# MINERvA
# Using Neutrinos to Study Nucleon Structure


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**Rutgers**, The State University of New Jersey

5th Workshop of the APS Topical Group on Hadronic Physics

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# Outline

- Why measure neutrino cross sections?
  - Support for oscillations
  - Nuclear physics
- Meet MINERvA
  - **M**ain **IN**jector **E**xpe**R**iment **v-A** (neutrino-nucleus)
  - The NuMI beam
  - The MINERvA Detector
- Preliminary Analyses
  - $\nu_\mu$ inclusive charged current scattering
  - $\nu_\mu$ charged current quasi-elastic scattering

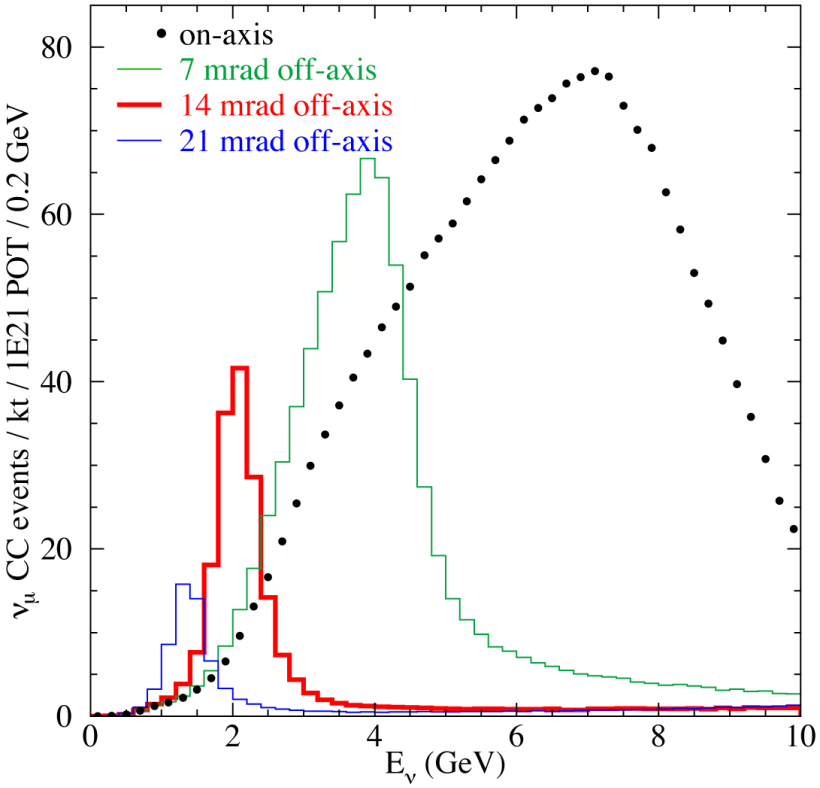
# Neutrino Oscillations

- Count $\nu_\mu$ interactions at two detectors, distance L apart.
- Fewer seen at far detector means $\nu_\mu$ oscillated to $\nu_\tau$.
- Rate of oscillation determined by intrinsic neutrino properties.

$$P(\nu_\mu \rightarrow \nu_\tau) = sin^2(2\theta_{23})sin^2\left(\frac{1.27\Delta m_{32}L}{E_\nu}\right)$$

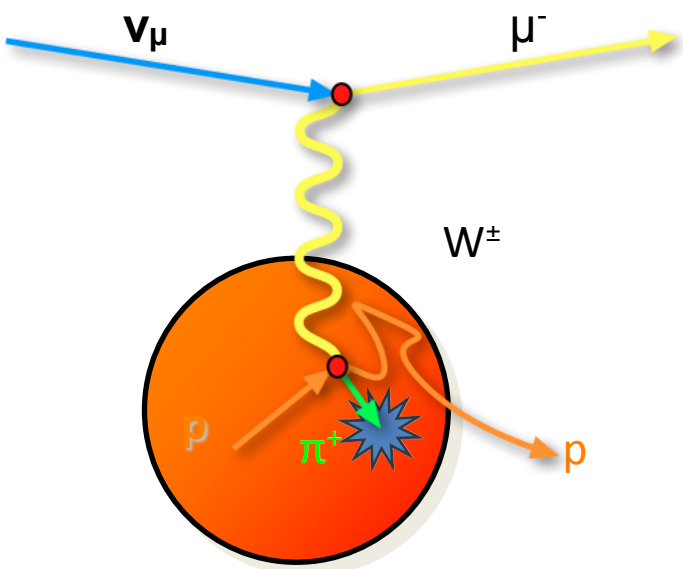
- Neutrino energy must be well reconstructed.

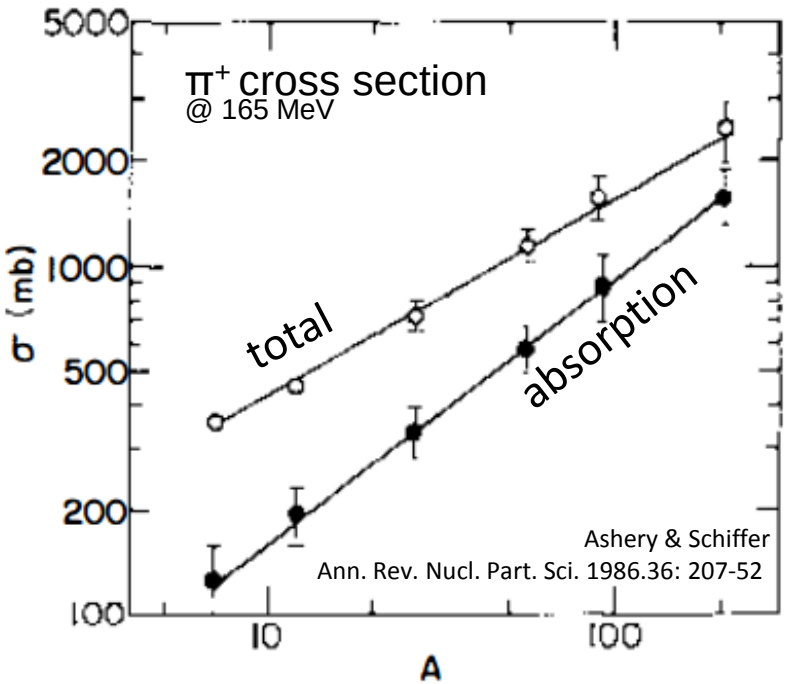
Predicted Neutrino Energy Distribution



# Reconstruction Problems
## Pion Absorption

- Pions can be absorbed in interaction nucleus.
- Cherenkov detectors reconstruct mu, e rings only.
  - Pion decay not seen if absorbed. Event is misidentified.
- Calorimetric detectors reconstruct mu + recoil.
  - Pion energy not seen by detector.



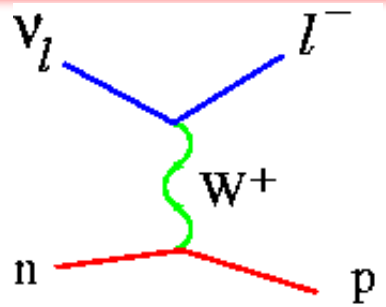
# Cross sections are significant sources of uncertainty on $\nu_\mu$-disappearance

Systematic uncertainties on T2K $\nu_\mu$-disappearance analysis.

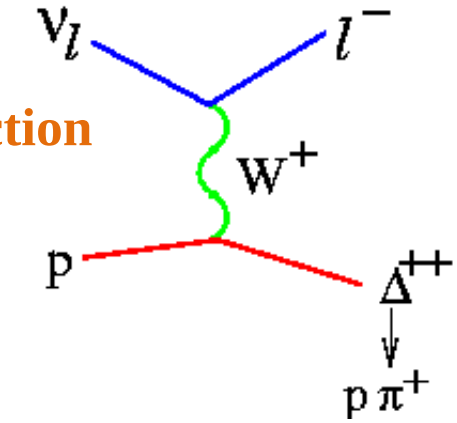
TABLE II. Systematic uncertainties on the predicted number of SK selected events without oscillations and for oscillations with $\sin^2(2\theta_{23}) = 1.0$ and $|\Delta m^2_{32}| = 2.4 \times 10^{-3}$ eV$^2$.

| Source | $\delta N^{exp}_{SK}/N^{exp}_{SK}$ (%, no osc) | $\delta N^{exp}_{SK}/N^{exp}_{SK}$ (%, with osc) |
|---|---|---|
| SK CCQE efficiency | ±3.4 | ±3.4 |
| SK CC non-QE efficiency | ±3.3 | ±6.5 |
| SK NC efficiency | ±2.0 | ±7.2 |
| ND280 efficiency | +5.5 -5.3 | +5.5 -5.3 |
| ND280 event rate | ±2.6 | ±2.6 |
| Flux normalization (SK/ND280) | ±7.3 | ±4.8 |
| CCQE cross section | ±4.1 | ±2.5 |
| CC1π/CCQE cross section | +2.2 -1.9 | +0.4 -0.5 |
| Other CC/CCQE cross section | +5.3 -4.7 | +4.1 -3.6 |
| NC/CCQE cross section | ±0.8 | ±0.9 |
| Final-state interactions | ±3.2 | ±5.9 |
| Total | +13.3 -13.0 | +15.0 -14.8 |

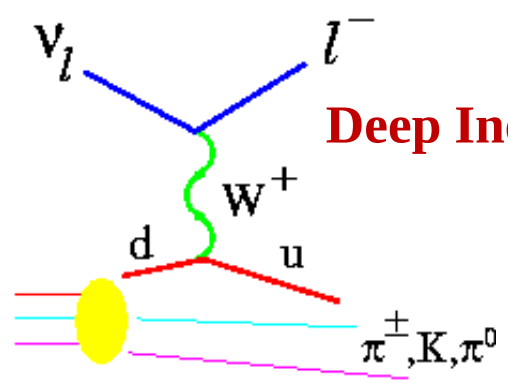
arXiv:1201.1386 [hep-ex]




**Quasi-Elastic (CCQE)**




**Resonance Production (CC1π)**




**Deep Inelastic Scattering (DIS)**

# Nucleon Axial Vector Form Factor

- Modeled as dipole.

$$F_A(Q^2) = \frac{g_A}{\left(1 + Q^2/M_A^2\right)^2}$$

$$g_A = 1.2694 \pm 0.0028$$

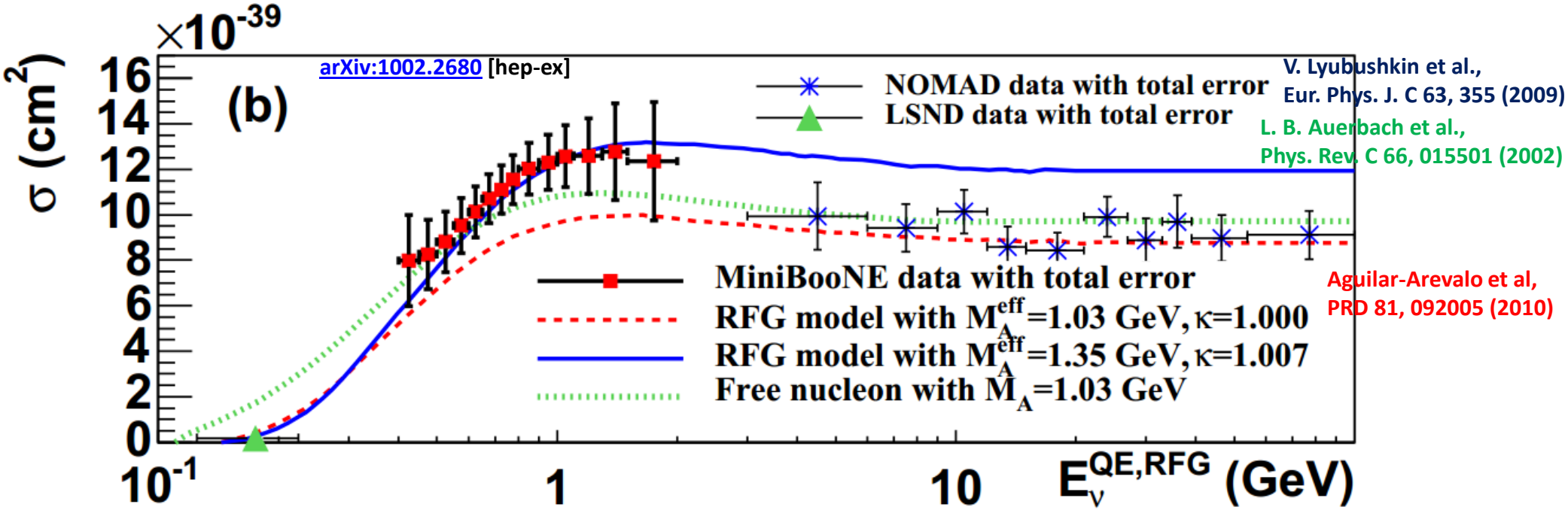
Nakamura, K., et al., 2010, J. Phys. G 37, 075021

Precisely measured from nuclear beta decay.

  - $M_A$ is "axial mass".
- Leading contribution to neutrino quasi-elastic cross section.
- Only poorly measured piece of neutrino quasi-elastic scattering cross section.
  - Poorly measured compared to electromagnetic form factors.

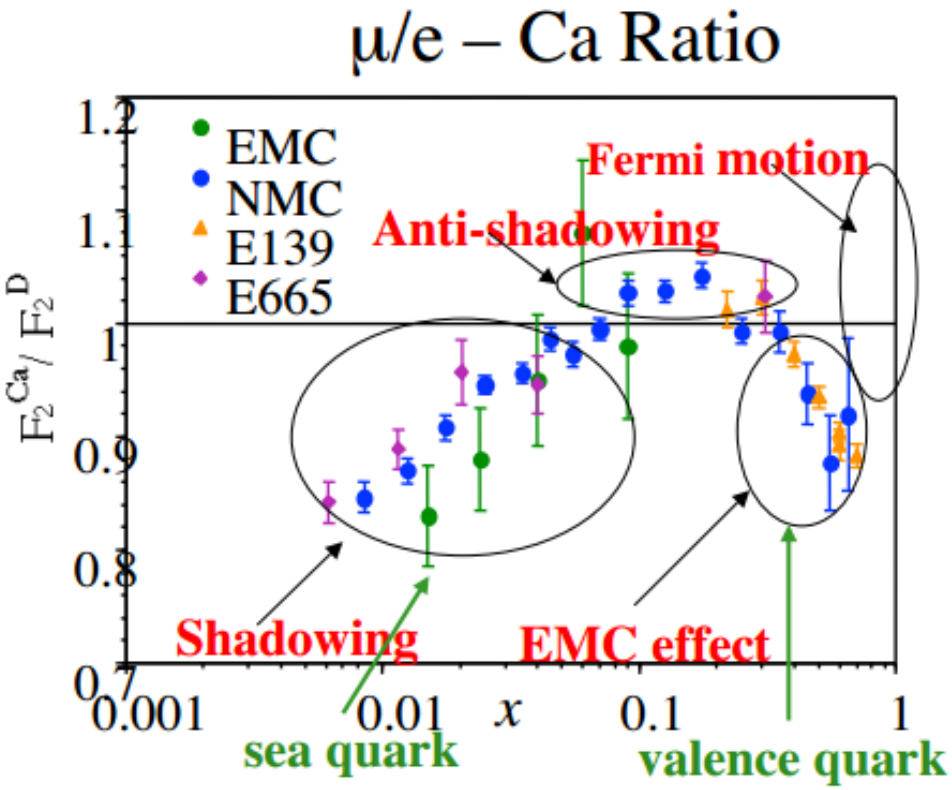
# Quasi-Elastic Cross Section

- Quasi-elastic scattering is frequently used as signal for oscillation searches because of simple topology.
- Tension in cross section measurements may indicate problems with quasi-elastic model.



# Probing Nucleon Structure

- Charged lepton data show $F_2$ deformed when nucleon is bound in a nucleus.
- A-dependence has not been measured in neutrino scattering directly. May differ. Owens et al., PhysRevD.75.054030

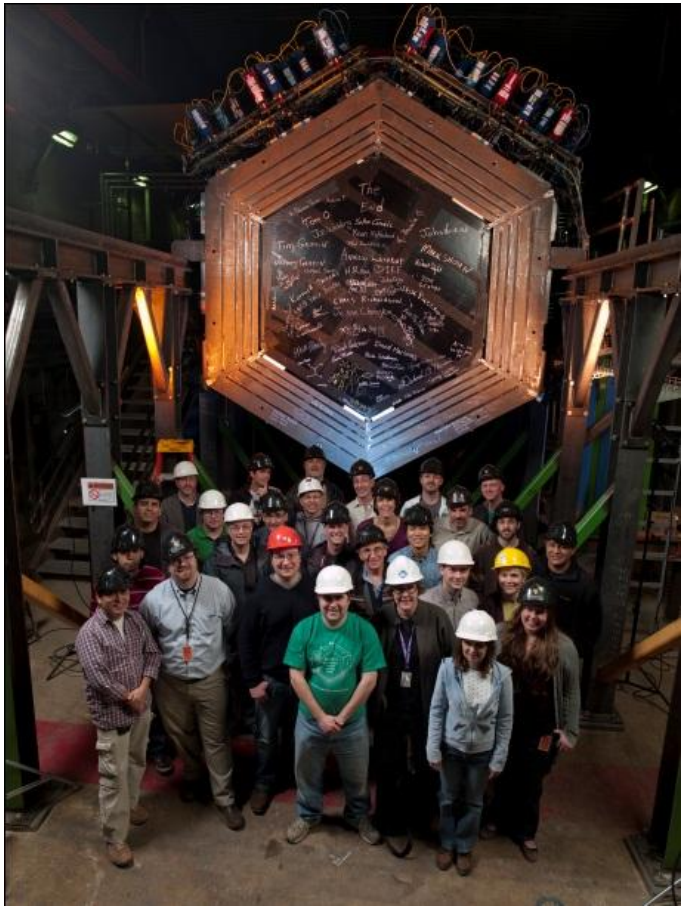



$F_2$ is a structure function, a parameterization for the structure of the proton.

$$\frac{d^2\sigma^\nu}{dx dQ^2} = \frac{G_F^2}{2\pi x}\Big[\frac{1}{2}\left(F_2^\nu(x,Q^2) + xF_3^\nu(x,Q^2)\right) + \frac{(1-y)^2}{2}\left(F_2^\nu(x,Q^2) - xF_3^\nu(x,Q^2)\right) - 2y^2 F_L^\nu x, Q^2)\Big].$$

# MINERvA
# Main INjector ExpeRiment v-A

- MINERvA is a neutrino scattering experiment at Fermilab in Batavia, IL, USA.
- Collaboration of 80 nuclear and particle physicists.



University of Athens
University of Texas at Austin
Centro Brasileiro de Pesquisas Físicas
Fermilab
University of Florida
Université de Genève
Universidad de Guanajuato
Hampton University
Inst. Nucl. Reas. Moscow
Mass. Col. Lib. Arts
Northwestern University
Otterbein 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 Duluth
Universidad Nacional de Ingeniería
Universidad Técnica Federico Santa María
William and Mary

# NuMI Beamline

Delivers ~35x10$^{12}$ protons on target (POT) per spill at ~0.5 Hz, a beam power of 300-350 kW.

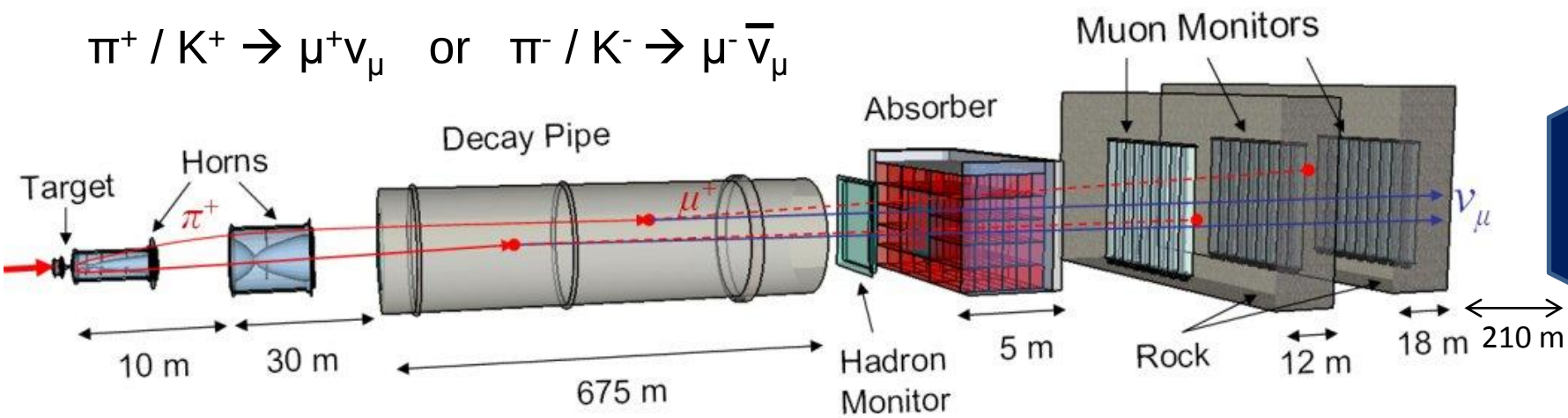
~7E9 neutrinos / m2 @ MINERvA

120 GeV proton → Carbon target

pC → $\pi^{\pm}$ and $K^{\pm}$

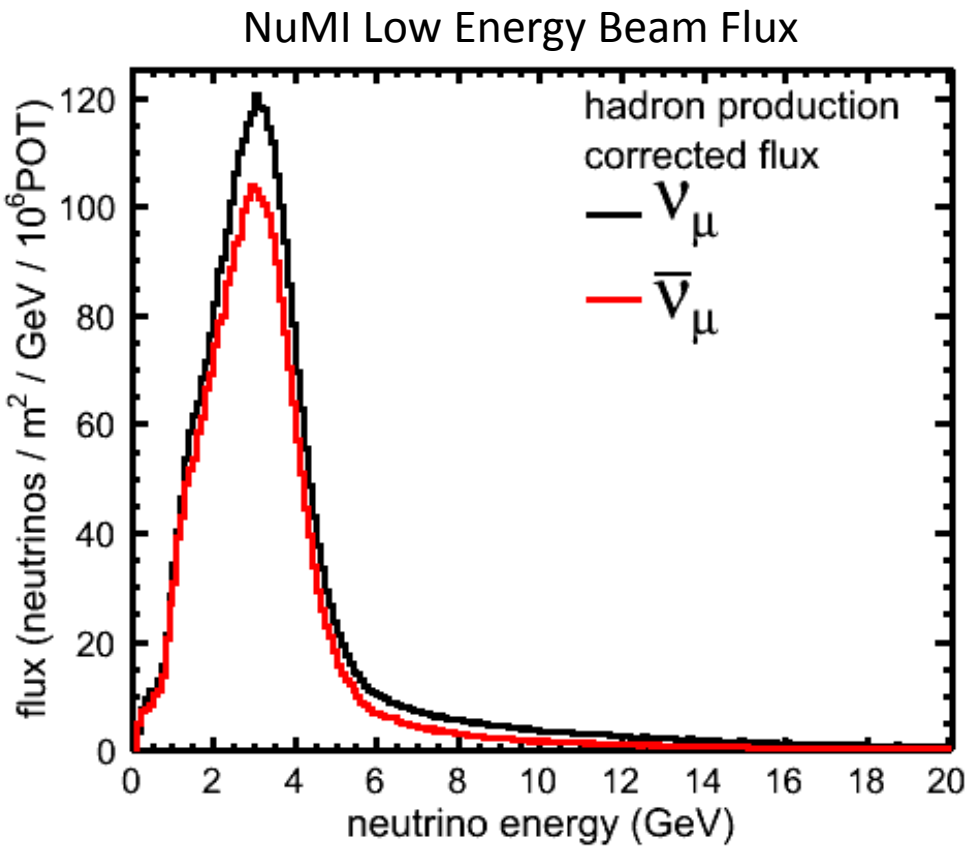
Magnetic horns focus + or -

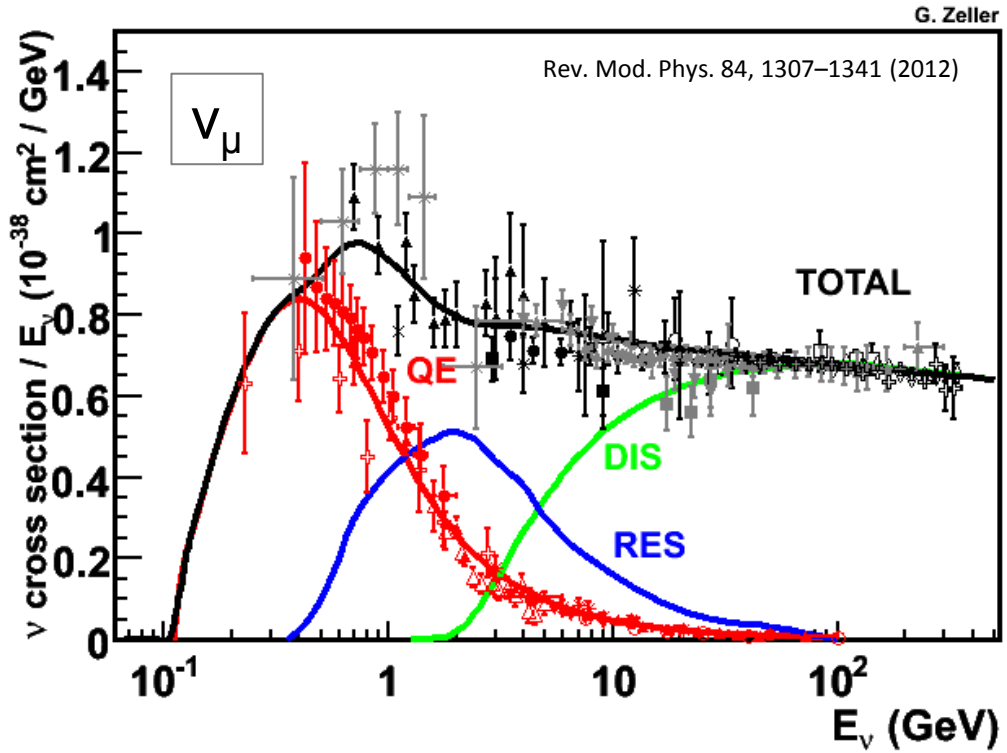
$\pi^+ / K^+ \rightarrow \mu^+ \nu_\mu$ or $\pi^- / K^- \rightarrow \mu^- \bar{\nu}_\mu$

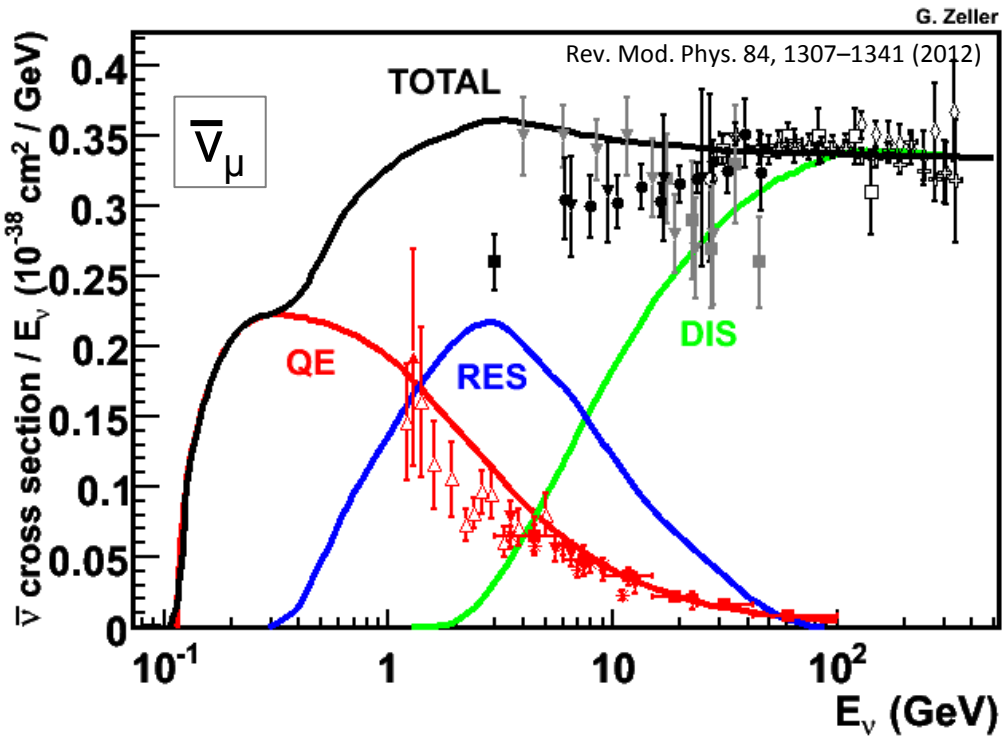



MINERvA

# Neutrinos Seen



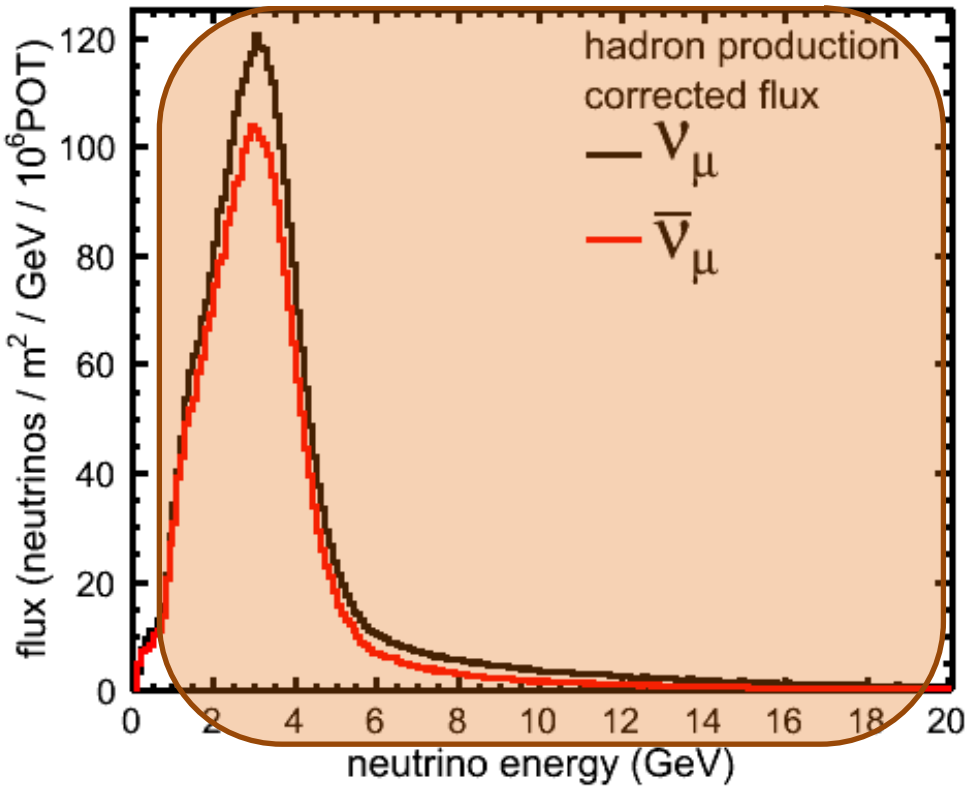

**Data collected:**

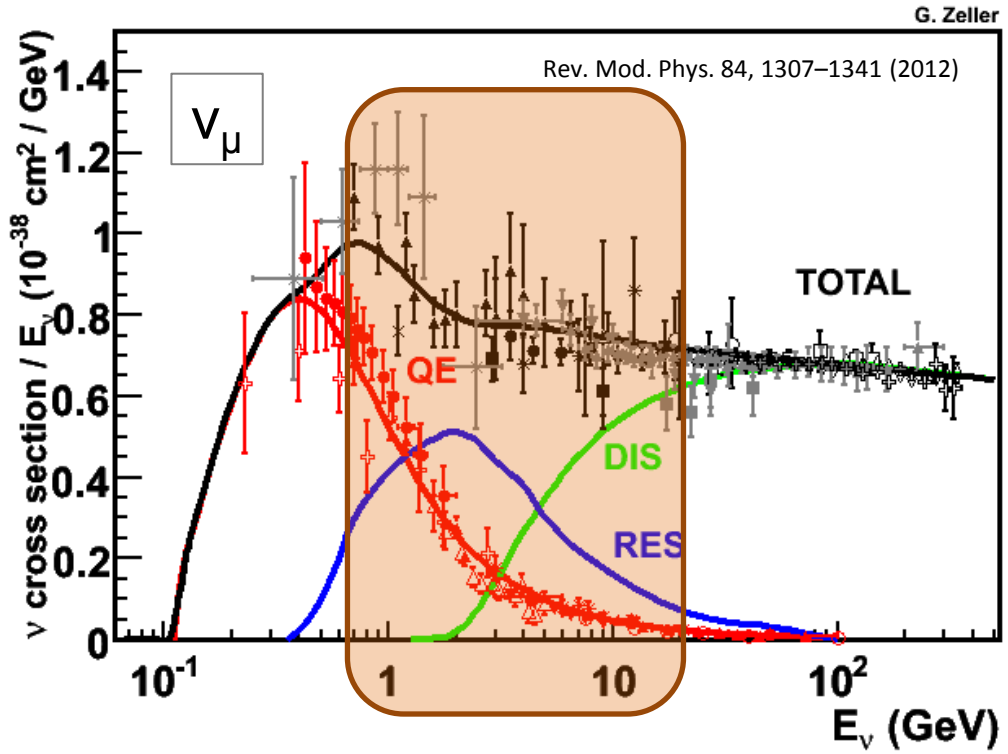
$\nu_\mu$ **LE** 4.0x10$^{20}$ POT

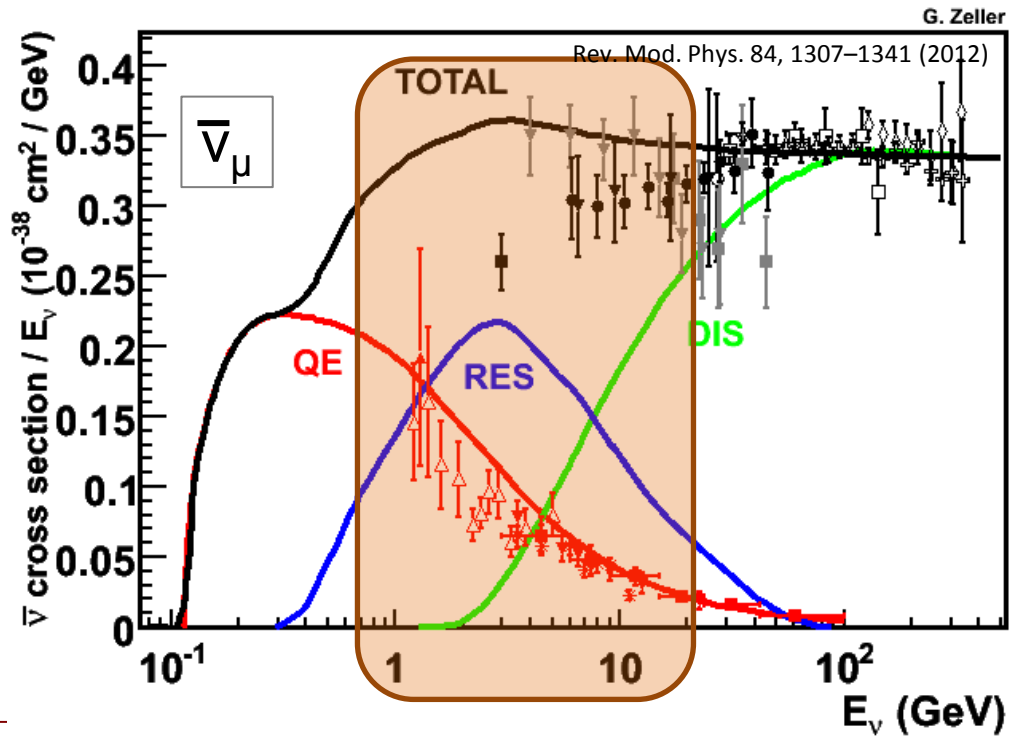
$\bar{\nu}_\mu$ **LE** 1.7x10$^{20}$ POT

# Neutrinos Seen

NuMI Low Energy Beam Flux



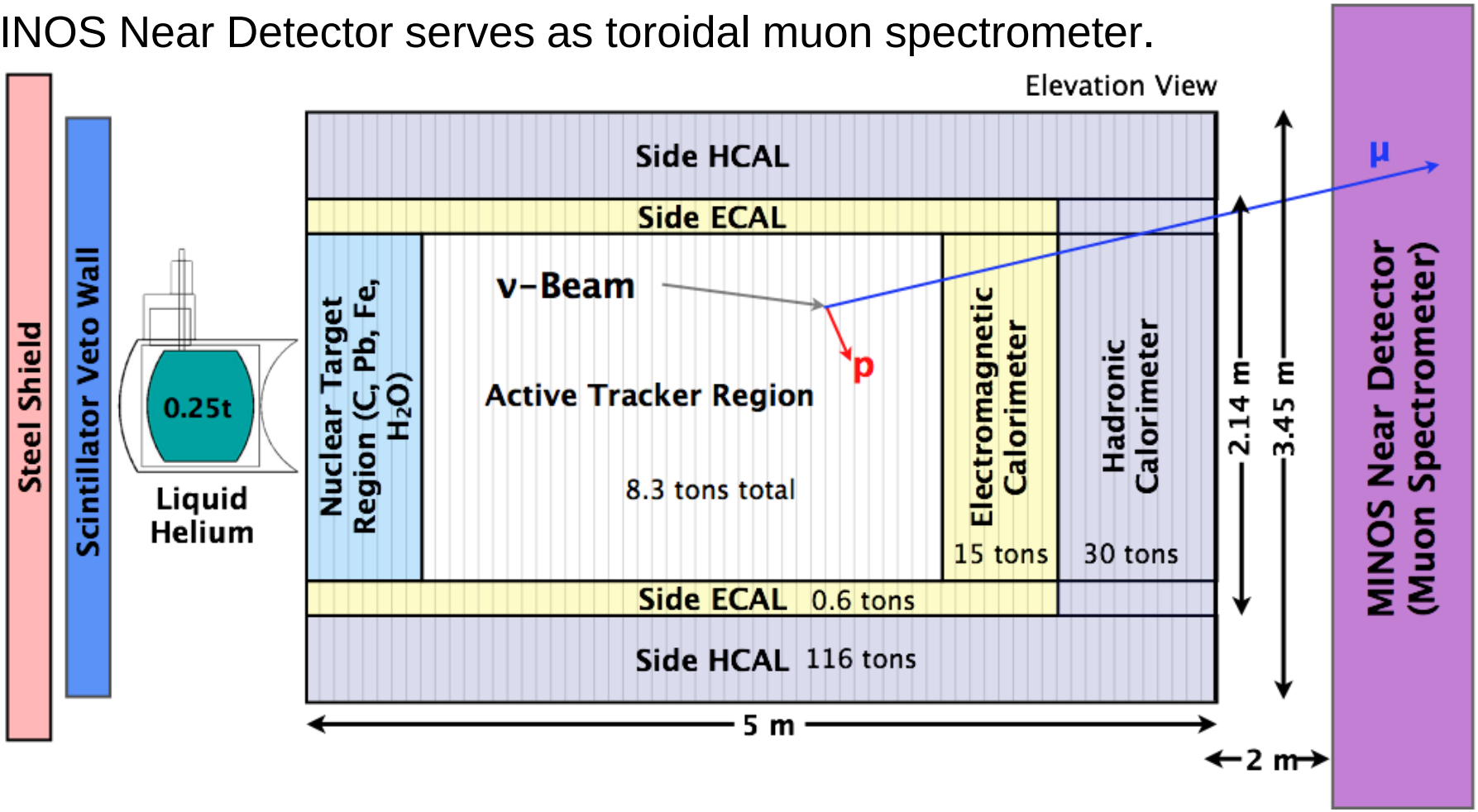

**Data collected:**

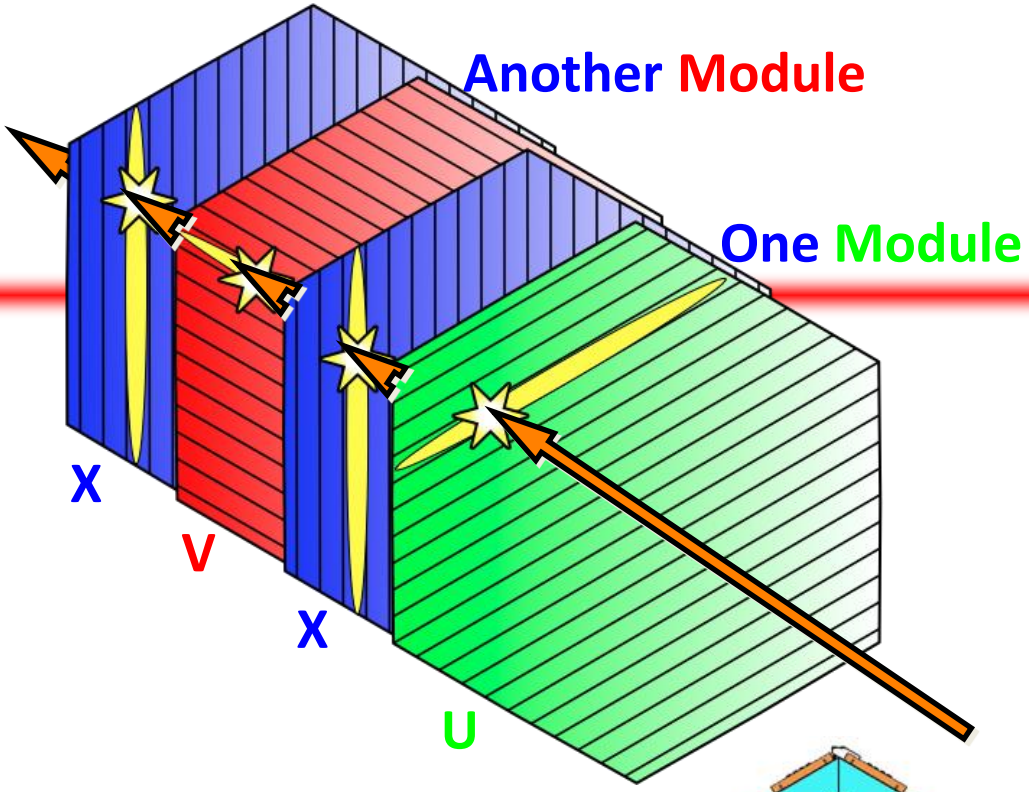
$\nu_\mu$ **LE** 4.0x10$^{20}$ POT

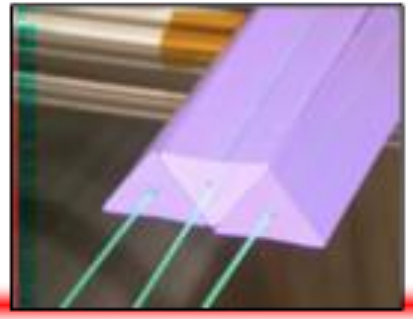
$\bar{\nu}_\mu$ **LE** 1.7x10$^{20}$ POT

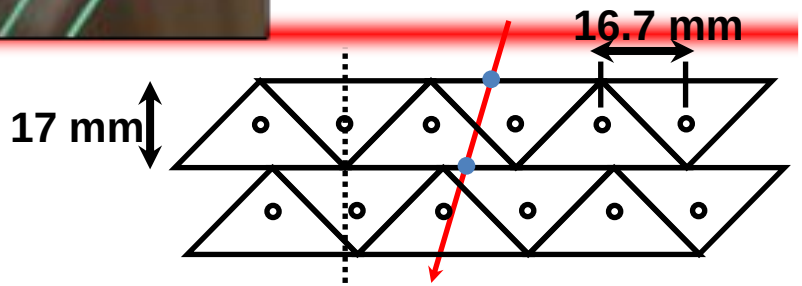
# MINERvA Detector

- 120 plastic scintillator modules for tracking and calorimetry (~32k readout channels).
- Construction completed Spring 2010. He and Water added in 2011.
- MINOS Near Detector serves as toroidal muon spectrometer.

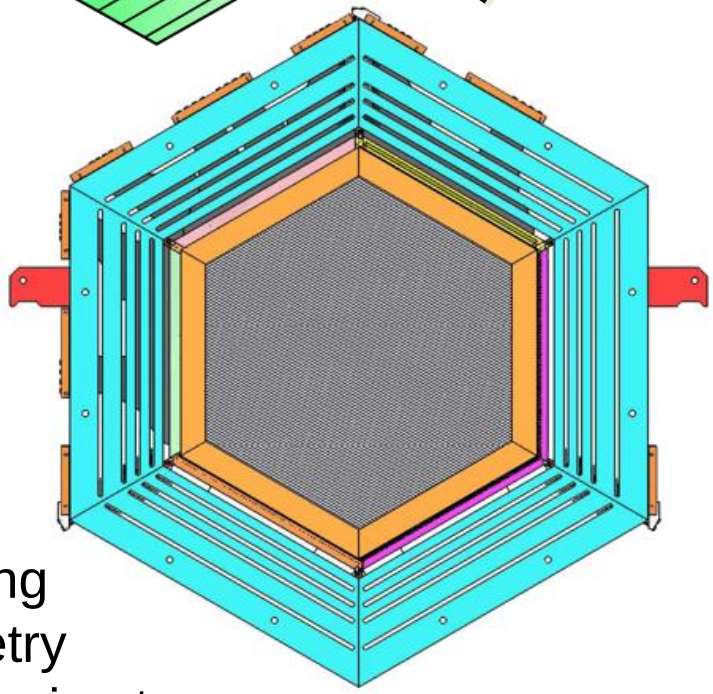


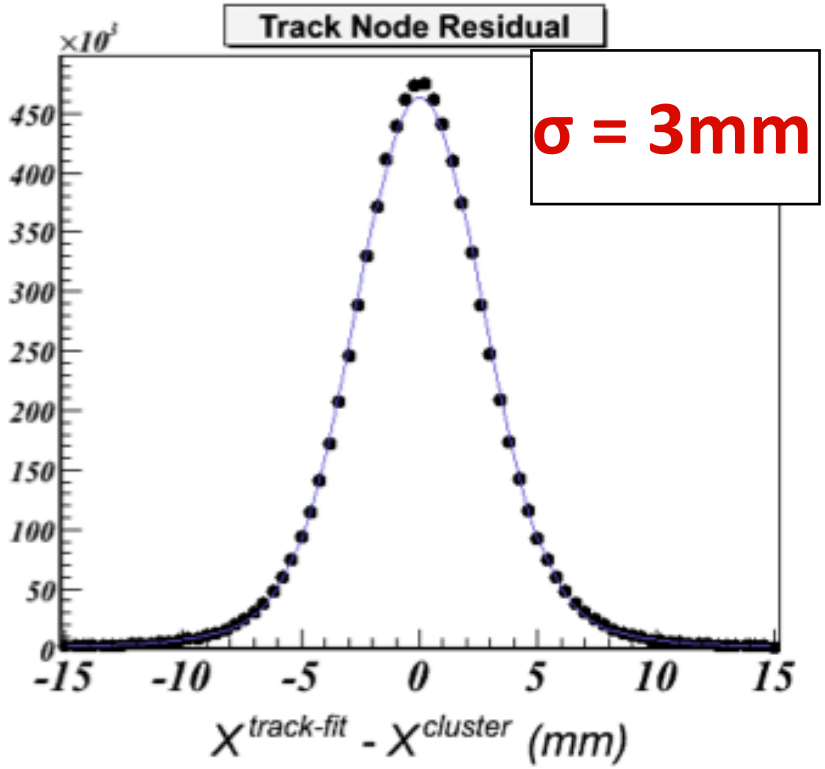





Charge sharing for improved position resolution (~3 mm) and alignment

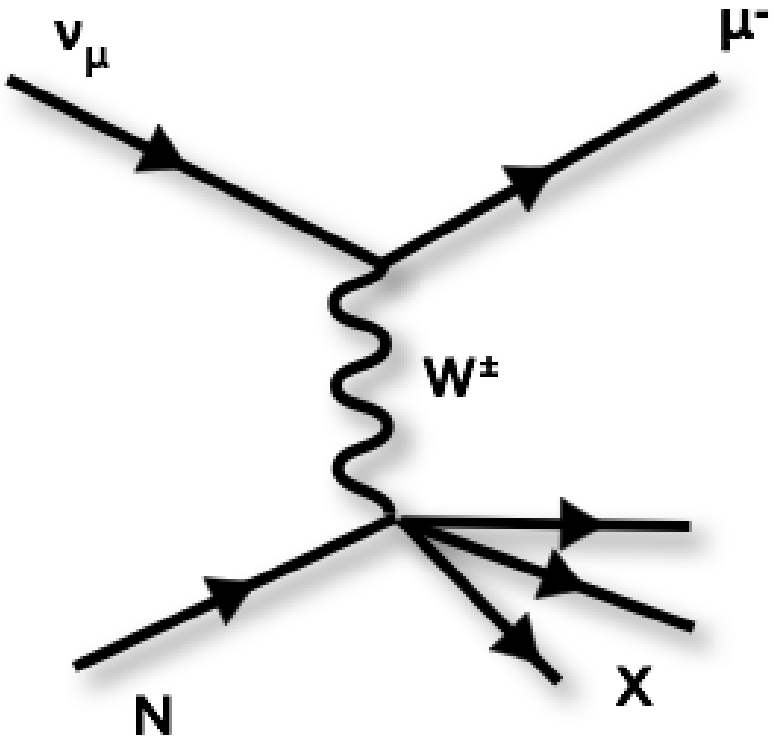




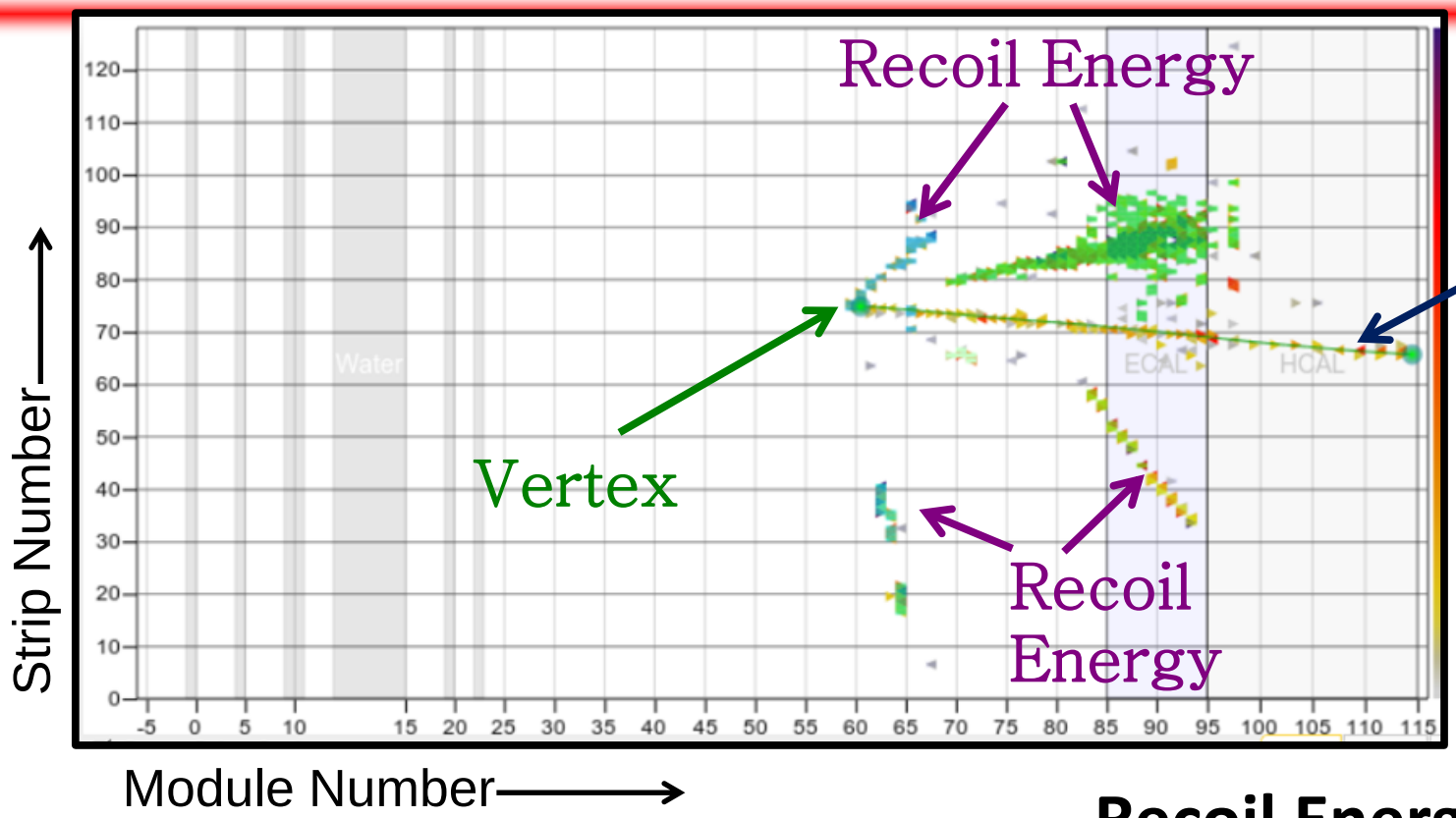

**Scintillator** - tracking
**Lead** - EM calorimetry
**Steel** - hadronic calorimetry

# Inclusive Charged Current Scattering

$CC\nu_\mu$



# Event Reconstruction




**Reconstructed objects**

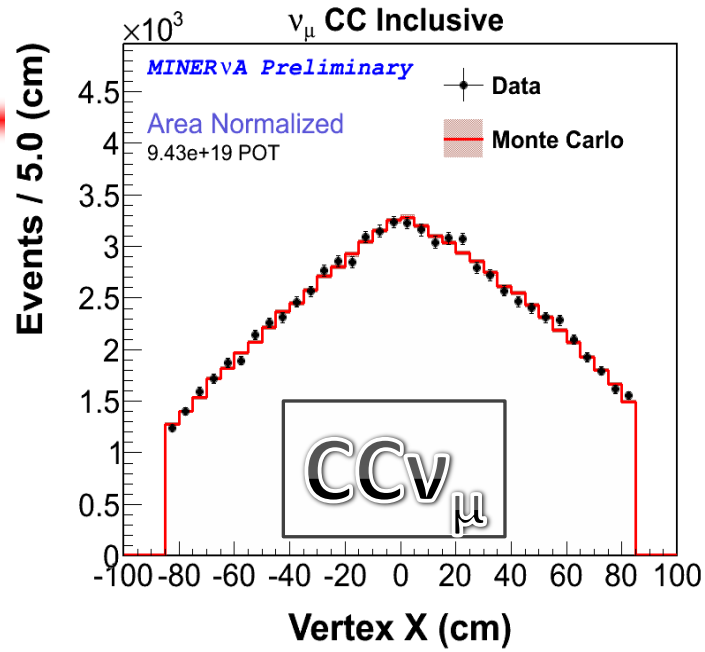
Tracks, vertices, hits

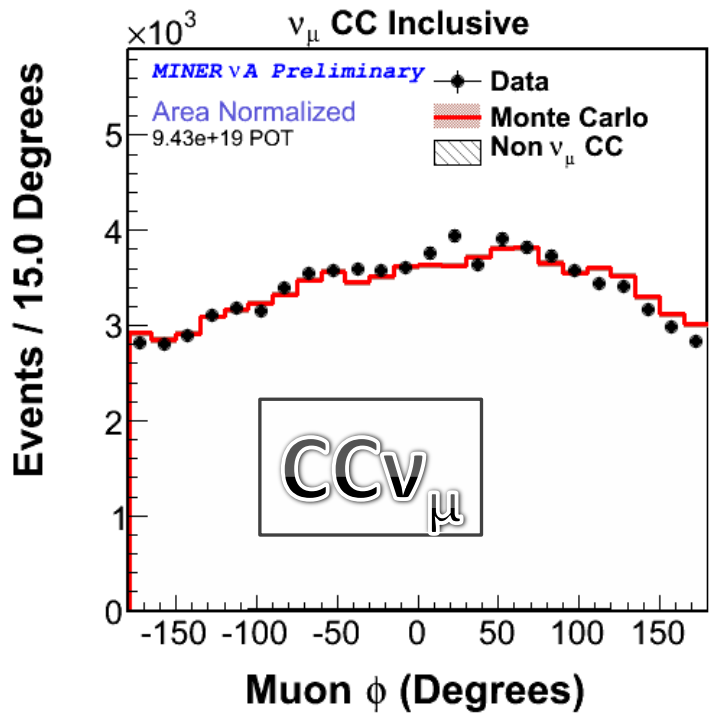
**Recoil Energy**

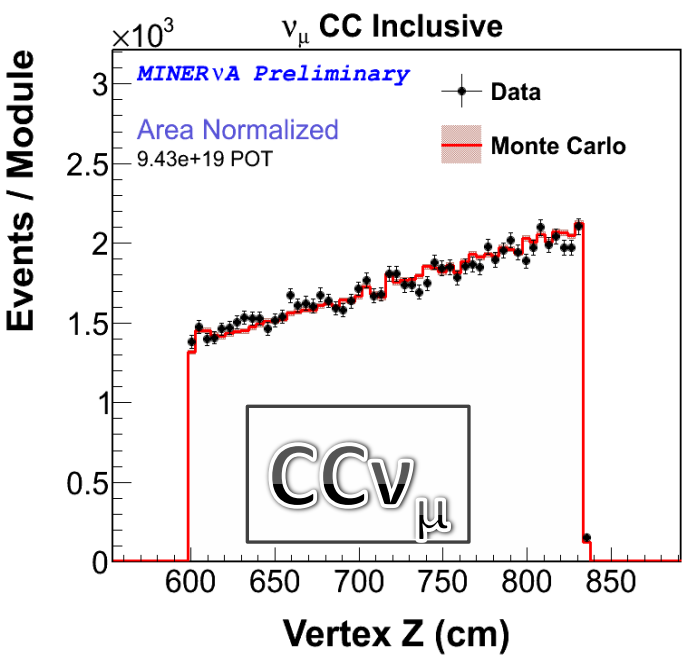
Sum of visible energy, weighted by amount of passive material

calorimetric $E_{recoil} = \alpha \times \sum_i c_i E_i$

# Vertex Distributions – Acceptance



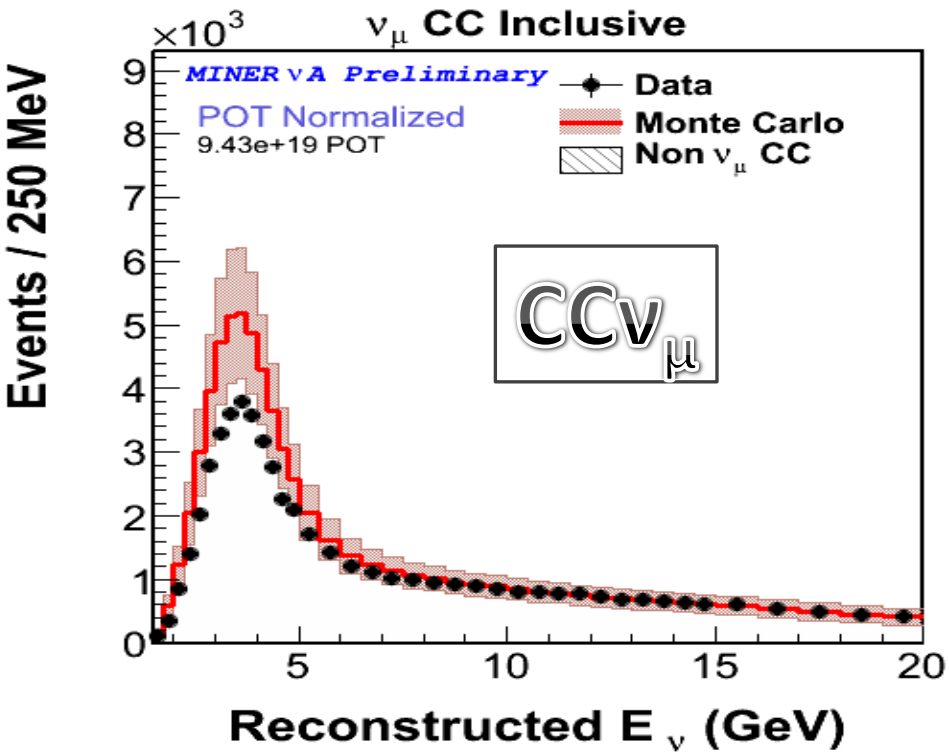



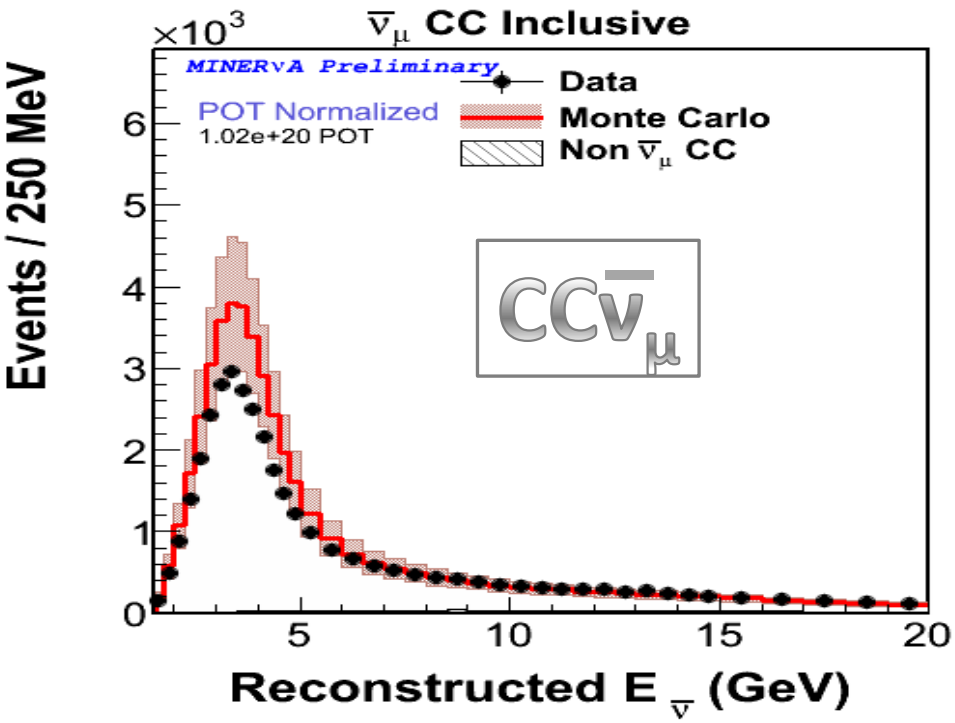




*"MINOS-matched" muons (for CC $\nu_\mu$ inclusives sample)*

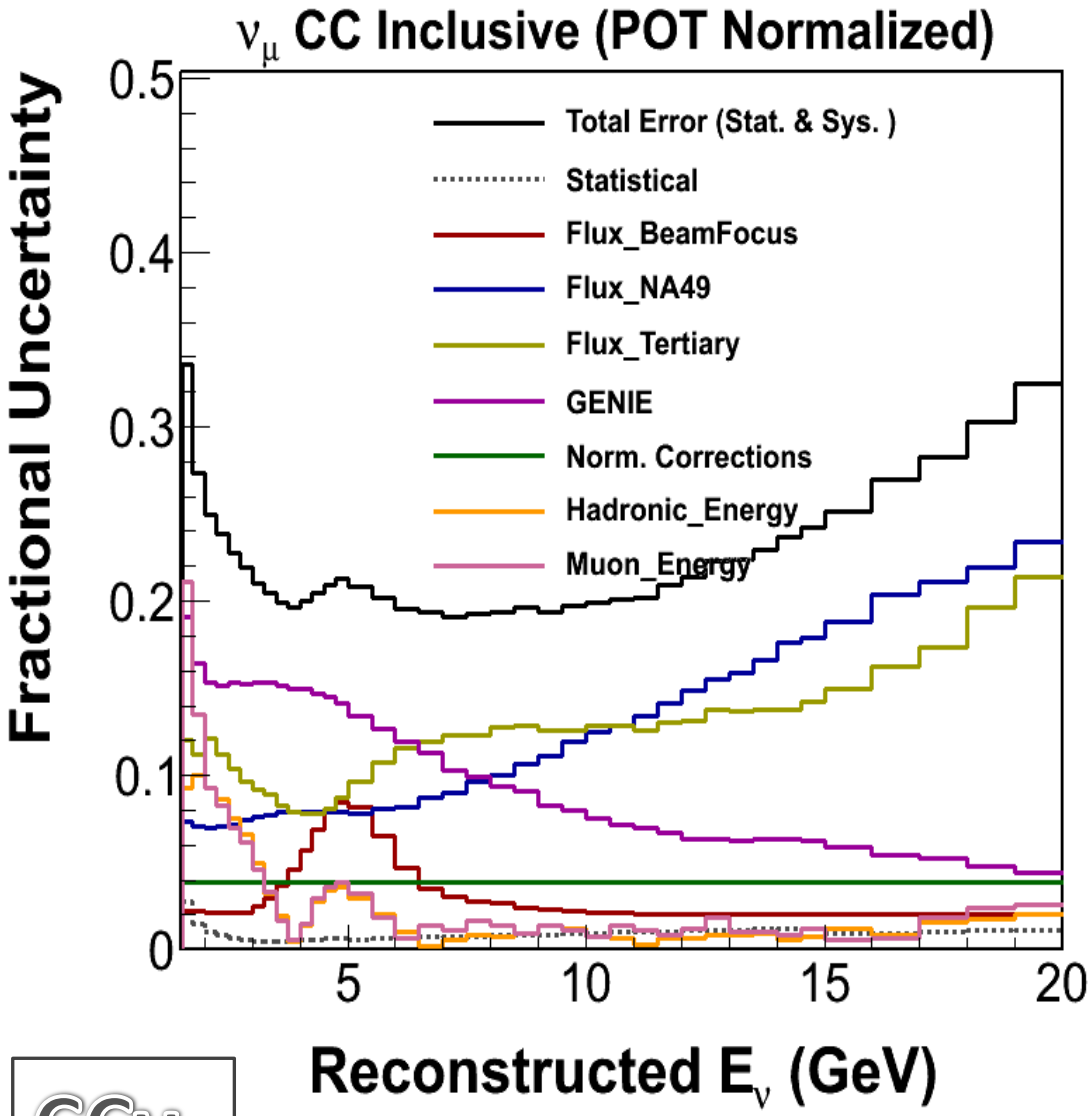
- Energy threshold ~2 GeV.
- Good angular acceptance up to scattering angles of about 10 degrees, with limit of about 20 degrees.
- Bias is complex but well understood.

# Neutrino Energy Distribution



# Uncertainties




$CC\nu_\mu$

**Beam Focus** – Magnetic horns focusing the charged mesons that decay to neutrino beam.

**NA49**– A CERN hadron production experiment that constrains flux simulation (pC->X).

**Tertiary**– Neutrinos produced by decay of products other than pC in the NuMI target.

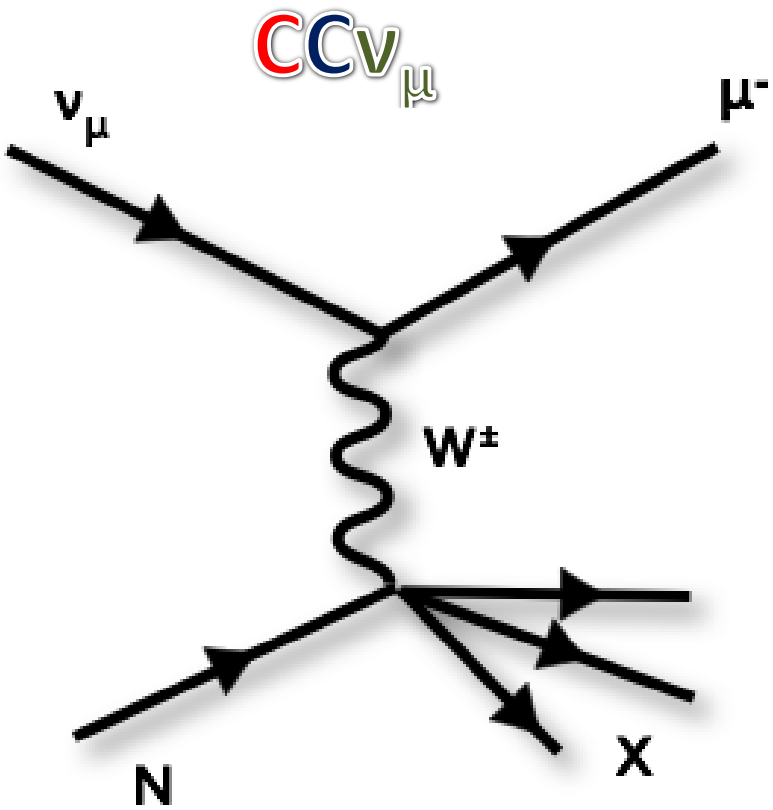
**GENIE**– Neutrino event generator. Uncertainties for cross section, final state interaction models. Not an uncertainty on our measurement.

**Norm. Corrections**– Uncertainty on flat normalization corrections applied to Monte Carlo.

**Hadronic Energy**– Uncertainty on calorimetric recoil energy reconstruction.

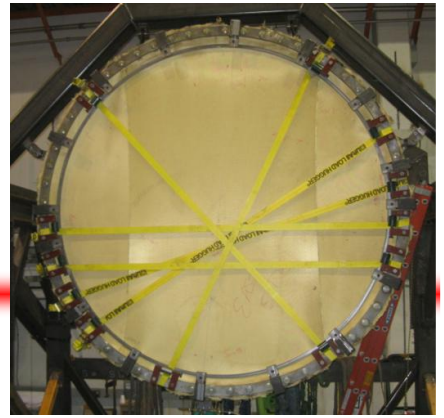
**Muon Energy**– Uncertainty on MINOS's momentum reconstruction (curvature or range) + energy loss in MINERvA.

# Nuclear Target Ratios Analysis

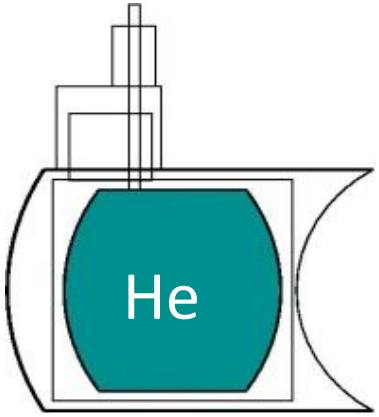


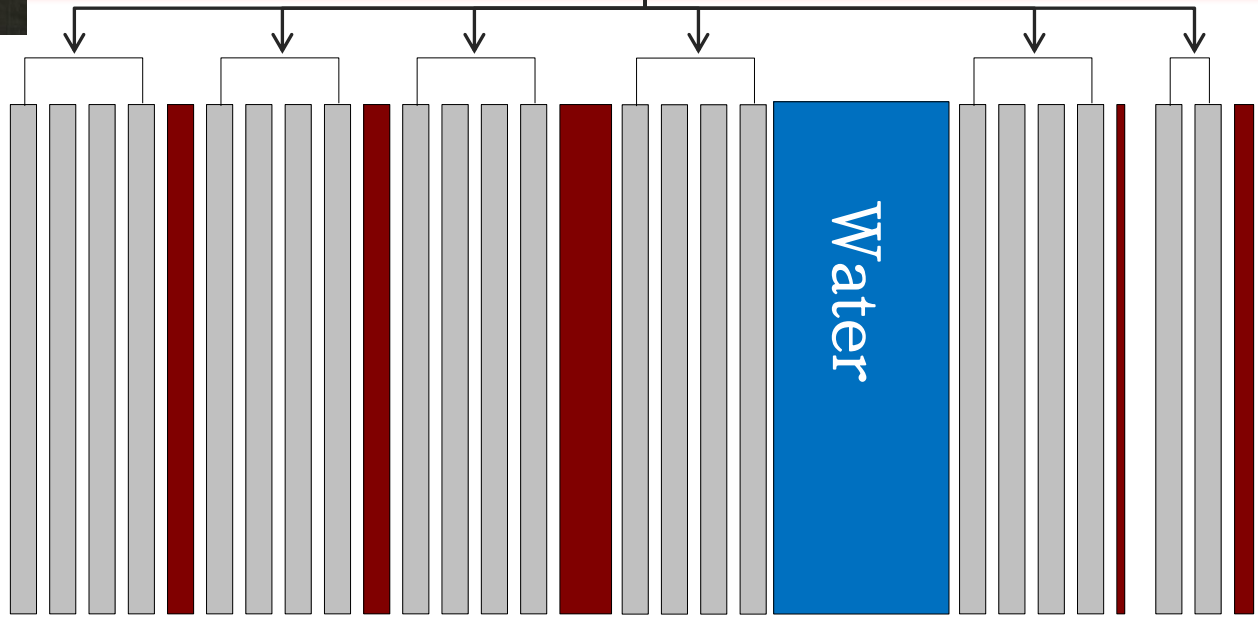
250 kg
Liquid He

452kg
Water



# Active Scintillator Modules



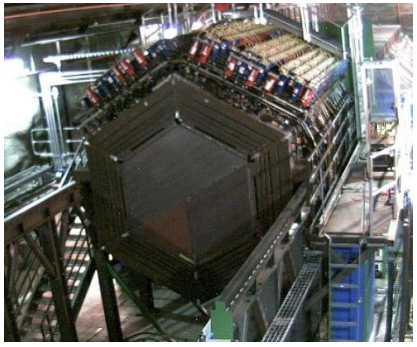




Tracking
Region

1” Fe / 1” Pb
322kg / 263kg

1” Pb / 1” Fe
263kg / 321kg

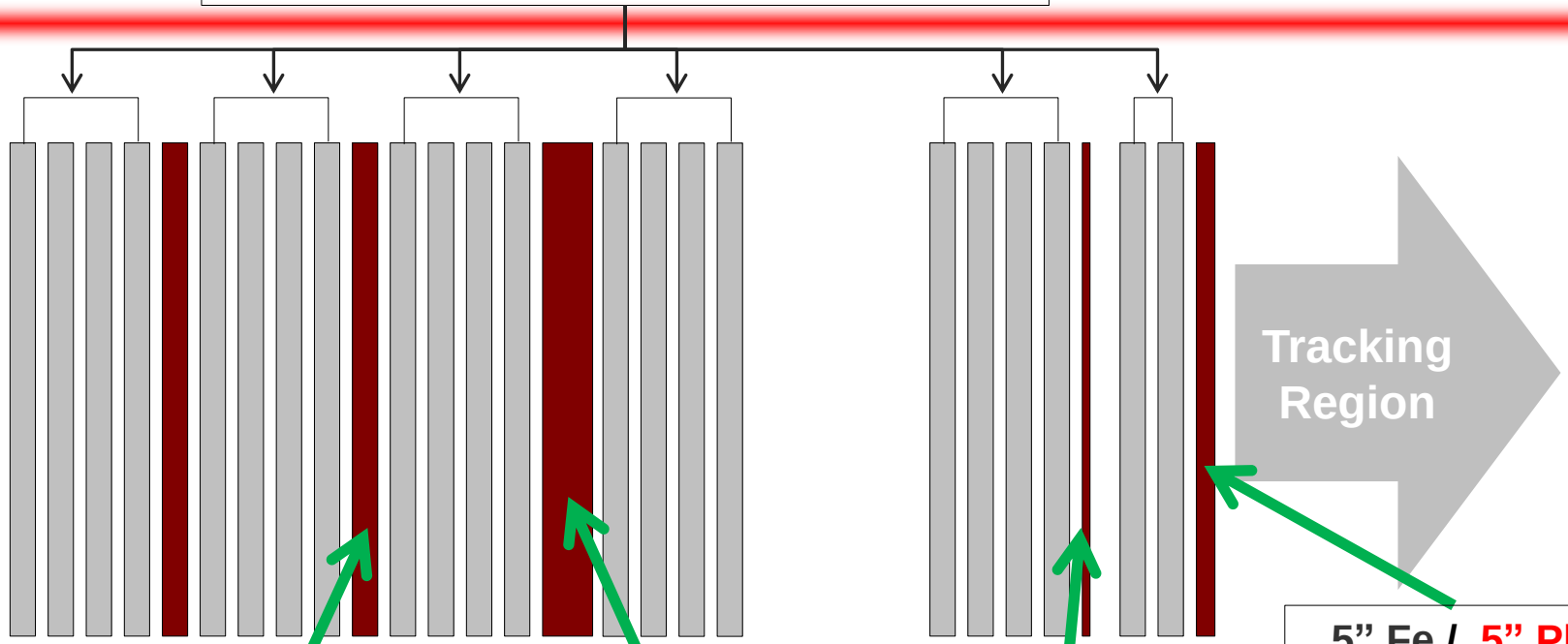
3” C / 1” Fe / 1” Pb
160kg / 158kg / 107kg



0.3” Pb
225kg

.5” Fe / .5” Pb
162kg/ 134kg

# Active Scintillator Modules

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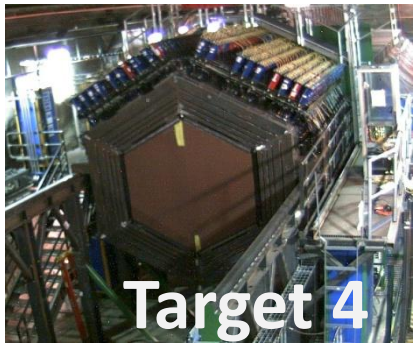
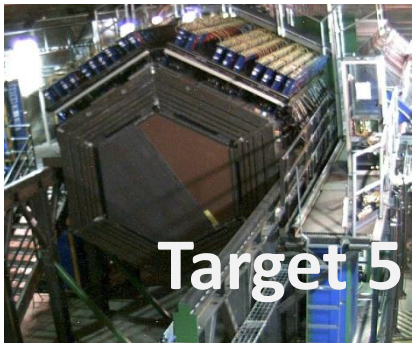
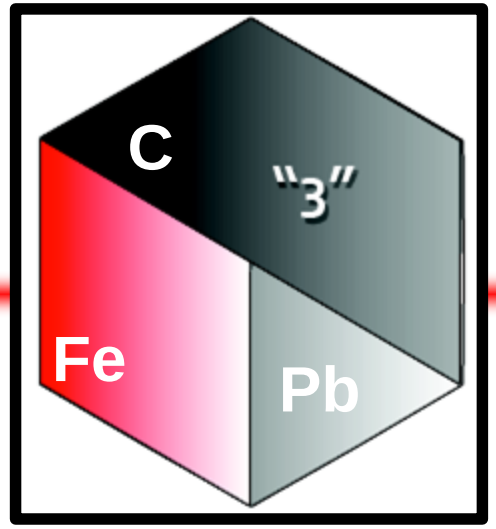
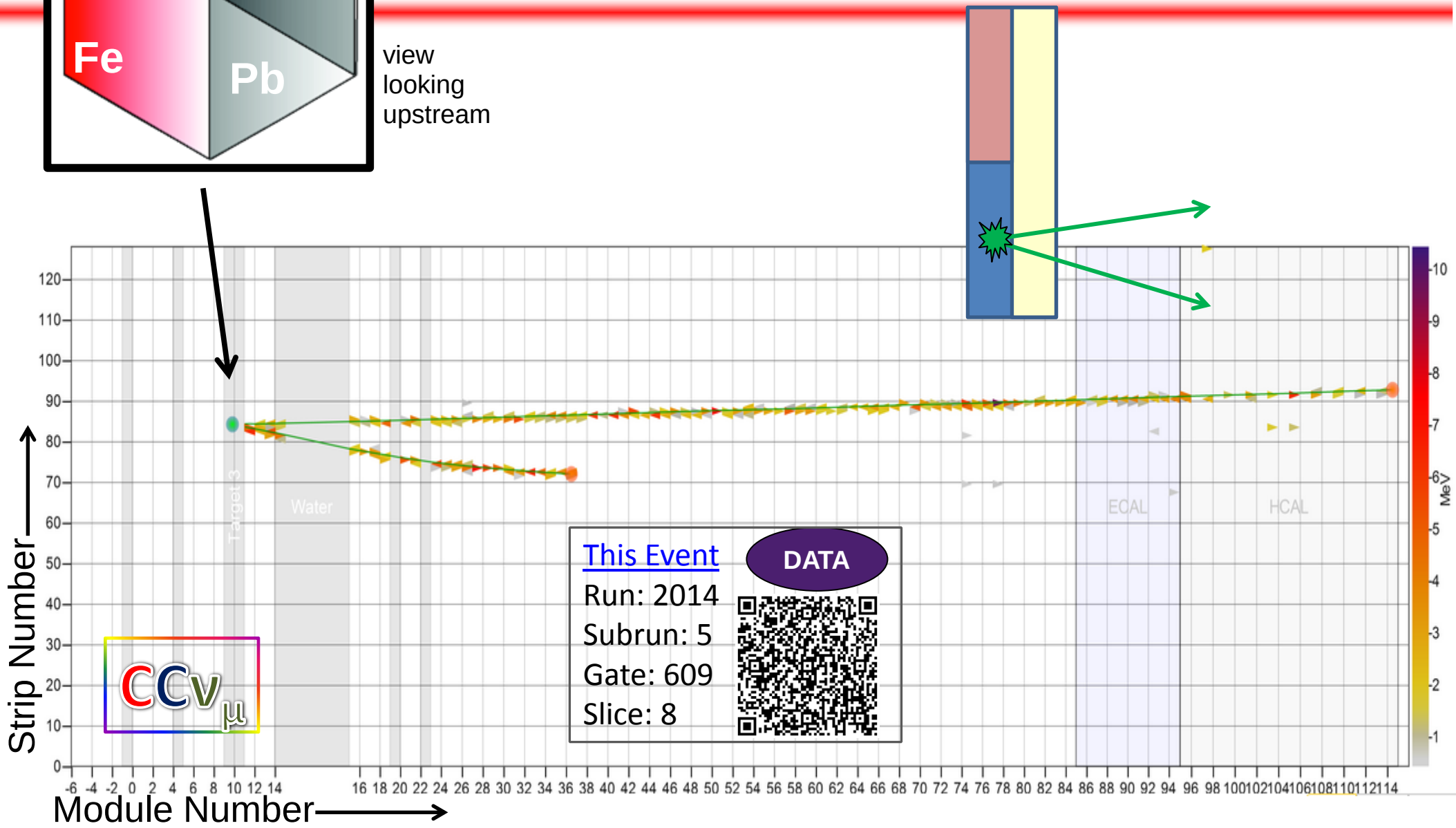


# An event from target 3
# Carbon candidate




view looking upstream



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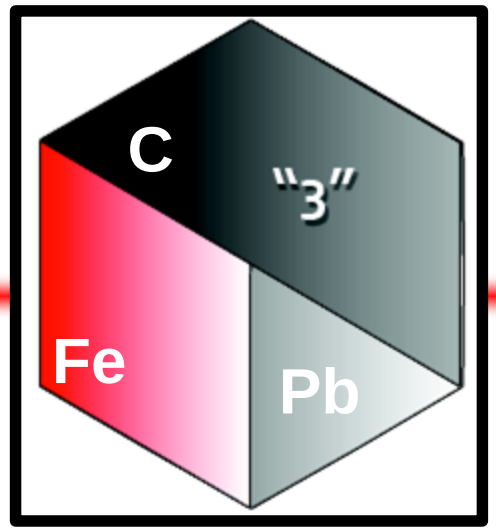
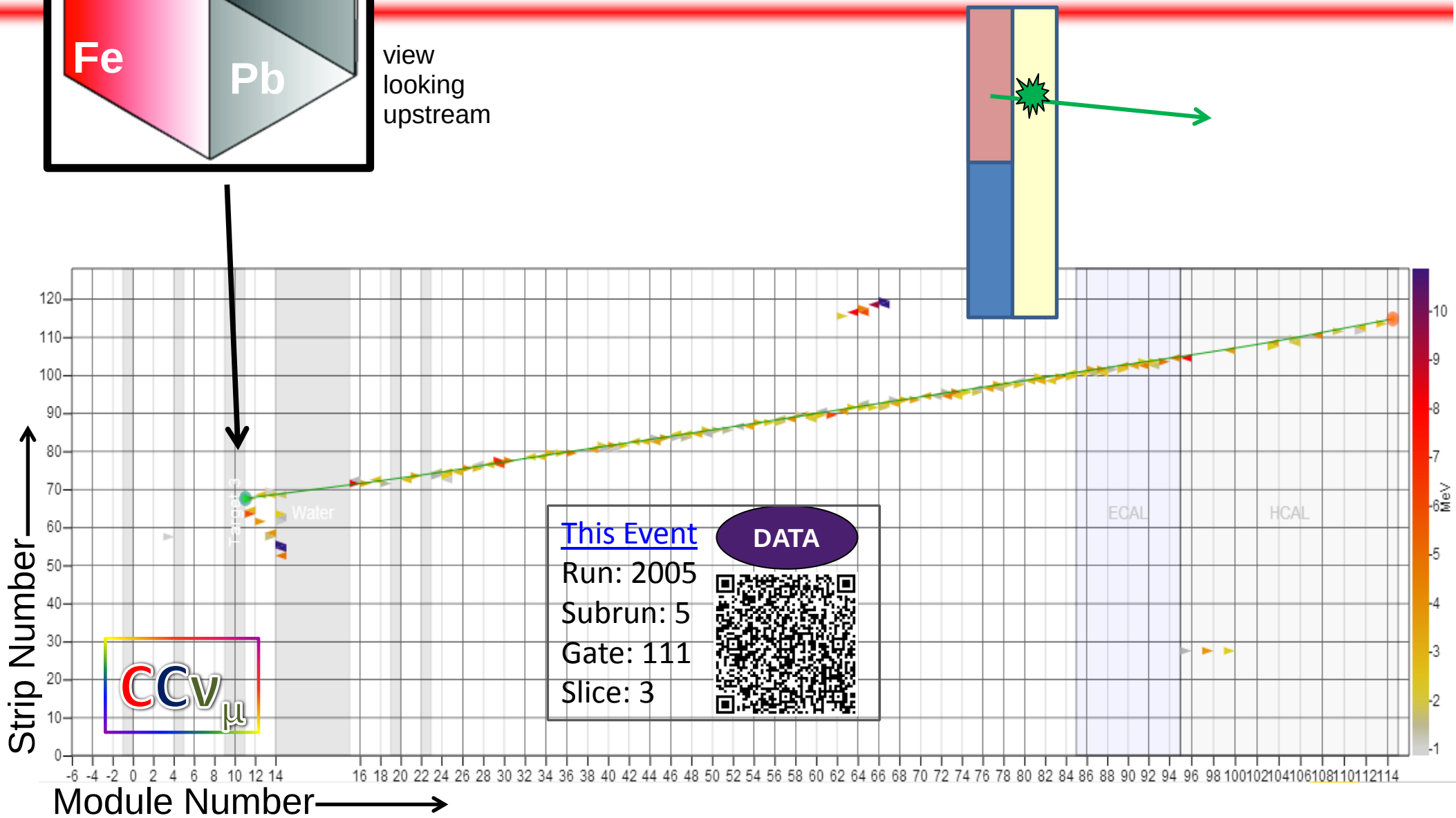
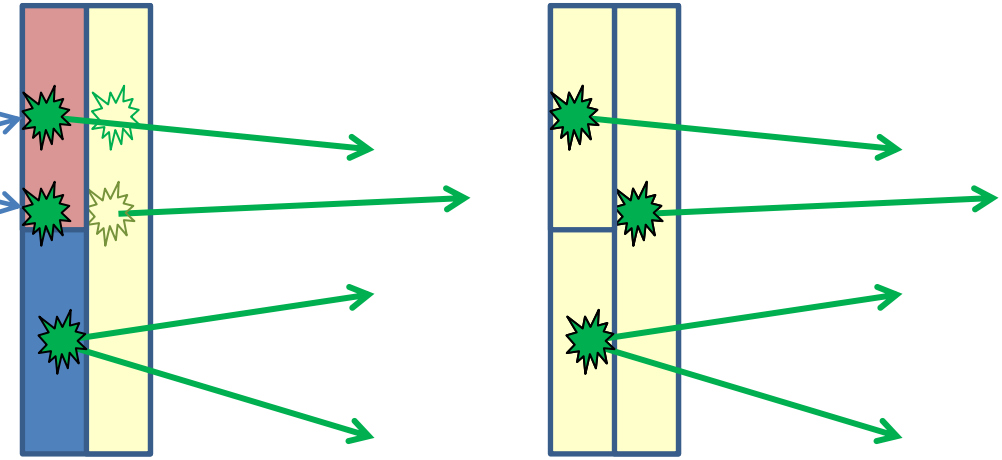


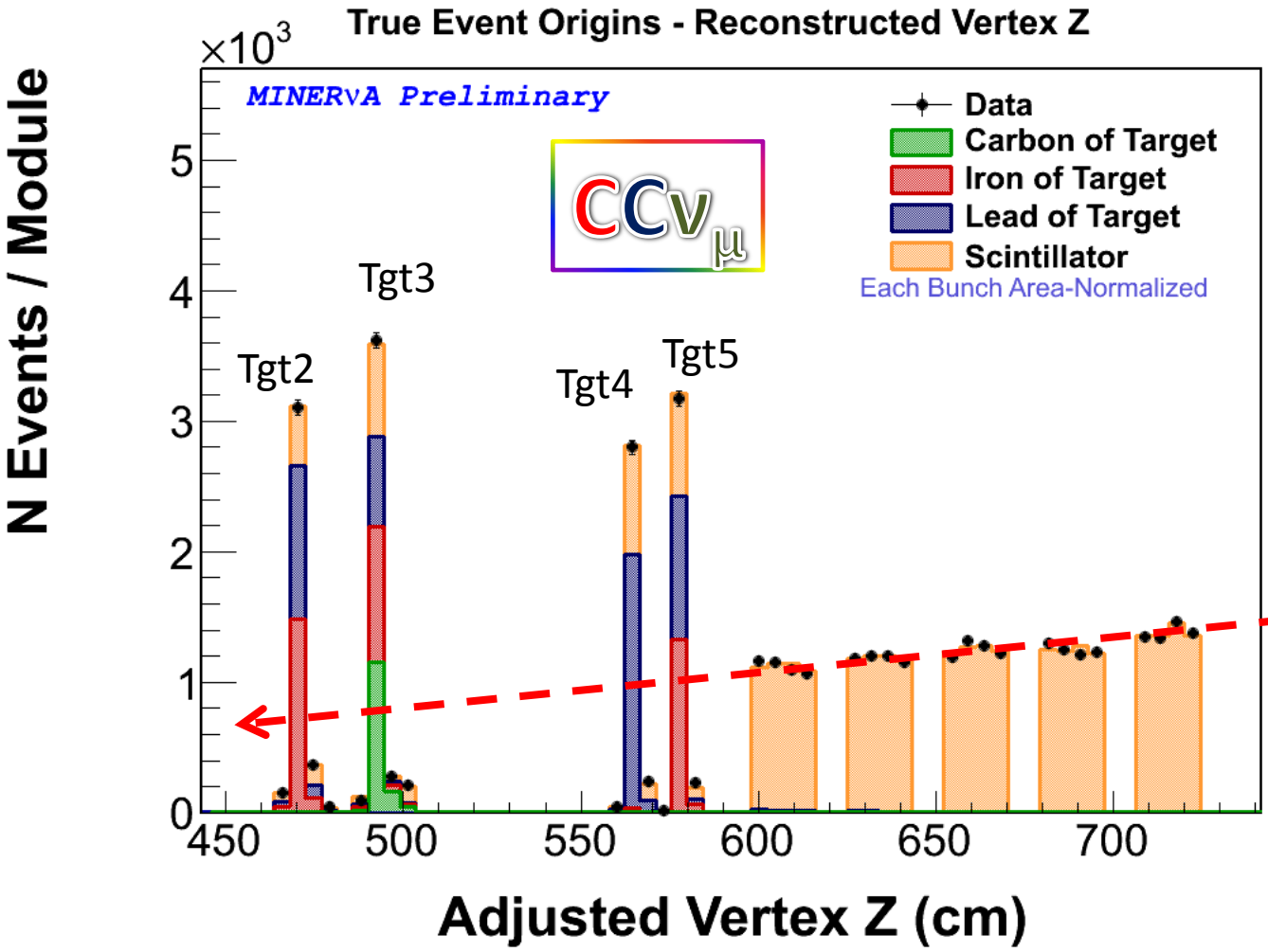

view
looking
upstream



Project the one track events to the passive target's center in Z.

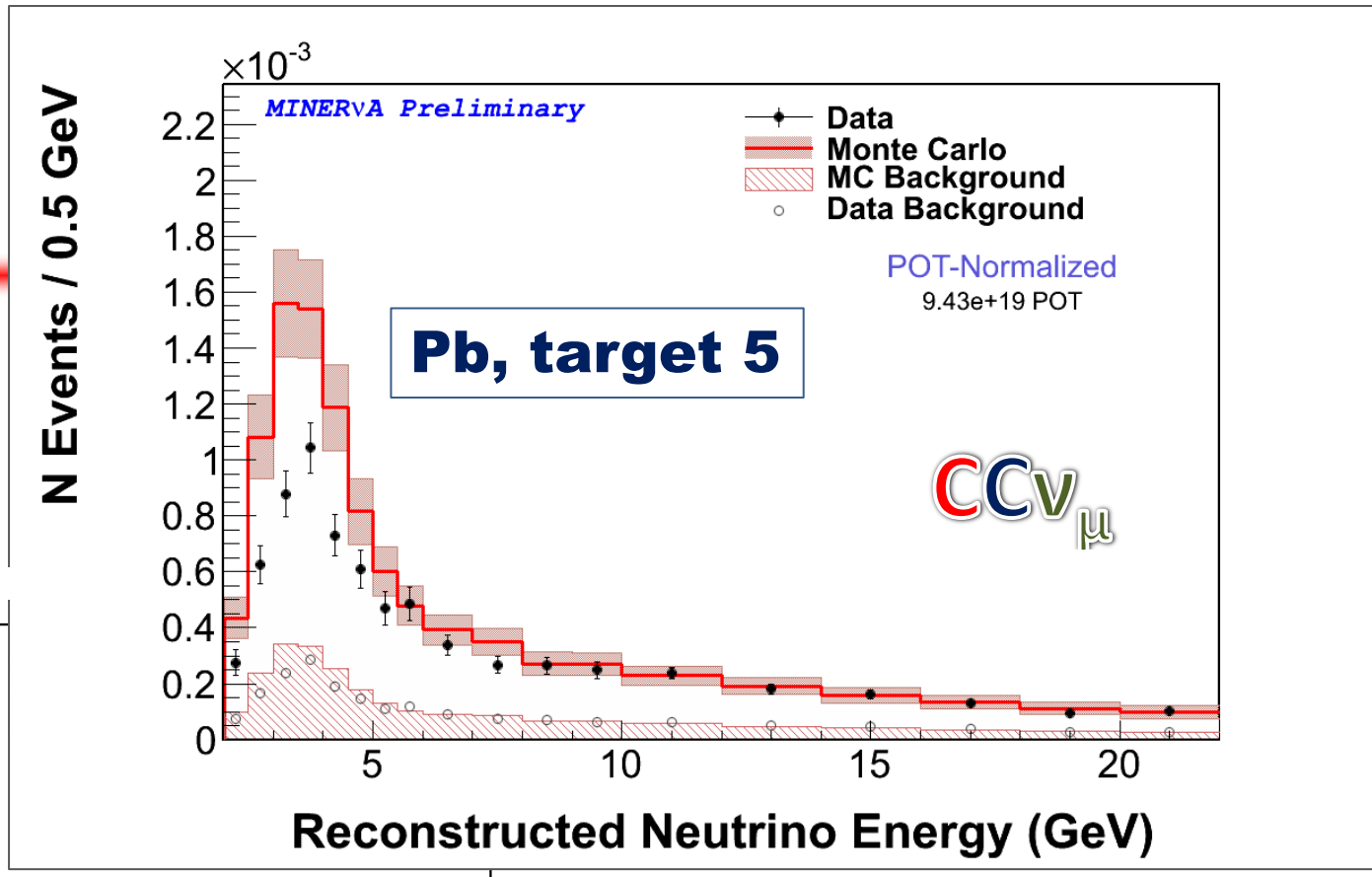
This is the best guess of the vertex.

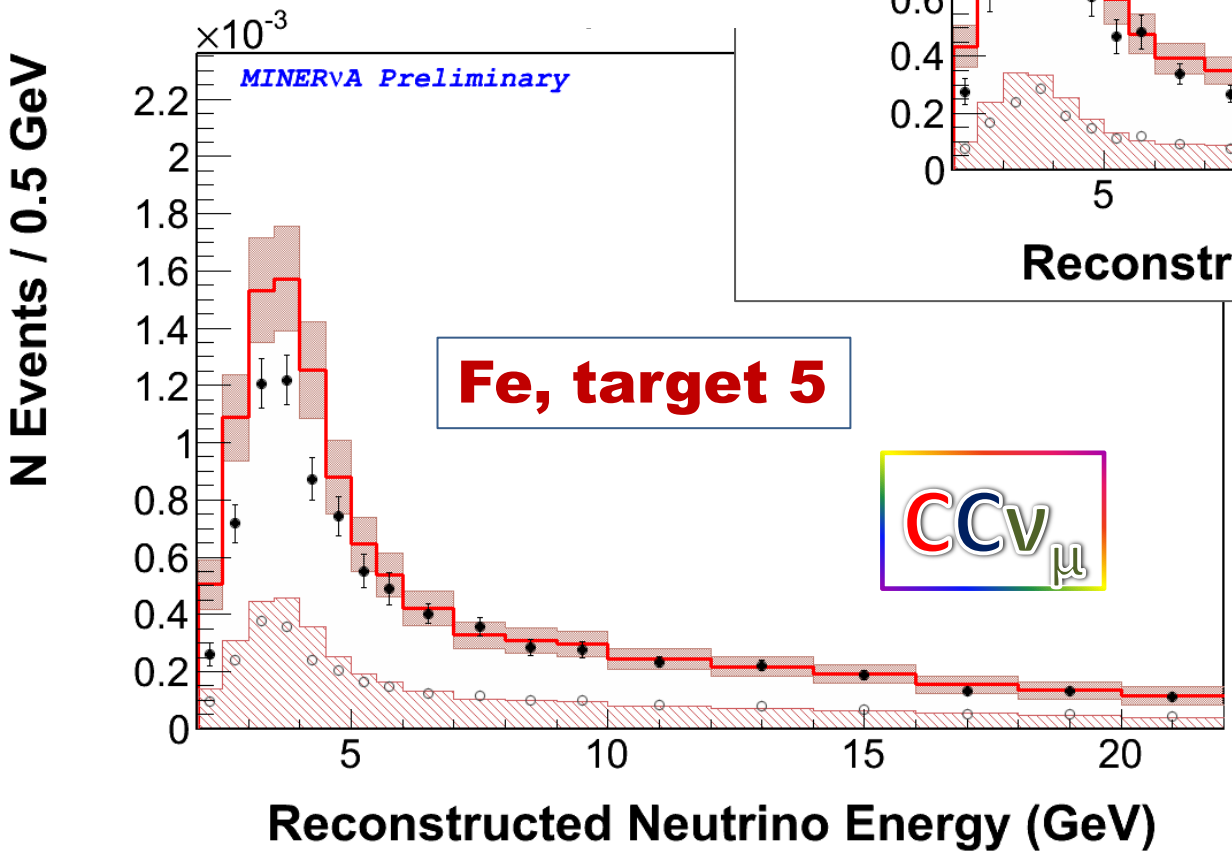





Use tracker modules to predict and subtract the plastic background.

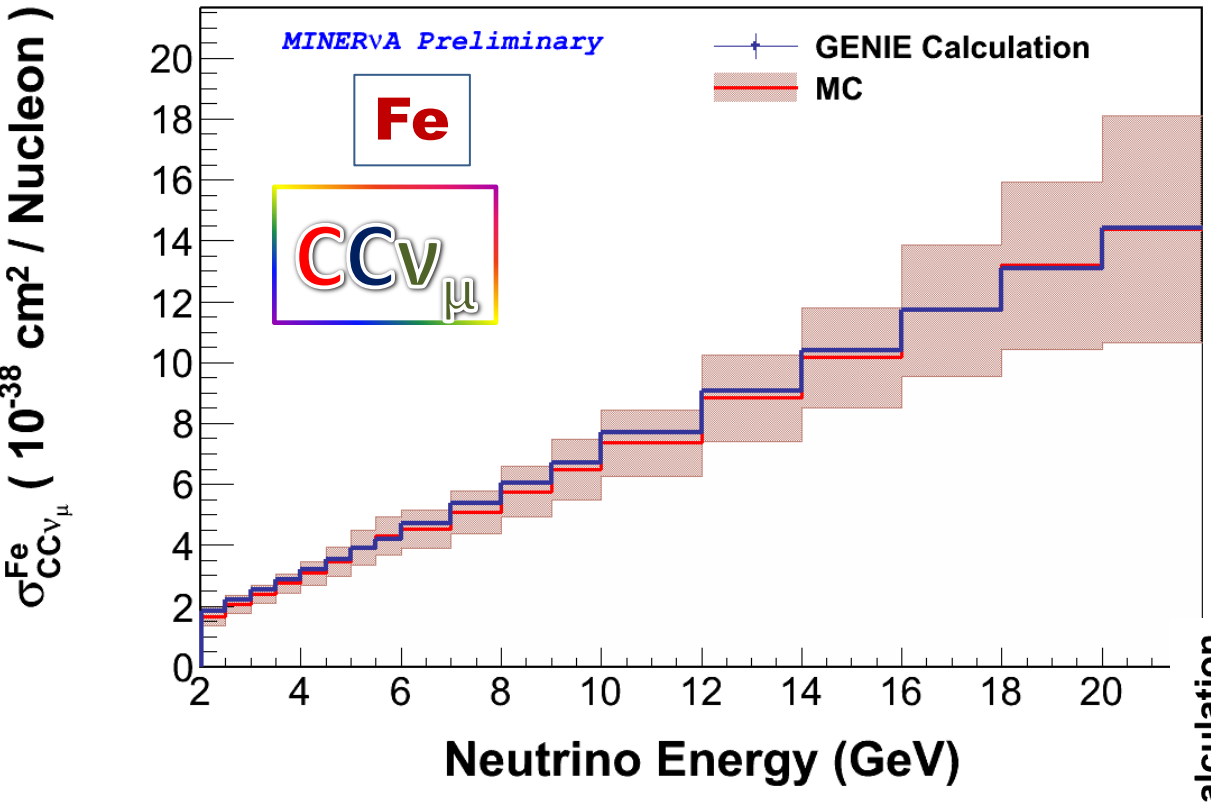
# Accepted Events and Background



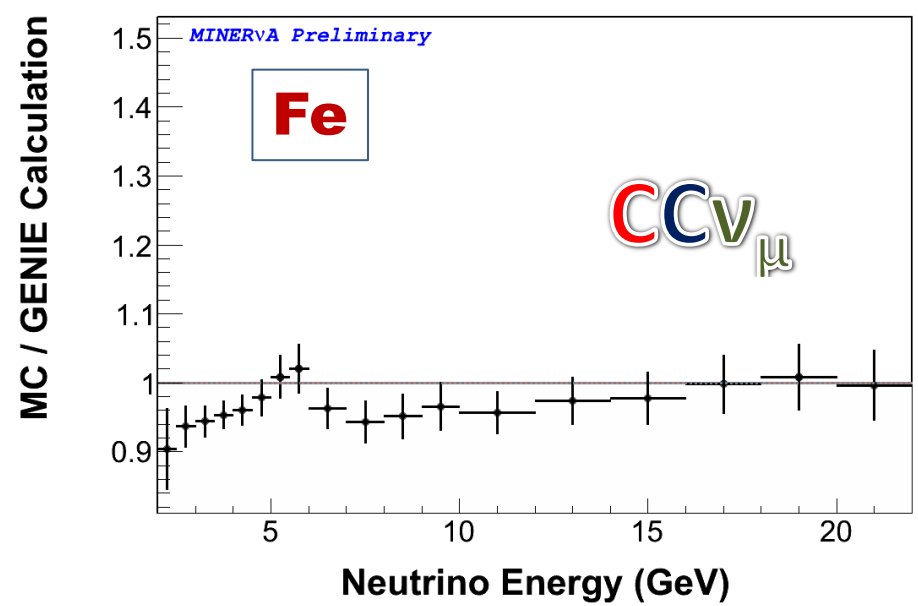




Uses ~25% neutrino data recorded and ~20% of target mass.

# Iron Cross Section

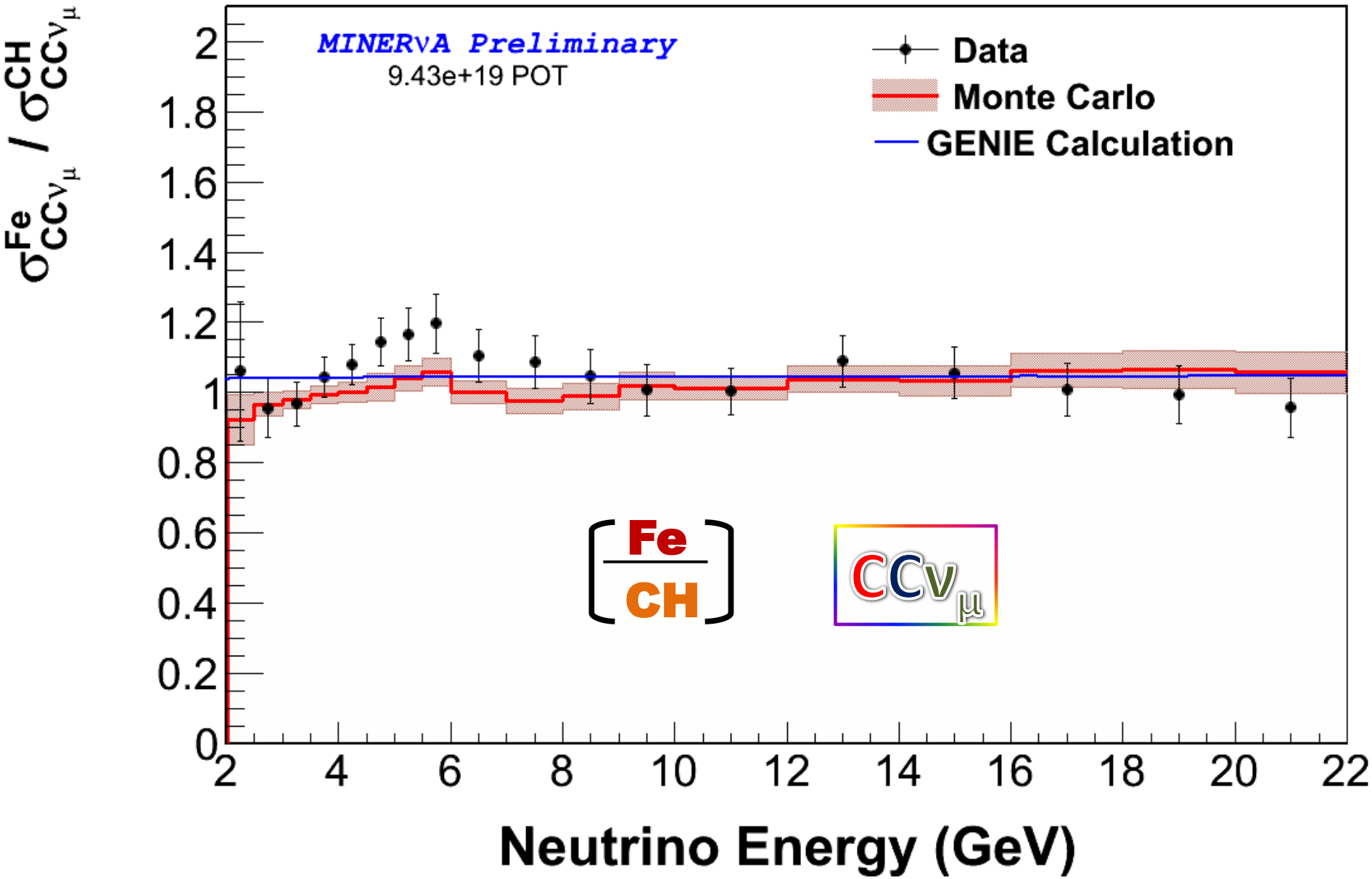



Uses ~25% neutrino data recorded and ~60% of target mass.

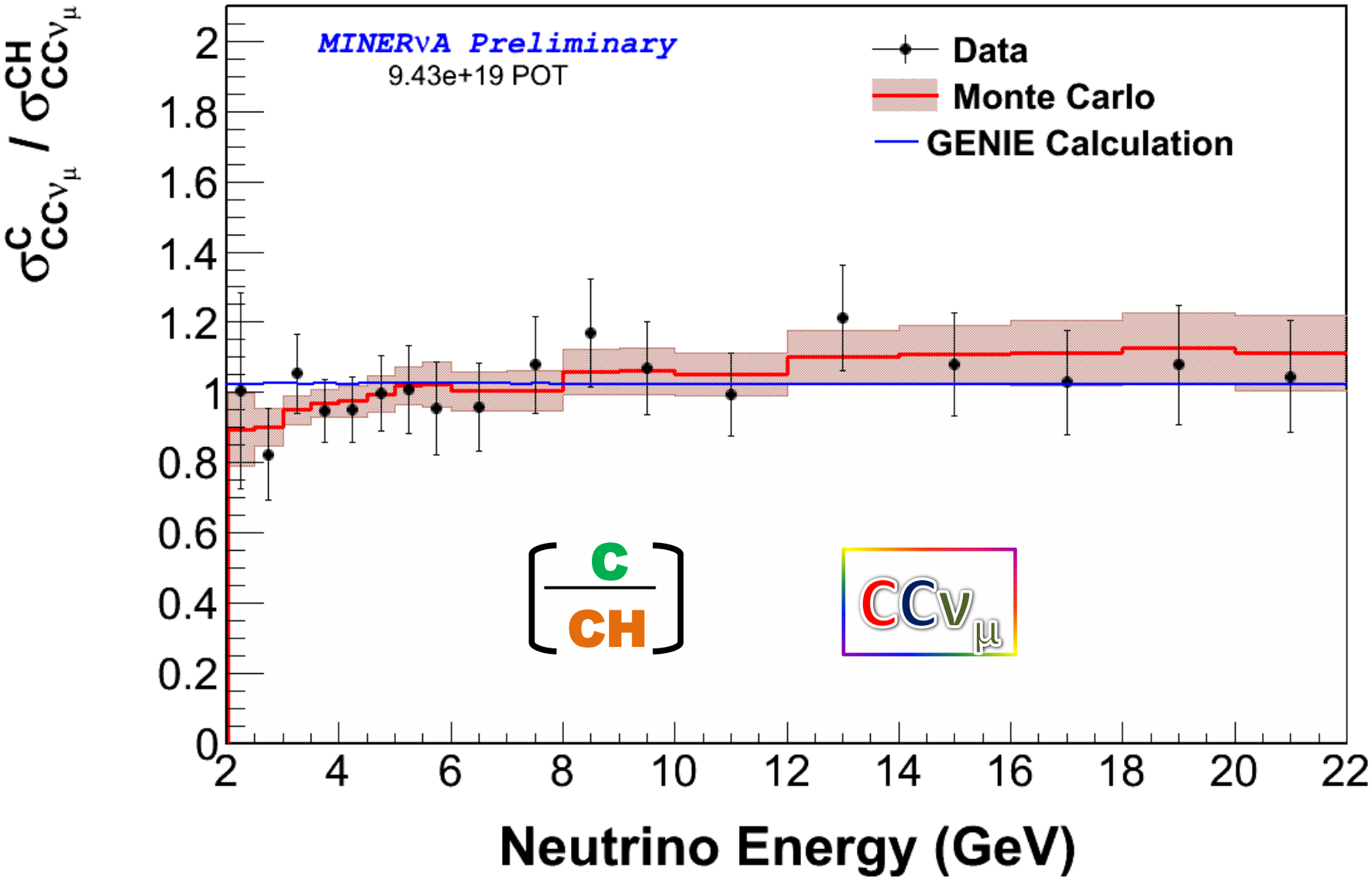



Discrepancy in is due to inaccuracy of plastic background subtraction in the upstream targets.

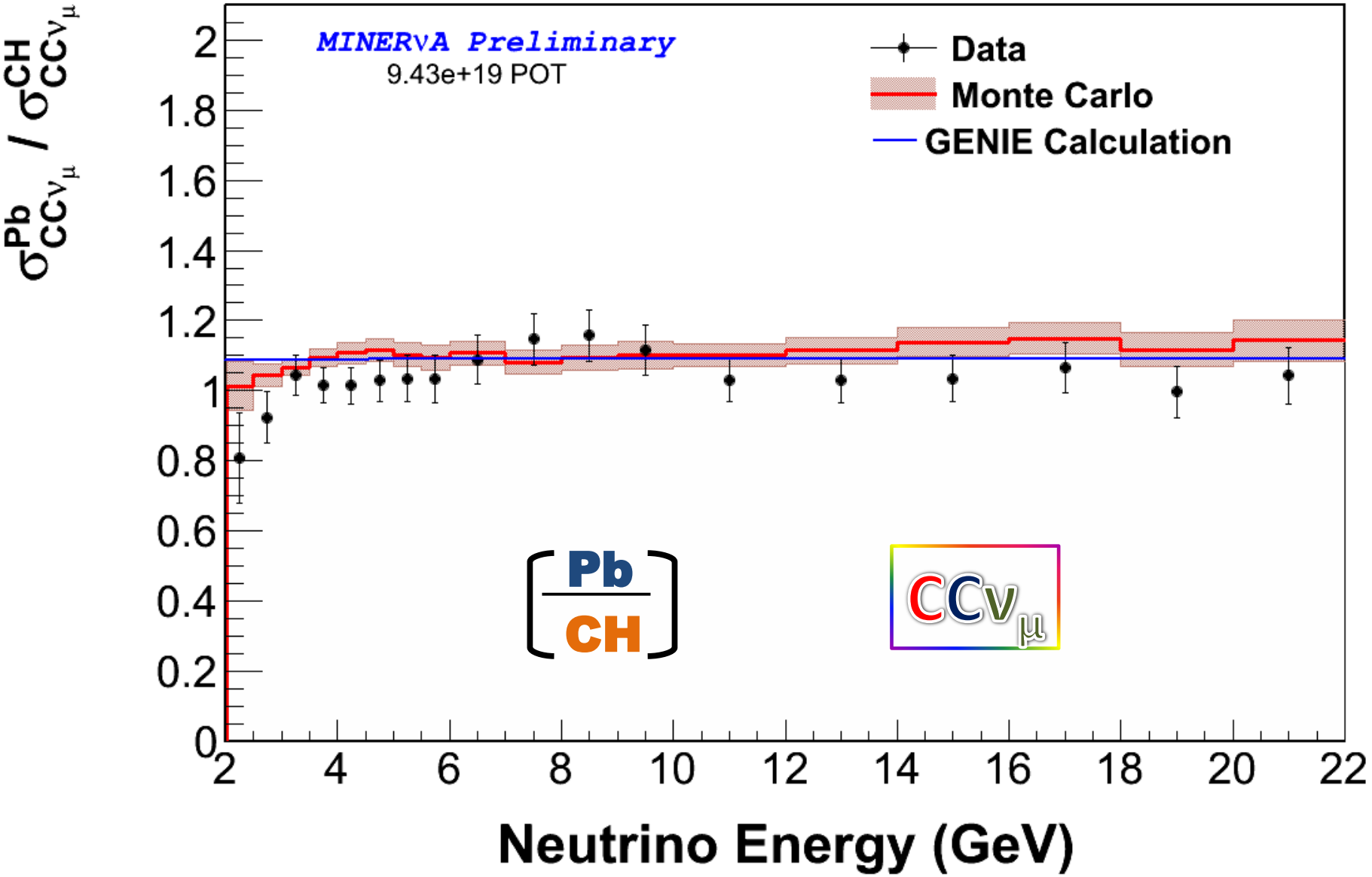
# Ratio of Iron to Scintillator Cross Section



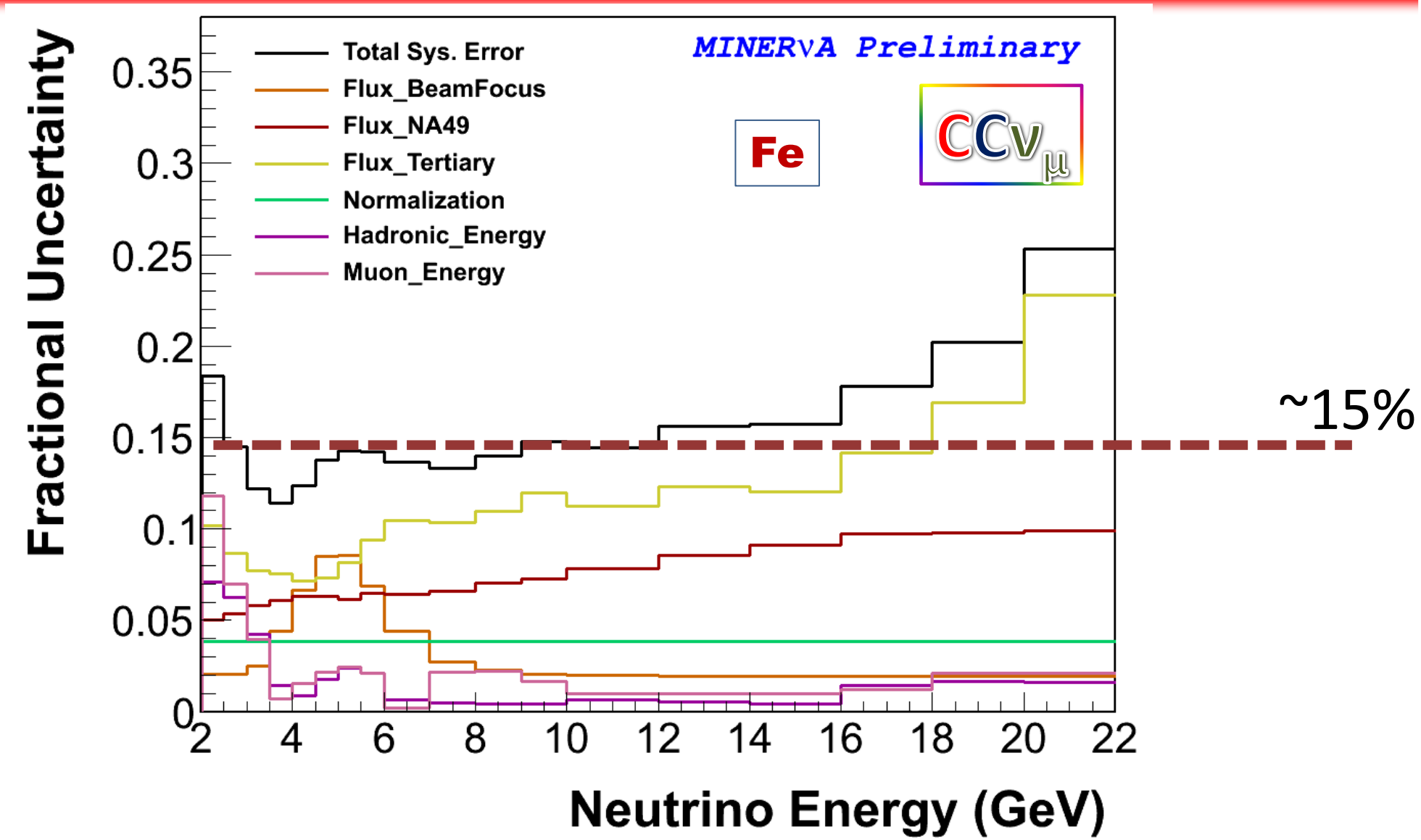
# Ratio of Carbon to Scintillator Cross Section



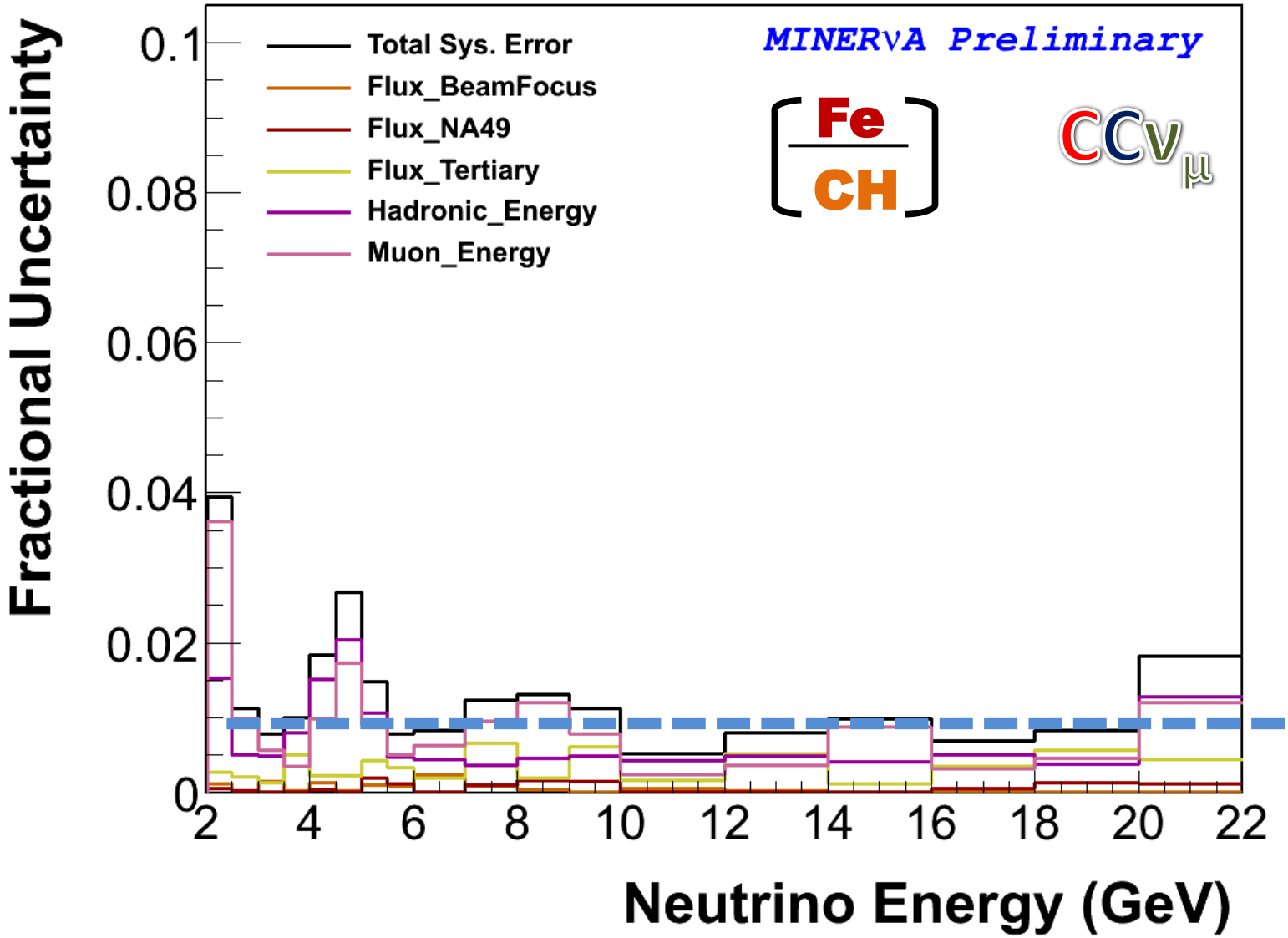
# Ratio of Lead to Scintillator Cross Section



# Systematic Errors – Fe Cross Section



# Systematic Errors - $\left[\frac{Fe}{CH}\right]$ Cross Section

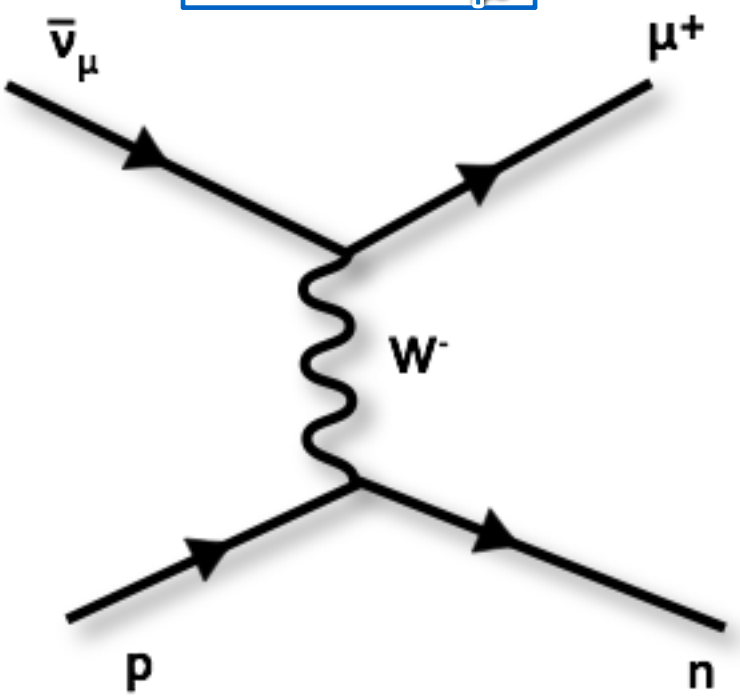



~15%

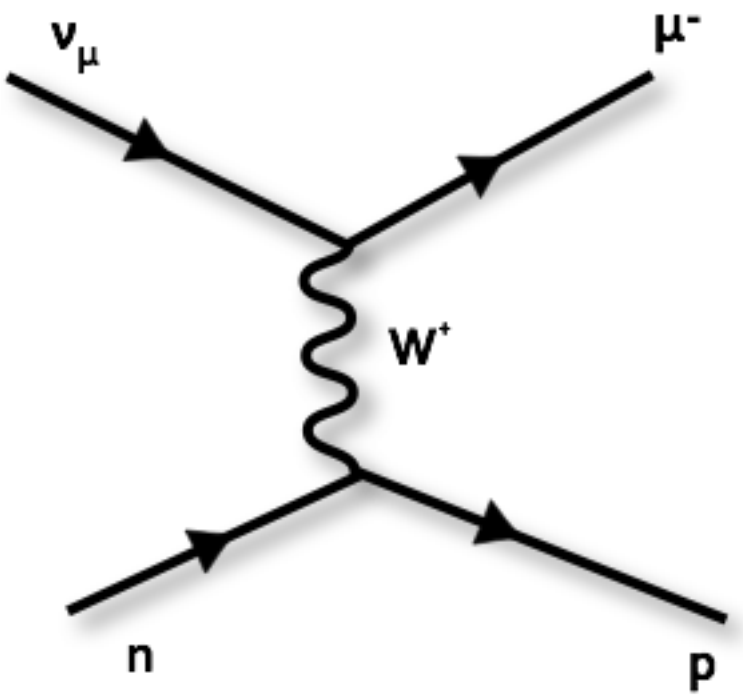
~1.5%

# Quasi-elastic Scattering

CCQE$\bar{\nu}_\mu$

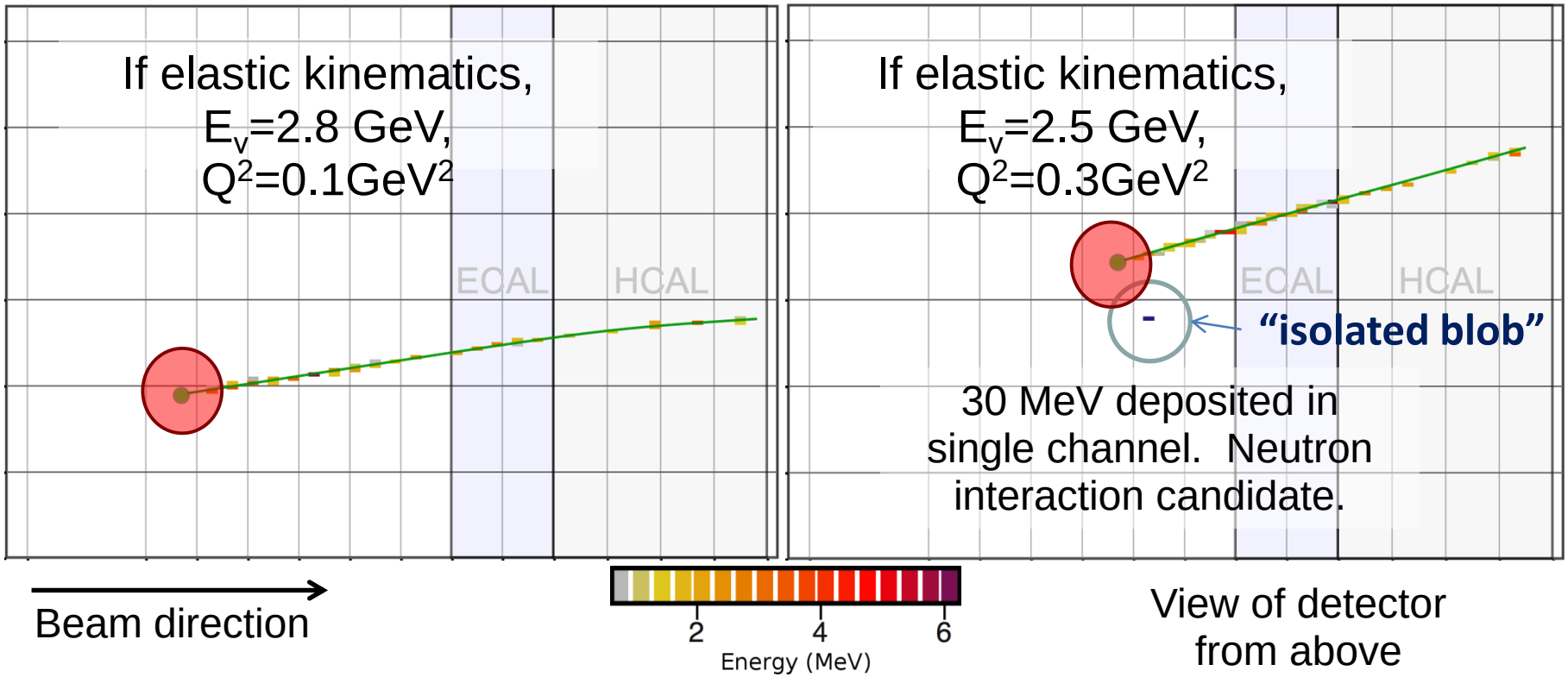



CCQE$\nu_\mu$




2trkCCQE$\nu_\mu$

# CCQE$\bar{\nu}_\mu$



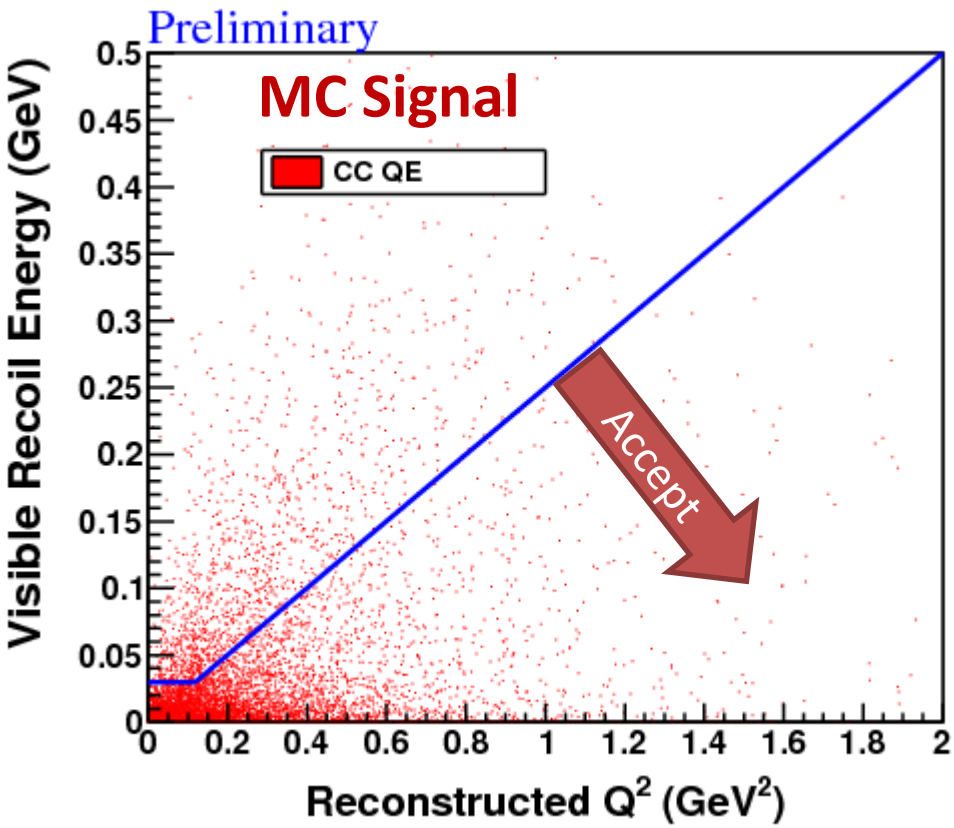

- Require a $\mu^+$ matched into MINOS.
- Require no other tracks.
- Require 0 or 1 isolated blob (neutron candidate).
- Require small recoil energy, excluding 10cm around vertex.

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

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

# Recoil Energy Cut

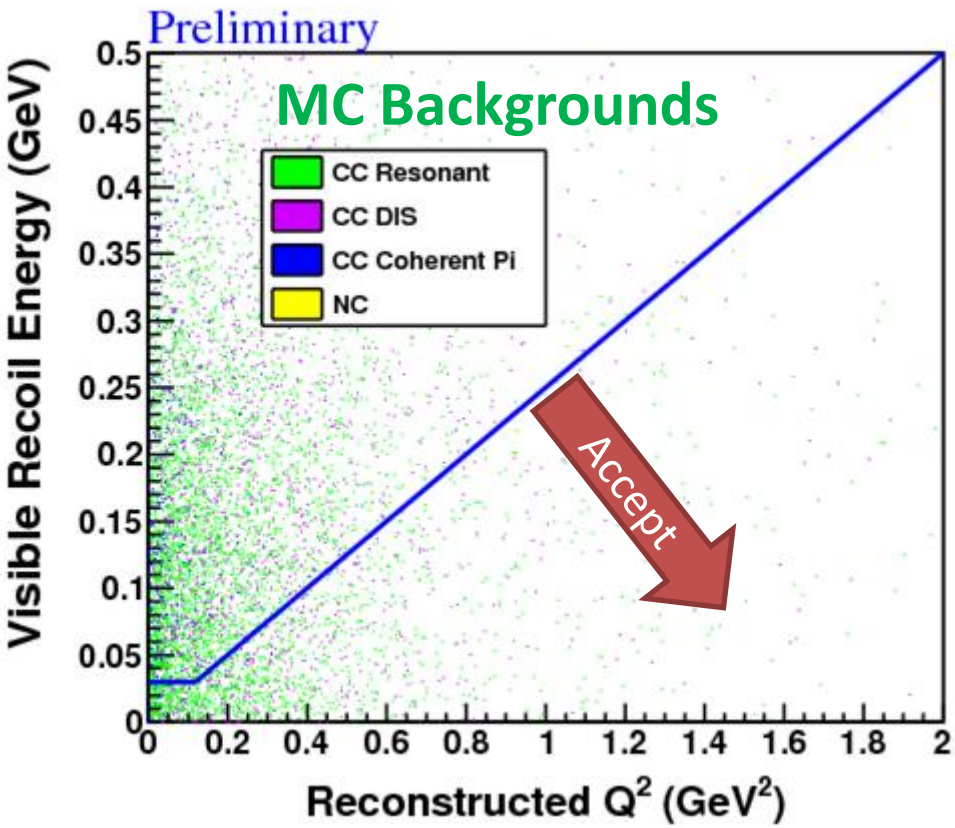
CCQE$\bar{\nu}_\mu$



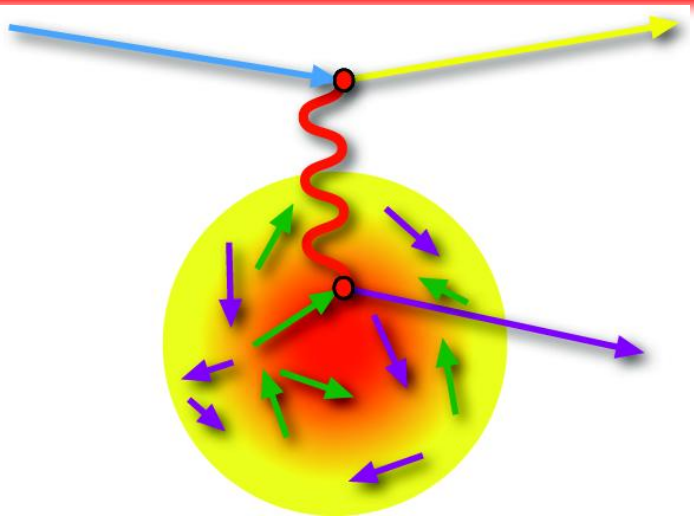

$$Q^2 = 2E_\nu(E_\mu - p_\mu \cos\theta_\mu) - m_\mu^2$$

Expect higher $Q^2_{QE}$ events to have more recoil energy.

Total selection purity is ~75%.



# Why don't we cut on vertex activity? We want to measure it!



Scattering off a nucleus can be messy, poorly simulated.

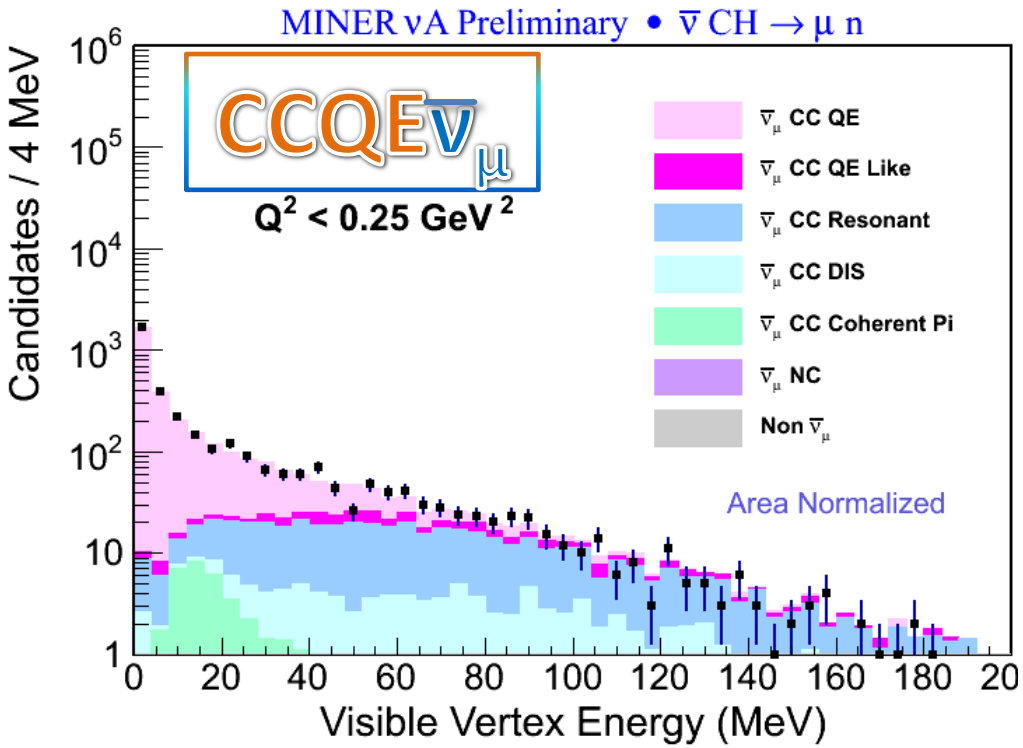
(multi-nucleon correlations, FSI)

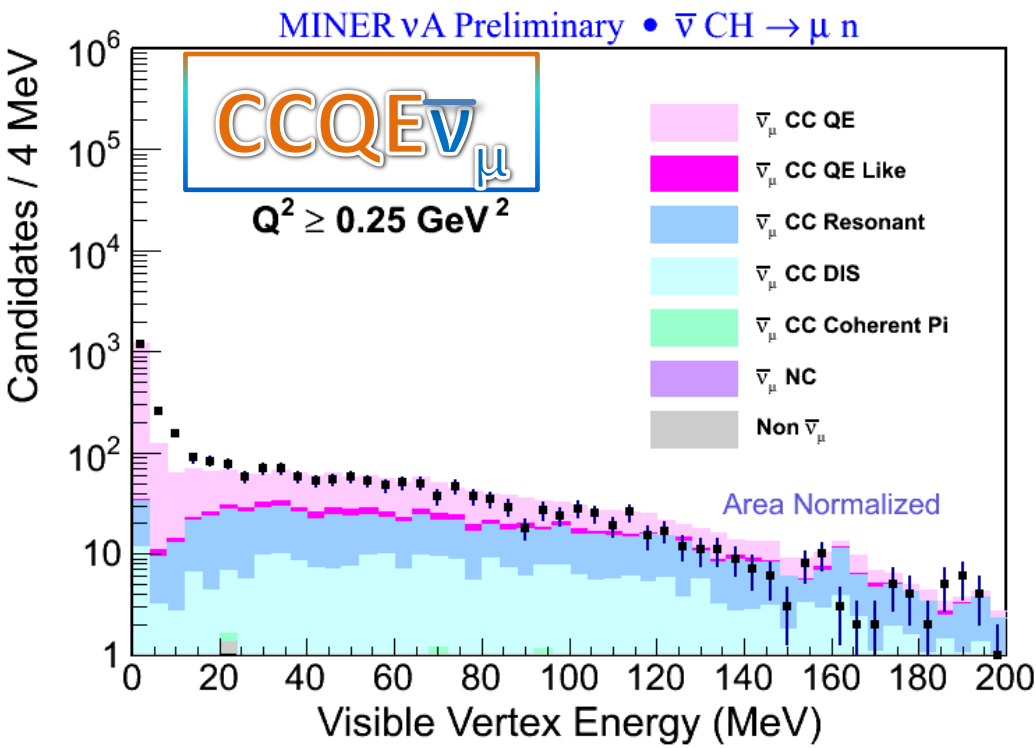
We must interrogate the final state products to allow testing of v-A and FSI models.

Illustration: Fermilab/Diana Canzone

# Vertex Energy Distributions

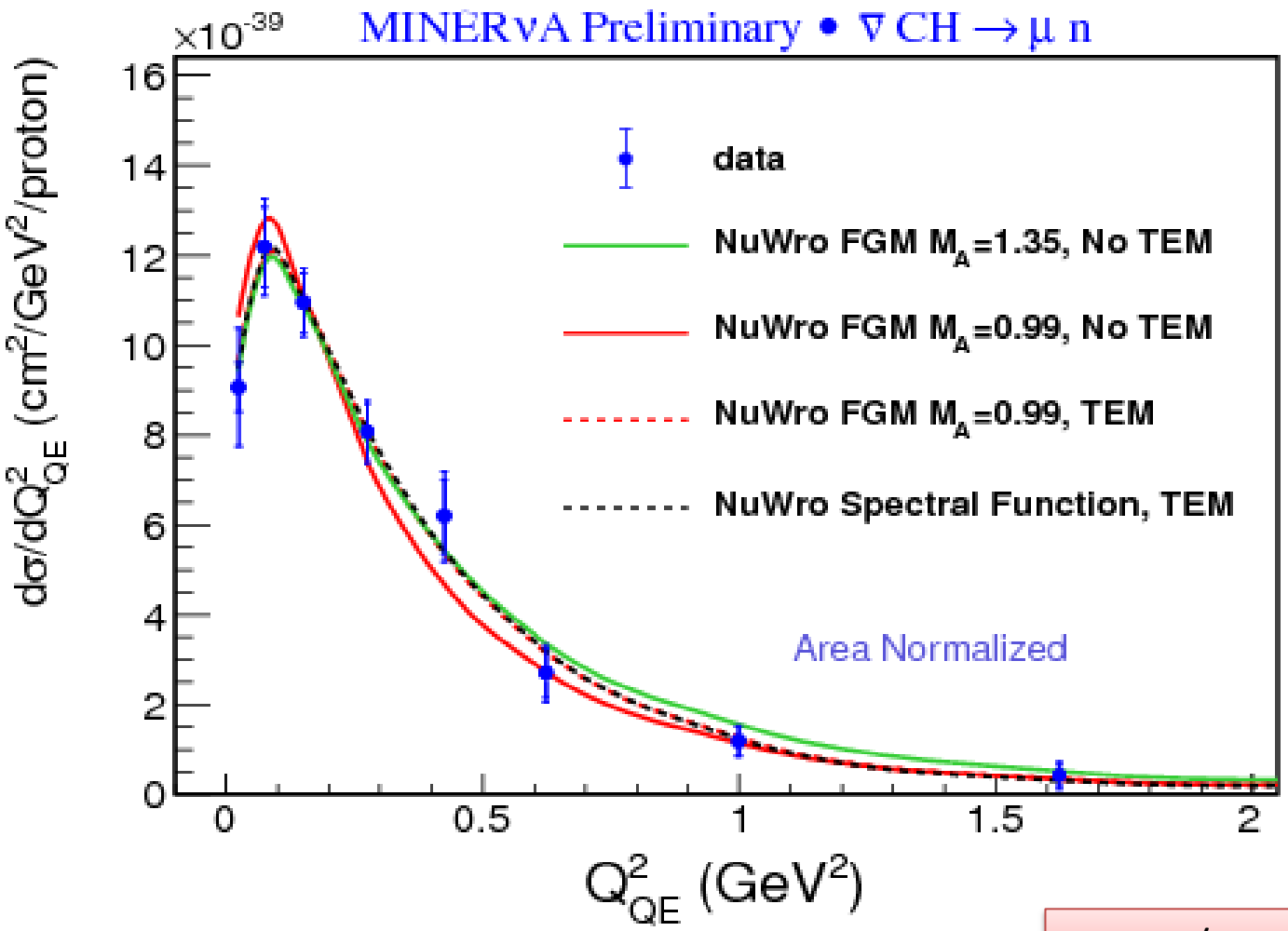
- If seen, excess vertex energy may be evidence of missing or poorly simulated interaction processes.



# $d\sigma/dQ^2_{QE}$

CCQE$\bar{\nu}_\mu$



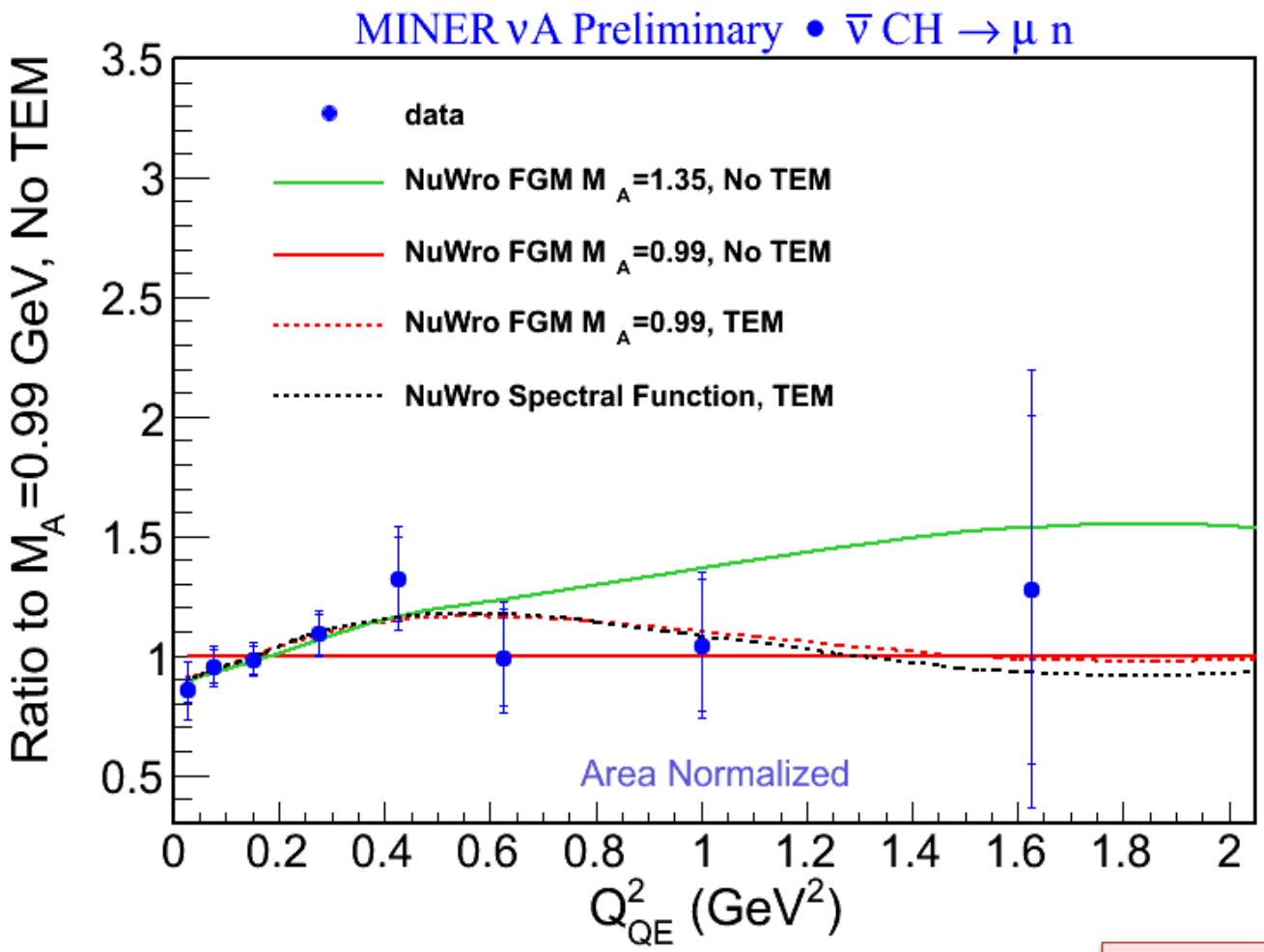

NuWro: Golal, Jusczak, Sobczyk arXiv:1202.4197

TEM/MEC model: Bodek, Budd, Christy
Eur. Phys. J. C(2011) 71:1726

Uses 1/3 exposure and 1/2 detector mass

# $d\sigma/dQ^2_{QE}$

CCQE$\bar{\nu}_\mu$




NuWro: Golal, Jusczak, Sobczyk arXiv:1202.4197

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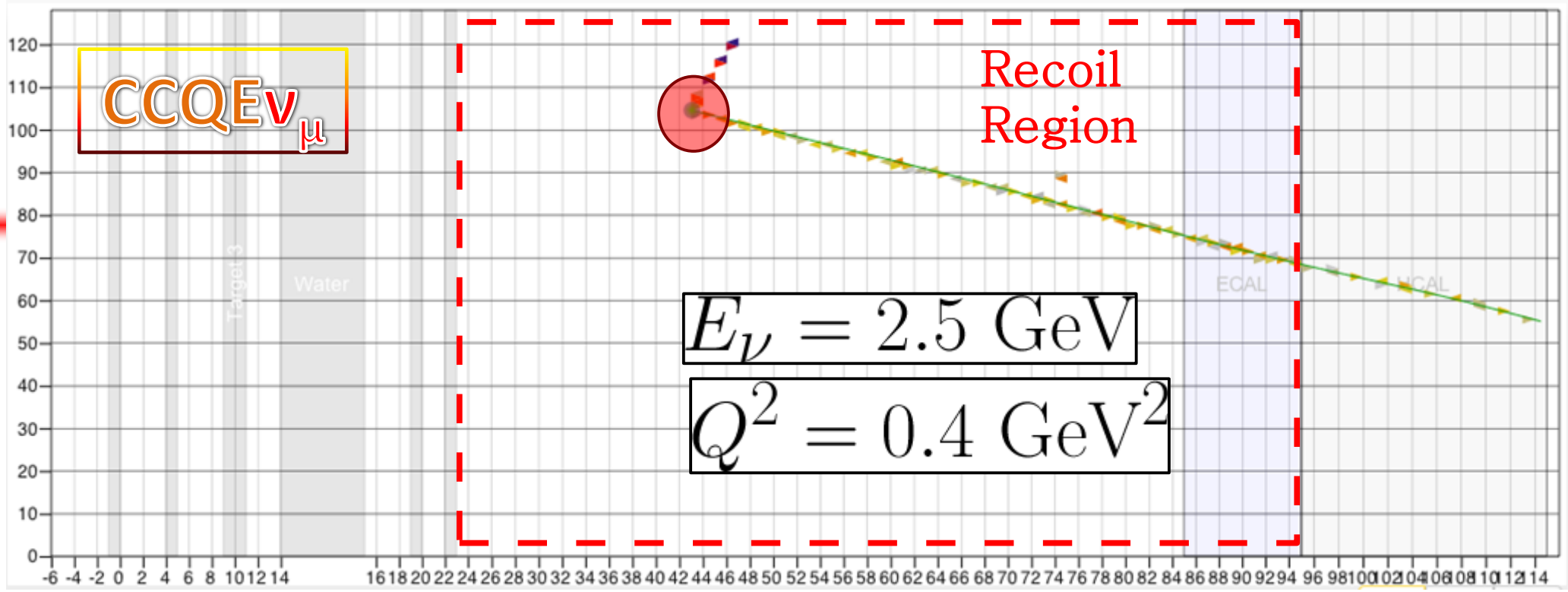
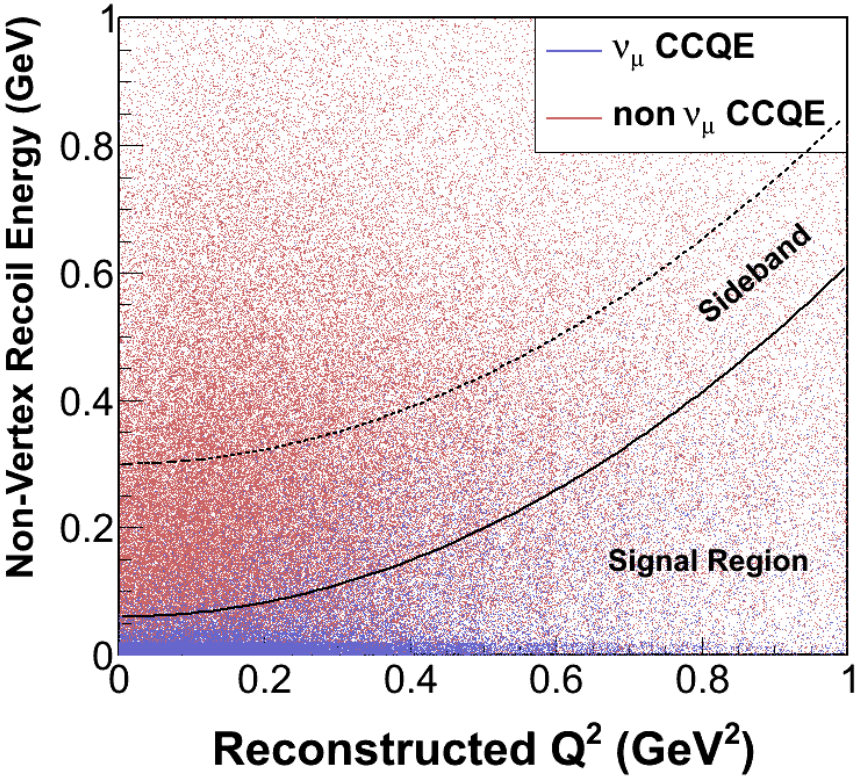



- Require a $\mu^-$ matched into MINOS.
- Require no other tracks.
- Require 0 or 1 isolated blob (untracked proton candidate).
- Require small recoil energy, excluding 10cm around vertex.

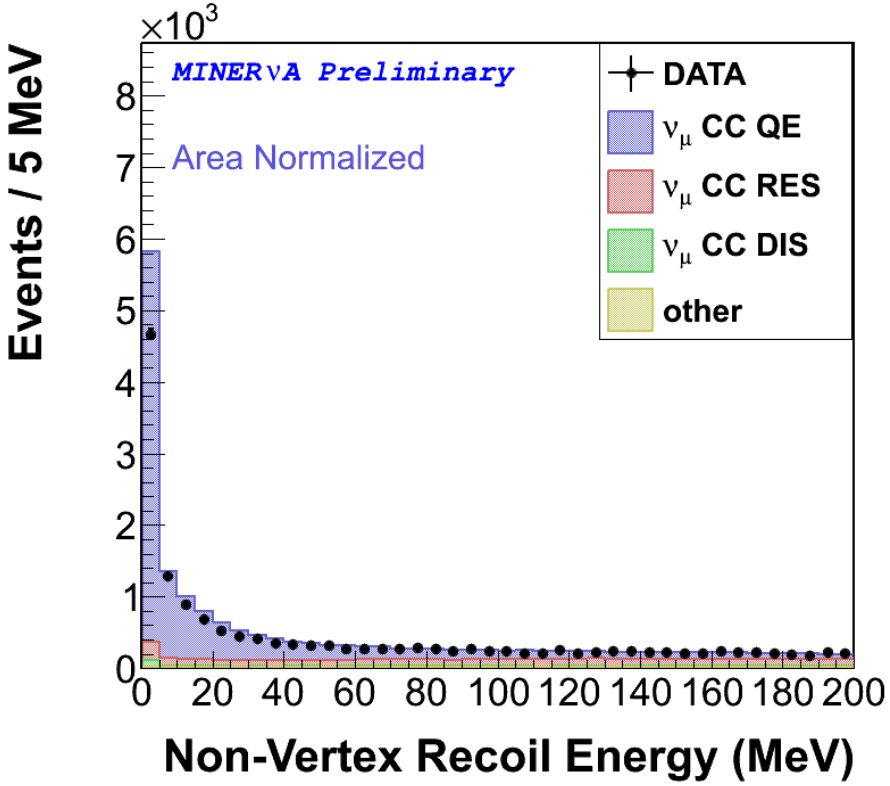
$$E_\nu = \frac{m_\mu^2 - (m_p - E_b)^2 - m_\mu^2 + 2(m_p - E_b)E_\mu}{2(m_p - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

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

# Recoil Energy Cut CCQE$\nu_\mu$

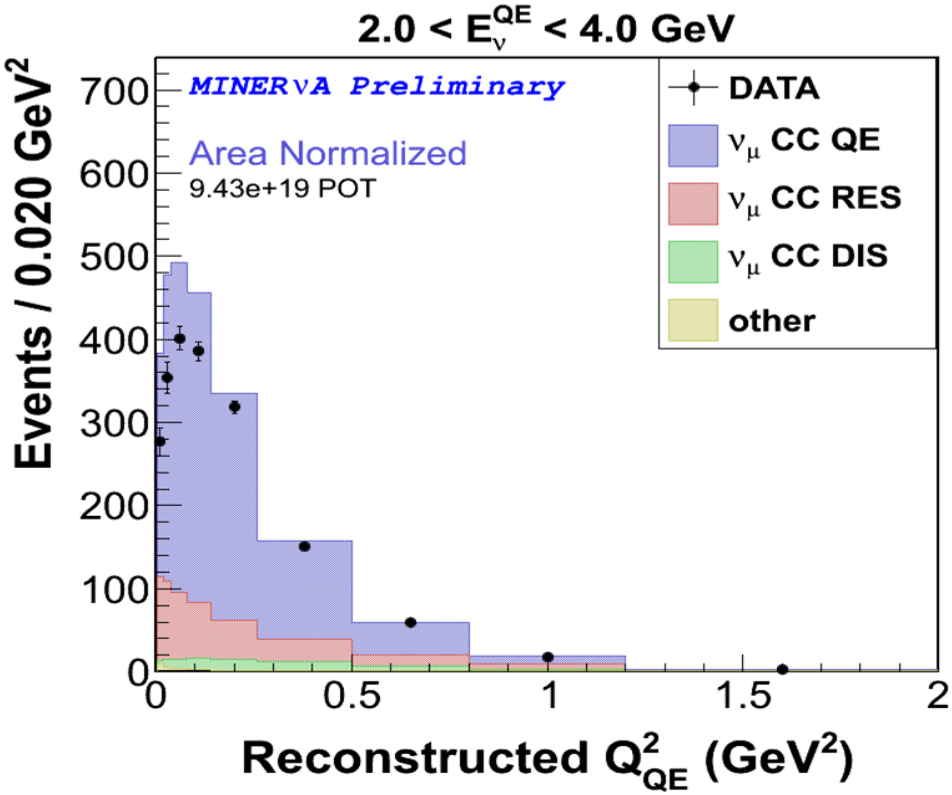



MC sideband scaled to data sideband.
Sets scale for subtraction of background in data.

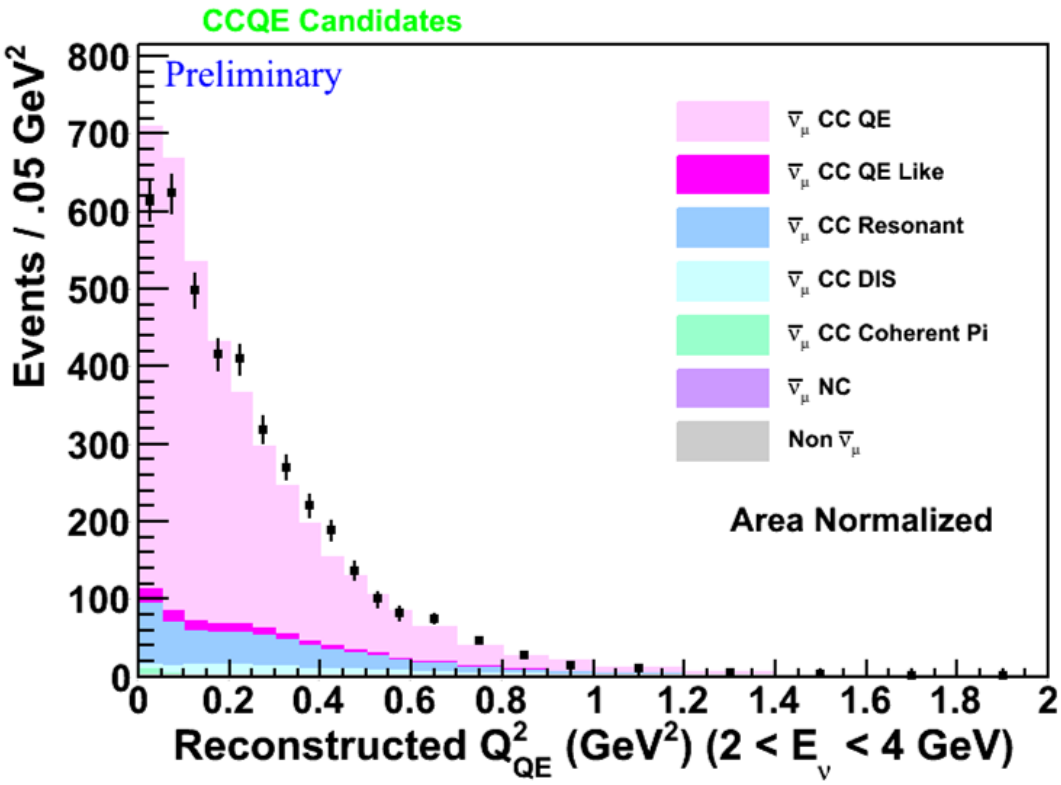


# Neutrino and Antineutrino CCQE 2-4 GeV

CCQE$\nu_\mu$

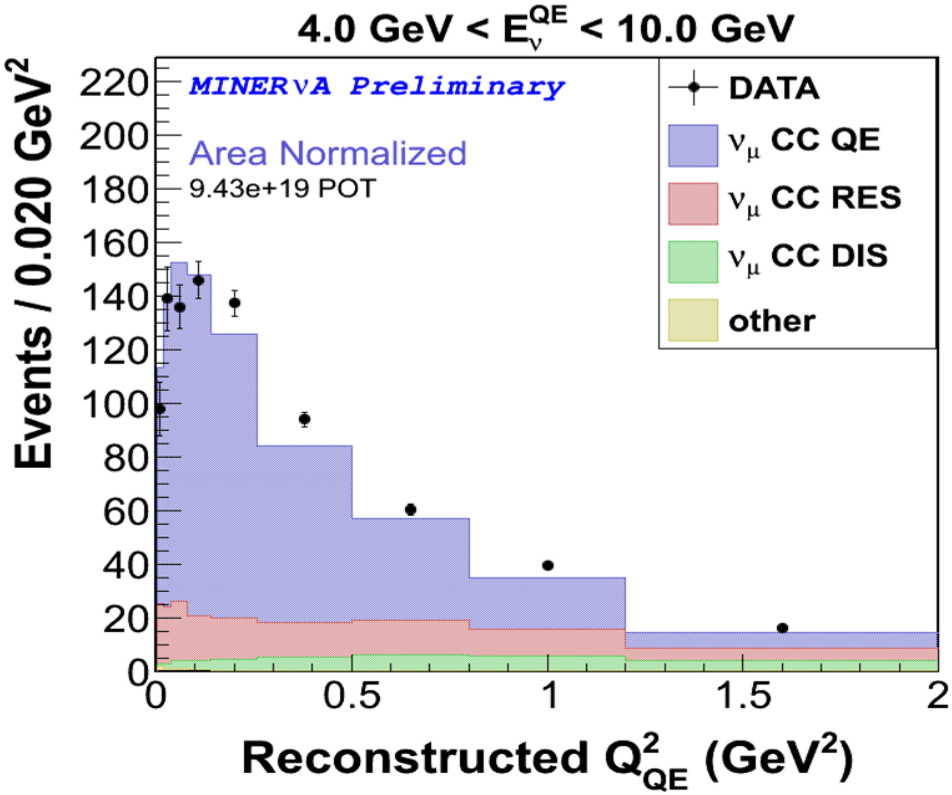



CCQE$\bar{\nu}_\mu$

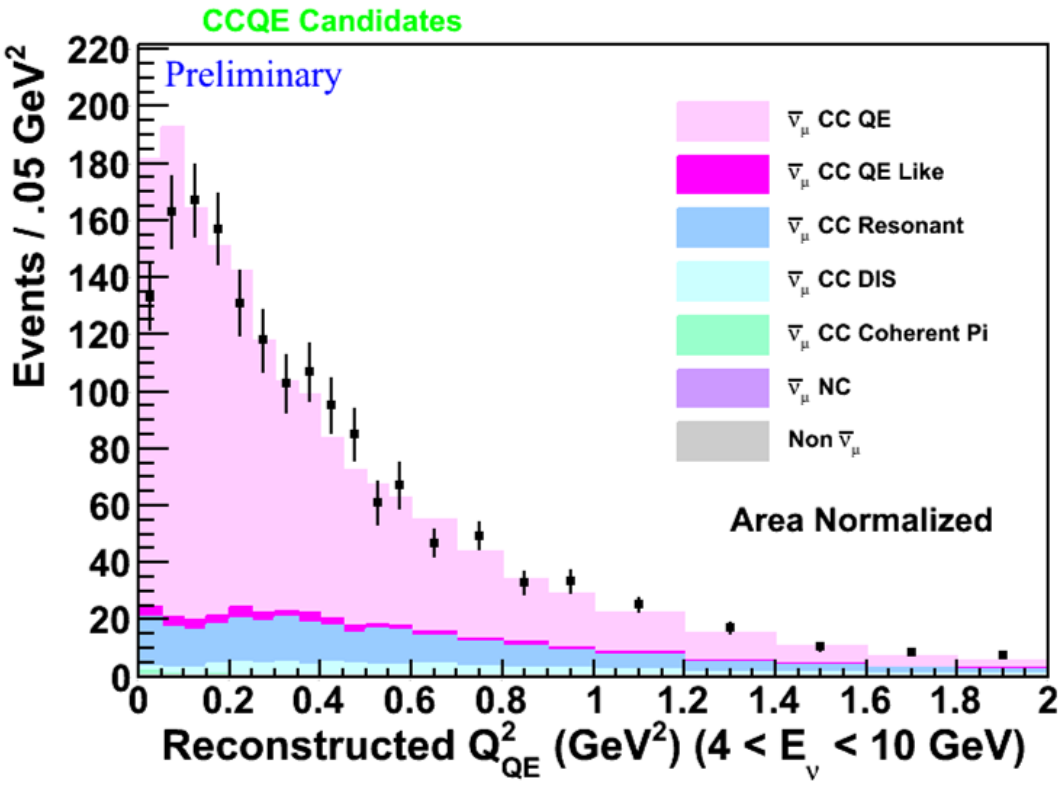


# Neutrino and Antineutrino CCQE 4-10 GeV

CCQE$\nu_\mu$



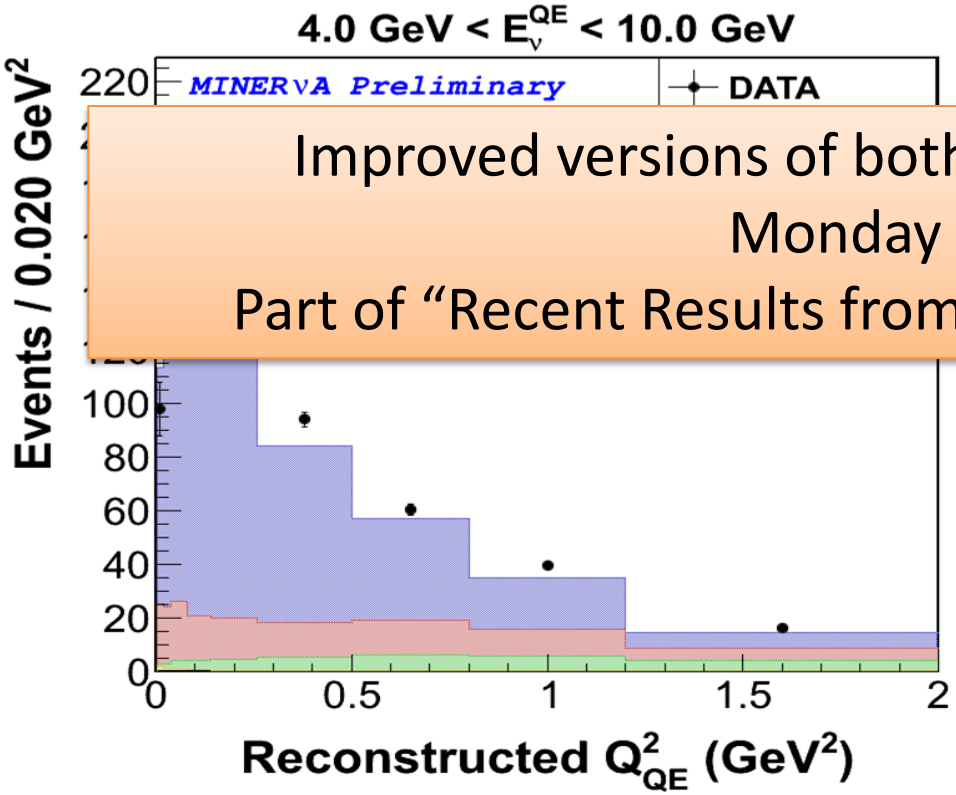

CCQE$\bar{\nu}_\mu$

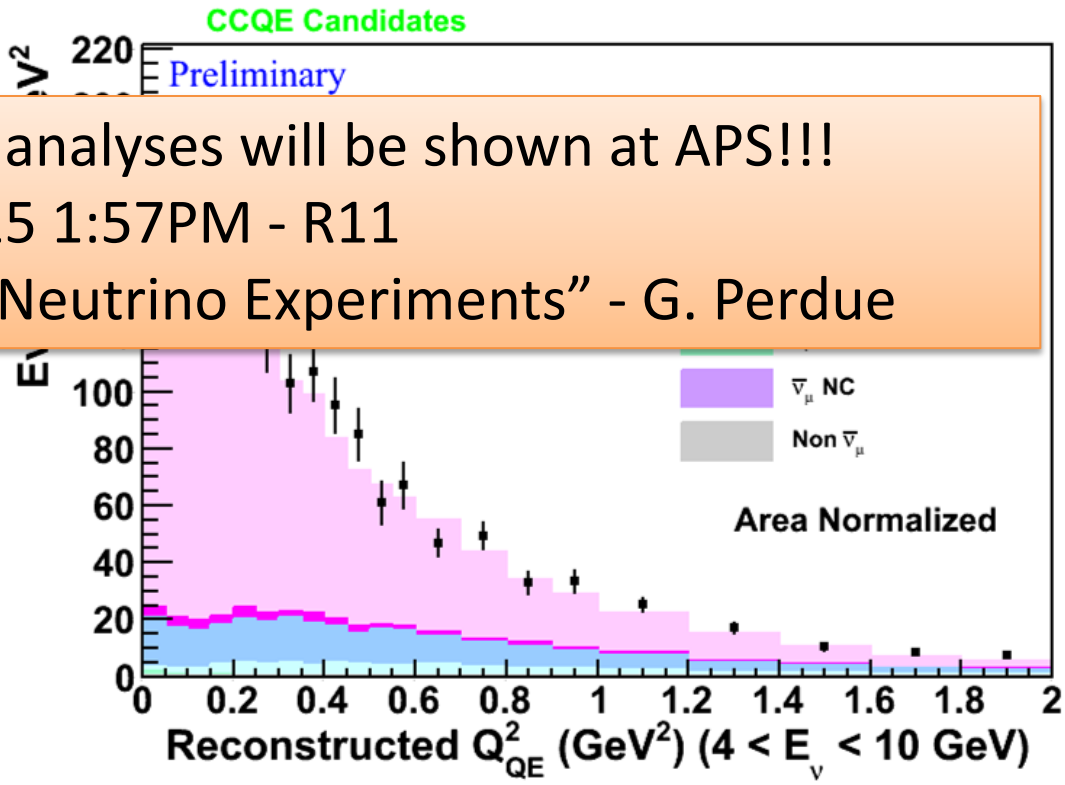


# Neutrino and Antineutrino CCQE 4-10 GeV

CCQE$\nu_\mu$

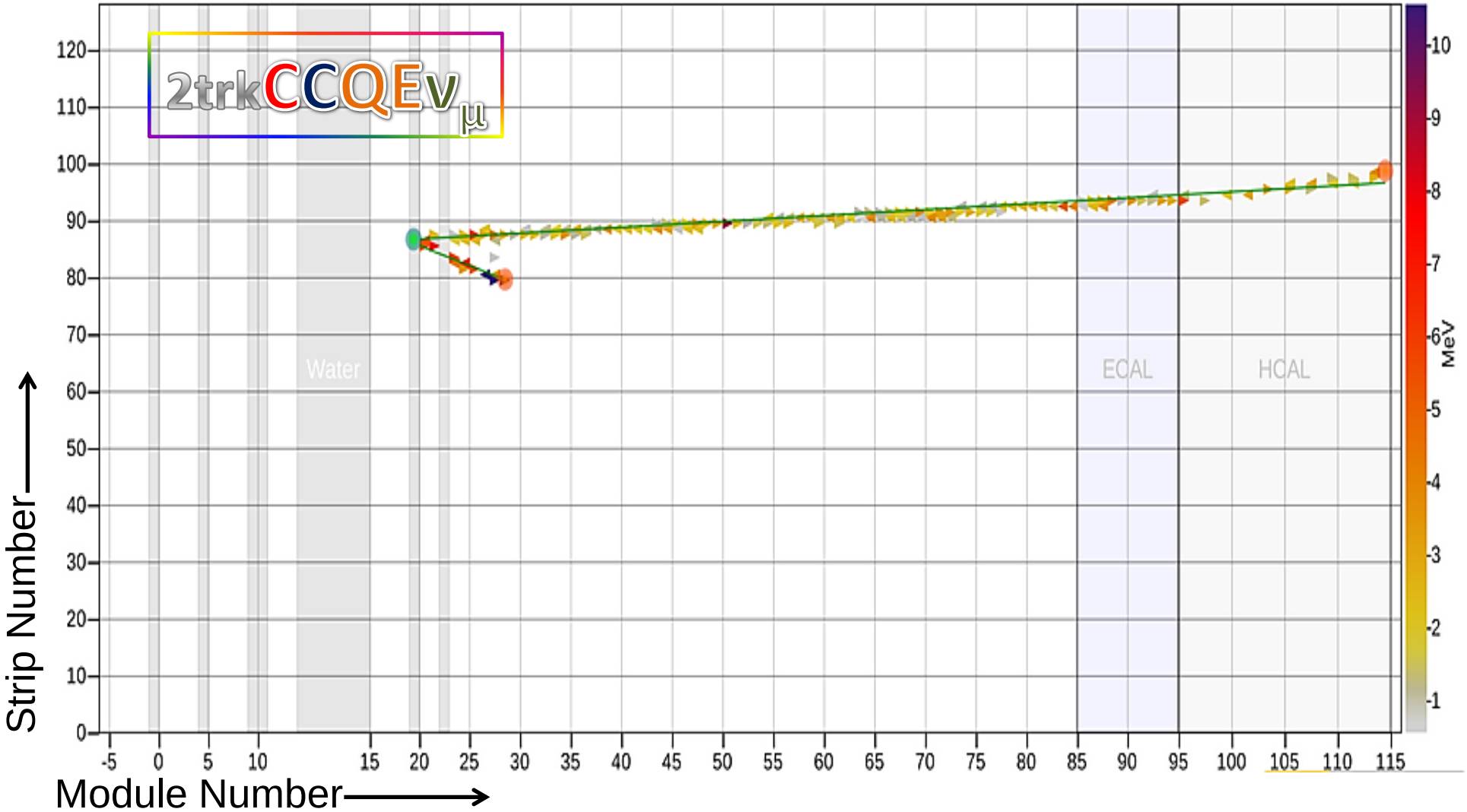
CCQE$\bar{\nu}_\mu$



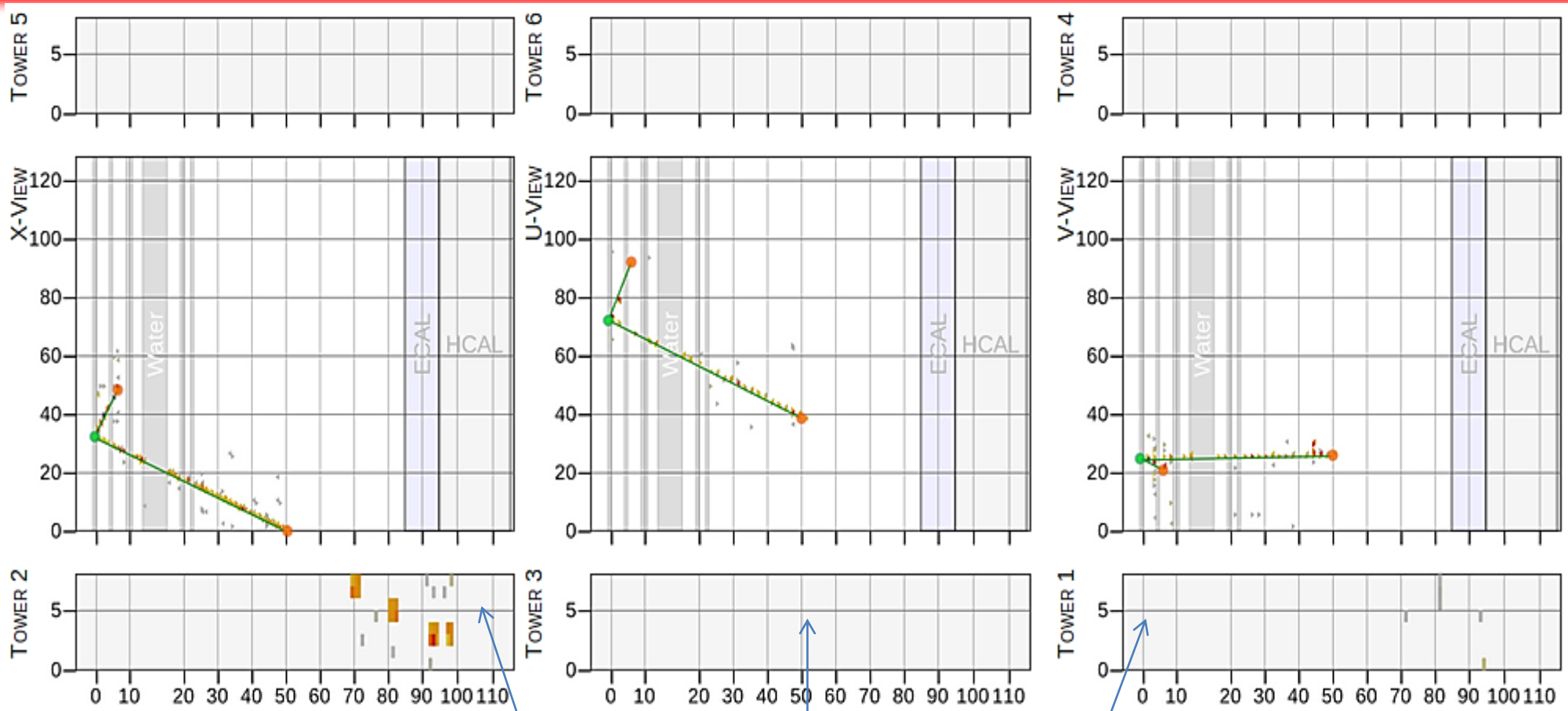

Improved versions of both analyses will be shown at APS!!!
Monday 15 1:57PM - R11
Part of "Recent Results from Neutrino Experiments" - G. Perdue

# 2-track Quasi-elastic Analysis on Nuclear Targets



# 2-track Quasi-elastic Analysis on Nuclear Targets

2trkCCQEν$_\mu$

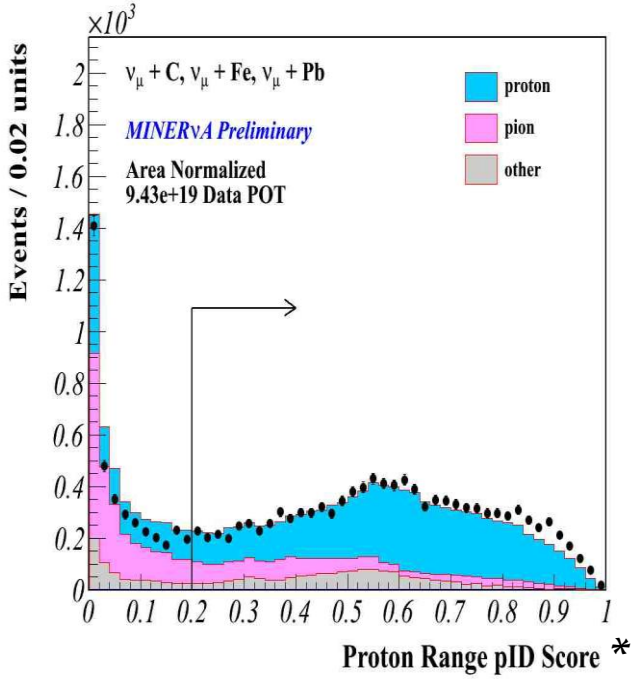


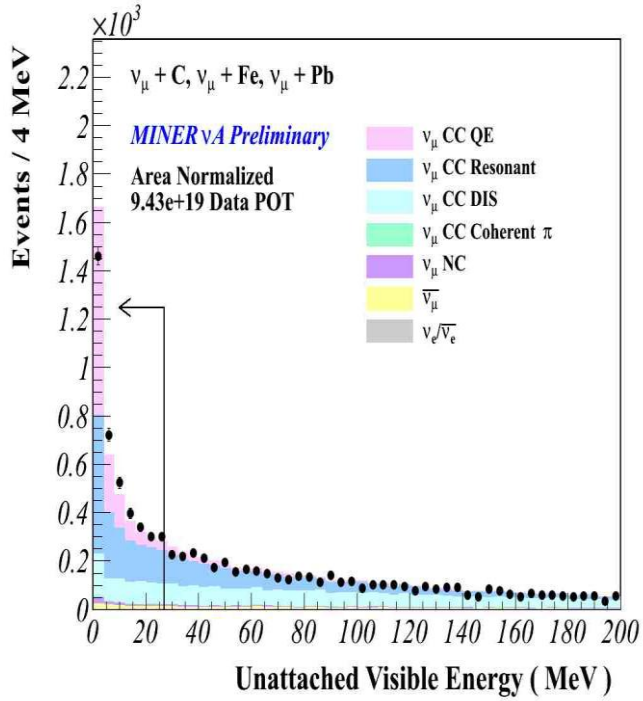

Outer detector sampling calorimeter "towers".

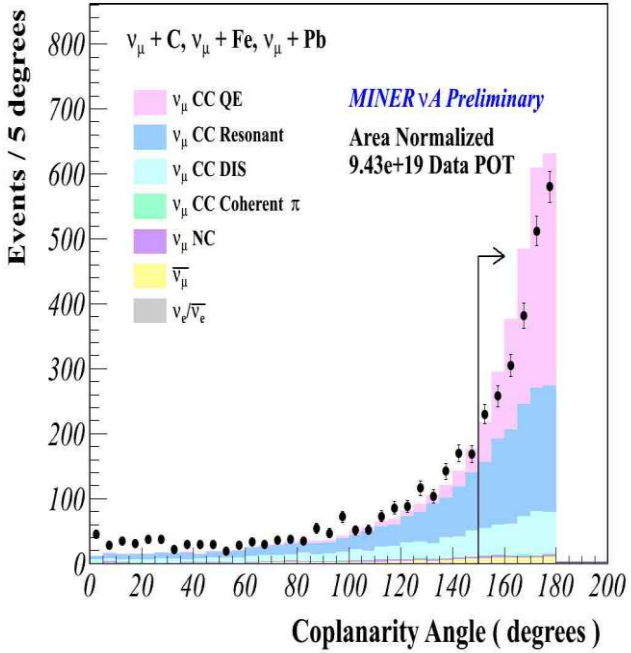
Muons in outer detector have neither charge nor good momentum reconstruction.
Interaction kinematics can be calculated from proton.

# Event Selection

2trkCCQE$\nu_\mu$




**Cut1:**
Tracked hadron is a proton.

**Cut2:**
Non-vertex recoil energy is small.

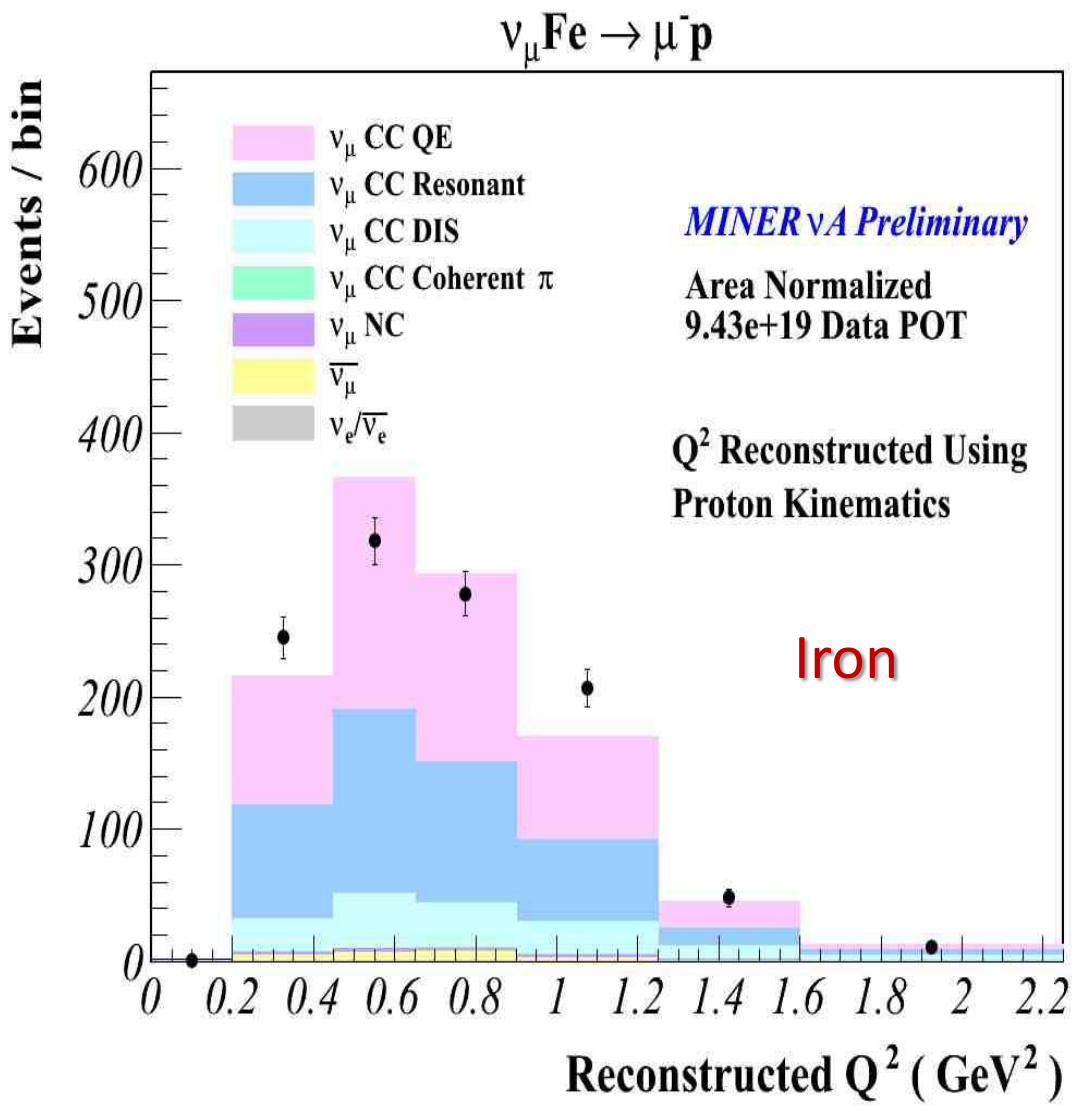
**Cut3:**
Muon and proton are back-to-back in beam frame.

* Score is combination of chi2 from fit to dEdx of proton and pion

**Purity is ~ 50% after cuts.**

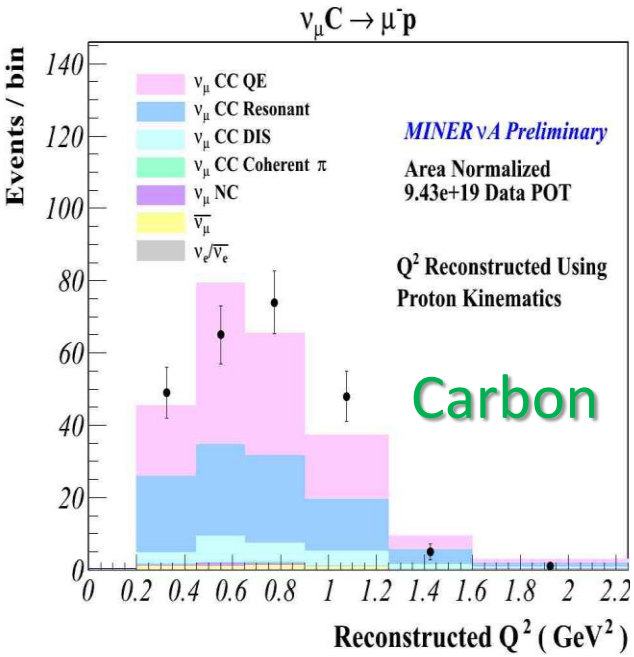
# $Q^2$ Calculated from Proton

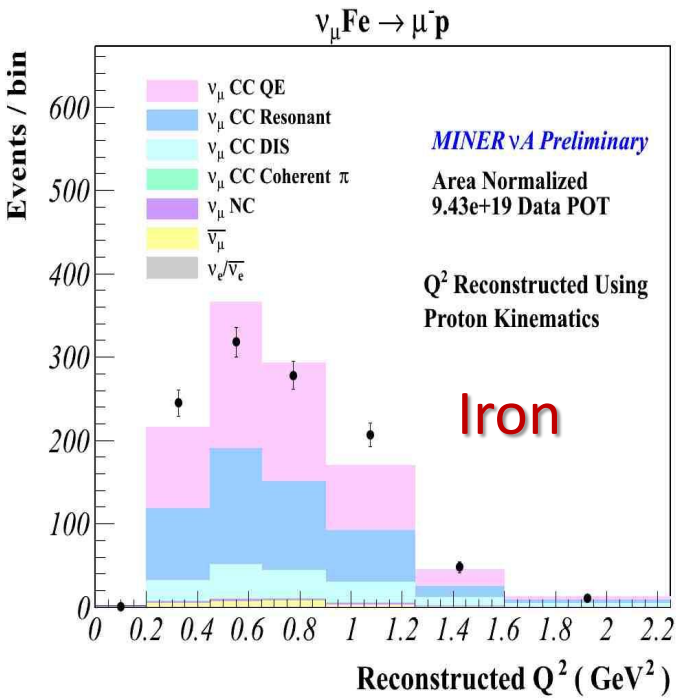
2trkCCQE$\nu_\mu$

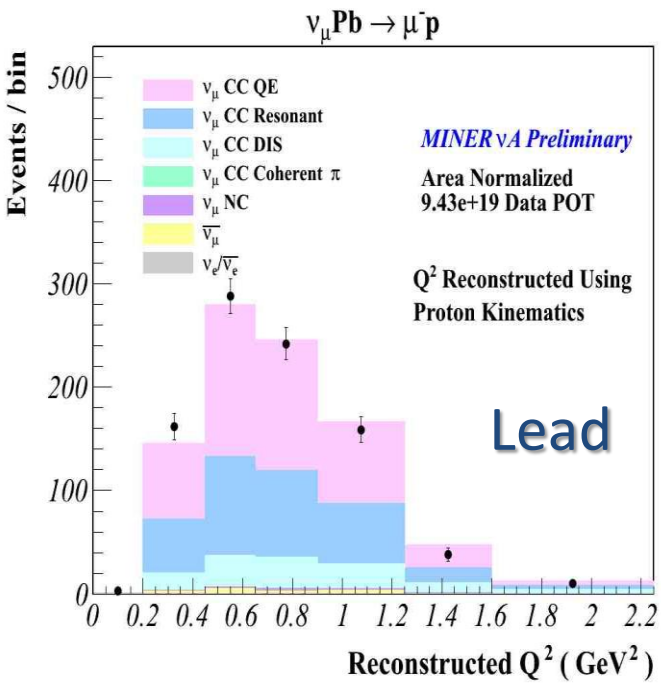


# $Q^2$ Calculated from Proton

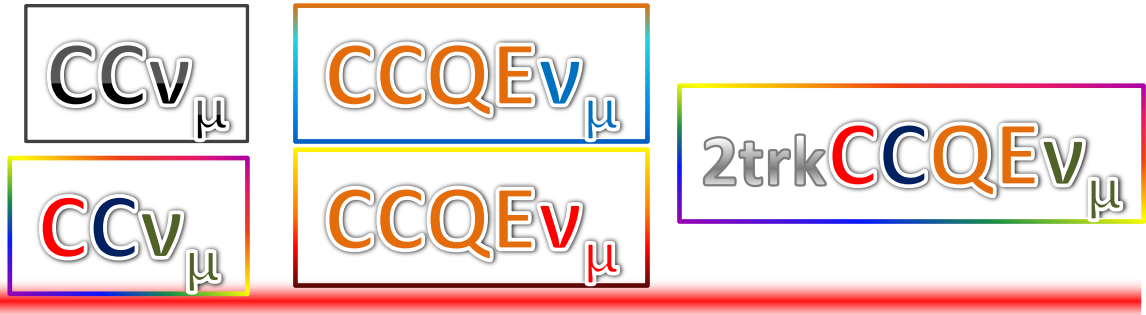
2trkCCQE$\nu_\mu$



# In closing…




- MINERvA: Built to study nucleon structure with neutrino interactions.
- Inclusive analyses in progress…
  - Cross sections on scintillator, carbon, iron, lead.
    - Ratios technique is promising.
  - Repeat inclusive analysis in NOvA-era run ( <3GeV> → <6GeV> ).
    - Extract structure functions with larger DIS sample.
- Quasi-elastic analyses near first maturity…
  - Neutrino and anti-neutrino cross sections compared to models.
    - Measures axial structure of nucleon in nuclear environment.
  - Vertex energy distributions study poorly know physics.
    - Possibly observe nucleon-nucleon correlation.

# Thank you!

More MINERvA next week…

Tuesday, April 16 11:45AM
Minerva Detector Calibration – L. Rakotondravohitra

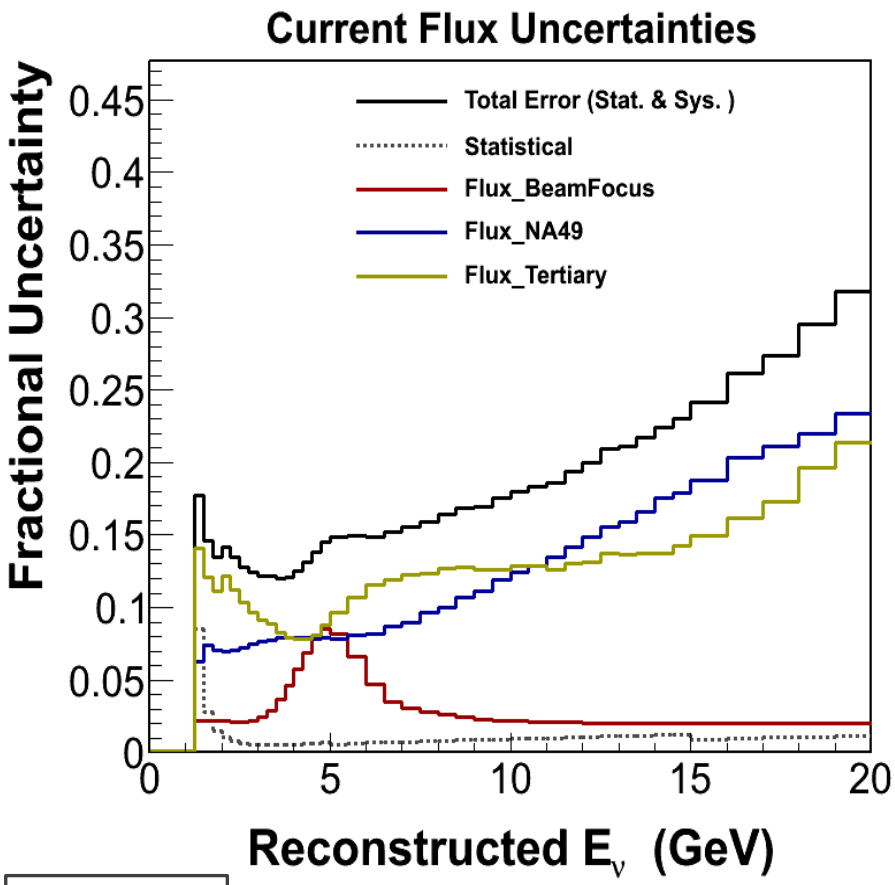
Tuesday, April 16 11:57AM
MINERvA CC Inclusive Analysis – D. Martinez

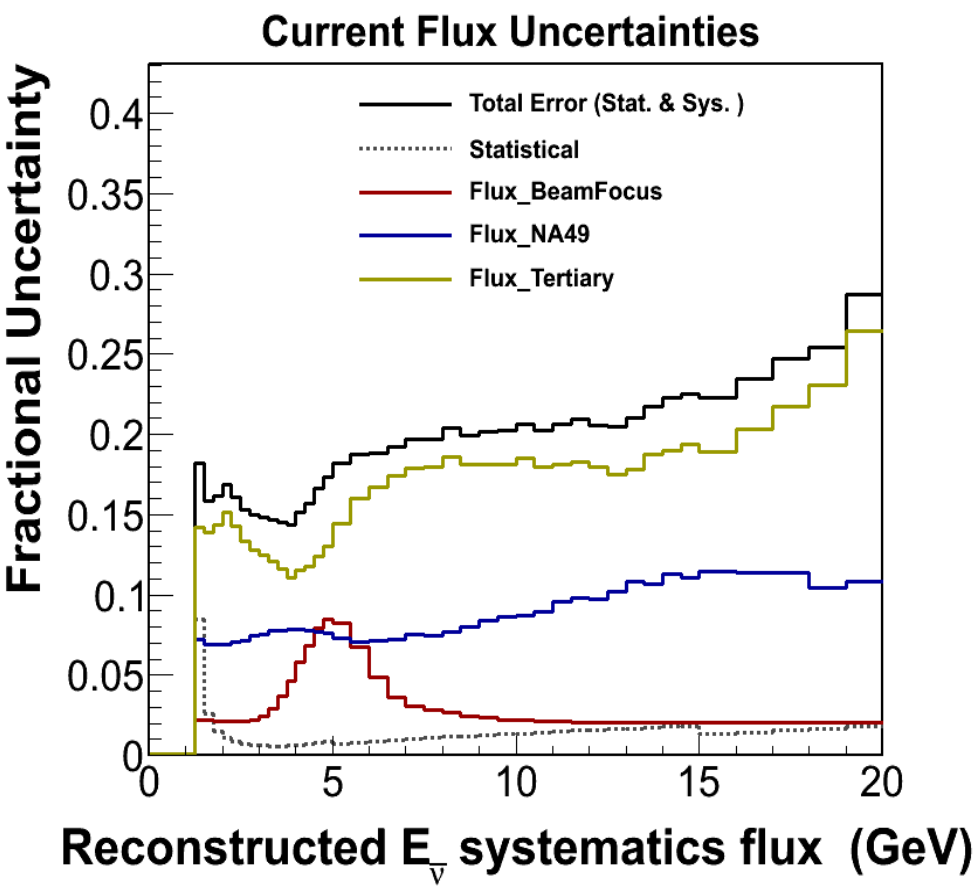
Tuesday, April 16 12:09PM
Inclusive Charged Pion Production at MINERvA – B. Eberly, C. Simon

Monday, April 15 1:57PM
Recent Results from Neutrino Experiments – G. Perdue

# Backup

# We have a plan to reduce flux uncertainties…

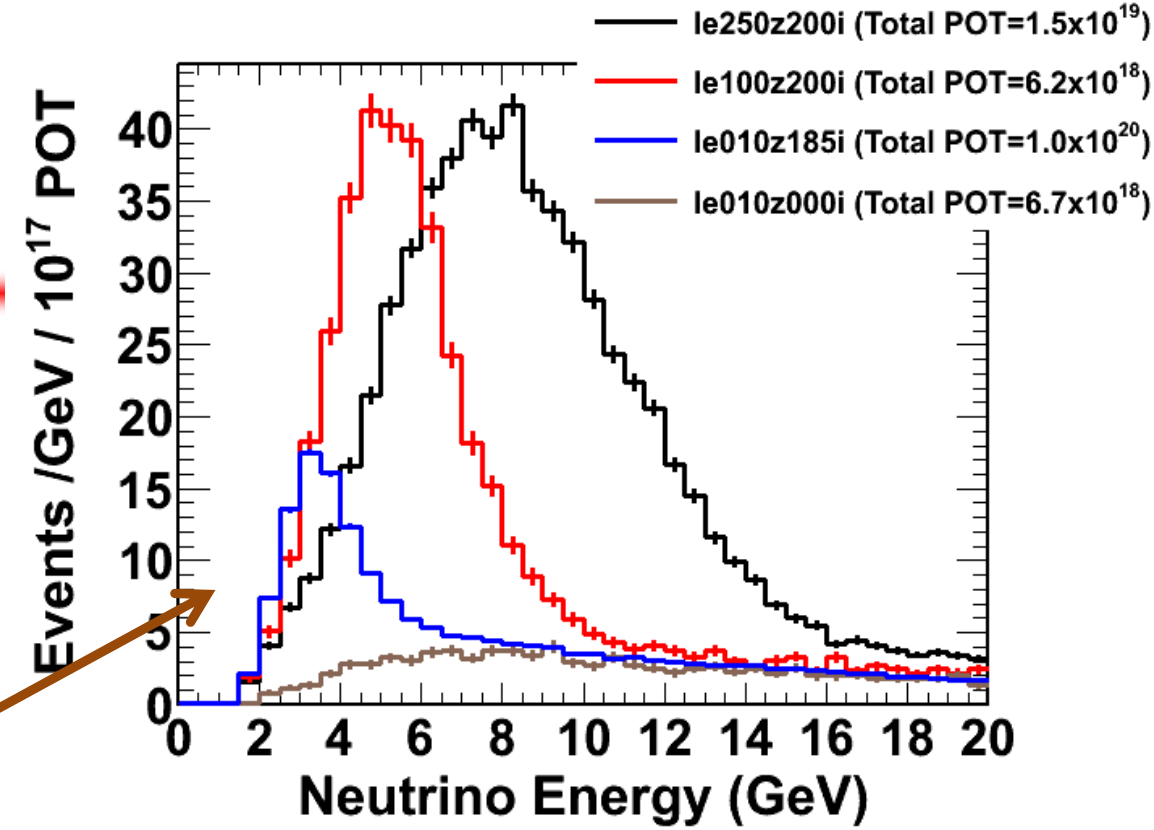



$CC\nu_\mu$

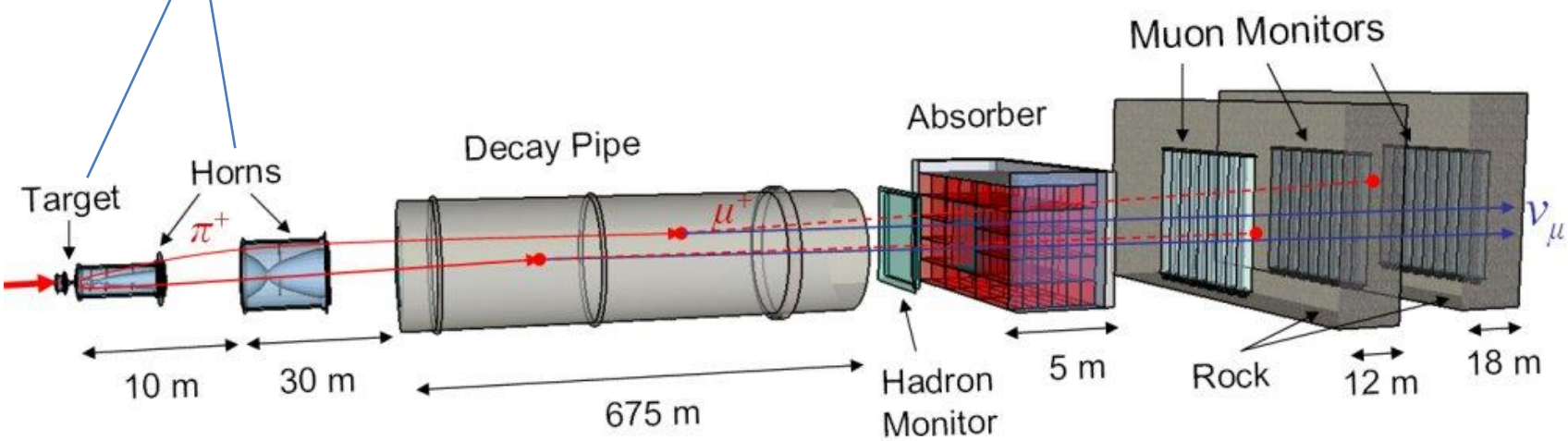
$CC\bar{\nu}_\mu$

# Understanding Our Flux




Vary the target position and the horn current to change the flux spectrum.

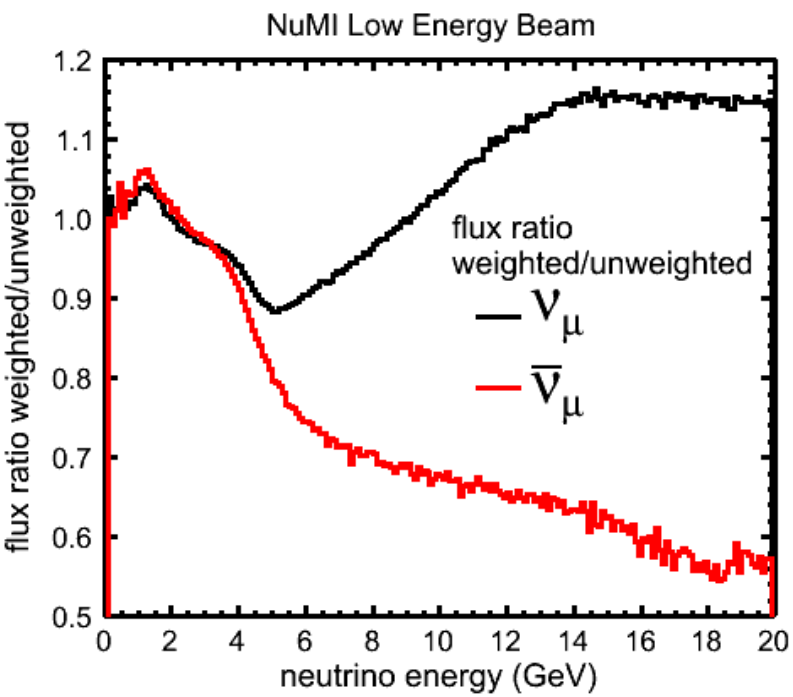
Monitor spread of μ± from π± decay

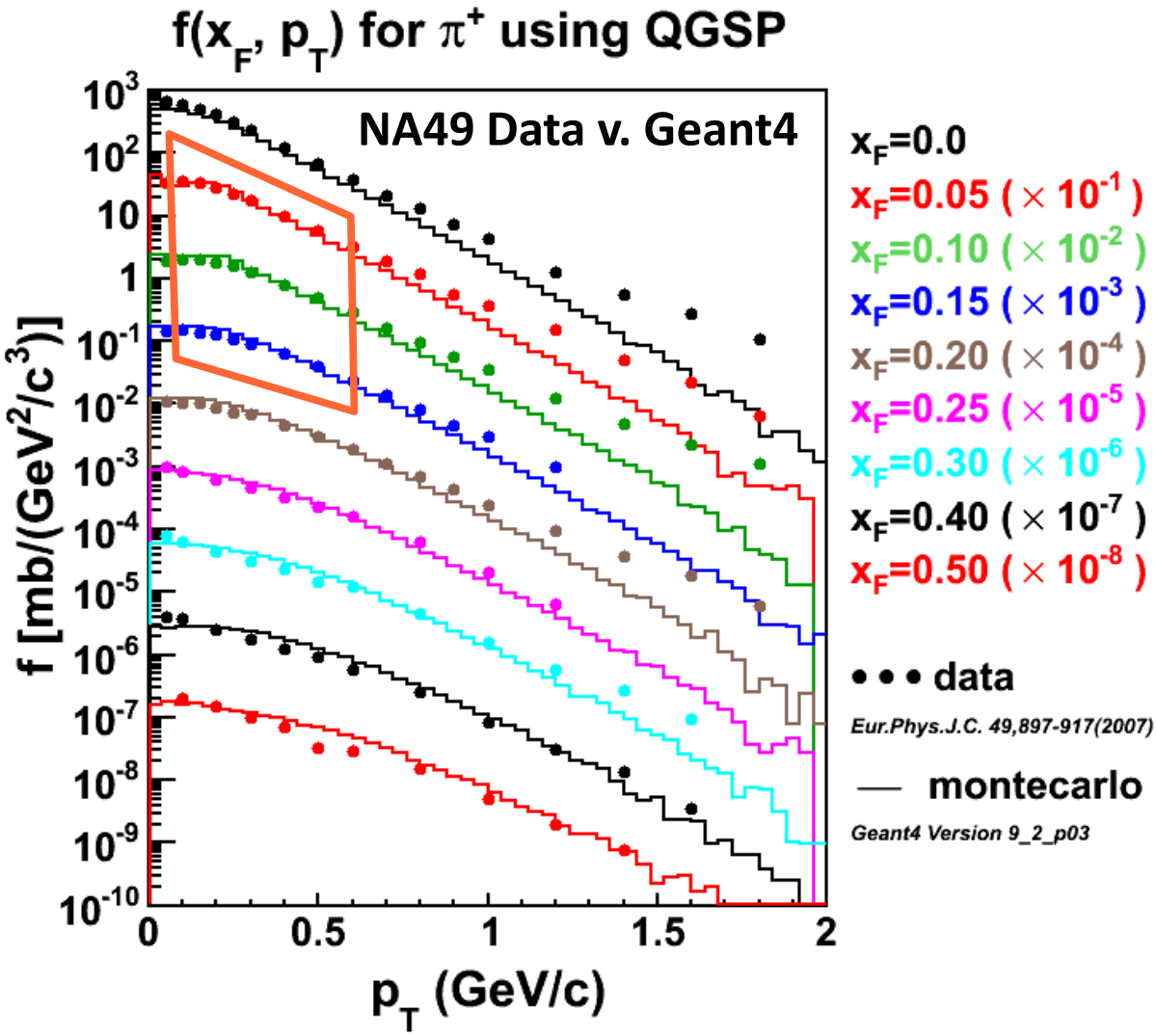



MINERvA

# Tuning to Hadron Production Data

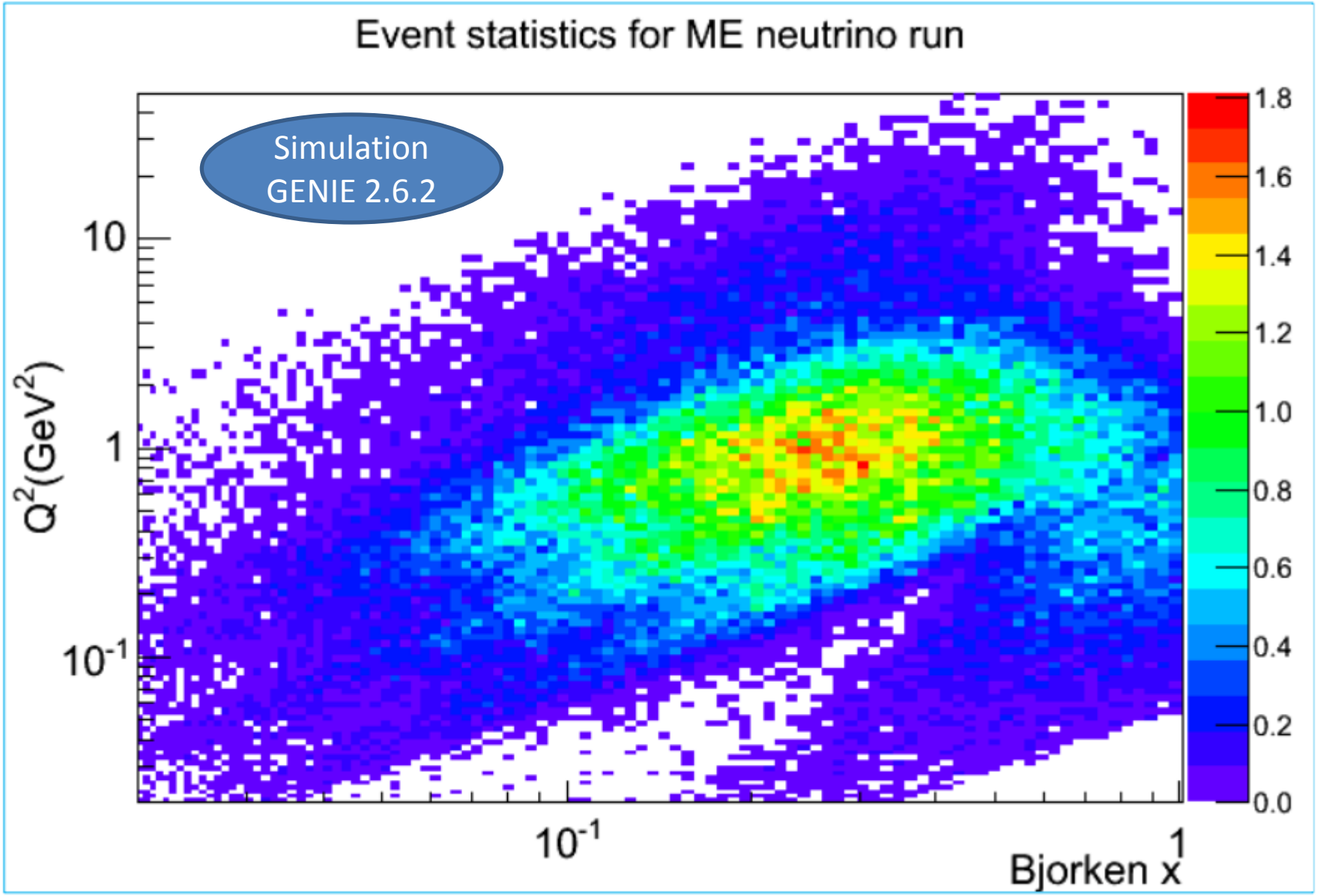
- Hadron production simulated with Geant4 to predict flux.
- Flux is reweighted based on hadron production data compared to Geant4.



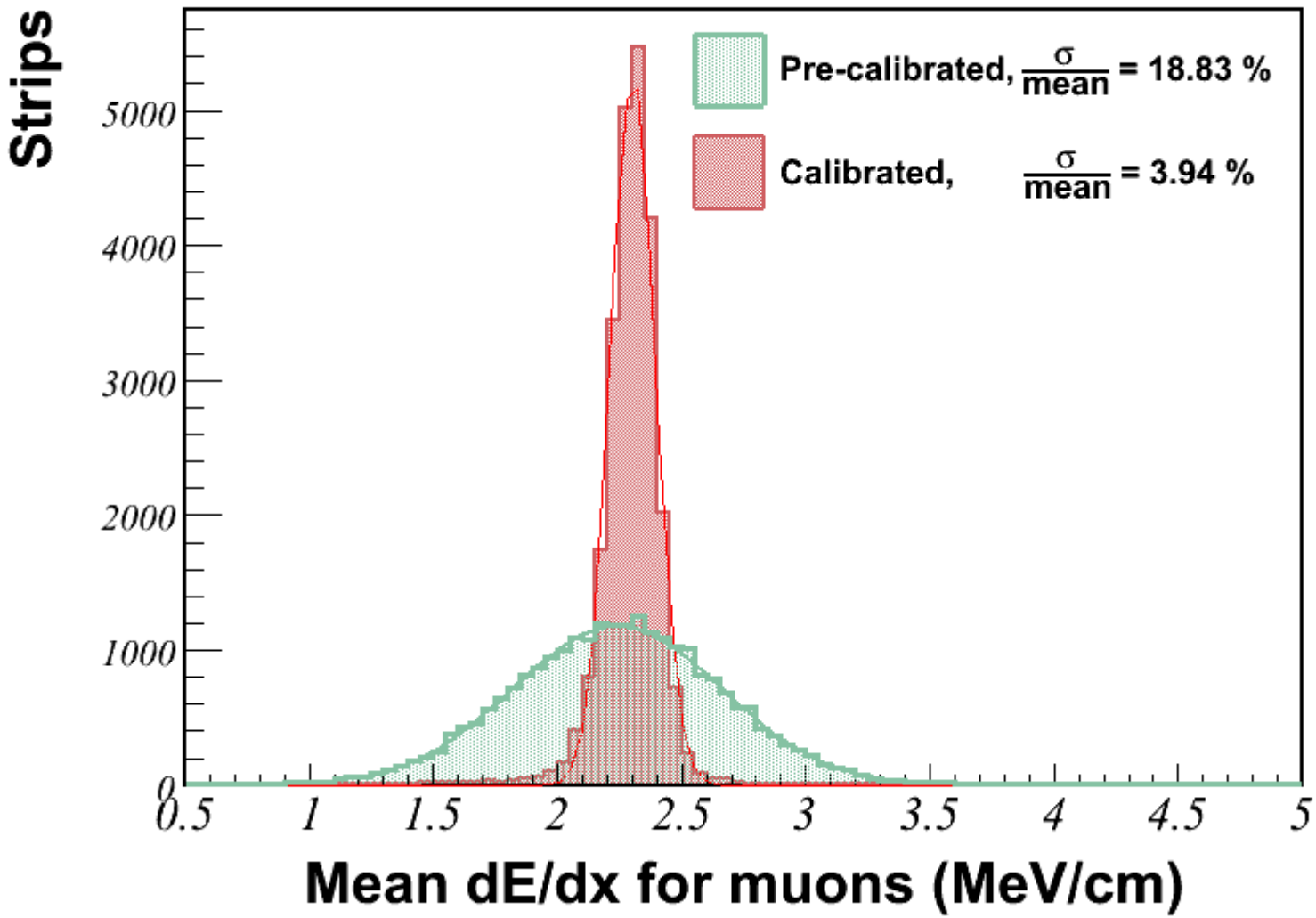



# Events accepted during NOvA run

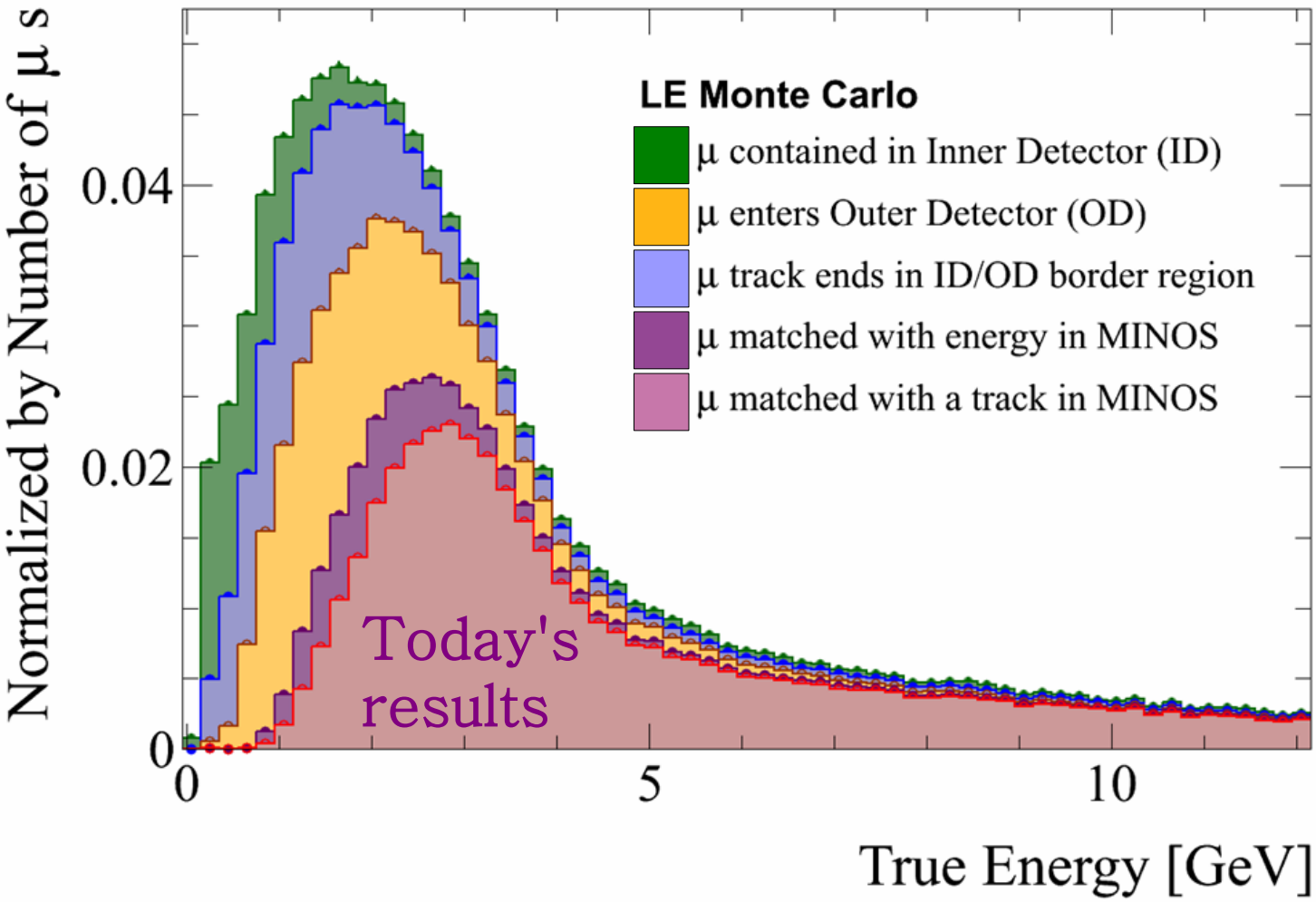
z axis in kiloevents/3 tons of carbon/6e20 POT



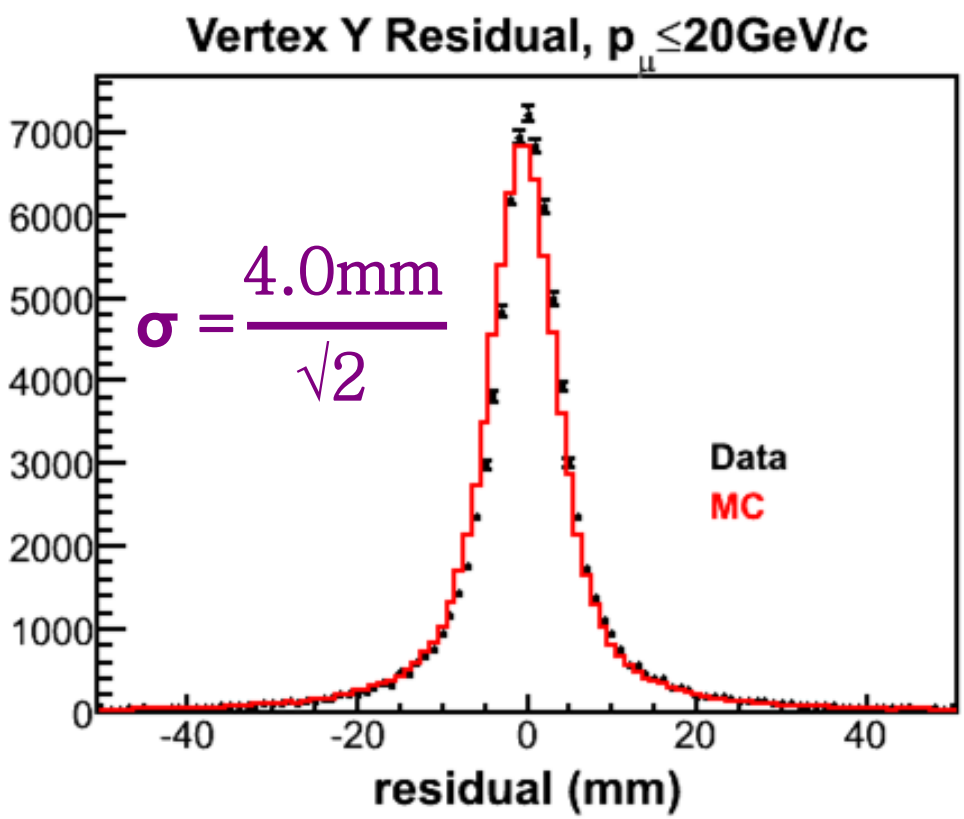
# Alignment and Strip Response

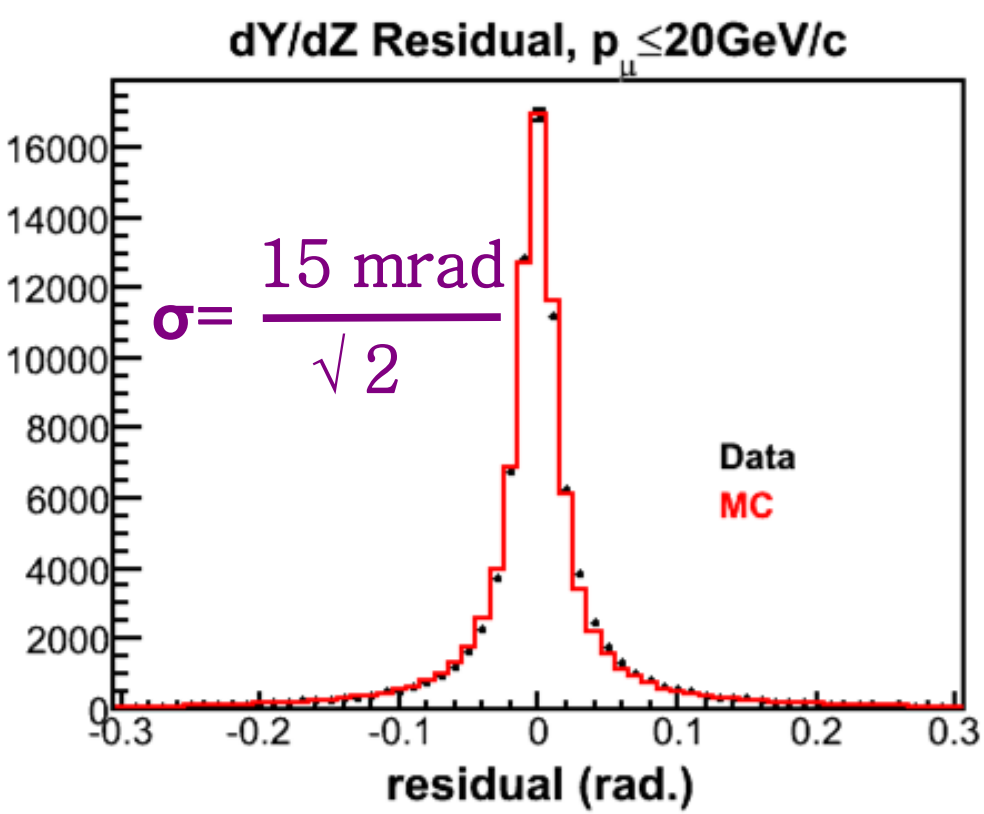


# Where do the muons go?



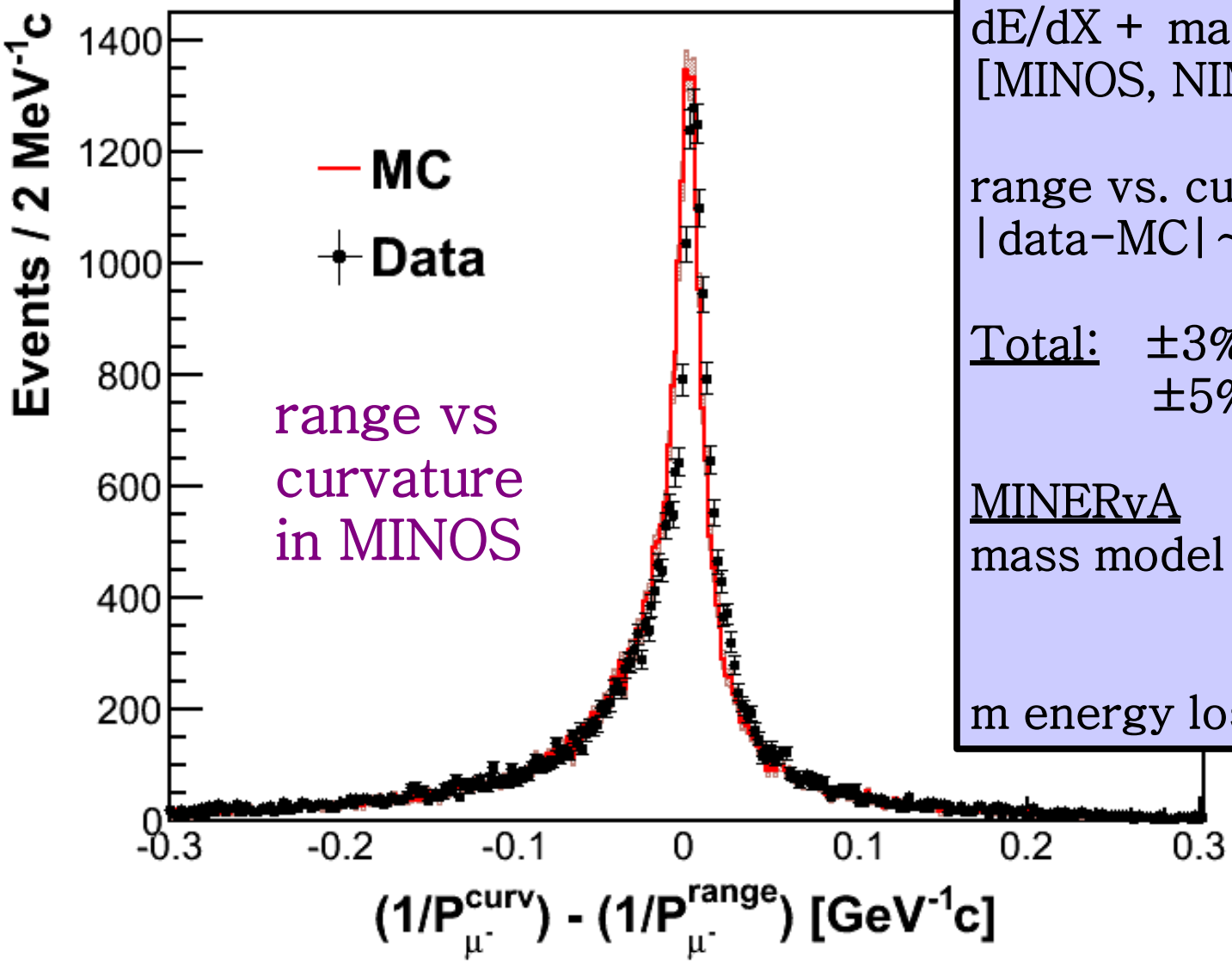
# Tracking Resolutions




Split-track study of rock m in tracker region

# Muon Energy Uncertainty




MINOS
dE/dX + mass model = 2%
[MINOS, NIM A 596, 190 (2008)]

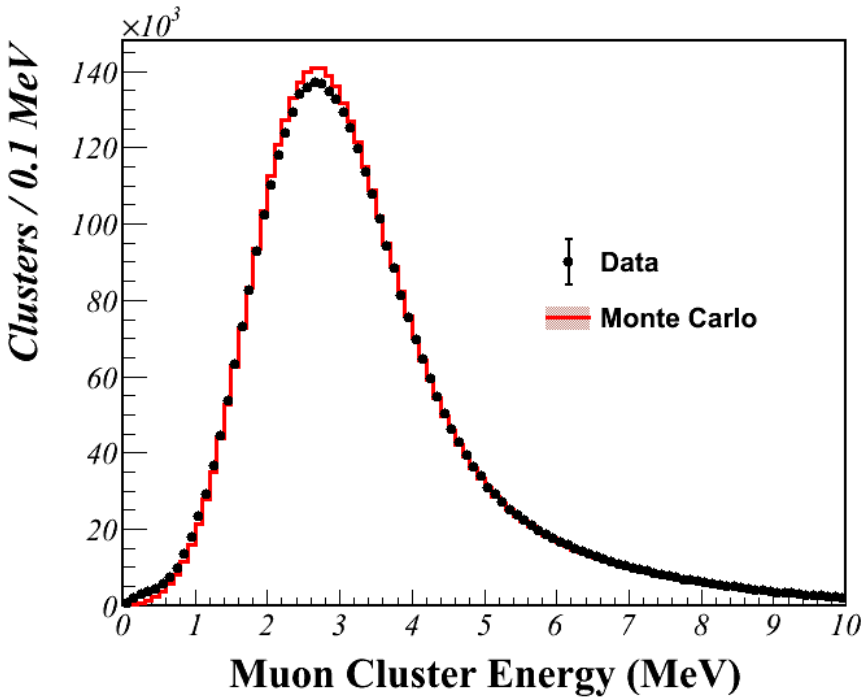
range vs. curvature
|data−MC| ~25 MeV

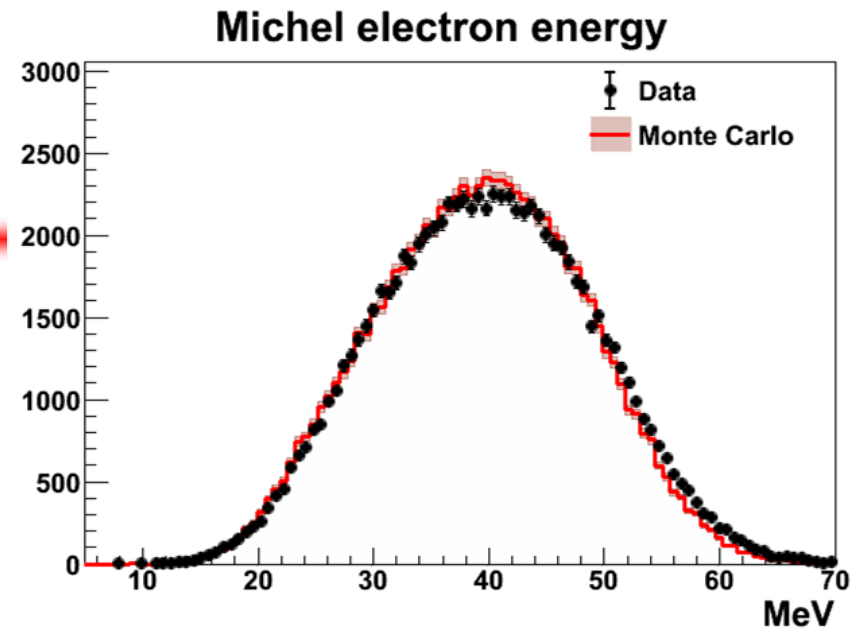
Total: ±3% p> 1.5 GeV
±5% P<1.5 GeV

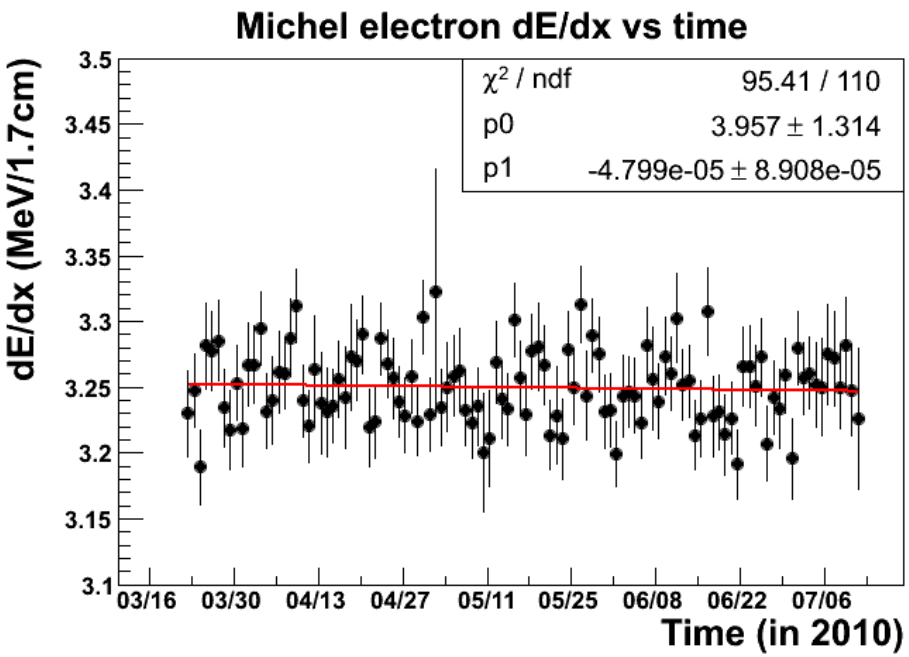
MINERvA
mass model = 11 MeV tracker
= 17 MeV Nucl.Tgts.

m energy loss = 30 MeV

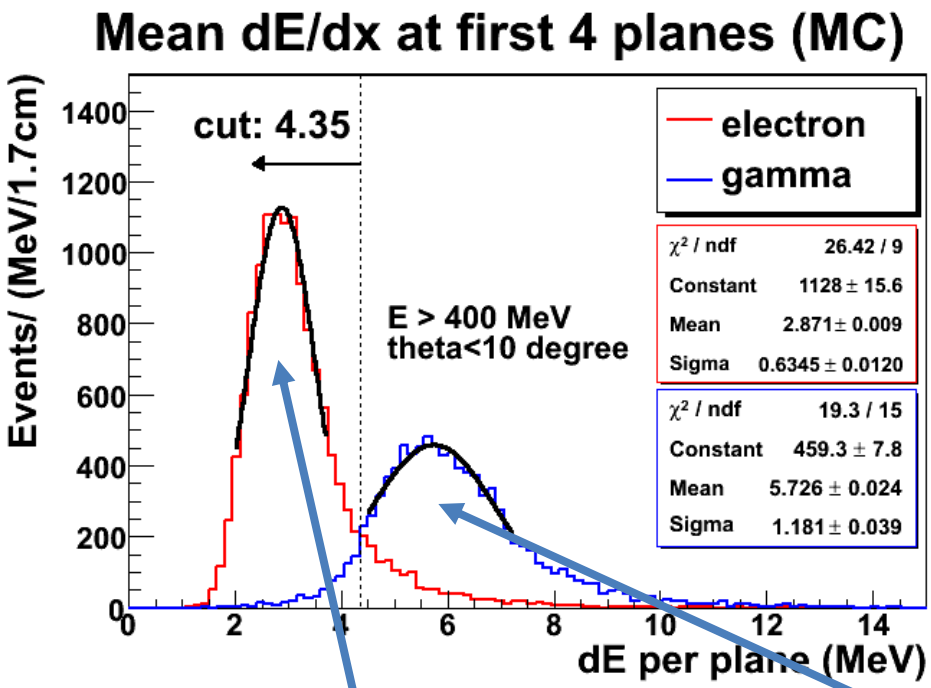
# Energy Scale and Stability

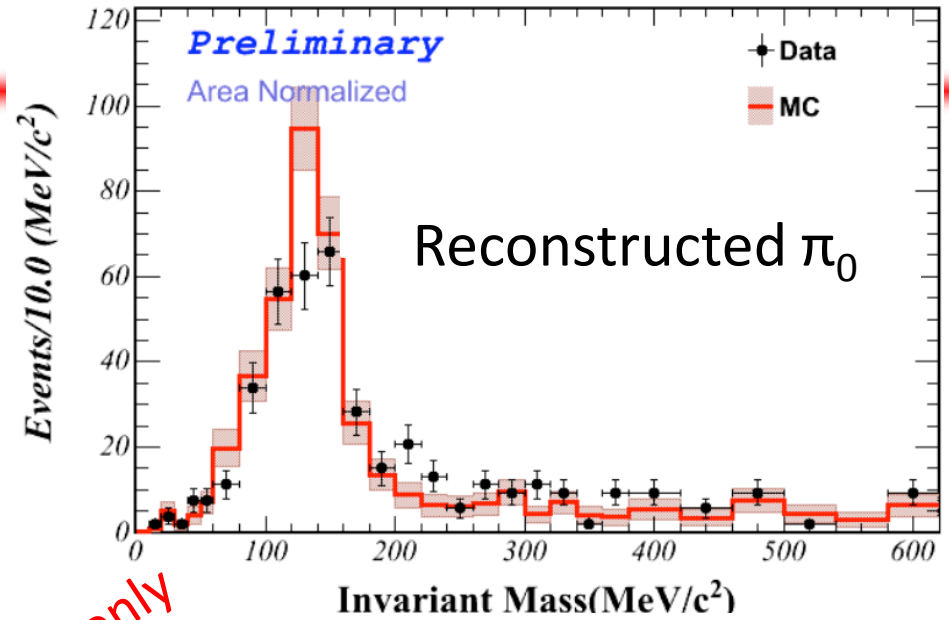


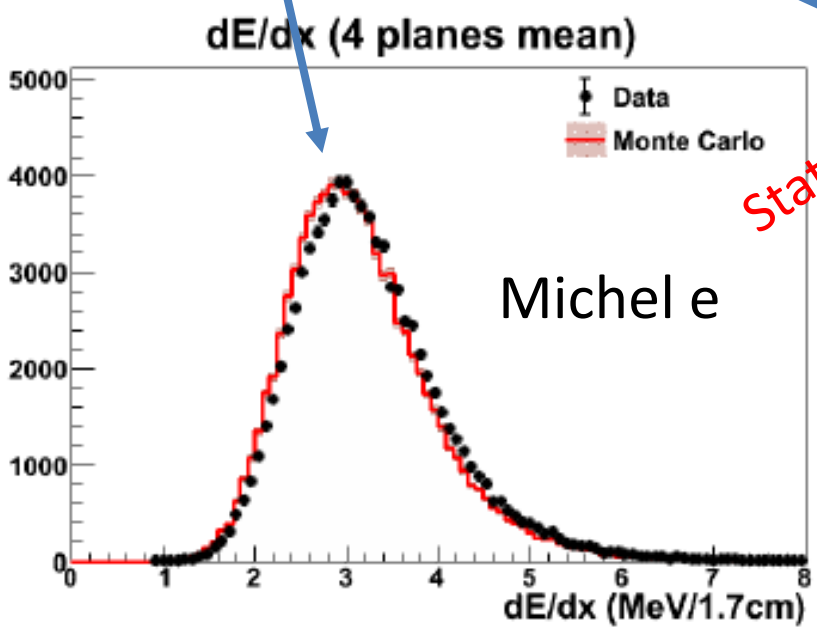



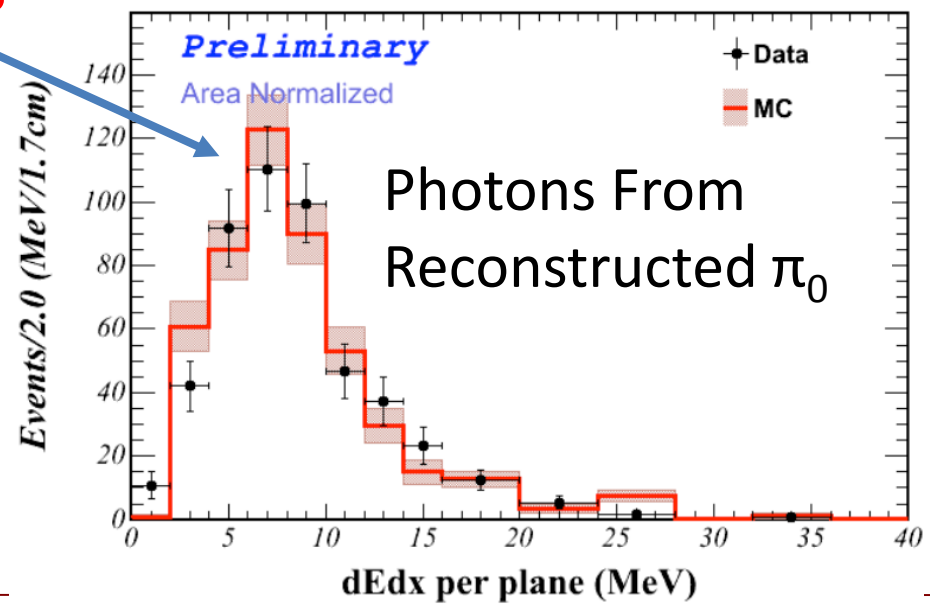
# Michels, $\pi_0$ and e/$\gamma$ Separation



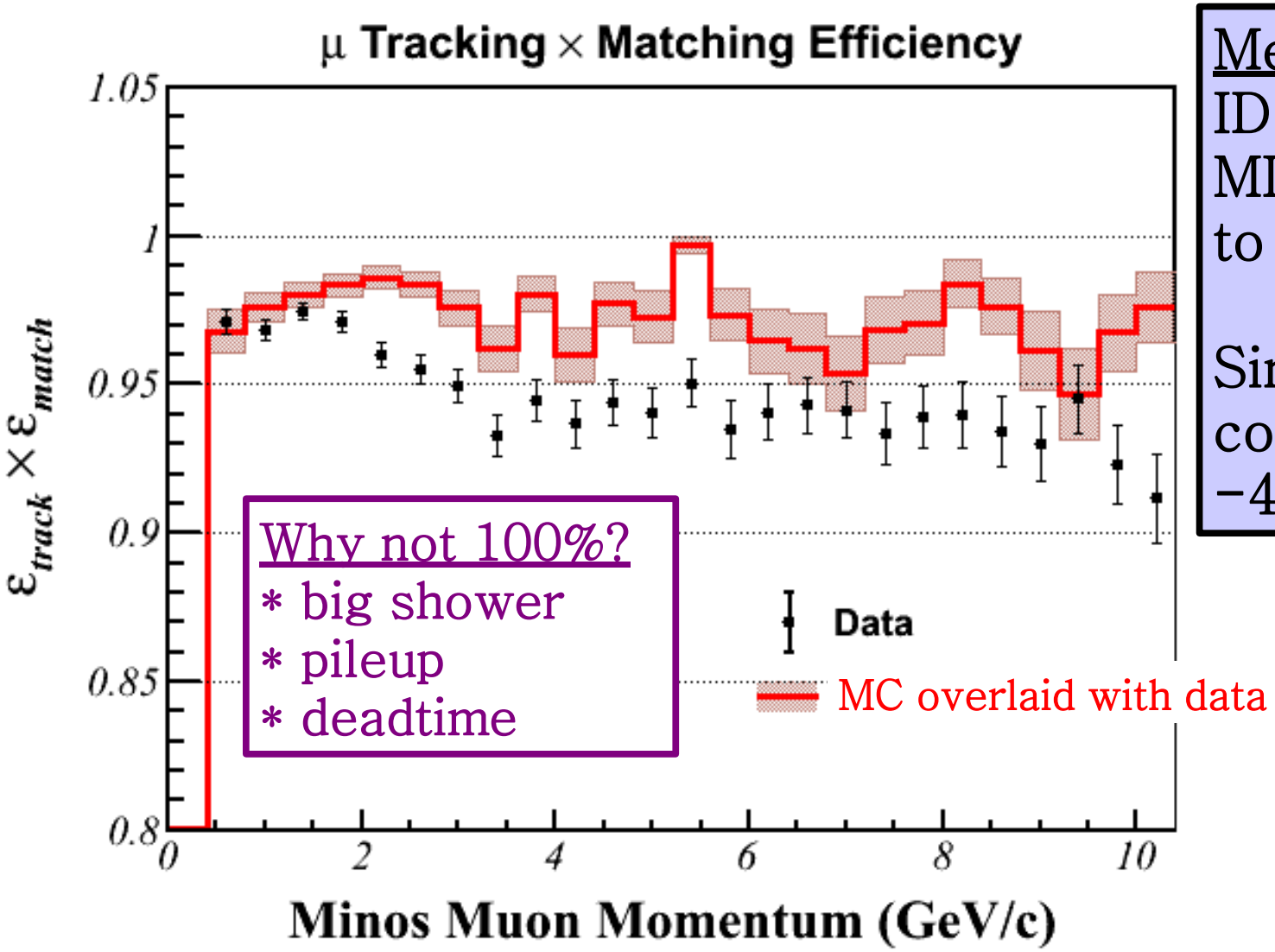




Statistical errors only



# Tracking x Matching Efficiency

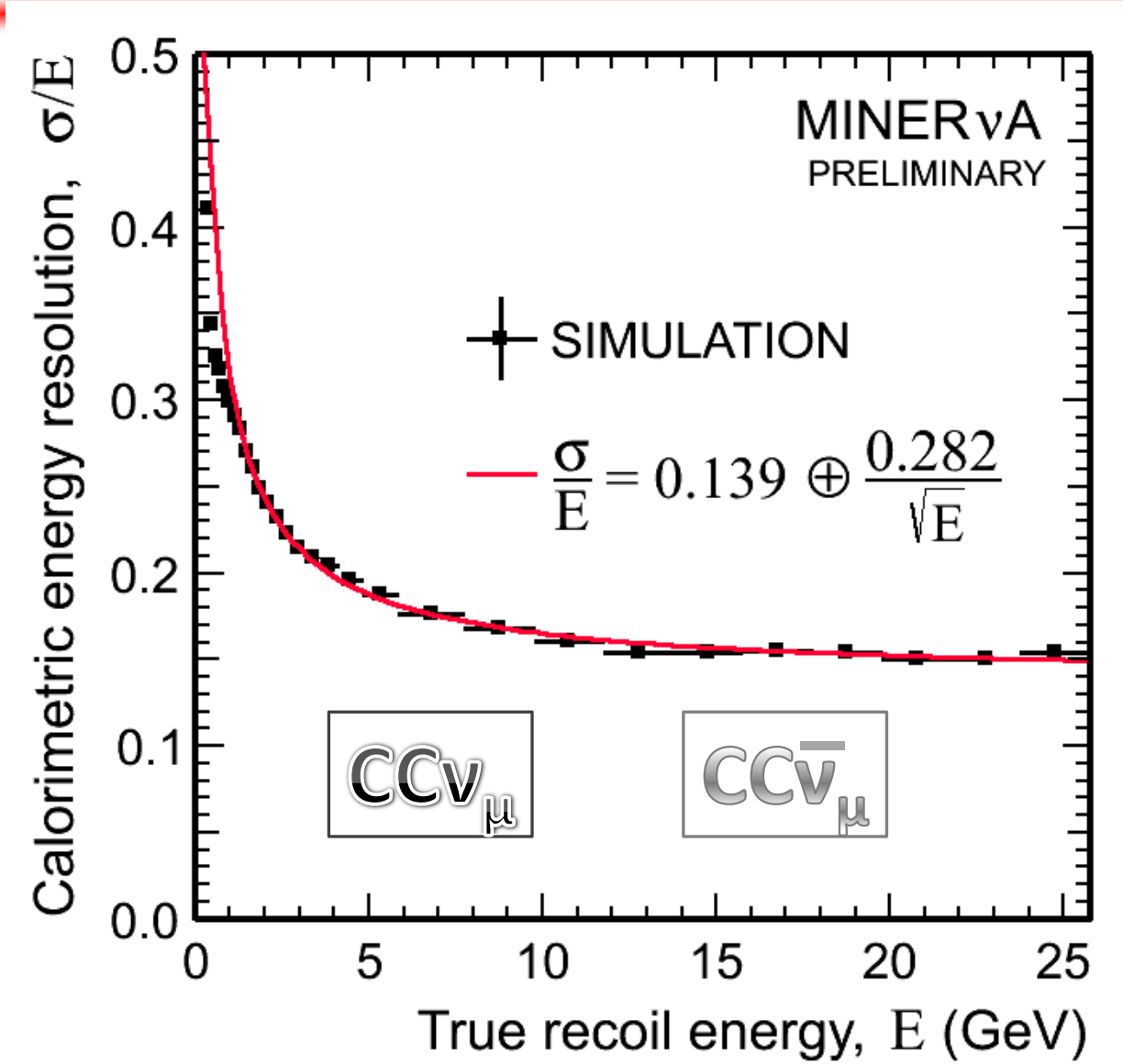



Why not 100%?
* big shower
* pileup
* deadtime

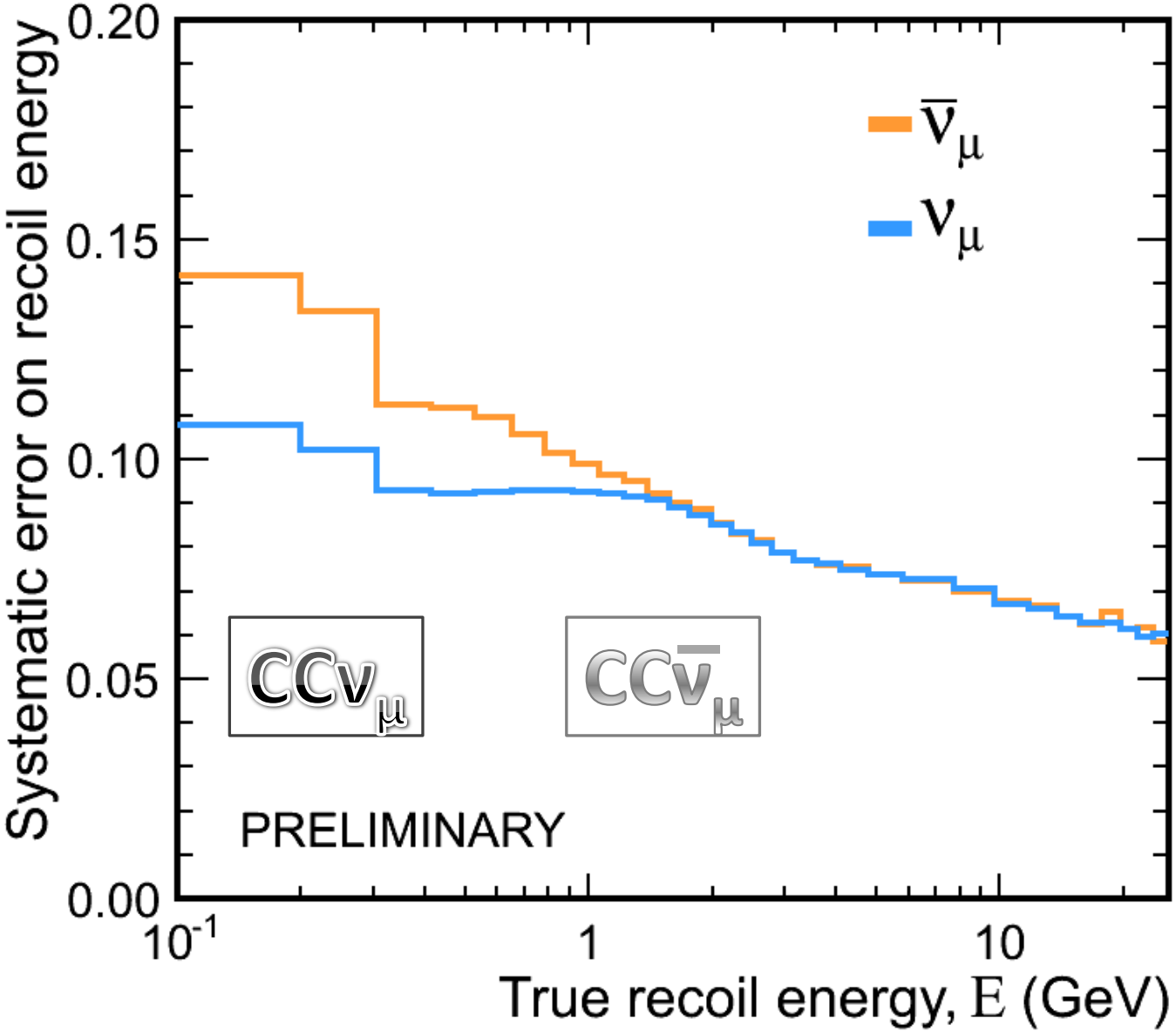
Method
ID clean μ in MINOS, point back to MINERvA

Single event MC correction
−4.6±2.5%

# Recoil Energy Resolution

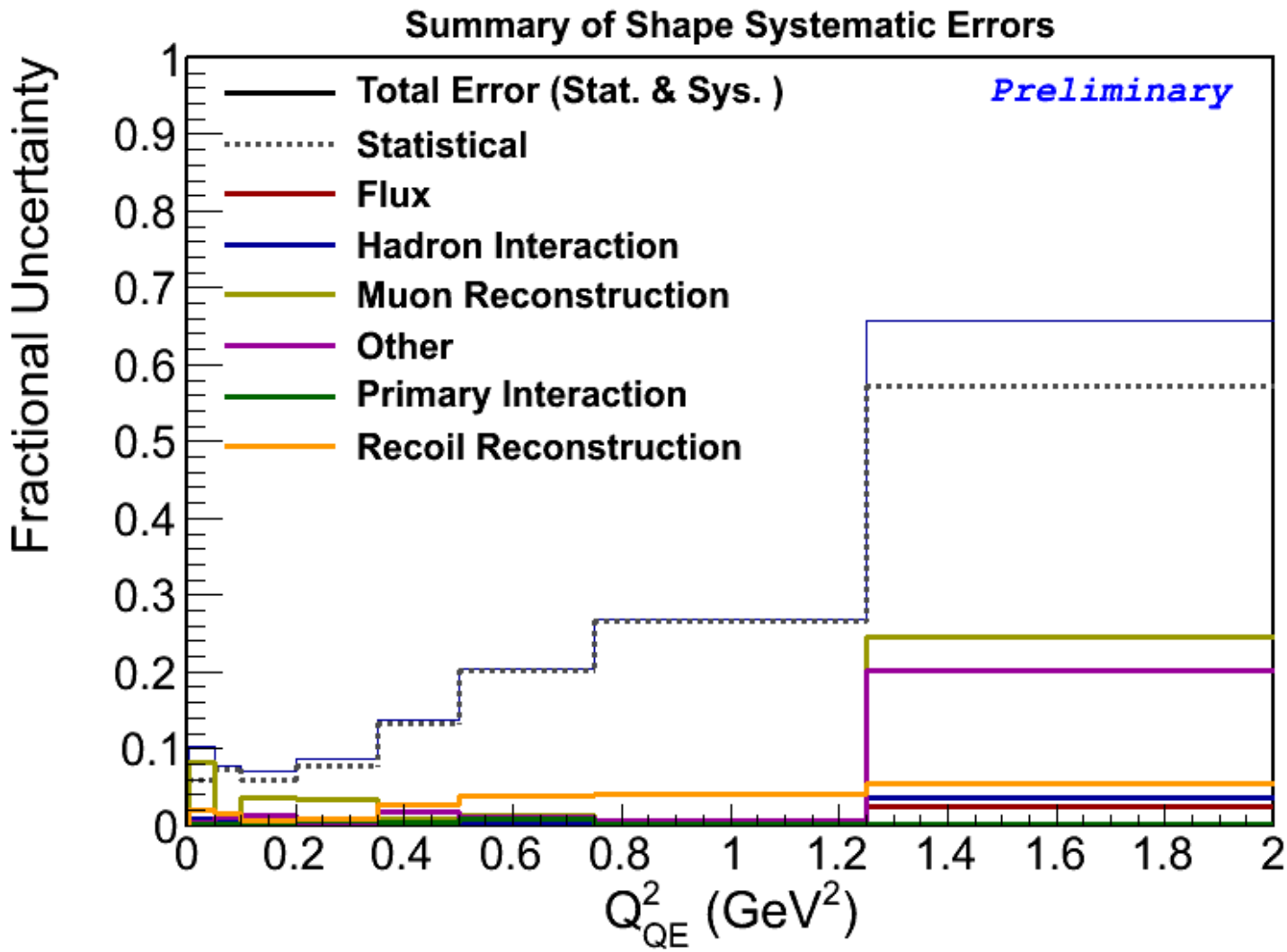


# Recoil Energy Error

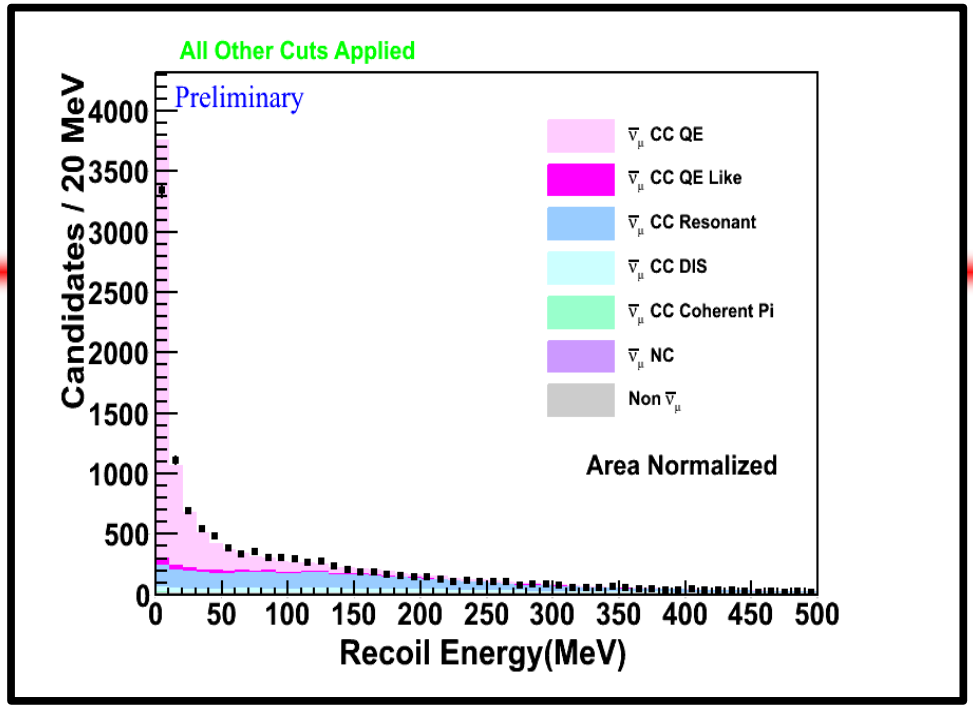


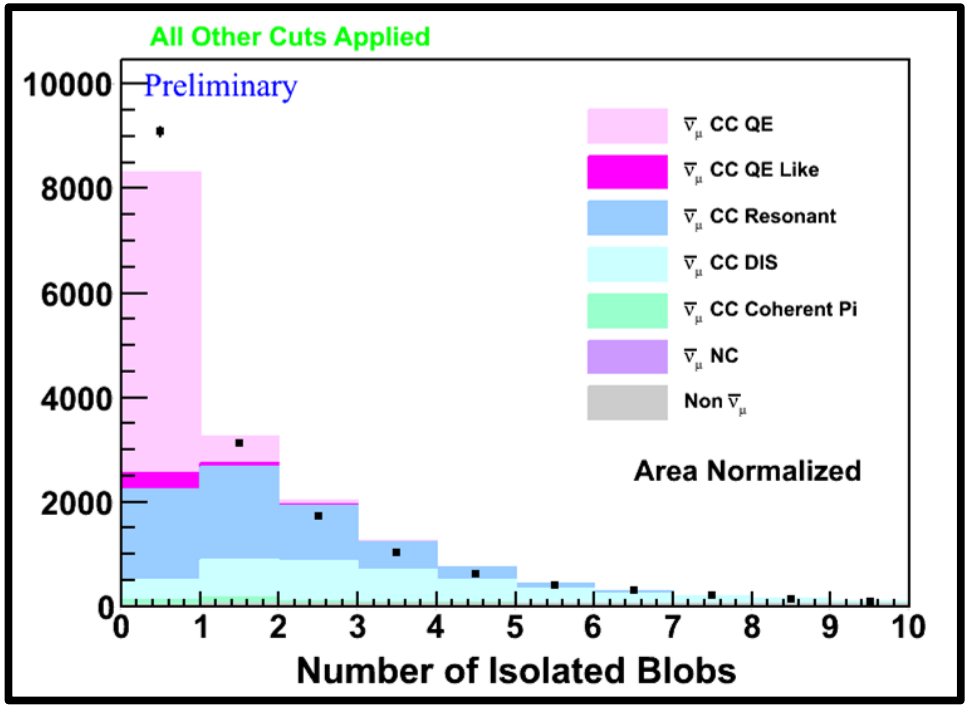

Convolution of single particle uncertainties
π,K = 5%
e,γ = 3%
p = 10%
n = 20%

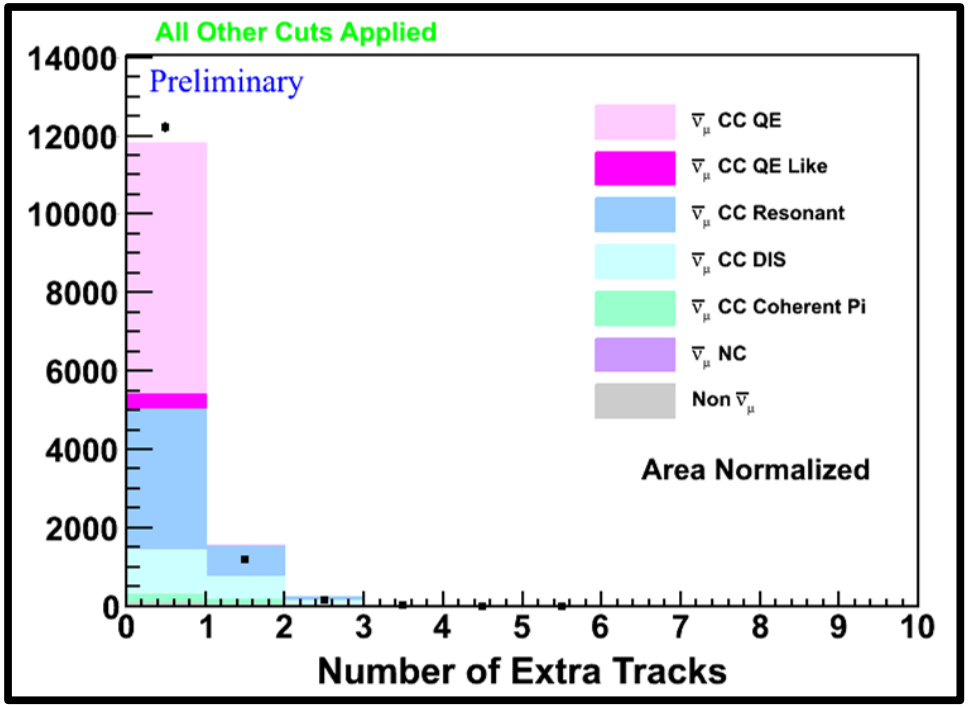
# CCQE$\bar{\nu}_\mu$



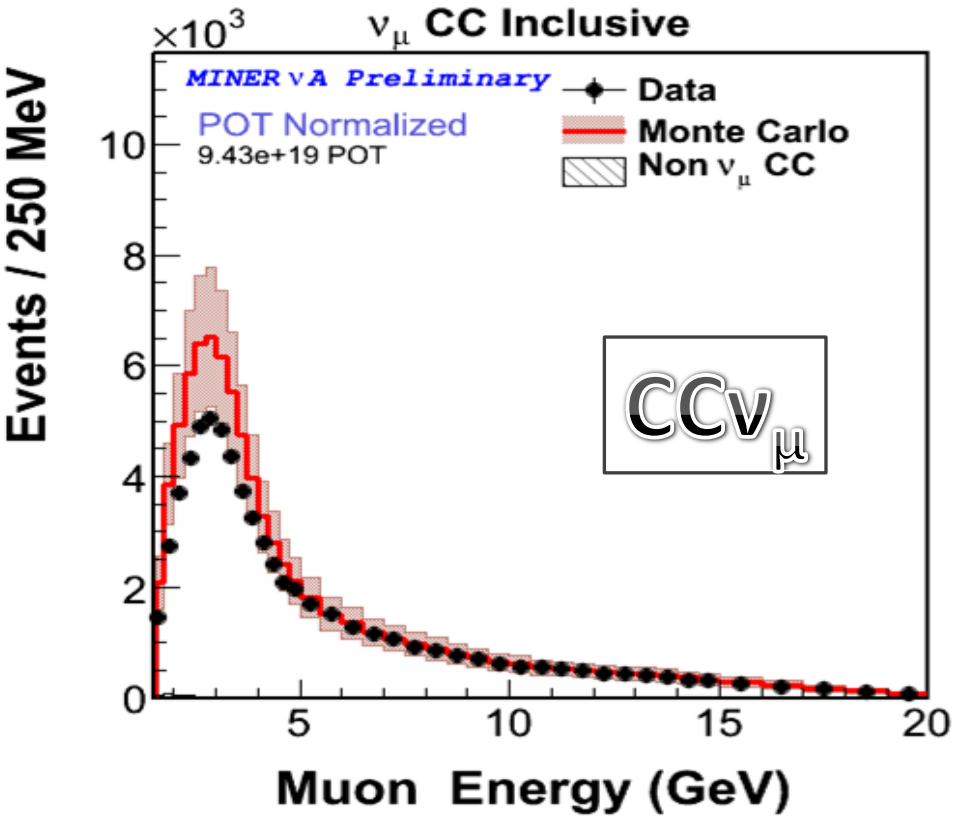
# CCQE$\nu_\mu$

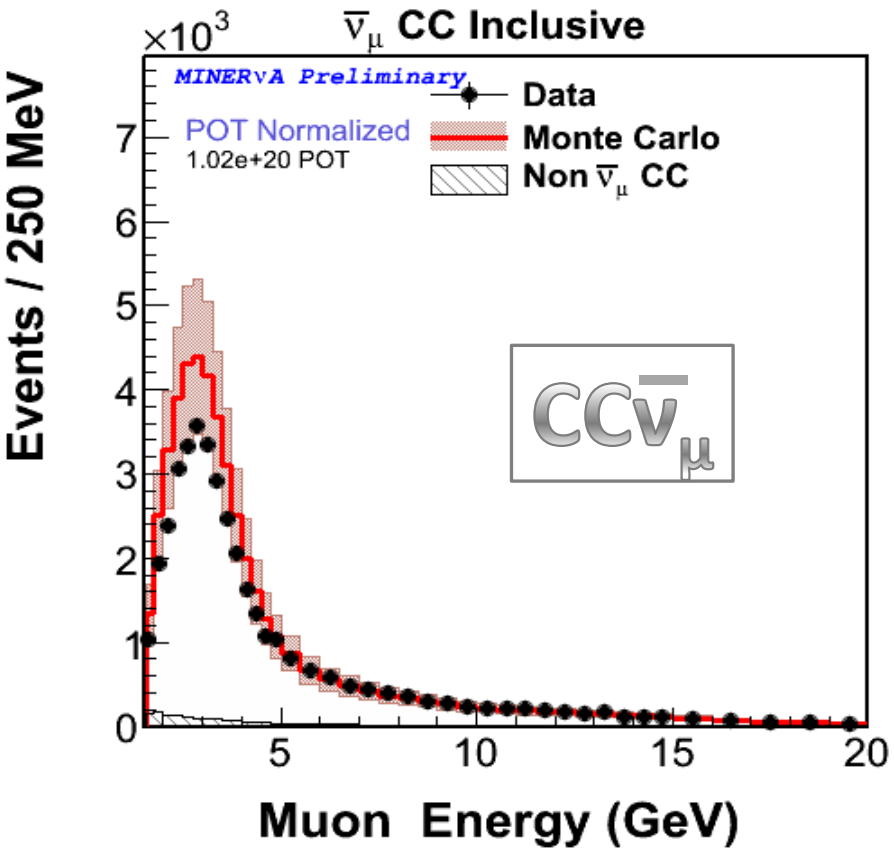

All Other Cuts Applied
Preliminary
Candidates / 20 MeV
Recoil Energy(MeV)
$\bar{\nu}_\mu$ CC QE
$\bar{\nu}_\mu$ CC QE Like
$\bar{\nu}_\mu$ CC Resonant
$\bar{\nu}_\mu$ CC DIS
$\bar{\nu}_\mu$ CC Coherent Pi
$\bar{\nu}_\mu$ NC
Non $\bar{\nu}_\mu$
Area Normalized


All Other Cuts Applied
Preliminary
Number of Isolated Blobs
$\bar{\nu}_\mu$ CC QE
$\bar{\nu}_\mu$ CC QE Like
$\bar{\nu}_\mu$ CC Resonant
$\bar{\nu}_\mu$ CC DIS
$\bar{\nu}_\mu$ CC Coherent Pi
$\bar{\nu}_\mu$ NC
Non $\bar{\nu}_\mu$
Area Normalized

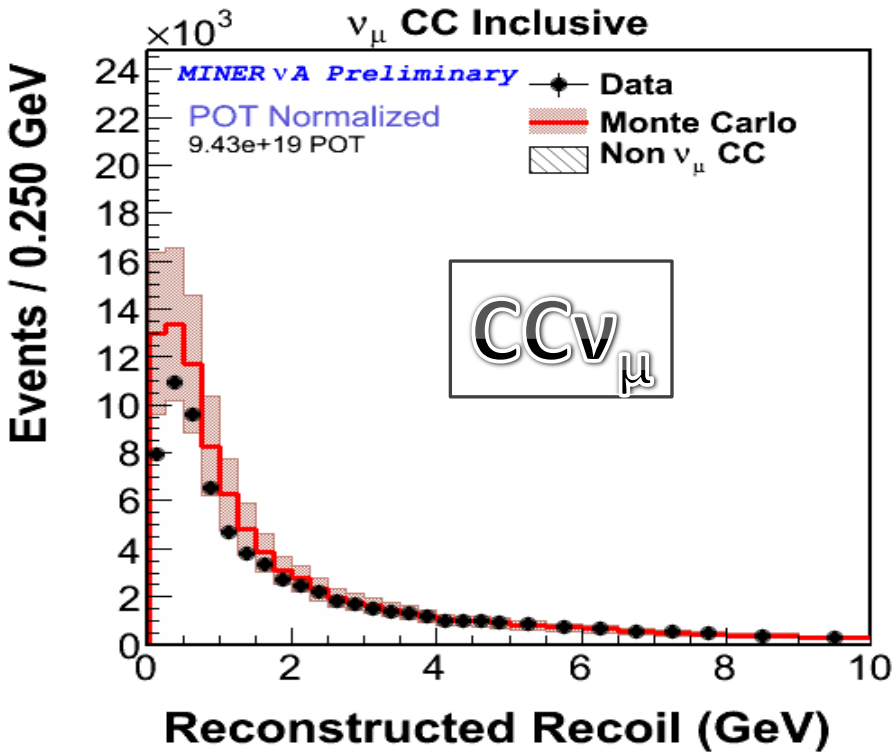

All Other Cuts Applied
Preliminary
Number of Extra Tracks
$\bar{\nu}_\mu$ CC QE
$\bar{\nu}_\mu$ CC QE Like
$\bar{\nu}_\mu$ CC Resonant
$\bar{\nu}_\mu$ CC DIS
$\bar{\nu}_\mu$ CC Coherent Pi
$\bar{\nu}_\mu$ NC
Non $\bar{\nu}_\mu$
Area Normalized

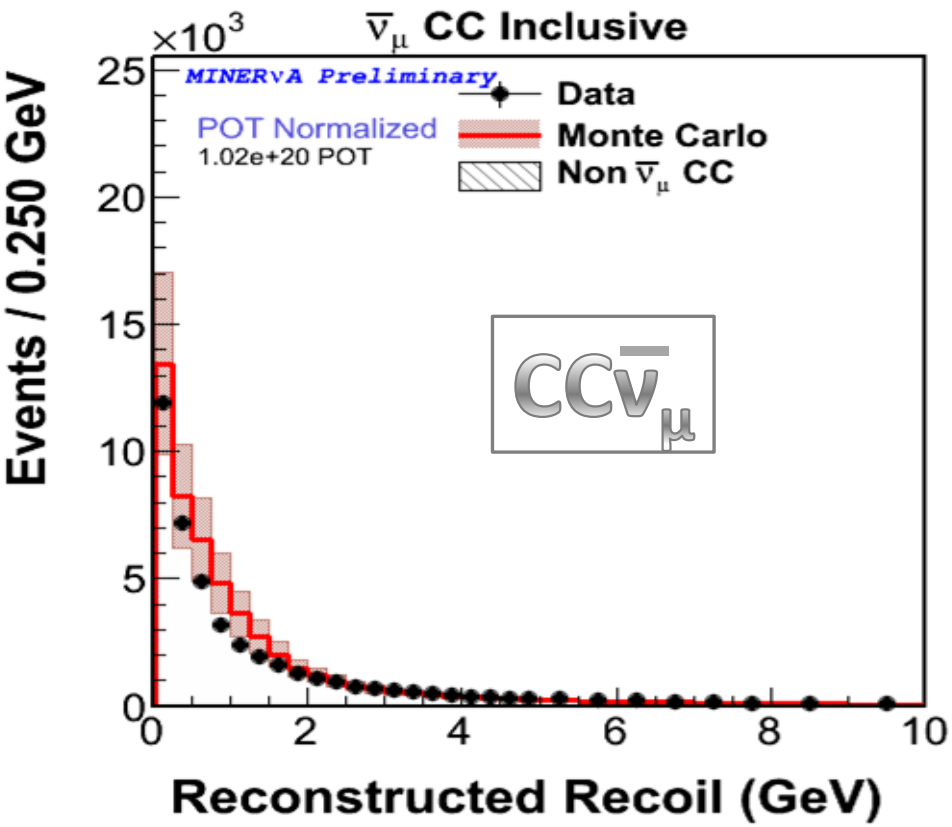
# Muon Energy Distribution



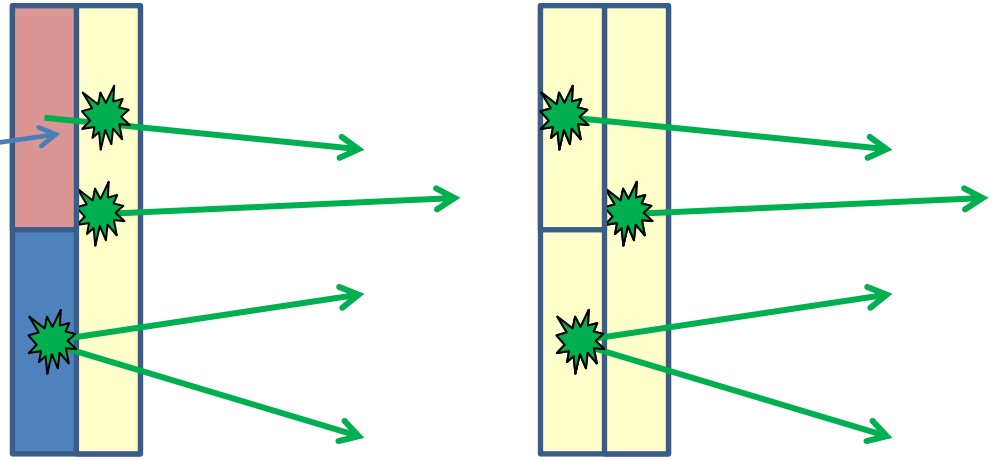
# Recoil Energy Distribution

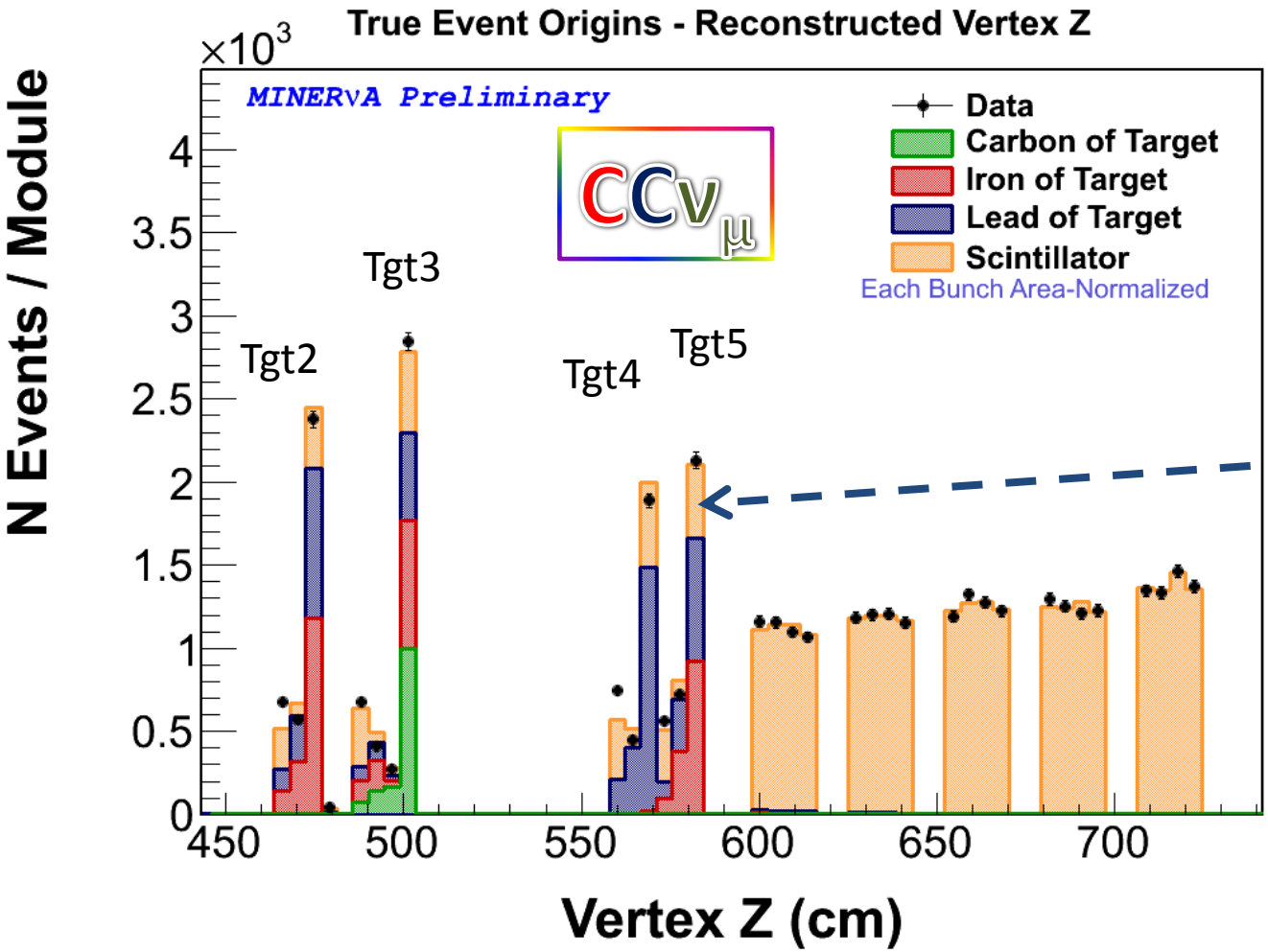



calorimetric $E_{recoil} = \alpha \times \sum_i c_i E_i$

One track events from passive target have a vertex in the first plane downstream of the target.

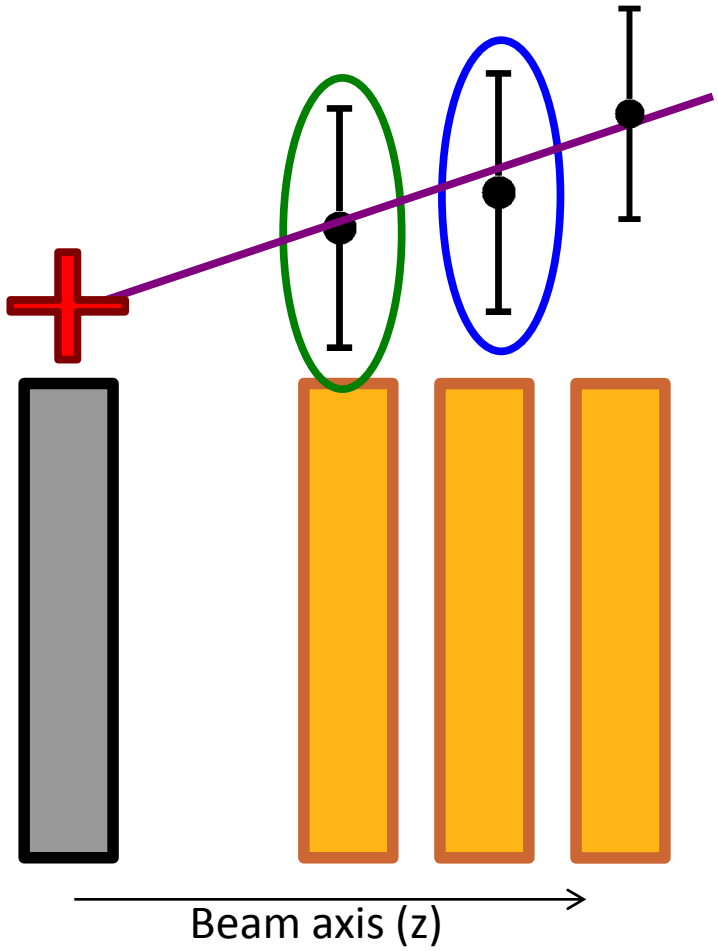


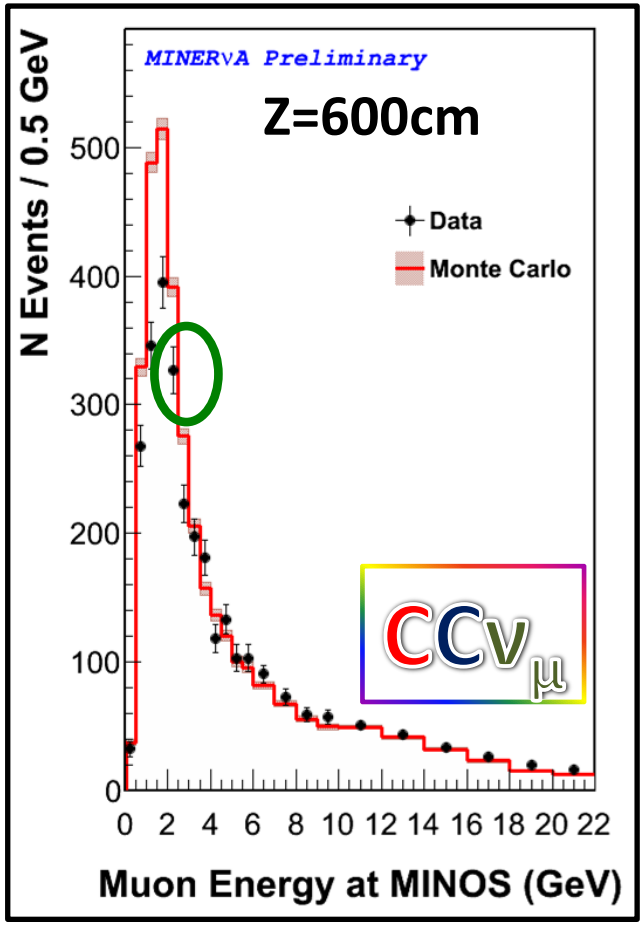


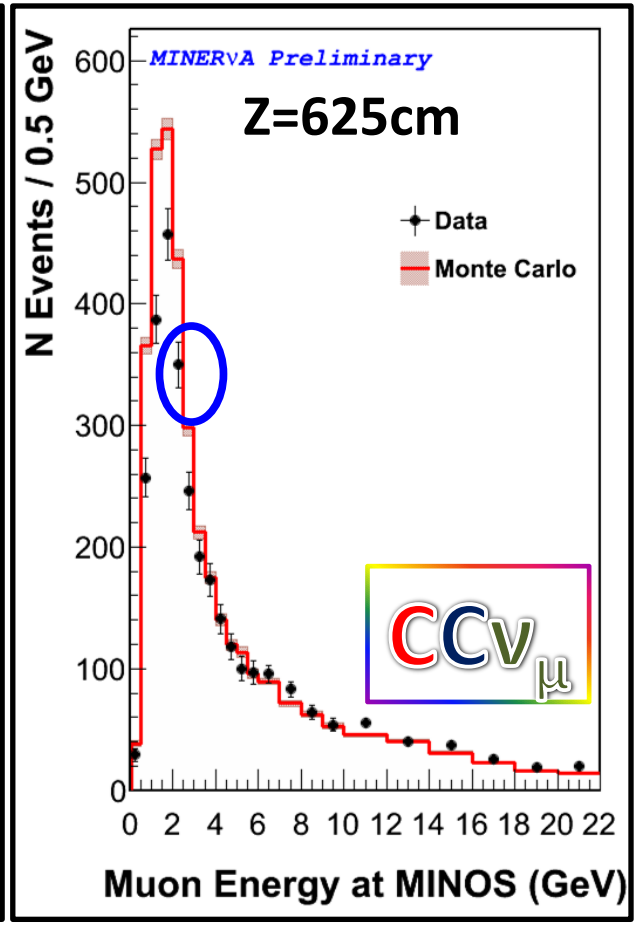

These peaks are at the location of the first module downstream of the passive targets.

# Background Subtraction

Use plastic reference targets to predict rate at the plastic background.



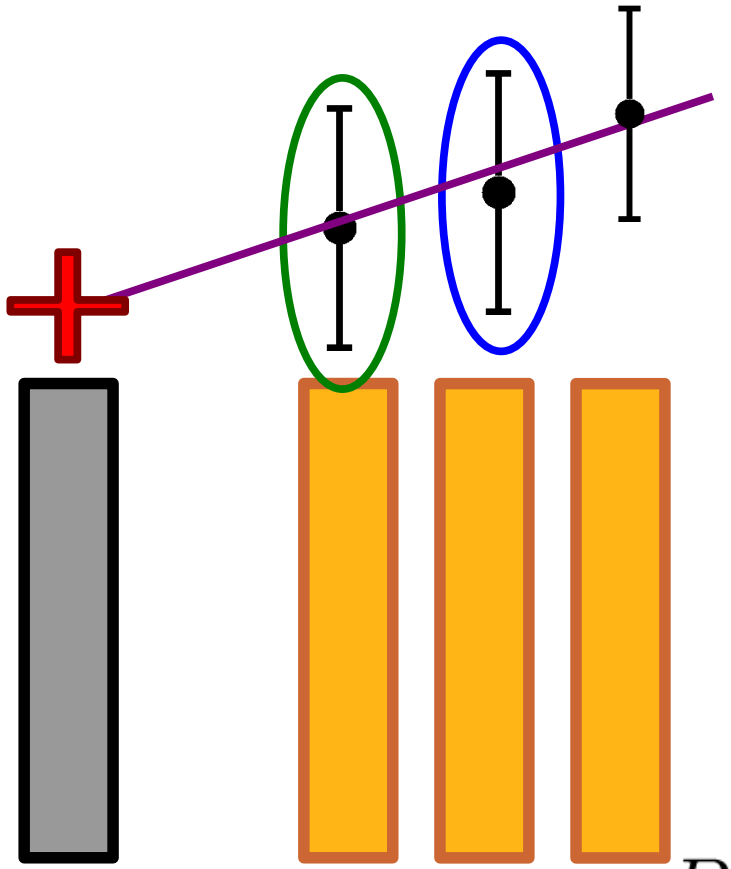



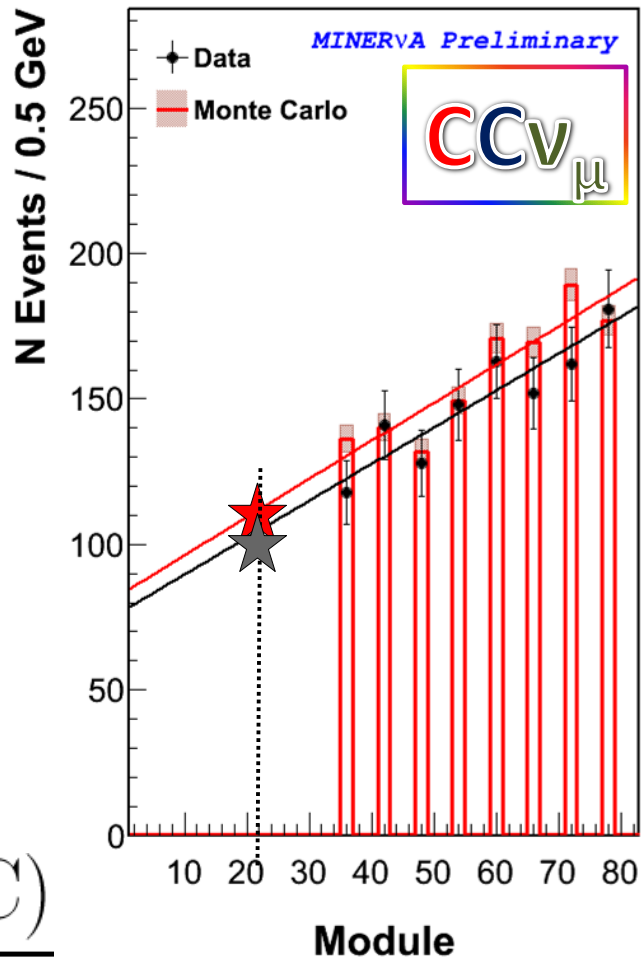

Prediction done in bins of muon momentum.

# Background Subtraction

Use plastic reference targets to predict rate at the plastic background.

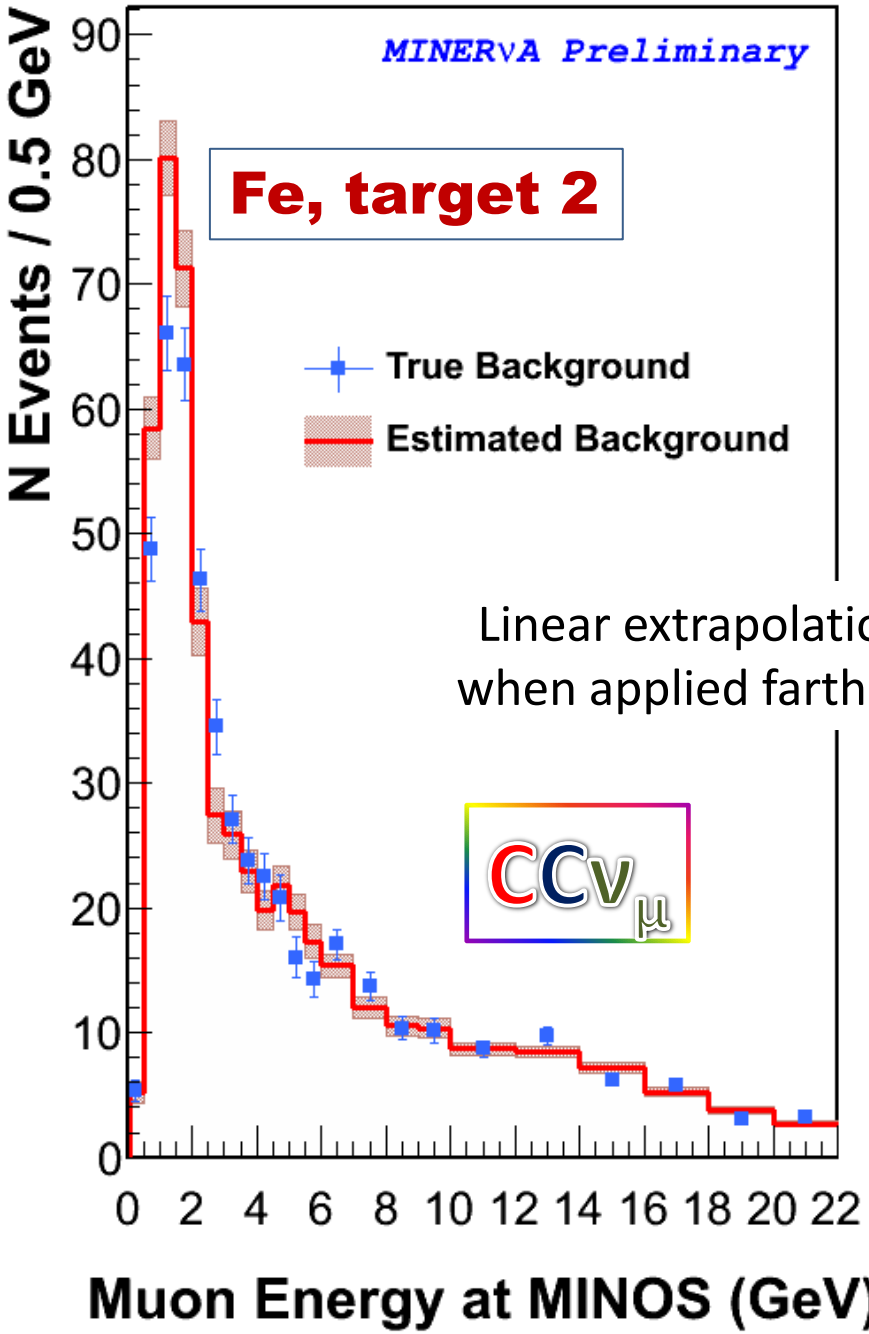


$$B(\text{data}) = P(\text{data})\frac{B(\text{MC})}{P(\text{MC})}$$

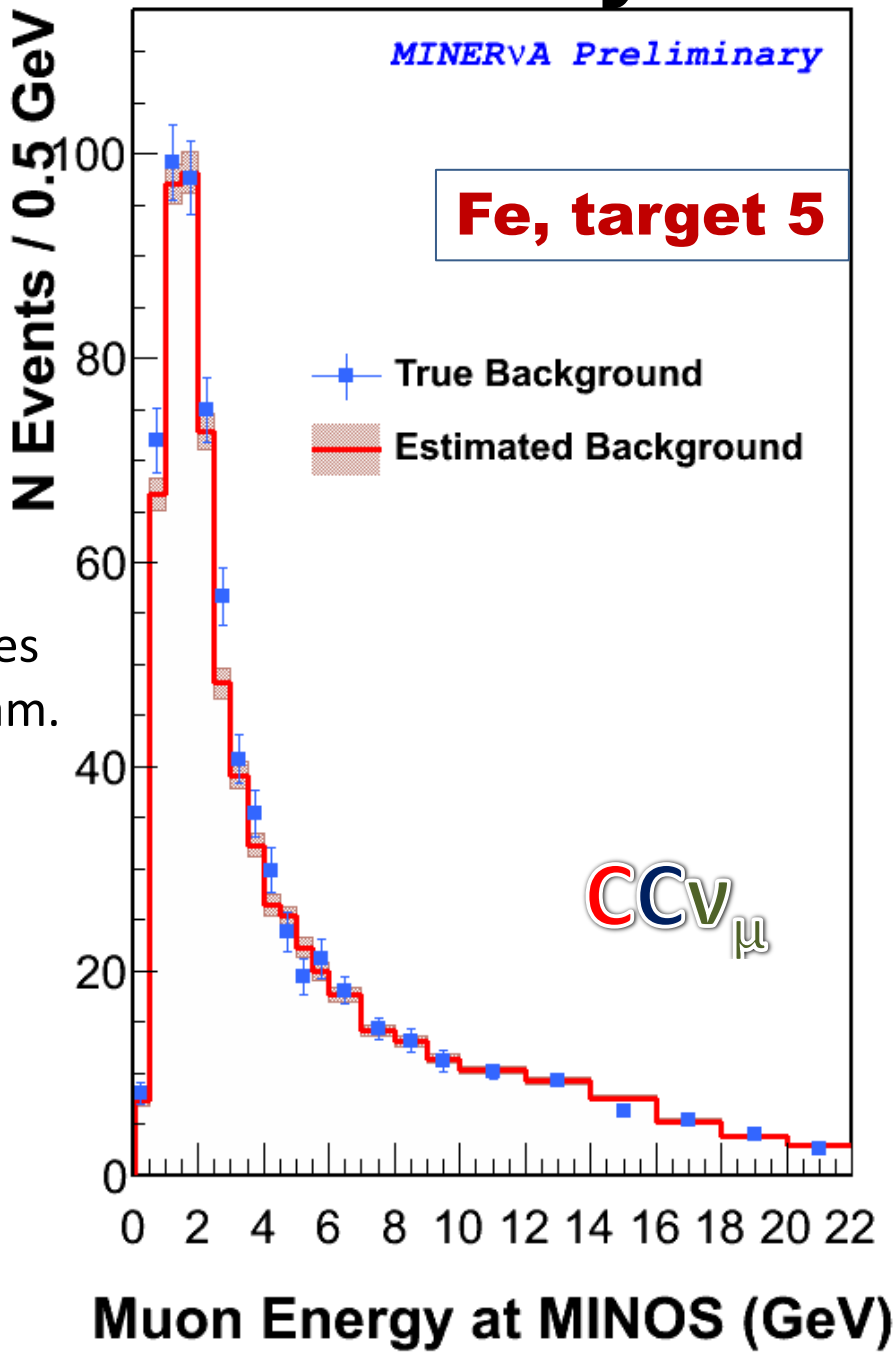



Background subtracted in both MC and data ~without using MC cross section model.

# Background Subtraction Accuracy




Linear extrapolation degrades when applied farther upstream.

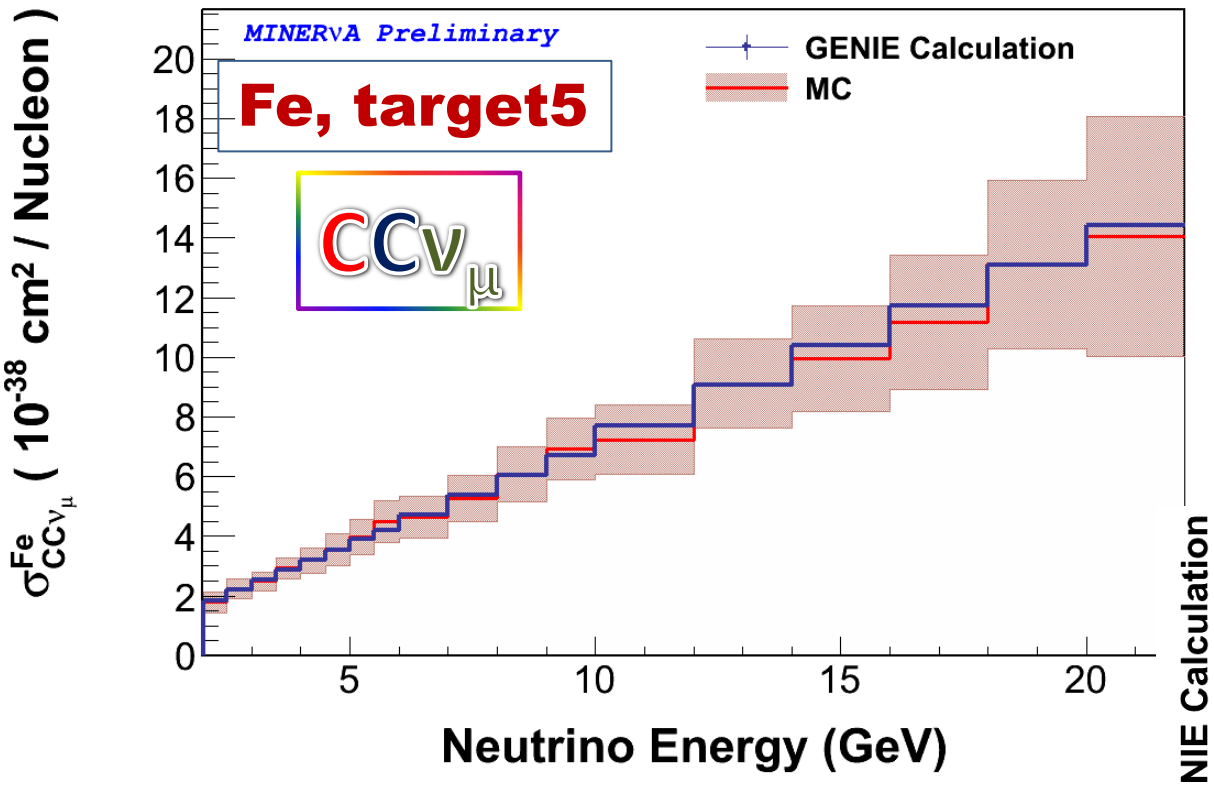


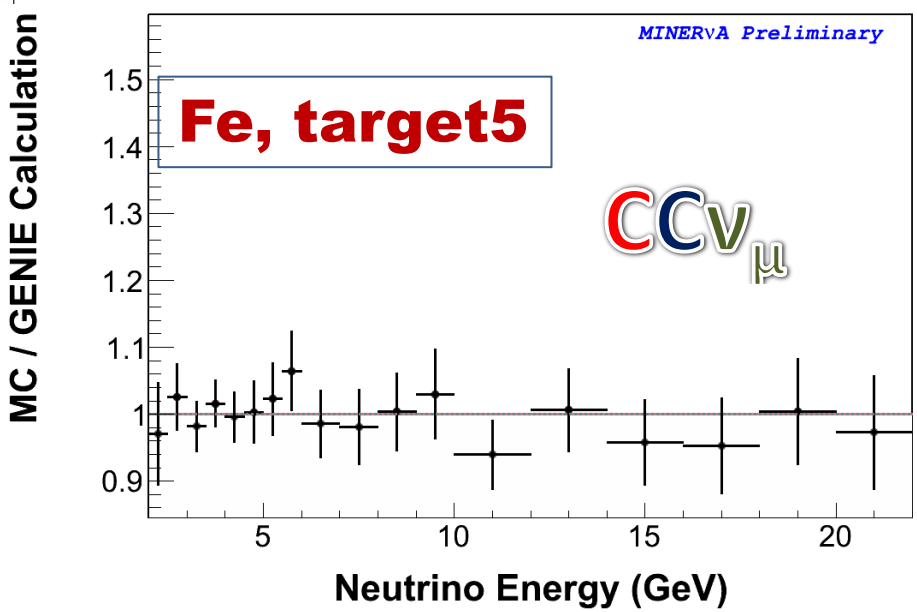
# Form a Cross Section
## (generic)

$$\left(\frac{d\sigma}{dx}\right)_i = \frac{\sum_j U_{ij}(d_j - bj)}{\epsilon_i(\Phi T)\Delta x_i}$$

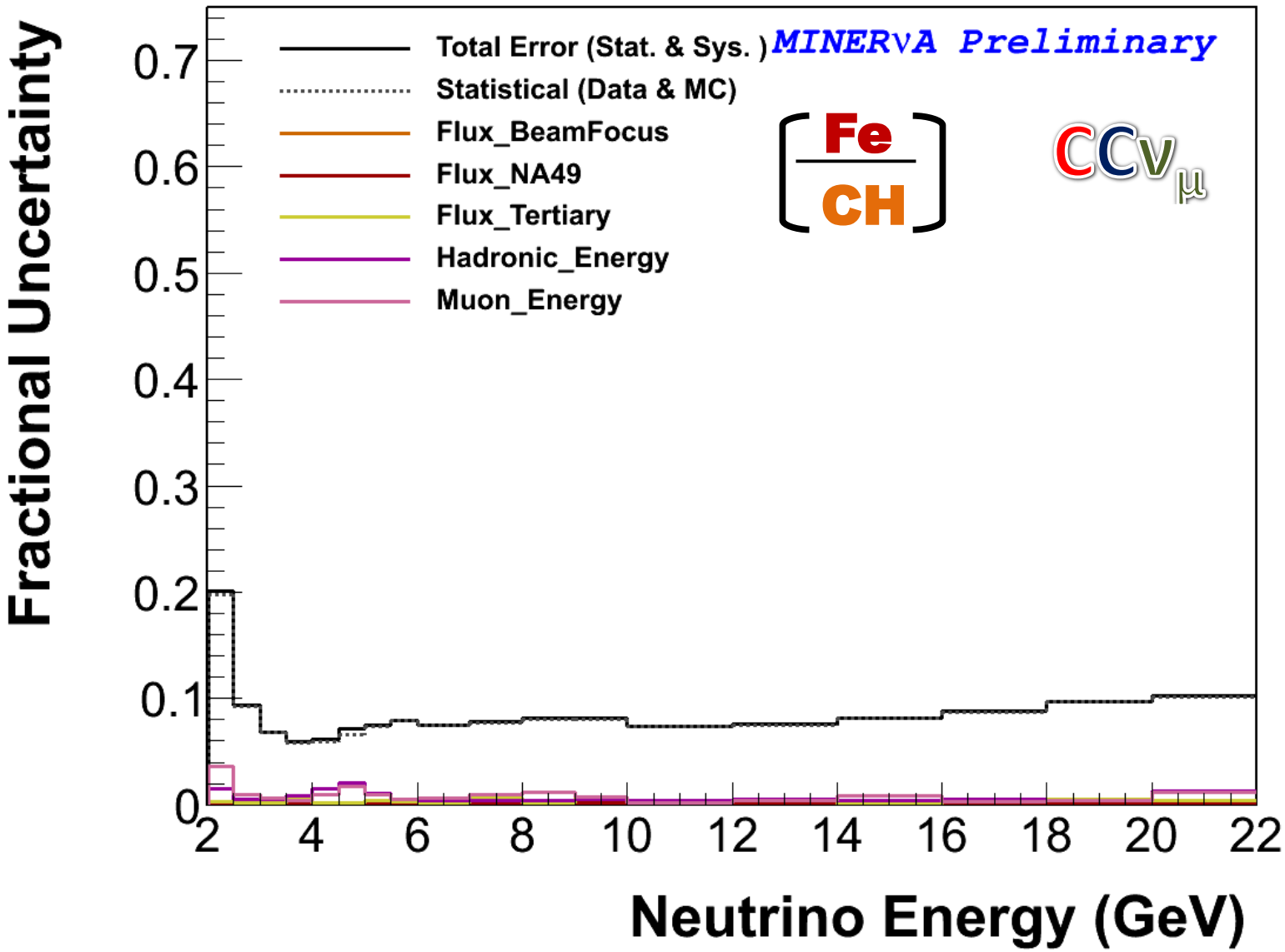
- $(d_j - b_j)$ data – background = signal
- $U_{ij}$ Unfolding matrix
  - From reco bin j to “true” bin i
- $\epsilon_i$ Efficiency for bin i
- $(\Phi T)$ Flux times target number
  - Flux may depend on bin
- $\Delta x_i$ Bin width

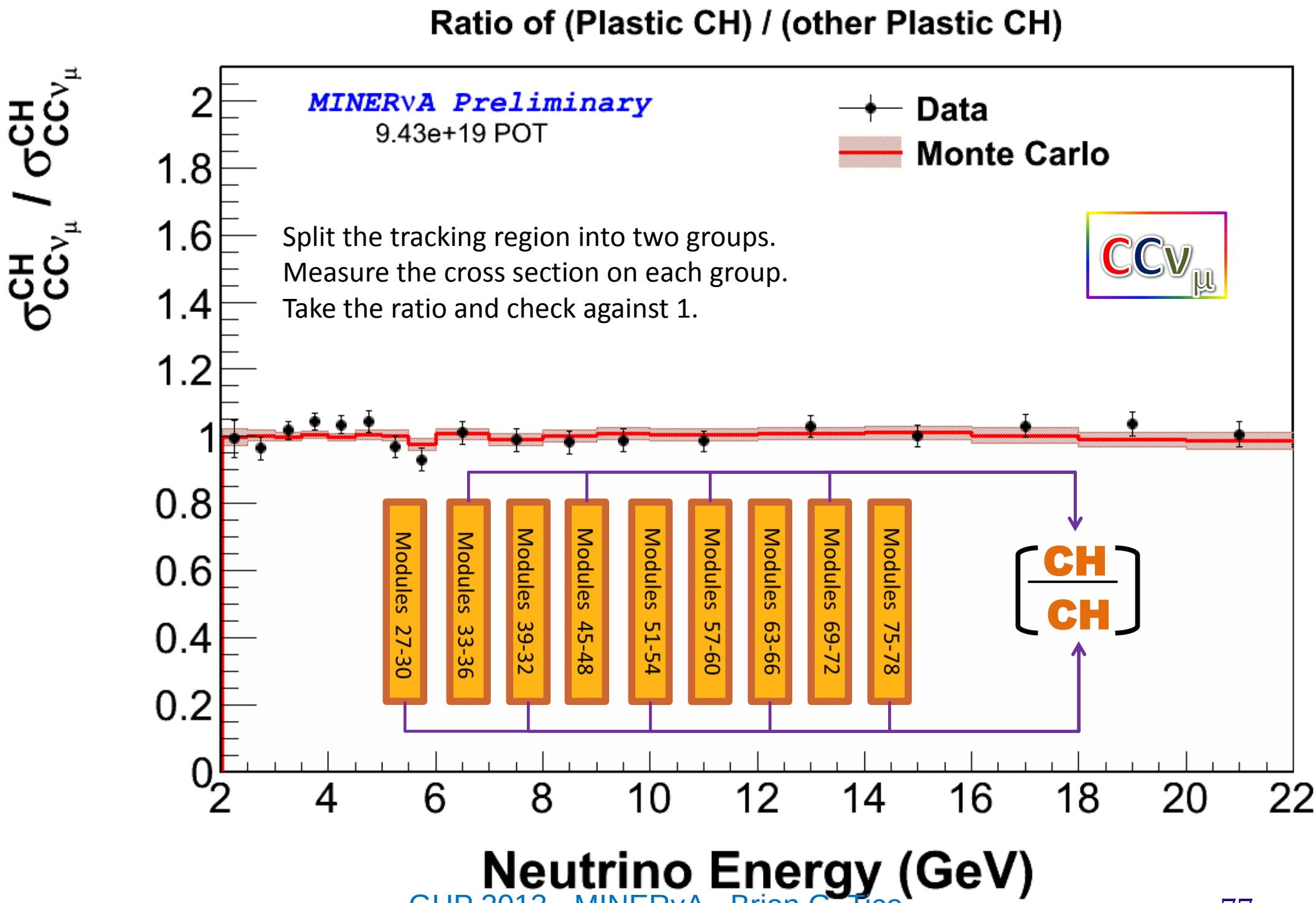
# Form a Cross Section
## with full MINERvA simulation



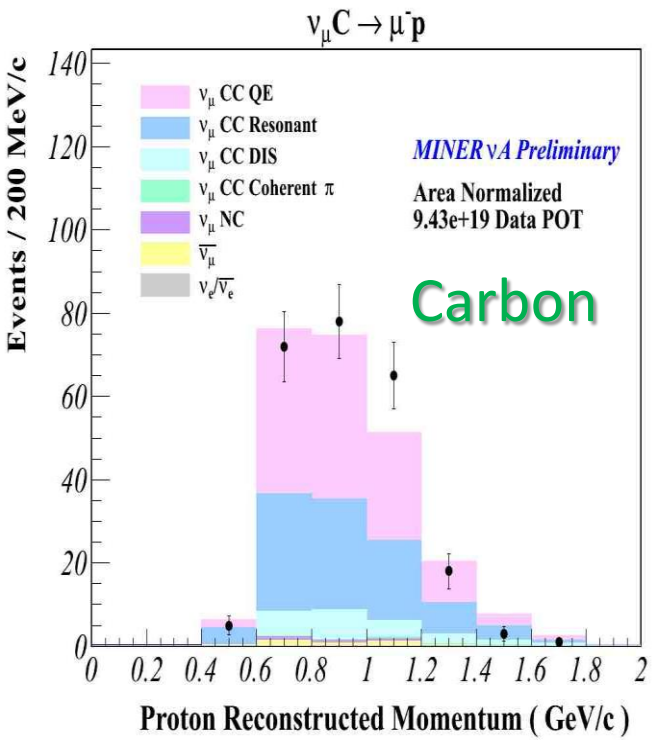
# Total Errors - $\left[\frac{Fe}{CH}\right]$ Cross Section

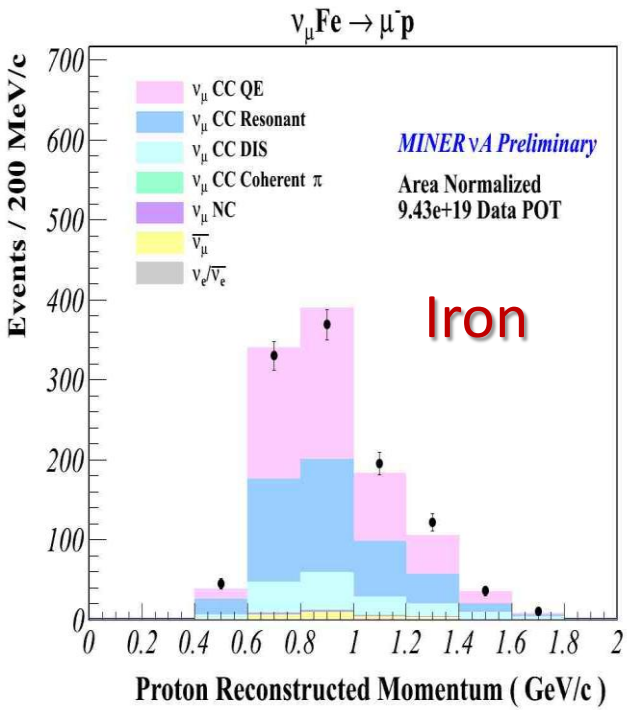


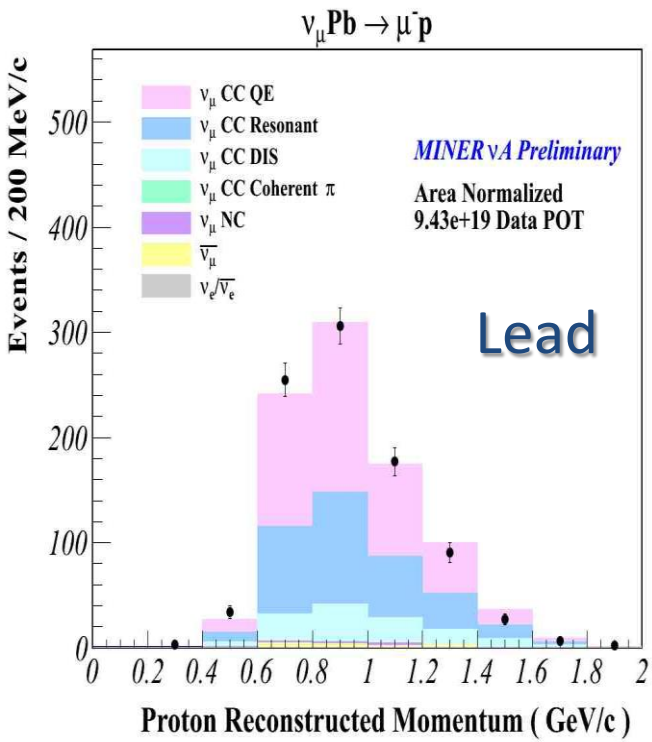

Ratio of (Plastic CH) / (other Plastic CH)
MINERvA Preliminary
9.43e+19 POT
Data
Monte Carlo
Split the tracking region into two groups.
Measure the cross section on each group.
Take the ratio and check against 1.
CCνμ
Modules 27-30
Modules 33-36
Modules 39-32
Modules 45-48
Modules 51-54
Modules 57-60
Modules 63-66
Modules 69-72
Modules 75-78
CH
CH
Neutrino Energy (GeV)

# Proton Momentum

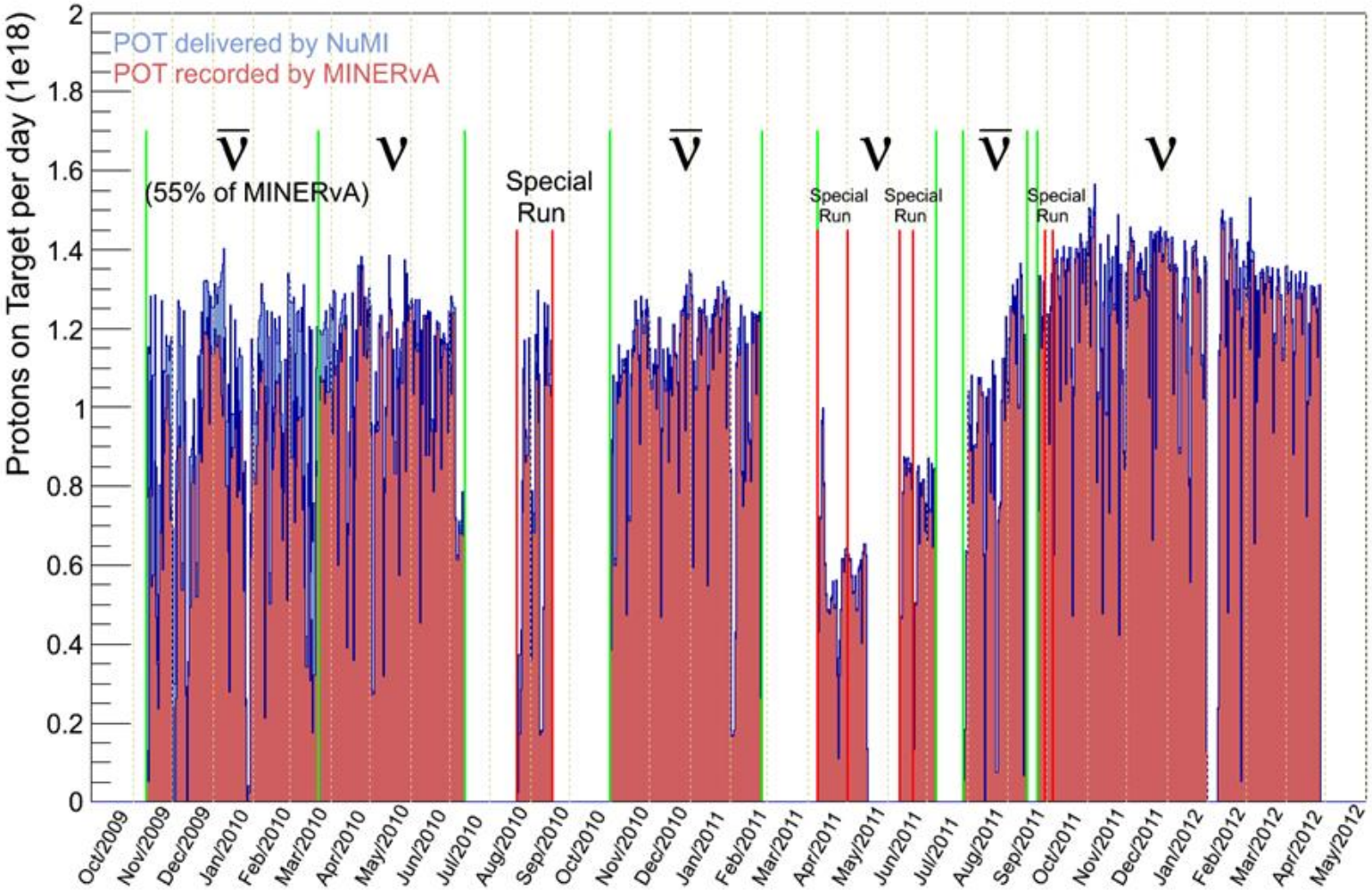
2trkCCQE$\nu_\mu$



# Run Plan



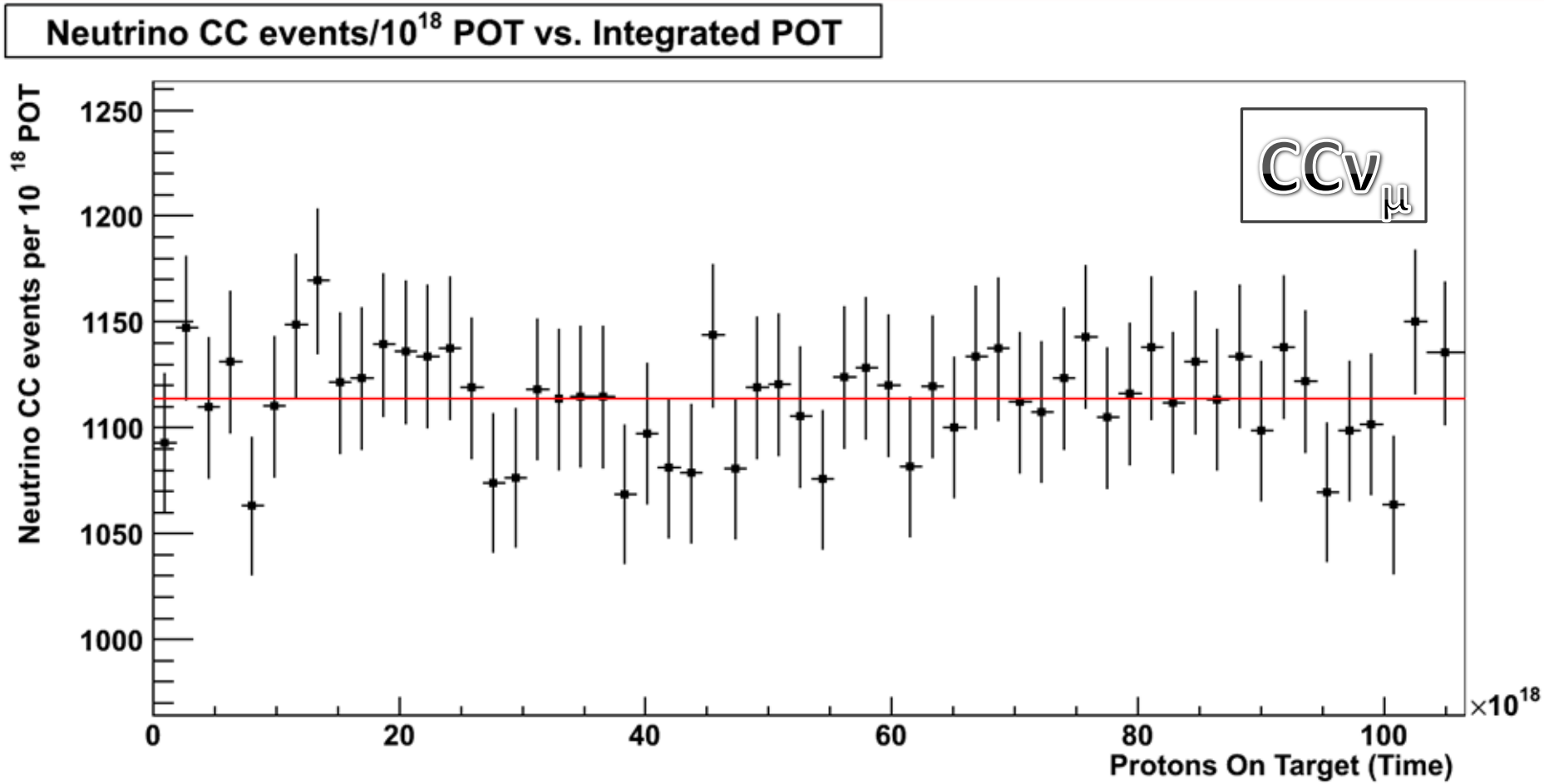

**Since 3/22/10**

**$\nu_\mu$ LE**
**3.98e20 POT**

**$\nu_\mu$ LE**
**1.70e20 POT**

**special runs**
**4.94e19 POT**

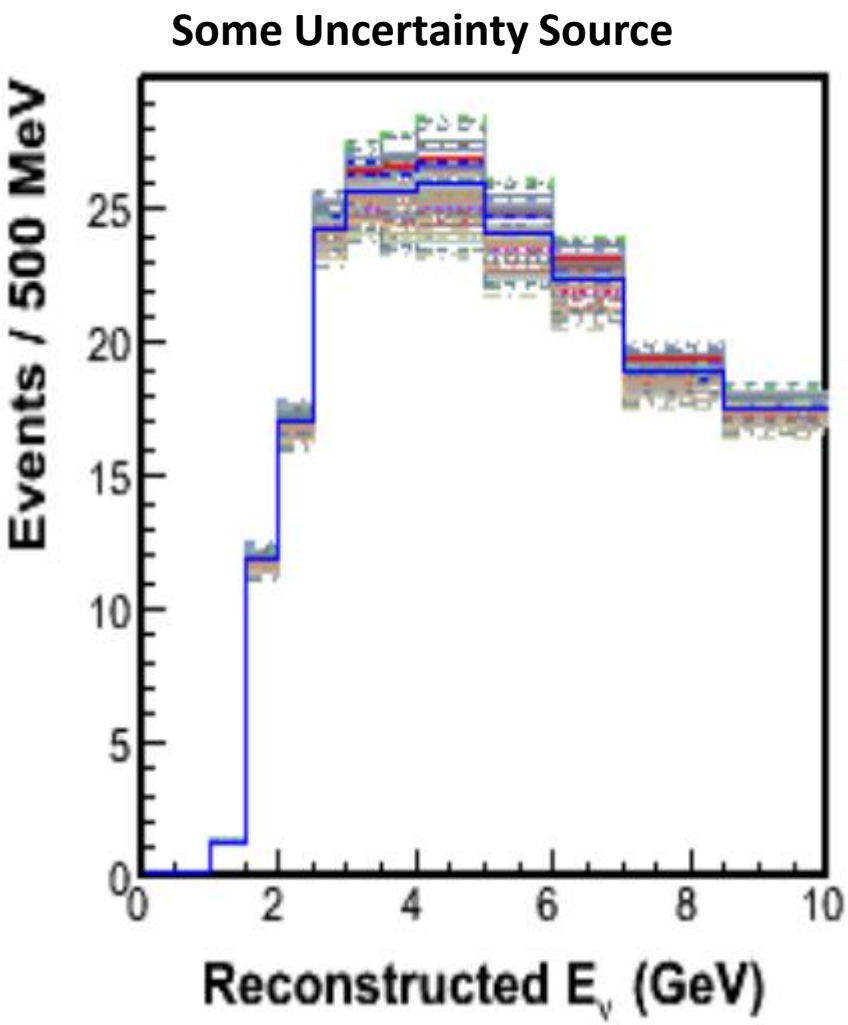
# Stability




March 22, 2010

July 12, 2010

# Determining Uncertainty




## Common Theme

Uncertainties on each systematic calculated in “many universes”.

Sample from a Gaussian around central value for a parameter.

Carry out analysis in each universe.

Uncertainty on result is the standard deviation of the many universes of results.