The MINERνA Experiment

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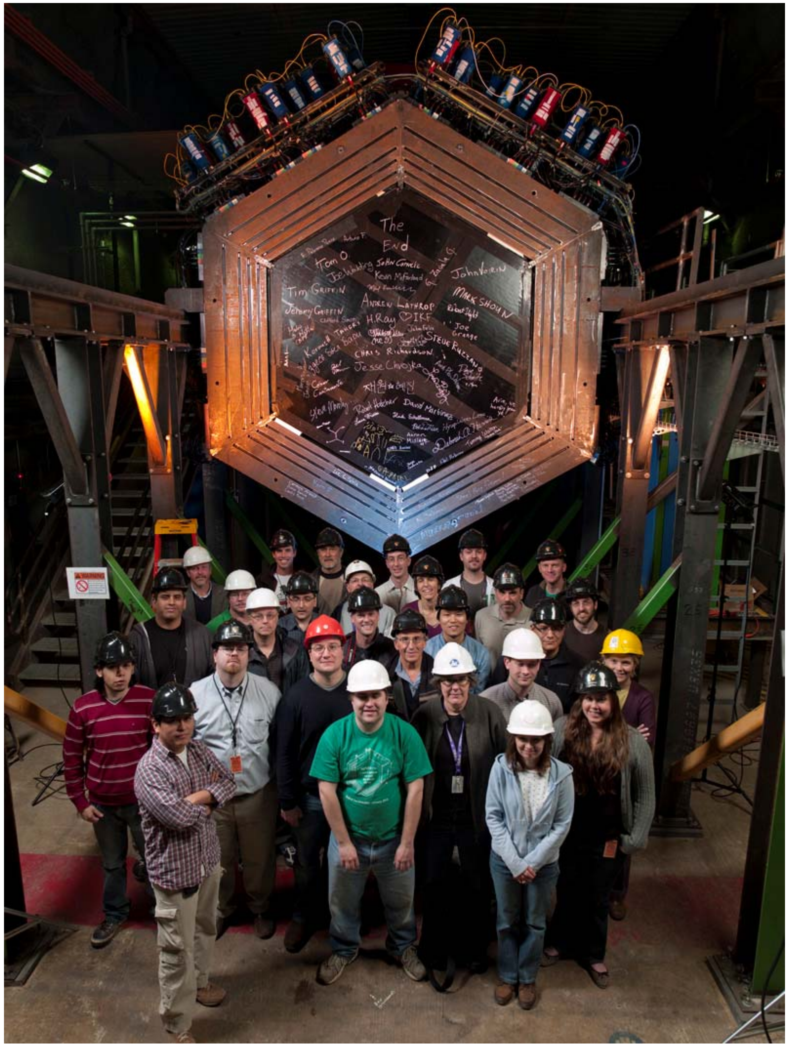
SLAC Summer Institute 2010

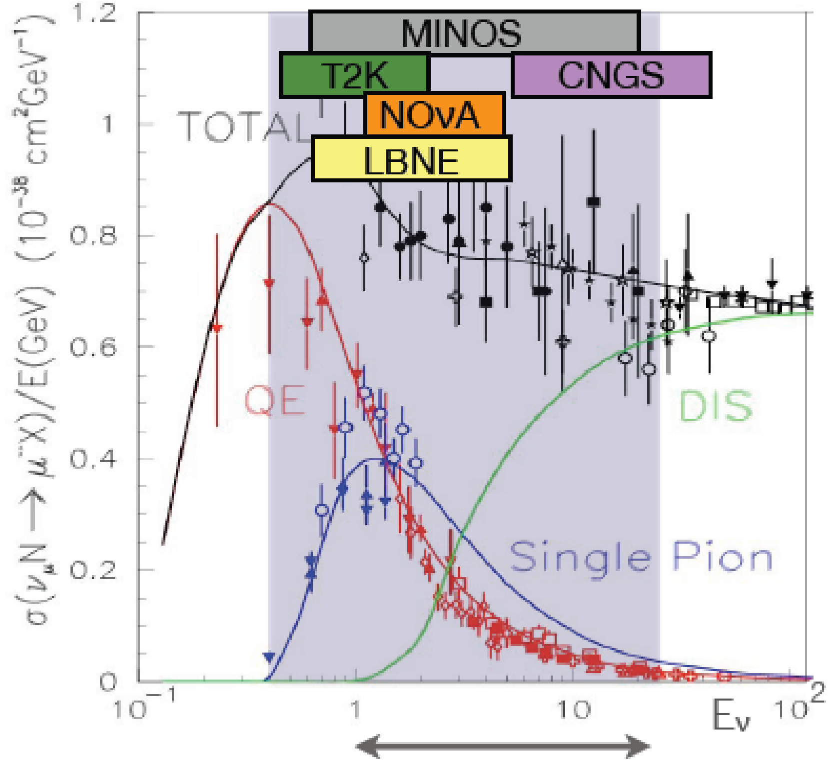
Outline

- Previous ν Results
- NuMI Beam & measuring the flux
- MINERνA Detector
- MINERνA Event Displays
- Kinematic Distributions
- Expectations on extracting $F_A(q^2)$ & cross section vs energy
- Test beam
- Summary



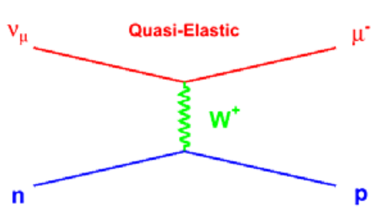
ν interaction physics

Plot from G. Zeller

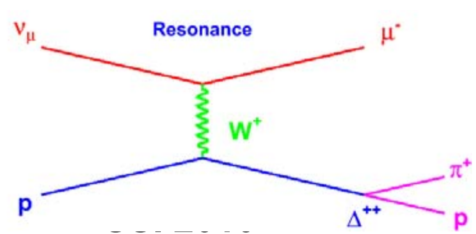


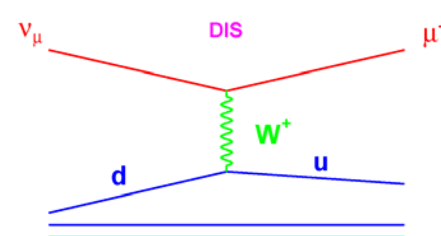
MINERvA Coverage

- ν oscillations need to understand ν reactions on nuclear targets in the 1-10 GeV region
- Older Data Problematic
  - 20-50% uncertainties, depending on process
- The nuclear physics was not well understood
- Causes uncertainty on prediction in far detector

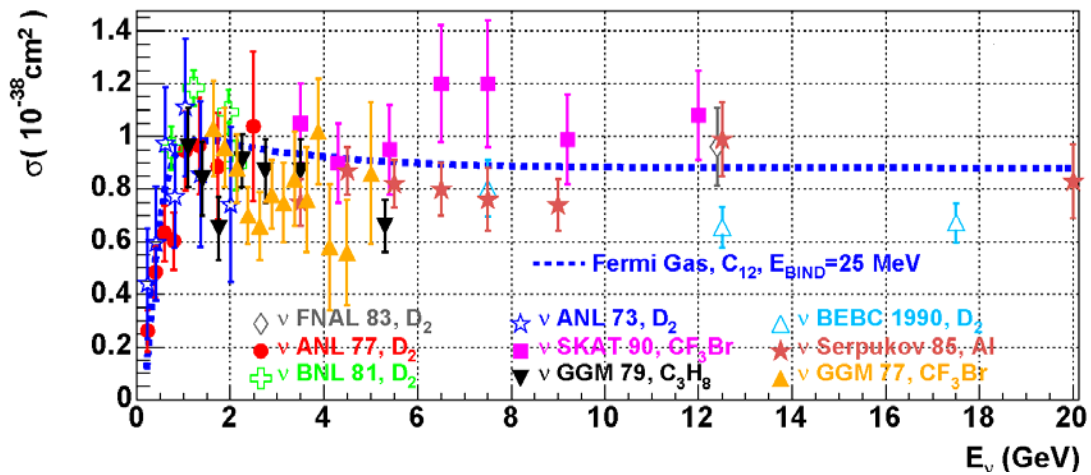


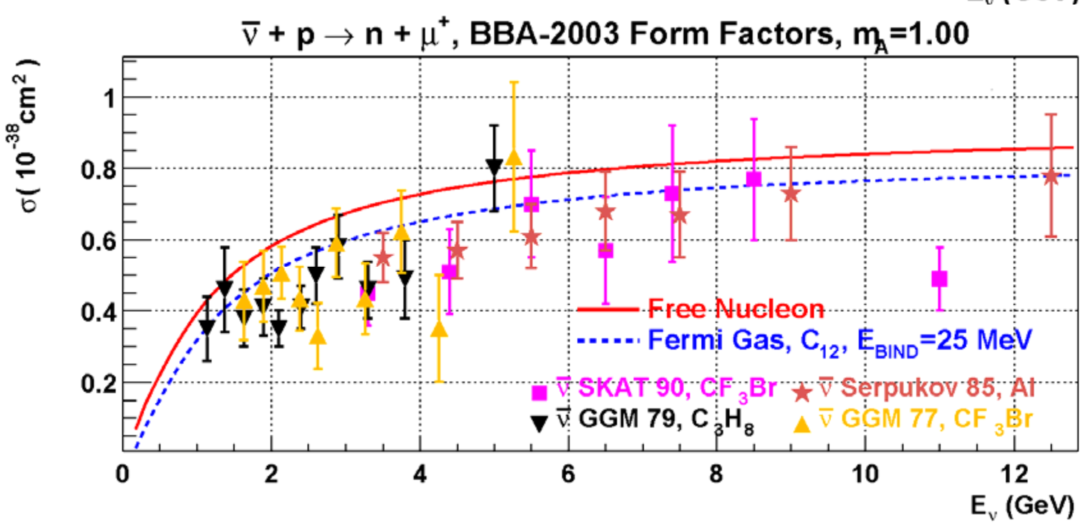
Single p

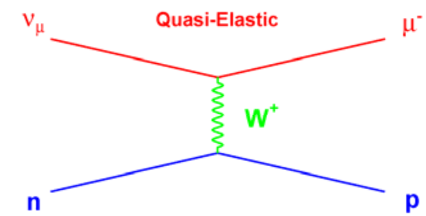




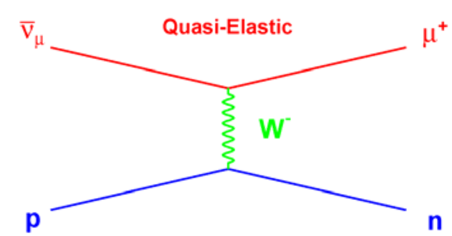
Earlier CCQE Results



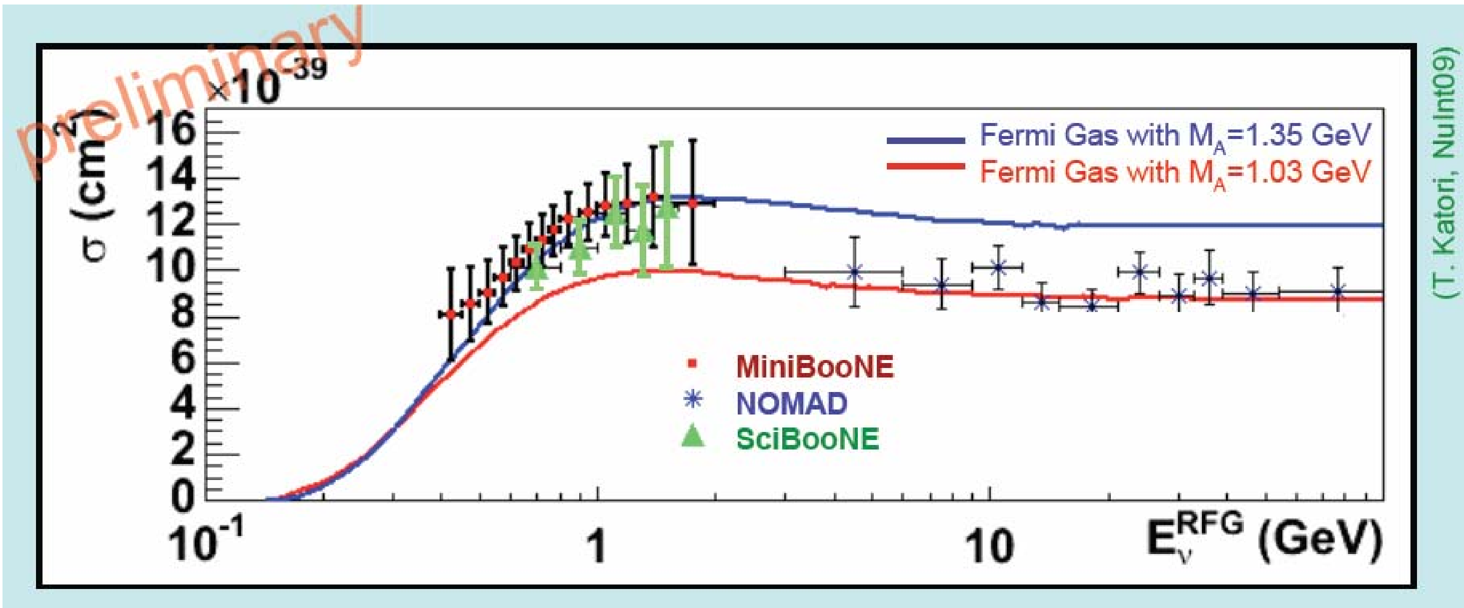




- Old data, next slide will have newer results
  - Most earlier results from bubble chambers
  - 20% uncertainty
- The anti-ν measurements are on nuclear targets
  - Statistics not very good
  - Large variation and they look low

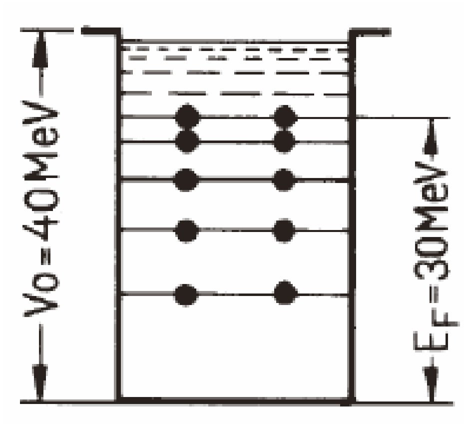


New Data, Still Inconsistent



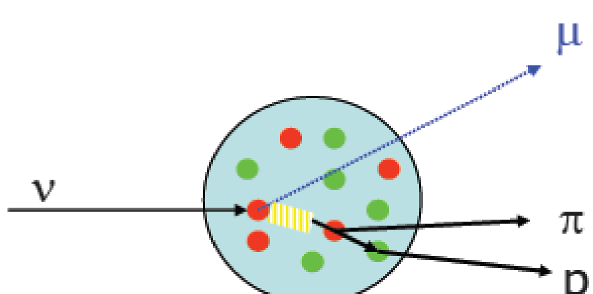
- New Data
- Clear inconsistency between MiniBooNE/SciBooNE and NOMAD results

Nuclear Effects, FGM & FSI

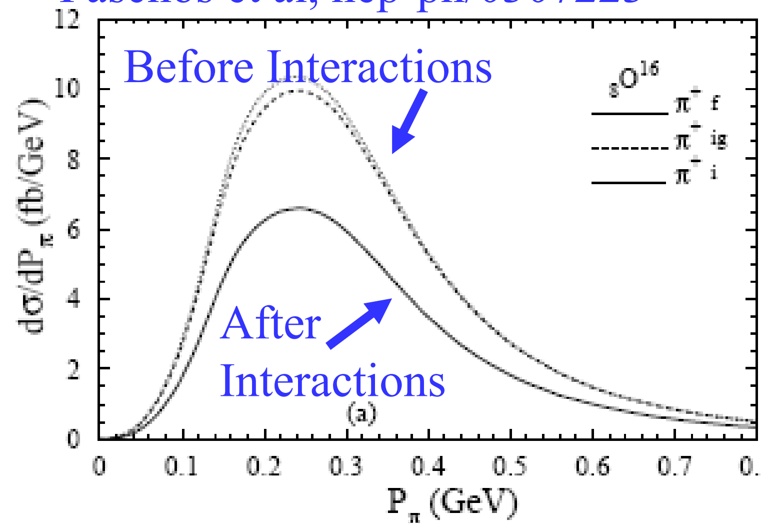


- Fermi gas model, nucleons obey Pauli exclusion principle
  - Nucleons fill up states to some Fermi momentum
  - Maximum momentum $k_F \sim 235$ MeV/c
- Nuclear binding, additional binding energy which in simple models is treated as a constant.
- Pauli blocking for nucleons not escaping nucleus, as states are already filled with identical nucleons

- Rescattering and Absorb in nuclear media
  - Resonance →QE, π is lost
  - Kinematics of event are modified



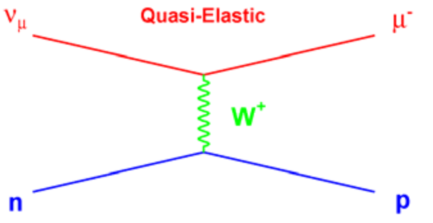
Paschos et al, hep-ph/0307223

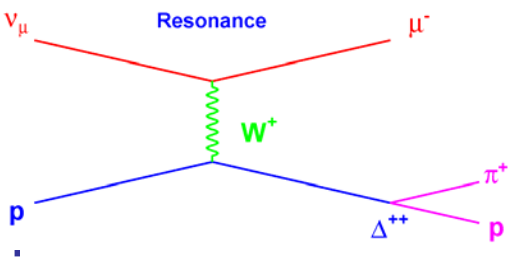


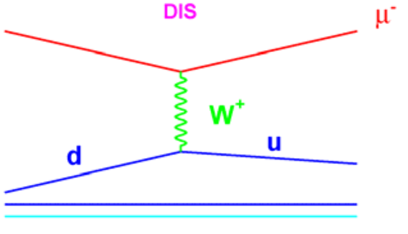
p_π distribution for π decay in Resonance production in Oxygen

MINERνA

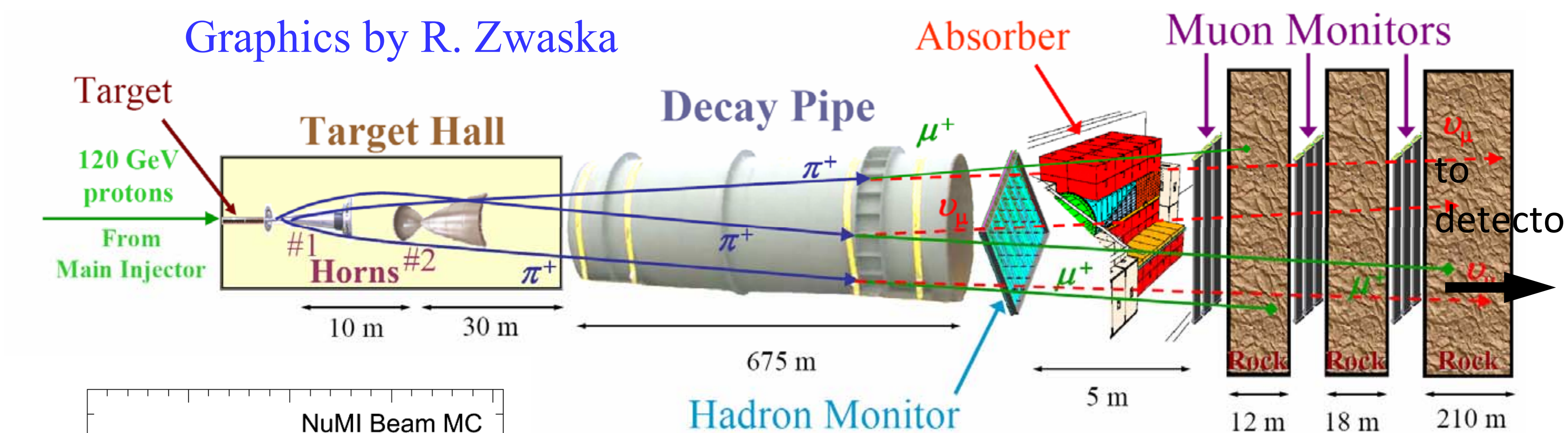
- Precision measurement of cross sections in the 1-10 Gev region
  - Understand the various components of cross section both CC and NC
    - CC & NC quasi-elastic
    - Resonance production, Δ(1232)
    - Resonance↔deep inelastic scatter, (quark-hadron duality)
    - Deep Inelastic Scattering
- Study A dependence of ν interactions in a wide range of nuclei
- Need high intensity, well understood ν beam with fine grain, well understood detector.

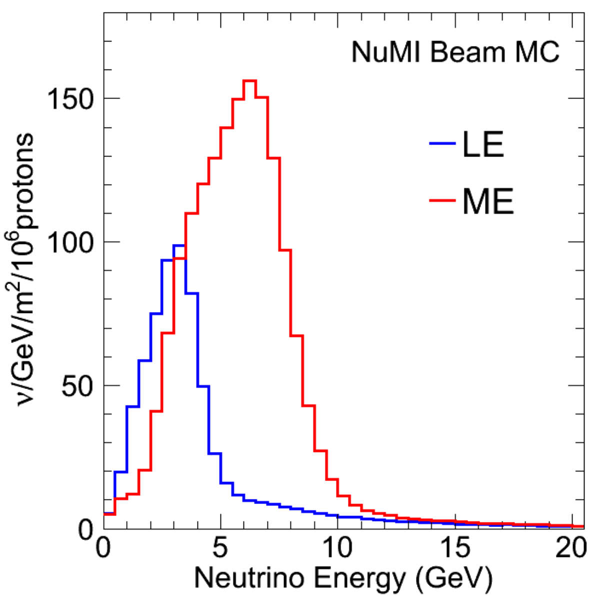






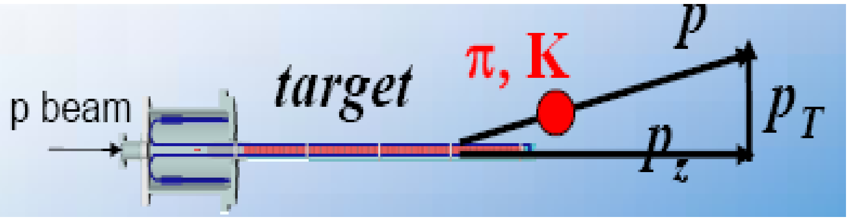
NuMI Beamline

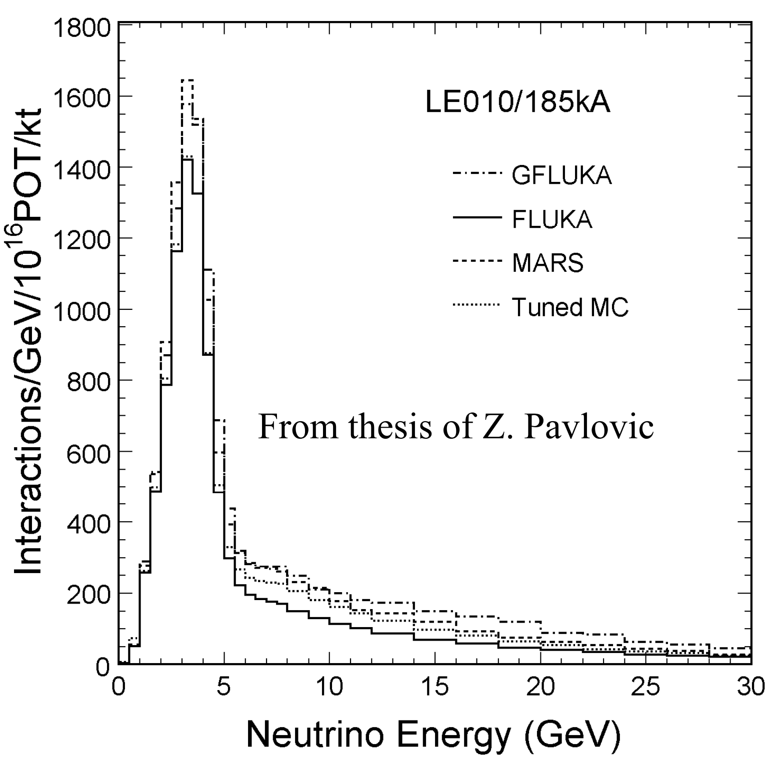




- 120 GeV P Beam → C target → π^{+-} & K^{+-}
- 2 horns focus π^+ and K^+ only
- Mean E_ν increased by moving target upstream
- π^+ and $K^+ \rightarrow \mu^+\nu_\mu$
- Absorber stops hadrons not μ
- μ absorbed by rock, ν → detector
- Before Mar 2012 LE beam, After 2012 ME beam

Understanding the Flux

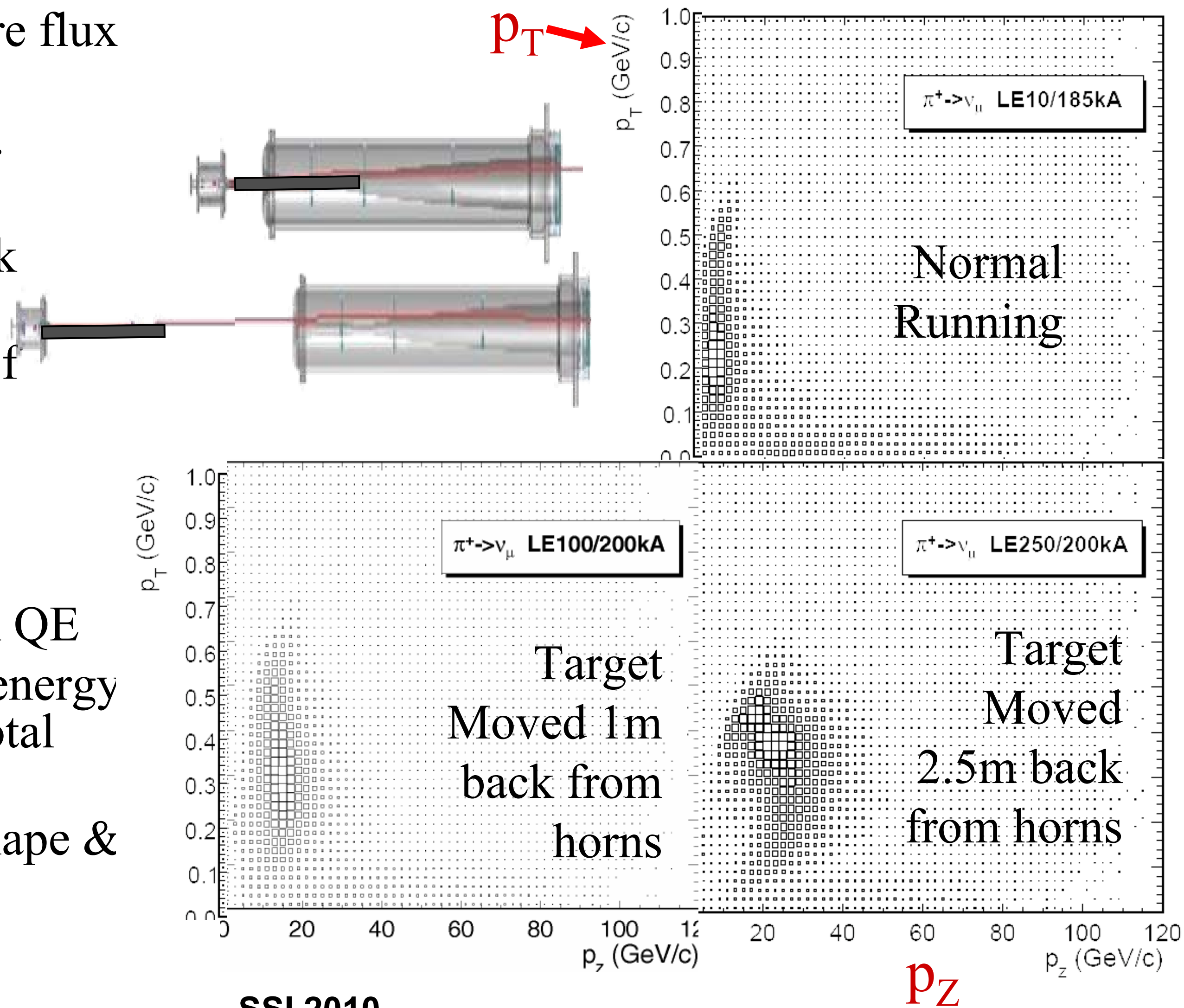




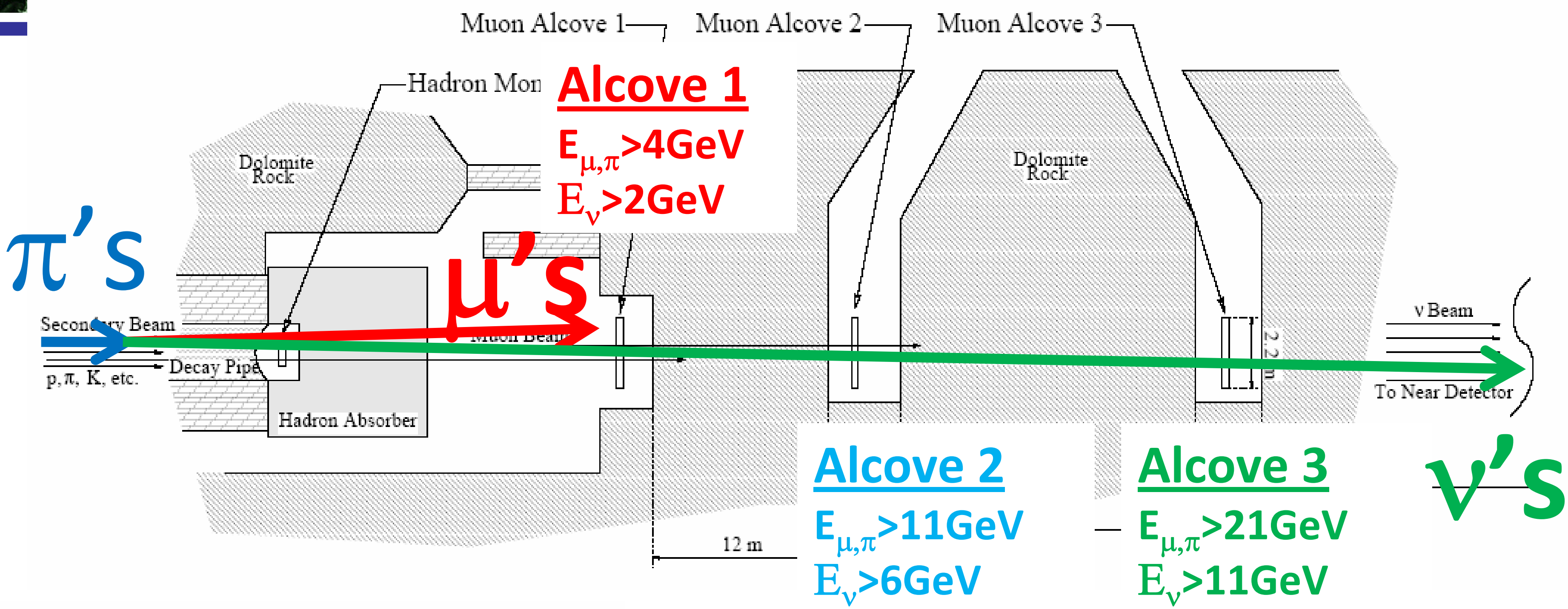
- Most ν experiments use a MC of beamline tuned to existing hadron production to simulate the production of the neutrinos in the beam line
- External hadron production data
  - Atherton 400 Gev/c p-Be
  - Barton 100 GeV/c p-C
  - SPY 450 Gev/c p-C
- New FNAL MIPP experiment uses 120 Gev/c P on replica of NuMI target
- Not easy to get flux precisely this way
- Plot shows prediction of CC interactions on MINOS with different production models each consistent with experimental production data.
  - Variations 15 to 40%
- In additional 2 to 10% error from horn angle offset &current errors and scrapping

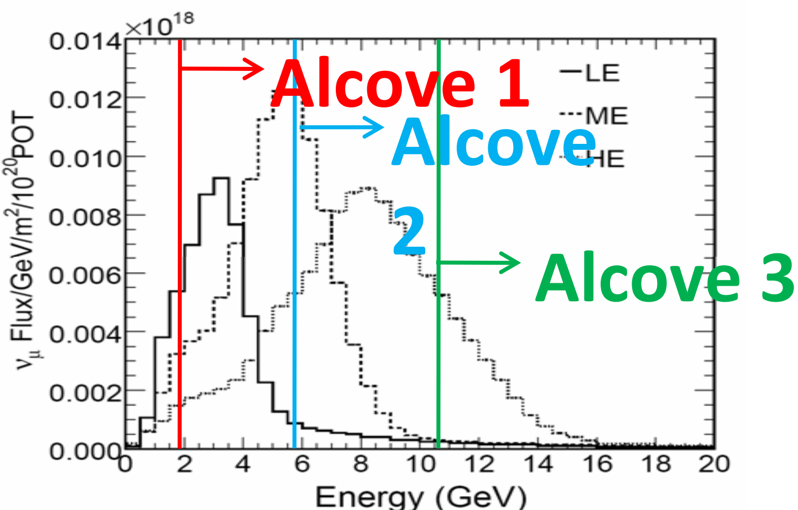
Measure Flux, Special Runs

- In situ method to measure flux
- Plots show (p_z ,p_T) of π^+ contributing to ν flux.
- "Special Runs" vary
  - Horn current (p_T kick supplied to π's)
  - Target Position (p_z of focused particles)
- Minerva will acquire data from total of 8 beam configurations
  - Measure events with QE
- Normalize flux at high energy using CCFR/CHARM total cross section
- Goal is 7% error flux shape & 10% error on flux normalization



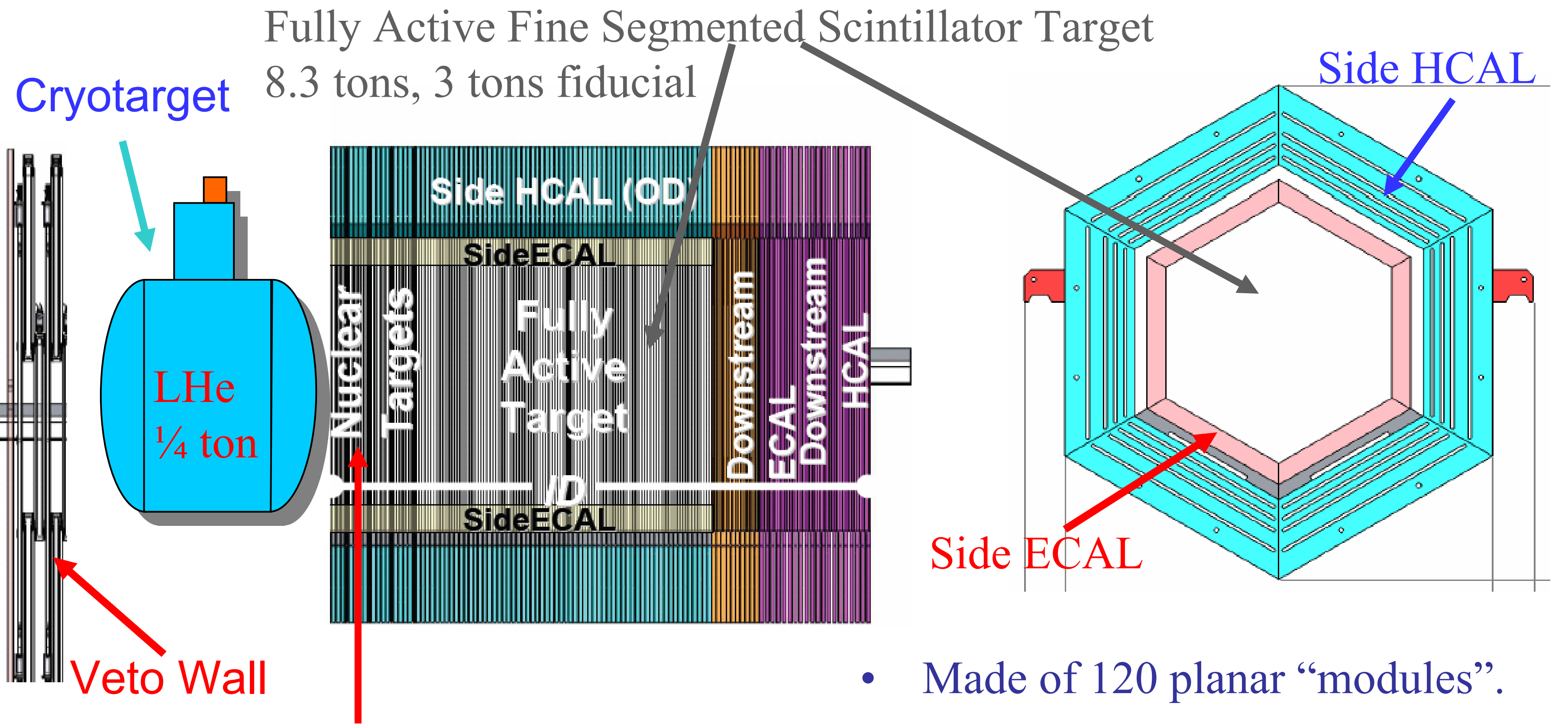
Absolute Flux with μ Monitors





- 3 arrays of ionization chambers, 4th chamber being added;
- Signal = ionized electrons.
- Sampling μ flux = Sampling hadrons off target = Sampling ν flux.
- Sample different energy regions of the flux.
- Goal of μ monitors is to understand flux normalization to 10%

MINERνA Detector



Nuclear Targets with Pb, Fe, C, H_2O,CH
In same experiment reduces systematic errors between nuclei

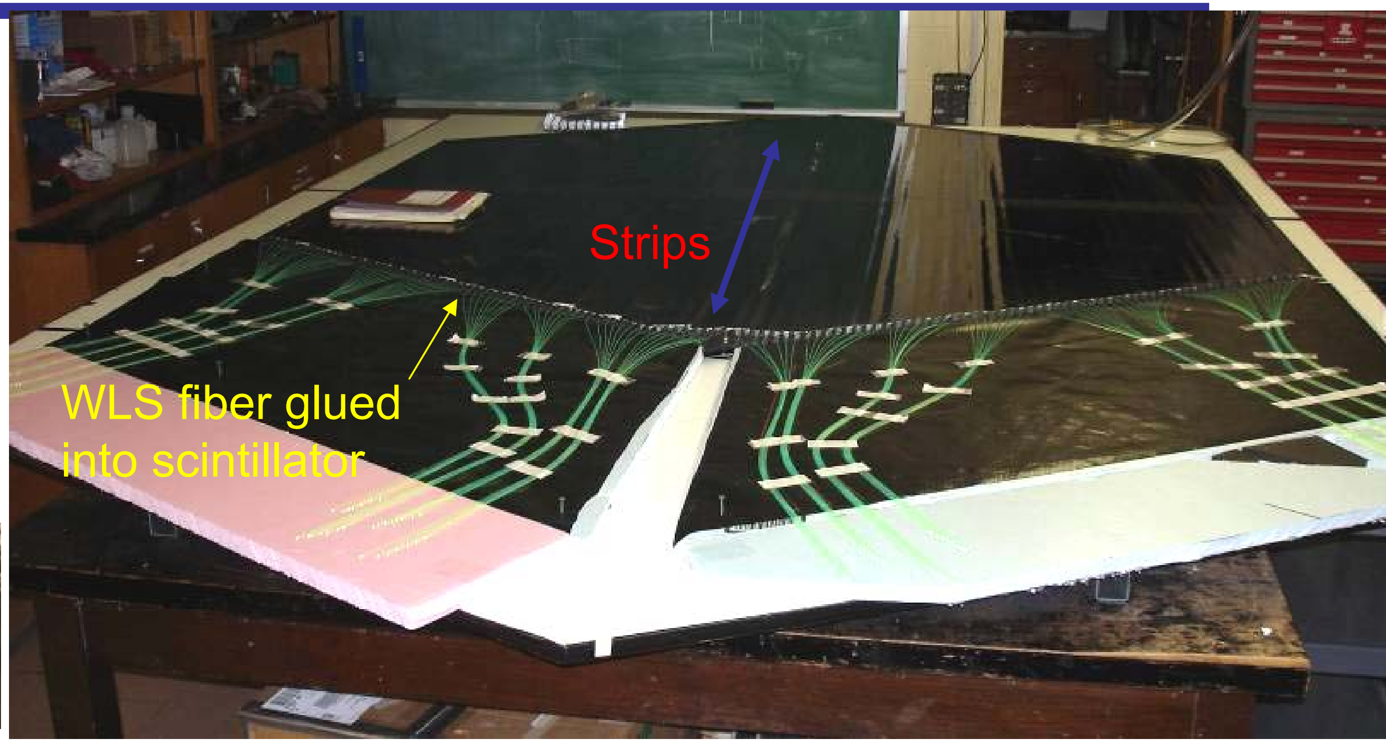
- Made of 120 planar "modules".
  - Total Mass: 200 tons
  - Total channels: ~32K

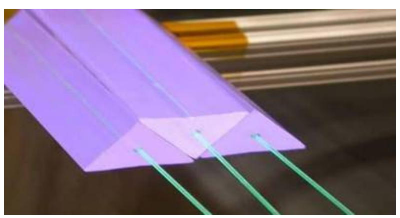
MINERνA μ Spectrometer

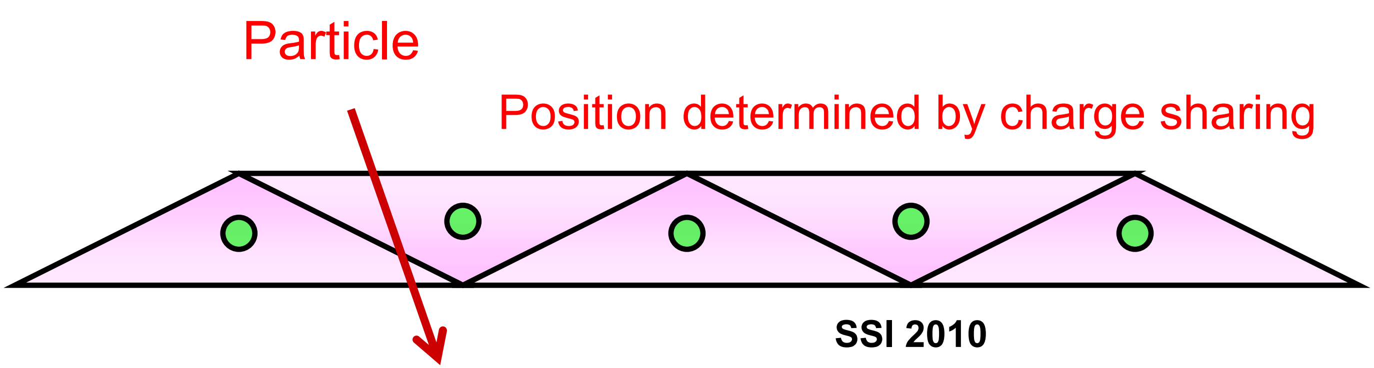
The MINOS Near Detector is MINERνA μ Spectrometer

Scintillator

Tracker scintillator packaged into planes.

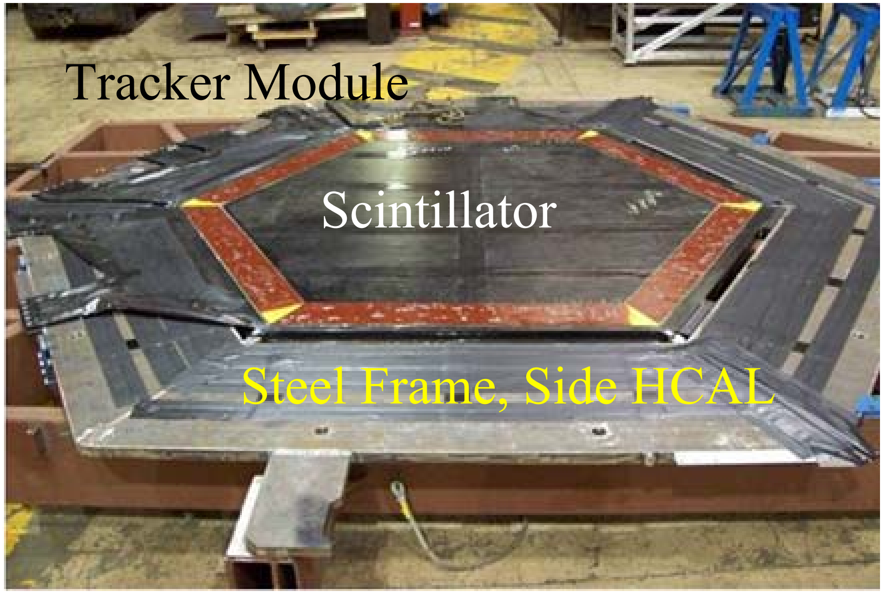






Fibers mirrored on far end. Near end terminated in optical connector, polished, and light-tightened.

Module



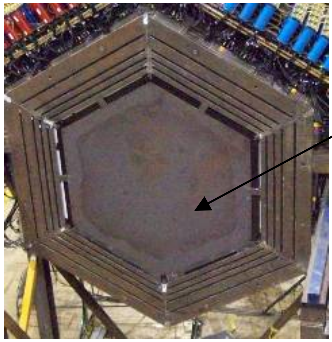
Steel + scintillator = module

Typical module:

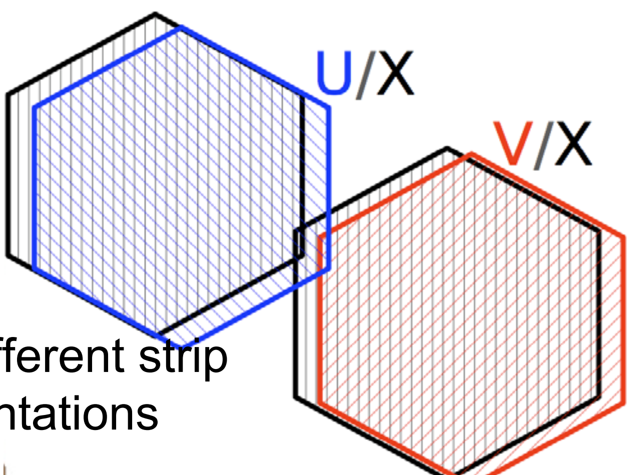
- has 302 scintillator channels
- weighs 3,000 lbs
- 3 types of modules

Full detector:

- 120 modules; ~32K channels.



HCAL modules include 1” steel absorber



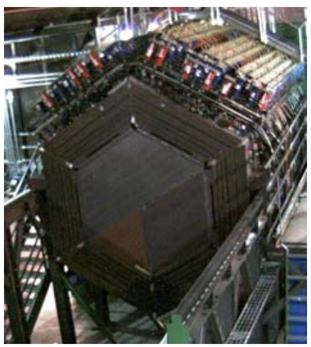
3 different strip orientations

ECAL modules incorporate 2mm-thick Pb absorber

Broad Range of Nuclear Targets

- 5 nuclear targets + water target
- Helium target upstream of detector
- Near million-event samples (4×10^{20} POT LE beam + 12×10^{20} POT in ME beam

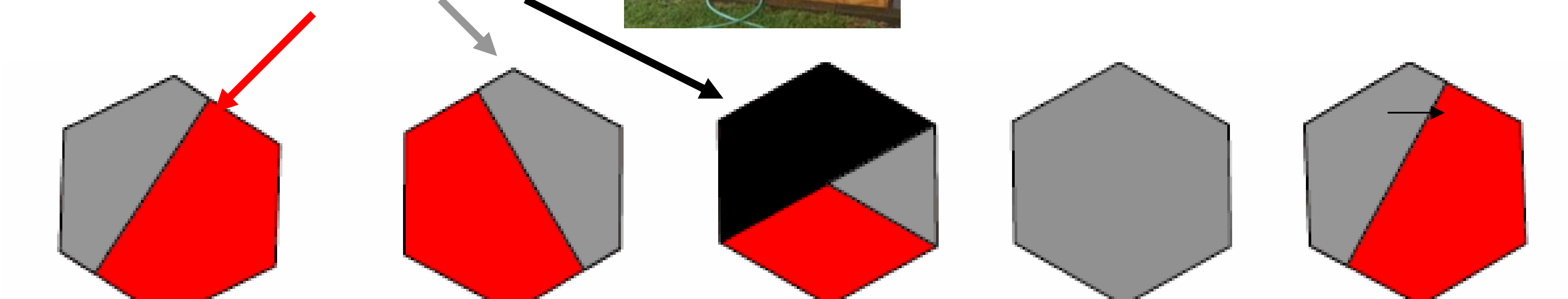
Target	Mass in tons	CC Events (Million)
Scintillator	3	9
He	0.2	0.6
C (graphite)	0.15	0.4
Fe	0.7	2.0
Pb	0.85	2.5
Water	0.3	0.9



Water target

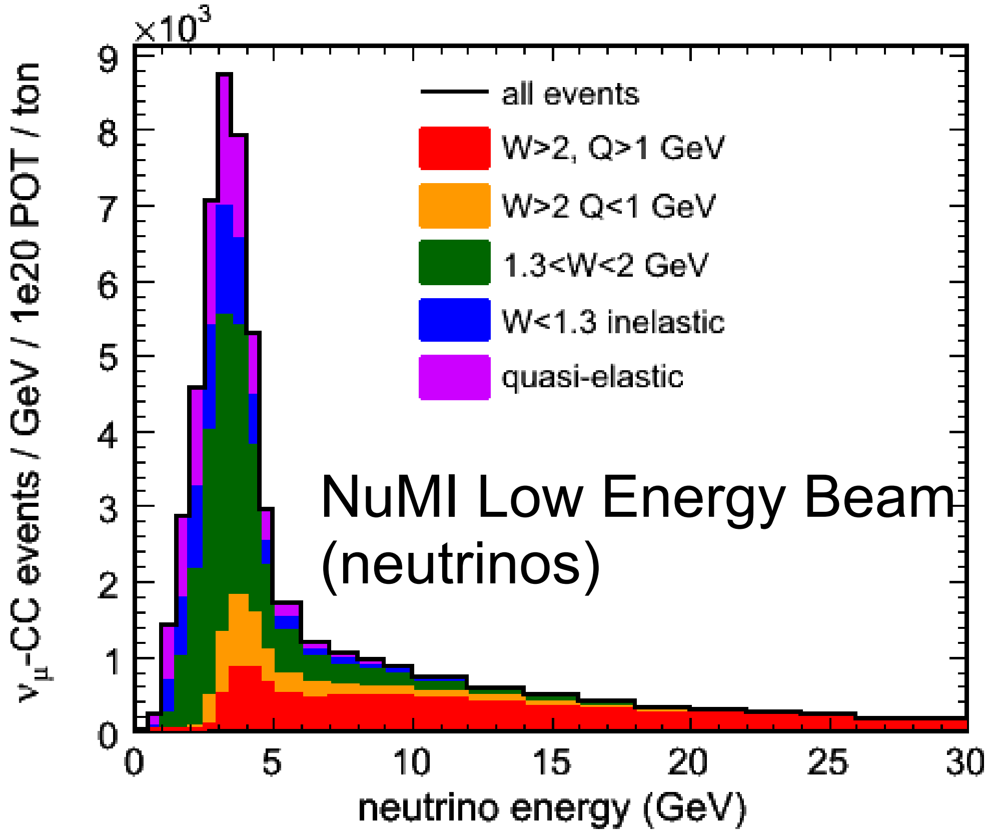
5 Nuclear Targets

Fe Pb C



CC Sample

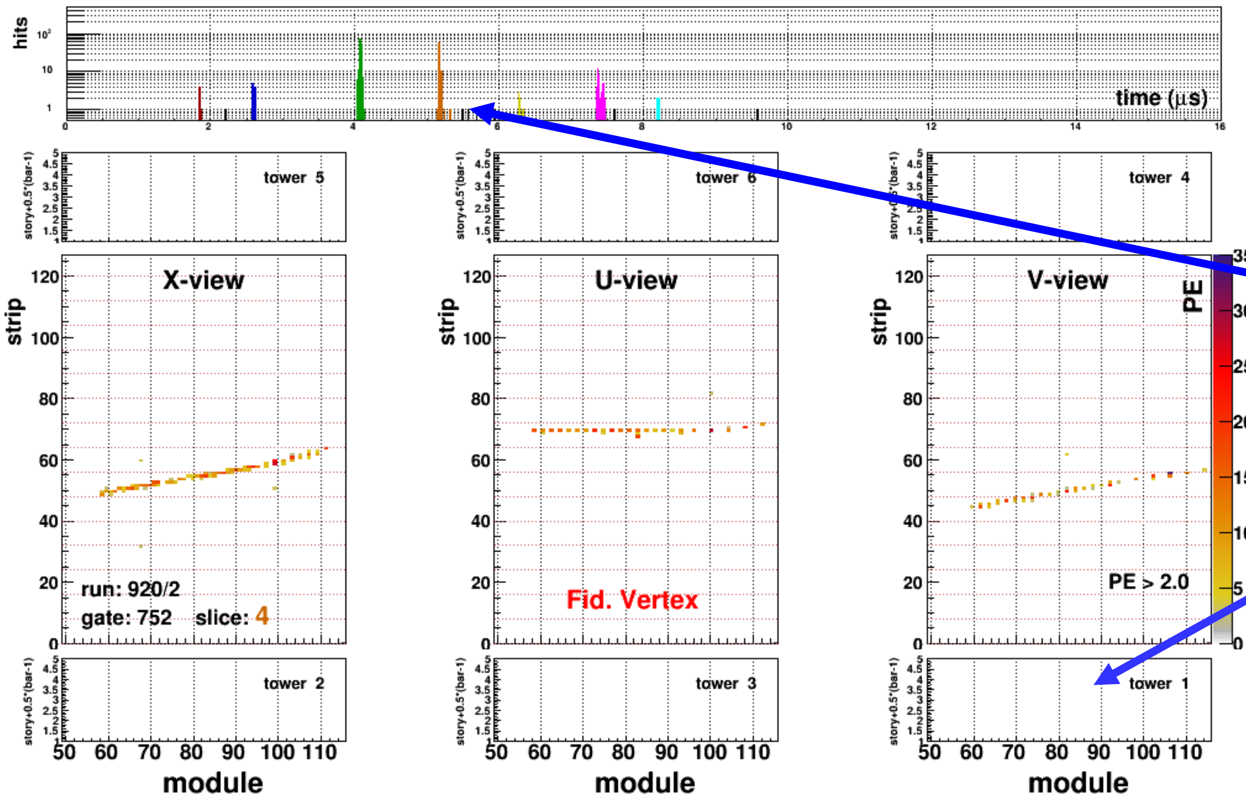
- Current run plan
  4×10^{20} POT LE beam
  12×10^{20} POT ME beam
- Yield: ~14M (CC events)
  - 9M in scintillator



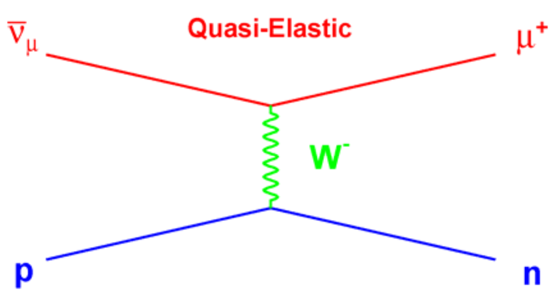
Quasi-elastic	**0.8 M**
Resonance production	**1.7 M**
Resonance to DIS transition region	**2.1 M**
DIS Low Q^2 region and structure functions	**4.3 M**

Coherent Pion Production	**CC 89k, NC 44k**
charm / strange production	**230 k**

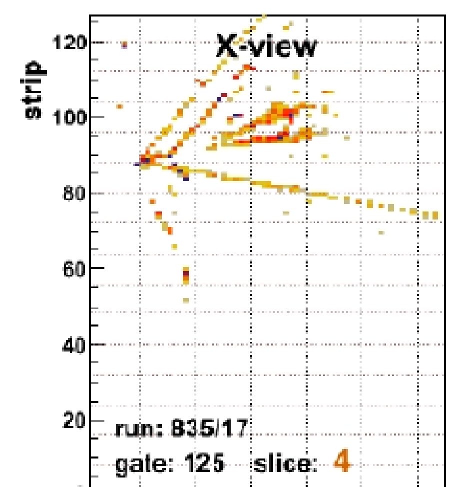
MINERνA Events
RHC, Anti-ν Beam



- CCQE anti-event
  - Information buffered in the ν spill and read out at end of spill
  - Timing for different slices (events)
  - 4^{th} slice
  - 3 view, x (top), & V
  - Outer calorimeter
- X view of other events

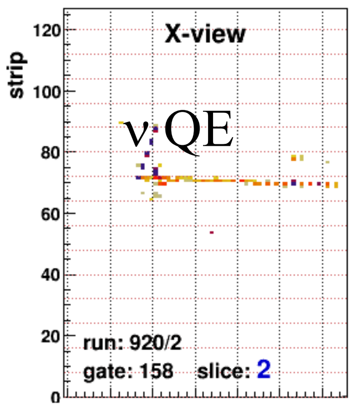


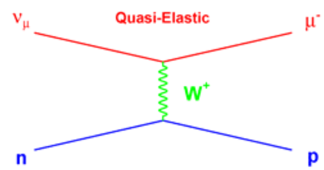
Event with π^0

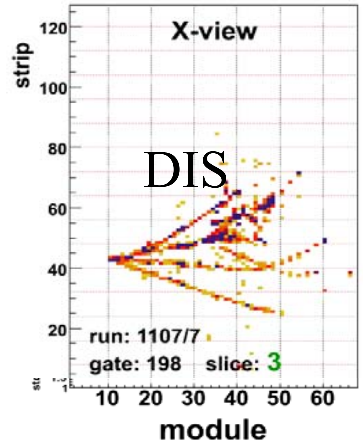


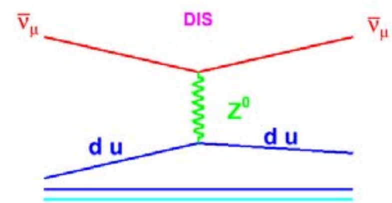
MINERνA Events

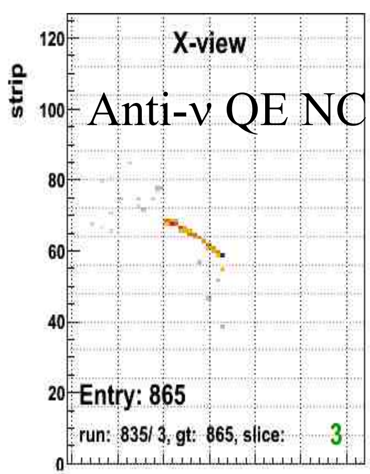
- Showing X view

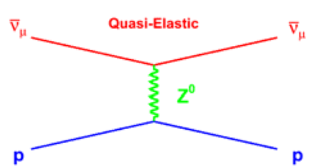


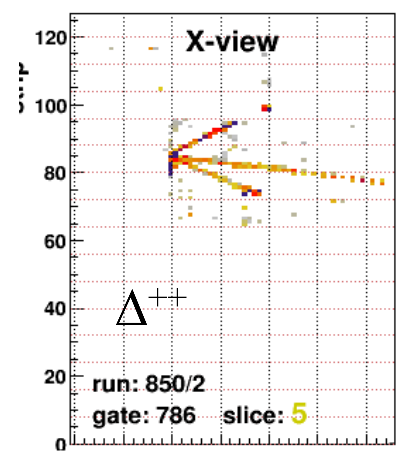


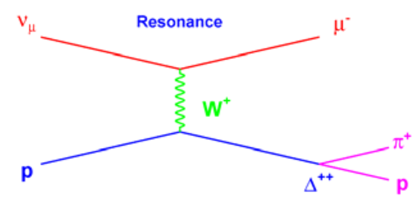




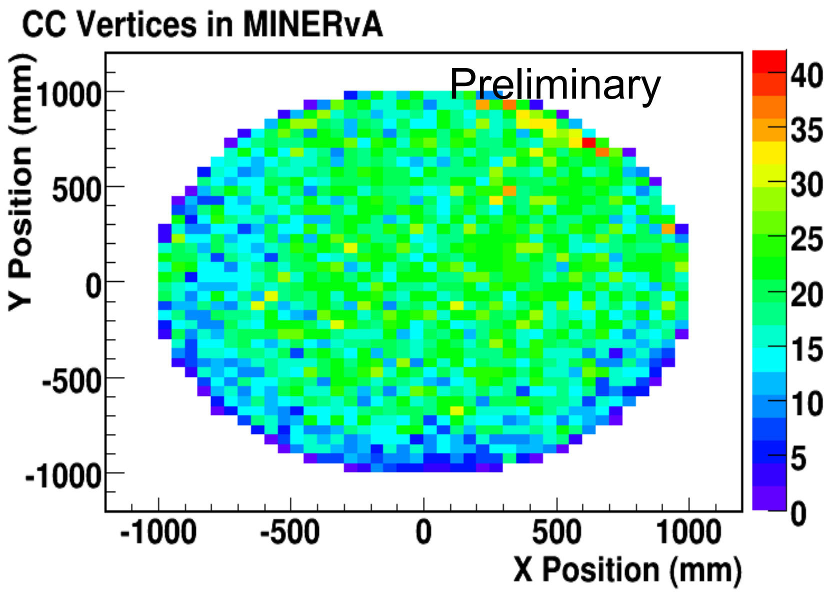


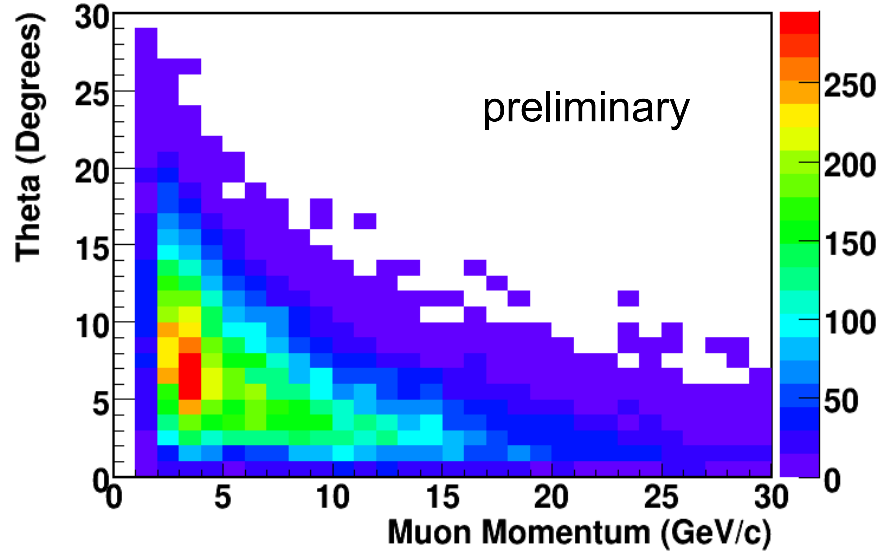






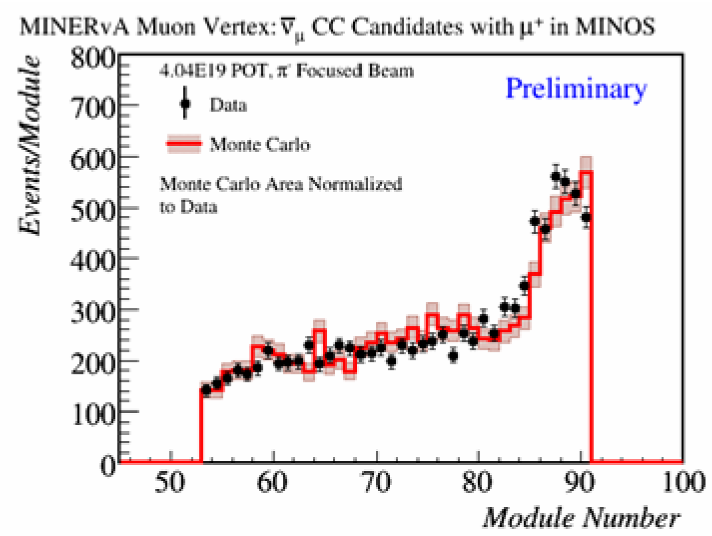
Kinematic Distributions
Anti-ν Inclusive CC Data

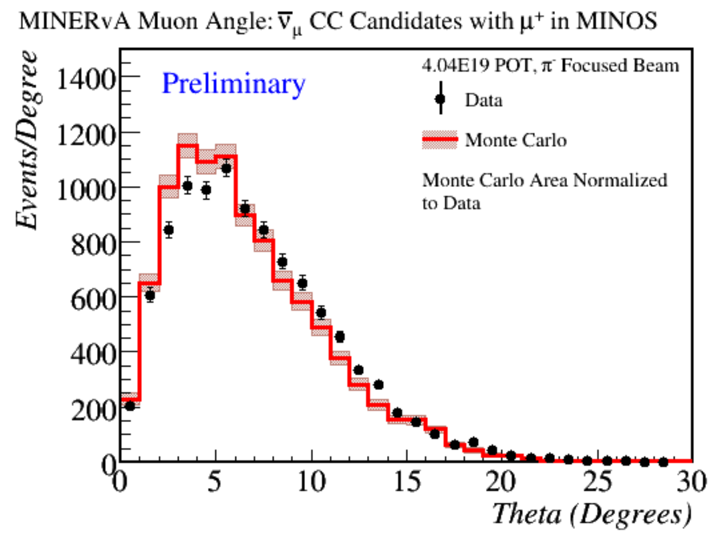




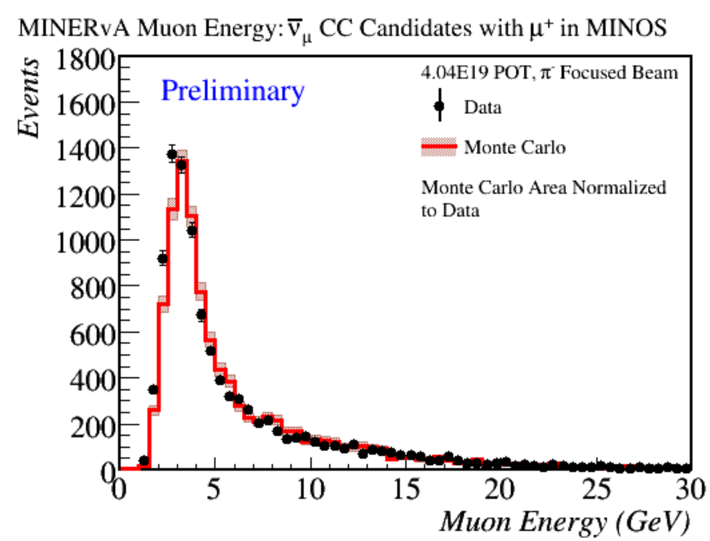
- Track in MINERνA which matches a track in MINOS, this imposes few GeV cut
  - Requires hits < 1m radius
  - X Y vertex distribution
  - Momentum from MINOS + de/dx in MINERνA

Distributions in Anti-ν Beam
Anti-ν CC, Data vs MC

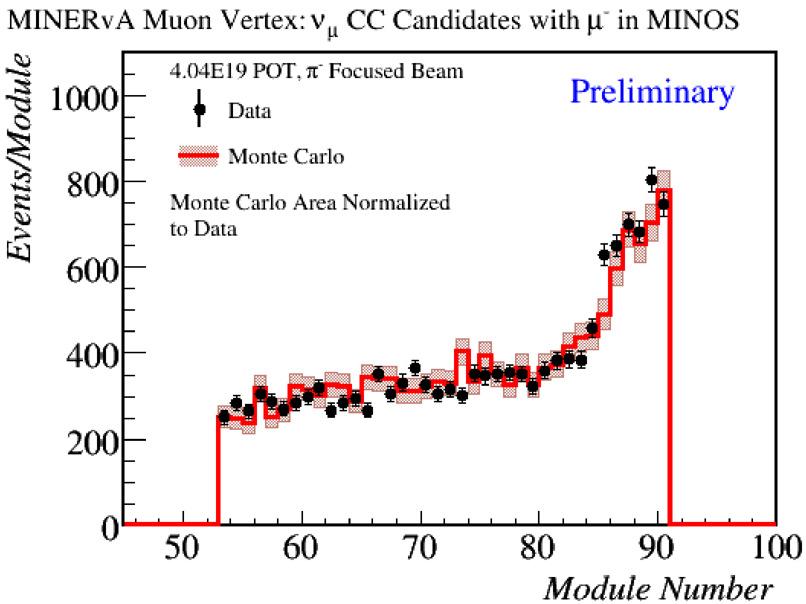


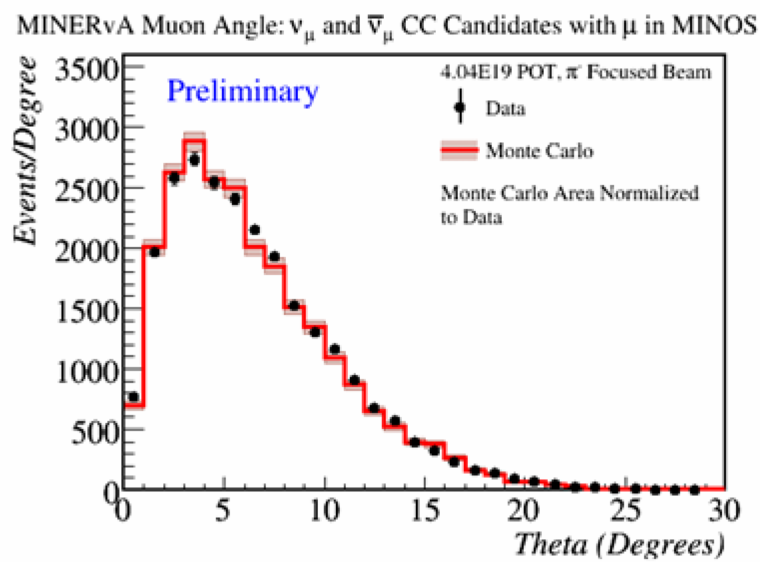


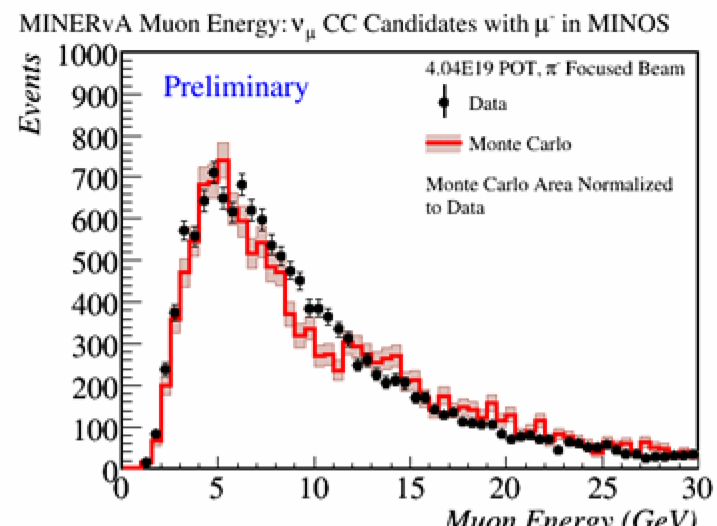
- 4.04×10^{19} POT in RHC, anti-ν mode
- MC generator GENIE v 2.6.0
  - GEANT4 detector simulation
  - 2×10^{19} POT MC , LE Beam MC anti-ν flux, untuned
  - Area normalized
- Require reconstructed muon in MINOS



Distributions in Anti-ν Beam ν CC, Data vs MC







- ν Distributions same conditions as before
- Very good agreement between Data and MC

CCQE, Measuring F_A

The hadronic current for QE neutrino scattering is given by:

$$< p(p_2)|J_\lambda^+|n(p_1) >= \overline{u}(p_2)\left[\gamma_\lambda F_V^1(q^2) + \frac{i\sigma_{\lambda\nu}q^\nu \xi F_V^2(q^2)}{2M} + \gamma_\lambda\gamma_5 F_A(q^2)\right]u(p_1) \quad (1)$$

The Dirac/Pauli form factors $F_V^1(q^2)$ and $\xi F_V^2(q^2)$ are given in terms of the Sachs form factors by:

$$F_V^1(q^2) = \frac{G_E^V(q^2) - \frac{q^2}{4M^2}G_M^V(q^2)}{1 - \frac{q^2}{4M^2}}, \xi F_V^2(q^2) = \frac{G_M^V(q^2) - G_E^V(q^2)}{1 - \frac{q^2}{4M^2}}.$$

CVC used to determine G_E^V and G_M^V from the electron scattering form factors G_E^p, G_E^n, G_M^p, and G_M^n:

$$G_E^V(q^2) = G_E^p(q^2) - G_E^n(q^2), G_M^V(q^2) = G_M^p(q^2) - G_M^n(q^2).$$

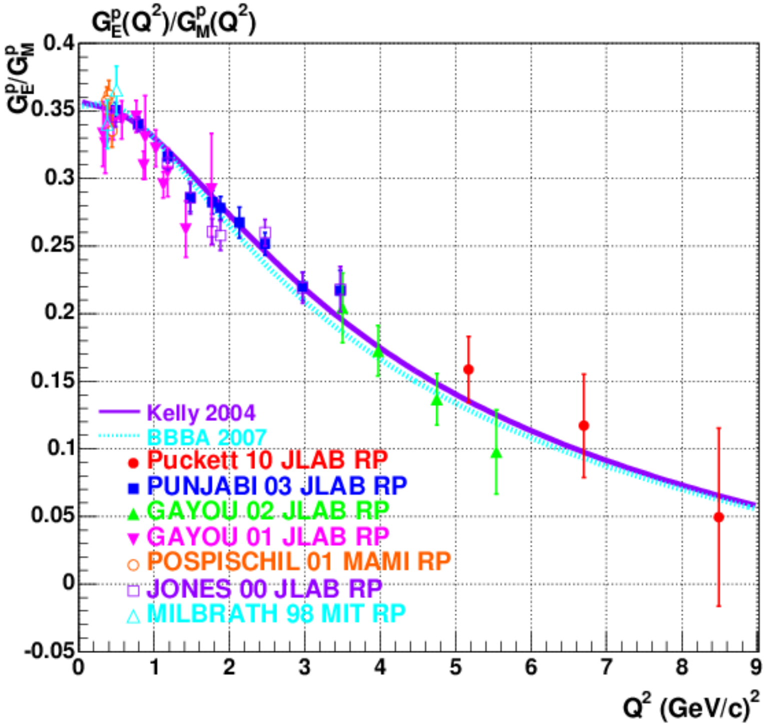
The dipole approximation:

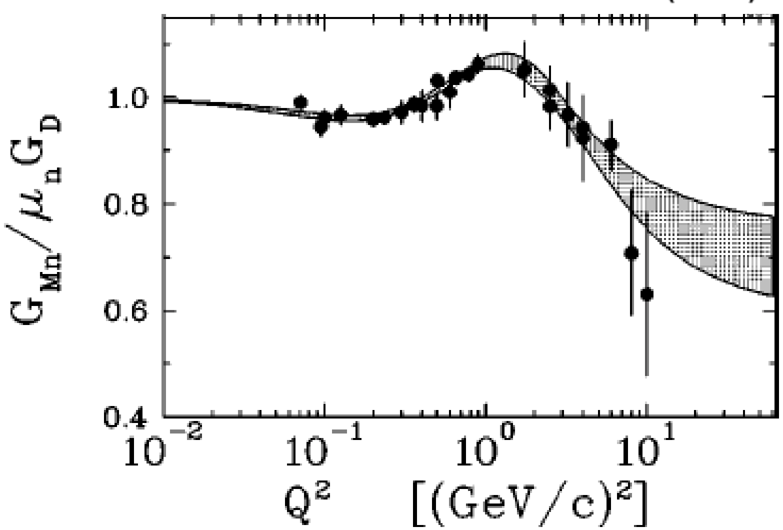
$$G_D(q^2) = \frac{1}{\left(1 - \frac{q^2}{M_V^2}\right)^2}, \quad M_V^2 = 0.71\ (GeV/c)^2, \quad F_A(q^2) = \frac{g_A}{\left(1 - \frac{q^2}{M_A^2}\right)^2}$$

$$G_E^p = G_D(q^2), \quad G_E^n = 0, \quad G_M^p = \mu_p G_D(q^2), \quad G_M^n = \mu_n G_D(q^2).$$

G_E^V and G_M^V are related in the non-relativistic limit to the charge and magnetic distribution.
In the dipole approximation, $\rho(r) = \rho_0 e^{-r/r_0}$, rms of radius ~ 0.81 fm.

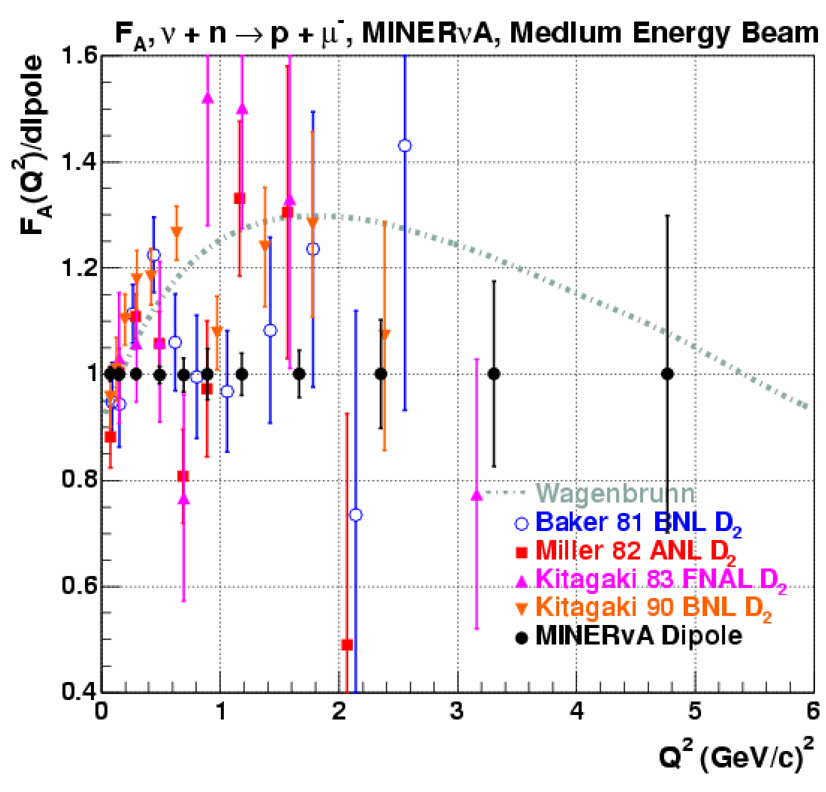
Form Factors Dipole?





- Previously, the vector factors form factors were assumed to be a dipole form
- However, there is no reason why they should be dipole
- During the last 10 years, the EM form factors have been measured with impressive accuracy
- Plot of G_E^P / G_M^P
  - From data compilation of JJ Kelly
  - Added lastest data from Puckett et al.PRL 104,242310 (2010)
  - If G_E^P and G_M^P were dipole with same M_V, this ratio would be flat.
- G_M^n/dipole- JJ Kelly, PRC 70, 068202 (2004)
- Hence, we can't assume F_A is dipole either.
- F_A is a major contribution to the cross section

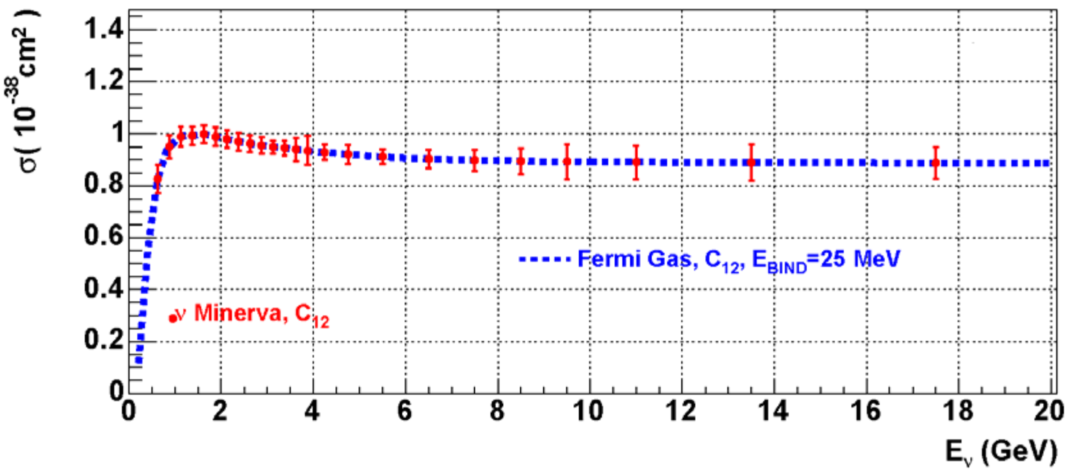
Extraction of F_A , ME Beam

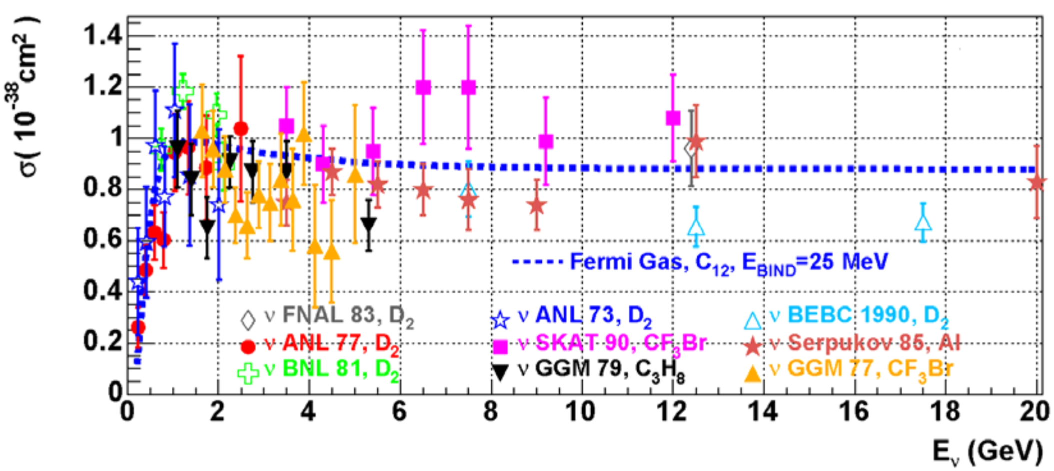


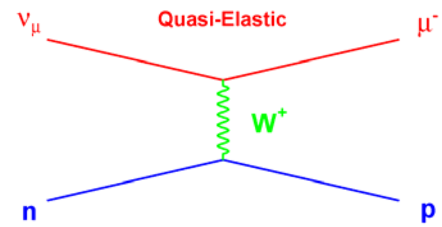
- Experiments assume F_A is a dipole & determine M_A by fit and/or normalization
- We can extract F_A directly
  - $\sigma = aF_A{}^2 + bF_A + c$
- a, b, c = ∫(vector ffs) over flux in bin
- Extraction of F_A for the D_2 experiments
- Hence, with the high statistics ME data we can extract F_A in bins of Q^2
  - 12×10^{20} POT
  - Expected errors with GEANT3 and NEUGEN & include detector resolution effects
  - Wagenbrunn constitutuent quark model (hep-ph[0212190]
  - The statistics give sensitivity for F_A at the few % level at moderate Q^2

The range of nuclear targets will allow us to study the nuclear dependence of the extracted F_A

Cross Section, LE beam

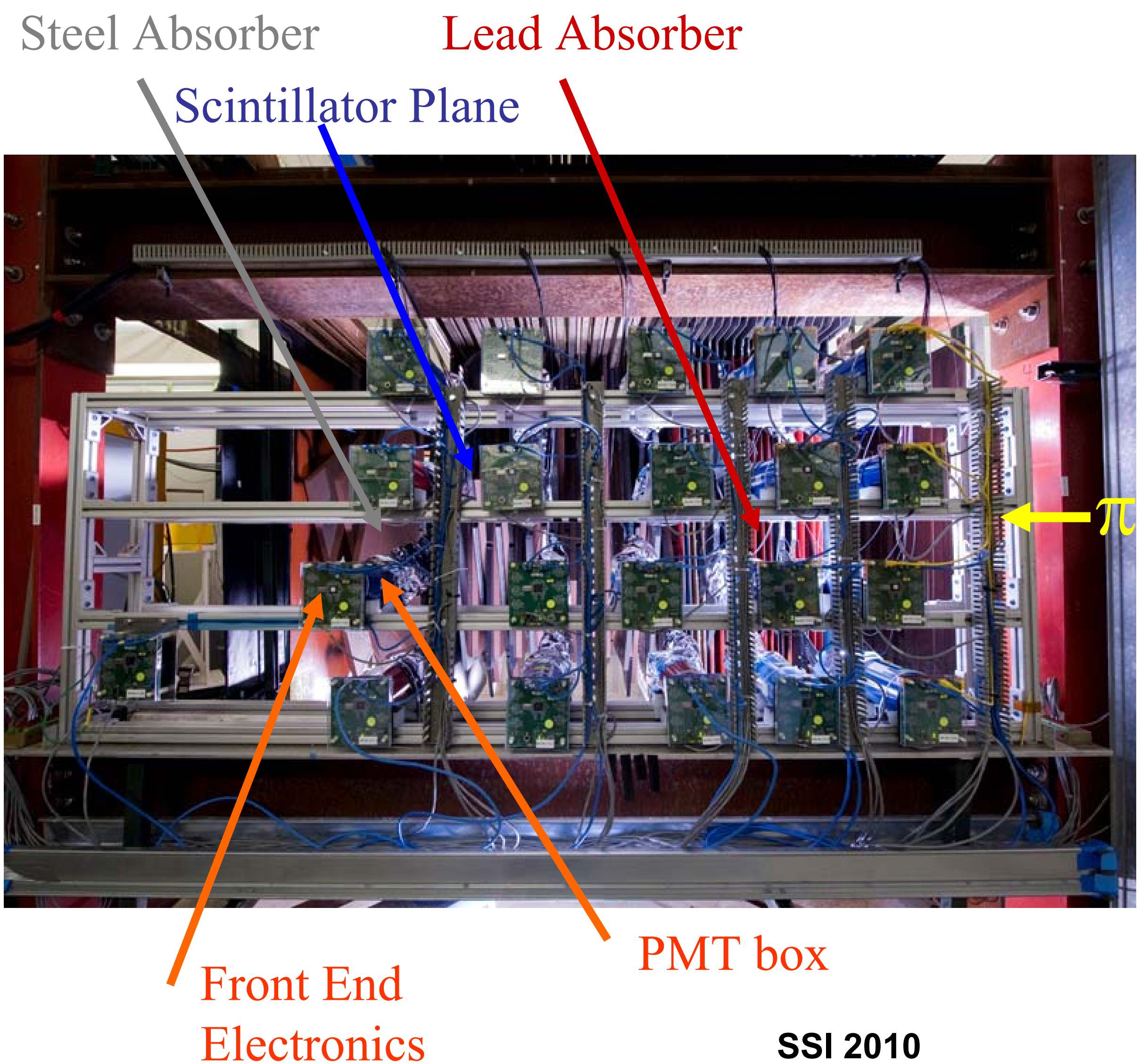






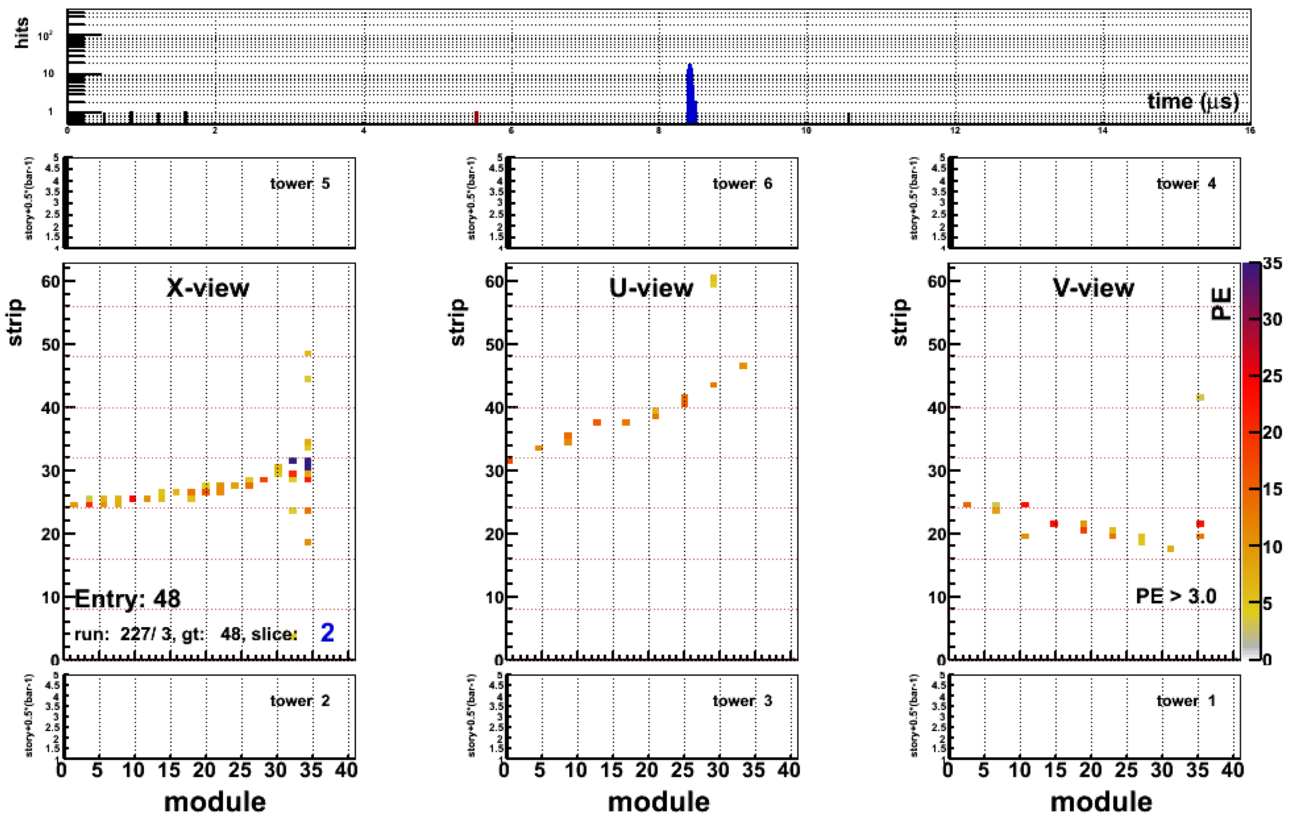
- Expected statistical errors in cross section for the LE ν beam
  - 4×10^{20} POT
- Include efficiencies and purities using NEUGEN and a GEANT 3 MC and includes detector resolution effects
- Goal of 7% flux errors on shape and 10% on absolute normalization

MINERνA Test Beam



- In order to make precise measurements we need a precise a calibration
  - Low energy calibration
- 40 planes, XUXV,1.07 m square
- Reconfigurable can change the absorber configuration. Plane configurations:
  - 20ECAL-20HCAL
  - 20Tracker-20ECAL
- Just finished 1st run – Jun 10-Jul 16

Test Beam π

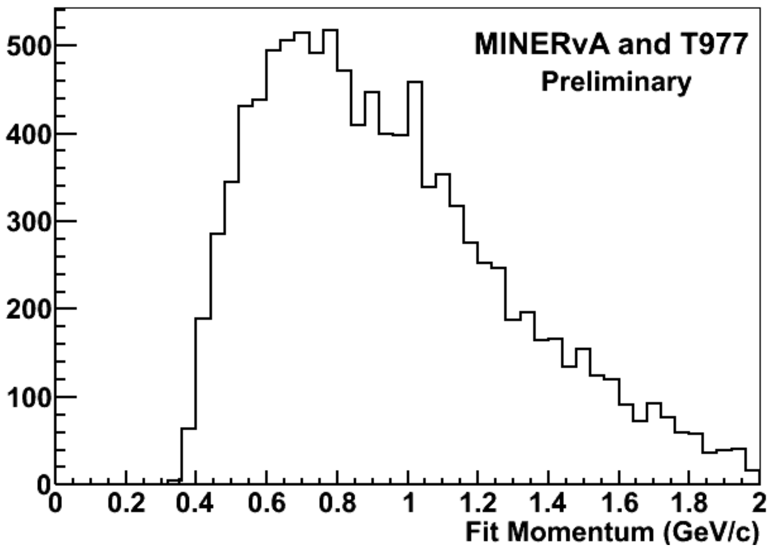


- Test beam event display
- 20 ECAL 20 HCAL
- 1.35 GeV interacting in HCAL
- Time for π

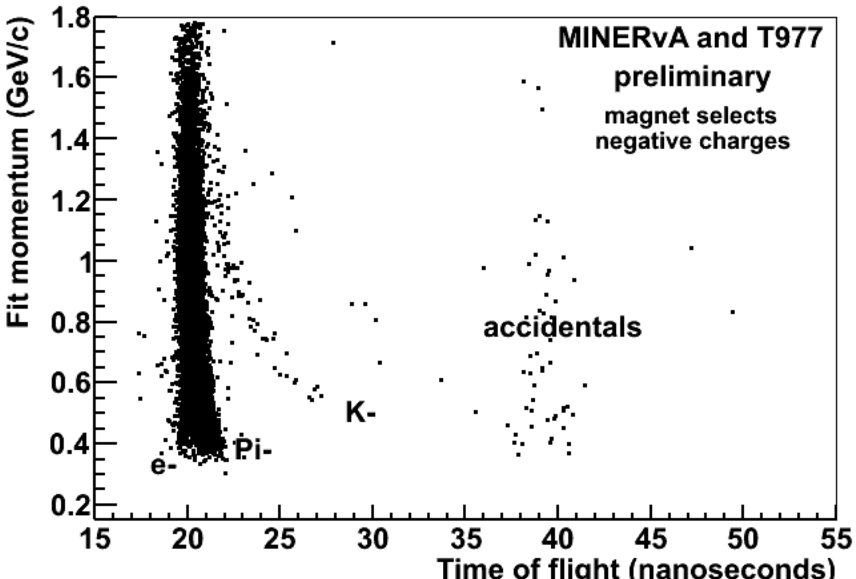
MTest Spectrometer

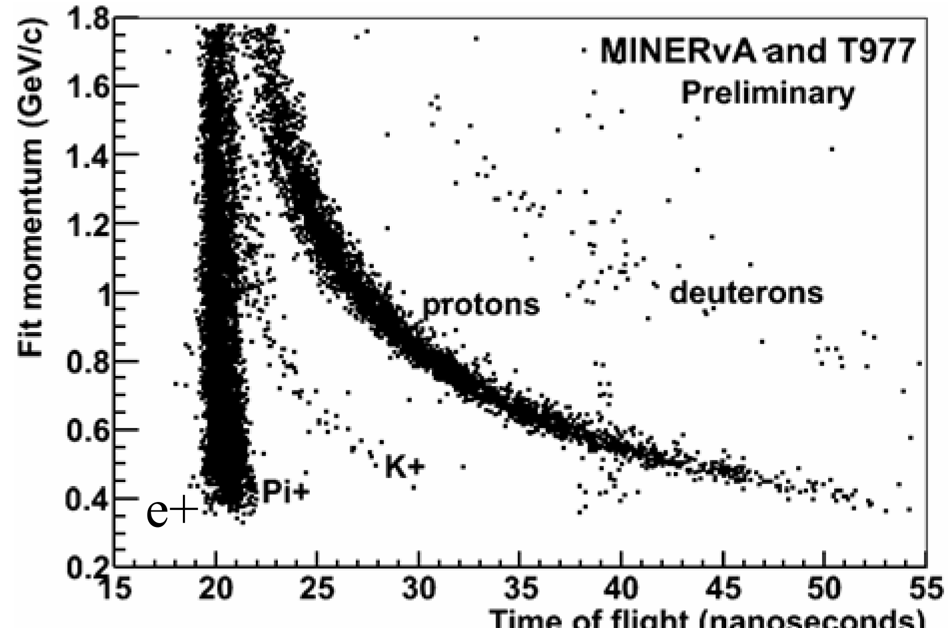
- Tertiary beam, built by the MINERνA collaboration in conjunction with Meson Beam Testbeam Facility
- In coming 16 GeV $\pi \rightarrow \pi$, proton beam from 0.4-1.5 GeV
- Time of flight (TOF) scintillator counters, measures transit time of particles
  - TOF 1 upstream of PWC1, TOF 2 downstream of PWC4
- The beamline and MINERνA DAQ merged for full event reconstruction

Beam Momentum vs TOF



- Energy distribution, 0.4 – 1.5 Gev
- TOF to distinguish π & protons
  - Momentum vs TOF
  - e, p, k, π, and deuterons



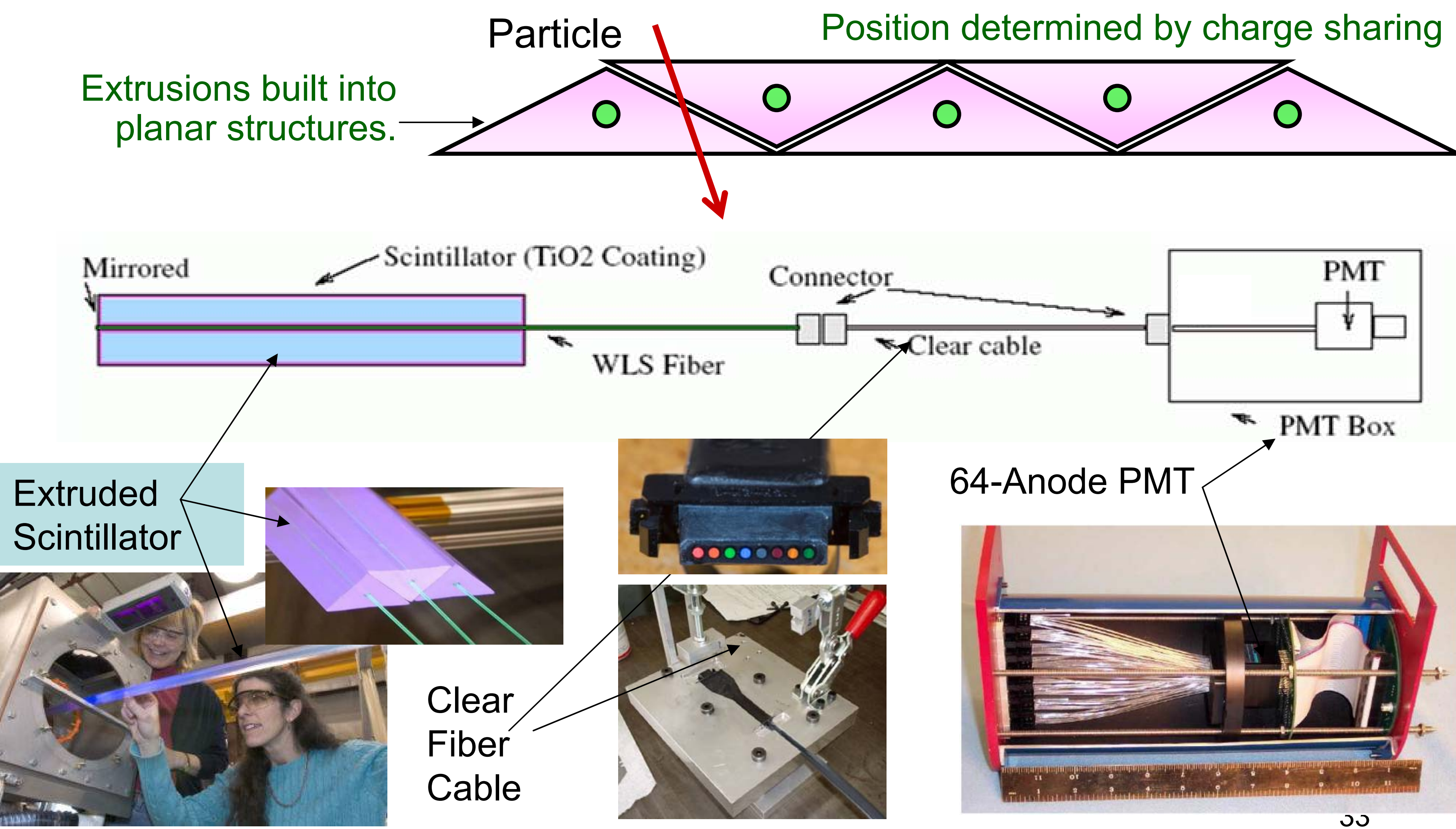


Summary

- The high statistics MINERνA is on the air !
- Using various techniques to understand the ν flux
- Precision Measurement of various cross section and support current and future ν experiments
  - QE, Resonance, DIS,
- Measure F_A & the nuclear dependence of F_A
- Detector working very well
- Analysis of data is proceeding, Expect preliminary results in the near future.

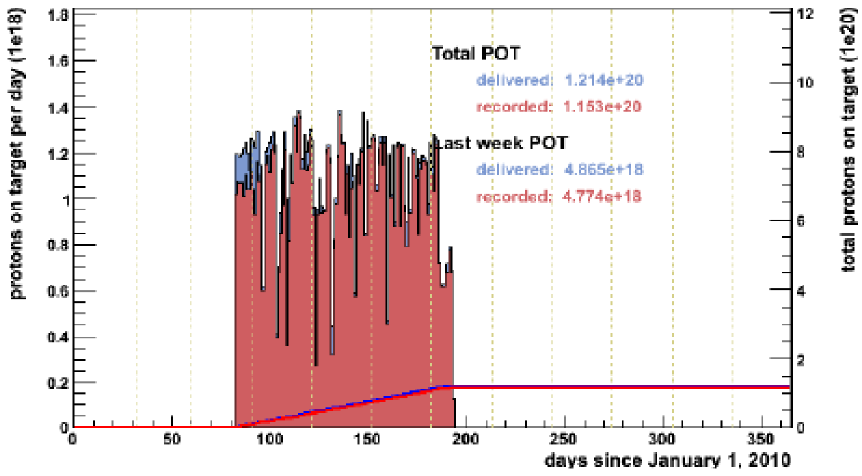
Back-up Slides

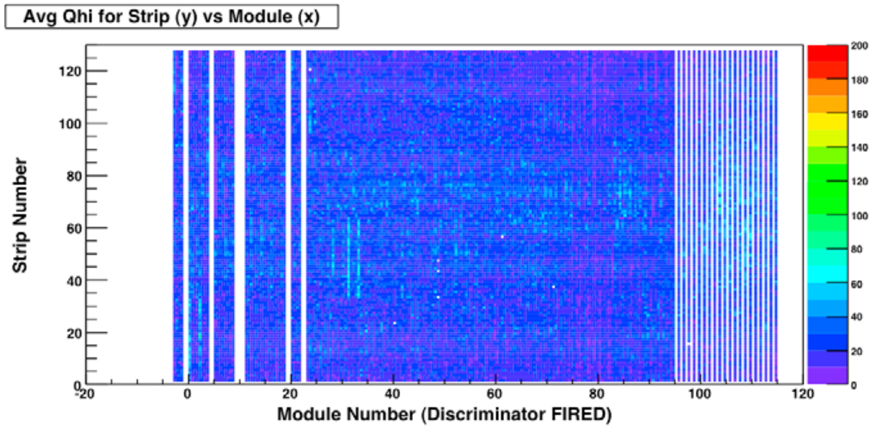
MINERνA Optics

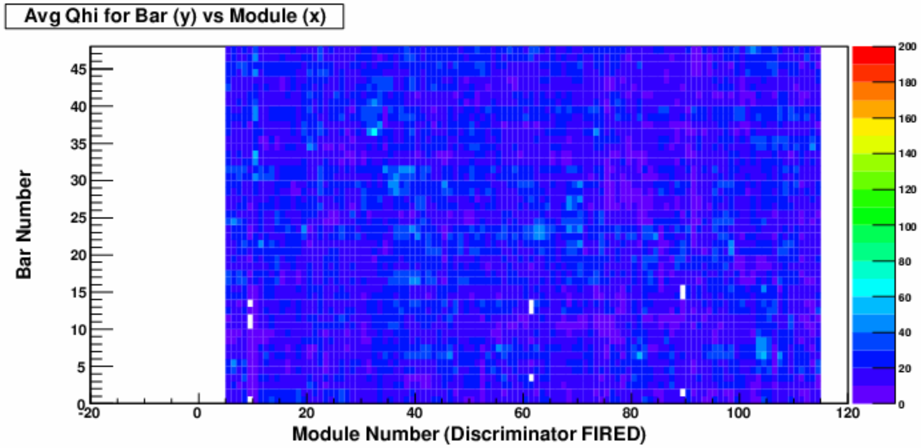


MINERνA Running Status

- Accumulated 0.84e20 Protons on Target of anti-ν beam with 55% of detector and Fe/Pb target
- Accumulated >1.21e20 Protons on target in Low Energy neutrino Running with full detector
- Detector Live times typically above 95%
- Less than 20 dead channels out of 32k channels







F_A contribution

- These plots show the contributions of the form factors to the cross section
  - The ff contribution is determined by setting all other ff to 0
  - This is d(dσ/dq2)/dff% - change in the cross section vs the % change in the form factors
  - The picture of the contribution of the ff is the same with both plots
  - F_A major component of cross section