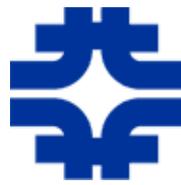


Results from MINER ν A

Rick Snider
Fermilab

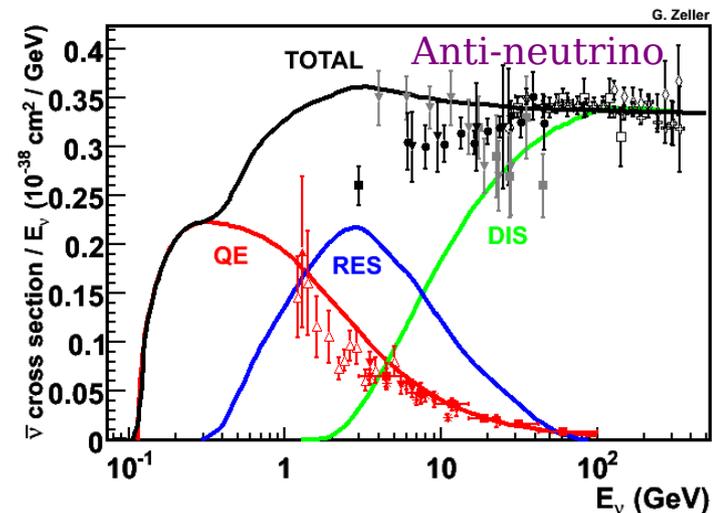
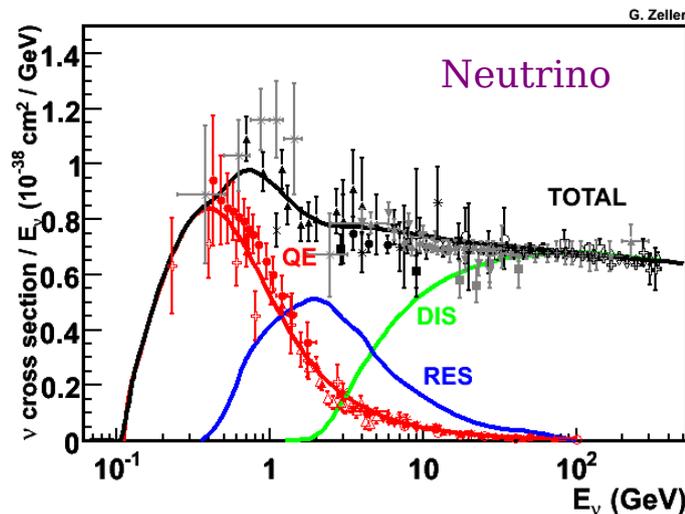
on behalf of
The MINER ν A collaboration

ICHEP 2012
Melbourne, Australia
7-July-2012

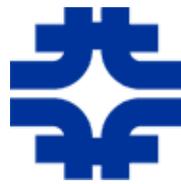


Introduction

- Cross sections for neutrino and anti-neutrino interactions in nuclear matter important for oscillation experiments
 - ◆ Cross sections not well measured in 1 - 10 GeV range

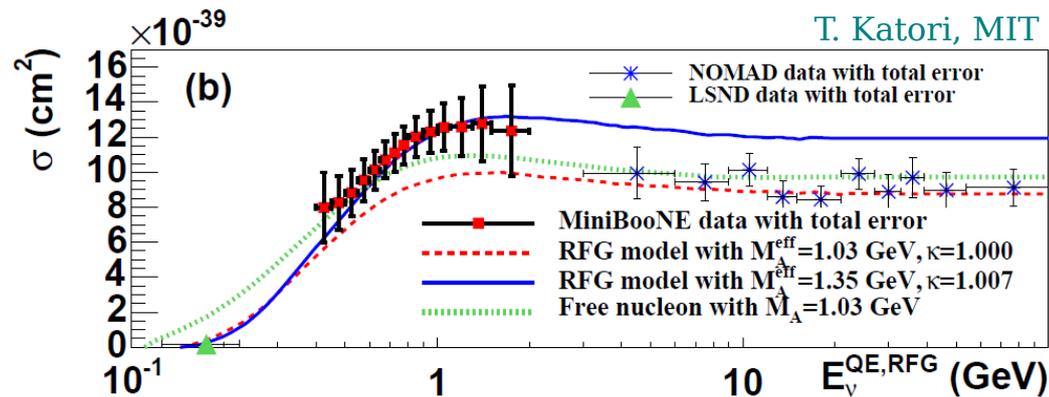


J.A. Formaggio and G.P. Zeller, "From eV to EeV: Neutrino Cross Sections Across Energy Scales", to be published in Rev. Mod. Phys., 2012.



Introduction

- Energy dependence of quasi-elastic cross section not understood
 - ◆ QE interactions an important signal channel for oscillation experiments
 - ◆ MINERvA well positioned to resolve apparent disagreement and shed light on the underlying dynamics



- Neutrinos a weak-interaction probe of nuclear structure
 - ◆ Complementary to charged lepton measurements
 - ◆ Unique probe of axial form factor, complementary probe of EMC effect
 - ◆ Flavor-sensitive probe of parton distribution functions



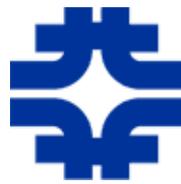
The MINERvA Collaboration (Main Injector Experiment ν -A)

University of Athens
University of Texas at Austin
Centro Brasileiro de Pesquisas Físicas
Fermilab
University of Florida
University of Geneva
Universidad de Guanajuato
Hampton University
Inst. Nucl. Res. Moscow
Mass. Col. Lib. Arts
Northwestern University

Ottebein University
Pontificia Universidad Catolica del Peru
University of Pittsburgh
University of Rochester
Rutgers University
Tufts University
University of California at Irvine
University of Minnesota at Deluth
Universidad Nacional de Ingeniería
Universidad Técnica Federico Santa María
William and Mary



A collaboration of about 80 nuclear and particle physicists from 22 institutions



The MINERvA Experiment

- Designed for detailed study of neutrino and anti-neutrino interactions with nuclei in the energy range $E_\nu = 1 - 10$ GeV
 - ◆ Fine-grained detector for excellent kinematic measurements
 - ◆ Multiple nuclear targets within the same detector and beam
- Many measurements to be pursued
 - ◆ Charged current (CC) inclusive cross sections
 - ◆ Charged current quasi-elastic (CCQE) cross sections
 - ◆ Pion production cross sections
 - ◆ Strangeness production cross sections
 - ◆ Inclusive cross section versus A: He, C, O, Fe, Pb
 - ◆ Structure functions
 - ◆ ...

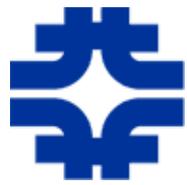


The MINERvA Experiment

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 - ◆ ...

This talk

See poster by
H. Ray!



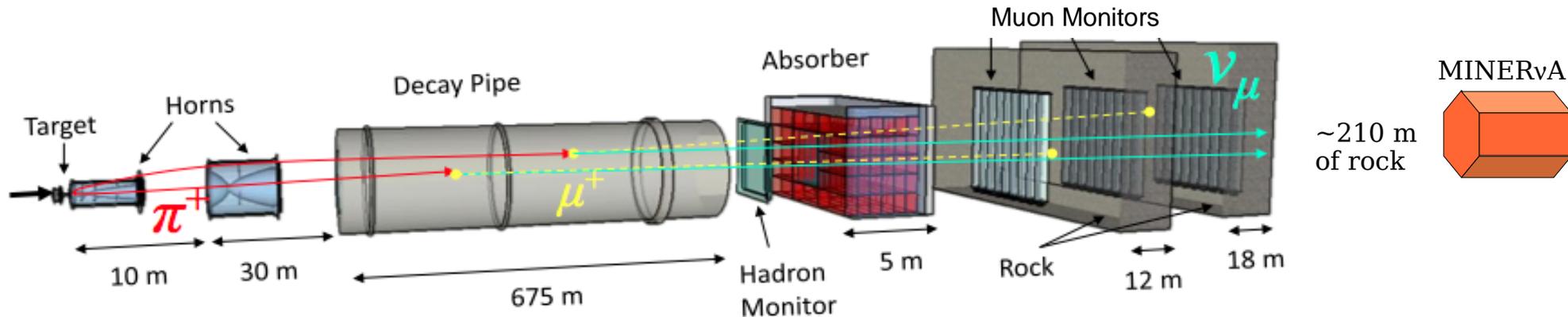
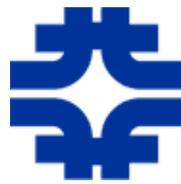
Outline

- Neutrino beam and flux
- The MINERvA detector
- Neutrino CC inclusive analysis
- Anti-neutrino CCQE cross section
- Neutrino CCQE analysis
- Summary



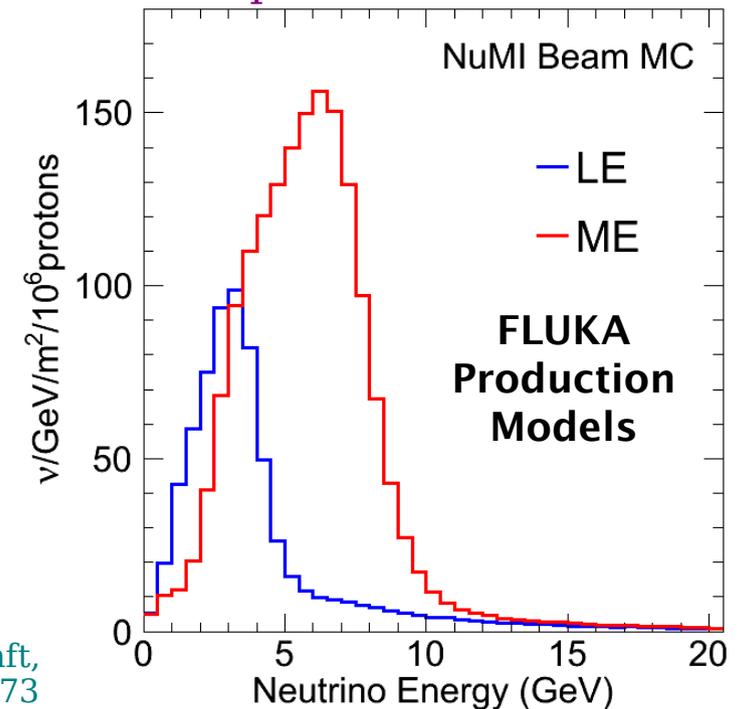
The NuMI beam line

(Neutrinos at the Main Injector)

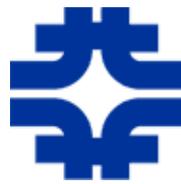


- ◆ 120 GeV p beam on C target
 - ▶ 35×10^{12} protons on target (POT) per “spill” at ~ 0.5 Hz
 - ▶ Beam power of 300–350 kW
- ◆ Focus π^+ and K^+ (or π^- and K^-) for ν_μ ($\bar{\nu}_\mu$) beam
 - ▶ $\pi^+, K^+ \rightarrow \mu^+ \nu_\mu$ in decay pipe
- ◆ Muon monitors to augment flux estimation
- ◆ Tune E_ν spectrum by moving target and horn
 - ▶ Will run in “low energy” and “medium energy” beam configurations

Expected neutrino flux



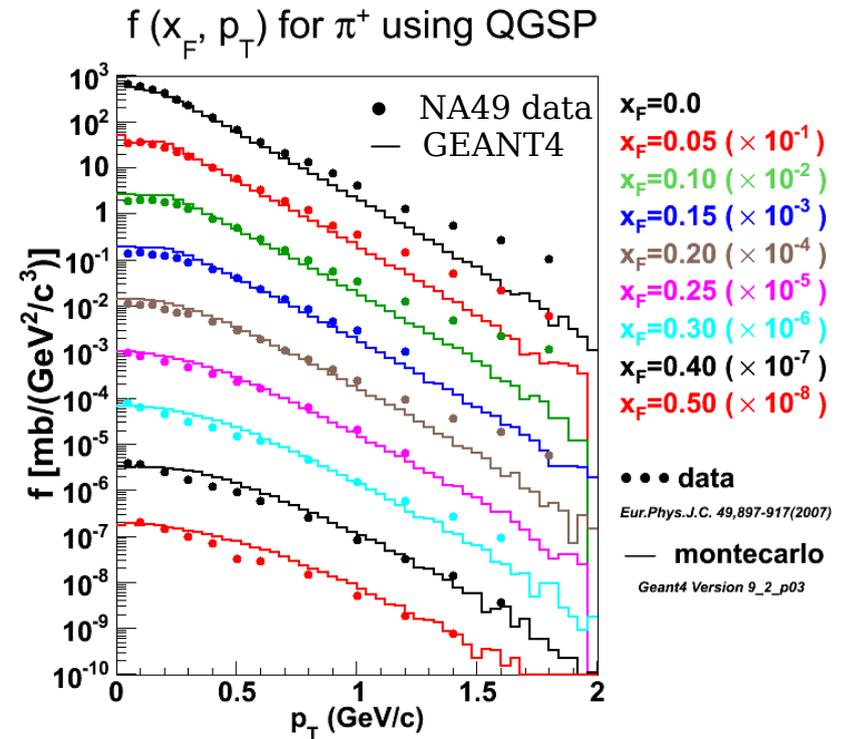
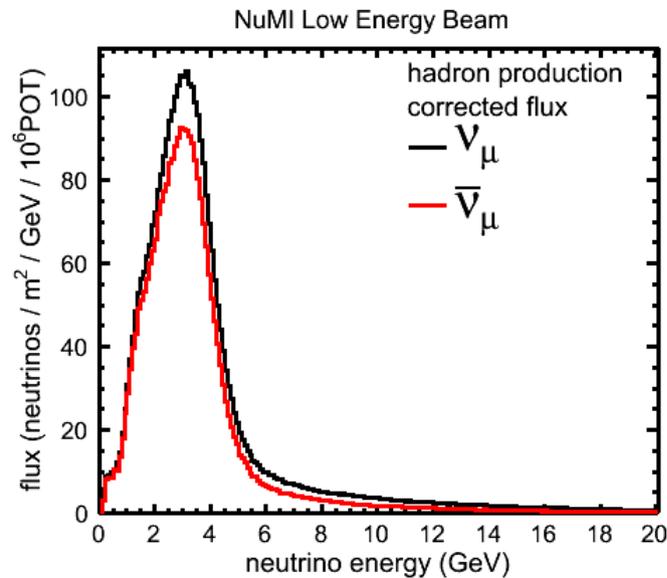
FLUKA: A. Ferrari, P.R. Sala, A. Fasso`, and J. Ranft, CERN-2005-10 (2005), INFN/TC_05/11, SLAC-R-773



Neutrino flux

- Estimate flux from hadron production

- ◆ Re-weight MC to match NA49 data
- ◆ Use GEANT4 to calculate flux
- ◆ Uncertainties from NA49 data and hadron production model



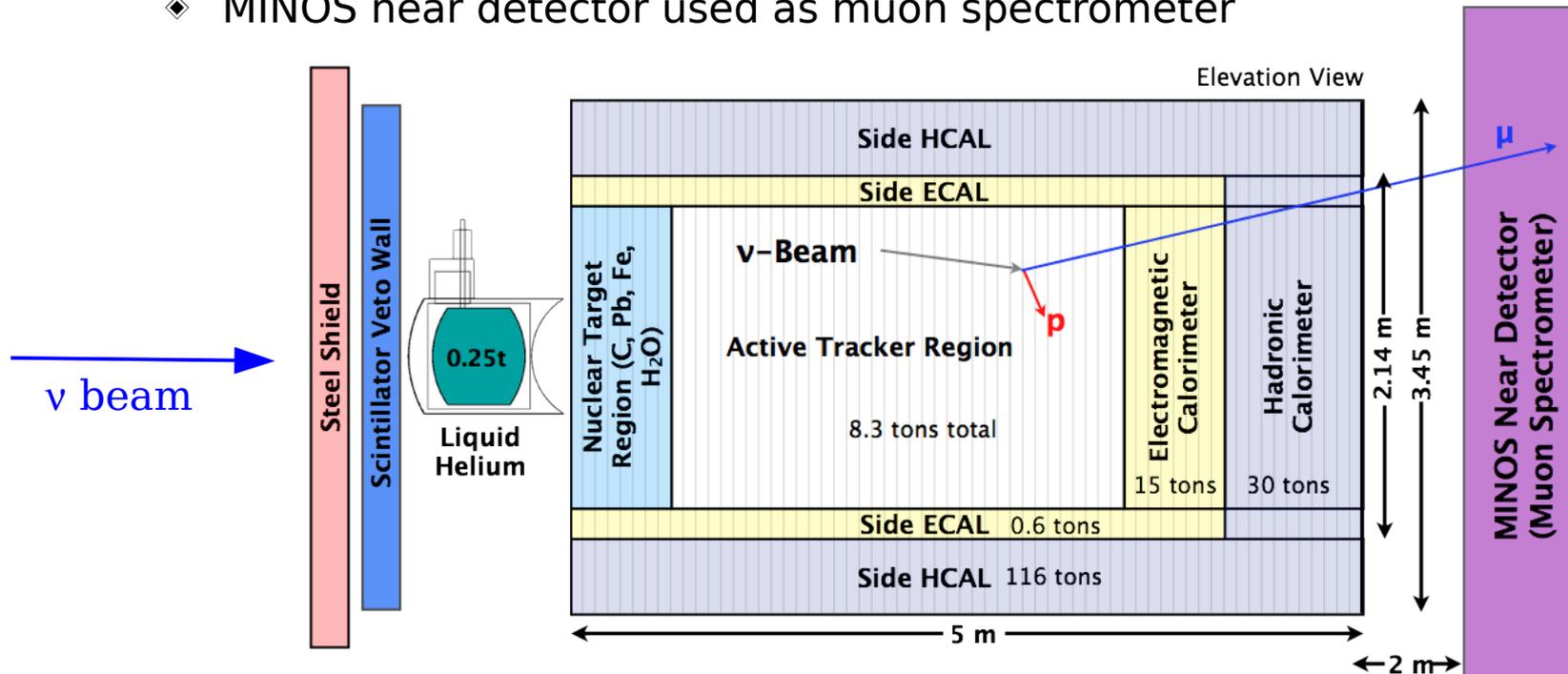
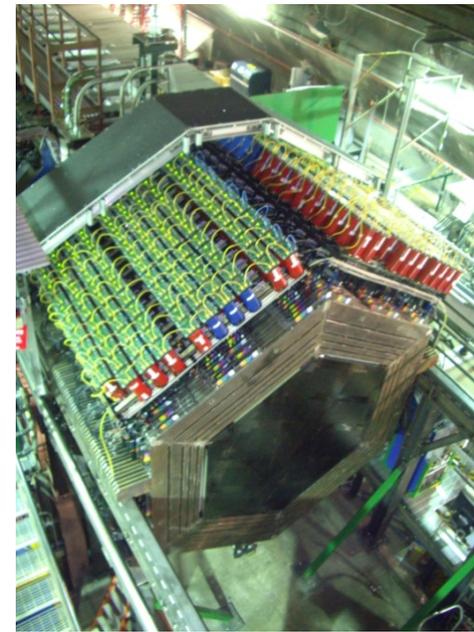
- Check with muon monitors
- Study with alternate beam configurations

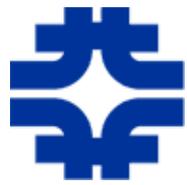
(Not yet included in flux estimates)



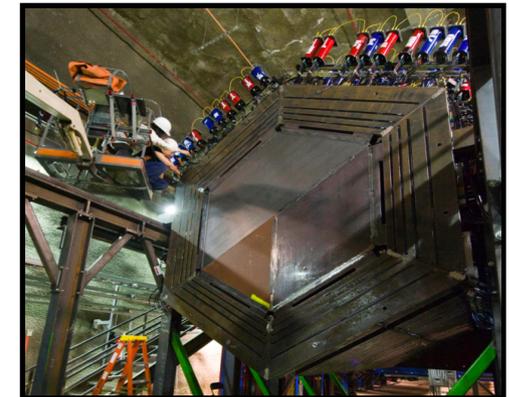
The MINERvA detector

- ◆ 120 stacked modules, mostly planes of scintillator strips
- ◆ Fully active, finely-segmented tracking region in center
- ◆ LHe and nuclear target region on upstream side
- ◆ Side and end EM and hadronic calorimeter regions
- ◆ MINOS near detector used as muon spectrometer

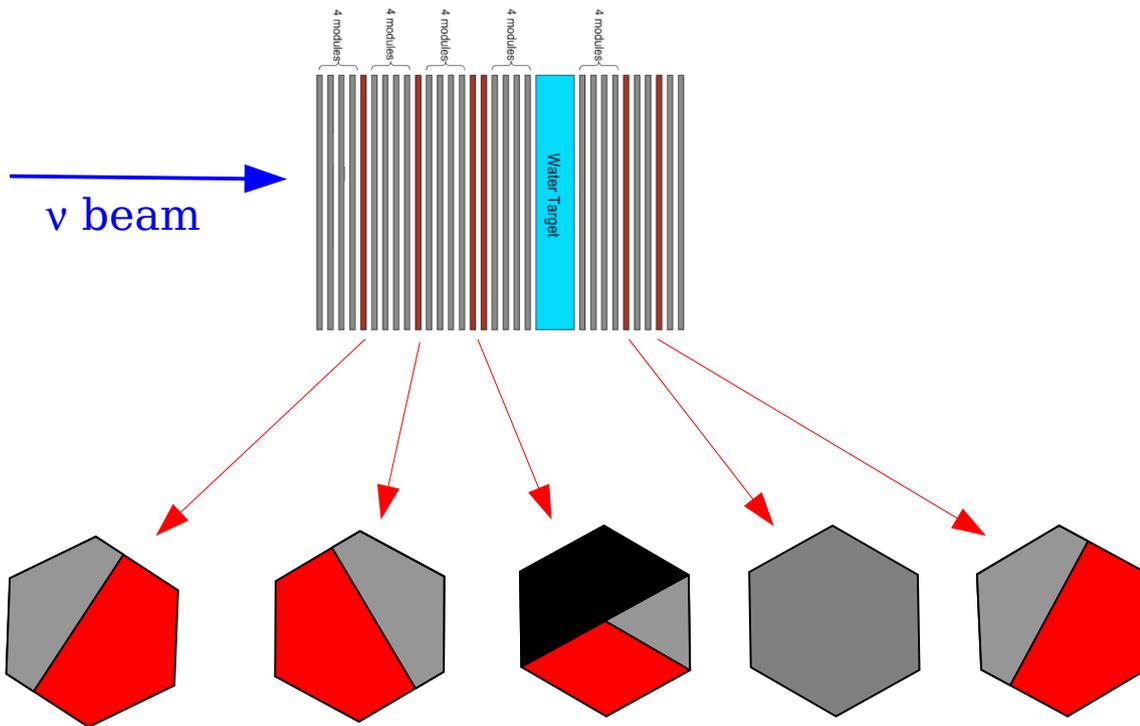




Nuclear targets



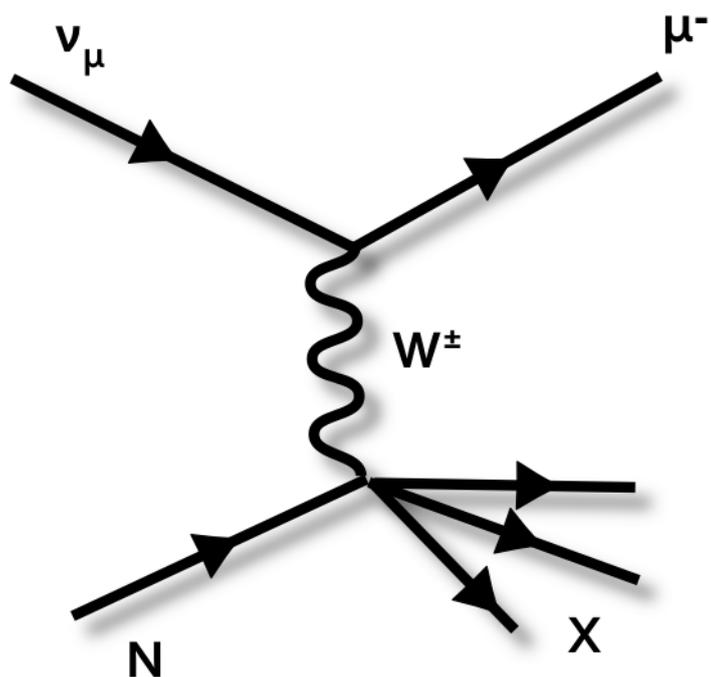
- 250 kg liquid He upstream of detector
- 5 sets of nuclear targets (C, Fe, Pb) + **water**



Nuclear Target	Fid. Vol (t)
CH (tracker)	6.43
He	0.25
C	0.17
Fe	0.97
Pb	0.98



Charged current inclusive analysis

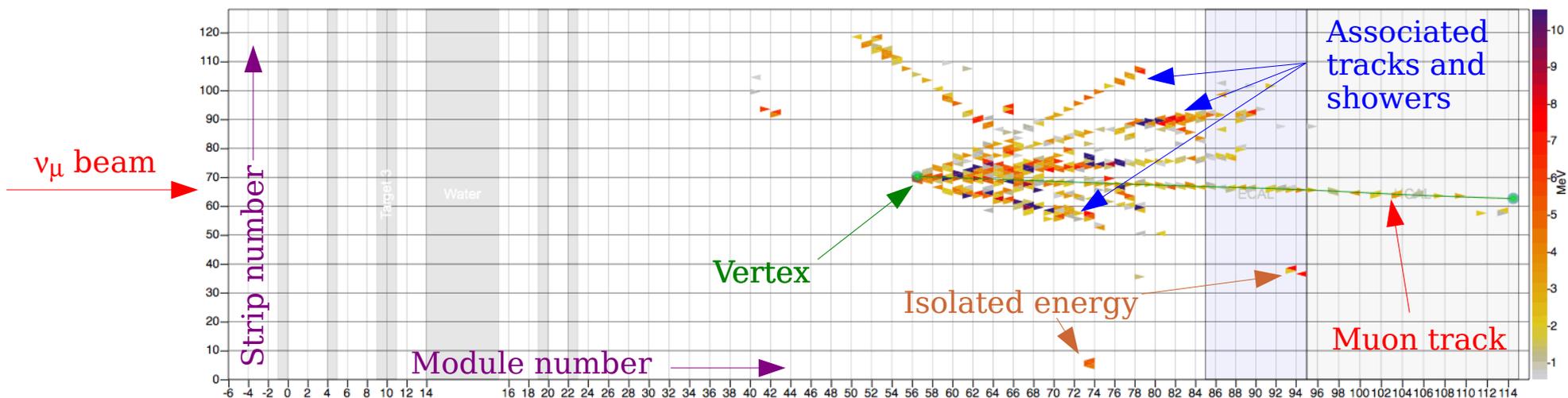


- $\nu_{\mu} + N \rightarrow \mu^{-} + X$
- Analysis uses 25% of available data



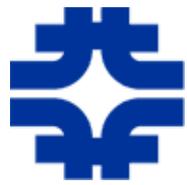
Neutrino CC inclusive analysis

- ◆ Signature: muon track + energy deposition associated with vertex

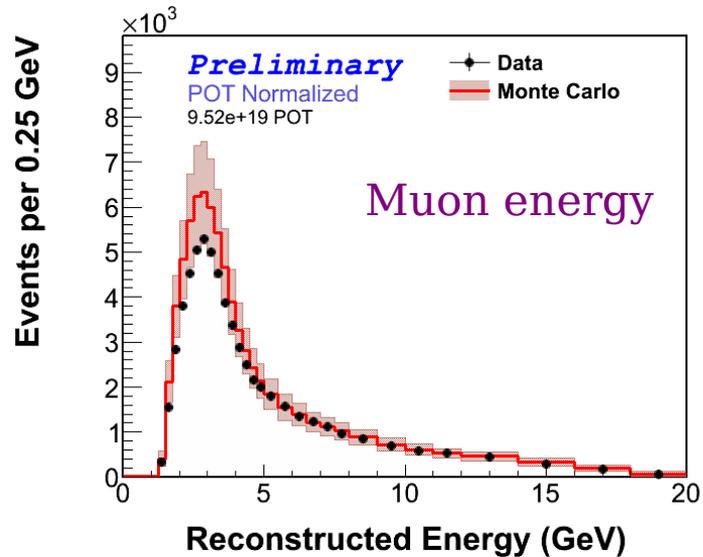
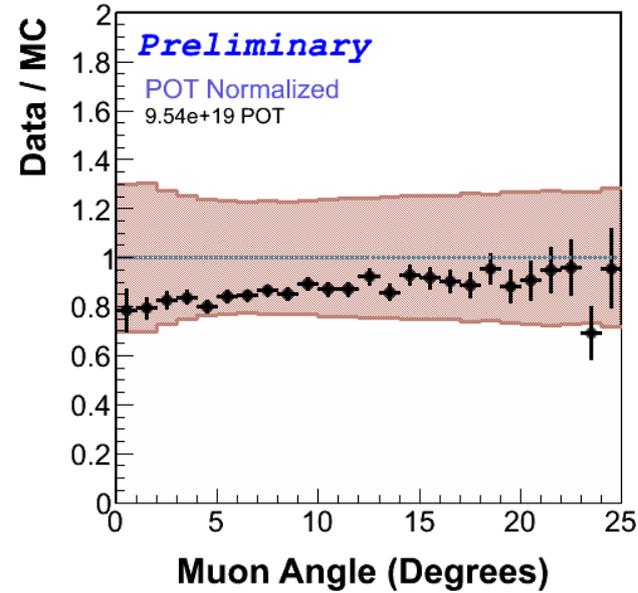
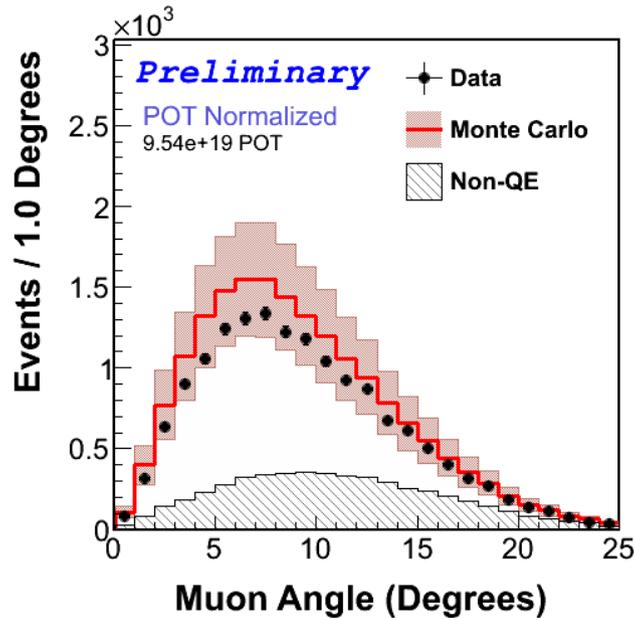


- ◆ Event selection and reconstruction:

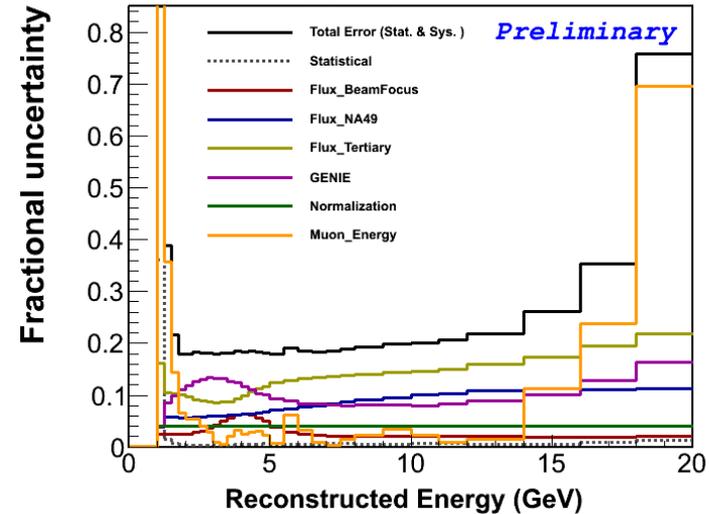
- ▶ A single MINOS-matched μ^- track candidate
- ▶ Reconstructed vertex in fiducial volume
- ▶ Measure recoil energy calorimetrically
 - ▷ Sum energy in other tracks, showers, isolated energy depositions in tracker and EM calorimeter

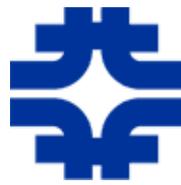


Neutrino CC inclusive kinematic distributions



Muon energy sys. uncertainties



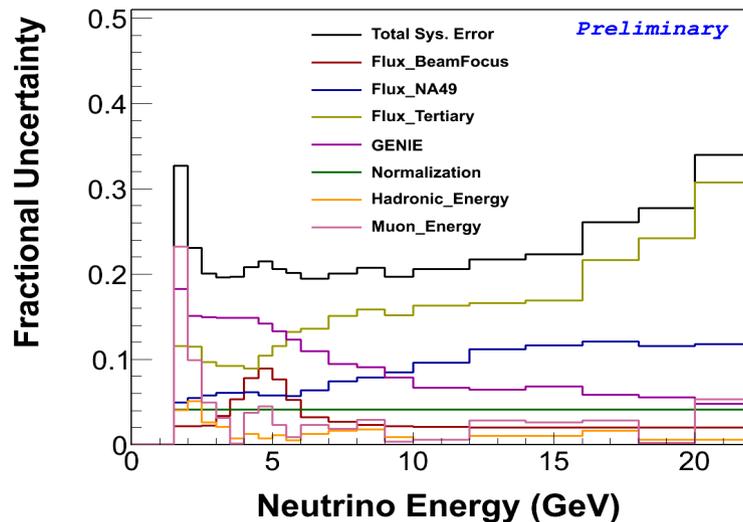


Neutrino CC inclusive A-dependence

- Measured ratio of CC inclusive cross sections in **Fe** and **Pb**
 - ◆ Systematic errors cancel in a double-ratio method
 - ◆ Achieve a statistics limited measurement

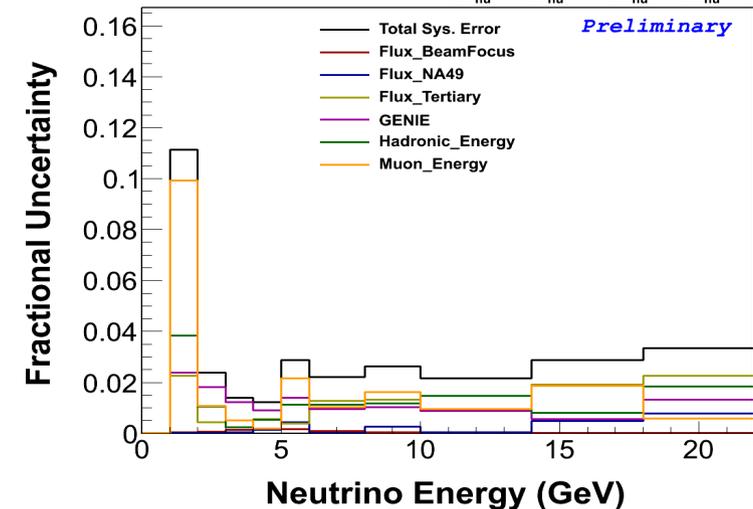
Systematic uncertainty for Fe

Systematic Error Sources on Signal in Iron of Target 5

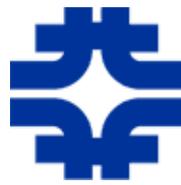


Sys. uncertainty for Pb/Fe double ratio

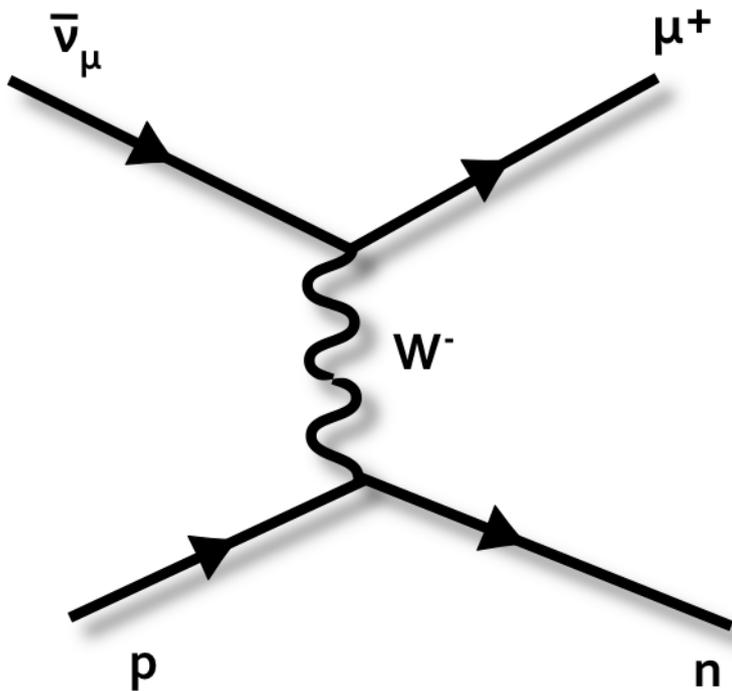
Systematic Error Sources on $(\frac{d\sigma^{Pb,5}}{dE_{\nu}} / \frac{d\sigma^{CH,15}}{dE_{\nu}}) / (\frac{d\sigma^{Fe,5}}{dE_{\nu}} / \frac{d\sigma^{CH,15}}{dE_{\nu}})$



See poster presented by H. Ray from Univ. of Florida for details!



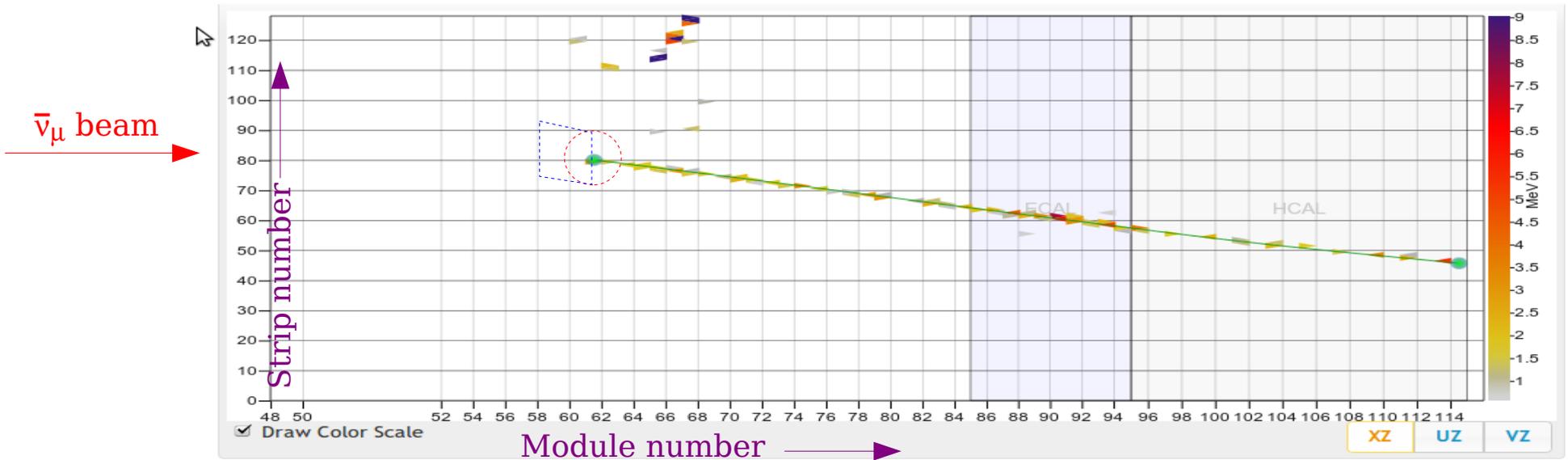
Anti-neutrino Charged Current Quasi-Elastic cross section



- $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$
- Analysis uses $\sim 20\%$ of available $\bar{\nu}$ data in a sub-sample collected with partially constructed detector (55%)

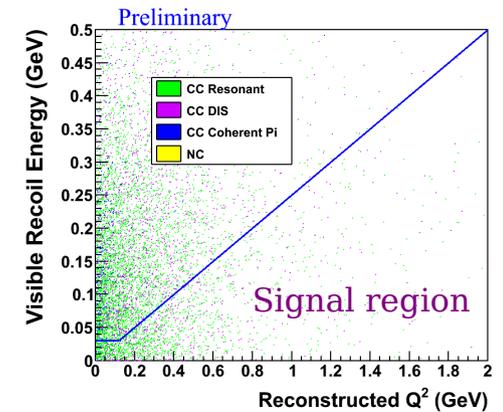
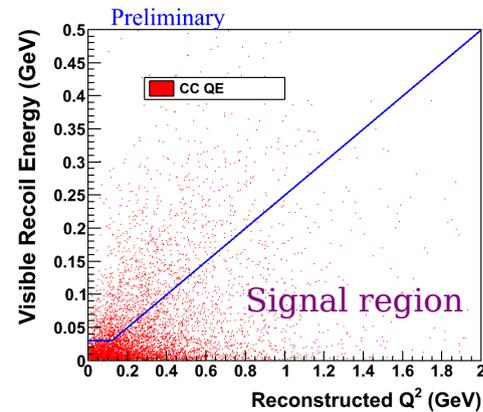
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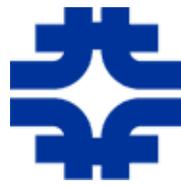
- Signature: muon track + energy deposition consistent with a neutron



Event selection:

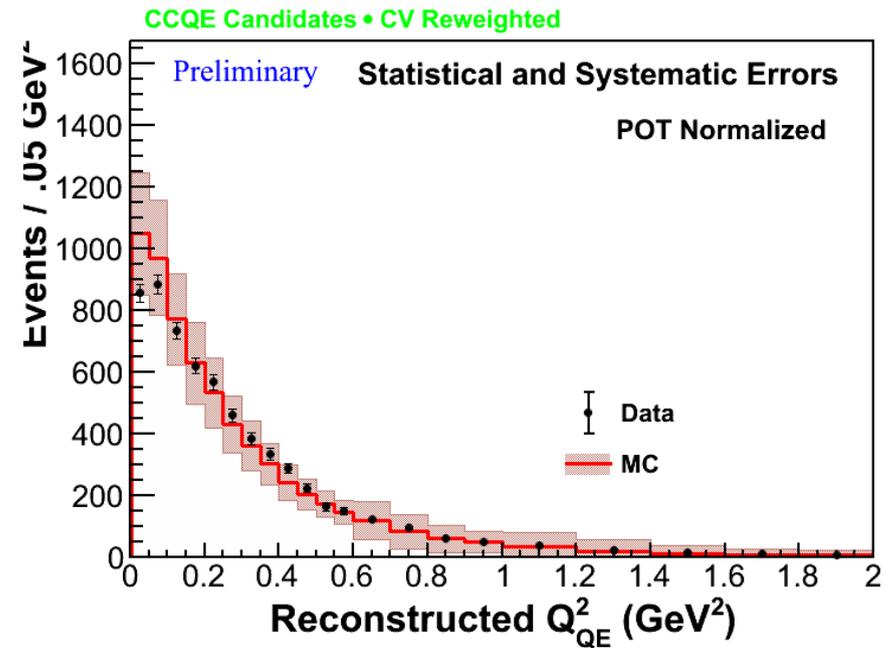
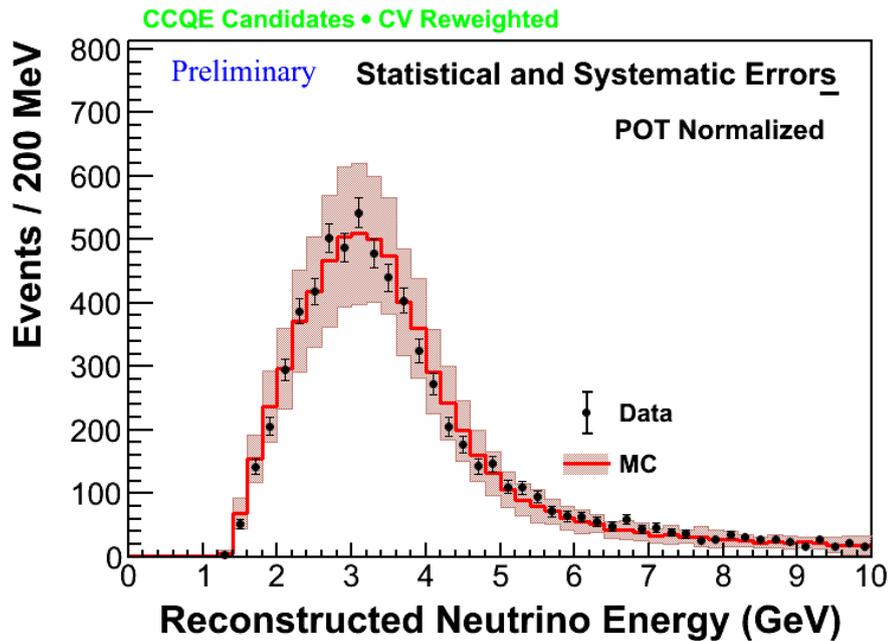
- ▶ MINOS-matched μ^+ track candidate
 - No activity in 4 planes upstream along track trajectory
- ▶ Reconstructed vertex in fiducial volume
- ▶ Number of shower activity regions ≤ 1
 - Recoil energy away from vertex (10 cm) $< Q^2$ -dependent maximum
- ▶ Reconstructed $\bar{\nu}$ energy < 10 GeV





Reconstructed kinematic distributions for $\bar{\nu}$ CCQE

- ◆ Use muon energy and direction to extract neutrino energy and Q^2 assuming 2-body kinematics with target proton at rest



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

(Nuclear binding energy $E_b = 30$ MeV)

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



$\bar{\nu}$ CCQE cross section

$$\left(\frac{d\sigma}{dQ^2}\right)_i = \frac{1}{\epsilon_i(\Phi T)\Delta Q_i^2} \times \sum_j \left(M_{ij} \left(N_{\text{data},j} - N_{\text{data},j}^{\text{bkdg}}\right)\right)$$

- Background subtraction

- ◆ Non-CCQE neutrino and anti-neutrino interactions:

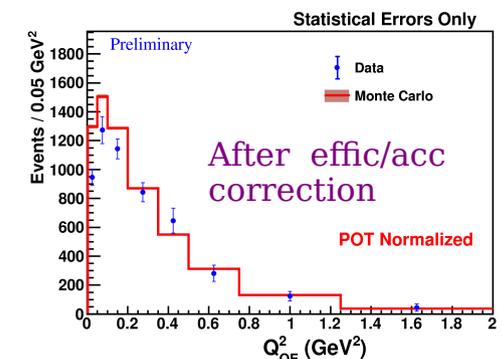
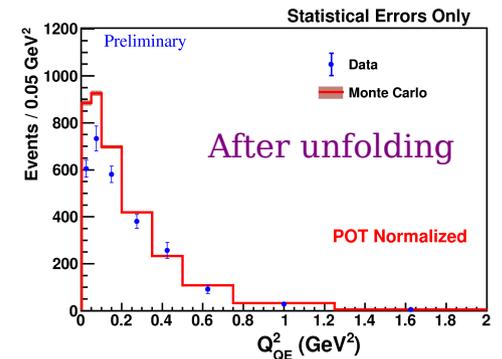
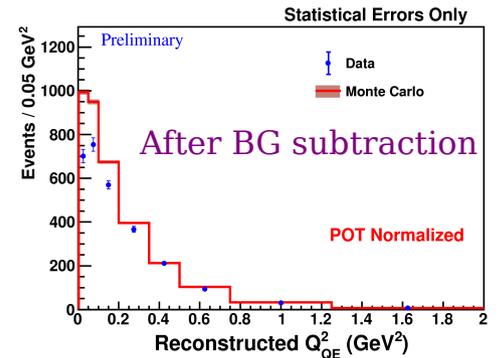
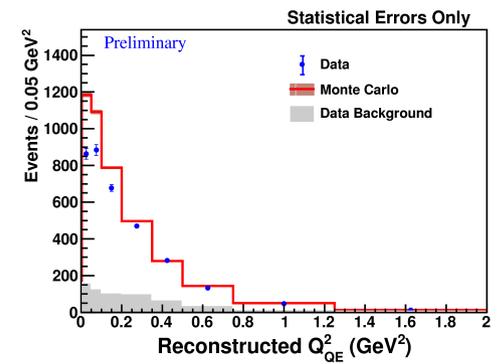
- ▶ Fit recoil energy distribution in bins of Q^2 to MC shape templates for BG

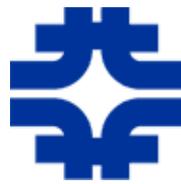
- Resolution unfolding estimated from MC

- ◆ Diagonal elements between about 0.5 to 0.9

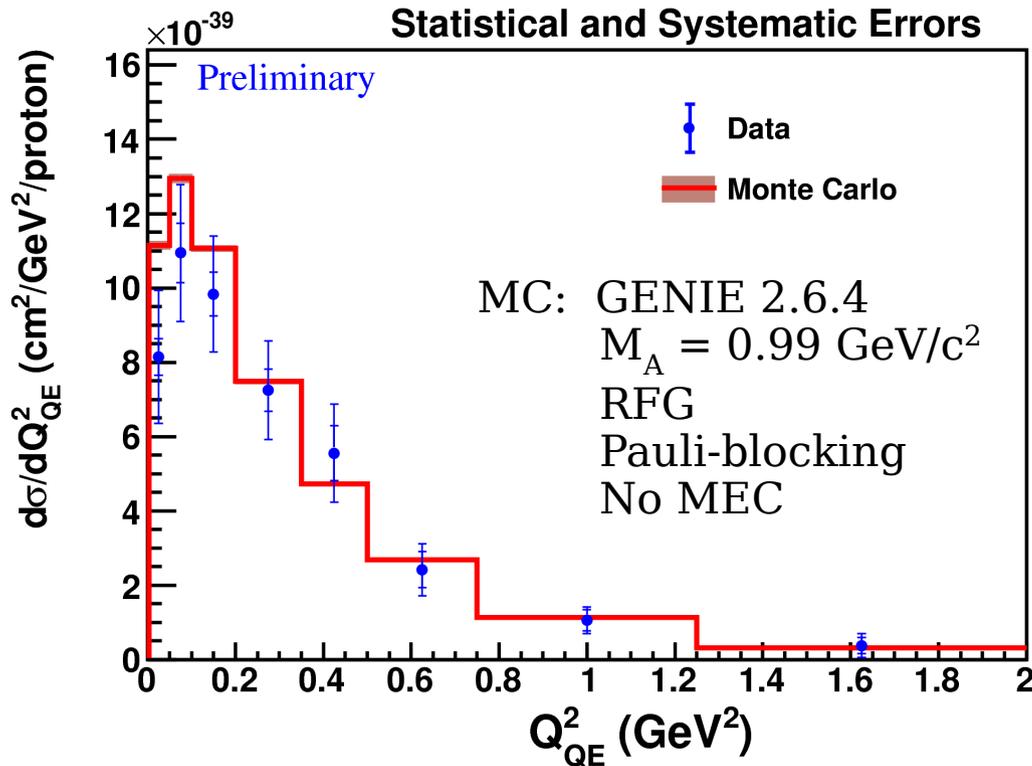
- Efficiency \times acceptance correction from MC

- ◆ About 0.65 at low Q^2 to 0.13 for Q^2 around 1.65 GeV^2





$\bar{\nu}$ CCQE cross section result

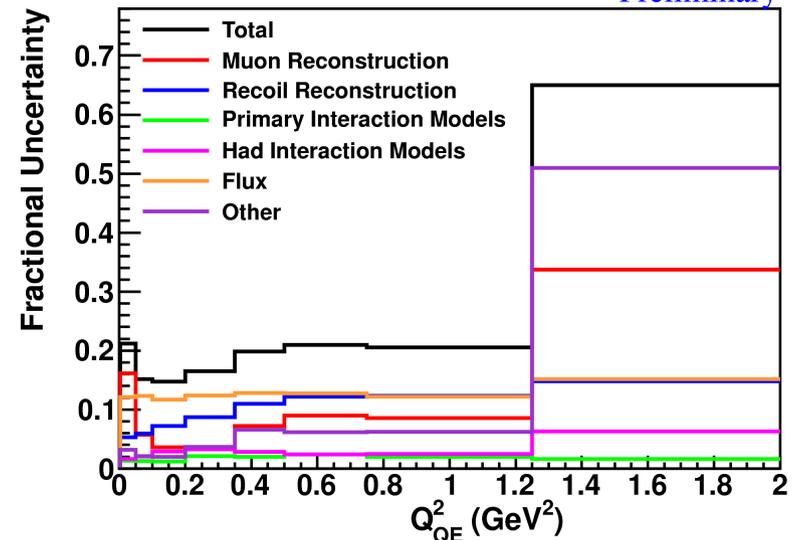


Systematic uncertainties

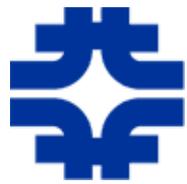
- ▶ Estimate by varying inputs within uncertainties, re-running analysis
- ▶ Extract uncertainty bands from the ensemble of results

Systematic uncertainties

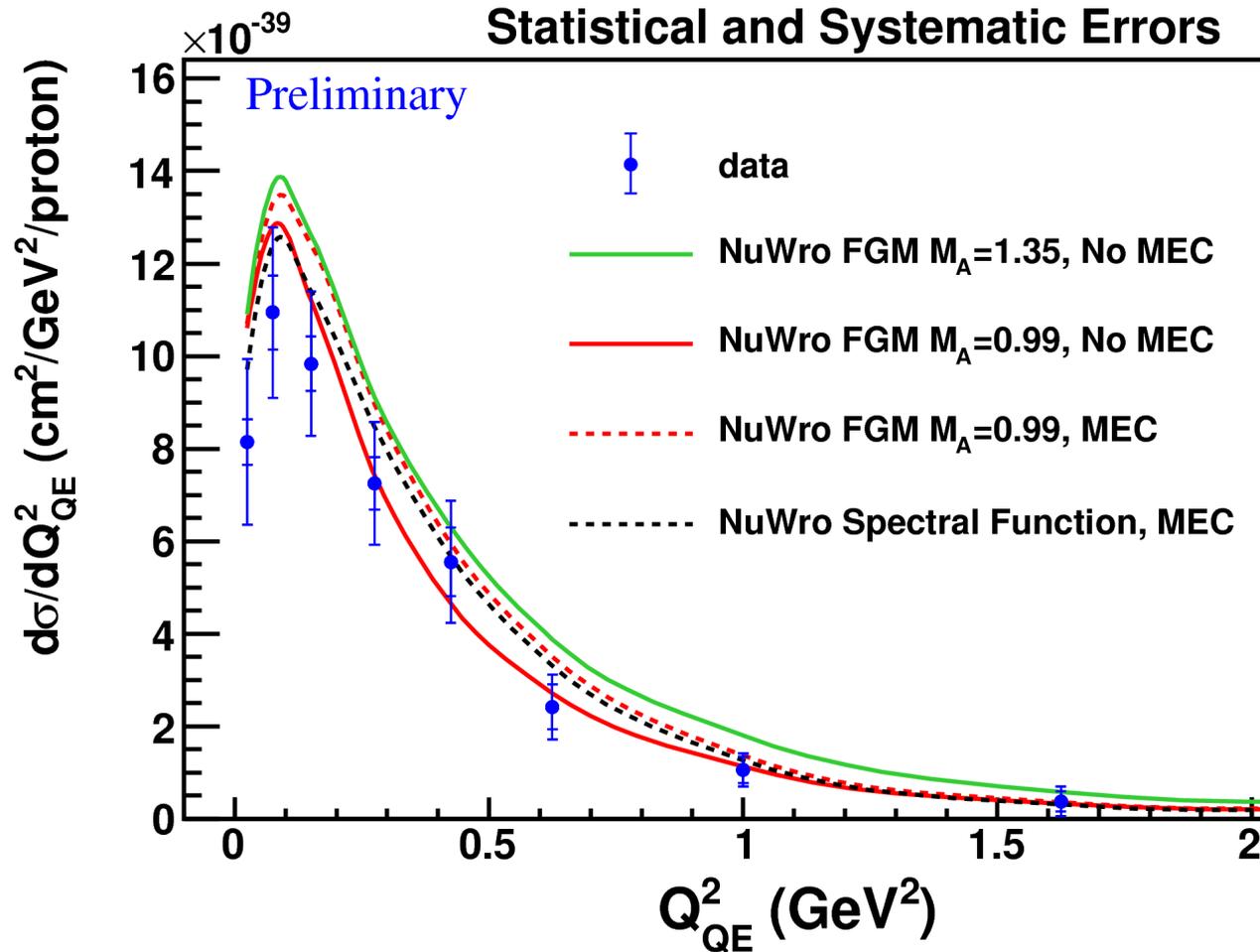
Preliminary



GENIE: www.genie.org, NIM **A614**, 87 (2010)



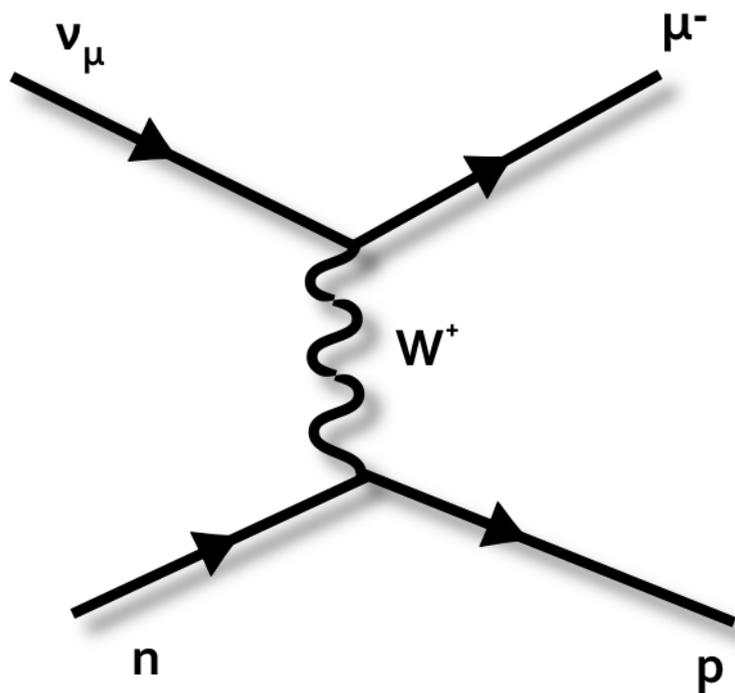
$\bar{\nu}$ CCQE cross section result



NuWro: Acta Phys. Polon. **B40**, 2507 (2009)



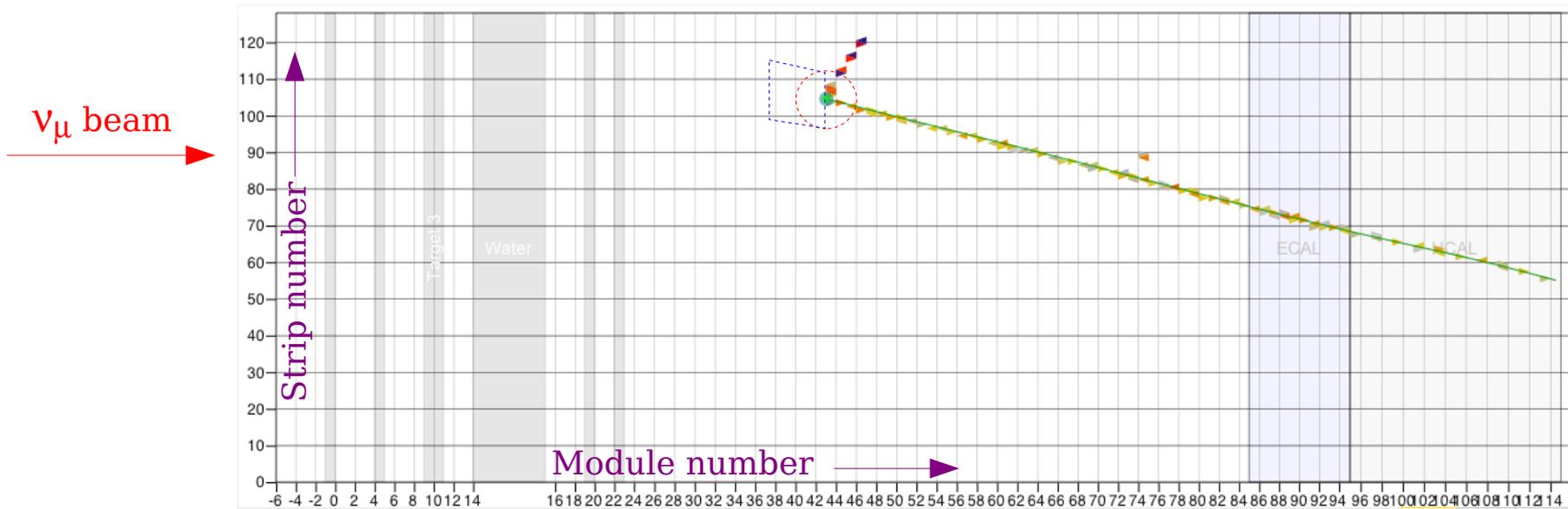
Neutrino CC Quasi-Elastic analysis



- $\nu_{\mu} + n \rightarrow \mu^{-} + p$
- Analysis uses 25% of available data

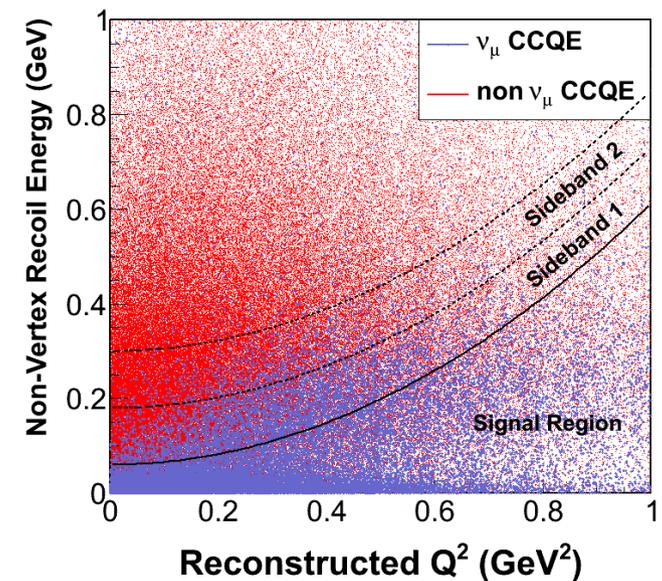
Neutrino CCQE analysis

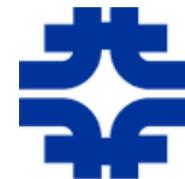
- ◆ Signature: muon track + recoil consistent with p



- ◆ Event selection:

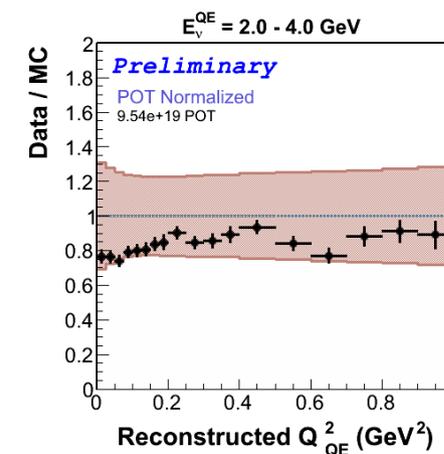
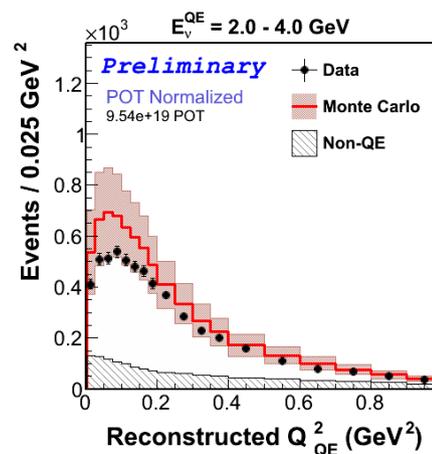
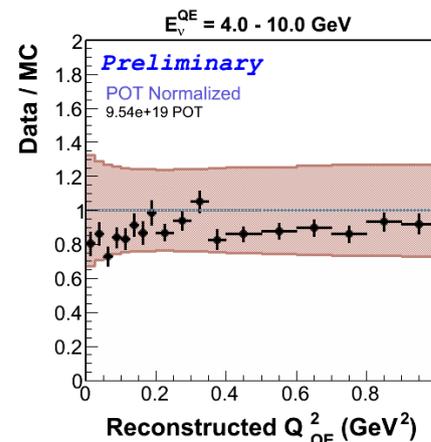
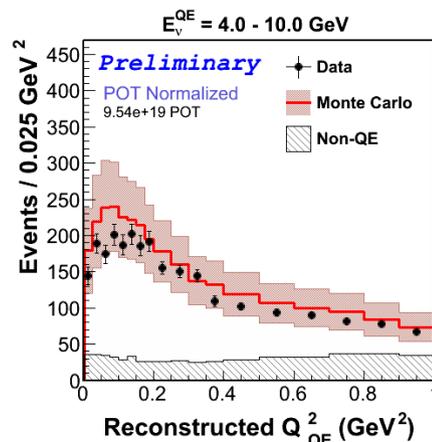
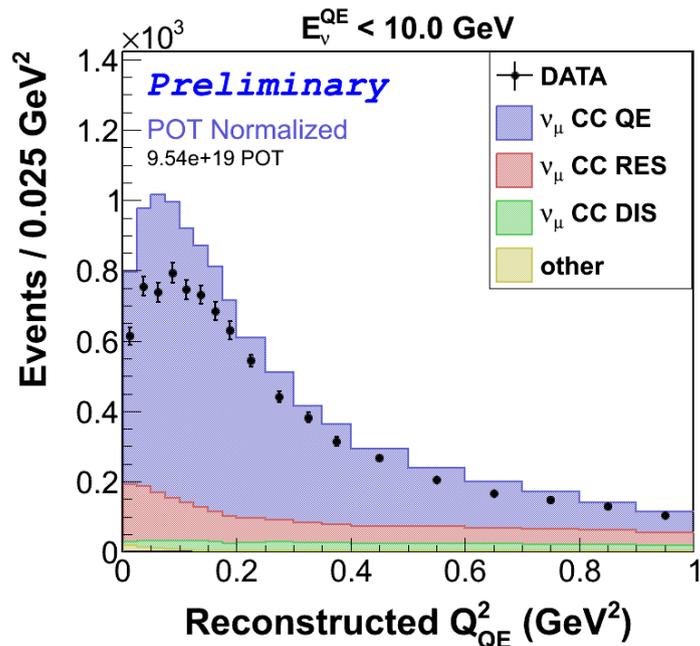
- ▶ MINOS-matched μ^- track candidate
 - ▷ No inactive strips along track trajectory in 4 planes upstream
- ▶ Reconstructed vertex in fiducial volume
- ▶ At most one other track associated with muon vertex
- ▶ Recoil energy away from vertex (10 cm) $< Q^2$ -dependent maximum

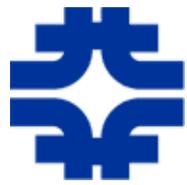




Neutrino CCQE Q^2 distributions

In bins of neutrino energy

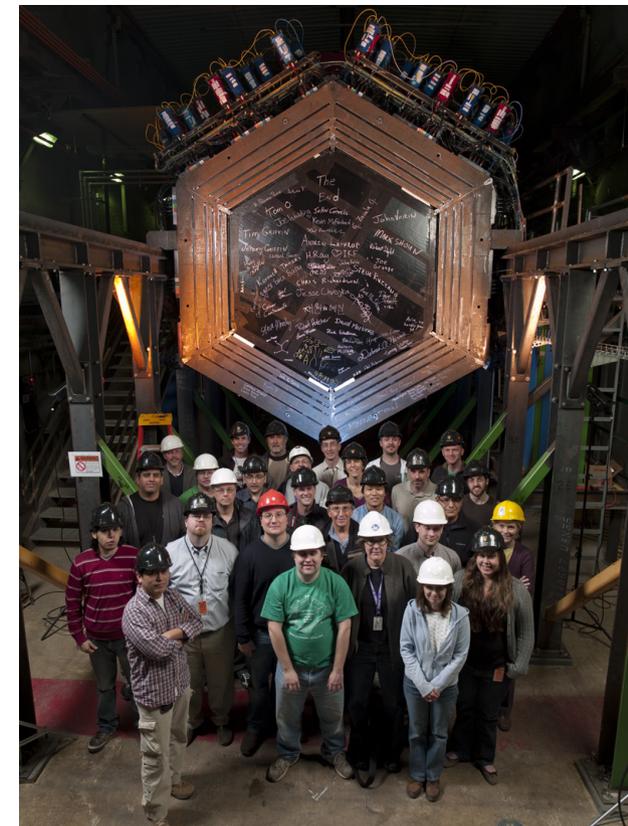


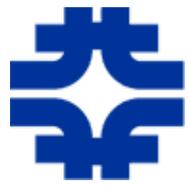


Summary

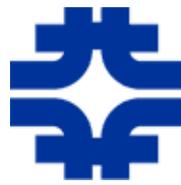
- MINERvA has completed data-taking run with low-energy beam
 - ◆ Detector is working well
 - ◆ Analysis of the first 25% of LE data is well underway
 - ▶ Preliminary results for CCQE cross section for $\bar{\nu}_\mu$
 - ▶ CC inclusive and CCQE analyses for ν_μ in advanced state
 - ◆ Now preparing to analyze the full LE dataset
- Greatly looking forward to medium energy run starting in 2013

See poster by H. Ray on A-dependence of inclusive cross section!!

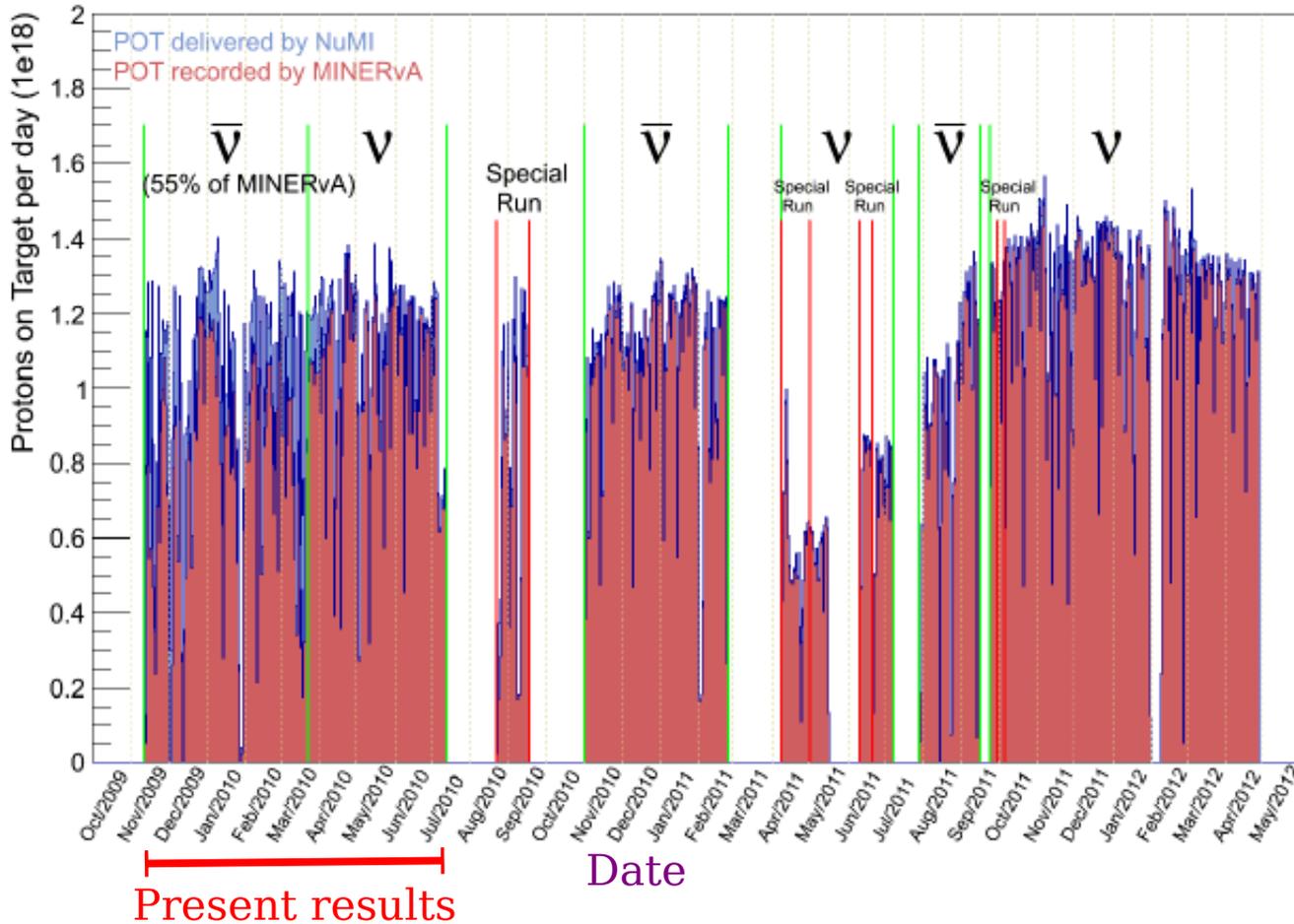




Backup



MINERvA data taking

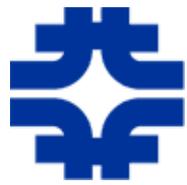


◆ Recently completed low energy running

- ▶ LE ν mode
 3.98×10^{20} POT
- ▶ LE $\bar{\nu}$ mode
 1.7×10^{20} POT
- ▶ Special runs
 4.94×10^{19} POT

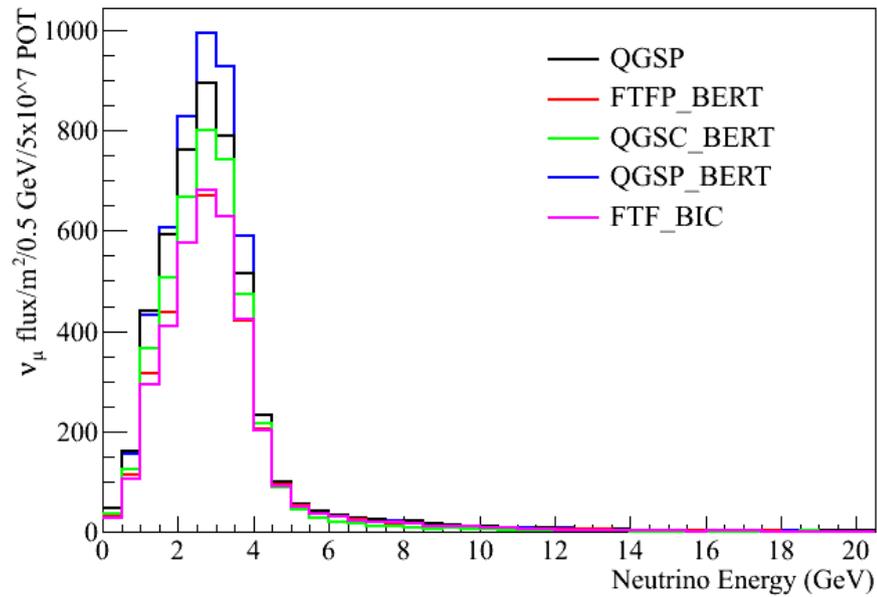
- ▶ Livetime
 - ▷ 97.1% MINERvA
 - ▷ 93.3% with MINOS ND

◆ Expect to begin medium energy run ~ spring 2013

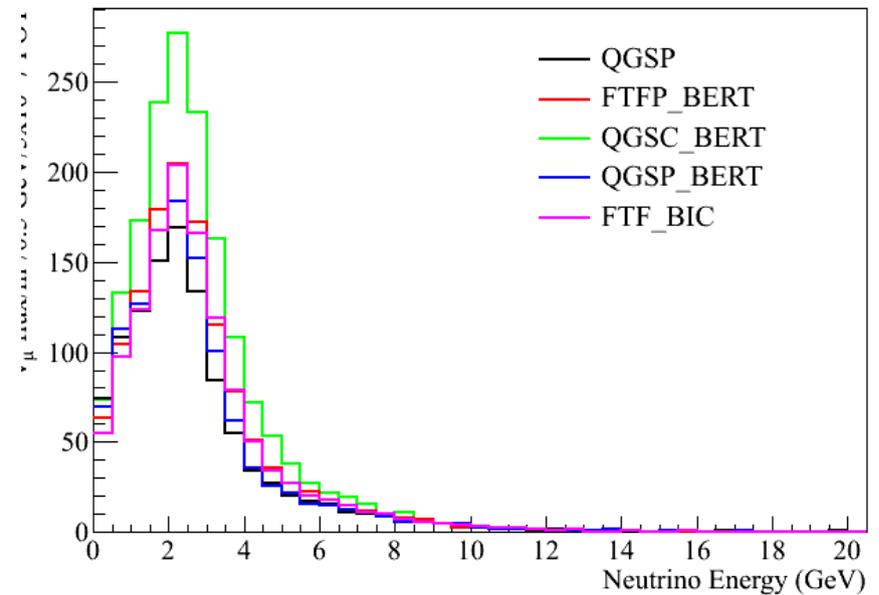


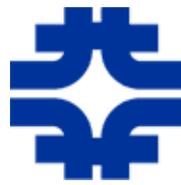
Neutrino production model spread

Re-interactions in target

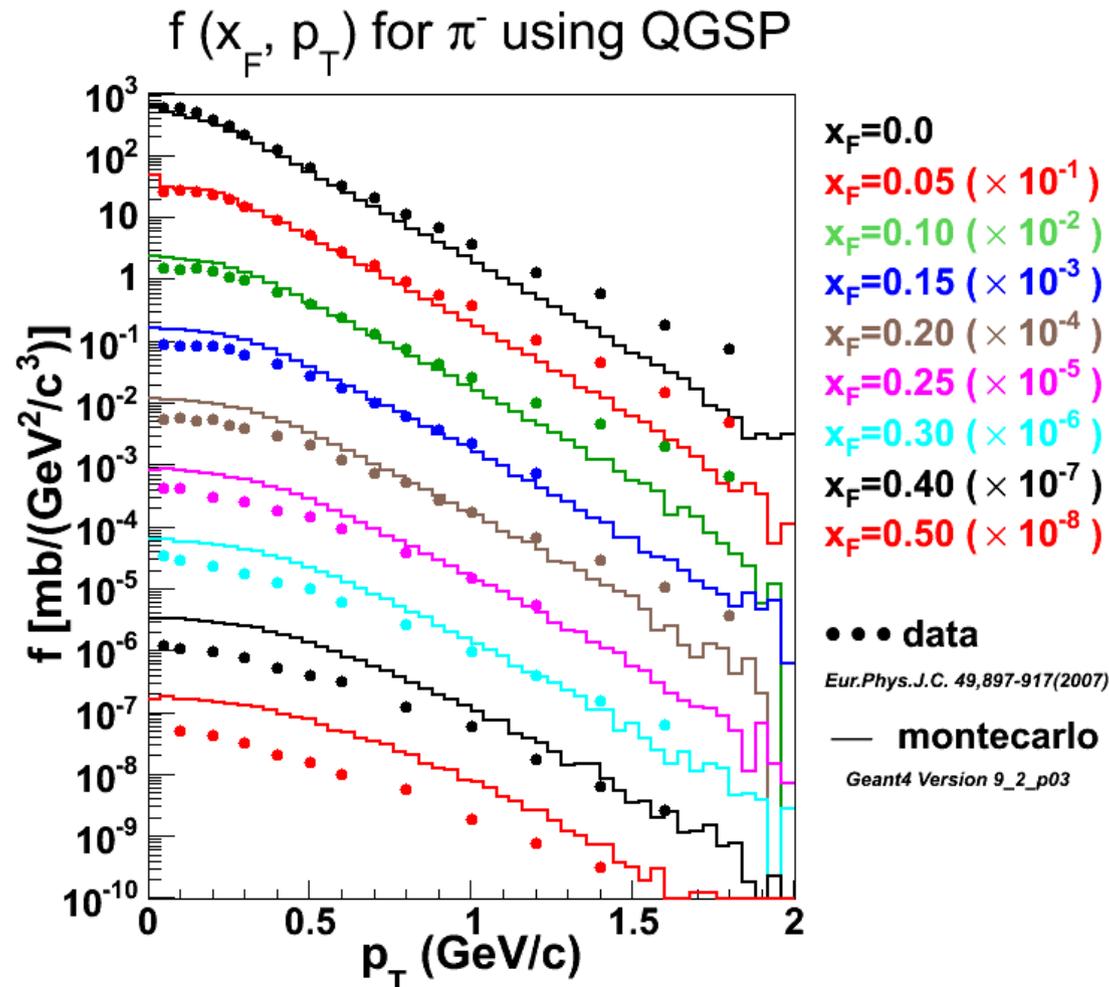


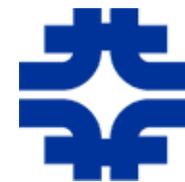
Tertiary production in horns



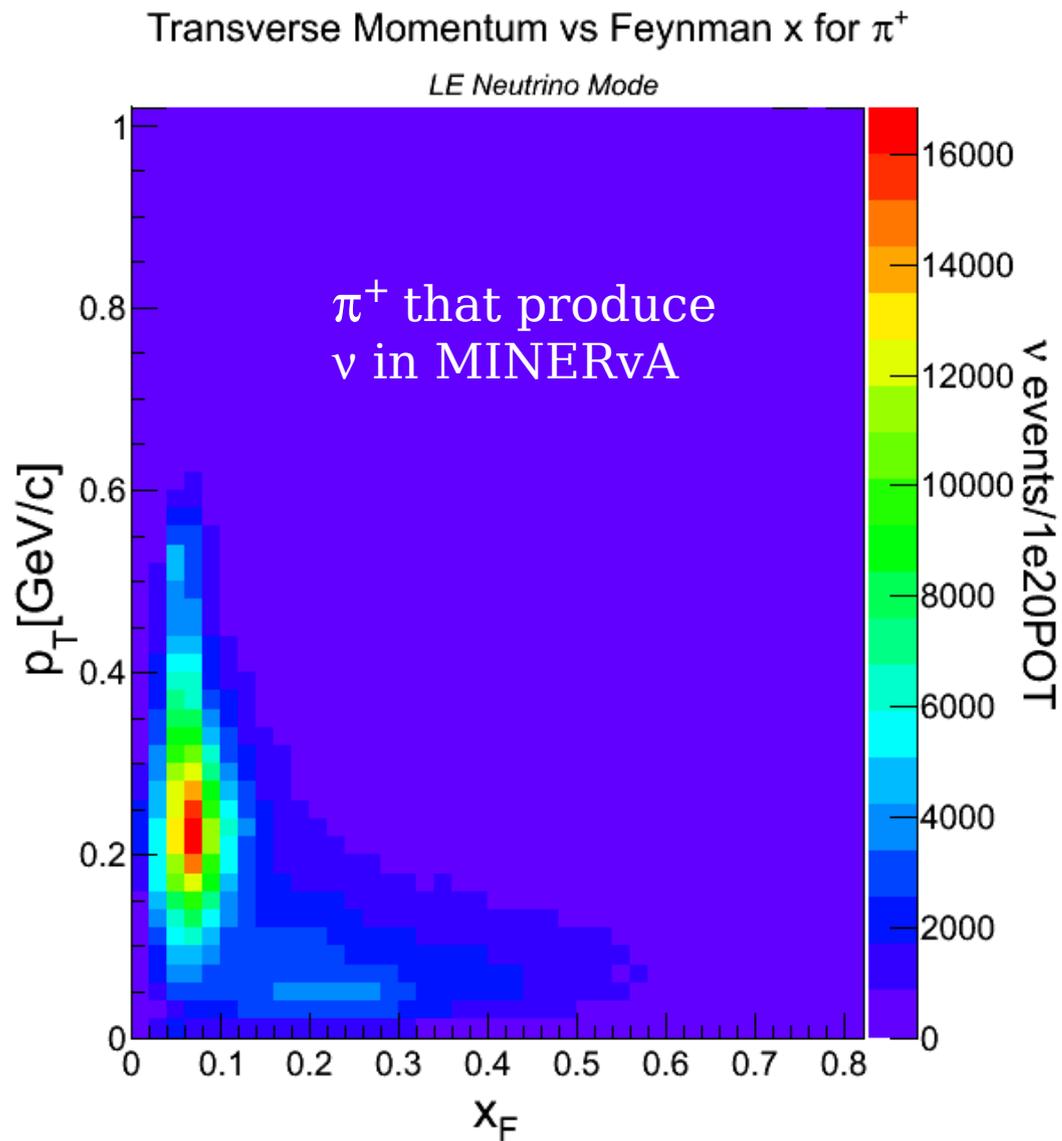


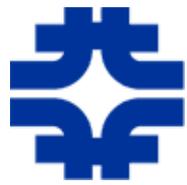
NA49 pi minus production





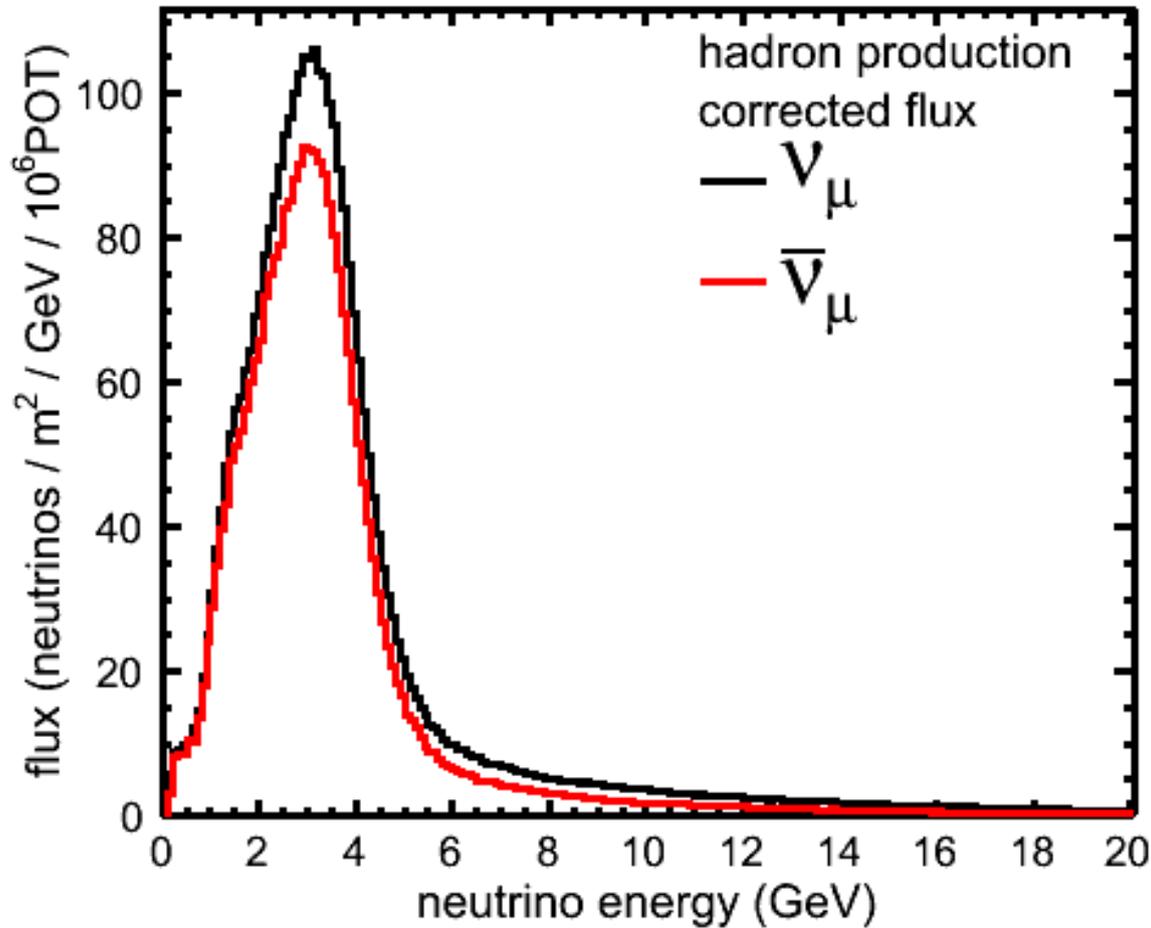
π^+ parents of neutrinos in MINERvA



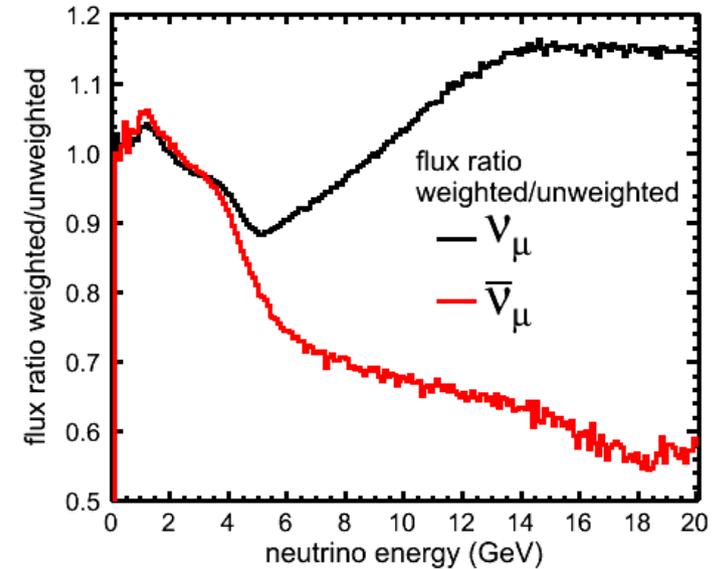


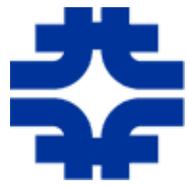
Neutrino flux – low energy beam

NuMI Low Energy Beam

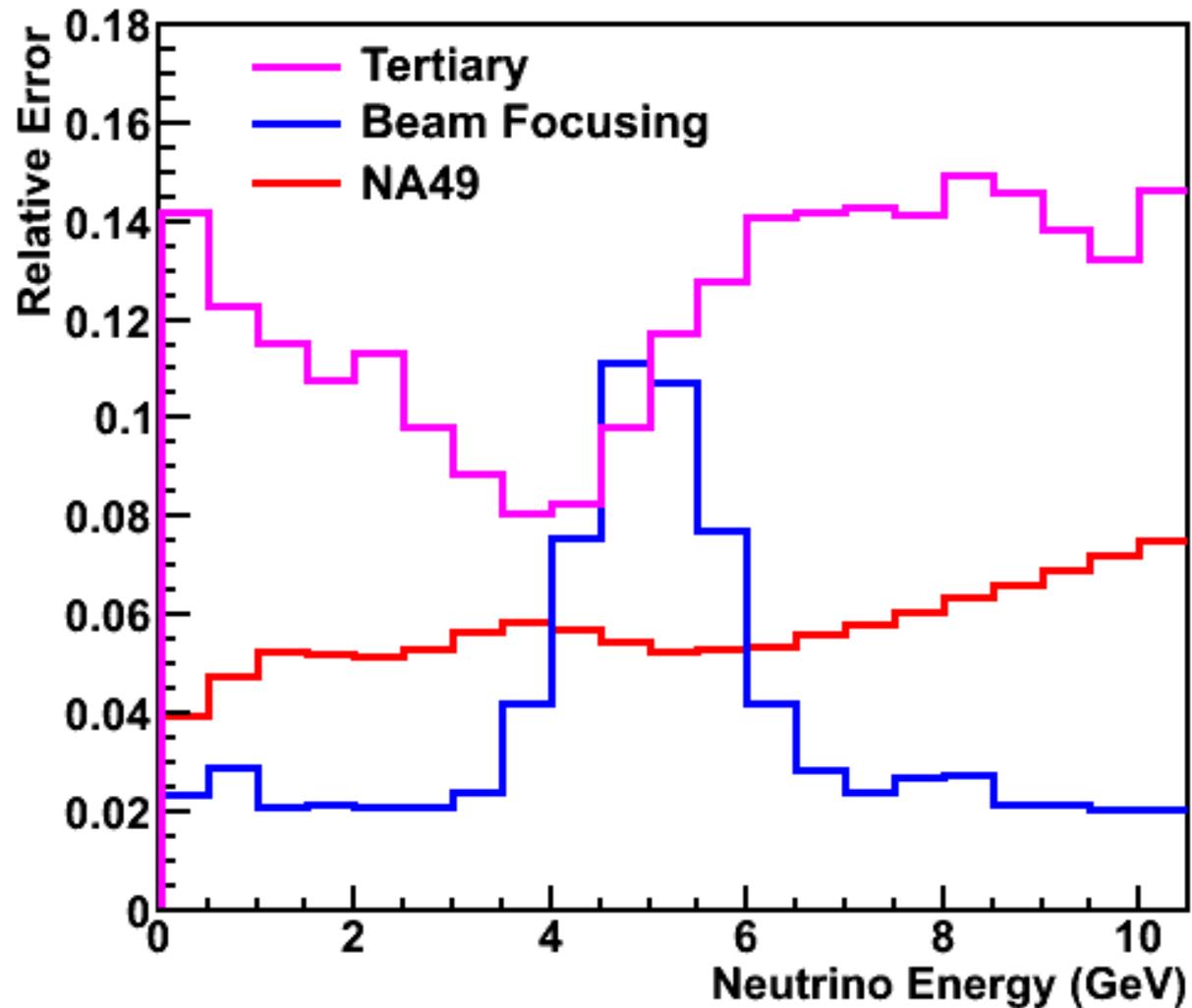


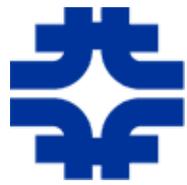
NuMI Low Energy Beam



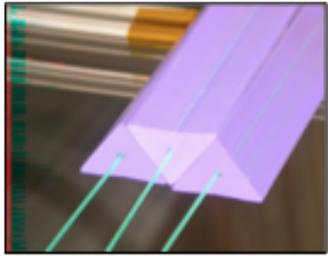


Neutrino flux uncertainties



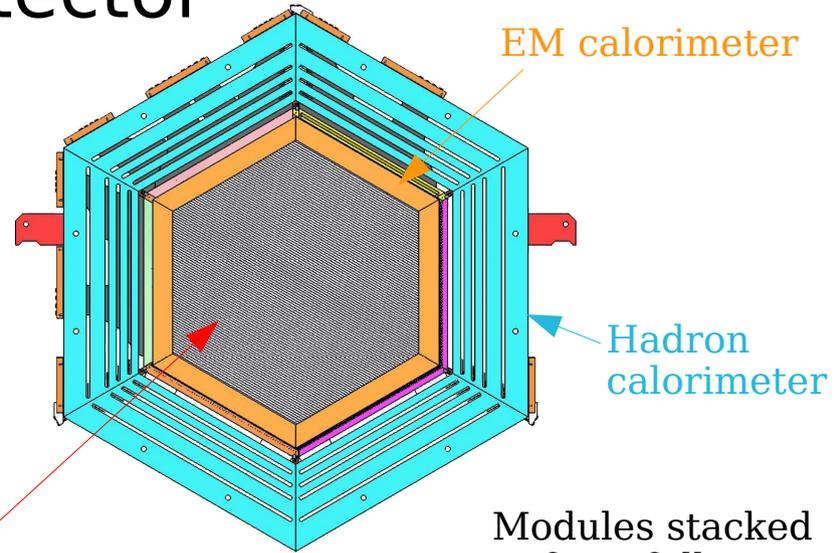


The MINERvA detector



Extruded plastic scintillator
+ wavelength shifters

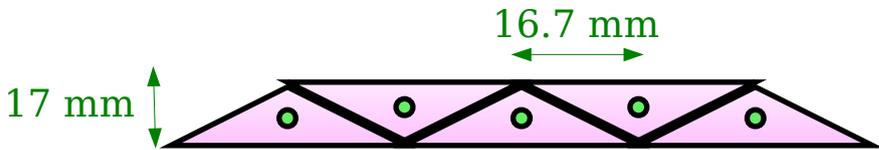
Triangular geometry allows
charge sharing for better
position resolution



Front elevation view

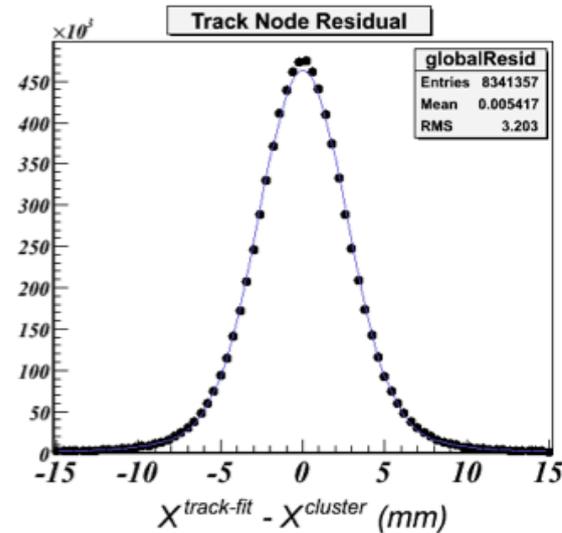
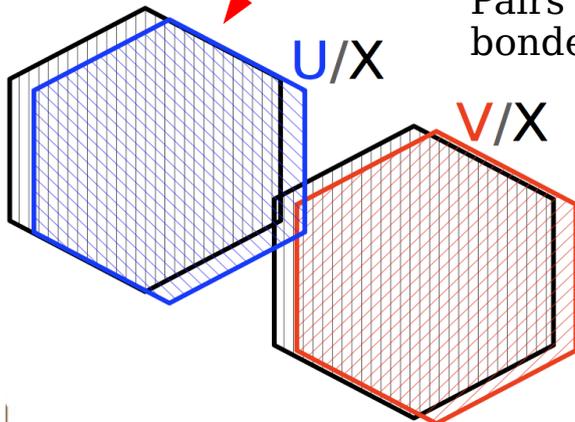
Modules stacked
to form fully
active tracker.

Surrounded by
electromagnetic
and hadronic
calorimeters.



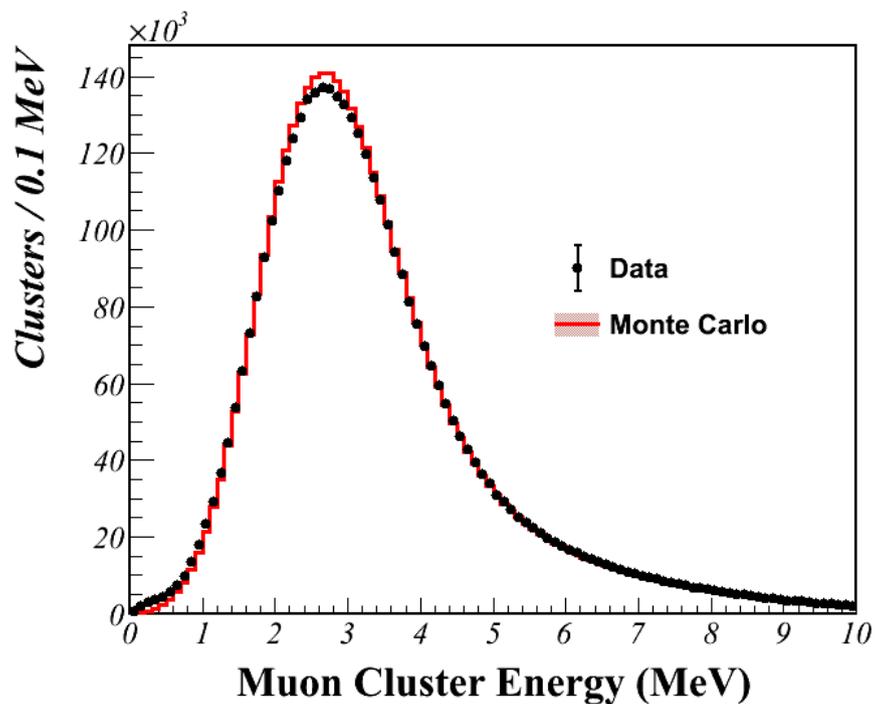
Strips arrange into planes.

Pairs of U/X and V/X planes
bonded to form modules

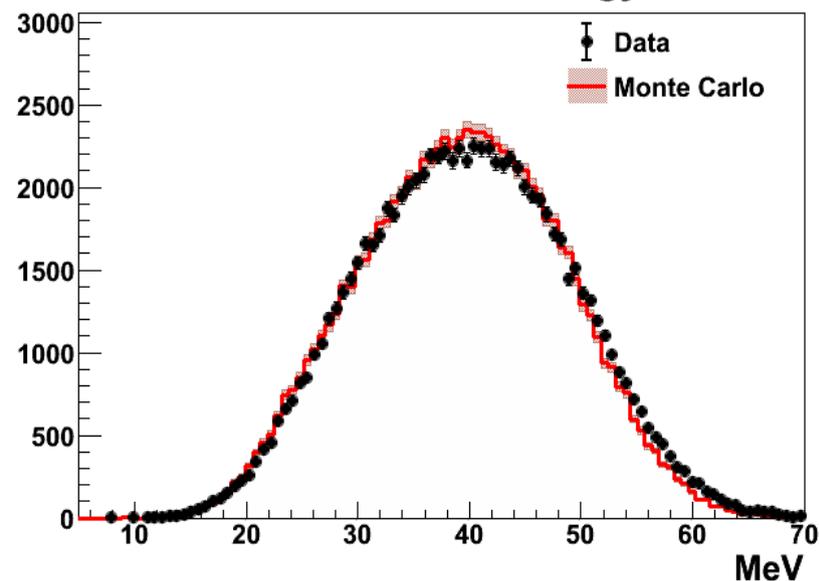




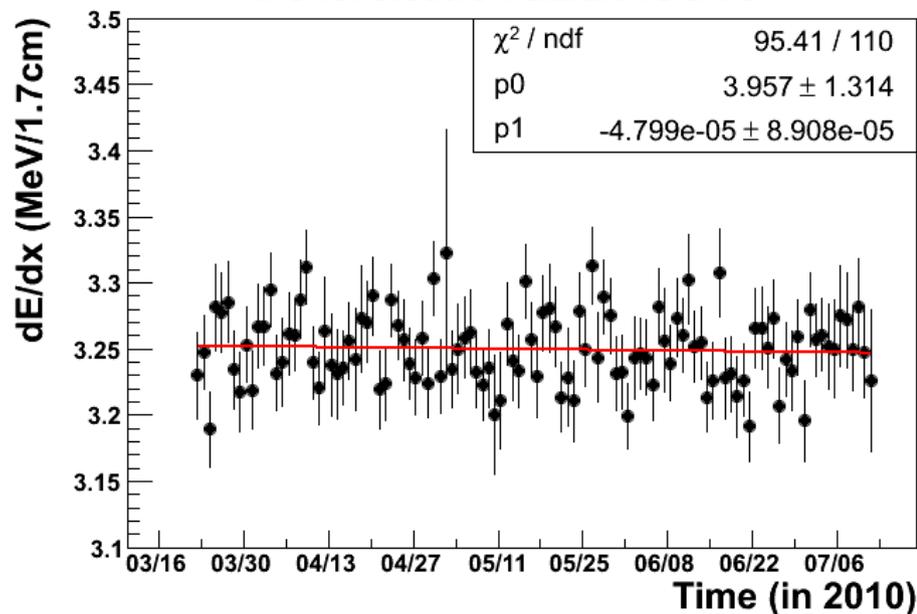
Energy scale and stability



Michel electron energy



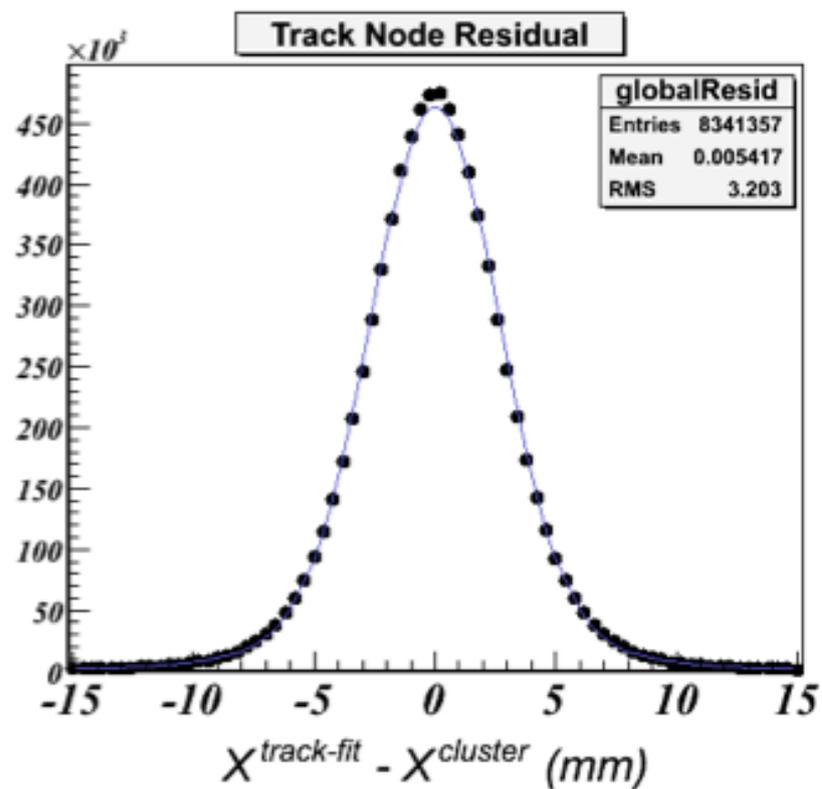
Michel electron dE/dx vs time

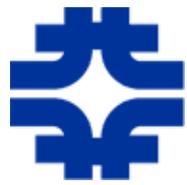




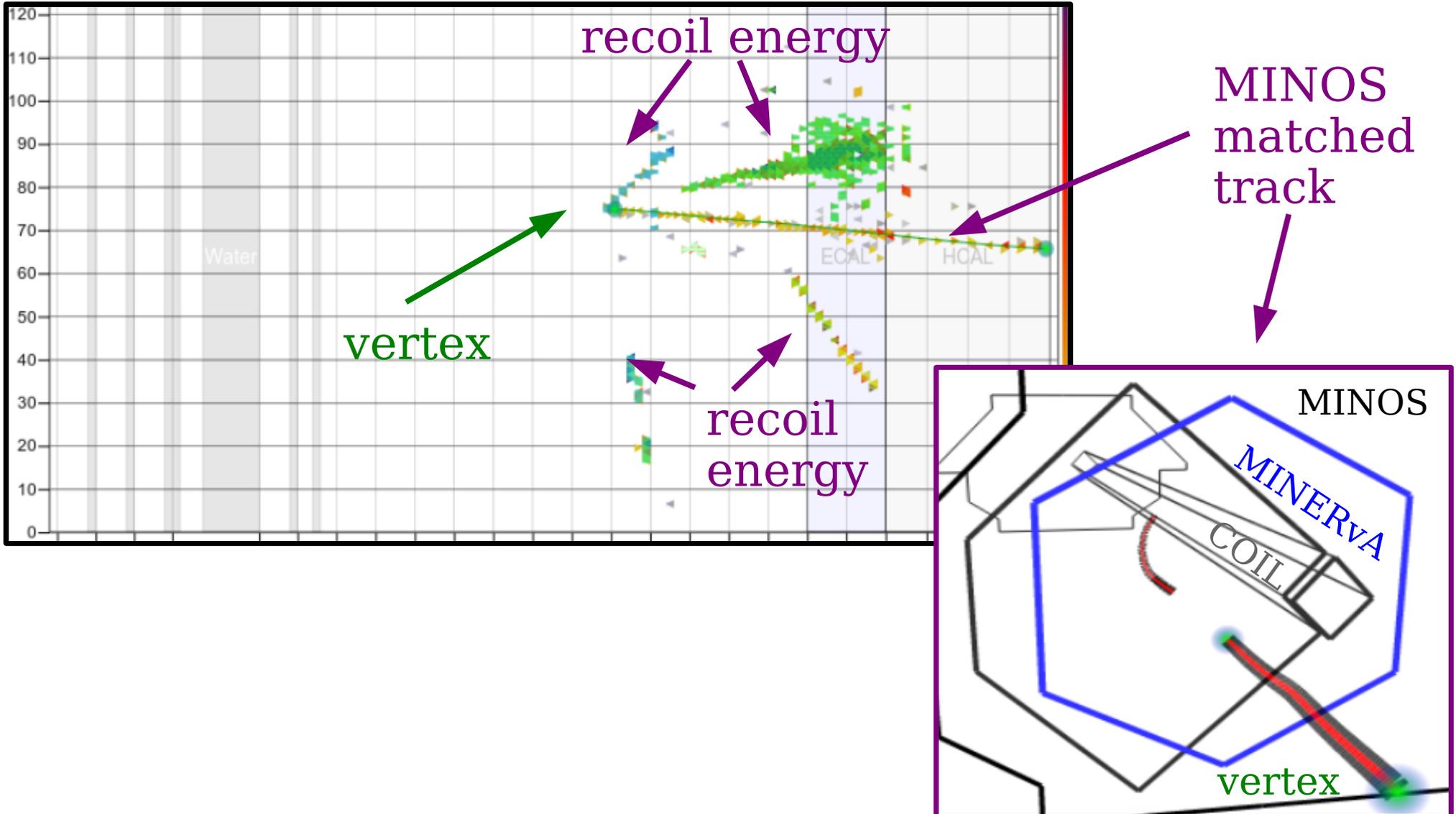
Track resolution

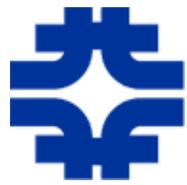
- Hit resolution = 3 mm





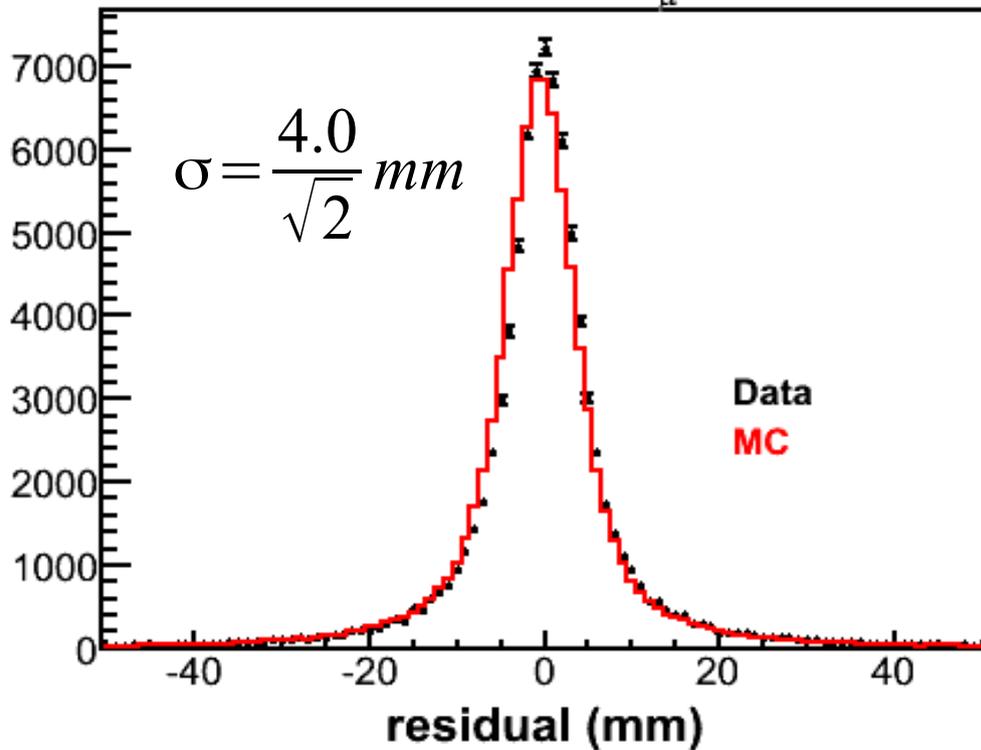
Reconstructed objects



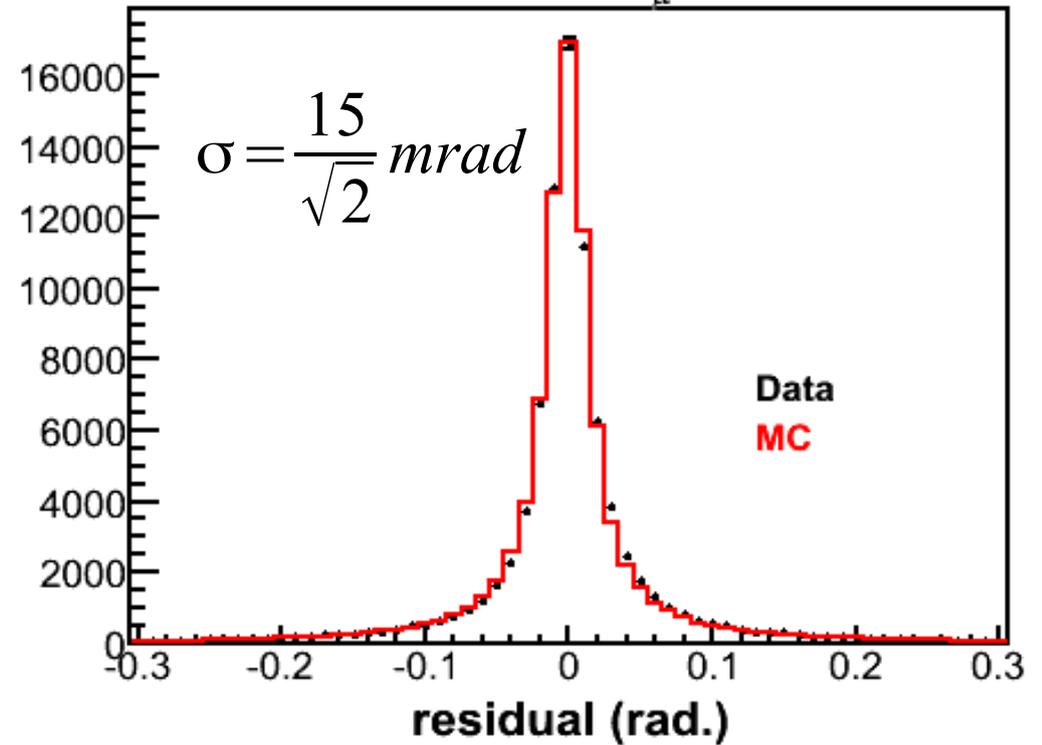


Reconstructed vertex resolution

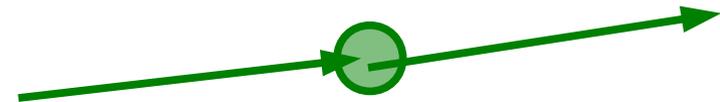
Vertex Y Residual, $p_{\mu} \leq 20 \text{ GeV}/c$



dY/dZ Residual, $p_{\mu} \leq 20 \text{ GeV}/c$

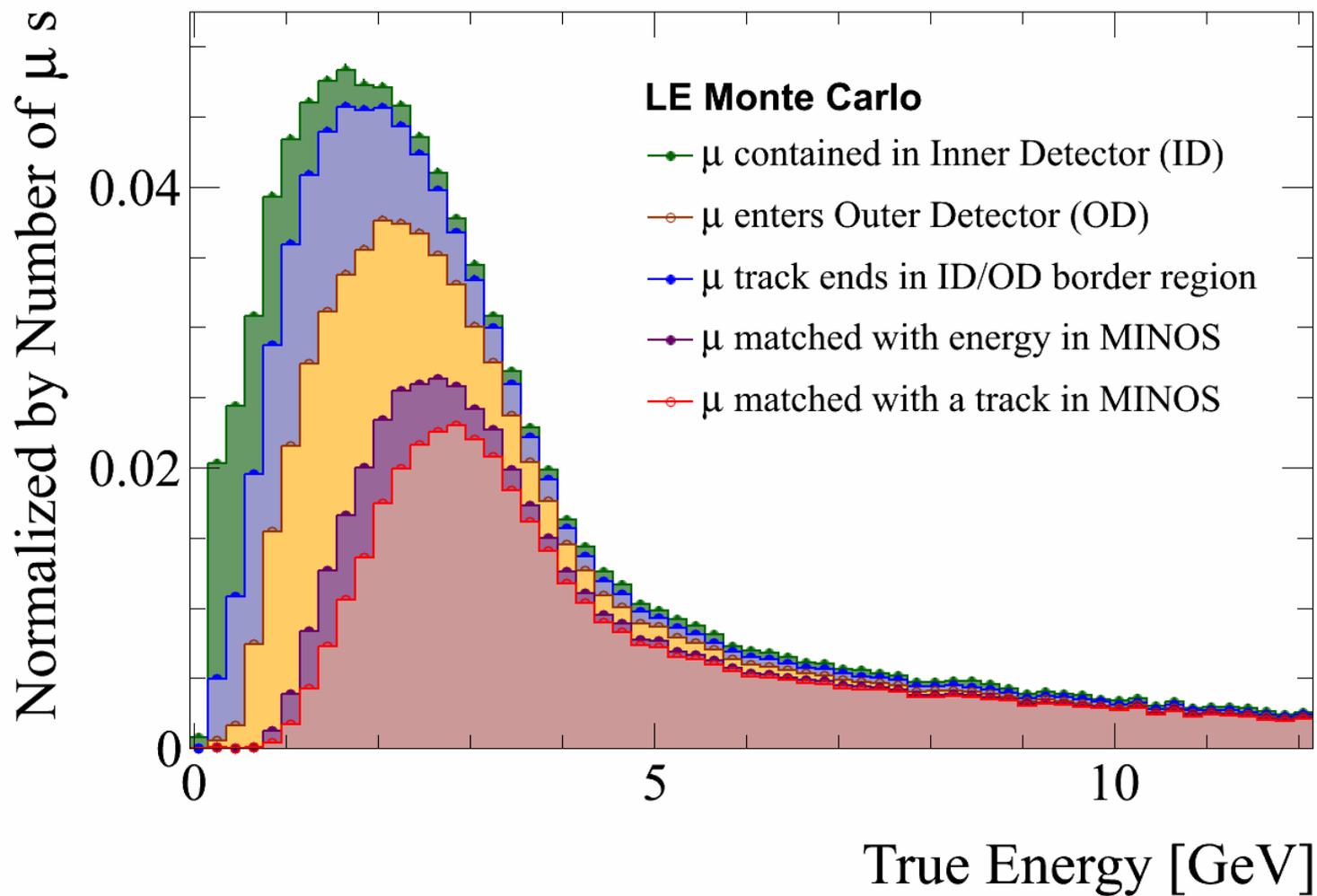


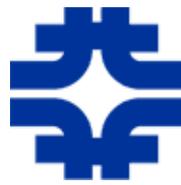
Based on split-track studies of muons produced in rock upstream of MINERvA



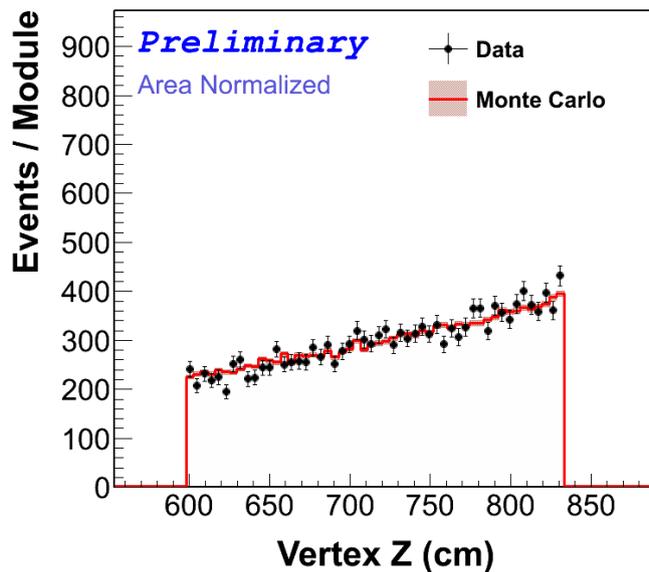
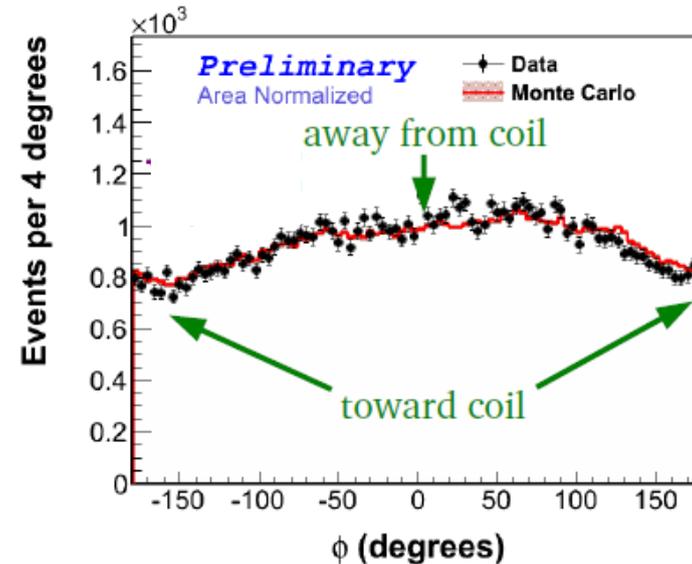
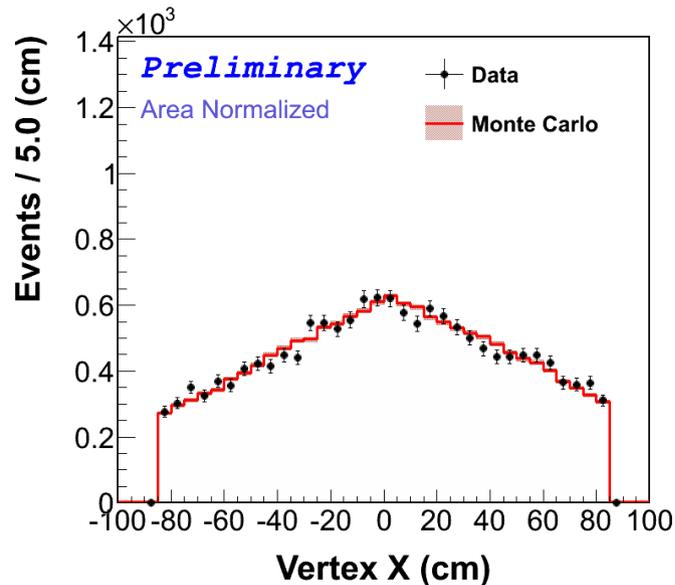


Where do muons go?

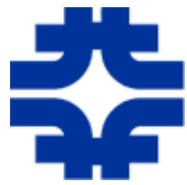




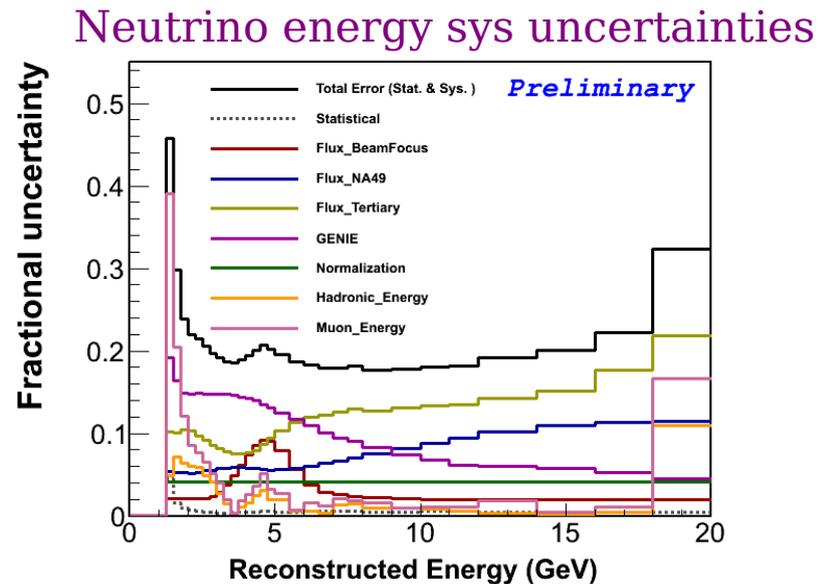
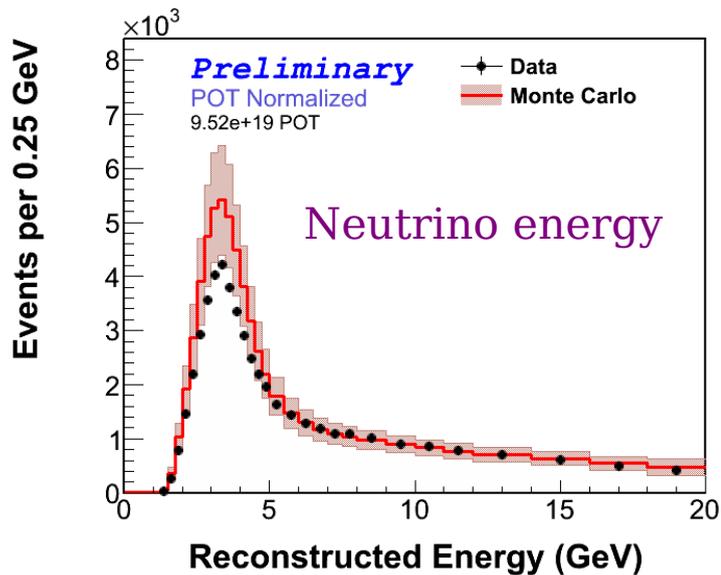
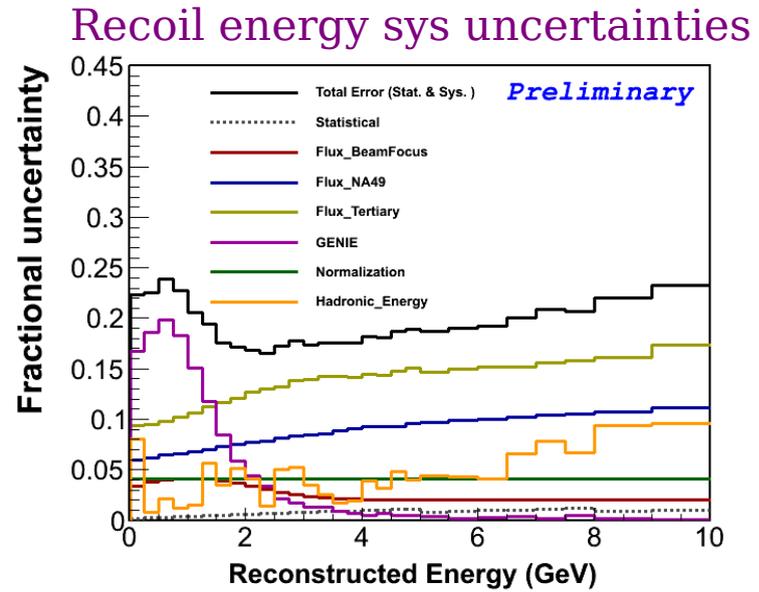
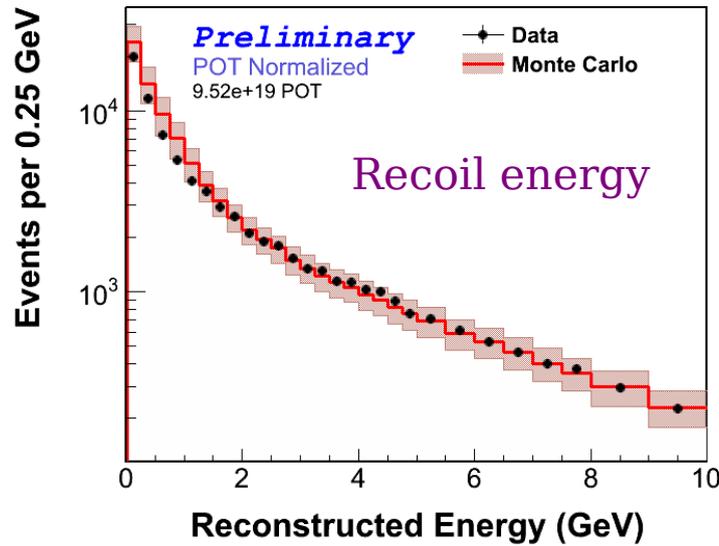
MINOS-matching affects acceptance

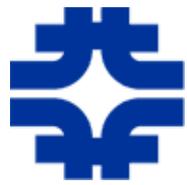


- ◆ Energy threshold ~ 2 GeV
- ◆ Good angular acceptance up to scattering angles of about 10 degrees, with limit of about 20 degrees
- ◆ Bias is complex, but well understood

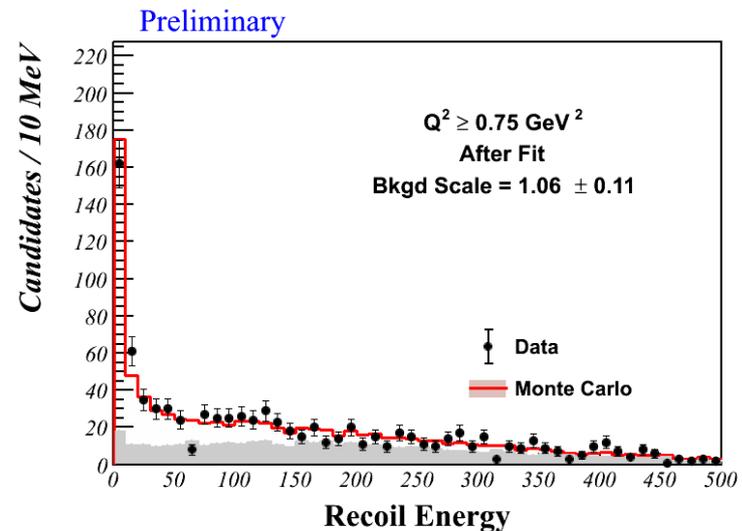
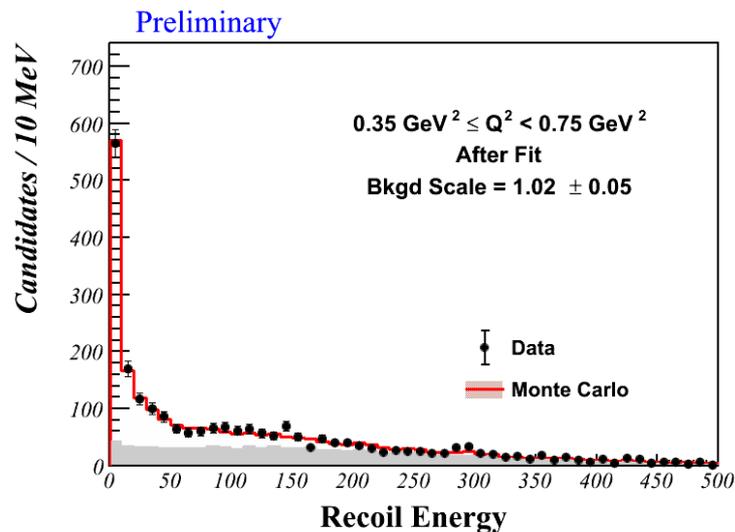
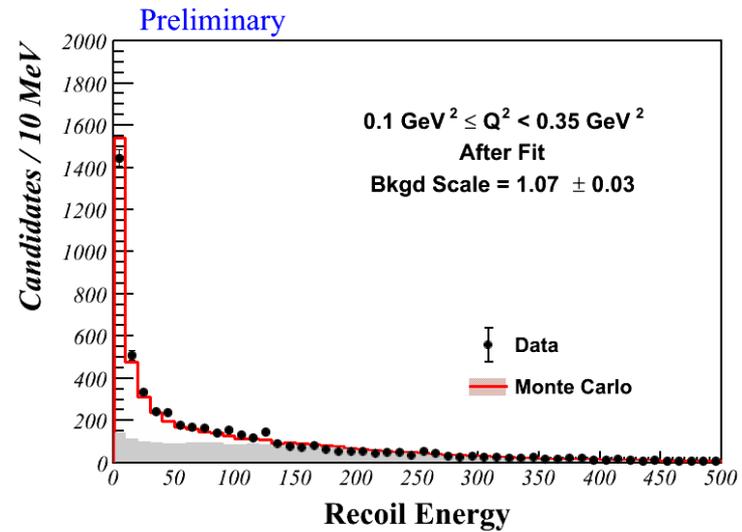
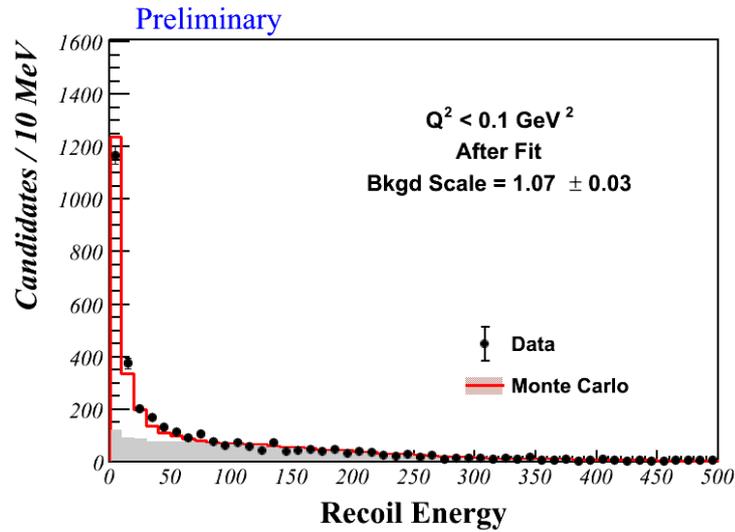


Neutrino CC inclusive kinematic distributions



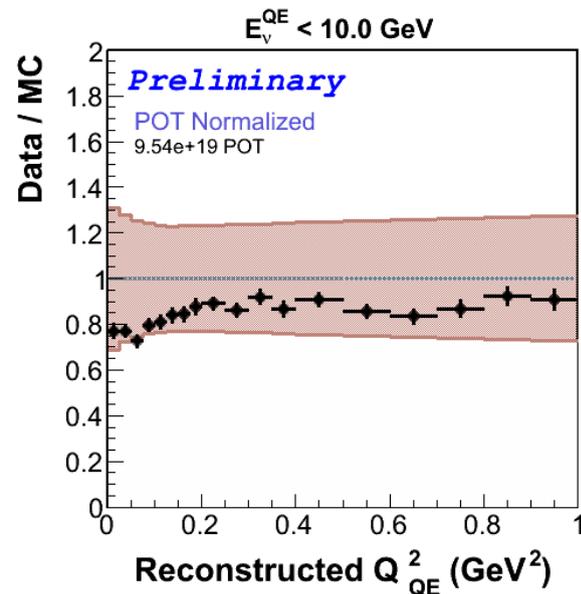
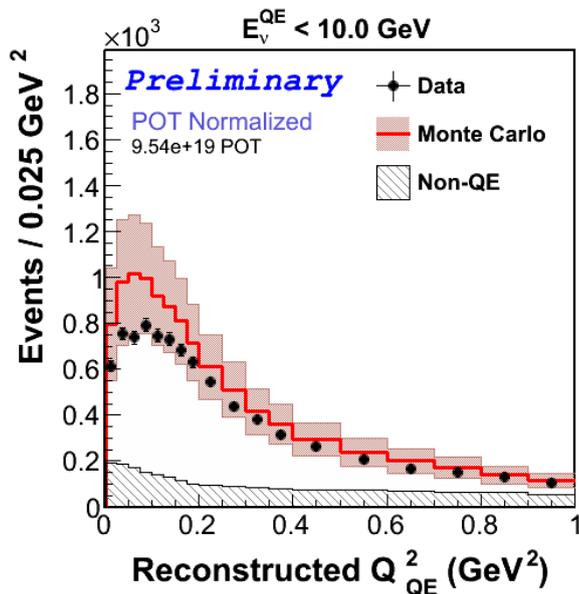
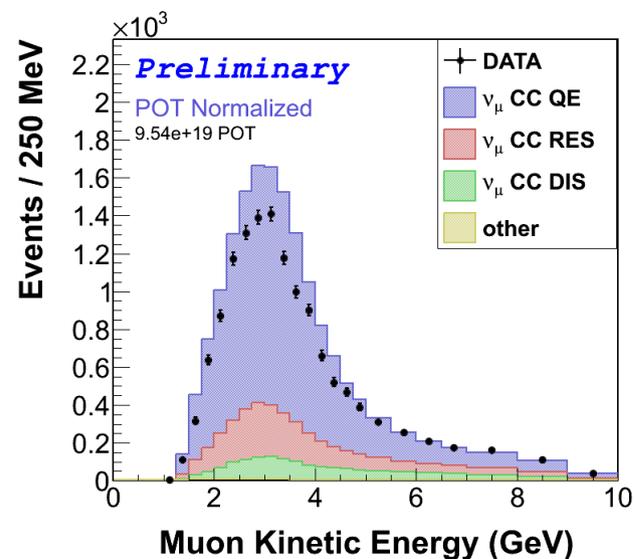


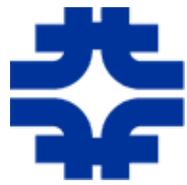
$\bar{\nu}$ CCQE: Recoil energy distribution fits for BG determination



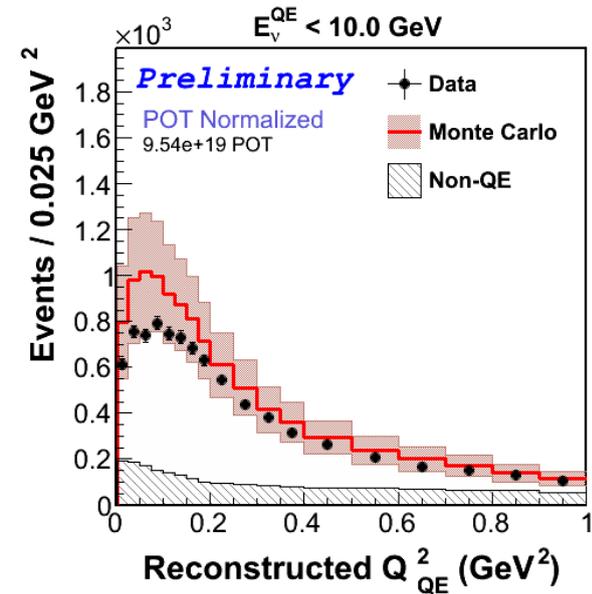
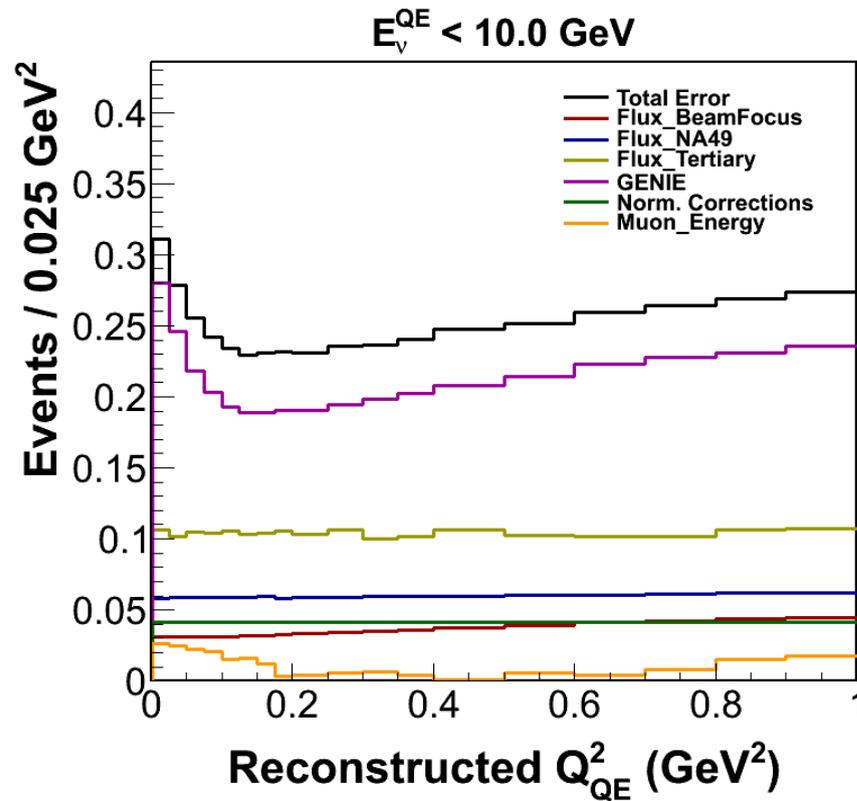


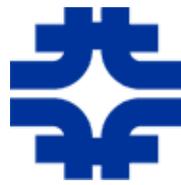
Neutrino CCQE kinematic distributions





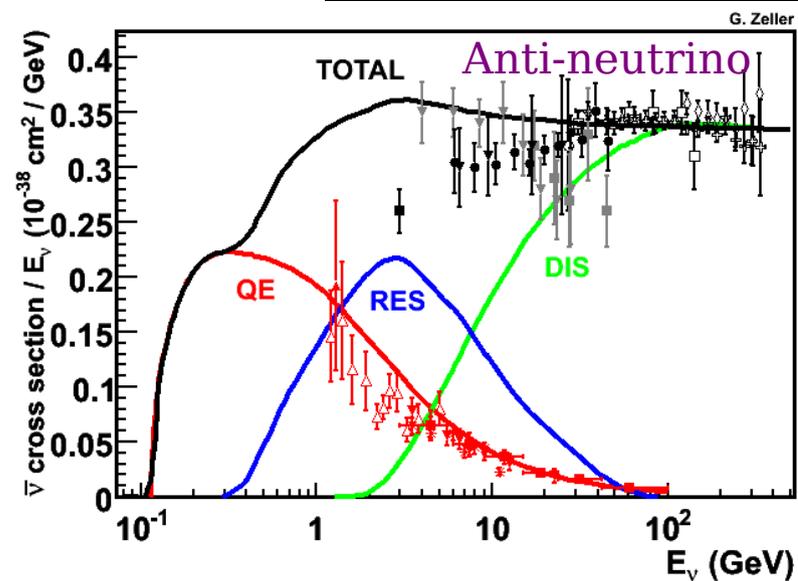
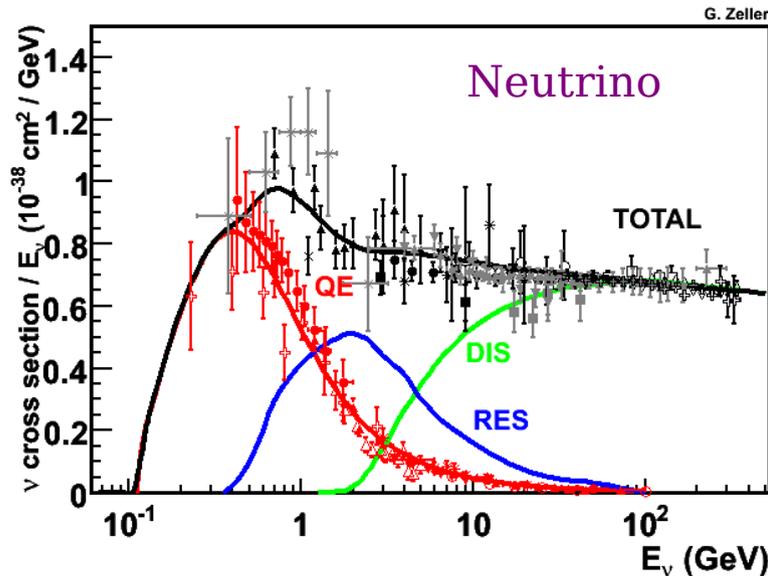
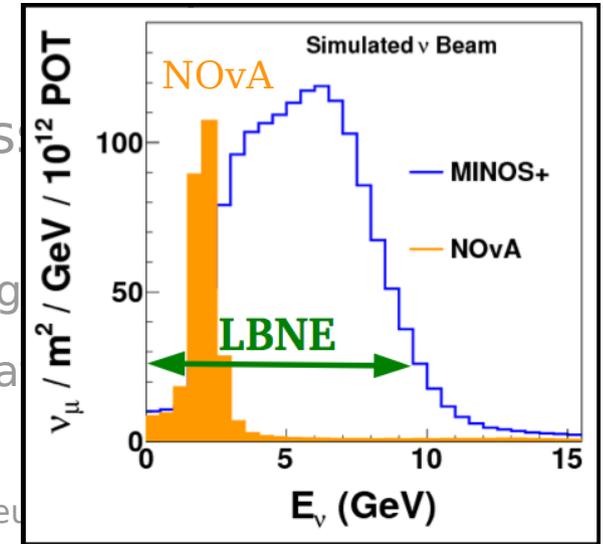
Neutrino CCQE Q^2 uncertainties





Introduction

- Neutrino-nucleus, anti-neutrino-nucleus cross sections are important for oscillation experiments
 - ◆ Cross sections not well measured in 1 - 10 GeV range
 - ◆ Quasi-elastic interactions a signal channel for oscillation experiments
 - ▶ Nuclear effects not well understood in QE interactions
 - ▷ Can alter details of 2-body kinematics often used to infer neutrino mass



J.A. Formaggio and G.P. Zeller, "From eV to EeV: Neutrino Cross Sections Across Energy Scales", to be published in Rev. Mod. Phys., 2012.