Pion Production in MINERνA

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University of Pittsburgh
July 27, 2012

On behalf of the MINERνA collaboration

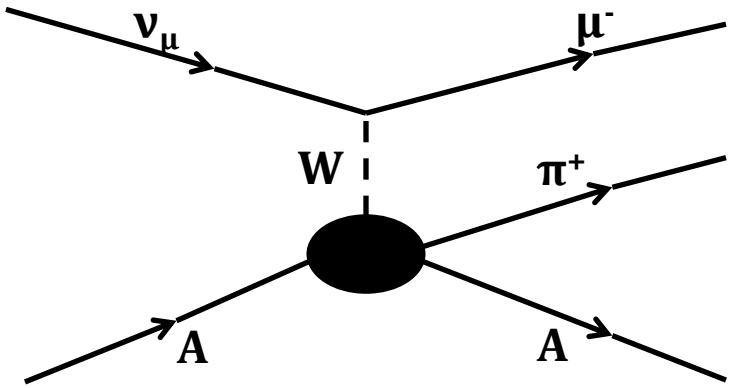
Outline

- Motivation:
  - CC coherent pion
  - CC charged pion production
- The NuMI beam and MINERνA detector
- Latest progress:
  - CC coherent pion production on scintillator
  - CC inclusive π^+ production on scintillator

CC Coherent Pion Production

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

- A is the ground state target nucleus

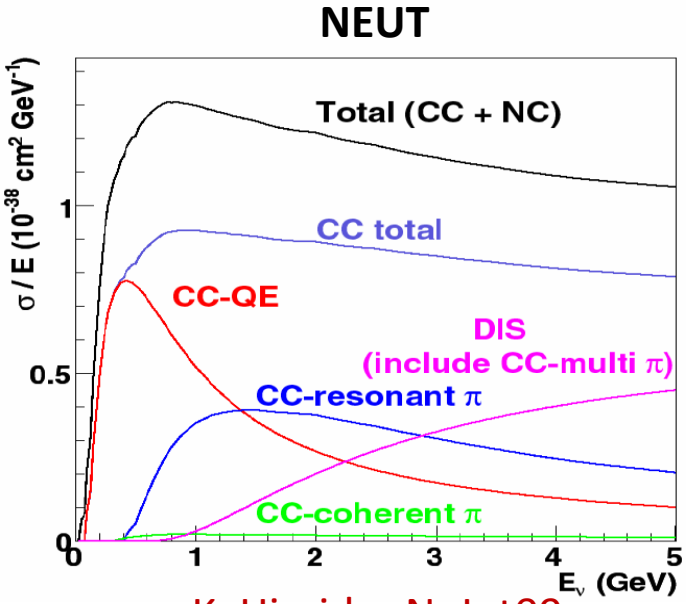


- Pion and muon tend to be forward; little momentum transfer to nucleus

- Small cross section compared to other processes

- Different modeling approaches:
  - PCAC: recent improvements
  - Microscopic: valid at $E_\nu < 2$ GeV

- Need to measure A dependence to constrain models

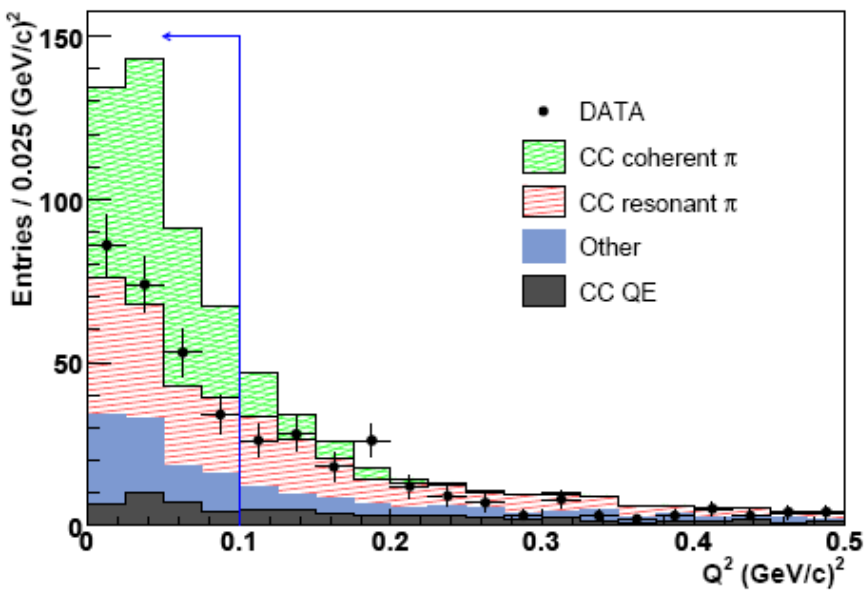


K. Hiraide -NuInt09

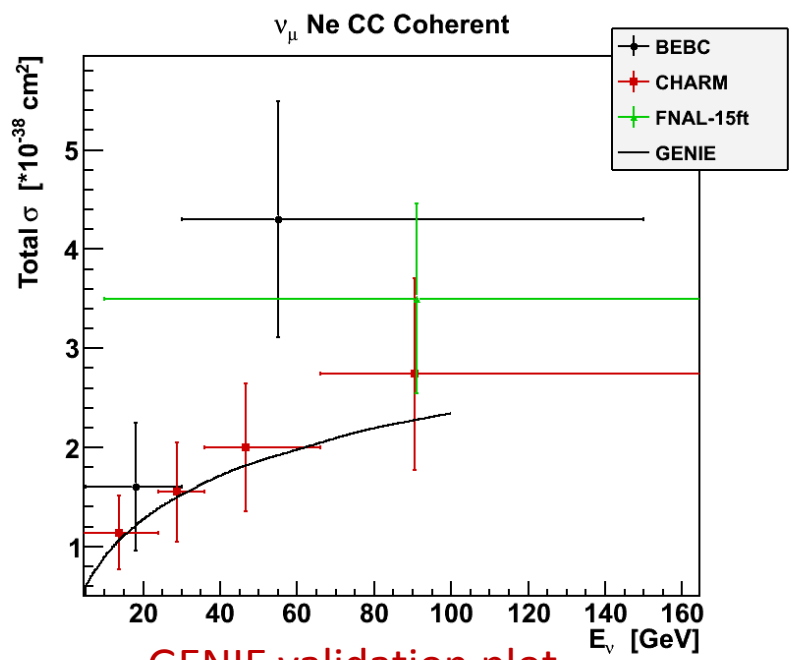
CC Coherent Pion Measurements

- Older measurements by SKAT, BEBC, CHARM, and FNAL E632 at higher energy and heavier targets

- More recent measurements by K2K and SciBooNE find no evidence of CC coherent pion production



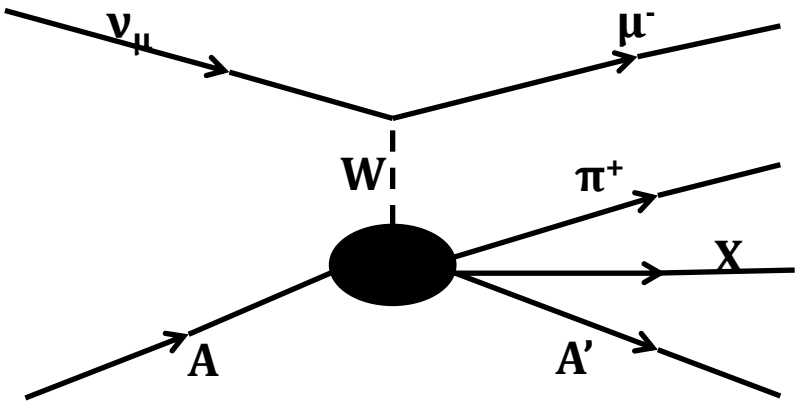
SciBooNE: Phys.Rev.D78:112004,2008



GENIE validation plot

CC Inclusive Pion Production

$\nu_\mu A \rightarrow \mu^- \pi^+ X$



- X represents the outgoing nucleus and any other particles in the final state, perhaps even other pions

- Pion must exit nucleus and is not necessarily created at interaction point; nuclear final state interactions (FSI) are folded into the channel definition

- Predominantly resonance and deep inelastic scattering (DIS) interactions

- Resonance component responsible for an important systematic in neutrino oscillation experiments, though W > 2 GeV is important as well

- Can be measured with very little model dependence, providing strong constraints on neutrino event generators and theoretical calculations

CC Inclusive Pion Measurements

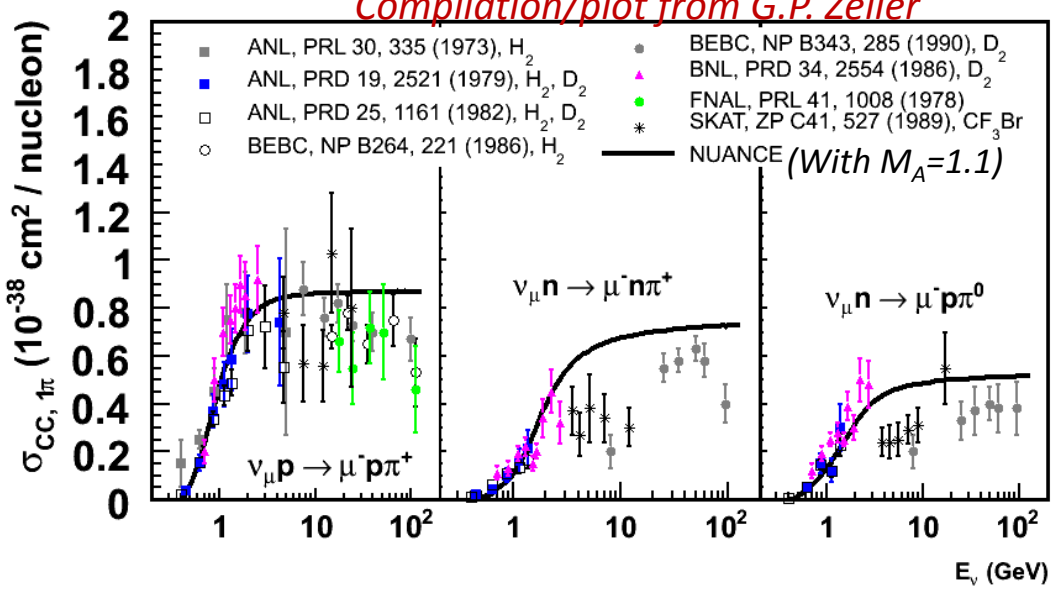
- Early experiments measured exclusive final states on H and D bubble chambers

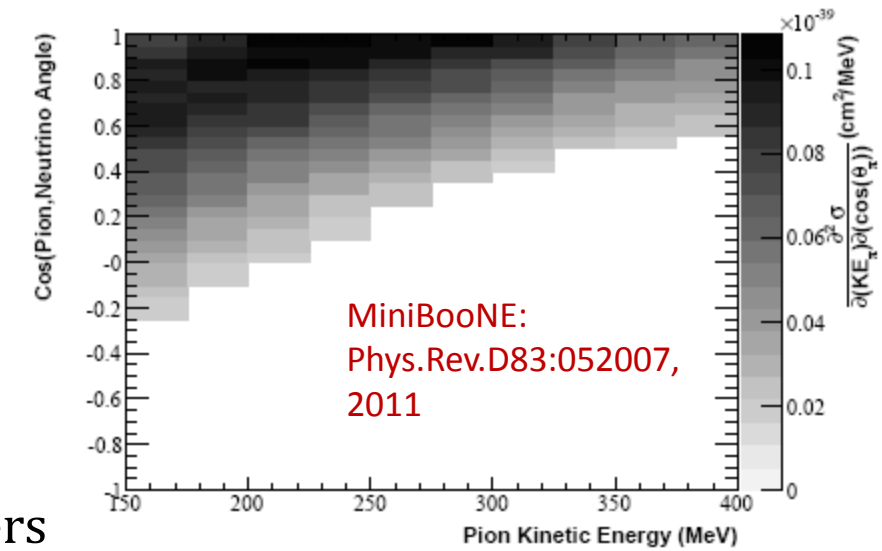
- The only high-statistics measurement is single π^+ inclusive by MiniBooNE on CH_2 at ~ 1 GeV (~48k candidates)

- Need to probe A-dependence to understand nuclear effects - ratio to other CC processes is useful

- Δ-rich sub-sample could be used to measure resonance form factor parameters

Compilation/plot from G.P. Zeller

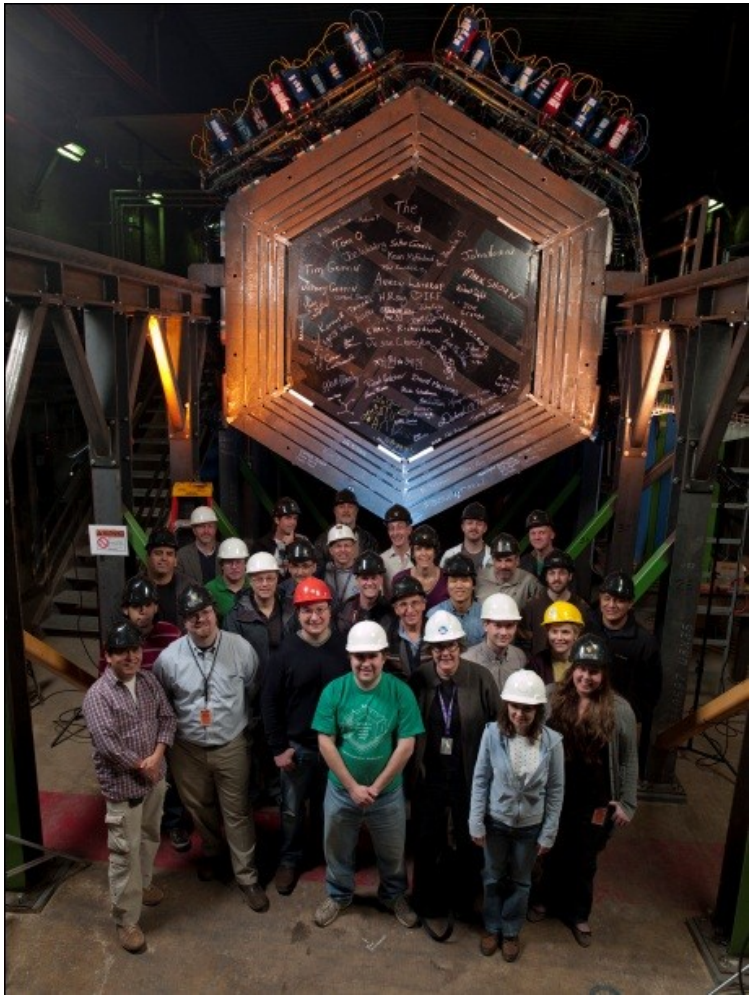




Introduction to MINERνA

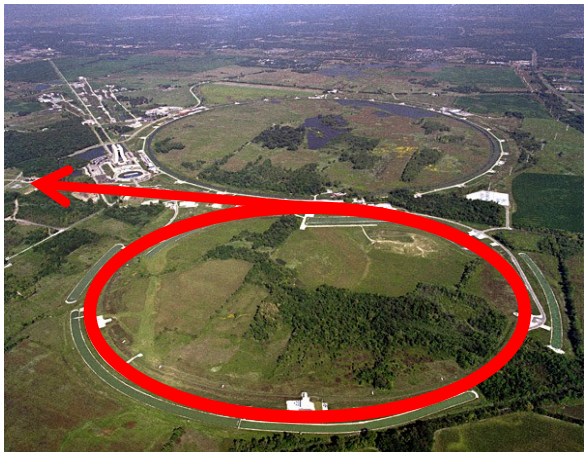
MINERνA: Main INjector ExpeRiment for ν-A

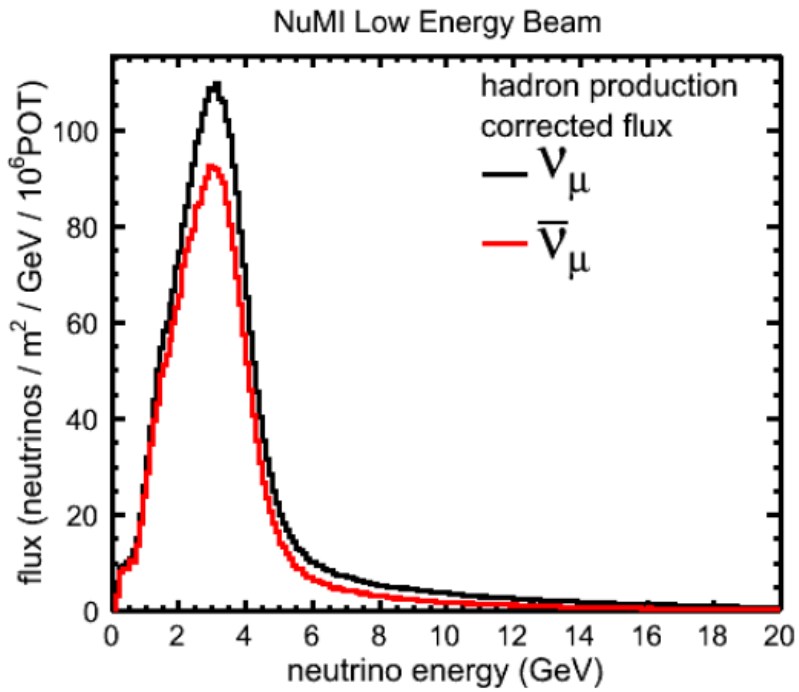
- Collaboration of 80 nuclear and particle physicists
- Detector installed upstream of the MINOS detector in the NuMI beamline at Fermilab
- Precision neutrino-nucleus cross section measurements at ~1-10 GeV

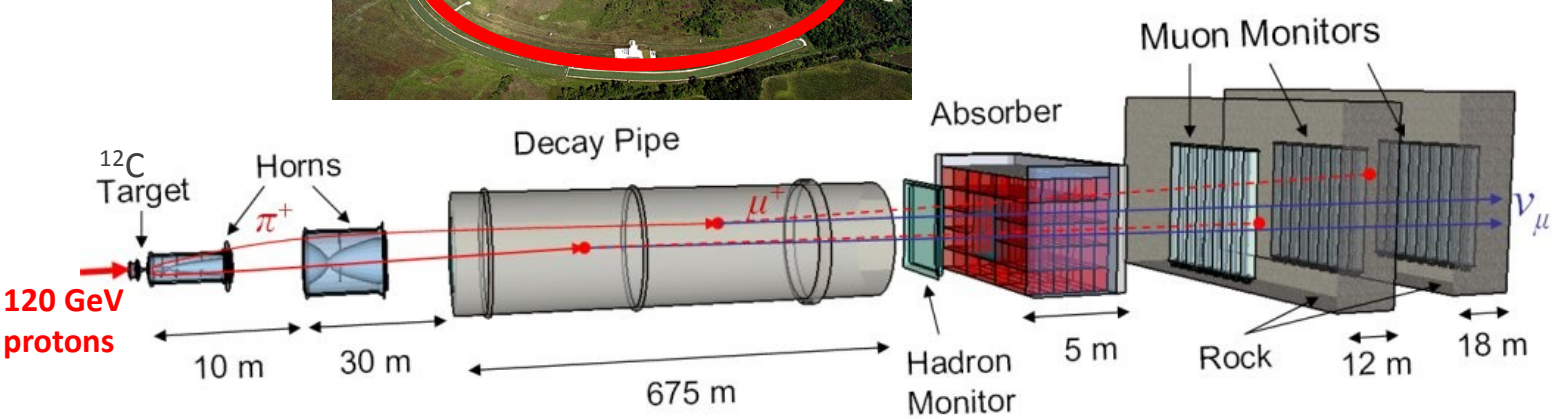


NuMI Beam

- Delivers ~35e12 protons on target (POT) per spill at ~0.5 Hz
- Moveable target for flux studies
- Magnetic horns focus + or – charged particles



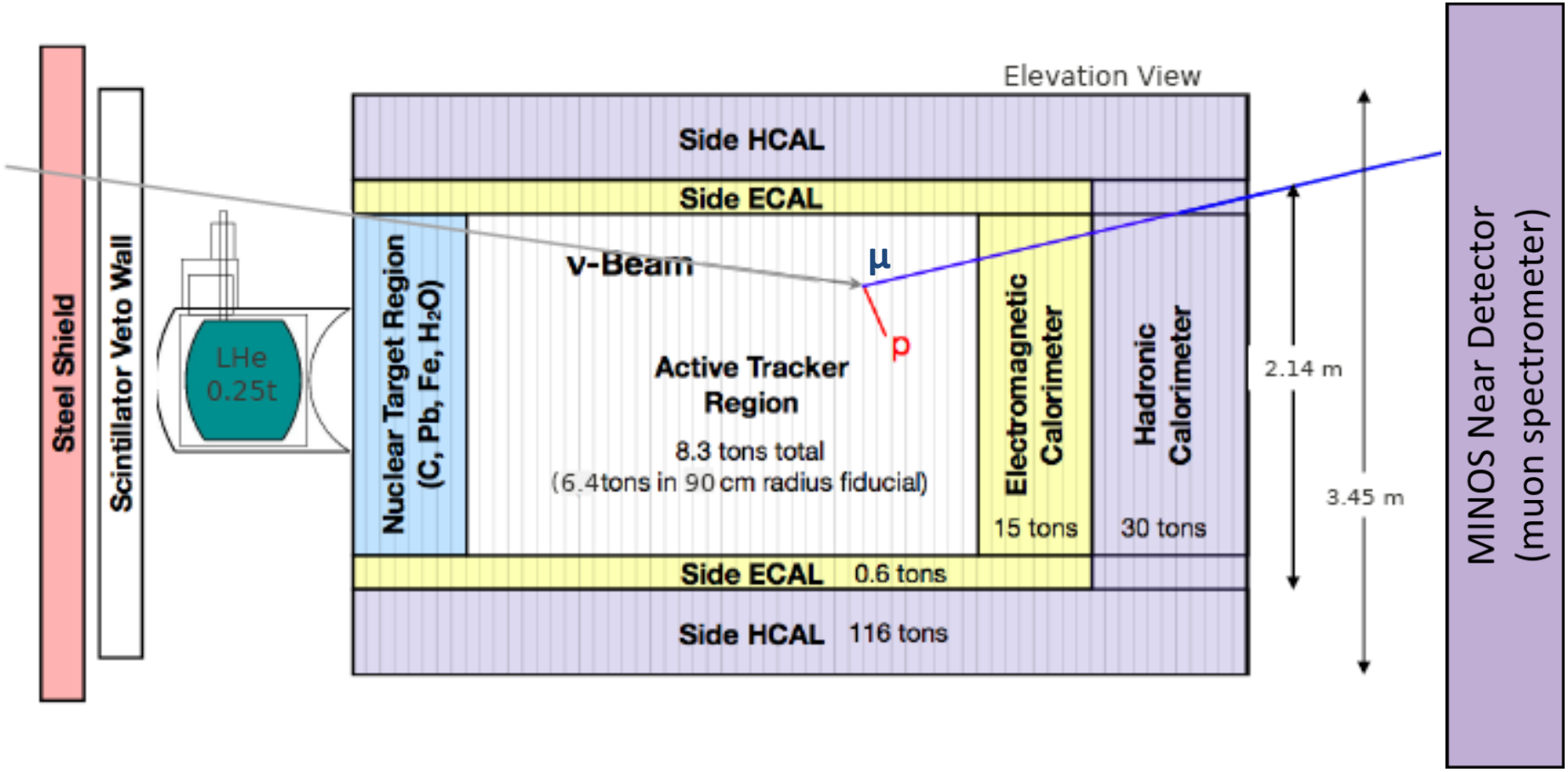




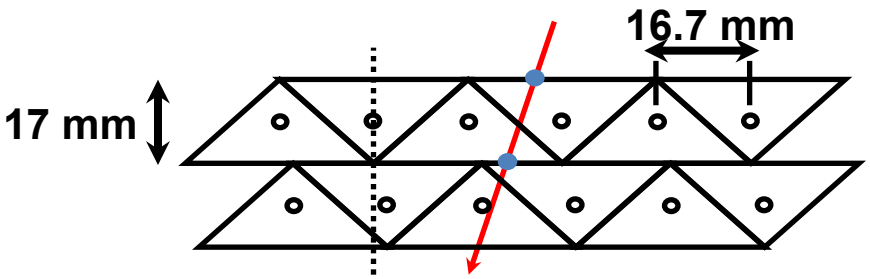
MINERvA

MINERνA Diagram

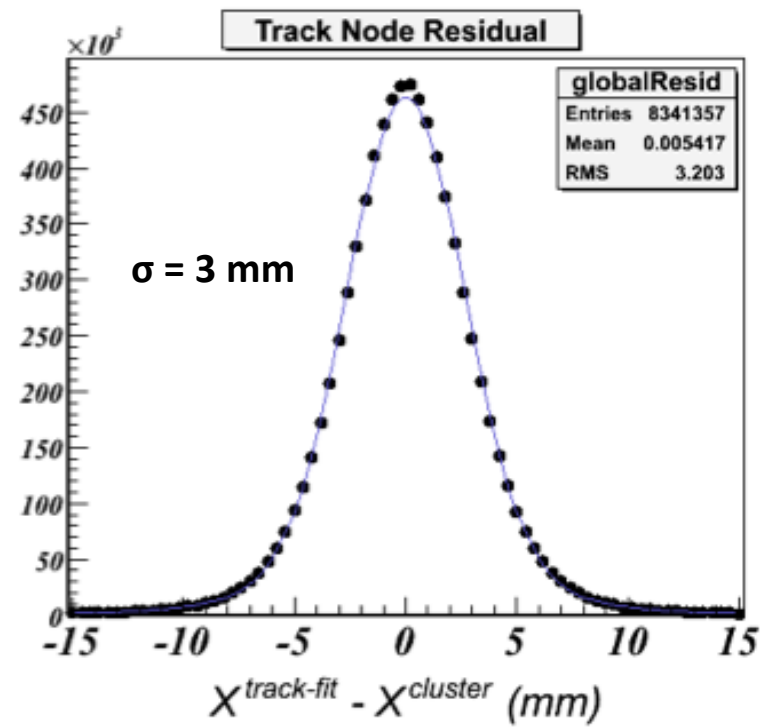
- Nuclear targets to study A dependence and nuclear effects
- Fully active, finely segmented scintillator tracking region
- MINOS Near Detector is our muon spectrometer

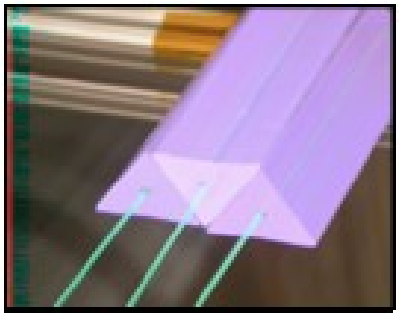


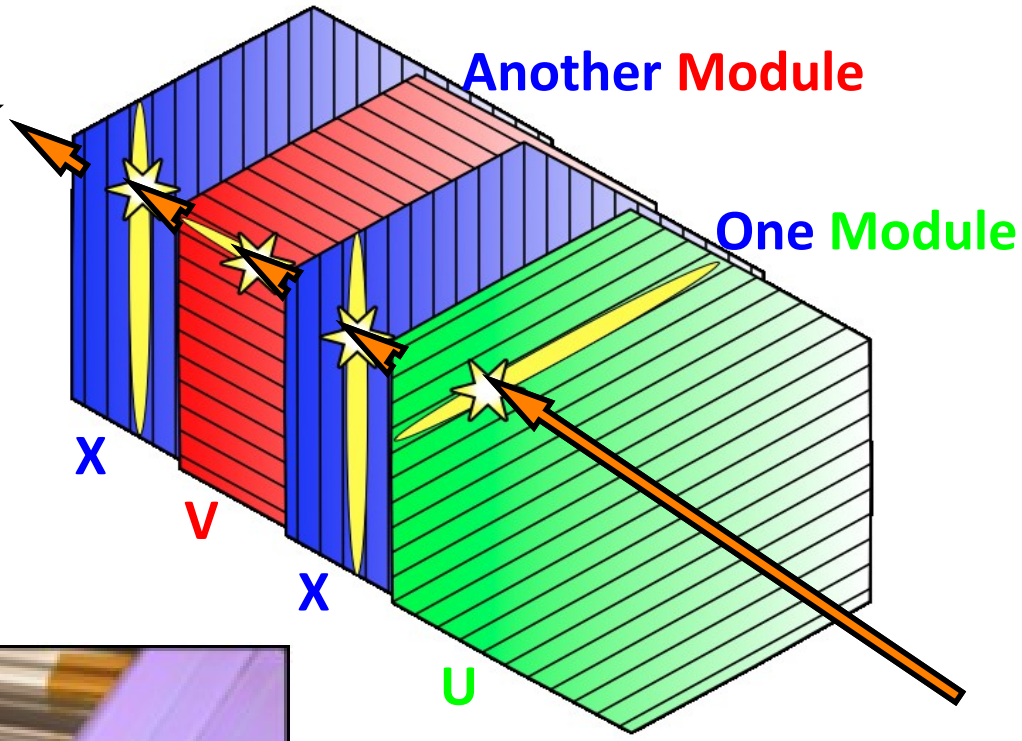
Planes and Optics



Triangular scintillator strips allows charge-sharing for good position resolution (3 mm)



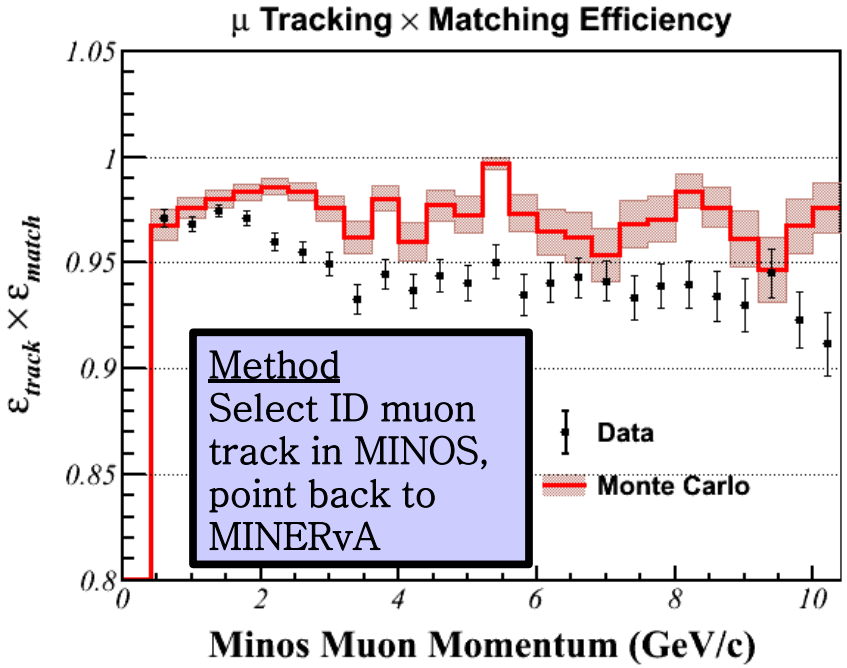


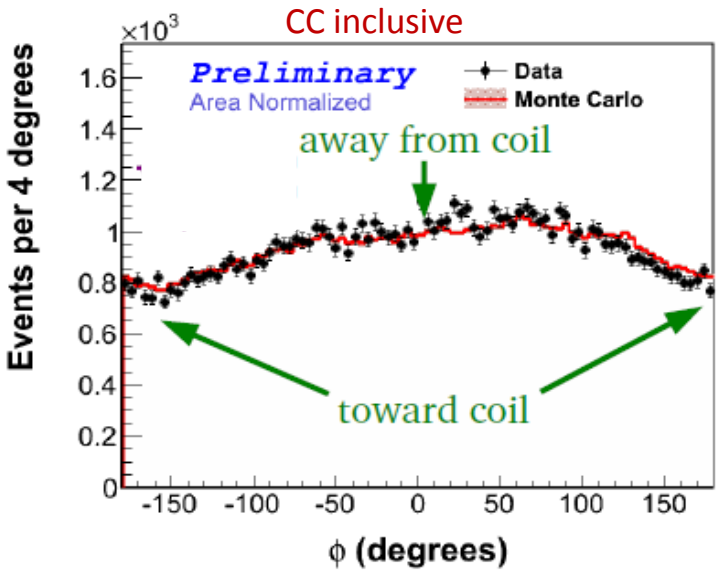


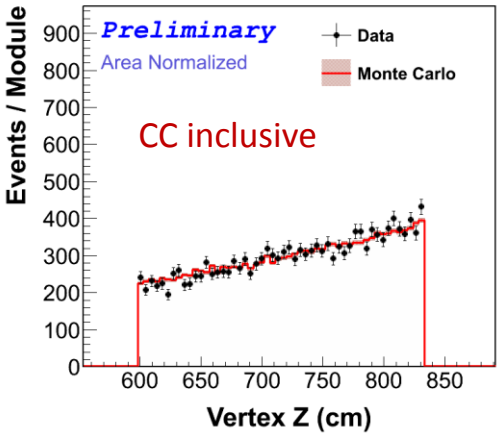
3 different rotated plane views to resolve high-multiplicity events

Muon Matching

- Both analyses shown today currently rely on MINOS-matched muons to identify CC events
- Energy threshold ~2 GeV with angular acceptance limit at ~20°
- Bias is complex but well understood





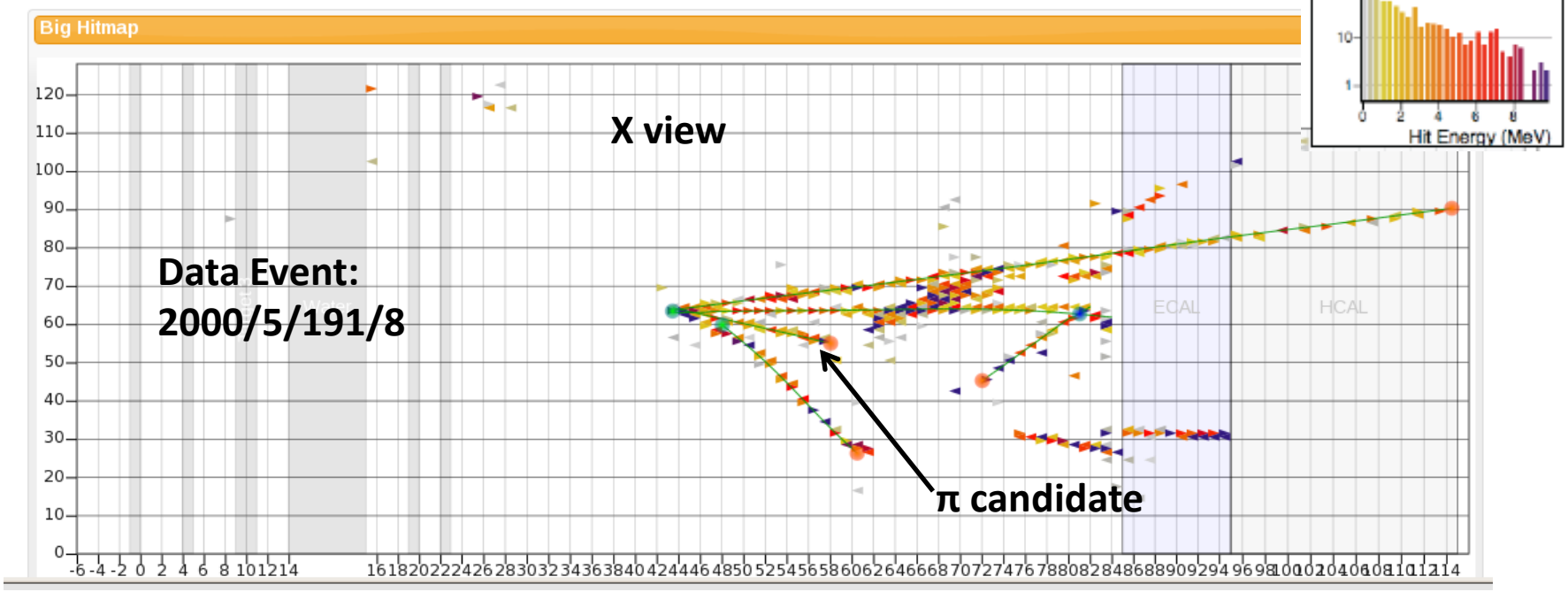


Pion Reconstruction

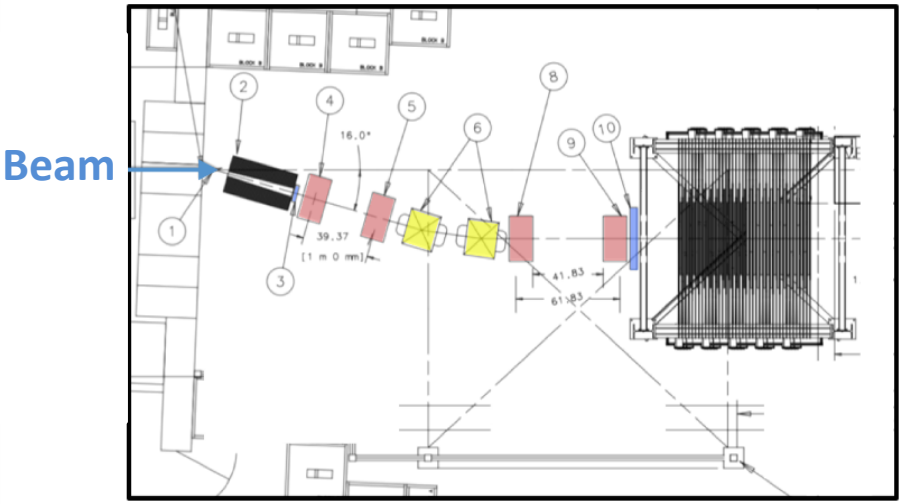
- Vertex-constrained tracking to find primary hadron and kinked hadron tracks

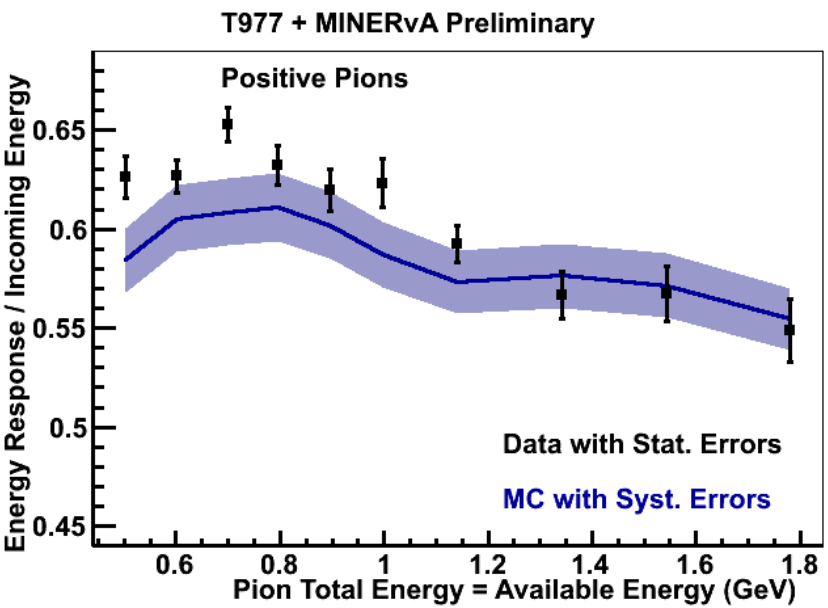
- Aggressive "track-cleaning" near the vertex to remove hadronic energy from the muon track – improves hadron tracking efficiency
  - currently CC inclusive pion analysis only

- dE/dx used for PID and momentum reconstruction – **actively working on this!**
  - Use calorimetry to improve momentum reconstruction in future



MINERνA TestBeam





- Mini-MINERνA planes installed in MTEST tertiary beamline
- 0.4-1.2 GeV pions for hadron response calibration
- Reconfigurable – collected data for:
  - 20ECAL-20HCAL
  - 20Tracker-20ECAL
- Current data/MC agreement for π^+ response is ~5% with well-modeled resolution.
  - π^- is slightly better
  - proton response ~10%

CC Coherent Pion Analysis

- MINERνA's multiple nuclear targets will allow us to measure the A-dependence of the CC Coherent reaction at $E_\nu \sim 1 - 10$ GeV

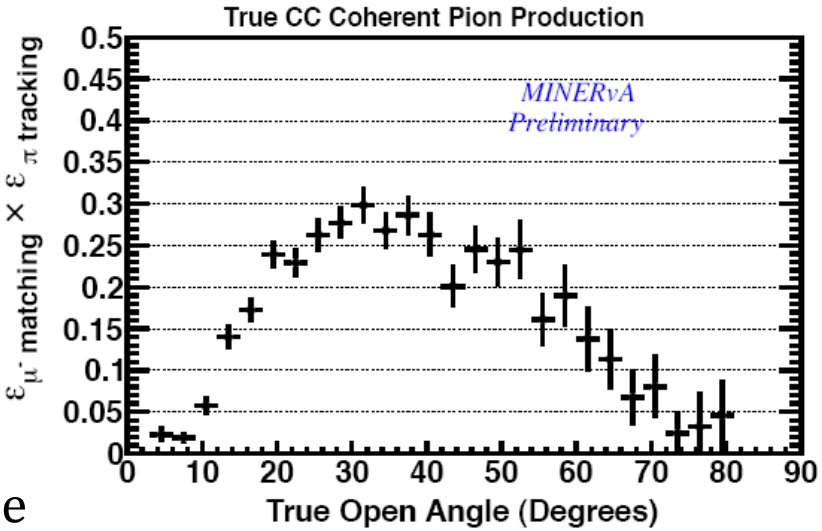
- Can compare neutrino and anti-neutrino coherent pion cross sections

- Fine-grained scintillator tracker allows for careful study of vertex-activity – a powerful tool to reject backgrounds

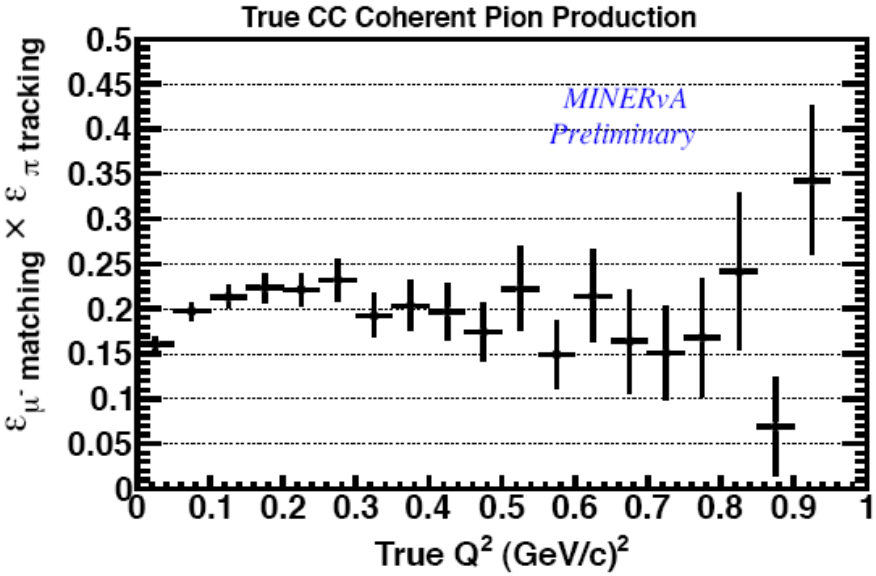
- Today I will show the current status of MINERνA's ν_μ CC coherent pion production analysis on scintillator

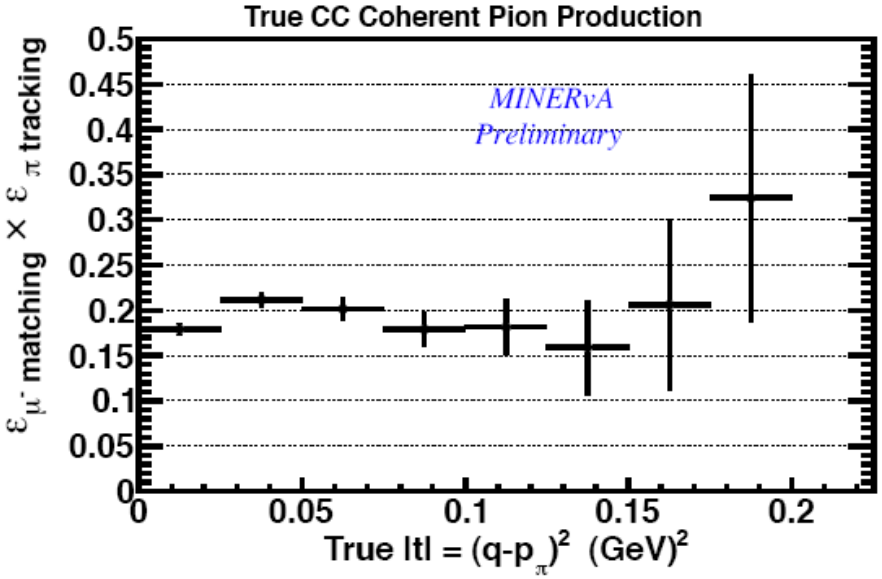
ν_μ CC Coherent Pion on CH

- Event pre-selection:
  - Vertex in scintillator fiducial volume
  - MINOS-matched muon
  - Muon Q/P < 0 (negative charge)
  - Exactly 2 tracks at interaction vertex



- Pre-selection flat in t and Q^2. Recent reco. improvements will help at small opening angle





ν_μ CC Coherent Pion on CH

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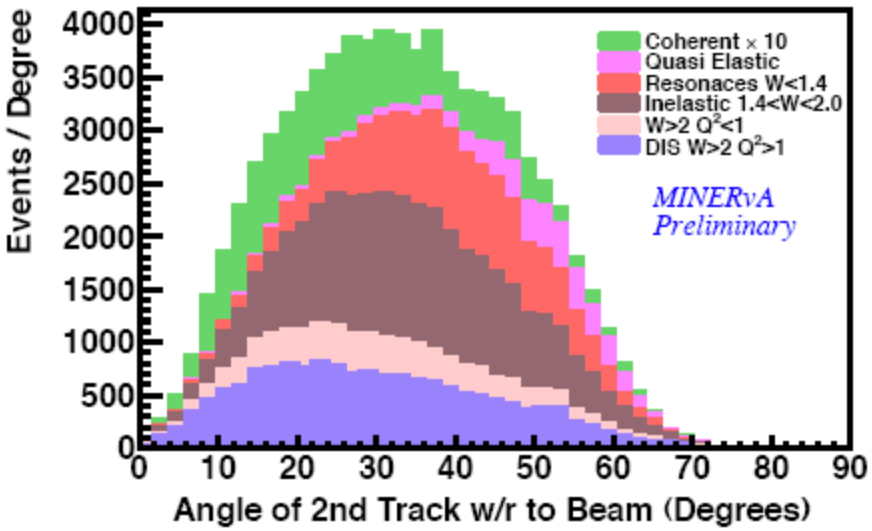
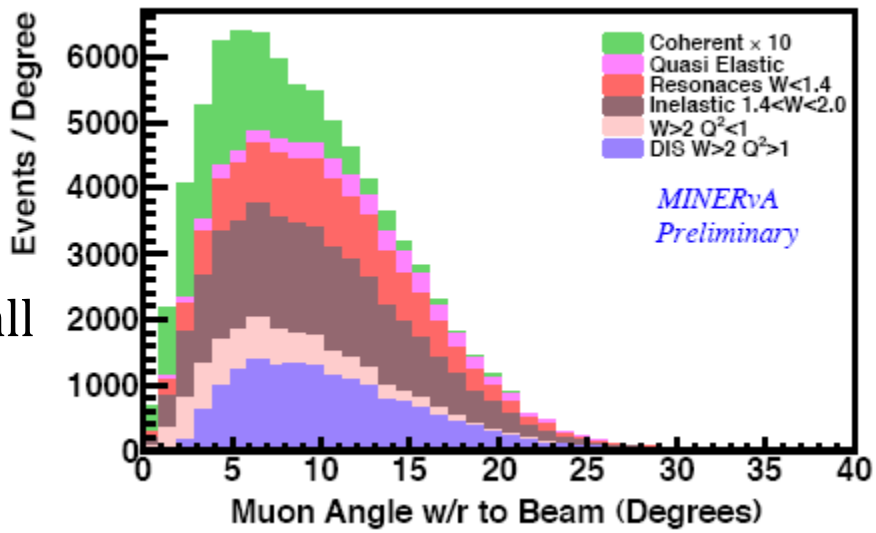


- Angular distributions show distribution of signal over background

  - Currently use PCAC Rein-Sehgal model (known poor angular dependence on light nuclei at MINERvA energies)

  - Need to improve measurement of pion energy to get t, x, and Q^2. Requiring small t is particularly effective at rejecting background



CC Inclusive Pion Analysis

- Minimize FSI model dependence by defining "signal" as CC events with a π^+ that exits the nucleus

- MINERνA will be able to measure A-dependence of neutrino pion production, as well as compare neutrinos and antineutrinos

- E_ν ~1-10 GeV is complementary to MiniBooNE's result at ~1 GeV

- Measure single and double-differential cross sections

- Can select exclusive final states from an inclusive sample, e.g. Δ production

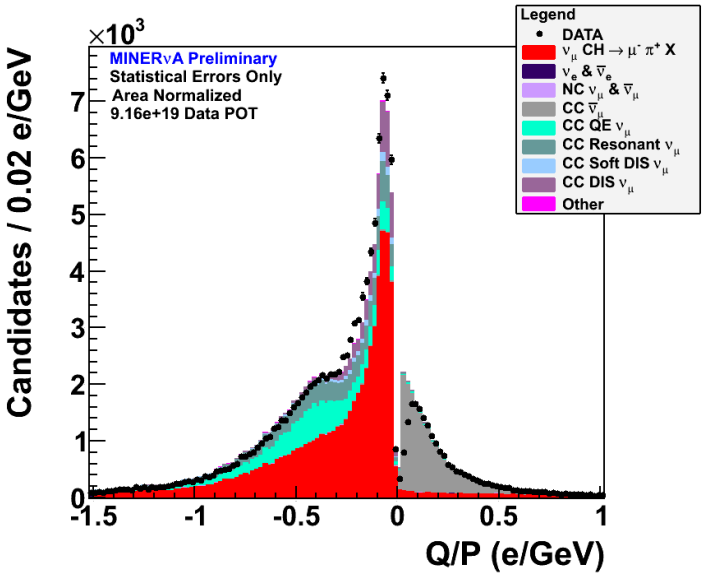
- Today I will show the current status of MINERνA's ν_μ CC inclusive pion production analysis on scintillator

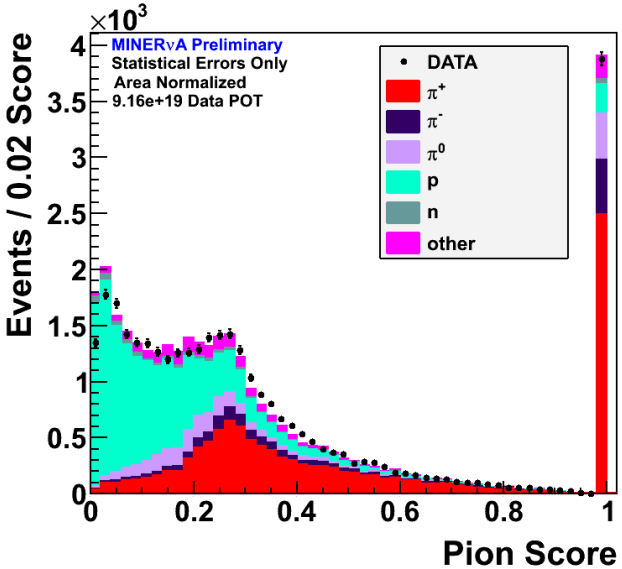
CC Inclusive Pion Analysis

- Event Selection:
  - Vertex in scintillator fiducial volume
  - MINOS-matched muon track
  - Muon Q/P < 0 (negative charge)
  - Total hadronic energy < 3 GeV
  - At least one hadron candidate track at vertex

- Requirements on pion candidate:
  - Contained in Inner Detector and is not kinked
  - Pion PID Score > 0.3

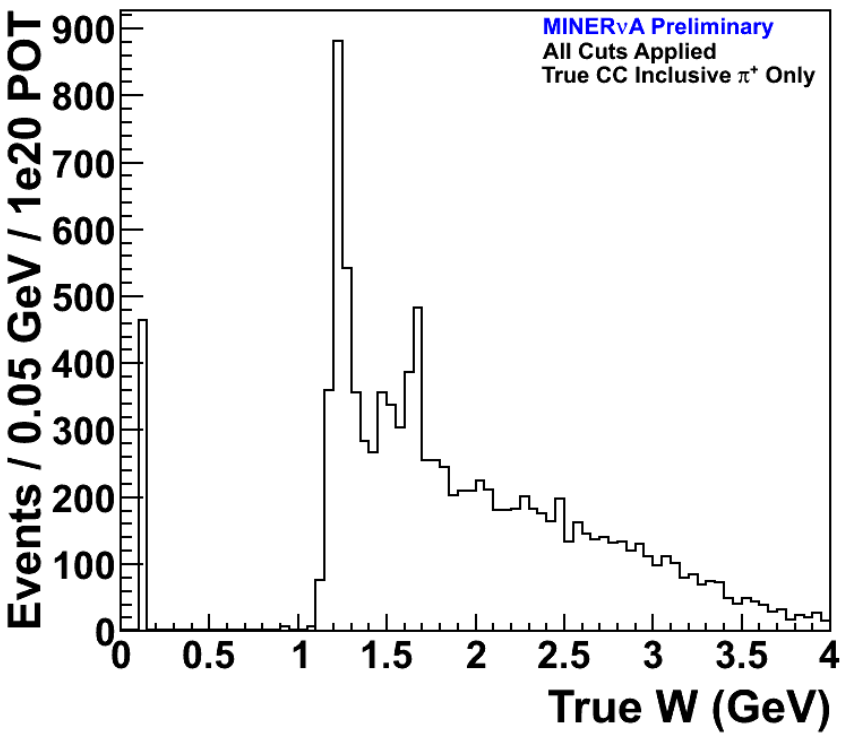
- Current selection purity: 80%

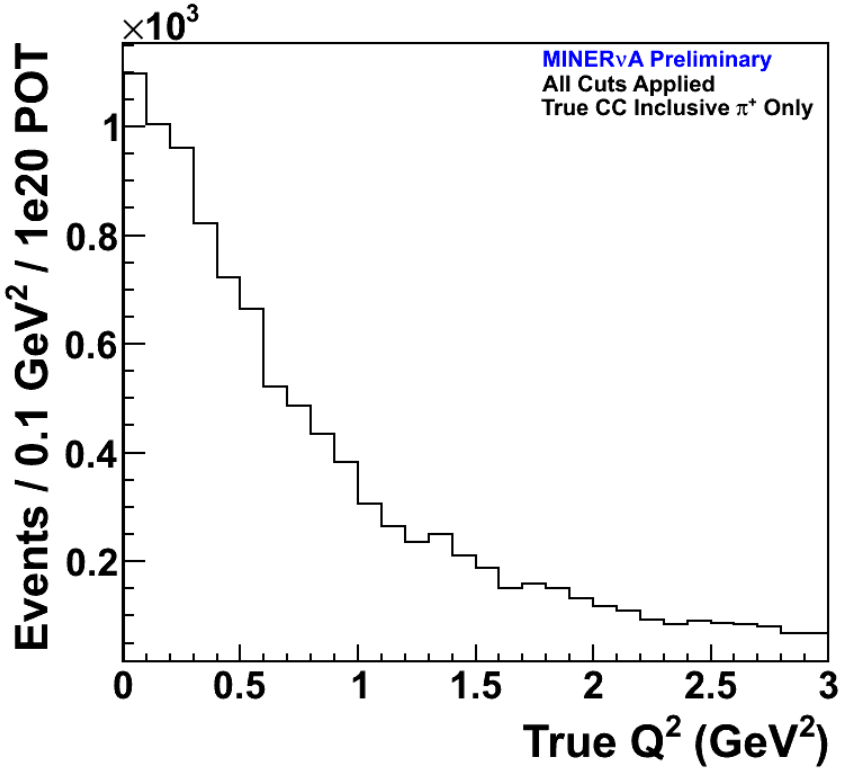




CC Inclusive Pion Analysis

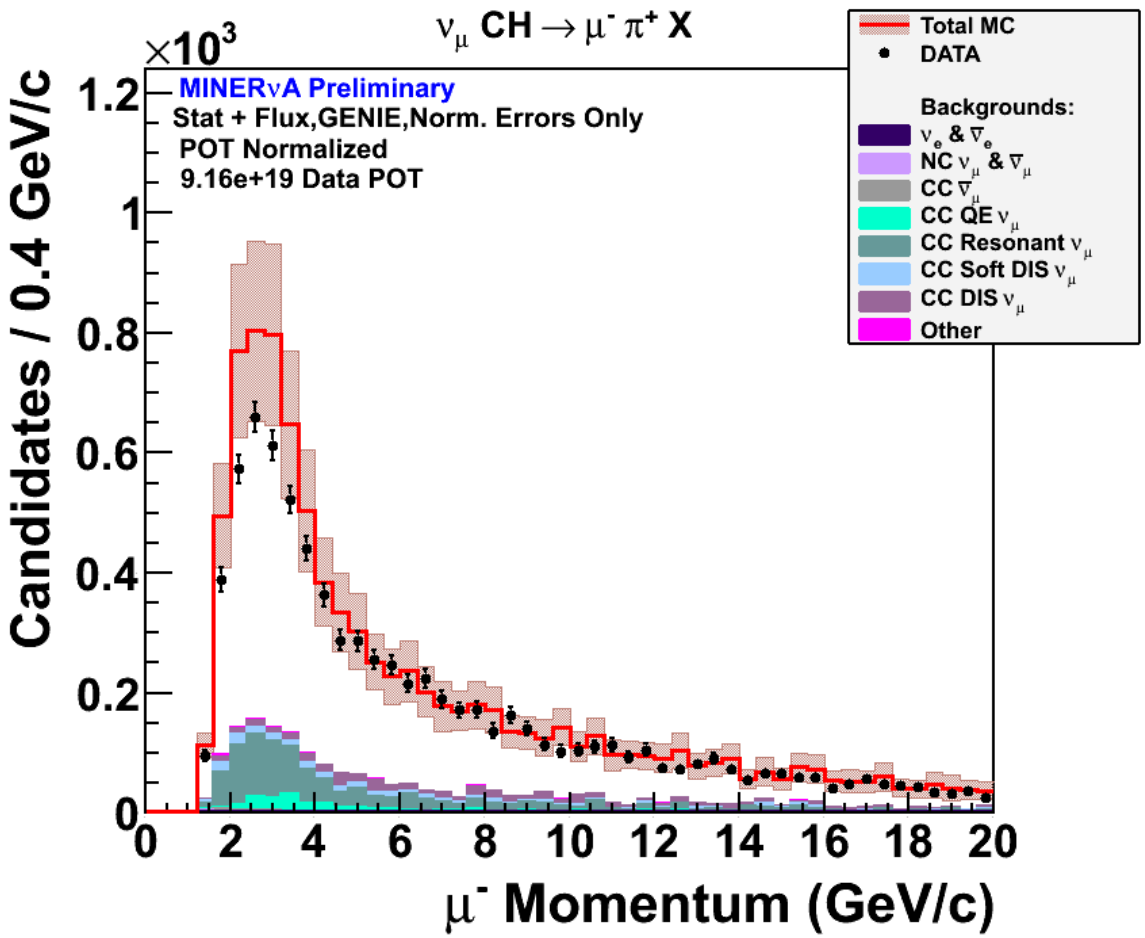
- Physics reach after applying all cuts is extensive
  - Δ's and higher order resonances
  - Events at larger Q^2





CC Inclusive Pion Analysis

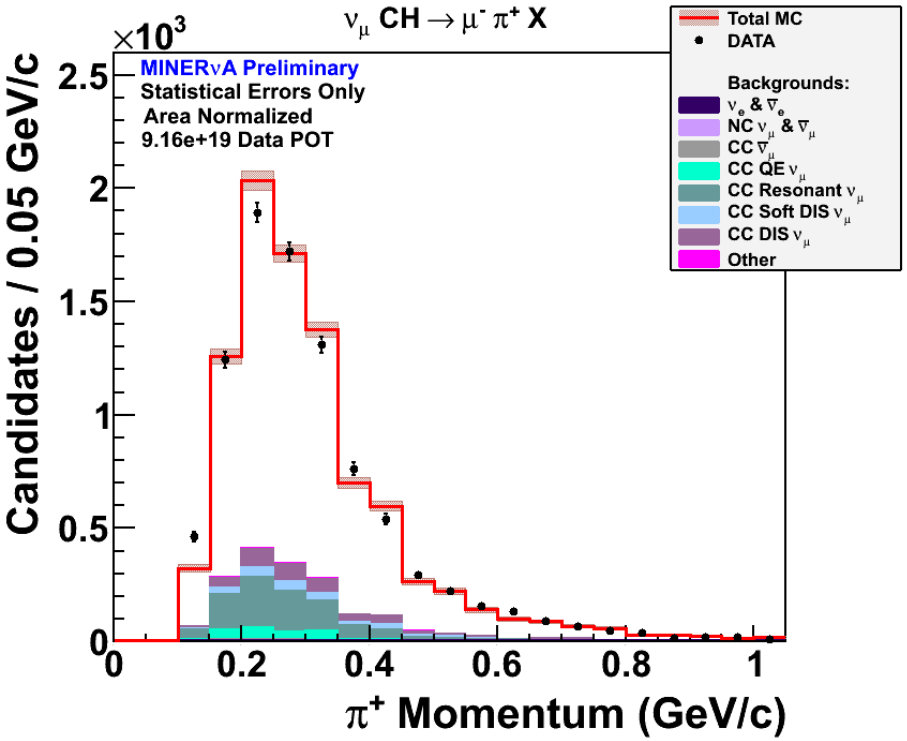
•Shape difference in reconstructed muon momentum mostly covered by flux+GENIE systematic errors

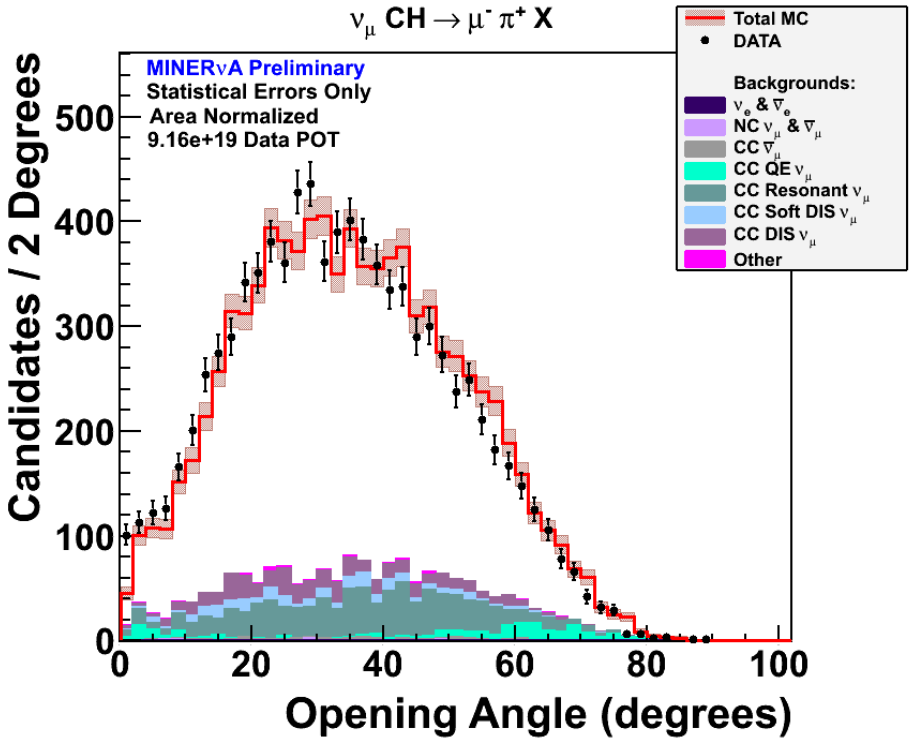


CC Inclusive Pion Analysis

No systematic uncertainties shown in these distributions!

- Currently reconstruct lower-energy pions
- Data excess at small opening angles is likely from background not modeled in current MC.





Conclusions

- Understanding neutrino-induced pion production on nuclei is important for both the neutrino oscillation and nuclear physics communities

- MINERνA understands its muon reconstruction very well; we continue to work hard on pion reconstruction!

- Both analyses shown today require better pion momentum reconstruction to move forward

- The CC coherent pion analyzers need a better MC model to move beyond the two-track pre-selection
    - Will also benefit from improvements to reconstruction used in the CC inclusive pion analysis

- The CC inclusive pion analyzers have developed selection criteria that yield an 80%-pure sample with high probability of correctly identifying the pion

The MINERνA Collaboration
Main Injector ExpeRiment ν-A

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

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

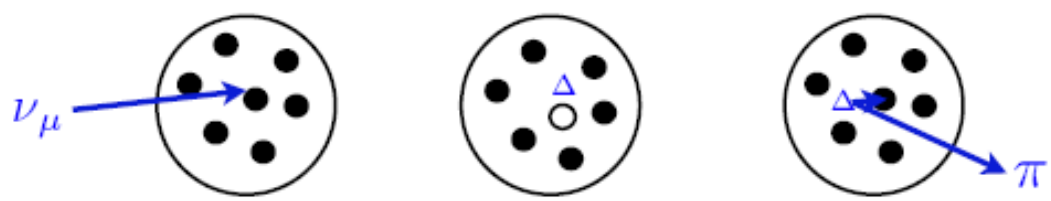
Backup Slides

CC Coherent Pion Models

- PCAC:

$$\frac{d\sigma}{dE_\nu dQ^2 dt} \propto \frac{G f_\pi^2}{2\pi} F(Q^2, \nu, E_\nu, m_\mu) \frac{d\sigma(\pi A)}{dt}$$

  - Relate neutrino coherent pion production to πA elastic scattering in $q^2 \rightarrow 0$ limit
  - Rein-Sehgal is a PCAC model widely-used in neutrino scattering, but has poor angular dependence for lighter nuclei and at low E_ν
- Microscopic:
  - Coherent pion production modeled as subset of all pion production through νN interaction
  - Best at low E_ν

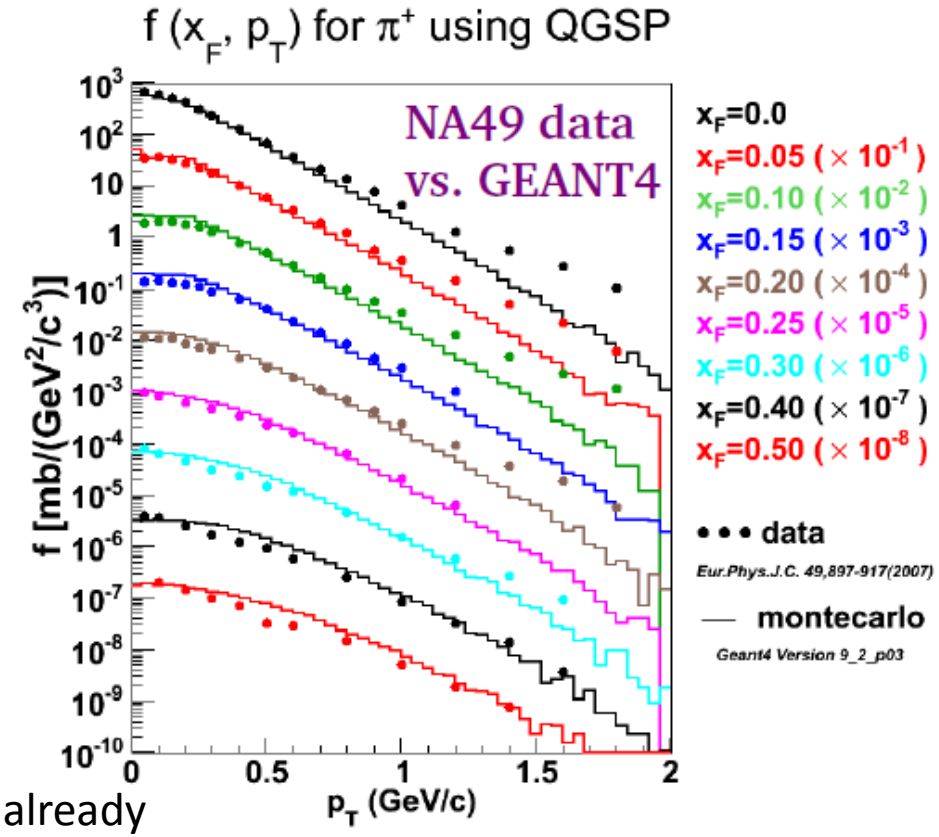


Beam Knowledge and Flux

- Today's results: Flux simulated by GEANT4 and reweighted to match hadron production data from NA49.
  - 7.5% statistical, 2-10% systematic uncertainties

- Future flux measurements will be improved by multi-pronged attack:
  - In situ measurement from muon flux via muon monitors
  - Data with different horn current and target position configurations
  - New hadron production data

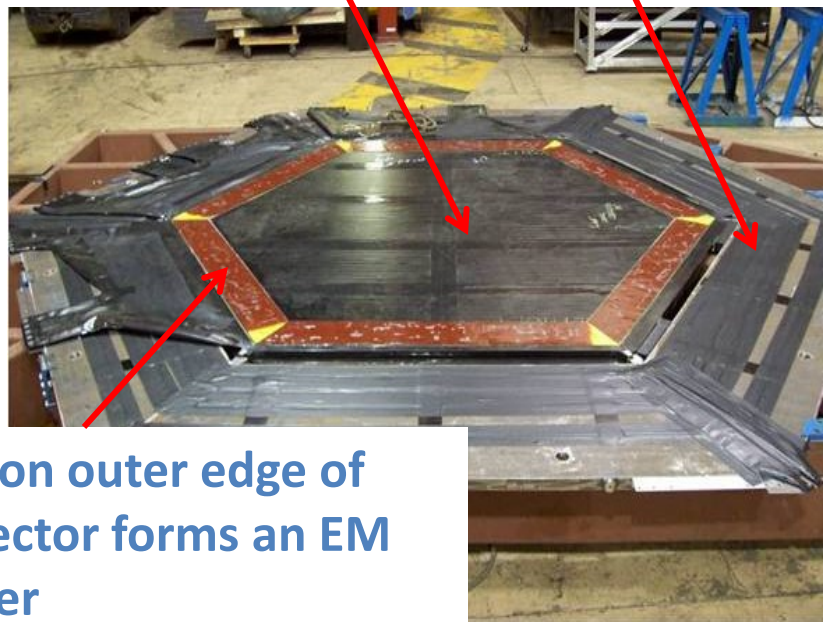
Data already taken!



- See Leo Aliaga's talk at this conference!

The detector (types of modules)

- Target Module (5 total):
  - Layer of target material (Fe, C or Pb)
  - Layer of scintillator
- Tracker Module(84 total):
  - 2 layers scintillator
  - 3.71 interaction lengths
- ECal module (10 total):
  - 2 sheets of lead
  - 2 layers of scintillator
  - 8.3 rad lengths.
- HCal module (20 total):
  - Layer of Fe
  - Layer of scintillator
  - 3.7 interaction lengths.



MINERvA module under construction

*slide from S. Manly

The detector (nuclear targets)

- 5 nuclear targets + water target interspersed in target region with tracking modules between
- Helium target upstream of detector
- Approved (for Physics) near million-event samples (4×10^{20} POT LE beam + 12×10^{20} POT in ME beam)

in hand!

Target	Mass in tons	CC Events (Million)
Scintillator	3	9
He	0.2	0.6
C (graphite)	0.15	0.4
Fe	0.7	2.0
Pb	0.85	2.5
Water	0.3	0.9

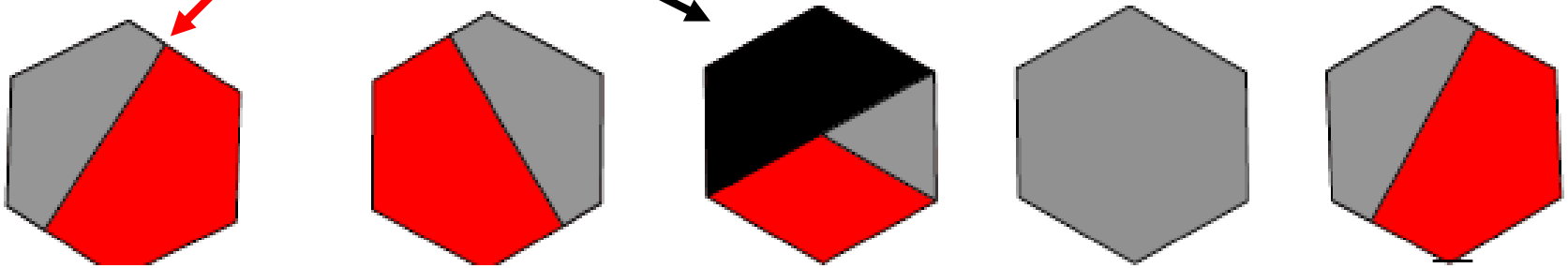
- NUGEN MC
- Only ν
- not acceptance corrected
- inside fiducial volume

Water target

He target

5 Nuclear Targets

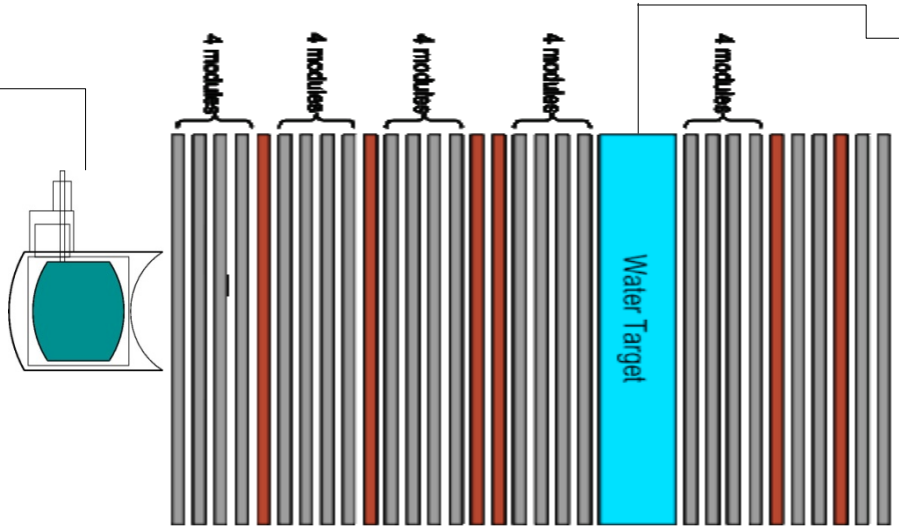
Fe Pb C



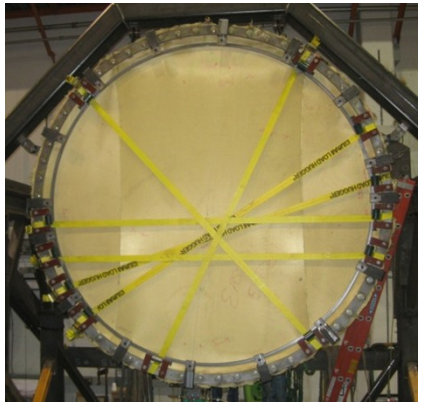
*slide from S. Manly

nuclear targets

250 kg
Liquid He



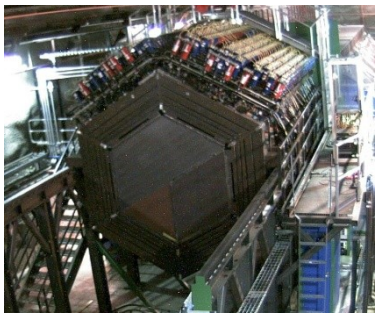
500kg
Water



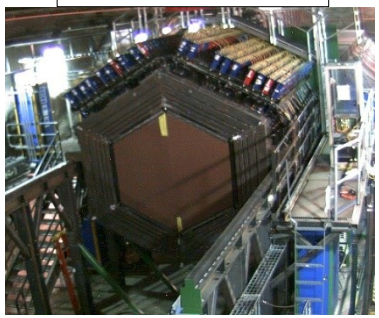
1.0” Fe / 1.0” Pb

1.0” Pb / 1.0” Fe

3.0” C / 1.0” Fe / 1.0” Pb



0.3” Pb

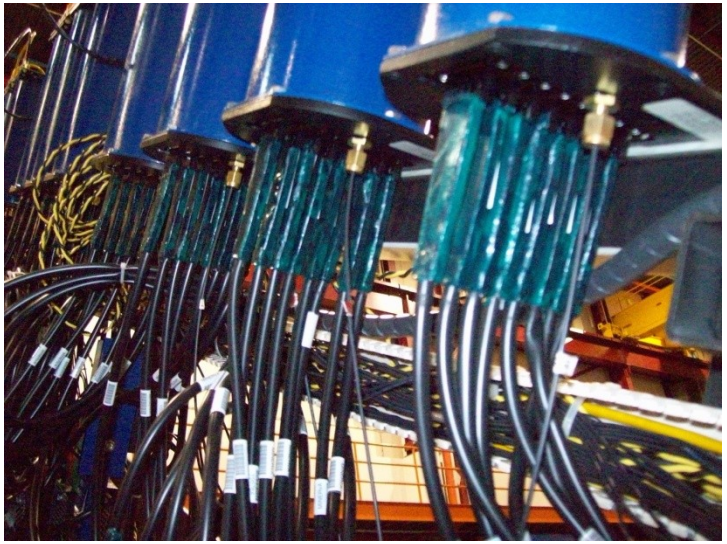


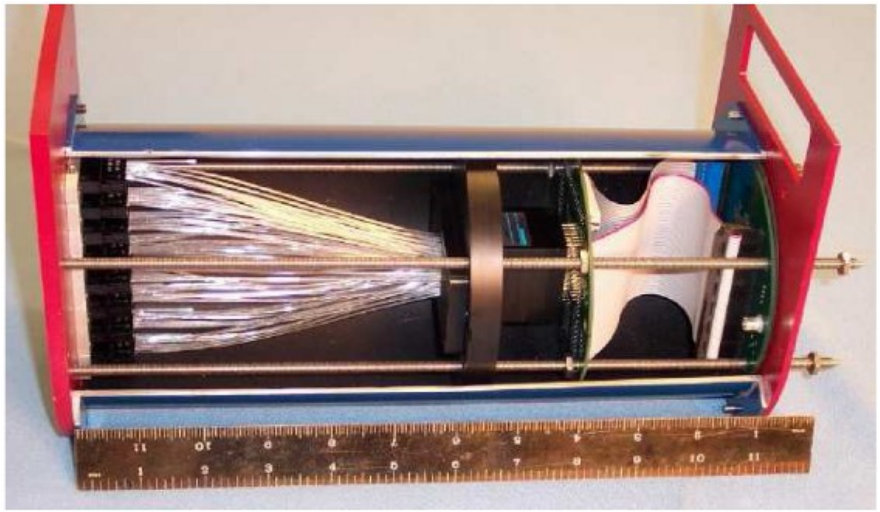
0.5” Fe / 0.5” Pb

*slide from S. Manly

Electronics

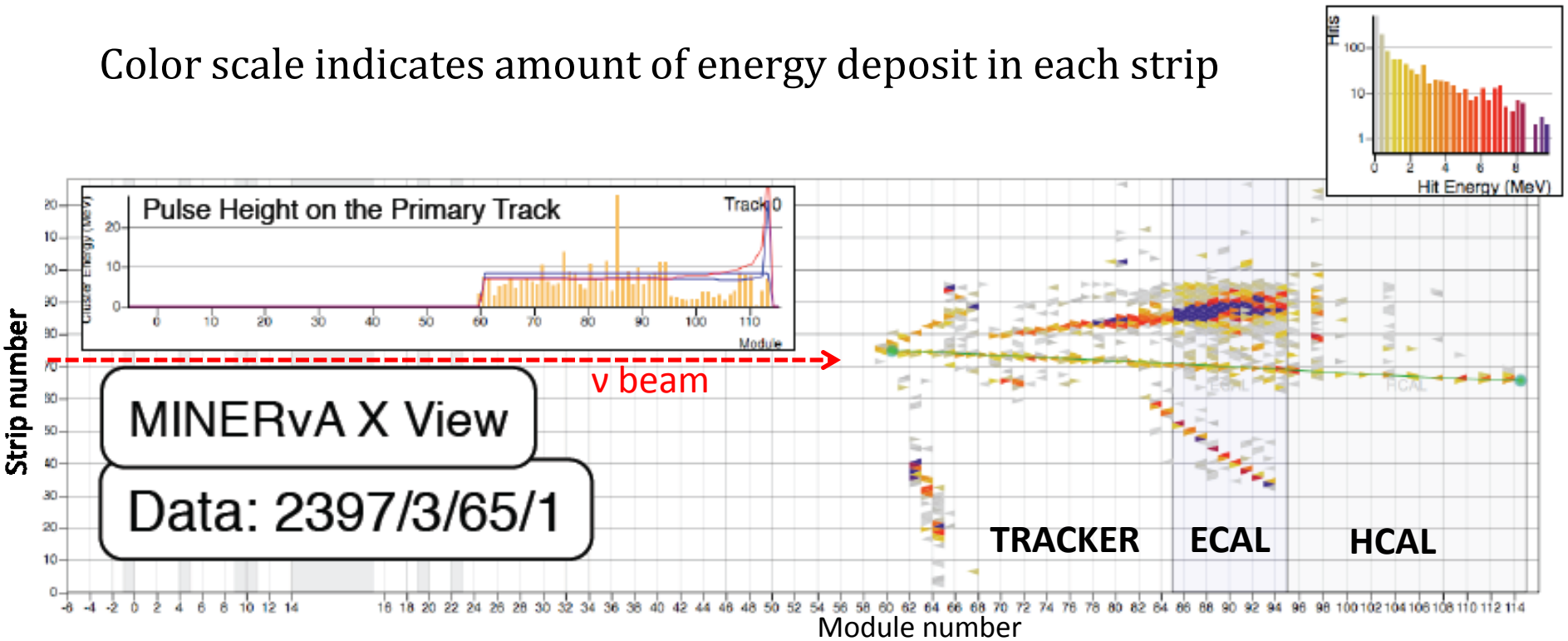
- Light measured by Hamamatsu 64 anode PMTs (newer version of MINOS model)
- Front end board (FEB) with Trip-t chips interface the PMTs
- Discriminators allow us to trigger at 1PE and resolve overlapping events during a spill





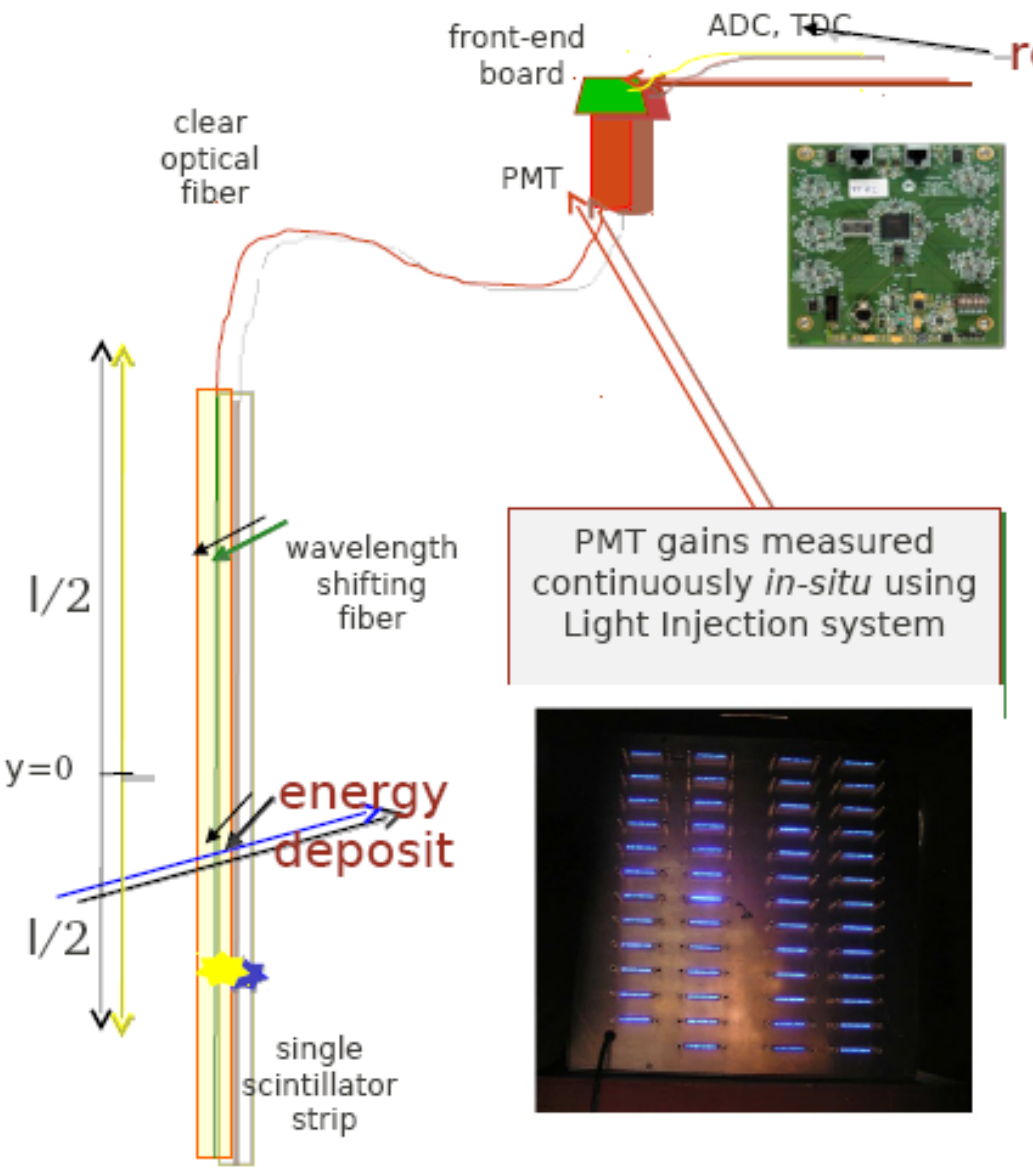
Sample Event Display

Color scale indicates amount of energy deposit in each strip



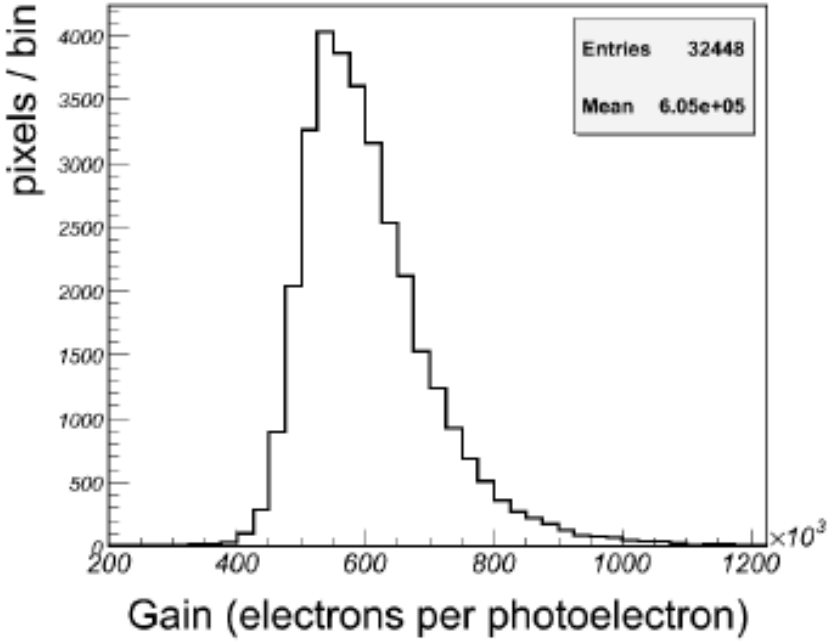
Only showing one view here – can clearly see two tracks emerging from the interaction vertex as well as neutral-induced shower activity that points back to the vertex.

Detector Calibration



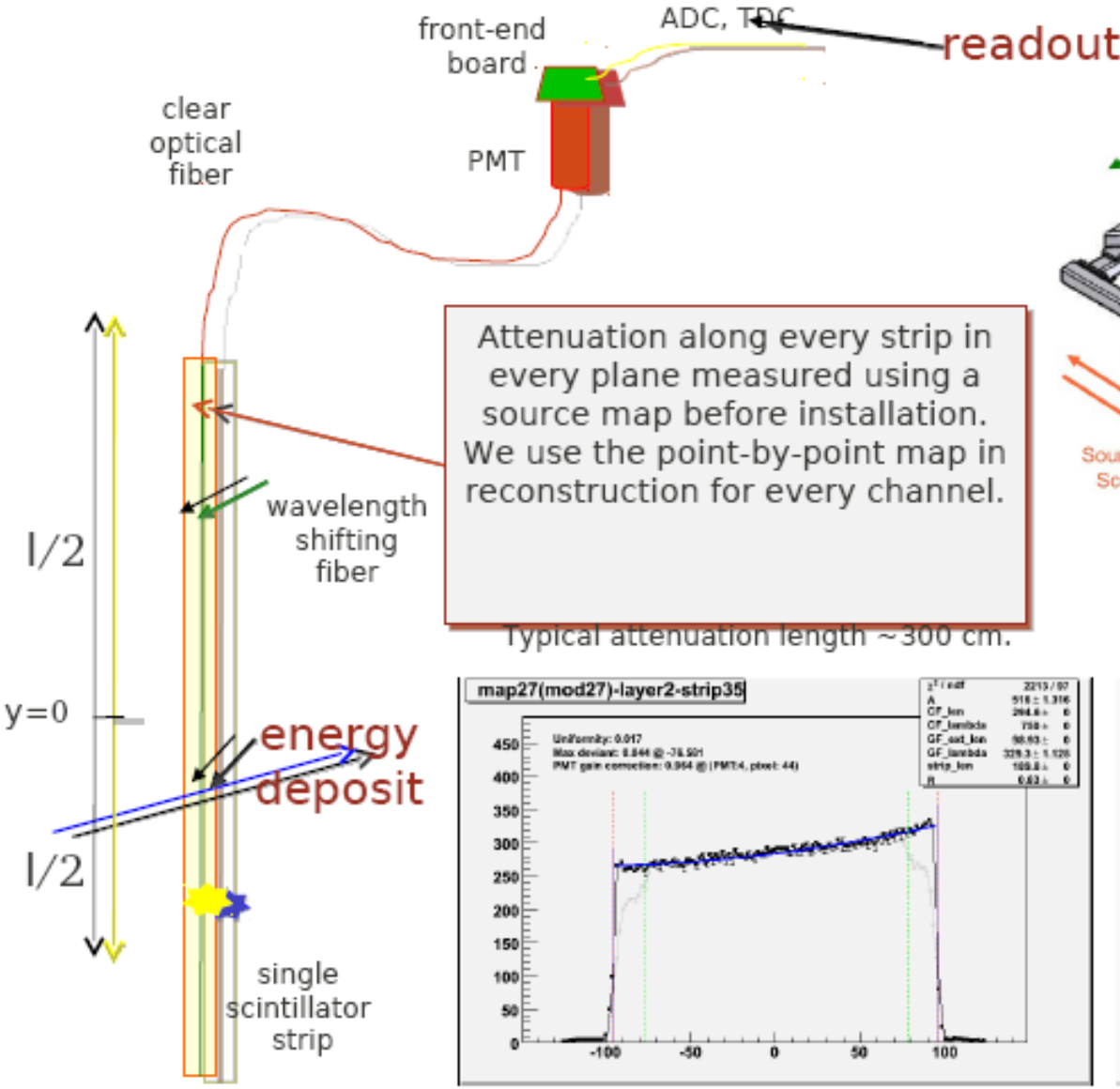
Charge to ADC conversion function measured on a test stand for every channel on every board before installation on the detector

PMT gains measured continuously *in-situ* using Light Injection system



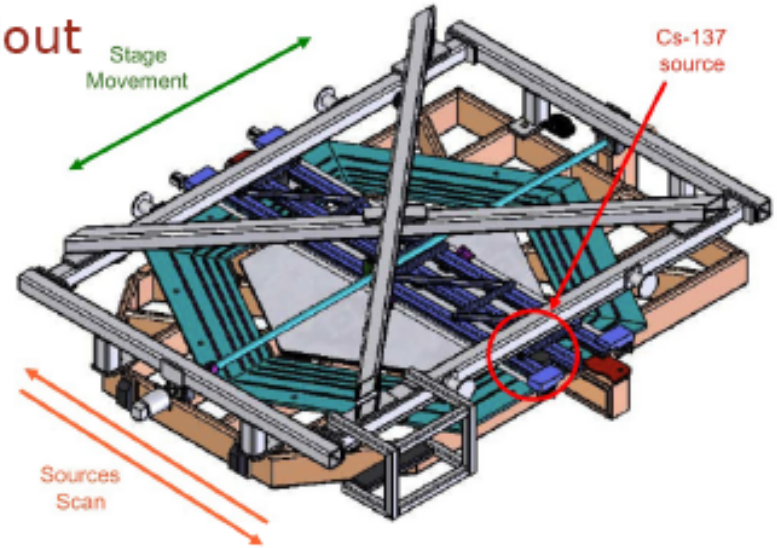
*slide from M. Kordosky

Detector Calibration

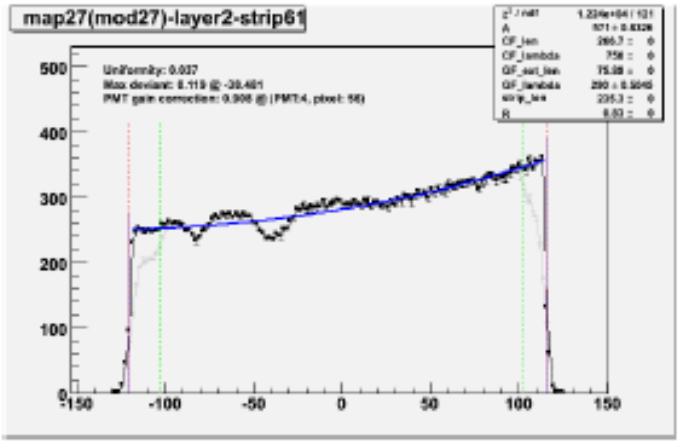


Attenuation along every strip in every plane measured using a source map before installation. We use the point-by-point map in reconstruction for every channel.

Typical attenuation length ~300 cm.

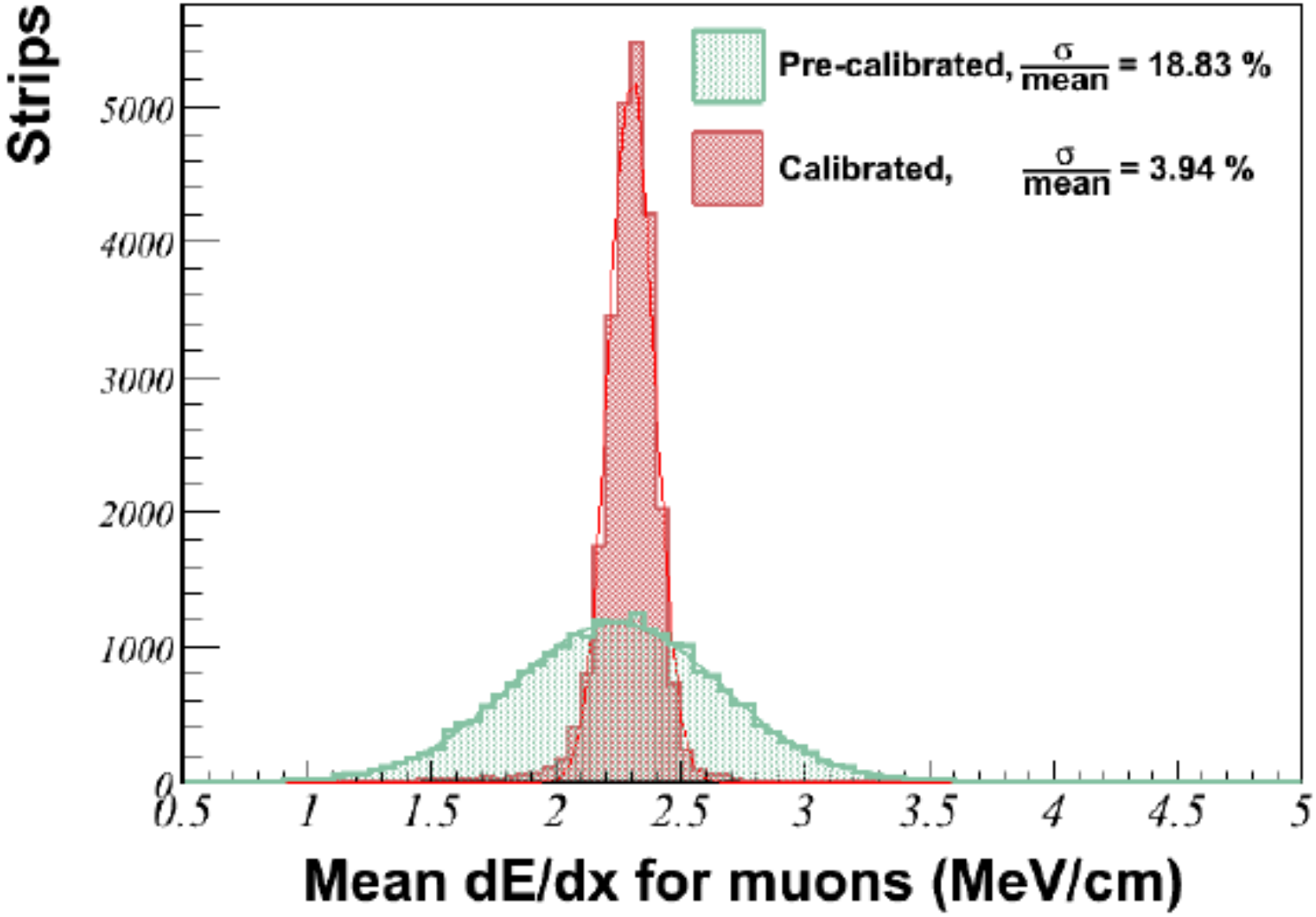


Map can find non-uniformities along the strip (e.g. air pockets in glue)



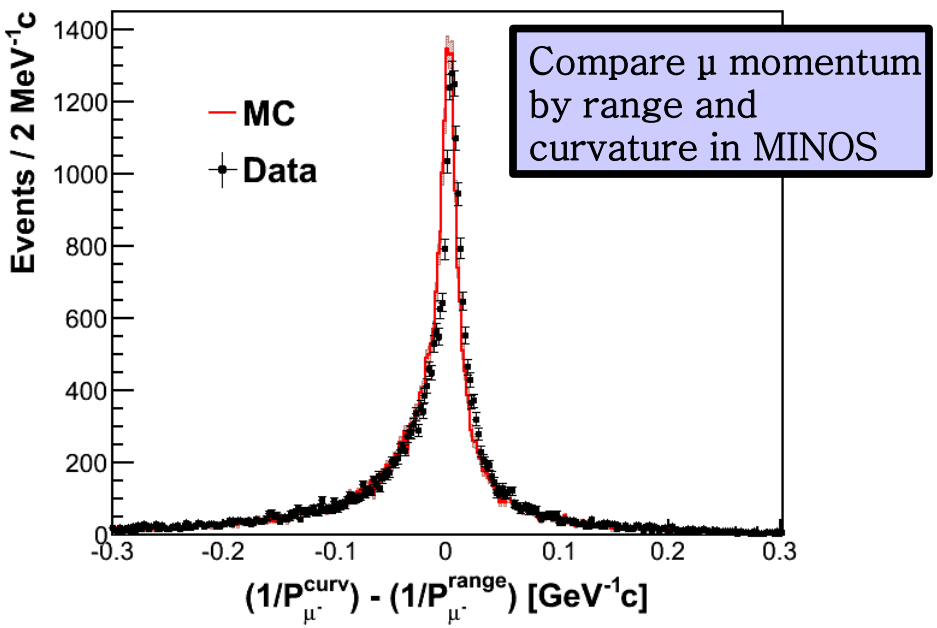
*slide from M. Kordosky

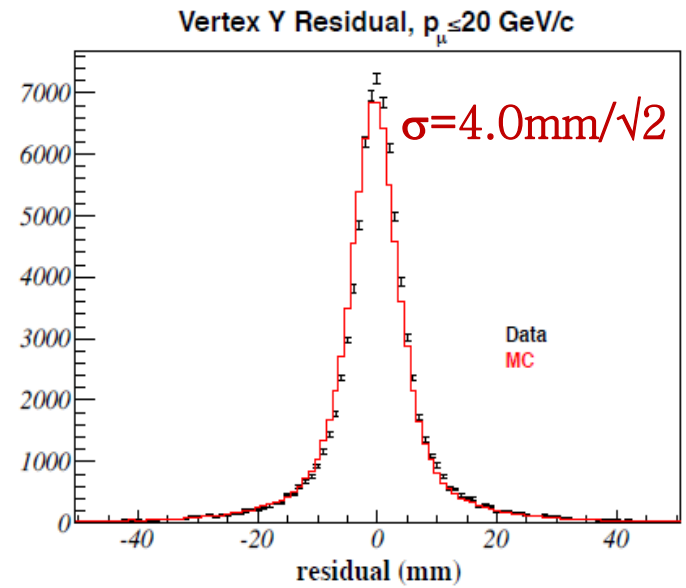
Alignment and strip response

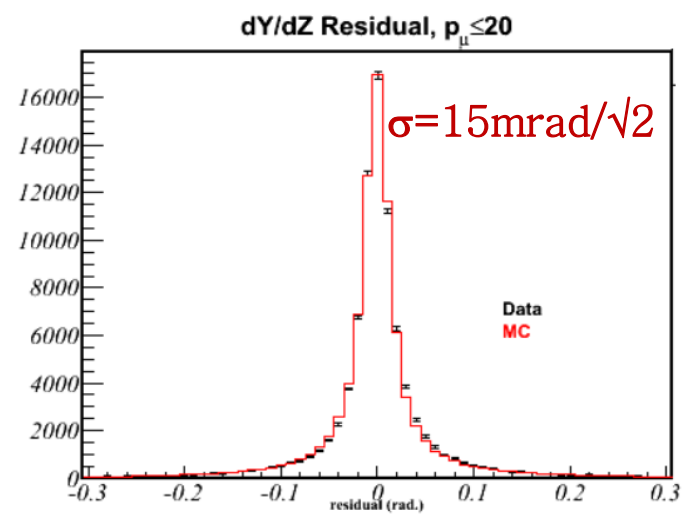


*slide from M. Kordosky

Muon Reconstruction



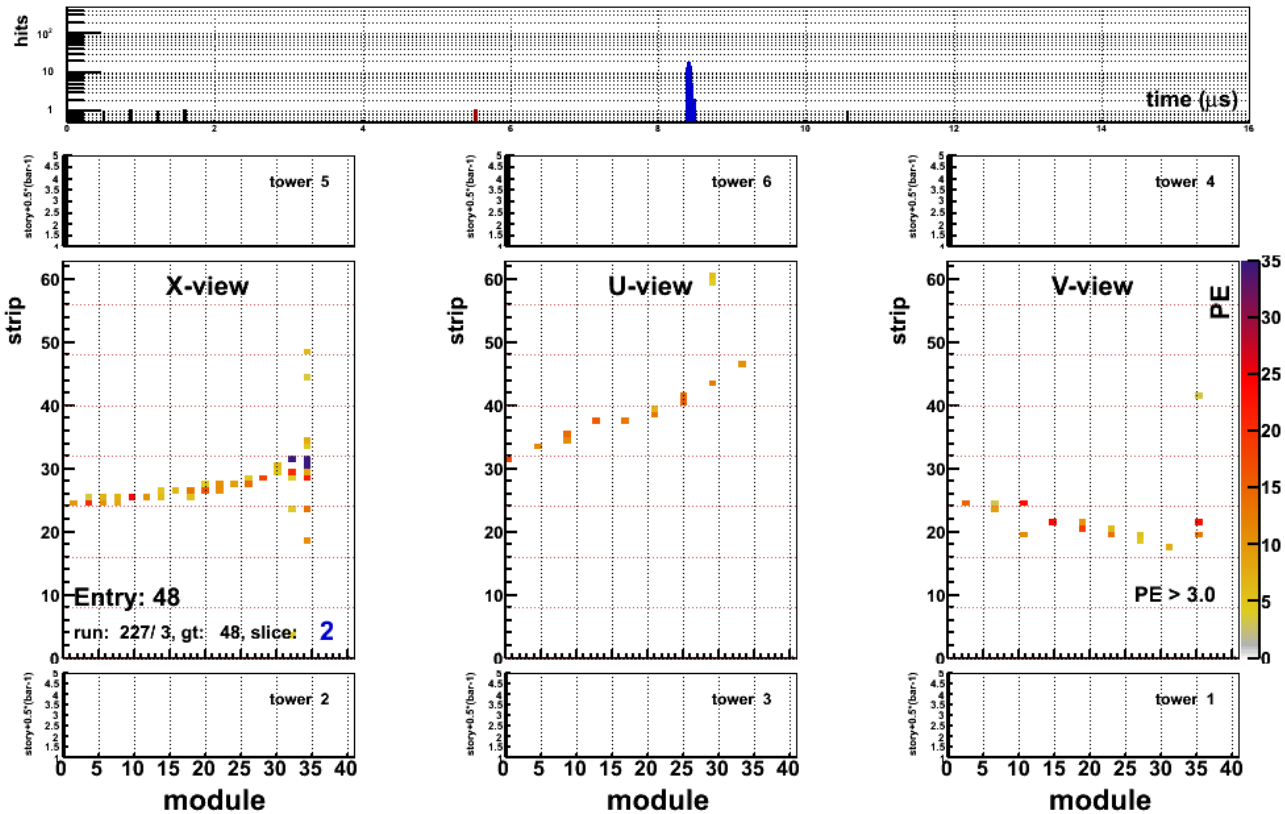




- Vertex and track slope residuals from split-track rock muon studies in tracker region

- Additional muon momentum uncertainties from dE/dX and mass models in MINOS, MINERvA

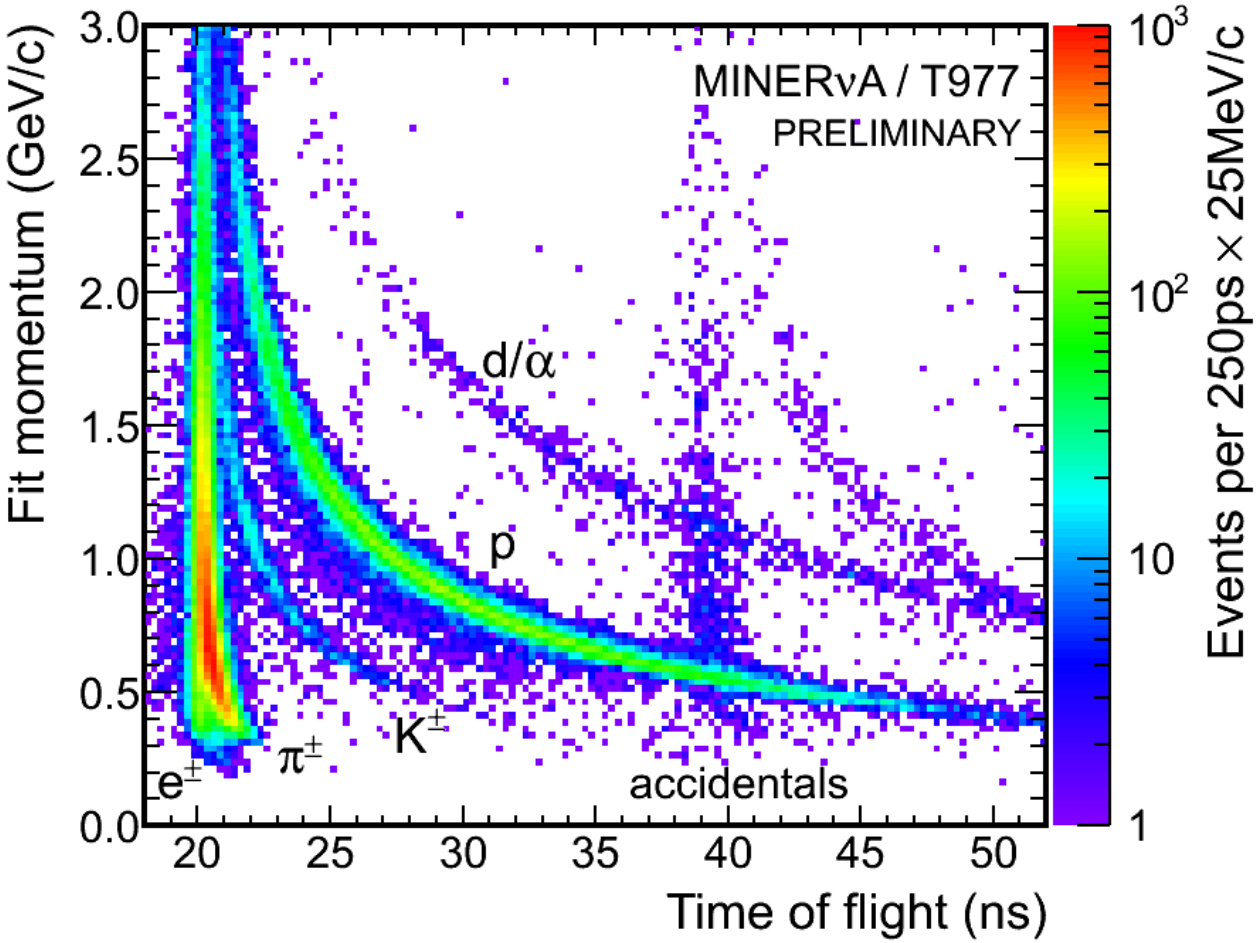
Test Beam π



- 20 ECAL 20 HCAL configuration
- 1.35 GeV interacting in HCAL

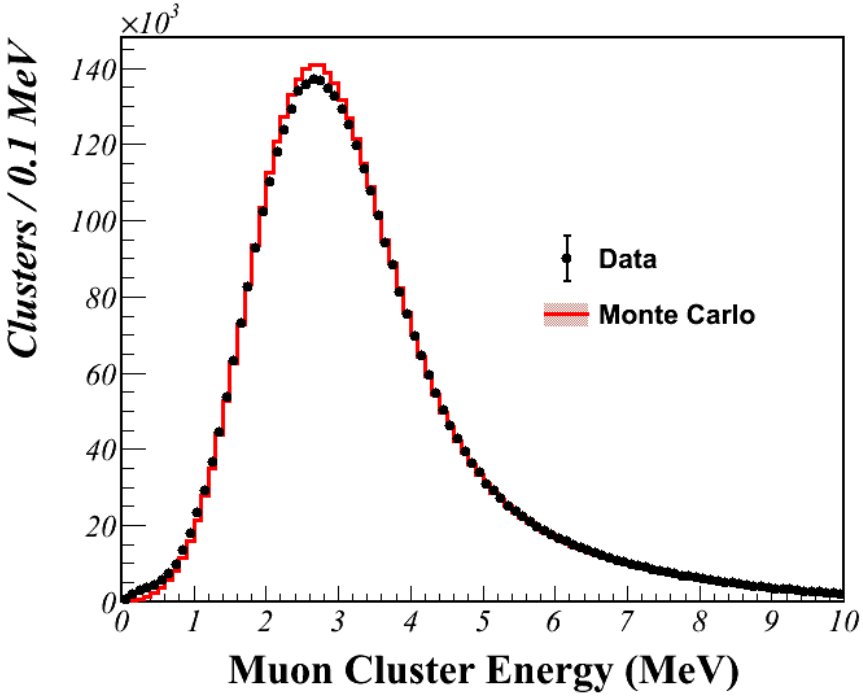
*slide from S. Manly

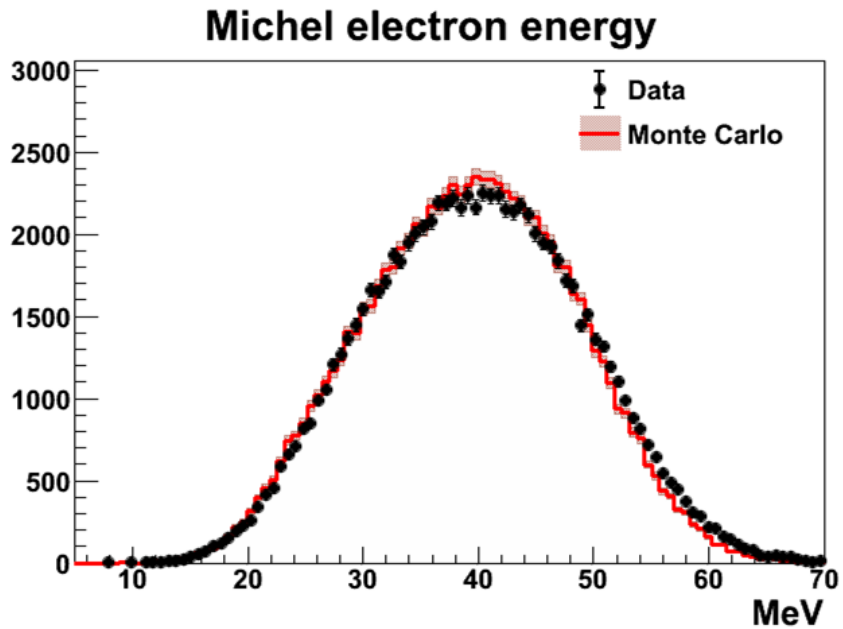
MINERνA Test Beam

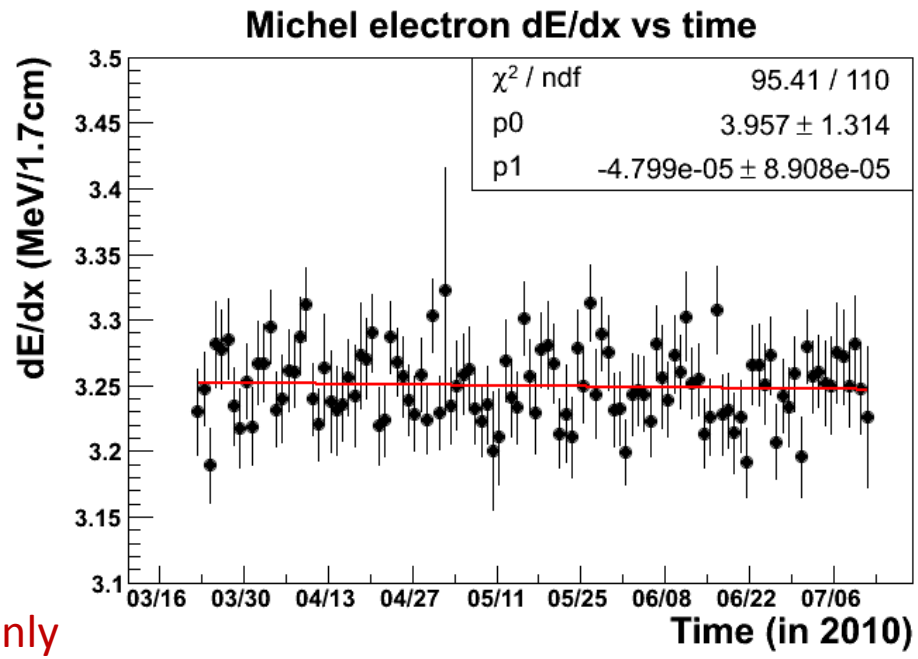


*slide from S. Manly

Energy scale and stability



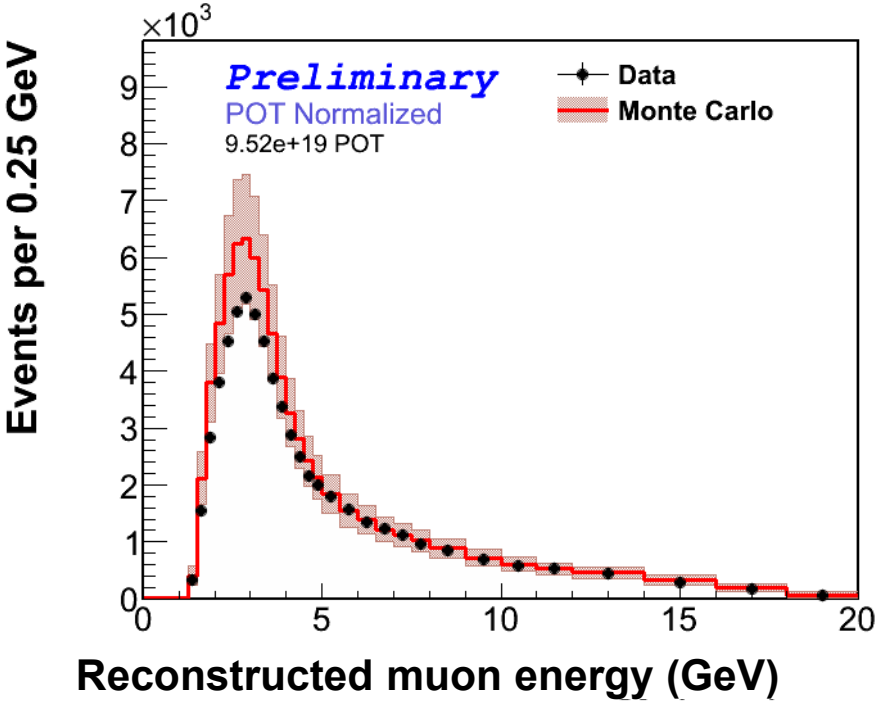


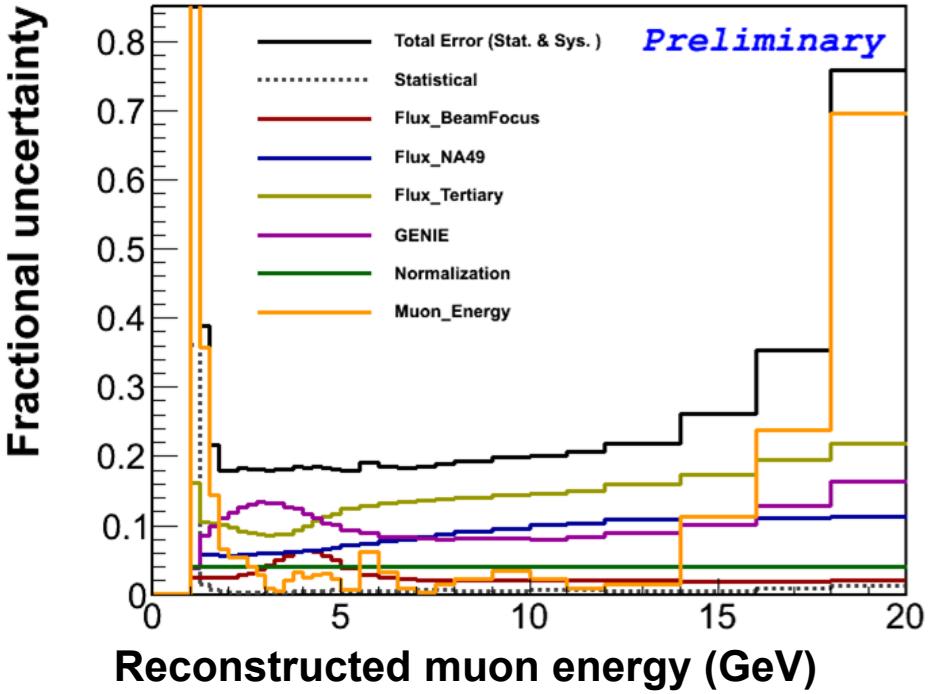


*slide from S. Manly

CC Inclusive Muon Energy

- MINERvA analysis of $\nu_\mu CH \rightarrow \mu^- X$
  - X is the recoil nucleus plus any number and type of hadrons



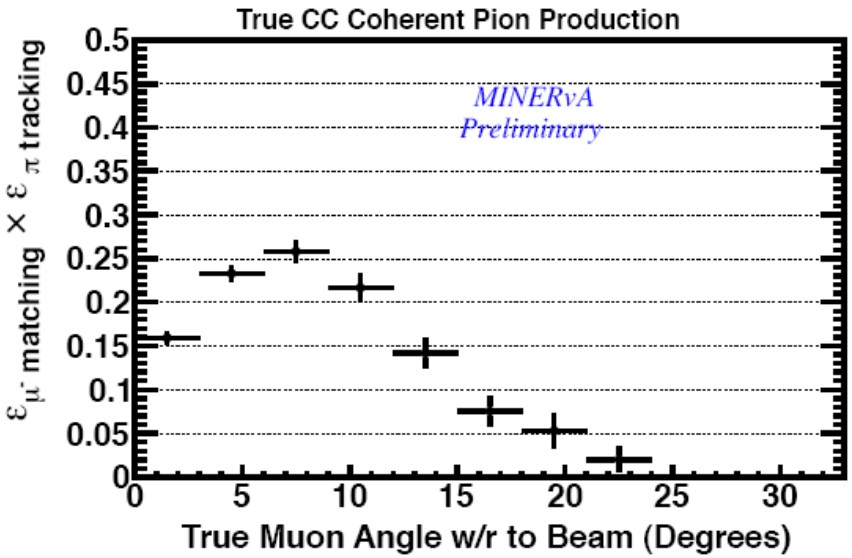


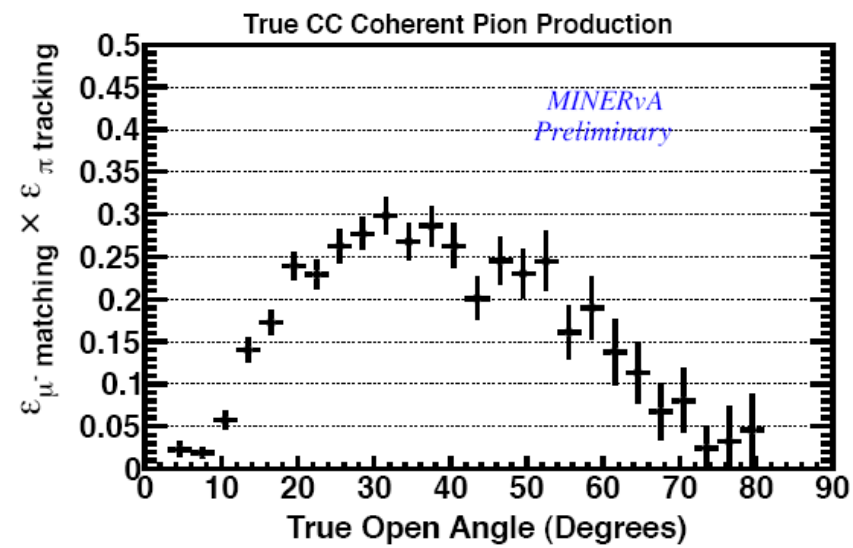
ν_μ CC Coherent Pion on CH

- Event pre-selection:
  - Vertex in scintillator fiducial volume
  - MINOS-matched muon
  - Muon Q/P < 0 (negative charge)
  - Exactly 2 tracks at interaction vertex

- Muons tend to be forward, so MINOS angular acceptance is not troublesome

- Low efficiency at small opening angle will be improved by recent advances in reconstruction

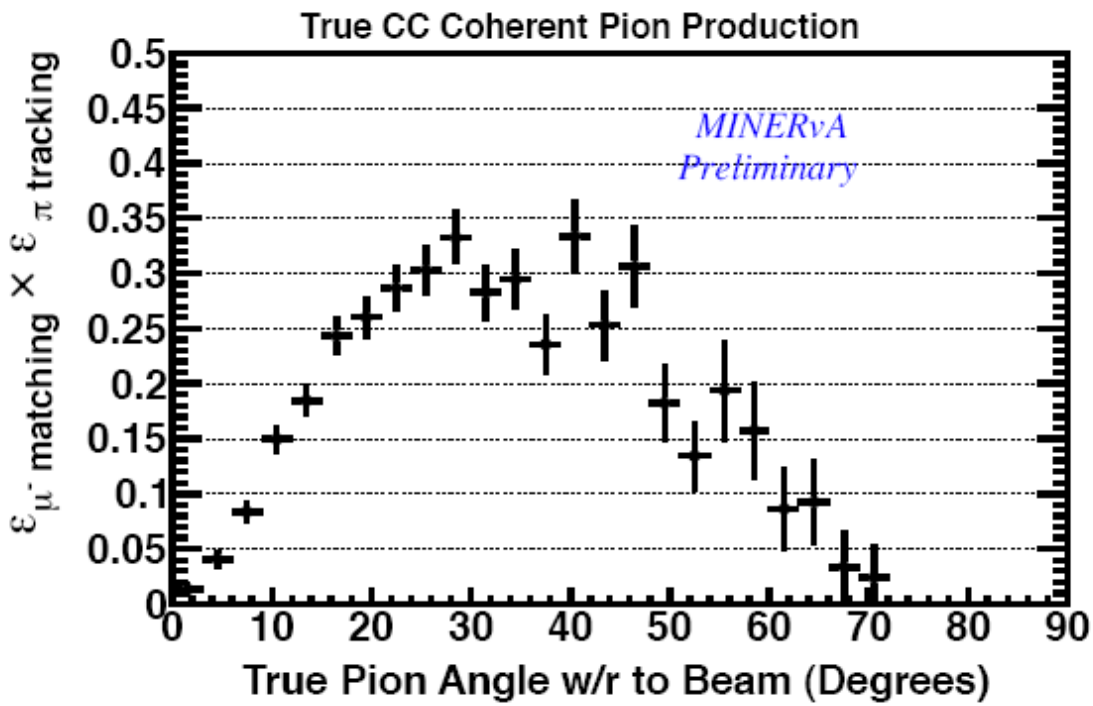




CC Coherent Pion Analysis

- Event pre-selection:
  - MINOS-matched muon with p < 20 GeV/c
  - Muon Q/P < 0 (negative charge)
  - Exactly 2 tracks at interaction vertex

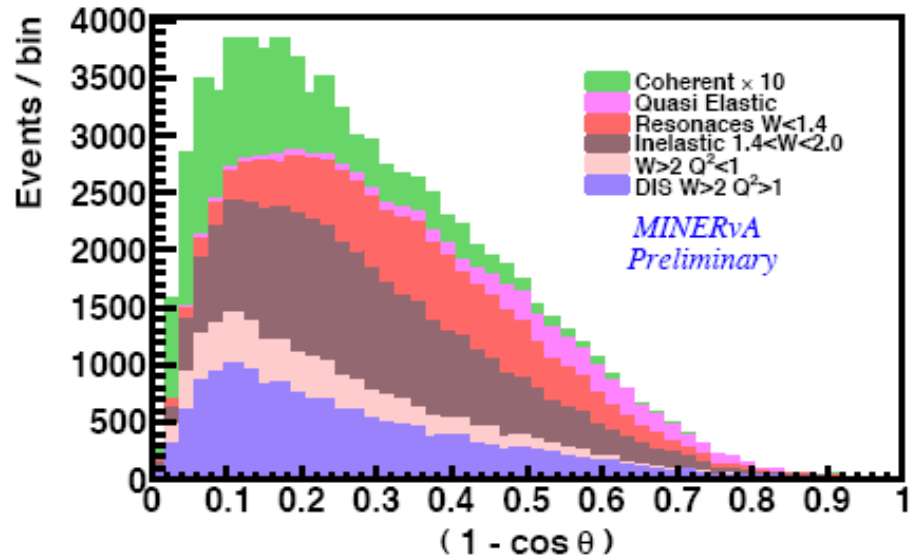
- Pion Angle efficiency follows the opening angle efficiency closely

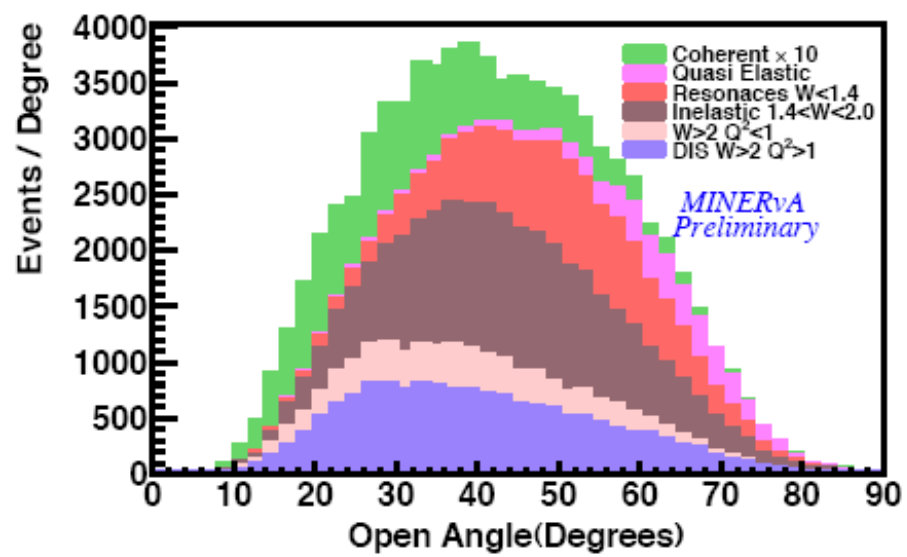


CC Coherent Pion Analysis

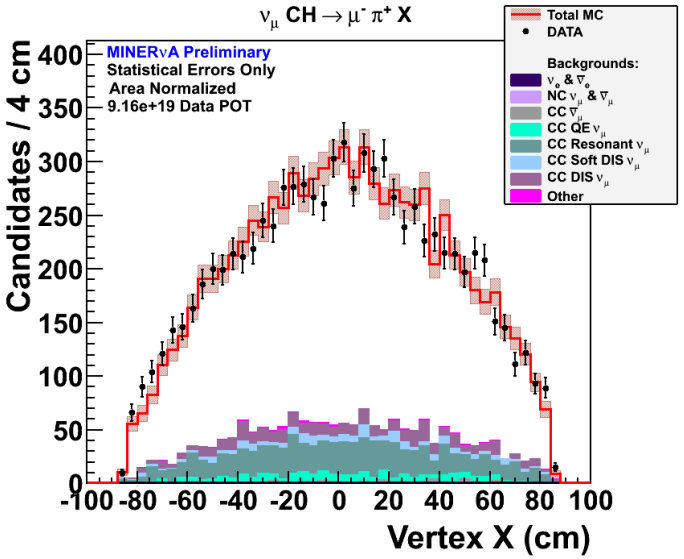
- Event pre-selection:
  - MINOS-matched muon with p < 20 GeV/c
  - Muon Q/P < 0 (negative charge)
  - Exactly 2 tracks at interaction vertex

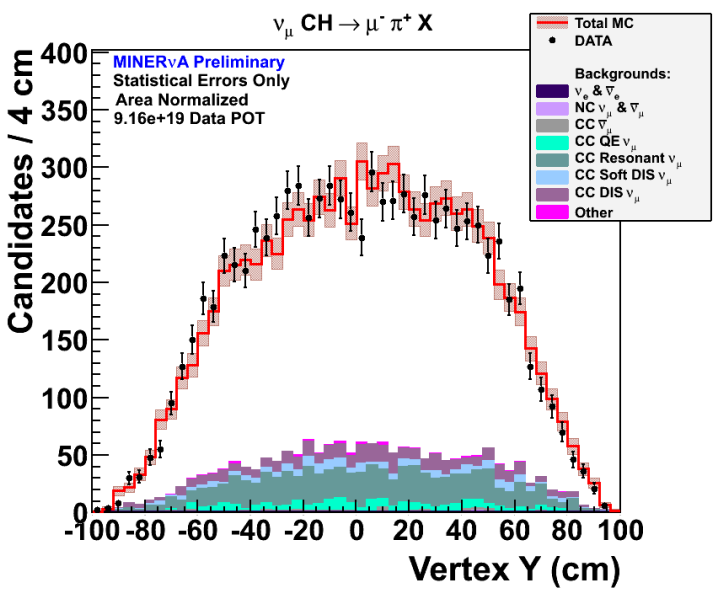
- Rein-Sehgal model predicts broad distribution of pion angle and opening angle compared to recent models

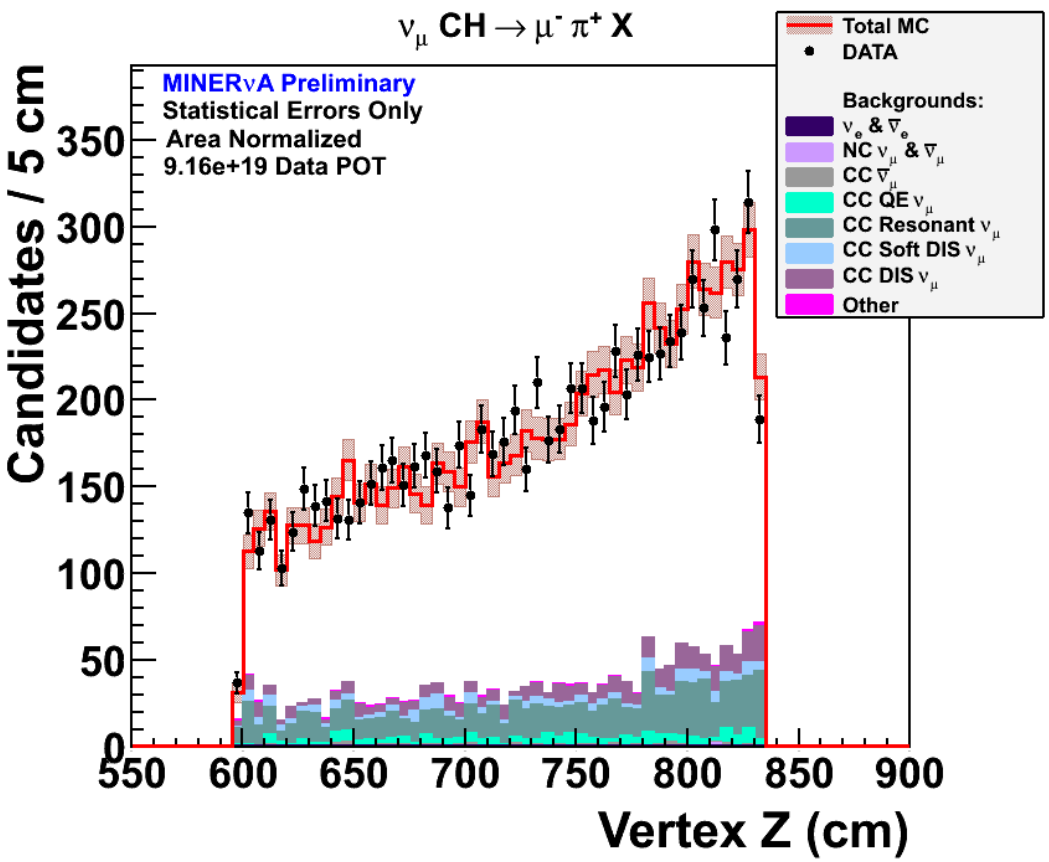
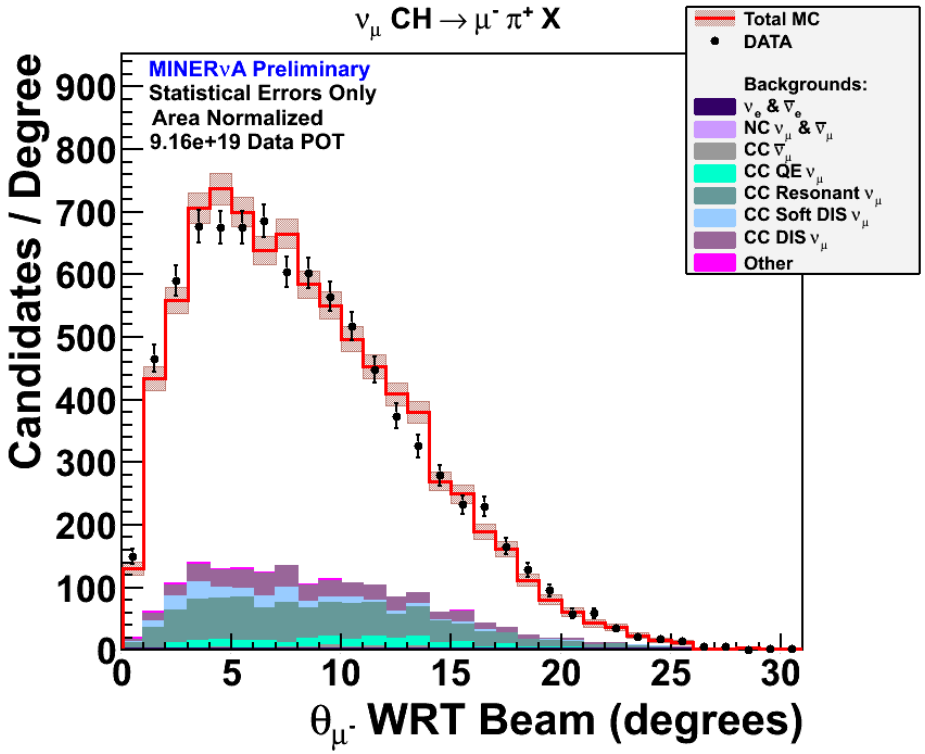
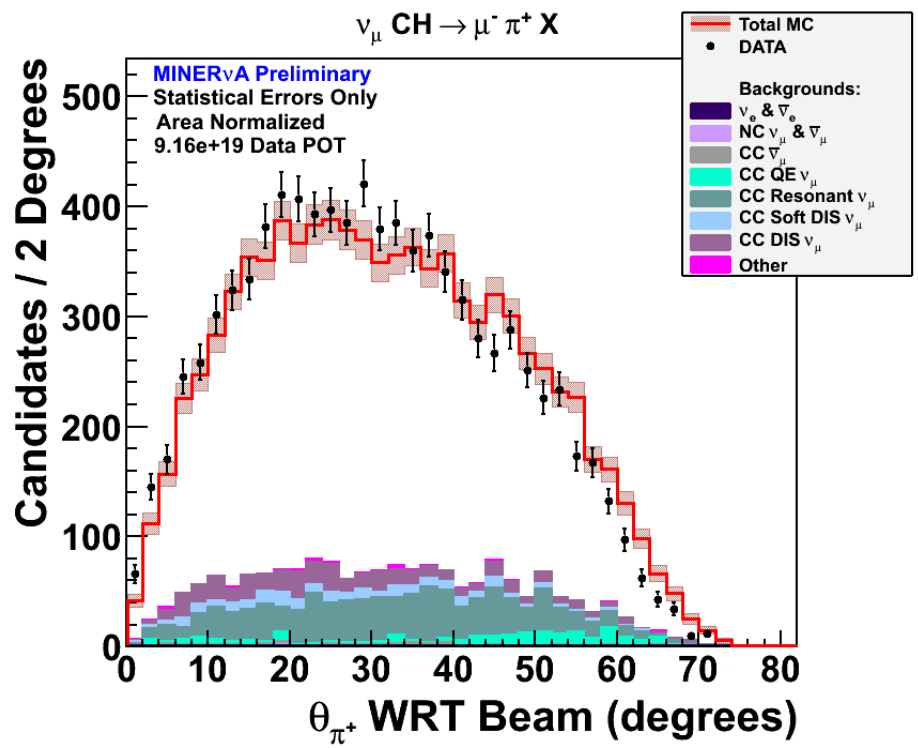




CC Inclusive Pion Analysis







CC Inclusive Pion Analysis