Study of Neutrino Quasi-elastic Scattering on Iron in the MINOS Near Detector

Nick Graf (Illinois Institute of Technology)
For the MINOS Collaboration

NuFACT
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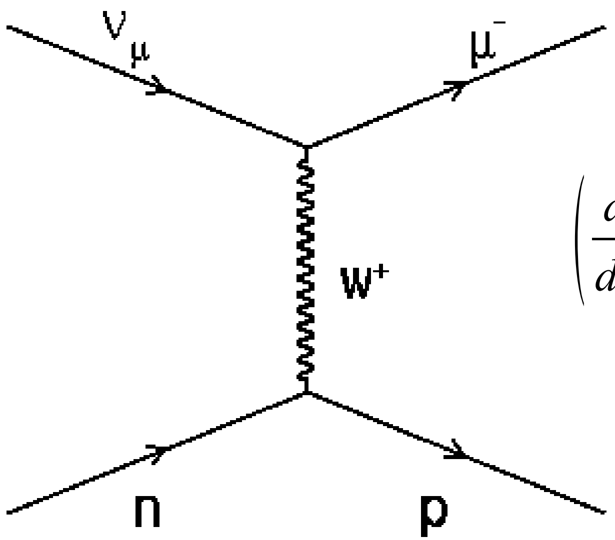
Outline

- Theory/Motivation
- MINOS Specifics
- Kinematics
- Characterizing the Background
    - Selection
    - Fit Procedure
    - Error Band
    - Discussion and Interpretation
- Quasi-elastic Axial Vector Mass Measurement
    - Selection
    - Fit Procedure
    - Results
    - Discussion and Summary

Overview of Theory

$$Q^2 = -q^2 > 0$$



Llwellyn-Smith formalism for neutrino scattering off a free nucleon.

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

Known from neutron beta-decay

$$F_A(Q^2) = \frac{F_A(0)}{\underbrace{\left(1+\frac{Q^2}{M_A^2}\right)^2}_{\text{'Dipole Form'}}}$$

The quasi-elastic axial-vector mass is the only free parameter

- *A,B,C* are functions of nucleon form factors and depend on:

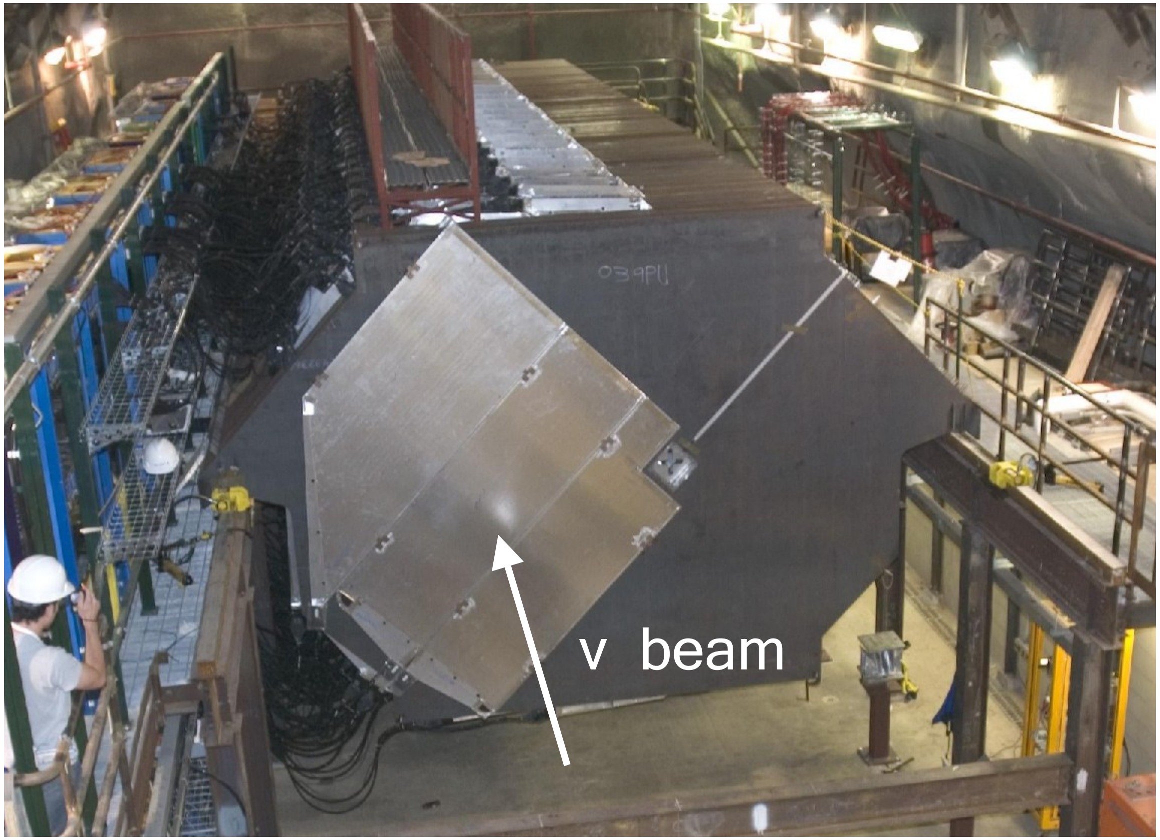
- Vector form factors measured in electron scattering.
- Dipole form of axial vector form factor. Axial form factor can only be determined from neutrino CCQE scattering.

Motivation

Experiment	Energy(GeV)	Target	M_A^{QE} (GeV)
D_2 B.C.	1	Deuterium	1.03 ± 0.05
NOMAD	3 to 100	Carbon	1.07 ± 0.09
K2K	1.0 to 2.5	O+Al, C	$1.2 \sim 1.3$
MiniBooNE	0.5 to 1.0	Carbon	$1.2 \sim 1.3$
Minerva	1-8	Carbon	Nuclear effects beyond RFG
MINOS	1-8	Iron	Results in this talk

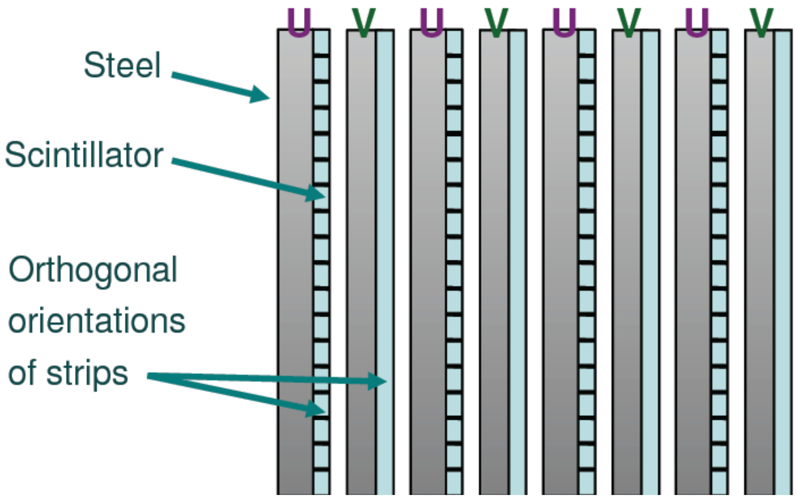
- Early neutrino bubble chamber experiments on deuterium measure M_A^{QE}~1.0 GeV.
- NOMAD uses a carbon target with higher energies and also measures M_A^{QE}~1.0 GeV.
- More recent experiments with carbon targets (K2K, MiniBooNE, SciBooNE) measure M_A^{QE}~1.25 GeV.
- MINOS has a high statistics sample of 189,000 QE candidates on iron recorded in a magnetized tracking spectrometer.

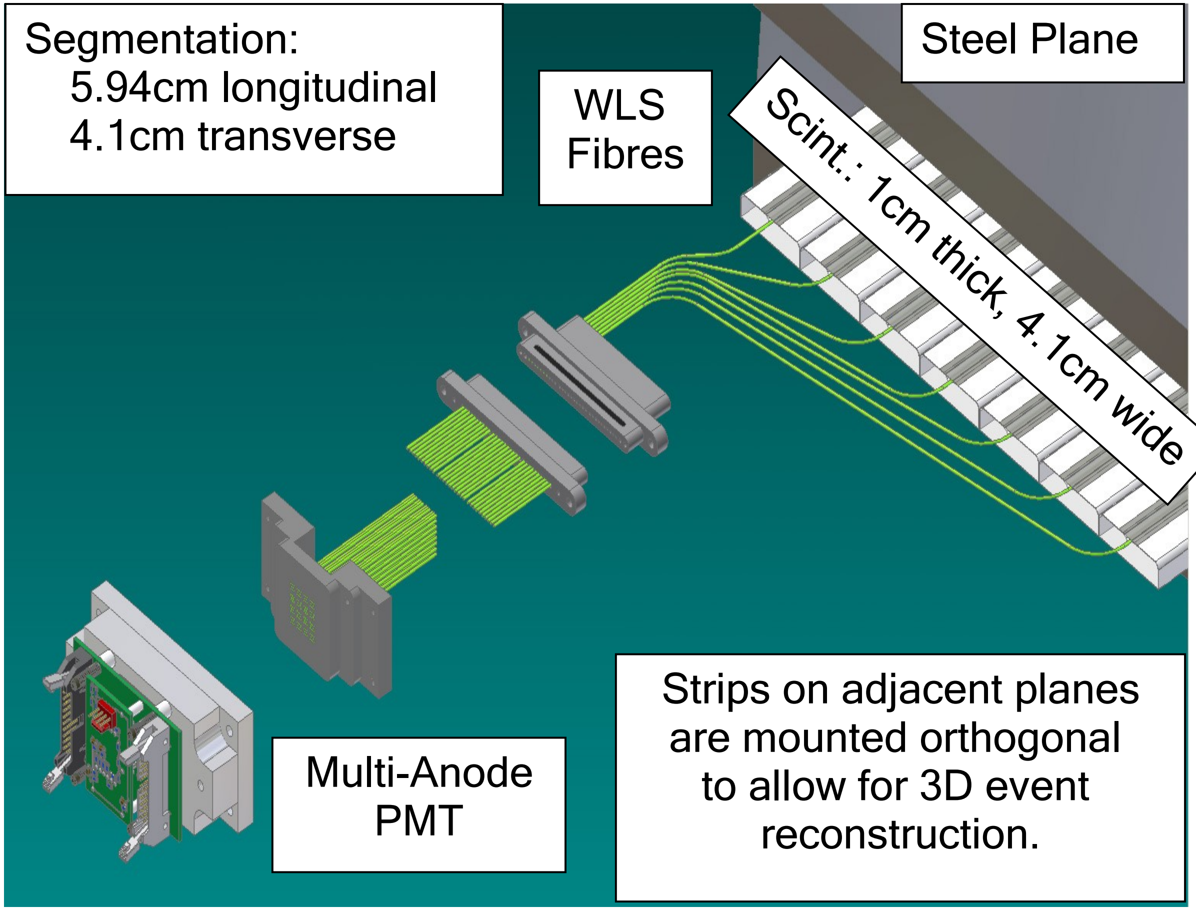
The MINOS Near Detector (ND)



- 1km from target.
- 0.98 kton (0.03 kton fiducial).
- 282 2.5 cm thick steel planes.
- Magnetized.
- P_μ from range and curvature.

The MINOS Near Detector (ND)

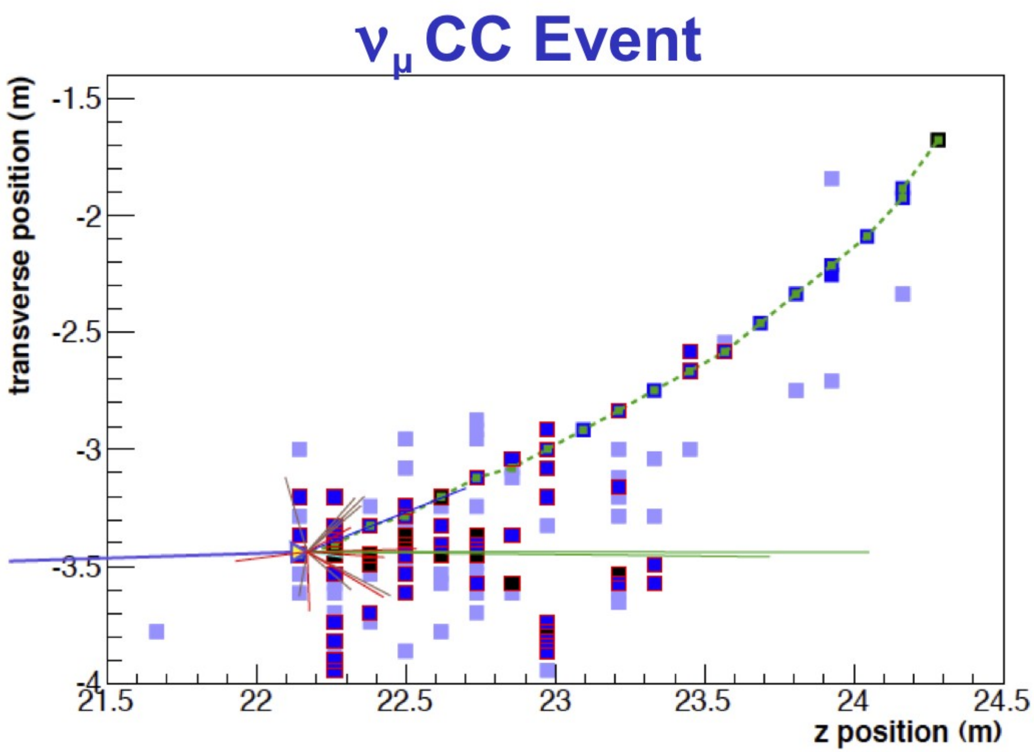


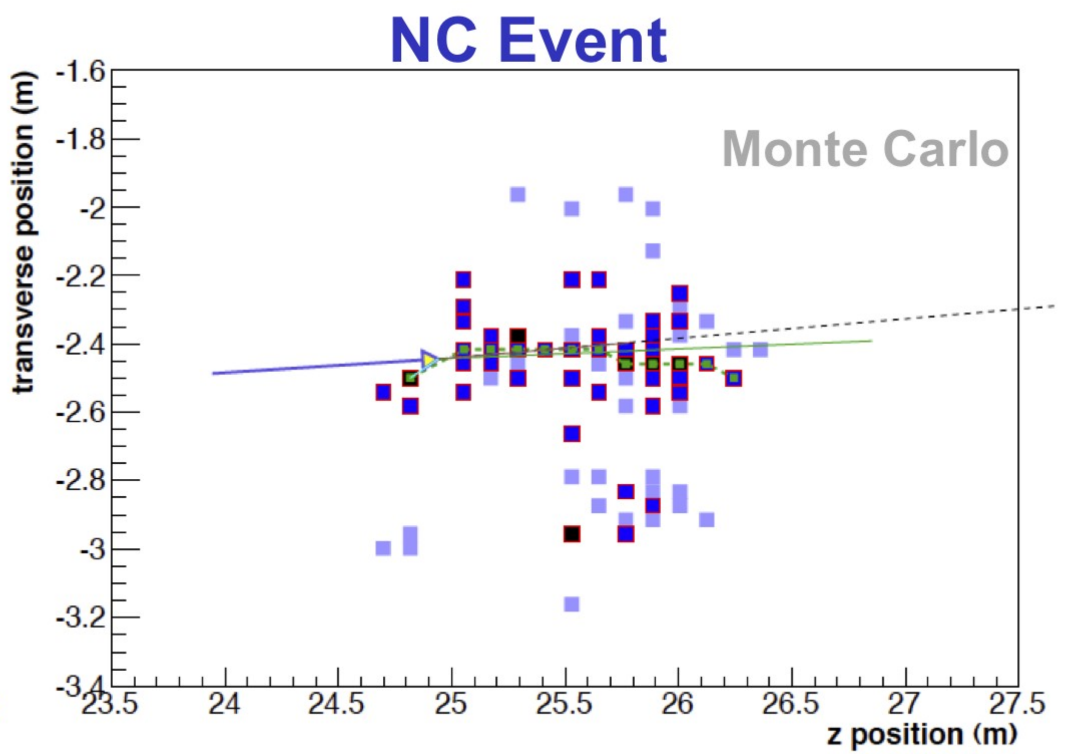


- High rates so ND is instrumented with no deadtime.

Selecting ν_μ-CC Events

- Select the majority of CC events by requiring a reconstructed track and then further enrich the sample using a multi-variate technique (kNN).
- The kNN combines variables that differentiate between muon tracks and the pion or proton tracks.
- 98% purity, 95% efficiency





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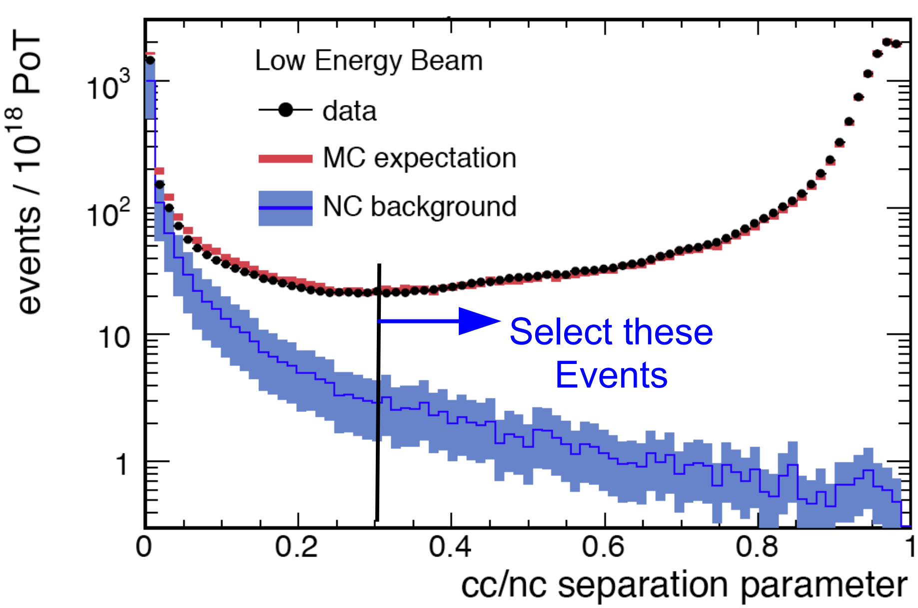
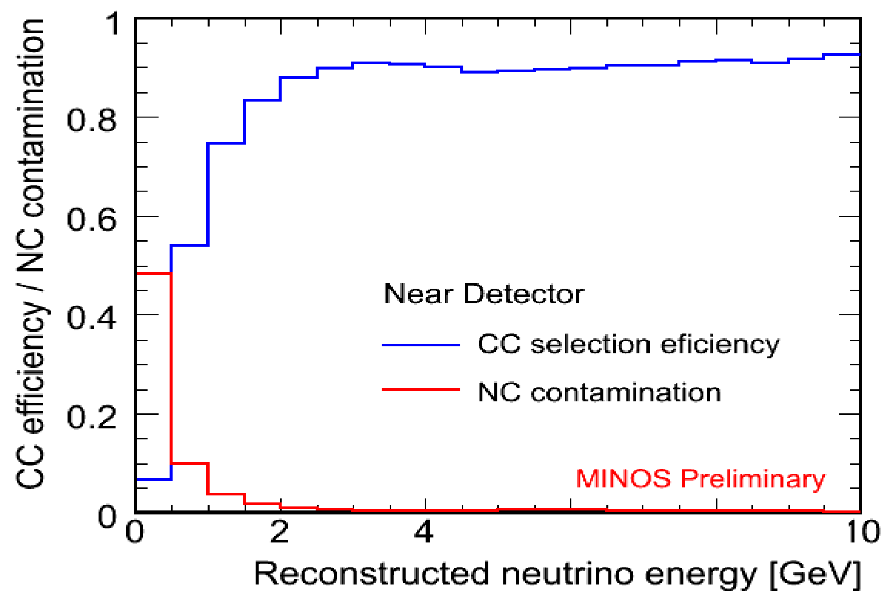
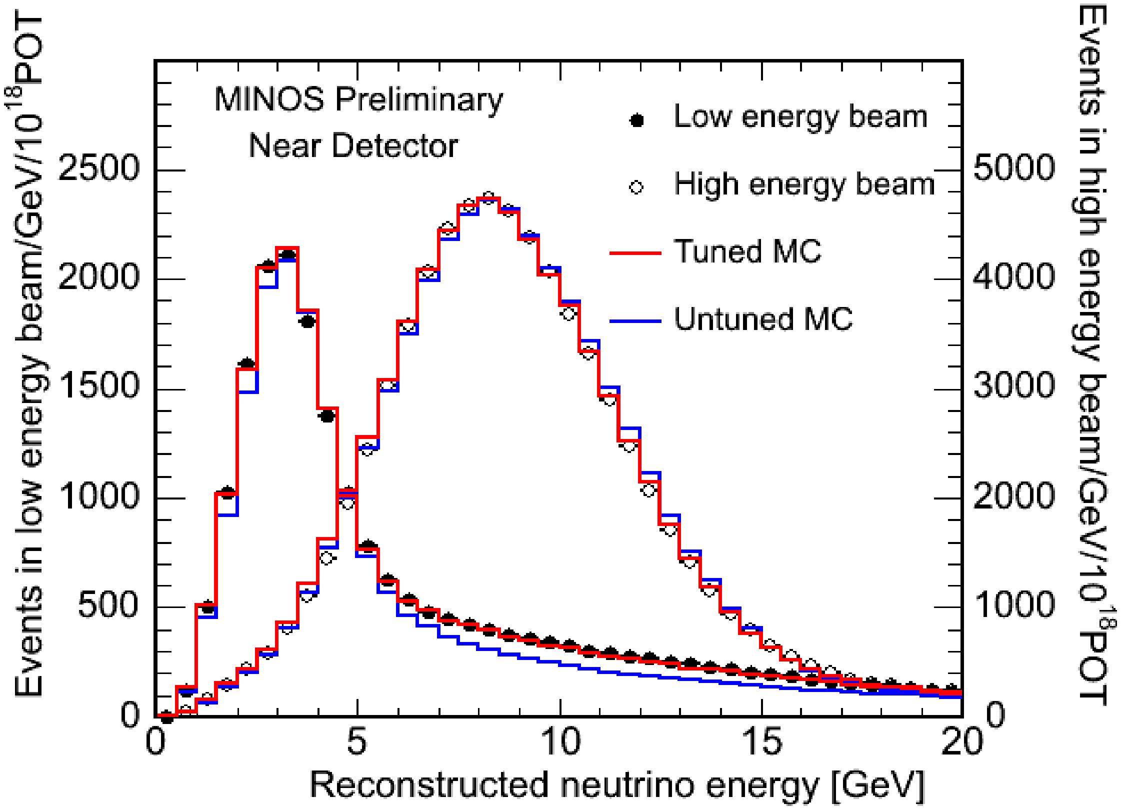


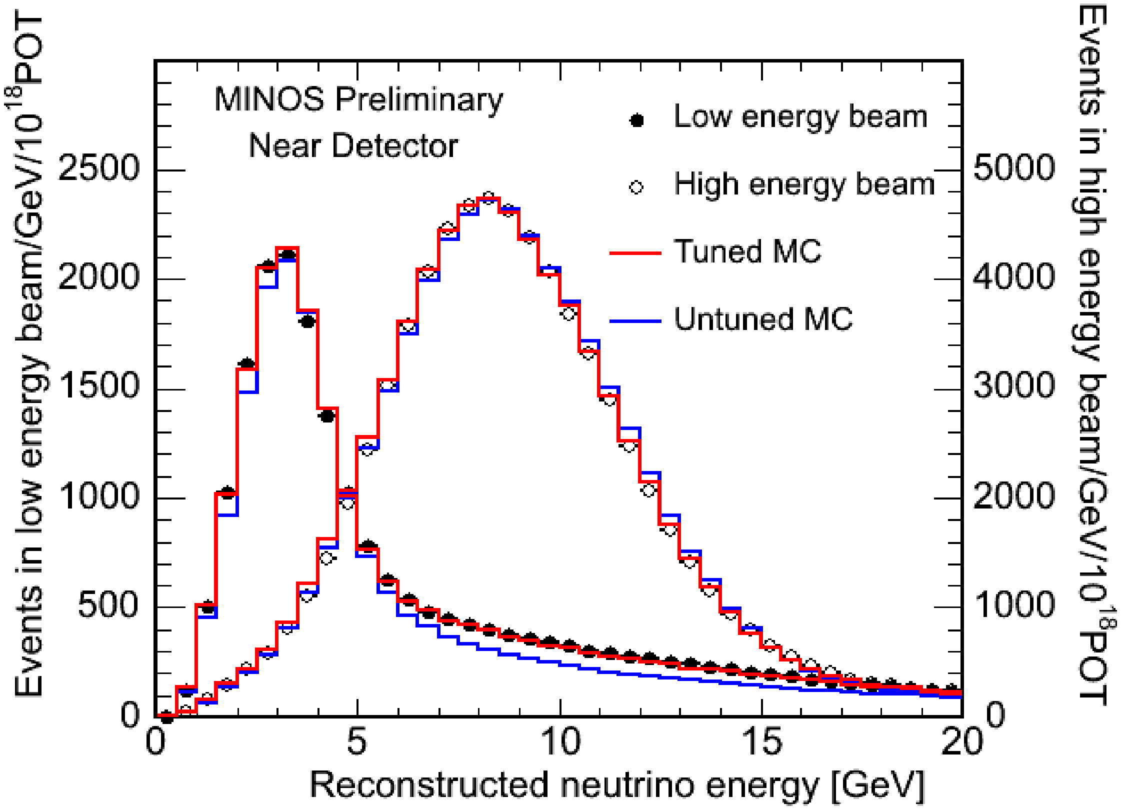


Energy Spectra and Flux Tuning



- Moving target longitudinally and varying horn current allows changing of neutrino spectrum.
- Different beam configurations sample different regions in parent hadron x_f and p_T.
- We tune our FLUKA hadron production model to match data.
- The fits also include nuisance parameters for beam optics effects, cross section and energy scales.

Energy Spectra and Flux Tuning



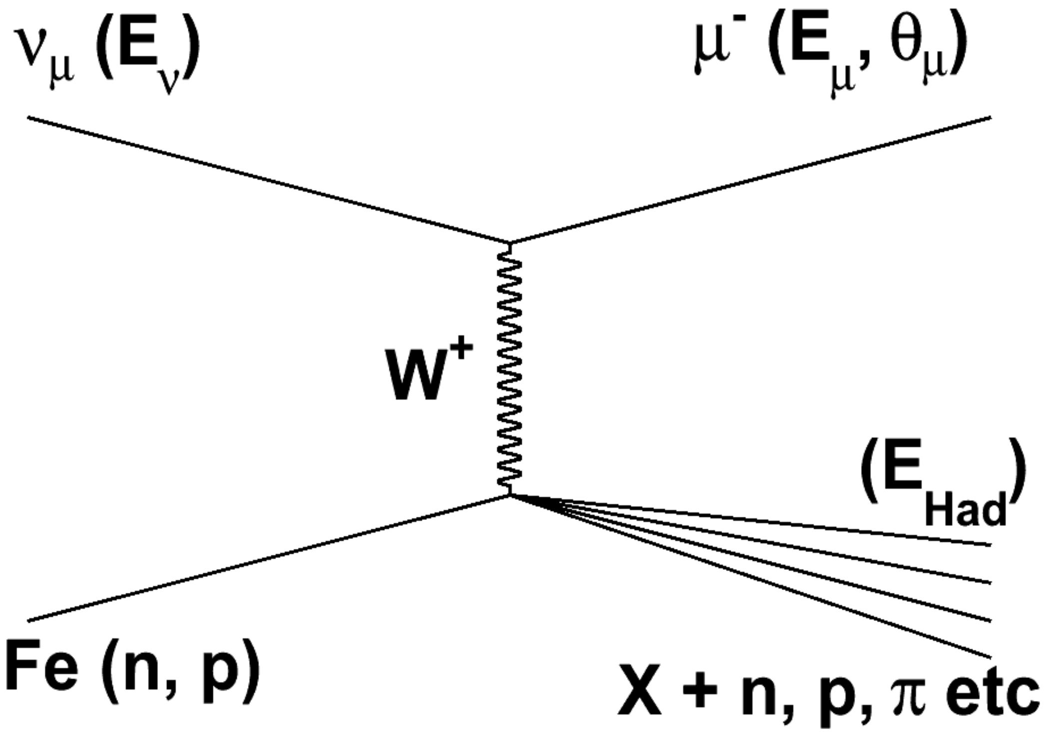
- Flux tuning procedure supported by cross section work.
- All of the MC distributions shown in my talk will use the tuned hadron production model.
- Our shape only result does not significantly depend on this tuning.

MINOS MC

Neutrino interactions simulated with the NEUGEN event generator (*Nucl. Phys. Proc. Suppl.* **112** *(2002) 188*), precursor to GENIE and very similar.

- Quasi-elastic interactions:
  - Llewellyn-Smith Model (*Phys. Rep.* **3** *(1972) 261*)
  - Custom Relativistic Fermi Gas (RFG) Nuclear Model
- Resonance Production:
  - Rein-Seghal Model (*Ann. Phys.* **133** *(1981) 79*)
- DIS interactions:
  - Modified Bodek-Yang model (*AIP Conf. Proc.* **721** *(2004) 358*)
    - KNO scaling at low invariant mass (*Nucl. Phys. B* **40** *(1972) 317*)
    - PYTHIA/JETSET at higher invariant mass (*JHEP* **0605** *(2006) 026*)

Kinematics



- MINOS can reconstruct everything about the muon: E_μ, p_μ, $\cos(\theta_\mu)$.
- Just the energy of the hadron shower: E_{had}.

Kinematics

Sideband Samples	QE-like Sample
$E_\nu = E_\mu + E_{had}$	$E_\nu^{QE} = \dfrac{(m_N - \epsilon_B) E_\mu + (2\mathrm{m}_N \epsilon_B - \epsilon_B^2 - m_\mu^2)/2}{(m_N - \epsilon_B) - E_\mu + p_\mu \cos(\theta_\mu)}$
$Q^2 = 2 E_\nu (E_\mu - p_\mu \cos(\theta_\mu)) - m_\mu^2$	$Q_{QE}^2 = 2 E_\nu^{QE} (E_\mu - p_\mu \cos(\theta_\mu)) - m_\mu^2$
$W^2 = m_N^2 + 2\mathrm{m}_N E_{had} - Q^2, \quad x_{Bjorken} = \dfrac{Q^2}{2\mathrm{m}_N E_{had}}$	

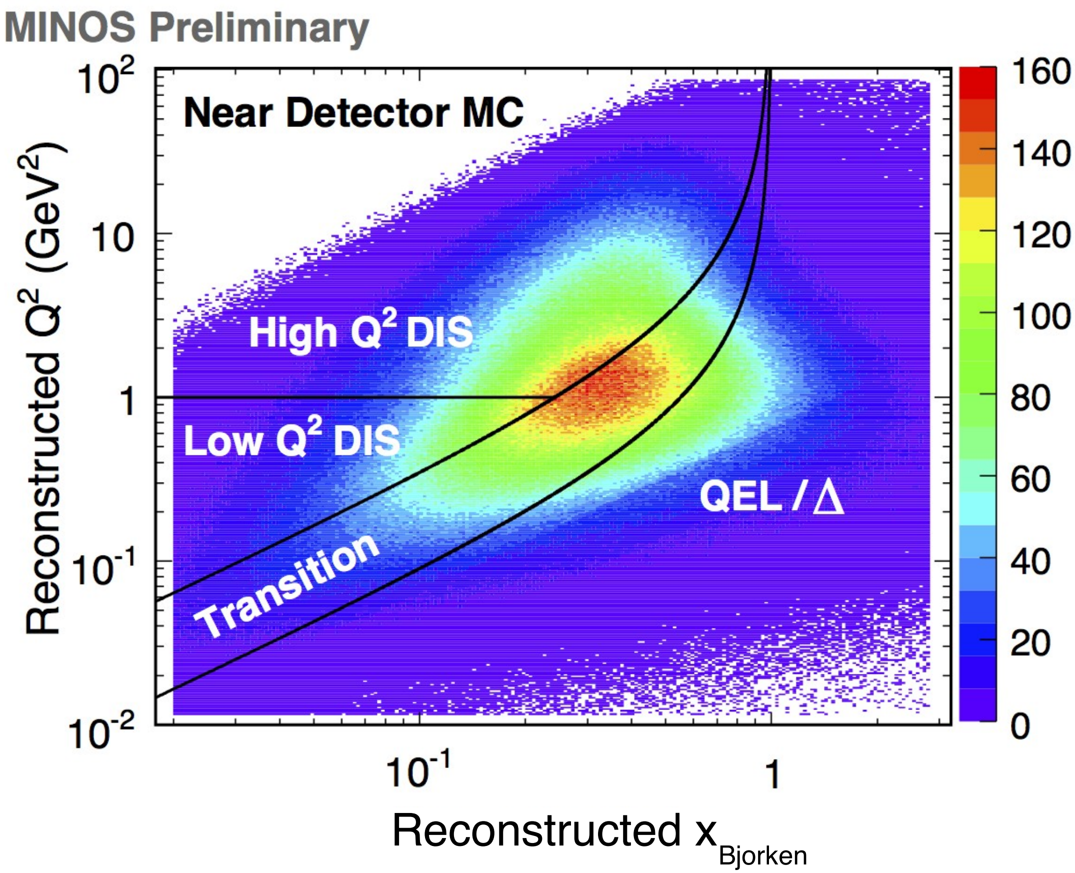
- MINOS can reconstruct everything about the muon: E_μ, p_μ, $\cos(\theta_\mu)$.
- Just the energy of the hadron shower: E_{had}.
- From these reconstructed variables we can calculate the above kinematic quantities.

Analysis Overview

- Sideband Samples
  - Simple selections on ν_μ-CC sample using reconstructed quantities motivated by how different models are joined together in MC.
  - Designed to isolate interaction types (RES,DIS) that are backgrounds in the signal sample.
  - Tune modeling of these backgrounds by comparing Data and MC.
- QE-like Sample
  - Selections to enrich quasi-elastic fraction of ν_μ-CC sample.
  - Apply tuning of background from sideband samples.
  - Extract M_A^{QE} from shape fit.

Sideband Samples

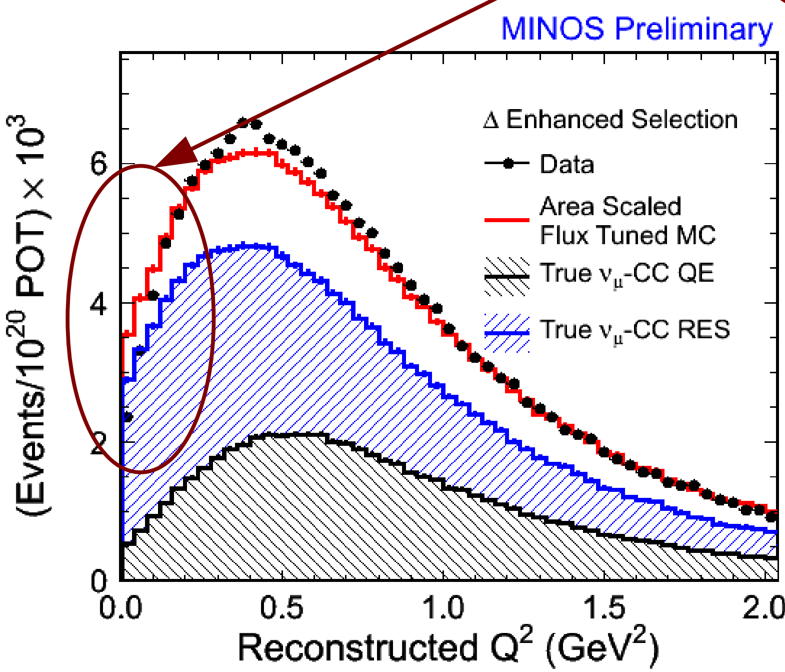
- Δ/N^* Enhanced Selection
  - E_{had} > 250 MeV,
  - W_{Reco} < 1.3 GeV
- RES to DIS Transition Selection
  - 1.3 < W_{Reco} < 2.0 GeV
- DIS Selection
  - W_{Reco} > 2.0 GeV

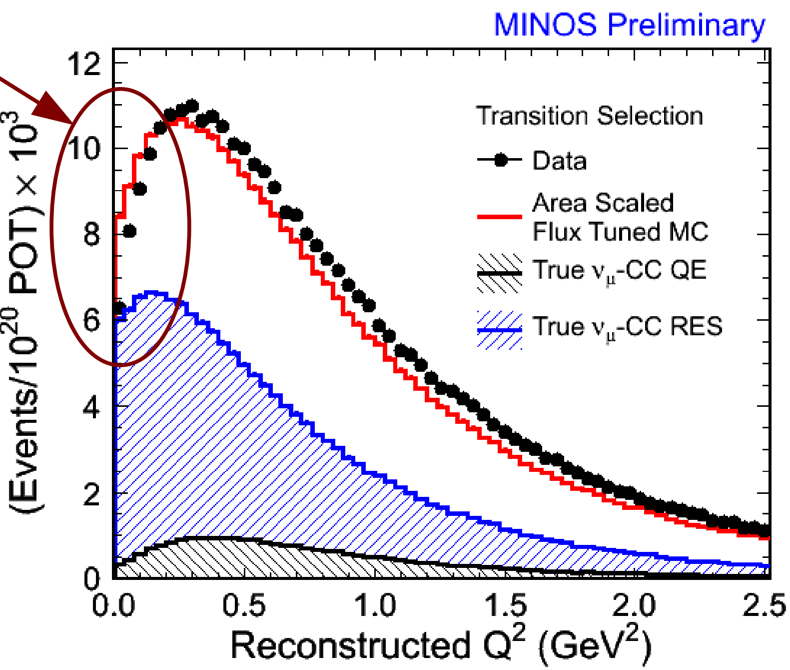


- These selections allow us to explore the different regions of our model using reconstructed variables.
- In this way we can compare how well different parts of our model are simulating the data.

Sideband Samples and Resonance Background

Two RES dominated subsamples have very different QE and DIS background mixes. MC prediction is high in lowest Q^2 bins for both.

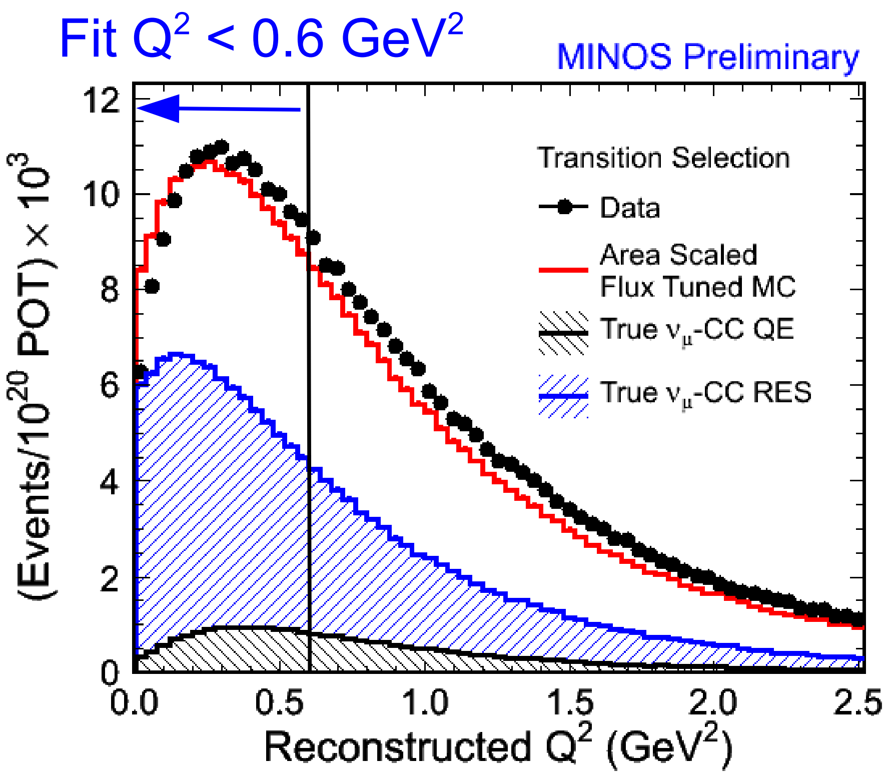


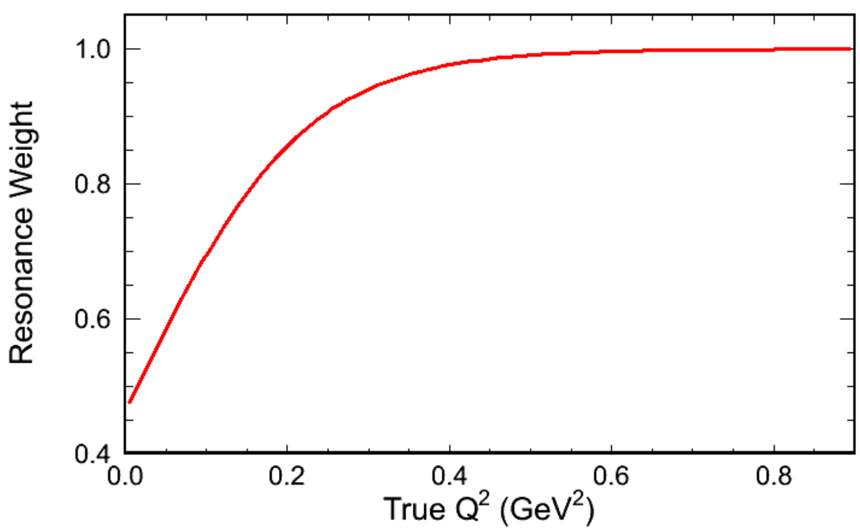


RES Enhanced Selection:
W_{reco} < 1.3 GeV
E_{had} > 250 MeV

RES to DIS Transition Selection:
1.3 < W_{reco} < 2.0 GeV

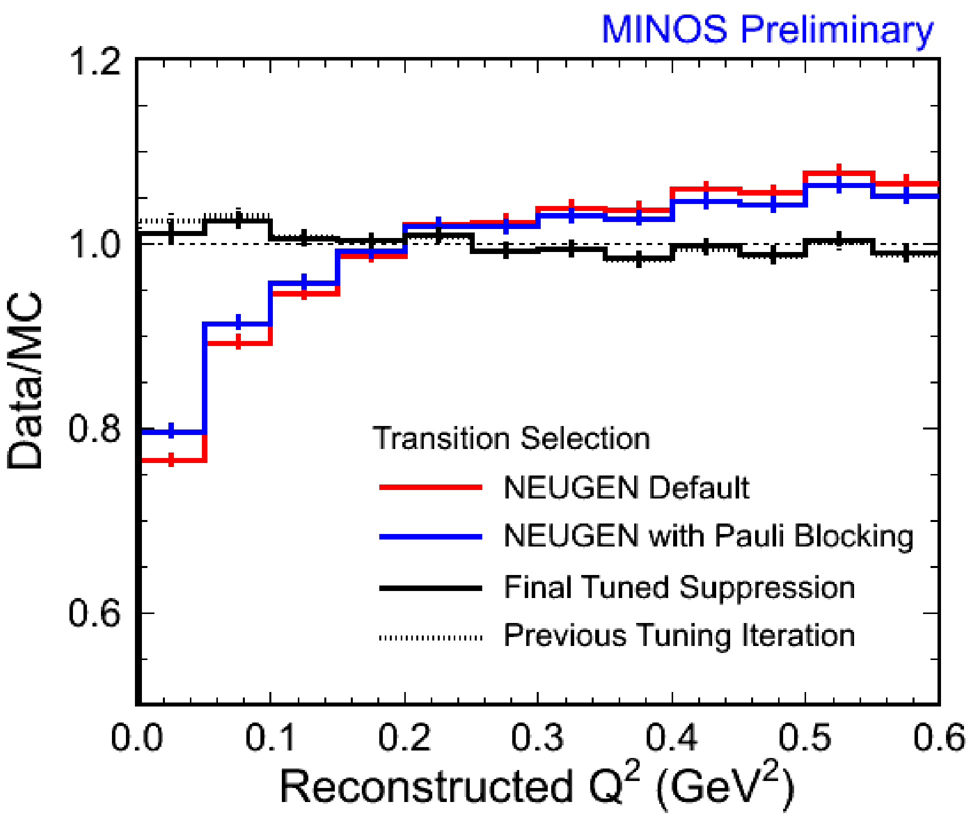
Fitting the Low Q^2 Region





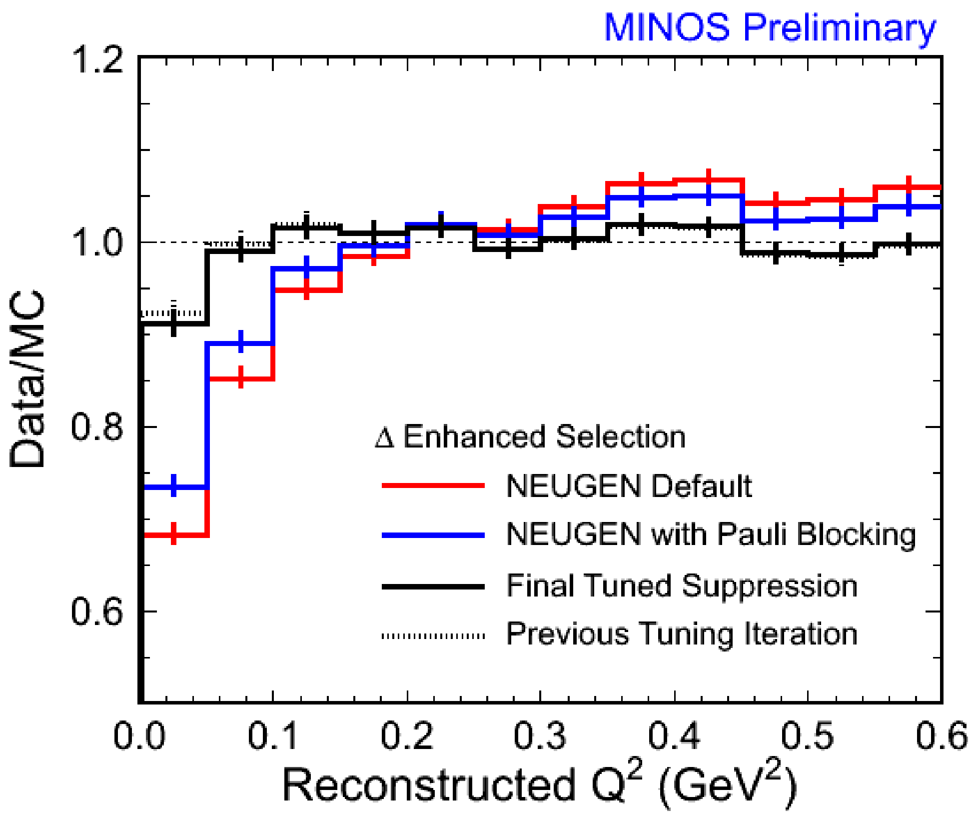
- Attempt to correct MC.
- Start with candidate shape derived from the Δ Enhanced and Transition sideband samples, in true Q^2.
- Apply these requirements:
  - Only tune the resonances.
  - Suppression turns off near 0.6 GeV^2.
  - Suppression function is smooth.
  - No other model parameters are tuned. Any correlations are dealt with in the error band.

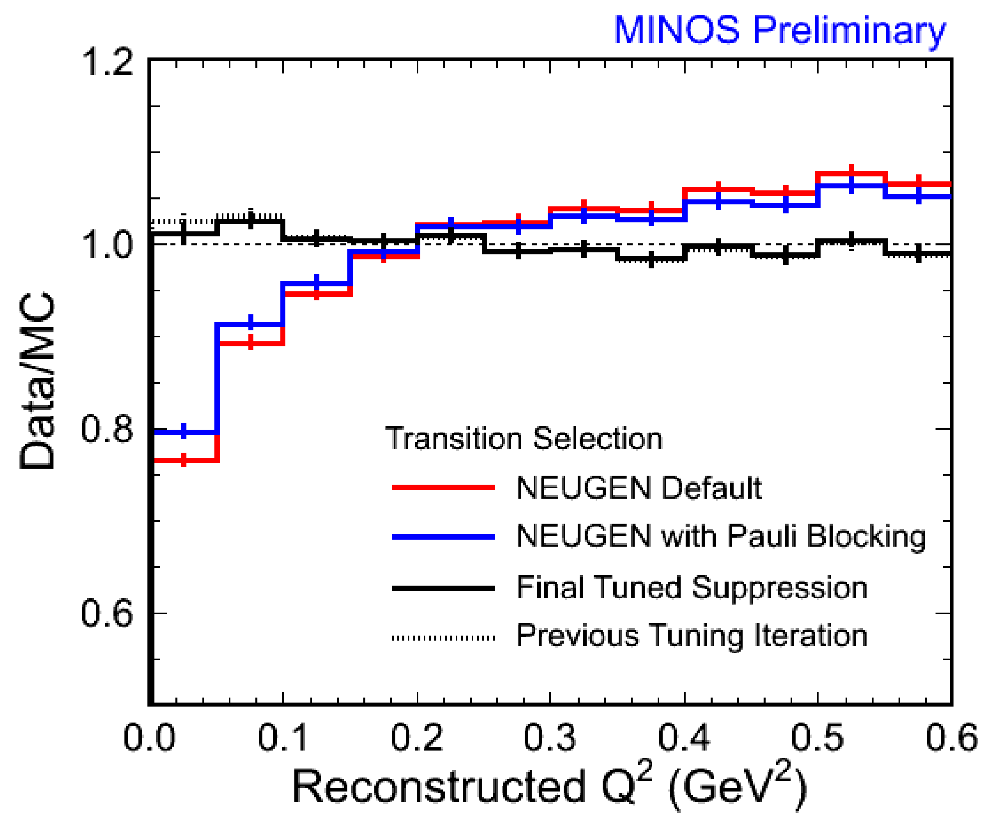
Fitting the Low Q^2 Region



- Shape only fit
- Two step iterative procedure:
  1. Tune individual points to reduce sum of squares of residuals and smooth.
  2. Fit for overall strength of suppression using scaling parameter.
- In each step both RES dominated samples, Δ Enhanced and Transition, are simultaneously fit in reconstructed Q^2.

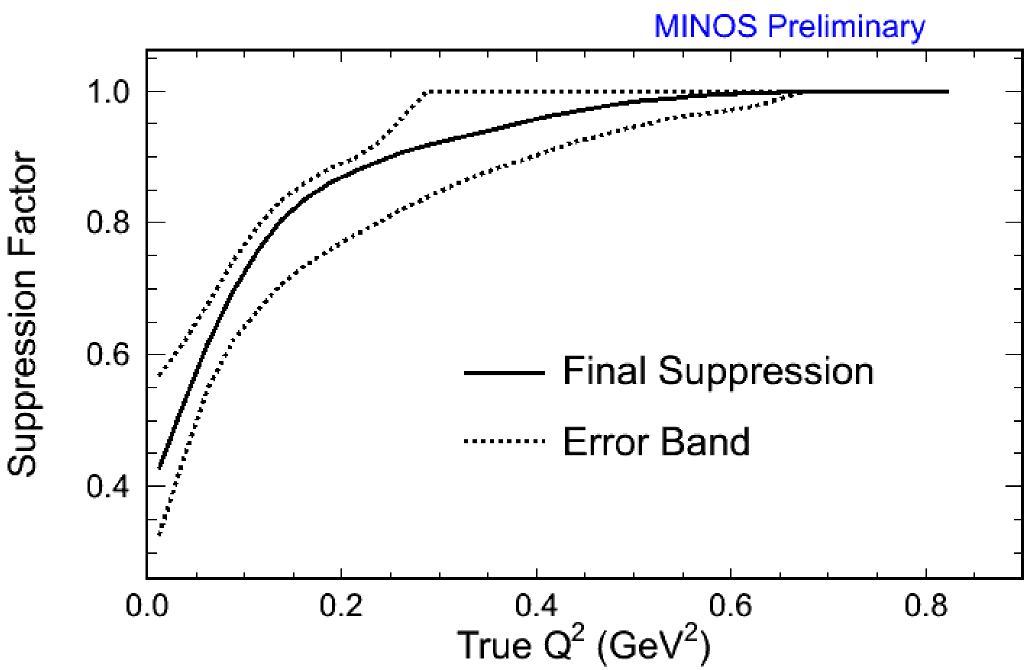
Fitting the Low Q^2 Region





- The RES re-weighting does a good job of describing two samples with very different backgrounds.
- Only significant deviation from unity in Data/MC is lowest Q^2 bin in Δ Enhanced sample, which has a larger QE component than Transition sample.

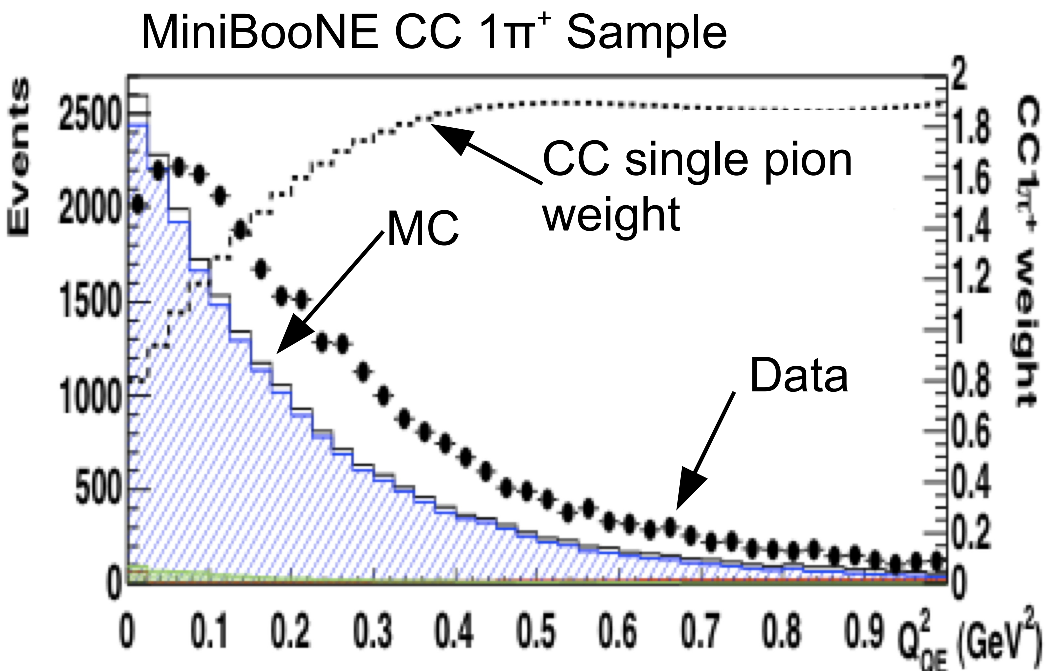
Background Weighting with Error Band



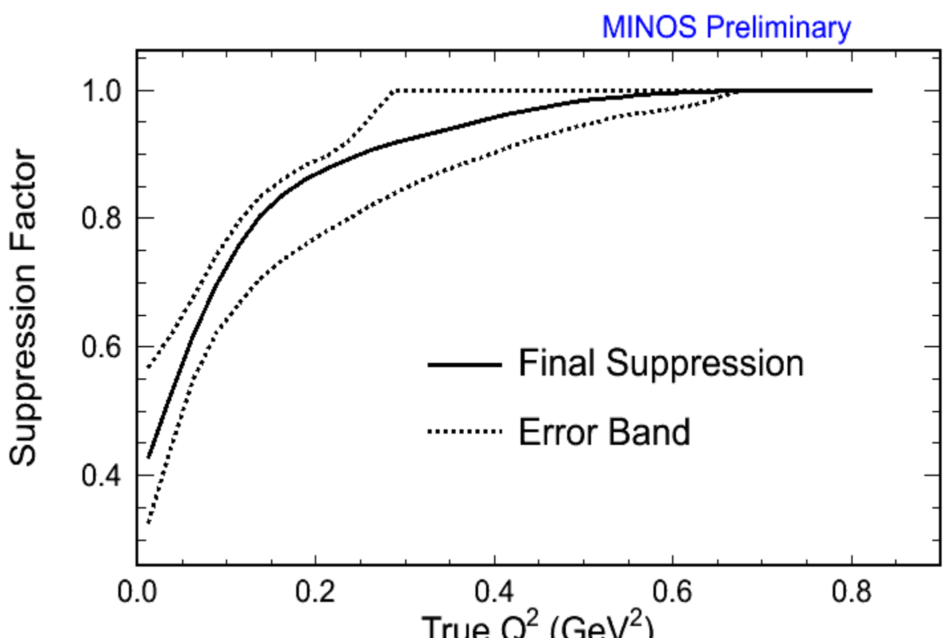
- Two alternative suppression shapes were considered.
  - A linear function that turns off at lower $Q^2 \sim 0.3$ GeV^2.
  - And a function that turns off at higher $Q^2 \sim 0.67$ GeV^2.
- These two shapes define the initial error band.

- We considered a variety of effects when constructing the error band. These include migration effects such as:
  - E_μ scale, E_{Had} scale, and low Q^2 DIS migration.
- And model differences such as:
  - Final state interactions, CC coherent, and the axial mass parameters.

Comparison with MiniBooNE



A.A. Aguilar-Arevalo, *et al.*, Phys. Rev. D **81** (2010) 092005.



Note that:

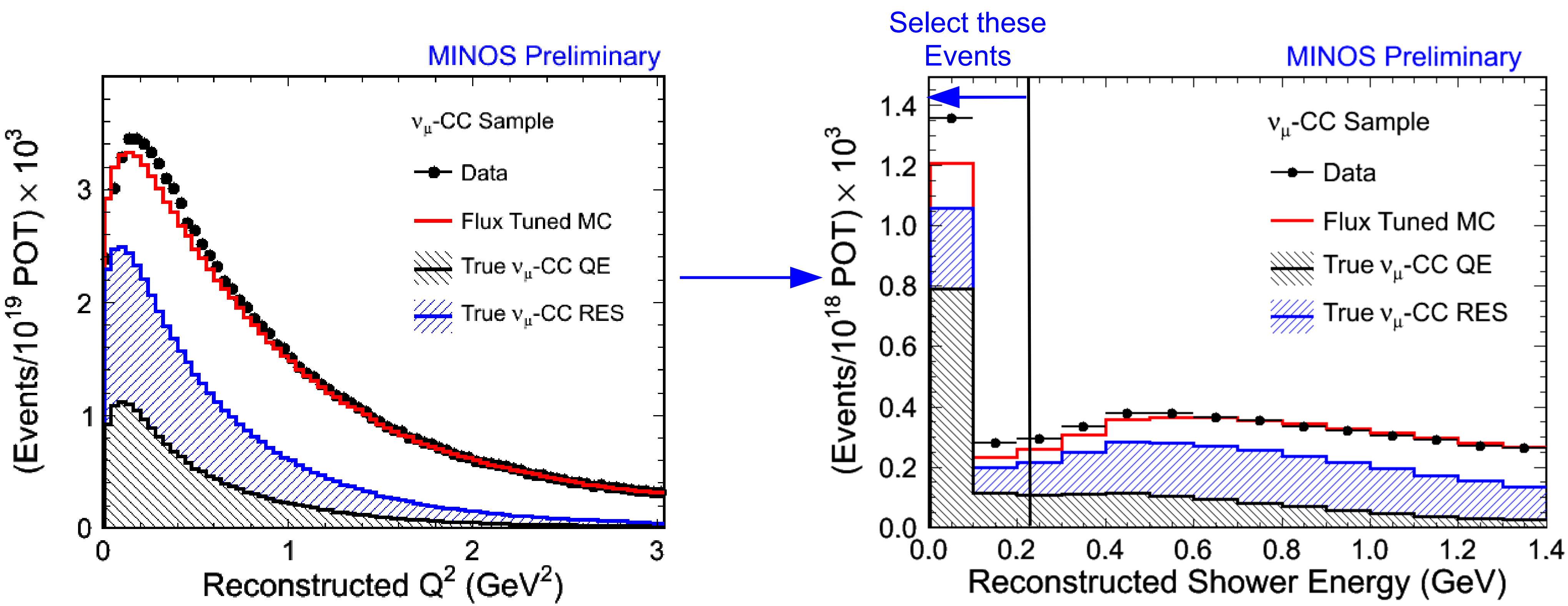
- MiniBooNE uses reconstructed Q^2_{QE}, MINOS uses true Q^2.
- MiniBooNE uses a POT normalized sample, MINOS area normalizes.
- MiniBooNE uses a carbon target, MINOS uses iron.

MINOS suppression shape agrees well with shape of MiniBooNE CC single pion weight function.

This observation of a need for low Q^2 RES suppression is interesting, as this region is not well understood.

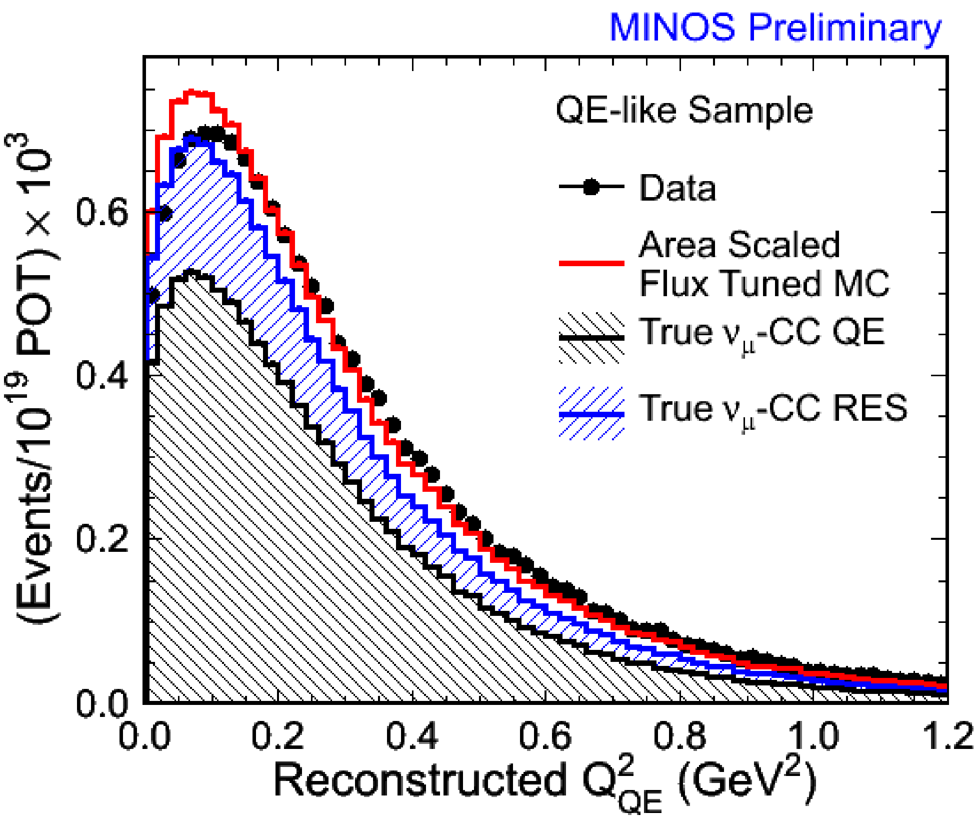
Quasielastic-like Selection

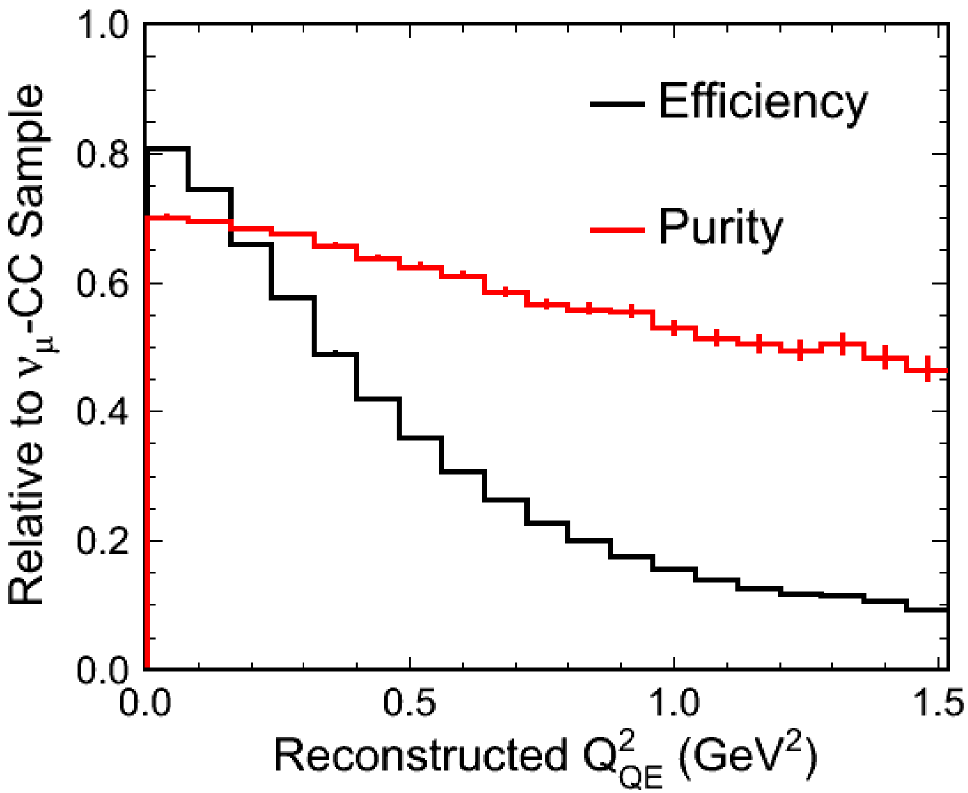
- Low E_{had}: Select from ν_μ-CC sample events with Reconstructed E_{had} < 225 MeV.
- Select events with muon tracks that stop in ND.
- Includes the RES re-weighting function.



Quasielastic-like Selection

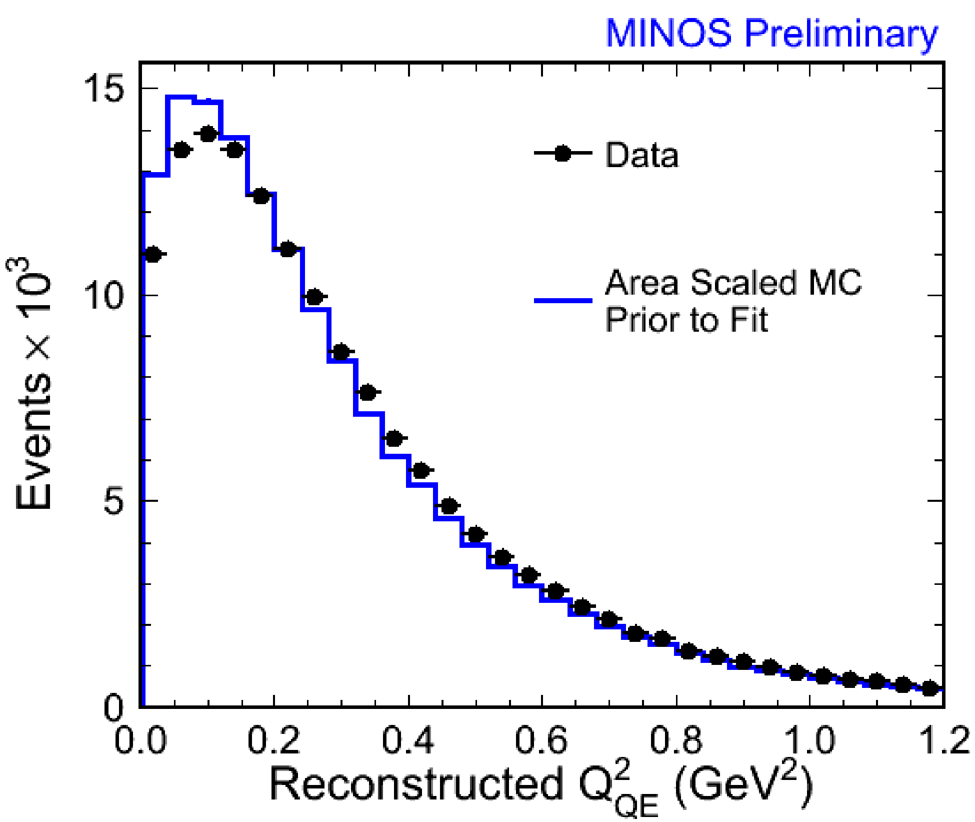
Selects QE events with 44% efficiency and 63% purity.





Method

- Extract M_A^{QE} from shape fit to Q^2 distribution.
- Three nuisance parameters included in fit:
  - Stopping muon energy scale: E_μ
  - Resonance axial mass: M_A^{RES}
  - Quasi-elastic Pauli blocking parameter: k^{QE}_{Fermi}



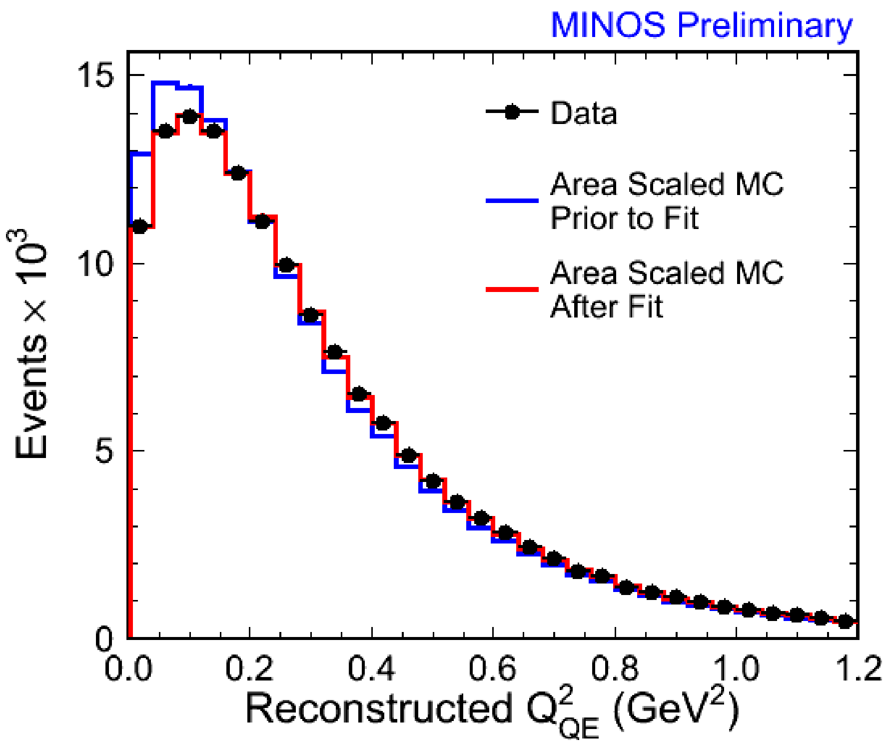
χ^2 includes MC statistics:

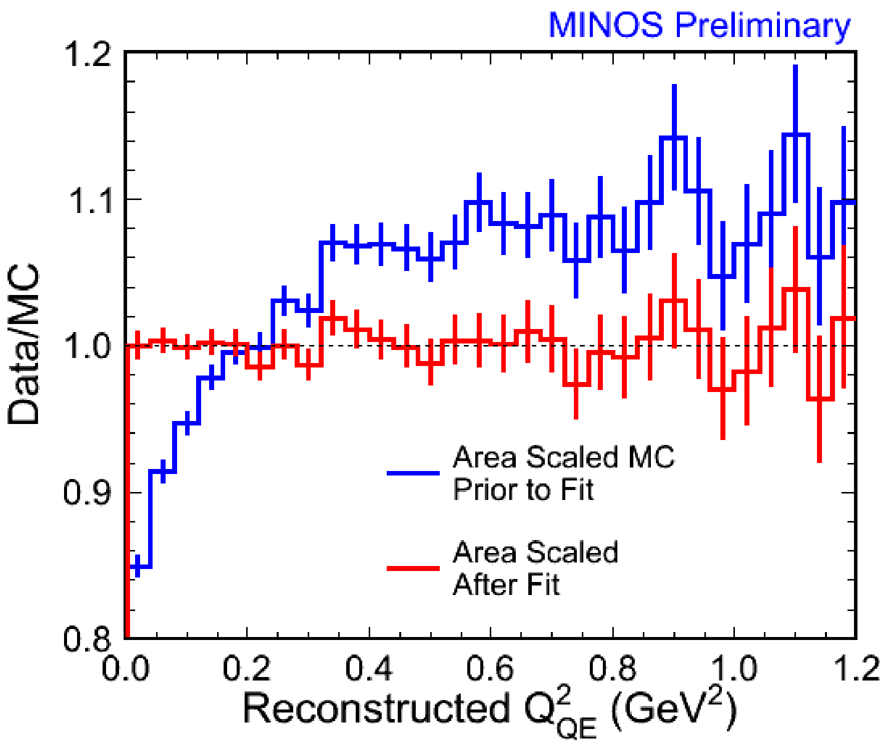
$$\chi^2 = \sum_{i=1}^{\#bins} \frac{(N_i^{obs} - N_i^{MC}(\alpha_1, \ldots, \alpha_N))^2}{(N_i^{obs} + S \cdot N_i^{MC}(\alpha_1, \ldots, \alpha_N))} + \sum_{j=2}^{N} \frac{\Delta\alpha_j^2}{\sigma_{\alpha_j}^2}$$

Best Fit Results

Result from the principal fit configuration.

	M_A^{QE} (GeV)	E_μ Scale	M_A^{RES} (GeV)	k^{QE}_{Fermi}
Principal: $0 < Q^2 < 1.2$	1.21 +0.18 -0.10	0.996 +0.007 -0.015	1.10 +0.15 -0.16	1.10 +0.02 -0.03

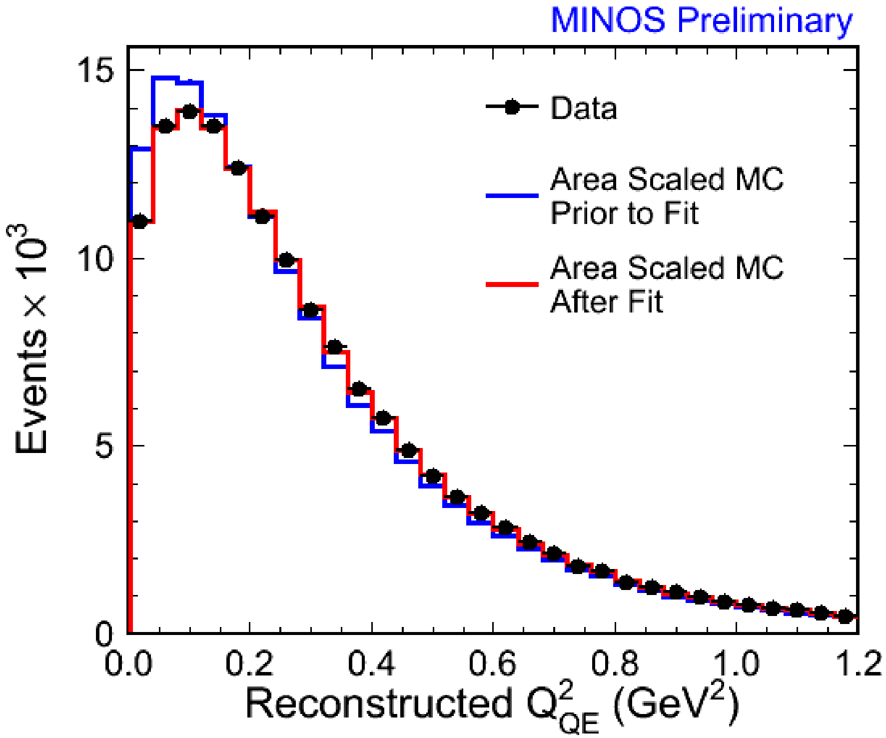


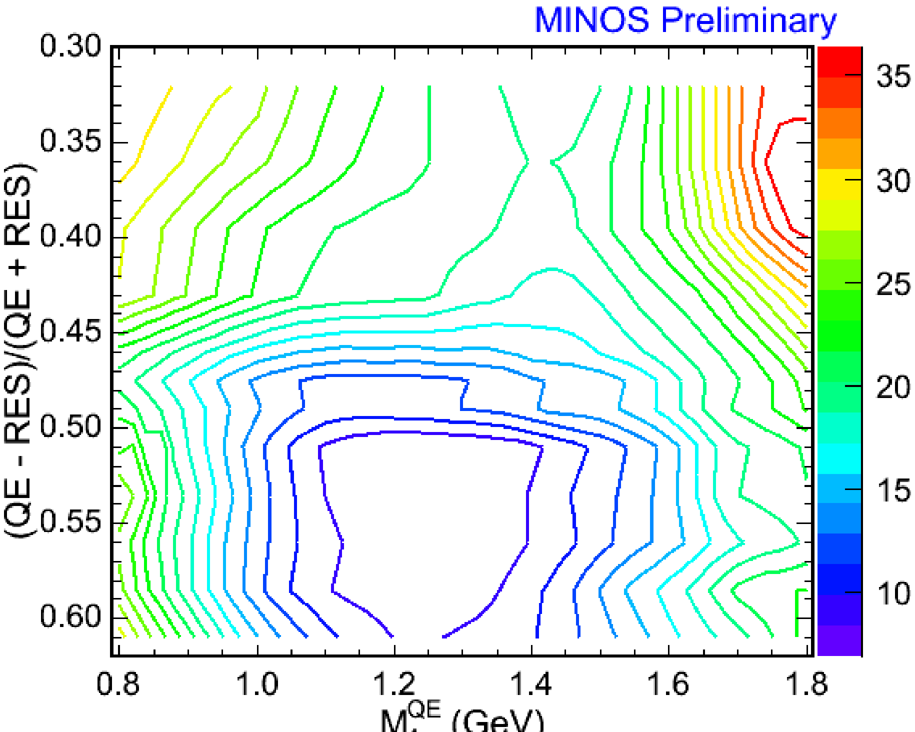


Best Fit Results

Results from the principal and alternative fit configurations.

	M_A^{QE} (GeV)	E_μ Scale	M_A^{RES} (GeV)	k^{QE}_{Fermi}
Principal: $0 < Q^2 < 1.2$	$1.21^{+0.18}_{-0.10}$	$0.996^{+0.007}_{-0.015}$	$1.10^{+0.15}_{-0.16}$	$1.10^{+0.02}_{-0.03}$
Alternative: $0.3 < Q^2 < 1.2$	$1.19^{+0.19}_{-0.17}$	$0.995^{+0.008}_{-0.016}$	$1.13^{+0.17}_{-0.18}$	Not fit





Systematic Error Table

Best Fit:

$$M_A^{QE} = 1.21^{+0.18}_{-0.10}(fit)^{+0.13}_{-0.15}(syst)\,GeV$$

Systematic Source	+ve Uncertainty (GeV)	-ve Uncertainty (GeV)
E_{had} selection cut	0.084	0.079
Neutrino flux	0.027	0.027
Vertex x, y	0.046	0.040
μ^- angular resolution	0.057	0.057
Hadronic energy offset	0.034	0.036
INTRANUKE parameters	0.053	0.053
DIS cross sections	0.026	0.021
RES nuclear effects	0.018	0.078
Quadrature Sum	0.134	0.150

Summary

- MINOS observes an deficit of low Q^2 RES events compared to our MC and has developed a data driven re-weighting function to better describe this region.

- Recent M_A^{QE} results are thought of as measuring an *effective* parameter that is convoluted with nuclear medium effects.

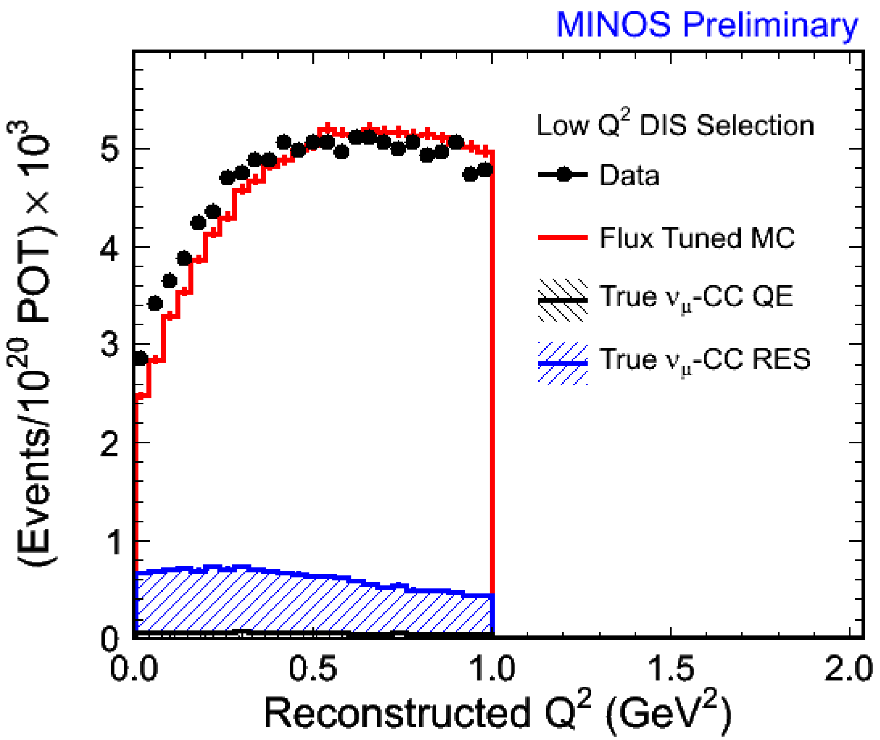
- MINOS reports results for an effective axial vector mass for quasi-elastic interactions on iron in the range $1 < E_\nu < 8$ GeV from two configurations:

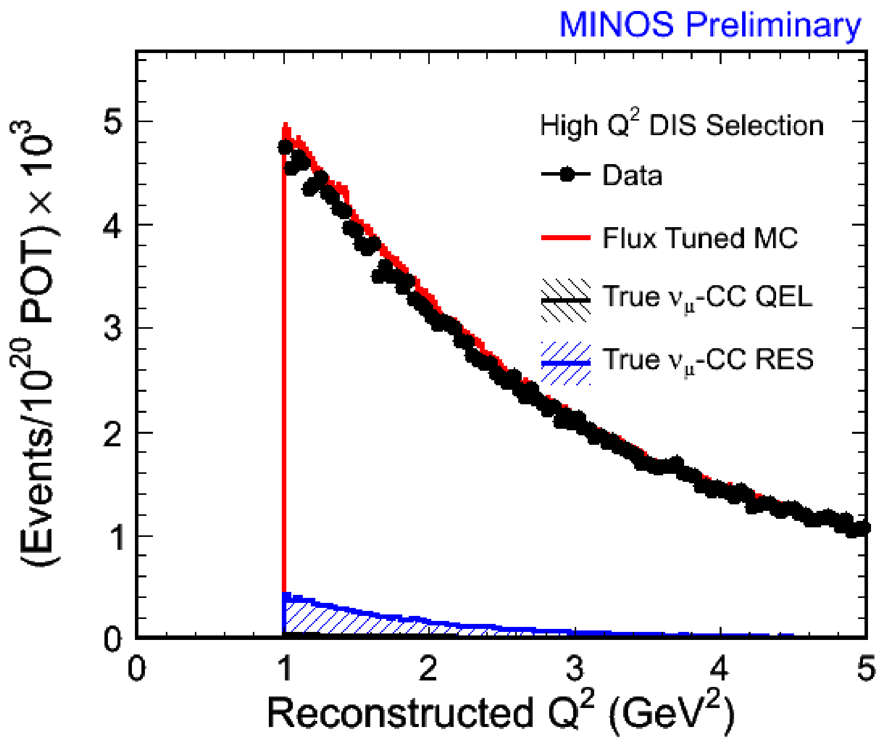
$$M_A^{QE} = 1.21^{+0.18}_{-0.10}(fit)^{+0.13}_{-0.15}(syst)\,GeV\ (0.0 < Q^2 < 1.2\,GeV)$$

$$M_A^{QE} = 1.19^{+0.19}_{-0.17}(fit)\,GeV\ (0.3 < Q^2 < 1.2\,GeV)$$

Backup Slides

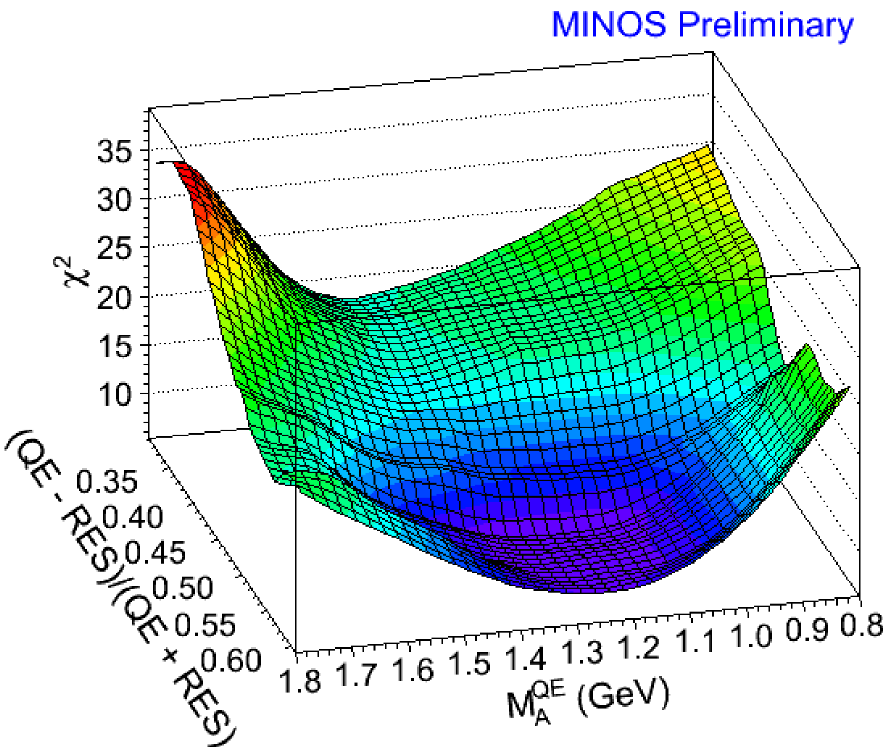
DIS Samples

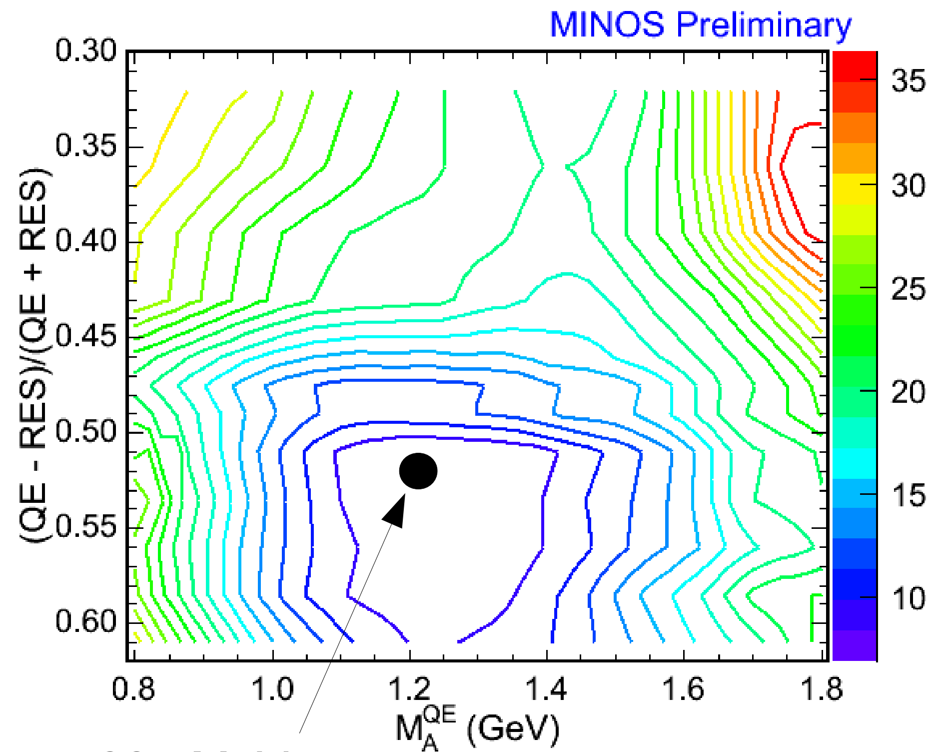




- Selecting W_{Reco} > 2.0 GeV provides a sample dominated by DIS.
- Flux tuning procedure pins the DIS rate.
  - Supporting evidence from cross section work.
- Able to consider other channels relative to DIS.

Optimization of Selection Cut





E_{shower} < 225 MeV
M_A^{QE} = 1.21 GeV

- Map of χ2 surface as a function of M_A^{QE} and hadronic shower energy cut, expressed as purity.
- Shows a well defined minimum.
- Allows for optimization of main selection cut: Reconstructed E_{shower} < 225 MeV.

Parameter Effects on Q^2