Status Update for the MINERvA Experiment

Rencontres de Moriond
Electroweak and Unified Theories
March 19, 2011

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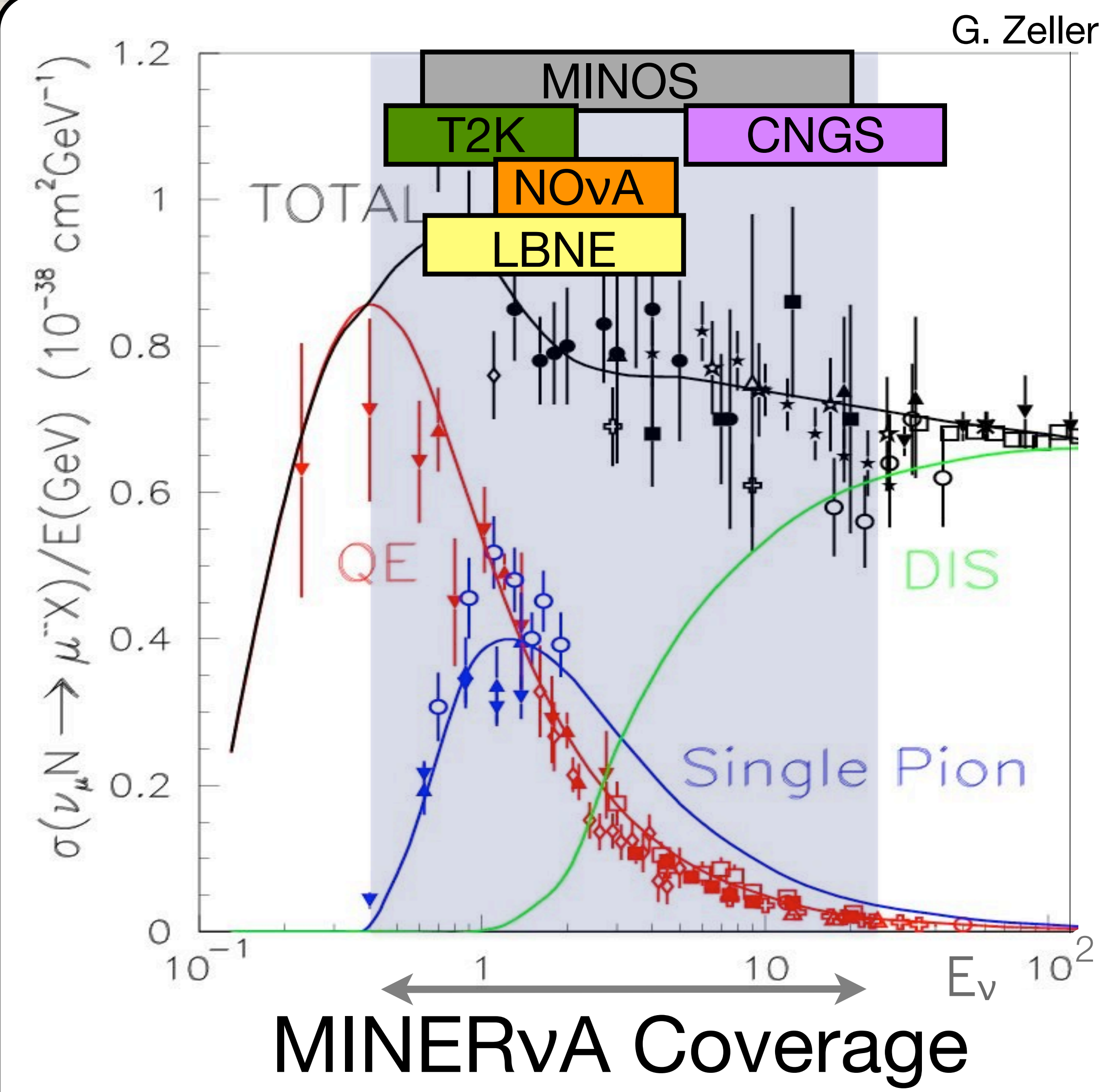
Outline

- **Introduction to MINERνA: ν-nucleus scattering experiment.**
- **Beam and Detector.**
  - **Flux Estimation.**
- **Current Analysis Efforts.**
  - **Quasi-Elastic Scattering.**
- **Calibration: The MINERνA Test Beam Program.**

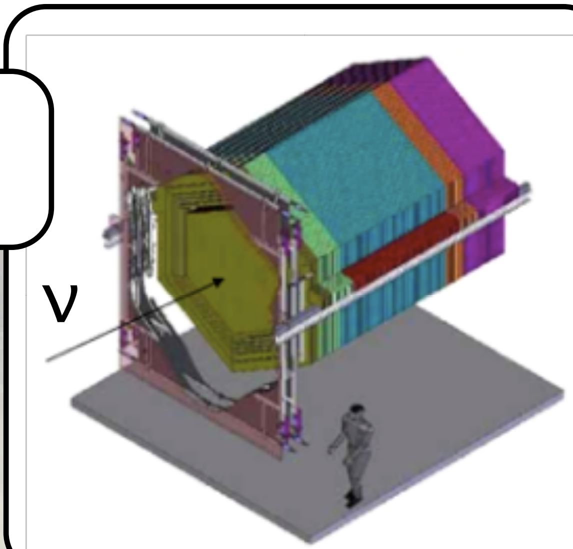
MINERνA

(Main INjector ExpeRiment ν-A)

- ***What***: Dedicated neutrino-nucleus cross-section experiment running at Fermilab in the NuMI (Neutrinos at the Main Injector) beamline.
- ***Why***: Low energy (less than 10 GeV) cross-sections are poorly measured.
- ***Why***: Provides critical input to future neutrino oscillation experiments.
- ***Why***: Unique (weak-only) probe of the nucleus. Many poorly measured quantities of interest (axial form factors as a function of A and momentum transfer (Q^2), quark-hadron duality, x-dependent nuclear effects, etc.).

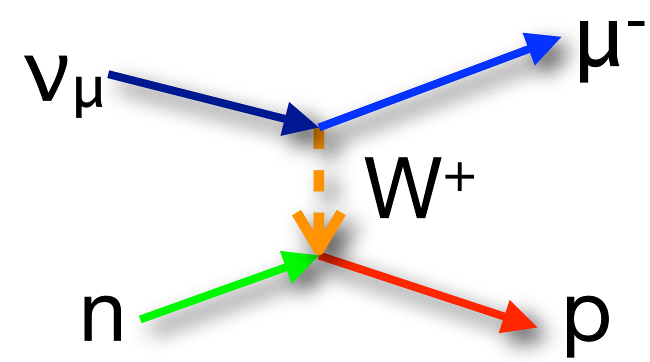


No MiniBooNE results on this plot, but hold that thought...

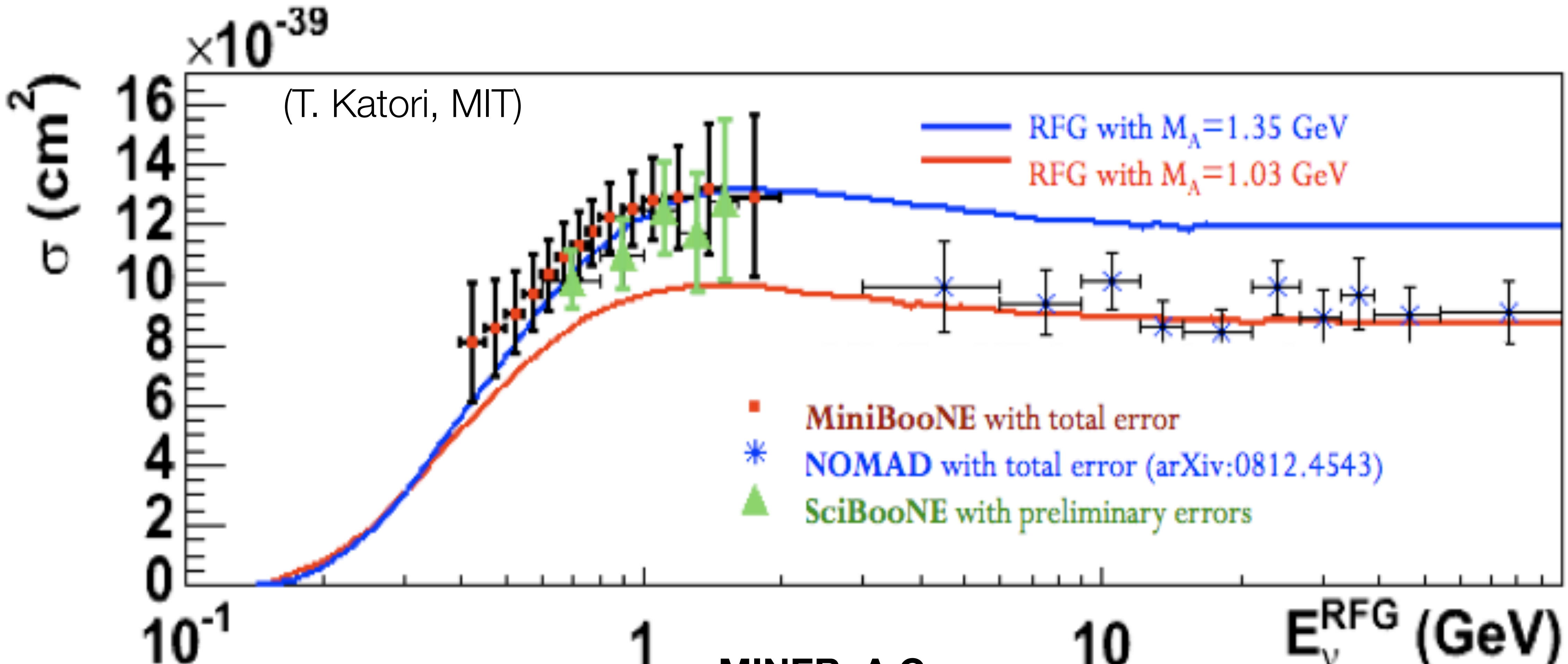


MINERνA

Charged Current Quasi-Elastic (CCQE) Scattering on Carbon



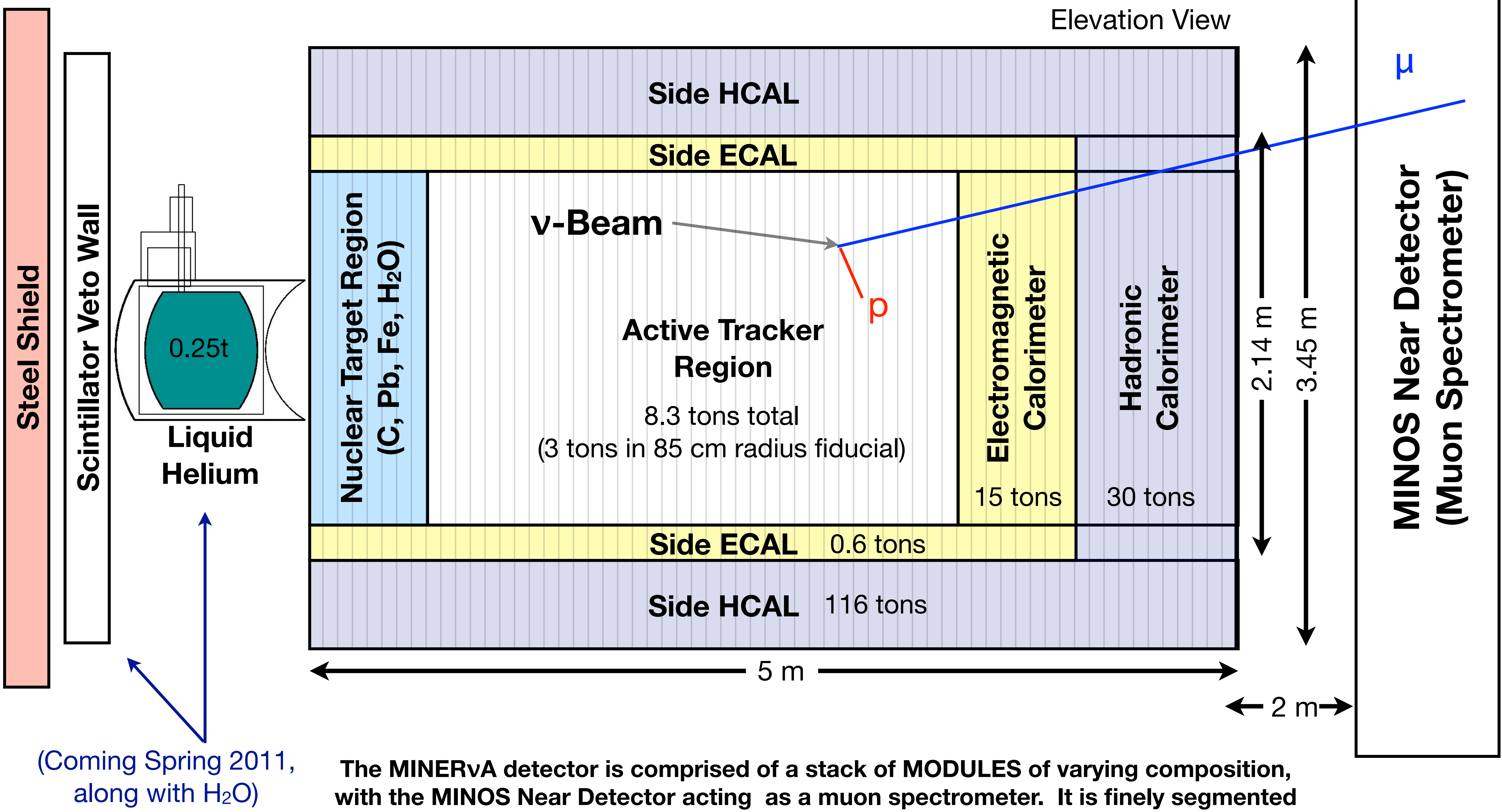
- Open questions in interaction physics abound. For example:
  - MiniBooNE & SciBooNE are in agreement, but conflict with NOMAD data at higher energy. MINERvA is well suited to address this discrepancy.
- Kind of a big deal - quasi-elastics are a primary signal in oscillation experiments!



MINERvA Coverage

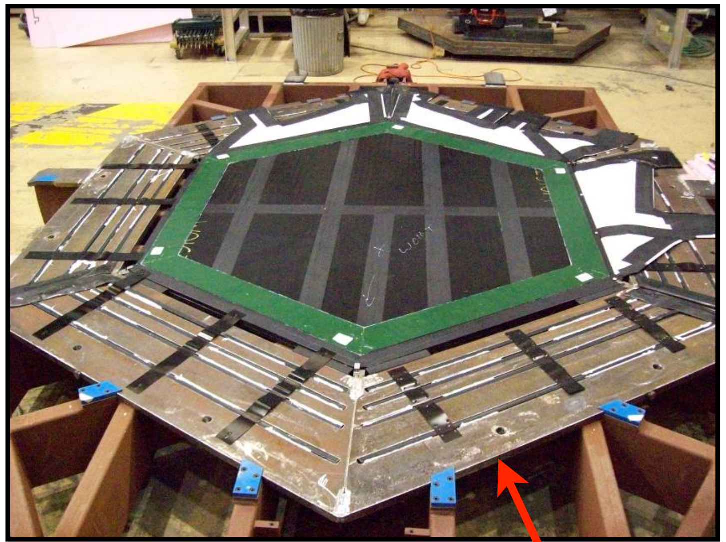
We will fill this gap!

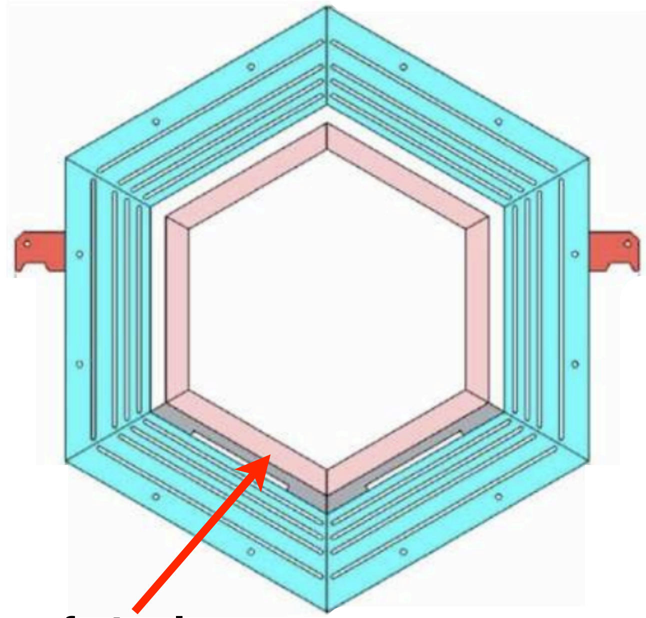
The Best Thing Since Sliced Bread...

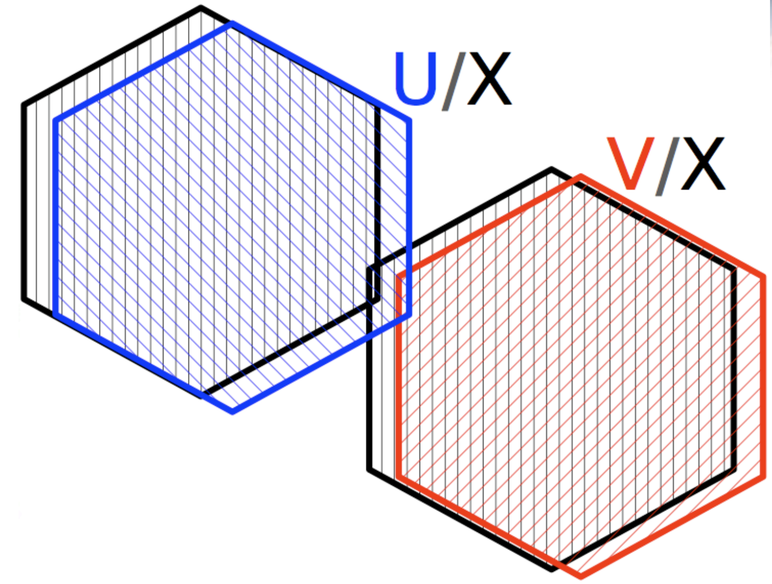


The MINERvA detector is comprised of a stack of MODULES of varying composition, with the MINOS Near Detector acting as a muon spectrometer. It is finely segmented (~32 k channels) with multiple nuclear targets (C, CH, Fe, Pb, He, H_2O).

MINERνA Modules

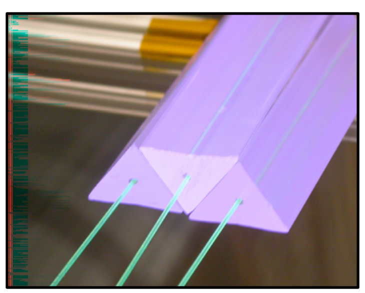




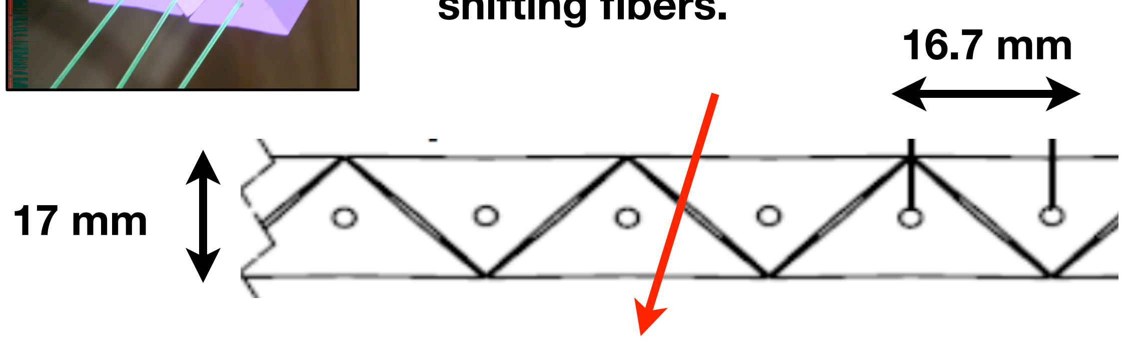


Modules have an outer detector frame of steel and scintillator and an inner detector element of scintillator strips and absorbers/targets.

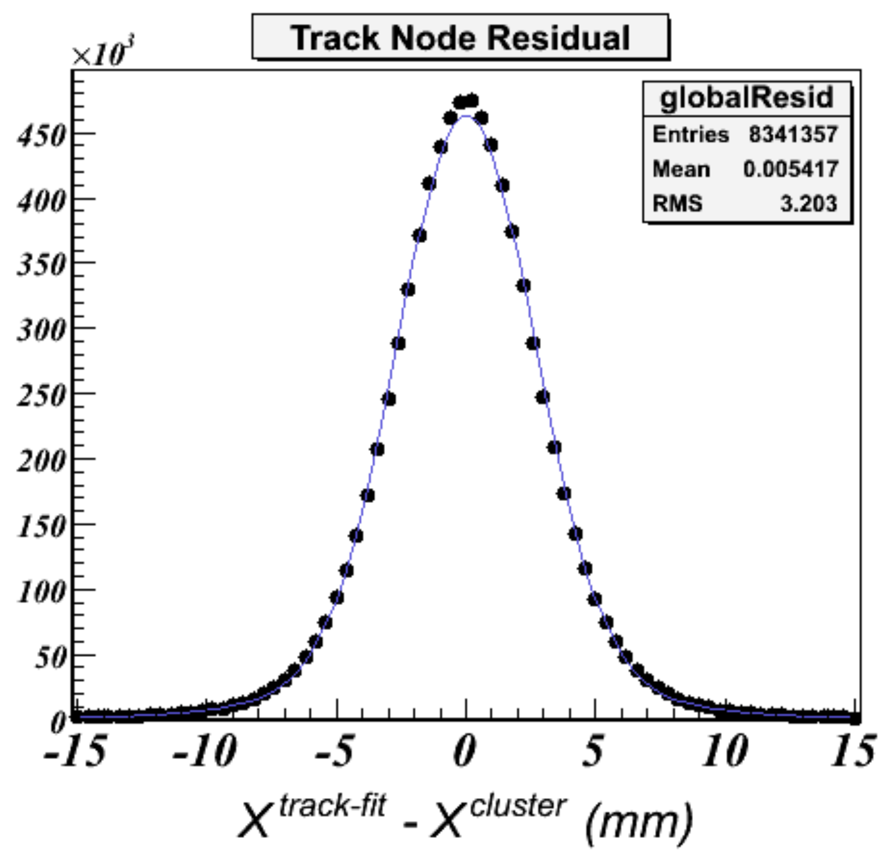
Planes are mounted stereoscopically in XU or XV orientations for 3D tracking.



Extruded scintillator & wavelength shifting fibers.



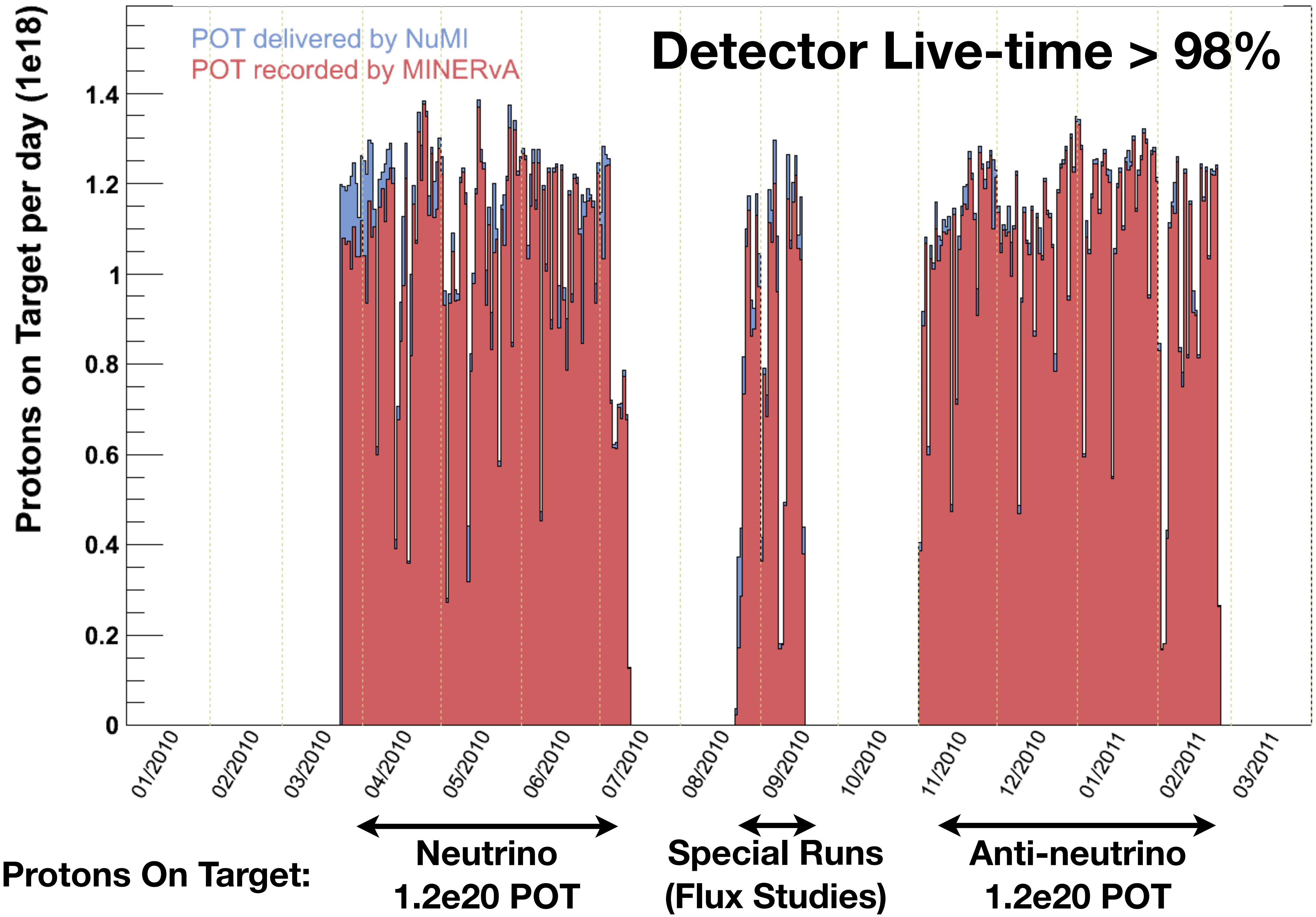
Charge-sharing for improved position resolution (~3.5 mm).



Residual between a fitted position along a track and the charge-weighted hit in that plane for a sample of through-going muons.

Data Collection

- Completed full detector installation in March, 2010.
- Running in NuMI "Low Energy" mode.



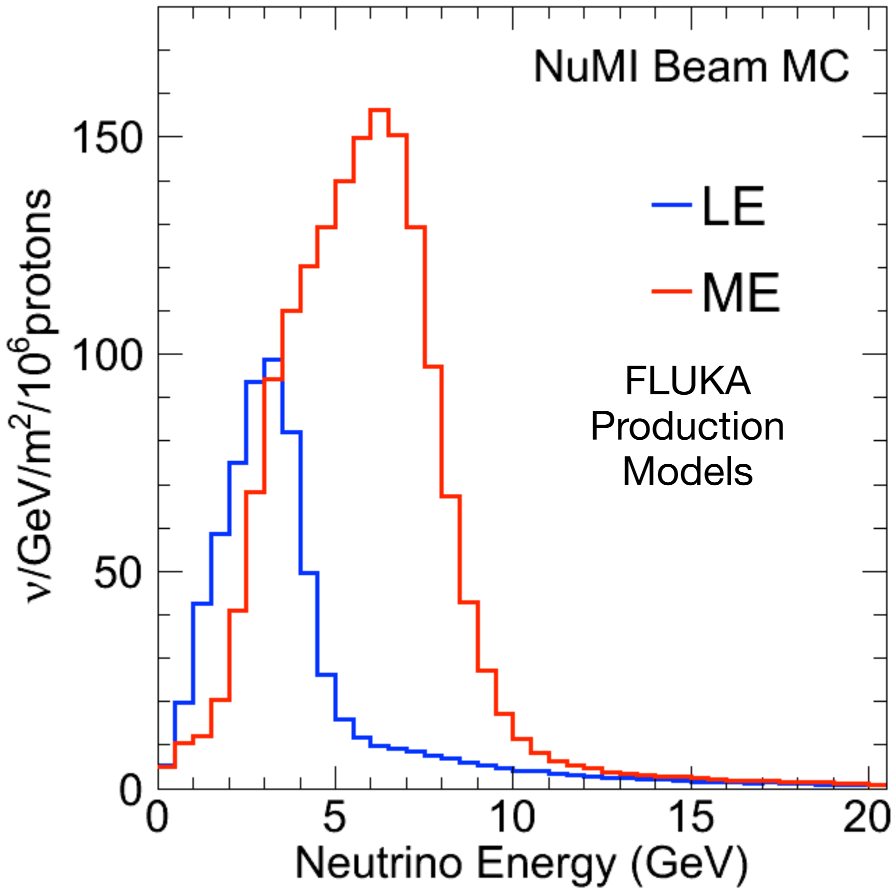
MINERvA Event Rates

Current Data Sample (GENIE 2.6.2 Generator Raw Events)*

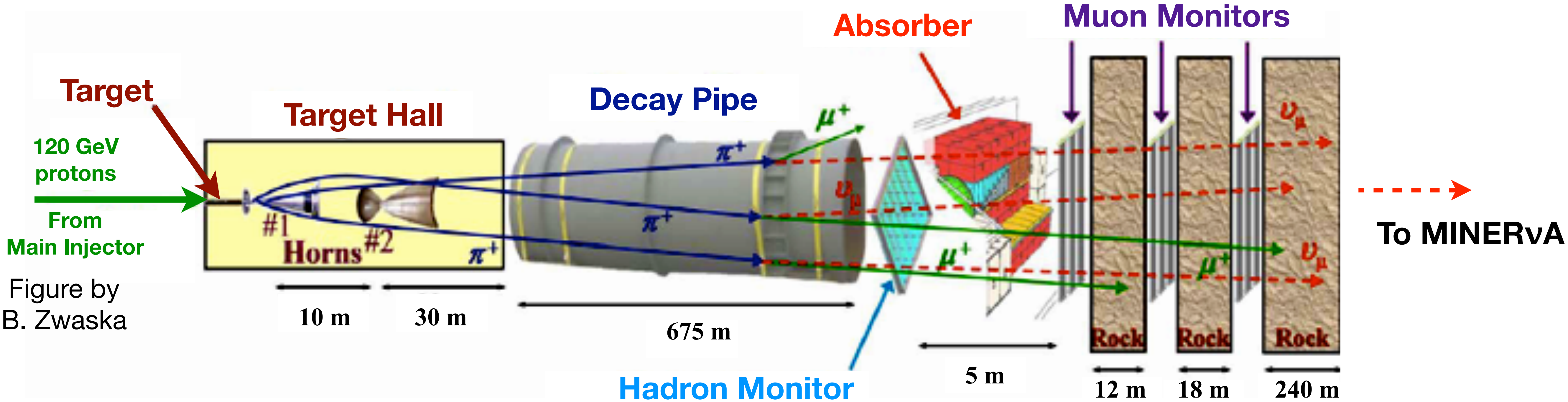
Target Masses: CH Fiducial = 6.43 tons, C = 0.17 tons, Fe = 0.97 tons, Pb = 0.98 tons w/ 90 cm vertex radius cut.
(* http://www.genie-mc.org)

	1.2e20 POT Low Energy Neutrino Mode	1.2e20 POT Low Energy Anti-neutrino Mode
Coherent Pion Production	4k	3k
Quasi-Elastic	84k	46k
Resonance Production	146k	62k
Deep Inelastic Scattering, Structure Functions, High-x PDFs	168k	19k
Carbon Target	10.8k	3.4k
Iron Target	64.5k	19.2k
Lead Target	68.4k	10.8k
Scintillator (CH) Tracker	409k	134k

The NuMI Beam



- The energy spectrum of the NuMI ν beam is tunable by changing the position of the target relative to the focusing horns.
    - Can produce “Low”, “Medium”, and “High” (not shown spectra).
    - By flipping horn current we can focus π^+ particles for “ν mode” or π^- particles for “anti-ν mode.”
- Extremely intense - <35e12> P.O.T. per spill at 120 GeV with a beam power of 300-350 kW at ~0.5 Hz.
- Current run plan is 4.9e20 P.O.T. in the “low-energy” (LE) neutrino configuration and 12e20 P.O.T. in the “medium-energy” (ME) configuration.



Measuring the Neutrino Flux

- Targeting ~10% flux uncertainty.
- Multi-prong approach:
  - In-situ measurements with muon monitors spaced through the rock shielding (different depths sample different momentum spectra).
  - Leverage existing hadron production data.
  - Vary the beam parameters (horn current, target position) to deconvolve systematics and tune production Monte Carlo's (MC's).
    - This last is the most novel of the three, and is a feature of the NuMI beamline.

By moving the target and changing the current, we focus different parts of the pion production spectrum.

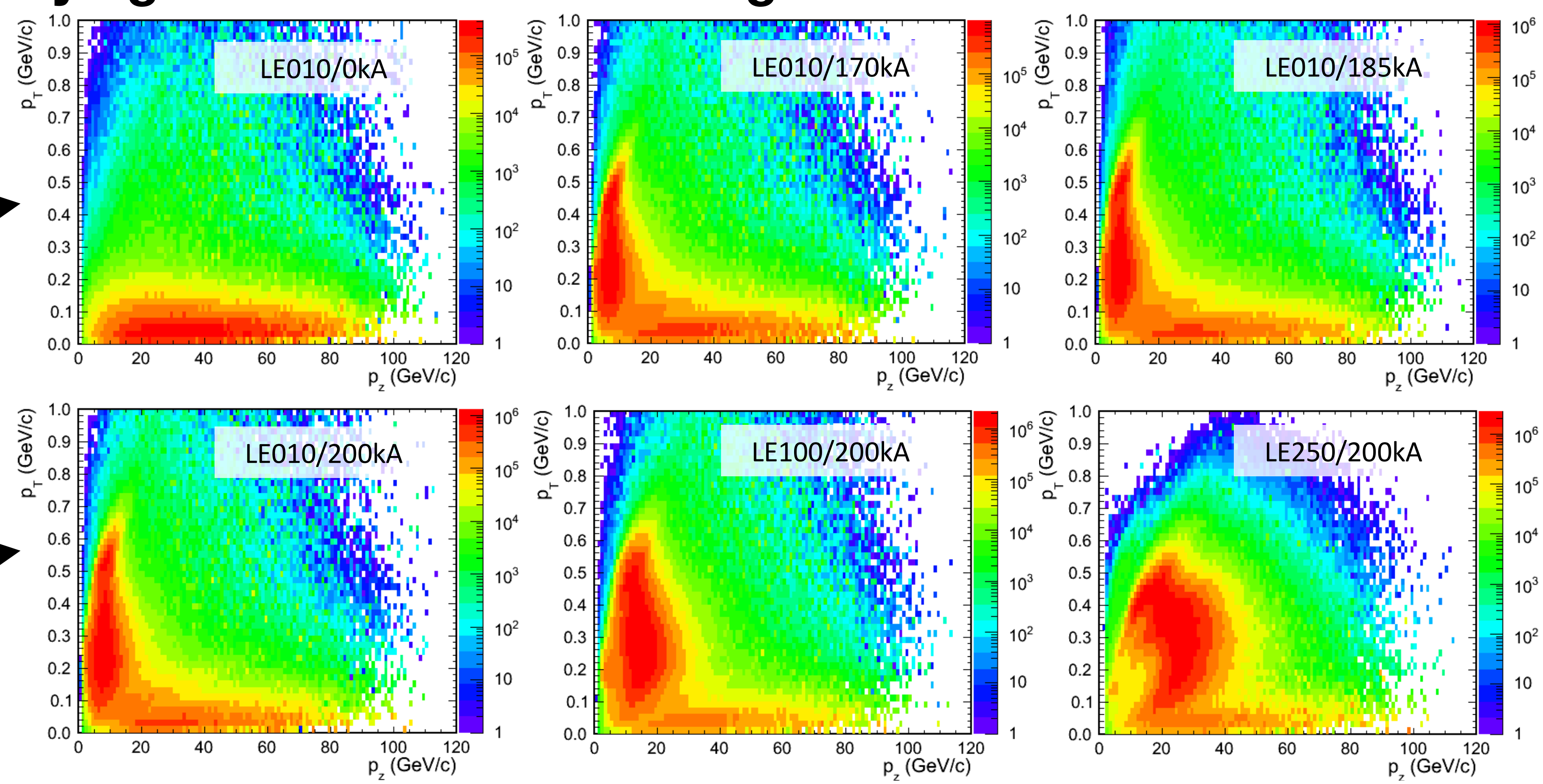
Measuring the Neutrino Flux

- **Largest uncertainty is hadron production on the target. Beamline uncertainties are easier to model.**
- **NuMI can provide a variable spectrum by focusing charged pions produced at the target. We can control:**
  - **Magnetic focusing horn current (focus different P_T's),**
  - **Target position (focus $x_F = P_Z/P_T$).**

Pion P_T vs. P_Z (GeV/c), *Weighted by Neutrino Events* for Varying Horn Currents and Target Positions

0kA, 170kA, etc. label the horn current. Higher currents focus higher P_T's.

LE010, LE100, etc. label the target position. Moving the target back (LE100 > LE010) focuses higher energy pions.



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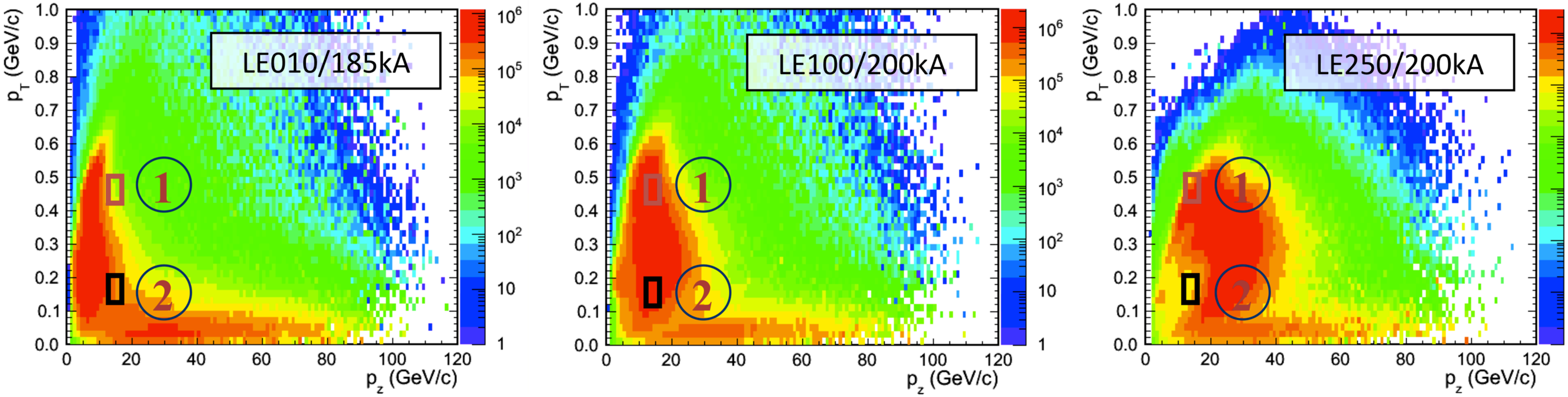
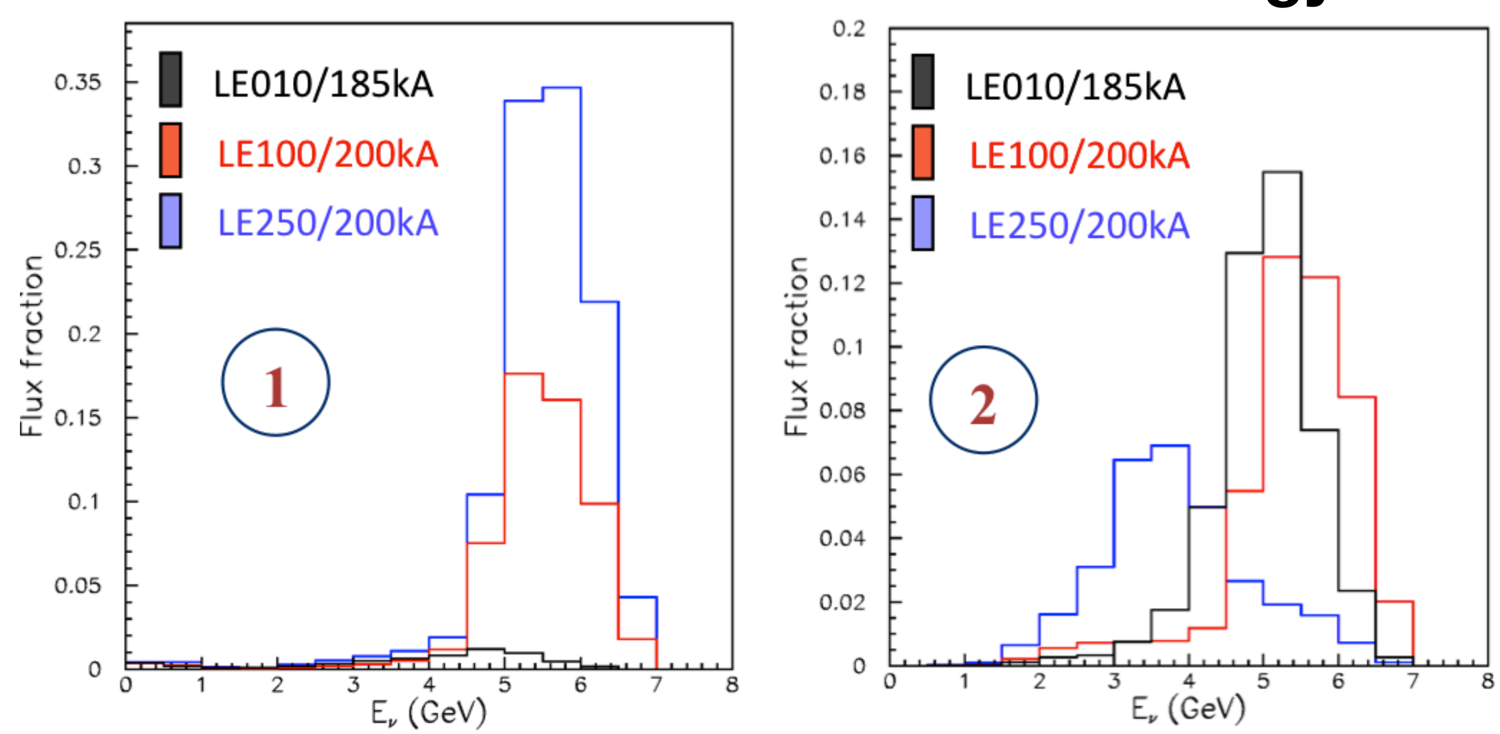
Measuring the Neutrino Flux



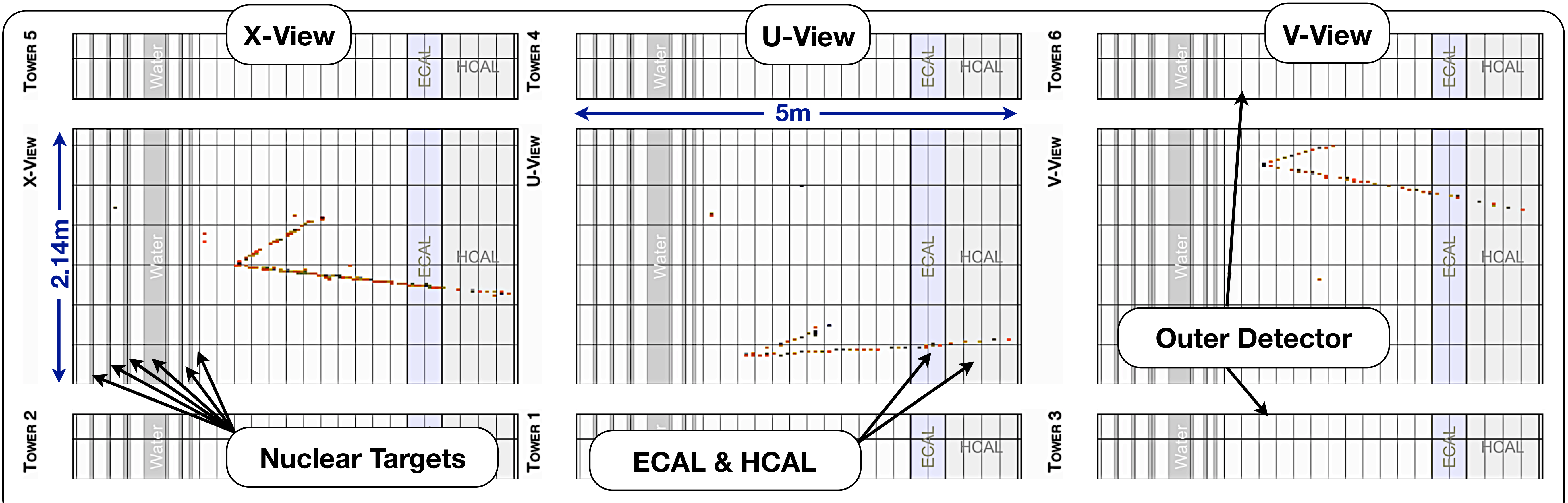
- Each (x_F,P_T) bin contributes with different weights in each beam configuration.
- Use a moderate Q^2 ($0.2 < Q^2 < 0.9$ GeV^2) Quasi-elastic “standard candle” (cross-section is a function of Q^2 and not energy) and normalize to high energy data sets to fix the normalization.
  - Cross-section ratio to reference provides weights in (x_F, P_T) for π/K yields.

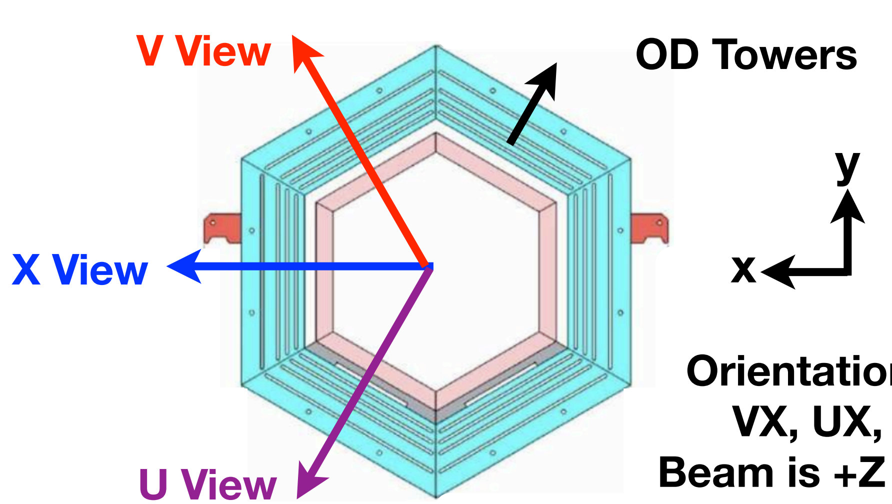
Flux Fraction vs. Neutrino Energy



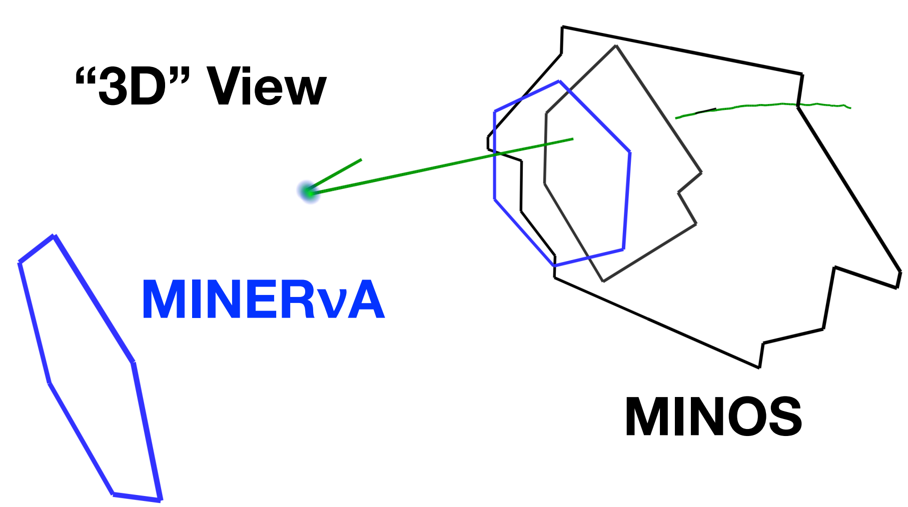
MINERνA Event Displays

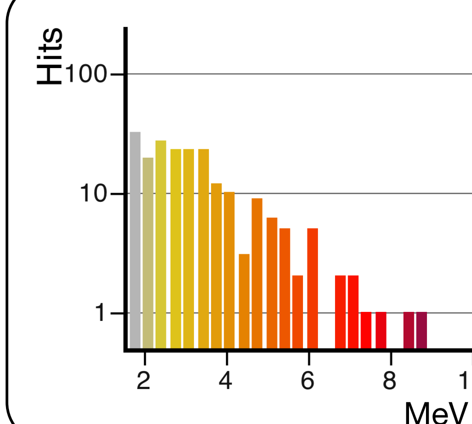
- Stereoscopic: 3 views X (view from above), U, V (∓60^0). X views are twice as dense!
- Strip vs. Module for the Inner Detector, Tower vs. Module for the Outer Detector.
- CCQEL Event Candidate.





Orientation in Z: UX, VX, UX, VX, etc. Beam is +Z (into page).





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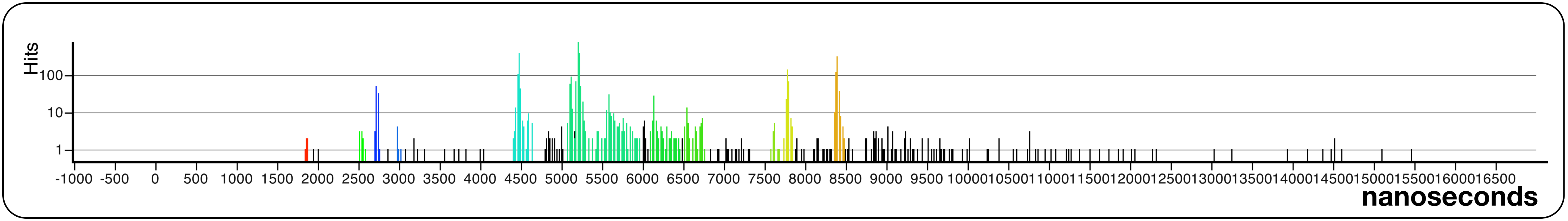
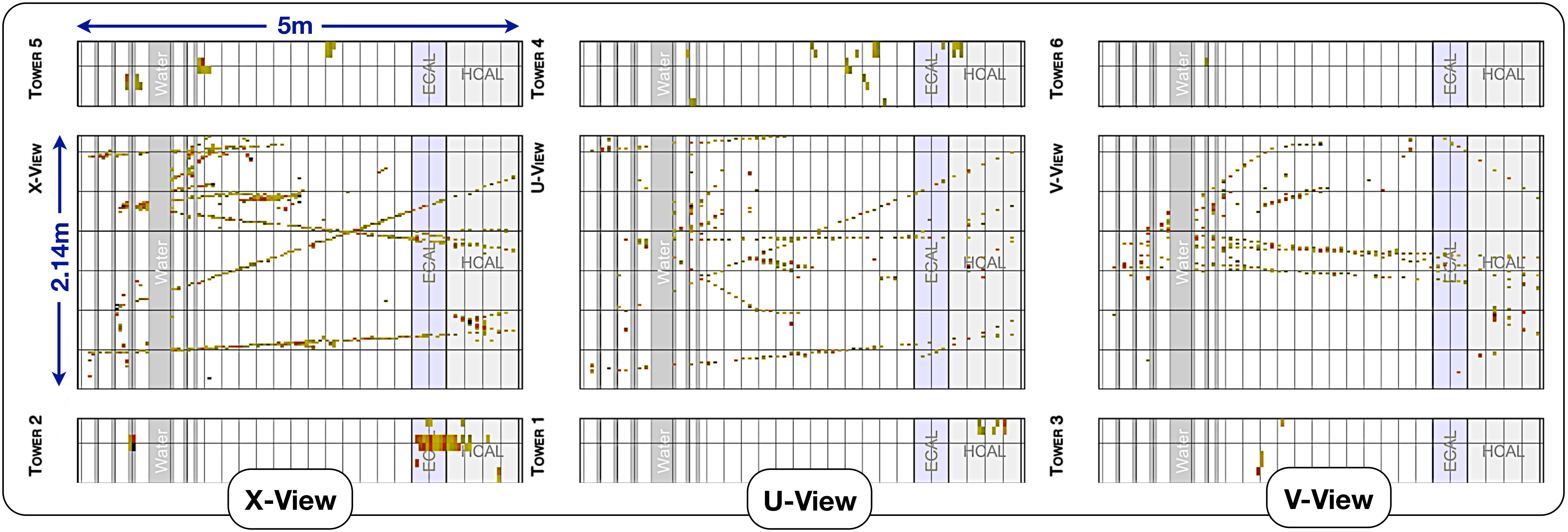
DATA: Run 2395/17/30/4

MINERνA Event Reconstruction

Record entire beam spills... Things look messy!
Timing comes to the rescue!

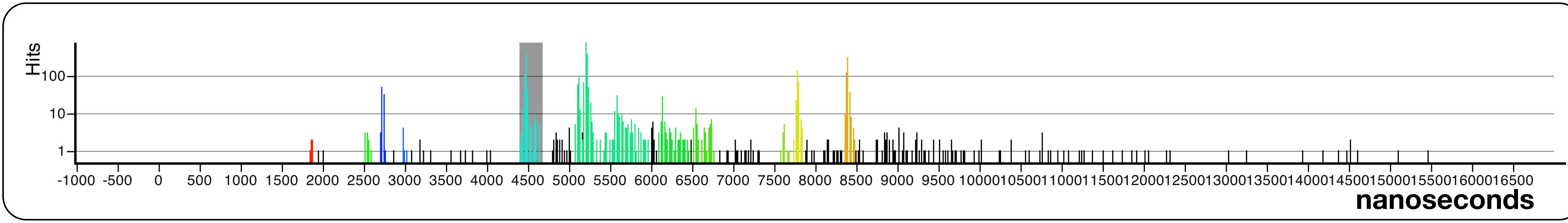


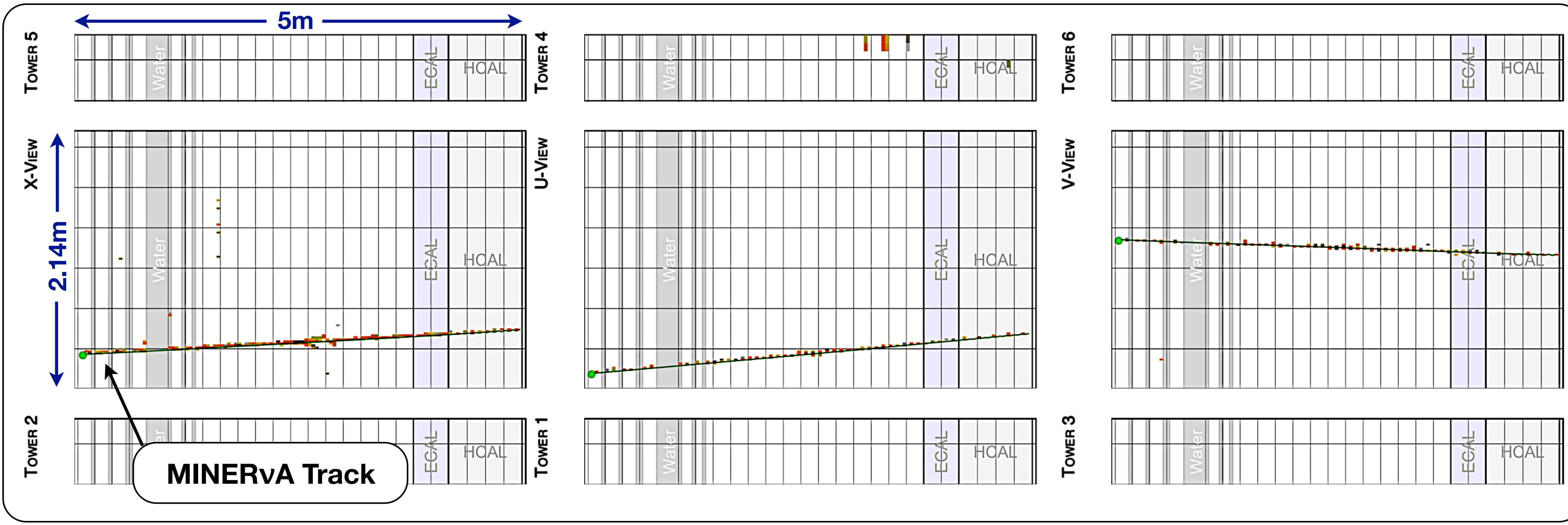


Bundle hits into "Time Slices." Beam spill is ~10 μs, data gate is ~16 μs. Slices are typically ~100 ns wide.

MINERνA Event Reconstruction

Can now pick out single interactions easily!
Note: Lot's of through-going "rock muons" in the data...



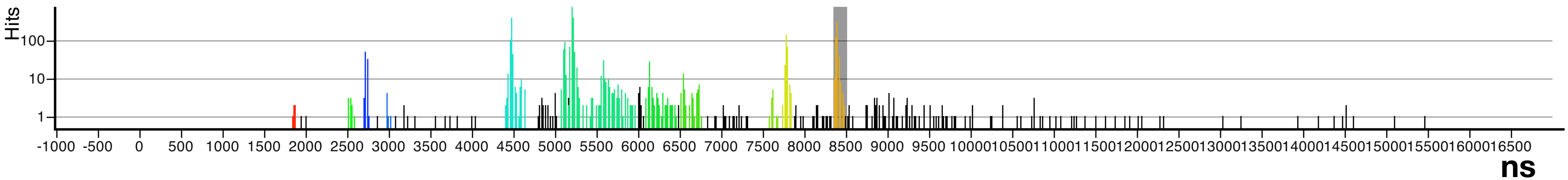


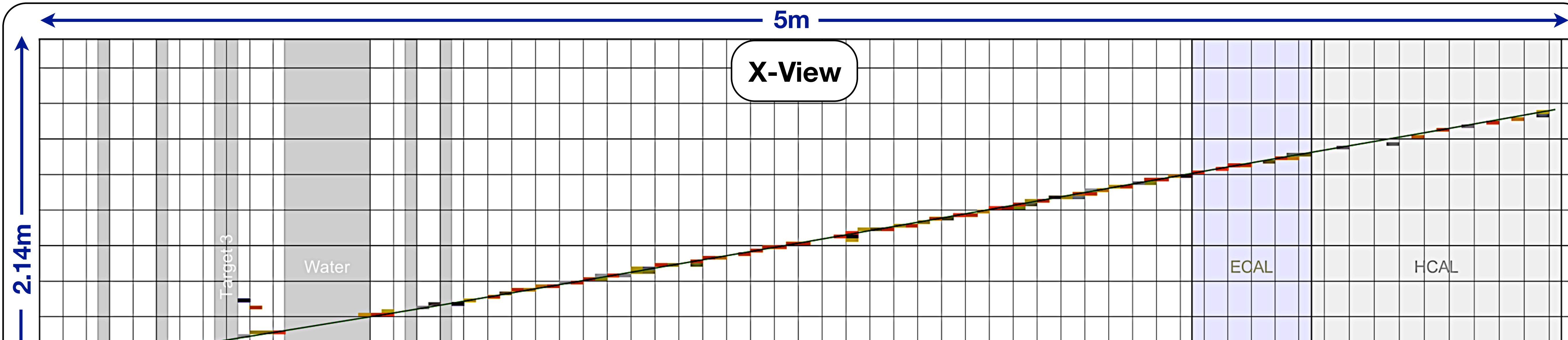
These come from neutrino interactions in the upstream rock and are a valuable calibration tool (no cosmic ray trigger for MINERνA).

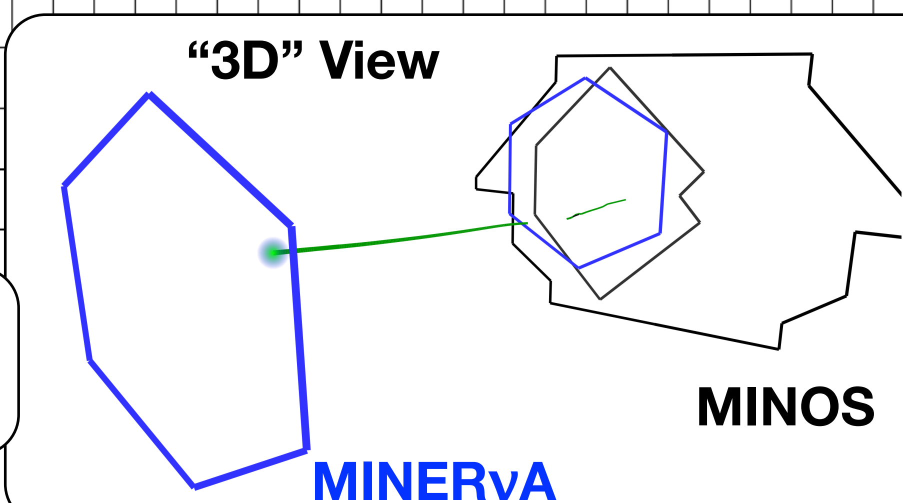
DATA: Run 2298/1/33/6

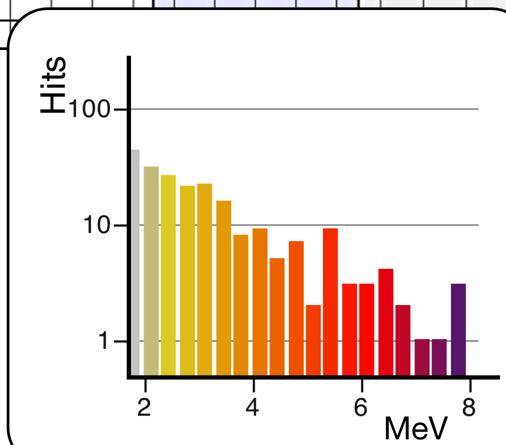
MINERνA Event Reconstruction

Tracking close-up... Focusing on muons now.







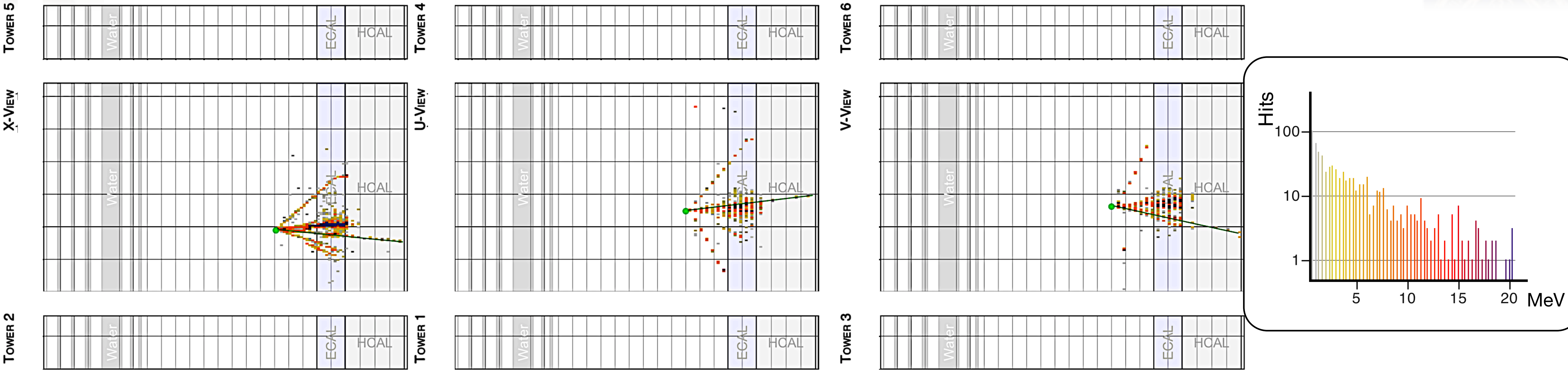


Charged Current Event Candidate on Iron Nuclear Target

DATA: Run 2298/1/33/12

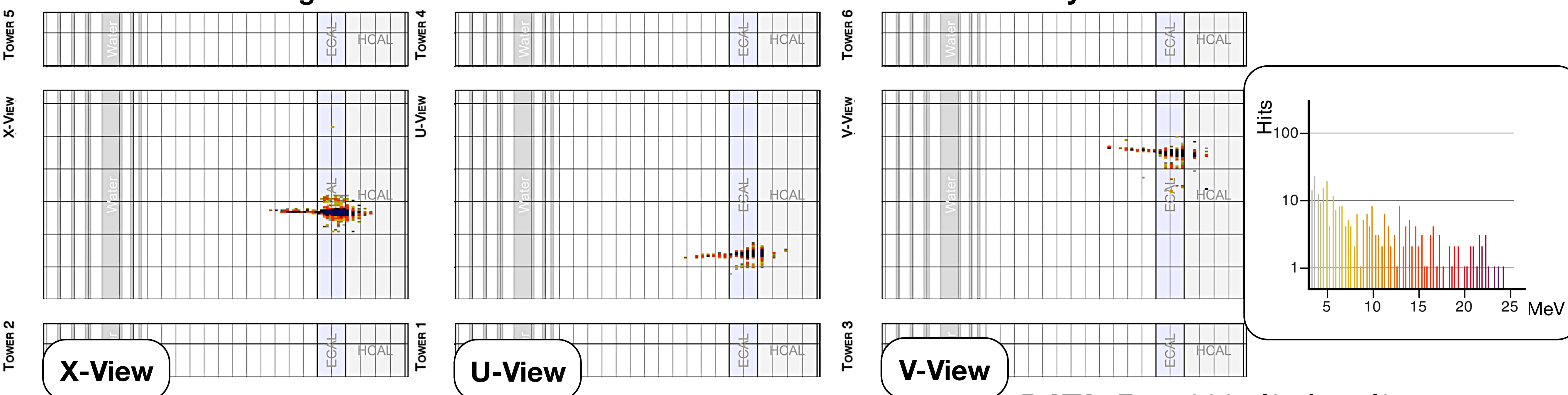
MINERνA's fine-grained tracker and calorimeters make a rich physics program possible.

CC Deep Inelastic Scattering Candidate. Track reconstructed through the shower!



DATA: Run 2359/1/29/5

Single Electron Candidate. Shower reconstruction underway.

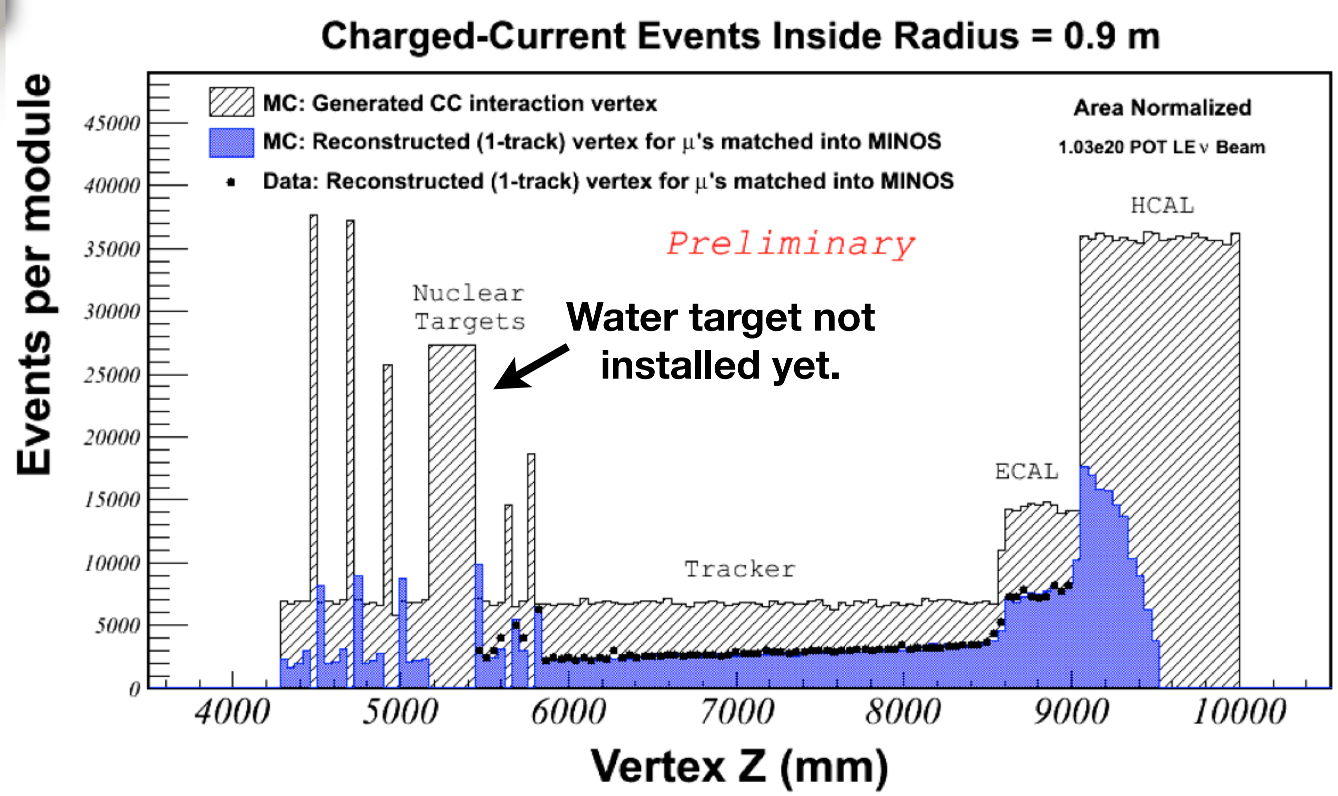


DATA: Run 2391/21/447/3

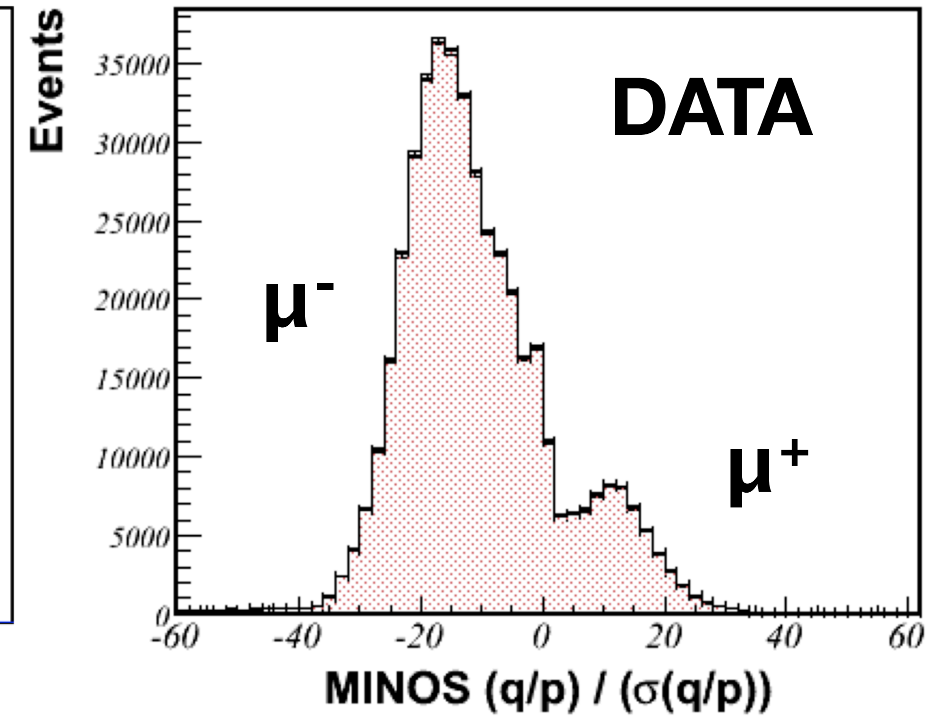
Area Normalized

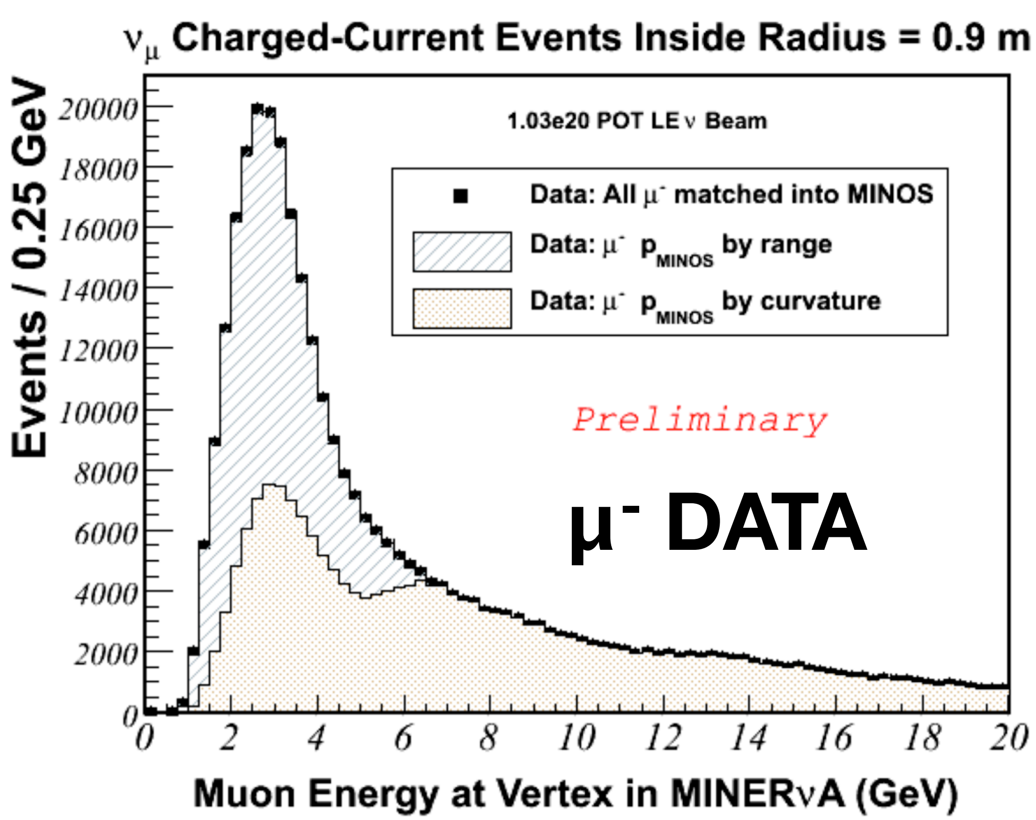
DATA: 1.03e20 POT LE Neutrino Mode

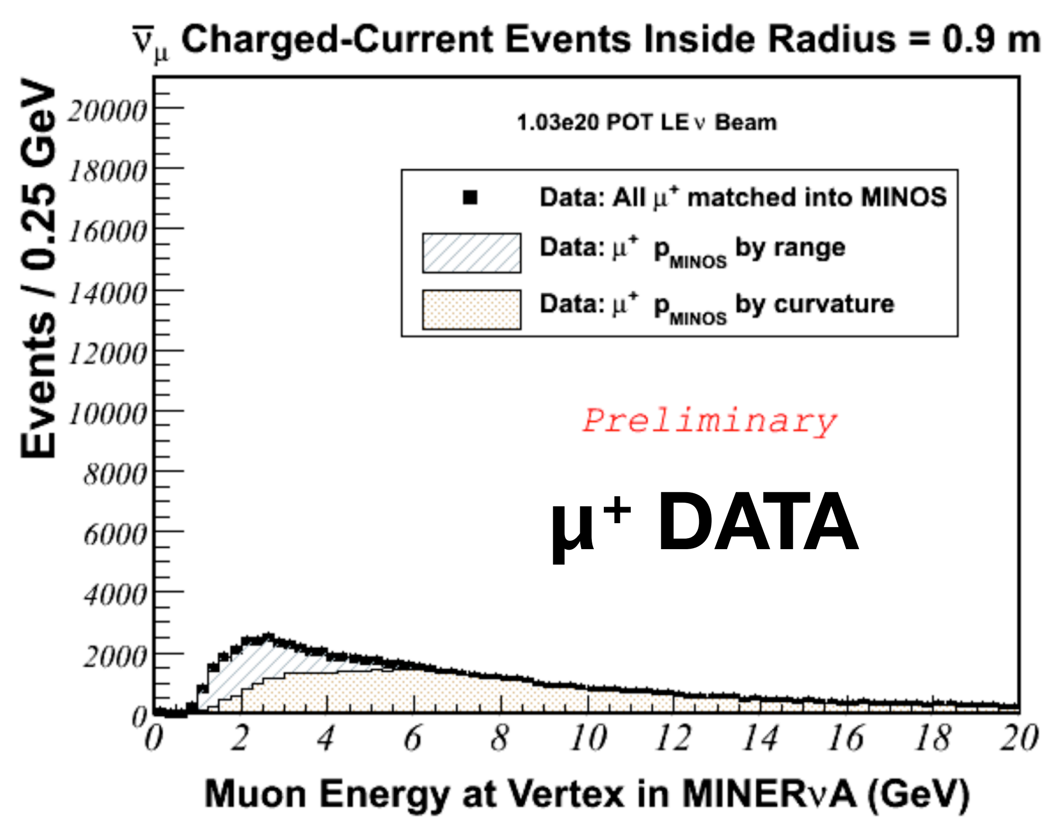
MC: 1.20e20 POT LE Neutrino Mode



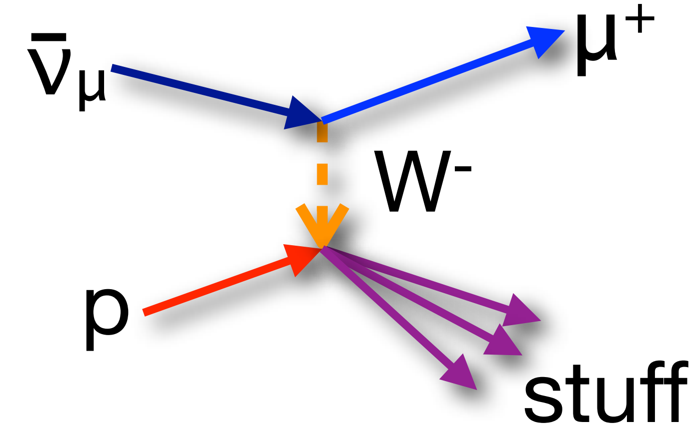
Muon Sign Selection





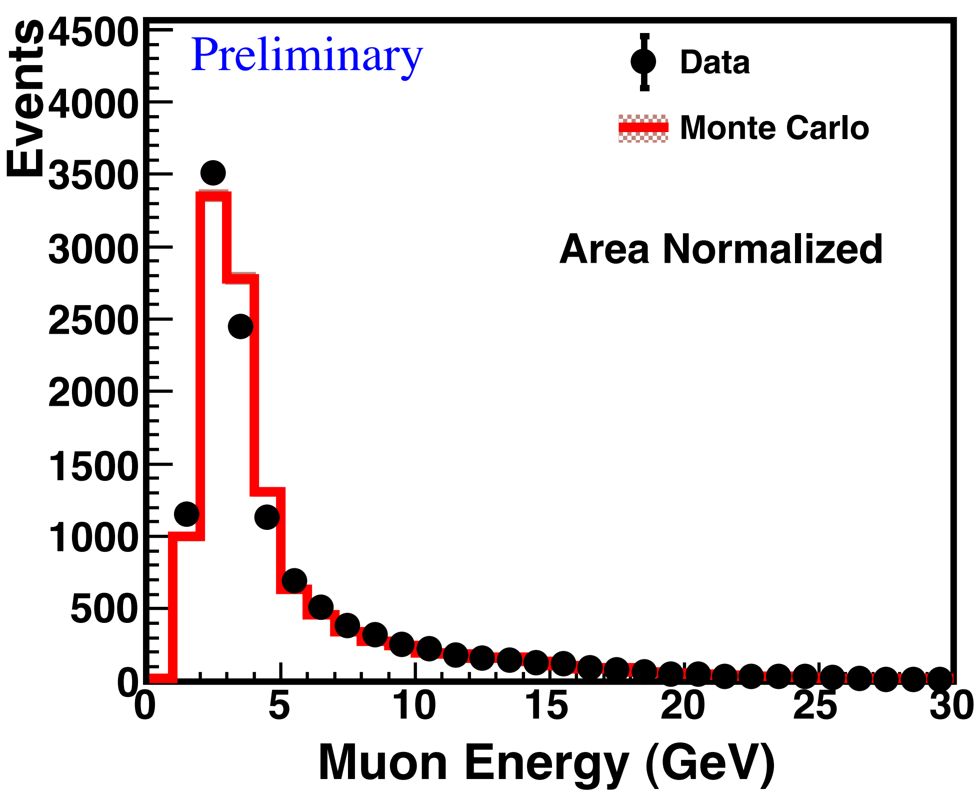


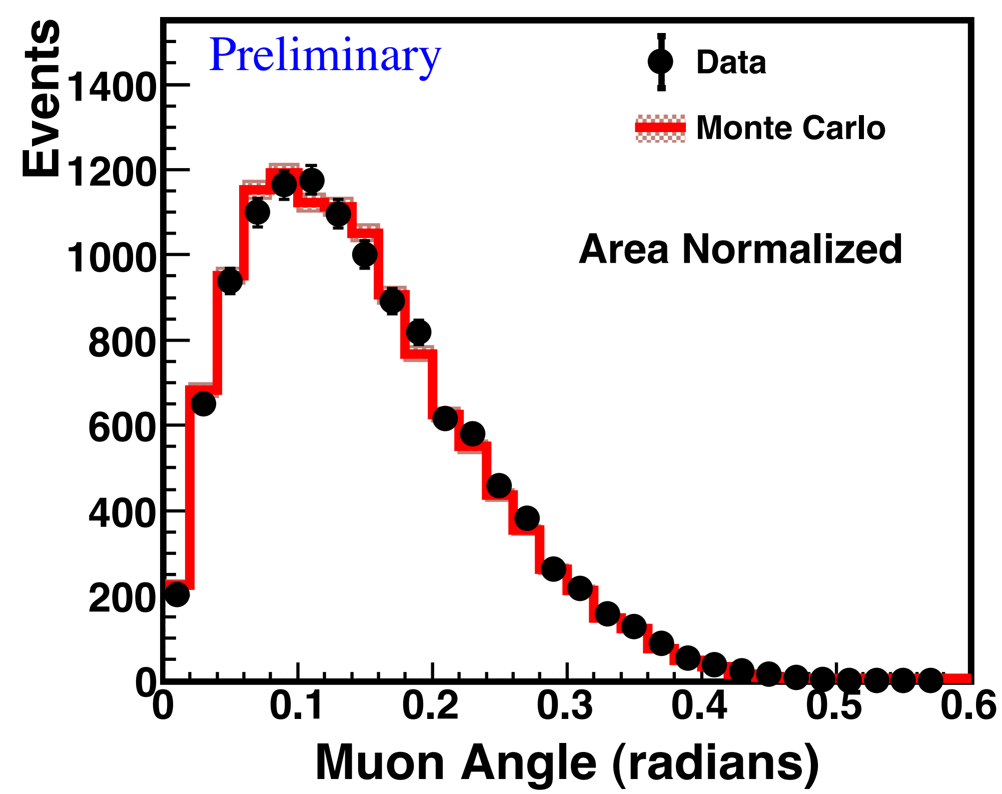
Inclusive Anti-ν Charged Current (CC)



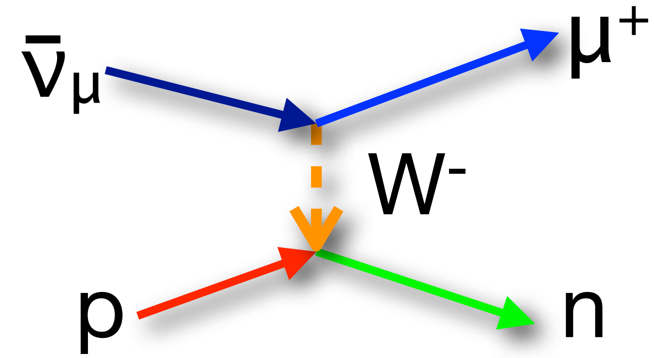
- CC signature is a muon from W exchange - excellent handle for events!
- We study tracks originating in the MINERνA tracker fiducial volume.
- Muon momentum and sign analyzed in MINOS. MINERνA energy loss computed using range.

Inclusive μ^+ Data & MC: Low Energy Anti-ν Beam



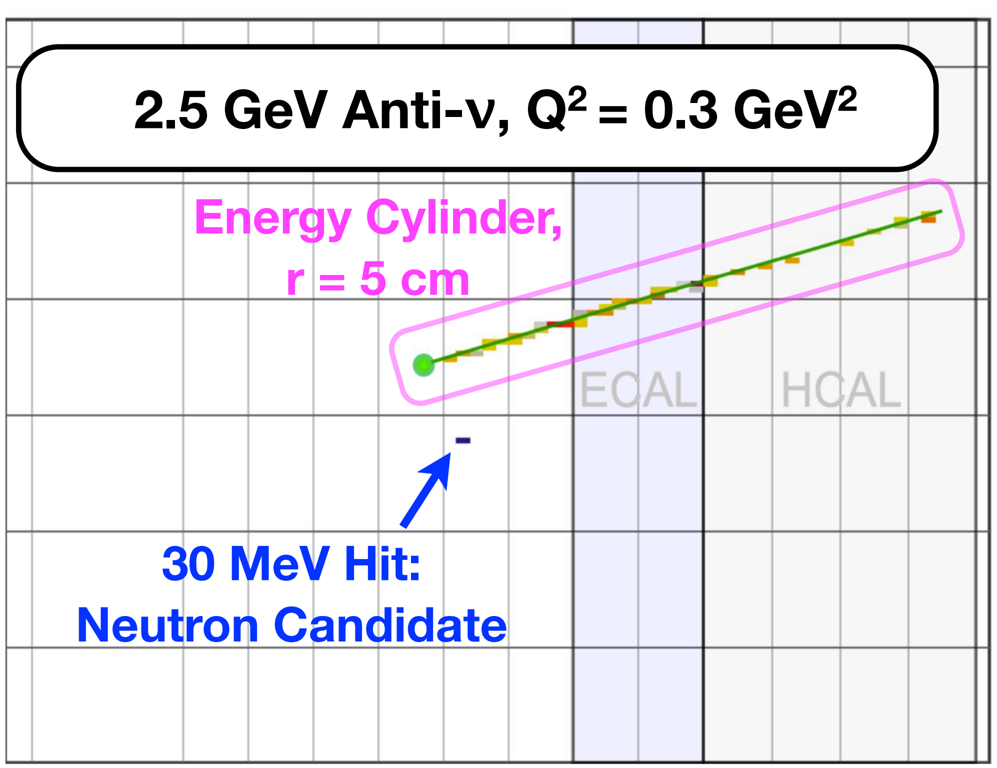


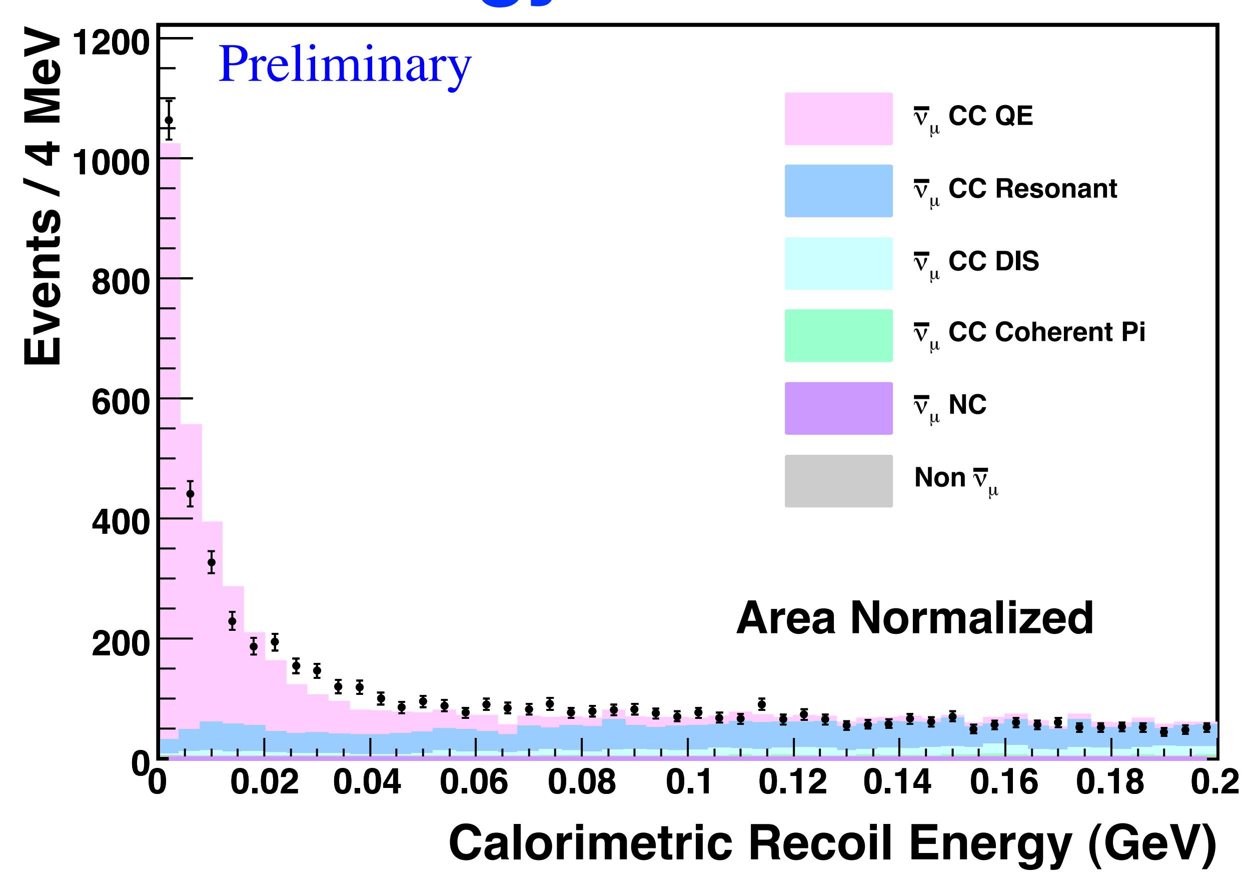
Anti-ν CCQEL



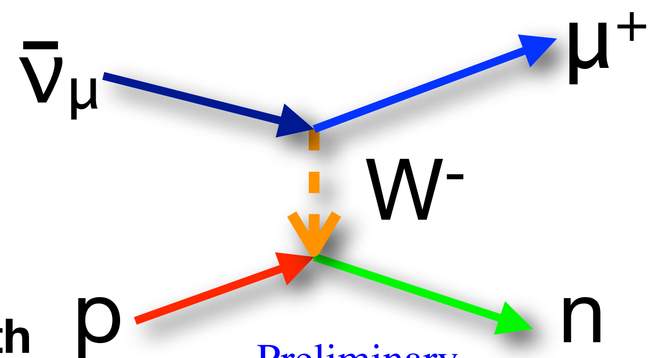
- Clean signature: the neutron is often invisible, the muon is easy to identify and precisely measure.
- Preliminary analysis using 4e19 POT in anti-ν mode recorded during detector construction (partial build with fiducial tracker volume of 2.86 tons of plastic scintillator).
- Selection Criteria:
  - μ^+ originating in the MINERvA tracker well-reconstructed in MINOS.
  - Minimal "recoil" energy (all energy outside a 5 cm radial cylinder around the track with a tight (100 ns) time cut) benchmarked against inclusive CC MC (GENIE 2.6.2 event generator, GEANT4 detector simulation with custom optical model, etc.).

Inclusive μ^+ Data & MC: Low Energy Anti-ν Beam





Anti-ν CCQEL

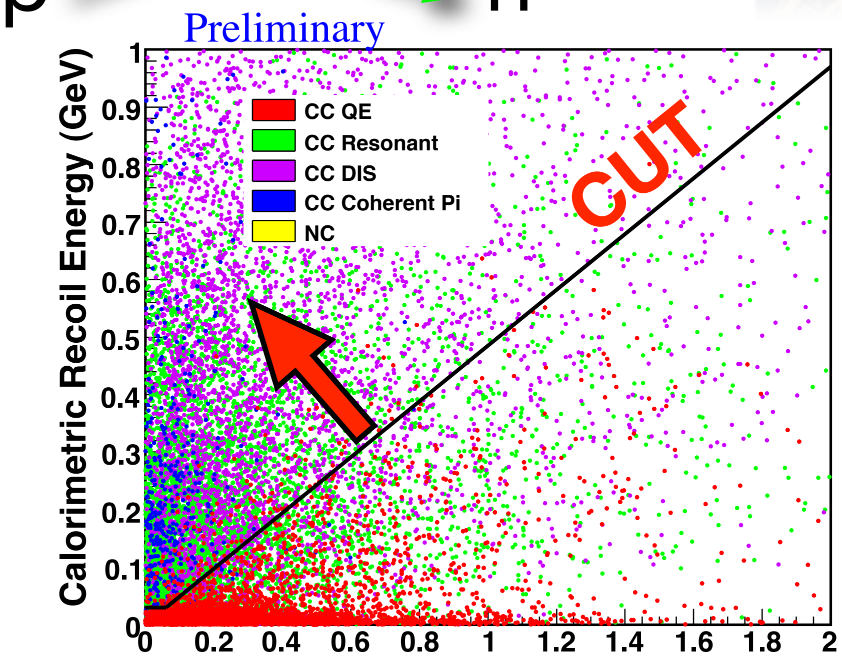


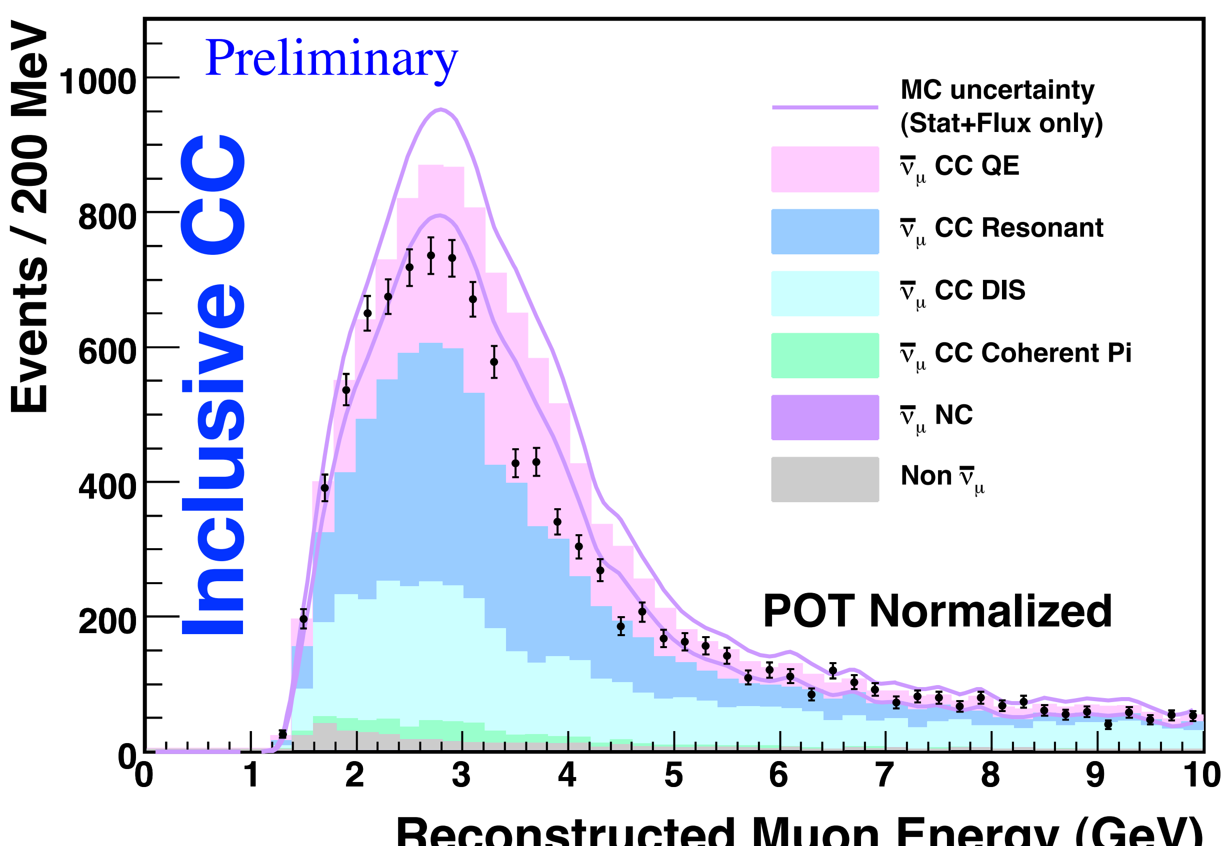
- **Under the quasi-elastic hypothesis, we can calculate the Q^2 with only muon information.**
- **By cutting on recoil energy vs. Q^2, we can purify a set of sample CCQEL candidates from our inclusive charged current sample.**

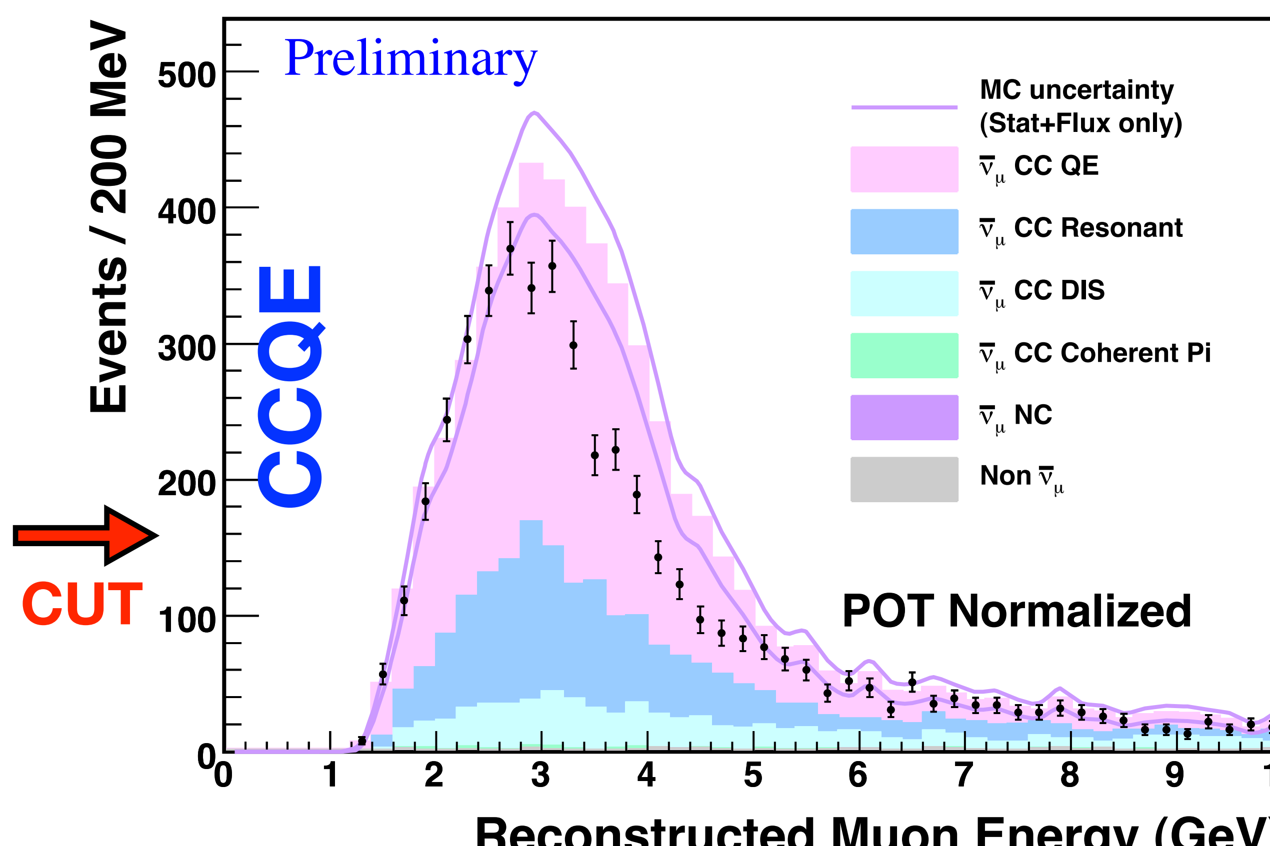
(Neutrino Energy; Flip nucleon masses for antineutrinos.)

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

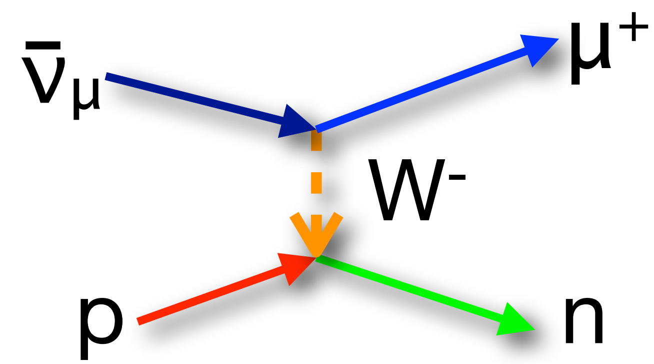
$$Q^2_{rec} = 2E_\nu^{rec}(E_\mu - p_\mu \cos\theta_\mu) - m_\mu^2$$





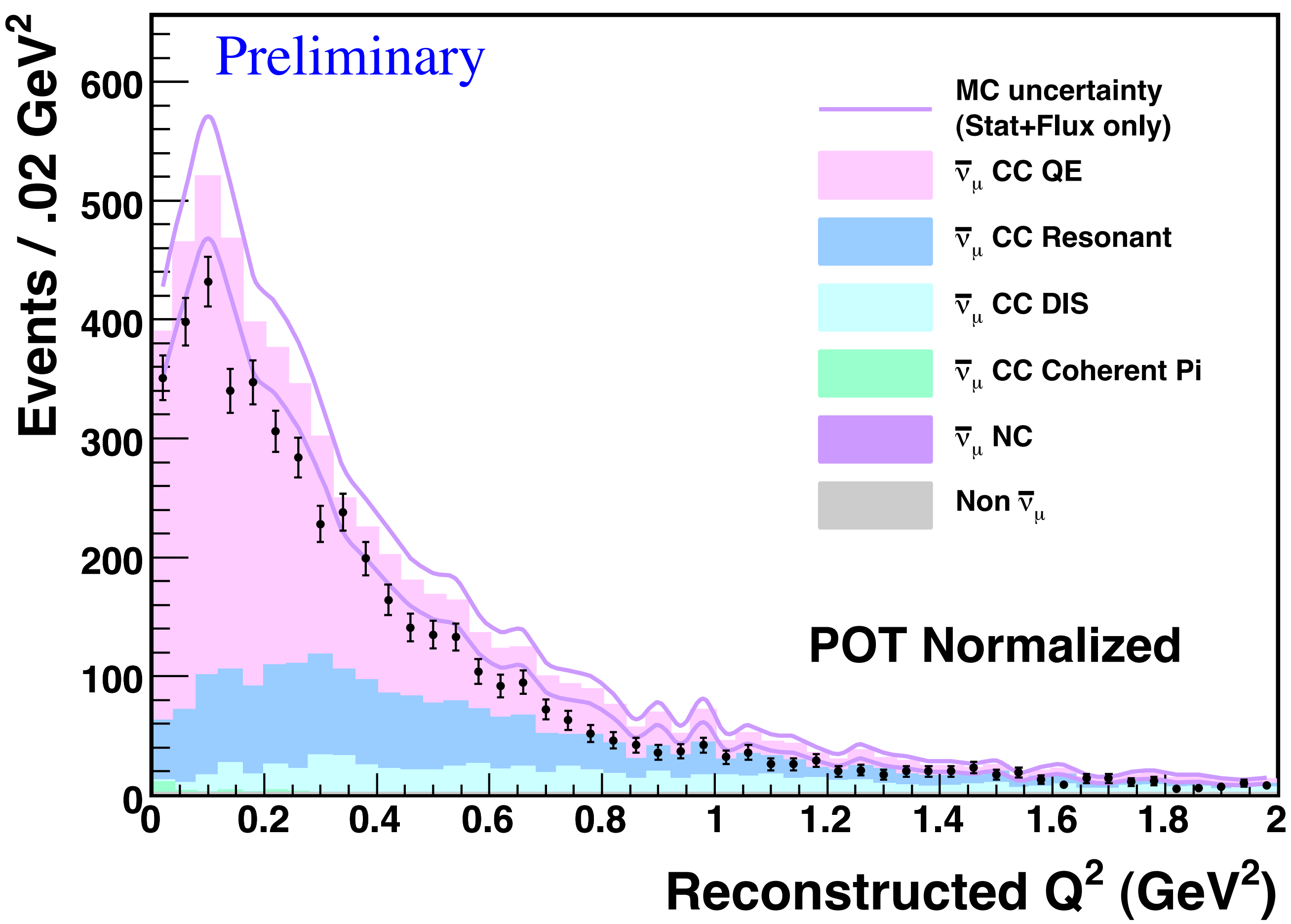


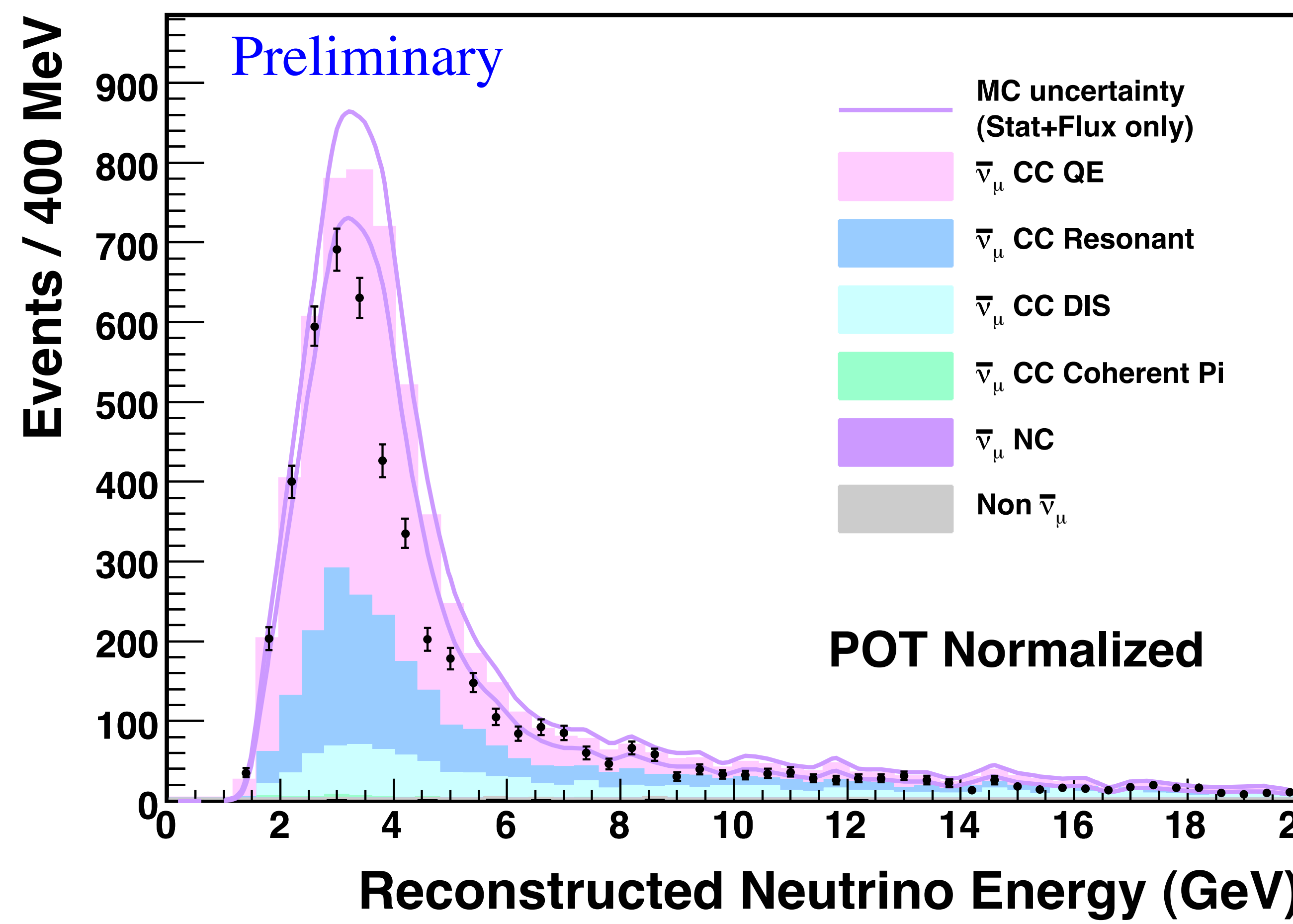
Anti-ν CCQEL



- **Reminder: Absolute predictions from our flux simulation (GENIE 2.6.2, GEANT4).**
- **Event deficit is flat in Q^2, but not E_ν.**

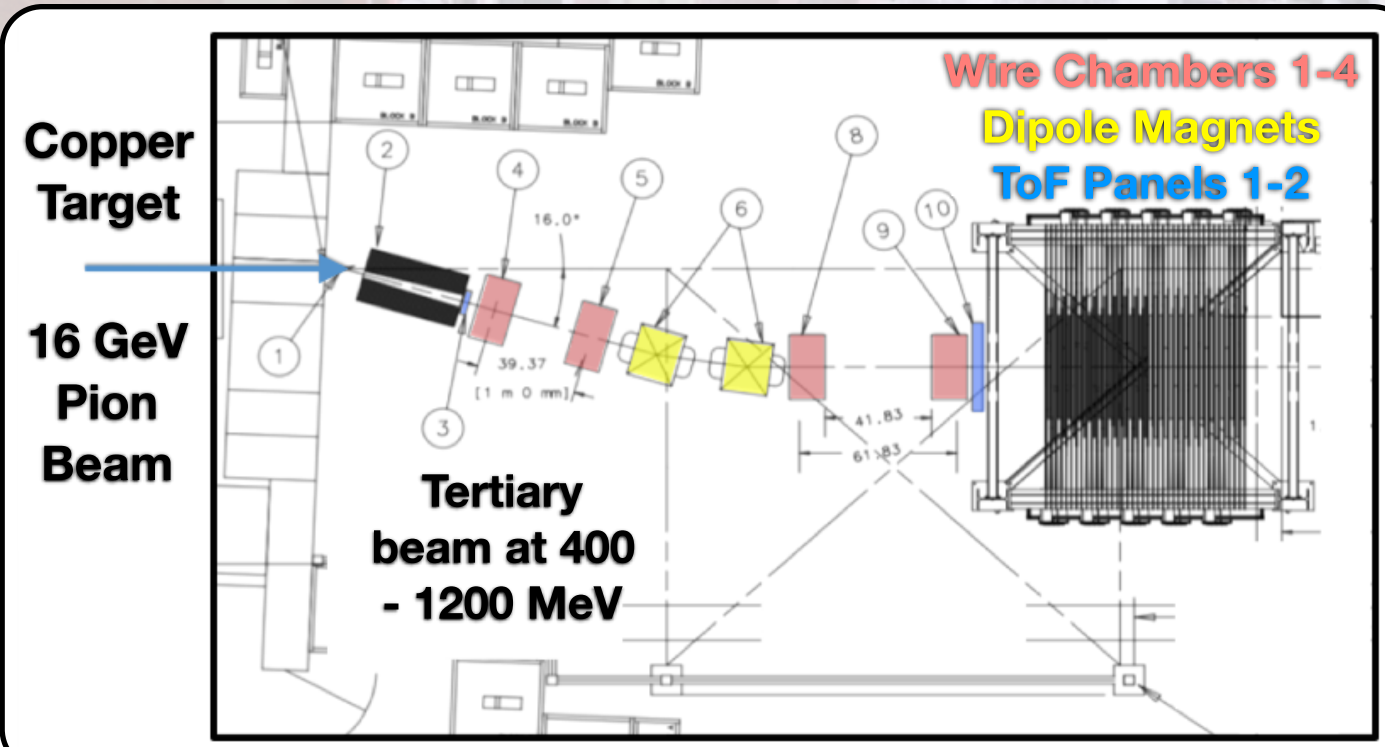
$\bar{\nu}p \rightarrow \mu^+ n$ Event Candidates: Low Energy Anti-ν Beam DATA & MC

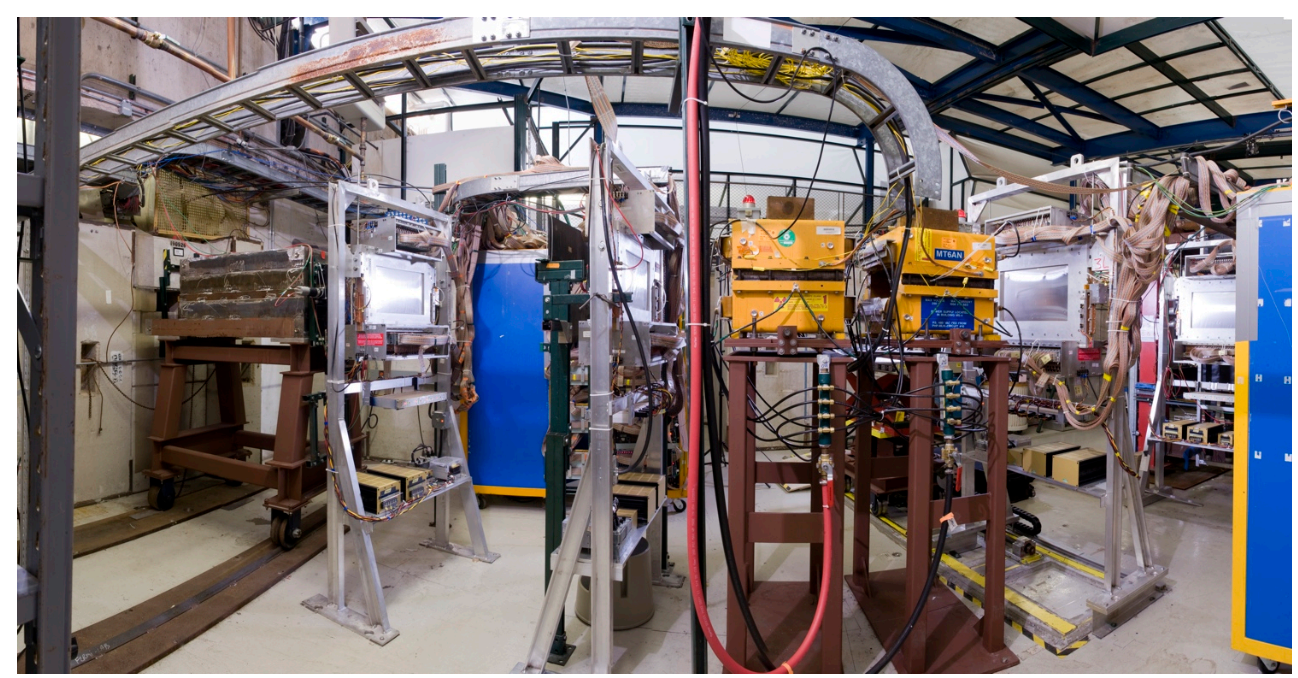




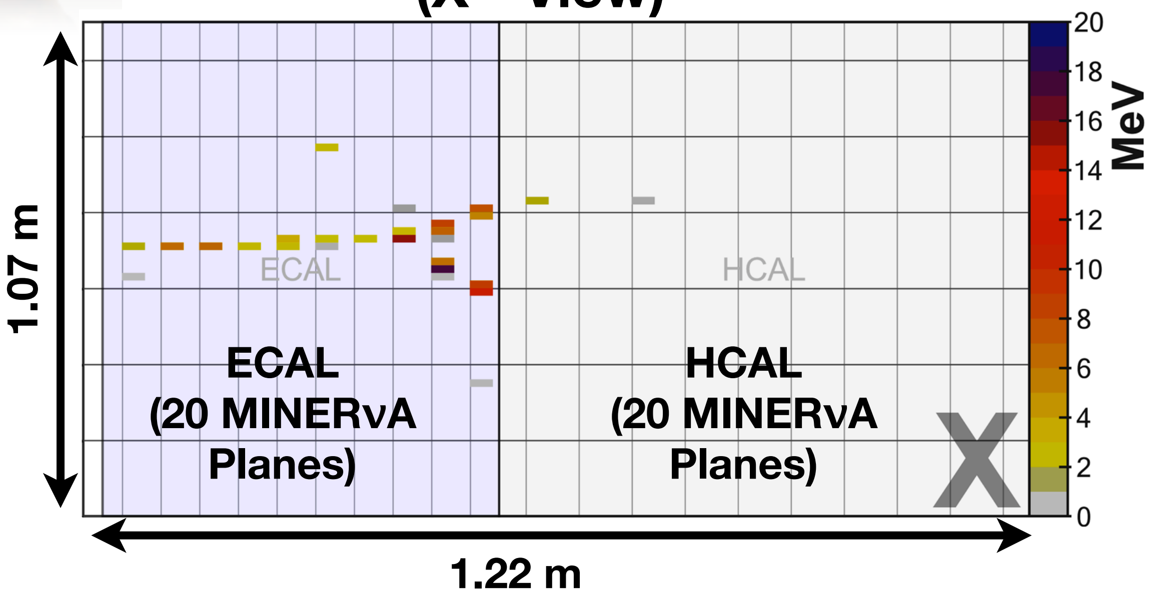
MINERvA Test Beam

- Calibration experiment at the FNAL Test Beam Facility (FTBF).
- Provide hadronic response calibration (ratio of π/μ) in the MINERvA Main Detector.
- MINERvA added a new copper target and collimator, four wire chambers, two dipole magnets, and a time-of-flight system for triggering to build a new tertiary beamline.
    - 16 GeV pion beam on a Cu target produces tertiary pion beam from 400 MeV to 1.2 GeV.
    - Now part of the facility and available for other experiments to use!

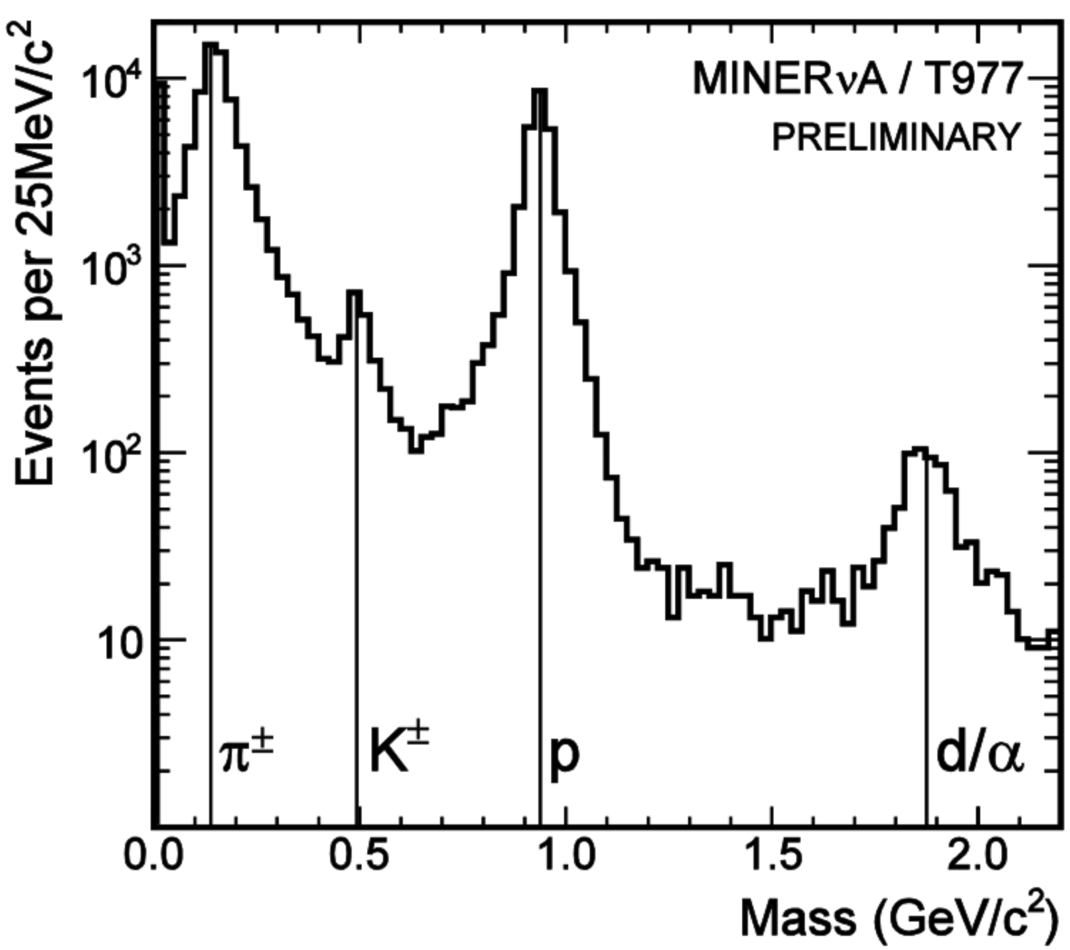


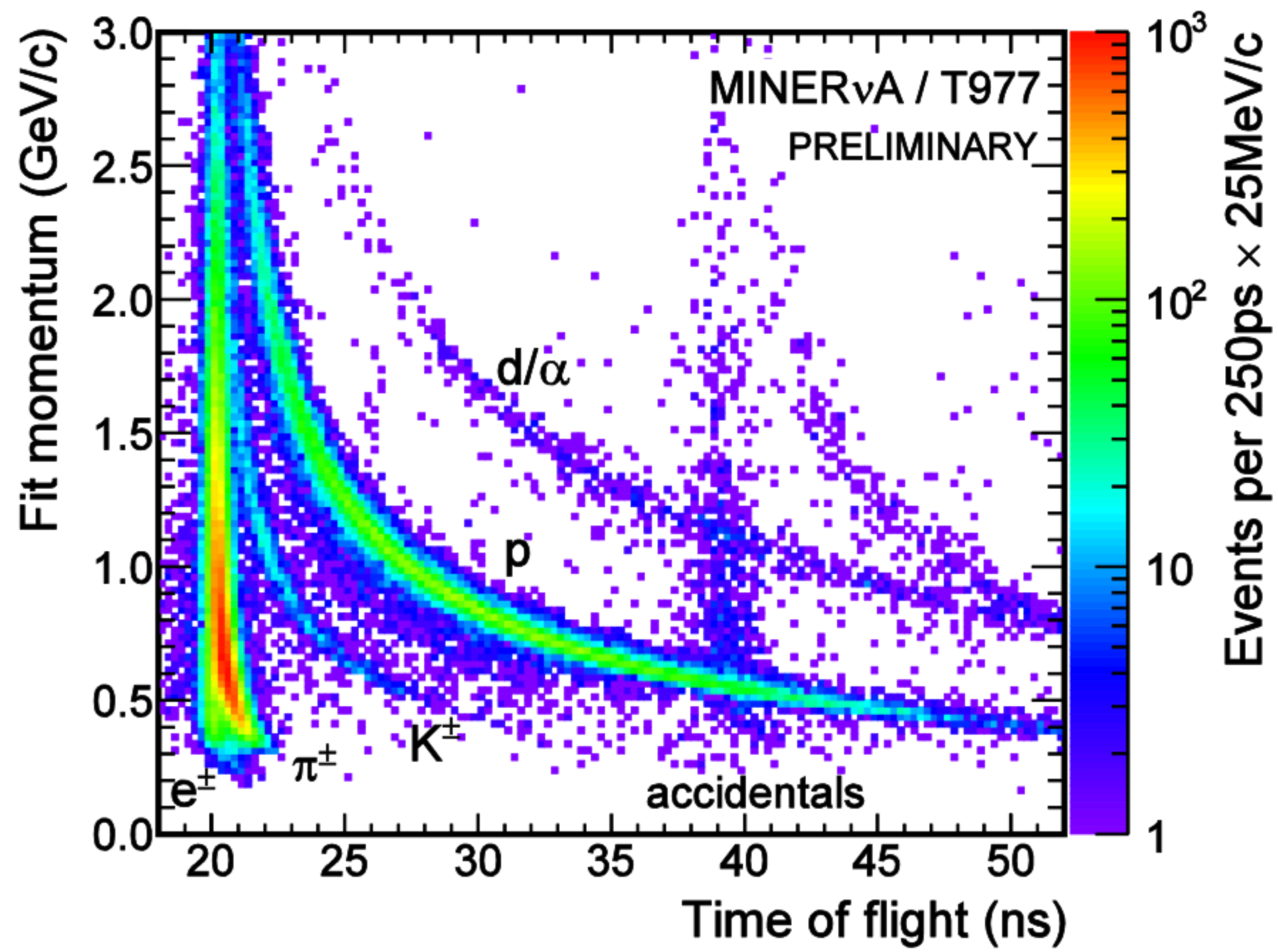


MINERνA Test Beam, Cont.



- 40 planes in XUXV stereoscopic orientation using the same scintillator and absorber geometry.
- Reconfigurable construction: took data in a 20 ECAL+ 20 HCAL configuration and in a 20 Tracker + 20 ECAL arrangement.
- Finished first physics run June 9 - June 28 (calorimetry configuration) & July 1 - July 17 (tracking configuration), 2010. Analysis is underway.





The MINERνA Collaboration

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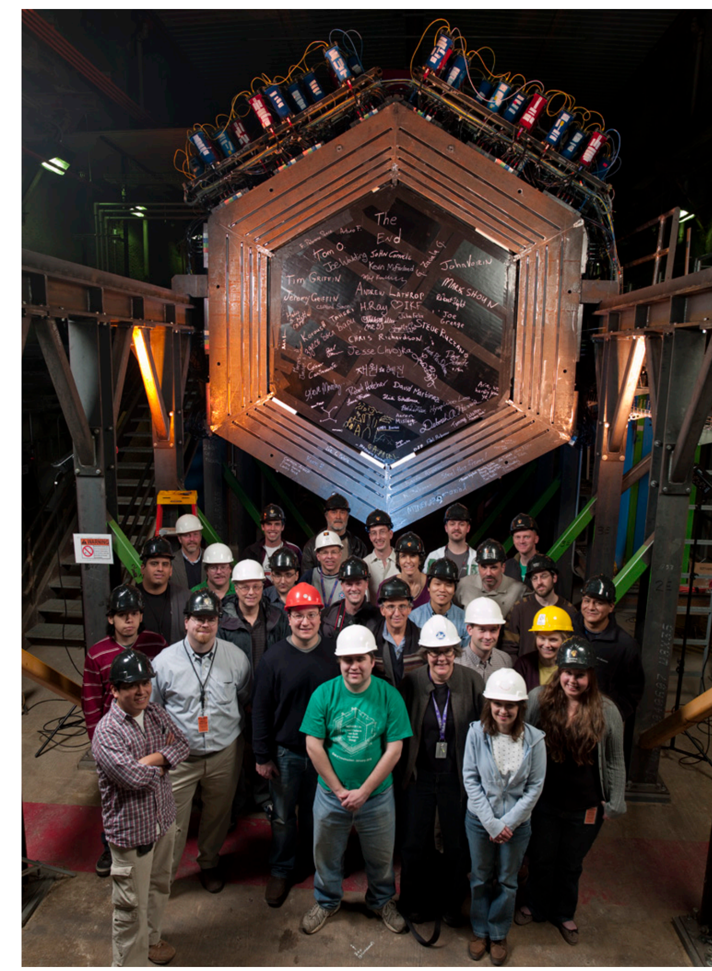


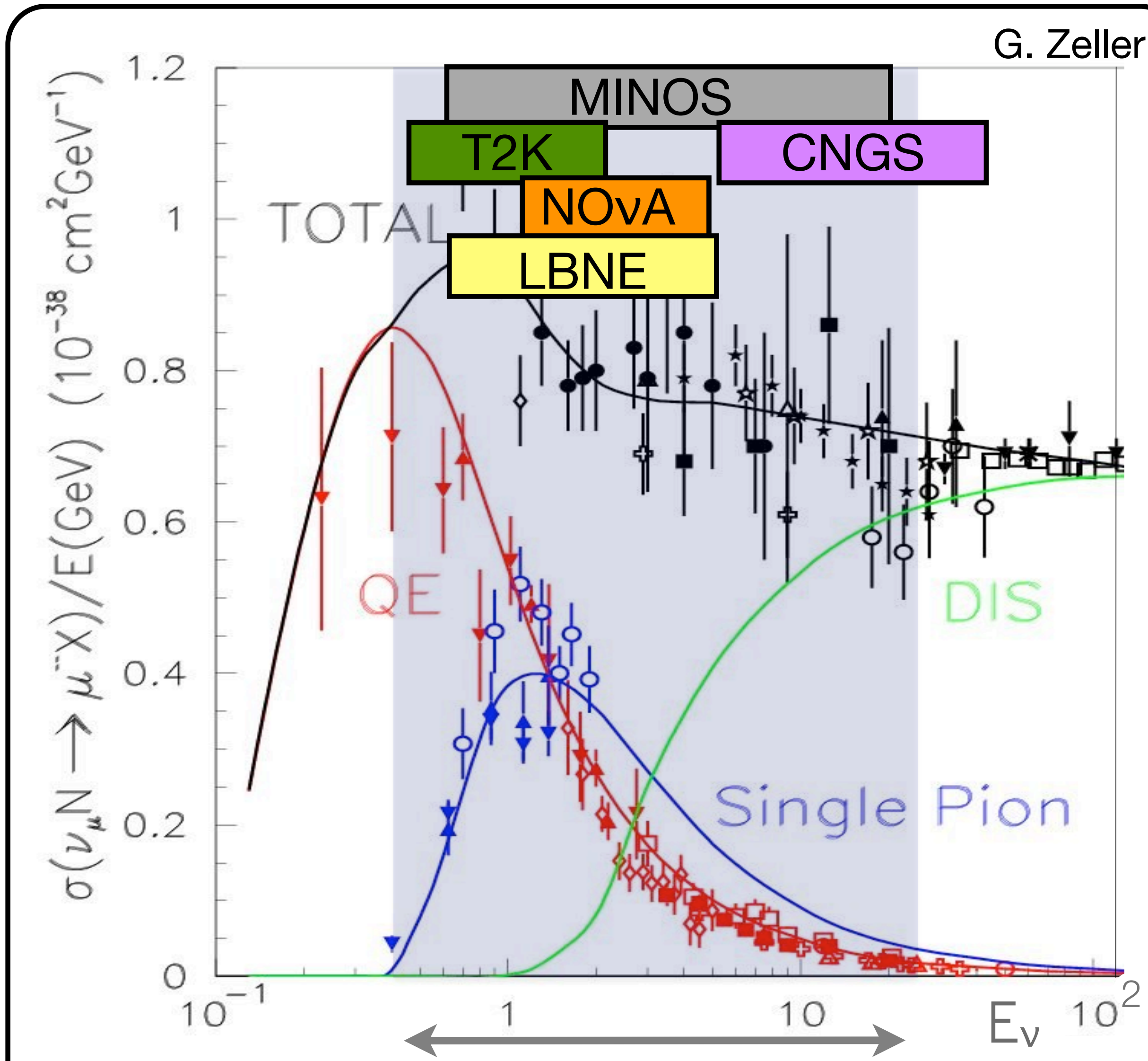
Thank You For Listening!

On behalf of the MINERνA Collaboration, I would additionally like to extend a special set of thanks to the conference organizers for inviting us to share our progress and for their diligent efforts at this conference!

Back-Up Slides

MINERνA Motivations

- **We are now entering a period of precision neutrino oscillation measurements.**
- **To maximize oscillation effects, need $\Delta m^2 \times L/E_{Beam} \sim 1$.**
- **For $\Delta m^2 \sim 2.5 \times 10^{-3}$ eV^2 and L ~ 100's of km, E_{Beam} ~ few GeV range.**
- **Therefore, we need precision measurements of neutrino cross sections in this range.**

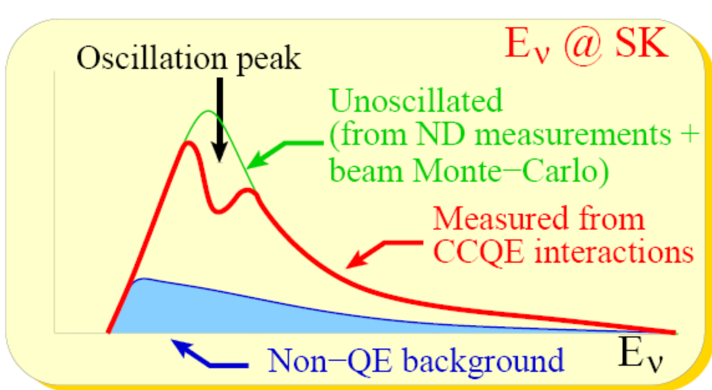


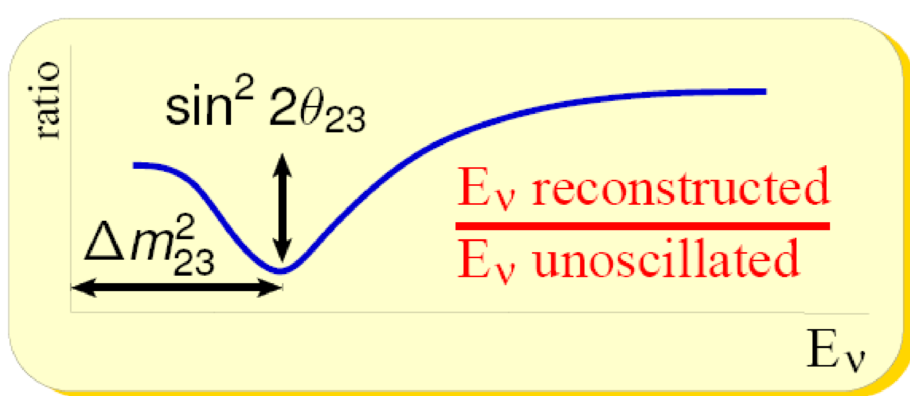
MINERνA Coverage

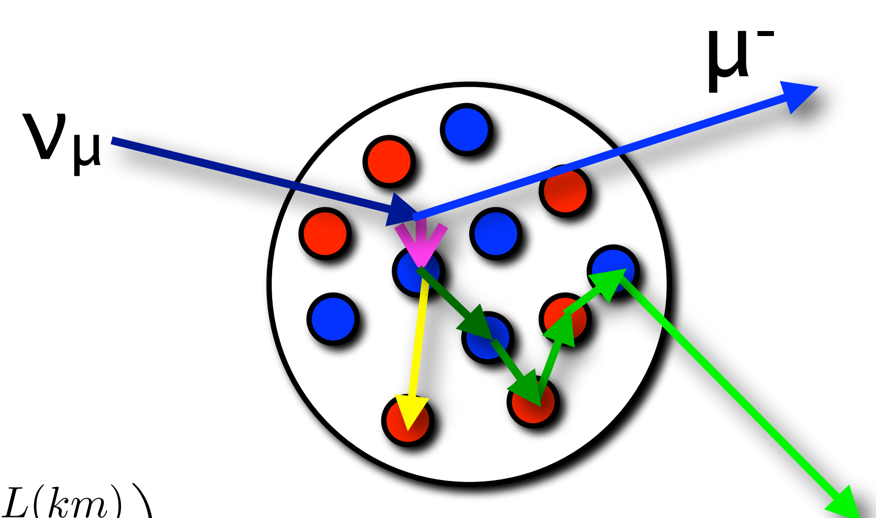
(No MiniBooNE results on this plot.)

Disappearance Oscillation Measurement

- **Recall oscillation probability depends on E_ν.**
- **However, experiments measure E_{vis}.**
- **E_{vis} depends on flux, σ, and detector response.**
  - **Final state interactions are important! ν interacts in dense nuclear matter, and products do not always cleanly exit the nucleus.**
- **E_{vis} is not equal to E_ν!**
- **Near/Far detector ratios cannot handle all the uncertainties because the E_{Near}/E_{Far} spectra are different due to matter effects, etc.**



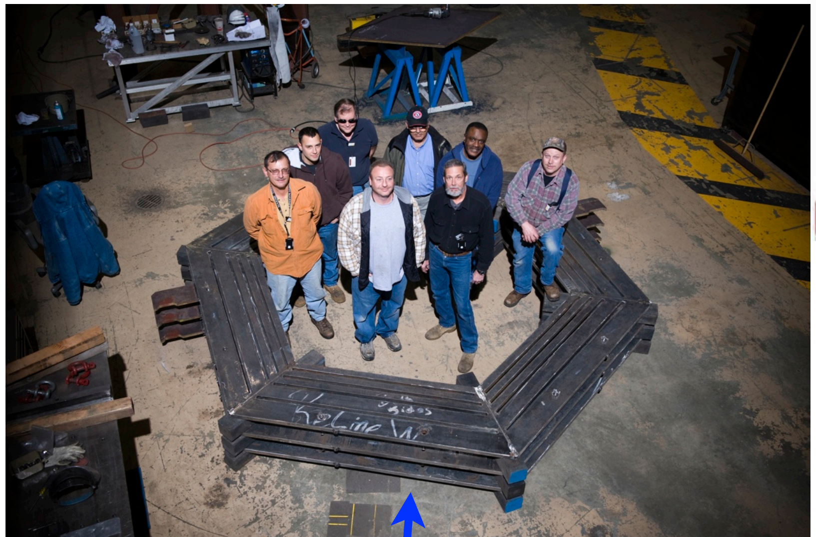


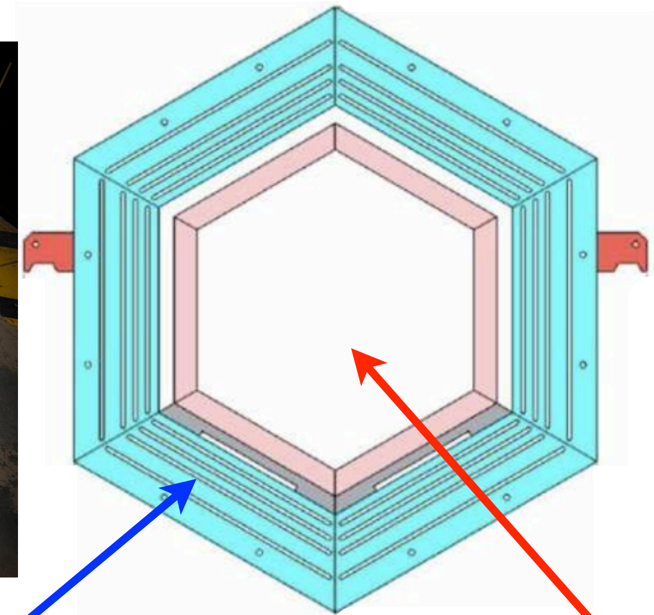


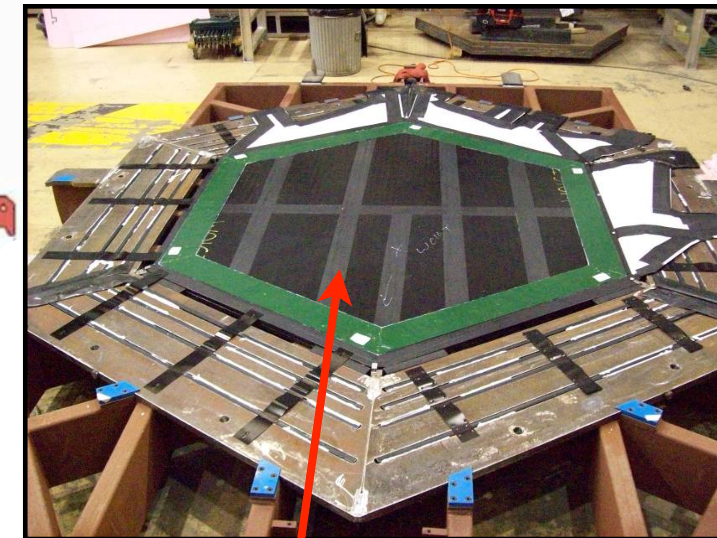
Figures courtesy of V. Paolone and the SuperK Collaboration.

$$P(\nu_\mu \to \nu_\mu) = 1 - \cos^4\theta_{13}\sin^2 2\theta_{23}\sin^2\left(\frac{1.27\Delta m^2_{23}(eV^2)L(km)}{E_\nu(GeV)}\right) - ...$$

MINERvA Modules

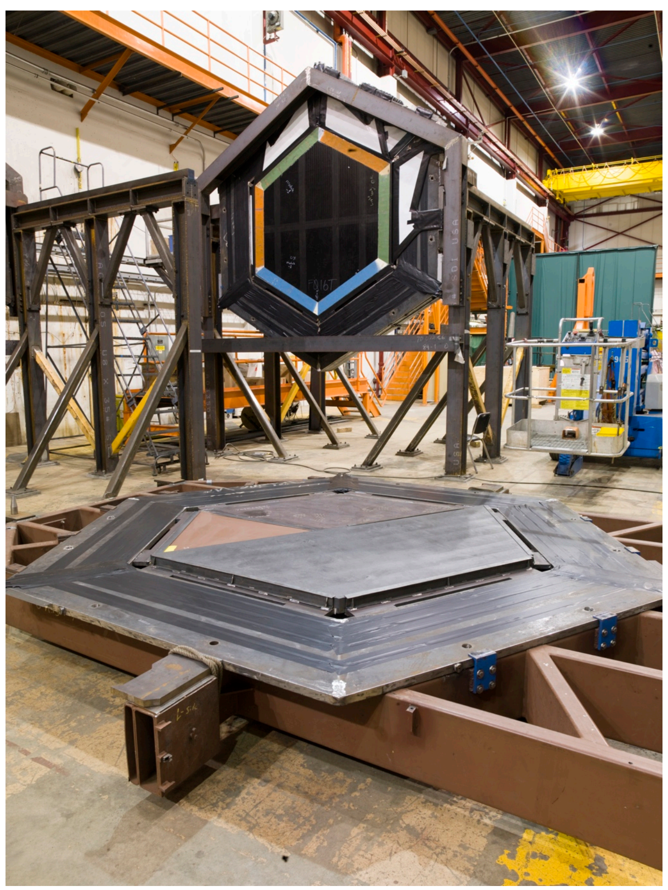






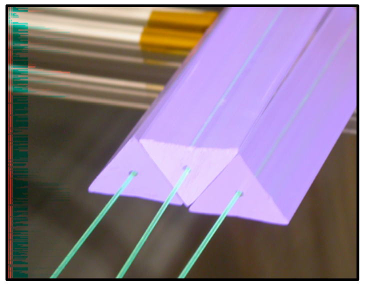
Modules have an outer detector frame of steel and scintillator...

...and an inner detector element of scintillator strips and absorbers/targets.

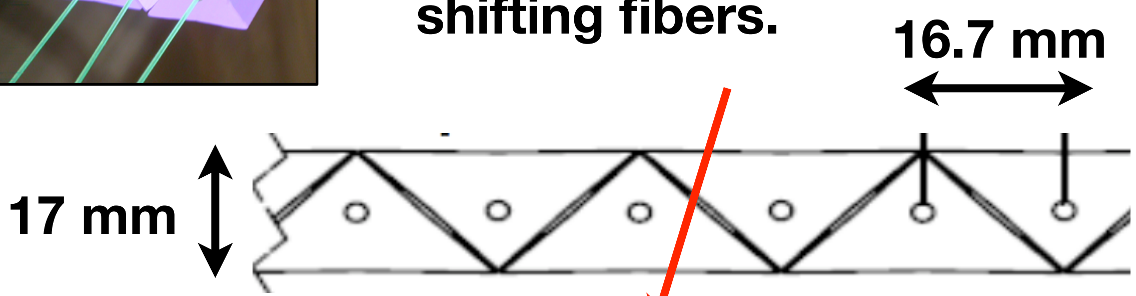


- Four basic module types:
  - Tracker: two scintillator planes in stereoscopic orientation.
  - Hadronic Calorimeter: one scintillator plane and one 2.54-cm steel absorber.
  - Electromagnetic Calorimeter: two scintillator planes and two 2-mm lead absorbers.
  - Nuclear Targets: absorber materials (some with scintillator planes).
- Instrumented outer-detector steel frames.
- 120 Total Modules: 84 Tracker, 10 ECAL, 20 HCAL, 6 Nuclear Targets.

Plastic scintillator strips form the active detector elements.



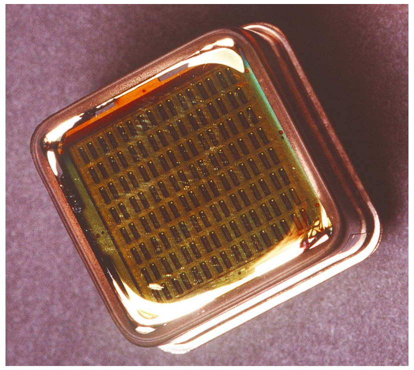
Extruded scintillator & wavelength shifting fibers.

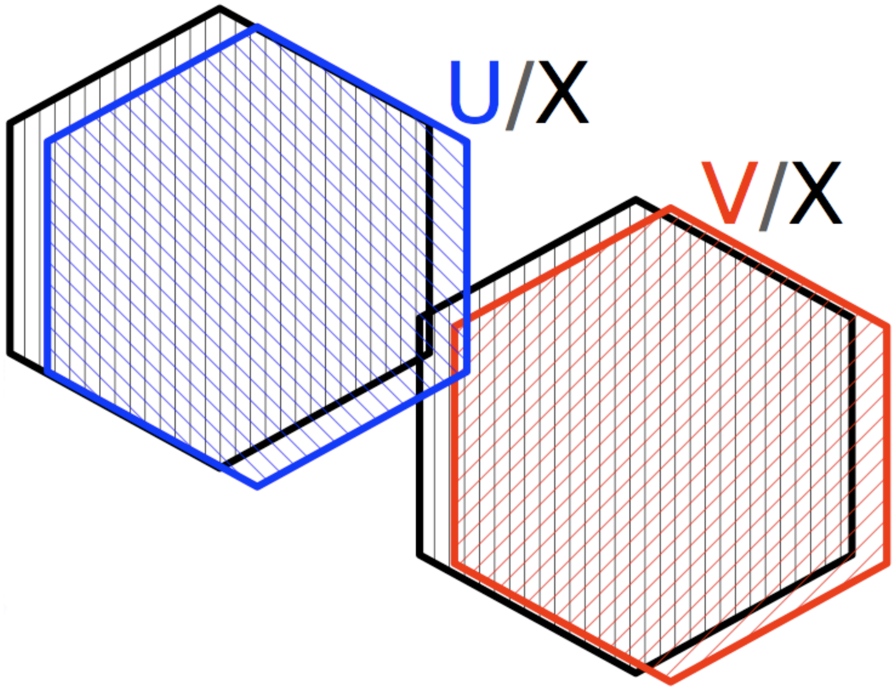


Charge-sharing for improved position resolution (~3.5 mm).

Strips are bundled into PLANES to provide transverse position location across a module.

Fibers bundled into cables to interface with 64 channel multi-anode PMT's.

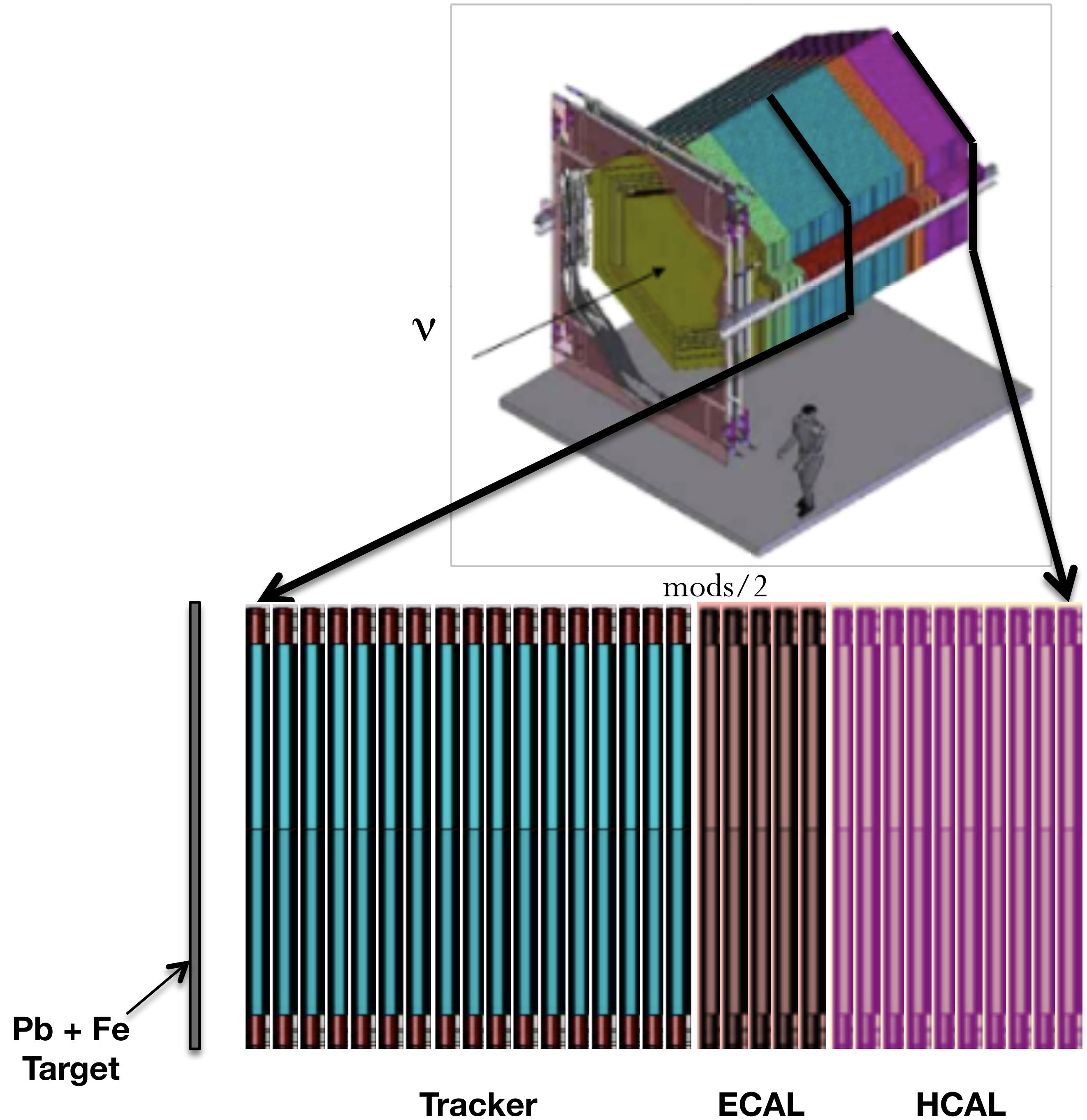




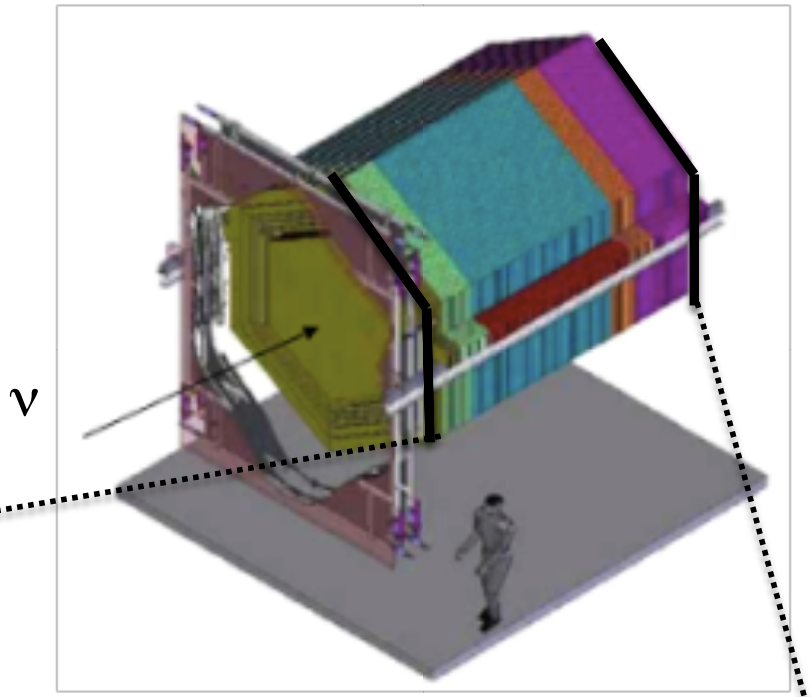
Planes are mounted stereoscopically in XU or XV orientations for 3D tracking.

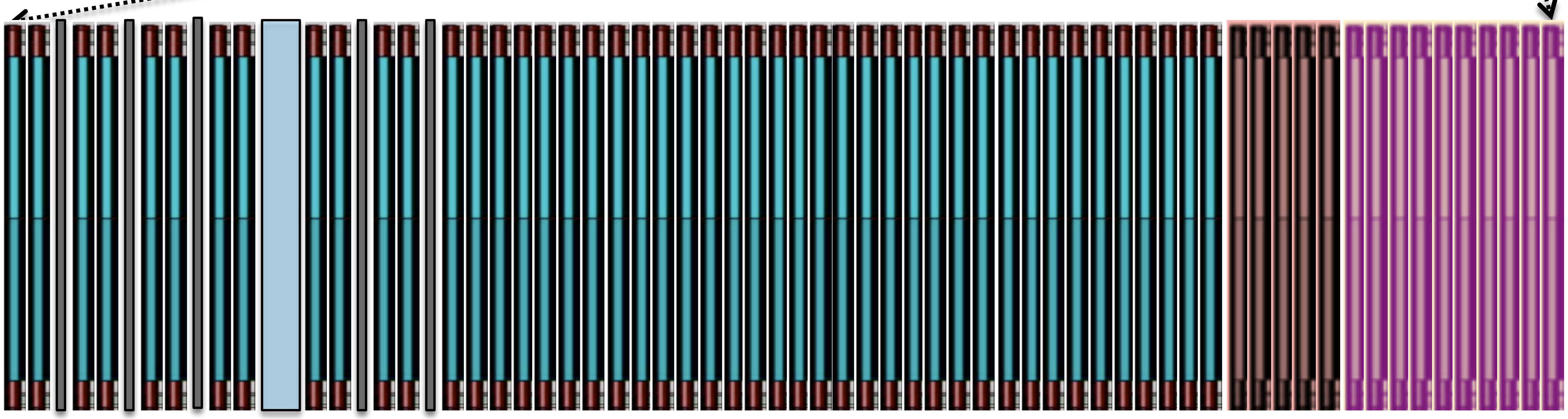
MINERνA "Frozen Detector"

- **Partial installation of 34 tracking, 10 ECAL, and 20 HCAL (full back calorimetry) completed November 12, 2009.**
- **Collected data in this configuration until early January, 2010 when we resumed installation (and continued data-taking with the "Downstream Detector").**
- **One nuclear target module (Fe, Pb) and one module instrumented as veto included for the "Frozen" period.**



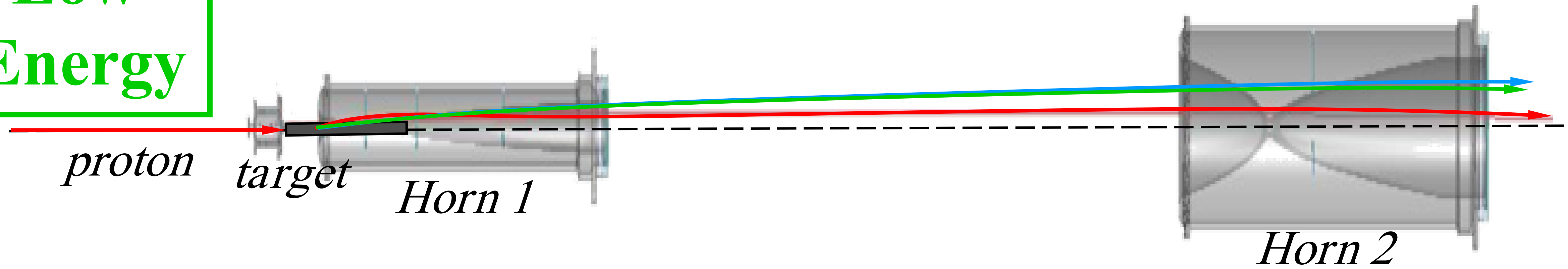
- **MINERνA installation finished in March, 2010.**
- **He/H2O targets to be installed in soon.**
- **Cross-section below is not to scale (the detector is approximately cubic).**





Flexible Energy in the NuMI Beam

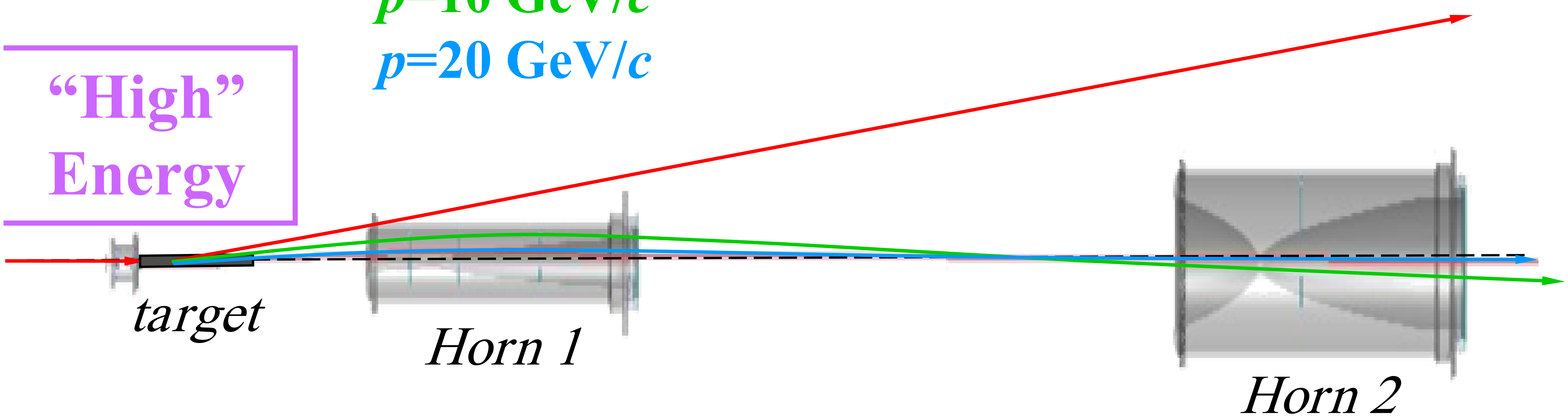
"Low" Energy



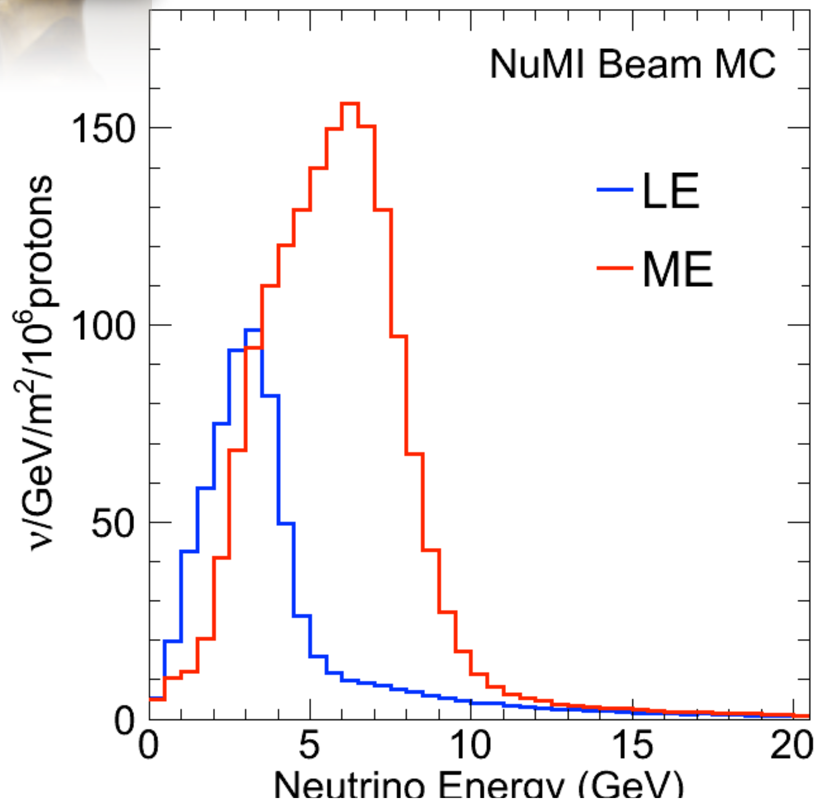
Pions with
p_T=300 MeV/*c* and
p*=5 GeV/*c
p*=10 GeV/*c
p*=20 GeV/*c

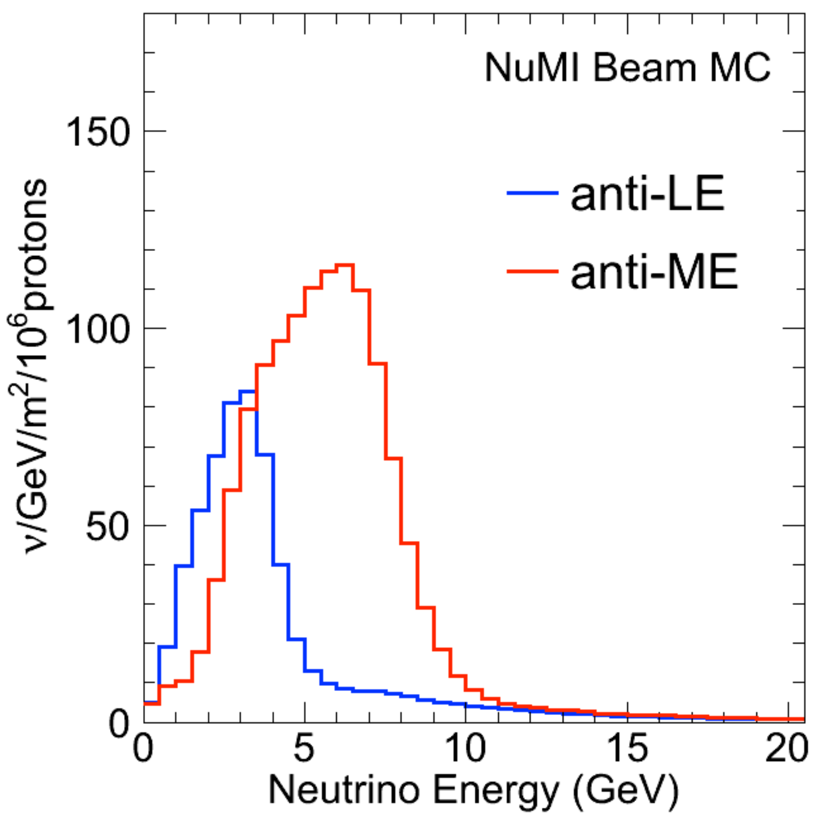
Vary ν beam energy by sliding the target in/out of the 1st horn

"High" Energy



The NuMI Beam - Flux



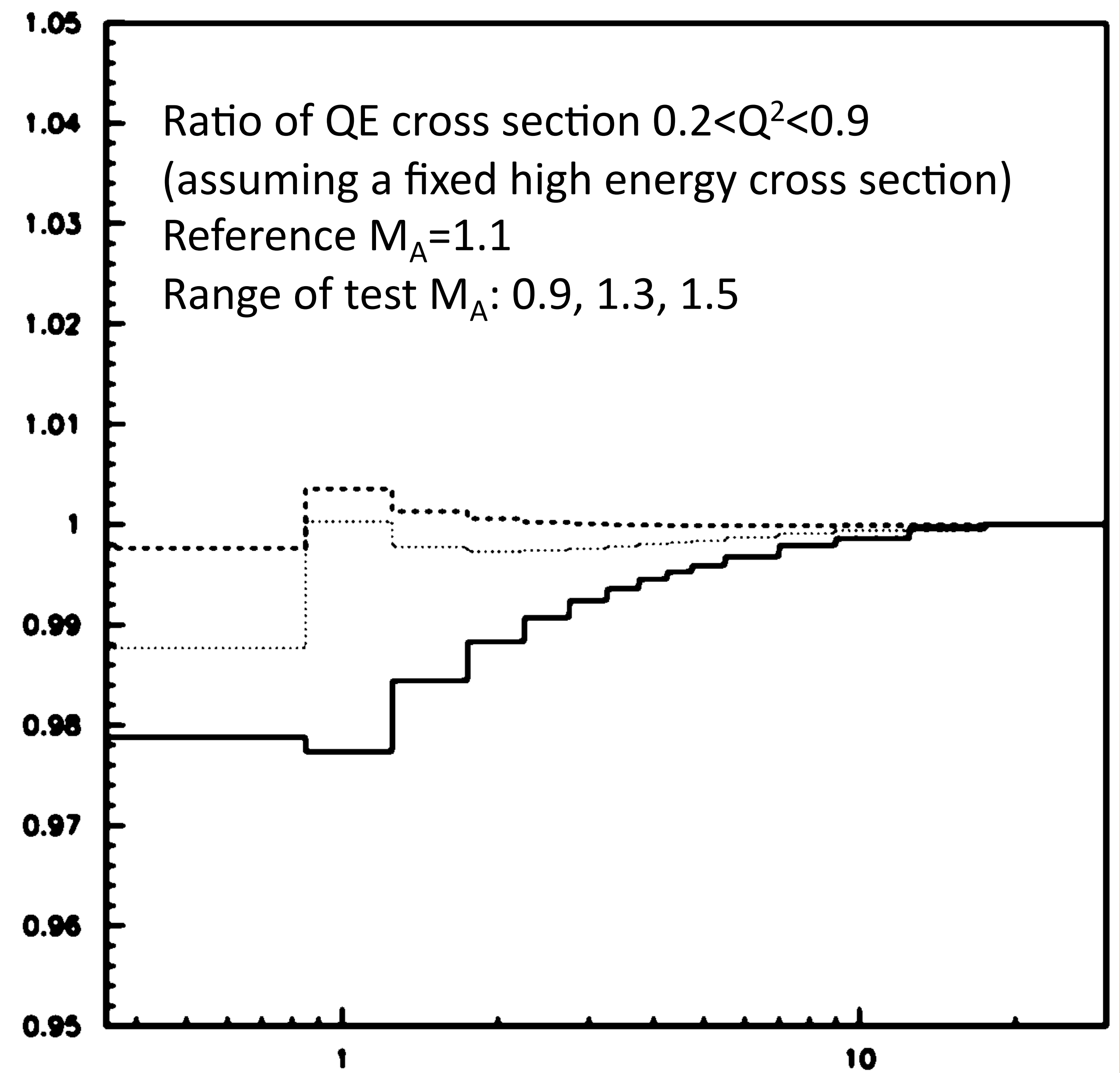


- **GEANT3−based Monte Carlo using FLUKA to calculate the flux of particles off the target.**
- **Evacuated decay pipe (now filled with He gas).**
- **Fluxes calculated at the center of the detector (1030.99m from the upstream end of horn 1).**
- **All fluxes (for display purposes) are plotted at a single point, whereas the MINERνA detector is large in transverse size. This is properly taken into account when calculating Monte Carlo data sets for MINERνA.**
- **Goal for the flux uncertainty is ~10%.**

LE = low energy target, horns separated by 10m, target at z= −10cm; LE010/185kA.
ME = low energy target, horns separated by 23m, target at z= −100cm; ME100/200kA

Measuring Flux: Fitting to Data

MINERvA's "standard candle" data set will be QEL events of moderate Q^2



Ratio of cross section of test M_A to reference M_A vs. E_ν

- QEL cross section on nucleons is a function of Q^2, independent of neutrino energy (even for extreme values of M_A)
- Low Q^2 events are excluded because of uncertainties due to nuclear effects
- High Q^2 events are excluded because of reconstruction difficulties
- Use inclusive CC sample above ~20GeV and compare to CCFR, CCFRR, and CDHSW data sets to fix the absolute normalization

M. Jerkins, NUINT 2011

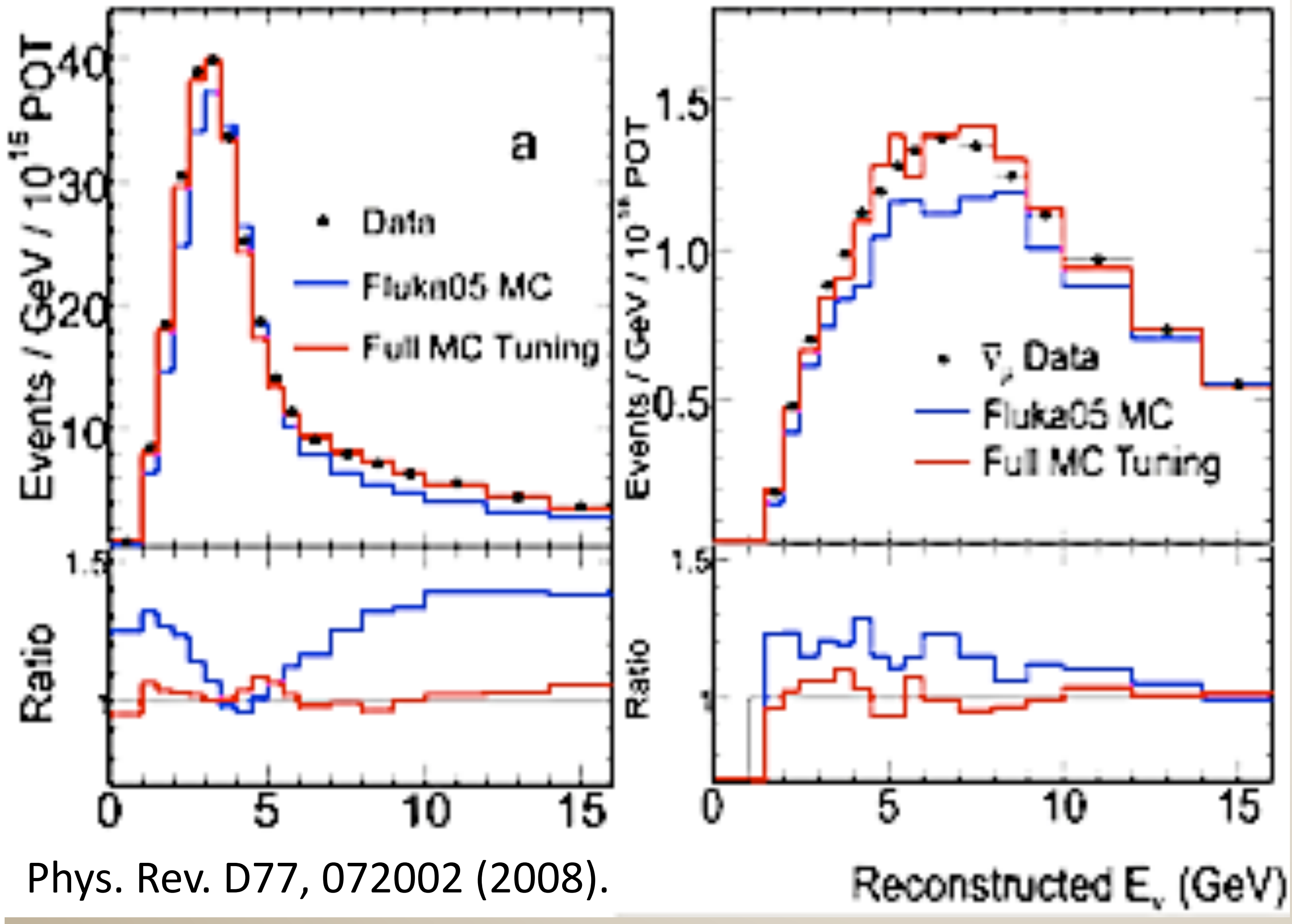
Measuring Flux: Fitting to Data

Result of fit = set of weights in (x_F,p_T) plane that should be applied to π/K yields

MINOS utilized such fits:

Flux uncertainty at far detector reduced (2-10)% → (1-4)%

$$weight = \frac{\left(d^2N/dx_F dp_T\right)_{tuned}}{\left(d^2N/dx_F dp_T\right)_{MonteCarlo}}$$



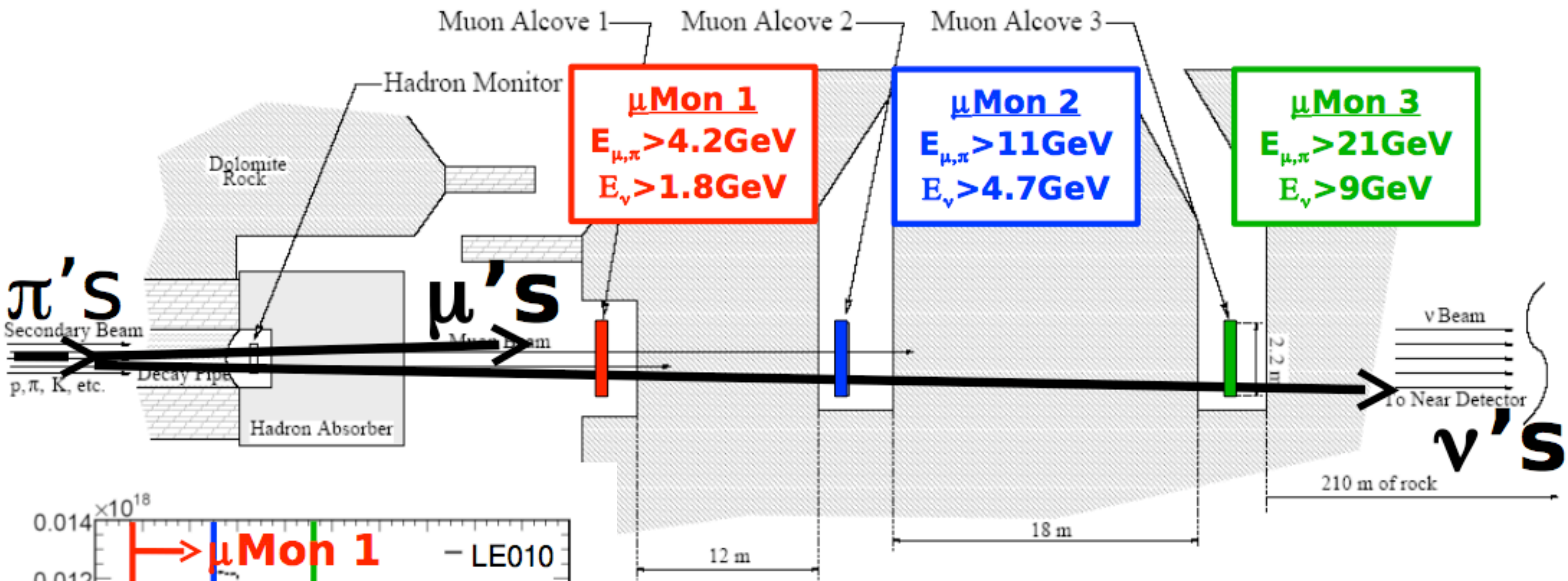
Phys. Rev. D77, 072002 (2008).

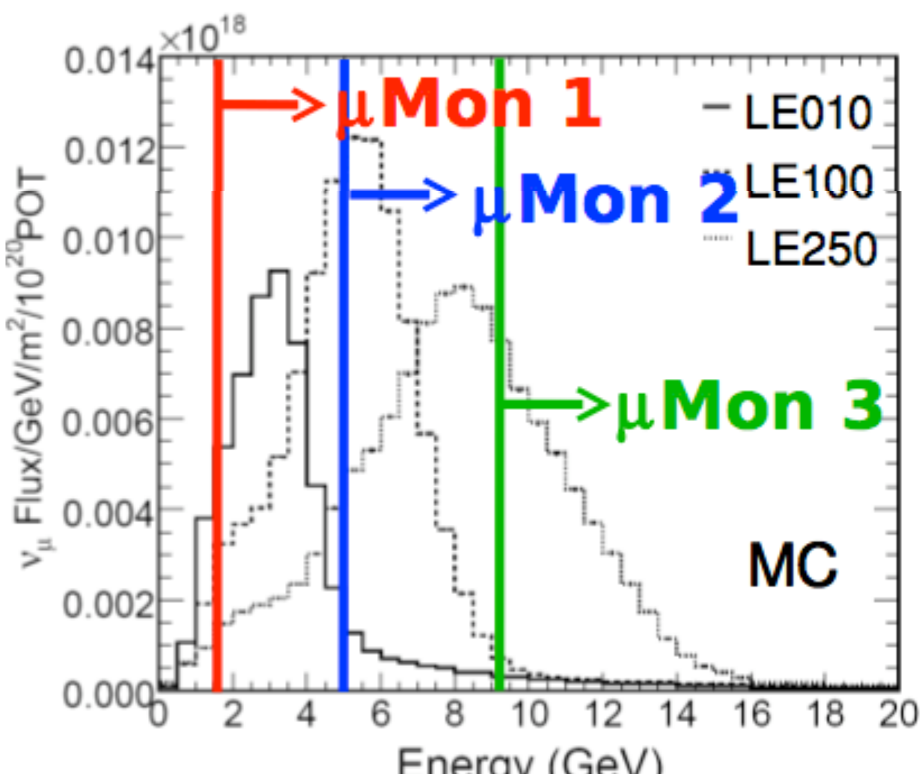
MINOS used inclusive event sample for its fits:

- Fine for Far/Near ratio … but not for xsec measurements
- QEL events provide a well-known process for MINERvA

M. Jerkins, NUINT 2011

Measuring Flux: Muon Monitors

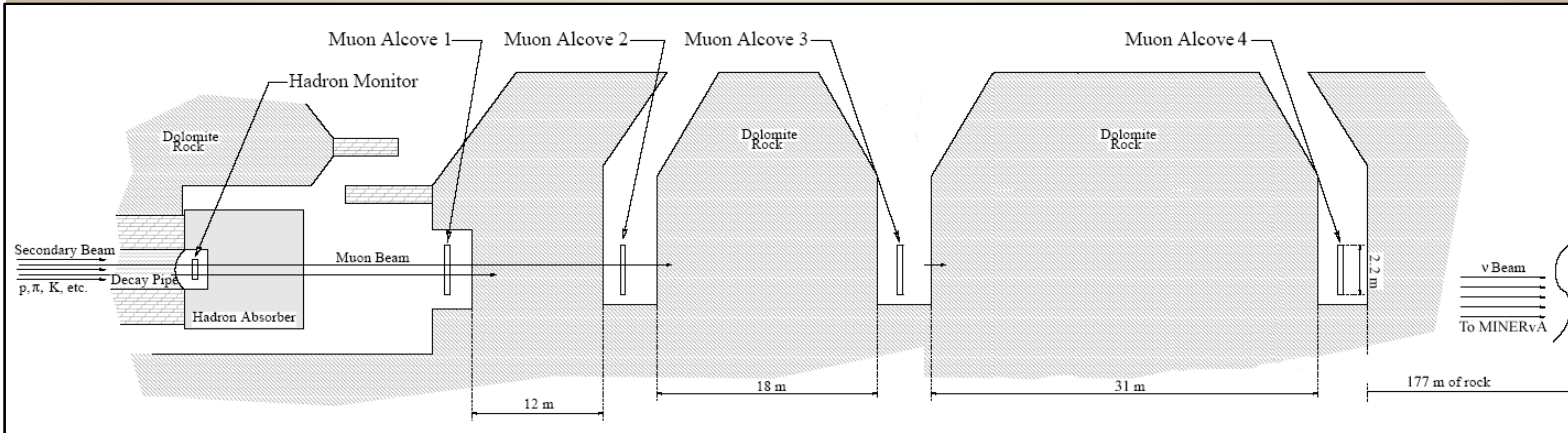




- Muon thresholds translate into ν thresholds
- Allows sampling of different energy regions of the flux
- 3 alcoves = poor granularity per measurement … but NuMI's flexible beam offers data from many (I_{horn},Z_{target}) combinations

M. Jerkins, NUINT 2011

Measuring Flux: Muon Monitors

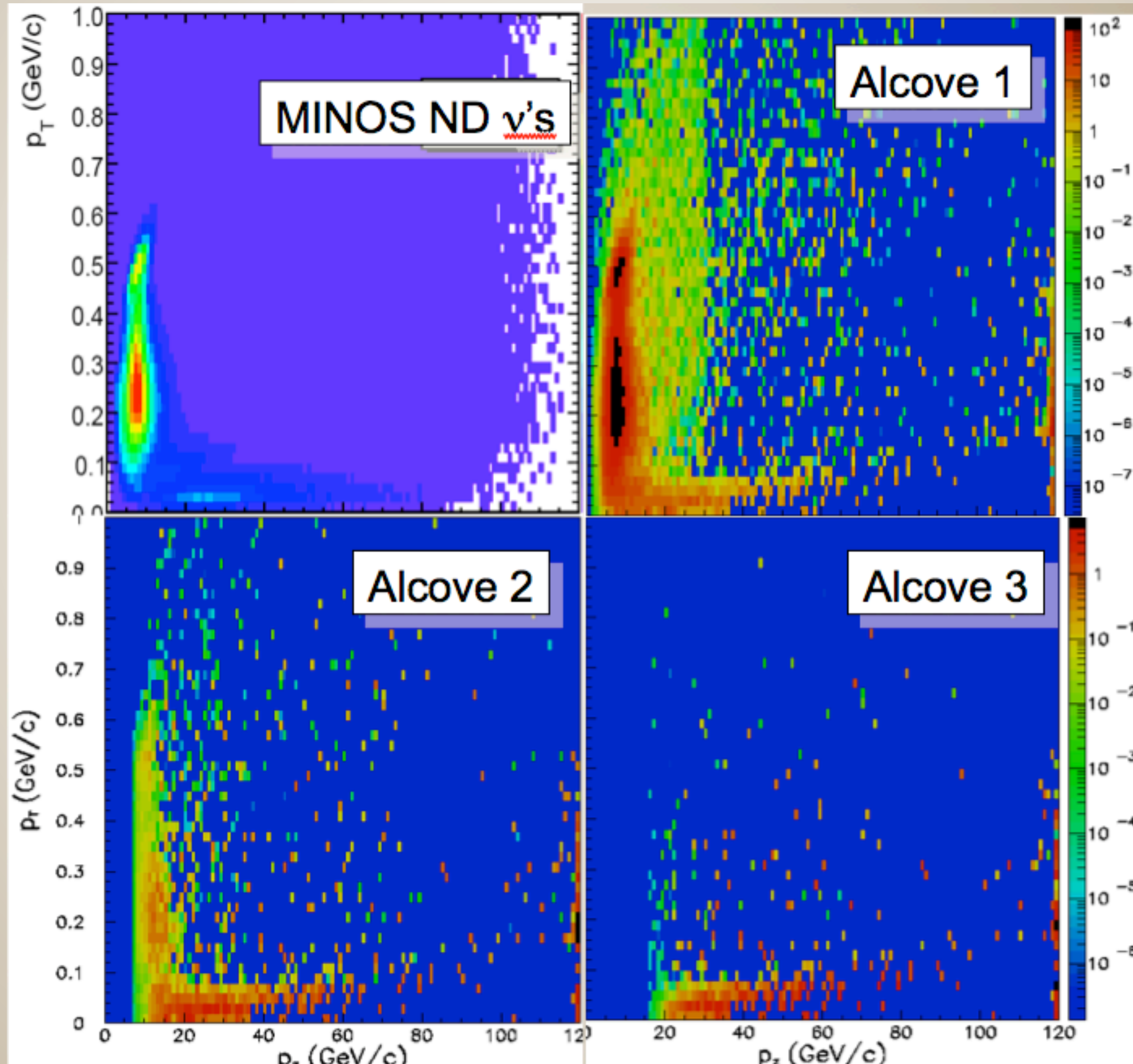


- 3 arrays of ionization chambers (2m x 2m)
- Plans to install a 4th chamber
- Beam μ's ionize He gas
- Signal = ionized electrons
- Sampling μ flux = hadrons off target = sampling ν flux
- Technique proven at CCFR, CERN-PS, CERN-SPS

M. Jerkins, NUINT 2011

Measuring Flux: Fitting to μMon

We can fit muon monitor data to obtain (x_F,p_T) in the same way we fit MINERvA data



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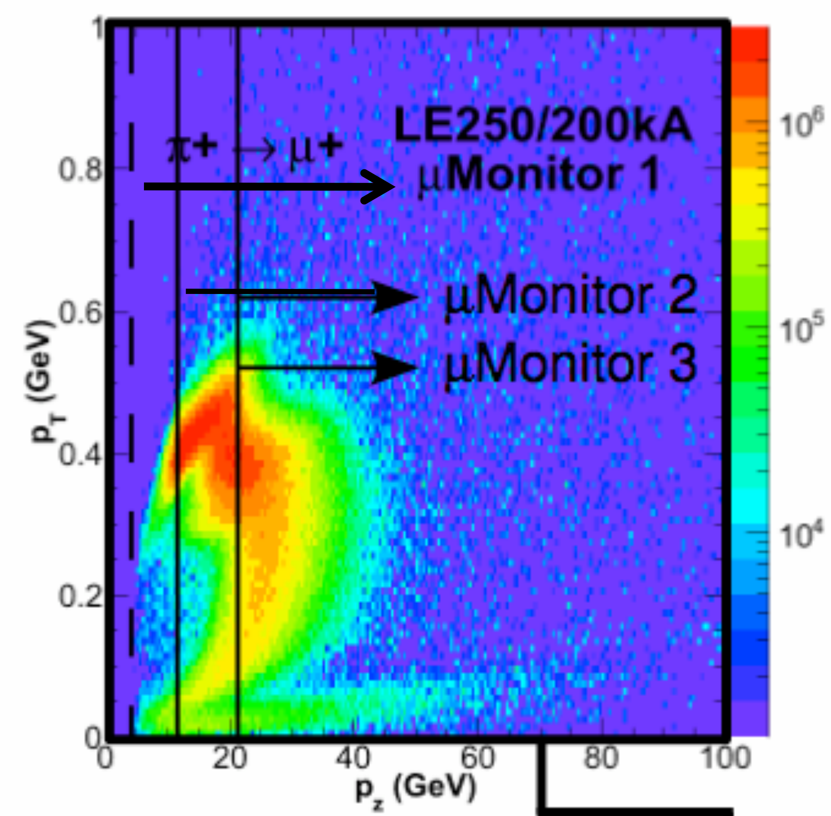
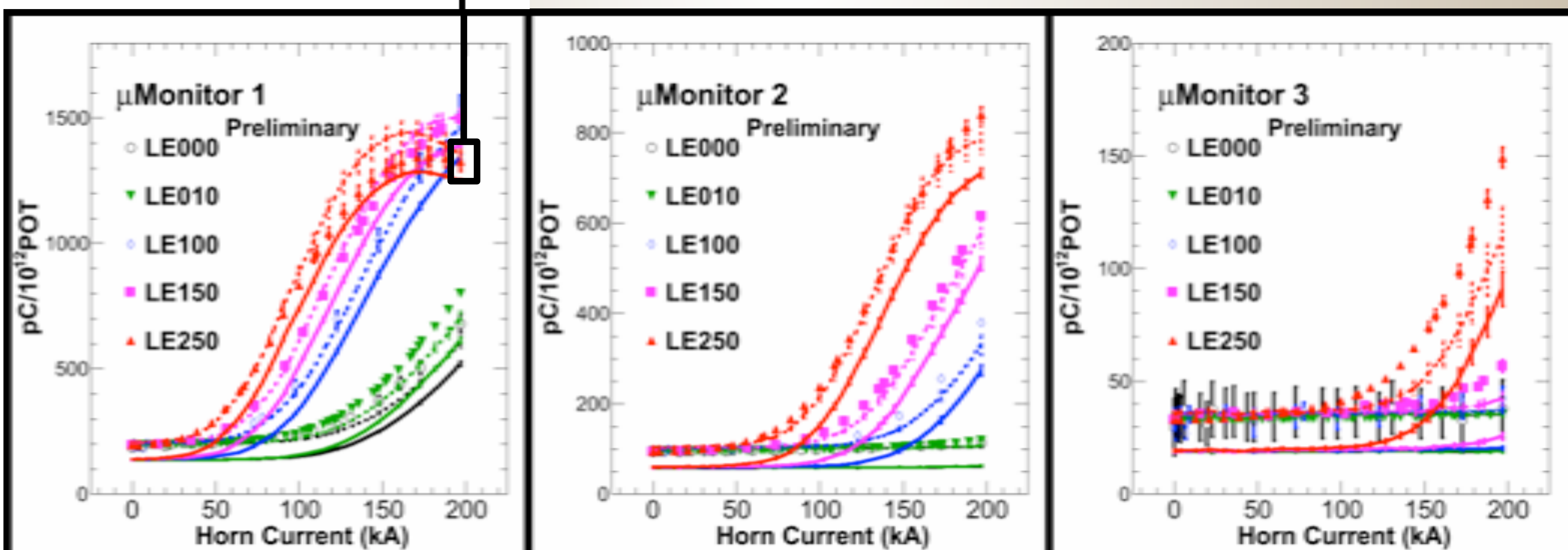
Measuring Flux: Fitting to μMon



Successfully tuned MC to match μMon data

- Empirical parameterization for hadron production
- Warp p_T and p_z to tune MC to μMon data
- Allow π^+ parameters to float
- Fix π^+/π^- ratio to NA49 and fix K/π ratio to MC

• Data ——— Monte Carlo – – – Tuned Monte Carlo



M. Jerkins, NUINT 2011

Measuring Flux: Fitting to μMon

Obtained a flux shape measurement from its μMonitors

Largest sources of error:

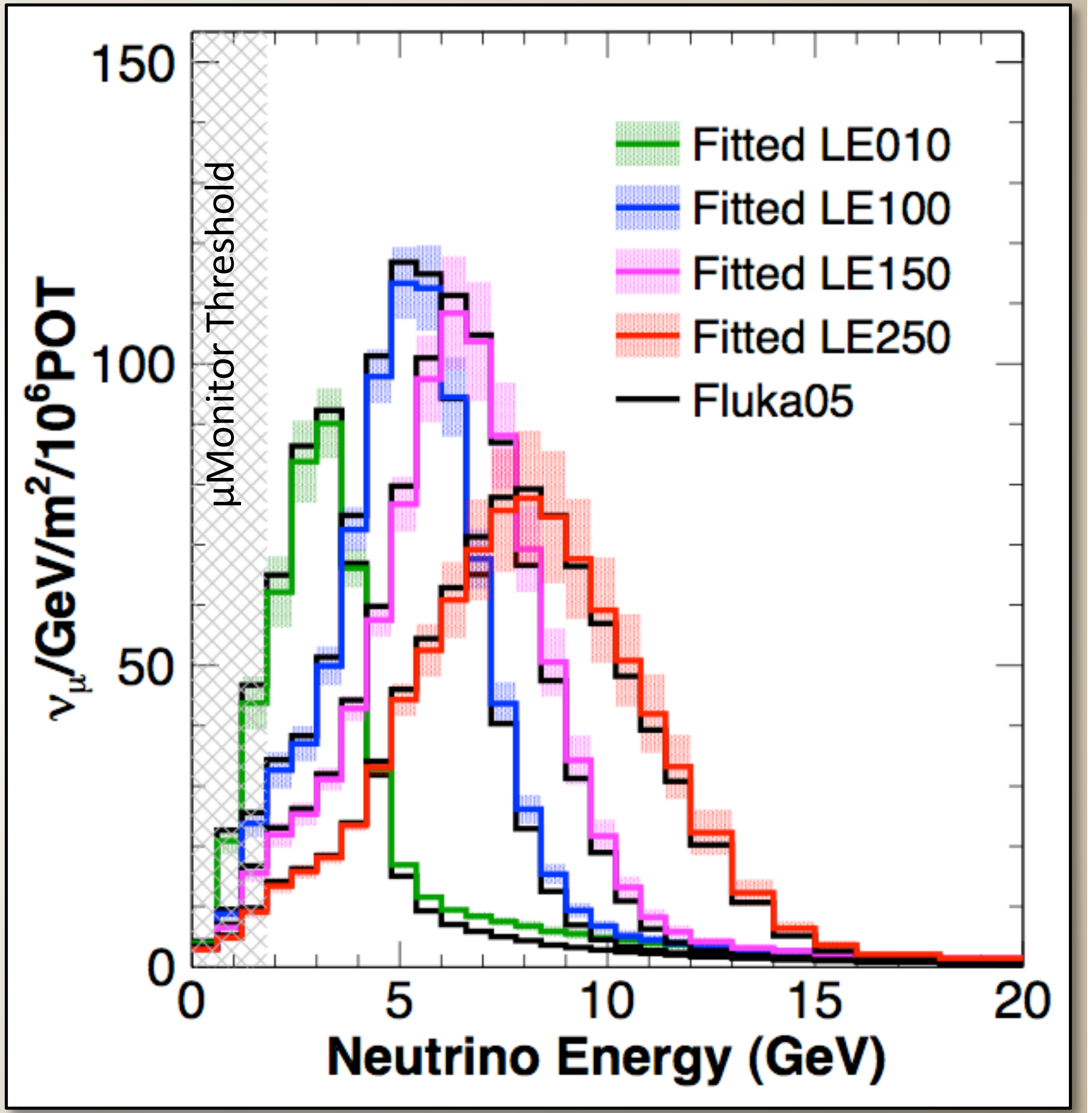
- Delta-rays
- Scaling pC/μ by ± 10%

Other sources of error:

- Bethe-Block energy deposition by μ in He
- Scaling K/π ratio by ± 10%
- Fixing π^+/π^- ratio to MC value
- Scale non-linearity correction in data ± 1σ
- Scale dump backgrounds ± 1σ

Due to large uncertainties, the flux was normalized to MINOS data for E_ν > 25 GeV.

How can MINERvA reduce those uncertainties?

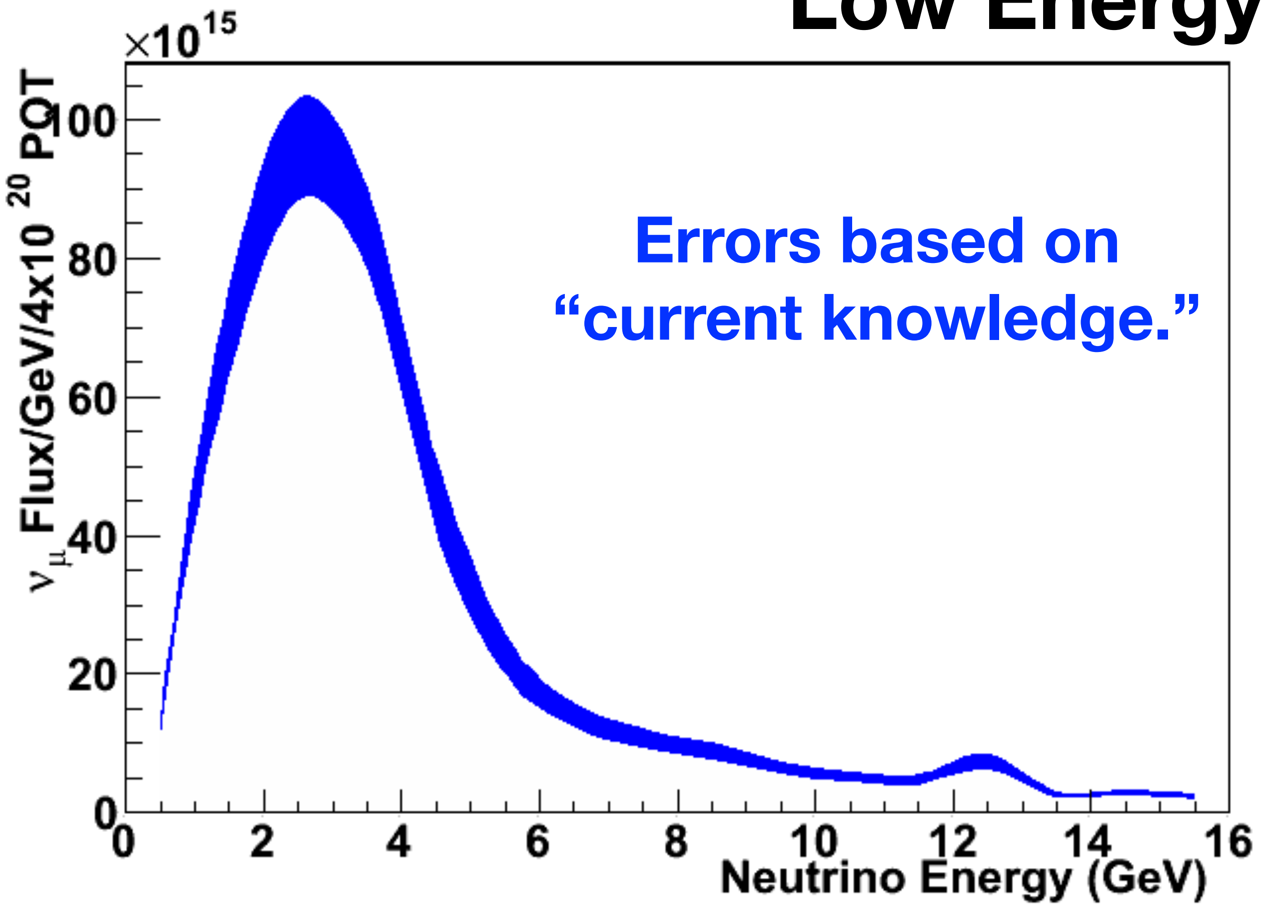


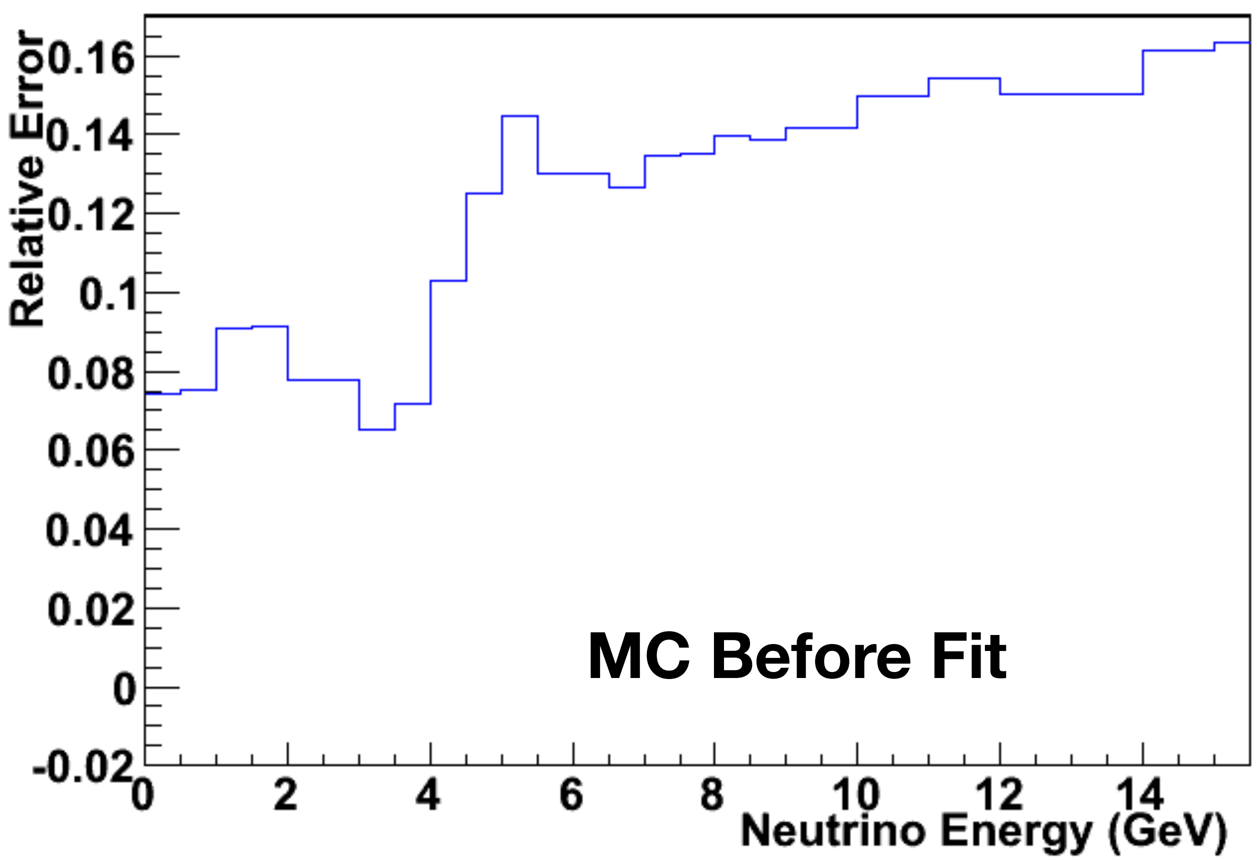
L. Loiacono, "Measurement of the Muon Neutrino Inclusive Charged Current Cross Section on Iron Using the MINOS Detector," PhD Thesis, UT Austin 2010

M. Jerkins, NUINT 2011

- We are planning a set of special runs varying the target position and horn current to sample different production spectra.
- We then plan to fit that data to model our baseline scenario. We are currently testing the procedure by tuning one MC against another.
- We have a small sample of special run data in hand, and plan to acquire more this Spring.
- Our total error estimate below includes beam focusing uncertainties, MC differences in π^+ production, and a 5% yield uncertainty for π^+ production on our target.

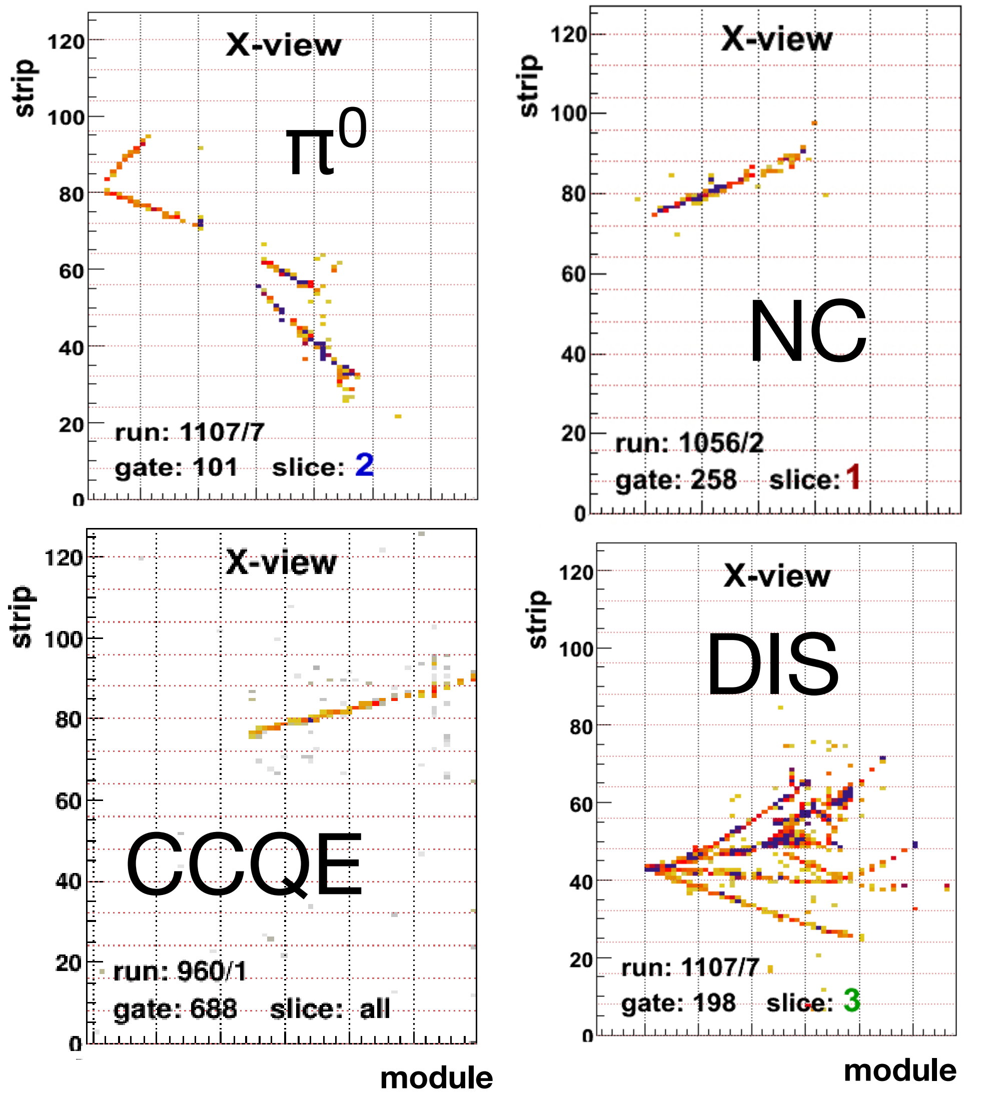
Low Energy Neutrino Mode



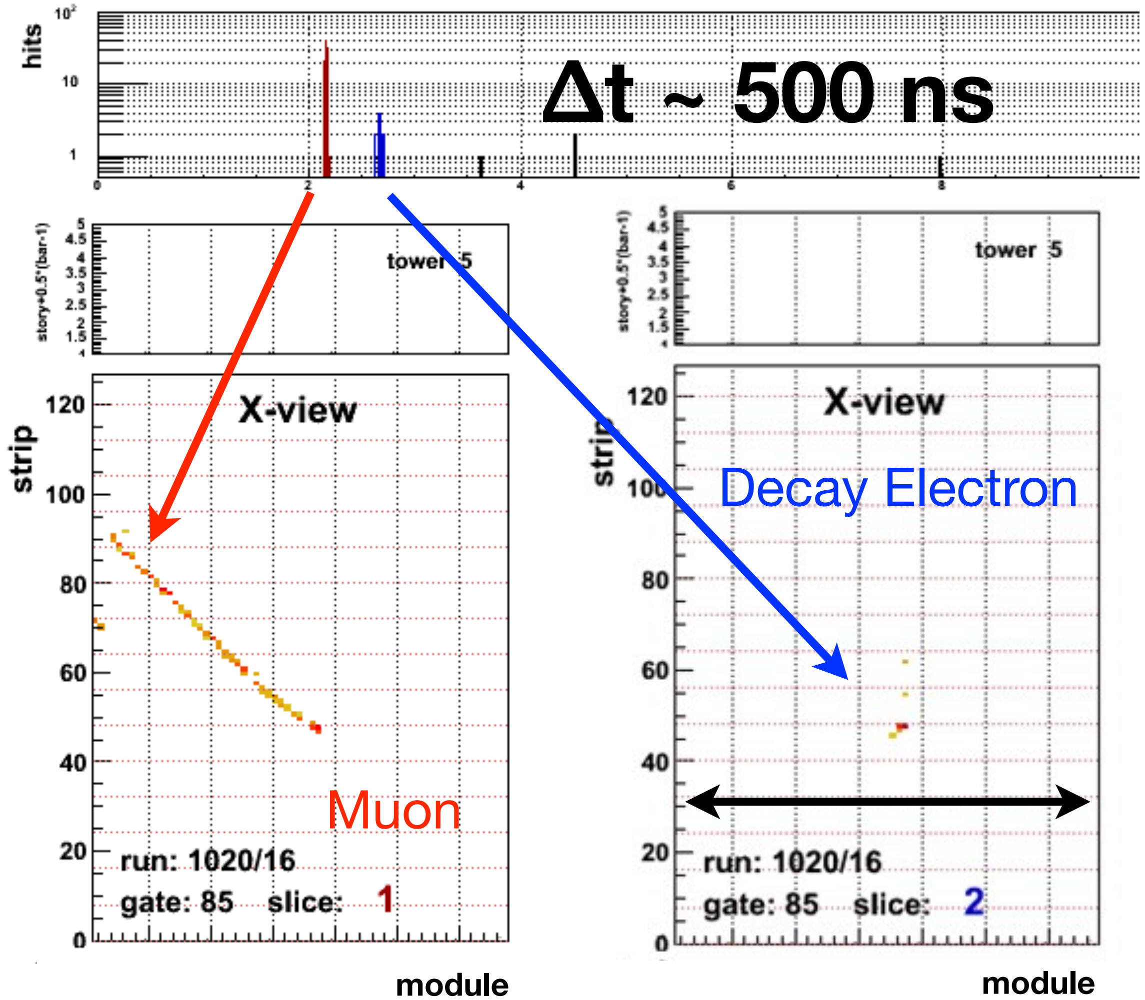


- **Overview of the flux error band:**
  - **Created by warping p_T of π^+ off the spectrum by 30 MeV. Observed change in flux due to the warping, and considered that to be a one sigma error band due to hadron production uncertainty.**
  - **Added in quadrature a 5% uncertainty due to overall uncertainty of yield off target.**
  - **Added in quadrature the focusing uncertainties estimated by Z. Pavlovic.**
- **Notes about what's not included in the large error band:**
  - **Differences in how models handle tertiary hadron production.**
  - **Differences in the mean p_T of π^-, K^+, and K^- off of the target.**

Anti-ν Event Candidates



Michel Electron Candidate



Beam Direction

64 Modules ~ 3.5 m

Timing Resolution ~4 ns.

$\bar{\nu}p \to \mu^+ n$ Event Candidates:
Low Energy Anti-ν Beam MC
True - Reconstructed : True