CCQE Analyses In MINOS and NOvA

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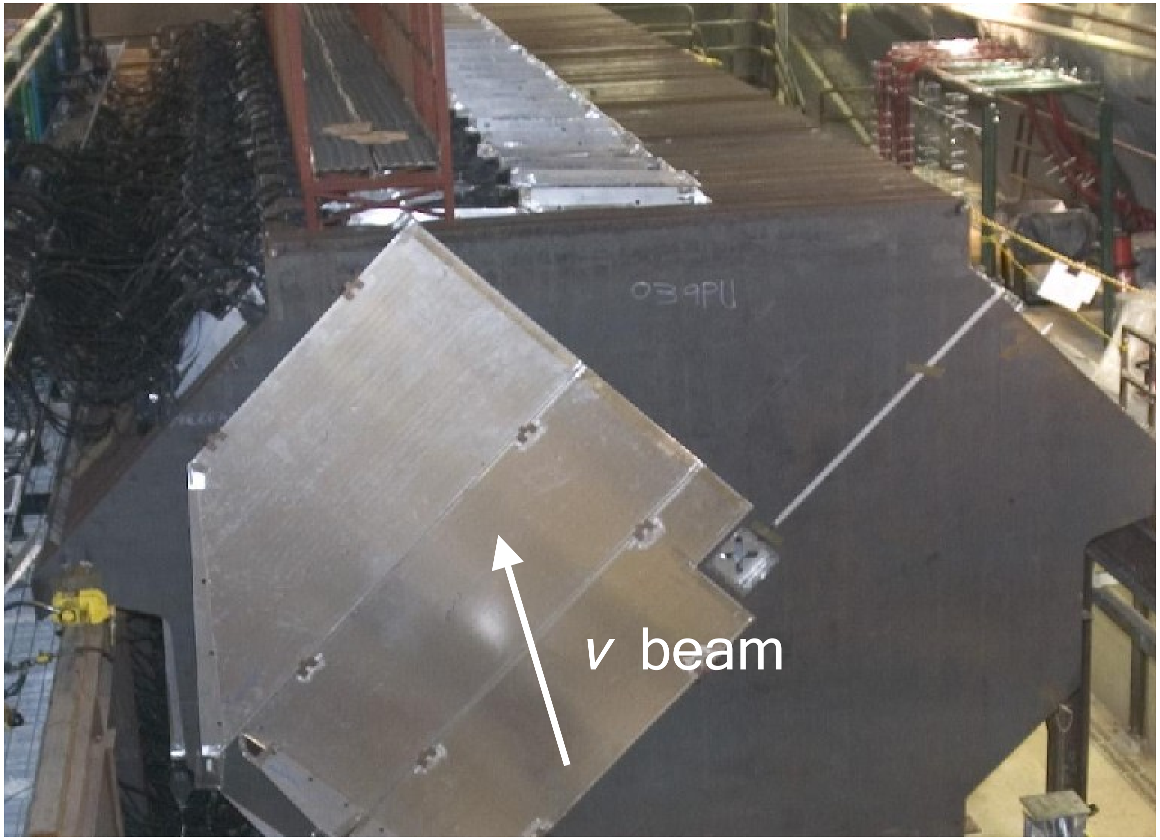
Outline

- MINOS
  - Detector
  - Spectra and Flux
  - Selecting QE and Non-QE
    - Characterizing Non-QE
  - Fit Procedure
  - Systematics
- NOvA
  - Detector
  - Spectra and Flux
  - Event Selection
  - Unfolding and Sytematics
- Summary Tables
- NuMI Flux Tables

MINOS CCQE Analysis

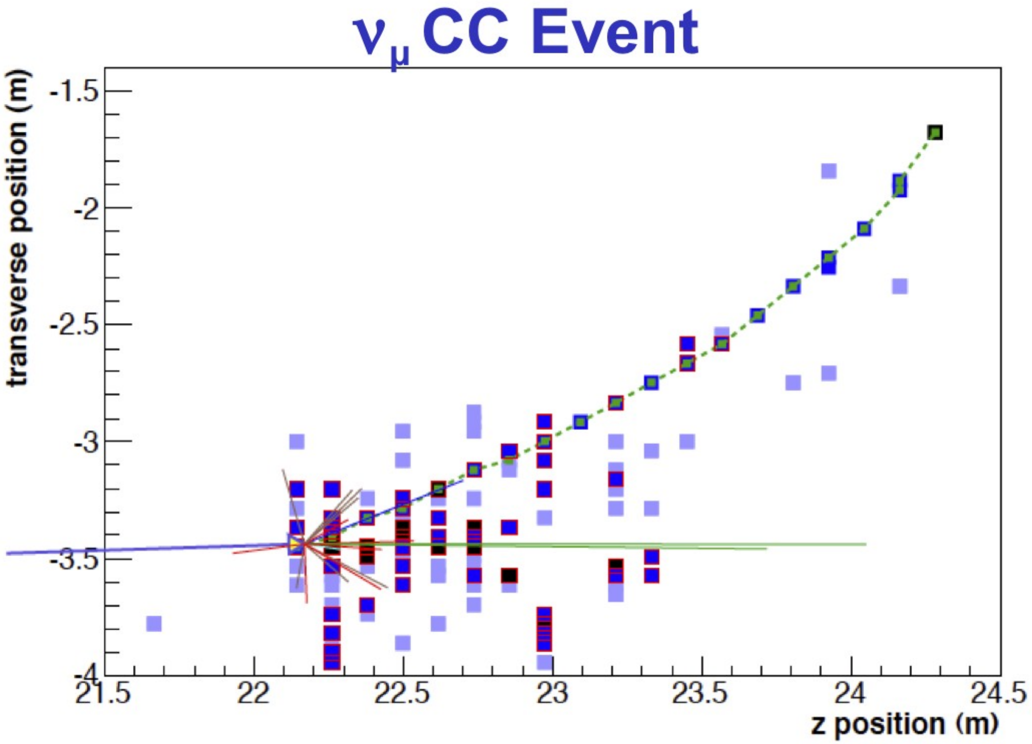
The MINOS Near Detector (ND)



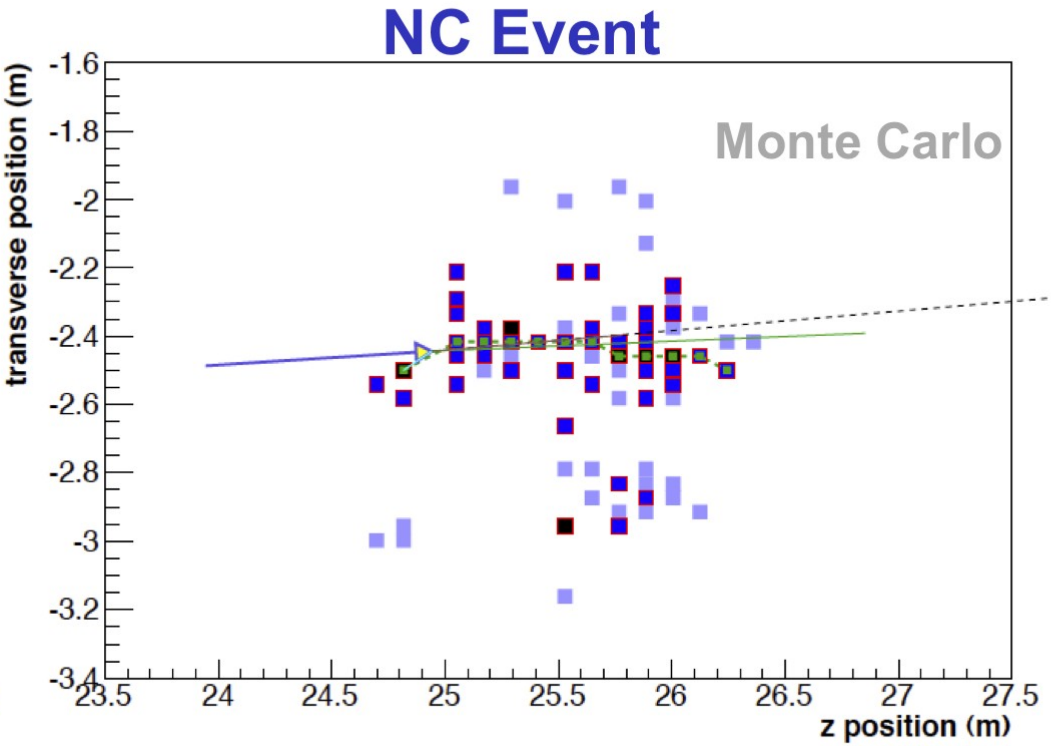
- 1km from target.
- 0.98 kton (0.03 kton fiducial).
- 282 2.5 cm thick steel planes.
- Magnetized.
- P_μ from range and curvature.

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

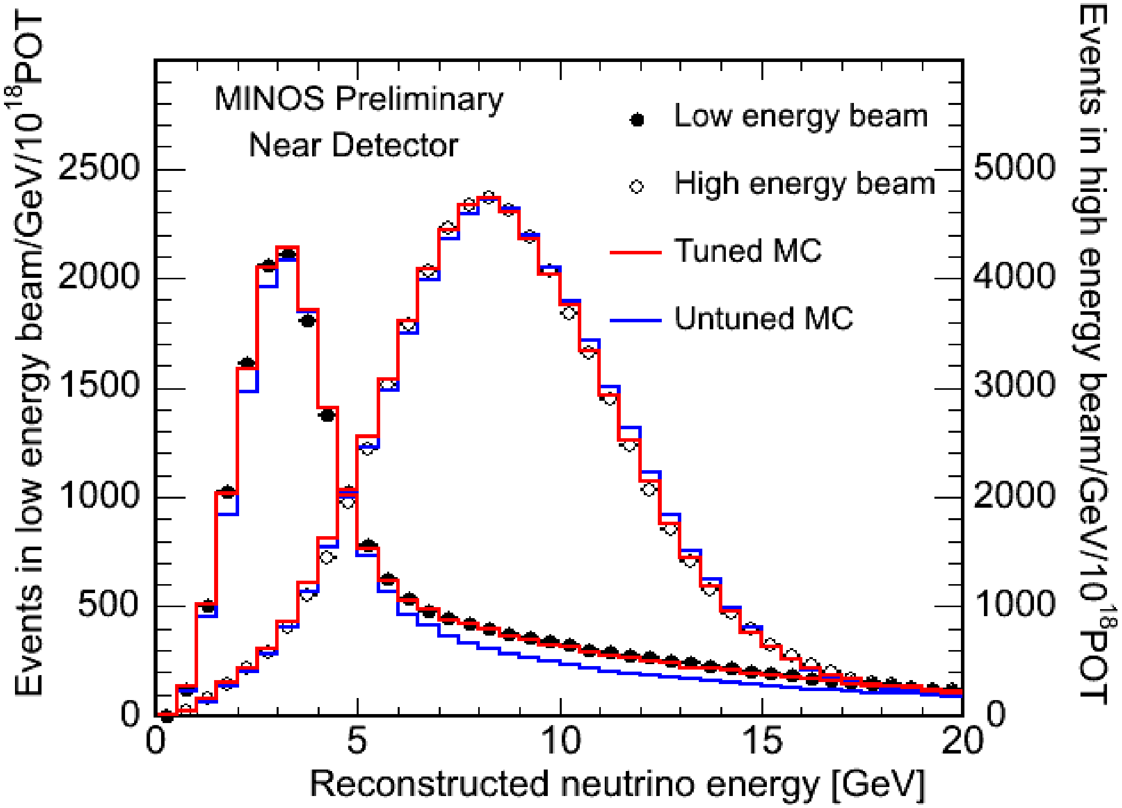


ν_μ CC Event



NC Event

Energy Spectra and Flux Tuning



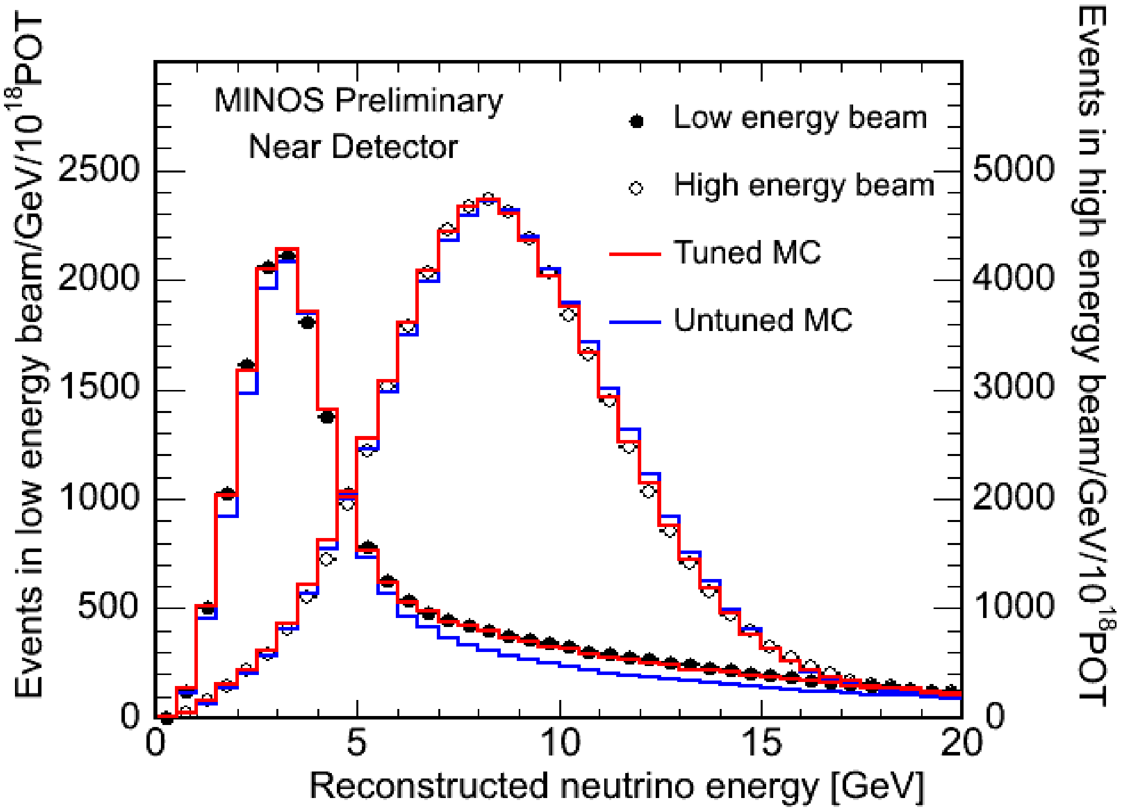
- Moving target longitudinally and varying horn current allows changing of neutrino spectrum.

- 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.

Kinematics

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

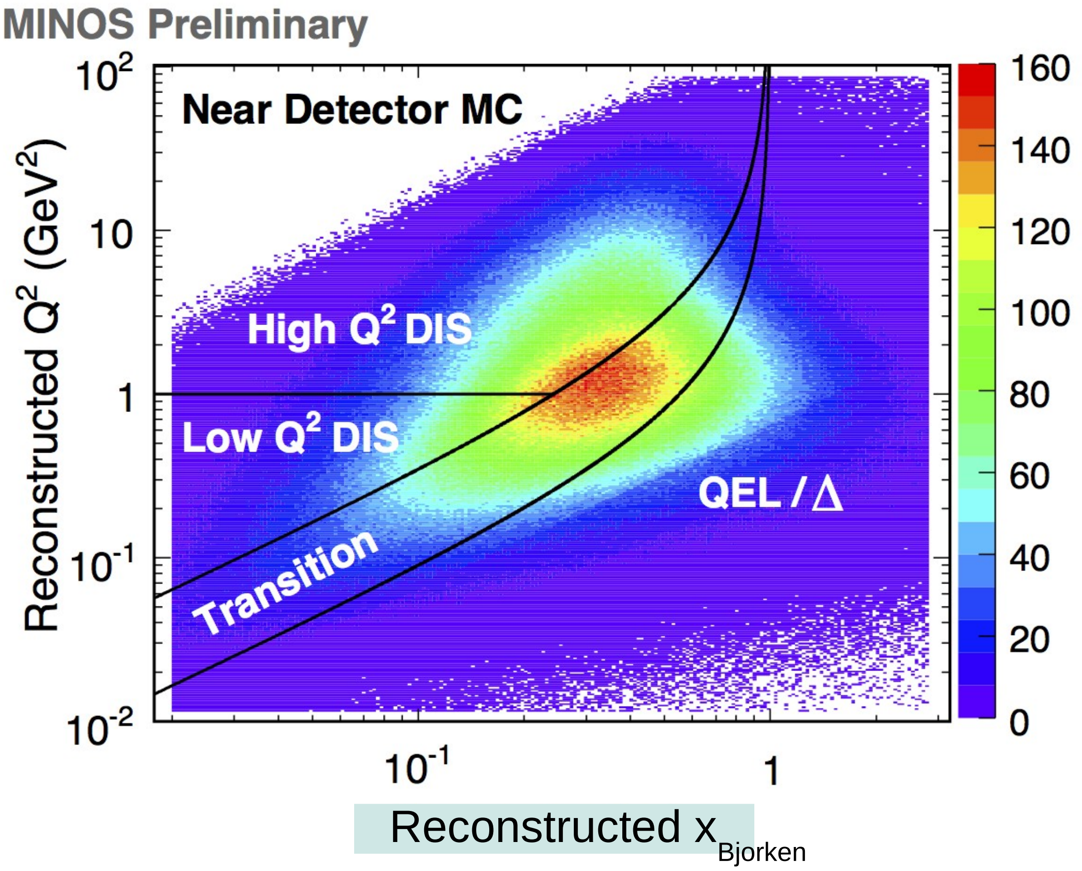
- MINOS can reconstruct everything about the muon: E_μ, p_μ, $\cos(\theta_\mu)$.
- Just the energy of the hadron shower: E_{had}.
- From these reconstructed variables we can calculate the above kinematic quantities.

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

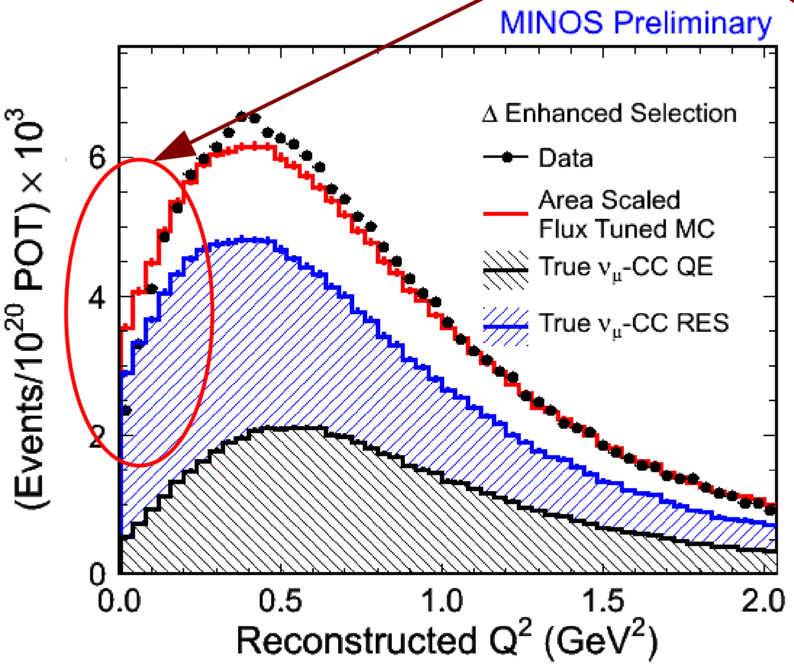
- Δ/N^* Enhanced Selection
  - $E_{had} > 250$ MeV,
  - $W_{Reco} < 1.3$ GeV
- RES to DIS Transition Selection
  - $1.3 < W_{Reco} < 2.0$ GeV
- DIS Selection
  - $W_{Reco} > 2.0$ GeV

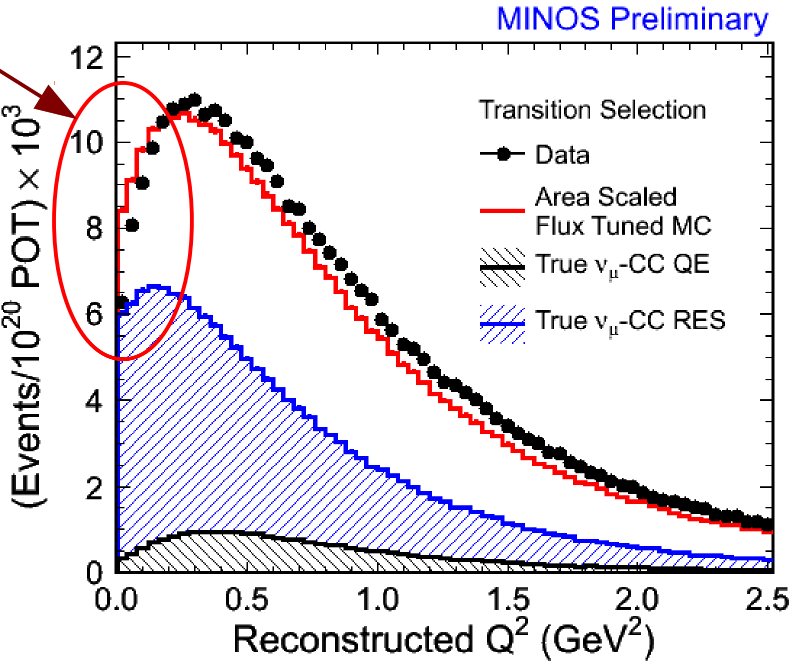


- These selections allow us to explore the different regions of our model using reconstructed variables.
- In this way we can compare how well different parts of our model are simulating the data.

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.

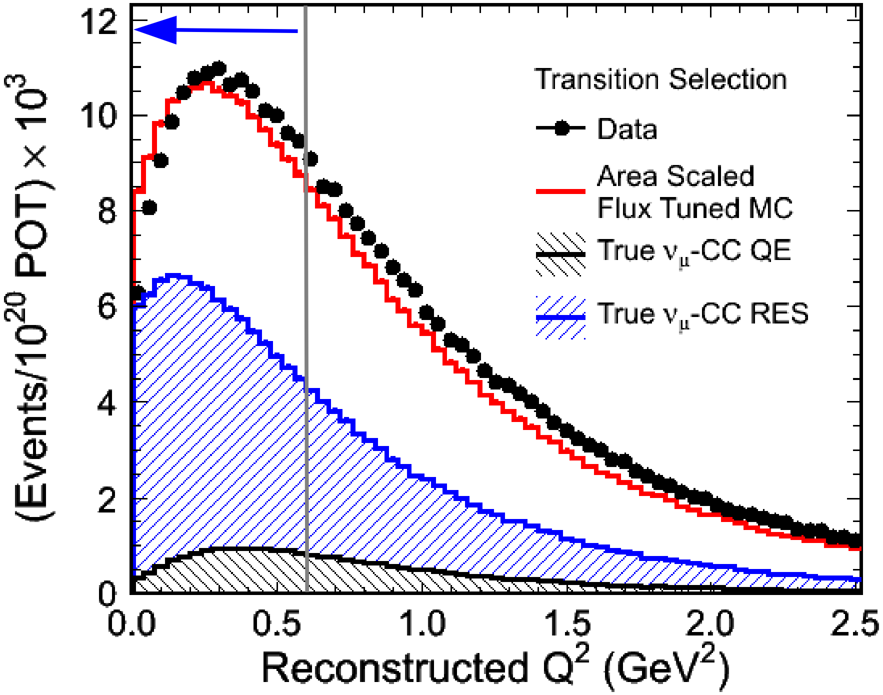




RES Enhanced Selection:
W_{reco} < 1.3 GeV
E_{had} > 250 MeV

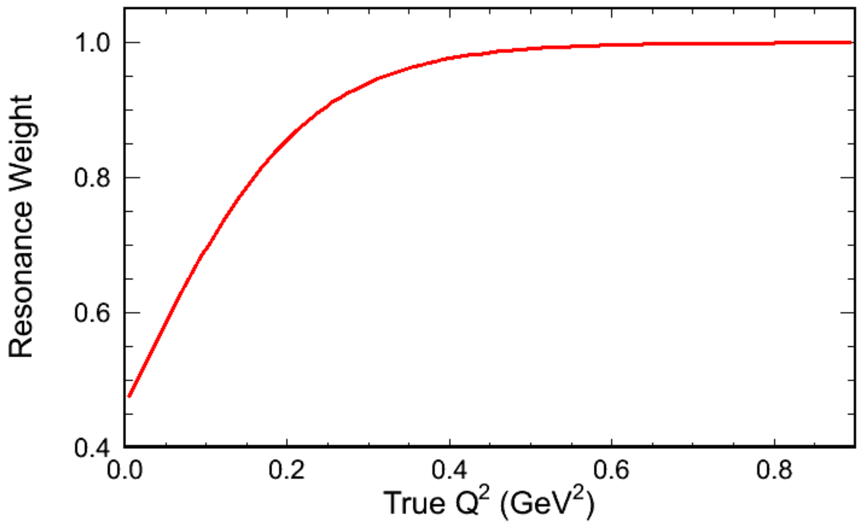
RES to DIS Transition Selection:
1.3 < W_{reco} < 2.0 GeV

Fitting the Low Q^2 Region



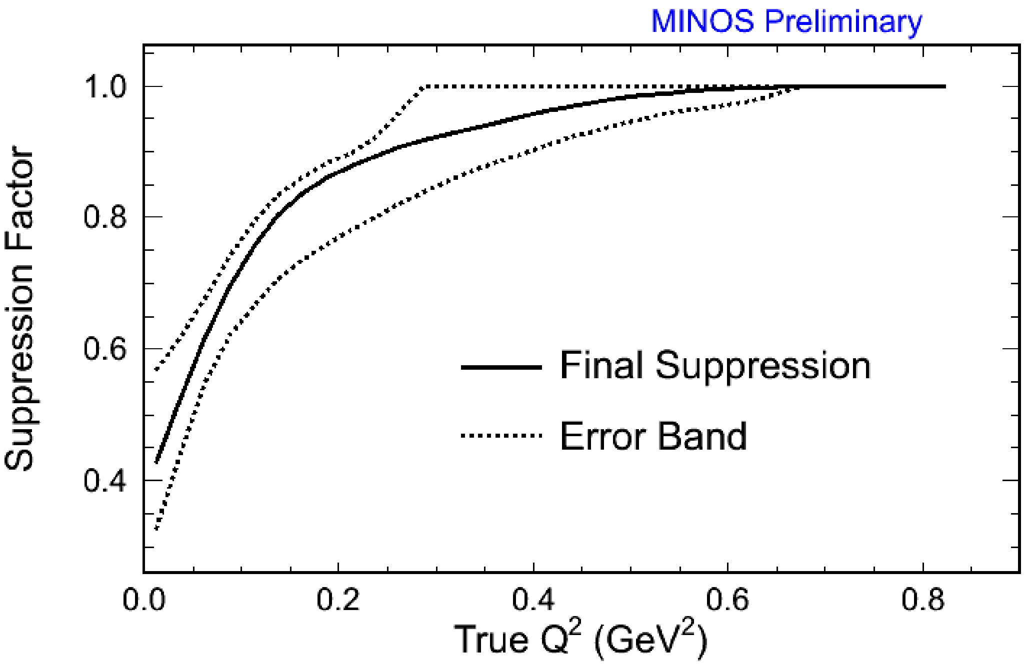
Fit $Q^2 < 0.6$ GeV^2

MINOS Preliminary



- 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.

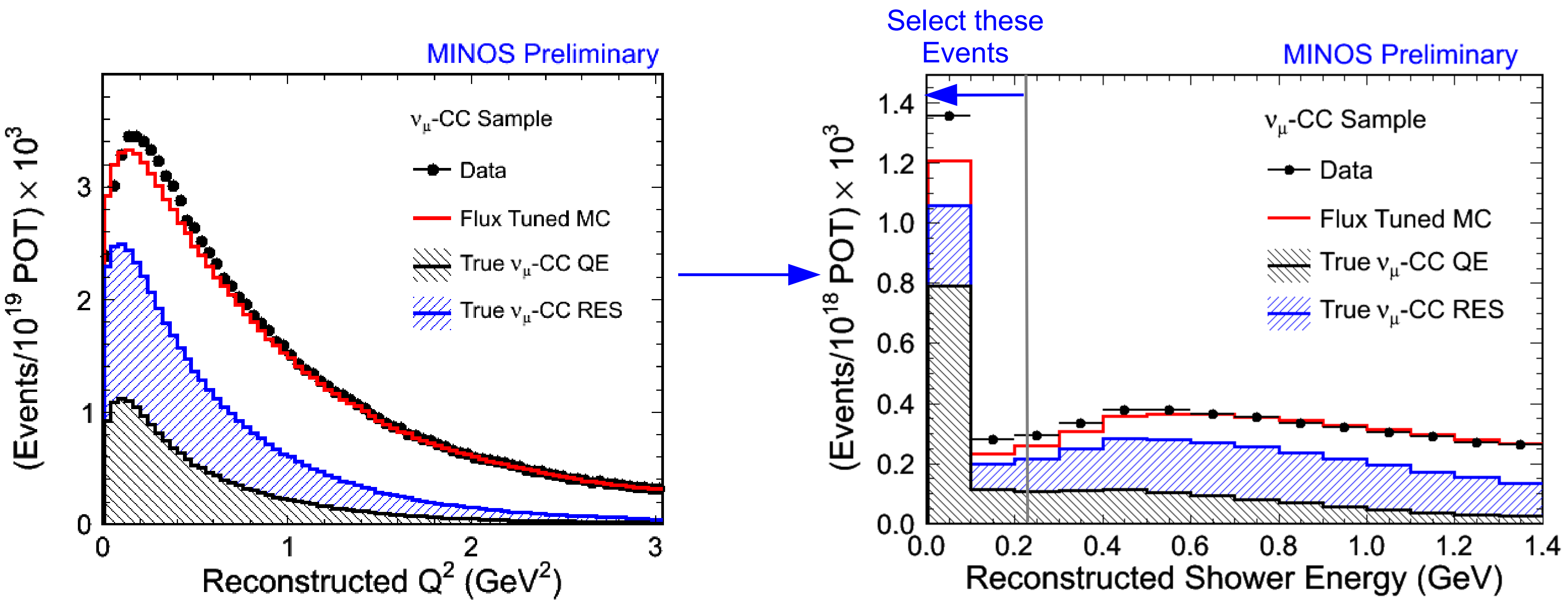
Background Weighting with Error Band



- Two alternative suppression shapes were considered.
    - A linear function that turns off at lower Q^2 ~ 0.3 GeV^2.
    - And a function that turns off at higher Q^2~ 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.

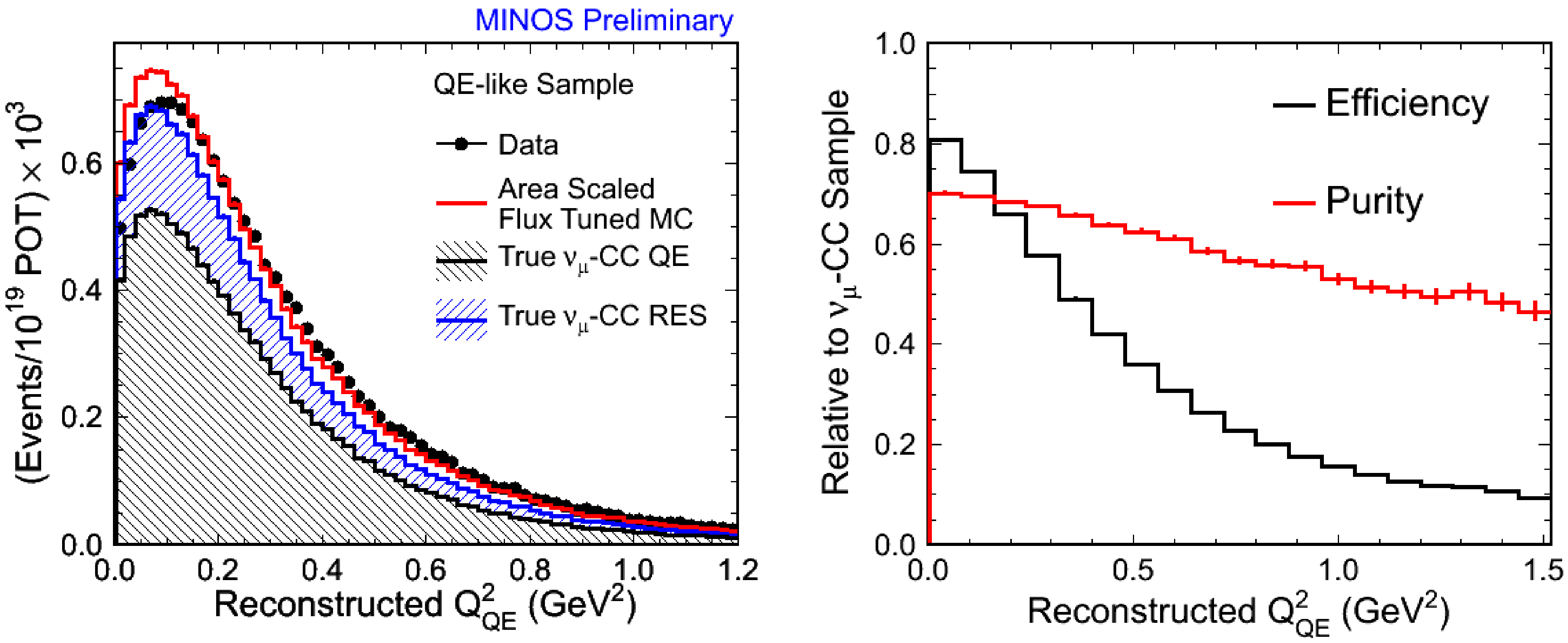
Quasielastic-like Selection

- 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

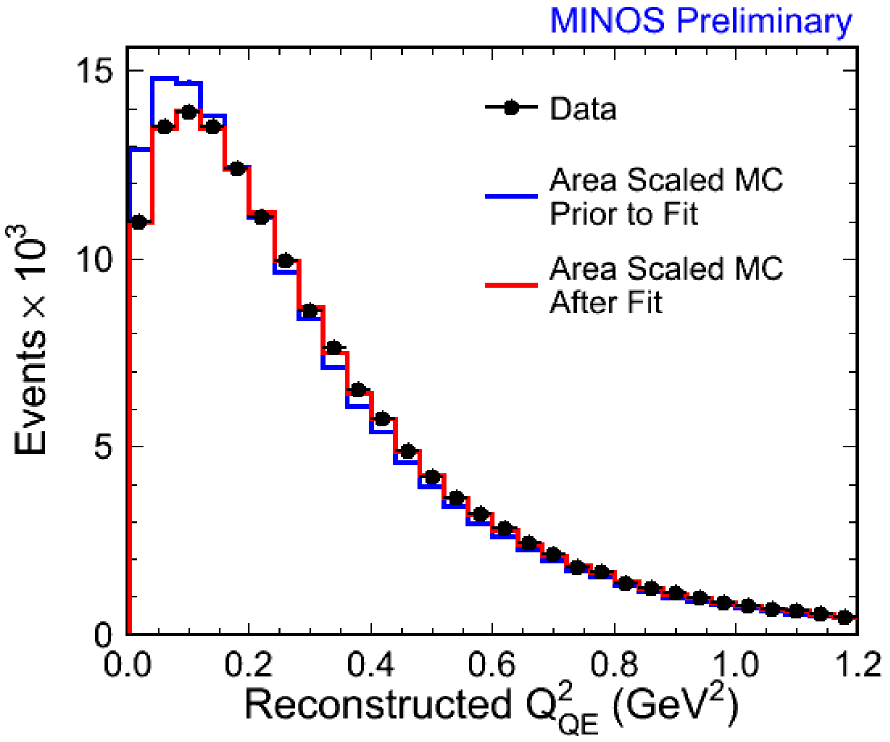
- Low E_{had}: Select from ν_μ-CC sample events with Reconstructed E_{had} < 225 MeV.
- Select events with muon tracks that stop in ND.
- Includes the RES re-weighting function.
- Selects QE Interactions with 44% Efficiency and 63% Purity

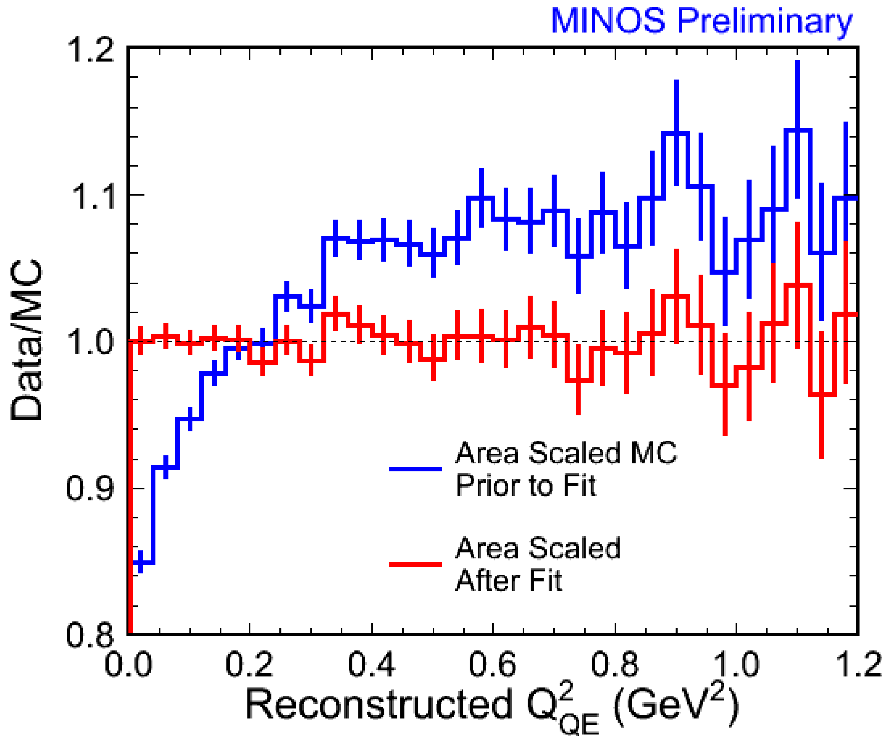


Best Fit Results

Result from the principal fit configuration.

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

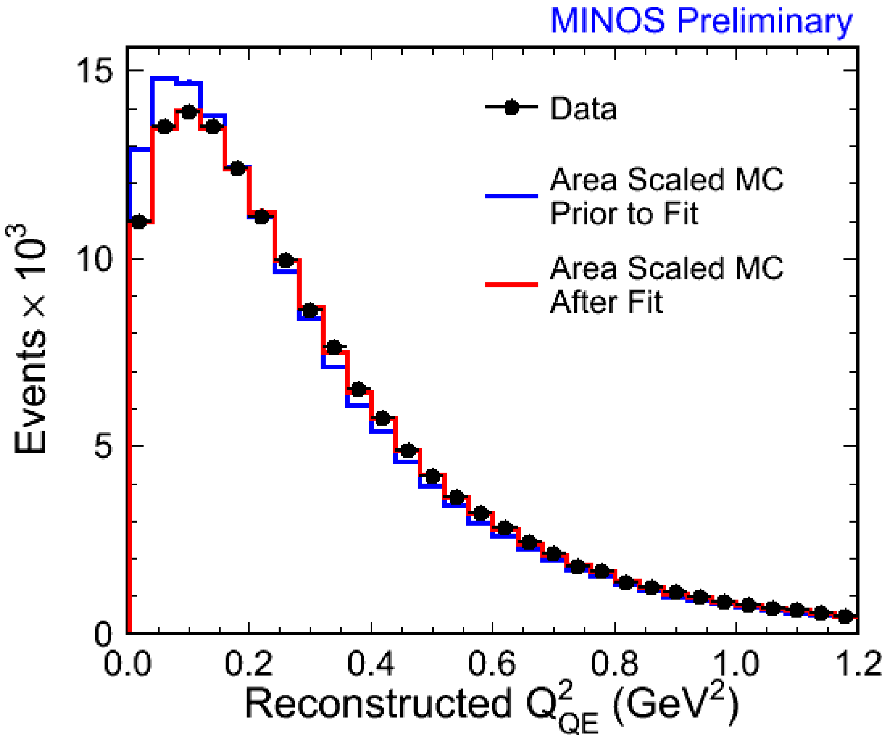


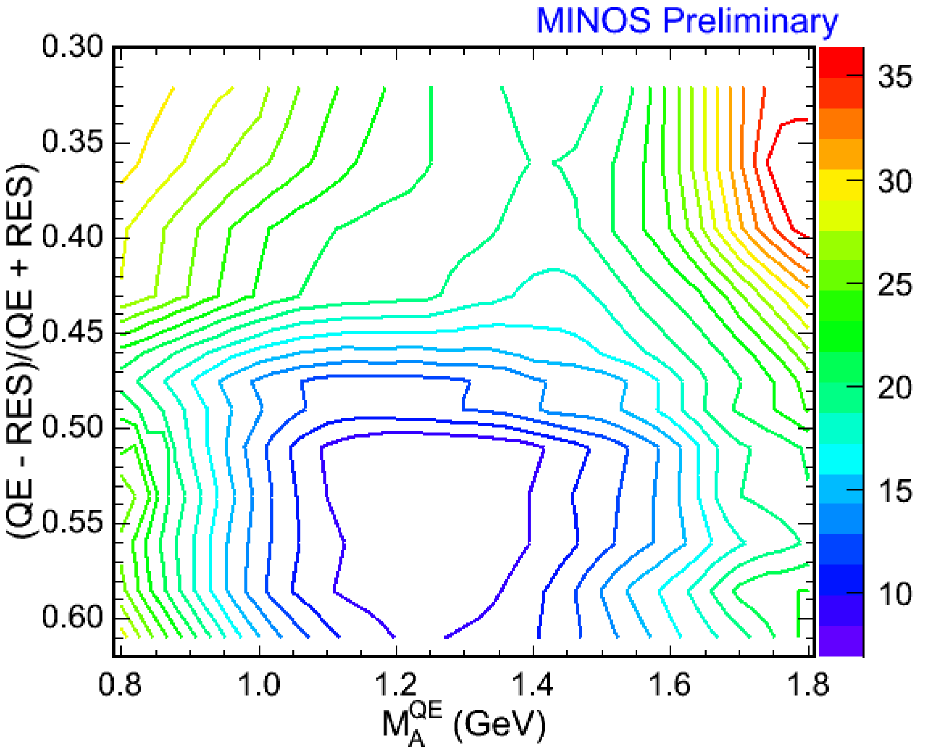


Best Fit Results

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

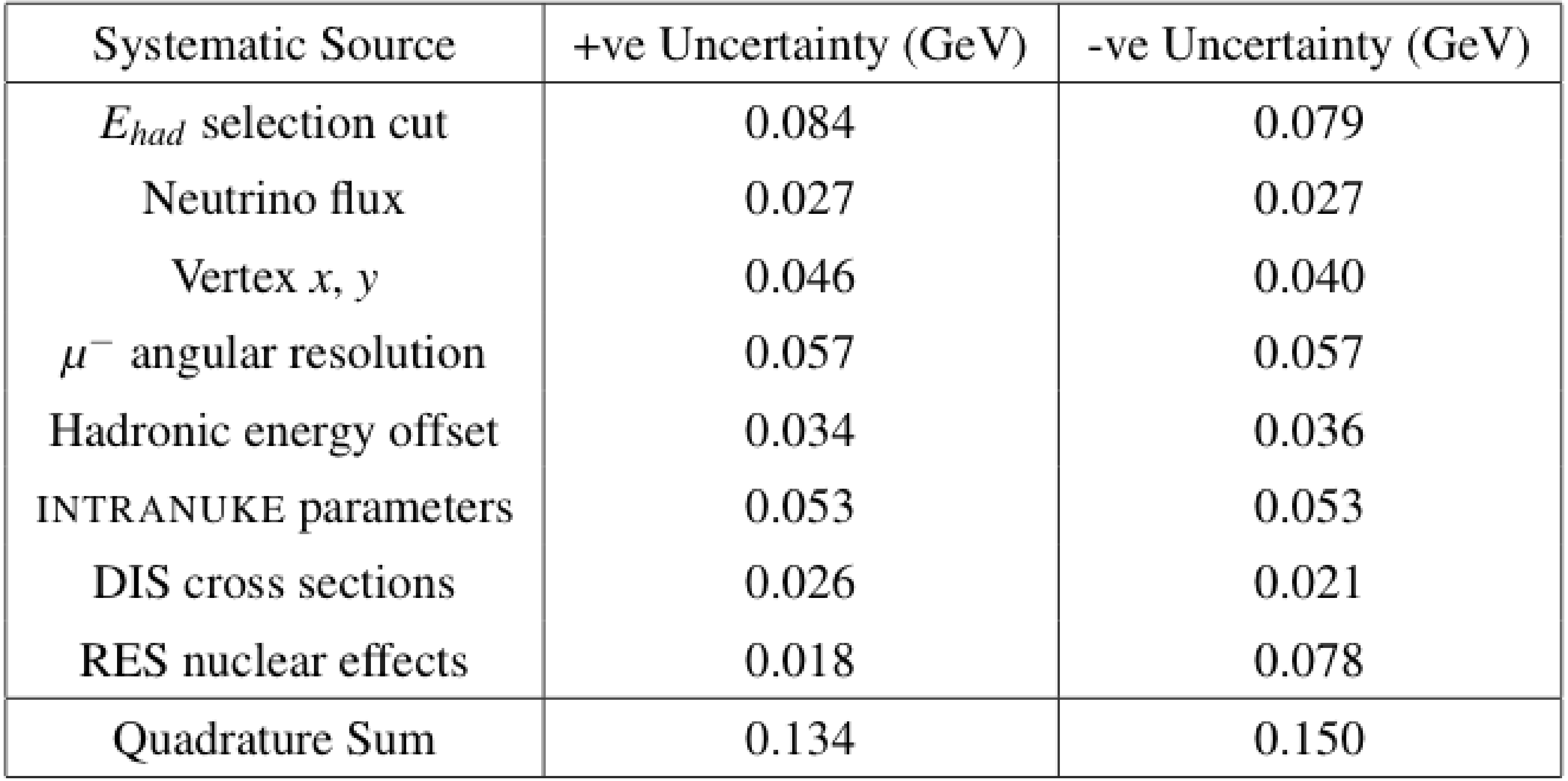




Systematic Error Table

Best Fit:

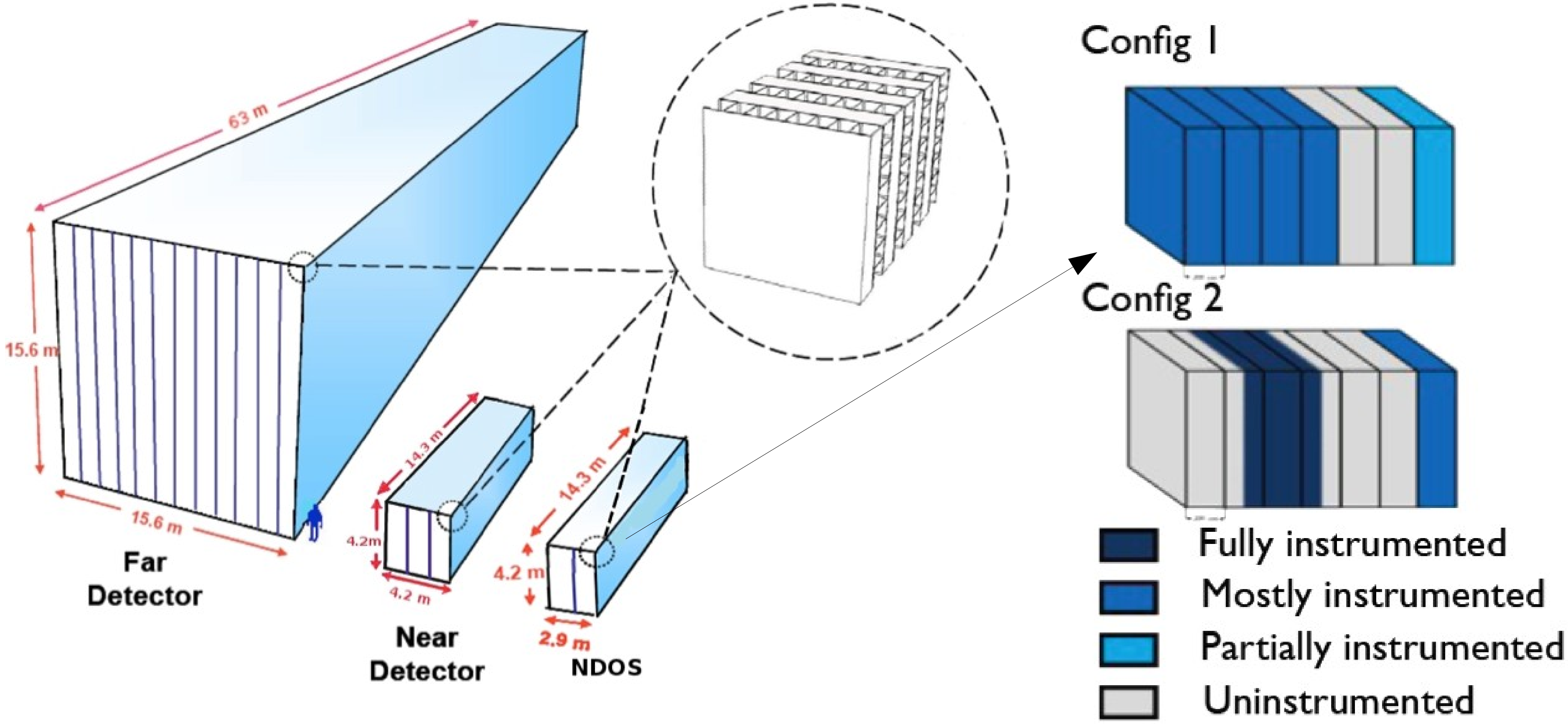
$$M_A^{QE} = 1.21^{+0.18}_{-0.10}(fit)^{+0.13}_{-0.15}(syst)\,GeV$$



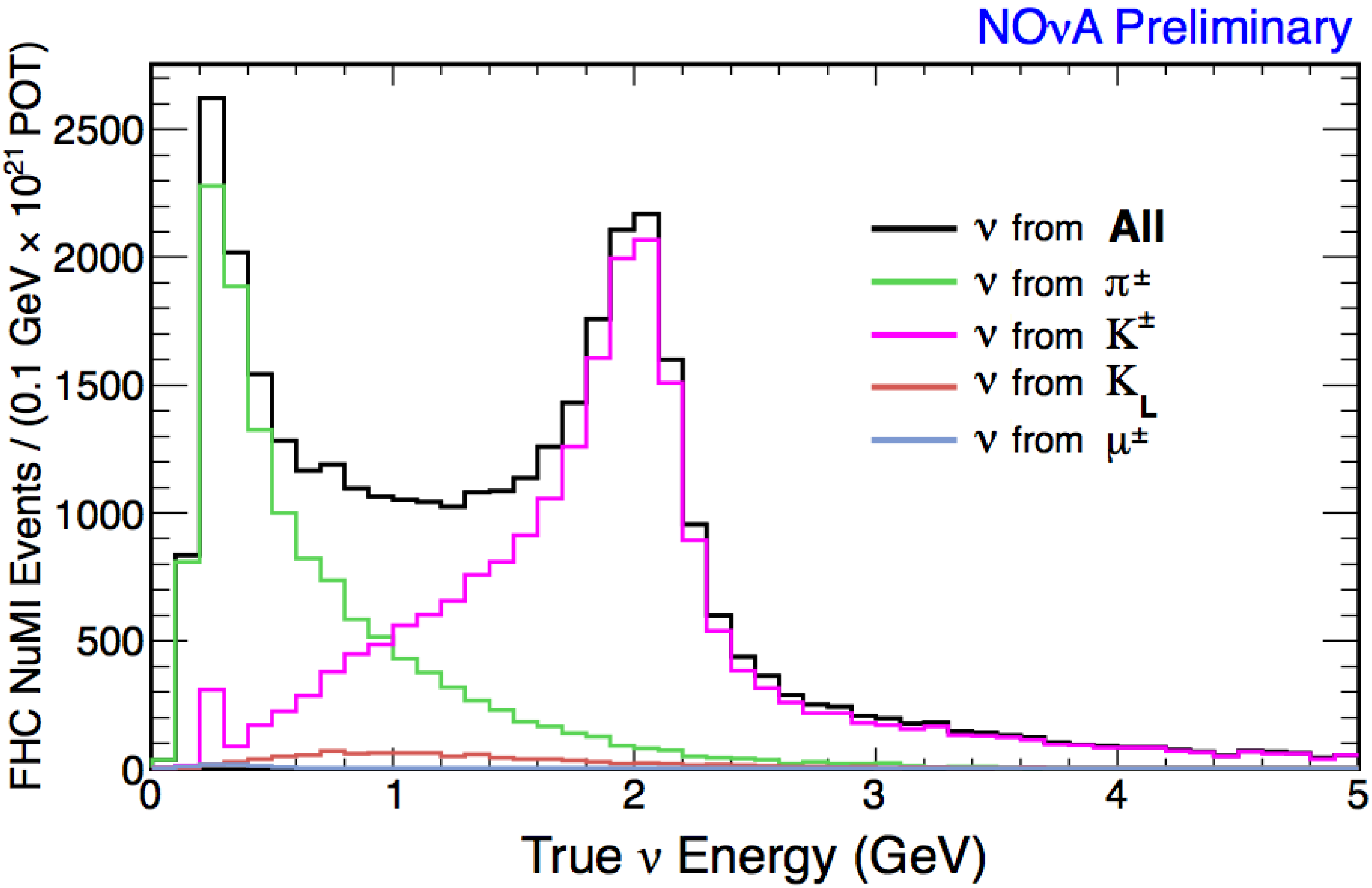
Systematic Source	+ve Uncertainty (GeV)	-ve Uncertainty (GeV)
E_{had} selection cut	0.084	0.079
Neutrino flux	0.027	0.027
Vertex x, y	0.046	0.040
μ^- angular resolution	0.057	0.057
Hadronic energy offset	0.034	0.036
INTRANUKE parameters	0.053	0.053
DIS cross sections	0.026	0.021
RES nuclear effects	0.018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

NOvA CCQE Analysis

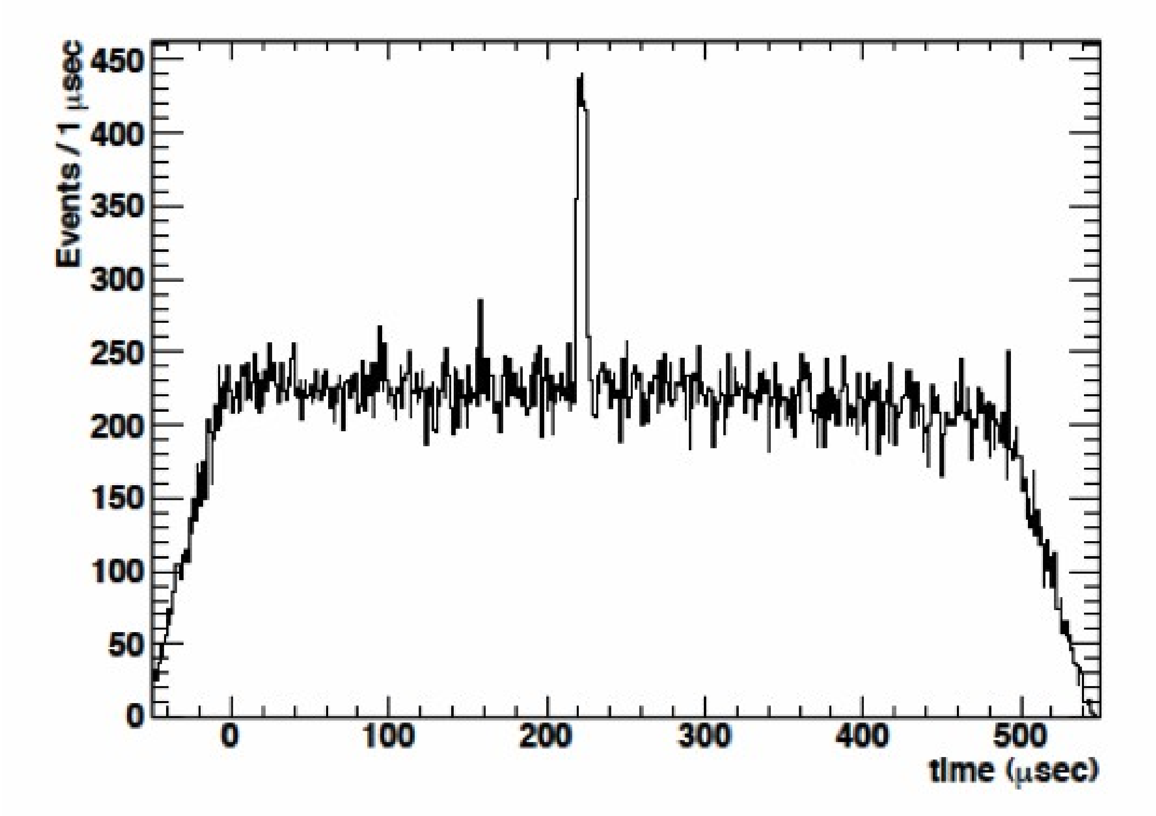
NOvA NDOS Detector

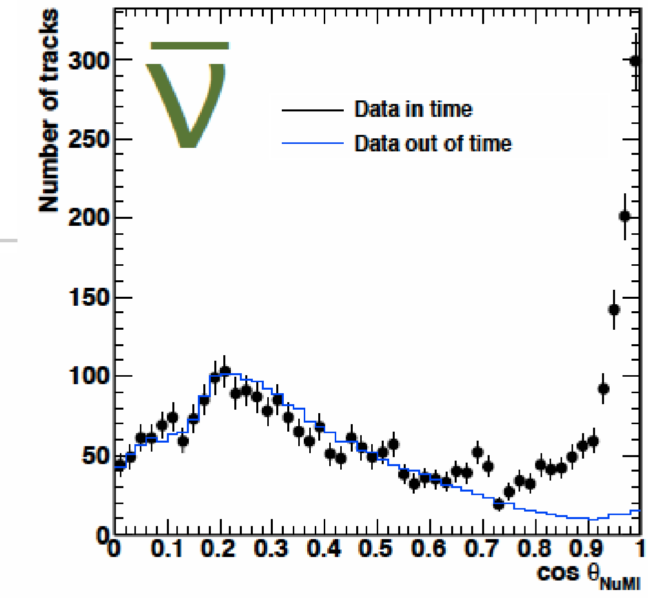


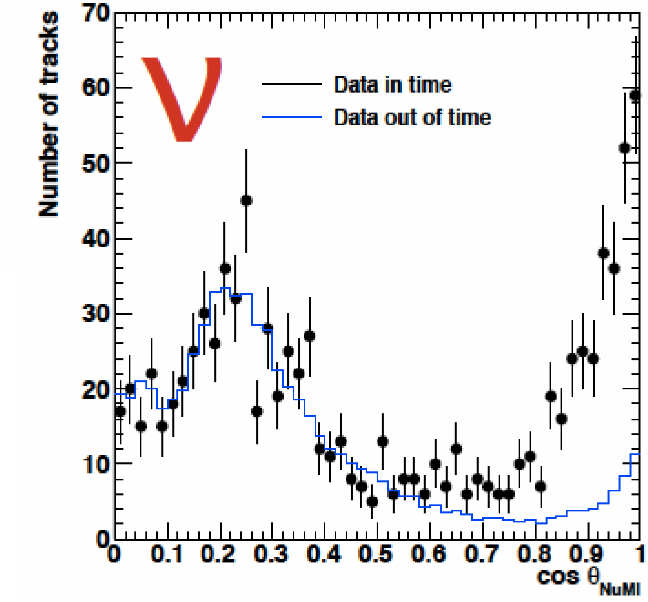
NOvA NDOS Spectrum



Finding NuMI Events In NDOS

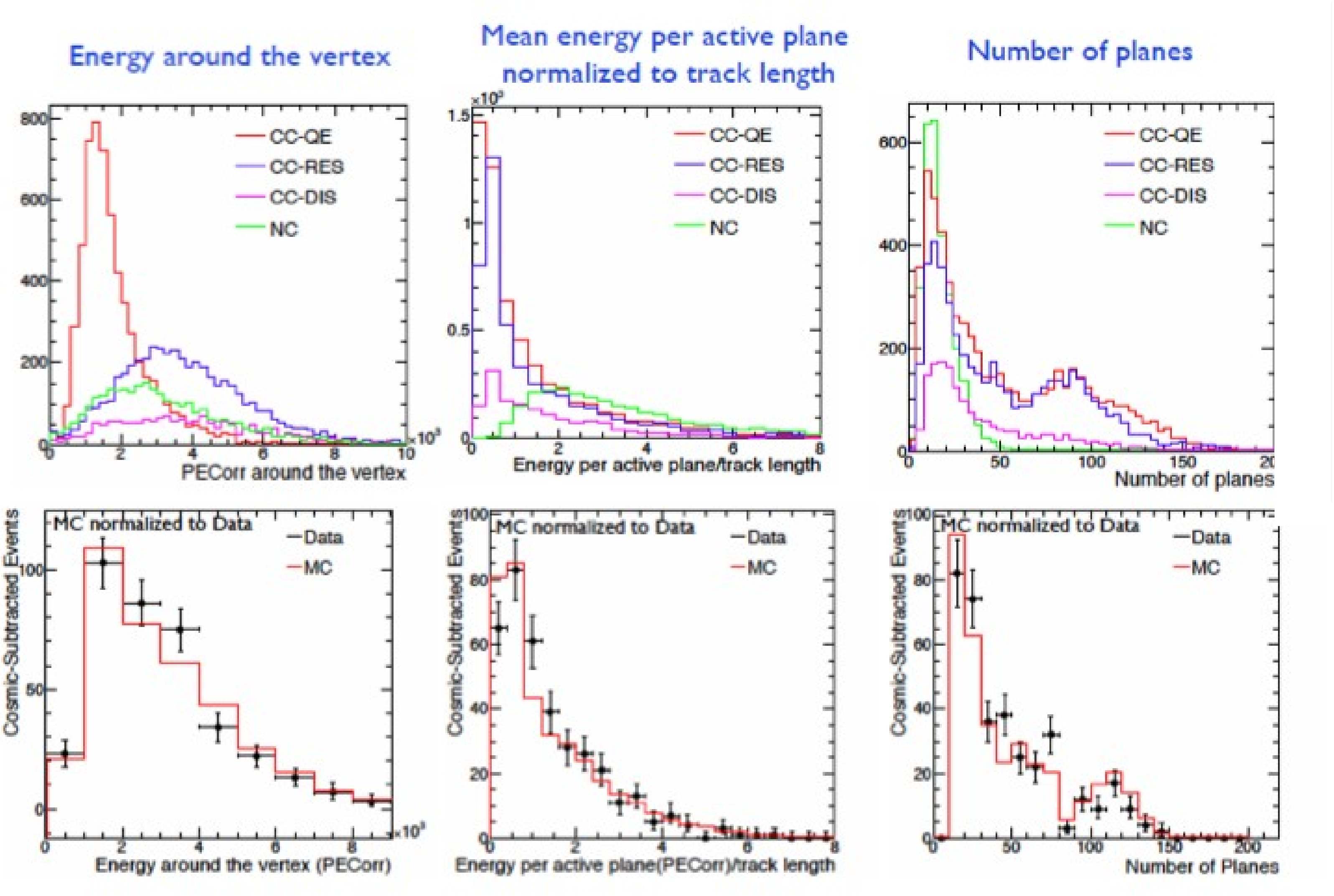






- Clear peak in timing distribution at expected position withing trigger time window.
- Clear excess of tracks along beam direction.

Selecting CCQE Interactions



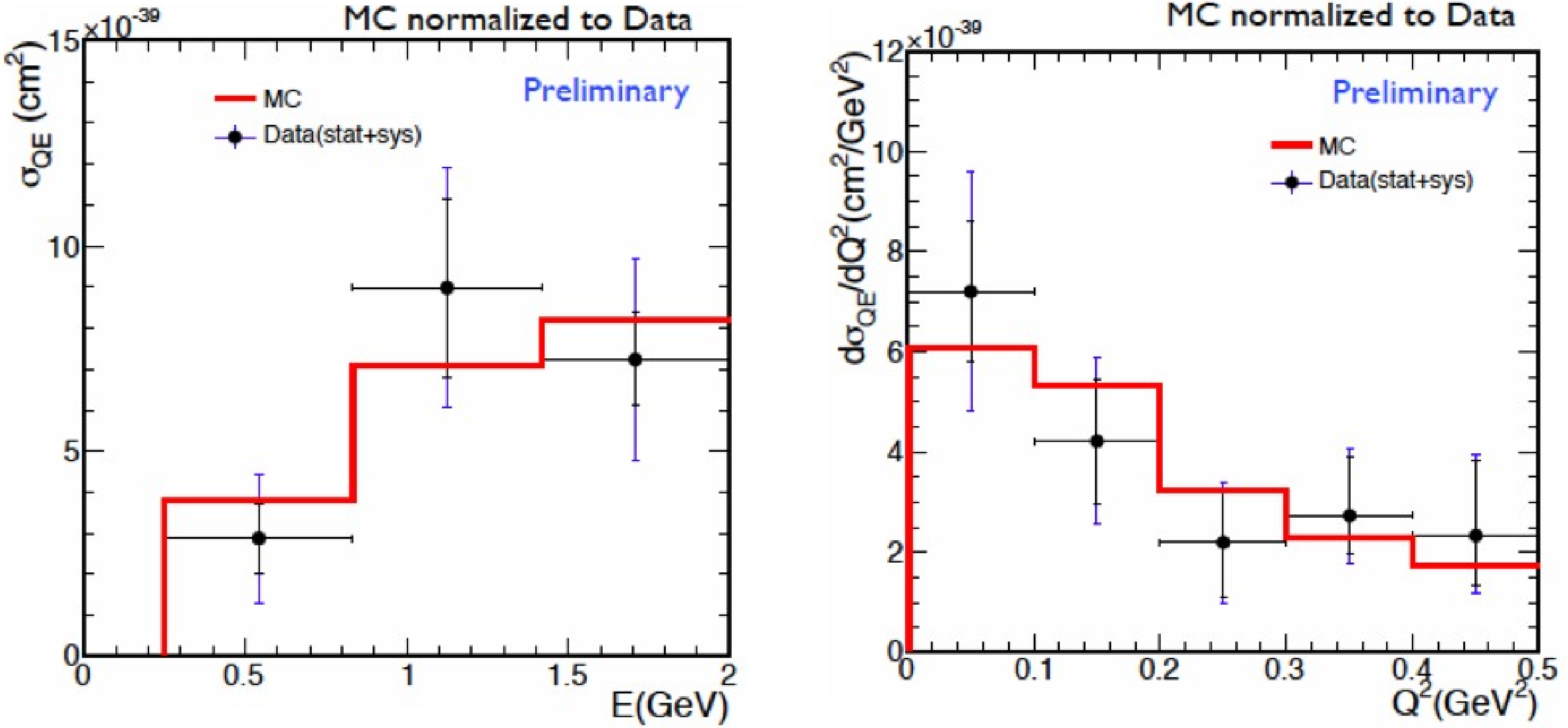
Energy around the vertex

Mean energy per active plane normalized to track length

Number of planes

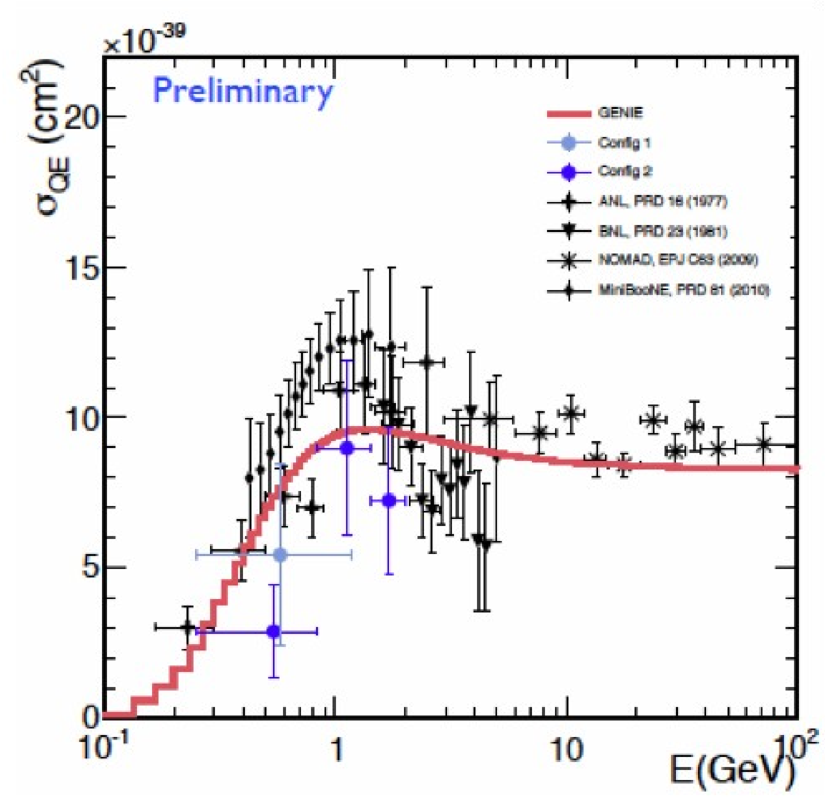
- Multivariate analysis based reconstructed quantities with power to separate CCQE from Non-CCQE interactions.
- Shapes of MC distributions agree well with data.

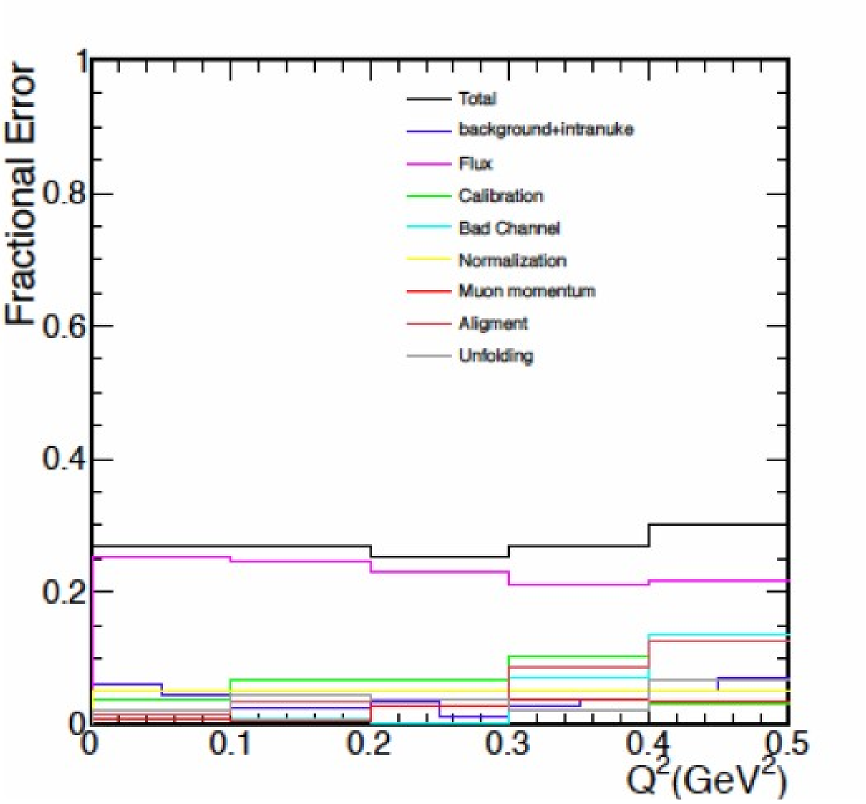
NDOS CCQE Cross-Section Measurement



- Distributions have been unfolded back to true, with efficiency corrections applied.

NDOS CCQE Cross-Section Measurement





Normalizing by predicted flux shows reasonable agreement to previous measurements for higher values of energy, but the flux prediction is still under investigation.

The ~25% uncertainty on the flux shown above is determined by comparing two MC simulations (Fluka to GEANT4).

MINOS

characteristics of selected CCQE events	**values**
QE event selection	1 muon, Hadronic Energy < 225 MeV
Nuclear Target	Iron
Neutrino Flux Range	$0.5 < E_\nu < \sim 6$ GeV
Sign Selection	Yes
Muon Energy range	$m_\mu < E_\mu < \sim 5$ GeV
Muon angular range	$0 < \theta_\mu < \pi$
Proton detection threshold	N/A
How is E_ν determined?	N/A
How is Q^2 determined?	$Q^2_{QE} = -m^2_\mu + 2E_\nu (E_\mu - p_\mu \mathrm{Cos}\ )$ *reported Q^2 from QE formula*
Monte Carlo Generator	NUGEN *(Smith-Moniz RFG with Bodek-Richie Tail)*
QE measurements and associated publications	Shape fit to Q^2 spectrum. Various Conference Proceedings, Student Thesis, PRD Type Paper in the works.

NOvA

characteristics of selected CCQE events	values
QE event selection	1 muon, multivariate ID
Nuclear Target	CH2
Neutrino Flux Range	$0.5 < E_\nu < 2$ GeV
Sign Selection	Yes
Muon Energy range	$m_\mu < E_\mu <$ ~1.5 GeV
Muon angular range	$0 < \theta_\mu < \sim\pi/4$
Proton detection threshold	N/A
How is E_ν determined?	E^{QE}, modified RFG *reported E is corrected back to true E_ν from RFG*
How is Q^2 determined?	$Q^2_{QE} = -m^2_\mu + 2E_\nu (E_\mu - p_\mu \mathrm{Cos}\;\;)$ *reported Q^2 from QE formula*
Monte Carlo Generator	GENIE *(Smith-Moniz RFG with Bodek-Richie Tail)*
QE measurements and associated publications	E^{QE} NuFact Conference Proceedings, Student Thesis, PRD Type Paper in the works.

NuMI Flux Generator

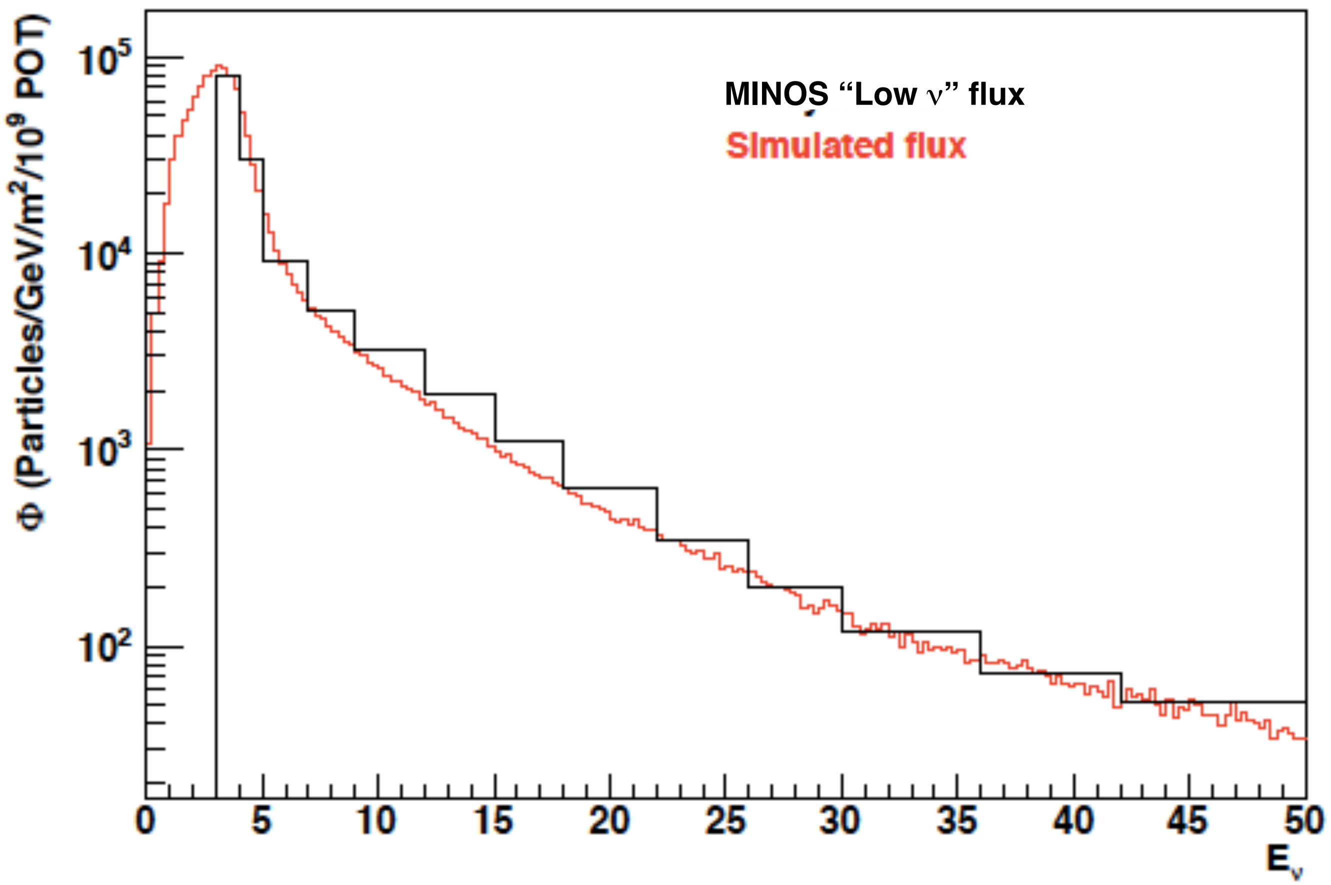
- MINOS
  - Generator-FLUGG
    - GEANT4 Geometry
    - FLUKA hadron production
- MINERvA
  - Generator-GEANT4
- NOvA
  - Generator-FLUGG
- ArgoNeuT
  - Generator-FLUGG

Summary

- MINOS
  - Shape Fit to Q^2 spectrum.
  - Iron Target.
  - Significant effort into characterizing non-QE background.
  - $M_A^{QE} = 1.21^{+0.18}_{-0.10}(fit)^{+0.13}_{-0.15}(syst)\,GeV$
- NOvA
  - Cross Section Measurements.
  - Large statistical uncertainty.
  - Large uncertainty on the Flux.

Backup

ArgoNeuT NuMI Flux



ARGONEUT collaboration,

"First Measurements of Inclusive Muon Neutrino Charged Current Differential Cross sections on Argon",

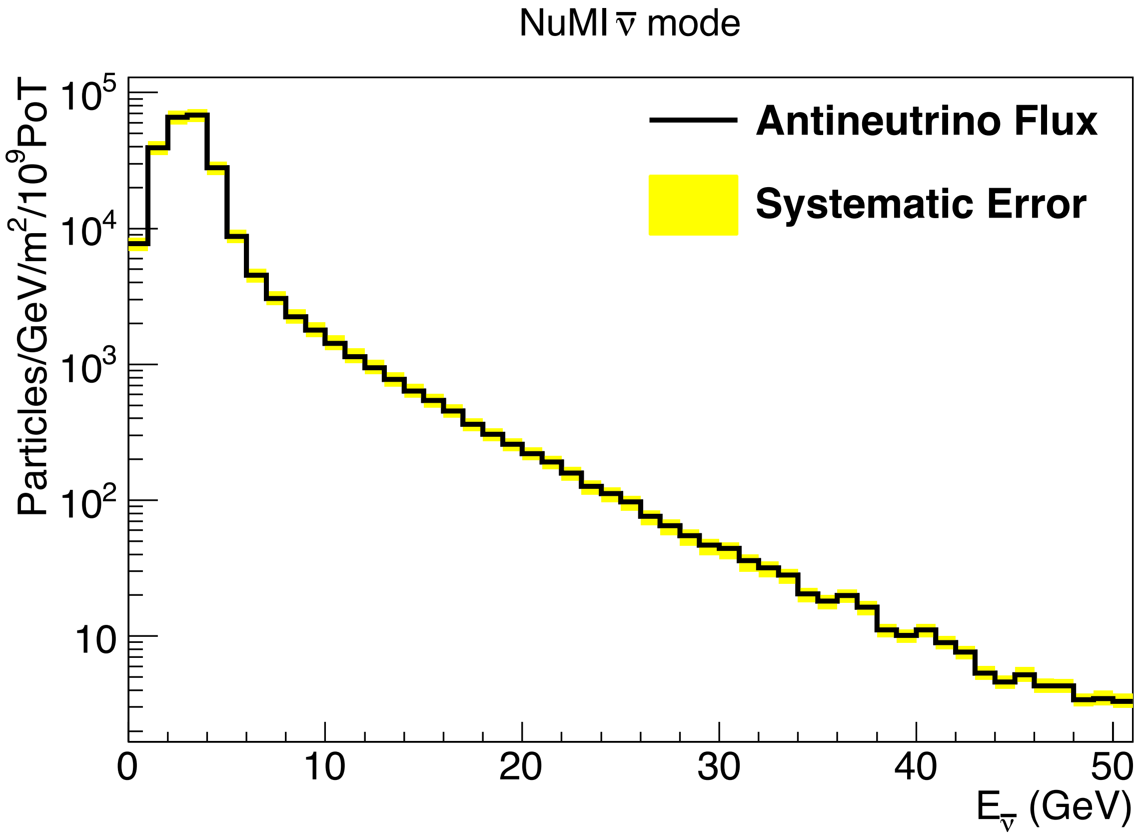
Phys. Rev. Lett. 108 **(2012) 161802**

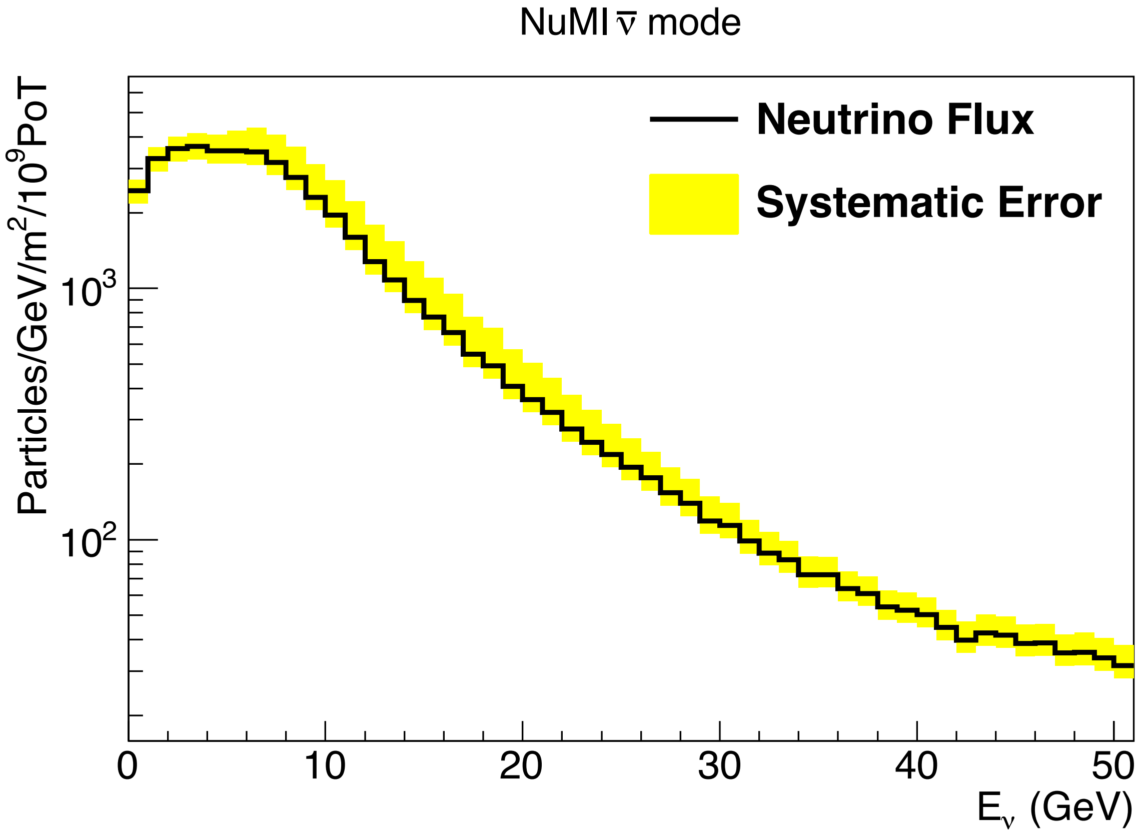
- The flux from **E**=3-50 GeV is from:

  P. Adamson et al. [MINOS Collaboration], Phys. Rev. D 77, 072002 (2008),
  "low hadronic energy transfer (ν)" *method*

- The For the 0-3 GeV range, the flux prediction is determined using a Monte Carlo simulation of the NuMI beamline (provided by the MINOS collaboration)
- The fractional error on the 0-3 GeV range is conservatively set to 35%

ArgoNeuT NuMI Flux (antineutrino mode)





- Flux is simulated using the FLUGG package, which combines GEANT4 geometry with FLUKA hadron production. 11% systematic error accounting for uncertainties in hadron production and beam line modeling (e.g. horn focusing) and is consistent with the MINERvA results

- Another flux constrained with MINOS Near Detector data[*] and NA49[**] hadron production measurements is considered for systematics
  - The difference between this flux and FLUGG flux is taken as a signed systematic error.
  - For antineutrinos, this additional error is less than 10%
  - For neutrinos, this additional error is up to 40%

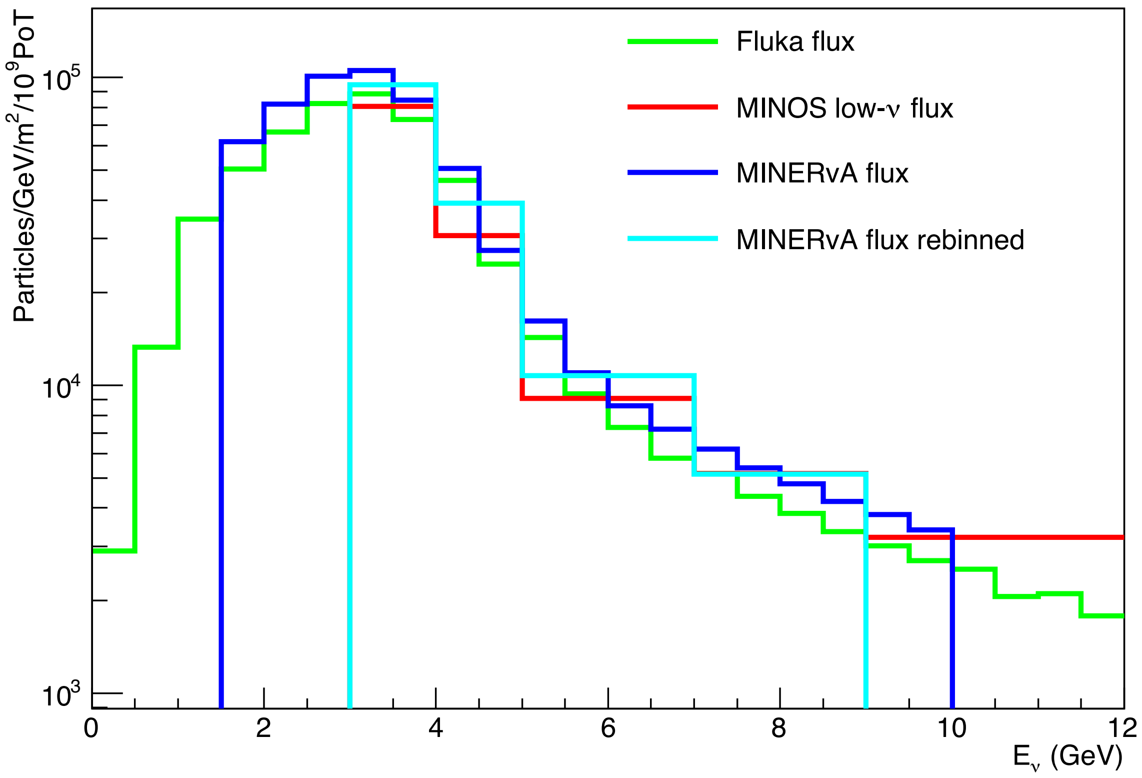
[*] P. Adamson et al. (MINOS Collaboration), Phys. Rev. Lett. 107, 021801 (2011).

[**] C. Alt et al. (NA49 Collaboration), Eur. Phys. J. C 49, 897 (2007).

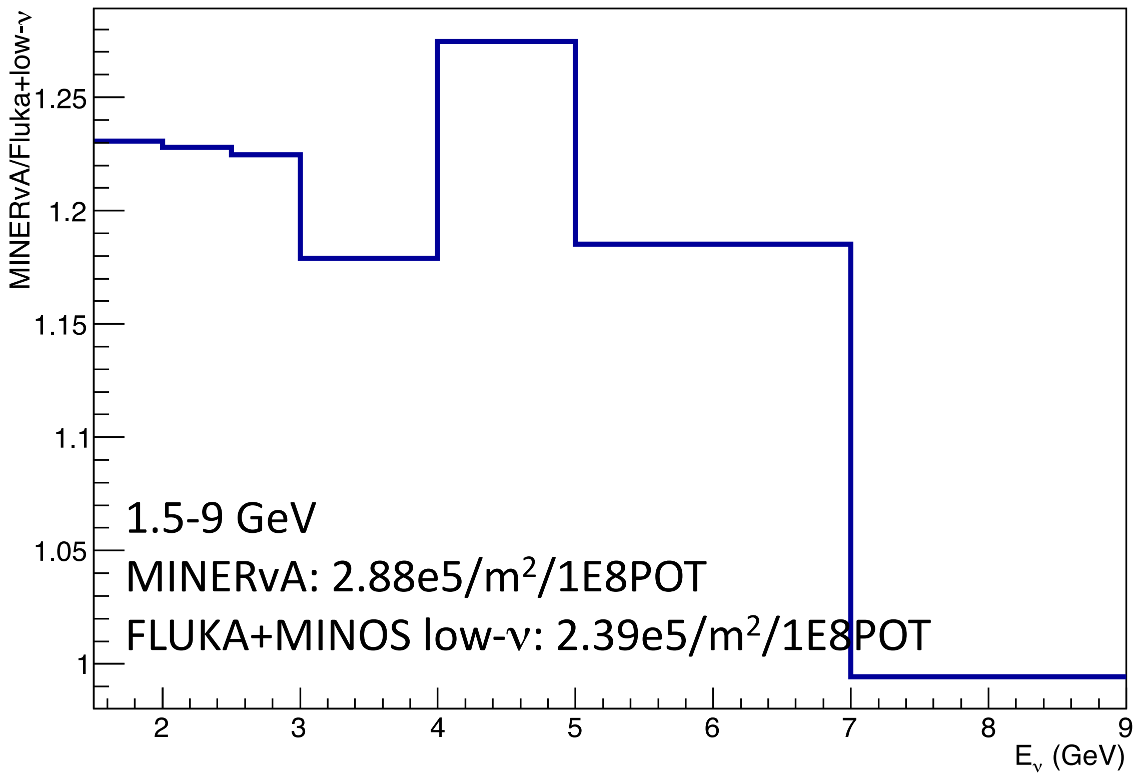
backup: Minerva/ArgoNeuT flux comparisons

Minerνa/ArgoNeuT flux comparisons

ν mode



ν mode

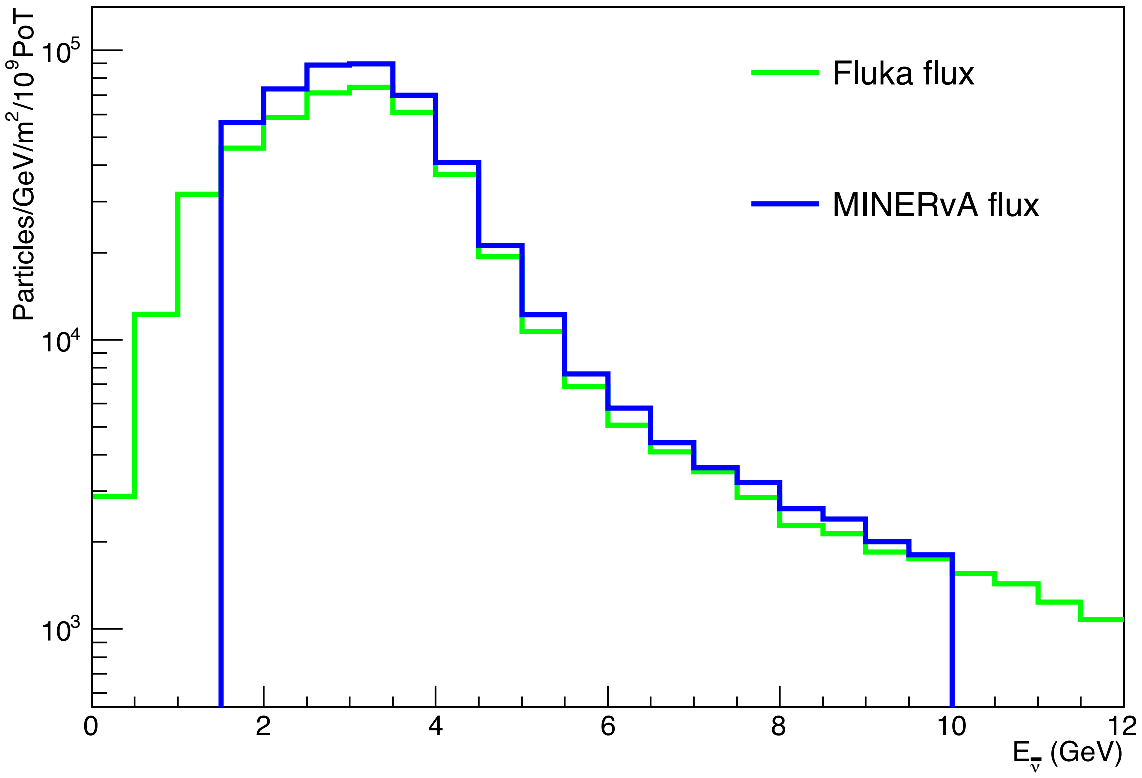


1.5-9 GeV

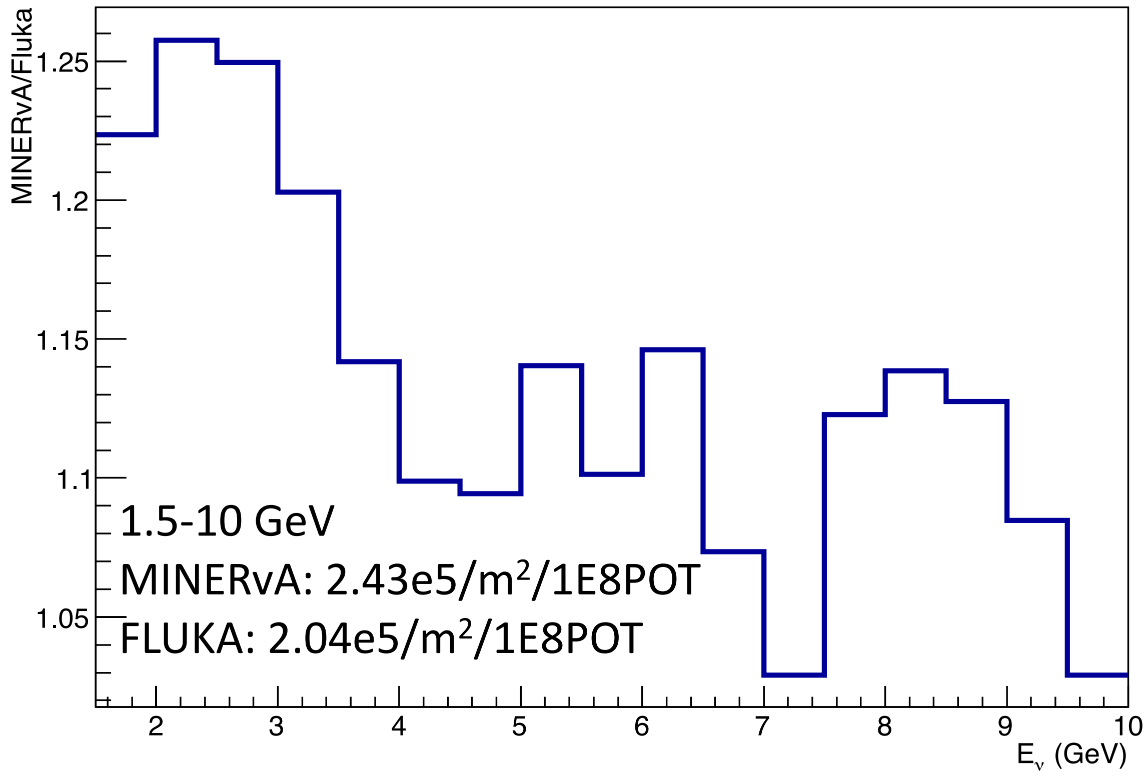
MINERvA: 2.88e5/m^2/1E8POT

FLUKA+MINOS low-ν: 2.39e5/m^2/1E8POT

$\bar{\nu}$ mode



$\bar{\nu}$ mode



1.5-10 GeV

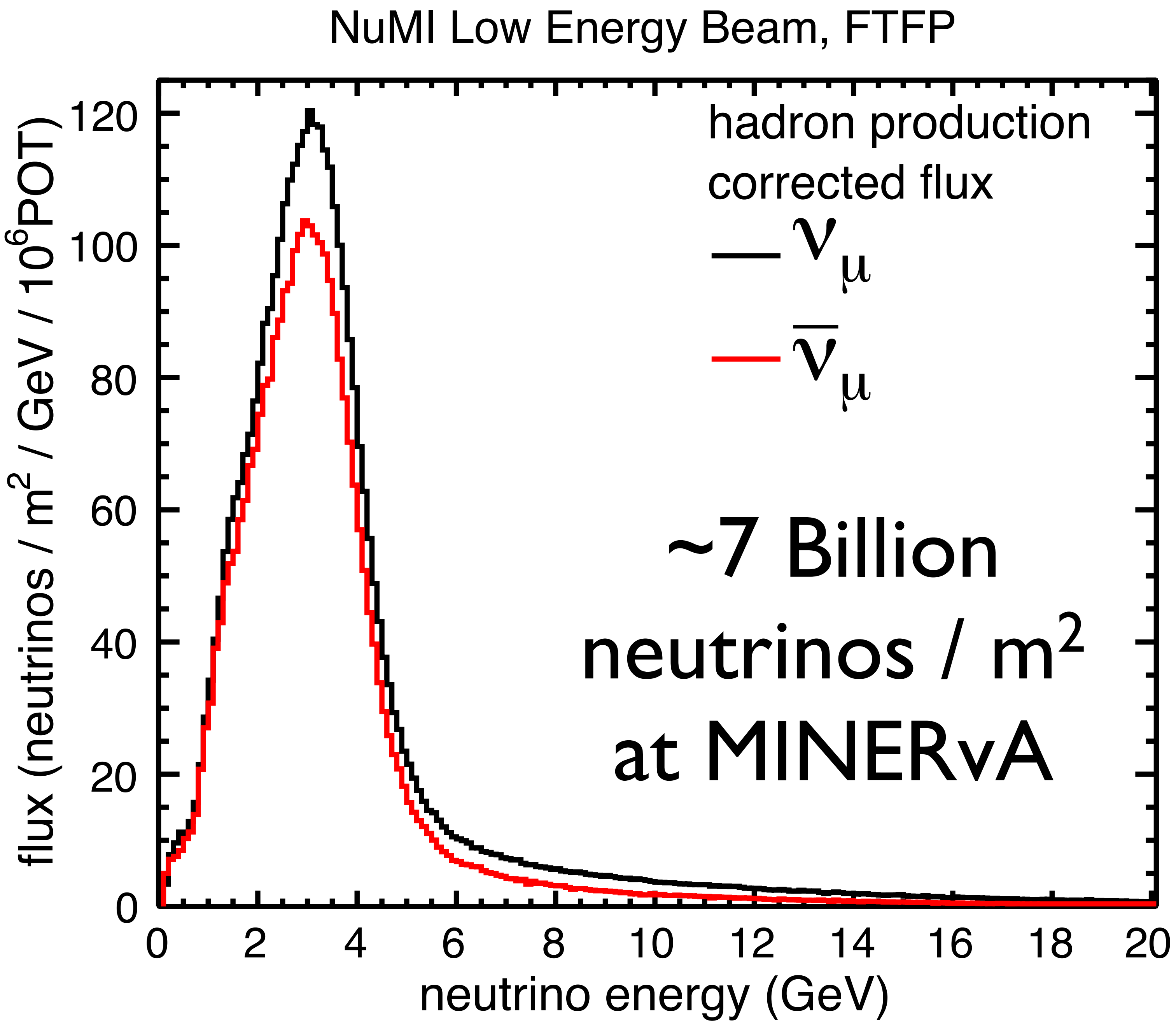
MINERvA: 2.43e5/m^2/1E8POT

FLUKA: 2.04e5/m^2/1E8POT

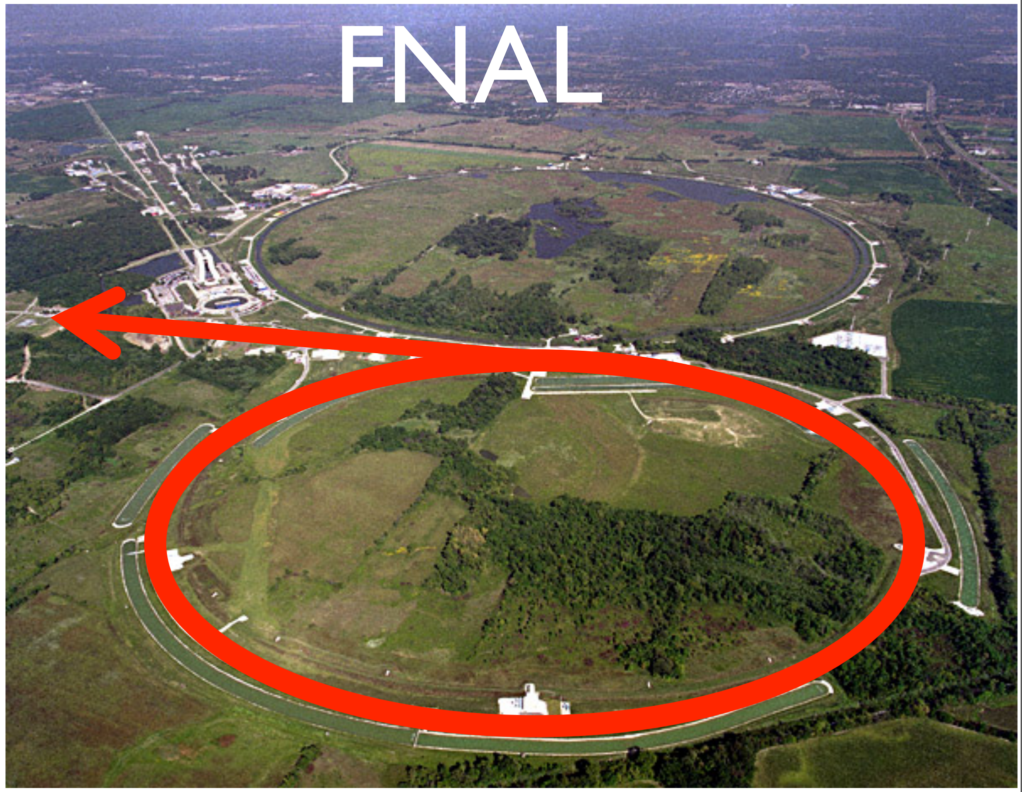
MINERvA Flux:
Executive Summary

- GEANT4 FTFP with central value re-weighting using NA49 data scaled to 120 GeV.
- ~10% uncertainty on the absolutely normalized $d\sigma/dQ^2$, roughly flat across Q^2. ~1% uncertainty on the shape-only $d\sigma/dQ^2$.
- Total uncertainties are computed by varying the event-weights within parameter uncertainties and re-doing the analysis. The RMS spread of the different outputs around the central value builds the uncertainty band and correlation matrix.

Neutrino Beam



~7 Billion neutrinos / m^2 at MINERvA



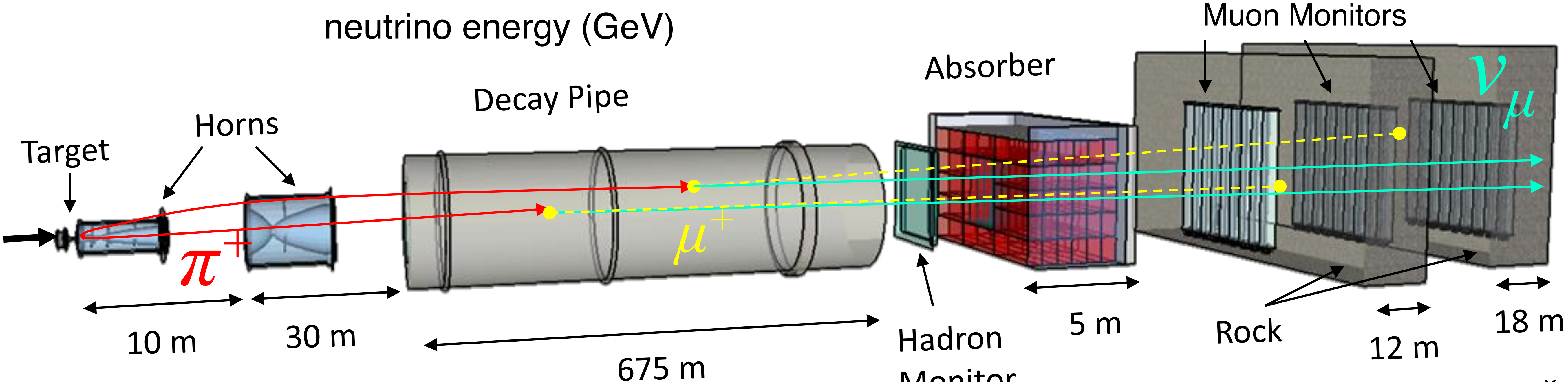


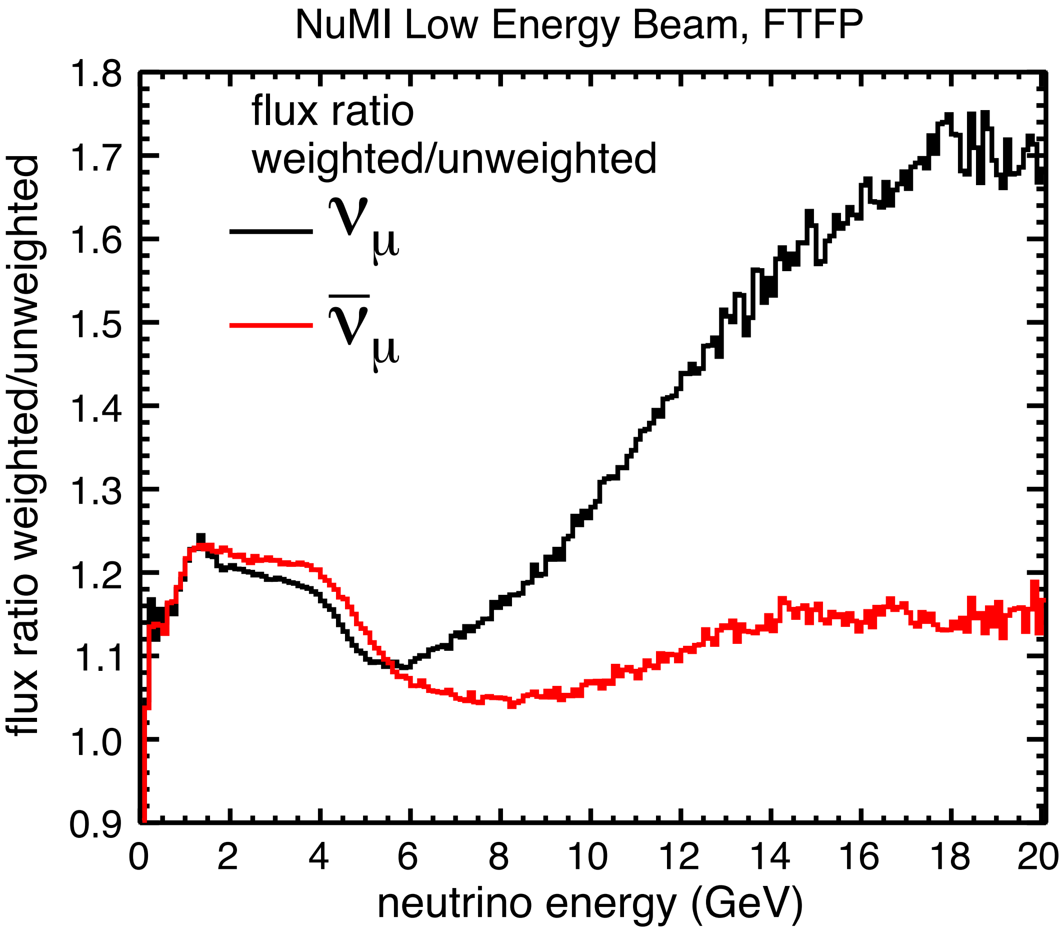
figure courtesy Ž. Pavlović

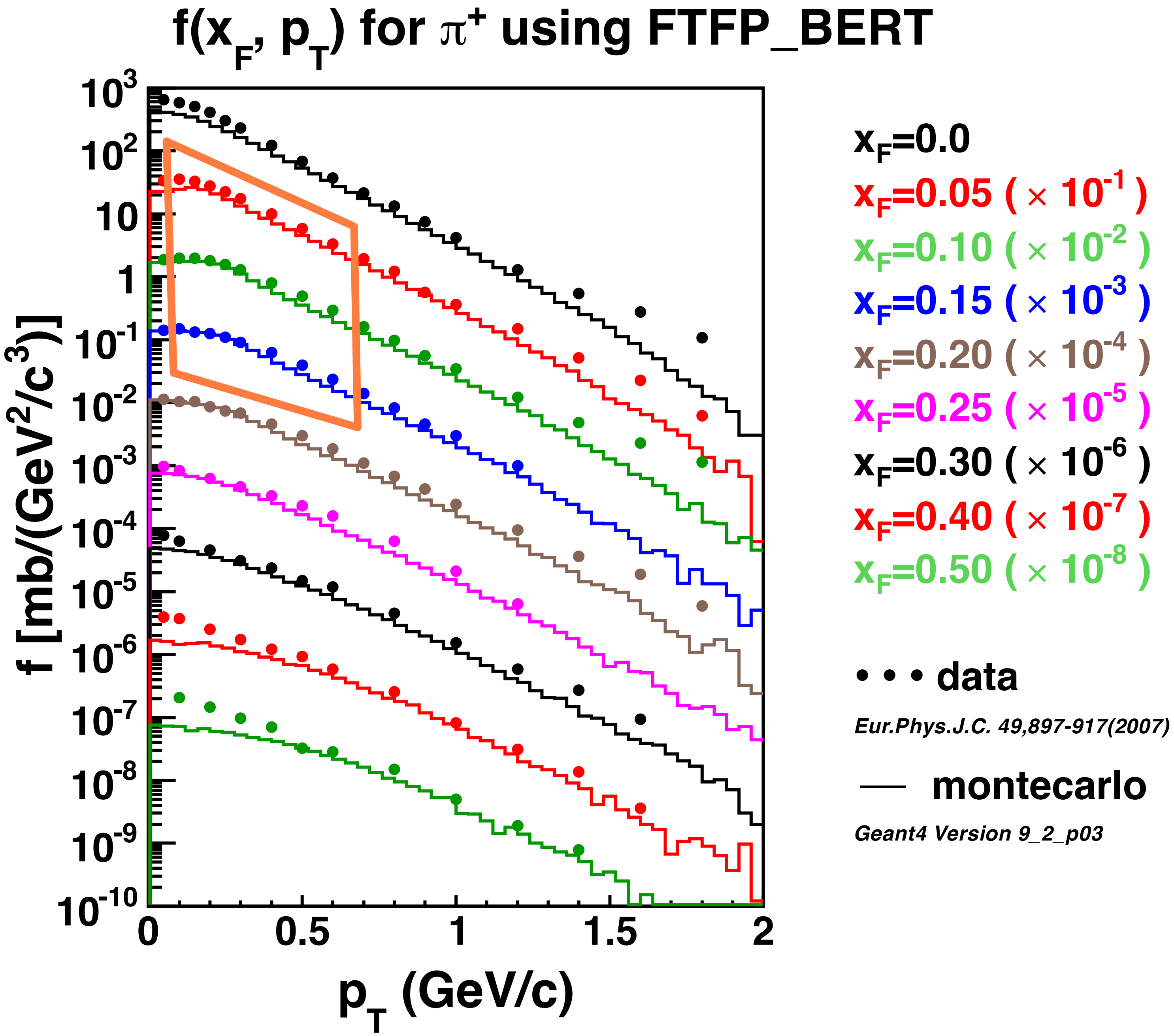
MINERvA Flux: Central Values

- The FTFP model of GEANT4 9_2_p03 is our baseline MC.
- We then re-weight proton-Carbon to charged-pion + X, charged Kaon + X, and proton/anti-proton + X over 12-120 GeV assuming that the data/MC ratio for invariant cross sections measured at 158 GeV can be used at all energies with a scaling correction.
- We use mostly data published by the NA49 collaboration for $x_F < 0.5$, and other data for $x_F > 0.5$, and we compute the scaling factor using FLUKA. We cross-check the scaling by using NA61 measurements at 31 GeV and find agreement.

Beam Flux

- Hadron production re-weighting is complicated by relatively sparse data, and the problems associated with thick targets.



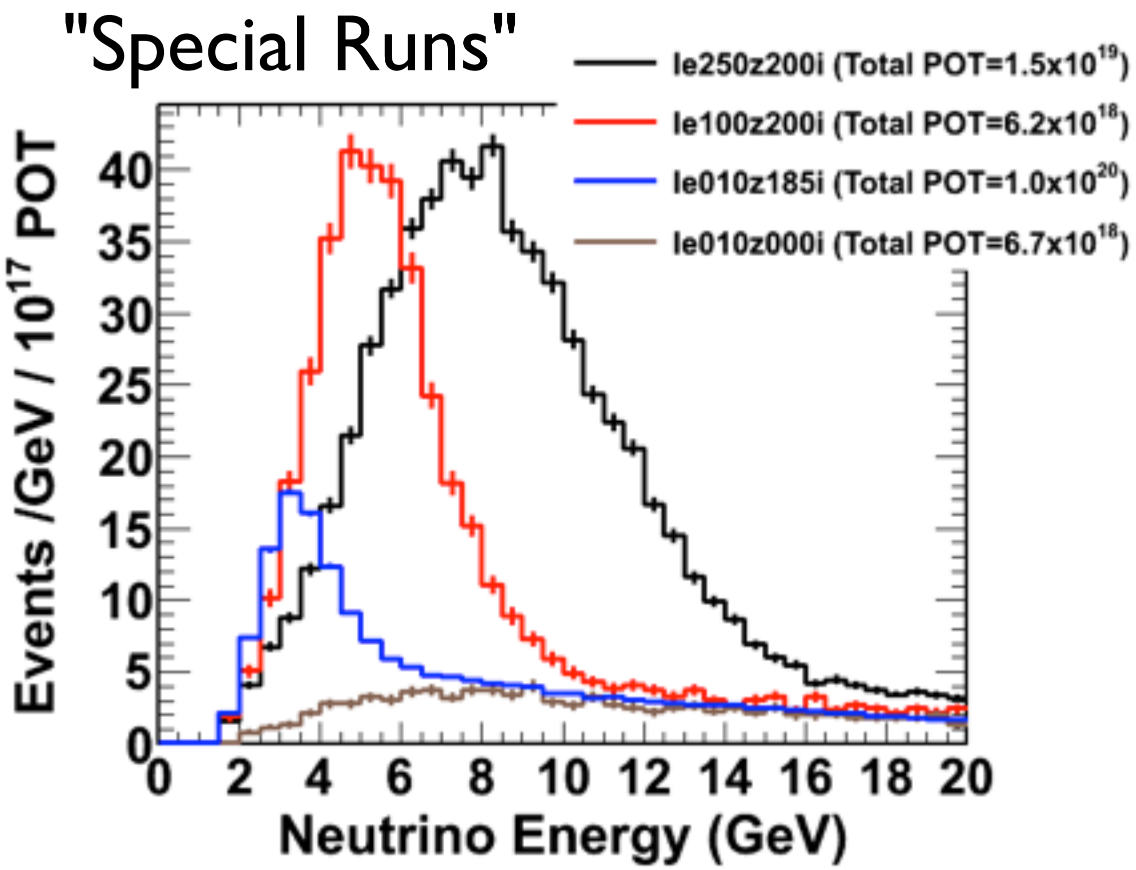


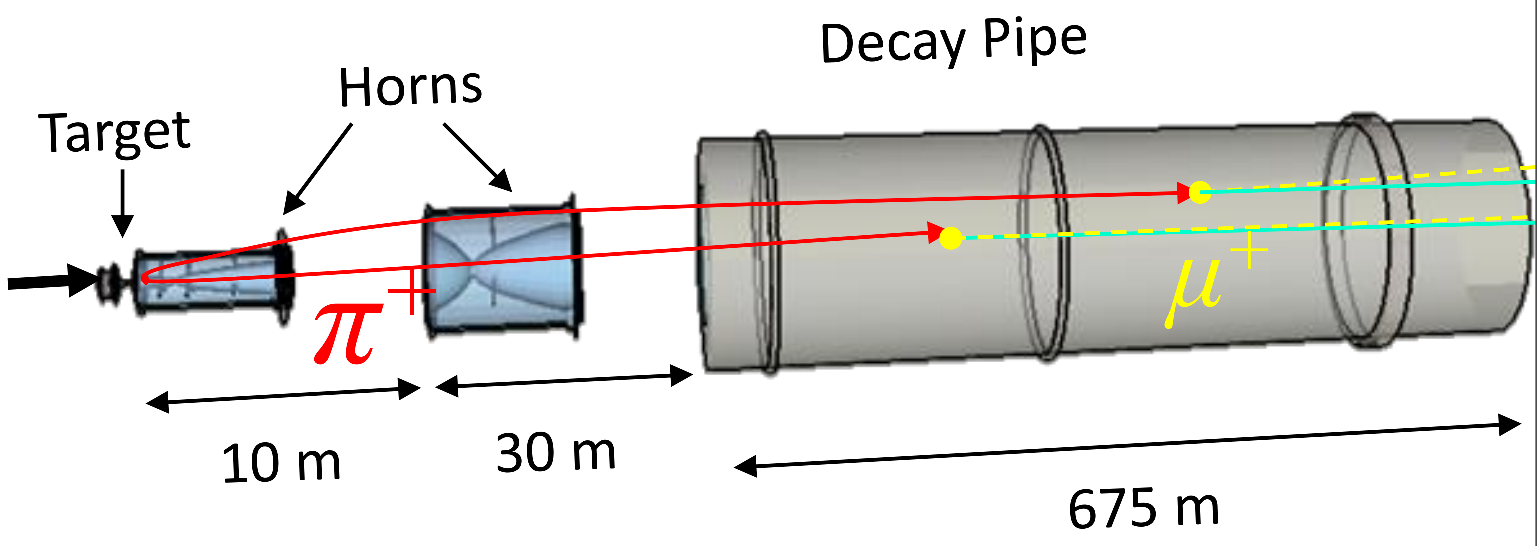
Special Runs / Beam Fits

- MINERvA recorded data with different horn currents and target positions to sample different regions of pion x_F and p_T.
- We adjust charged pion and kaon yields as functions of x_F and p_T, with some hadron production constraints (pion/kaon ratios) enforced.

ν_μ	$\bar{\nu}_\mu$
`LE010z185i`	`LE010z-185i`
`LE100z200i`	`LE100z-200i`
`LE010z000i`	`LE010z000i`
`LE250z200i`	

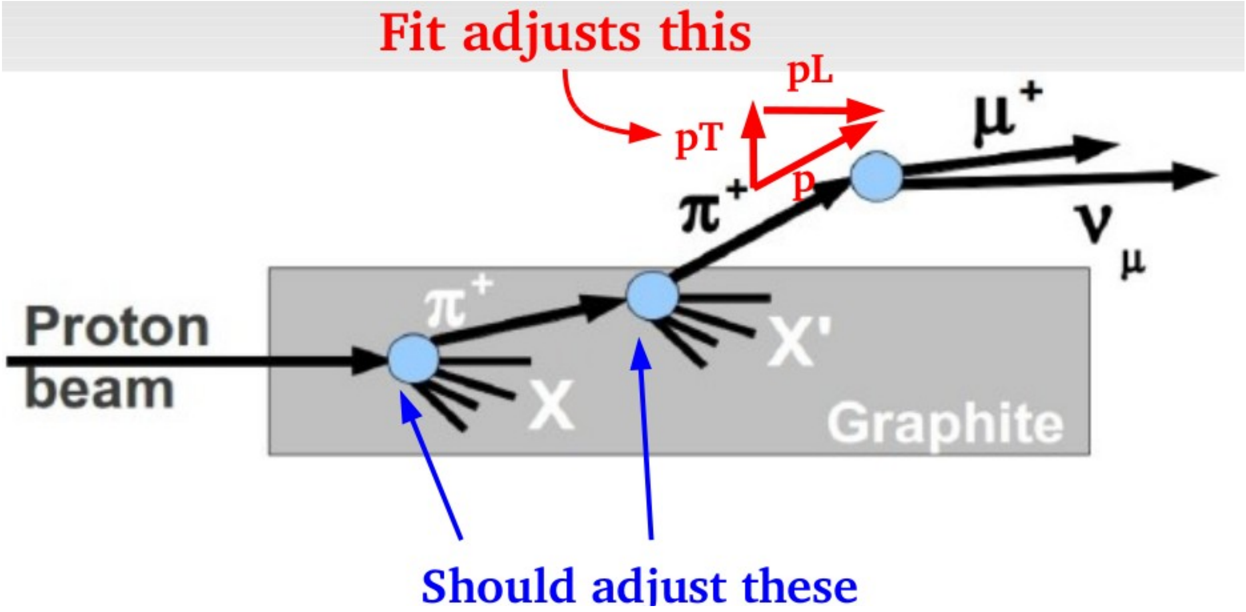
Beam Flux

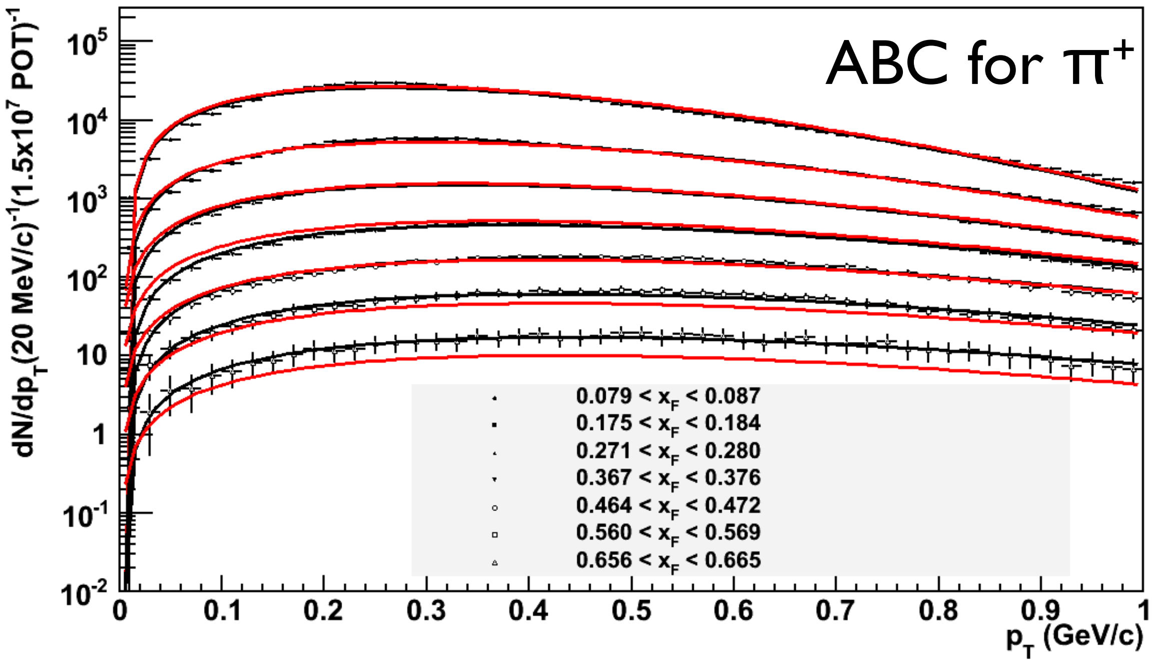




Vary target position and horn current.

$$\frac{d^2 N}{dx_F\,dp_T} = [A(x_F) + B(x_F)\,p_T + D(x_F)\,p_T^2]\,e^{-C(x_F)\,p_T^{E(x_F)}}$$





Dots: FTFP
Solid: ABC
Solid: Parameterized ABC

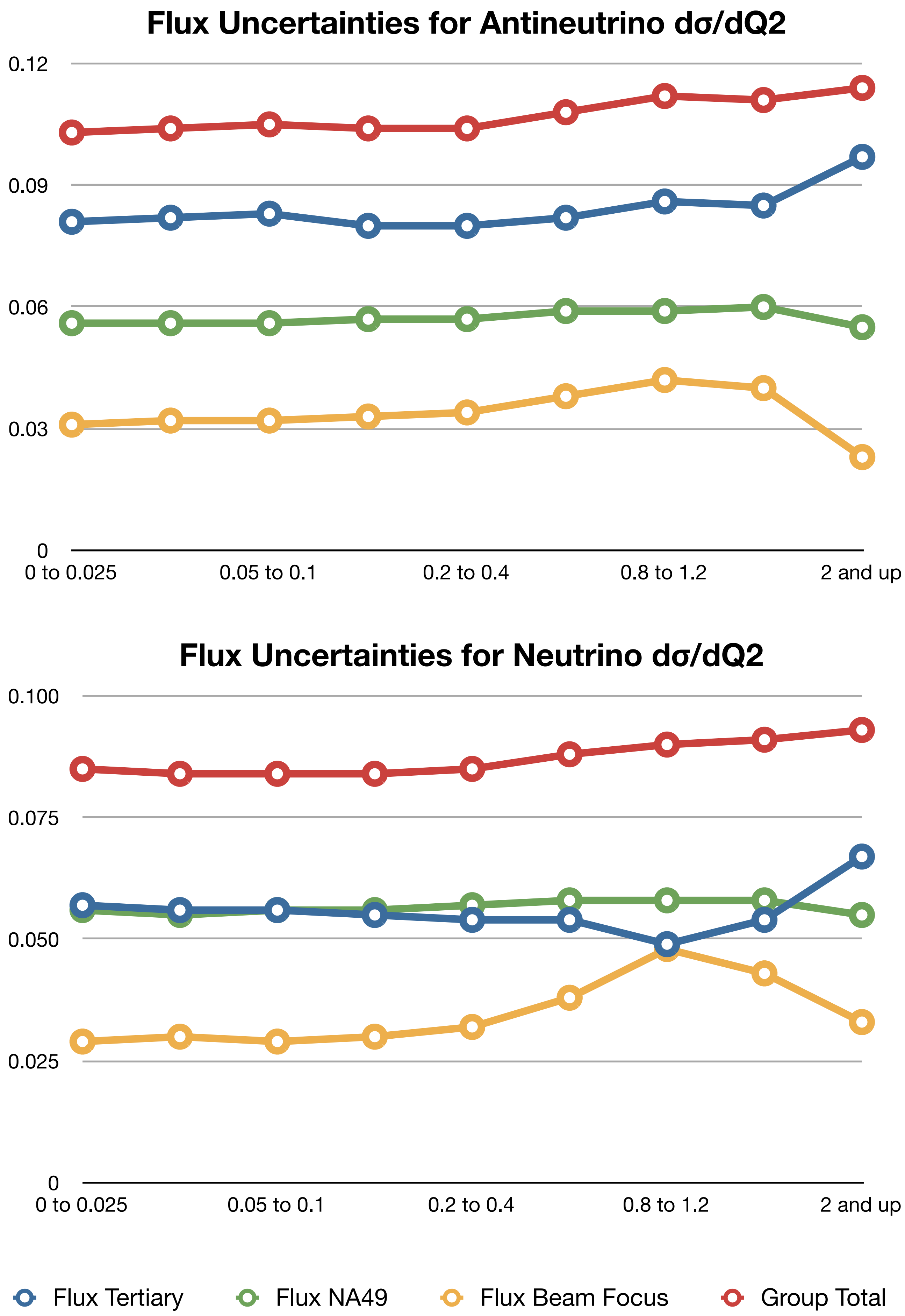
Thick targets!

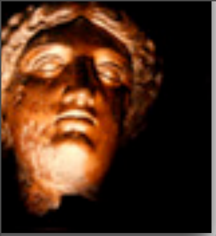
Other Refinements & Cross-Checks

- Low-nu measurements.
  - See, for example: A. Bodek et al Eur Phys J C72 (2012) 1973, and D. Naples et al Phys Rev D 81 (2010) 072002
- Neutrino-electron scattering.
  - Precision process, but low statistics.

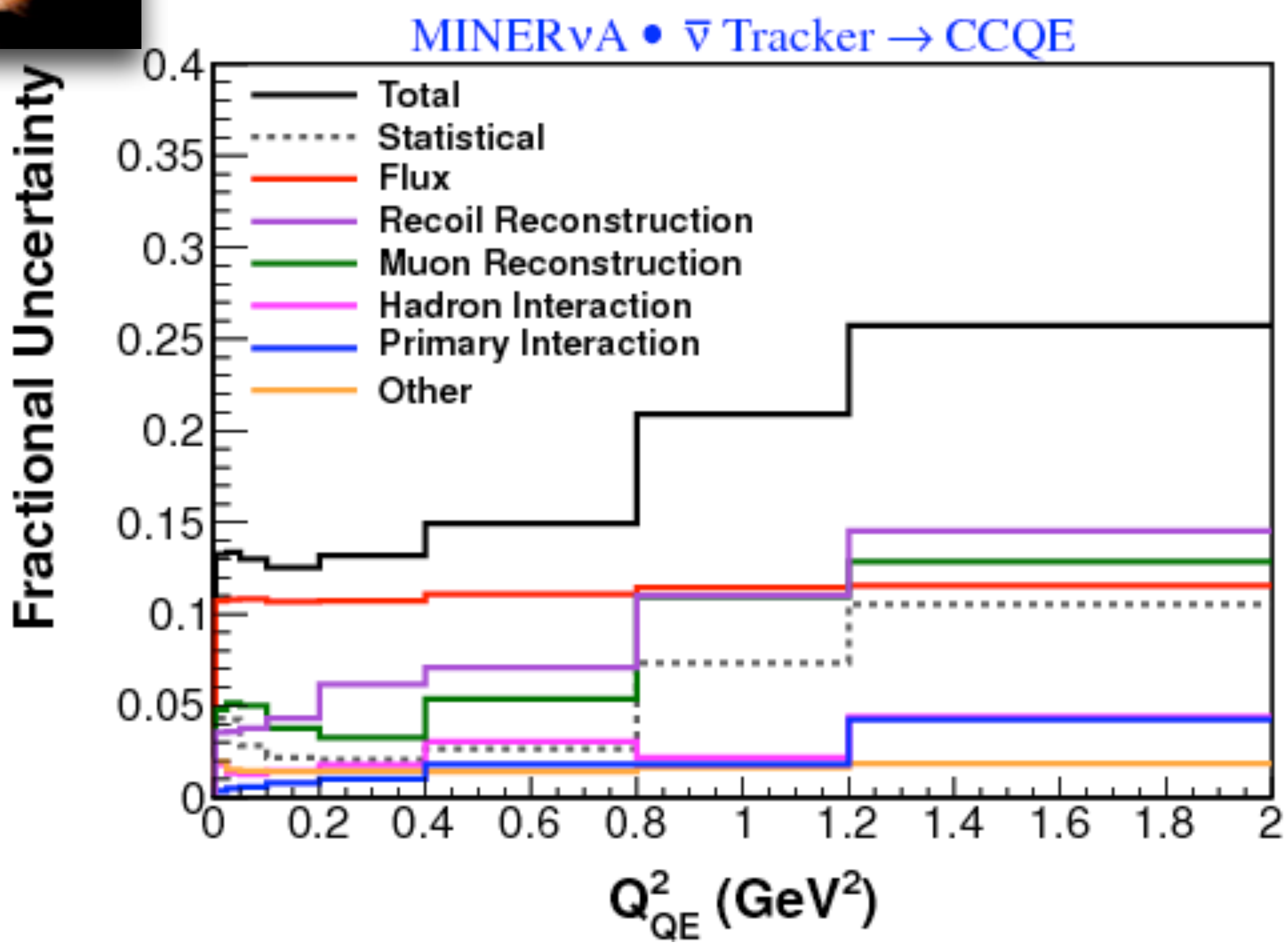
Uncertainties

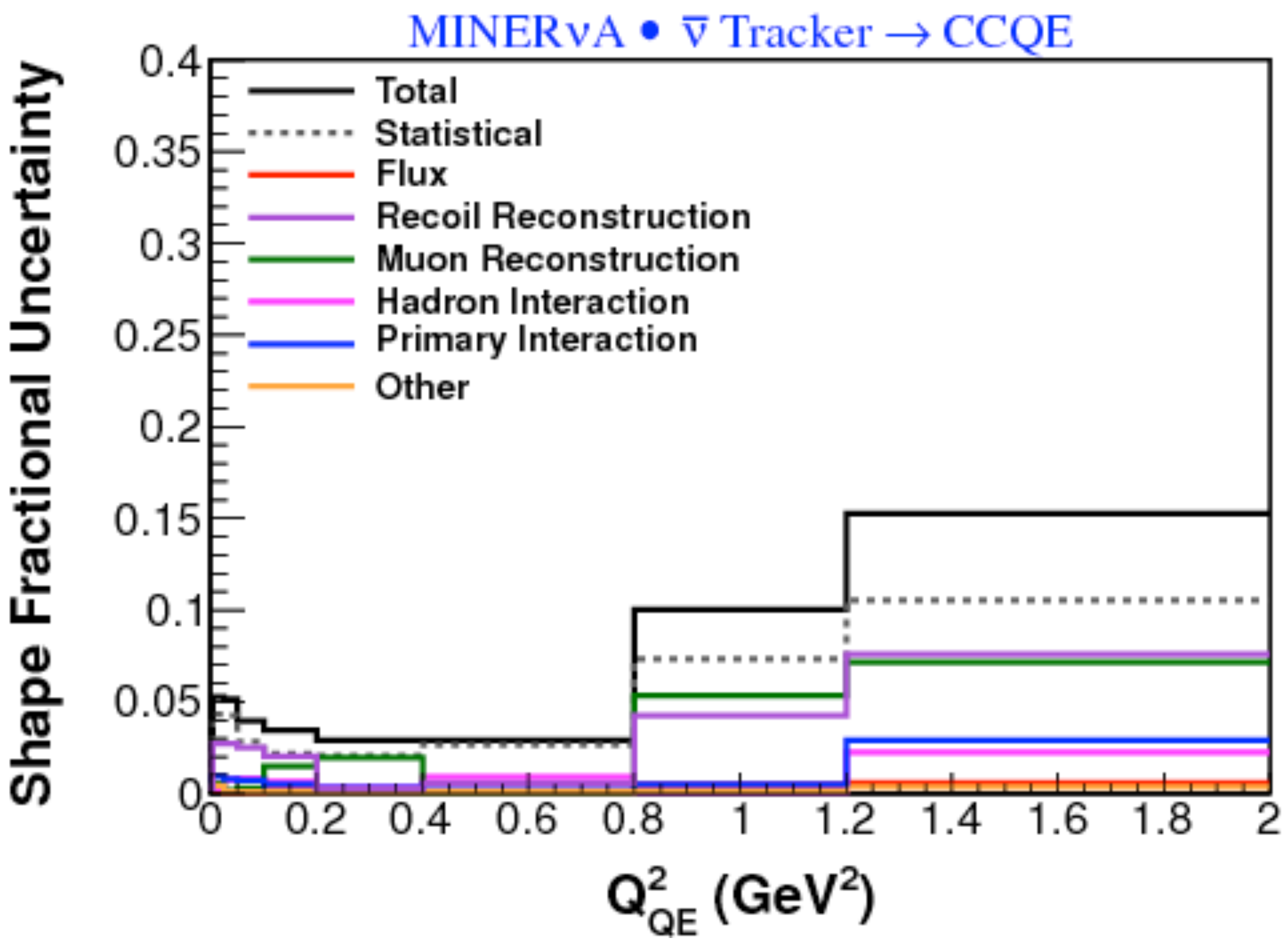
- Three pieces:
    - NA49 - Published uncertainties on the data used for re-weighting.
    - Beam-Focusing - MINOS Thesis (Z. Pavlovic).
    - Tertiary Production - All production not re-weighted by NA49. Computed by model spread from different MC predictions.

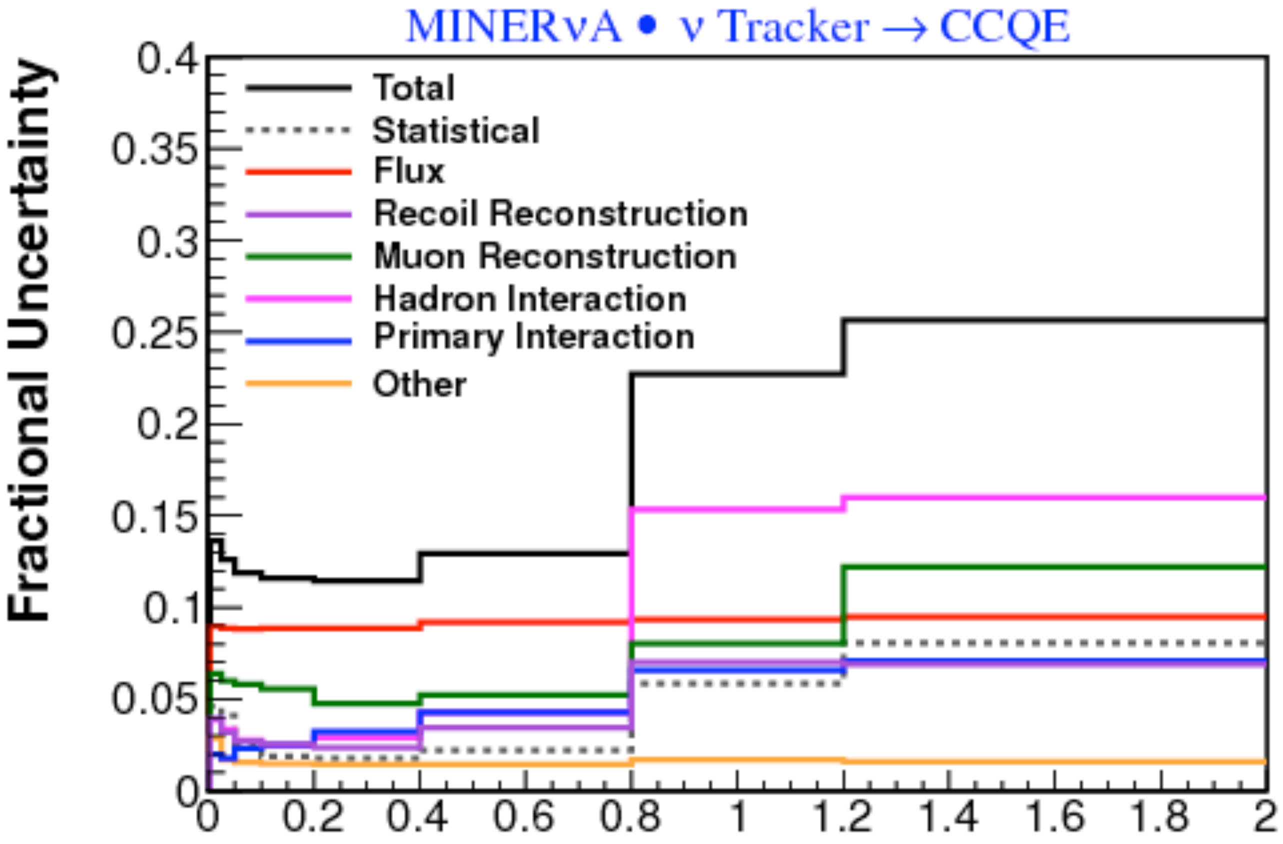


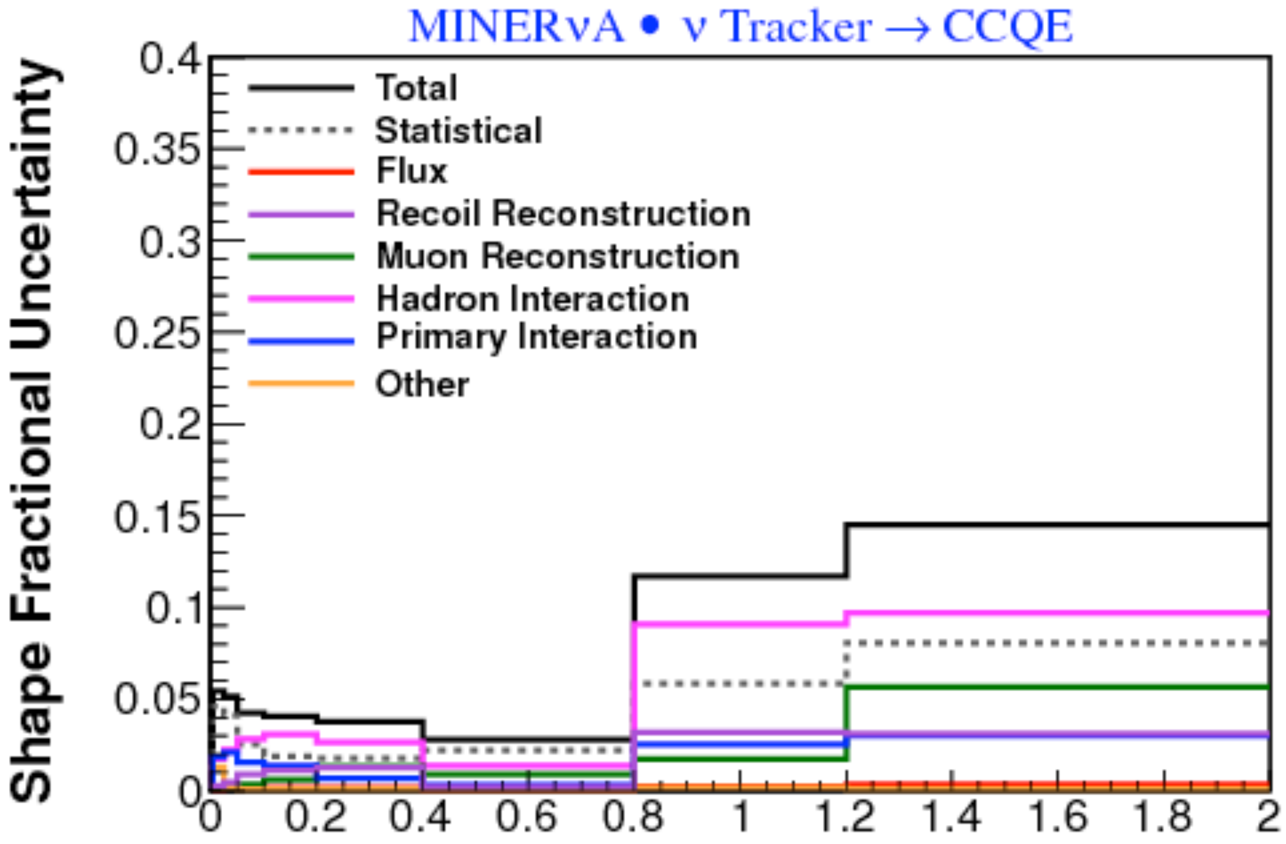


Absolute → Shape Only


MINERvA • $\bar{\nu}$ Tracker → CCQE


MINERvA • $\bar{\nu}$ Tracker → CCQE


MINERvA • ν Tracker → CCQE


MINERvA • ν Tracker → CCQE