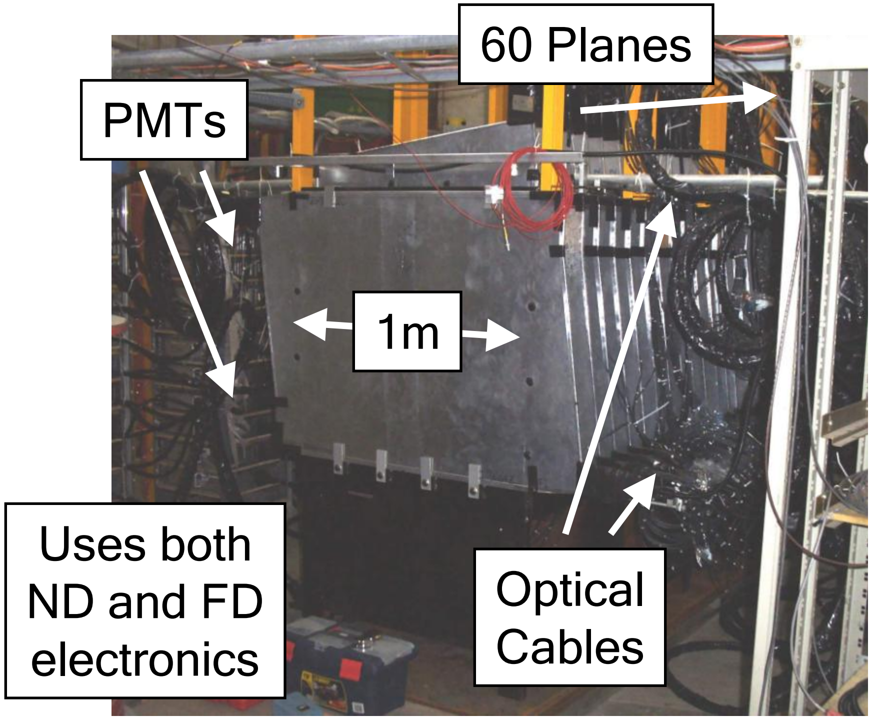


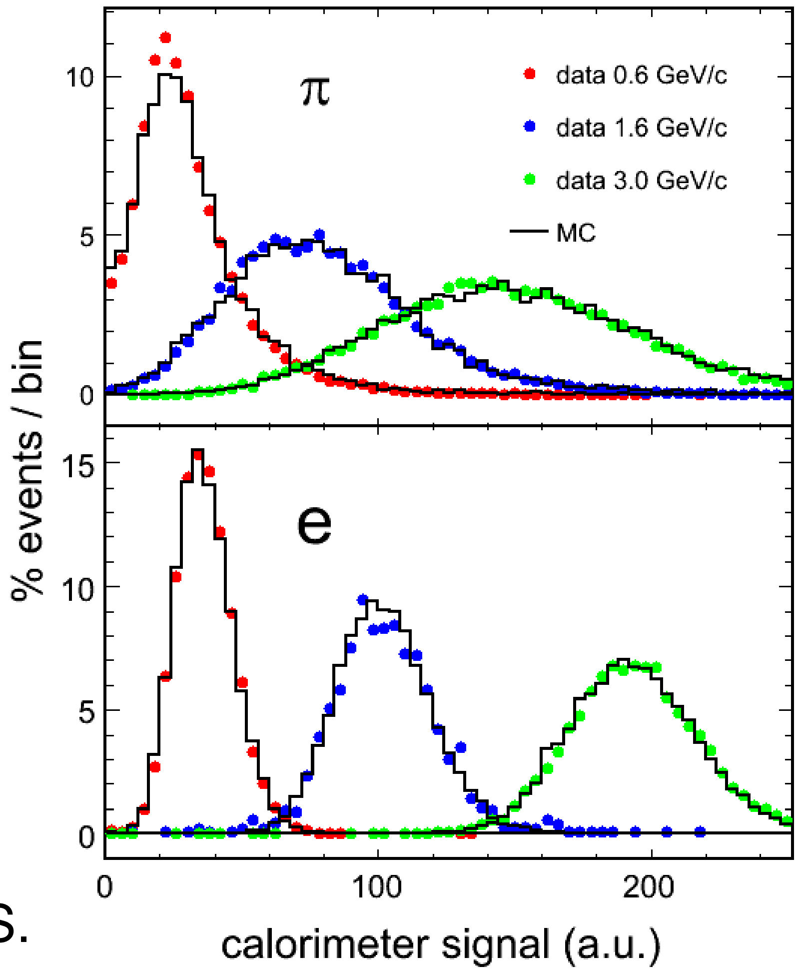


- Cosmic ray muons remove variations between and along strips.

- LED-based light injection system and cosmic muons track channel gains over time.

The Calibration Detector

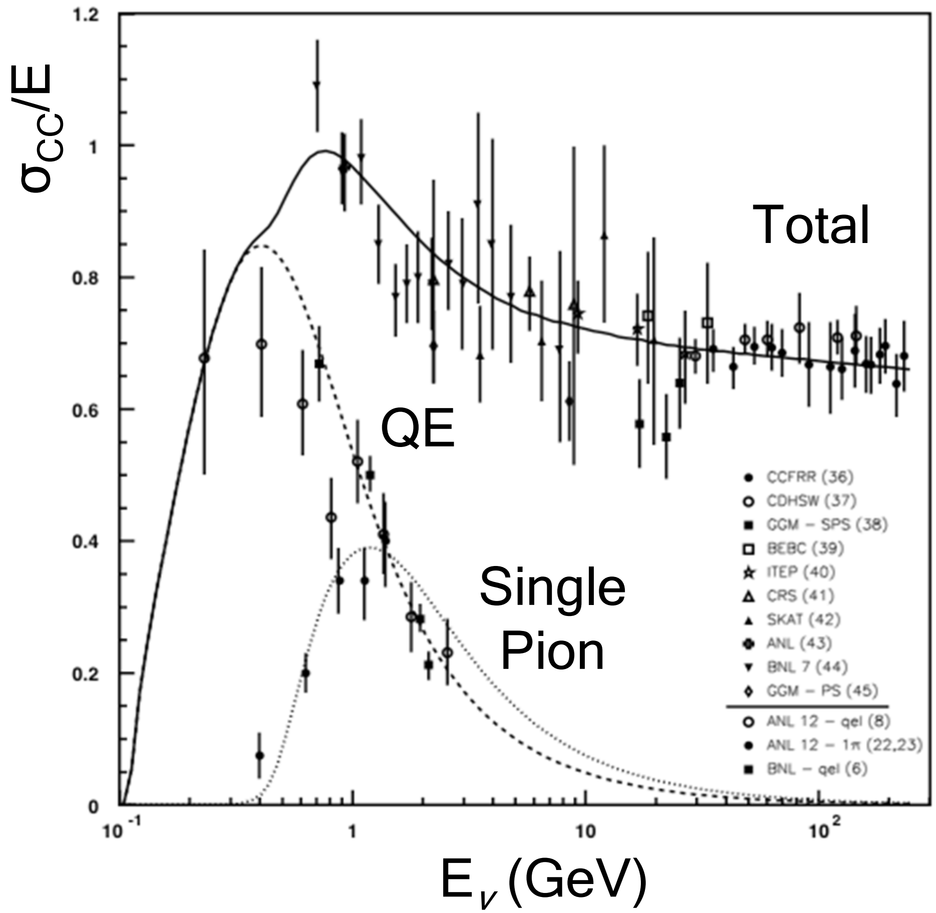




- A dedicated detector that took data at the CERN PS and provides the absolute energy calibration for MINOS.

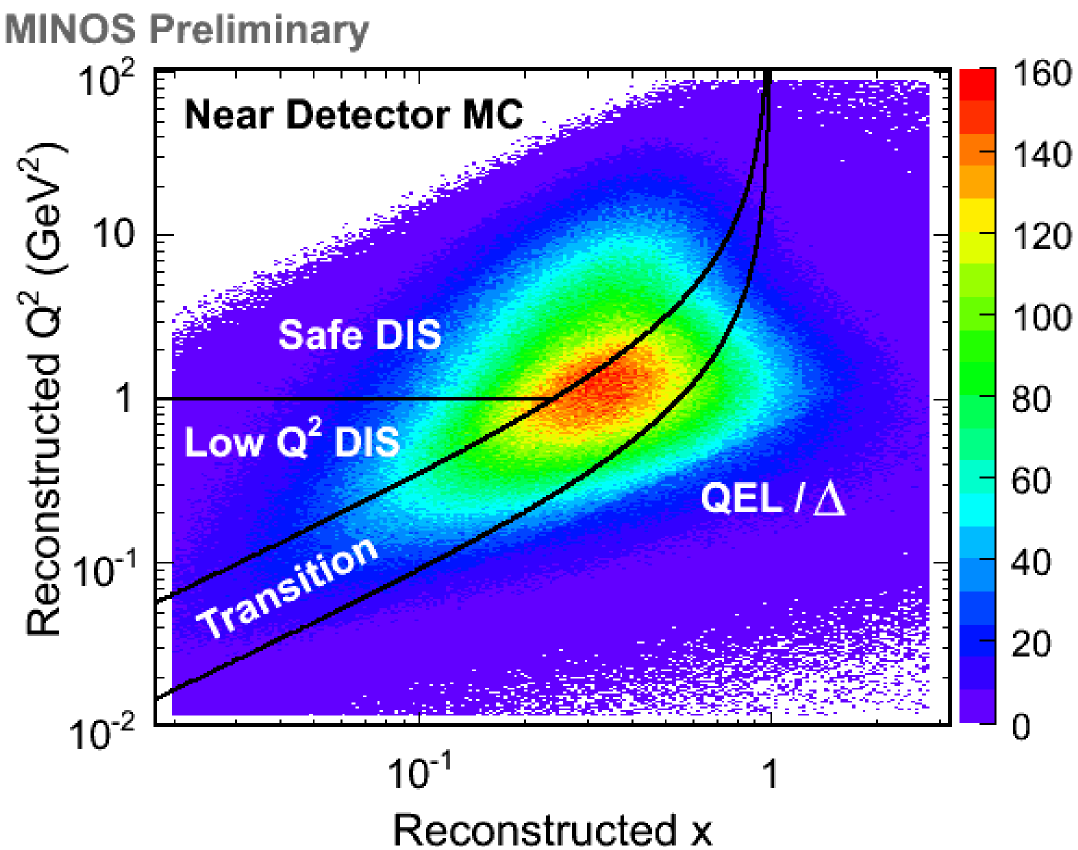
Event Generation

- NEUGEN3 event generator
- QE: BBA05 vector form factors, dipole F_A with $M_A^{QE} = 0.99$ GeV
- Resonances: Rein-Seghal model
- DIS: Bodek-Yang modified LO model, tuned to e and n data in resonance/DIS overlap region
- Coherent production
- Nuclear model: relativistic Fermi Gas (Pauli-blocking of QE)
- FSIs: nucleons and pions



- Hadronization: KNO-scaling -> PYTHIA/JETSET as W increases

CC Sample Kinematic Coverage



Sample	Selection Criteria	% of Tuned MC
Safe DIS	Q>1, W>2	32
Low Q^2 DIS	Q<1, W>2	12
Transition	1.3<W<2	24
QE / Δ	W<1.3	32

The MINOS ND sees interactions over a large region of x and Q^2.

- These sub-samples correspond roughly to kinematic regions where the event generator is using a different piece of the interaction model.

MiniBooNE Result (Pre-NUINT09)

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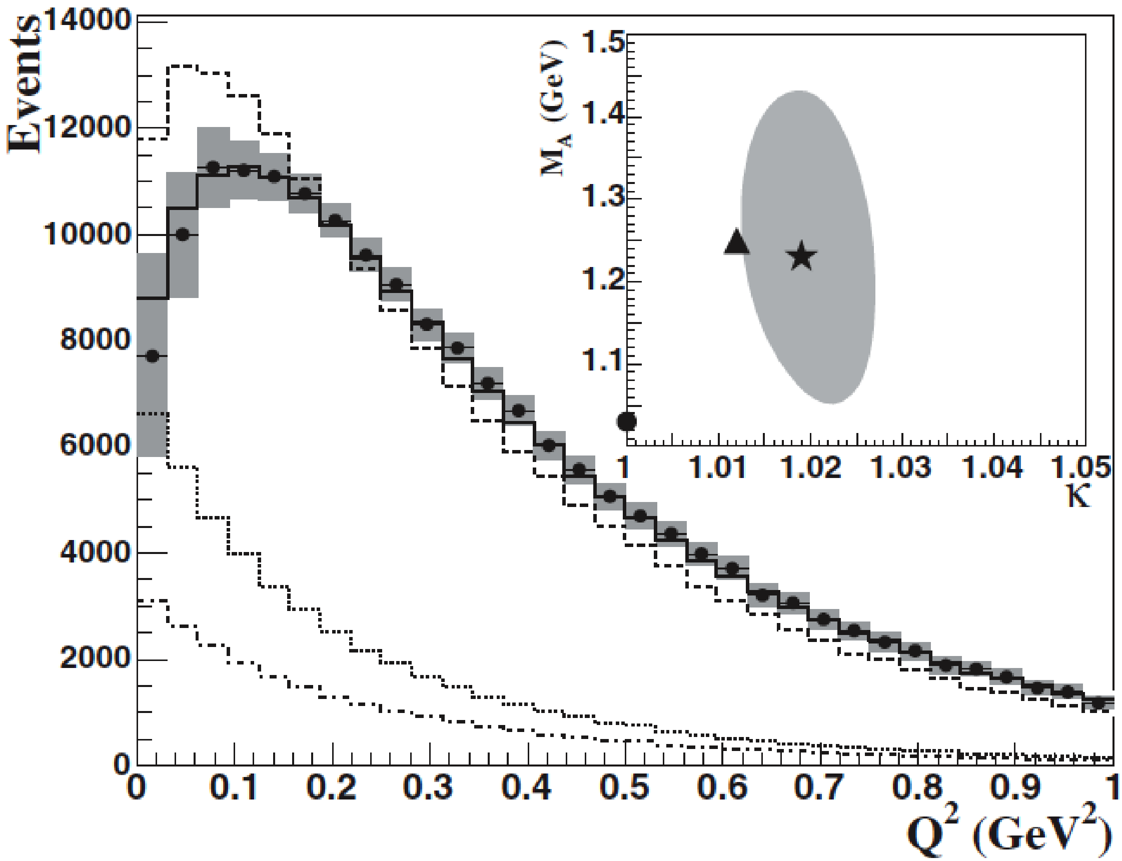

- On Carbon
- Extra low Q^2 suppression wanted by data.
- Region below 0.2 is fit with κ (= extra Pauli-blocking) .

M_A^{QE} = 1.23 ± 0.2

K2K Result

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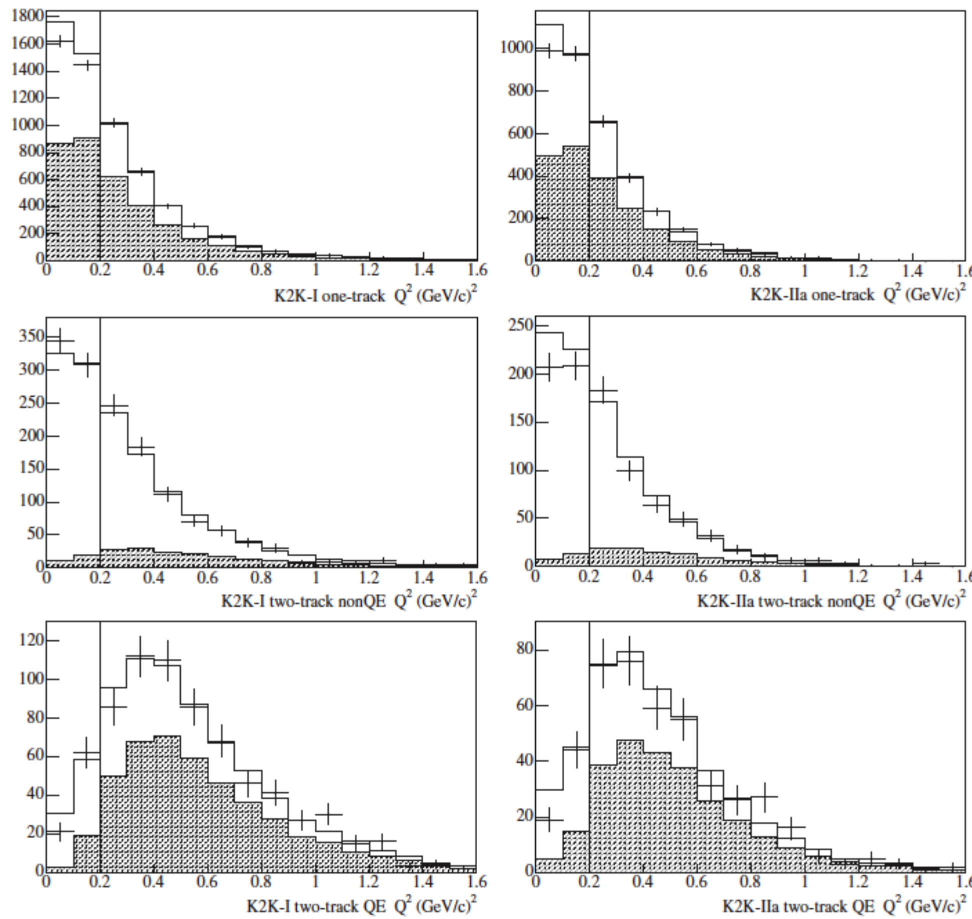
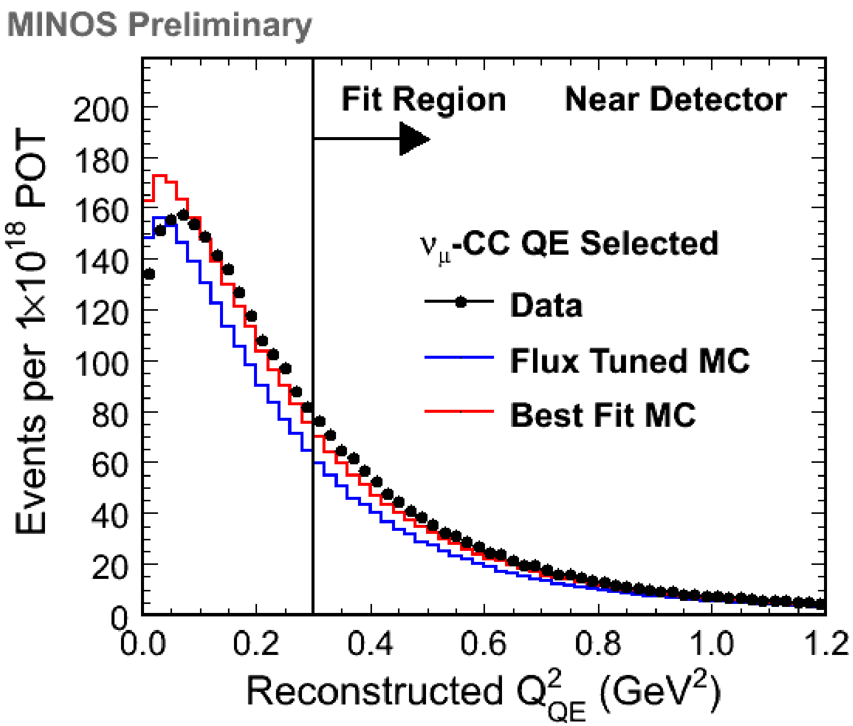
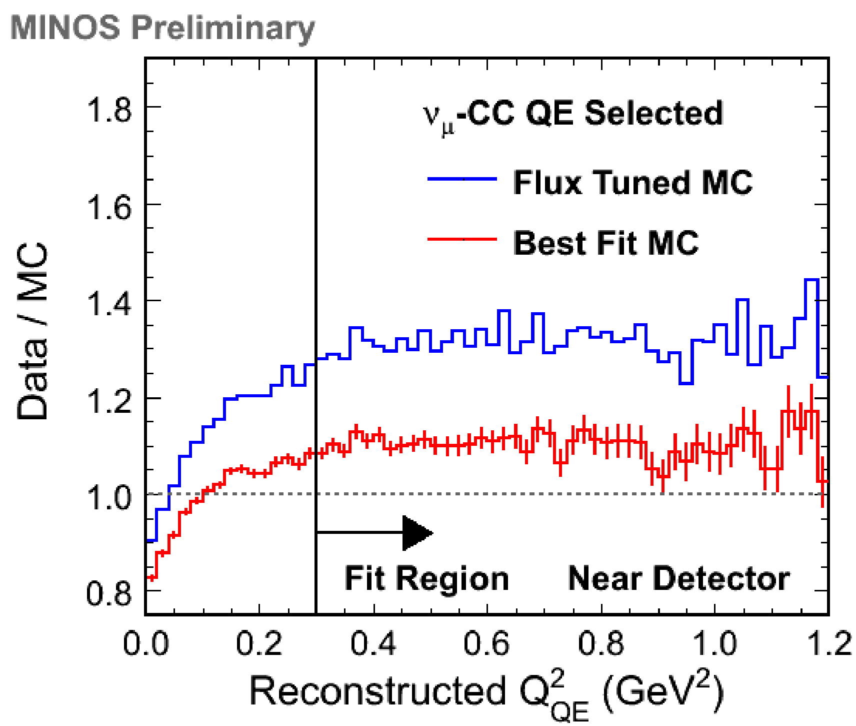
- On Oxygen
- Extra low Q^2 suppression wanted by data but no attempt to include in model or fit.
- Region below 0.2 is not fit.

$M_A^{QE} = 1.20 \pm 0.12$



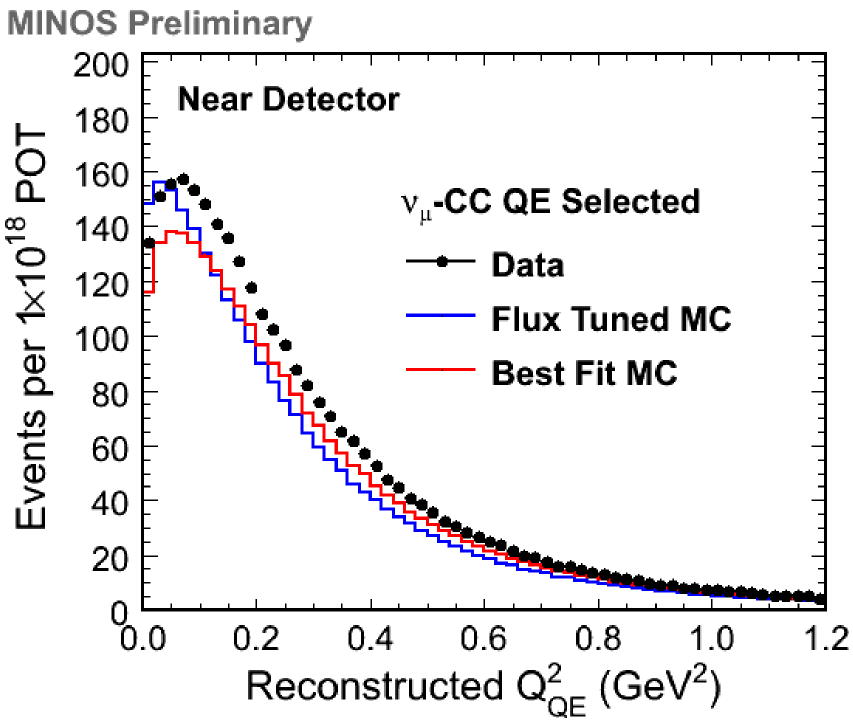
>0.3 GeV^2 Fit: Absolute Normalisation

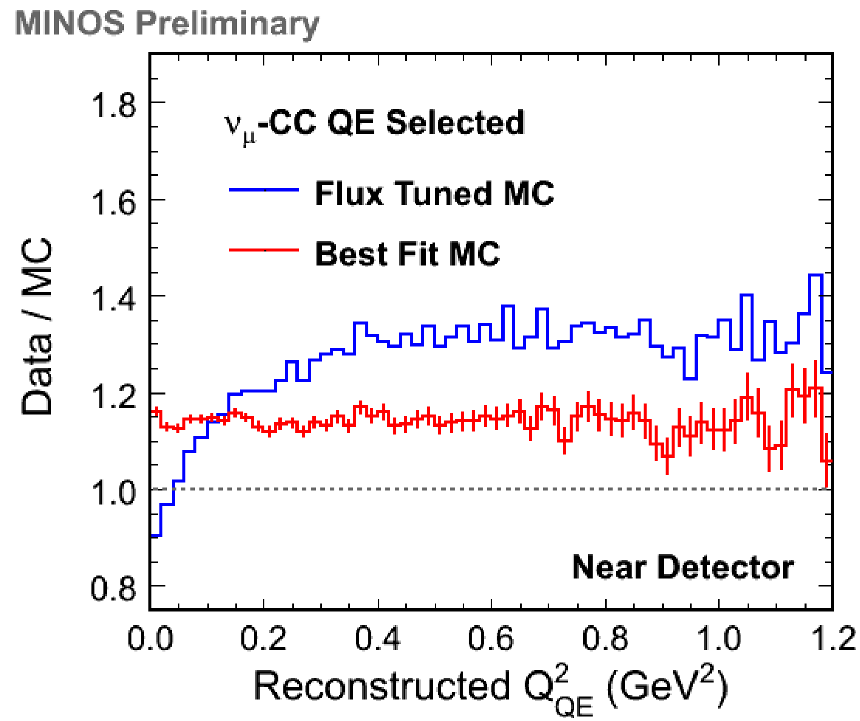




- MC is now normalized to the POT of the data. The best fit parameters do not fully correct the rate but systematic errors, such as from the flux and intra-nuclear re-scattering, would likely cover the difference.

>0.0 GeV² Fit: Absolute Normalisation





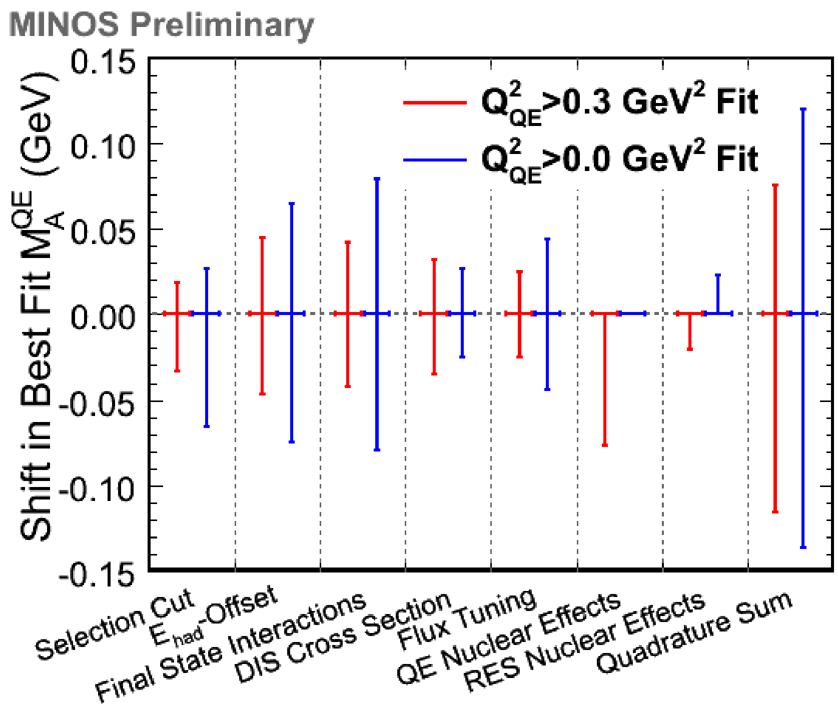
- MC is now normalized to the POT of the data. The best fit parameters do not fully correct the rate but systematic errors, such as from the flux and intra-nuclear re-scattering, would likely cover the difference.

>0.0 GeV^2 Fit: Correlation Matrix

Fit Parameter	M_A^{QE} Scale	E_μ Scale	M_A^{RES} Scale	k_{Fermi} Scale
M_A^{QE} Scale	1.00	-0.71	-0.53	-0.85
E_μ Scale	-0.71	1.00	-0.09	0.55
M_A^{RES} Scale	-0.53	-0.09	1.00	0.26
k_{Fermi} Scale	-0.85	0.55	0.26	1.00

MINOS Preliminary

Comparison of Systematic Shifts



- Comparison of the shifts in the best fit M_A^{QE} for the two fits along with the quadrature sum of the positive and negative shifts in each case.