Muon Neutrino Quasielastic Scattering On Iron Using the MINOS Near Detector

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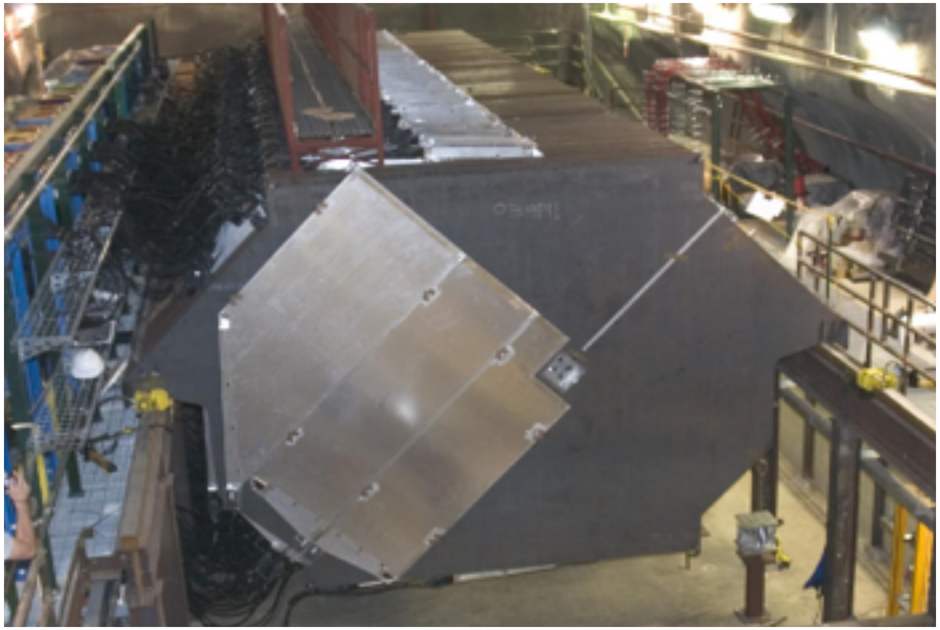
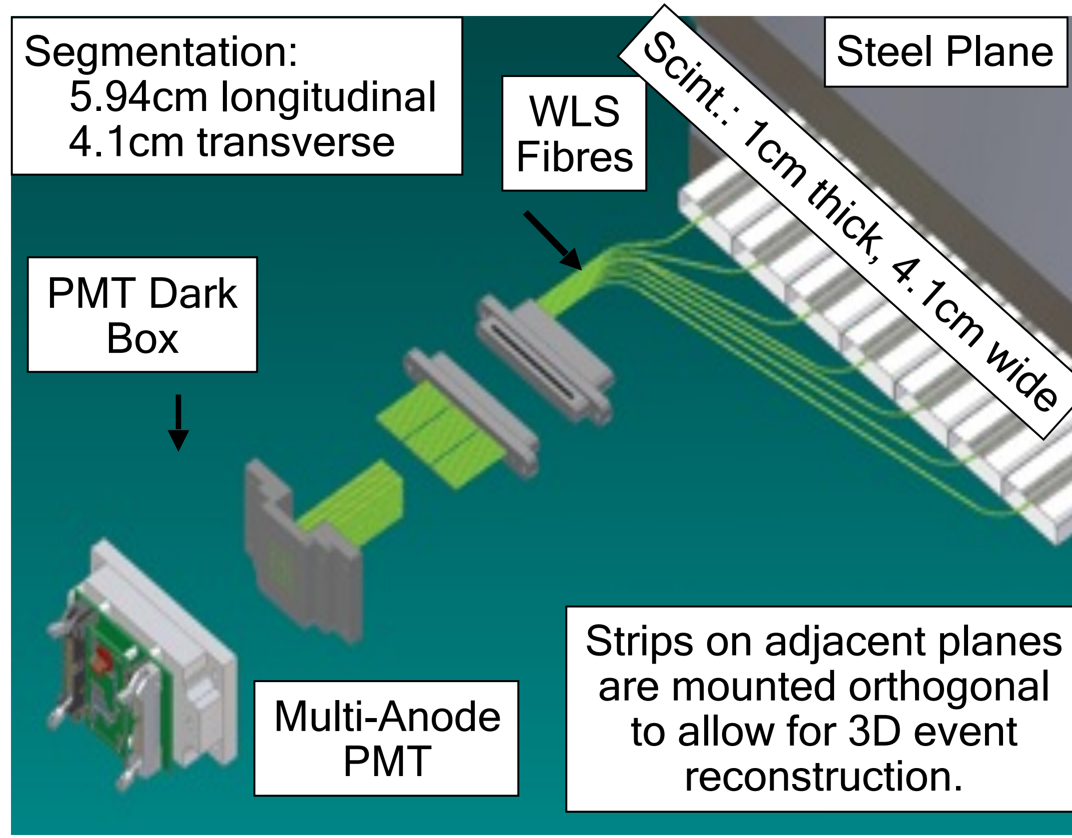
Topics

- MINOS Near Detector
- Motivation and the CCQE interaction
- Reconstructing MINOS Low Q^2 interactions
- Event selection
  - Charged Current
  - CCQE and sideband selection
- Data driven background treatment
- Fit Procedure and final results
- Systematic uncertainties
- Conclusion

The MINOS Near Detector (ND)

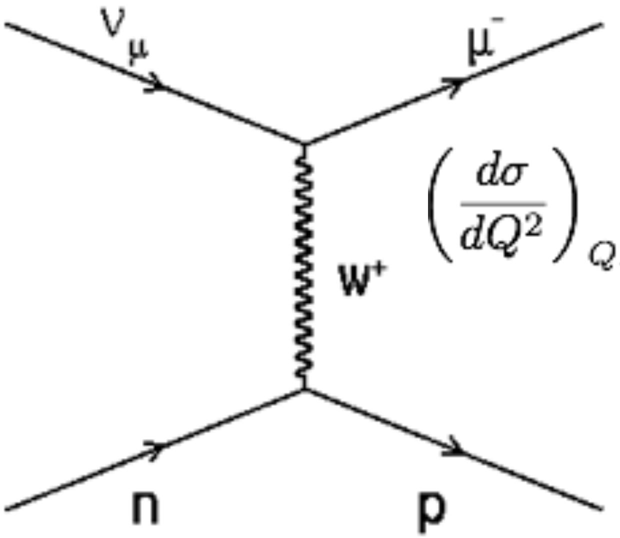




- 1km from target
- 0.98 kton, 30 ton fiducial
- 282 steel planes
- B = 1.2 T

- Instrumented with QIE electronics (Zero deadtime)
- Scintilator tracking calorimeter.

The CCQE Interaction



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

$$F_A(Q^2) = \frac{F_A(0)}{\underbrace{\left(1+\frac{Q2}{M_A^2}\right)}}$$

'Dipole Form'

The quasielastic axial-vector mass

- *A,B,C* are function of the nucleon form factors, 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 scattering.

Motivation

Experiment	Energy (GeV)	Target	M_A^{QE}
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	This Talk

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- NOMAD with C target, higher E_ν also measures M_A^{QE}~1.0 GeV.
- **More recent experiments with carbon targets (K2K, MiniBooNE, SciBooNE) measure M_A^{QE}~1.25 GeV.**

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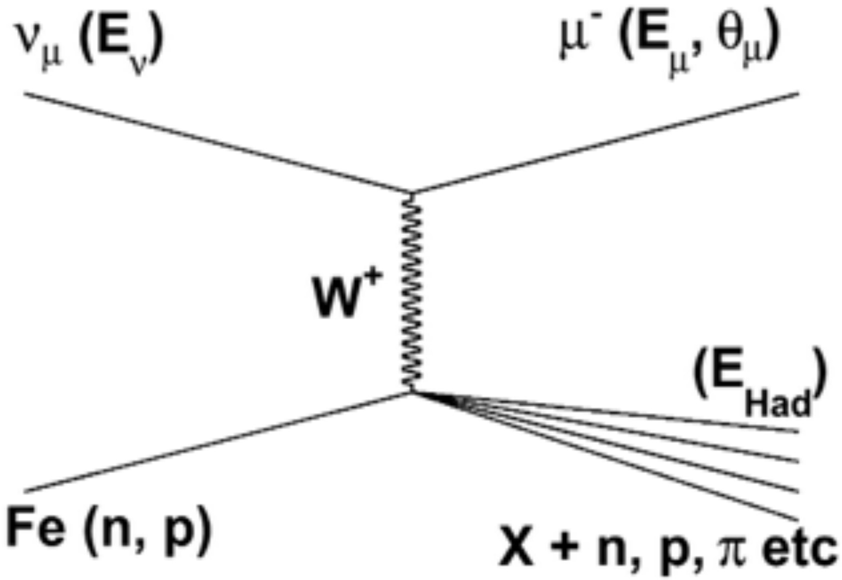
- NOMAD with C target, higher E_ν also measures M_A^{QE}~1.0 GeV.
- MINERvA CCQE finds M_A^{QE}~1.0 GeV, however these results use the so called TEM model as well, which is a tuning of the vector FF as well.
- **MINOS has a high statistics sample of 189,000 QE candidates on iron recorded in a magnetized tracking spectrometer**

Reconstruction



- Reconstruct full muon kinematics
- Reconstruct the Energy of Hadron Shower
- From these variables calculate the following kinematic quantities:

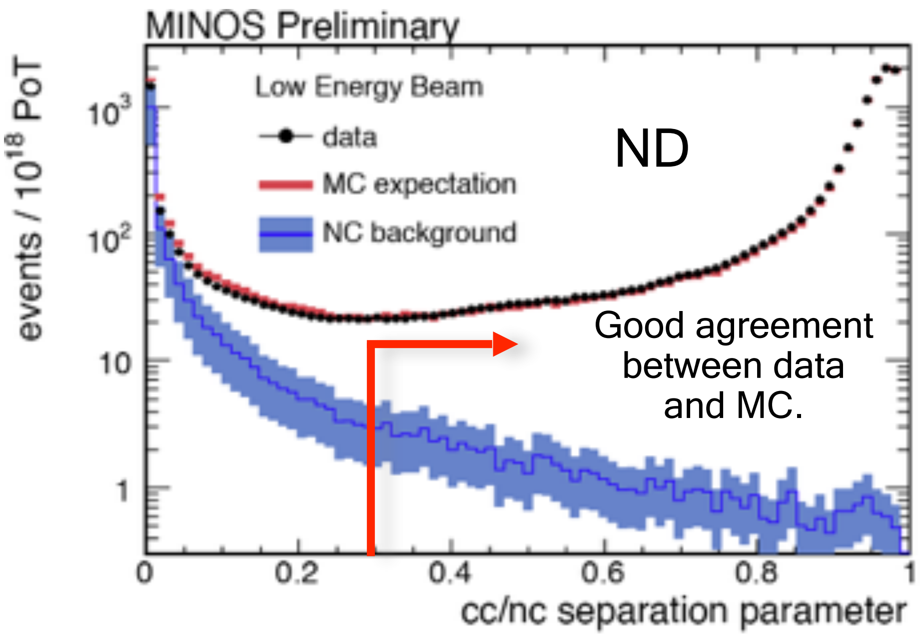
$$E_\nu = E_\mu + E_{Had} \quad \text{or} \quad E_\nu^{QE} = \frac{(m_N - \epsilon_B)E_\mu - 2(m_N \epsilon_B + \epsilon_B^2 + m_\mu^2/2)}{m_N - \epsilon_B - E_\mu + p_\mu \cos(\theta_\mu)}$$

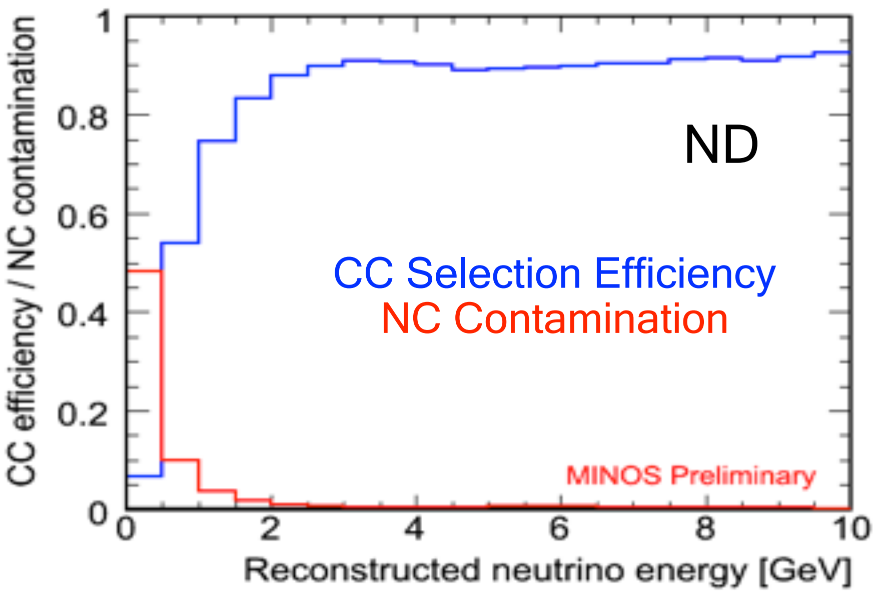
$$Q^2 = -2E_\nu(E_\mu - p_\mu \cos(\theta_\mu)) + m_\mu^2 \quad \text{or} \quad Q_{QE}^2 = -2E_\nu^{QE}(E_\mu - p_\mu \cos(\theta_\mu)) + m_\mu^2$$

$$W^2 = m_N^2 + 2m_N E_{Had} - Q^2$$

Event Selection (Charged Current)

- First remove majority of NC events by requiring at least 1 track
  - Further enrich sample using multi-variate technique (kNN)
- kNN combines variables that differentiate between muons and protons/pions seen in NC interactions.

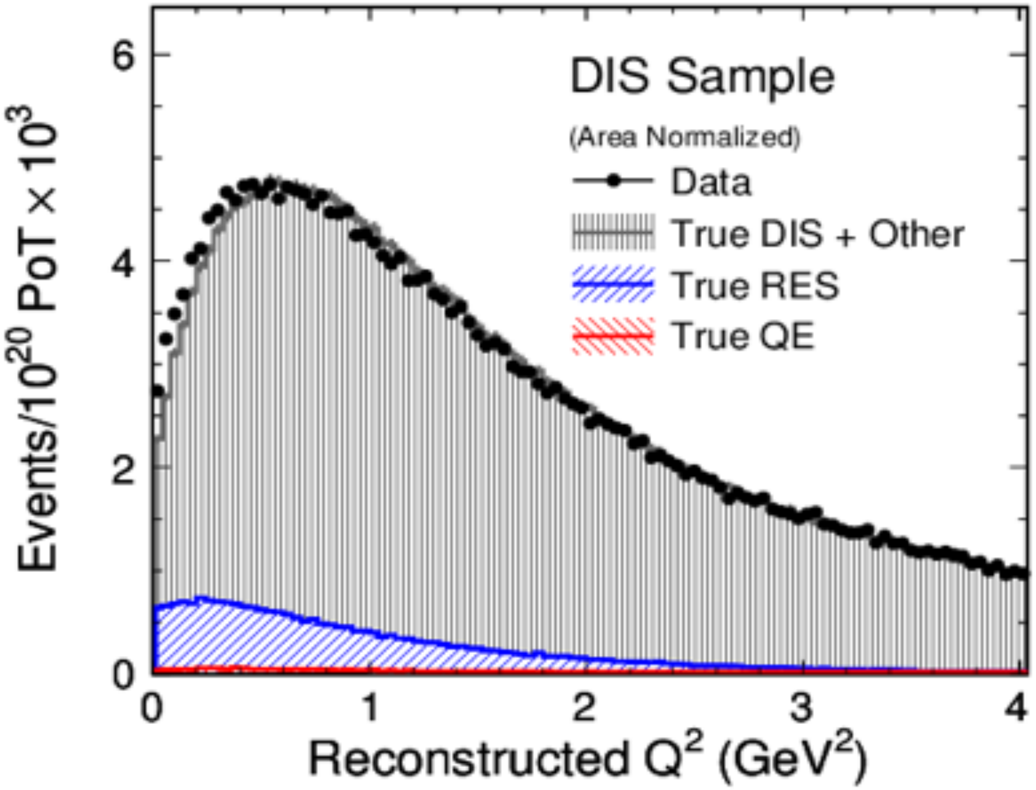




Event Selection (CCQE & Sidebands)

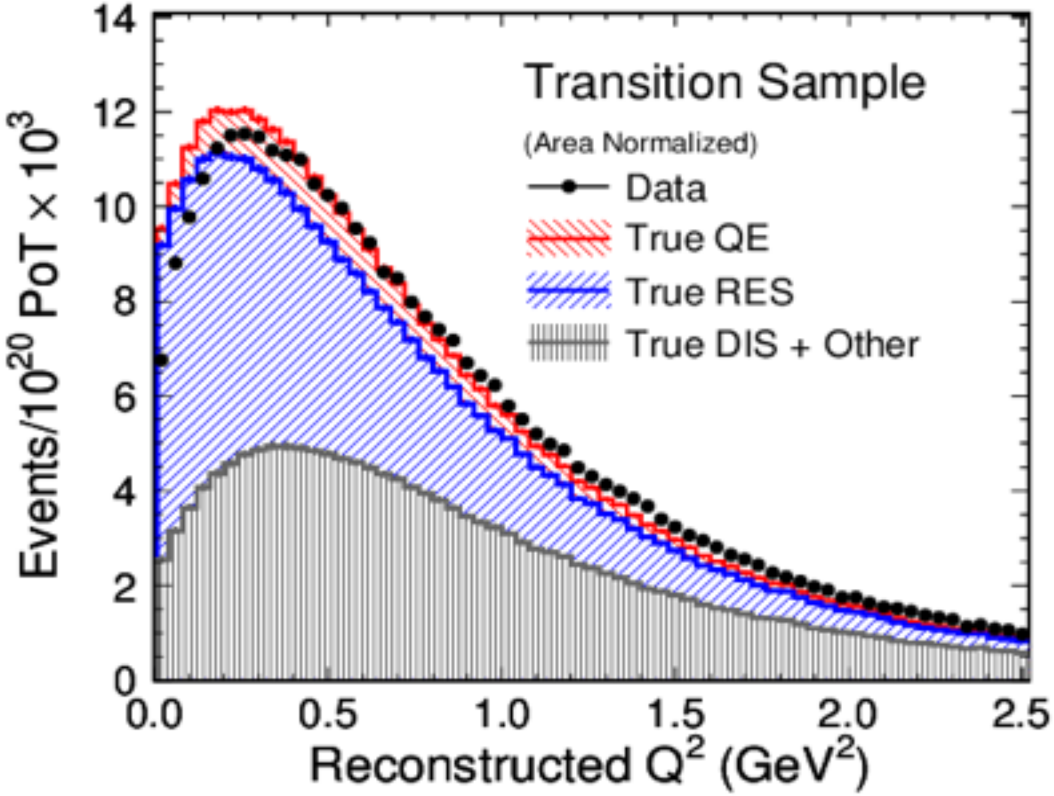
- CC selected events are divided into several sub-samples
  - DIS, Δ-enhanced and transition (resonance) , QE.
  - primarily by the hadronic invariant mass W.
- These sub-samples are either
  - Analyzed as signal
  - Used to characterize the non-QE background within the signal sub-sample.

Event Selection (CC-DIS)



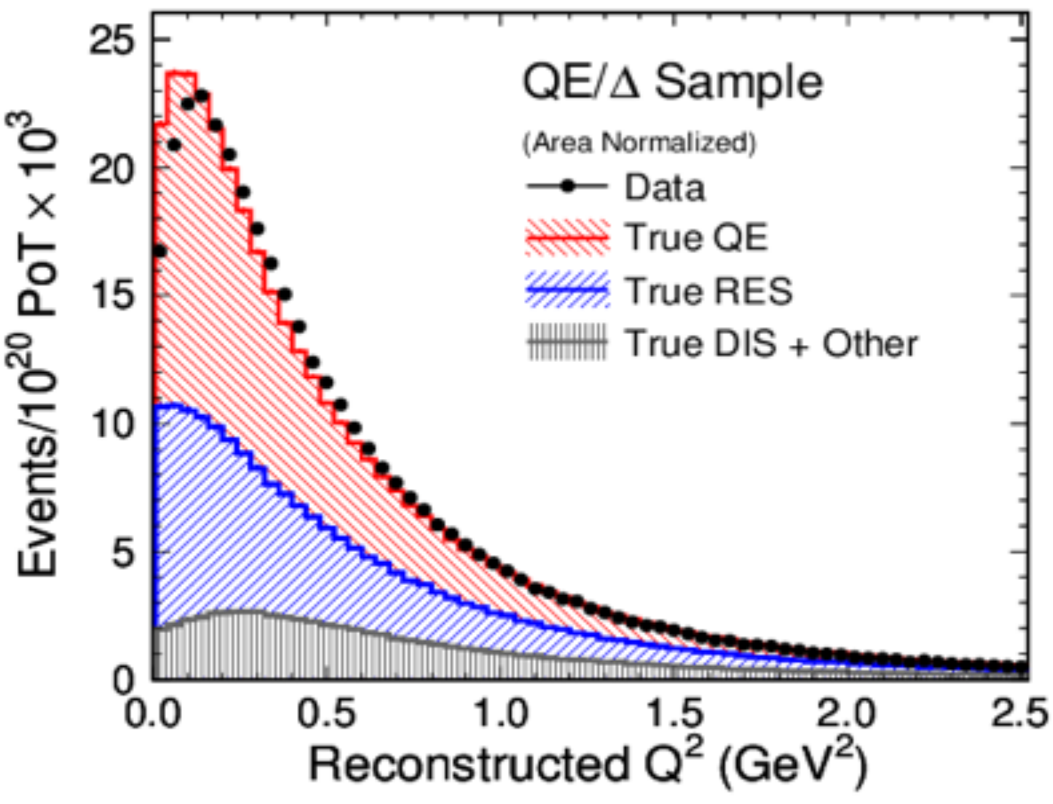
- W > 2.0 GeV
- Examine low/high Q^2 separately.
- High Q^2 DIS sample matches data well.
- Low Q^2 has:
  - RES/QE component.
  - Data/MC disagreement.

Event Selection (RES to DIS Transition)



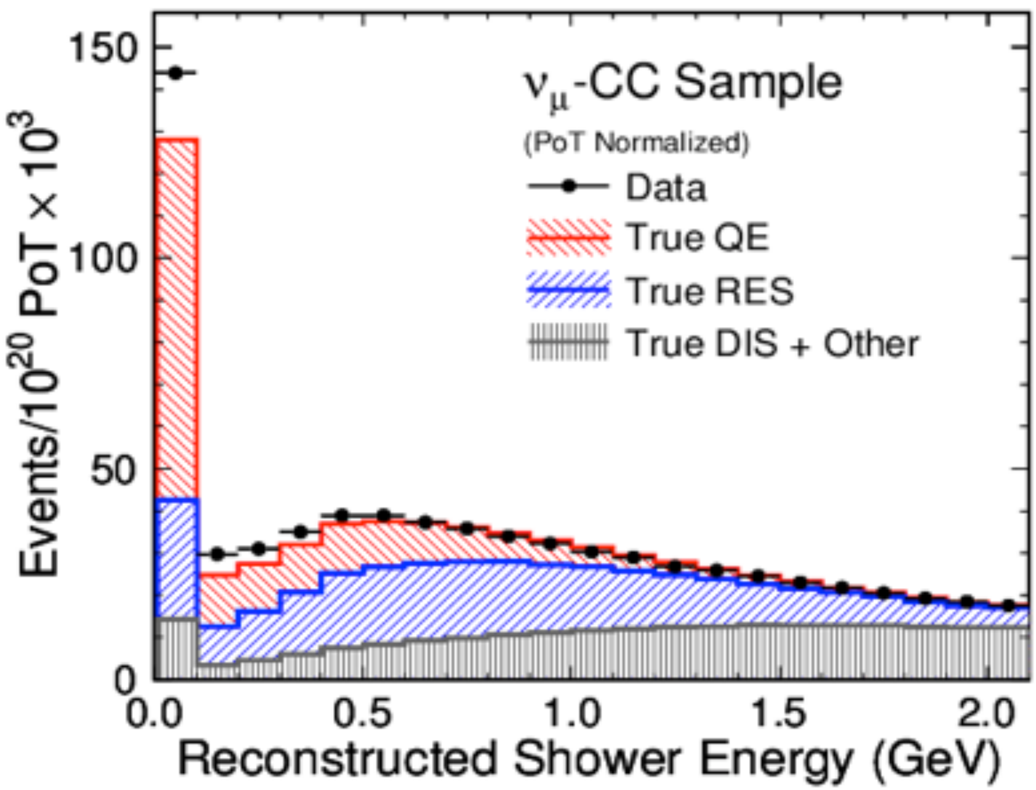
- $1.3 < W < 2.0$ GeV
- Dominated by baryon resonance production.
- Low Q^2 discrepancy can not be due to QE alone.

Event Selection (QE/Δ)



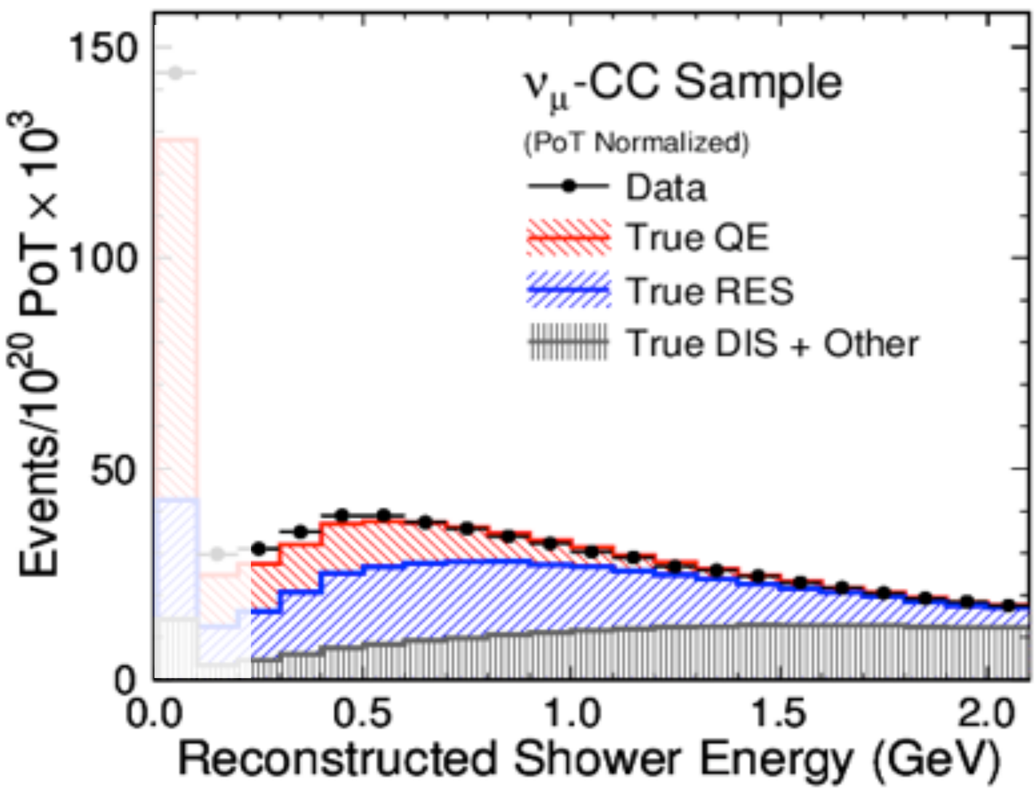
- W < 1.3 GeV
- Model over predicts data at low Q^2.
- Not used directly in the analysis
- Divided by E_{had} into
  - CCQE sample
  - Δ-Enhanced sideband

Event Selection (Δ-Enhanced)



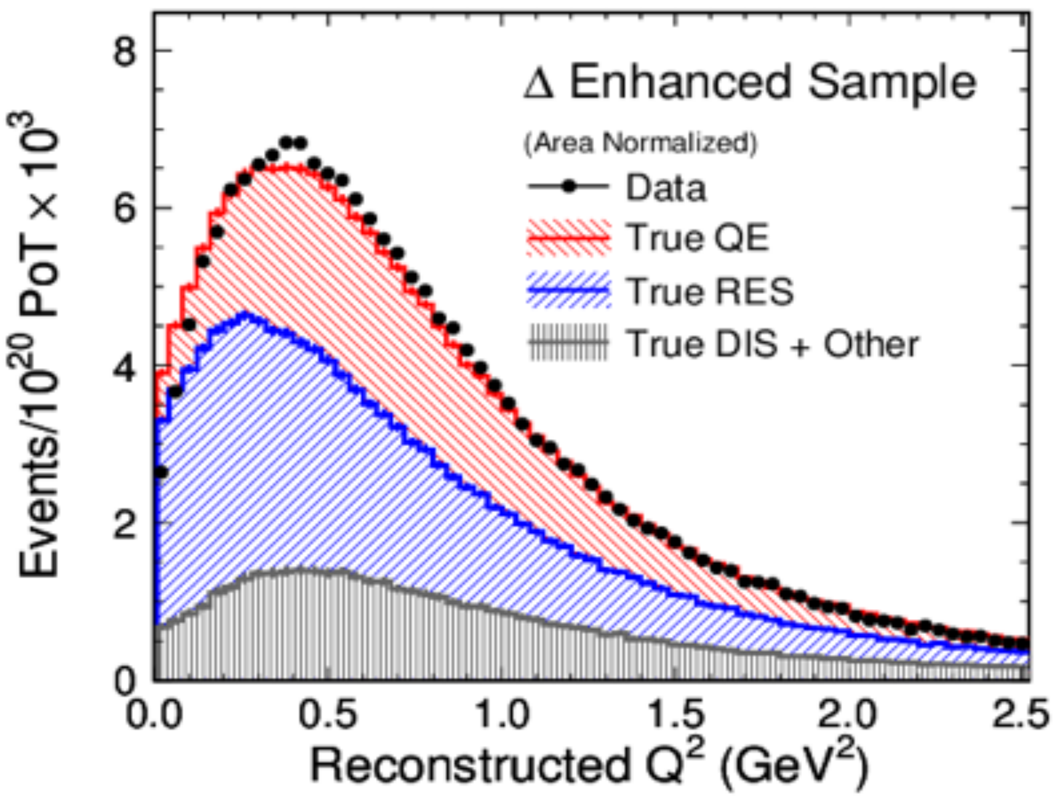
- QE/Δ & E_{Had}>250 MeV

Event Selection (Δ-Enhanced)



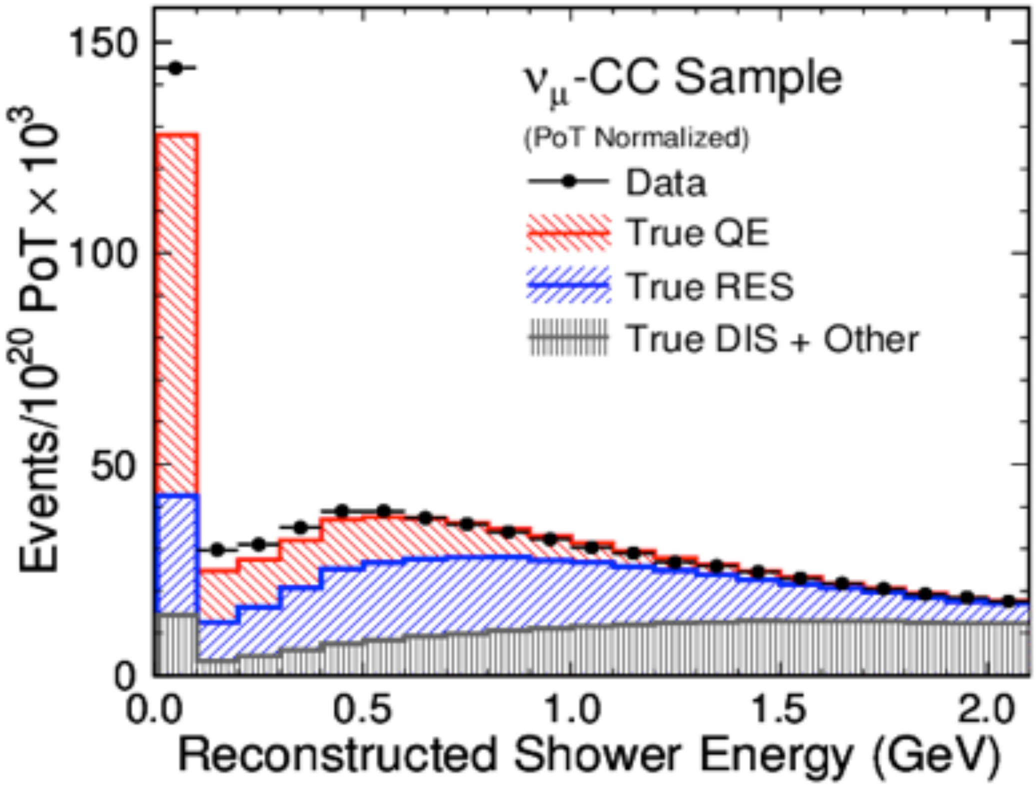
- QE/Δ & E_{Had}>250 MeV
- E_{had}, total energy in the hadron system
  - CCQE expected to have less E_{had} than other interaction types.

Event Selection (Δ-Enhanced)



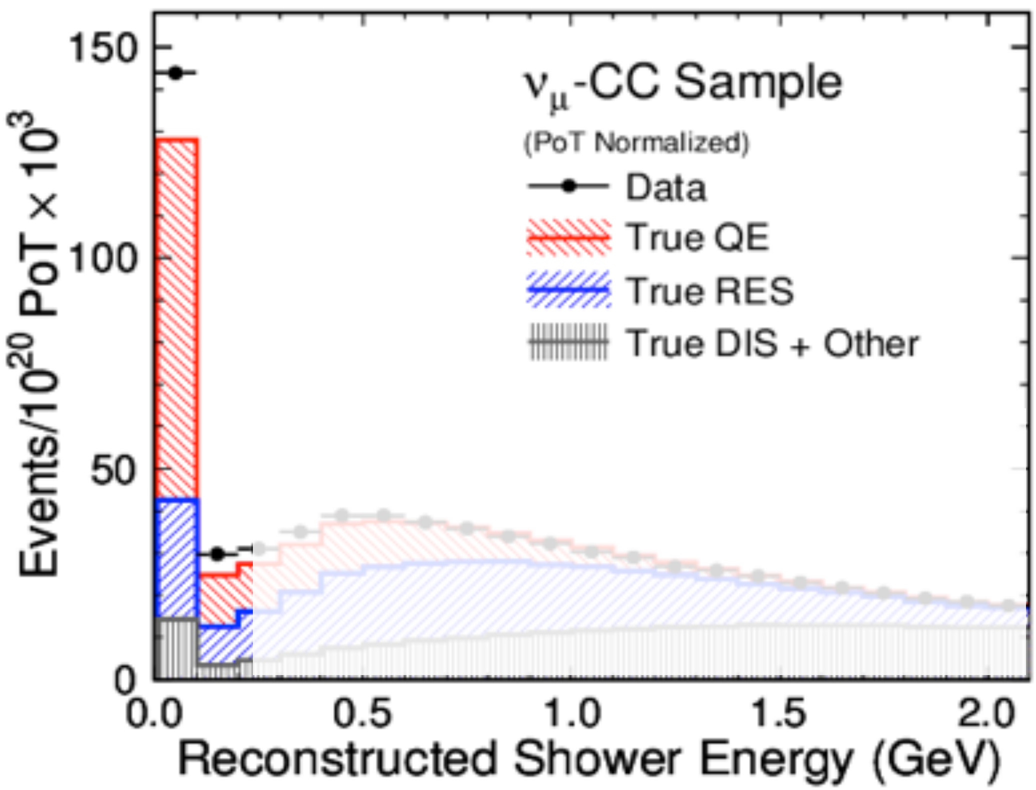
- QE/Δ & E_{Had}>250 MeV
- Dominated by RES particularly in the $Q^2 < 0.5$ GeV region.
- Significant QE contribution.

Event Selection (QE-Enhanced)



- QE/Δ & E_{Had}<225 MeV

Event Selection (QE-Enhanced)



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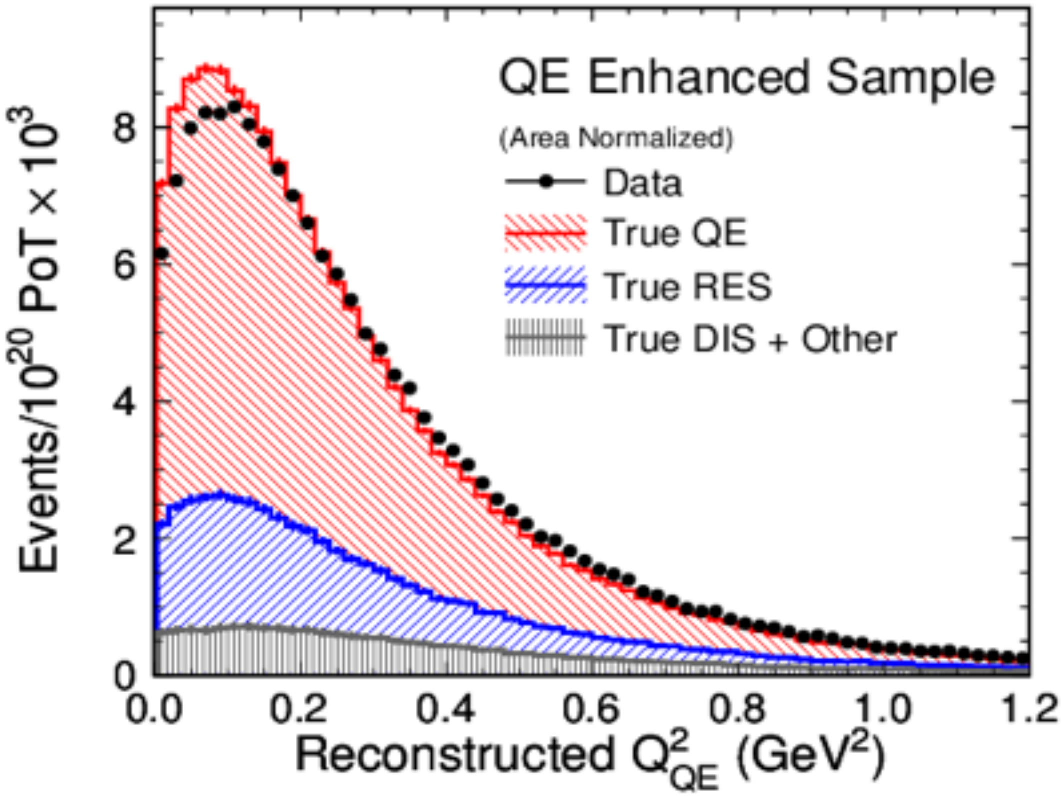
Event Selection (QE-Enhanced)



- QE/Δ & E_{Had}<225 MeV
- Dominated by QE
- RES and DIS contamination.

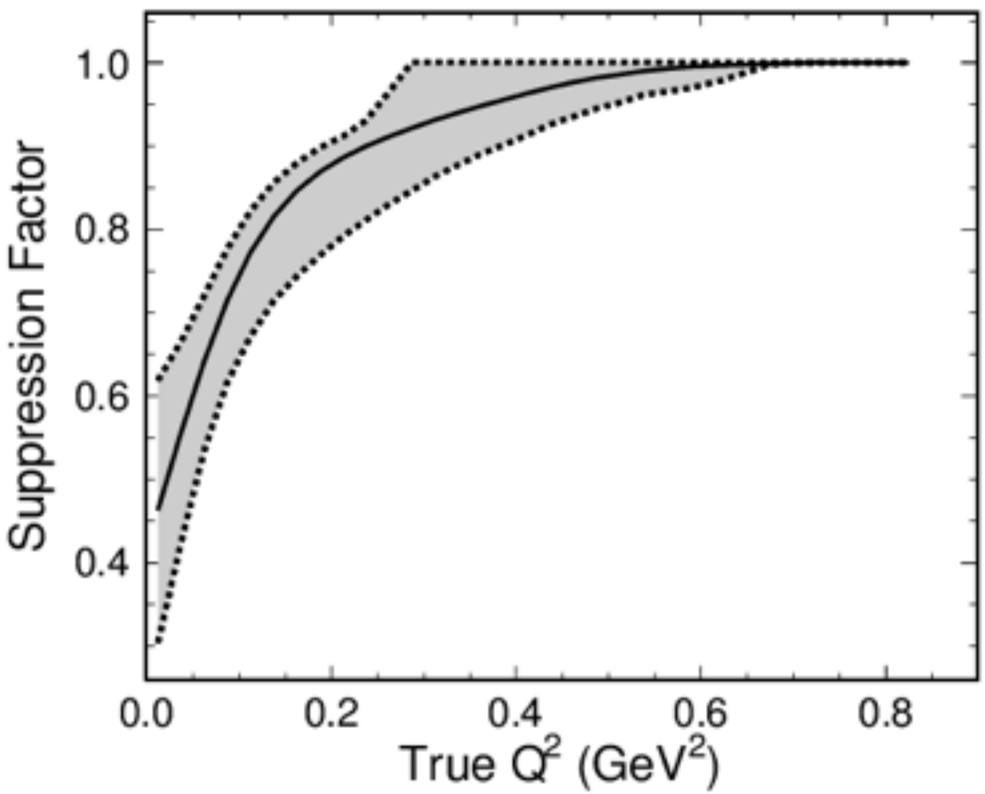
Data Driven Background Treatment

- When DIS dominate the MC, data well is described.
- When resonances dominate the MC, data is not well described.
- Resonance nuclear model is simplified RFG, with no Pauli-Blocking.
- Use data sidebands to determine a function that better describes the data when resonances dominate.

Data Driven Background Treatment

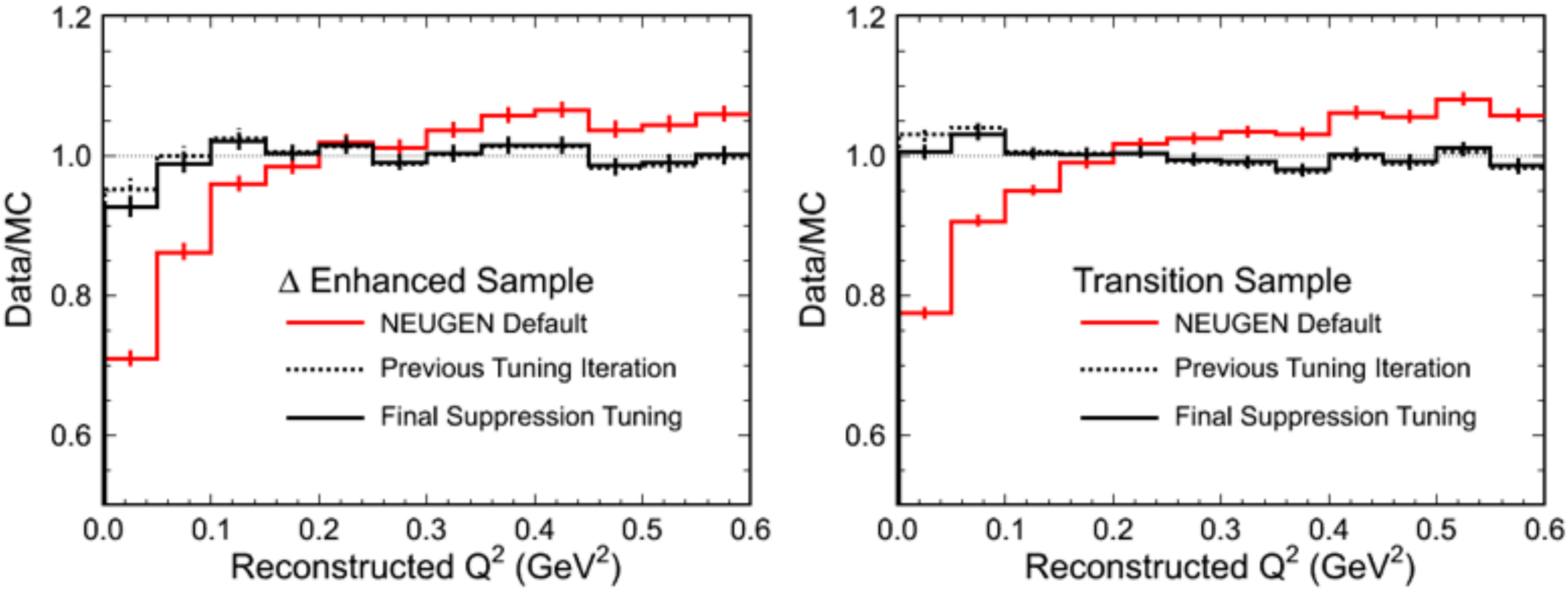
- Transition and Δ-Enhanced sub-samples
  - Used to constrain resonances in QE-Enhanced sub-sample.
- Fit to characterize the low Q^2 suppression was performed using the following procedure :
  - Transition and Δ-Enhanced samples simultaneously tuned in bins of true Q^2
  - minimize data-MC residuals in reconstructed Q^2 (area-normalized).
  - Smoothing procedure applied at each step.
  - Final 1-parameter fit determines the strength of the suppression function.

Data Driven Background Treatment



- The error band includes systematic errors.
- Systematic errors determined using alternative shapes, along with various model considerations, and reconstruction issues.
  - Alternative shapes dominate the error contribution for $Q^2 > 0.3$ GeV^2.
  - Physics considerations dominate for $Q^2 < 0.3$ GeV^2.

Data Driven Background Treatment



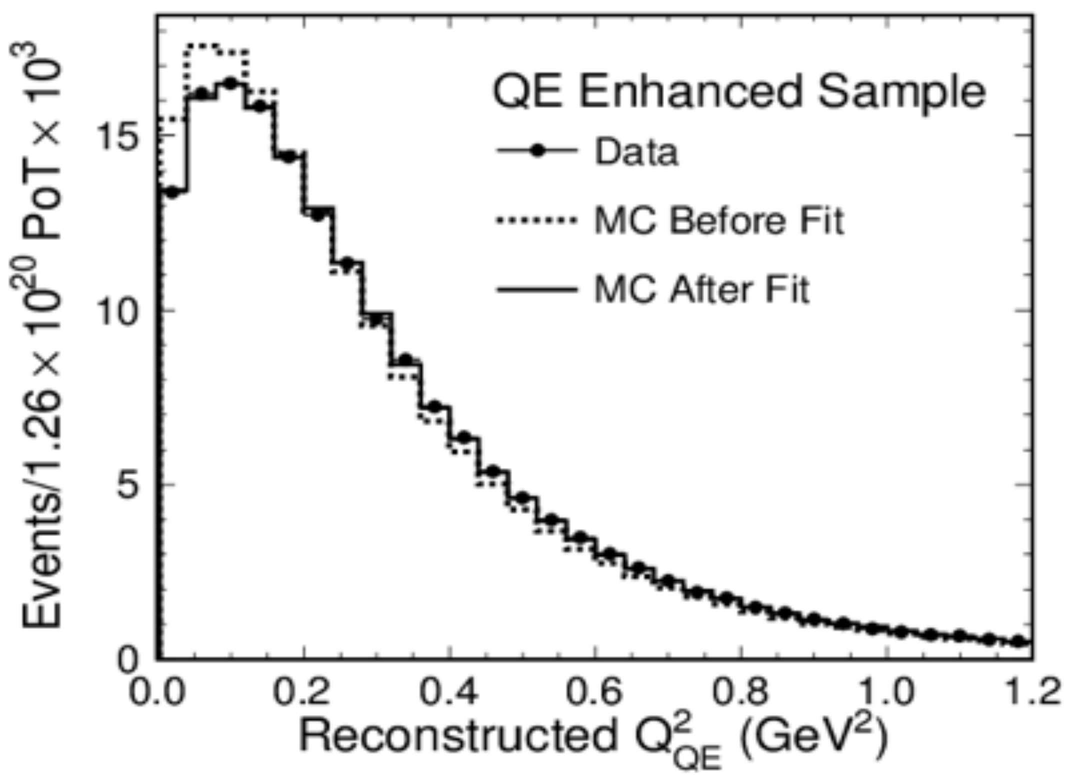
- The fitting does a good job of describing both samples simultaneously.
- The only discrepancy is in the Δ-enhanced sample which also has the largest QE contamination.

Fit Procedure:
Extract Effective M_A^{QE} From Shape Fit to Q^2

- Three nuisance parameters included in fit:
  - Stopping muon energy scale: E_μ
  - Resonance axial mass: M_A^{RES}
  - Quasi-elastic Pauli blocking parameter: $k^{QE}{}_{Fermi}$
- Secondary Fit also performed
  - $0.3 < Q^2 < 1.2$ (GeV)
  - $k^{QE}{}_{Fermi}$ not used.

χ^2 includes MC statistics:

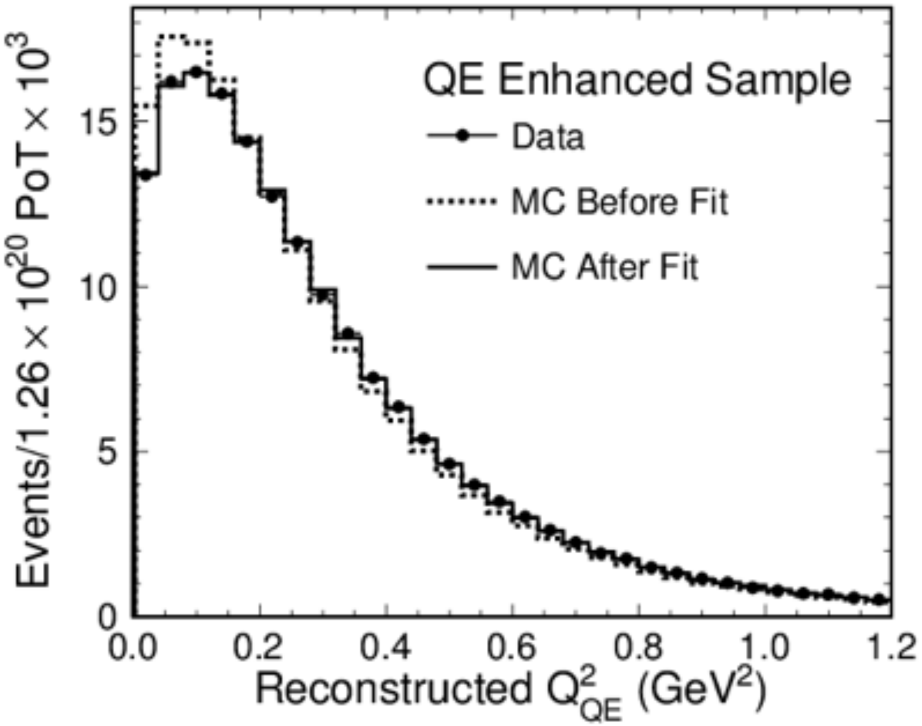
$$\chi^2 = \sum_{i=1}^{\#bins} \frac{(N_i^{obs} - N_i^{MC}(\alpha_1, \ldots, \alpha_N))^2}{(N_i^{obs} + S \cdot N_i^{MC}(\alpha_1, \ldots, \alpha_N))} + \sum_{j=2}^{N} \frac{\Delta\alpha_j^2}{\sigma_{\alpha_j}^2}$$



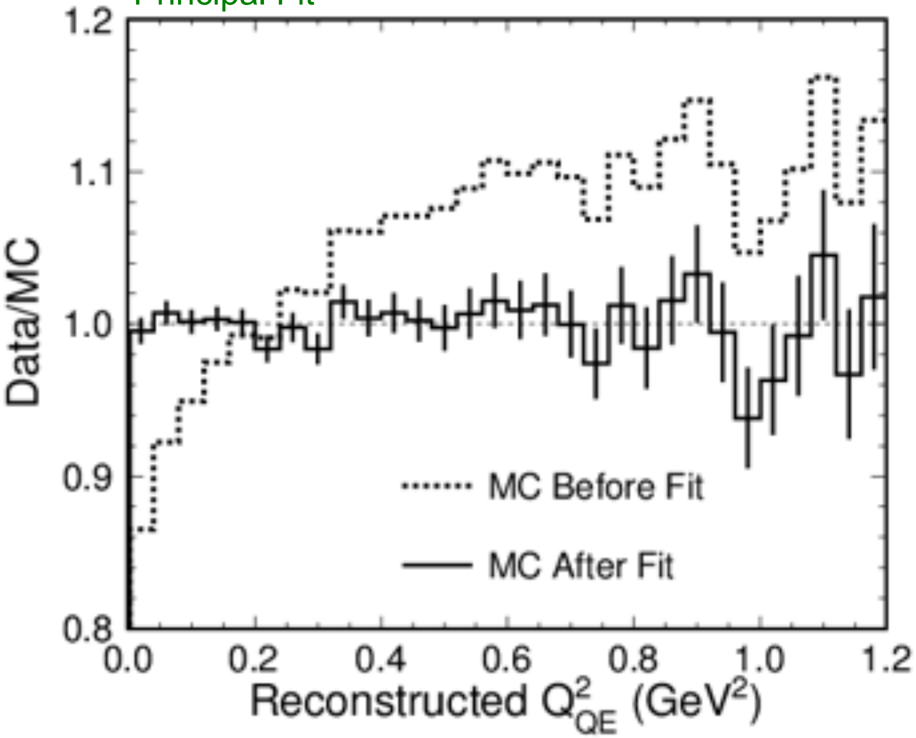
Fit Results

	M_A^{QE} (GeV)	E_μ-Scale	M_A^{Res} (GeV)	k_{Fermi}^{QE}
Principal: $0.0 < Q^2 < 1.2$	1.23 +0.13 -0.09	1.00±0.01	1.09 +0.14 -0.15	1.06±0.02
Alternate: $0.3 < Q^2 < 1.2$	1.22 +0.18 -0.11	1.00 +0.01 -0.02	1.09 +0.15 -0.16	Not fit

Principal Fit



Principal Fit



Systematic Errors

$$M_A^{QE} = 1.23^{+0.13}_{-0.09}(fit)^{+0.12}_{-0.15}(syst)\,GeV$$

Systematic Error Source	Fit Q^2 Range $0.0 < Q^2 < 1.2$ (GeV)	
	+ shift (GeV)	- shift (GeV)
CCQE E_{had} Selection	0.062	0.062
Δ/N^* Low Q^2 Suppression	0.005	0.088
Intranuclear Scattering	0.066	0.066
Detector Model in *x,z*	0.059	0.059
Other Systematics	0.056	0.053
Quadrature Sum	0.122	0.149

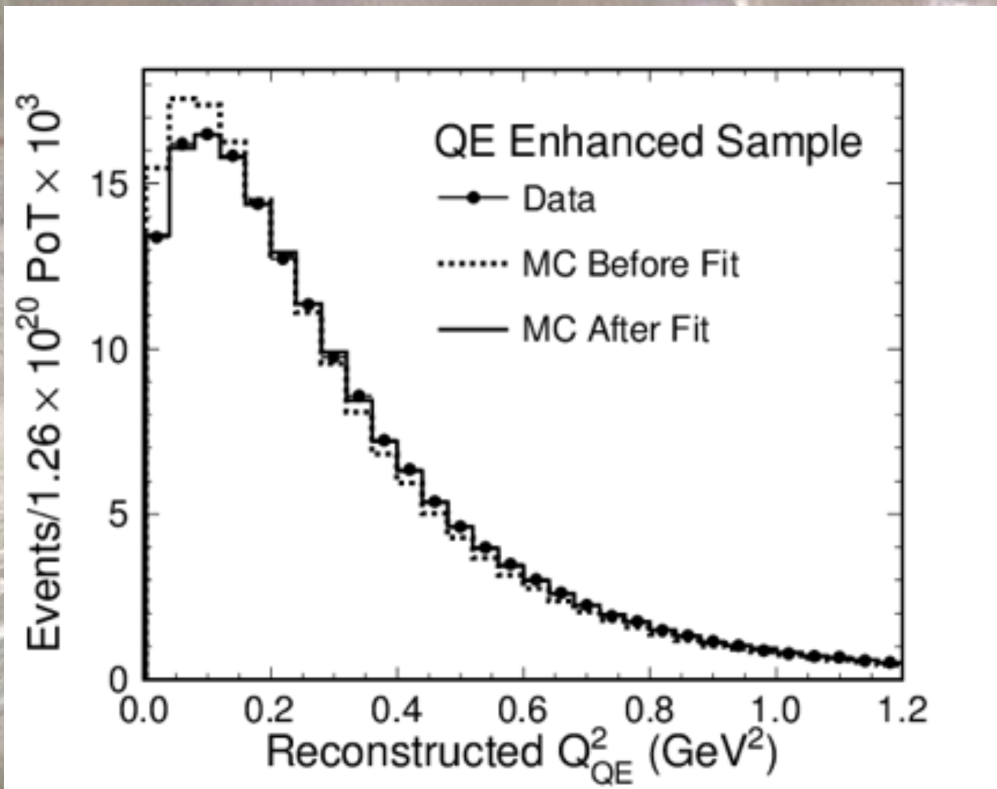
Conclusion

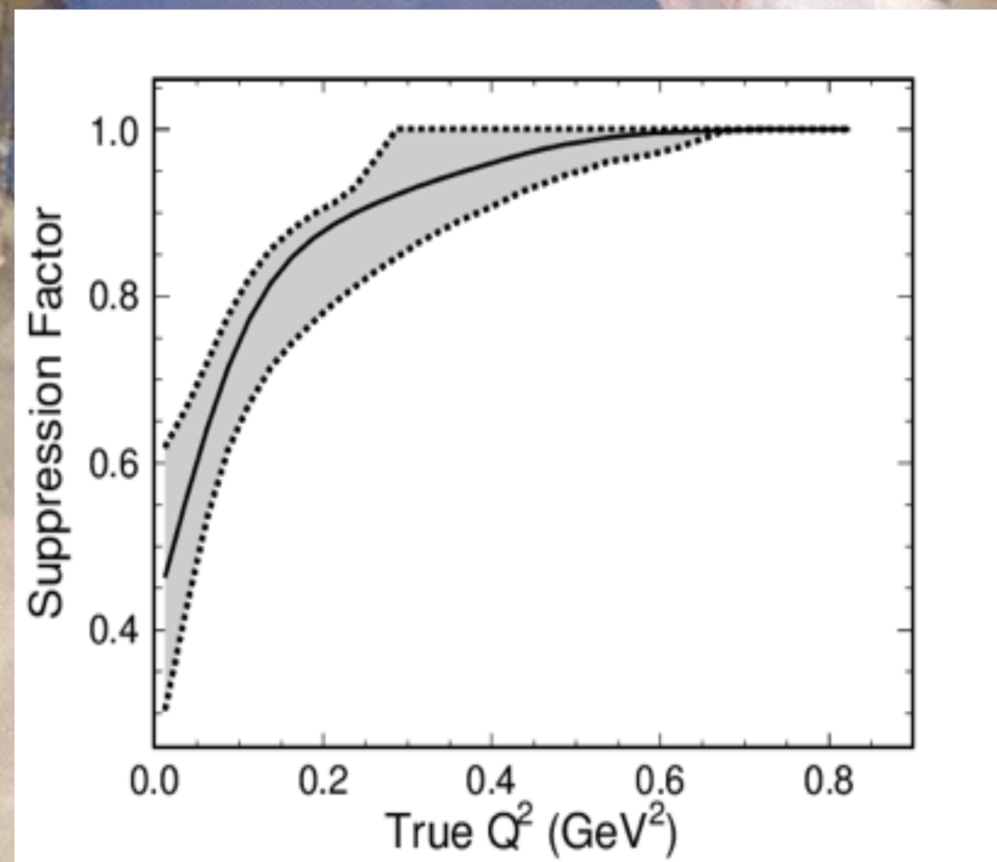
- In the resonance sector MC over-estimates the data by 20%.
- Excess primarily in low Q^2 region.
- Fitting procedure developed to describe this behavior.
- Suppresses low Q^2 resonance.
- Single resonance suppression function describes both resonance dominated sub-samples.

Conclusion

- Using a fit to the shape of the Q^2 distribution we extract a effective value to the axial vector mass.
- Measured effective axial vector mass is:
$M_A^{QE} = 1.23^{+0.13}_{-0.09}(fit)^{+0.12}_{-0.15}(syst) GeV$
- Increased value for axial mass, deficit in low Q^2 resonance production. Interpreted as nuclear medium effects off of Iron.

Thank You!


QE Enhanced Sample
Data
MC Before Fit
MC After Fit
Events/1.26 × 10^{20} PoT × 10^{3}
Reconstructed Q^2_{QE} (GeV^2)
0
5
10
15
0.0
0.2
0.4
0.6
0.8
1.0
1.2


Suppression Factor
True Q^2 (GeV^2)
0.4
0.6
0.8
1.0
0.0
0.2
0.4
0.6
0.8

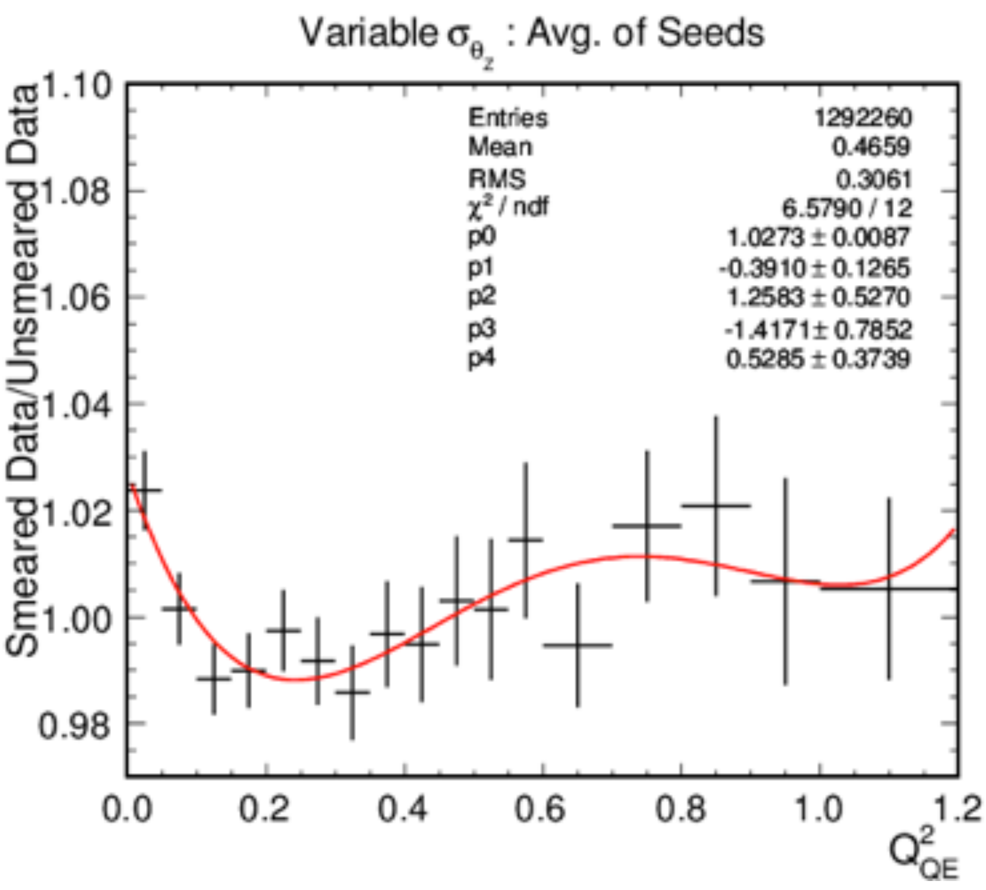
Backup Slides

Muon Scattering Angle Resolution

Track Length (planes)	Peak Mom. (GeV/c)	MC – Data (mrad)
15 - 45	1.6	16.0 ± 2.0
45 - 60	2.2	12.2 ± 2.5
60 - 75	2.6	14.1 ± 1.6
75 - 105	3.1	10.5 ± 1.0
105 - 150	4.3	4.1 ± 2.2
150 - 240	6.2	-2.1 ± 3.4

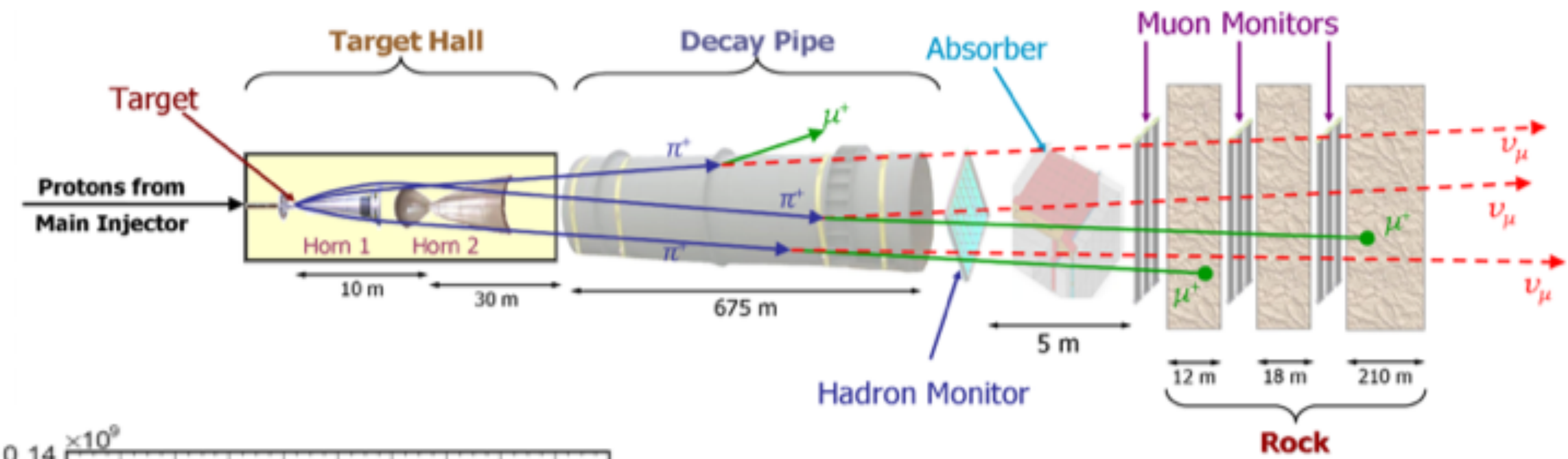
- This discrepancy in the angular resolution between data and MC gives rise to mild flattening of the MC Q^2.
- Because this is attributable to mis-modeling in the MC it must be accounted for to minimize it's effect on the final results.

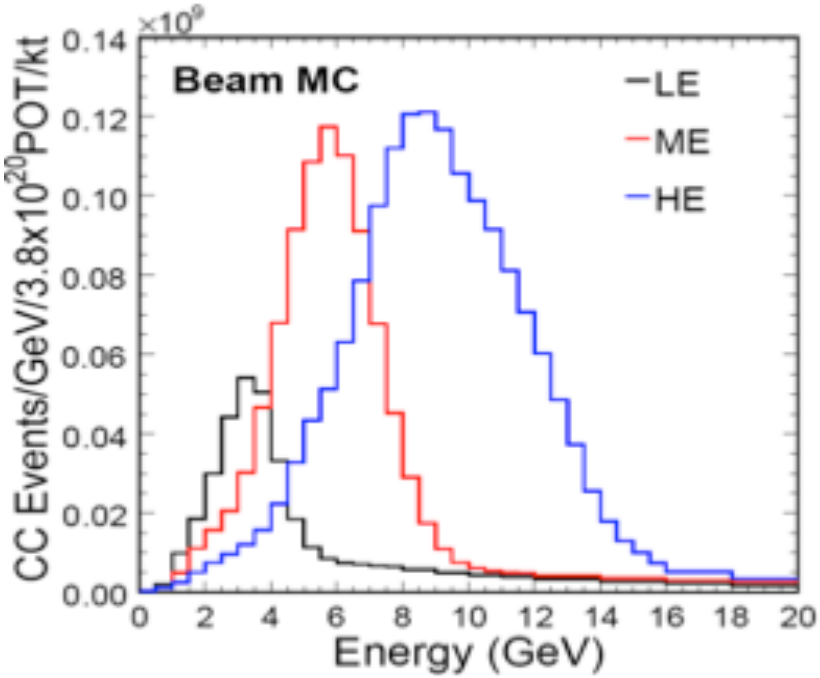
Muon Scattering Angle Resolution



- We characterized this discrepancy by adding additional smearing to the <u>data</u> in a manner that matches the behavior of the MC and comparing it to the un-smeared <u>data</u>.
- The resulting ratio is fit to a 4th order polynomial.
- The inverse of this polynomial is applied as a correction to the MC

The NuMI Beam

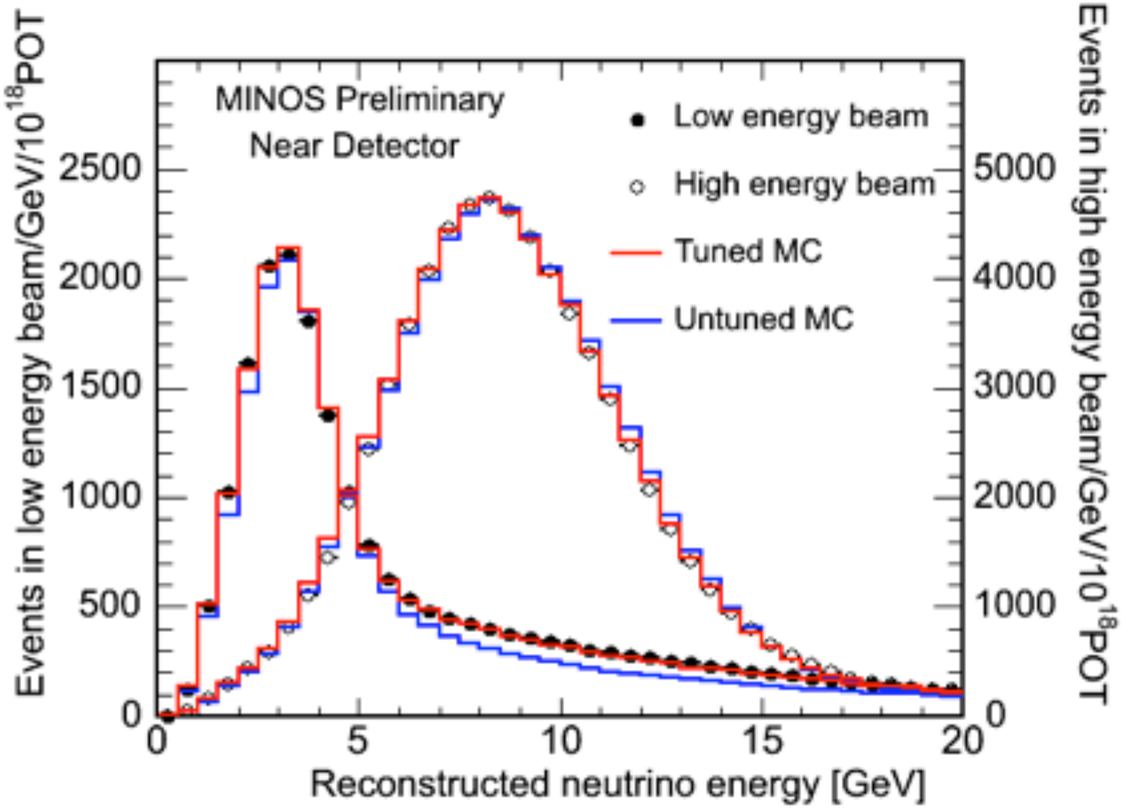




- The distance between the target and the first horn could be changed to give a variable beam energy.
- This was used to break correlations between beam flux effects and cross section effects.
- In the low energy configuration the beam comprises:

$$92.9\%\ \nu_\mu,\ 5.8\%\ \bar{\nu}_\mu,\ 1.3\%\ \nu_e + \bar{\nu}_e$$

Energy Spectra and Flux 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, NC cross section 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.