CCQE Results from MINERvA

NuInt 2012

Laura Fields
Northwestern University
For the MINERvA Collaboration

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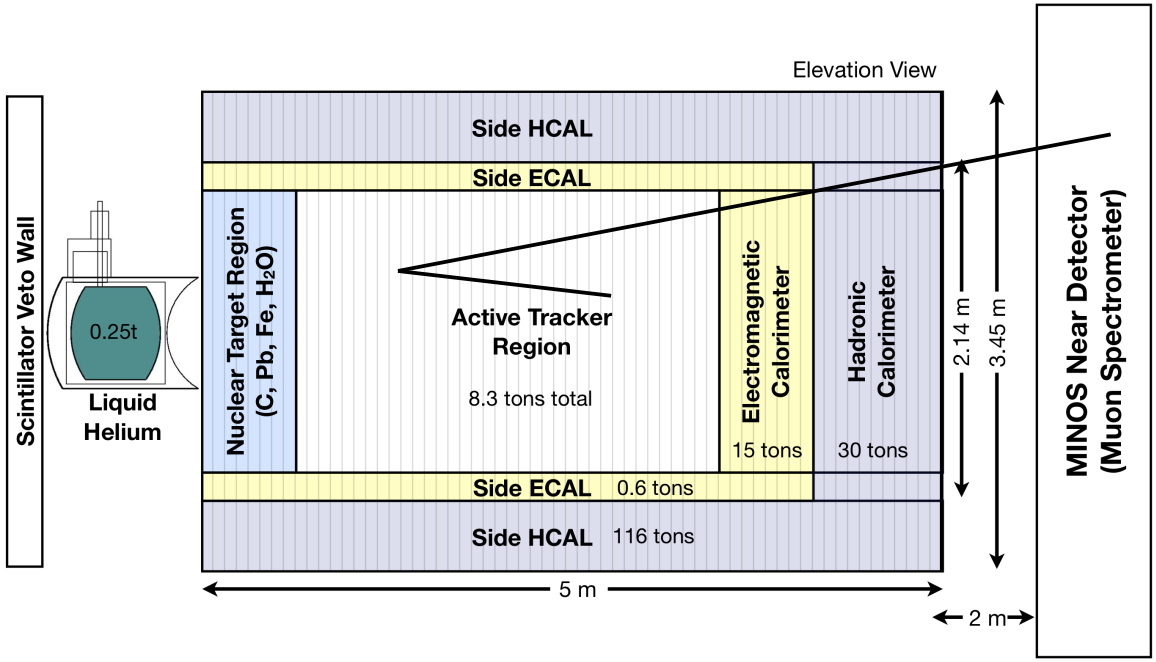
Outline

- Introduction
  - MINERνA QE Analysis Strategies
  - Challenges to Reconstructing QE at MINERνA
- Quasi-elastic Analyses
  - One-Track Anti-Neutrino
  - One-Track Neutrino
  - Two-Track Neutrino (Targets)
- Conclusions/Outlook

Introduction

- The MINERνA detector offers a wealth of possibilities for quasi-elastic reconstruction:



Can reconstruct one or two tracks

→ **Similar to NOMAD**

Can add a michel veto to reject pion backgrounds

→ **Similar to MiniBooNE**

Can add a veto of high calorimetric recoil to reject backgrounds

→ **Employed by many of our early analyses**

Another analysis choice:

Can reconstruct muons in MINERvA + MINOS

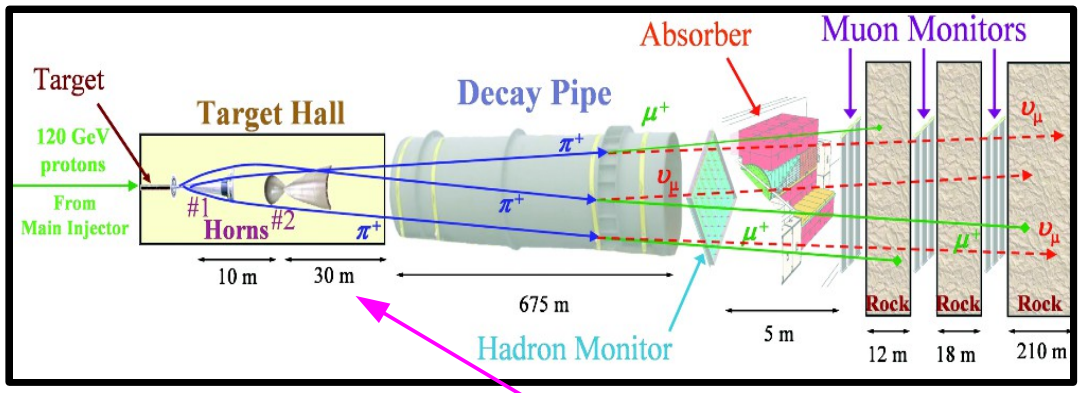
→ Good momentum & charge measurement, but narrow angular acceptance

Or can reconstruct muons in MINERvA only

→ Poorer momentum (and no charge) measurement but good angular acceptance

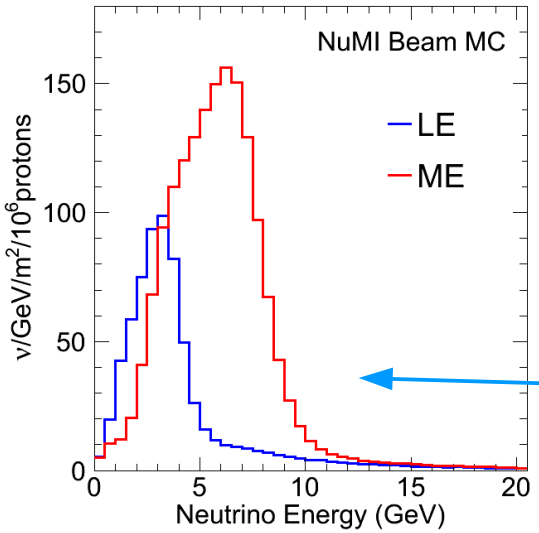
Introduction

- The NuMI beam line also offers various options:



MINERvA

MINOS Near Detector



Horn current direction selects neutrino or anti-neutrino enhance samples

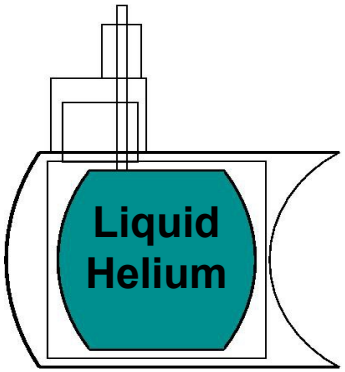
NOvA era running (starting in 2013) will provide higher energy beam

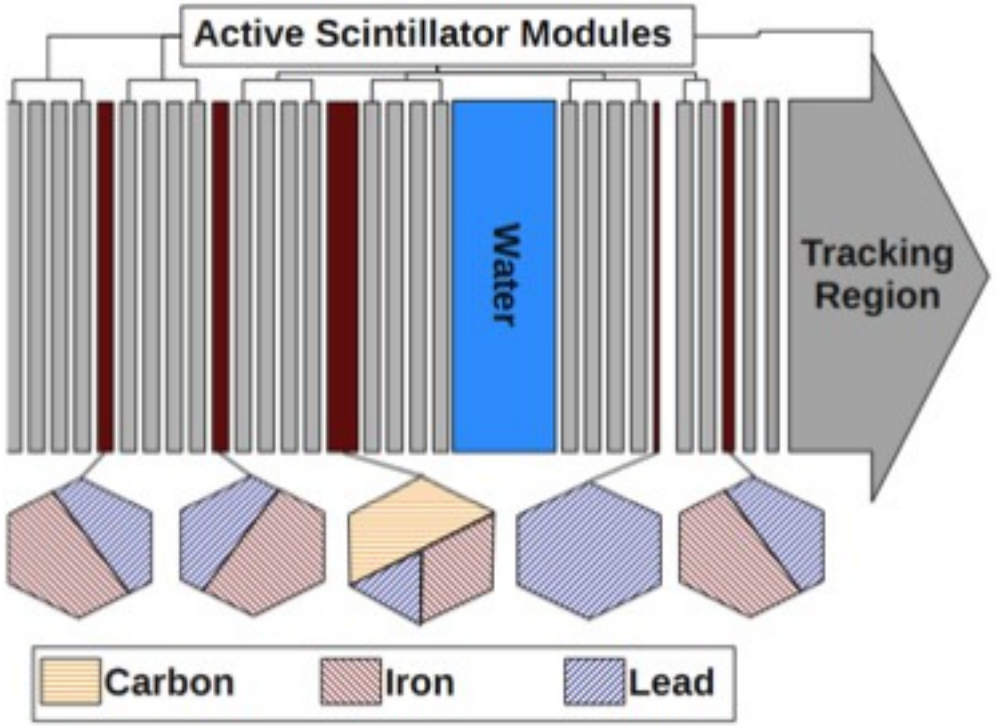
Low energy run is complete

Final POT Counts:

Neutrino	3.98e20
Anti-Neutrino	1.7e20

Introduction





Addition of nuclear targets adds possibility of CCQE measurements in six different materials

Estimated event rates for complete LE neutrino run

Material	Mass (kg)	QE Events (Before Acceptance)
Plastic Scintillator	5470	200,222
Fe	951	40838
Pb	971	48114
C	163	6340

Introduction

- Multiple reconstruction methods + Multiple beam configurations + multiple target nuclei = dozens of potential MINERvA CCQE analyses
  - But we have to start somewhere!
  - At NuInt 2011, we premiered our first QE analysis:

Beam	Target	Muon Rec	Number of Tracks	Background Supression
LE anti-nu	Scintillator	MINERvA + MINOS	1	Calorimetric recoil

Introduction

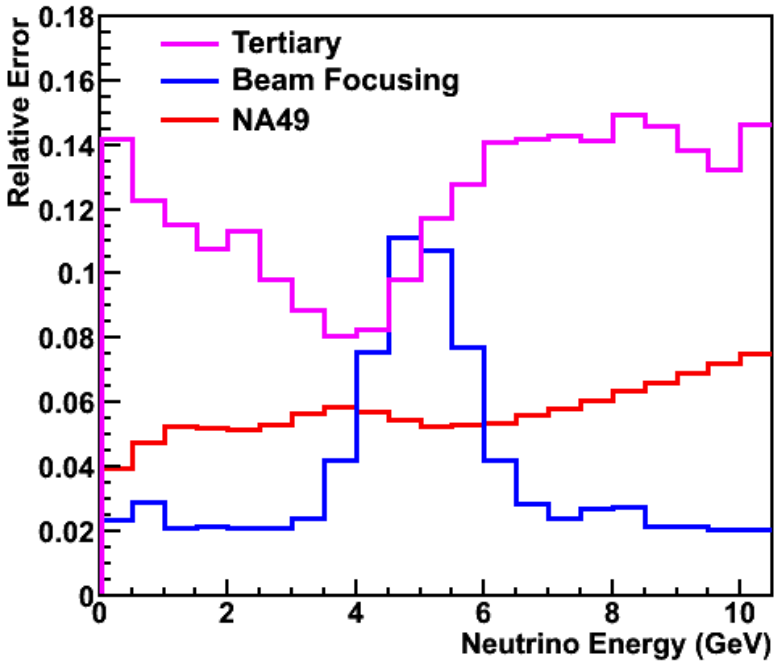
- Today we are proud to present results from three QE analyses
  - An update to our initial QE result w/ unfolded $d\sigma/dQ^2$
  - Plus two new analyses

Beam	Target	Muon Rec	Number of Tracks	Background Supression
LE anti-nu	Scintillator	MINERvA + MINOS	1	Calorimetric Recoil
LE nu	Scintillator	MINERvA + MINOS	1	Calorimetric Recoil
LE nu	Fe, Pb, C	All	2	Recoil + Kinematics

Introduction

- Challenges to QE analyses at MINERνA:

For more info, see MINERvA's Flux Poster



- NuMI flux currently has large uncertainties
  - Currently estimated using GEANT4 (v9.4.p02) simulation constrained by input from NA49 where possible
    - A large portion of the flux is currently unconstrained
  - Uncertainties combine errors from NA49, beam focusing and model spread (for unconstrained portion of flux)

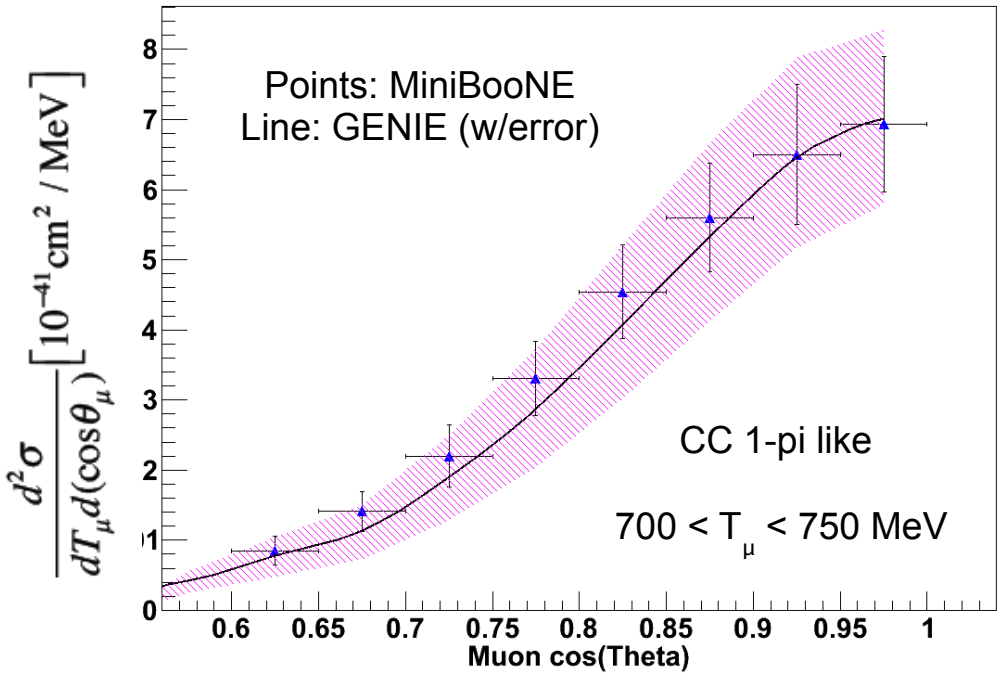
MINERvA is currently transitioning from QGSP to FTFP GEANT4 Physics Lists

Some analyses presented here (the anti-nu analysis) use QGSP while others (the neutrino analyses) uses FTFP

MINERvA is currently executing a program that will substantially reduce the flux uncertainties.

Introduction

Challenges to QE analyses at MINERνA:

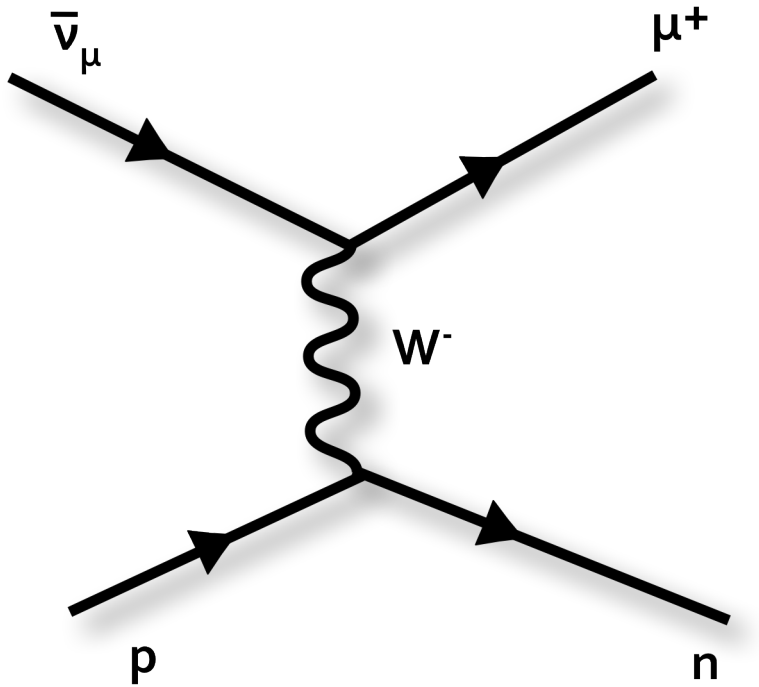


- Measurements depend heavily on the simulation of backgrounds, obtained from GENIE:
  - QEL: BBA05 FF, M_A = 0.99 GeV
  - Resonance: Rein-Segal
  - Coherent: Rein-Segal
  - DIS: GRV94/GRV98 with Bodek-Yang
  - DIS & QEL charm (Kovalenko, Sov.J.Nucl.Phys.52:934 (1990))

Nuclear Model

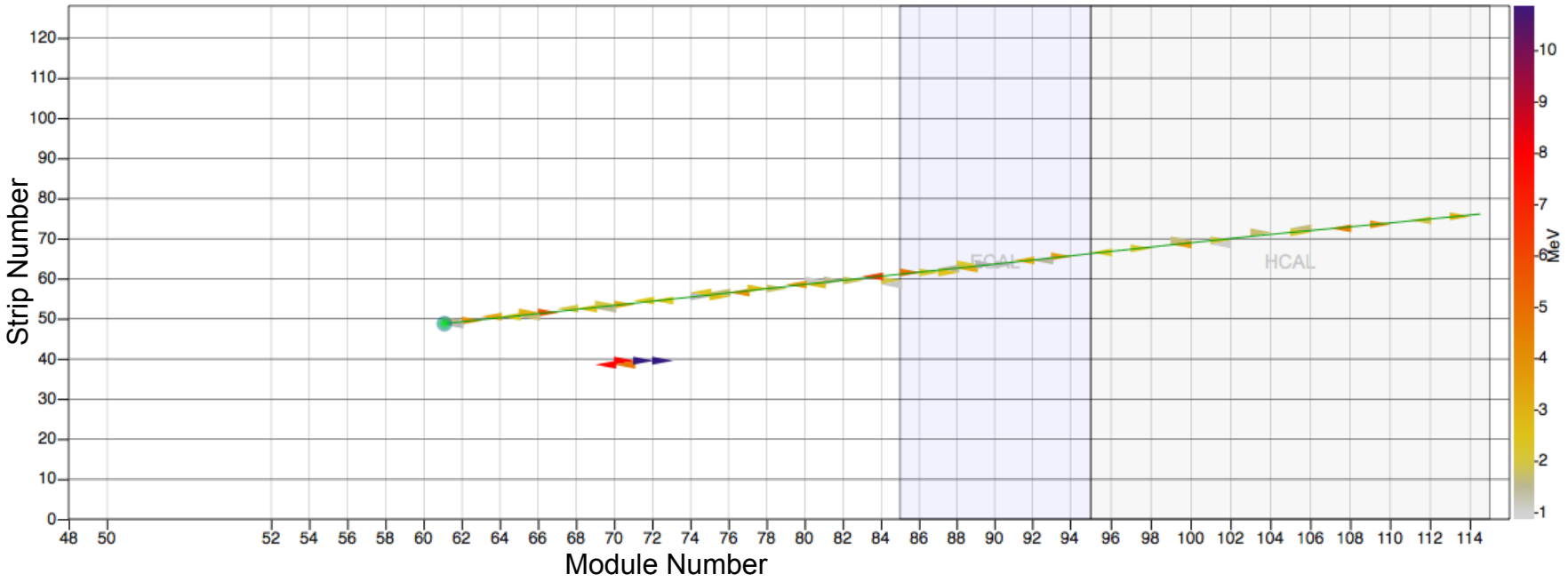
RFGM with NN correlations
Hadronization Model: AGKY – transitions between KNO-based and JETSET (T. Yang, AIP Conf. Proc.967:269-275 (2007))
Formation zone: SKAT $\mu^2 = 0.08$ GeV^2
Intranuclear Rescattering: cascade model; INTRANUKE-hA (*S. Dytman, AIP Conf Proc, 896, pp. 178-184 (2007)*) anchored to π,p/n-Fe data

Anti-Neutrino CCQE Analysis



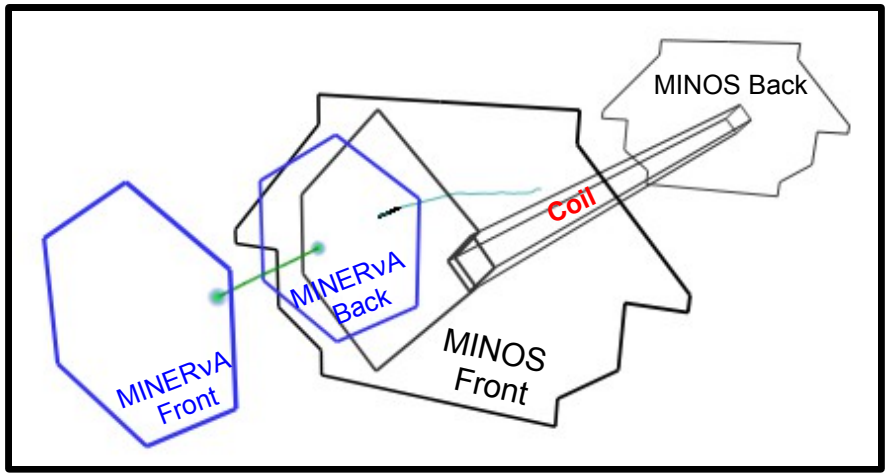
Uses ~1/3 of POT on tape
And partial detector

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

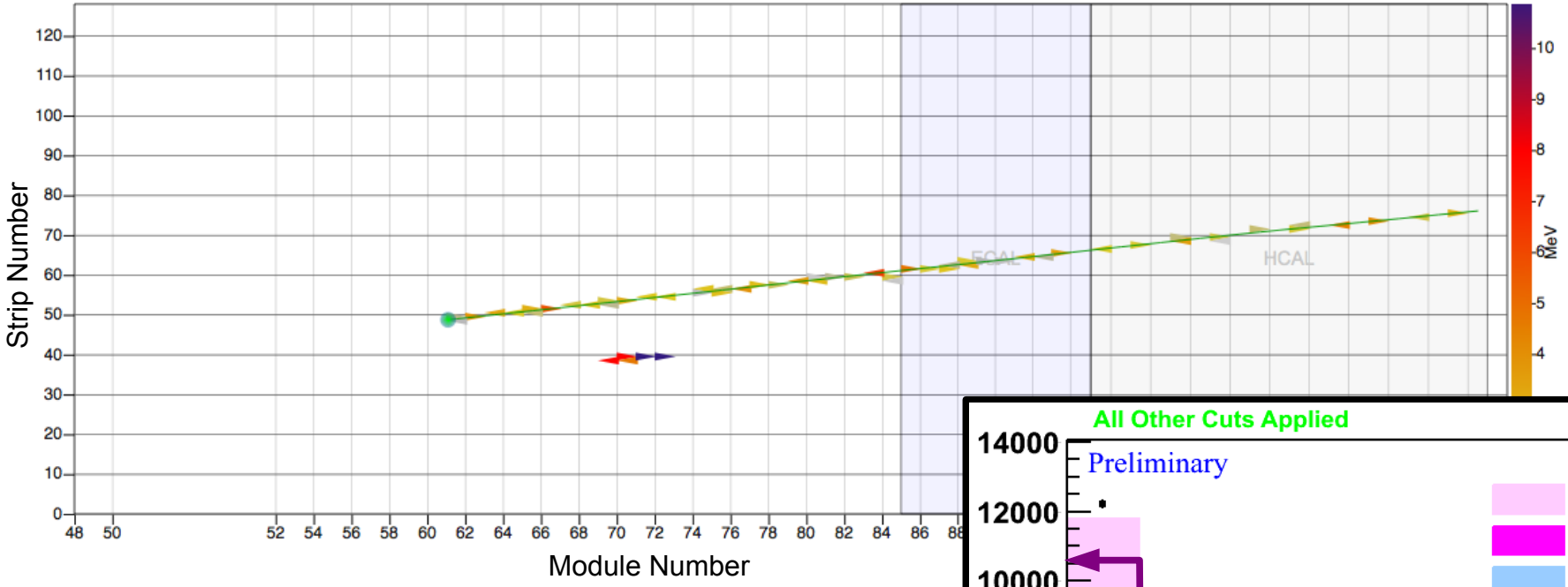


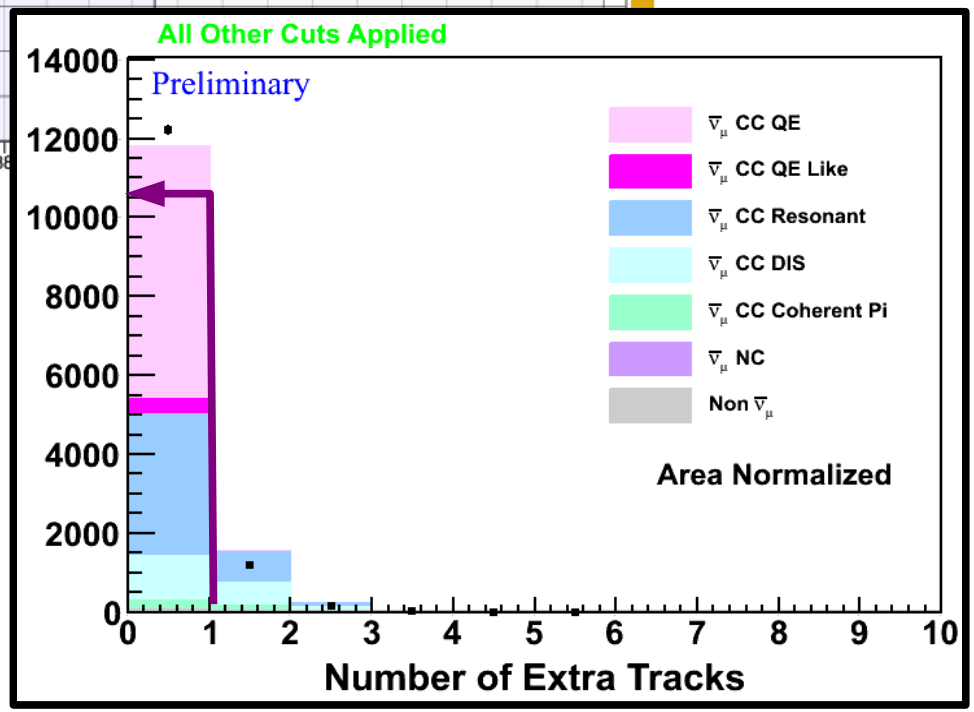
Start by reconstructing a track in MINERvA

Must be matched to a track in MINOS with positive charge



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

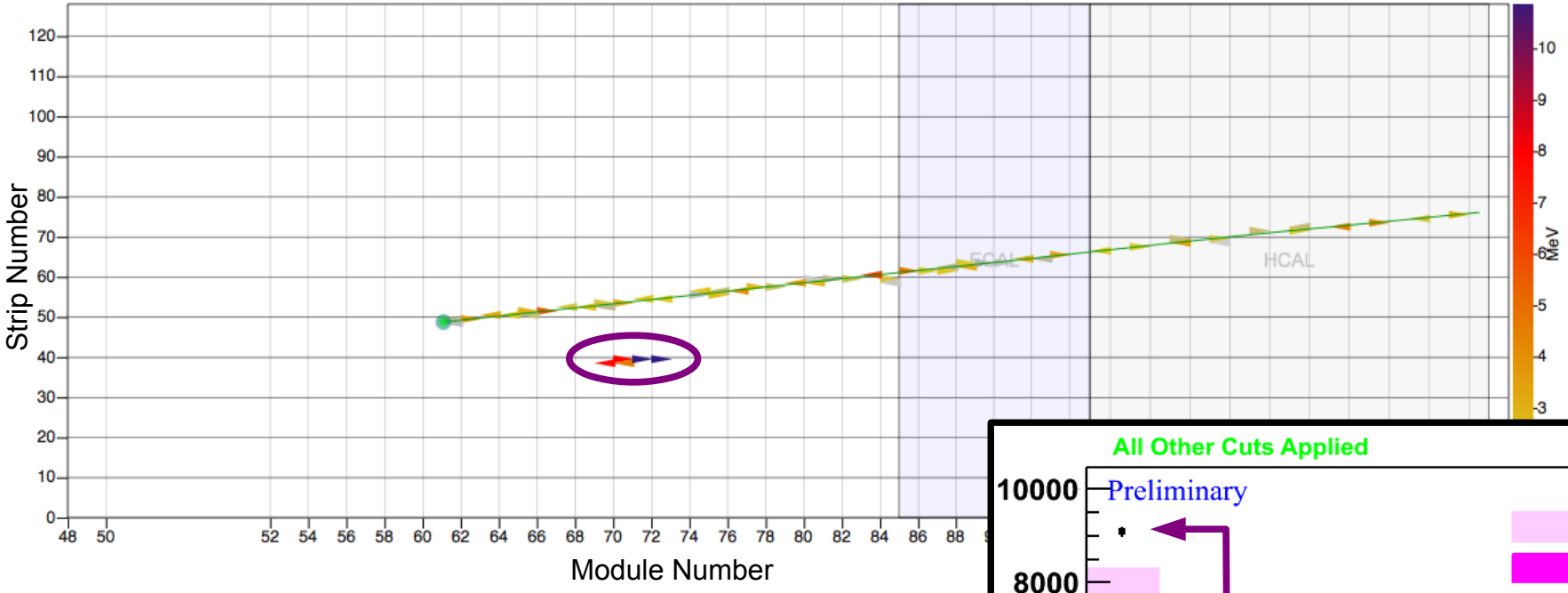


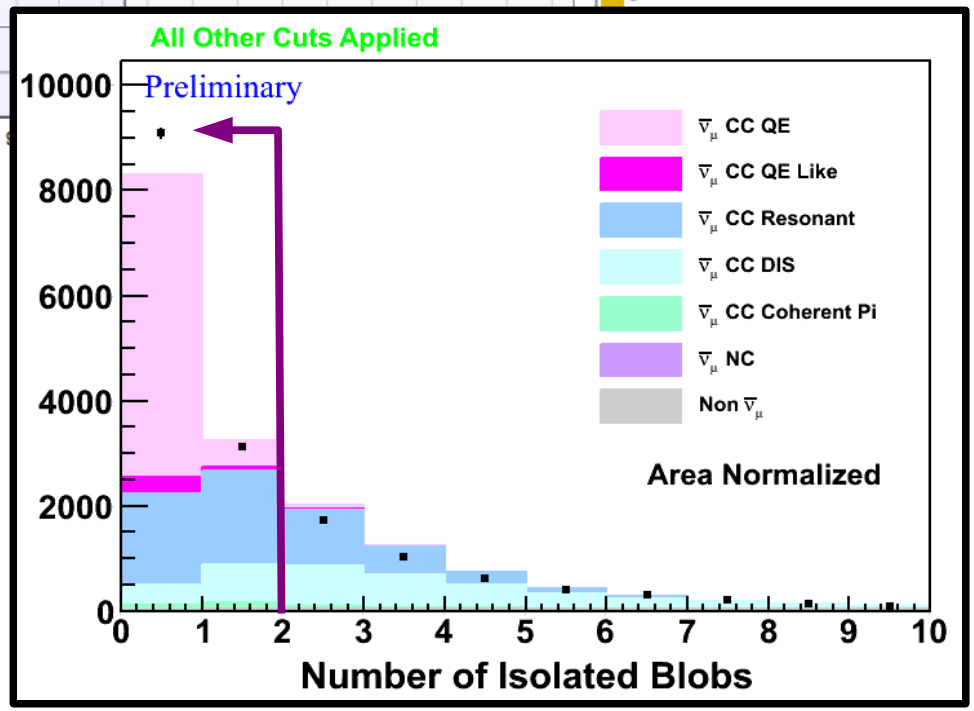


Require no additional tracks

Neutron from true $\bar{\nu}_\mu$ CCQE generally does not create a track

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

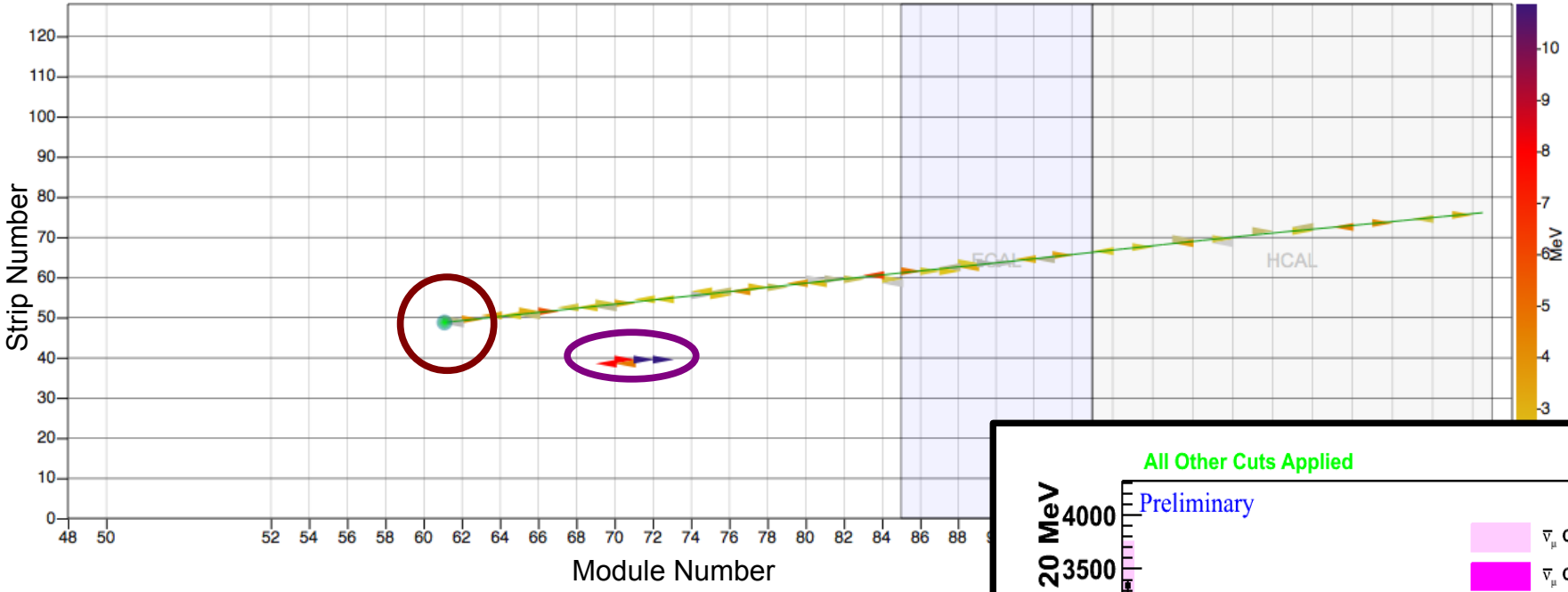


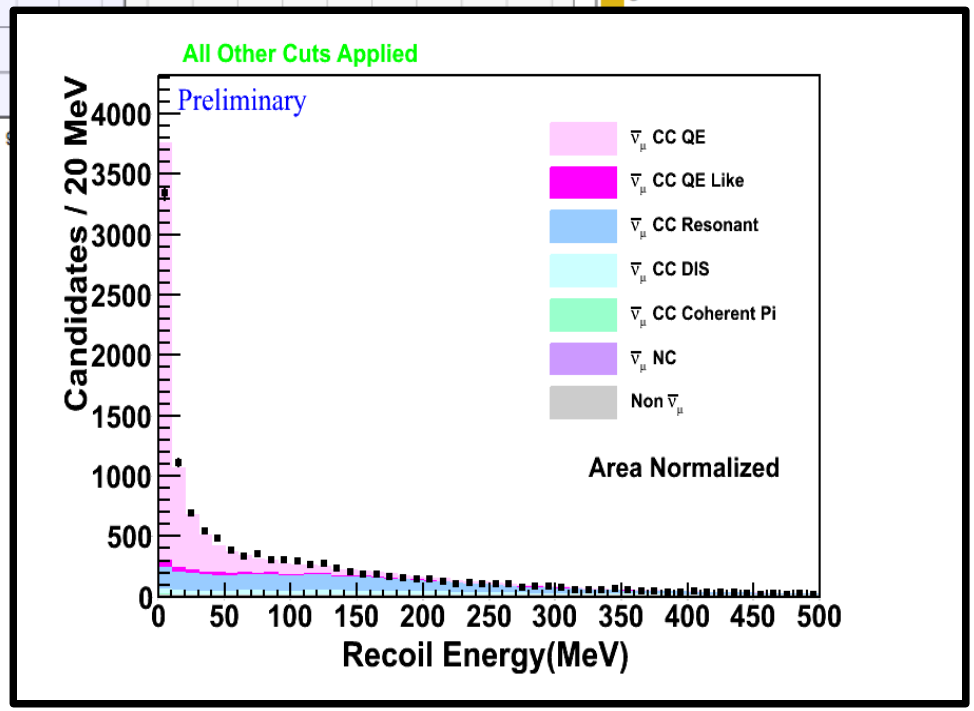


Require no more than one "isolated blob" of energy

Neutron from true $\bar{\nu}_\mu$ CCQE generally leaves at most one large energy deposition

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



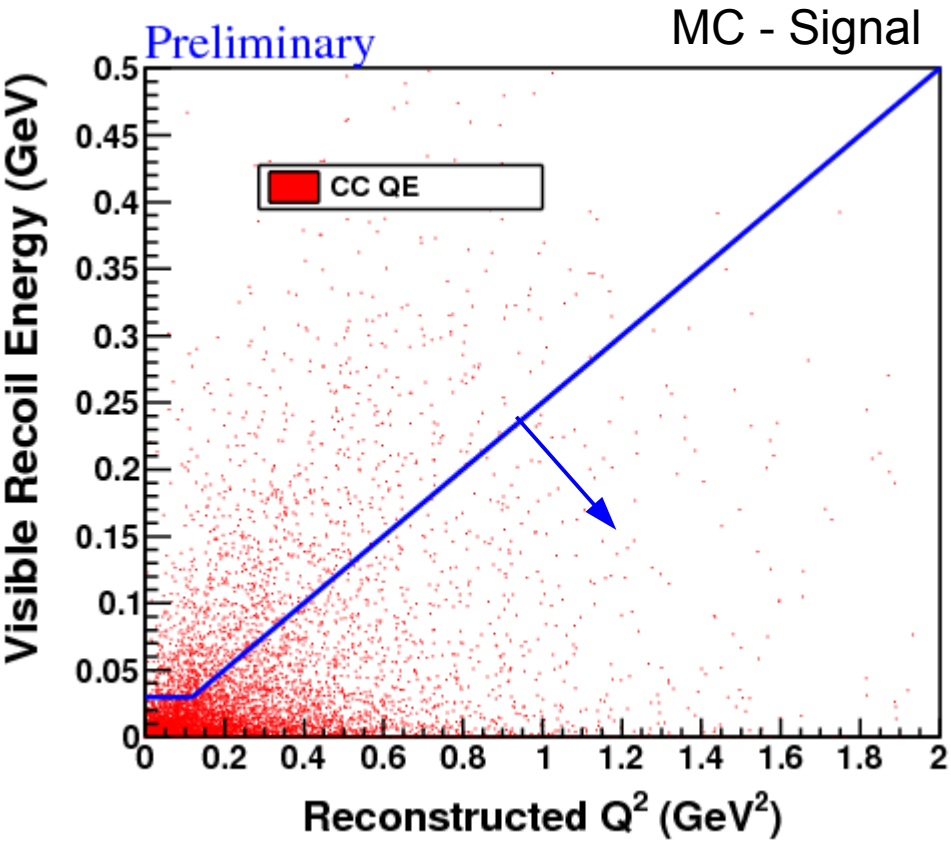


Sum all non-track energy in tracker + ECal

Excluding very low energy and likely xtalk hits
Excluding 10 cm radius around vertex

More on vertex energy coming up!

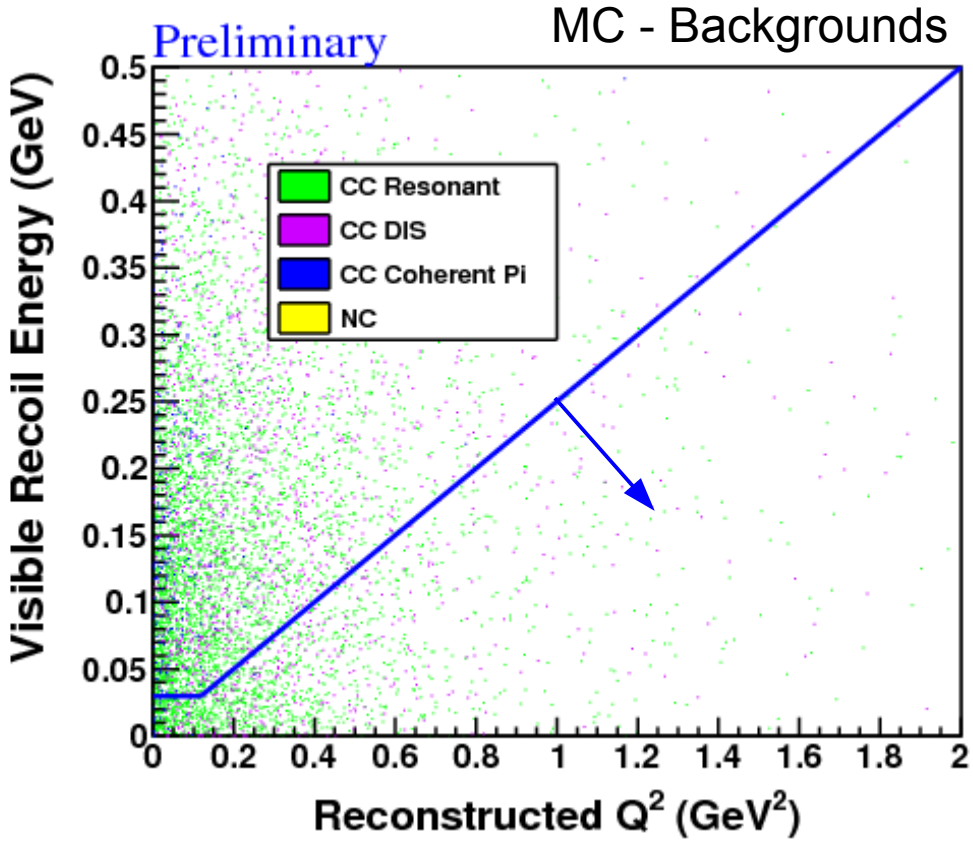
$\bar{\nu}_\mu$ CCQE Analysis



Require less than 30 MeV of recoil at low Q^2

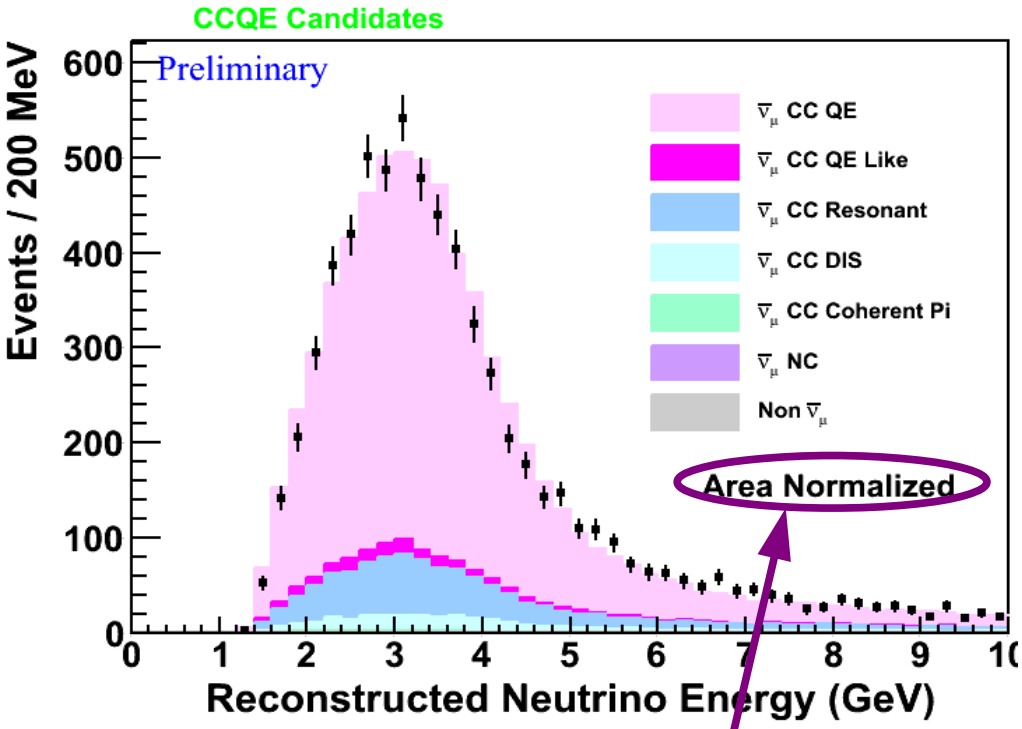
Cut increases to $Q^2/4$ at higher Q^2

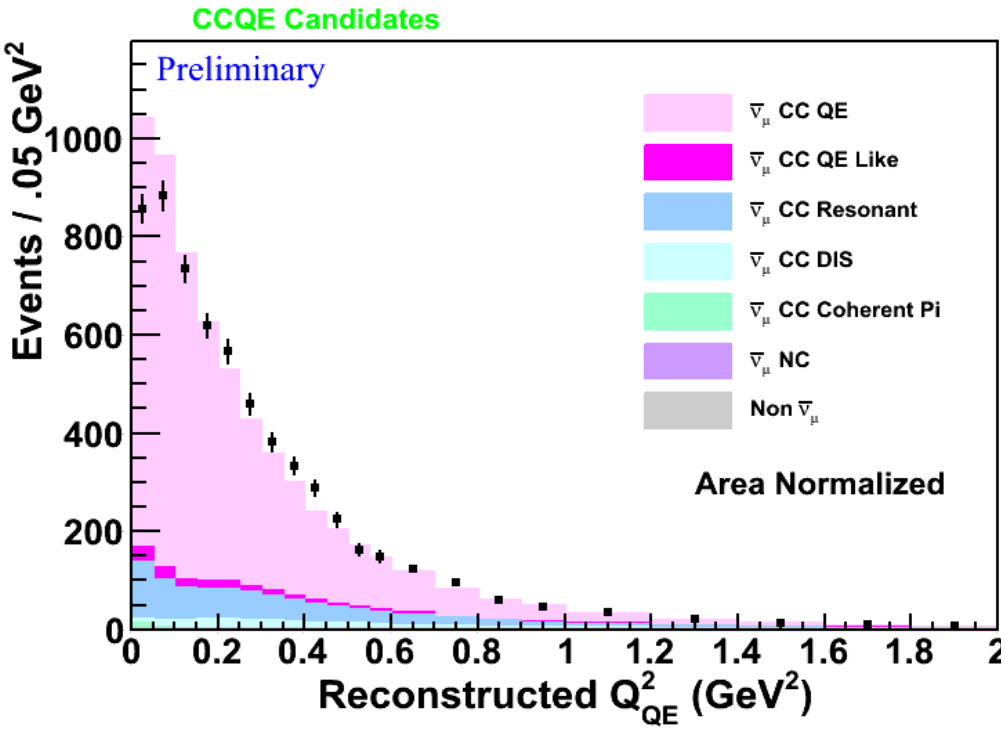
Total efficiency: ~40%
Total purity: ~75%



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

- Neutrino energy and Q2 in the final sample:





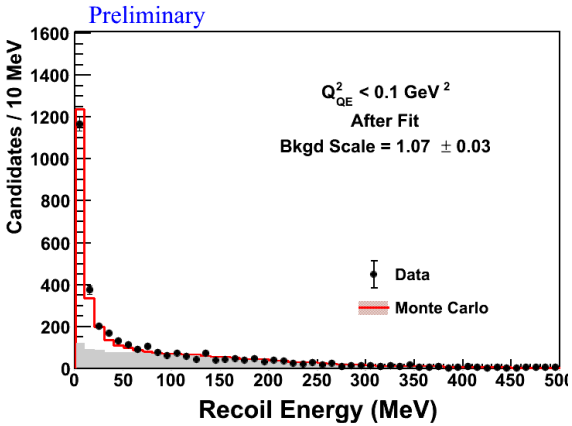
$$E_\nu = \frac{m_\mu^2 - (m_p - E_b)^2 - m_\mu^2 + 2(m_p - E_b)E_\mu}{2(m_p - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

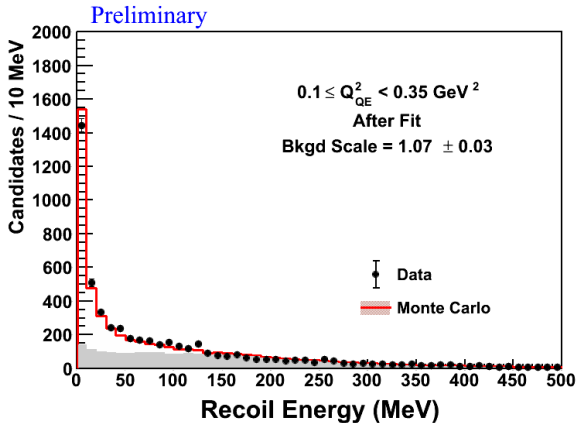
$$Q^2 = 2E_\nu(E_\mu - p_\mu \cos\theta_\mu) - m_\mu^2$$

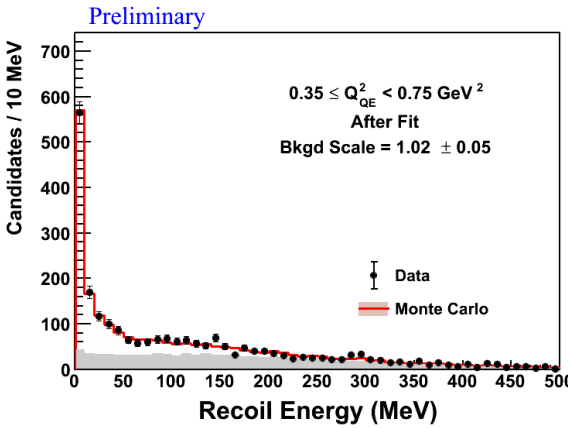
"Area Normalized" used here (and throughout this talk) to denote comparisons of shapes between data and MC.

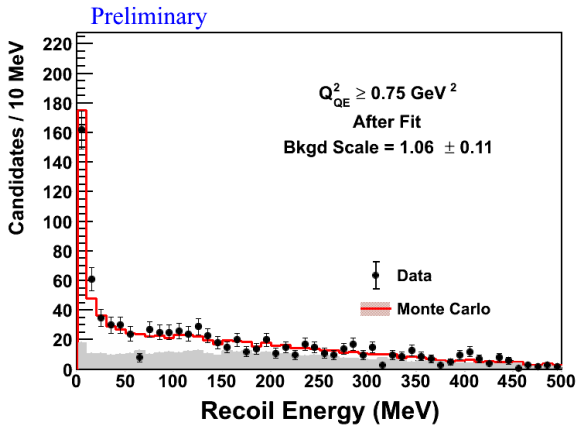
$\bar{\nu}_\mu$ CCQE Analysis

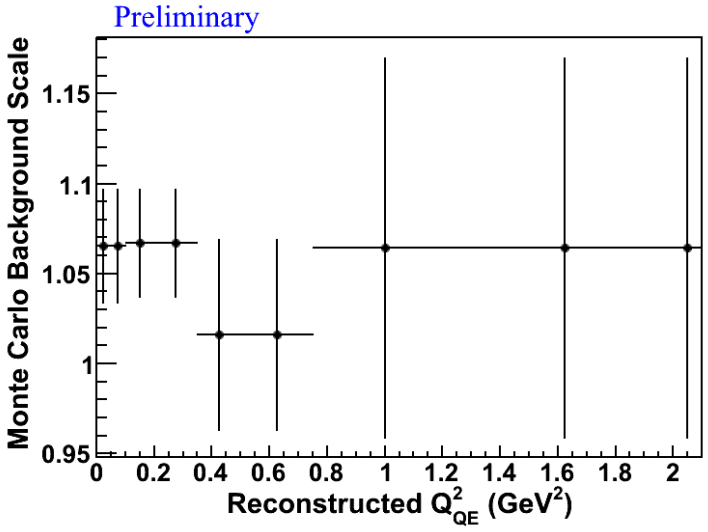
- Background levels are estimated by fitting recoil distributions:





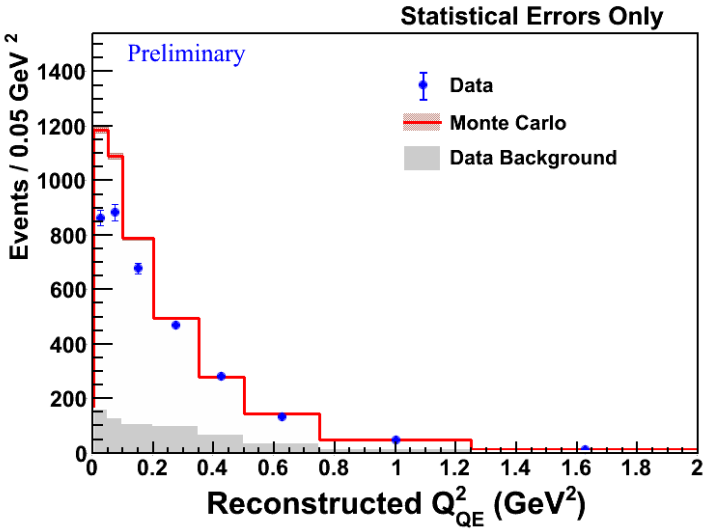




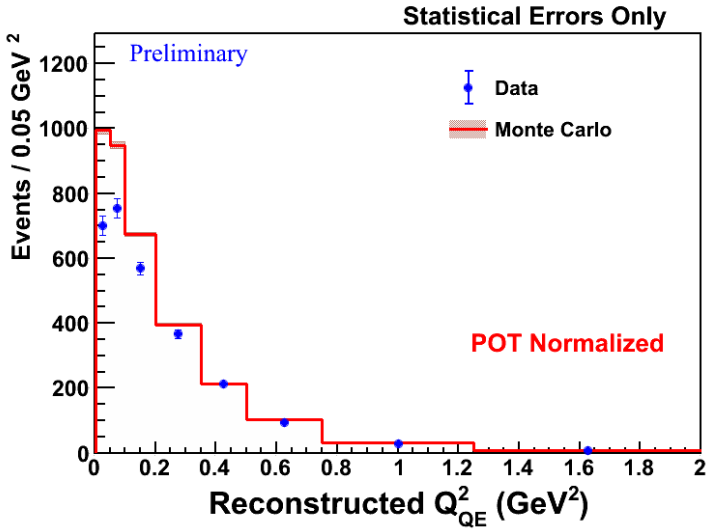


$\bar{\nu}_\mu$ CCQE Analysis

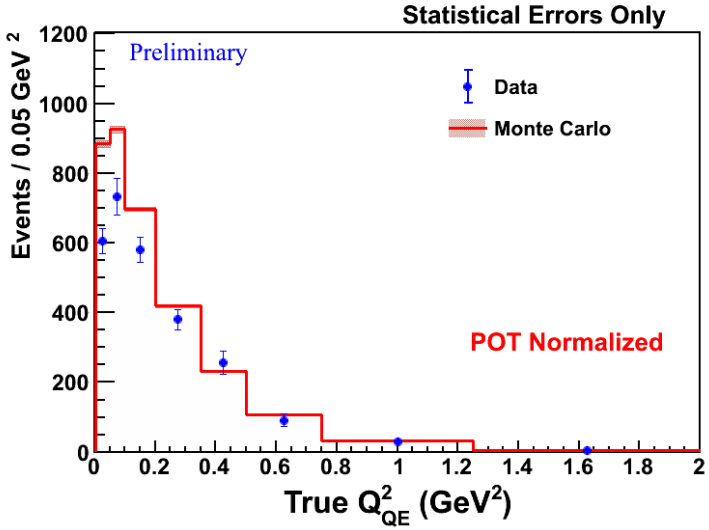
- Background Subtracted Distributions are unfolded::



Background Subtraction



Unfolding

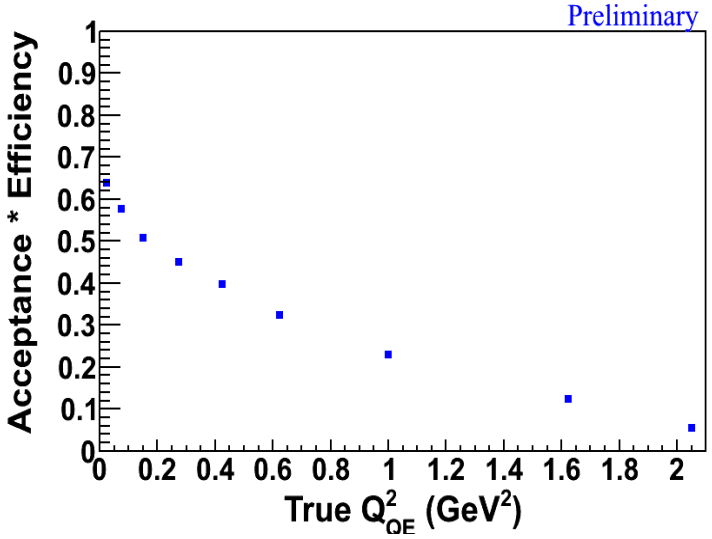


This analysis currently uses the simple matrix inversion method of unfolding

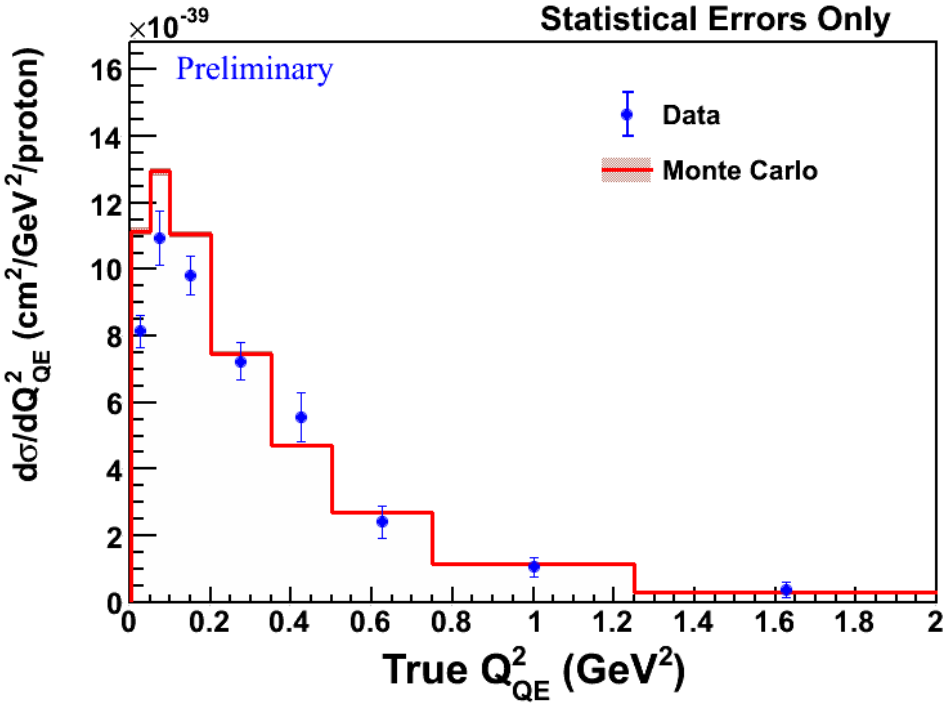
Other unfolding methods are being studied

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

- Unfolded distributions are normalized by efficiency, flux & proton number to produce final cross-sections:



Here (and in other analyses in this talk), we correct to GENIE-defined CCQE definition (not CCQE-like, which may come in the future)

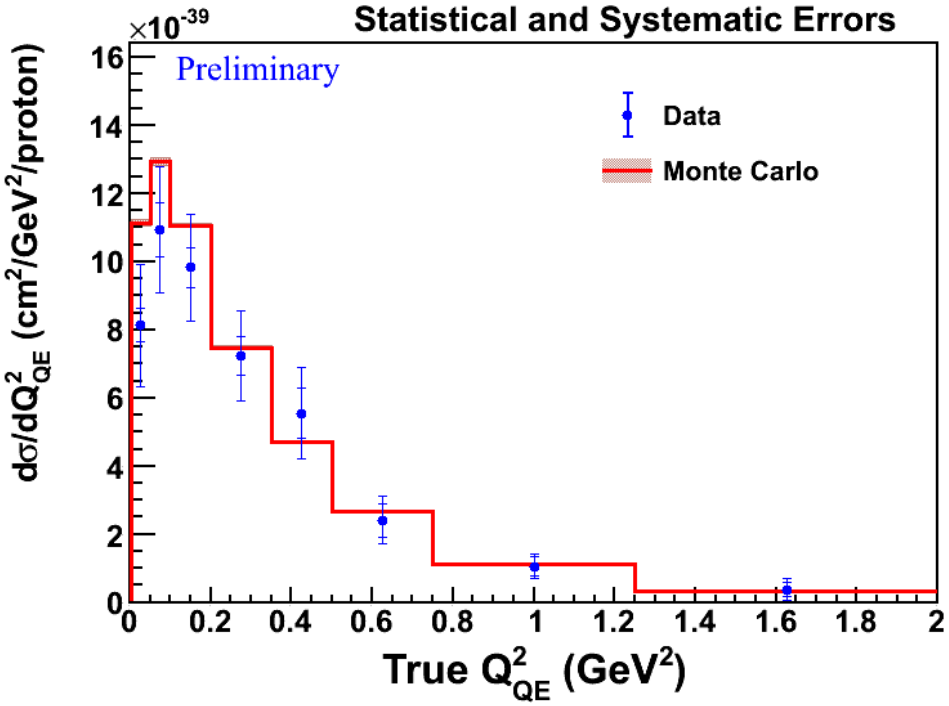


Monte Carlo Model:

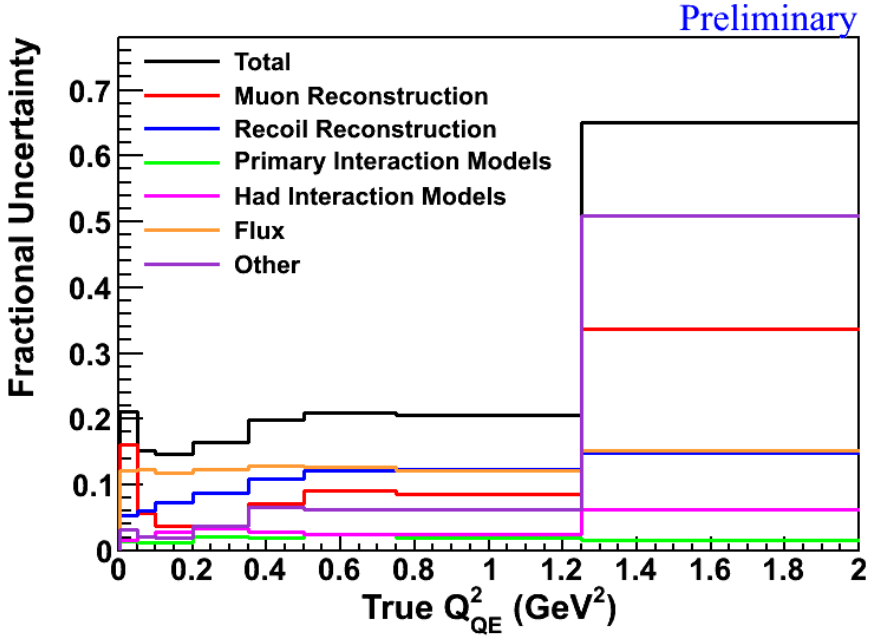
GENIE 2.6.4; M_A = 0.99 GeV; RFG; Pauli-blocking; No MEC

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

- We have also made a first estimate systematic uncertainties:

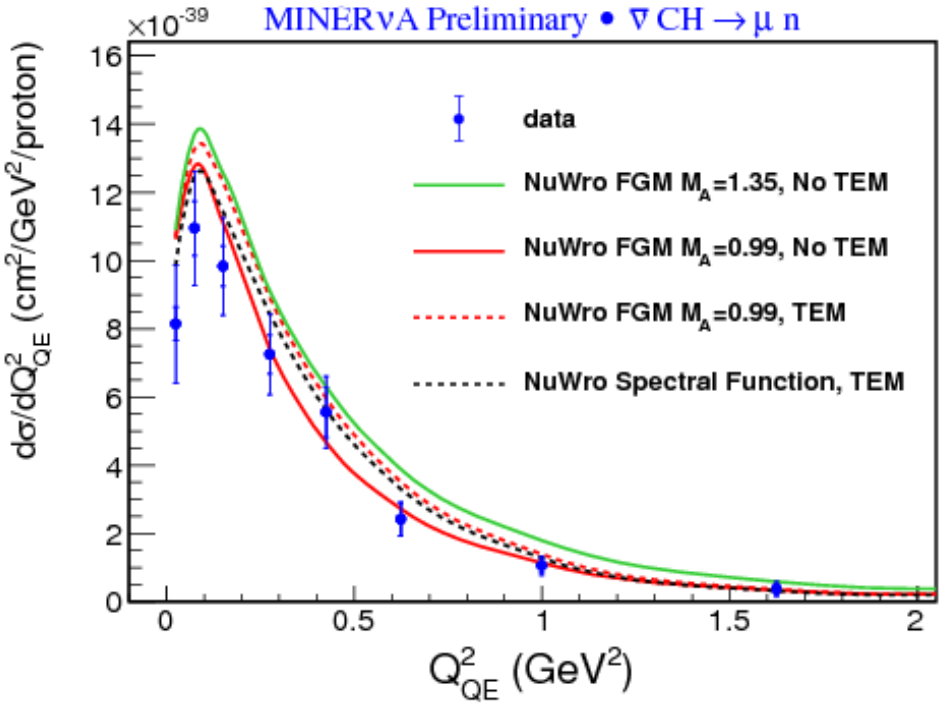


Largest systematic uncertainties are from flux and recoil reconstruction



We expect nearly all systematics to be significantly lower in the future

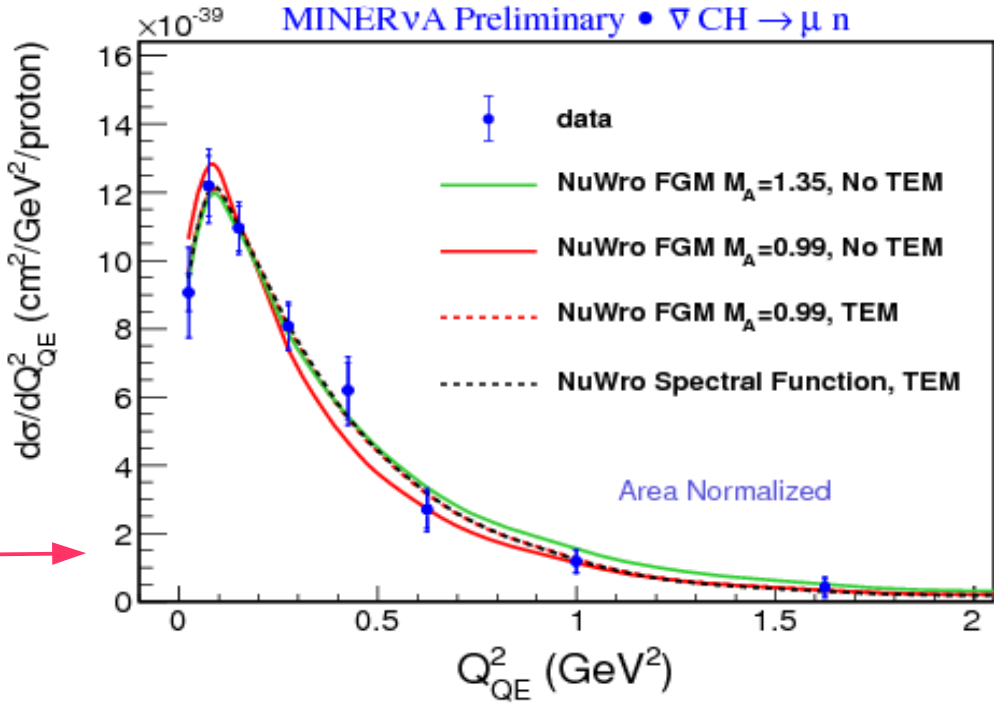
$\bar{\nu}_\mu$ CCQE Analysis



Comparison with Models

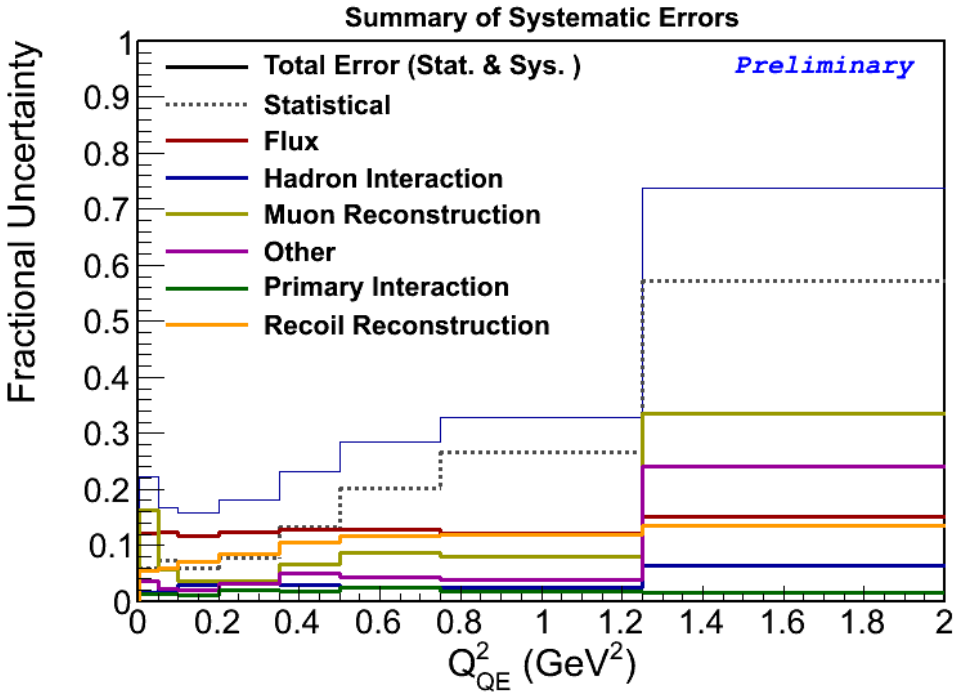
NuWro: Golal, Jusczak, Sobczyk
arXiv:1202.4197

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



Shown for the first time at NuInt
a shape-only comparison of data/models

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



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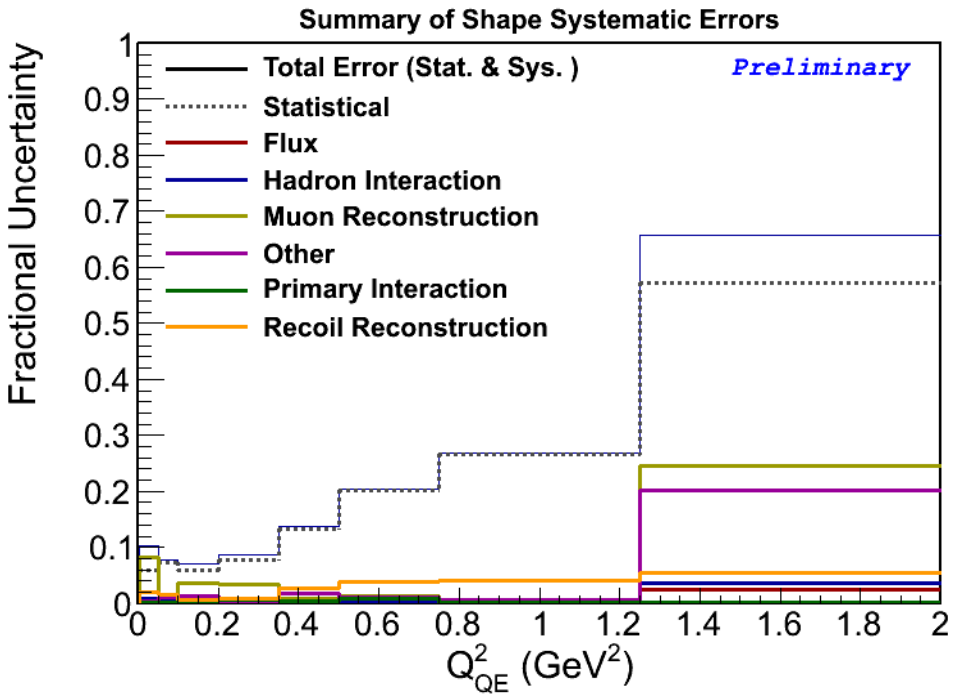
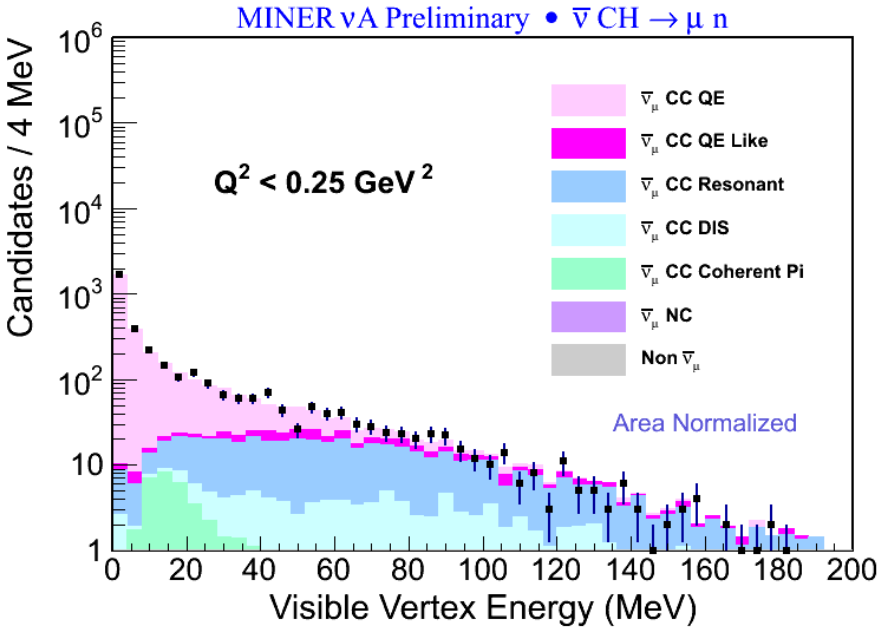


Shown for the first time at NuInt

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

- Also new for NuInt

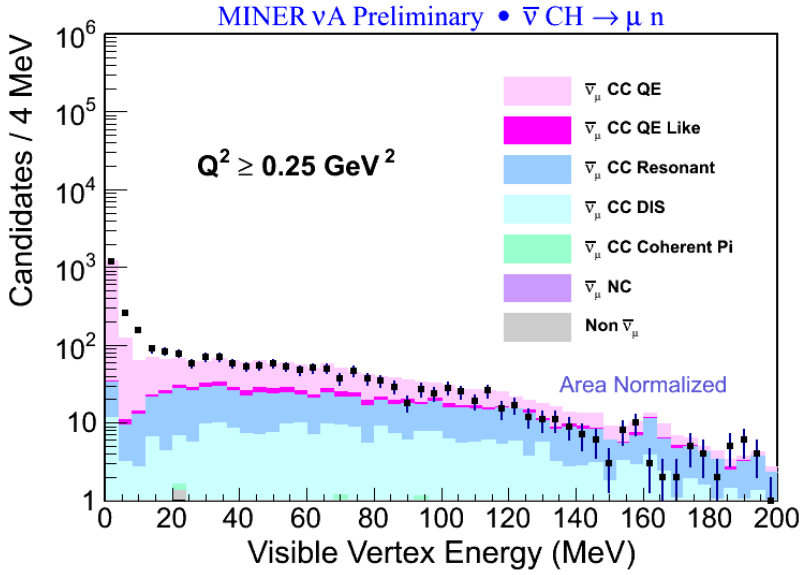


Data agrees well with GENIE at low Q^2, but has excess in 0-20 GeV region at high Q^2

A first peak inside "the vertex box"

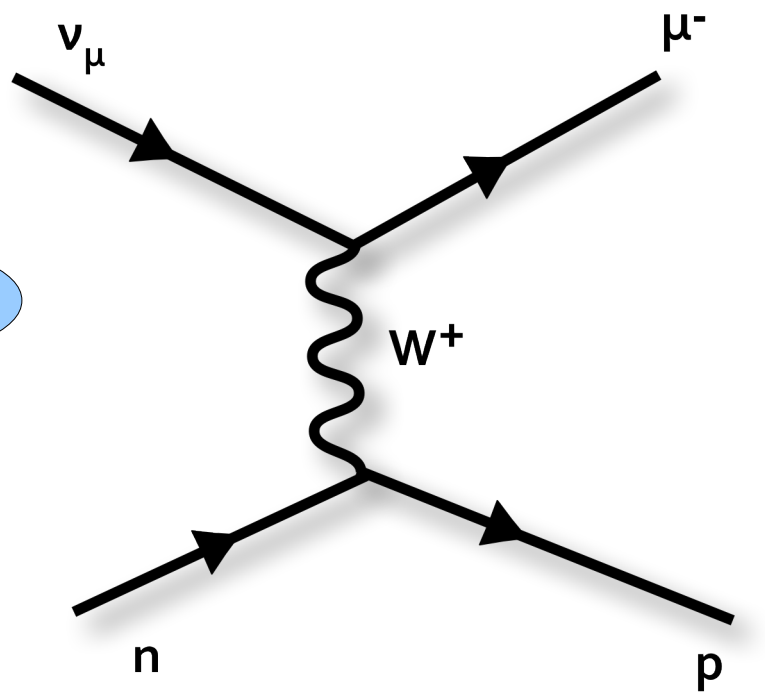
Measurements of **visible** energy in a 10mm radius around the vertex

This energy is **excluded** from our standard recoil energy definition



New for NuInt!

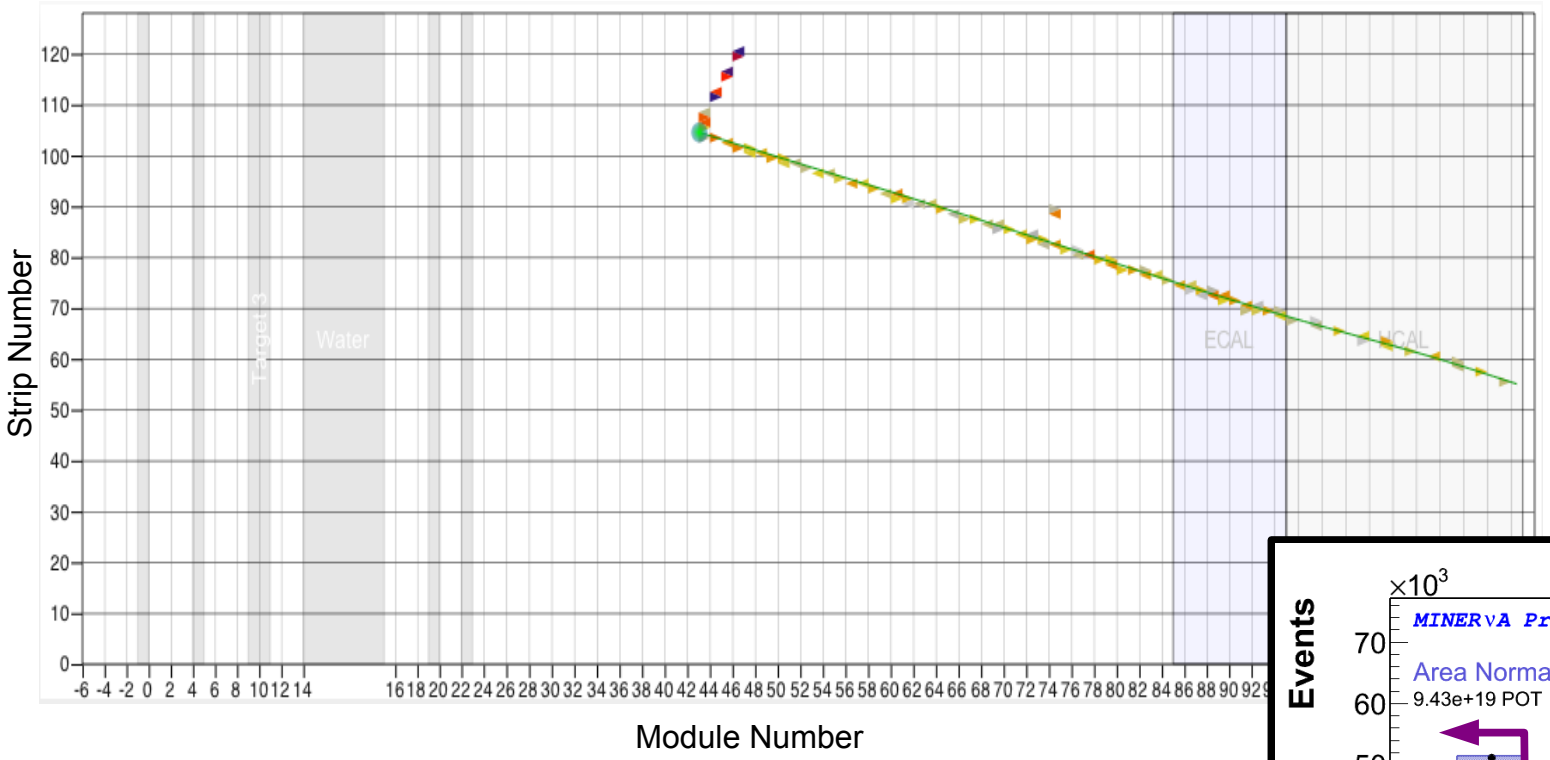
1-Track Neutrino CCQE Analysis

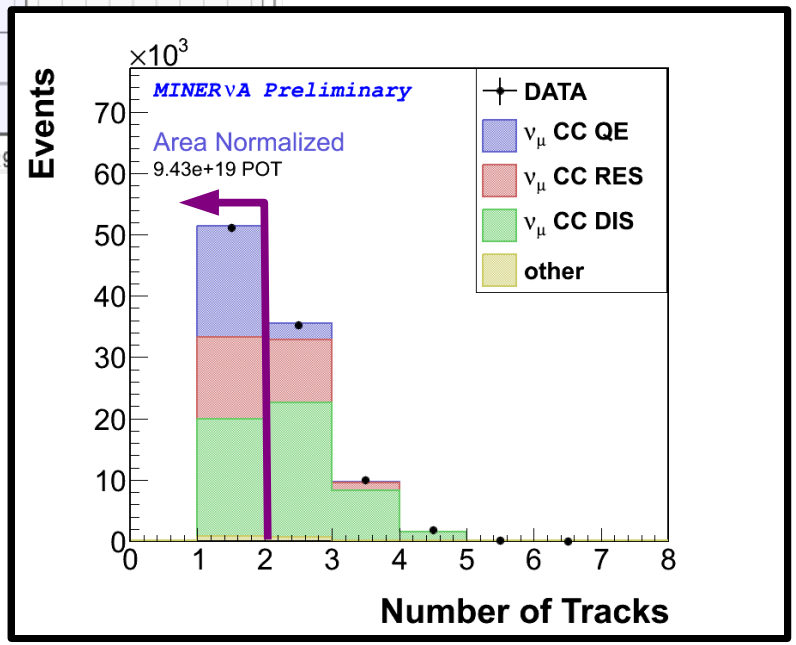


For more info, see our poster on this topic

Uses ~1/4 of POT on tape

1–Track ν_μ CCQE Analysis

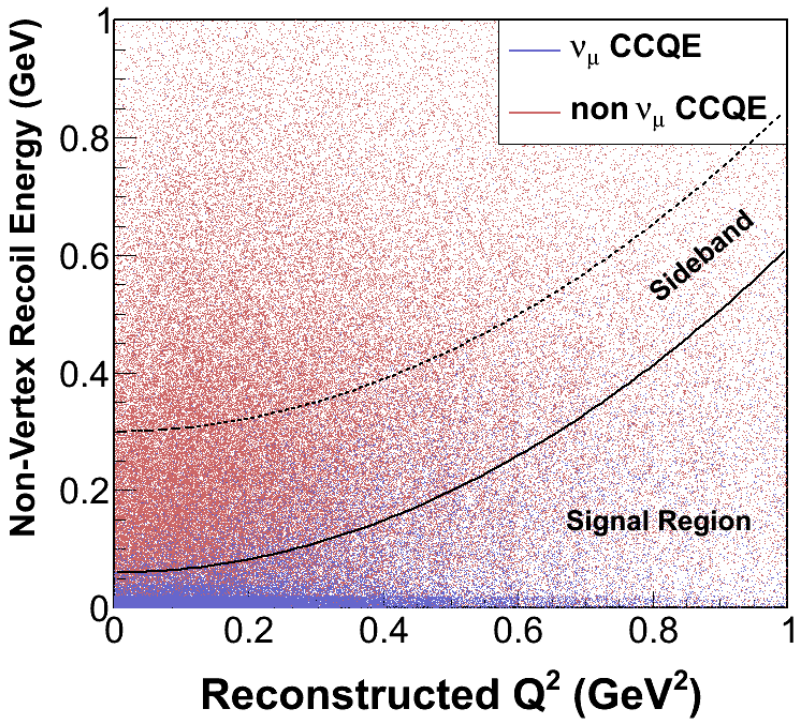


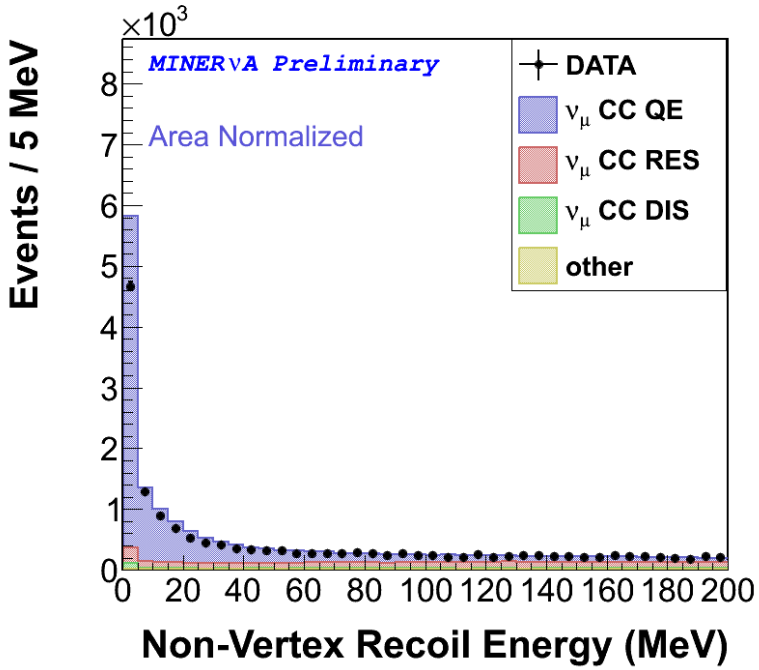


Sample selection very similar to anti-nu analysis

Requires MINOS-matched track, no extra tracks, less than two isolated blobs and little recoil energy (with vertex energy excluded)

1–Track ν_μ CCQE Analysis



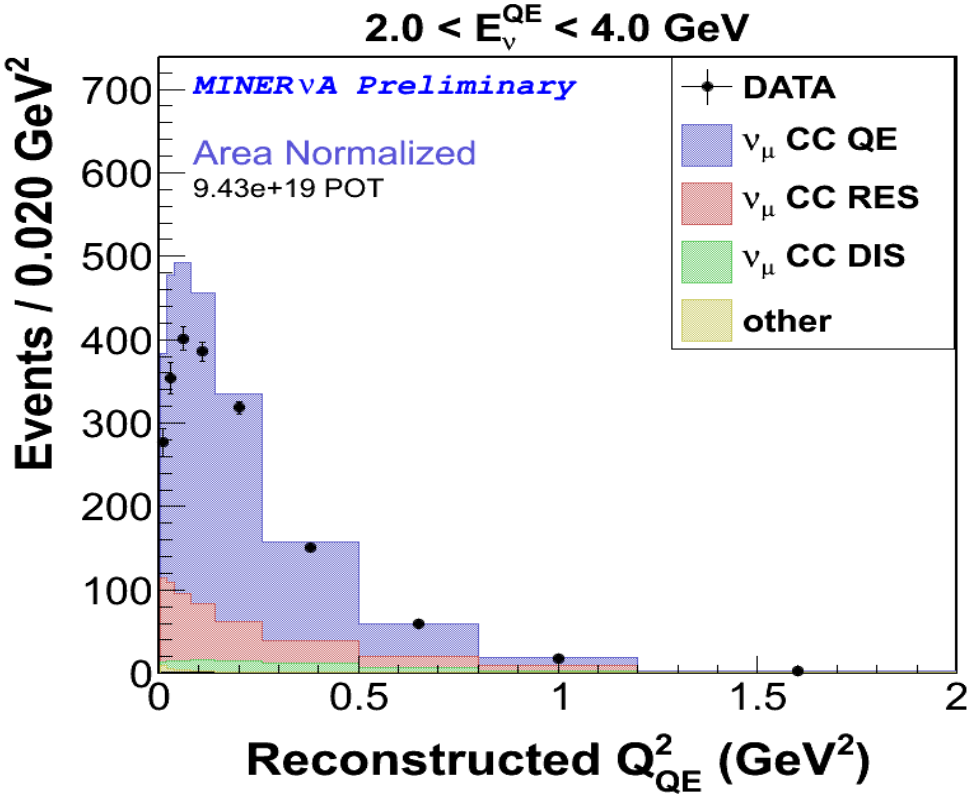


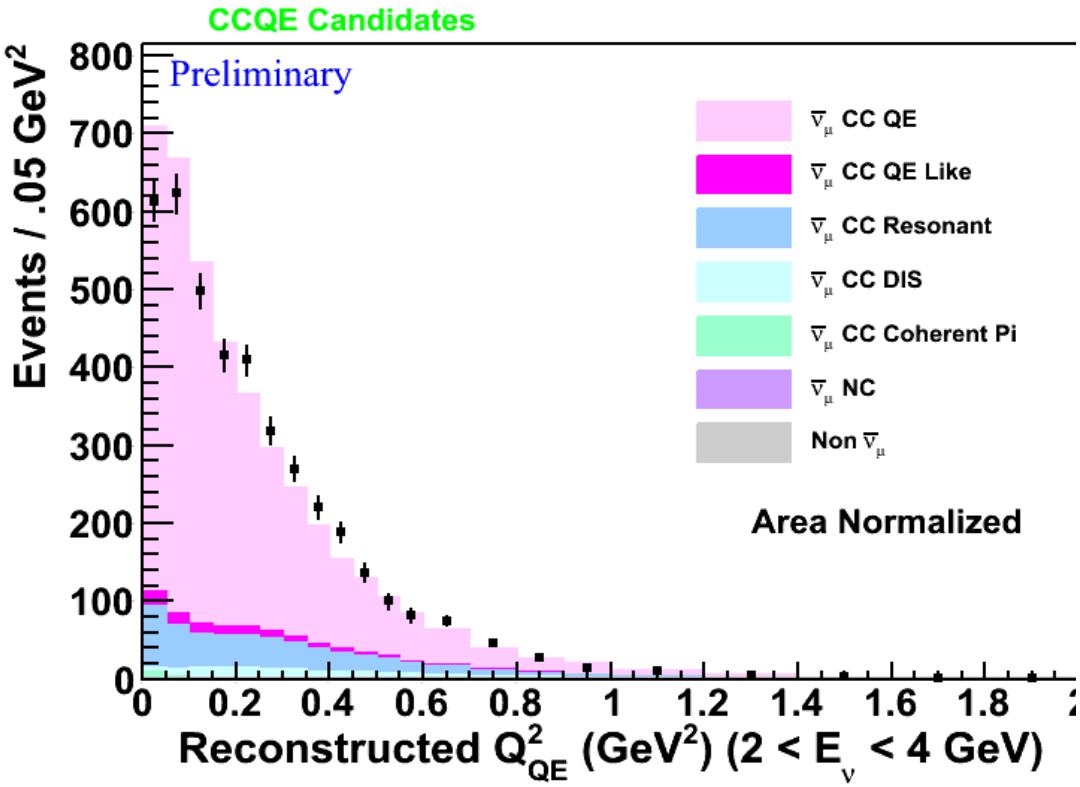
Sample selection very similar to anti-nu analysis

Recoil distributions have slightly different structure (due to presence of proton rather than neutron in final state)
-> recoil cut has different shape than anti-ν analysis

1–Track ν_μ CCQE Analysis

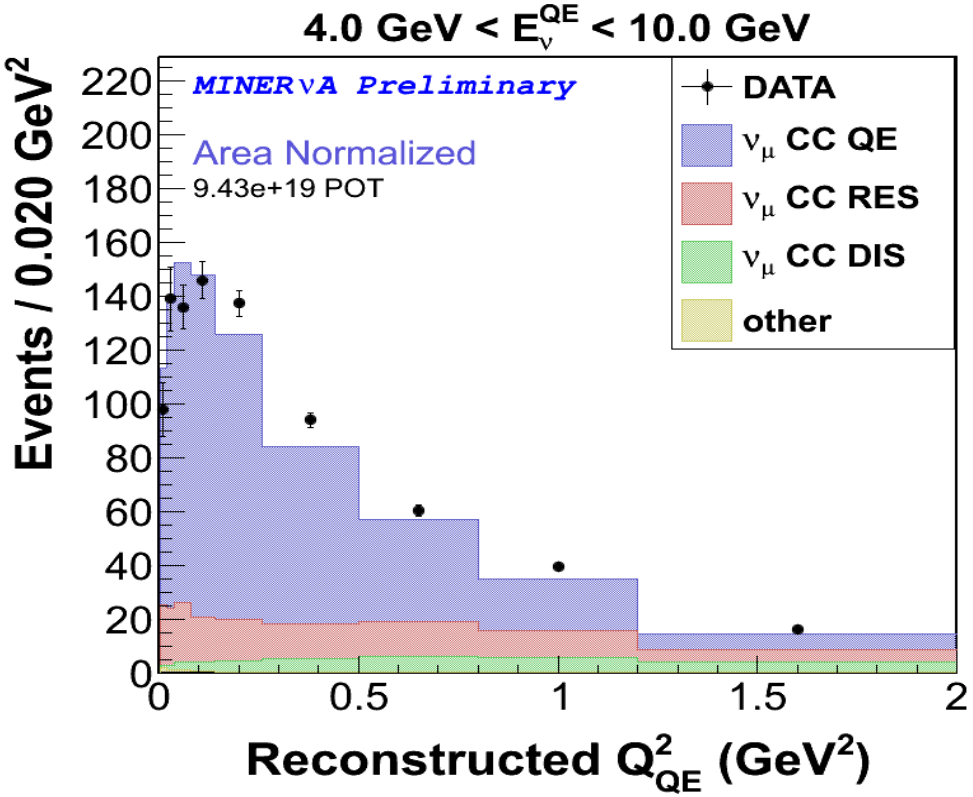
- Comparing the neutrino and anti-neutrino 1-track QE samples:

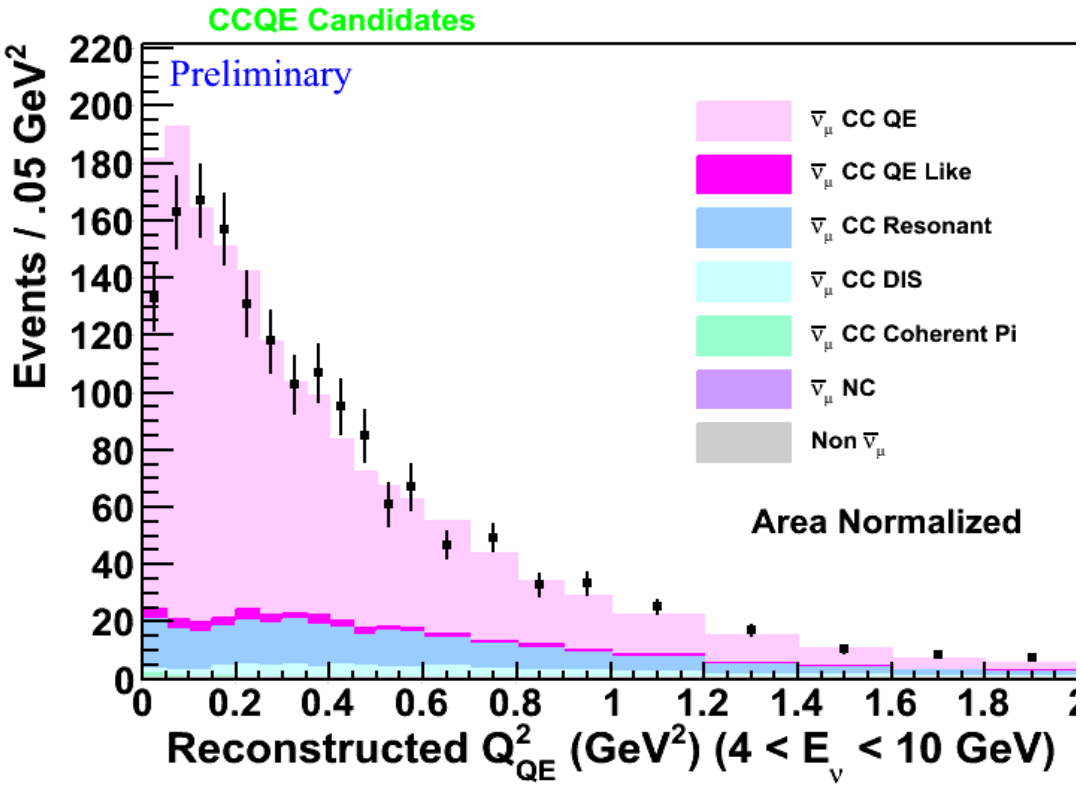




1–Track ν_μ CCQE Analysis

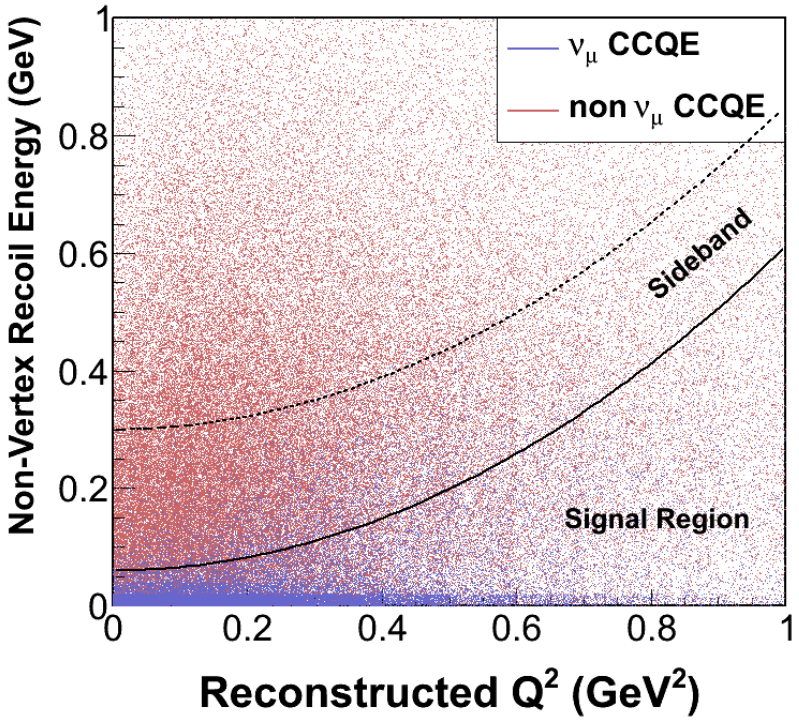
- Comparing the neutrino and anti-neutrino 1-track QE samples:





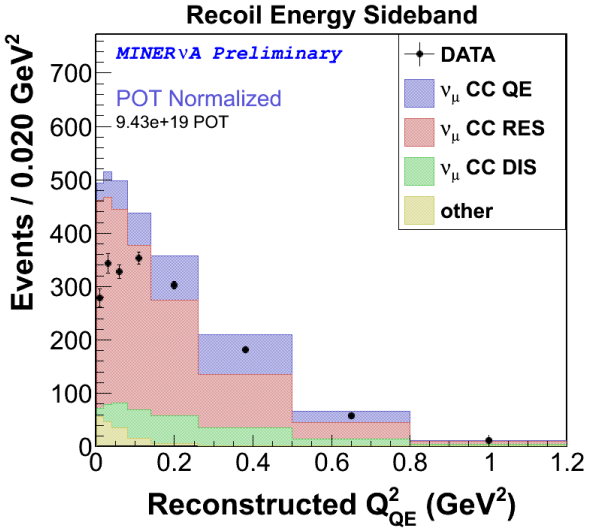
1–Track ν_μ CCQE Analysis

- Background estimates are estimated slightly differently:



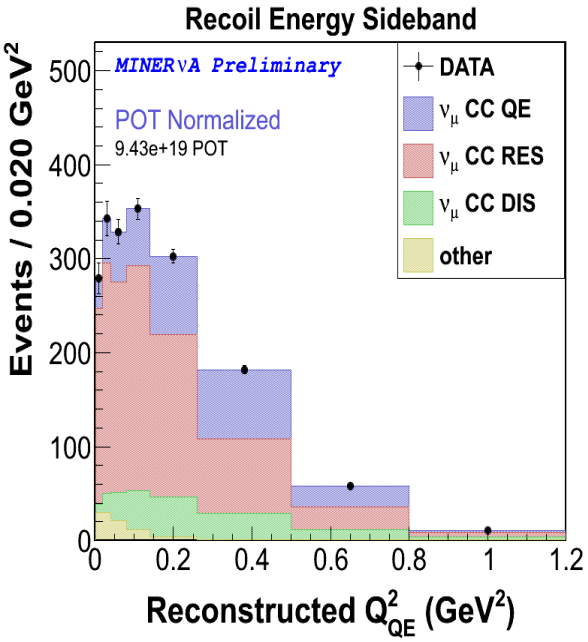
Sideband region is identified in recoil vs Q2 plane

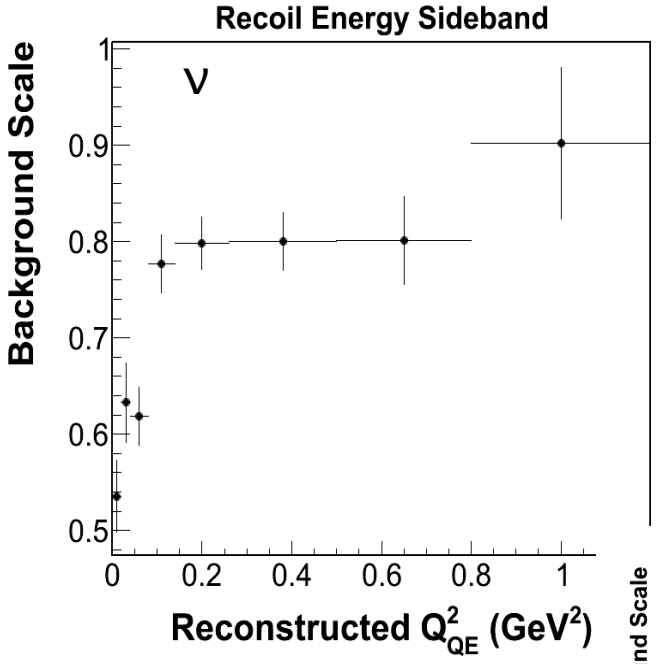
Q2 distributions (in the background-dominated region) are compared between data/MC



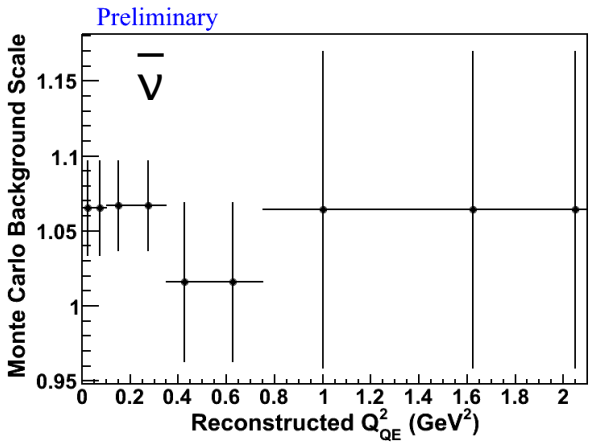
1–Track ν_μ CCQE Analysis

- MC backgrounds are scaled so that MC and data match perfectly:



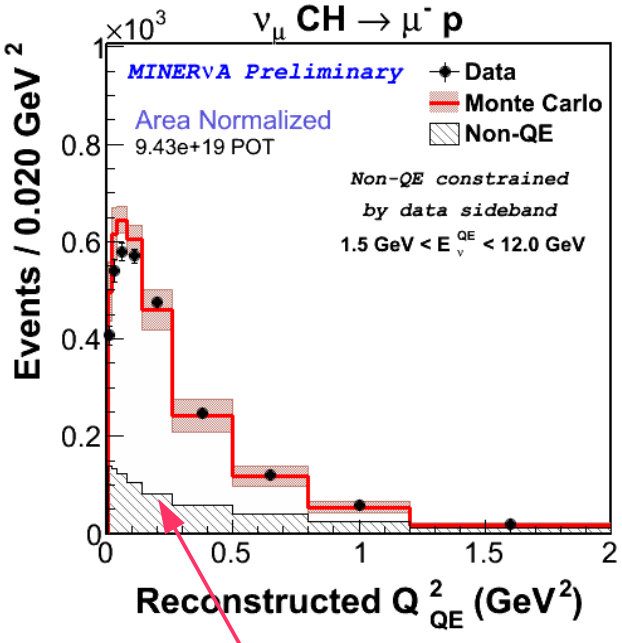


MC backgrounds are scaled down significantly at low Q2 (different from anti-nu analysis)

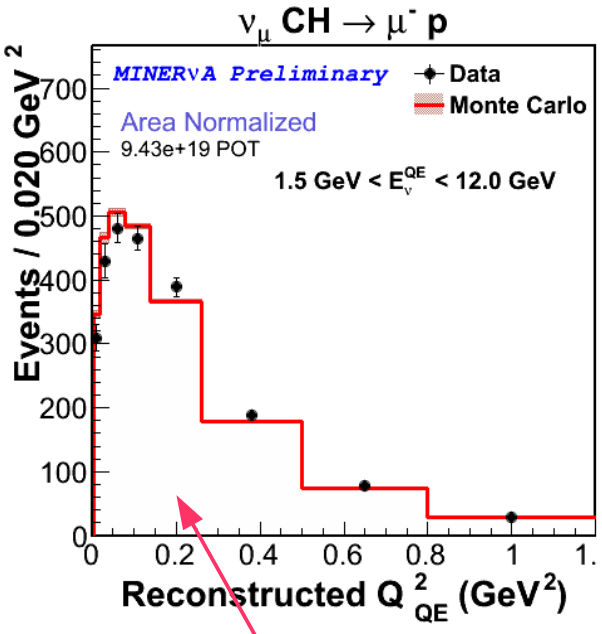


1–Track ν_μ CCQE Analysis

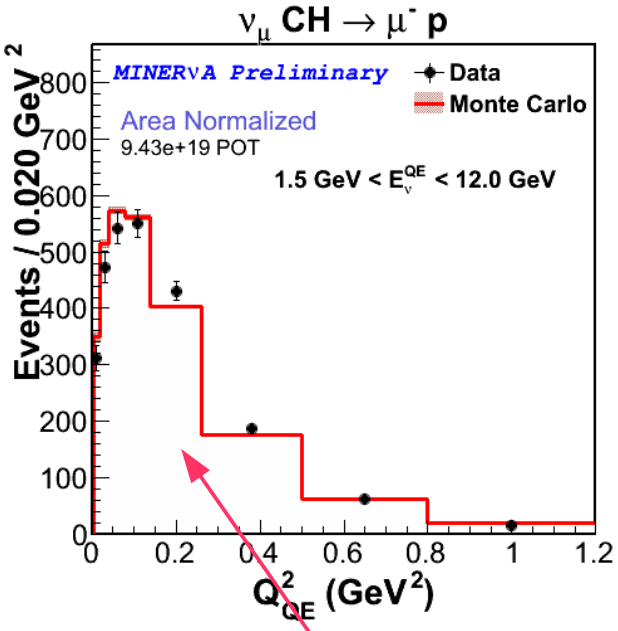
- Unfolding method is also different than anti-nu analysis – the nu-mode analysis uses iterative Bayesian unfolding:



Raw



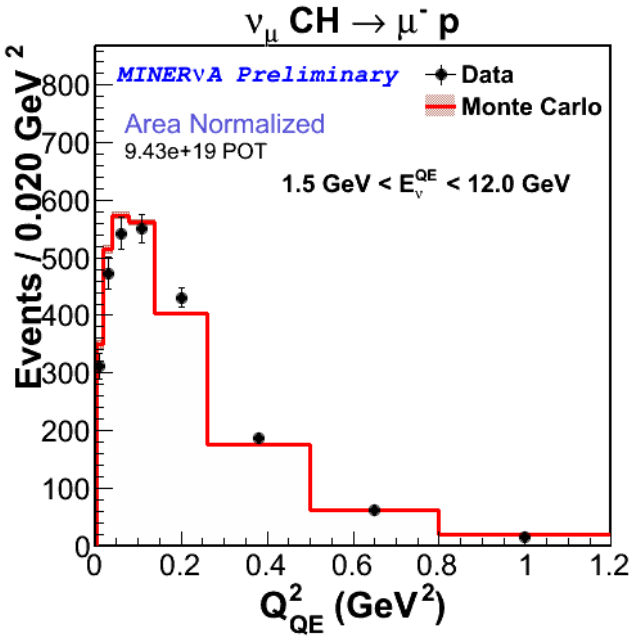
Background Subtracted

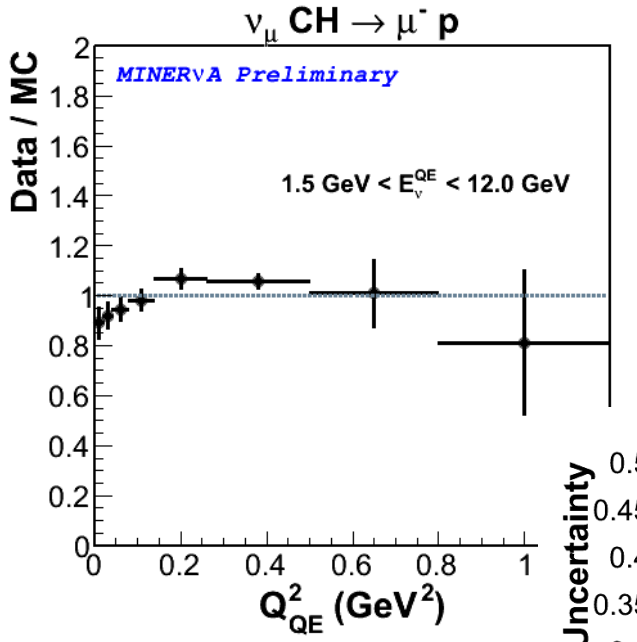


Unfolded

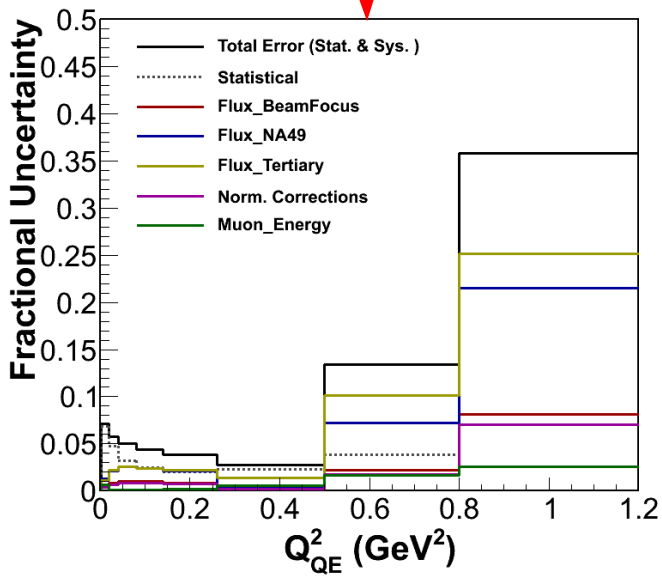
1–Track ν_μ CCQE Analysis

- A closer look at the unfolded distribution:





Error bars include partial systematic uncertainties, summarized here

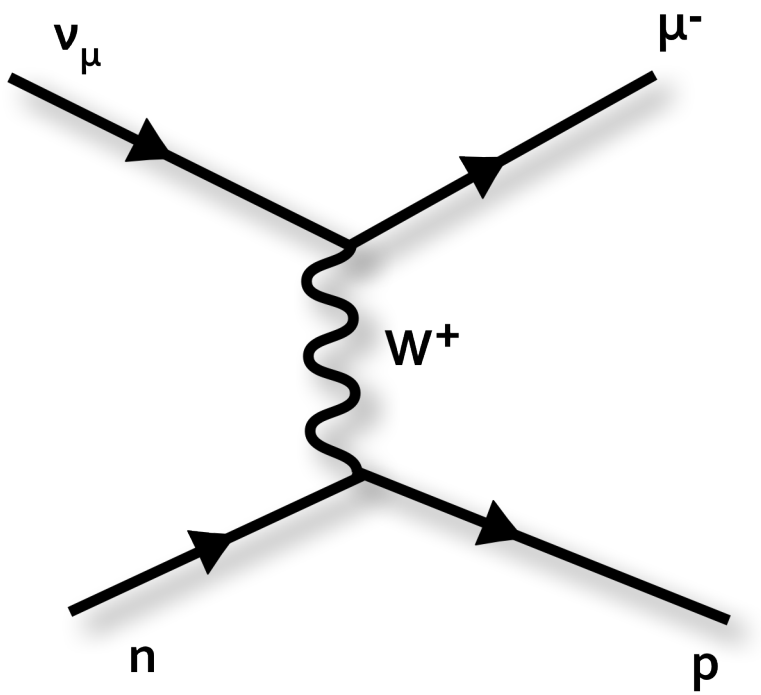


Shape appears consistent with Genie (M_A = 0.99, RFGM) currently.

Improved uncertainties and full efficiency corrected cross-sections coming soon!

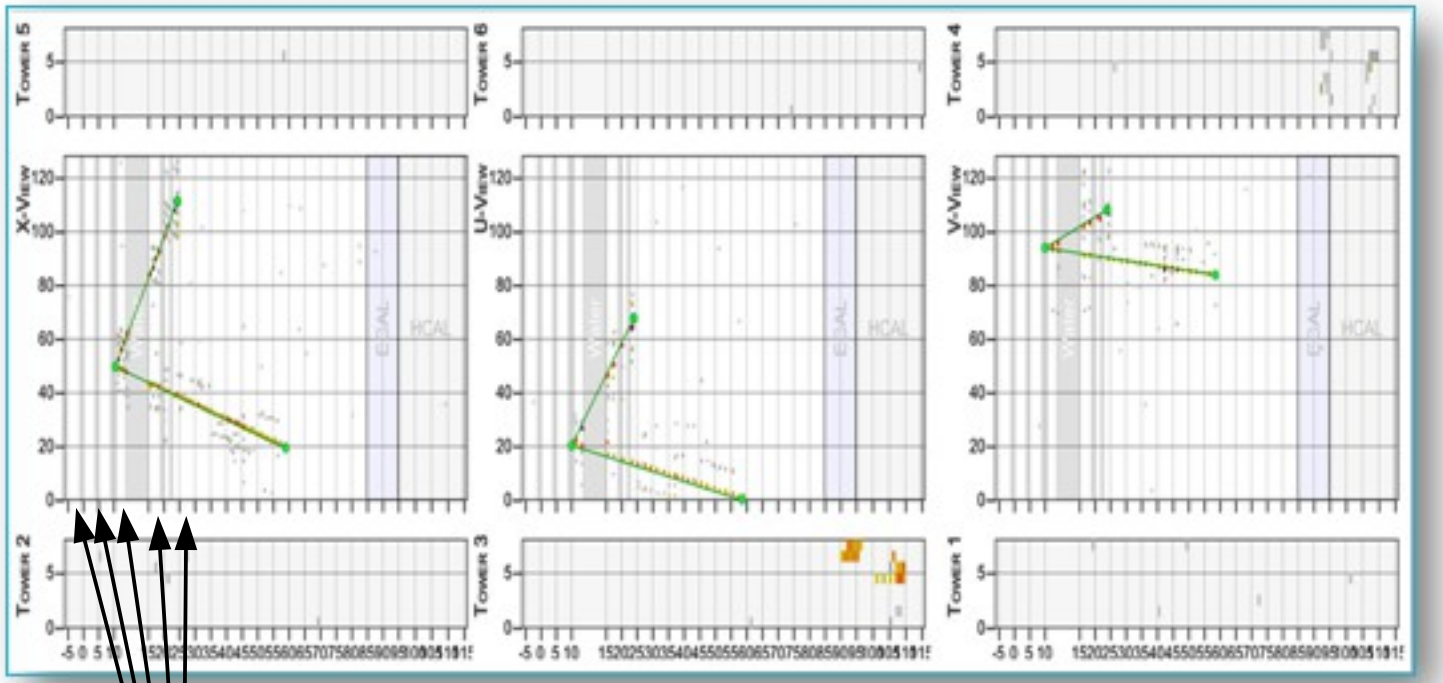
New for NuInt!

2-Track Neutrino CCQE in Iron, Lead and Carbon



Uses ~1/4 of POT on tape

2-Track ν_μ CCQE in Fe, Pb and C

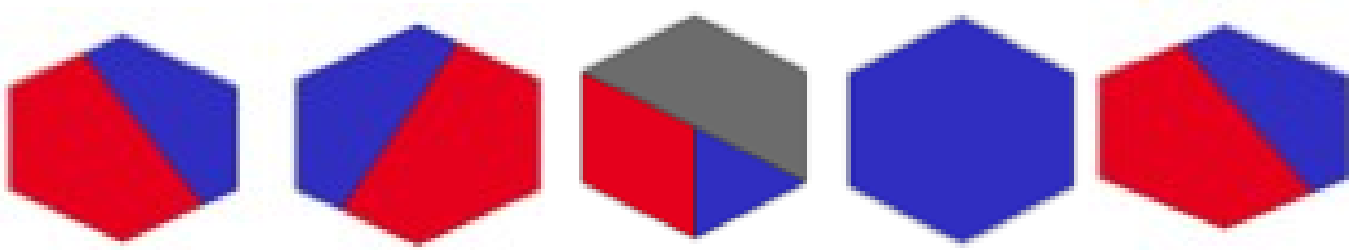


This is the first analysis to use non-MINOS matched muons

In most cases, only a lower limit on the muon momentum is known, and the muon charge is unknown

This analysis reconstructs 2-track QE candidates in targets 1,2,3,4 and 5
He & H20 targets were not yet filled for this data set.

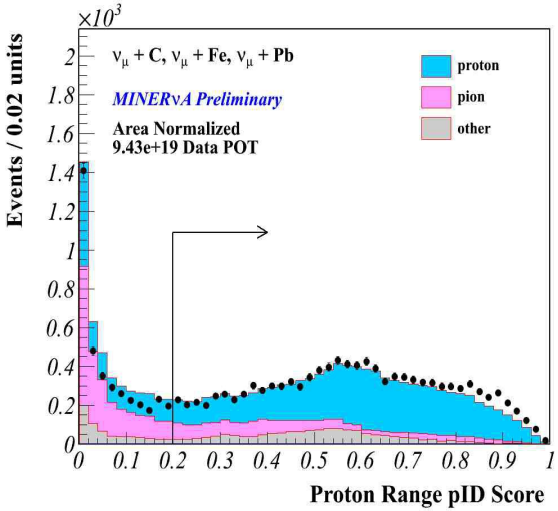
Blue=Lead Grey=Carbon Red=Iron



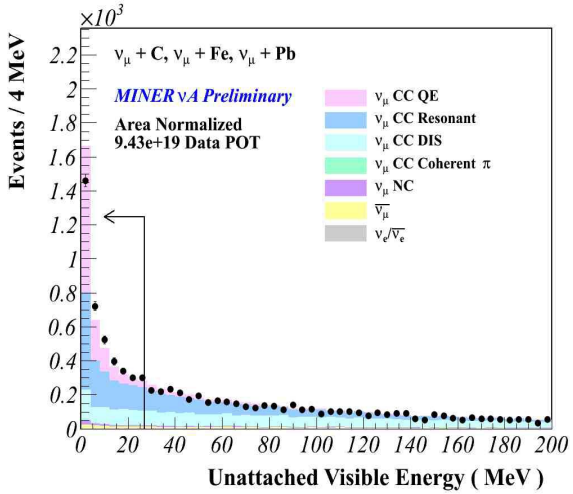
2.5 cm | 2.5 cm | 2.5/7.5 cm | 0.75 cm | 1.25 cm

2-Track ν_μ CCQE in Fe, Pb and C

- Analysis starts by reconstructing two tracks
  - Reconstruction of proton allows background supression beyond what's available to the 1-track analyses:

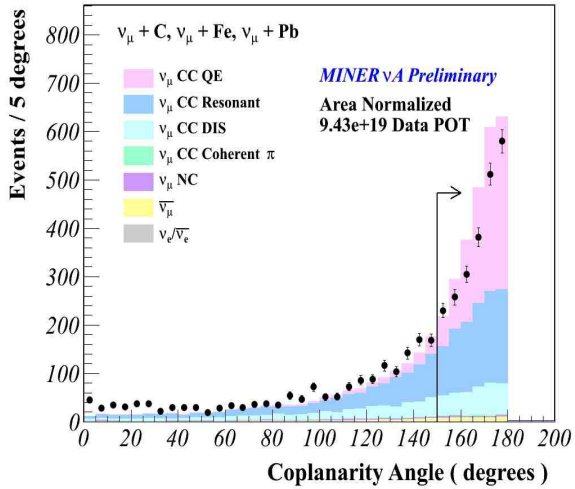


Require dE/dX profile is consistent with a proton



And small amounts of additional detector energy

Analagous to recoil cuts in 1-track analyses



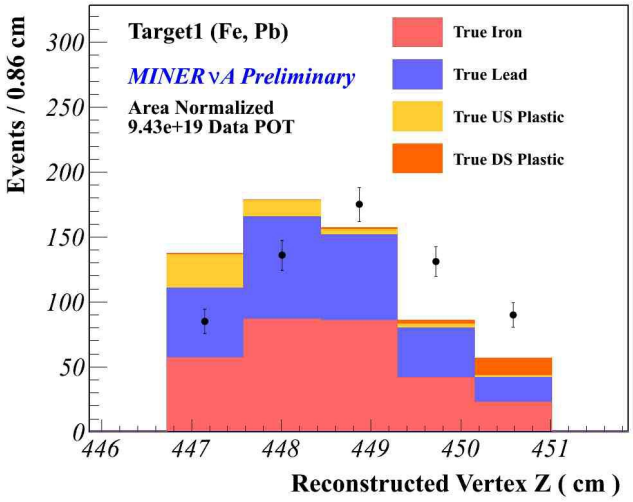
And coplanarity consistent with QE hypothesis

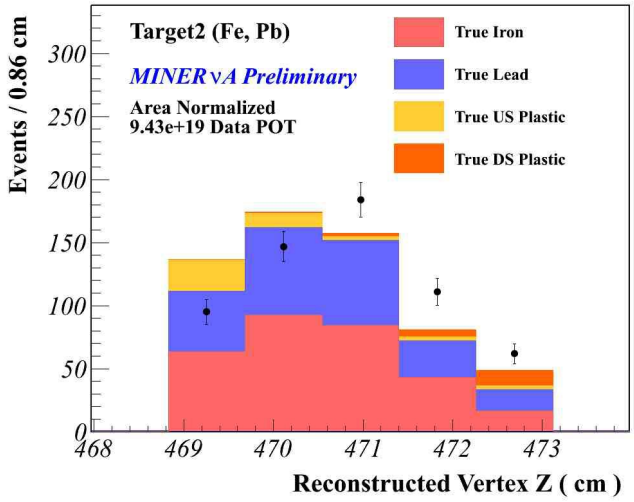
Coplarity angle = angle between ν−μ and ν-p planes

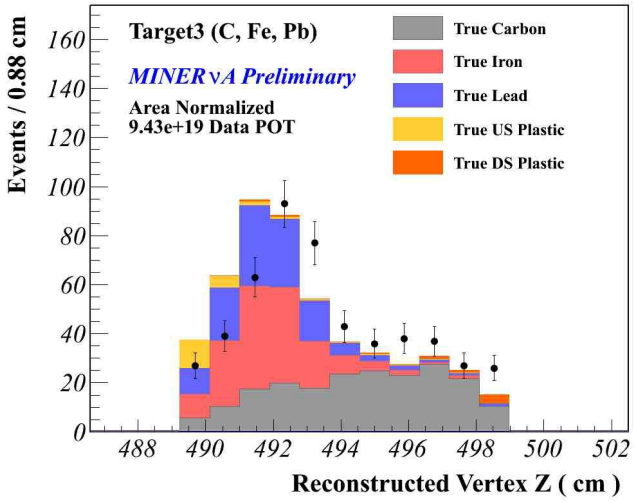
2-Track ν_μ CCQE in Fe, Pb and C

- Vertex Z positions of all candidates passing cuts:

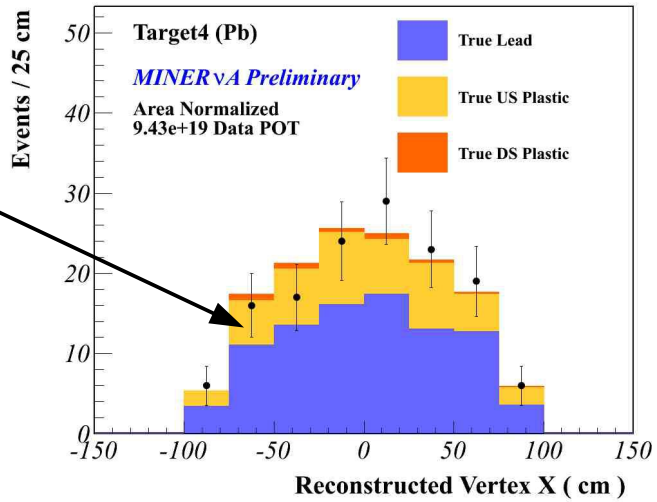
Carbon present only in target 3

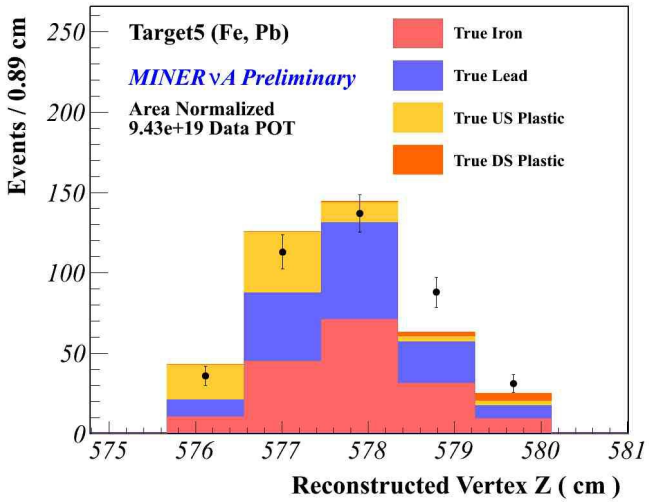






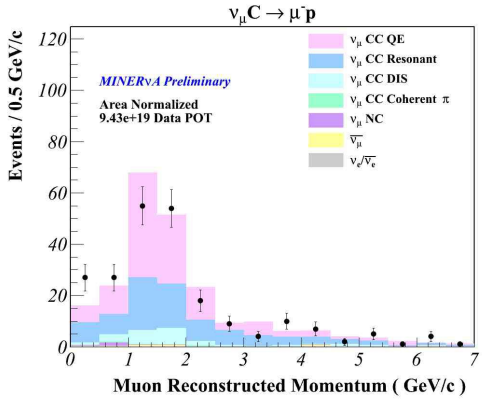
Plastic contamination is largest in thinnest target

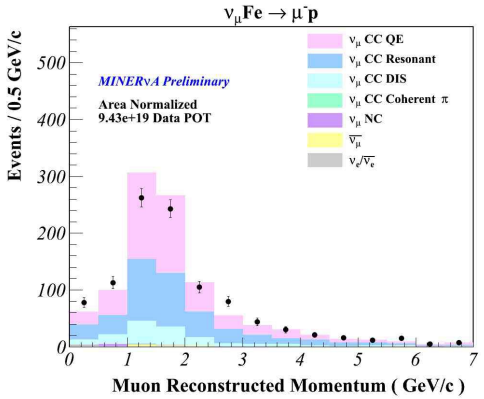


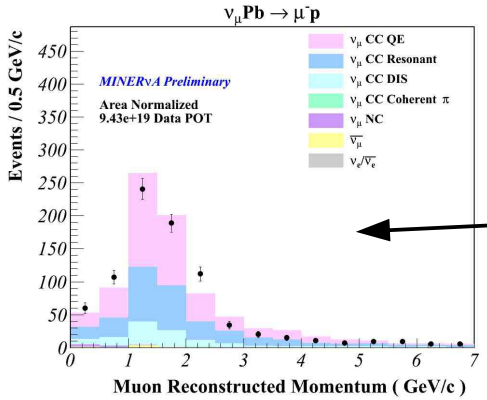


2-Track ν_μ CCQE in Fe, Pb and C

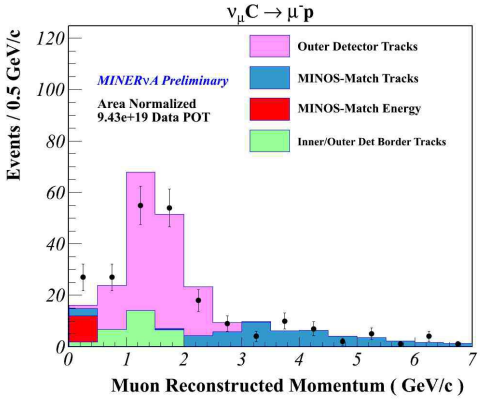
- Muon momentum in all candidates passing cuts:

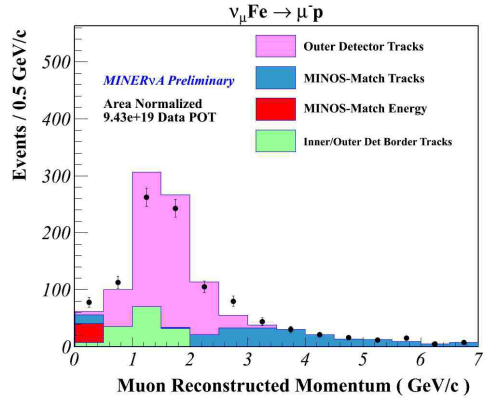


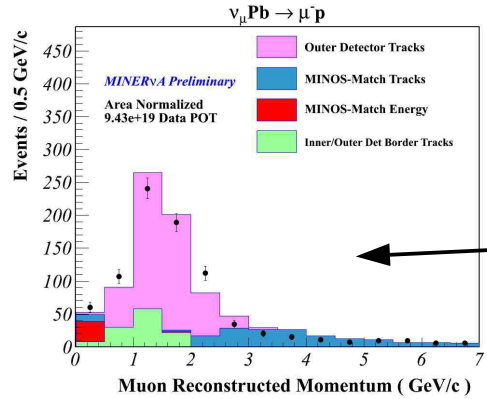




MC colors show GENIE process type; pink in signal (~60% purity)





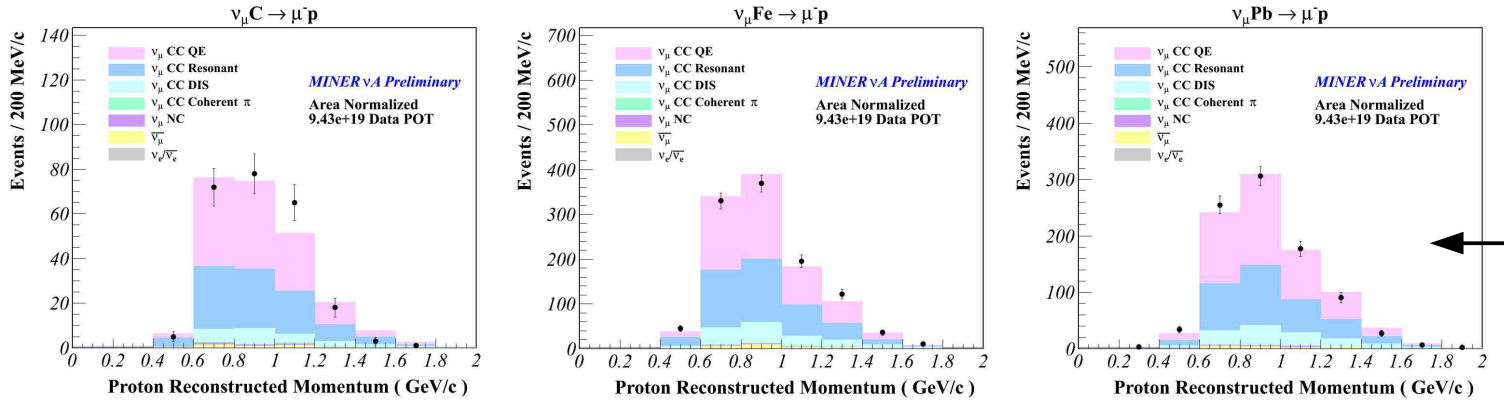


MC colors show muon reconstruction method; most tracks enter outer detector (side HCAL)

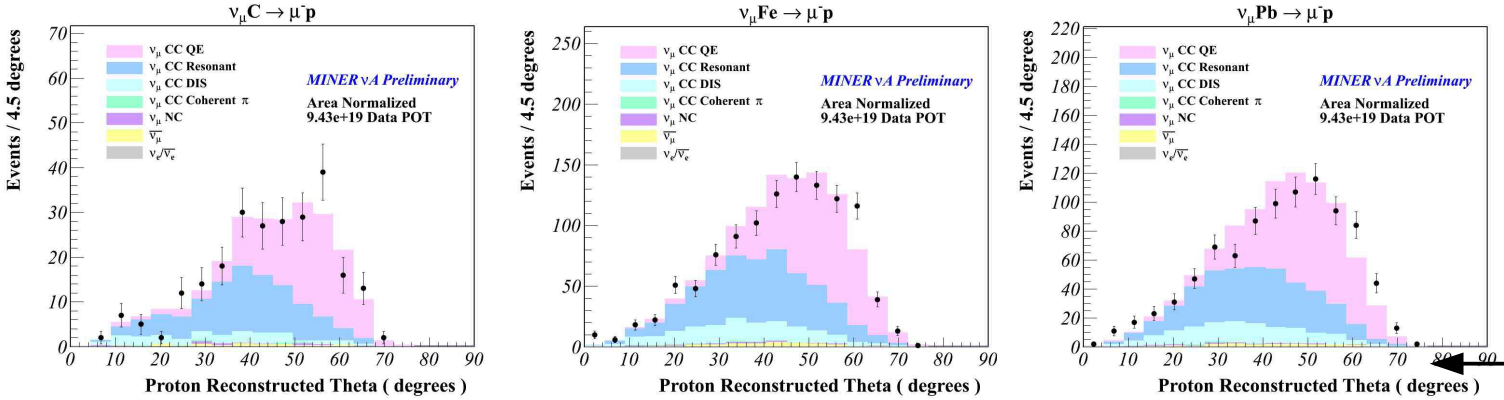
Momentum is lower limit only for exiting tracks.

2-Track ν_μ CCQE in Fe, Pb and C

- Proton distributions for candidates passing all cuts:



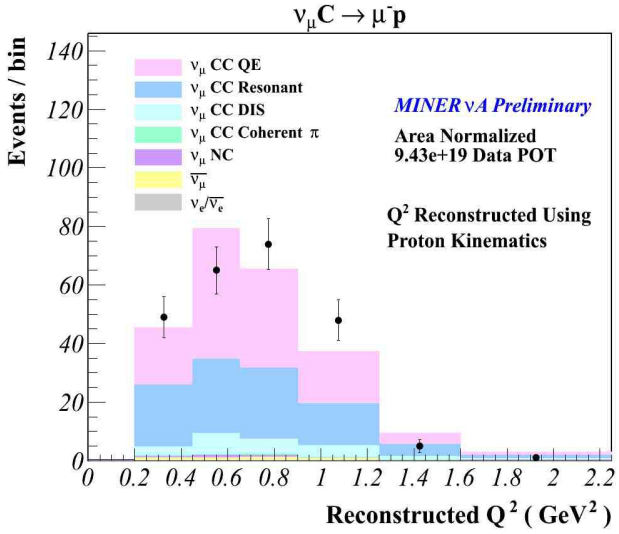
Proton momentum

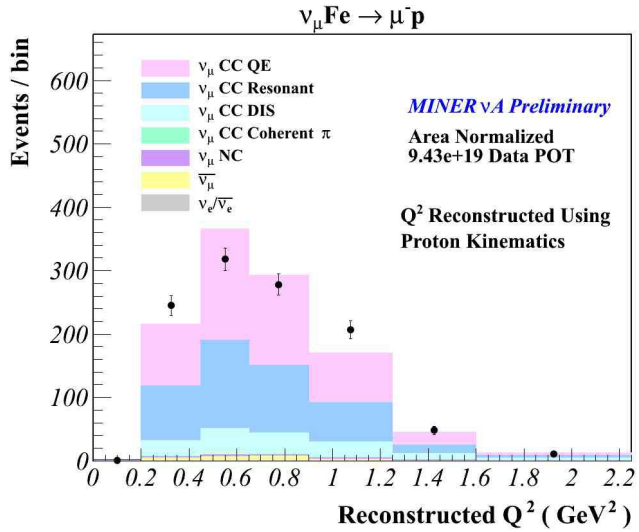


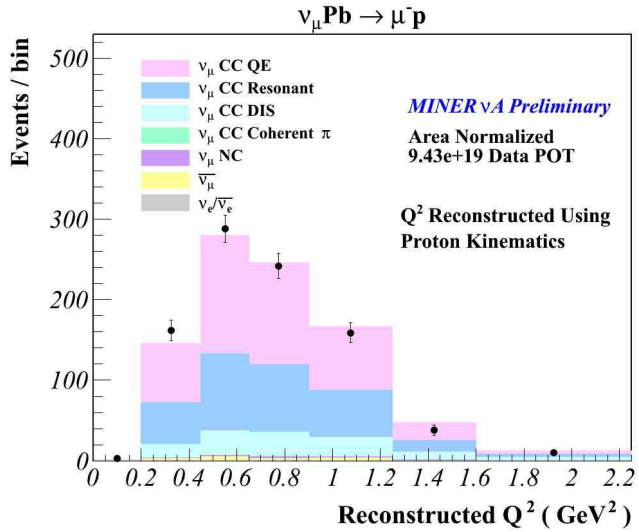
Proton angle (wrt beam)

2-Track ν_μ CCQE in Fe, Pb and C

- Q^2 distributions for candidates passing all cuts:







Q2 shapes match GENIE relatively well at this level of statistics.

Coming soon: background subtraction, target ratios.

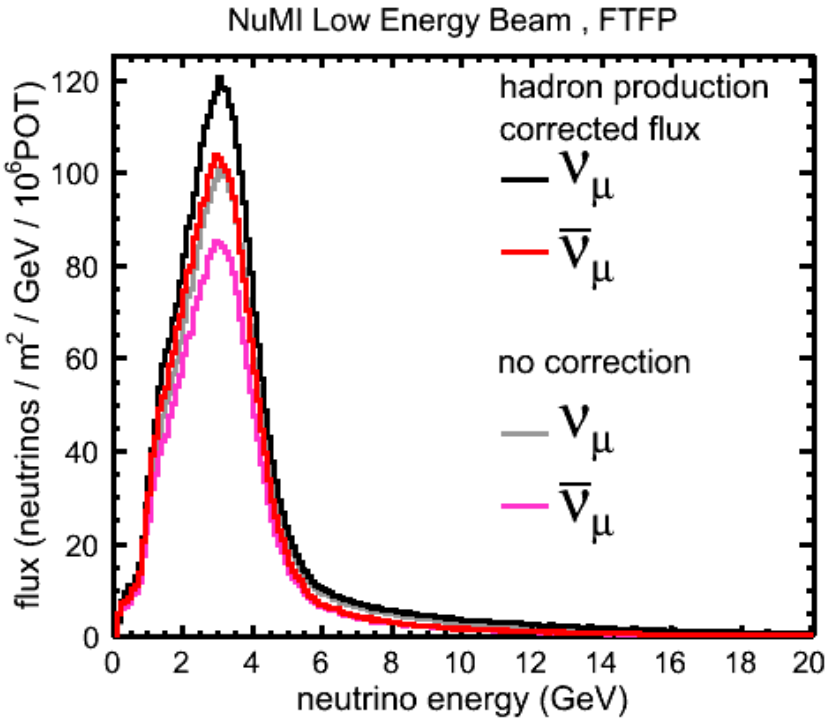
Conclusion/Outlook

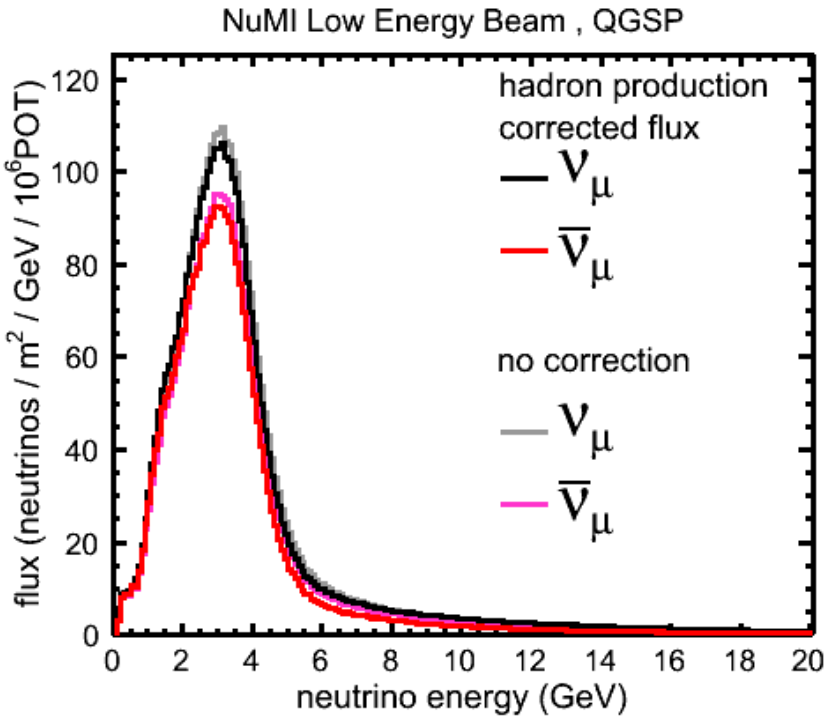
- MINERvA is making lots of progress towards high precision QE measurements
  - First 1-track analyses will be published in the next year
  - First QE analysis in nuclear targets illustrates more complex reconstruction possibilities: multiple tracks, nuclear targets, non-minos-matched muons
- Much more to come soon:
  - Michel veto + increased muon acceptance
  - Combination and comparison of 1- and 2-track analyses
  - Further probes of vertex activity
  - Improved flux → $d\sigma/dE$ and double differentials

Obrigada!

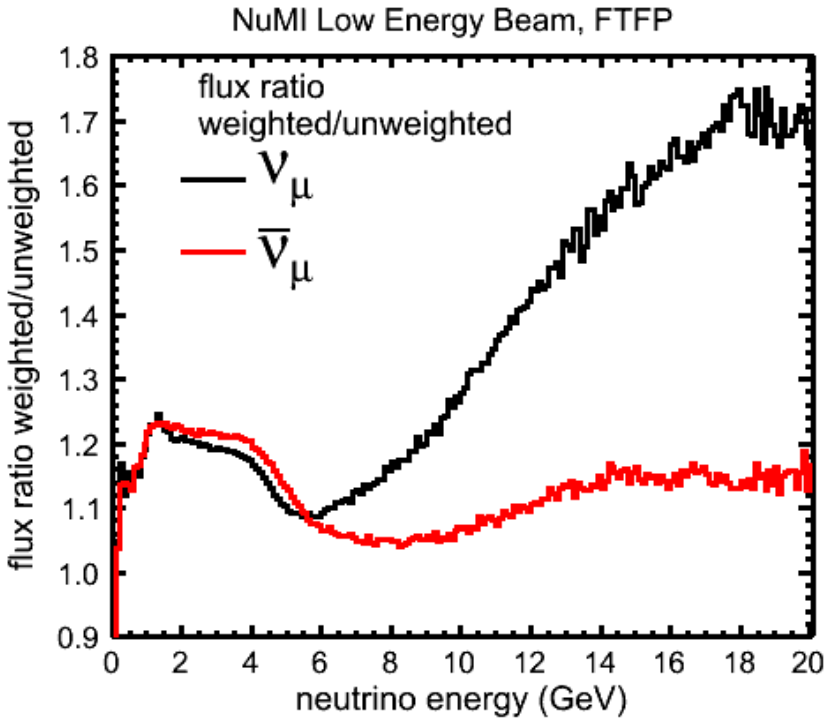
Backup Slides

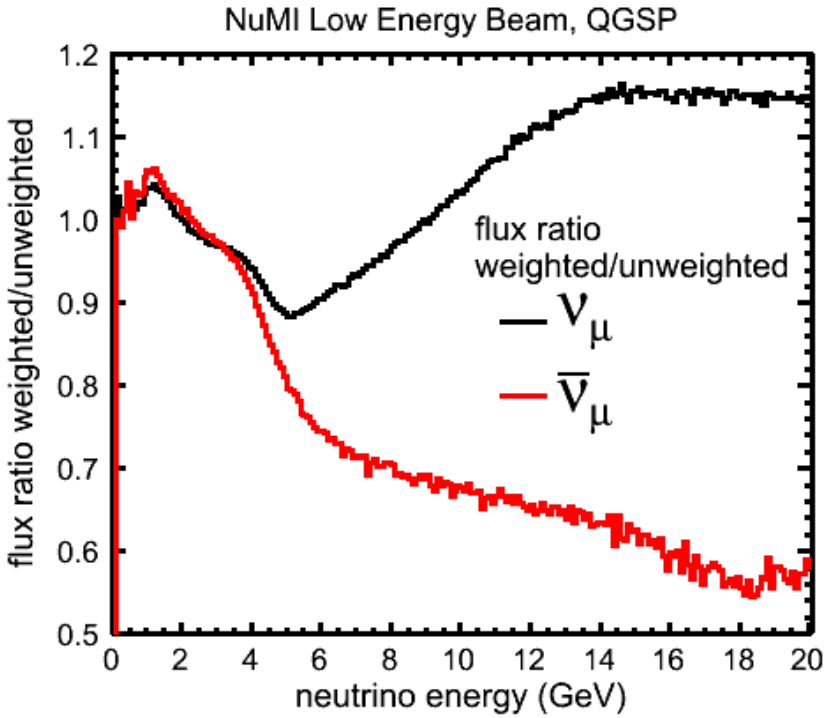
Backup -- Flux


NuMI Low Energy Beam , FTFP
flux (neutrinos / m^2 / GeV / 10^{6}POT)
neutrino energy (GeV)
hadron production
corrected flux
ν_μ
$\bar{\nu}_\mu$
no correction
ν_μ
$\bar{\nu}_\mu$

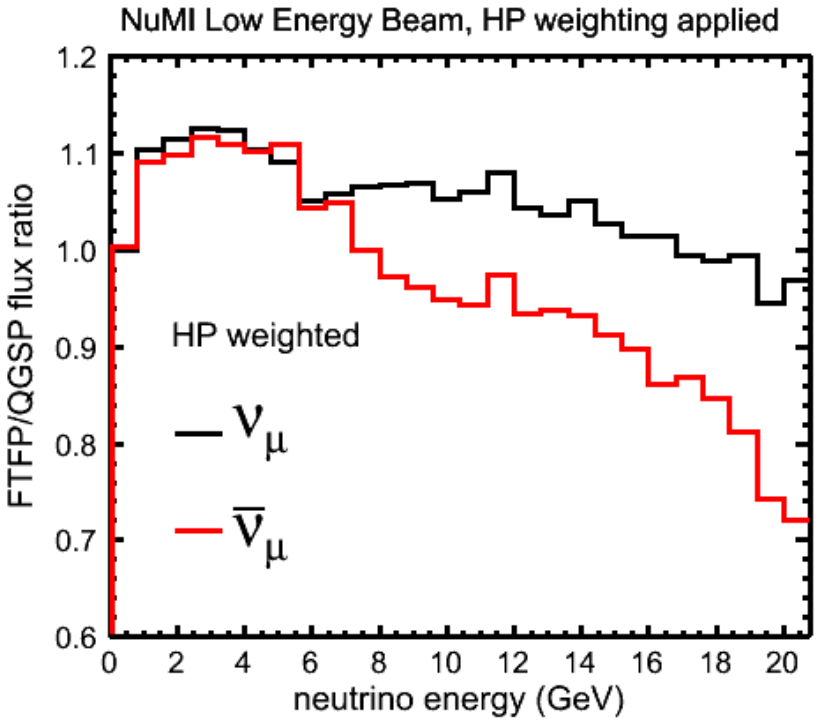

NuMI Low Energy Beam , QGSP
flux (neutrinos / m^2 / GeV / 10^{6}POT)
neutrino energy (GeV)
hadron production
corrected flux
ν_μ
$\bar{\nu}_\mu$
no correction
ν_μ
$\bar{\nu}_\mu$

Backup -- Flux


NuMI Low Energy Beam, FTFP
flux ratio
weighted/unweighted
ν_μ
$\bar{\nu}_\mu$
flux ratio weighted/unweighted
neutrino energy (GeV)
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0
2
4
6
8
10
12
14
16
18
20


NuMI Low Energy Beam, QGSP
flux ratio
weighted/unweighted
ν_μ
$\bar{\nu}_\mu$
flux ratio weighted/unweighted
neutrino energy (GeV)
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0
2
4
6
8
10
12
14
16
18
20

Backup -- Flux


NuMI Low Energy Beam, HP weighting applied
FTFP/QGSP flux ratio
1.2
1.1
1.0
0.9
0.8
0.7
0.6
HP weighted
ν_μ
$\bar{\nu}_\mu$
0
2
4
6
8
10
12
14
16
18
20
neutrino energy (GeV)

Backup – Model Uncertainties

Cross Section Model Uncertainties

Uncertainty	1 σ
M_A (Elastic Scattering)	± 25%
Eta (Elastic scattering)	± 30%
M_A (CCQE Scattering)	+25% −15%
CCQE Normalization	+20% −15%
CCQE Vector Form factor model	on/off
CC Resonance Normalization	± 20%
M_A (Resonance Production)	± 20%
M_V (Resonance Production)	± 10%
1pi production from $\nu p / \bar{\nu} n$ non-resonant interactions	± 50%
1pi production from $\nu n / \bar{\nu} p$ non-resonant interactions	± 50%
2pi production from $\nu p / \bar{\nu} n$ non-resonant interactions	± 50%
2pi production from $\nu n / \bar{\nu} p$ non-resonant interactions	± 50%
Modfiy Pauli blocking (CCQE) at low Q^2 (change PB momentum threshold)	± 30%

•*Intranuclear Rescattering Uncertainties*

Uncertainty	1 σ
Pion mean free path	± 20%
Nucleon mean free path	± 20%
Pion fates – absorption	± 30%
Pion fates – charge exchange	± 50%
Pion fates – Elastic	± 10%
Pion fates – Inelastic	± 40%
Pion fates – pion production	± 20%
Nucleon fates – charge exchange	± 50%
Nucleon fates – Elastic	± 30%
Nucleon fates – Inelastic	± 40%
Nucleon fates – absorption	± 20%
Nucleon fates – pion production	± 20%
AGKY hadronization model – x_F distribution	± 20%
Delta decay angular distribution	On/off
Resonance decay branching ratio to photon	± 50%

References: (1) www.genie-mc.org, (2) arXiv:0806.2119, (3) D. Bhattacharya, Ph. D Thesis (U. Pittsburgh) 2009.

Backup – Cross Section Formula

$$\sigma = \frac{N_{obs} - N_{bgd}}{\Phi * N_{targets} * \varepsilon}$$

Number of neutrinos (flux)

Number of nuclei

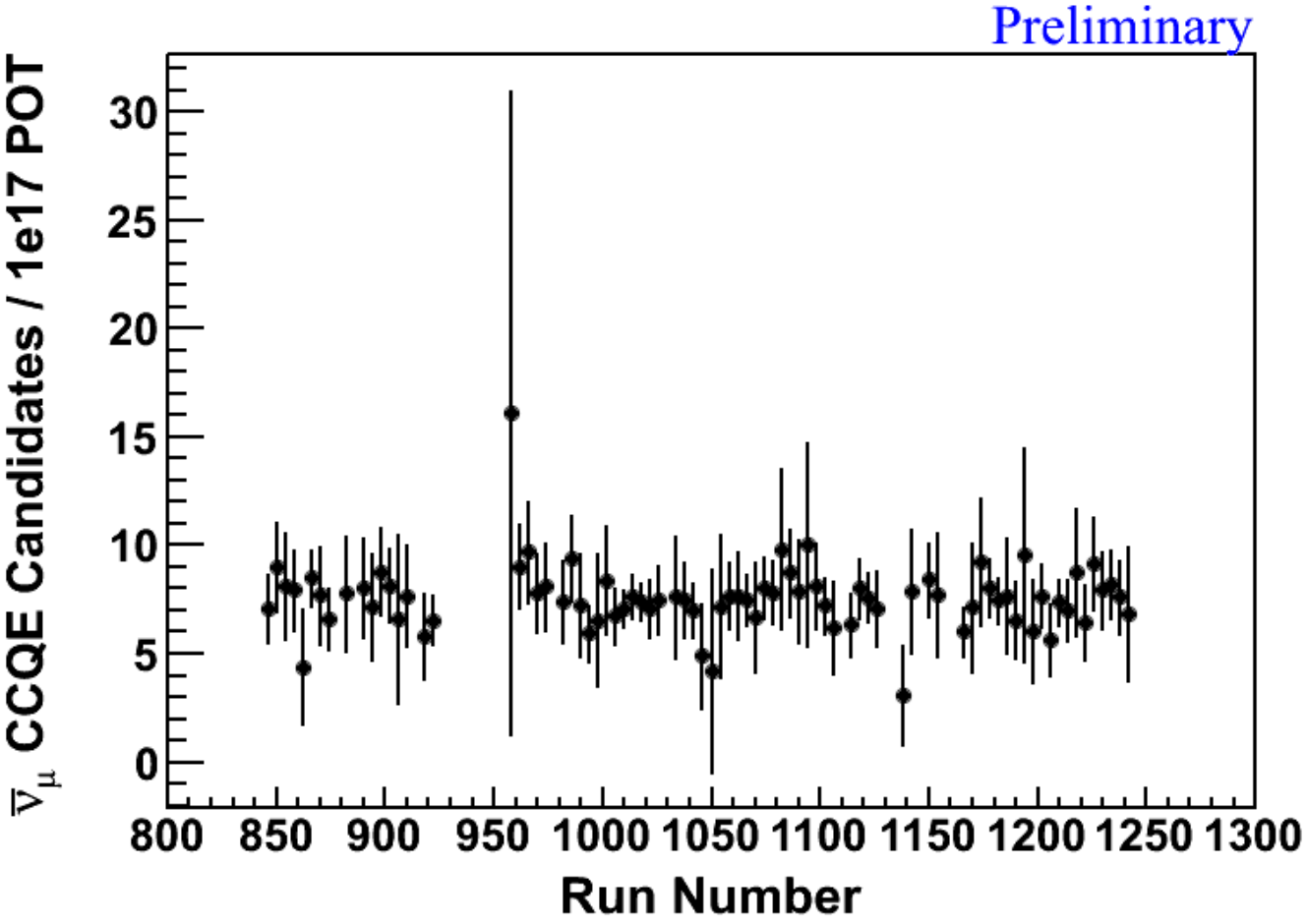
Reconstruction efficiency

Backup Slides

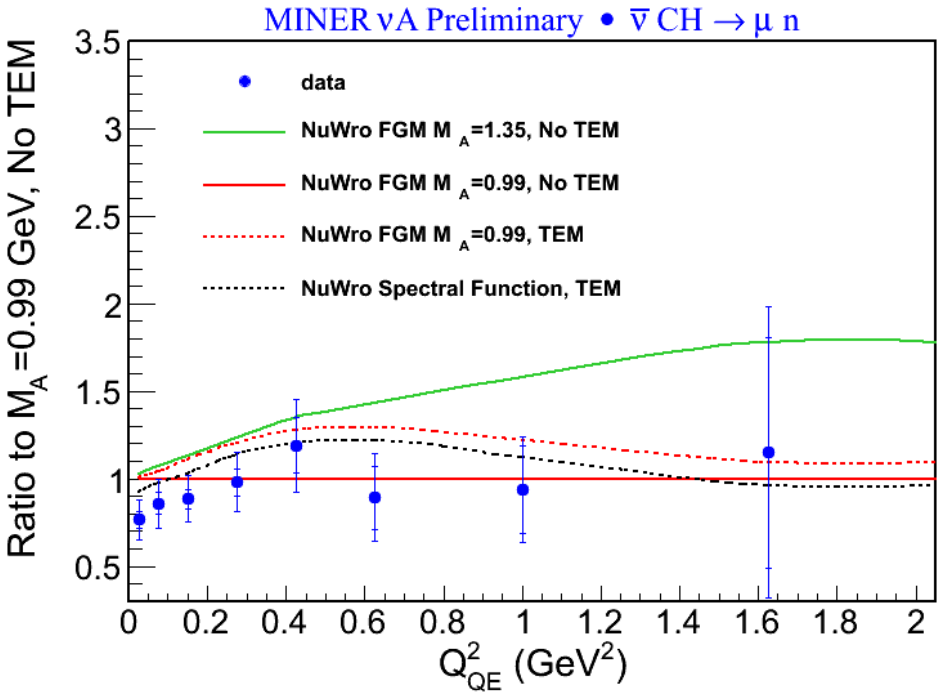
Anti-ν CCQE Analysis

Backup -- Anti-ν CCQE

- Detector Stability:



Backup -- Anti-ν CCQE

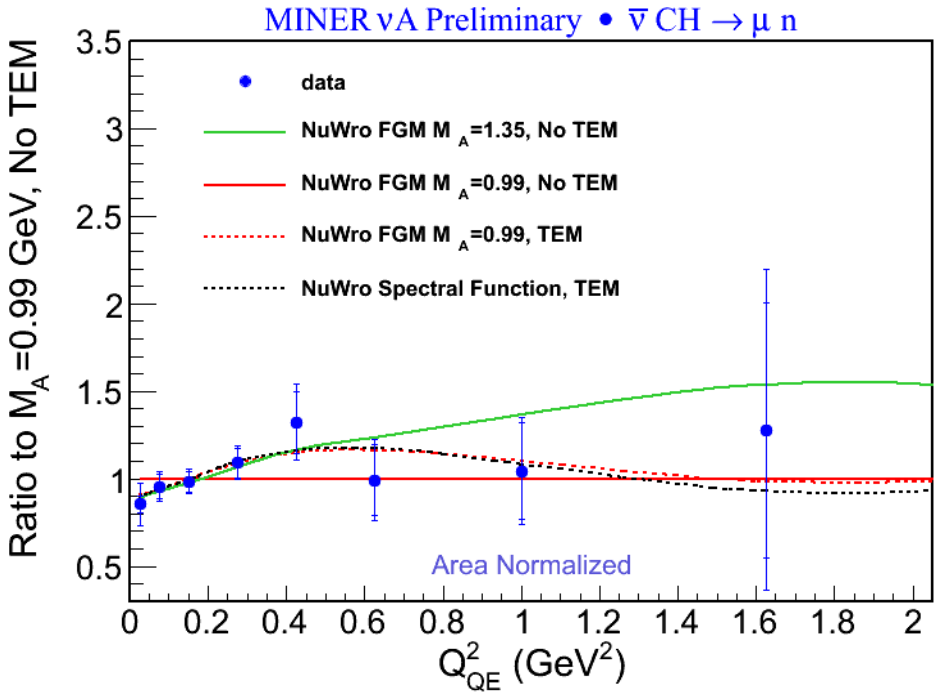


Shown for the first time at NuInt

Comparison with Models

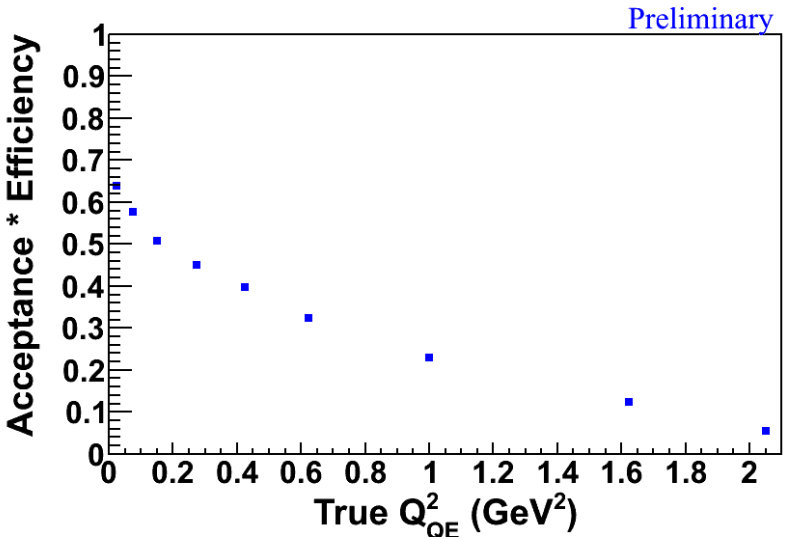
NuWro: Golal, Jusczak, Sobczyk
arXiv:1202.4197

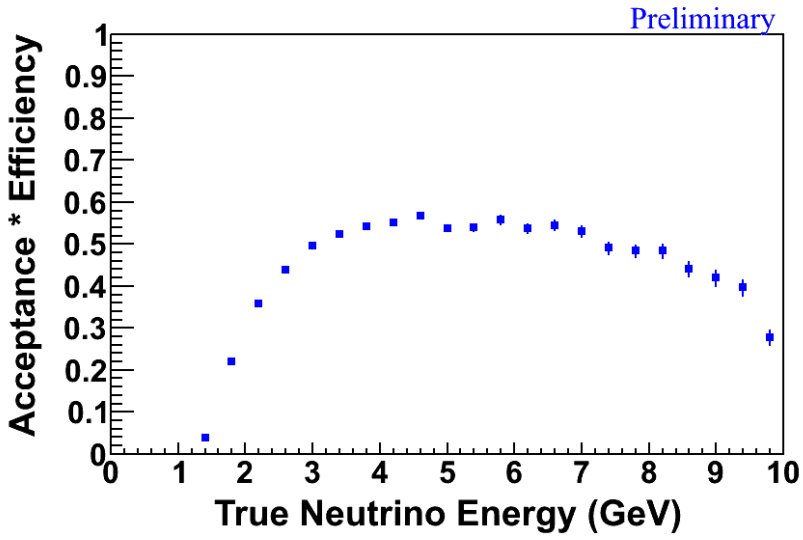
MEC model: Bodek, Budd, Christy
Eur. Phys. J. C(2011) 71:1726

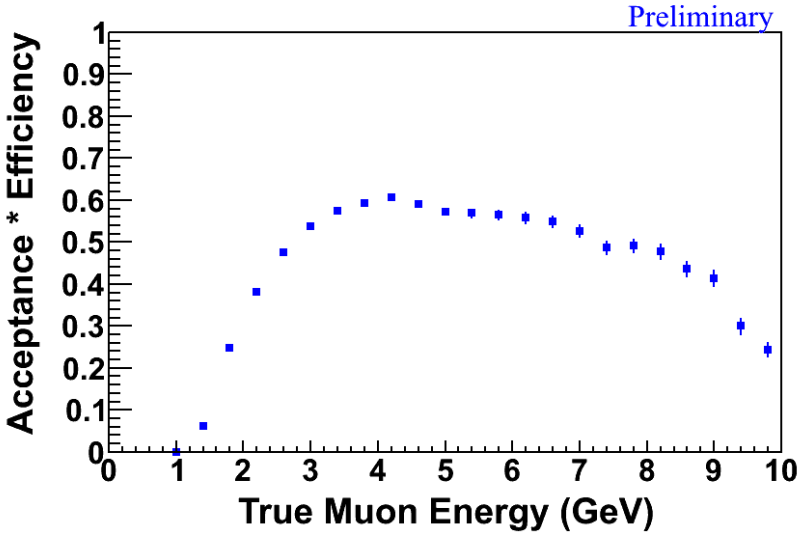


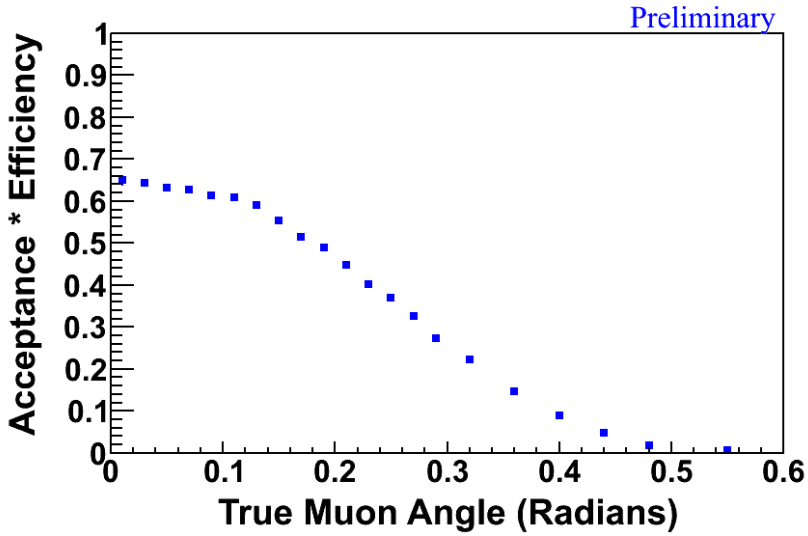
Backup -- Anti-ν CCQE

- Efficiency times acceptance:



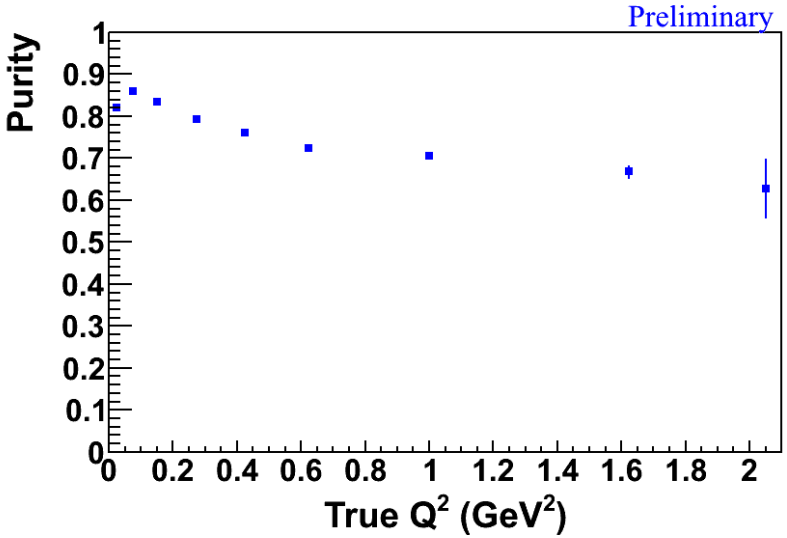


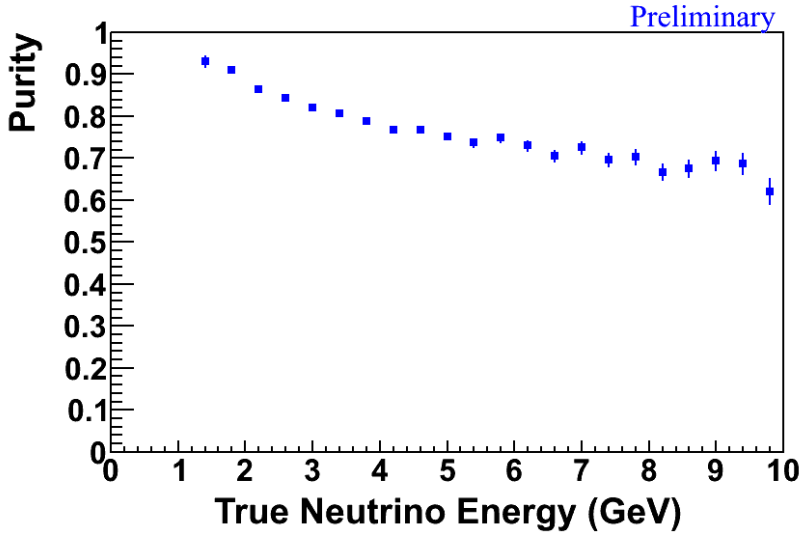


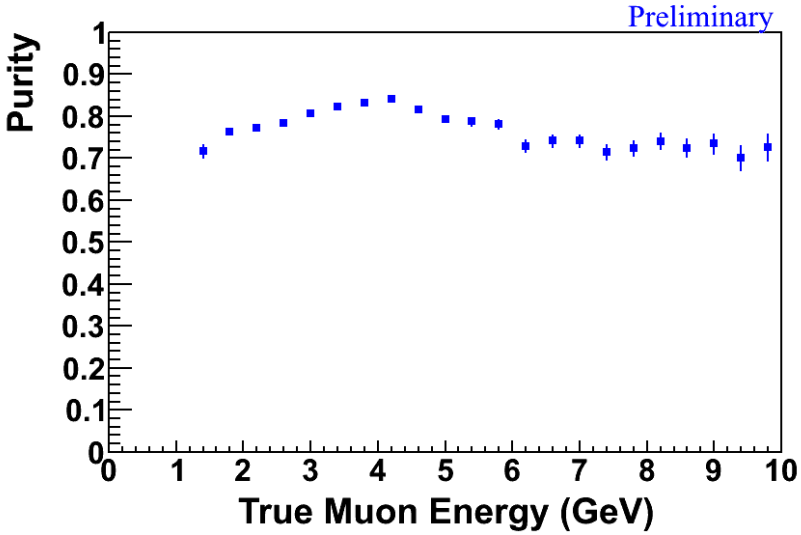


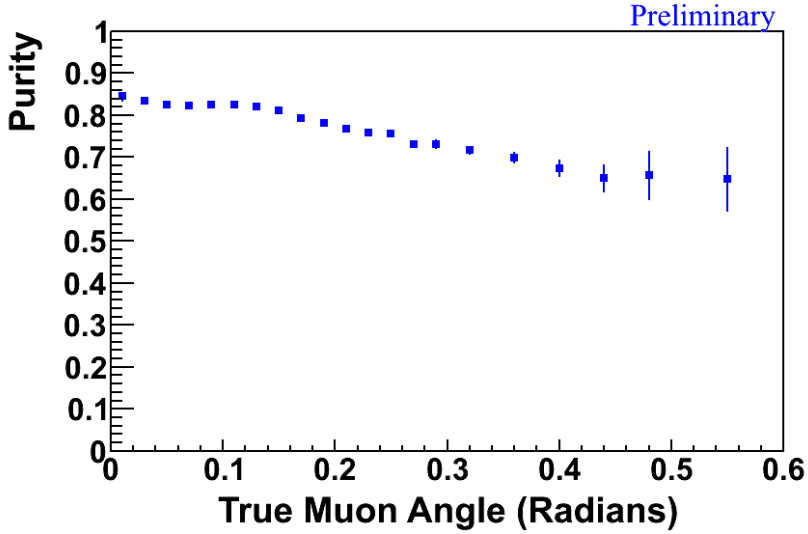
Backup -- Anti-ν CCQE

- Purity:



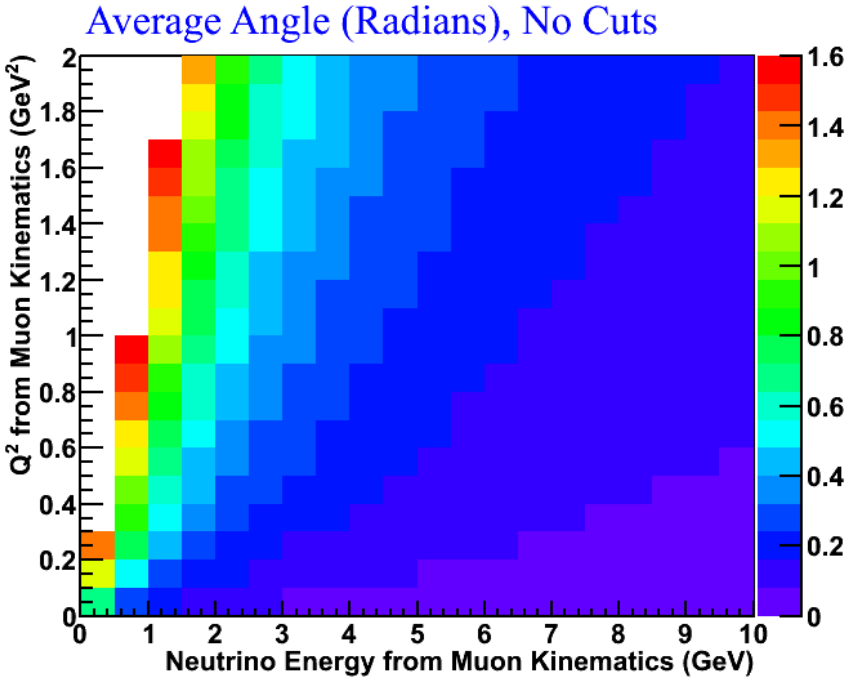




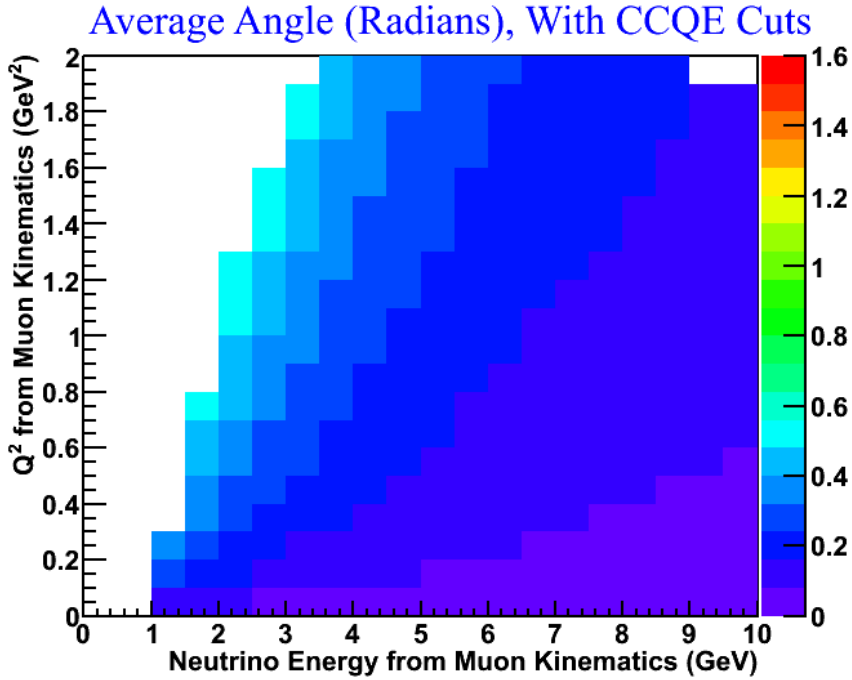


Backup -- Anti-ν CCQE

- Q2 vs neutrino energy vs angle:



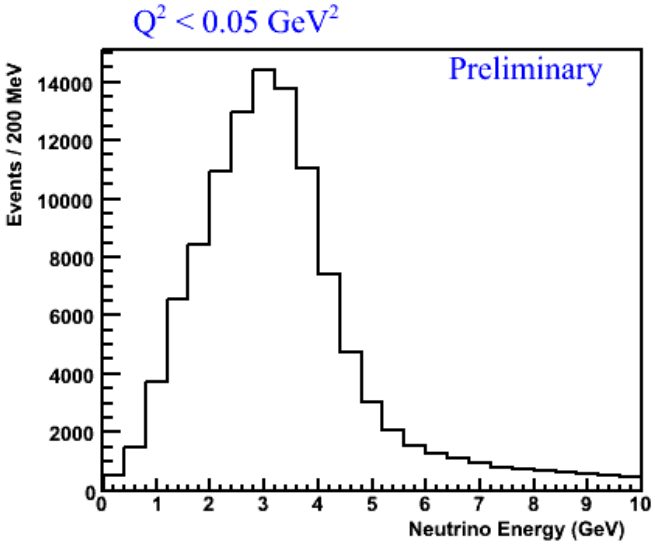
All CCQE generated

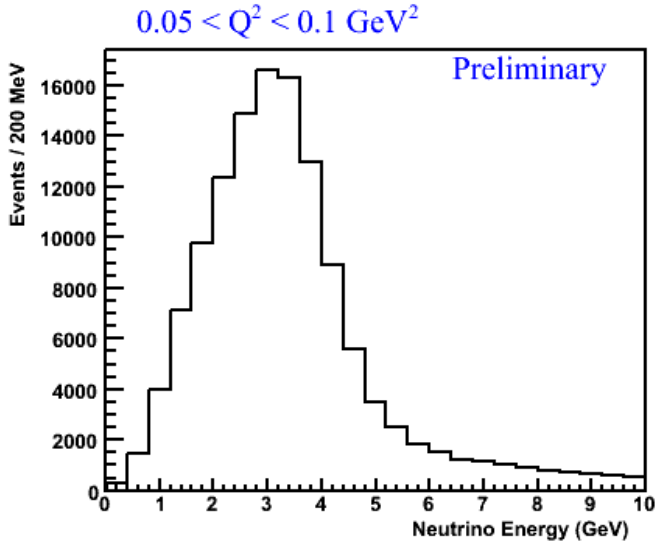


All CCQE reconstructed

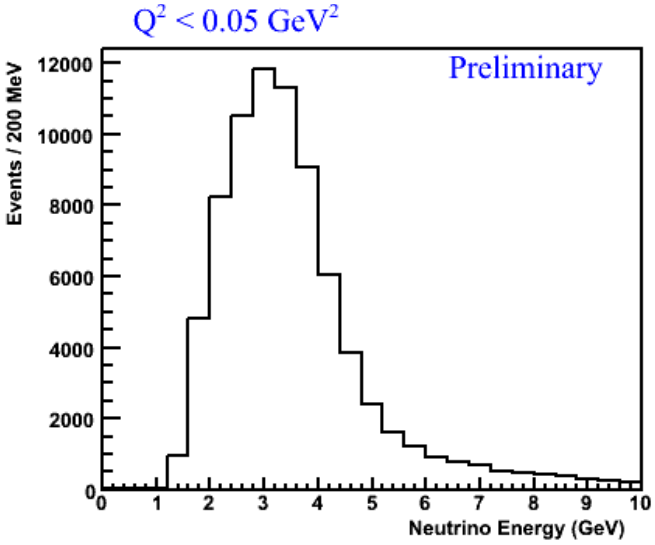
Backup -- Anti-ν CCQE

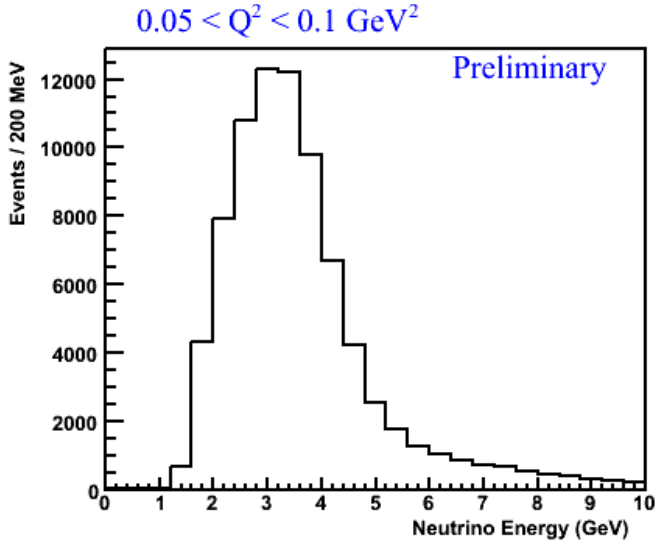
- True neutrino energy in Q2 bins:





No CCQE Cuts

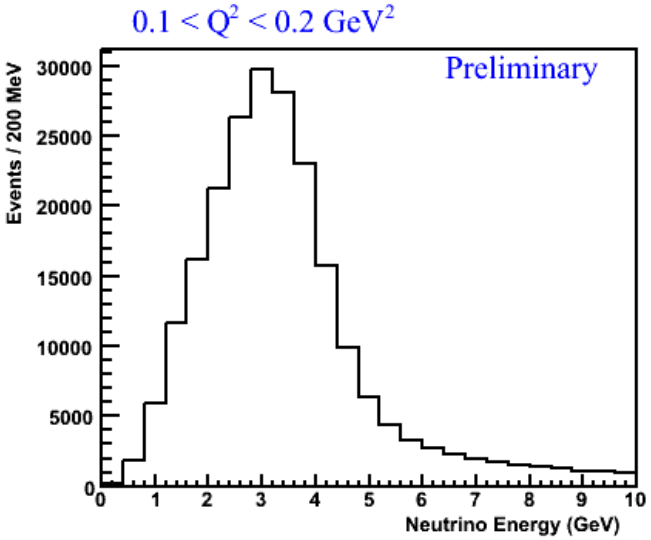


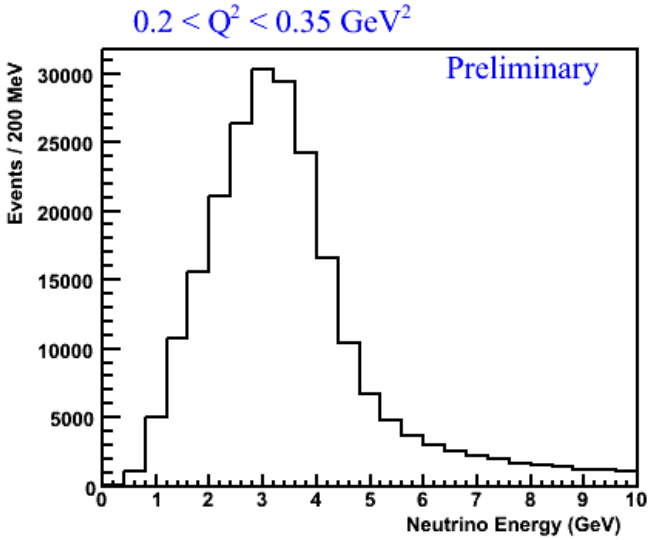


With CCQE Cuts

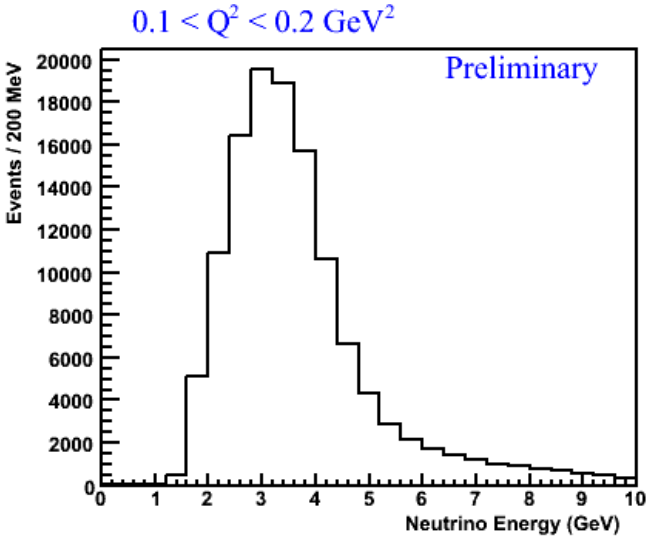
Backup -- Anti-ν CCQE

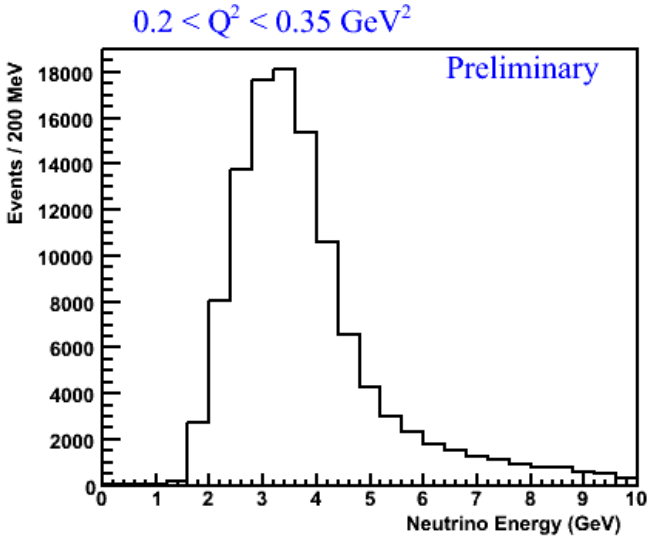
- True neutrino energy in Q2 bins:





No CCQE Cuts

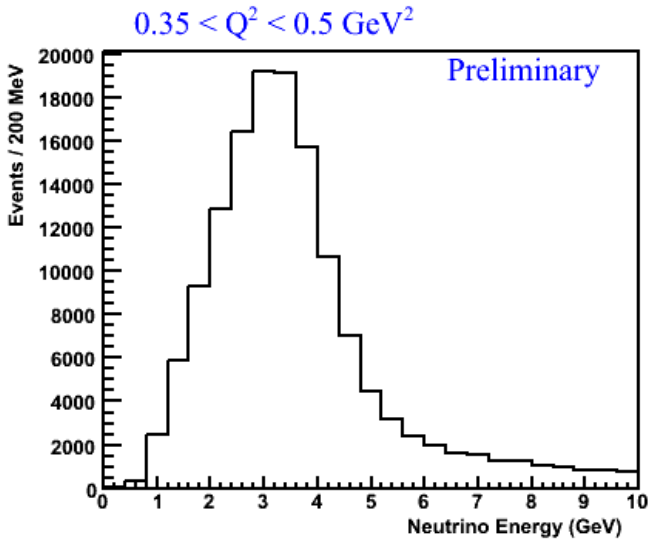


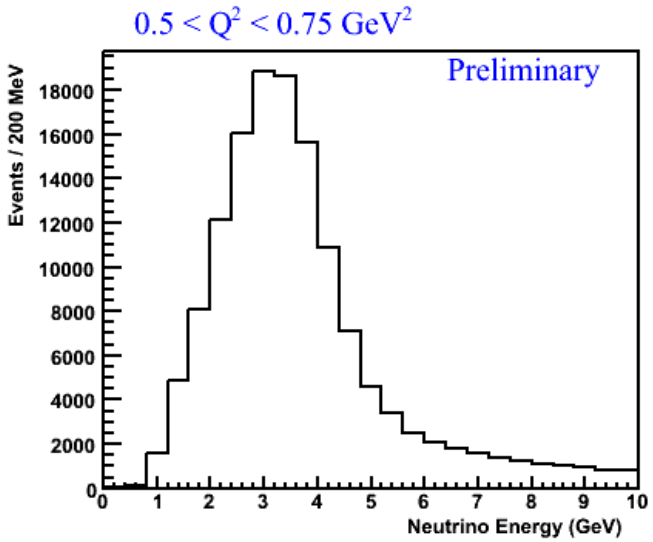


With CCQE Cuts

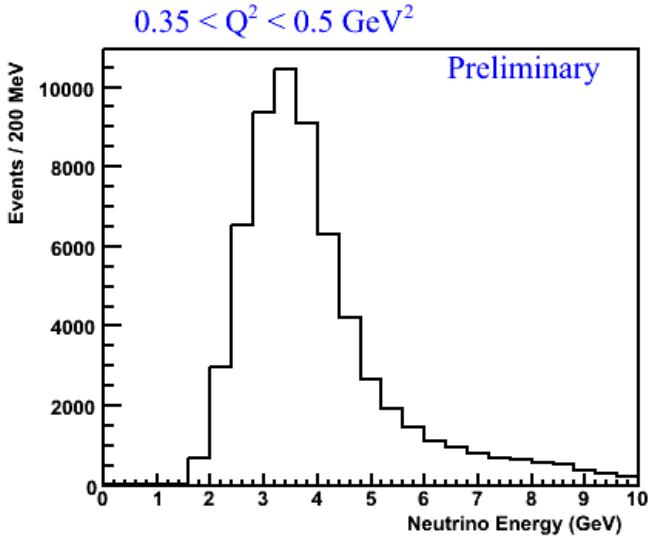
Backup -- Anti-ν CCQE

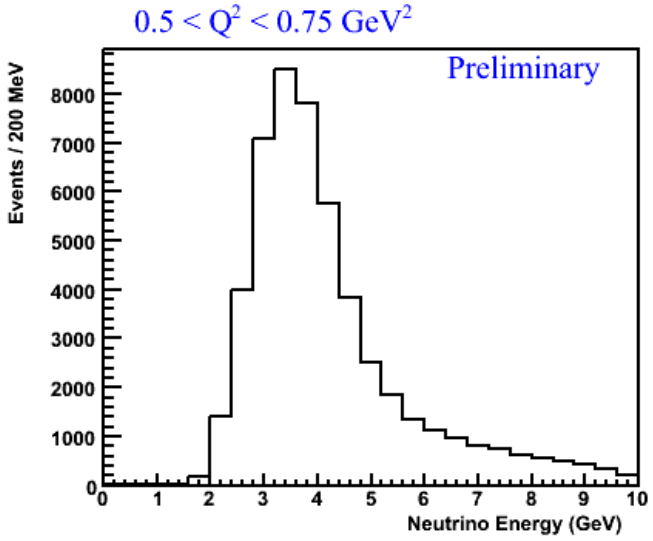
- True neutrino energy in Q2 bins:





No CCQE Cuts

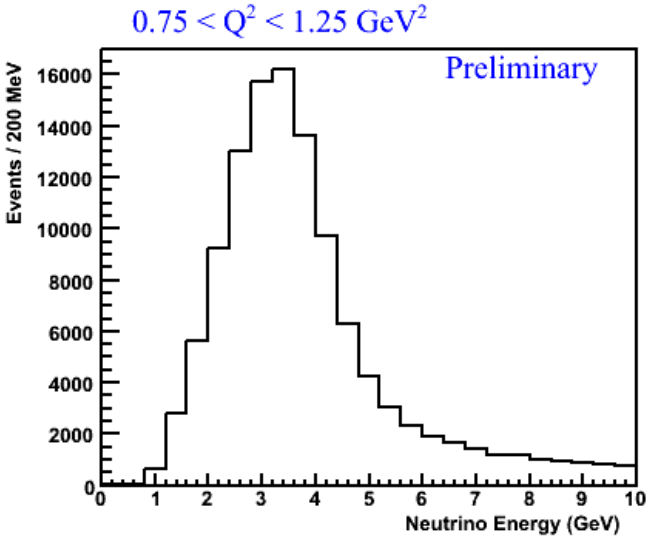


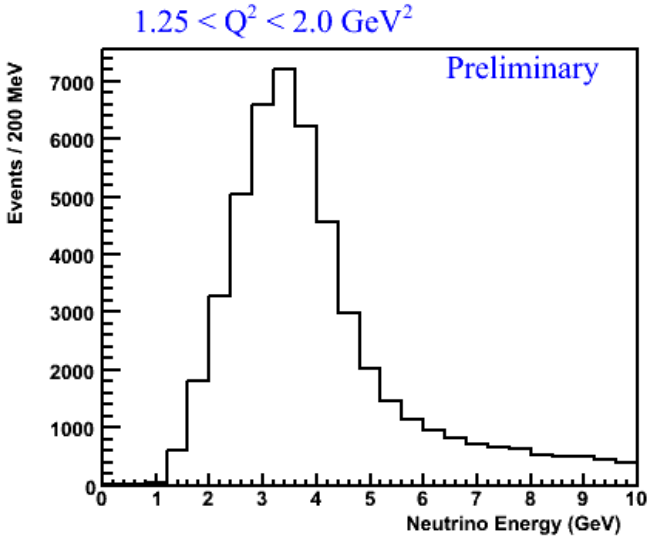


With CCQE Cuts

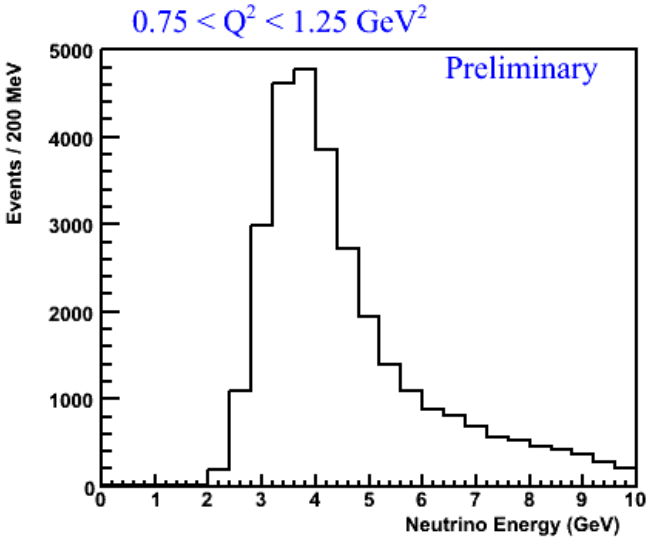
Backup -- Anti-ν CCQE

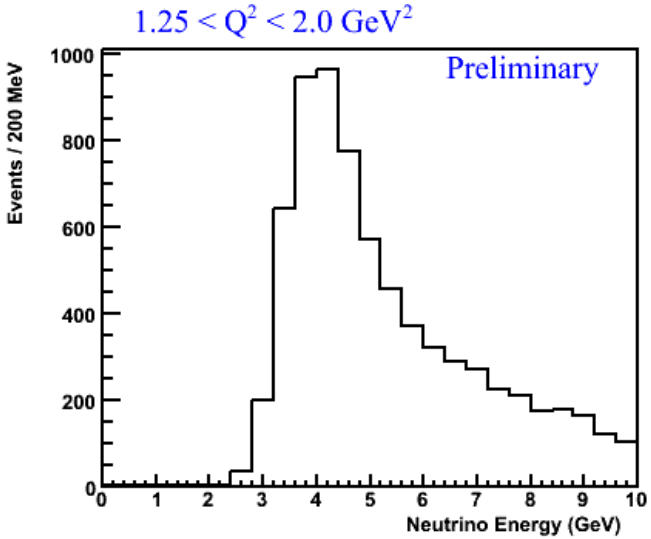
- True neutrino energy in Q2 bins:





No CCQE Cuts

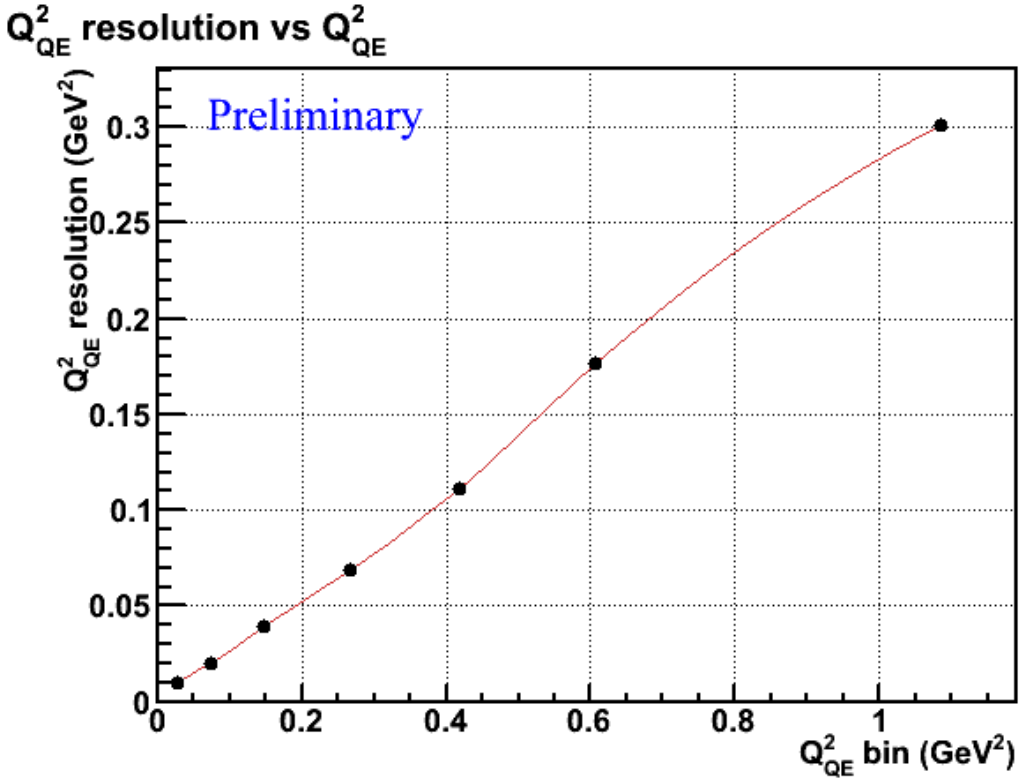




With CCQE Cuts

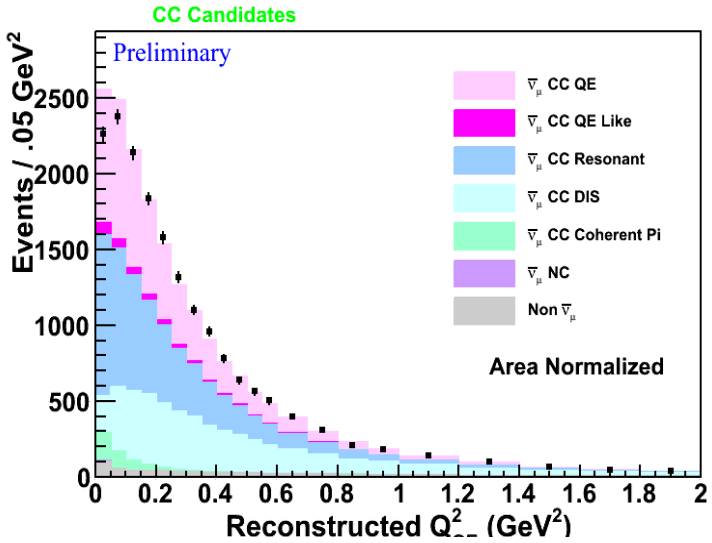
Backup -- Anti-ν CCQE

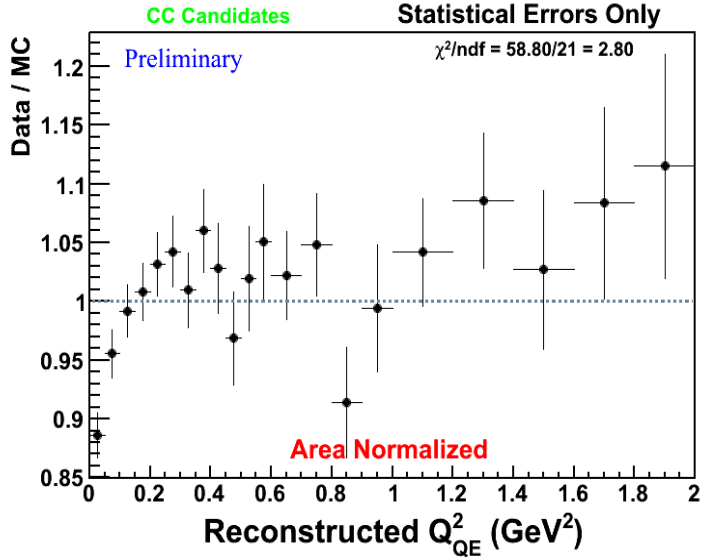
- Resolution -- Q2:

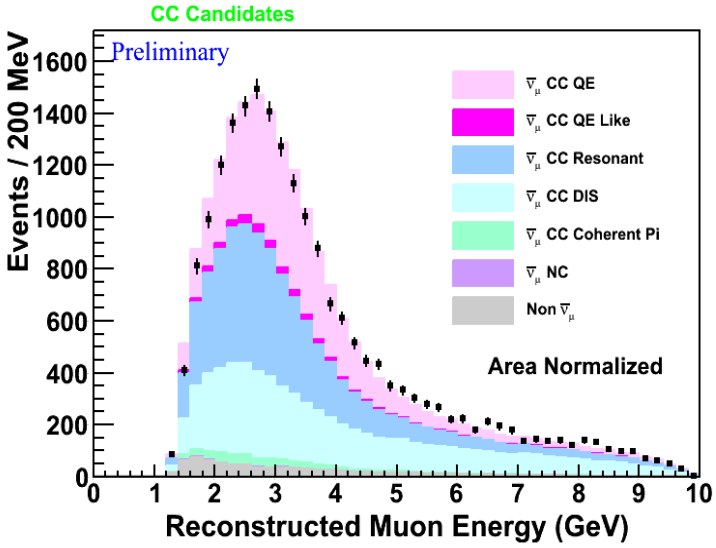


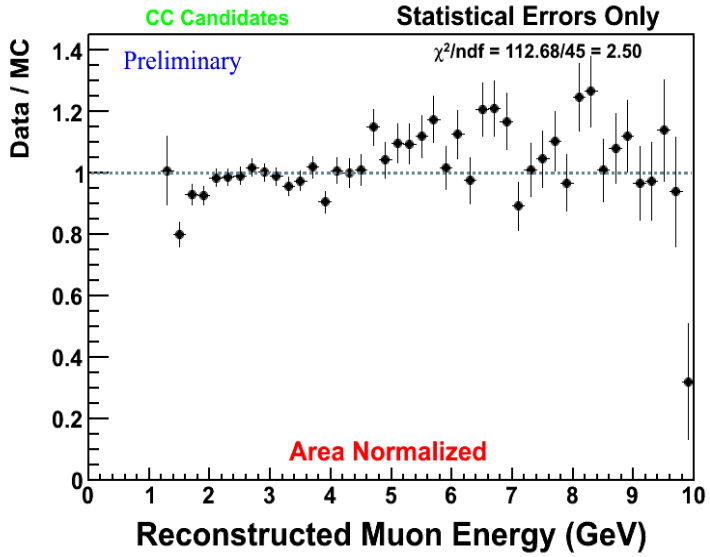
Backup -- Anti-ν CCQE

- Kinematic distributions before recoil cuts:



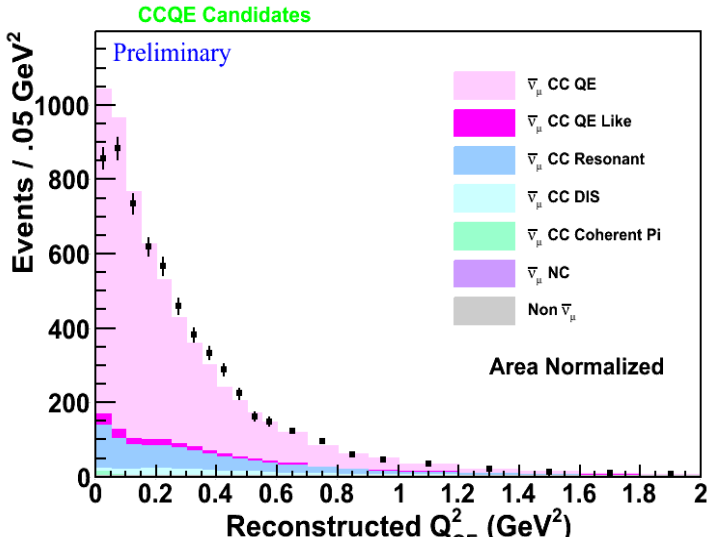


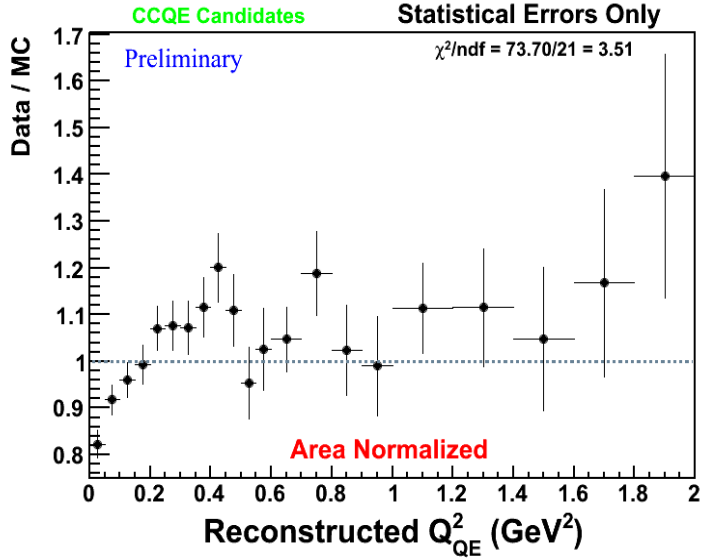


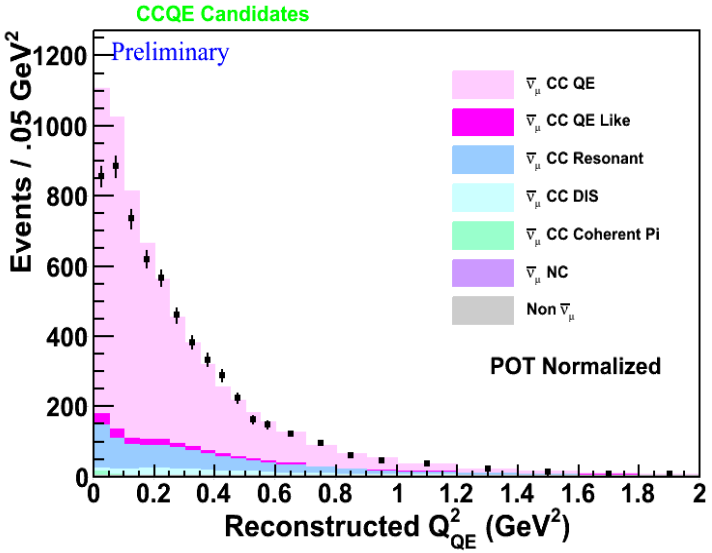


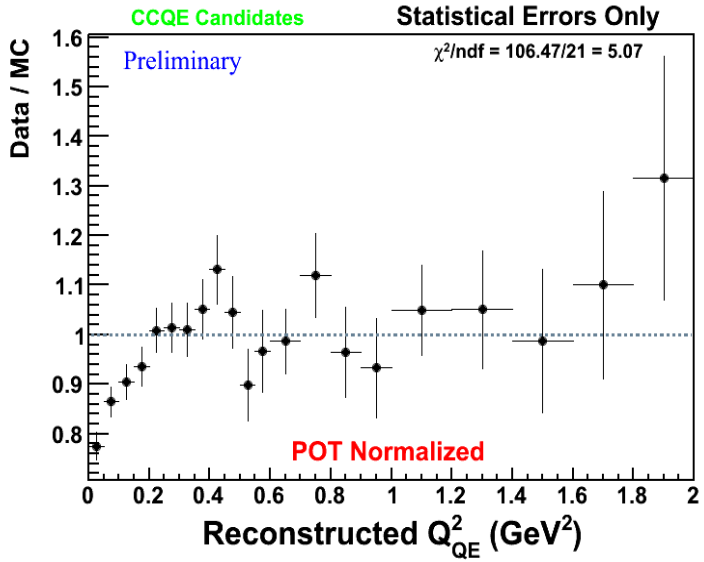
Backup -- Anti-ν CCQE

- Kinematic distributions after recoil cuts:



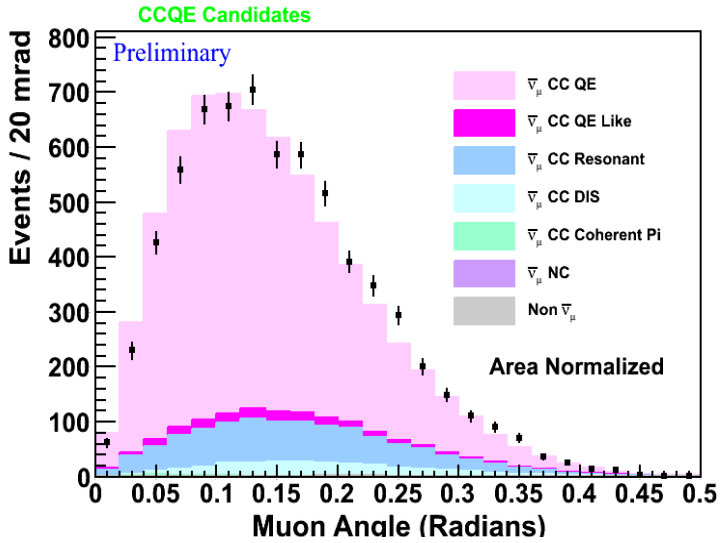


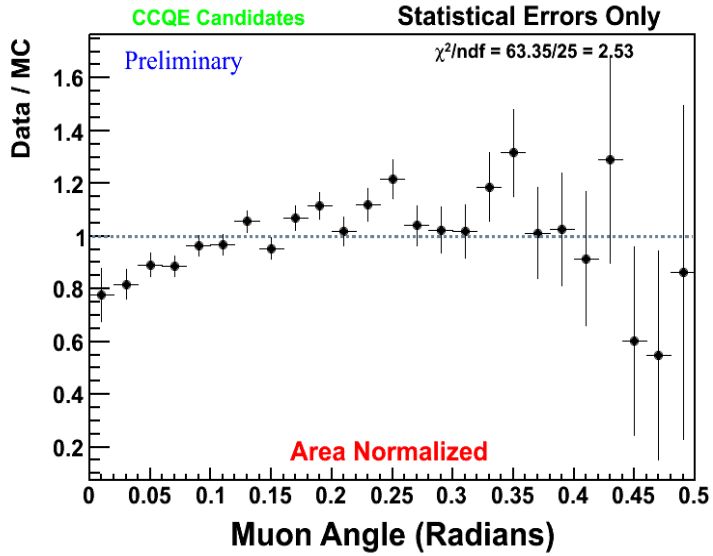


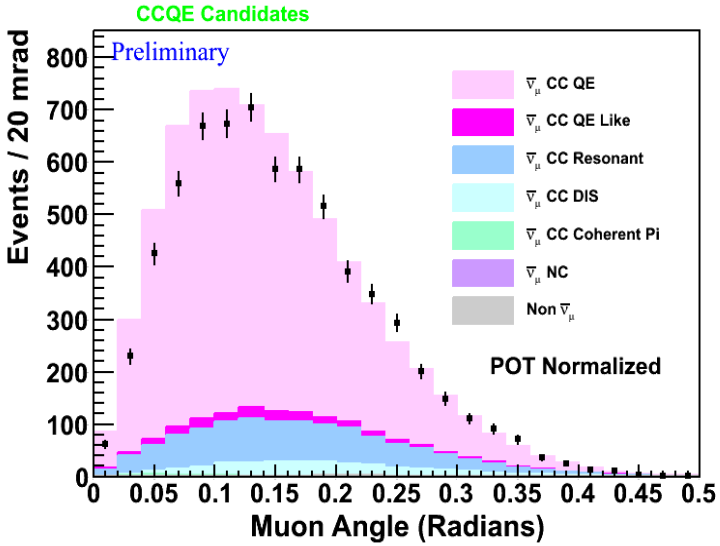


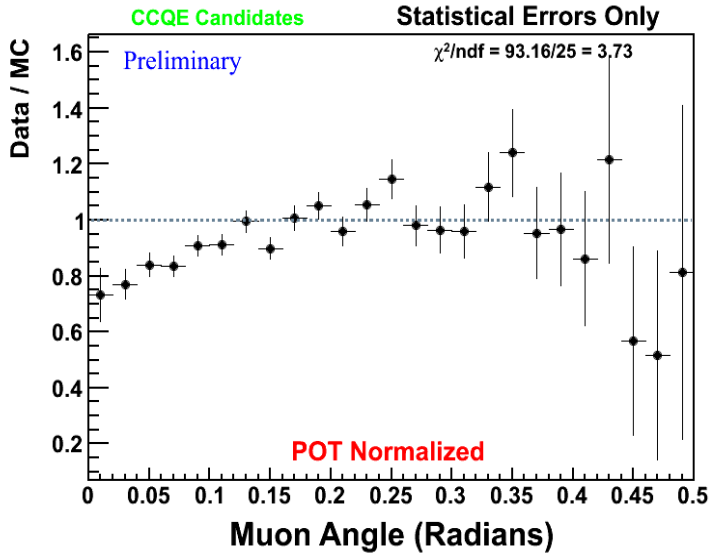
Backup -- Anti-ν CCQE

- Kinematic distributions after recoil cuts:



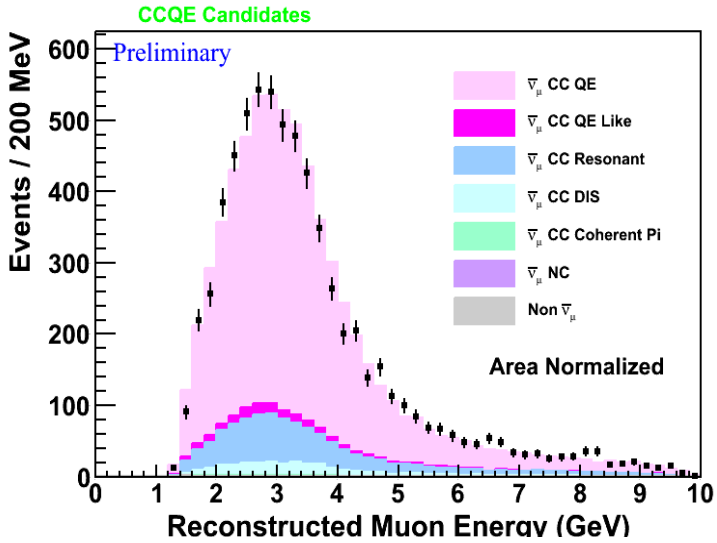


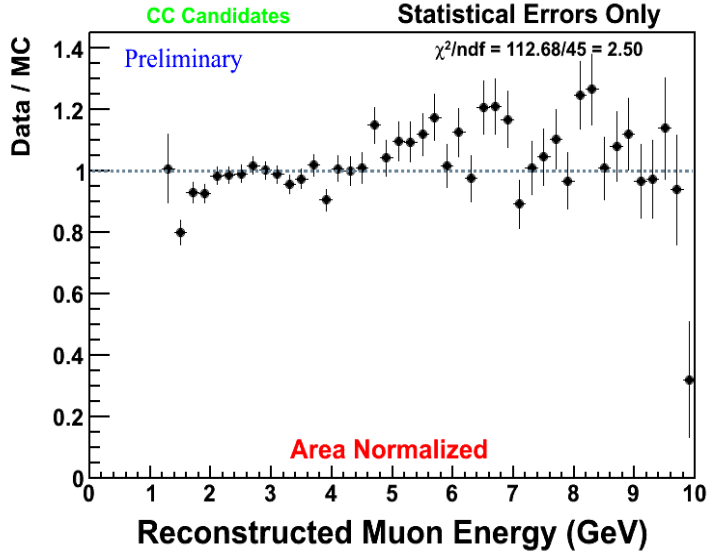


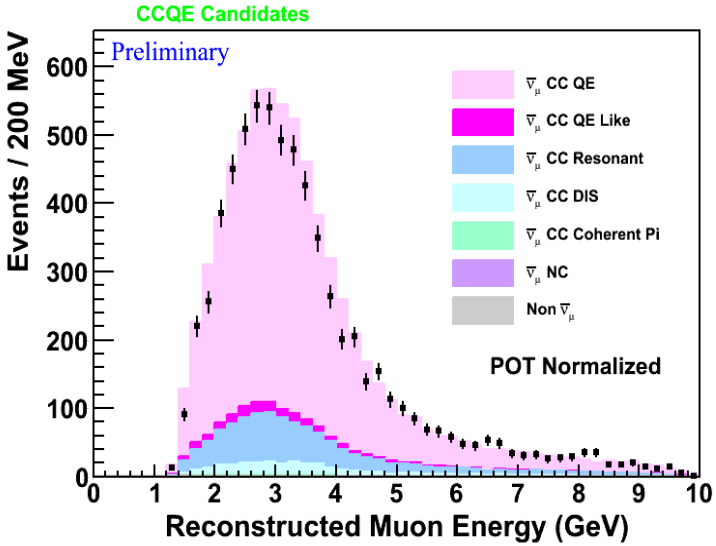


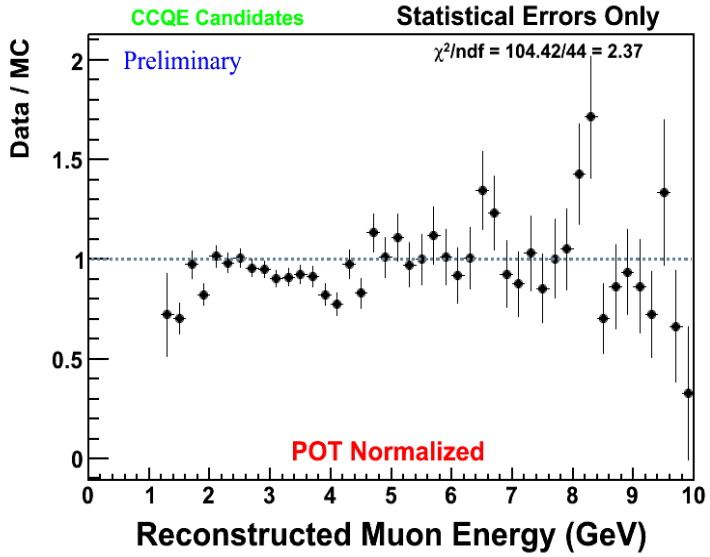
Backup -- Anti-ν CCQE

- Kinematic distributions after recoil cuts:



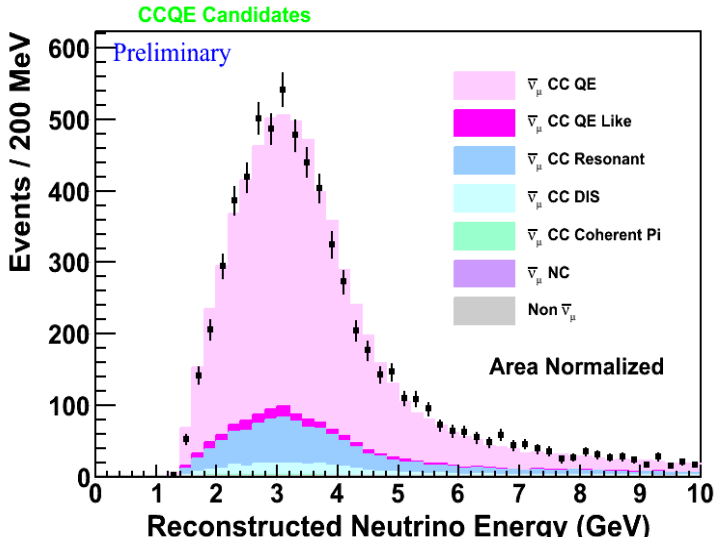


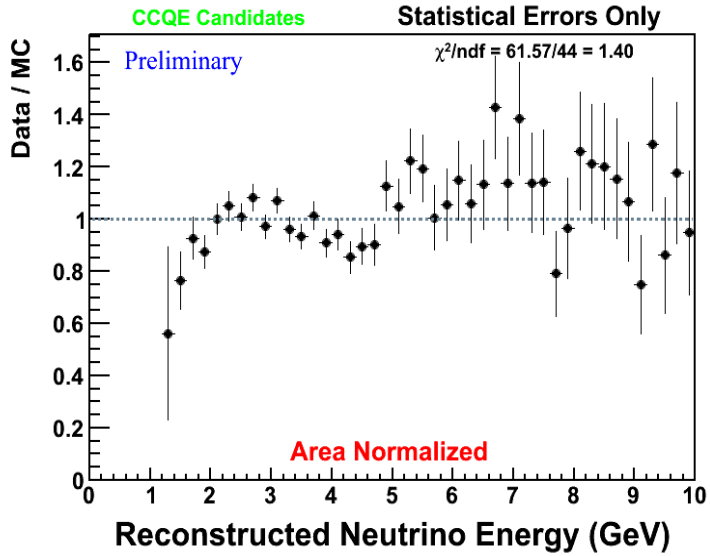


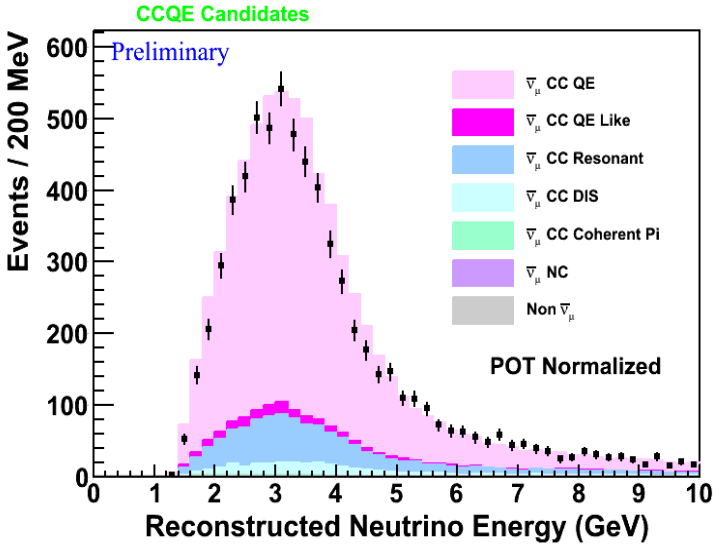


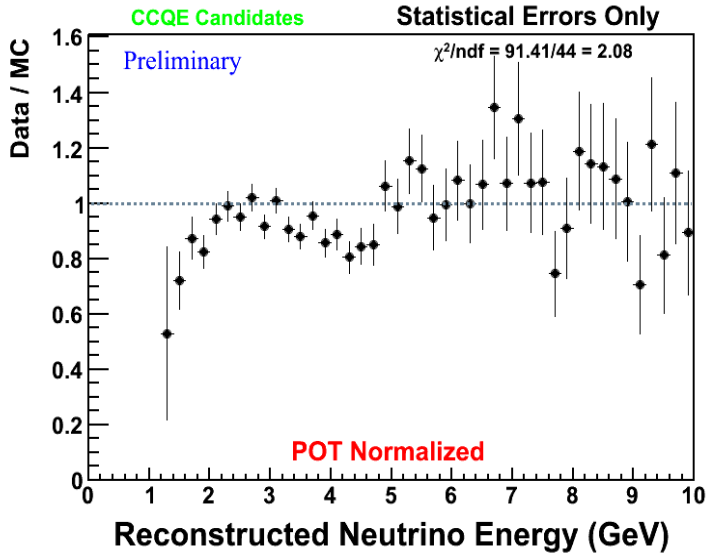
Backup -- Anti-ν CCQE

- Kinematic distributions after recoil cuts:



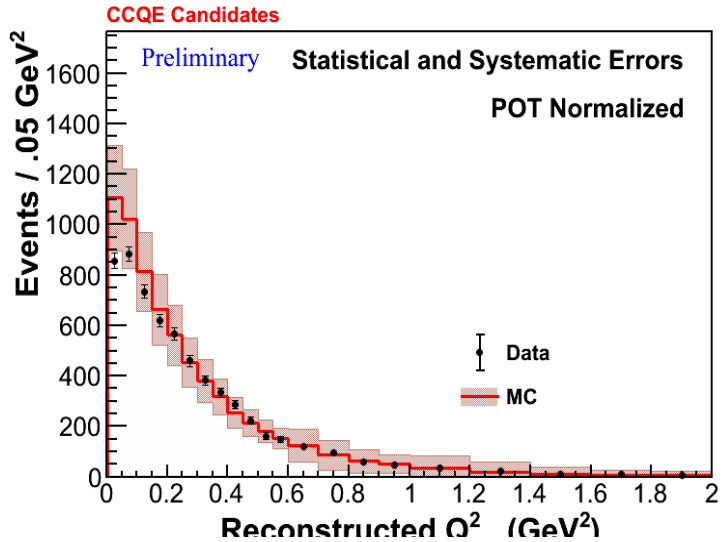


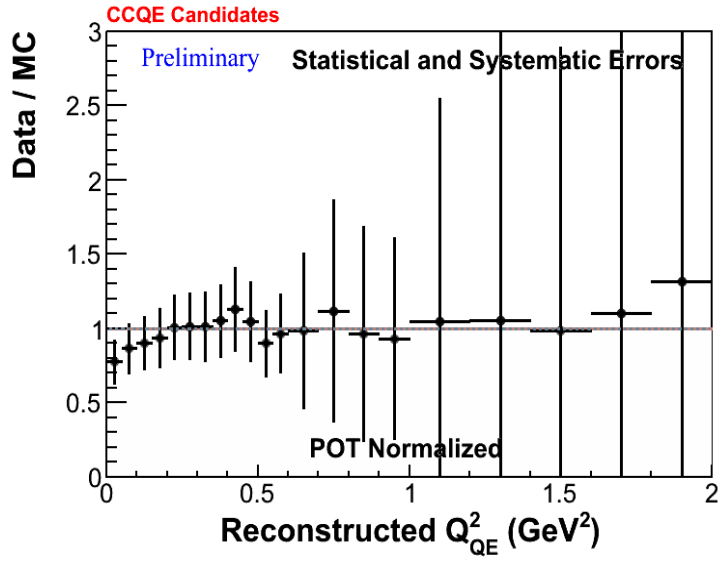


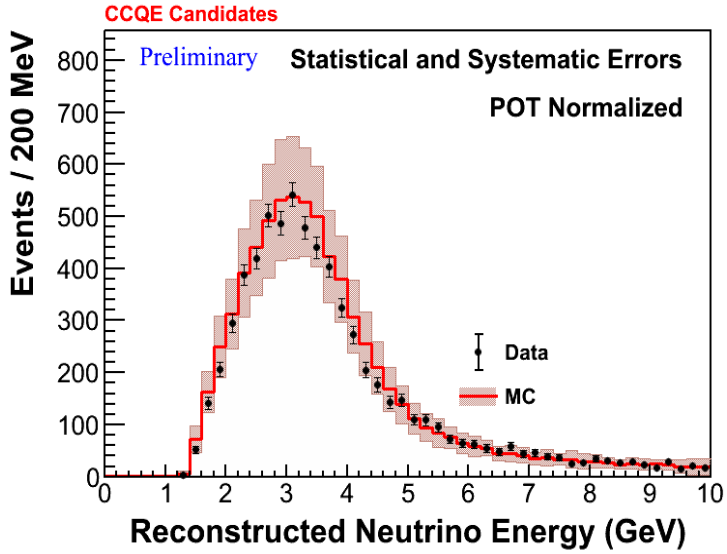


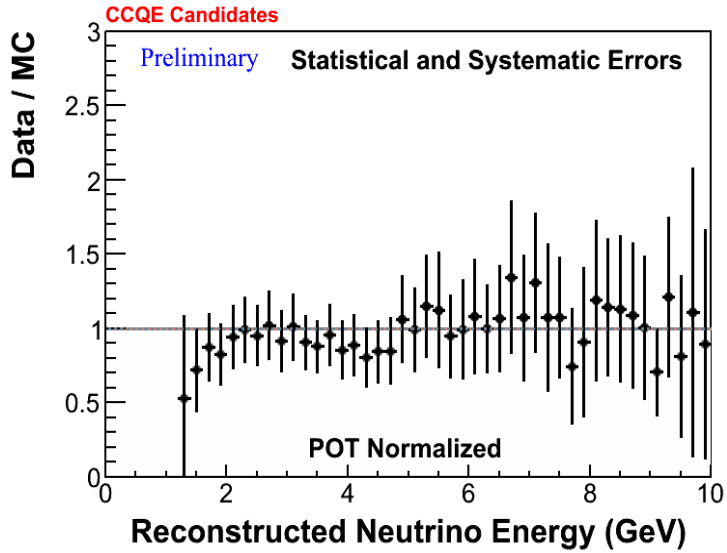
Backup -- Anti-ν CCQE

- Kinematic distributions after recoil cuts:



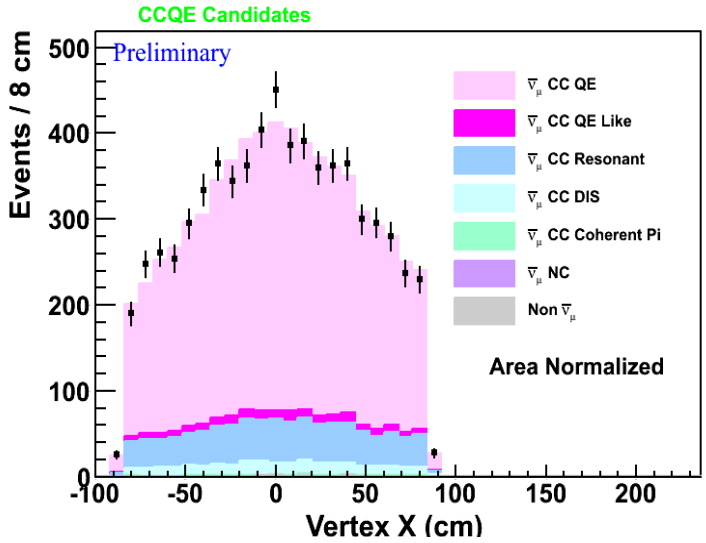


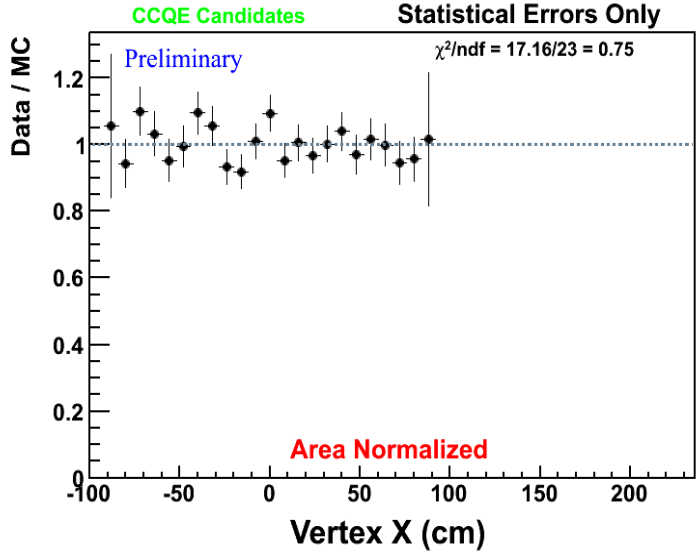


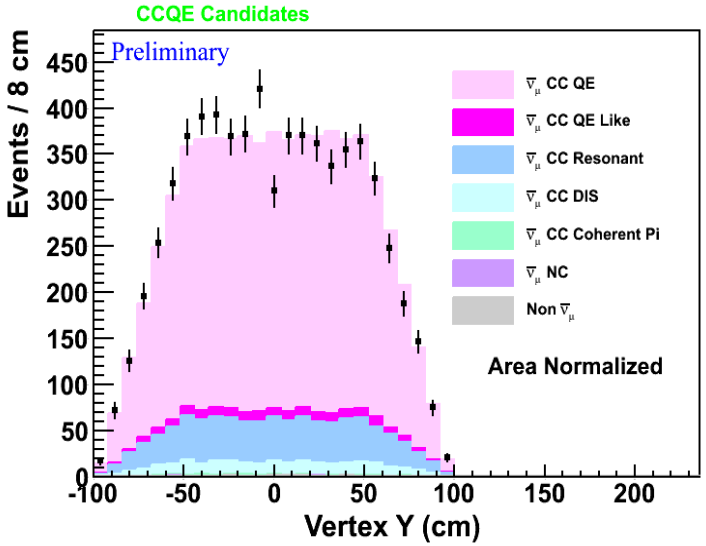


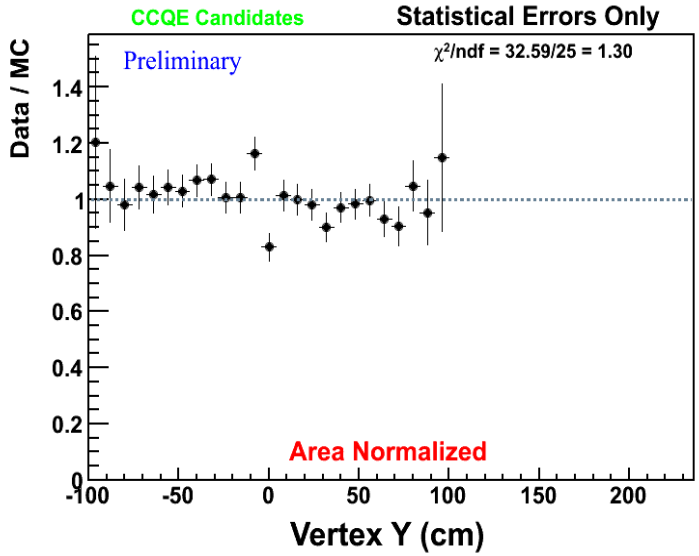
Backup -- Anti-ν CCQE

- Vertex X & Y Distributions:



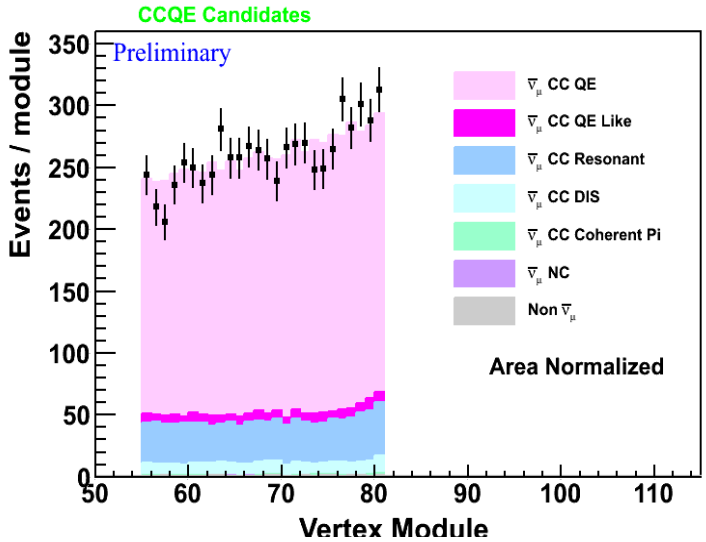


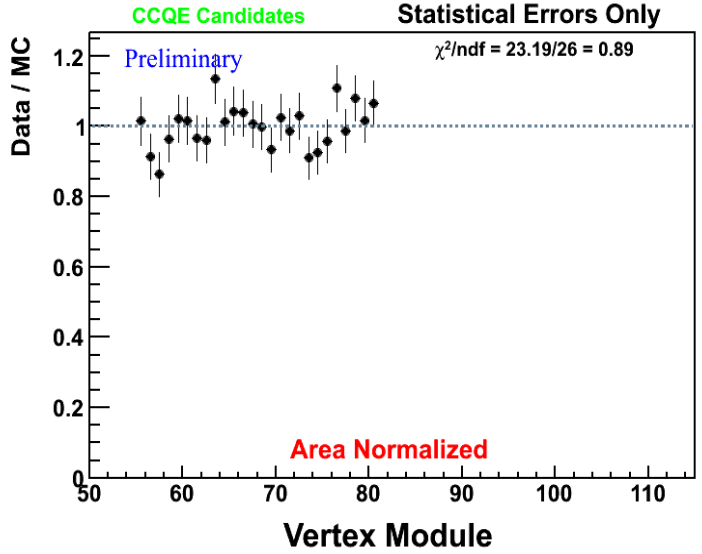


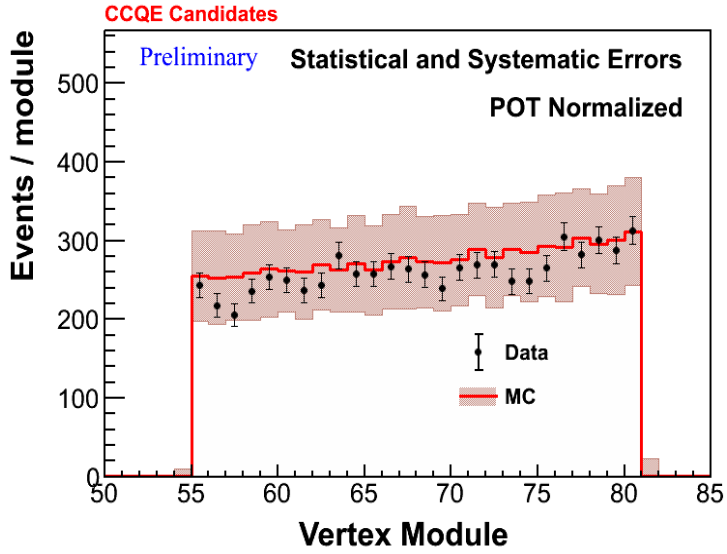


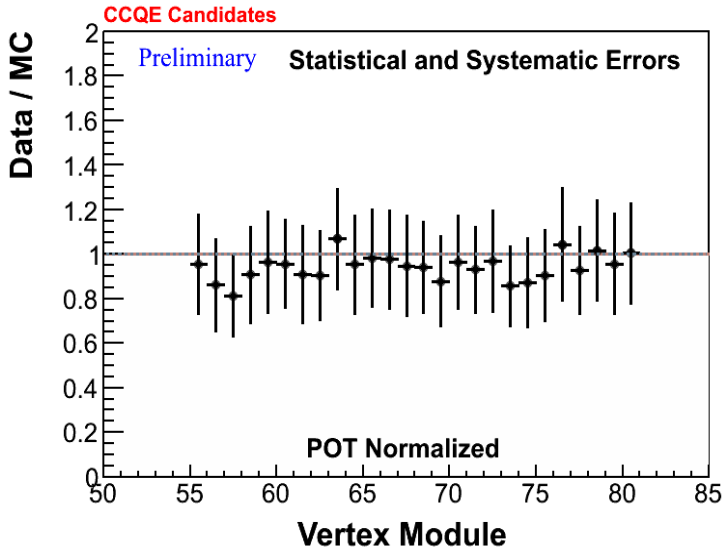
Backup -- Anti-ν CCQE

- Nuisance Plots – Vertex Module Distribution:





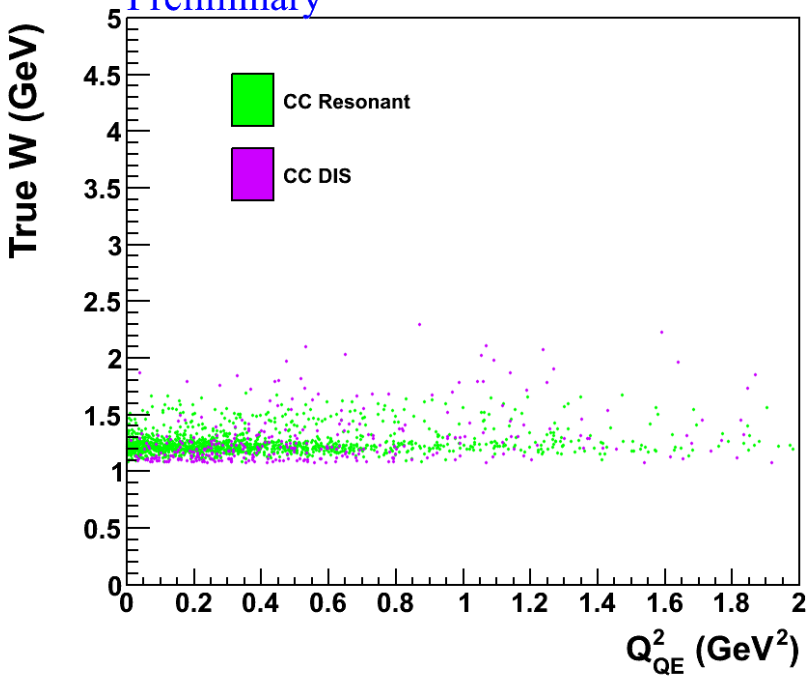




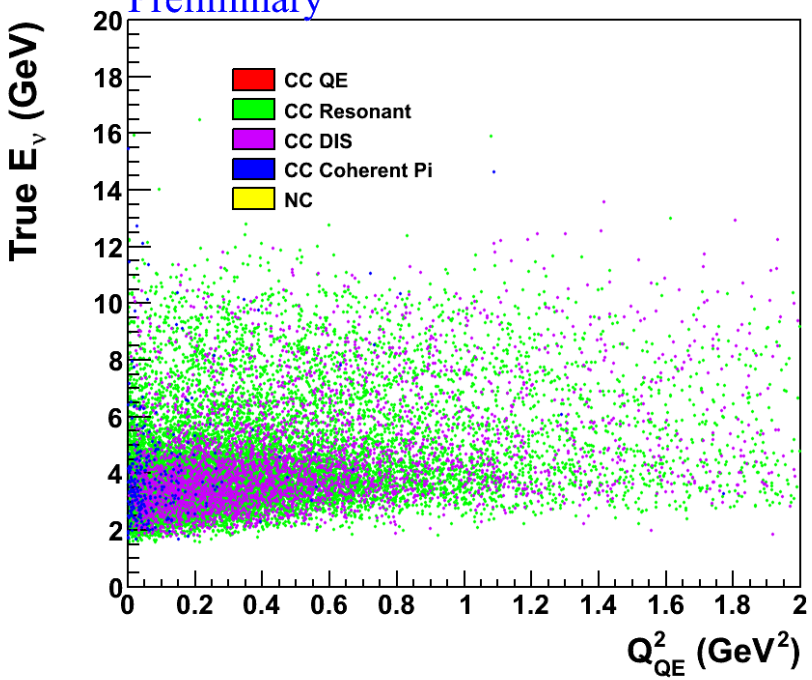
Backup -- Anti-ν CCQE

- Background Truth Information:

Preliminary



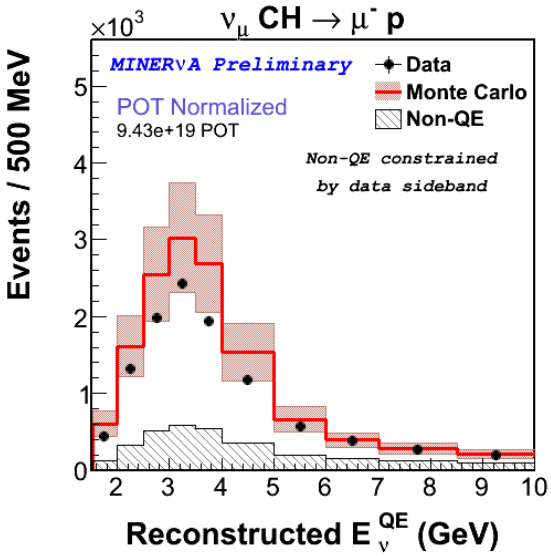
Preliminary

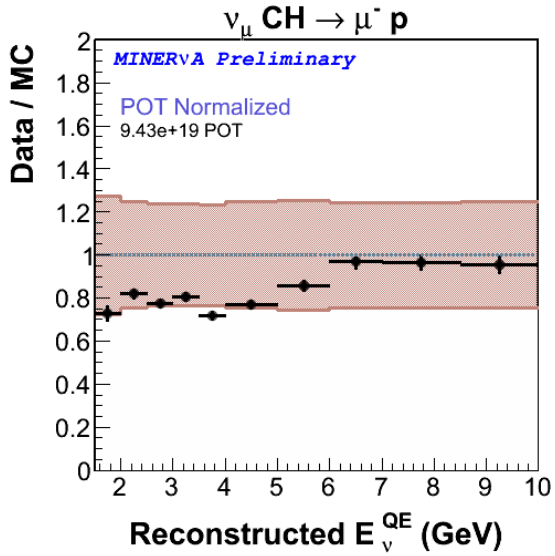


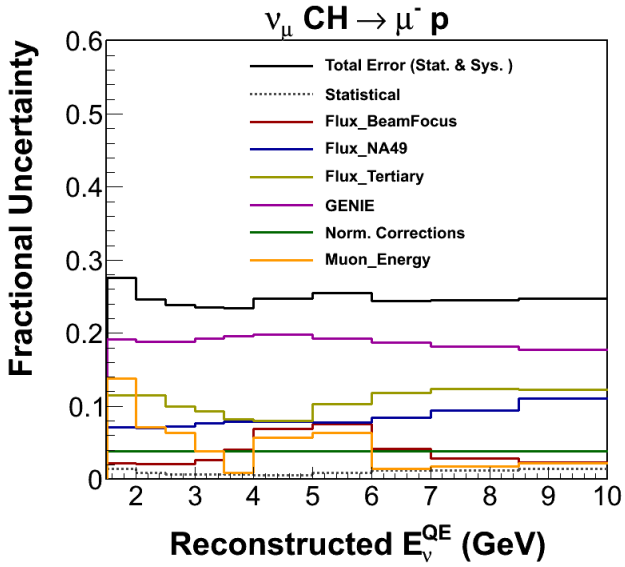
Backup Slides

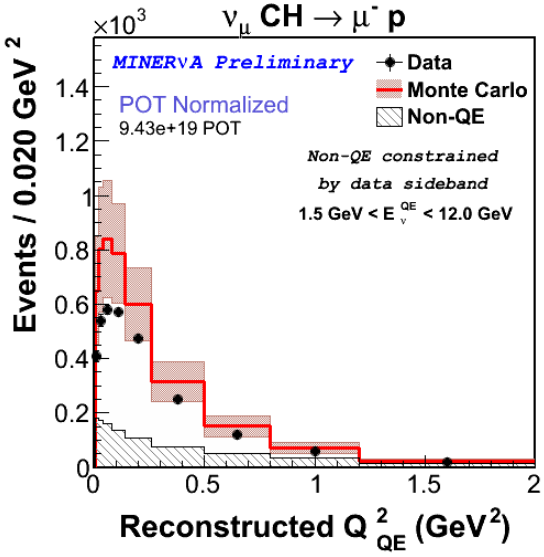
ν 1-Track CCQE Analysis

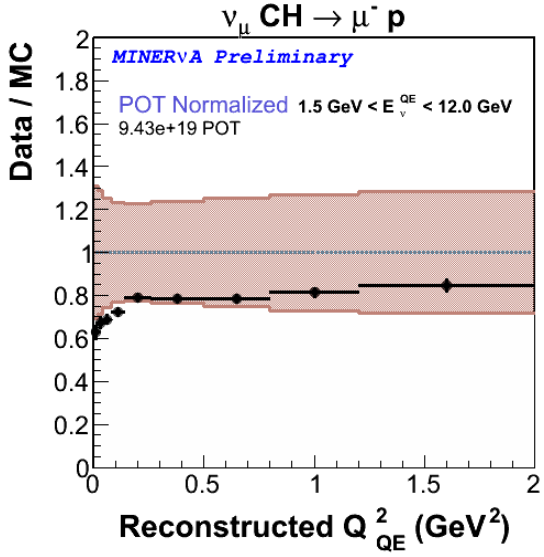
Backup – ν CCQE 1-Track

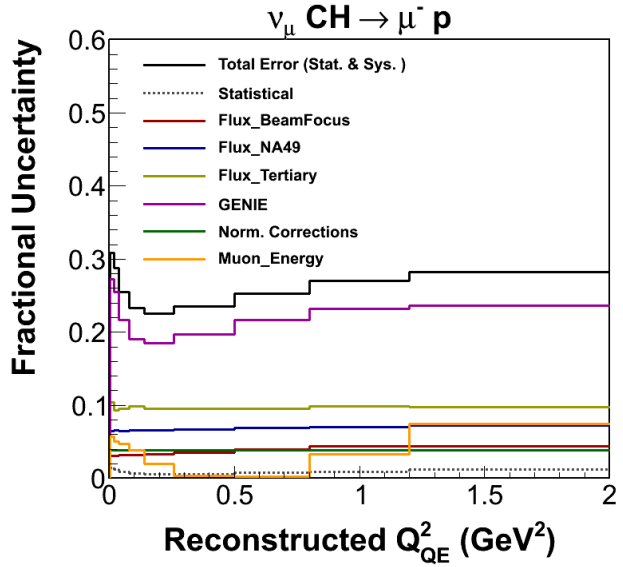




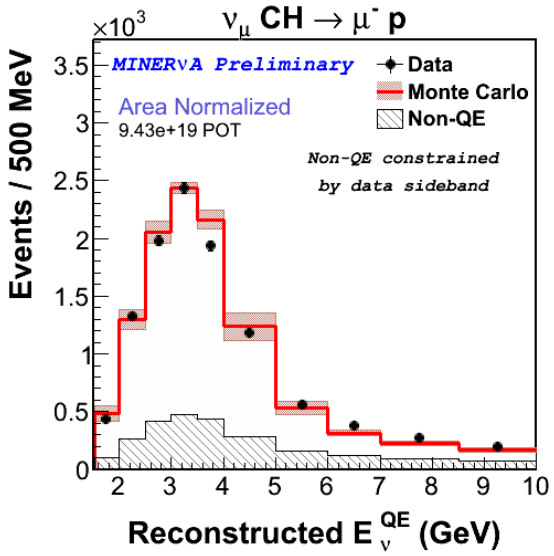


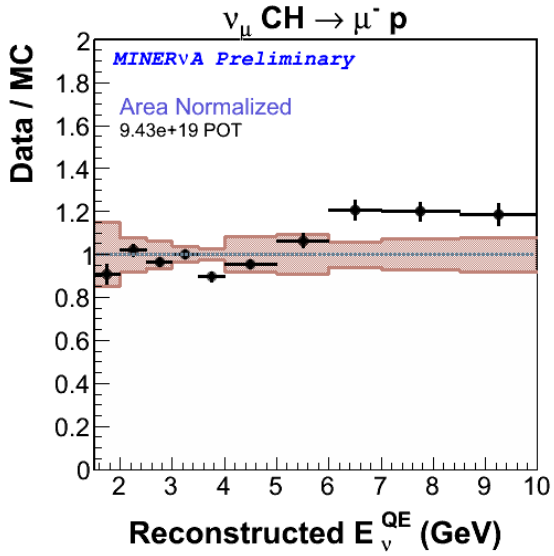


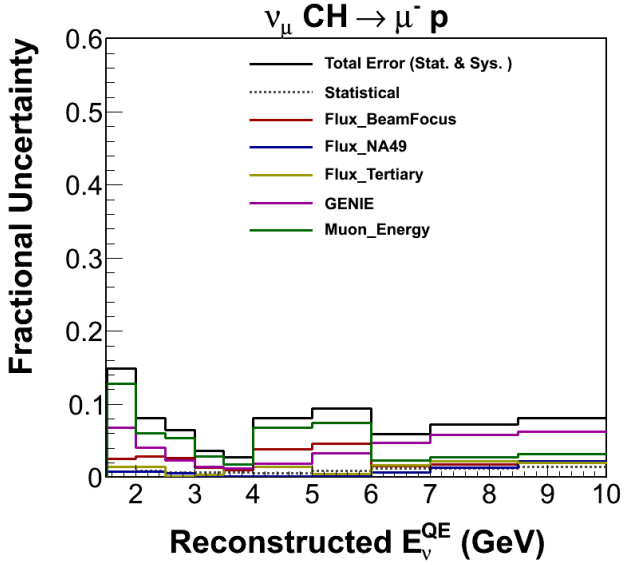


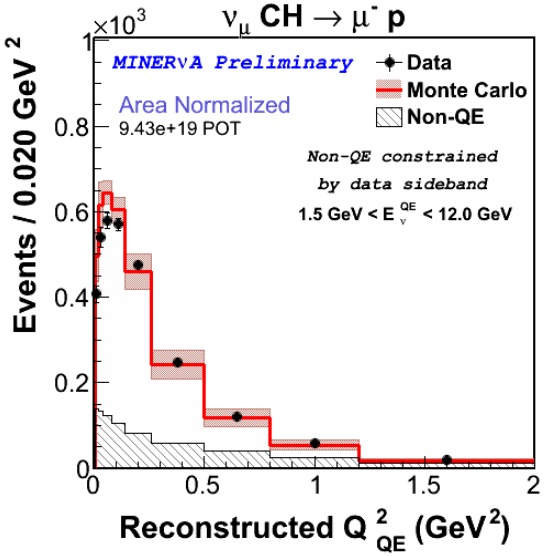


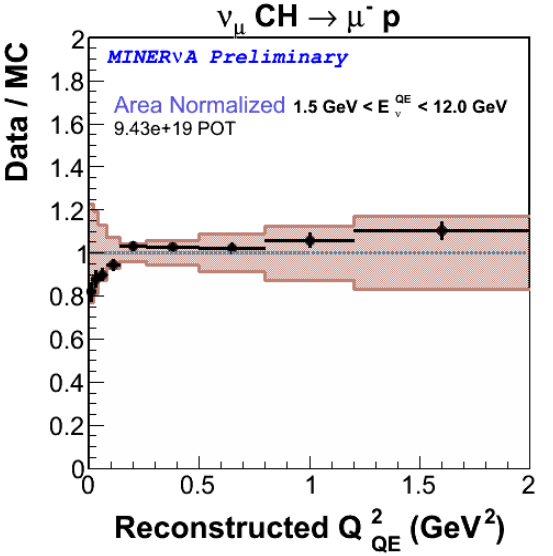
Backup – ν CCQE 1-Track

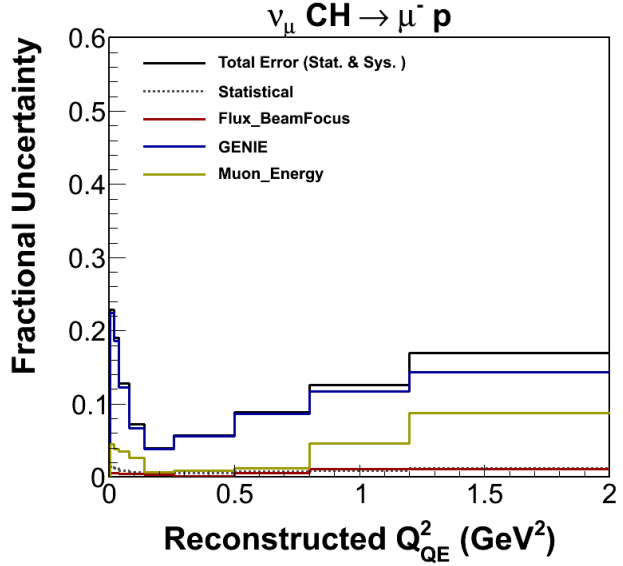










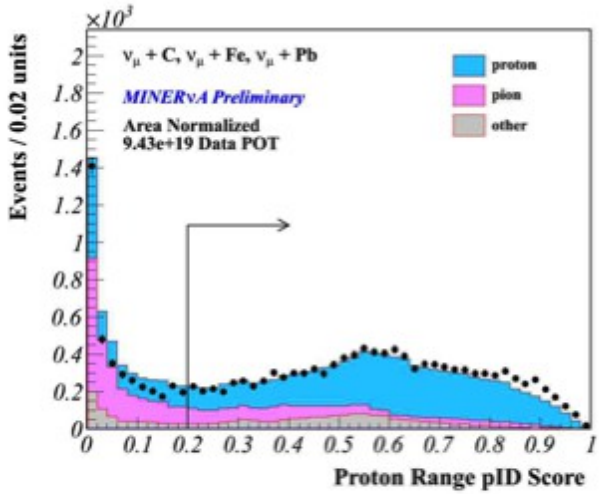


Backup Slides

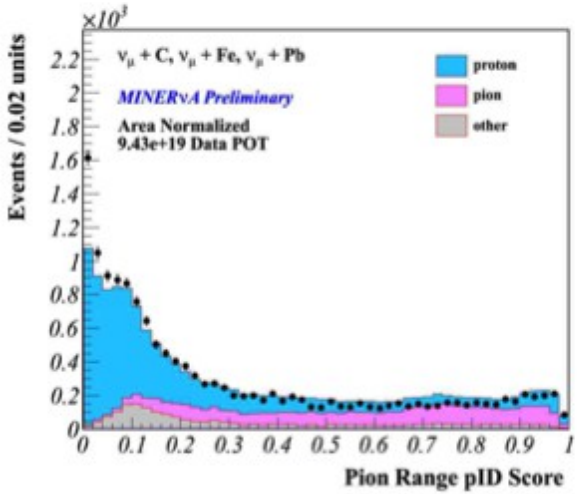
2-track ν CCQE on C, Fe and Pb

2-Track ν_μ CCQE in Fe, Pb and C

- Particle ID:

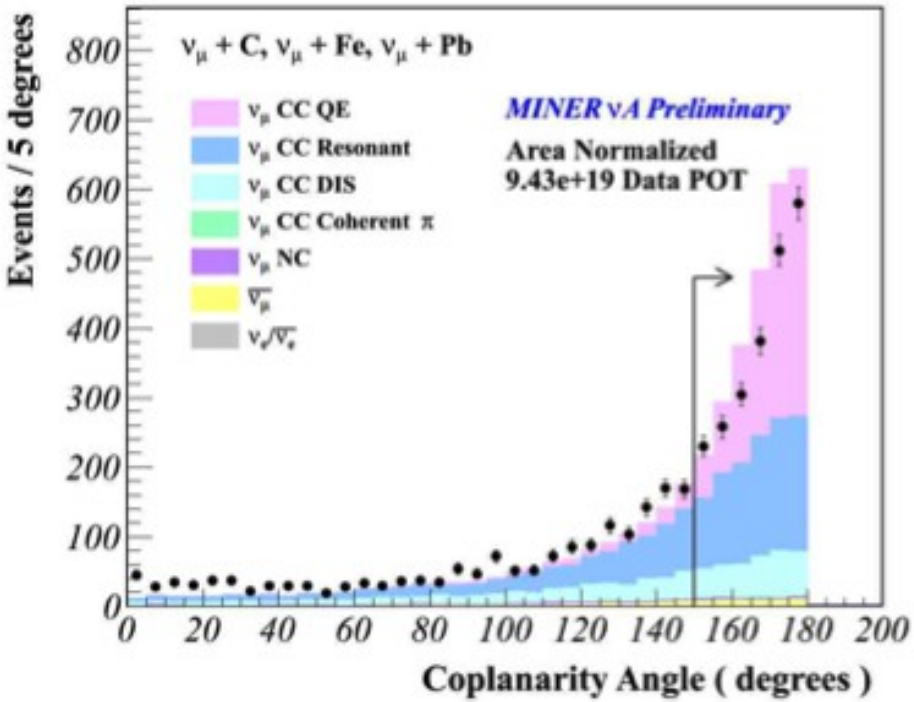


$$score_{p(\pi)} = 1.0 - \frac{\left(\chi^2/ndf\right)_{p(\pi)}}{\sqrt{\left(\left(\chi^2/ndf\right)_p\right)^2 + \left(\left(\chi^2/ndf\right)_\pi\right)^2}}$$



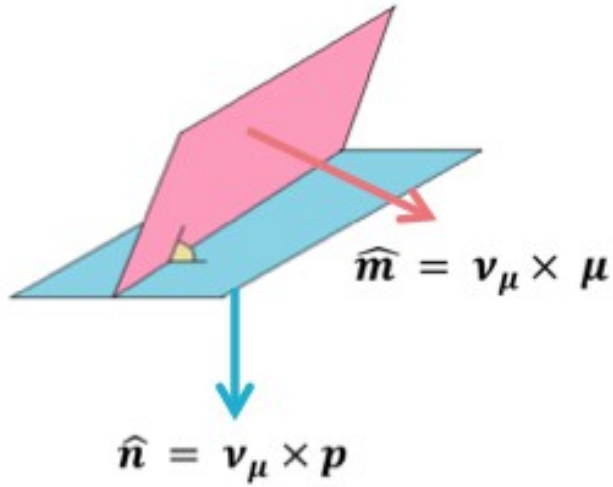
2-Track ν_μ CCQE in Fe, Pb and C

- Coplanarity Angle:



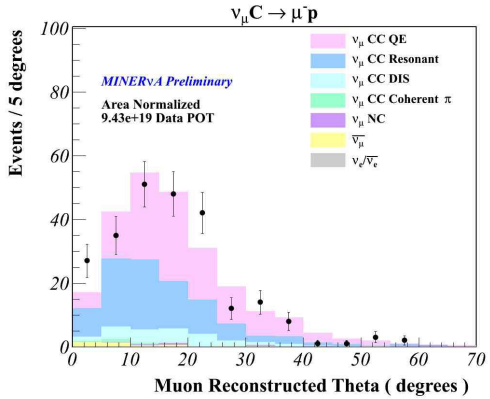
Coplane Angle:

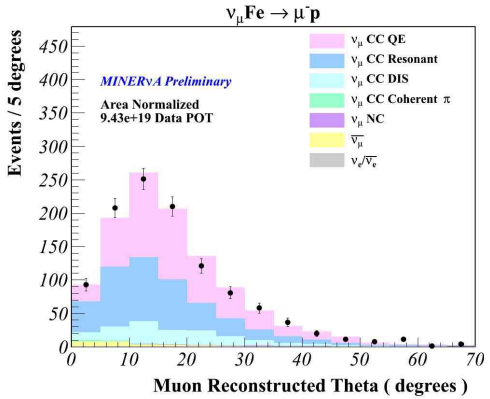
- Angle between the neutrino-muon and neutrino-proton planes.

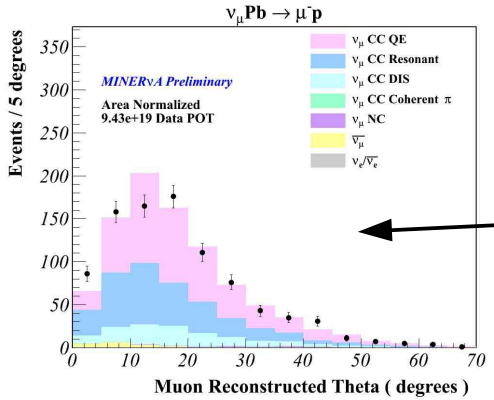


2-Track ν_μ CCQE in Fe, Pb and C

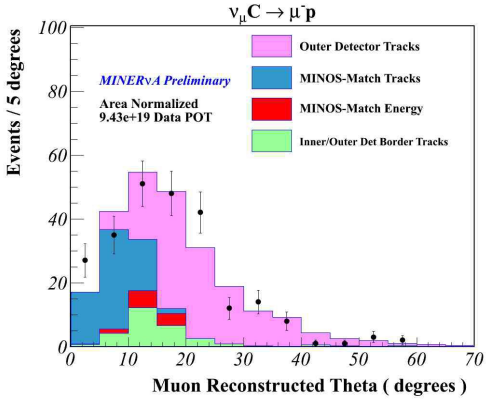
- Muon theta in all candidates passing cuts:

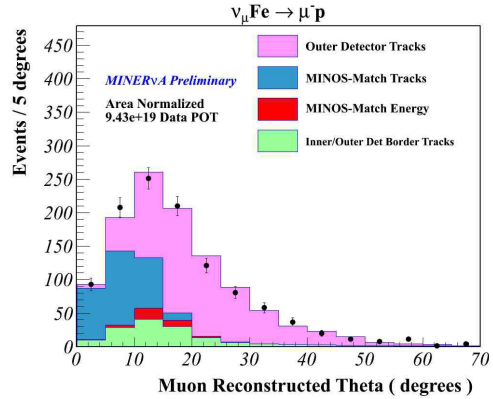


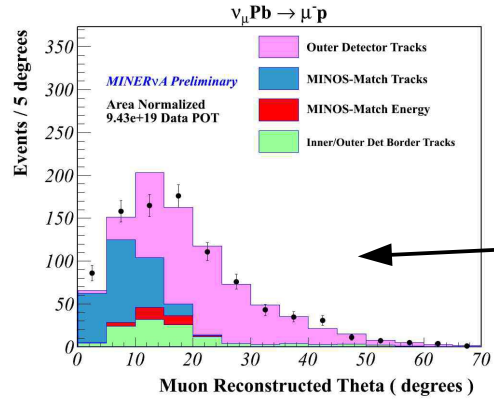




MC colors show GENIE process type; pink in signal (~60% purity)



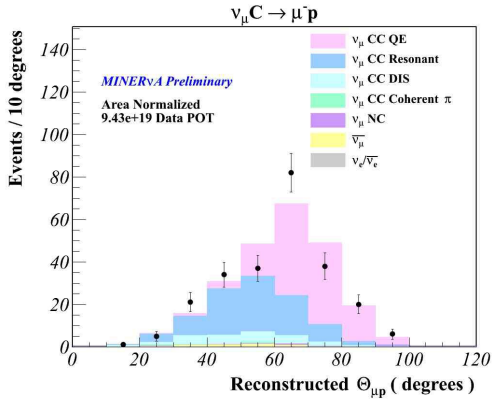


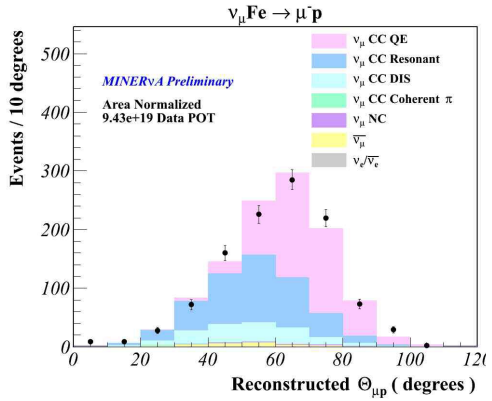


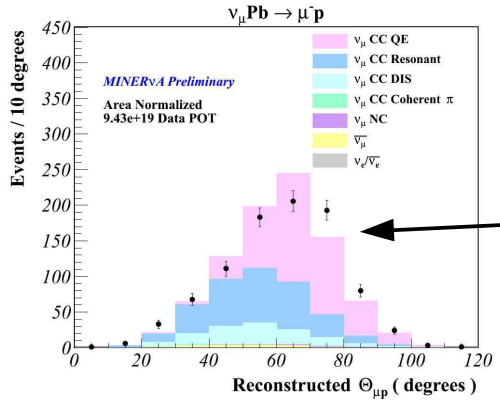
MC colors show muon reconstruction method; most tracks enter outer detector (side HCAL)

2-Track ν_μ CCQE in Fe, Pb and C

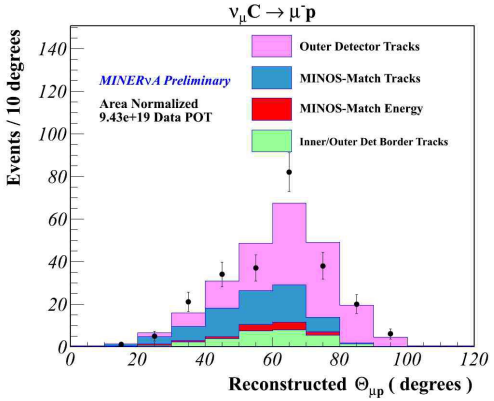
- Mu/p opening angle in all candidates passing cuts:

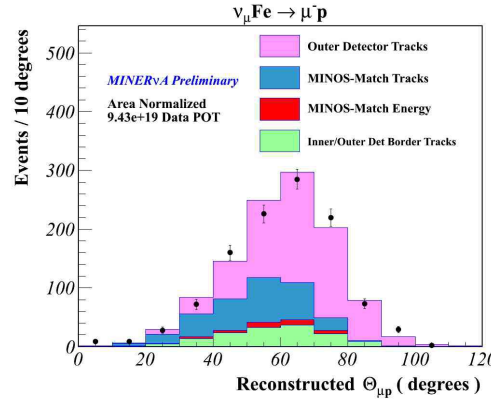


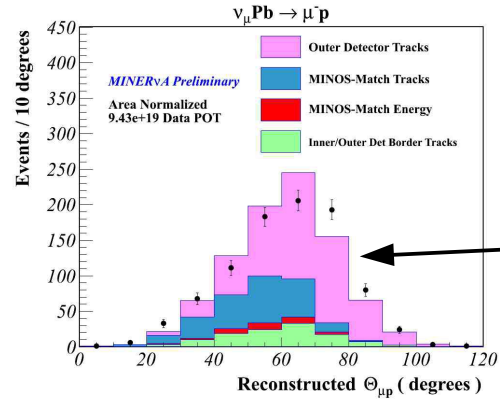




MC colors show GENIE process type; pink in signal (~60% purity)



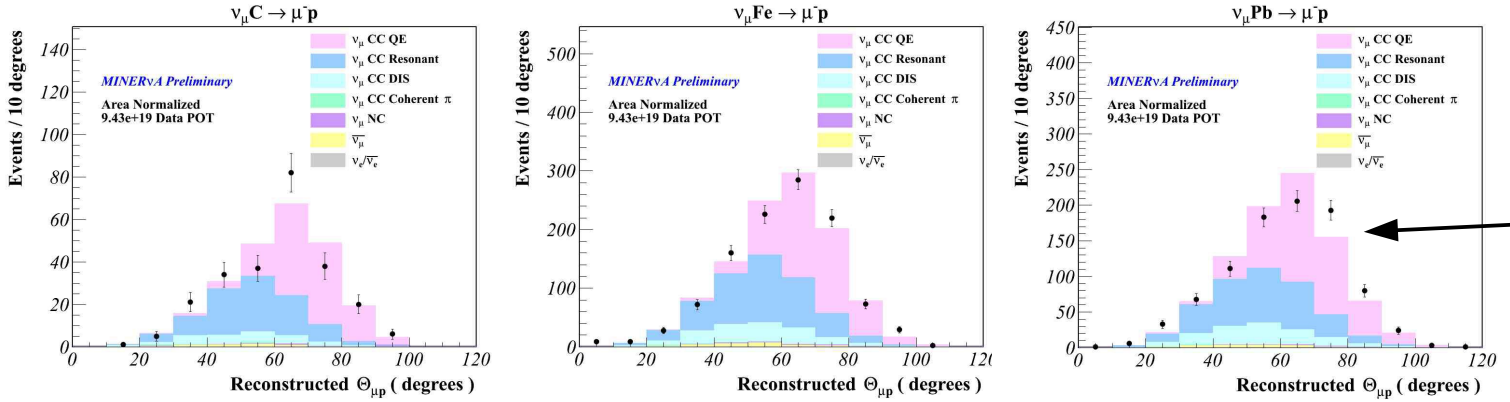




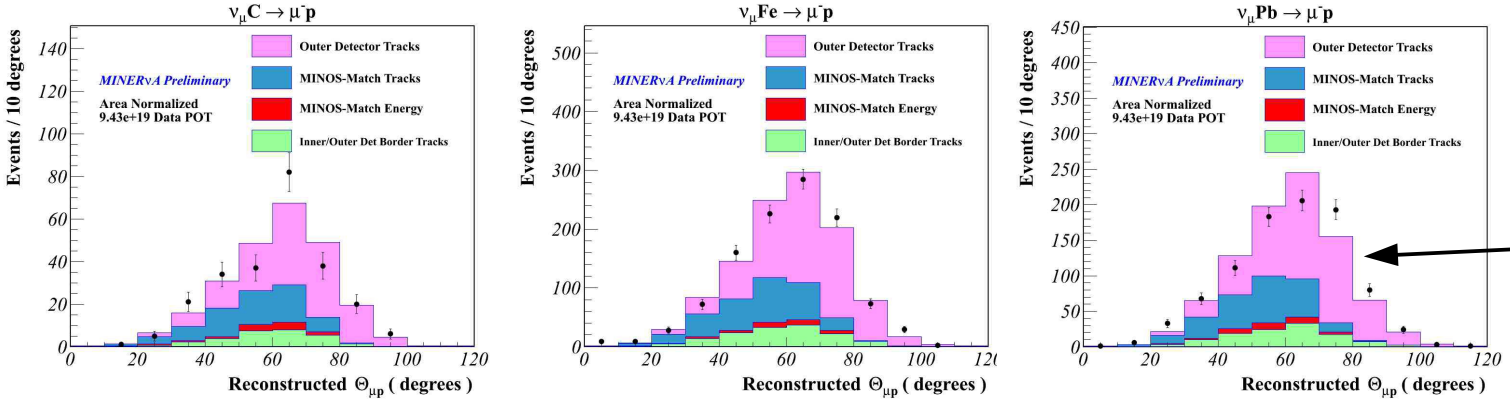
MC colors show muon reconstruction method; most tracks enter outer detector (side HCAL)

2-Track ν_μ CCQE in Fe, Pb and C

- Mu/p opening angle in all candidates passing cuts:



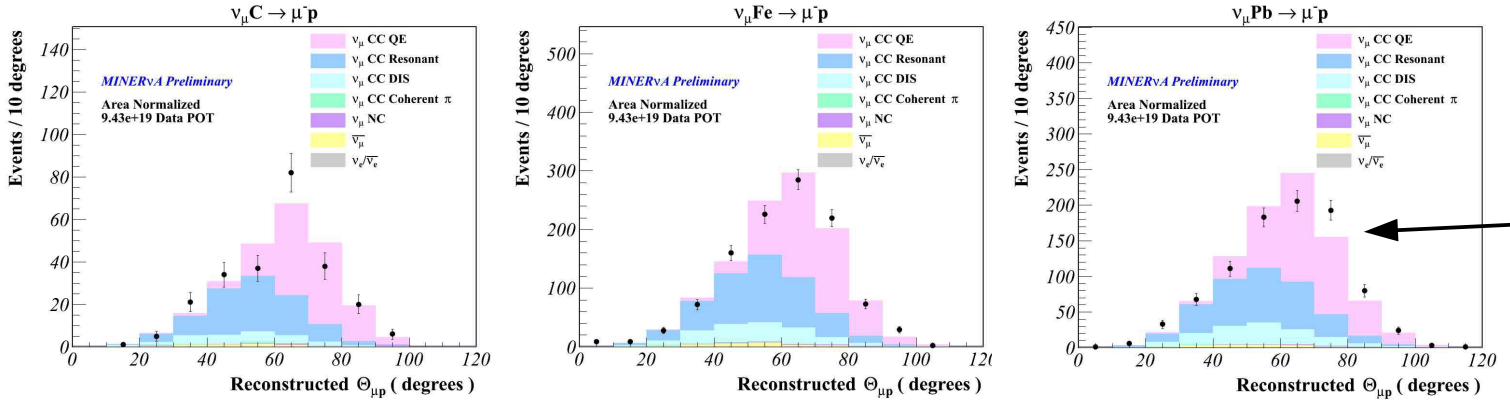
MC colors show GENIE process type; pink in signal (~60% purity)



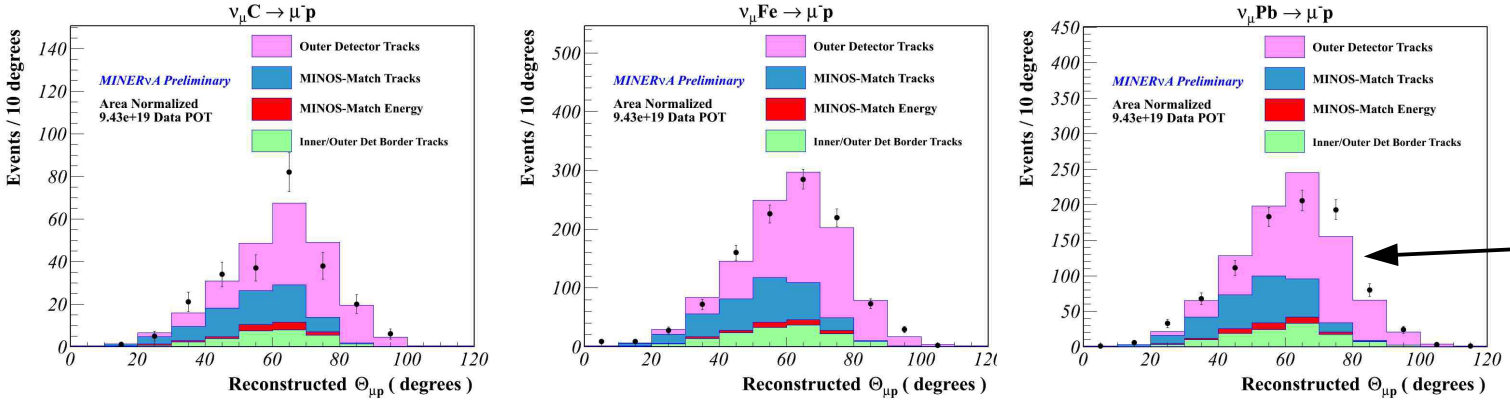
MC colors show muon reconstruction method; most tracks enter outer detector (side HCAL)

2-Track ν_μ CCQE in Fe, Pb and C

- Mu/p opening angle in all candidates passing cuts:



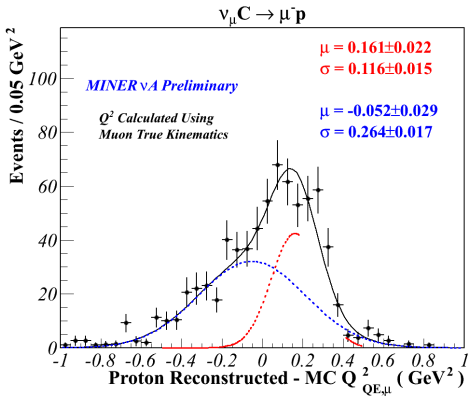
MC colors show GENIE process type; pink in signal (~60% purity)

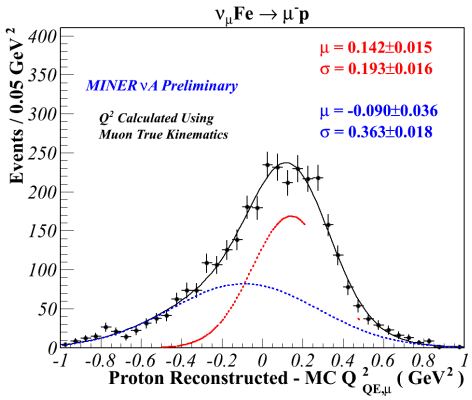


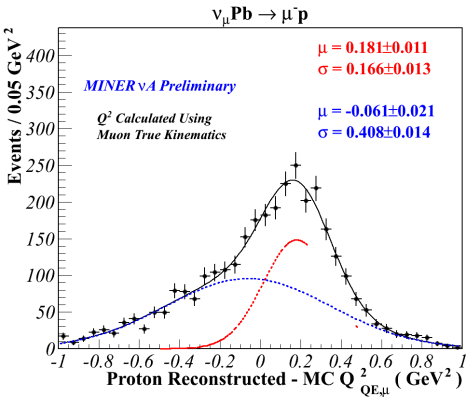
MC colors show muon reconstruction method; most tracks enter outer detector (side HCAL)

2-Track ν_μ CCQE in Fe, Pb and C

- Q2 (using muon) resolution:

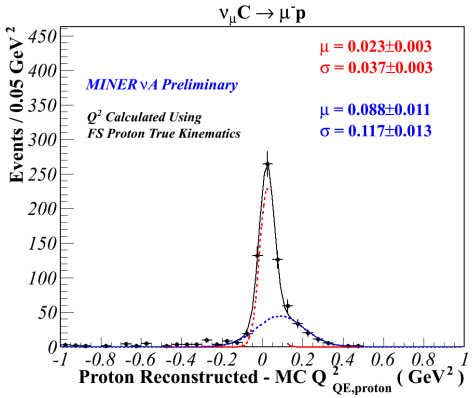


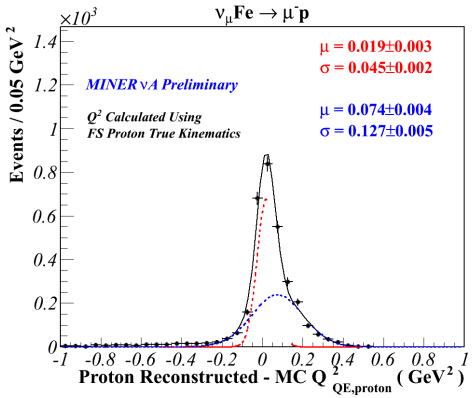


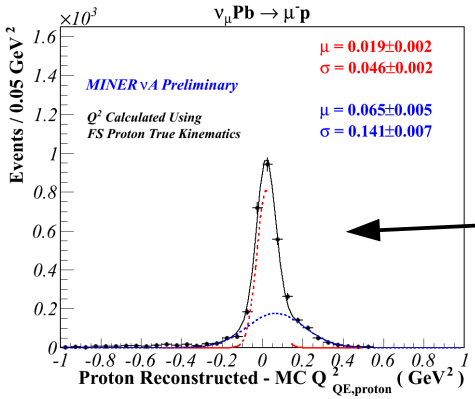


2-Track ν_μ CCQE in Fe, Pb and C

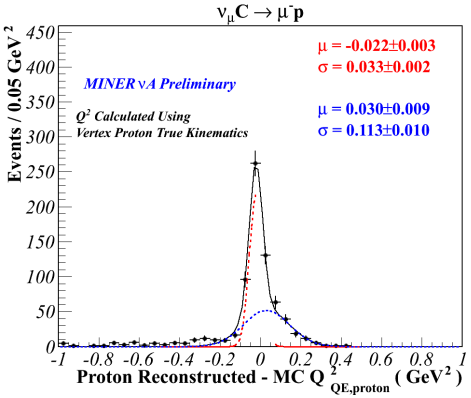
- Q2 (using proton) resolution:

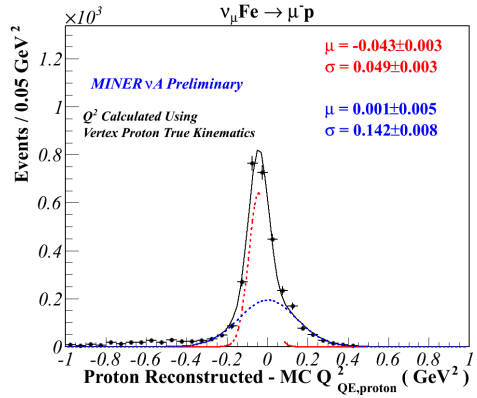


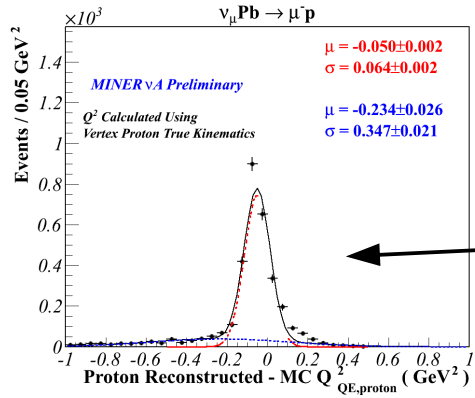




True Q2 from proton after exiting nucleii



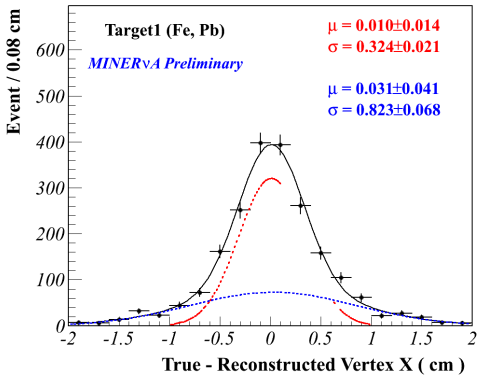


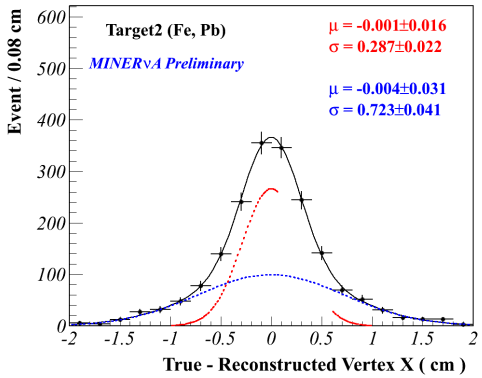


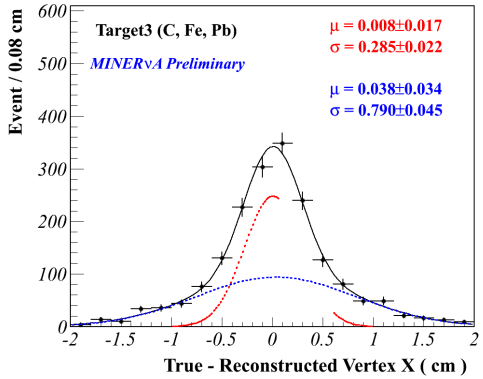
True Q2 from proton before FSI

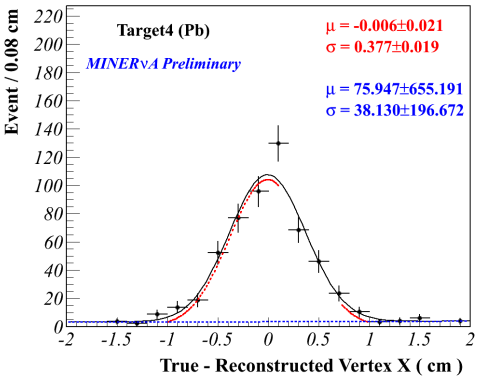
2-Track ν_μ CCQE in Fe, Pb and C

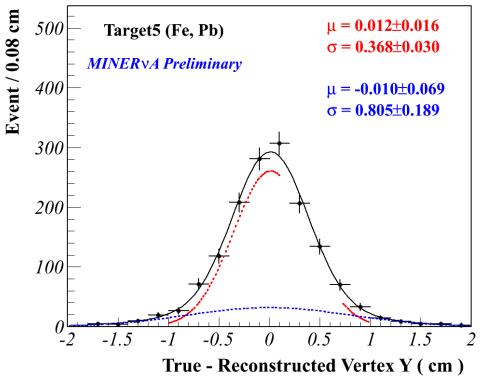
- Vertex x resolution:





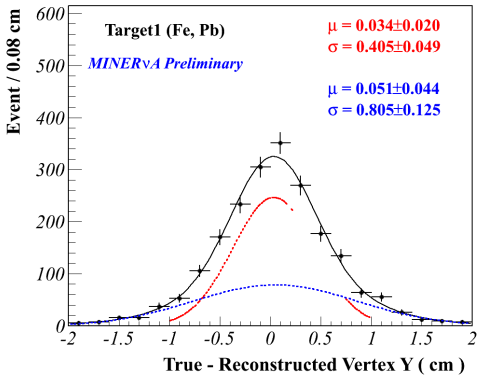


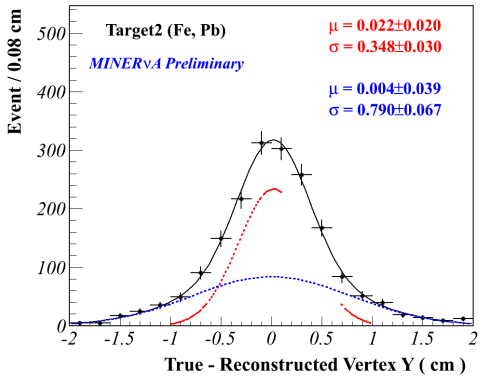


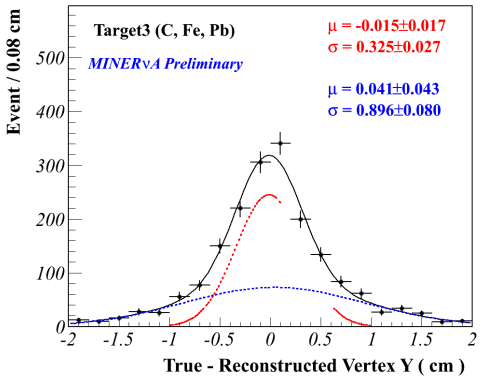


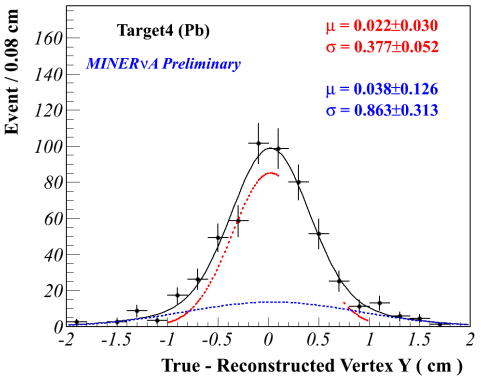
2-Track ν_μ CCQE in Fe, Pb and C

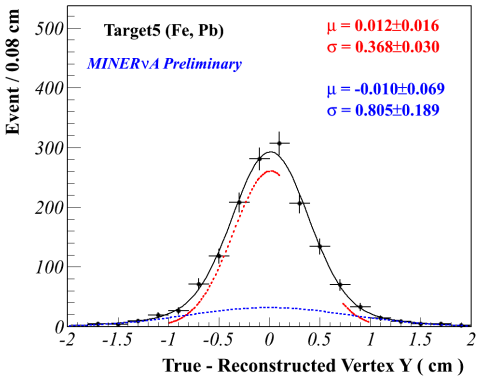
- Vertex y resolution:











2-Track ν_μ CCQE in Fe, Pb and C

- Vertex z resolution: