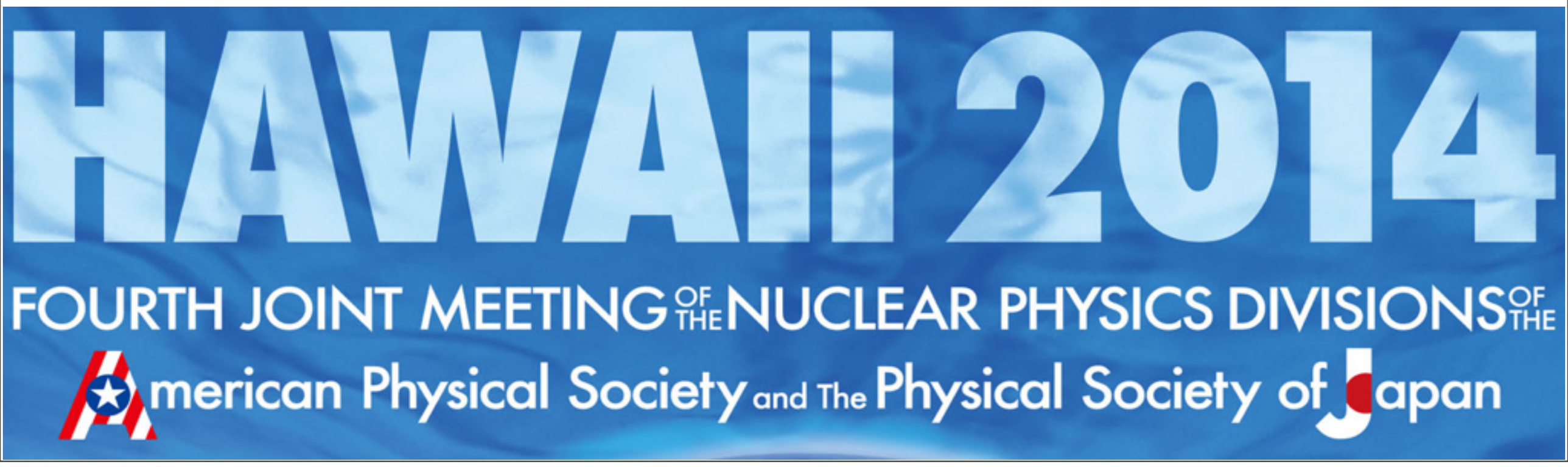
Probing Quasi-elastic Scattering with Neutrinos in MINERνA

Jyotsna Osta
Fermi National Accelerator Laboratory
October 10, 2014



Neutrinos + Nucleus = Very Exciting Physics !

..... especially for exclusive states in the low energy regime

Neutrinos + Nucleus = Very Exciting Physics !

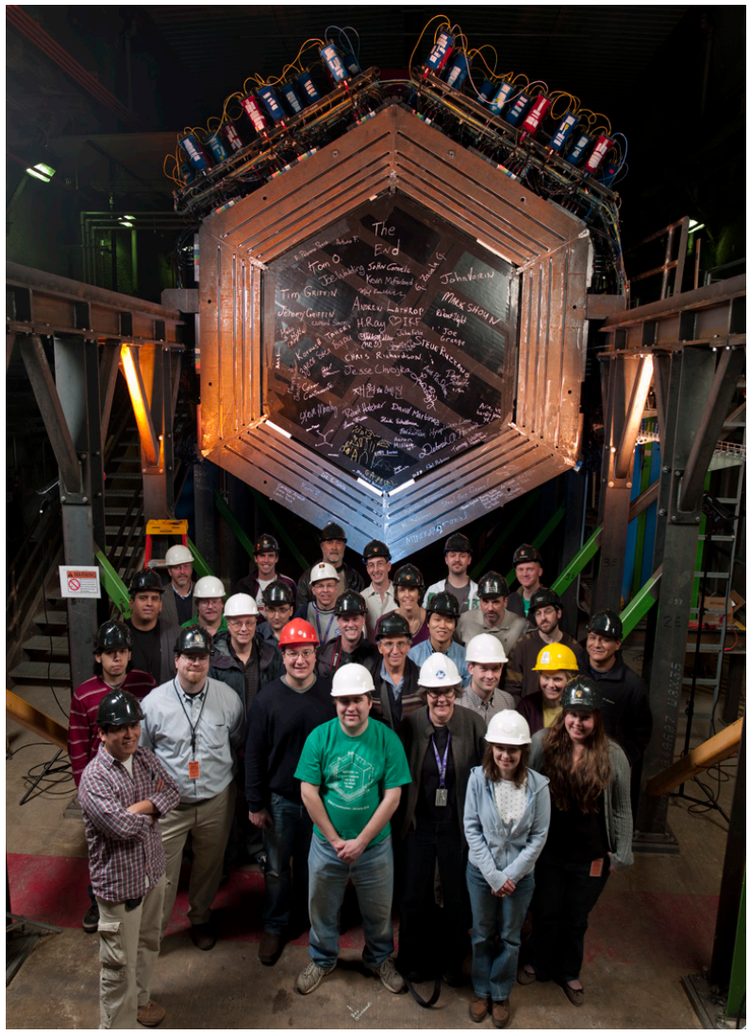
..... especially for exclusive states in the low energy regime

An experiment dedicated to exploring the realm of neutrino-nucleus interactions at the few-GeV energies !

MINERvA Collaboration

Collaboration of ~ 80 Nuclear and Particle Physicists

Centro Brasileiro de Pesquisas Físicas
University of California at Irvine
University of Chicago
Fermi National Accelerator Laboratory
University of Florida
Université de Genève
Universidad de Guanajuato
Hampton University
Inst. Nucl. Reas. Moscow
Massachusetts College of Liberal Arts
University of Minnesota at Duluth
Universidad Nacional de Ingeniería
Northwestern University
Otterbein University
Pontifica Universidad Catolica del Peru
University of Pittsburgh
University of Rochester
Rutgers, The State University of New Jersey
Universidad Técnica Federico Santa María
Tufts University
College of William and Mary



Overview of Talk

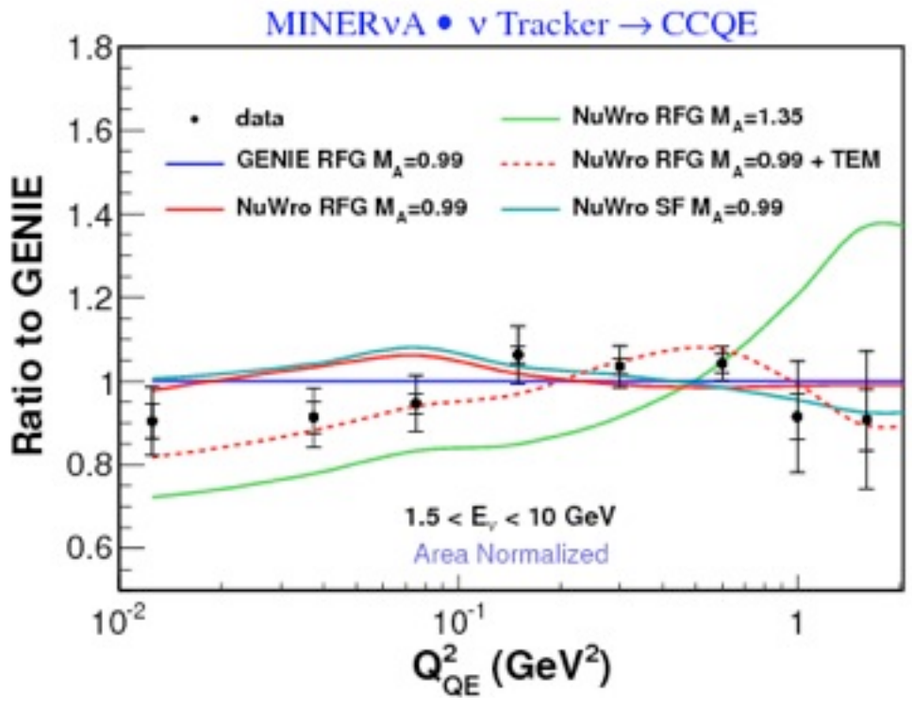
- Motivation:
  - Neutrino cross sections.
- The experiment:
  - The NuMI beam line at Fermilab.
  - The MINERvA detector.
  - Quasi-elastic Scattering.
- Motivation for double differential cross section measurements.
- The analysis:
  - Signal selection.
  - Kinematic phase space of selected sample.
  - Recoil and Michel electron sidebands.
- Summary and Outlook.

Neutrino Cross sections

- Precision neutrino oscillation parameters
  - Oscillation measurements use dense targets for statistics. Understanding neutrino interactions in nuclear media is crucial.
  - Quasi-elastic processes are the signal channel for current oscillation measurements. An accurate measurement of the neutrino energy is essential for precision oscillation analyses.
- Probing the nuclear structure
  - Interaction of axial vector current with nuclei has not been systematically studied.
  - The ability of neutrinos and anti-neutrinos to taste different flavors of quarks can help isolate PDFs and structure functions.

MINERvA QE Analyses

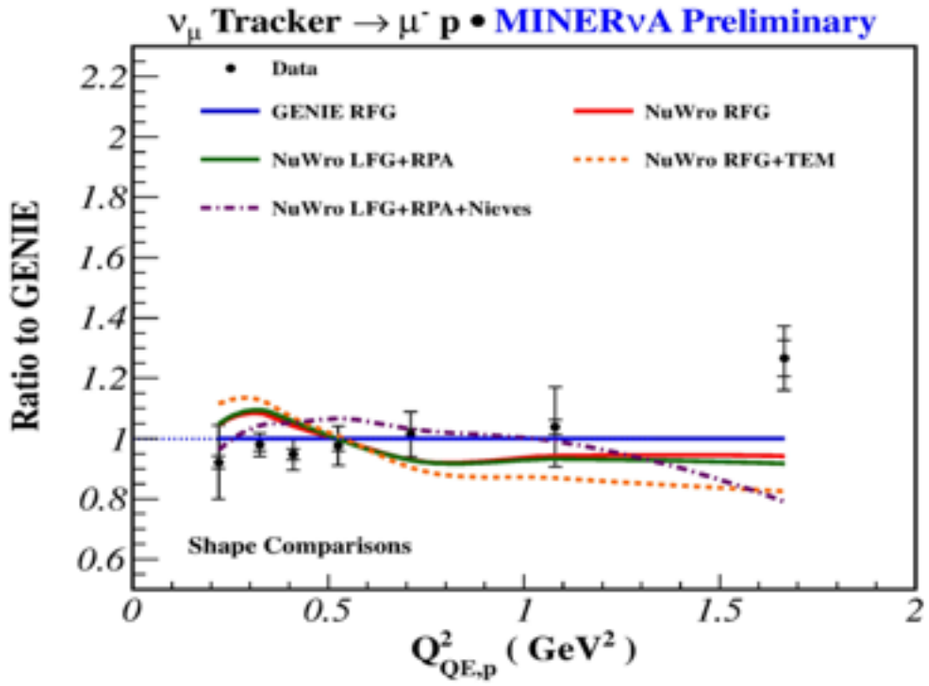
$d\sigma/dQ^2$ from MUON kinematics



$\nu_\mu \longrightarrow$ Phys. Rev. Lett. 111, 022502 (2013)

$\overline{\nu}_\mu \longrightarrow$ Phys. Rev. Lett. 111, 022501 (2013)

$d\sigma/dQ^2$ from PROTON kinematics

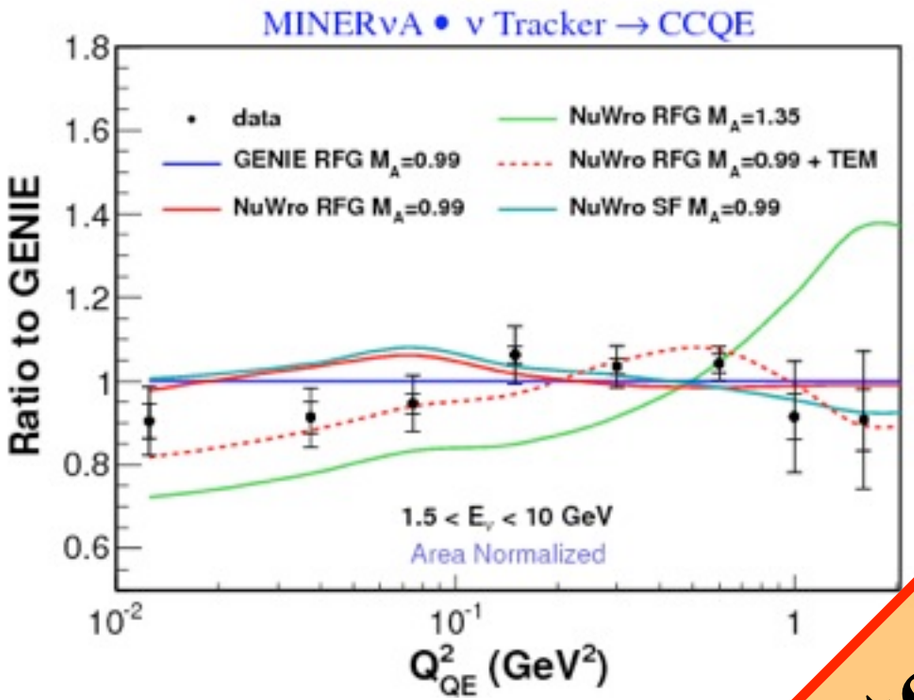


$\nu_\mu \longrightarrow$ arXiv:1409.4497 [hep-ex]

- The muon and proton measurements are sensitive to the nuclear models in different ways.
- The best-fit model for the muon results is based on electron scattering data.
- However this model is not the best fit for the proton results !
- No one nuclear model consistently describes both results.

MINERvA QE Analyses

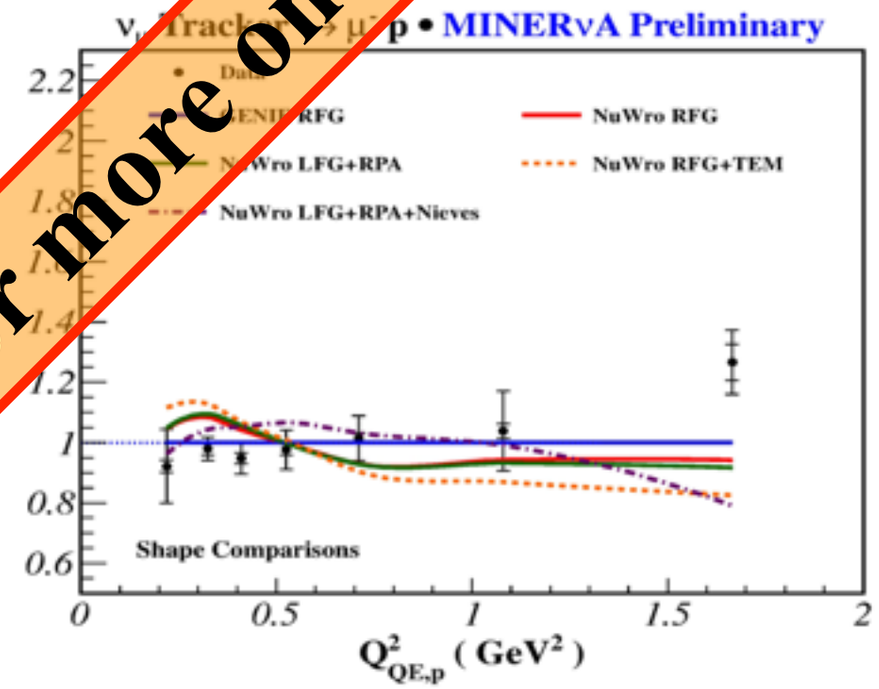
$d\sigma/dQ^2$ from MUON kinematics



$\nu_\mu \longrightarrow$ Phys. Rev. Lett. 111, 022502 (2013)

$\bar{\nu}_\mu \longrightarrow$ Phys. Rev. Lett. 111, 022501 (2013)

$d\sigma/dQ^2$ from PROTON kinematics



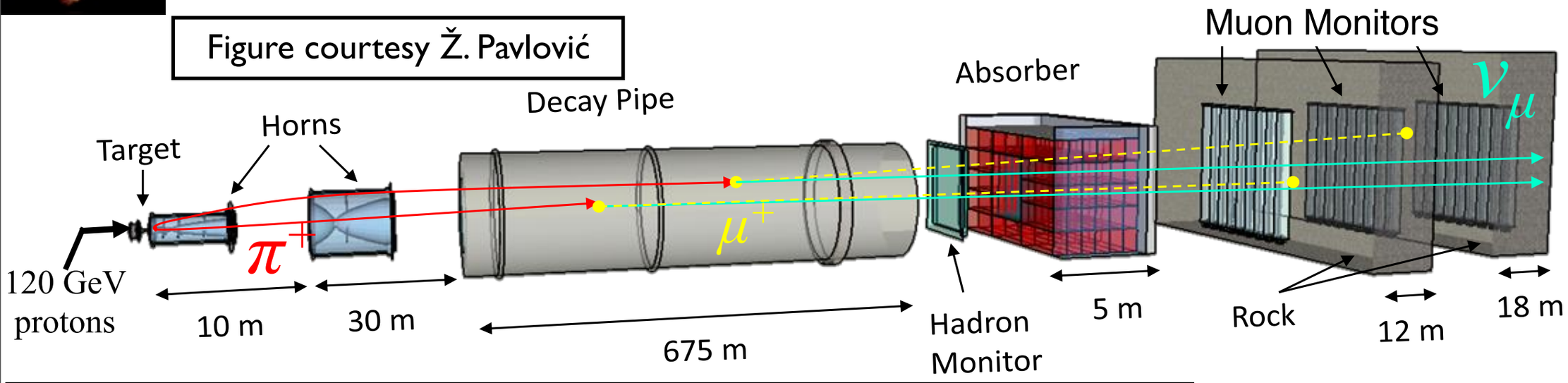
$\nu_\mu \longrightarrow$ arXiv:1409.4497 [hep-ex]

See B. Tice's talk tomorrow for more on this

- The muon and proton measurements are sensitive to the nuclear models in different ways.
- The best-fit model for the muon results is based on electron scattering data.
- However this model is not the best fit for the proton results !
- No one nuclear model consistently describes both results.

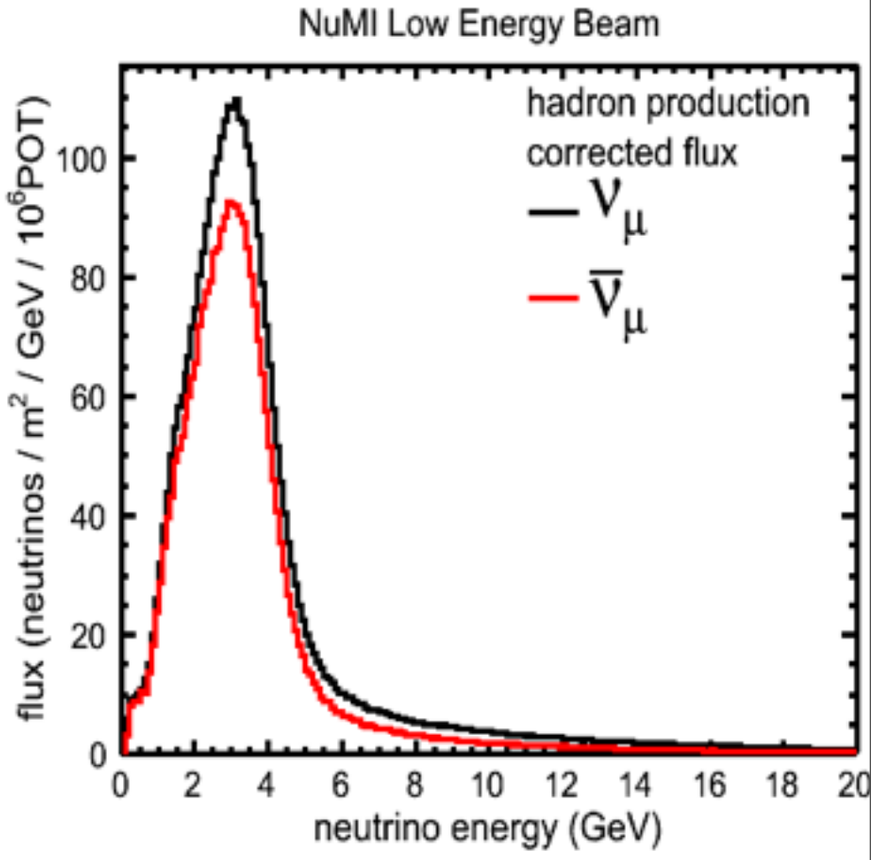
The NuMI (Neutrinos at the Main Injector) beam line

Figure courtesy Ž. Pavlović

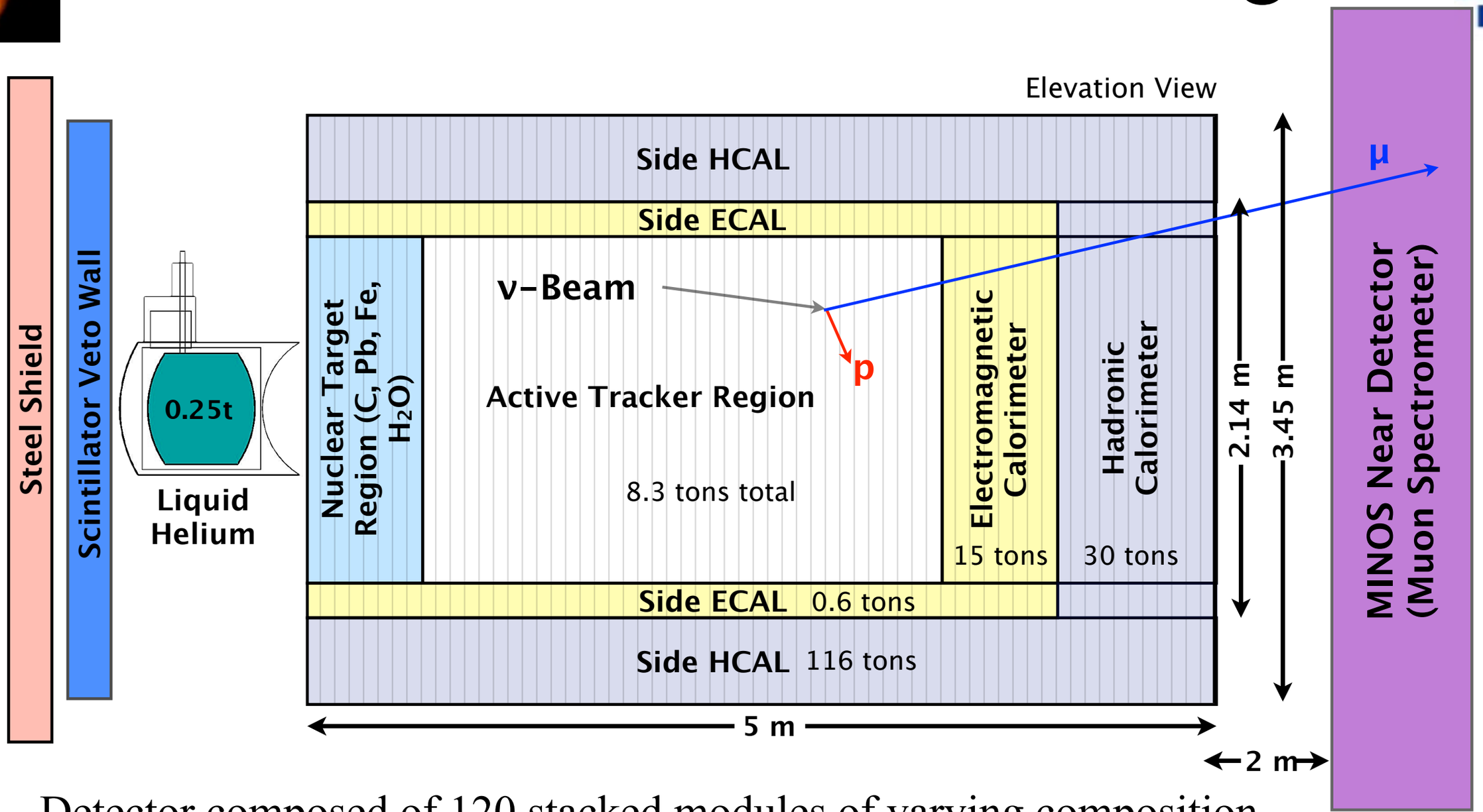


MINERvA

- 120 GeV/c protons on carbon target produce pions.
- Pions decay into muons and neutrinos.
- Horns focus positive or negative pions depending on their polarity.
- Produces neutrino or anti-neutrino beam.
- MINERvA took data in the “low energy” beam configuration from Nov. 2009 - May 2012.
- **Data for analysis being shown here.**
- MINERvA is taking data in the “medium energy” beam configuration at present.



MINERvA - the detector design

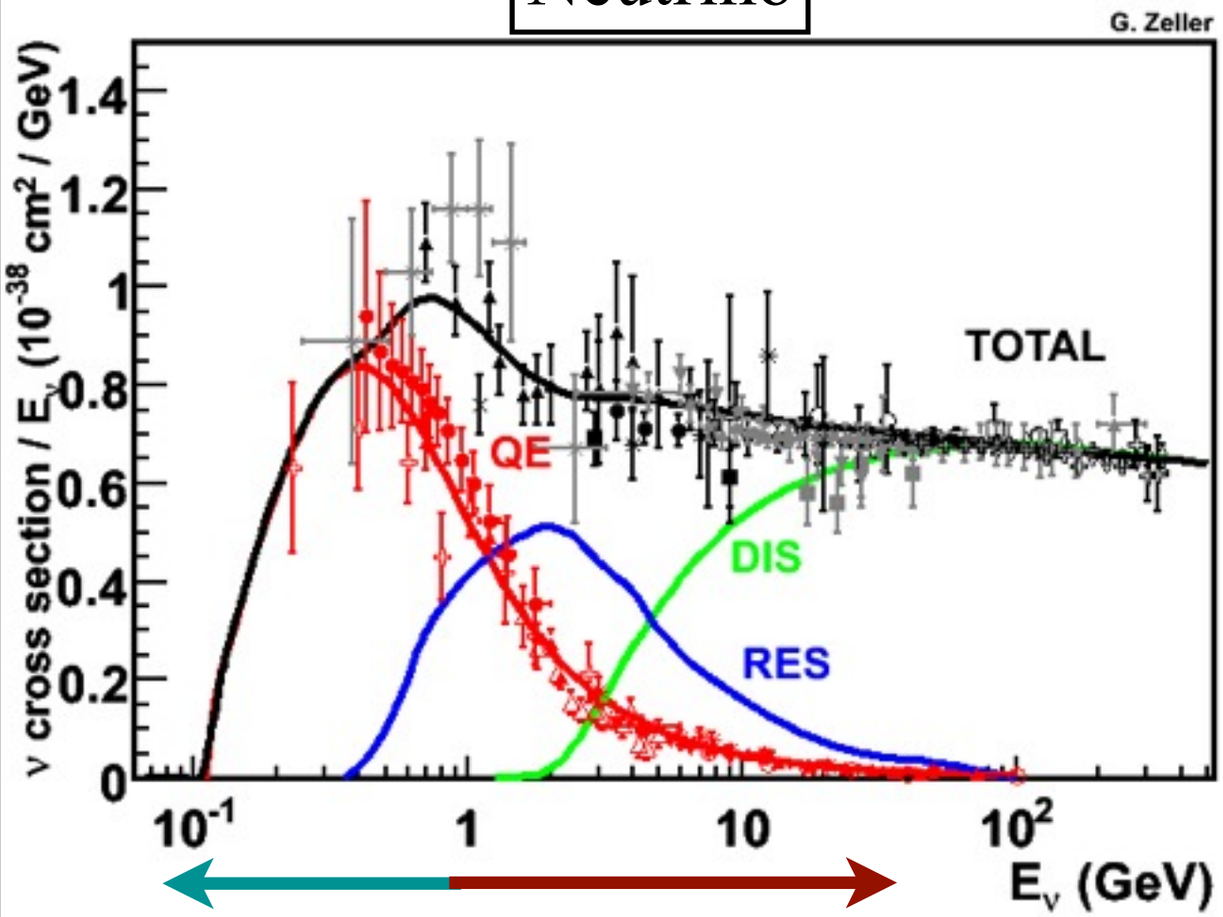


- Detector composed of 120 stacked modules of varying composition.
- Finely segmented (~32 K readout channels), side ECAL & HCAL well instrumented
- MINOS near detector acts as magnetic spectrometer ➛ muon charge and momentum

Design, Calibration and Performance of the MINERvA Detector
Nucl. Inst. and Meth. A743 (2014) 130

Quasi-elastic Scattering

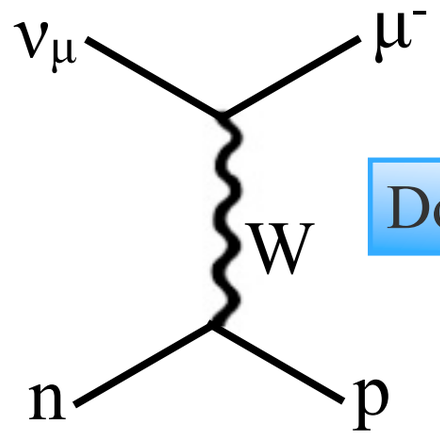
Neutrino



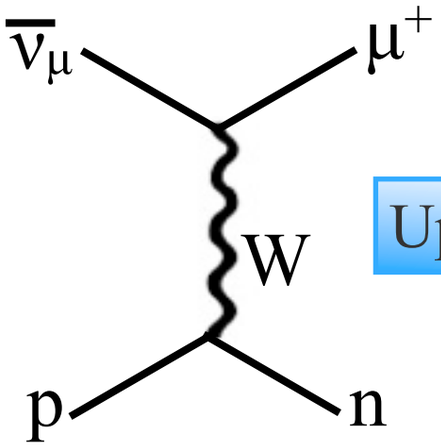
BooNEs, T2K

MINERvA, NOvA, MINOS, LBNE

CC Quasi-elastic
Nucleon changes but doesn't break up



Down → Up quark



Up → Down quark

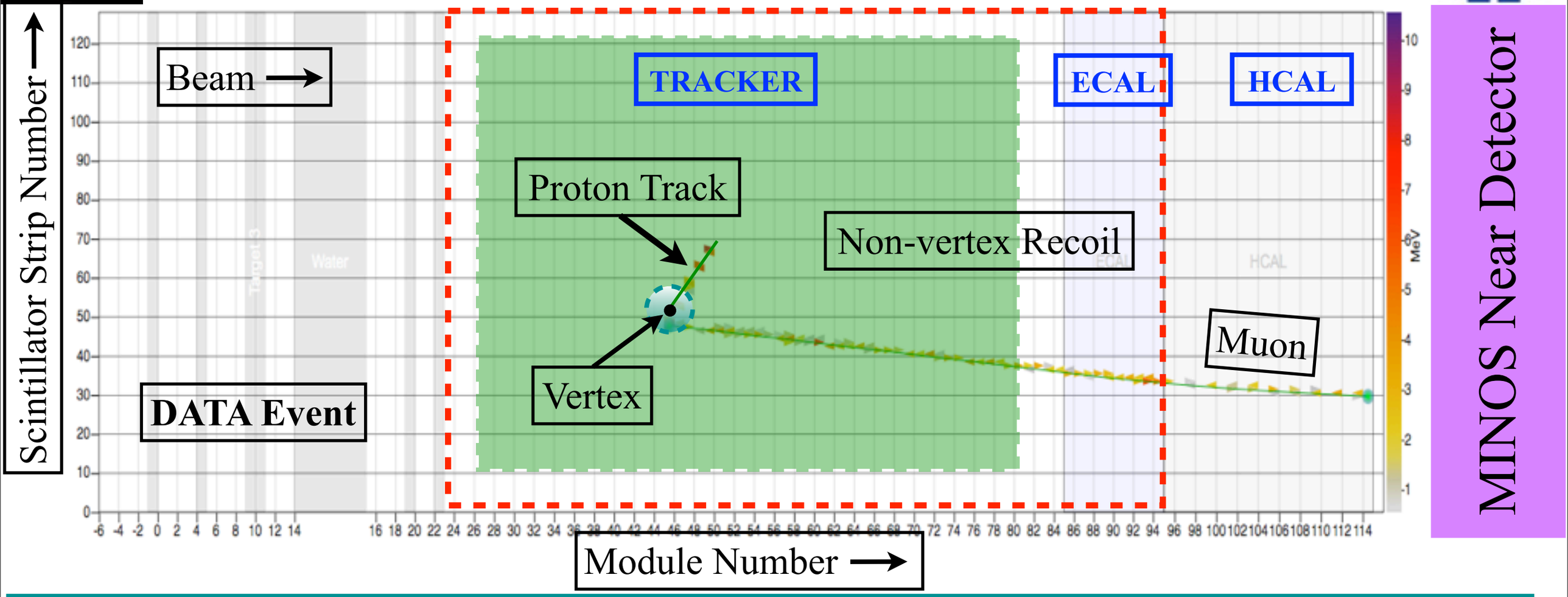
- For quasi-elastic, neutrino energy can be obtained from Final State lepton information.
- For resonance and DIS, neutrino energy is the sum of lepton and recoil energies.

Motivation: Why P_T and P_Z ?

$$\frac{d^2\sigma}{dP_{T_\mu} dP_{Z_\mu}}$$

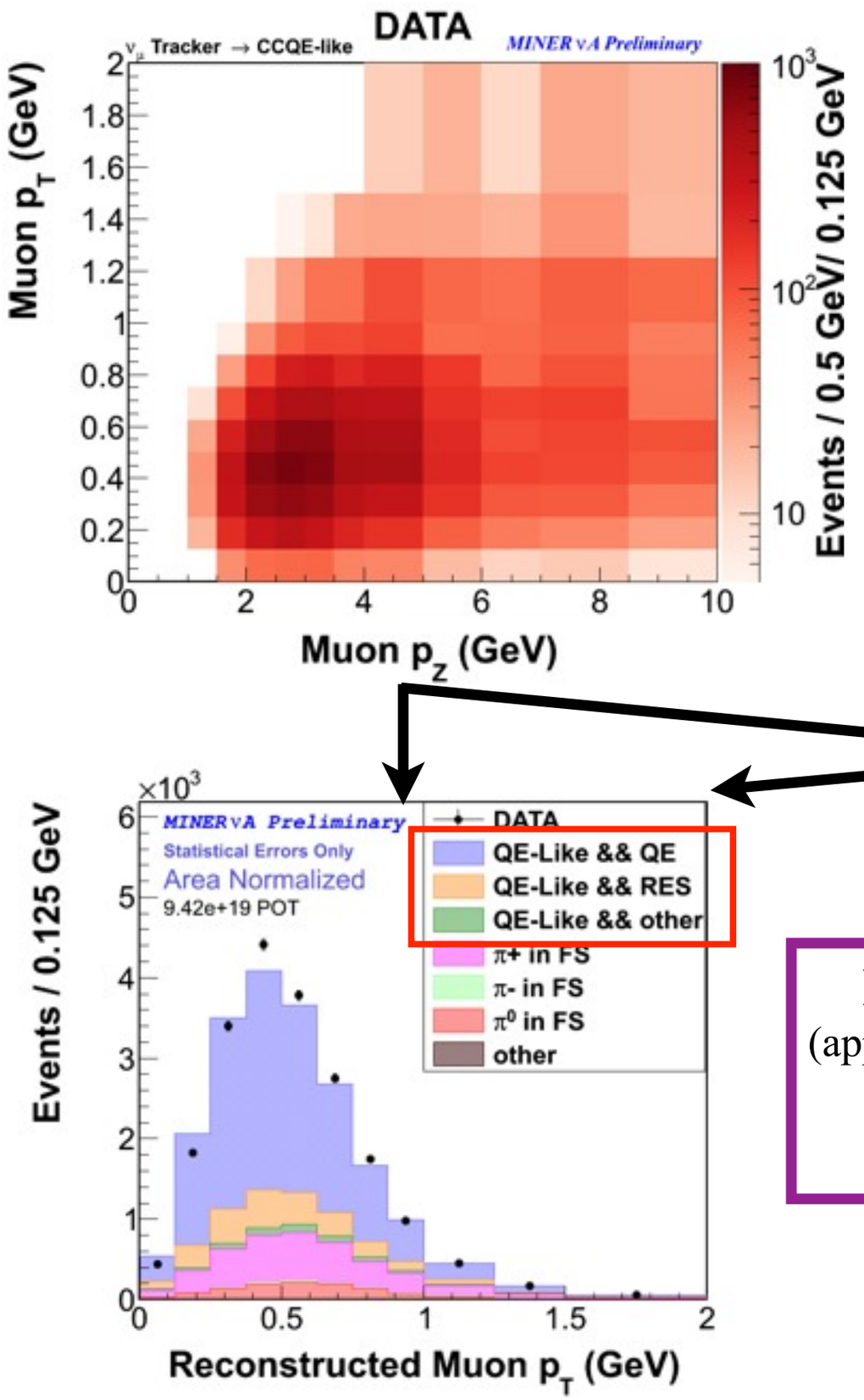
- We would also like to report cross sections in terms of directly measured observables.
  - Q^2 is a derived quantity computed with a model.
- P_T of muon is independent of the boost of the neutrinos.
- P_Z of muon is proportional to the beam energy.
- Double differential cross sections show the correlations between the two different bins of systematic errors.
- Event signature is based on what we measure in our detector.

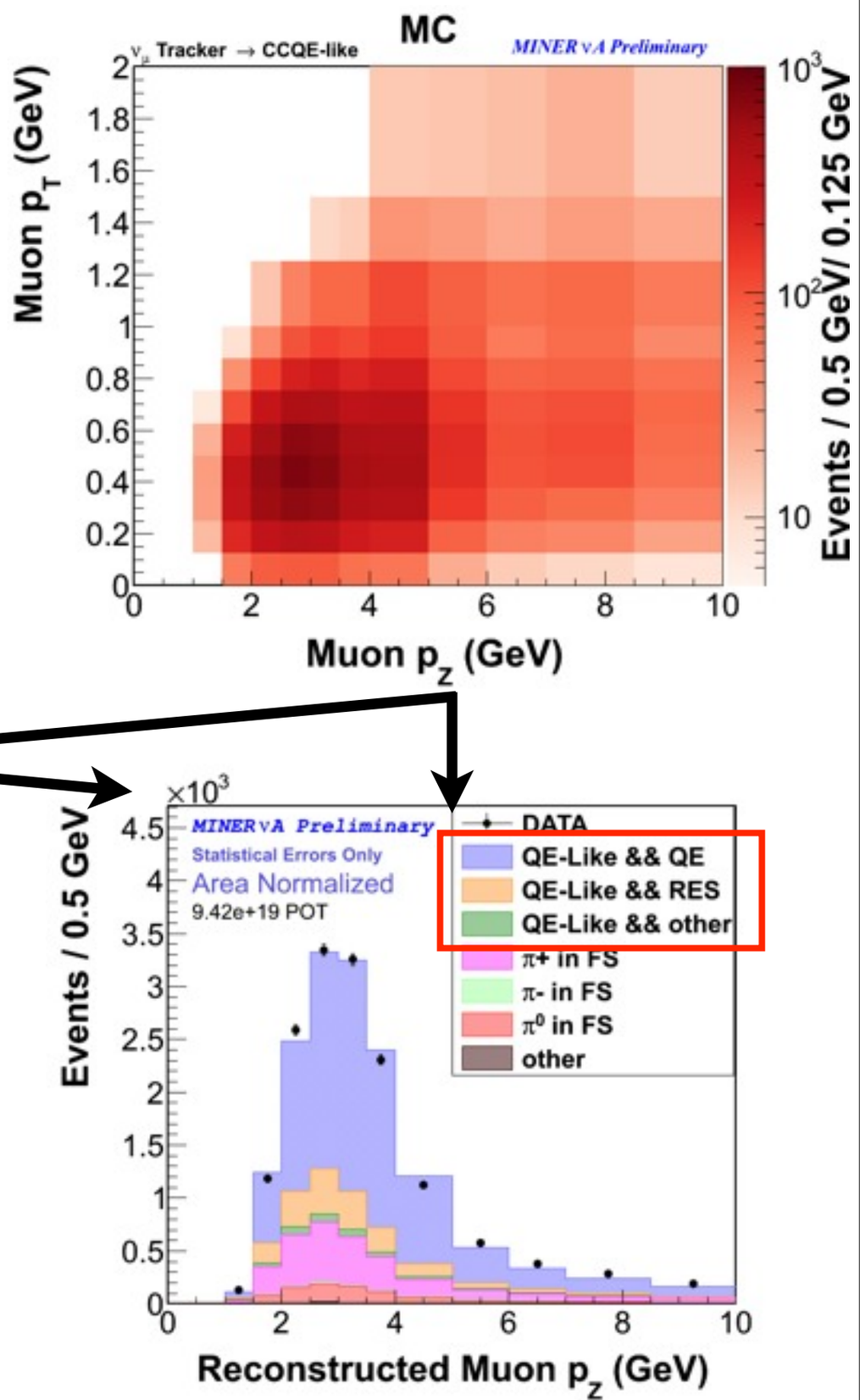
Signal Definition



- Muon track in MINERvA extending into MINOS for obtaining charge and momentum.
- Reconstructed and identified proton using energy loss profile.
- “QE-like”: any number of nucleons, but no pions.
- Minimal recoil (exclude 15 g/cm^2 around vertex) required.

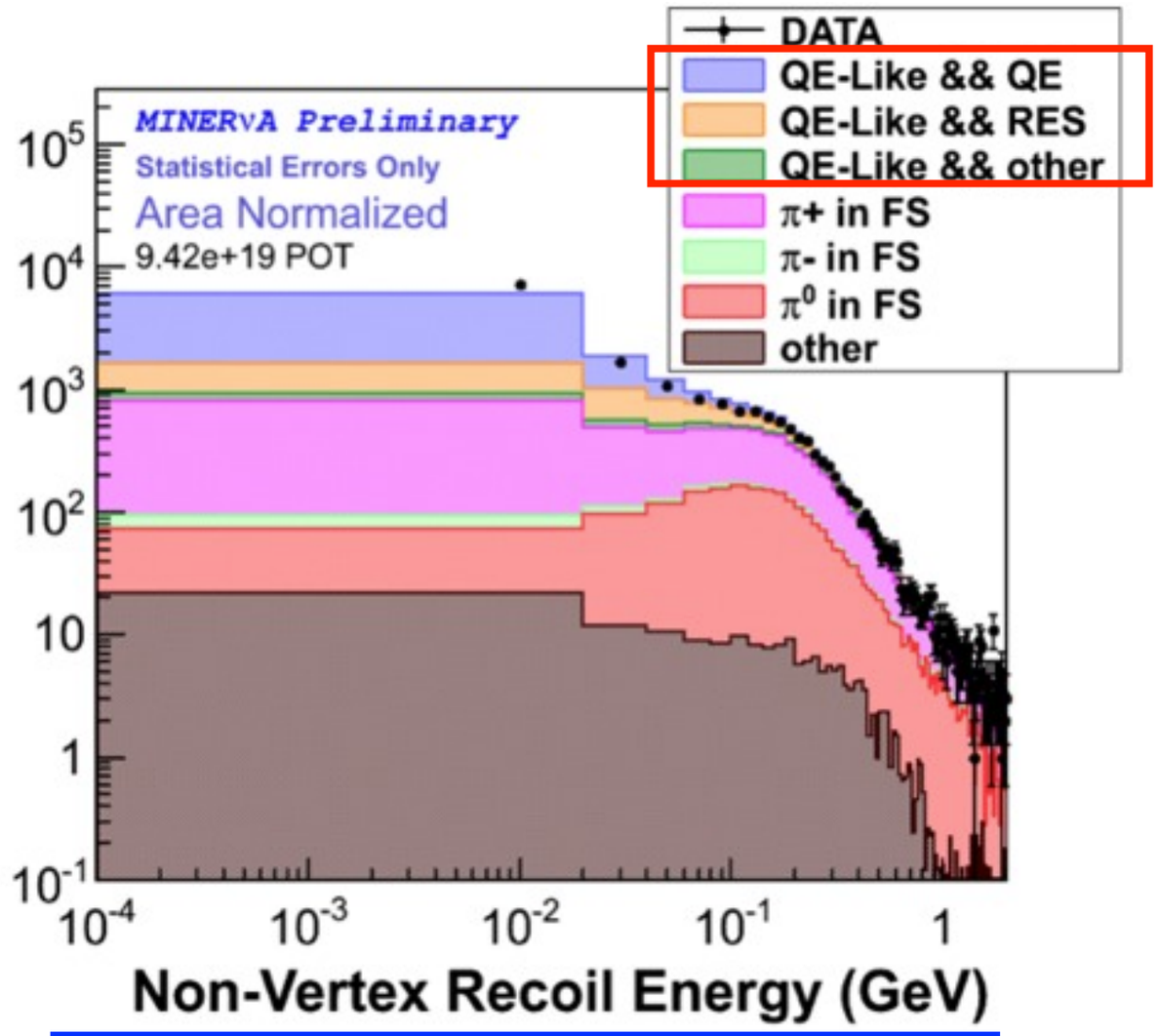
Kinematic Phase Space



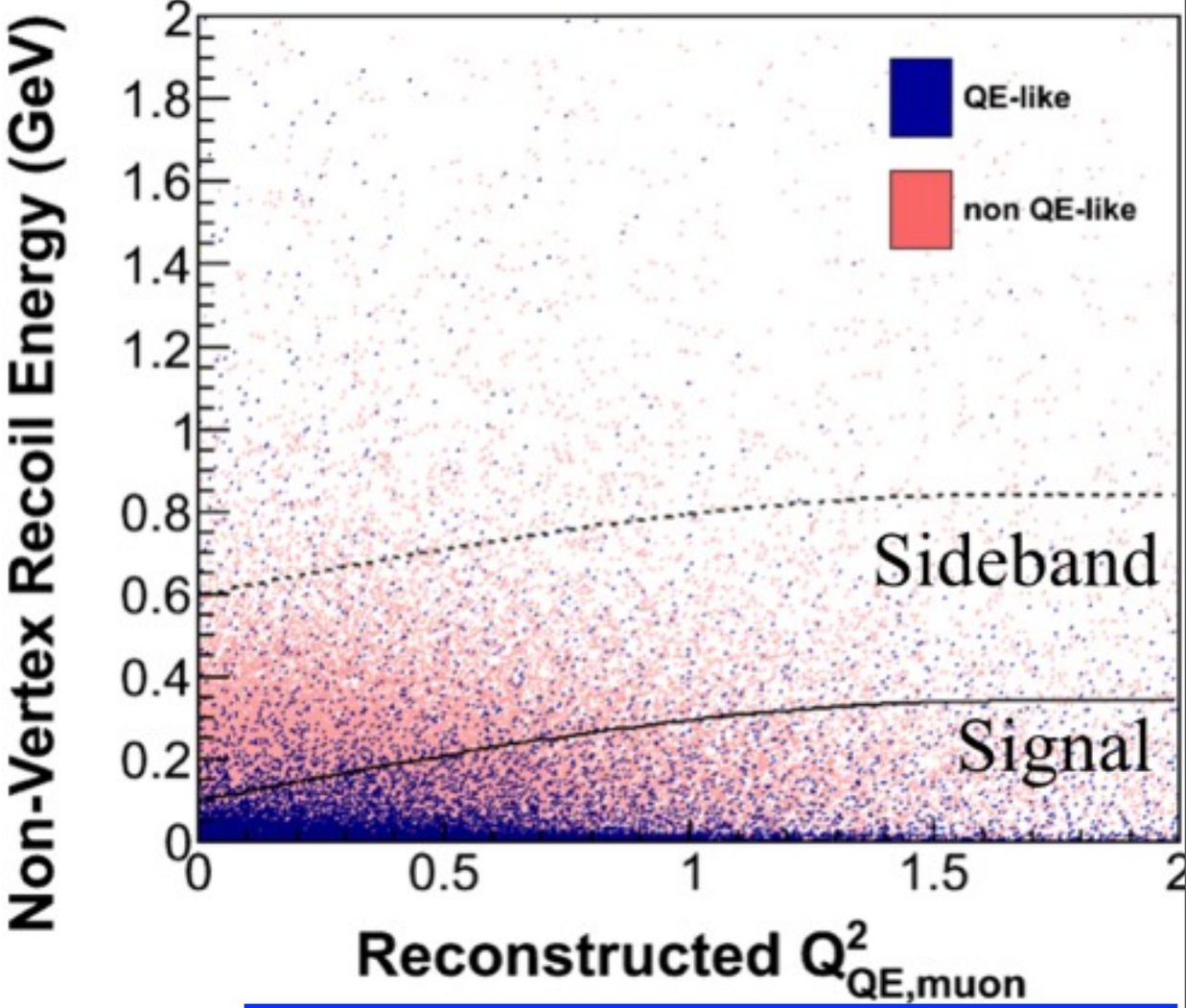


Data: 21K events
(approx. 1/3 of full data set)
Purity: 77%
Efficiency: 40%

Recoil (away from vertex)



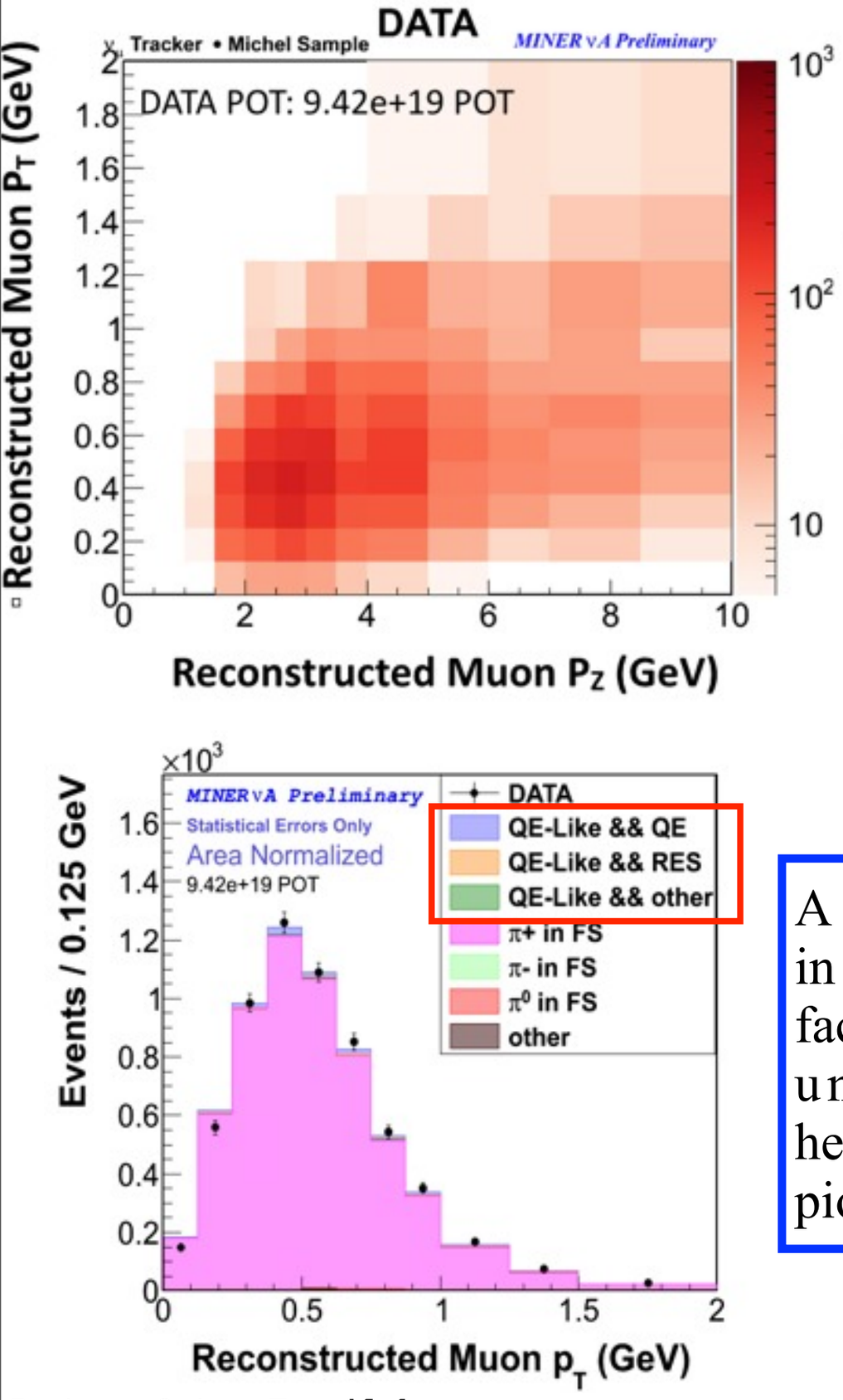
Recoil distribution after requiring no pions and minimal activity in events



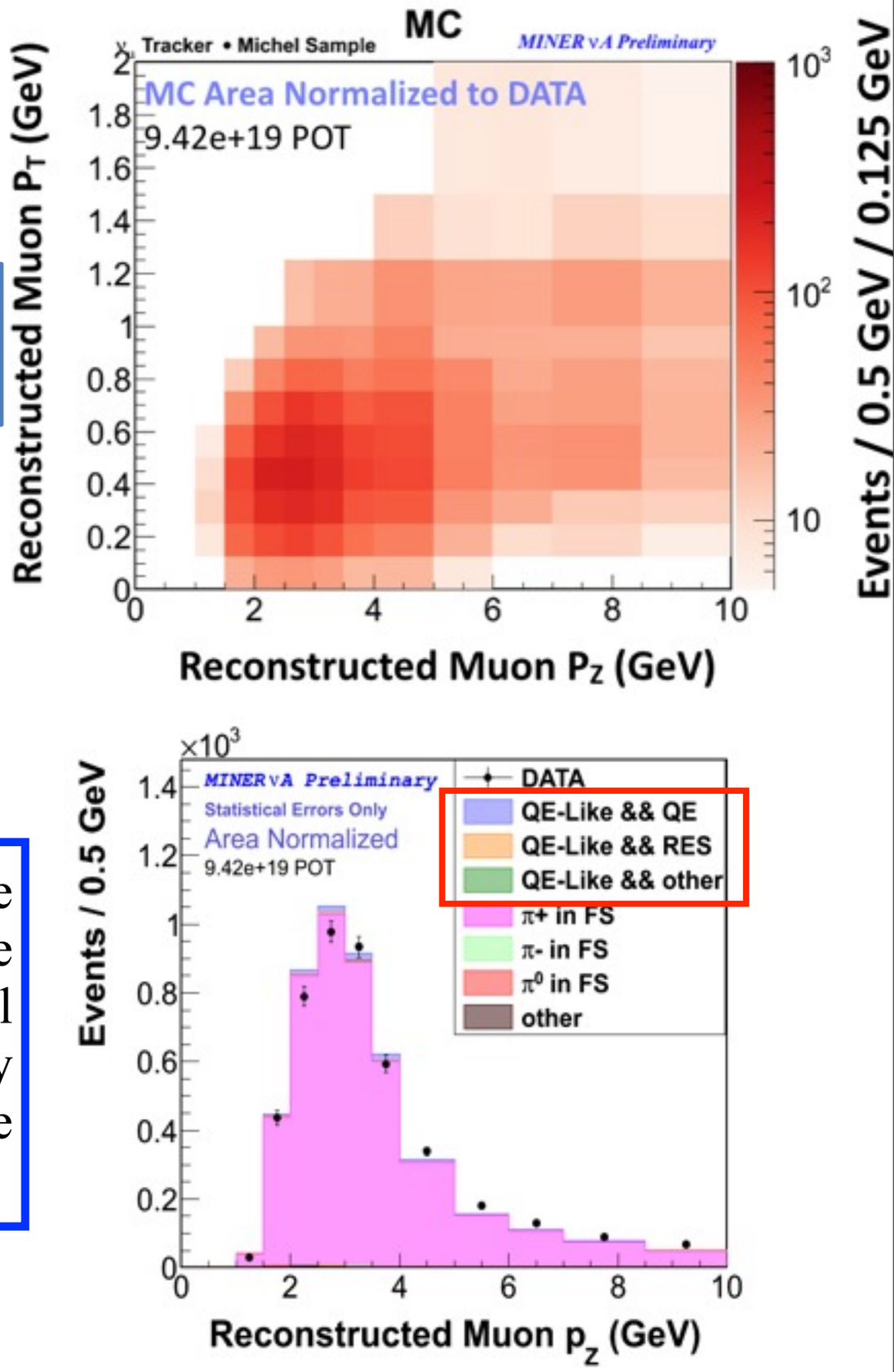
Optimized function for selecting events bearing QE-like topologies

- We use the recoil side band region for constraining the amount of background in our selected sample region.
- Background currently constrained by comparing recoil distributions in MC and Data for different muon P_T bins.

Michel Electron Veto



$\pi^+ \rightarrow \mu^+ \nu_\mu$
$\hookrightarrow e^+ \nu_e \bar{\nu}_\mu$



A pion rich sample in Data helps in the face of large model uncertainties by helping constrain the pion backgrounds.

Summary

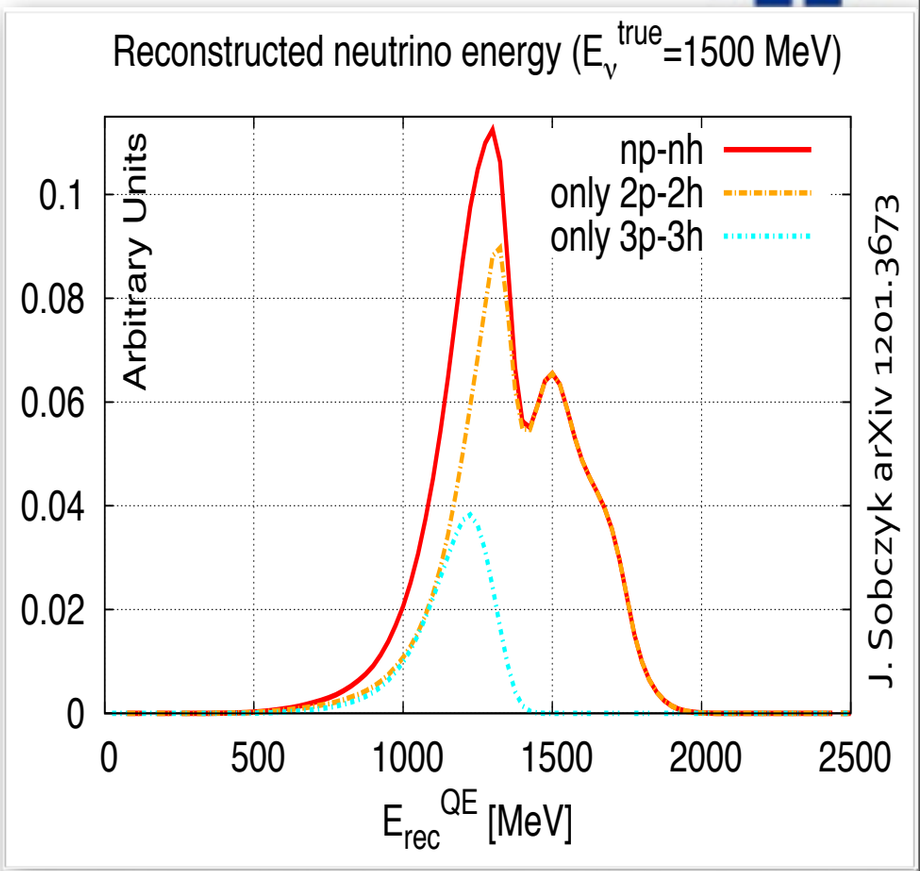
- This ongoing analysis in MINERvA will deliver cross sections in the phase space of the observed longitudinal and transverse muon momenta for neutrino induced quasi elastic processes in the nuclear medium.
- We are working on constraining the background and implementing a complete suite of systematics at present.
- More quasi-elastic analyses are underway with the medium energy data set that MINERvA is recording.
  - Single and double differentials for the scintillator (CH) medium. Measurements across the different nuclear targets (C, Fe, Pb, etc.).
- These analyses are attempting to reconstruct complex topologies from neutrino interactions. Thus they are exercising and advancing the full suite of reconstruction and particle identification tools in MINERvA.
- Please stay tuned to http://minerva.fnal.gov for resulting publications in the near future !

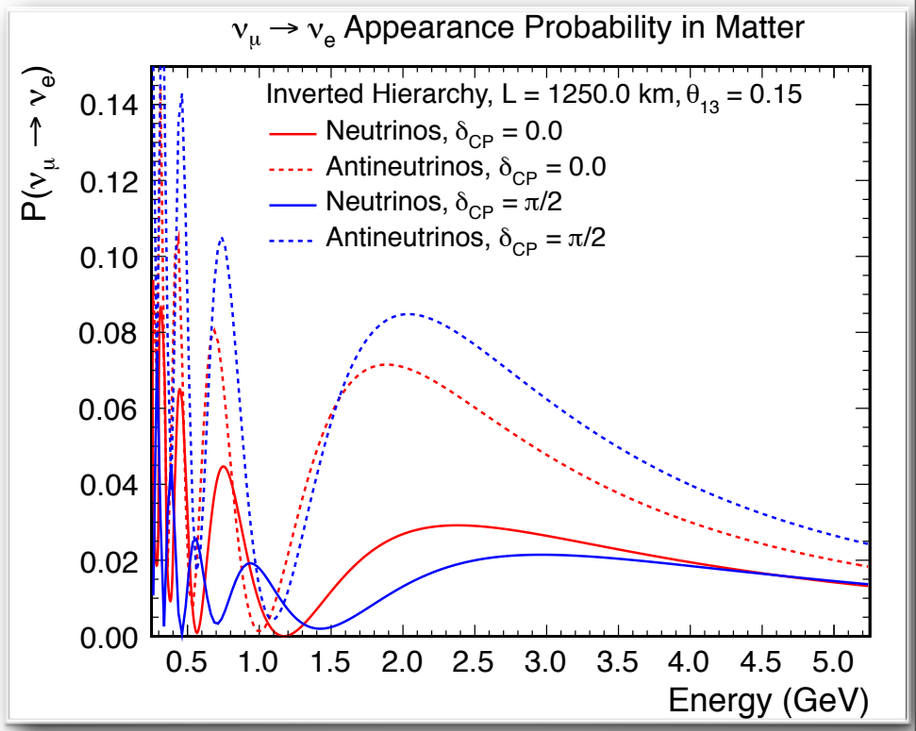
BACKUP SLIDES

Neutrino Oscillations

Precision neutrino oscillation parameters :

- Cross-sections are an important systematic, precision measurements of them help nail precise oscillation parameters.
  - Oscillation measurements use dense nuclear targets for statistics. Understanding neutrino-induced interactions in nuclear media is crucial.
  - Quasi-elastic interactions provide inputs for neutrino oscillation measurements (neutrino energy & interaction probability).
    - Relationships between observables (E_{lepton}, Θ_{lepton}) and output are modified by nucleus. Dynamics are not clear !
- Searches for CP violation will involve ~% level measurements of oscillation probabilities, both for neutrinos and anti-neutrinos (Schwetz et. al. JHEP 0803 (2008) 021).
  - Relative cross-section error can affect the CP sensitivity.





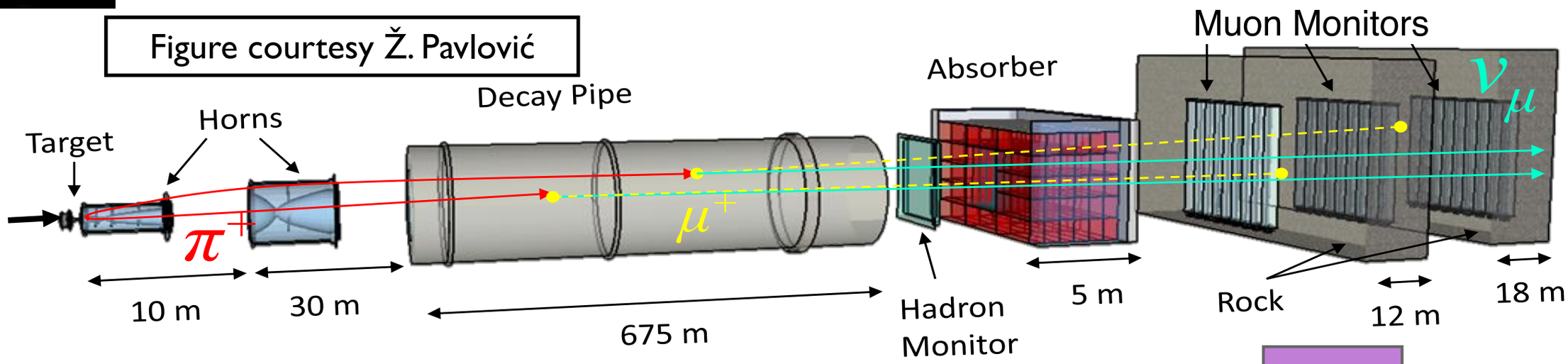
Probe the Nuclear Medium

Extracting nuclear effects from neutrino interactions :

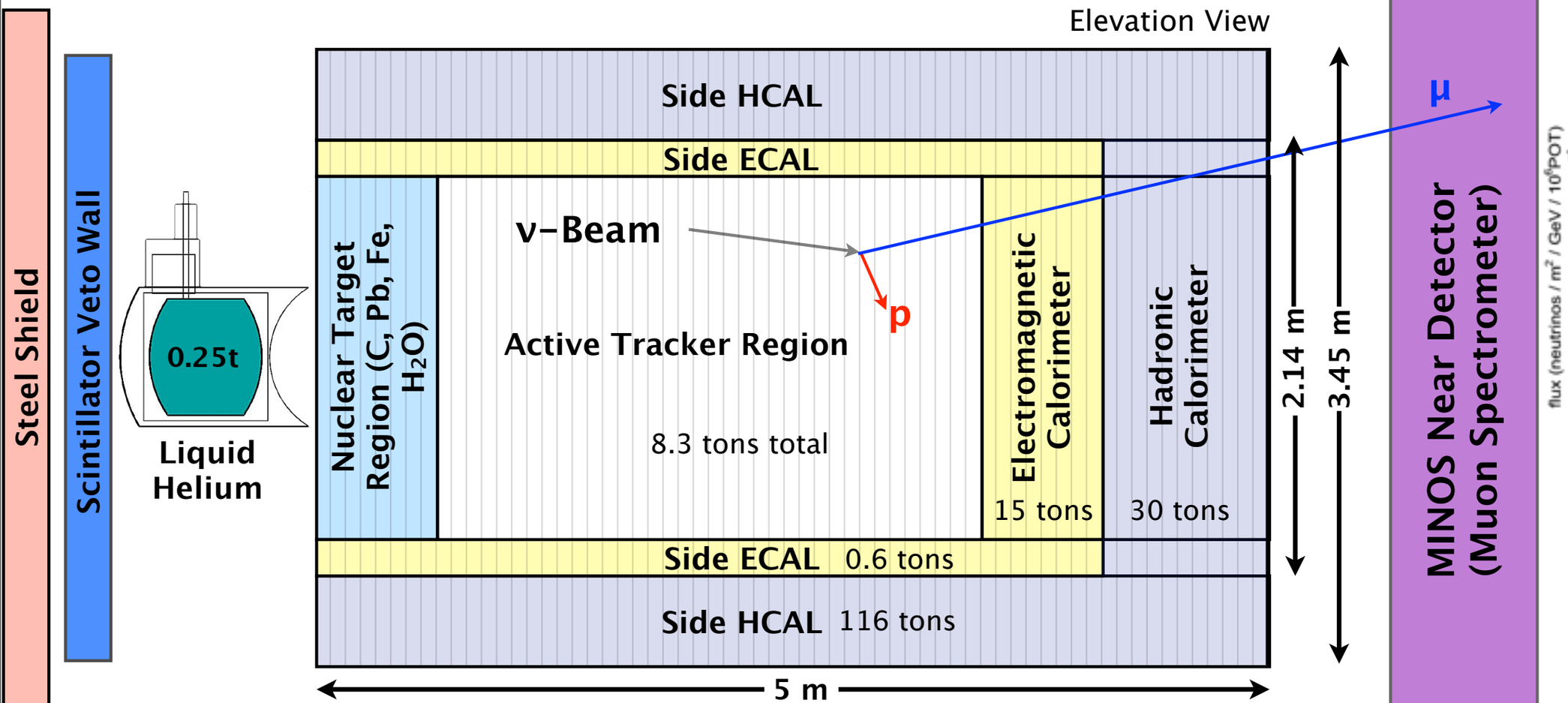
- Neutrinos are a Weak, hence unique probe of the nuclear structure.
  - They help compare and contrast to electron scattering results.
  - Axial form factors in structure functions determined via neutrino scattering.
  - The ability of neutrinos and anti-neutrinos to taste different flavors of quarks can help isolate PDFs and structure functions.
  - EMC (nuclear modifications) effects have been studied in detail in electron scattering experiments.
    - use neutrinos as a complimentary probe for these.
  - With theoretical input we may disentangle a challenging mix of multiple nuclear effects e.g. np-nh and Final State Interactions (FSI).

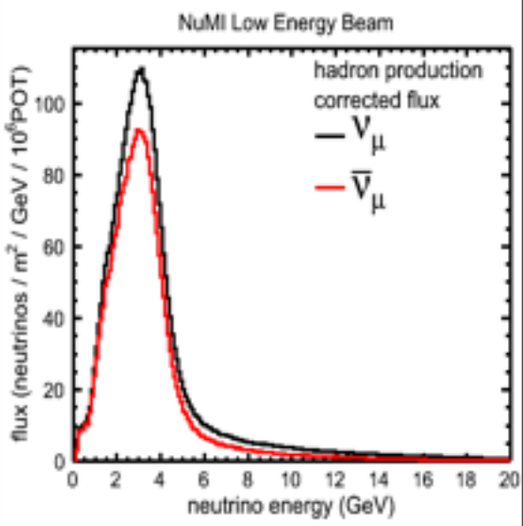
NuMI & MINERvA

Figure courtesy Ž. Pavlović



MINERvA

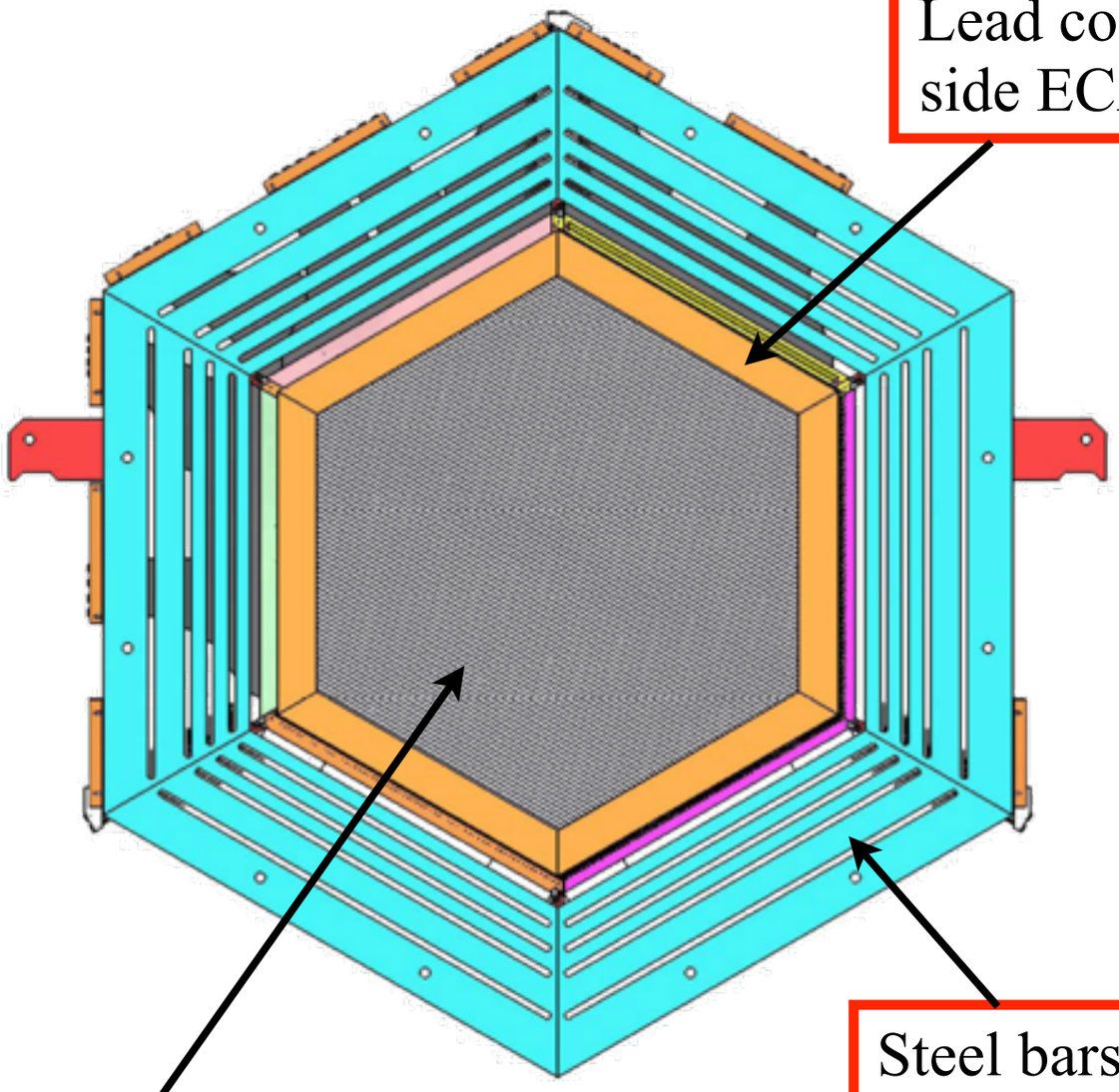




Design, Calibration and Performance of the MINERvA Detector
Nucl. Inst. and Meth. A743 (2014) 130

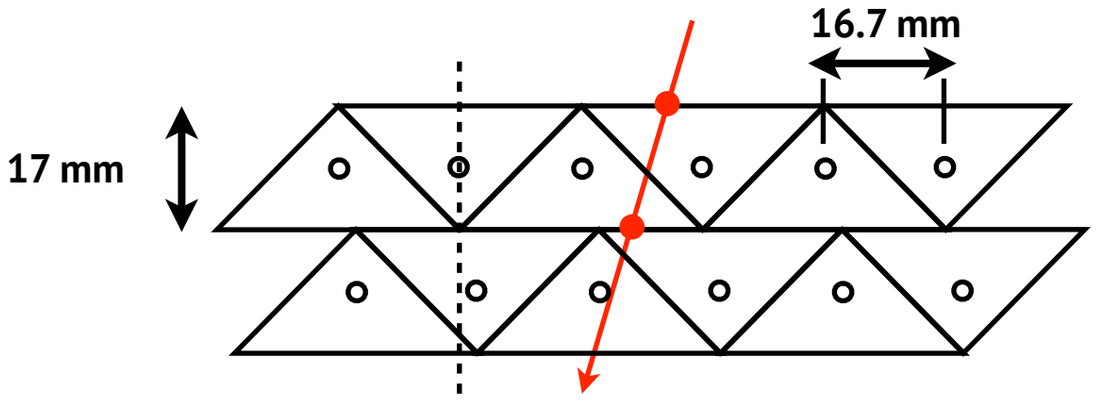
MINERvA Detector

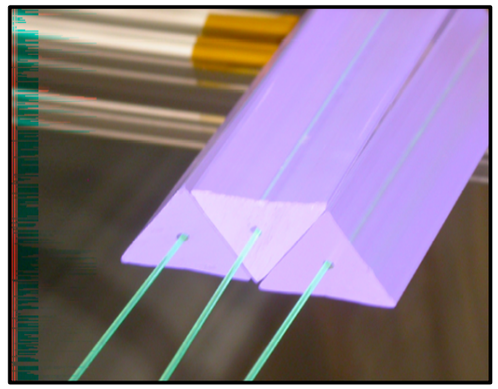
Front view of a tracker module

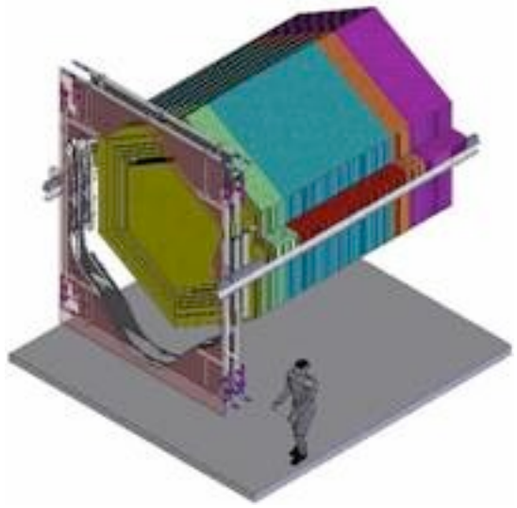


Front face of MINERvA before installation of cryo target

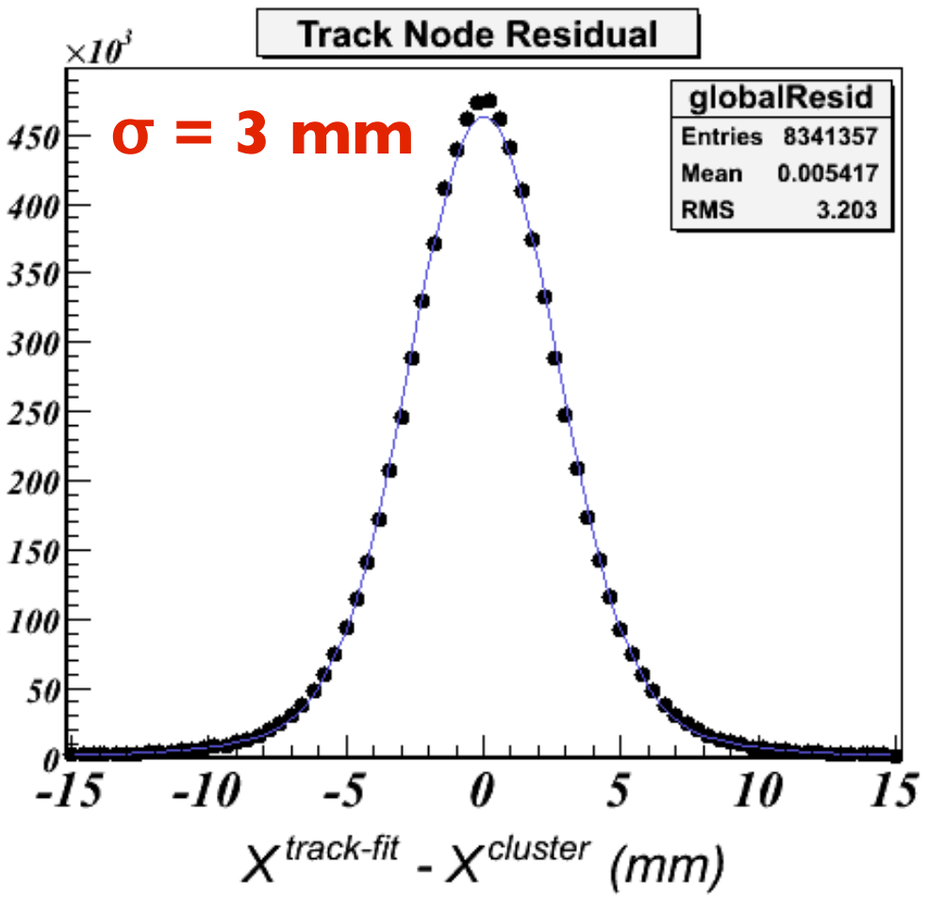
Detector Components

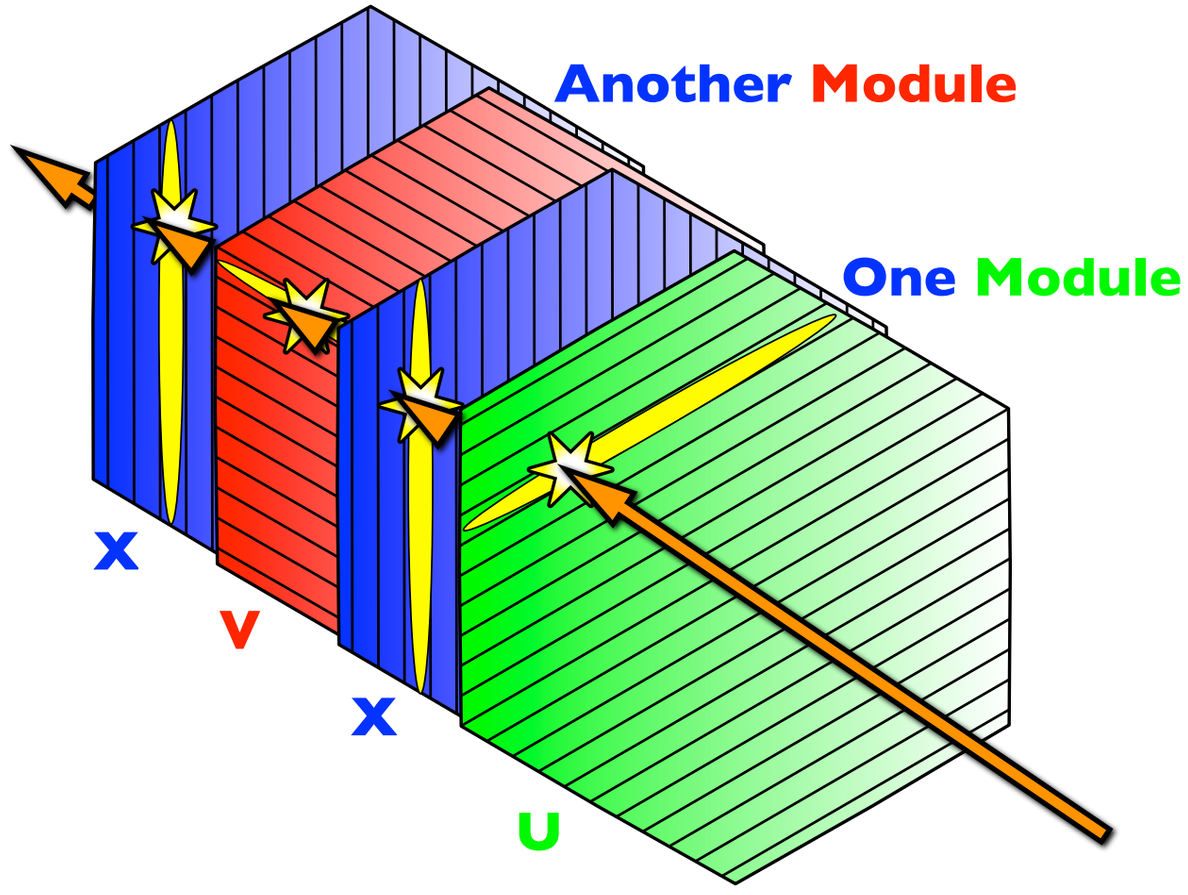






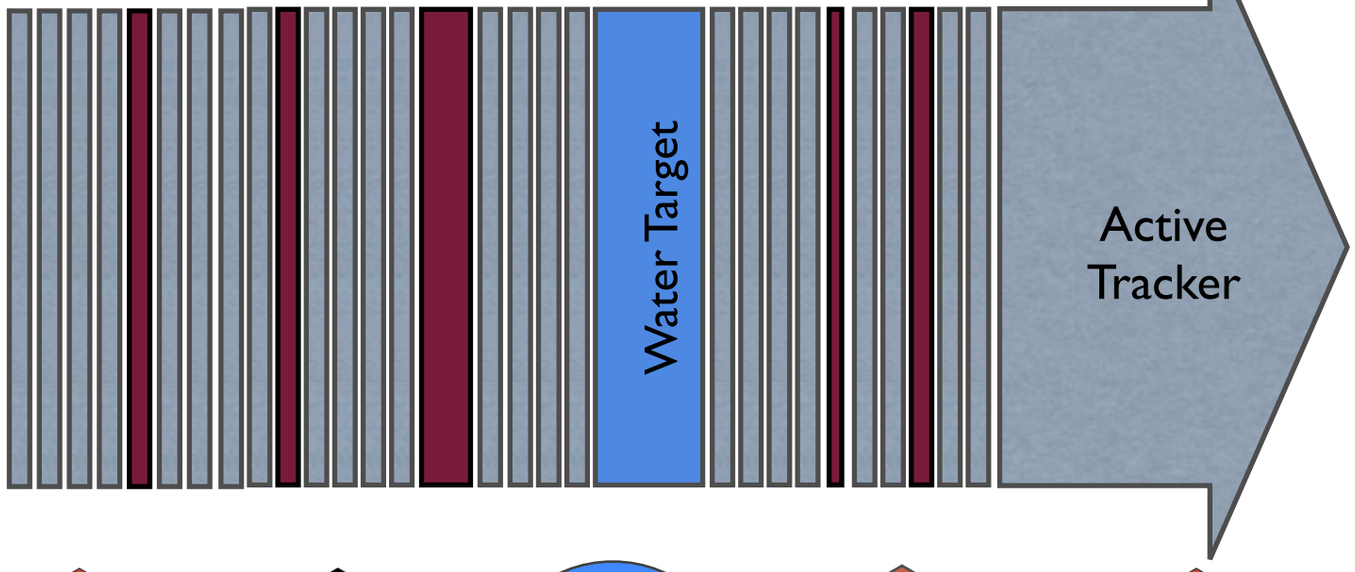
Triangular strips allow for charge sharing for improved position resolution (~3 mm) and alignment

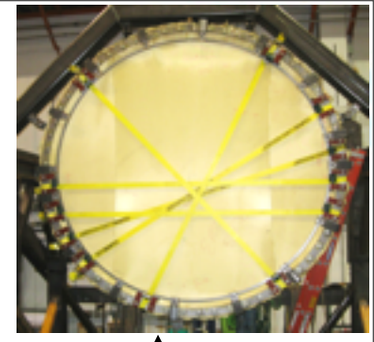




Stereoscopic combination for 3D reconstruction

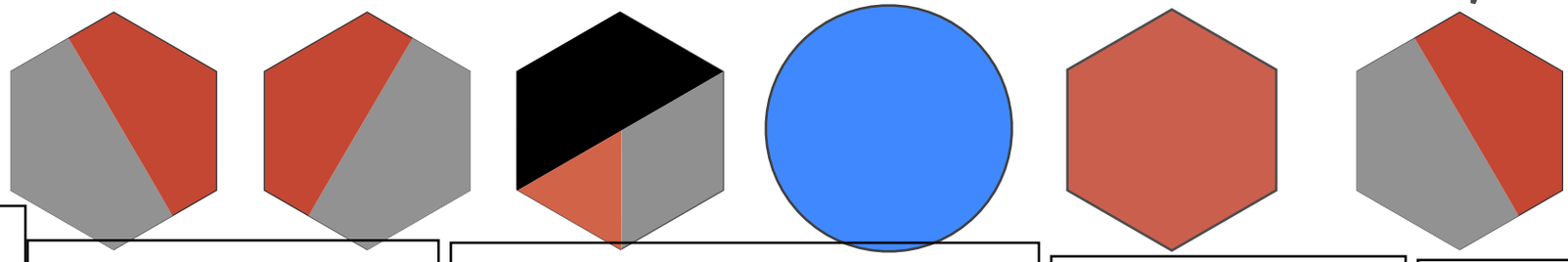
Nuclear Targets





Helium Target
Fiducial Mass :
250 kg

WATER TARGET
Fiducial Mass :
625 kg H_20



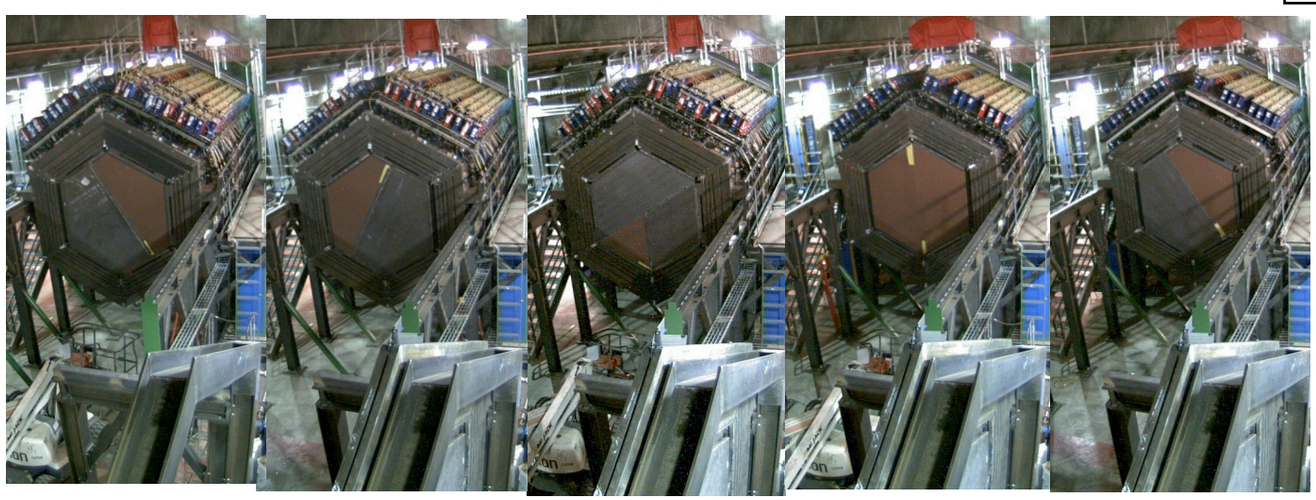
NUC. TARGET 1
Fiducial Mass :
Fe: 323 kg/
Pb: 264 kg
Iron/Lead

NUC. TARGET 2
Fiducial Mass :
Fe: 323 kg/
Pb: 266 kg
Lead/Iron

NUC. TARGET 3
Fiducial Mass :
C: 166 kg
Fe: 169 kg/Pb: 121 kg
Lead/Iron
Graphite

NUC. TARGET 4
Fiducial Mass :
Pb: 228 kg
Lead

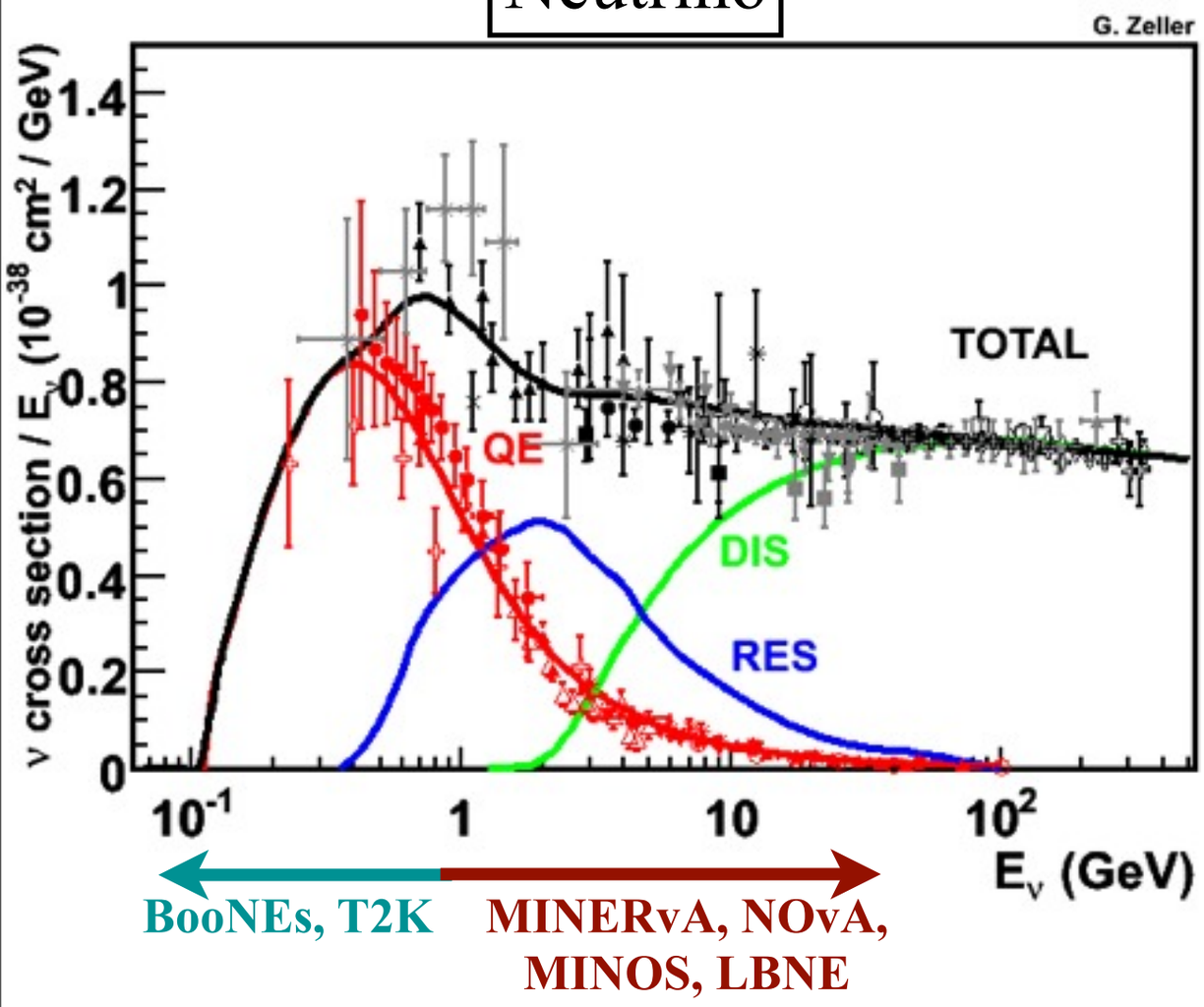
NUC. TARGET 5
Fiducial Mass :
Fe: 161 kg/
Pb: 135 kg
Iron/Lead



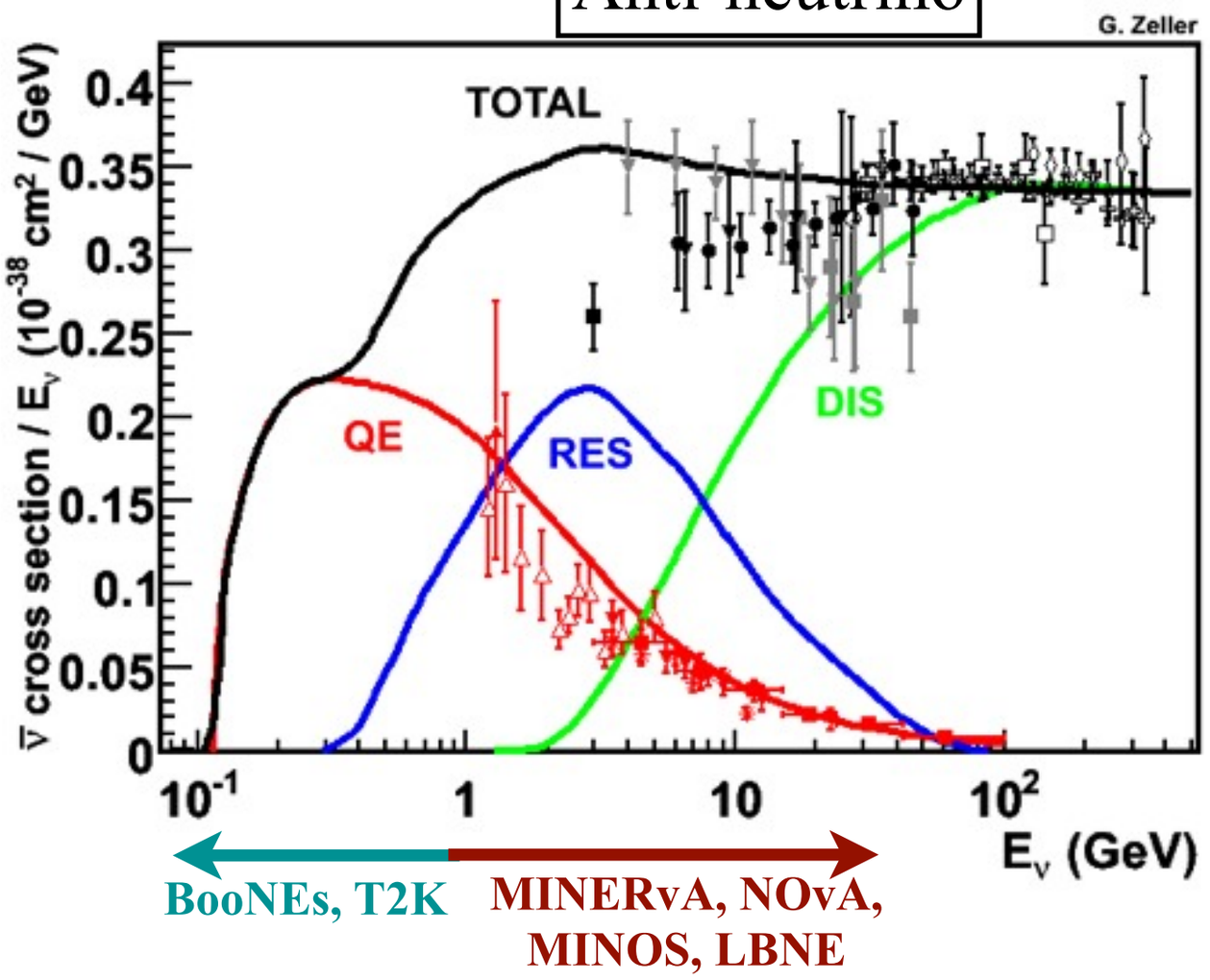
3/15 3/10 3/08 2/19 2/16

Neutrino Cross sections

Neutrino



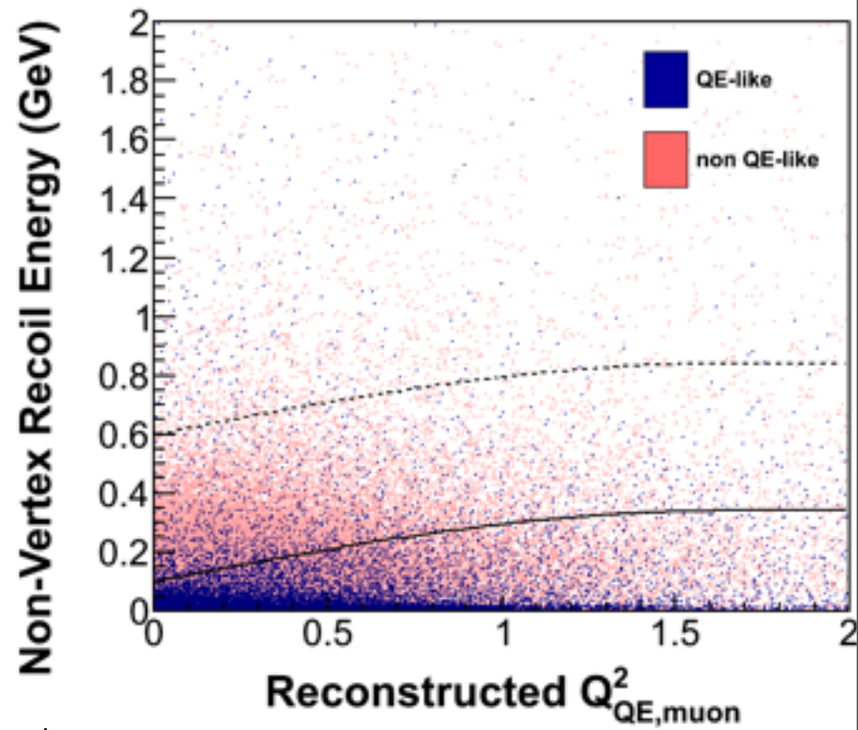
Anti-neutrino



- Need for more data especially in 0.1-10 GeV energy range, both for neutrinos and anti-neutrinos.
- The distinctions between channels are with respect to final state multiplicity, pion production and event kinematics.

Signal Selection

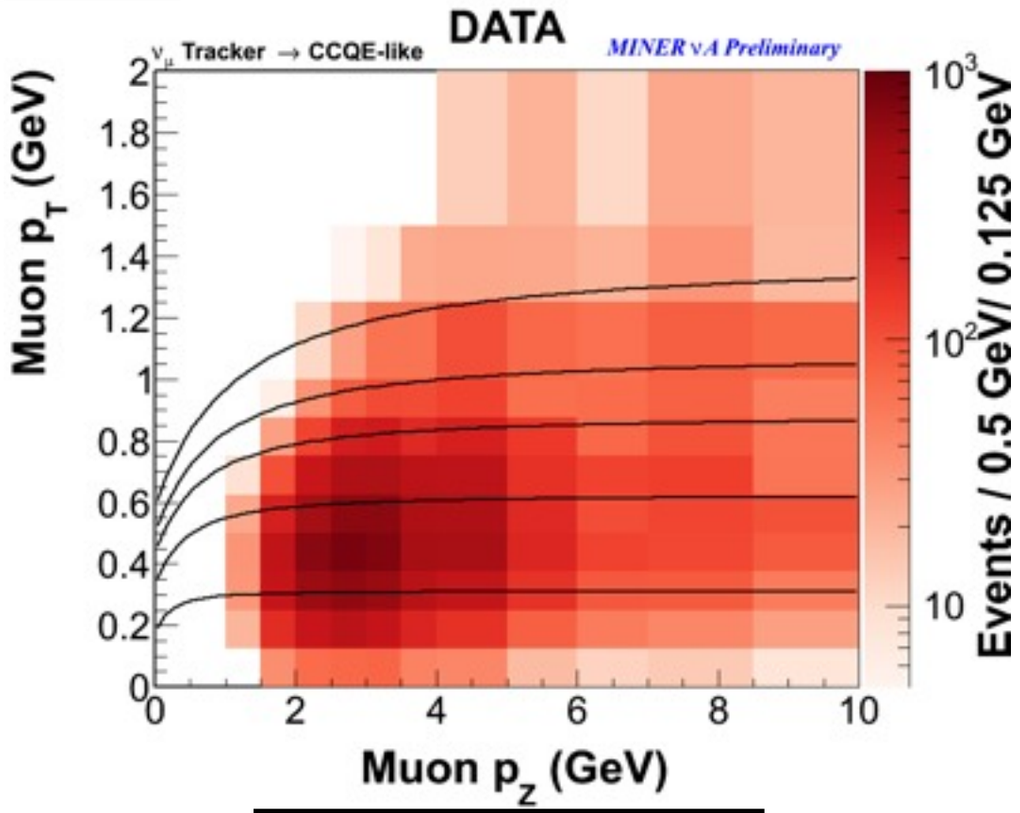
- Charged current ν_μ (ν_μ bar) event:
  - A muon track in MINERvA matched into MINOS ND.
  - Momentum and charge-analyzed.
  - Interaction vertex in fiducial volume of tracking region.
- Track and identify the proton using dE/dx information.
- Look for Michel electrons at vertices to identify and remove events with pions.
- Avoid events with large recoil:
  - Minimal number of shower-like activity regions present (≤ 1).
  - Neutrino energy ≤ 10 GeV.
- Select events bearing quasi-elastic like topologies using a recoil energy vs. Q^2 cut:
  - Q^2 is the four momentum transfer of the event.
  - Recoil present away from a 15 g/cm^2 vertex region (Tracker + ECAL).
    - Shower-like clusters present near the vertex are part of vertex activity.



Quasi-elastic like Signature

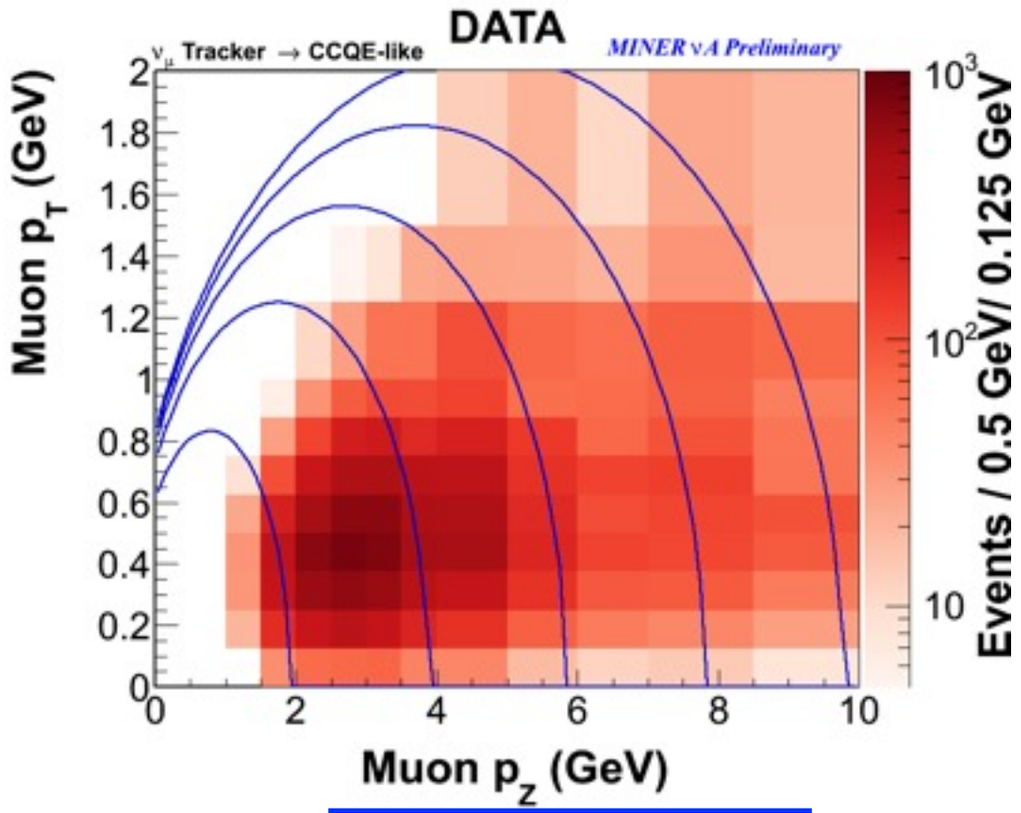
- Charged current quasi-elastic topology to reduce model dependency:
  - Events with one muon and any number of nucleons in the final state are allowed.
    - No final state mesons allowed.
    - No final state photons, heavy baryons allowed.
- Events with pions that were absorbed in the nucleus might be present.

E_ν & Q^2 in the Phase Space



Constant Q^2_{QE} Lines

(a) Q^2_{QE} = 0.1 GeV^2
(b) Q^2_{QE} = 0.4 GeV^2
(c) Q^2_{QE} = 0.8 GeV^2
(d) Q^2_{QE} = 1.2 GeV^2
(e) Q^2_{QE} = 2.0 GeV^2

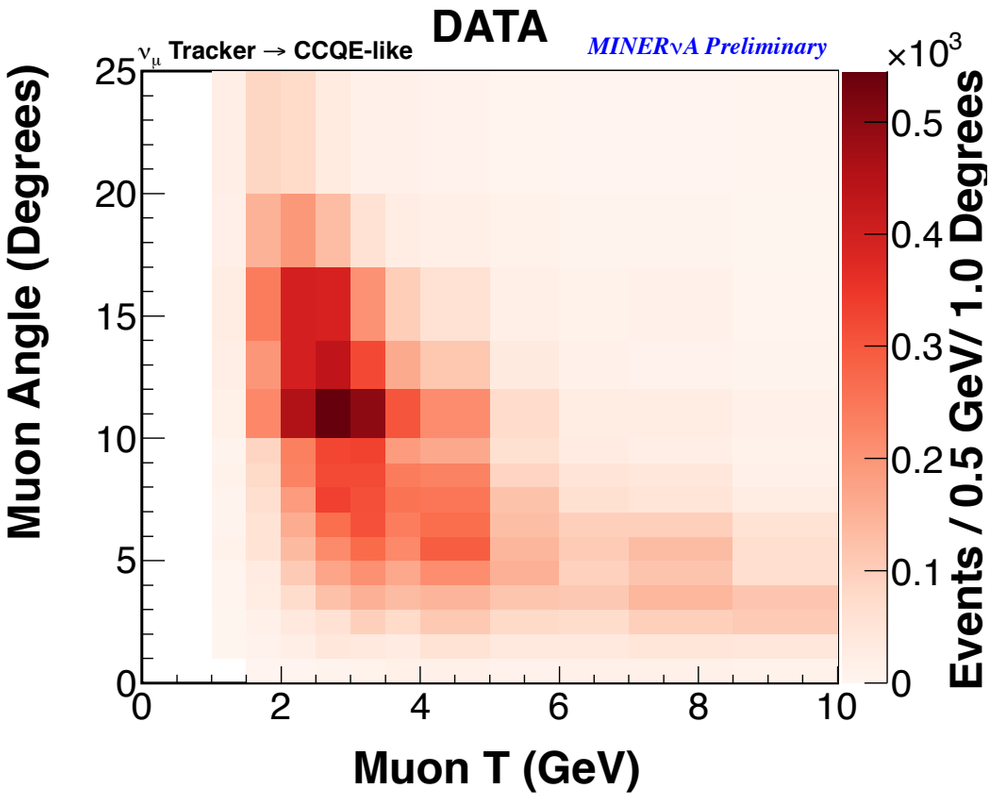


Constant $E_{\nu,QE}$ Lines

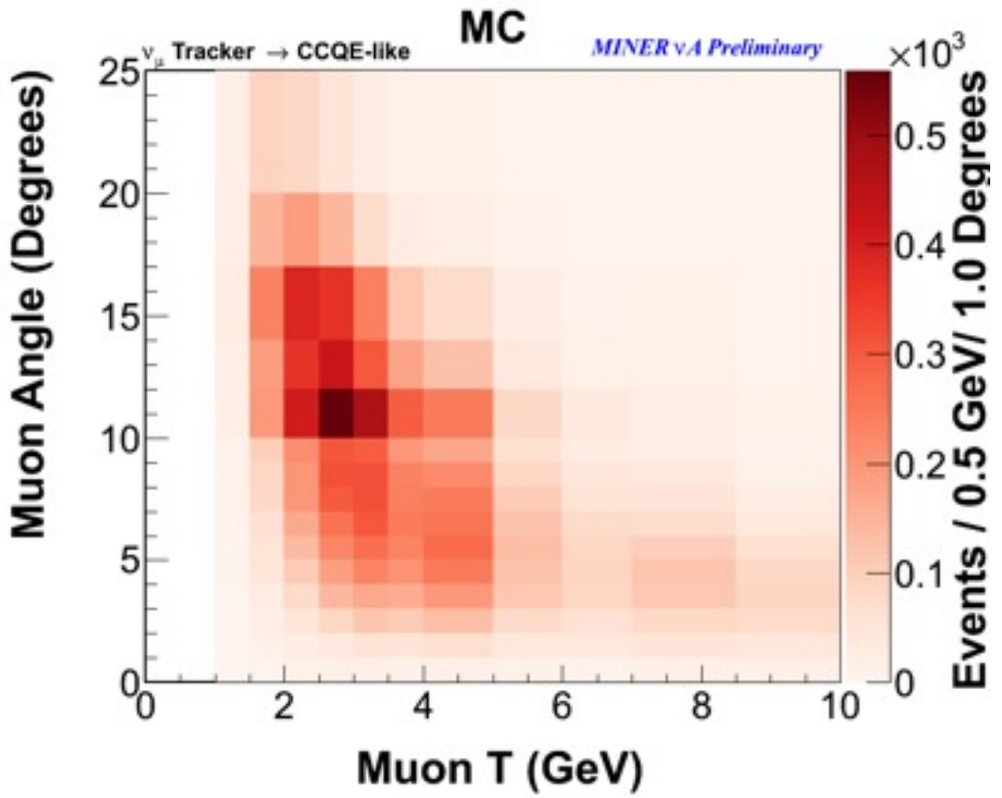
(a) $E_{\nu,QE}$ = 2 GeV
(b) $E_{\nu,QE}$ = 4 GeV
(c) $E_{\nu,QE}$ = 6 GeV
(d) $E_{\nu,QE}$ = 8 GeV
(e) $E_{\nu,QE}$ = 10 GeV

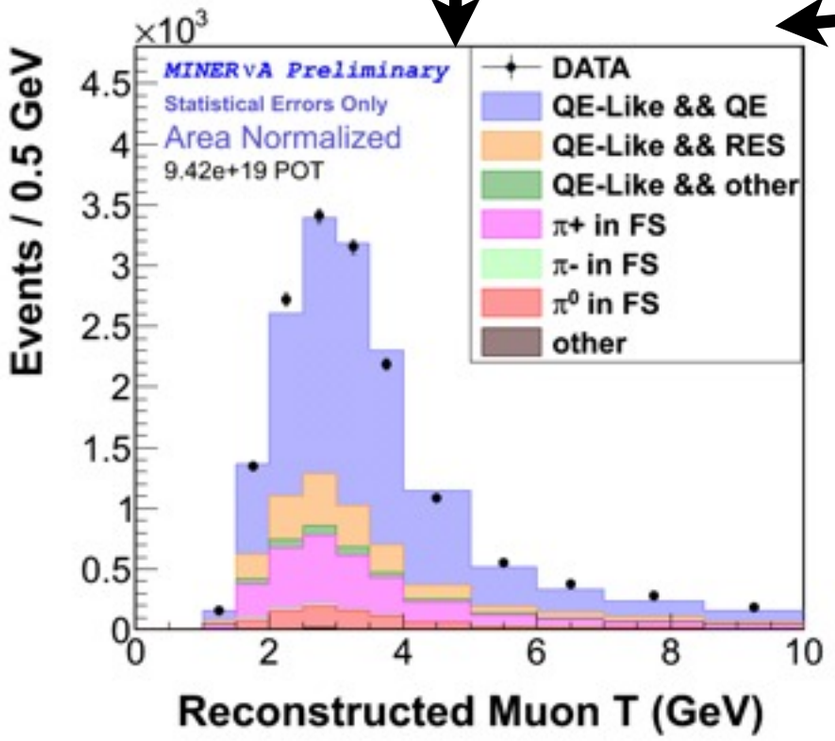
- Q^2 lines are fairly horizontal, except at low muon pZ.
- E_ν lines are fairly vertical for low muon pT, curve for higher pT values.

Muon Kinetic Energy and Angle

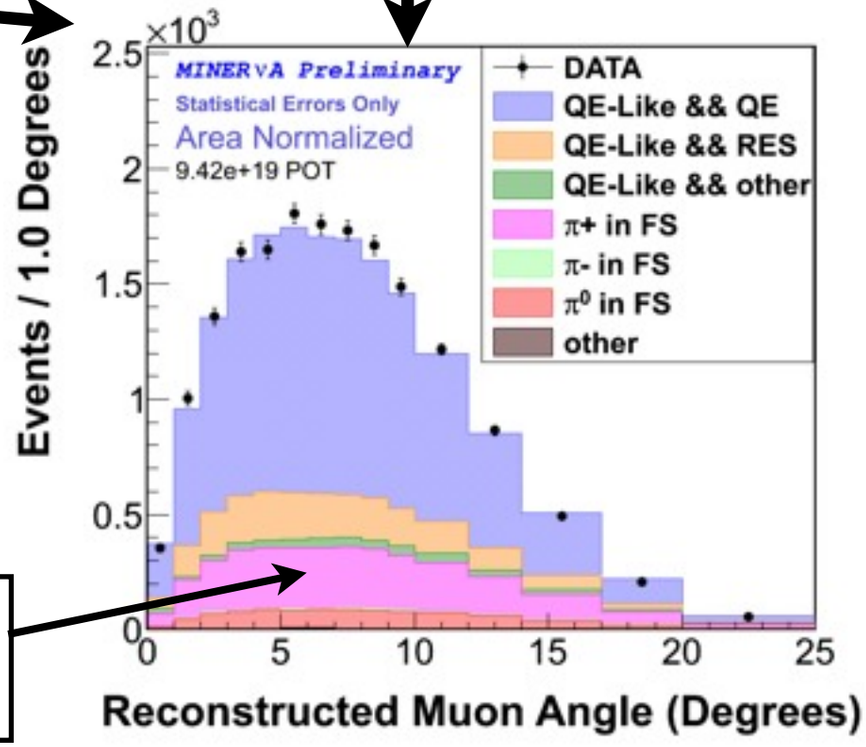


Data: 21,055 events
Purity: 77%
Efficiency: 40%

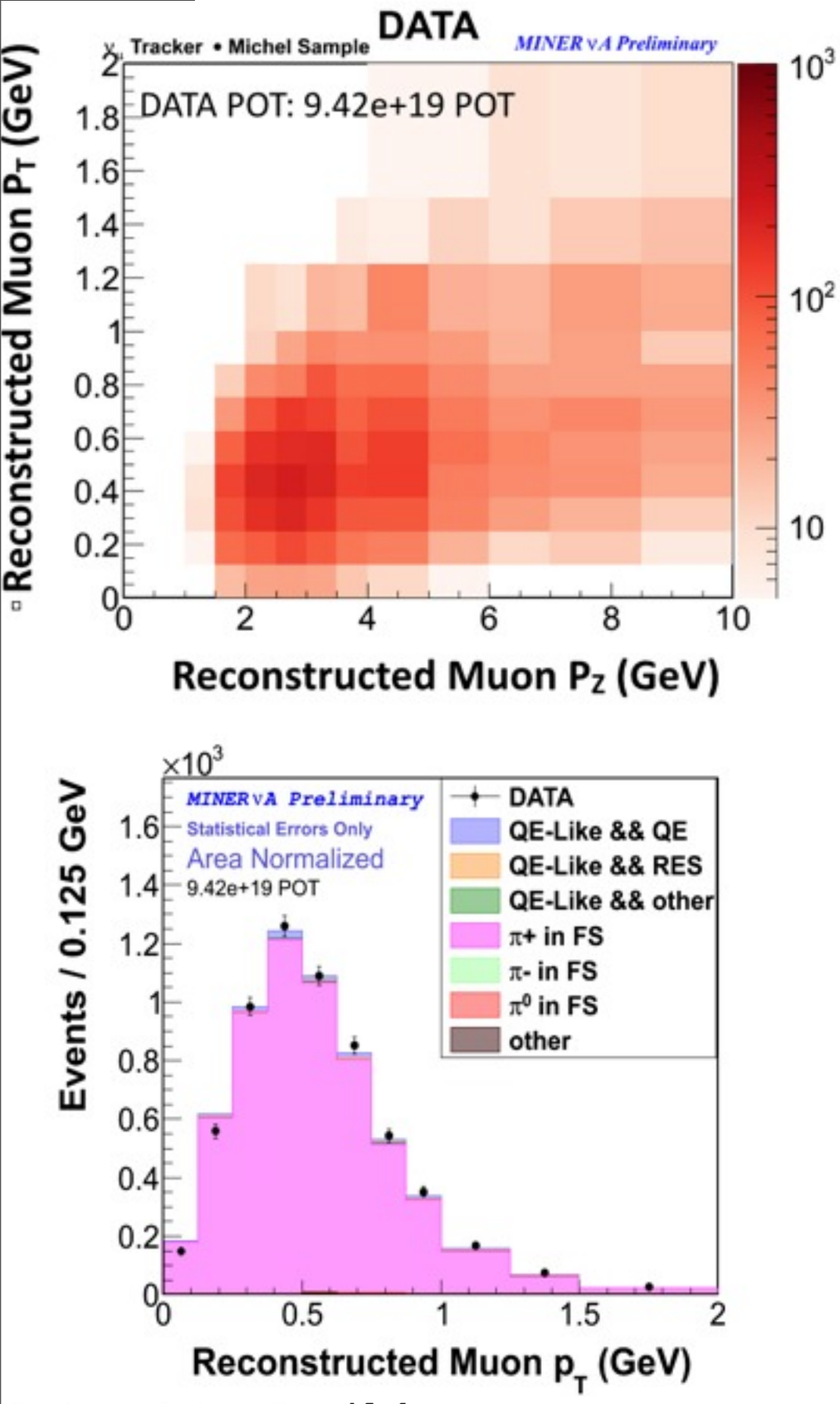




Events with π^+ in the final state are the largest background

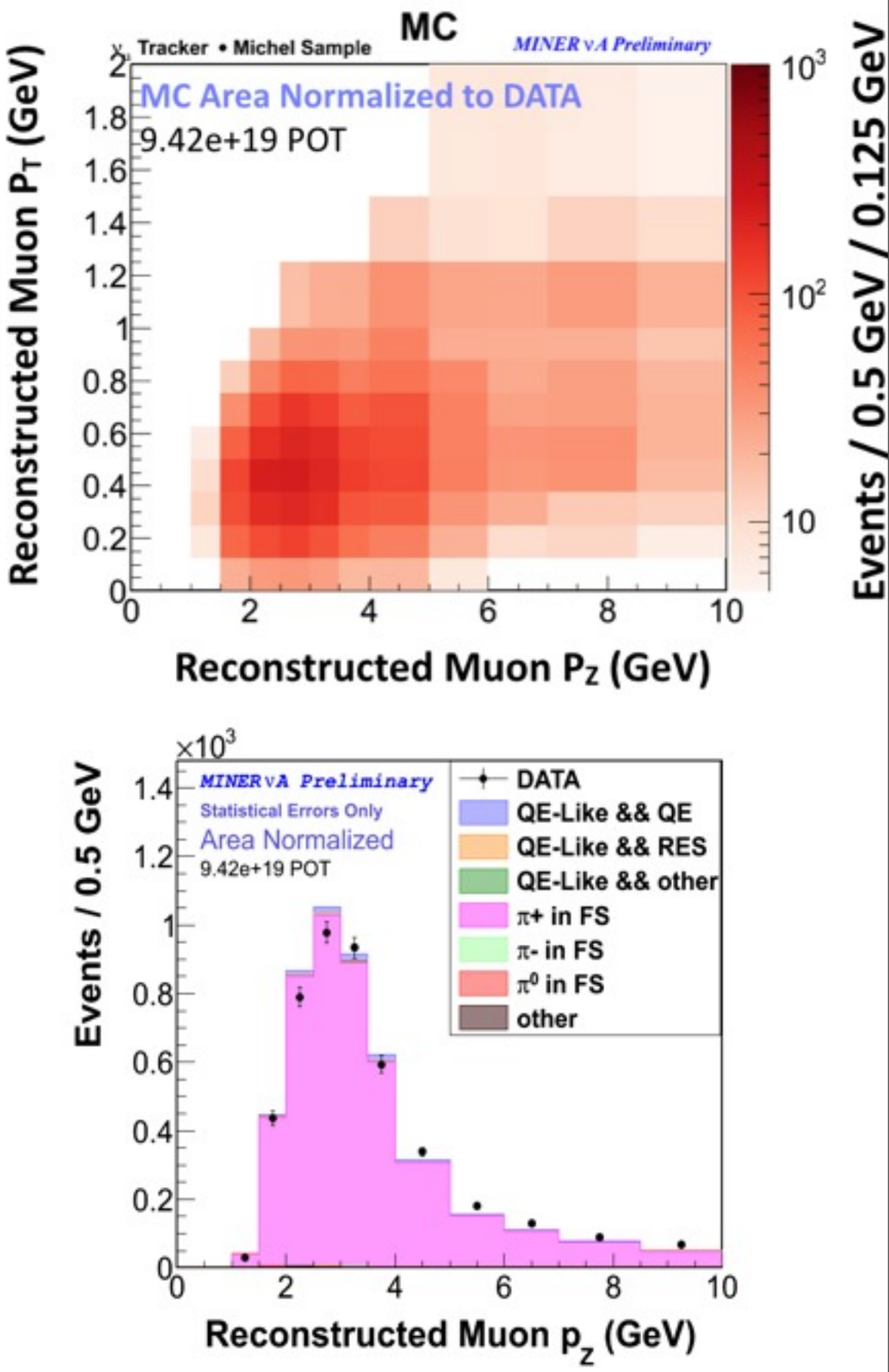


Michel Electron Background

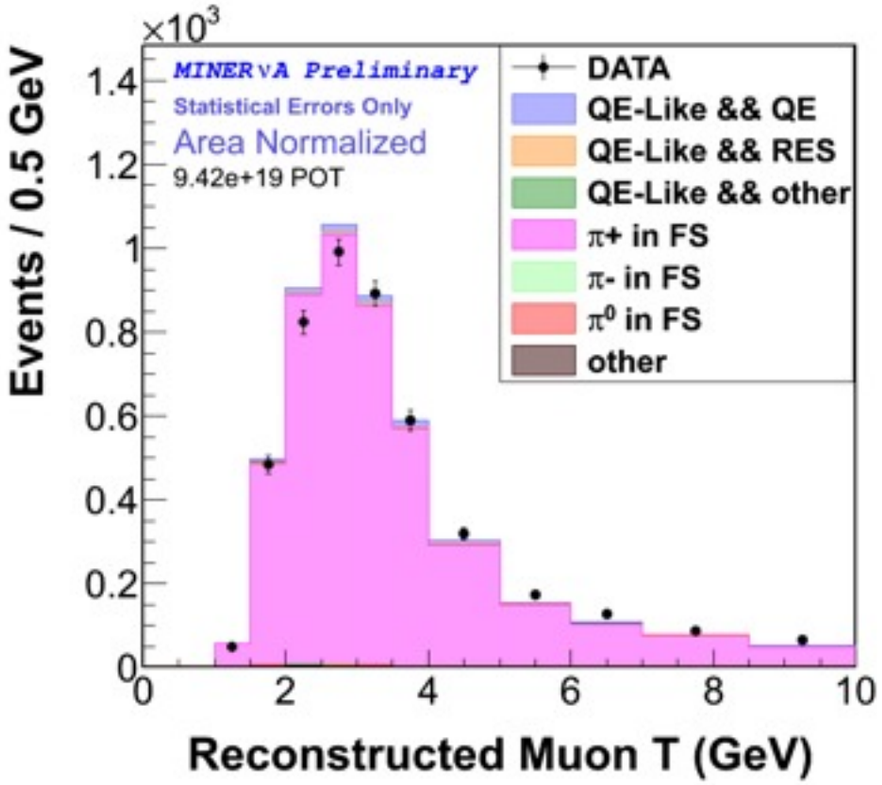


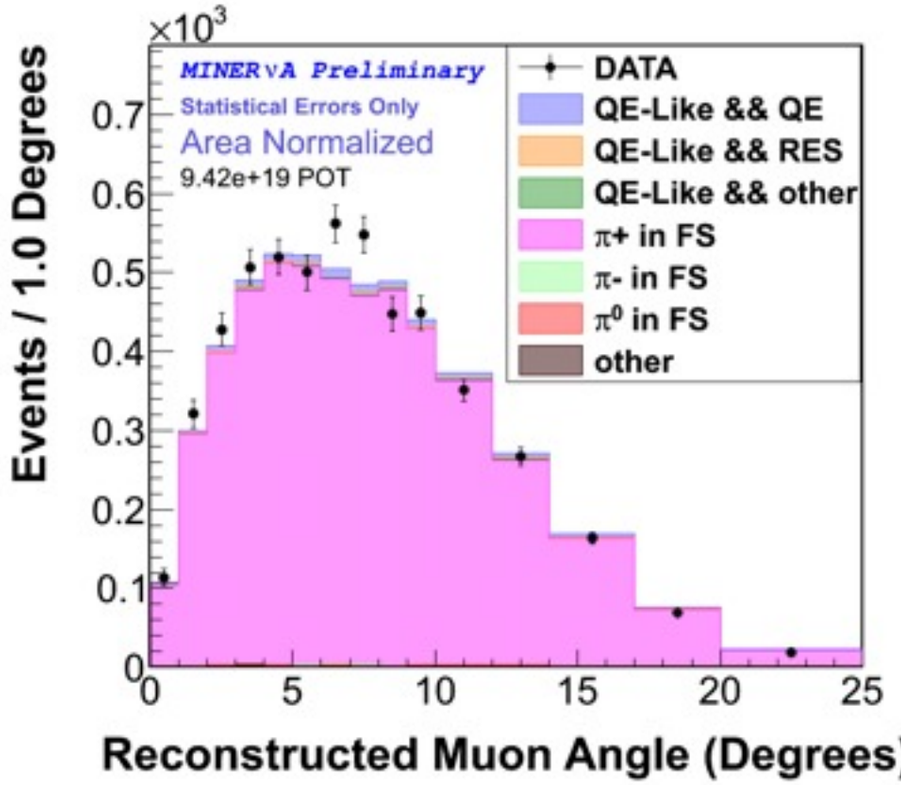
$\pi^+ \rightarrow \mu^+ \nu_\mu$

$\hookrightarrow e^+ \nu_e \bar{\nu}_\mu$



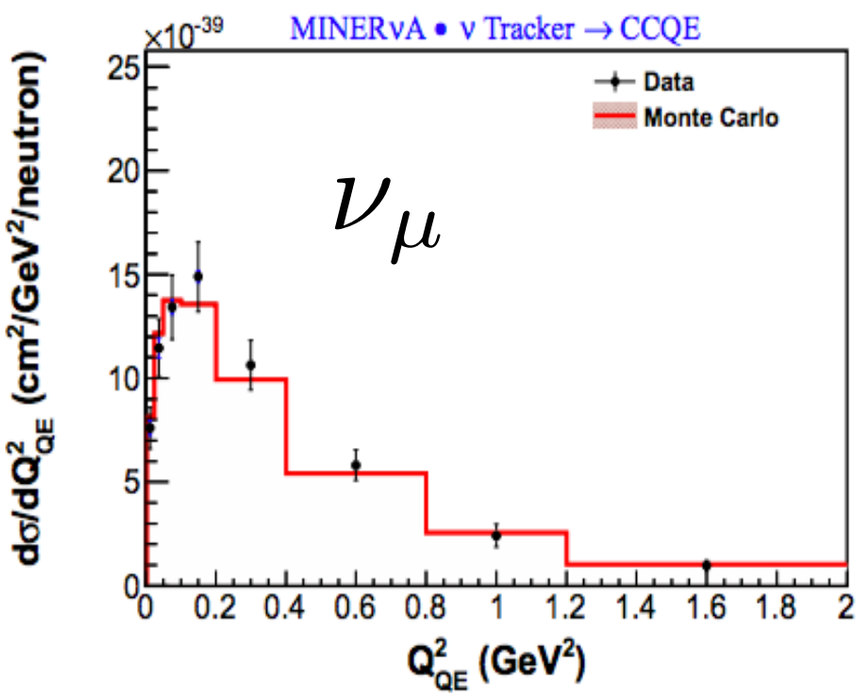
Michel Electron Background

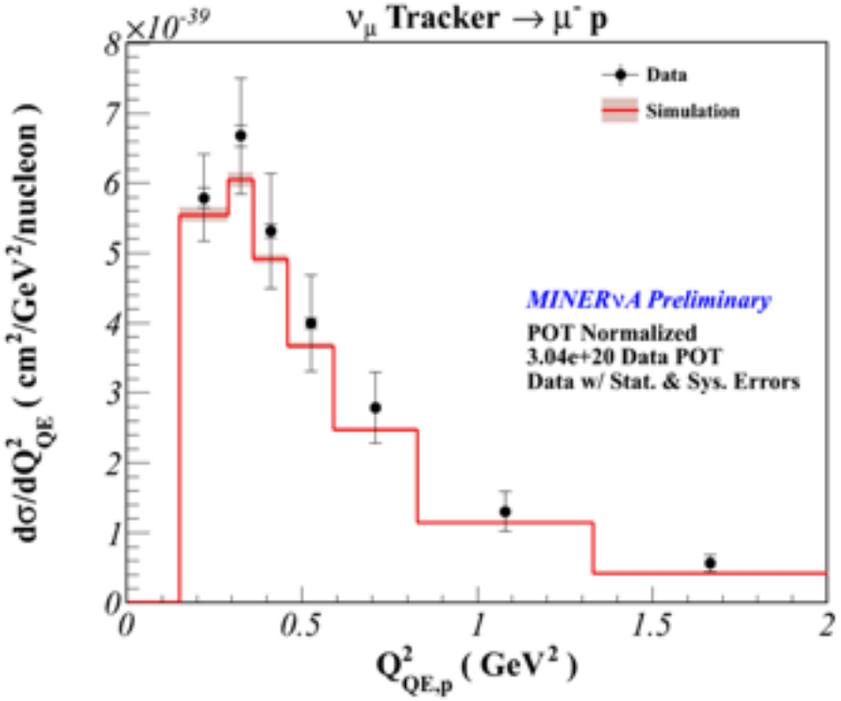




- The cross section and final state interaction models have large uncertainties in theoretical models.
  - Hence constraining backgrounds with data is valuable.
- The Michel background sample will allow us to do the above.

MINERvA QE Analyses





- The muon arm measurement is sensitive to the nuclear models in a different way than the proton arm measurement.
- The results agree with different models for similar processes.
- We do not have one consistent nuclear model that describes both results.

Phys. Rev. Lett. 111, 022501 (2013)

Phys. Rev. Lett. 111, 022502 (2013)

arXiv:1409.4497 [hep-ex]