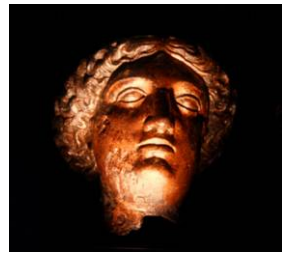
# Introducing MINERνA

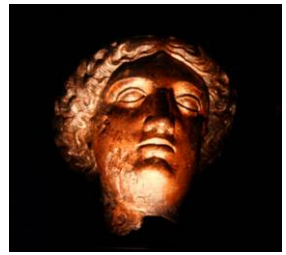
Kevin McFarland
University of Rochester
30 March 2006

# MINERvA in a Nutshell



- MINERvA is a dedicated neutrino cross-section experiment operating in the NuMI near hall
  - in a unique position to provide critical input for world neutrino oscillation program
    - “neutrino engineering” for NuMI program *et al.*
  - provides an opportunity for studies of proton structure and nuclear effects in axial current
    - “Jefferson Lab west”

# The MINER*v*A Collaboration




D. Drakoulakos, P. Stamoulis, G. Tzanakos, M. Zois
*University of Athens, Greece*

D. Casper#, J. Dunmore, C. Regis, B. Ziemer
*University of California, Irvine*

E. Paschos
*University of Dortmund*

D. Boehnlein, D. A. Harris#, N. Grossman, M. Kostin, J.G. Morfin*, A. Pla-Dalmau, P. Rubinov, P. Shanahan, P. Spentzouris
*Fermi National Accelerator Laboratory*

I. Albayrak, M.E. Christy, C.E. Keppel, V. Tvaskis
*Hampton University*

R. Burnstein, O. Kamaev, N. Solomey
*Illinois Institute of Technology*

S. Kulagin
*Institute for Nuclear Research, Russia*

I. Niculescu. G. Niculescu
*James Madison University*

R. Gran
*University of Minnesota-Duluth*

G. Blazey, M.A.C. Cummings, V. Rykalin
*Northern Illinois University*

W.K. Brooks, A. Bruell, R. Ent, D. Gaskell, W. Melnitchouk, S. Wood
*Jefferson Lab*

L. Aliaga, J.L. Bazo, A. Gago,
*Pontificia Universidad Catolica del Peru*

S. Boyd, S. Dytman, M.-S. Kim, D. Naples, V. Paolone
*University of Pittsburgh*

S. Avvakumov, A. Bodek, R. Bradford, H. Budd, J. Chvojka, P. de Barbaro, R. Flight, S. Manly, K. McFarland*, J. Park, W. Sakumoto, J. Seger, J. Steinman
*University of Rochester*

R. Gilman, C. Glasshausser, X. Jiang, G. Kumbartzki, R. Ransome#, E. Schulte
*Rutgers University*

A. Chakravorty
*Saint Xavier University*

D. Cherdack, H. Gallagher, T. Kafka, W.A. Mann, W. Oliver
*Tufts University*

R. Ochoa, O. Pereyra, J. Solano
*Universidad Nacional de Ingenieria. Lima, Peru*

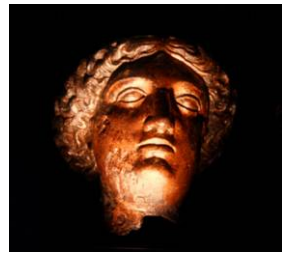
J.K. Nelson#, F.X. Yumiceva
*The College of William and Mary*

* Co-Spokespersons

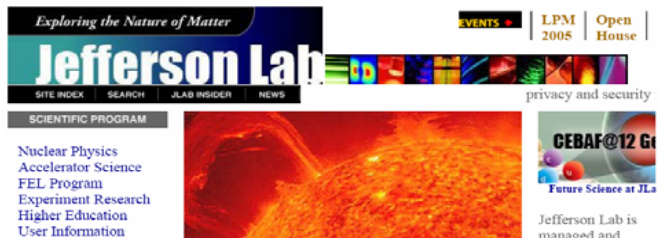
\# MINERvA Executive Committee


A collaboration of Particle, Nuclear, and Theoretical physicists

# HEP/NP Partnership



- This partnership is truly a two-way street
  - significant NP participation in MINERvA because of overlap of physics with Jefferson Lab community




**Neutrino Physics Comes to JLab**

The inner workings of the sun, the mysteries of dark matter and dark energy and the structure of the early universe all may be unlocked by one cosmic key: neutrinos. Now, new research carried out in Jefferson Lab's experimental Hall C may help provide insight into neutrinos, the force that governs their behavior and, surprisingly, the structure of the nucleus of the atom.

**Fermilab Today**

**Nuclear Option: MINERvA Attracts Nuclear Physicists**

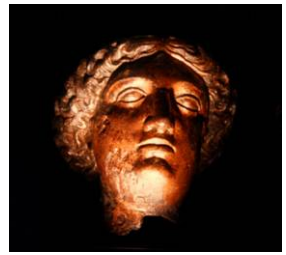
*This is the fourth article in a series on the MINERvA neutrino experiment.*

"MINERvA offers us the possibility of making a bridge in our understanding between the longer distance-scale properties of the nuclear force--responsible for the properties of nuclei--and the very short-distance scales explored in particle physics," says Ransome. "And this intermediate distance scale is of great interest to both communities."

- JLab program (JUPITER)
  - data for neutrino cross-section modeling
  - already run one dedicated experiment

# physics case for MINERvA

# MINERvA and Oscillations

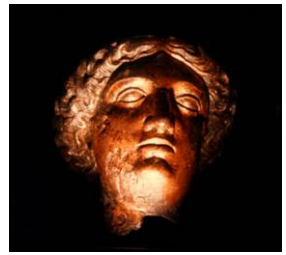


The recent ***APS Multidivisional Neutrino Study Report*** predicated its recommendations on a set of assumptions about current and future programs including:

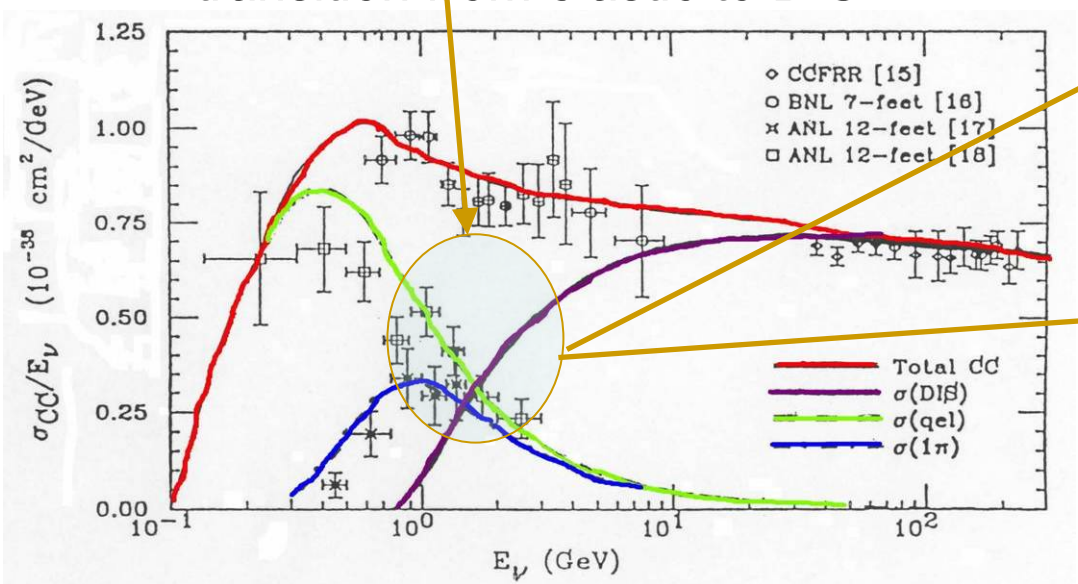
support for current experiments, international cooperation, underground facilities, R&D on detectors and accelerators, and

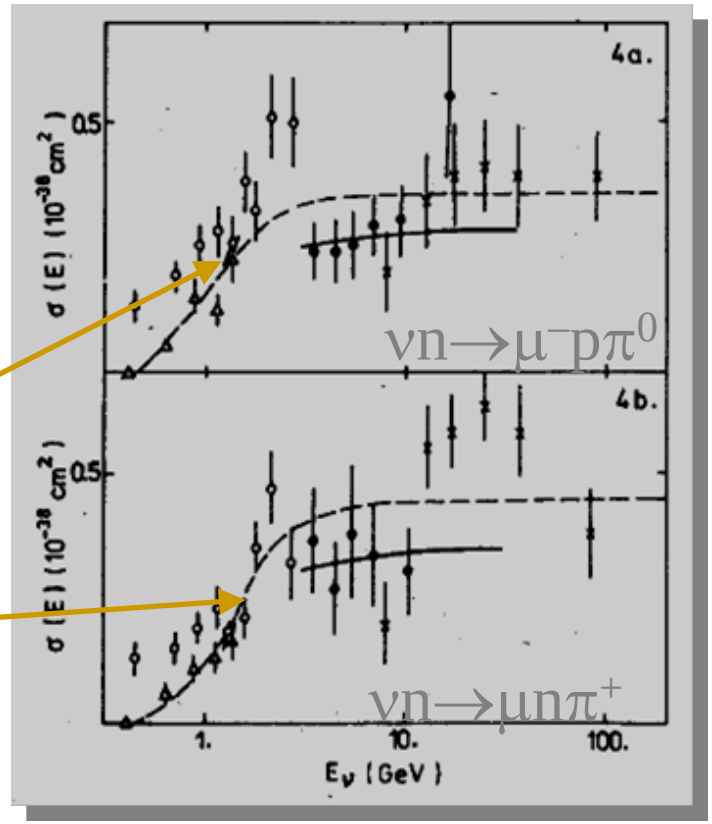
*"determination of the neutrino reaction and production cross sections required for a precise understanding of neutrino-oscillation physics and the neutrino astronomy of astrophysical and cosmological sources. Our broad and exacting program of neutrino physics is built upon precise knowledge of how neutrinos interact with matter."*

# Why do we need to know more about neutrino cross-sections?

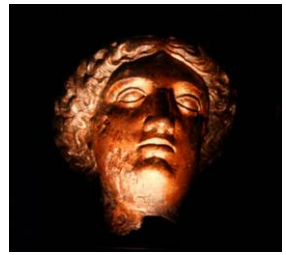


- At 1-few GeV neutrino energy (of interest for osc. expt's)
  - Experimental errors on total cross-sections are large
    - almost no data on A-dependence
  - Understanding of backgrounds needs *differential* cross-sections on target
  - Theoretically, this region is a mess... transition from elastic to DIS



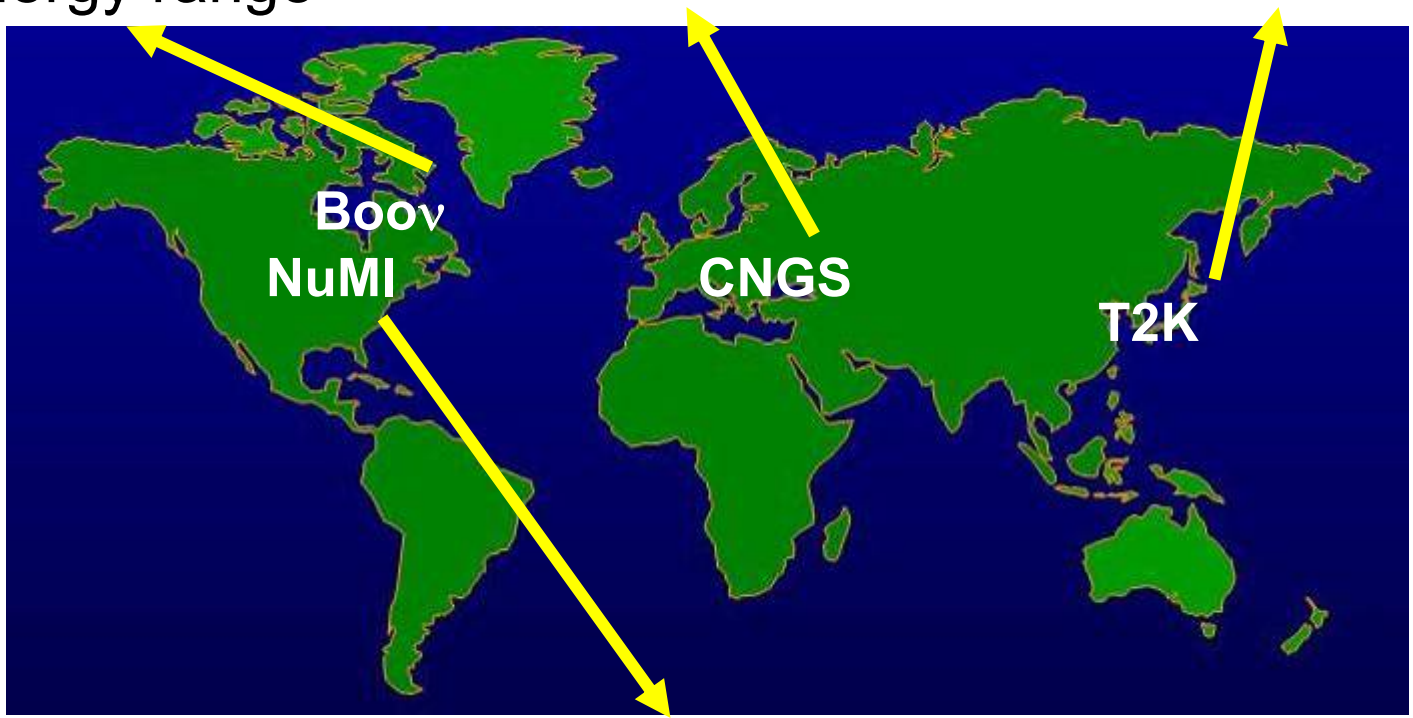
# NuMI: Unique in the World



no near hall, limited energy range

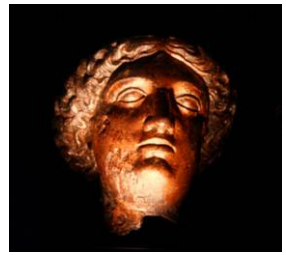
no near hall

near detectors off-axis in E~700 MeV beam

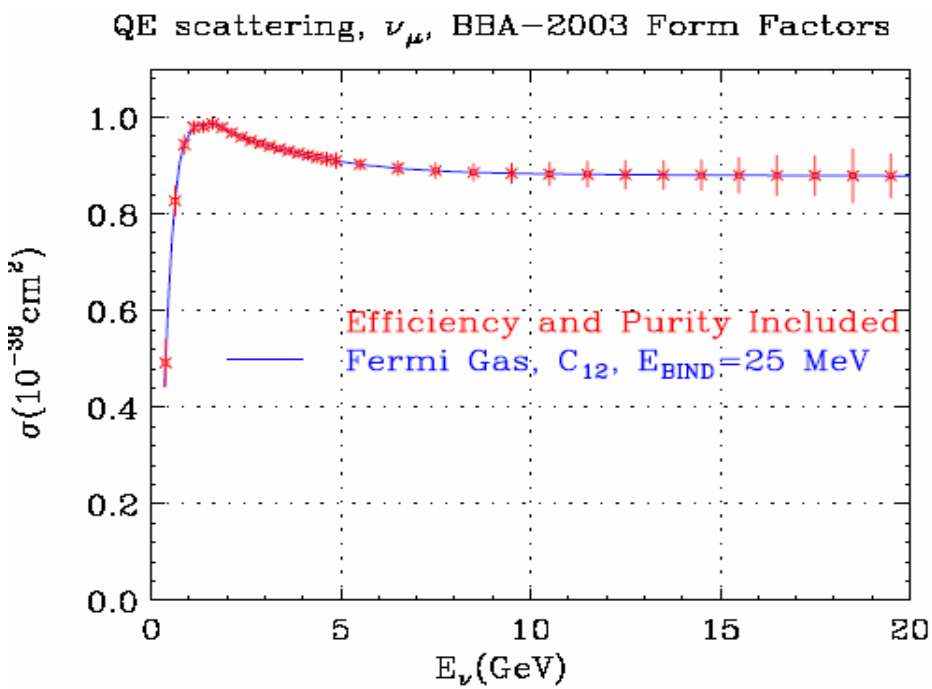



tunable, broadband beam energy from resonance to deep inelastic regime, spacious near hall, expecting a long run…

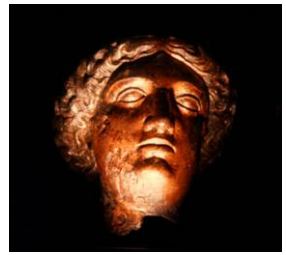
# CC Quasi-Elastic



- Quasi-elastic ($\nu n \rightarrow \mu^- p$)
  - high efficiency and purity
    - 77% and 74%, respectively
  - Precise measurement of $\sigma(E_\nu)$ and $d\sigma/dQ^2$
    - absolute normalization from beam flux
  - Nuclear effects
    - C, Fe and Pb targets

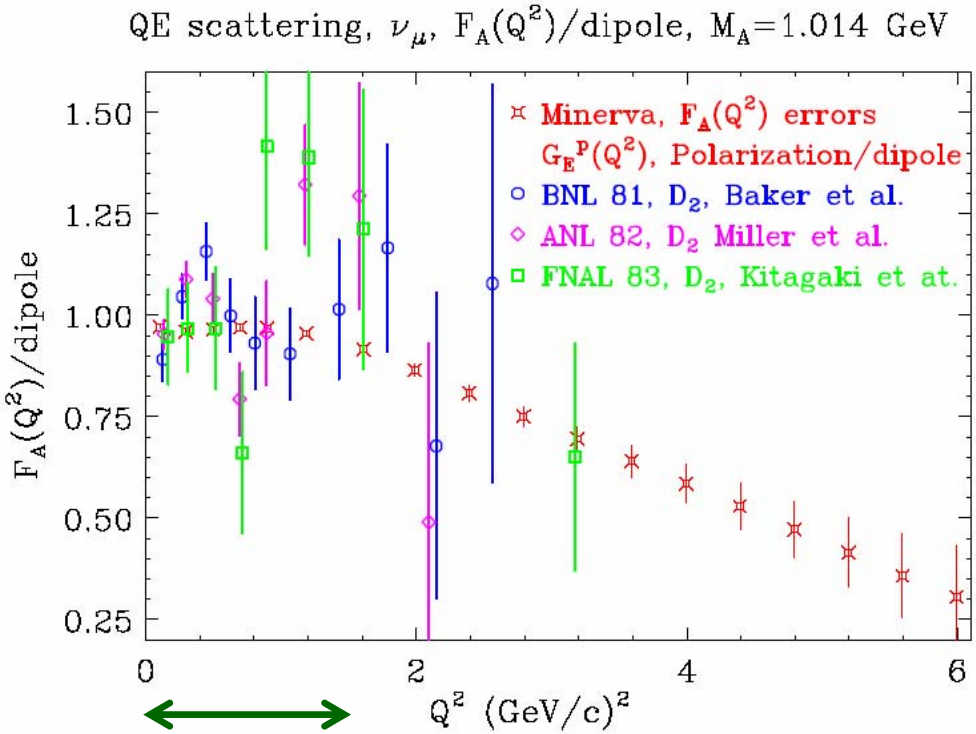


# CC QE: Form Factors



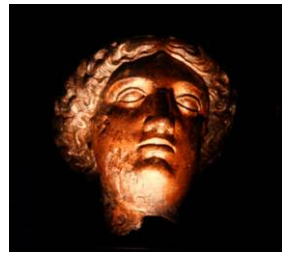
- Vector form factors measured with electrons
- $G_E/G_M$ ratio varies with $Q^2$ - a surprise from JLab
- Axial form factor poorly known
- Medium effects for $F_A$ measurement unknown
  - Will check with C, Fe, & Pb targets

**Projected MINER*ν*A Measurement of Axial FF**

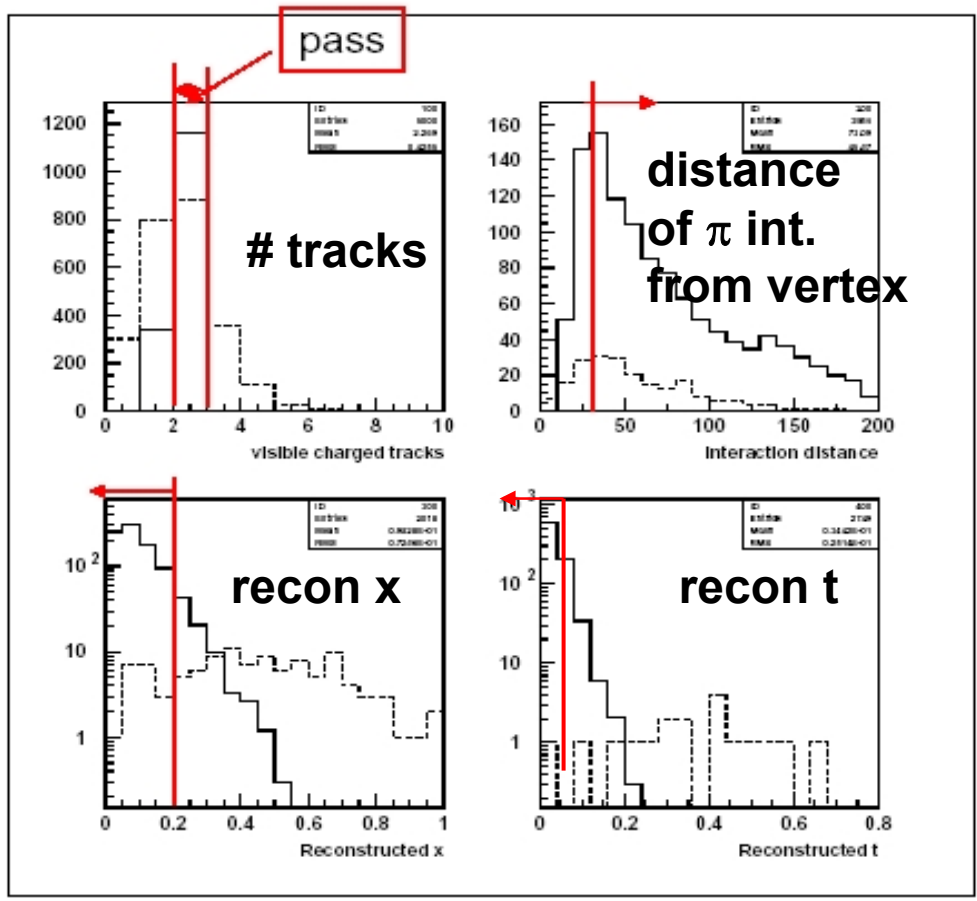



**Range of MiniBooNE & K2K measurements**

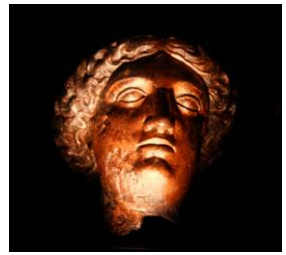
# Coherent Pion Production

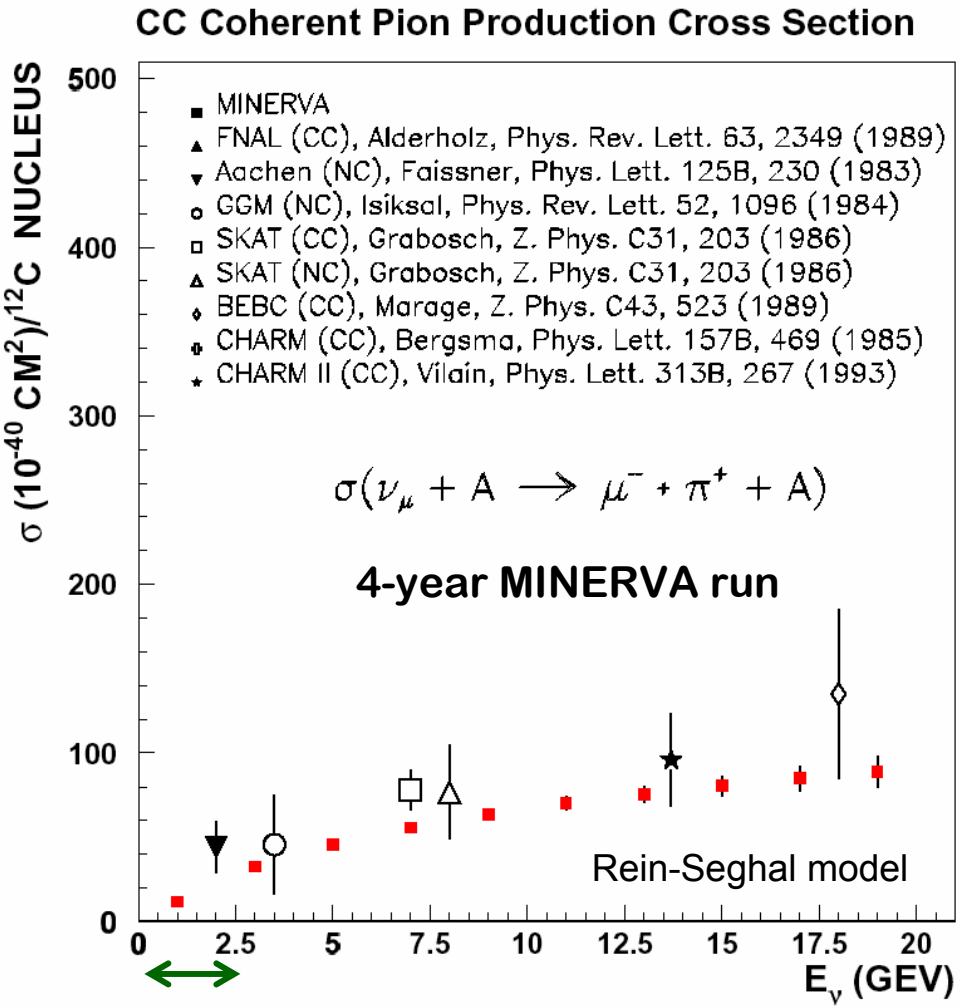


- Precision measurement of σ(E) for CC channel
  - Reconstruct 20k CC / 10k NC (Rein-Seghal model)
  - In NC channel, can measure rate for different beams to check σ(E)
- Measure A-dependence
- Good control of coherent vs. resonance, esp. at high E
  - CC selection criteria reduces signal by factor of three
  - but reduces background by factor of 1000



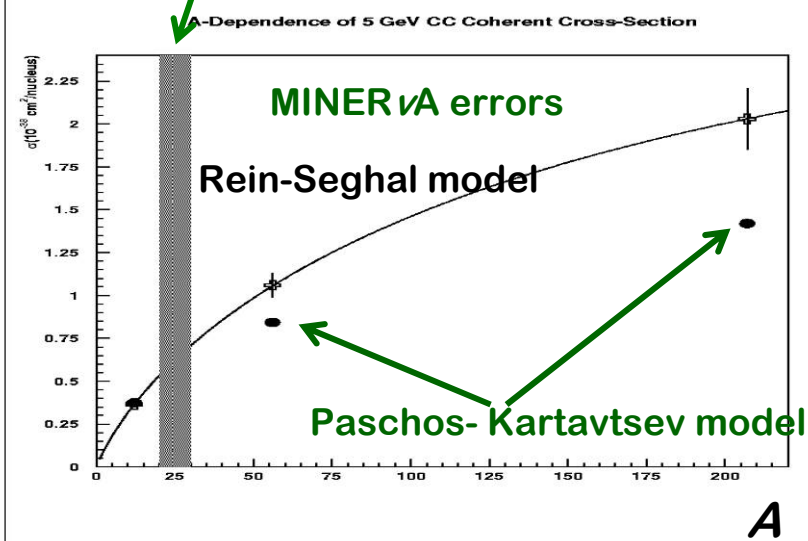
# Coherent Pions (cont'd)





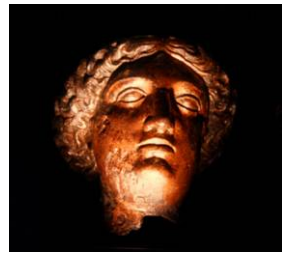

**MiniBooNe & K2K measurements**

**A-range of current measurements before K2K !**




**MINERνA's nuclear targets allow the first measurement of the *A*-dependence of $\sigma_{coh}$ across a wide *A* range**

# Oscillation Measurements and Neutrino Interaction Uncertainties



- Current Generation's Primary Goal:
  - Precise $\Delta m^2$ measurement from $\nu_\mu$ disappearance measurements vs. neutrino energy
  - Biggest systematic concern: how do you know you're really measuring the energy correctly?

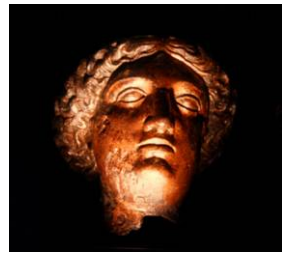
MINOS

- Next Generation's Primary Goal:
  - Search for $\nu_\mu \rightarrow \nu_e$ transitions at one neutrino energy
  - Biggest systematic concern:
    - Predicting Background accurately
    - At first, claiming discovery based on an excess above background!
    - Later, precision measurements with neutrinos and anti-neutrinos

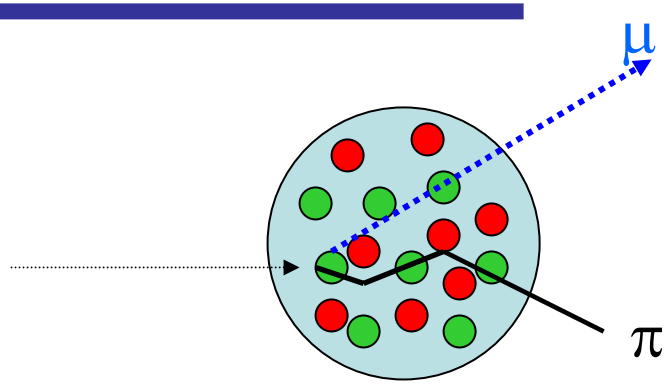
NOvA, T2K

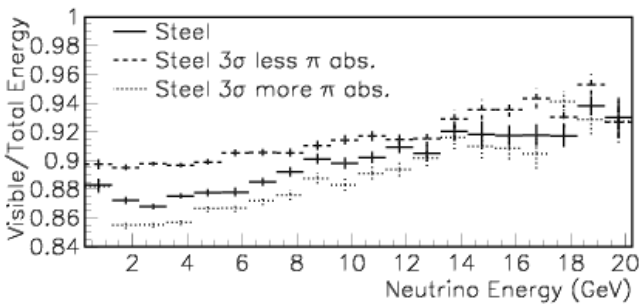
- Next Generation's "guaranteed" measurement
  - More precise $\Delta m^2$ measurement, if you can understand the backgrounds in narrow band beam

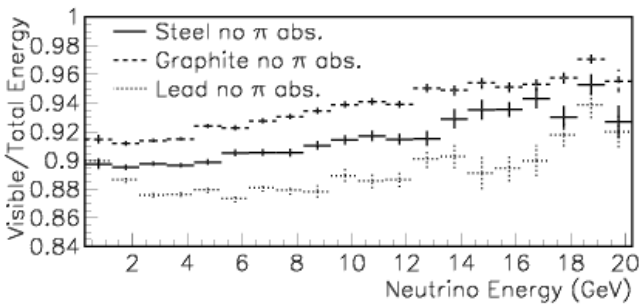
# How MINOS will use MINERνA



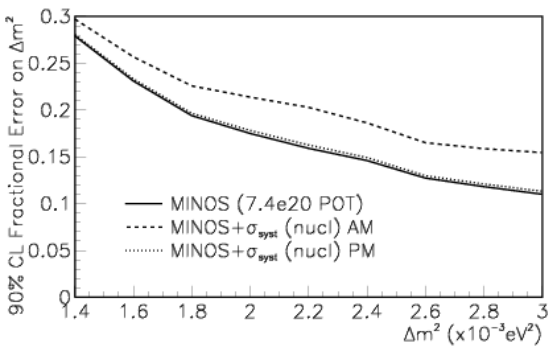
- Visible Energy in Calorimeter is NOT ν energy!
  - π absorption, rescattering
  - final state rest mass

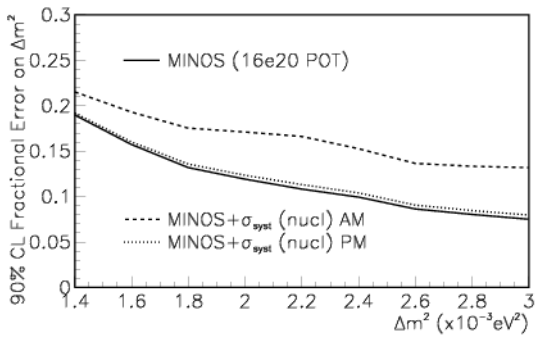


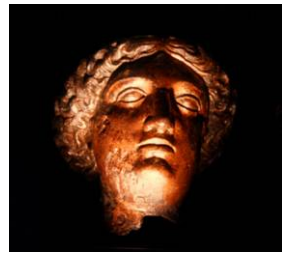



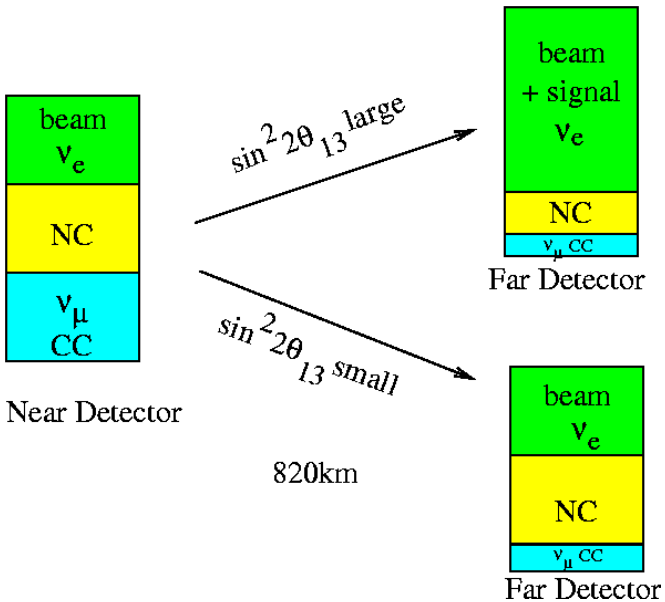

Nuclear Effects Studied in Charged Lepton Scattering, from Deuterium to Lead, at High energies, but nuclear corrections may be different between e/μ and ν scattering

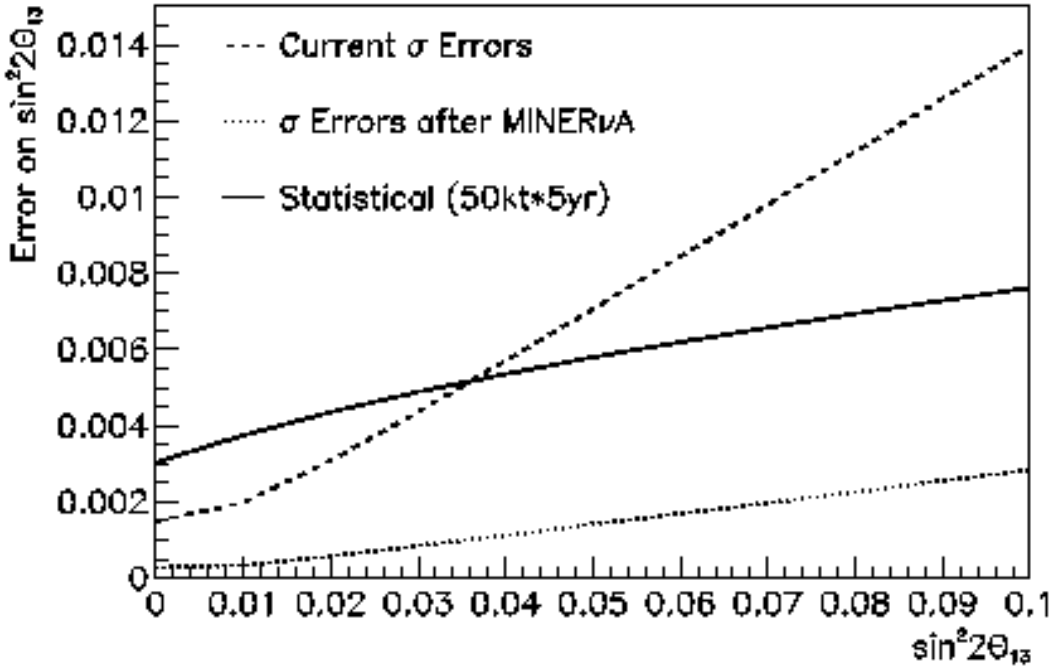


# How NOνA will use MINERνA Measurements



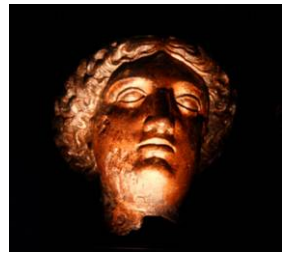


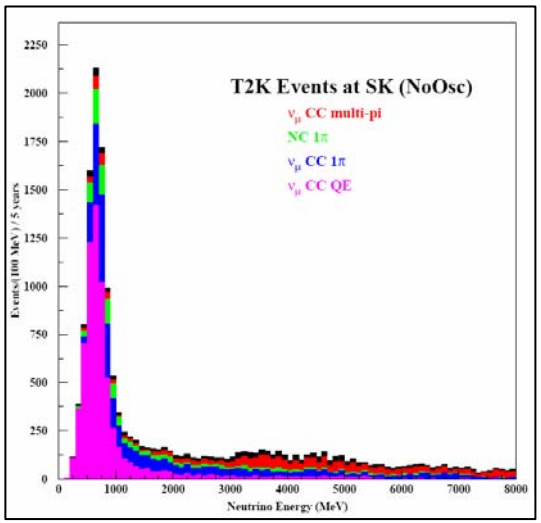



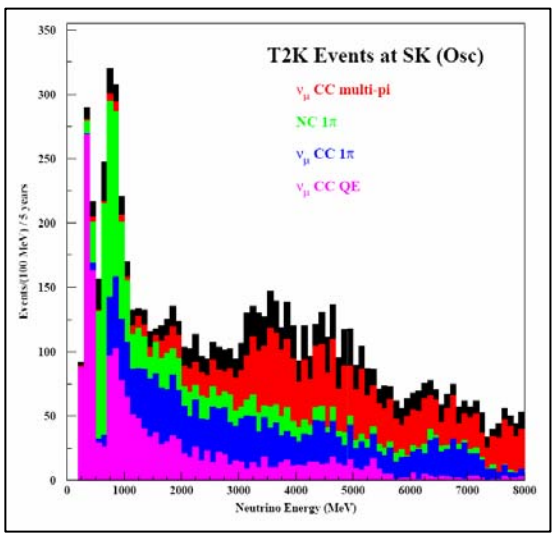

| Process | QE | RES | COH | DIS |
|---|---|---|---|---|
| $\delta\sigma/\sigma$ NOW (CC,NC) | 20% | 40% | 100% | 20% |
| $\delta\sigma/\sigma$ after MINERνA (CC/NC) | 5%/na | 5%/10% | 5%/20% | 5%/10% |

Without MINERνA, NOνA risks being limited by cross section uncertainties

# How will T2K use MINERvA measurements






Note that as in NOvA, T2K's near detector will be a very different mix of events than the far detector.

To make accurate prediction, need

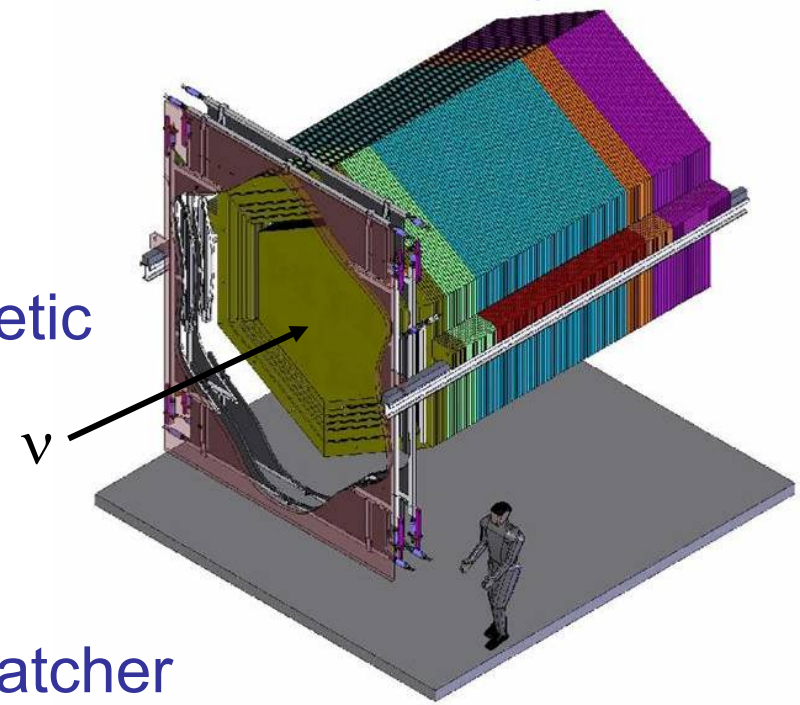
- 1 - 4 GeV neutrino cross sections
- Energy Dependence of cross sections

MINERvA can provide these with NuMI beamline Low Energy running!

# Overview and Performance of MINERvA Detector

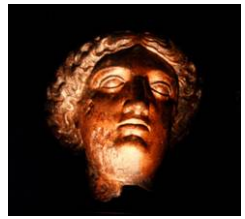
# Basic Detector

- MINER*v*A proposes to build a low-risk detector with simple, well-understood technology
- Active core is segmented solid scintillator
  - Tracking (including low momentum recoil protons)
  - Particle identification
  - 3 ns (RMS) per hit timing (track direction, stopped *K*±)
- Core surrounded by electromagnetic and hadronic calorimeters
  - Photon ($\pi^0$) & hadron energy measurement
- MINOS Near Detector as muon catcher



# MINERvA Optics

(Inner detector scintillator and optics shown,
Outer Detector has similar optics but rectangular scintillator)

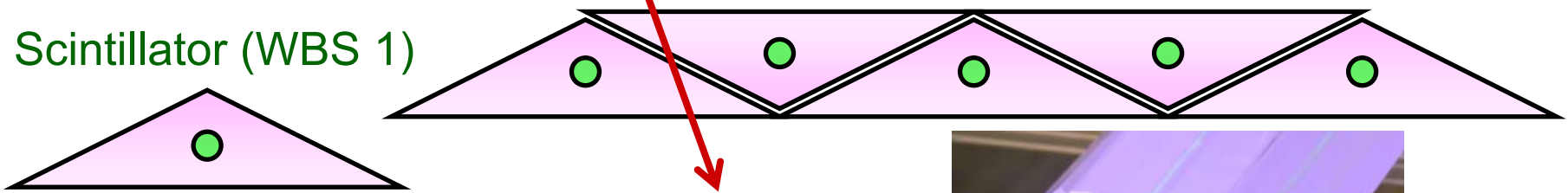


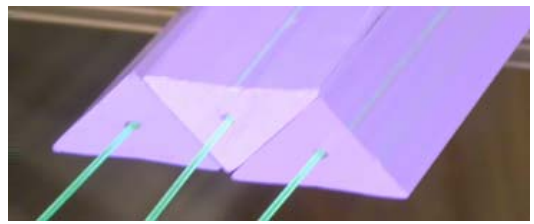
Particle

For the Inner Detector, (WBS 3) scintillator is assembled into 128 strip scintillator planes

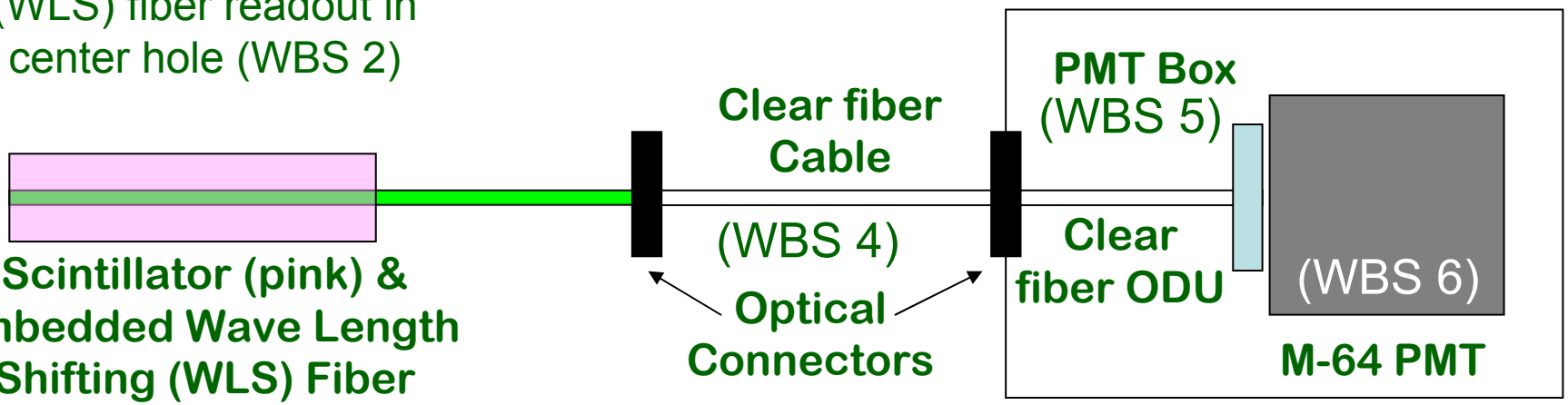
Position determined by charge sharing

Scintillator (WBS 1)

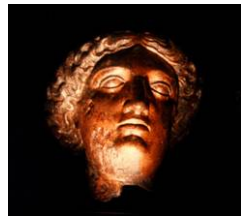




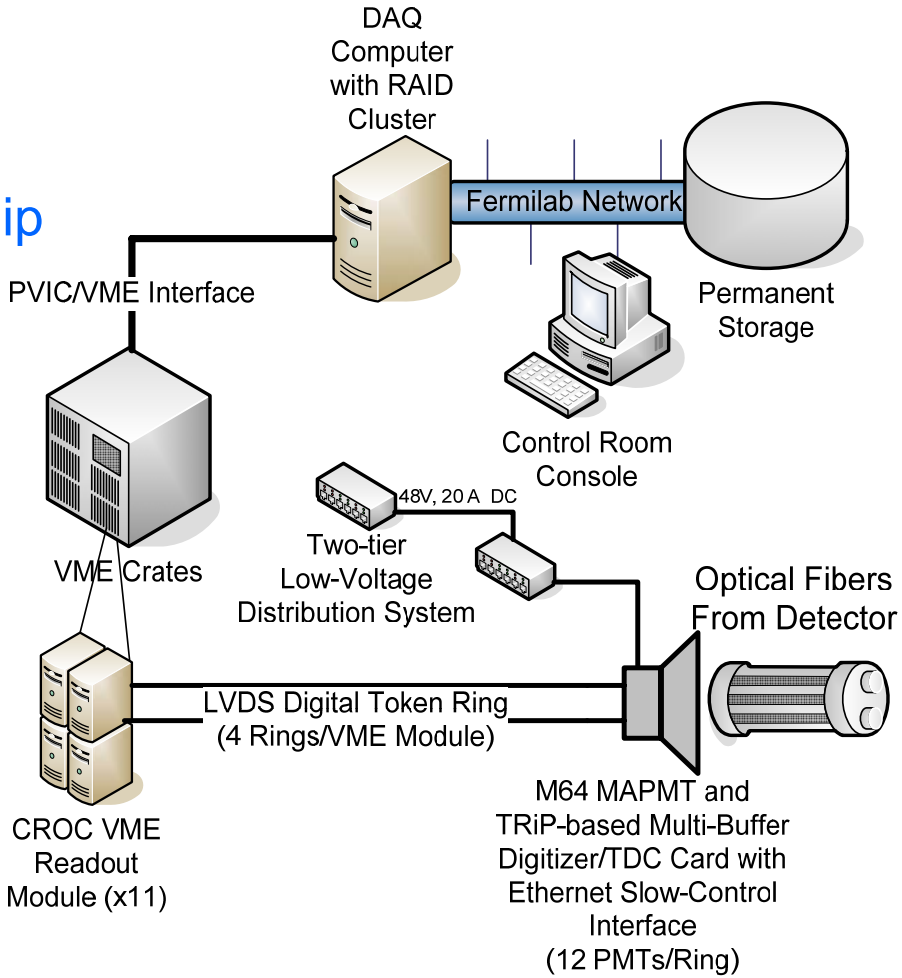
1.7 × 3.3 cm$^2$ strips
Wave Length Shifting (WLS) fiber readout in center hole (WBS 2)



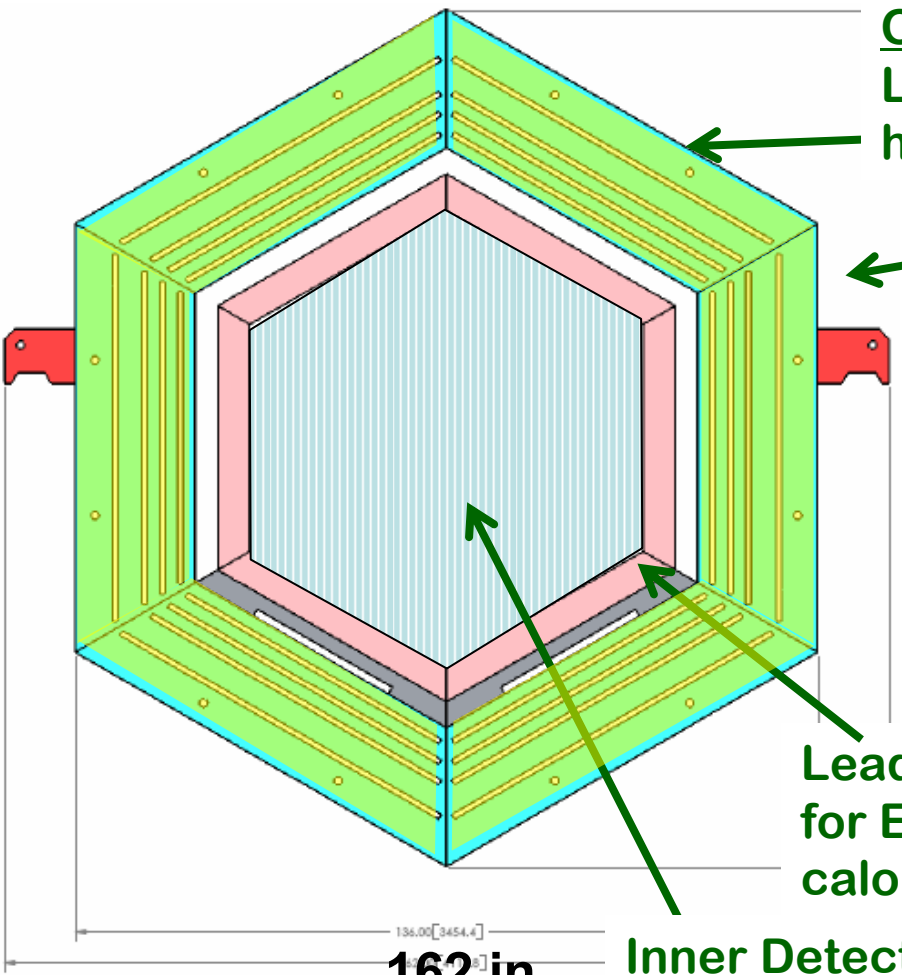
# Electronics



- Front-end Electronics (WBS 7.1)
  - Digitize charge and time
  - use FNAL-developed TriP-t chip
  - High-voltage for MAPMTs
- DAQ and Slow Control (7.2,7.3)
  - Front-end/computer interface
  - Distribute trigger and synchronization
- Power and Rack Protection (7.4)
  - 7 kW total LV power to electronics



# MINERvA Detector Module




**Outer Detector (OD)**
**Layers of iron/scintillator for hadron calorimetry. 6 "Towers"**

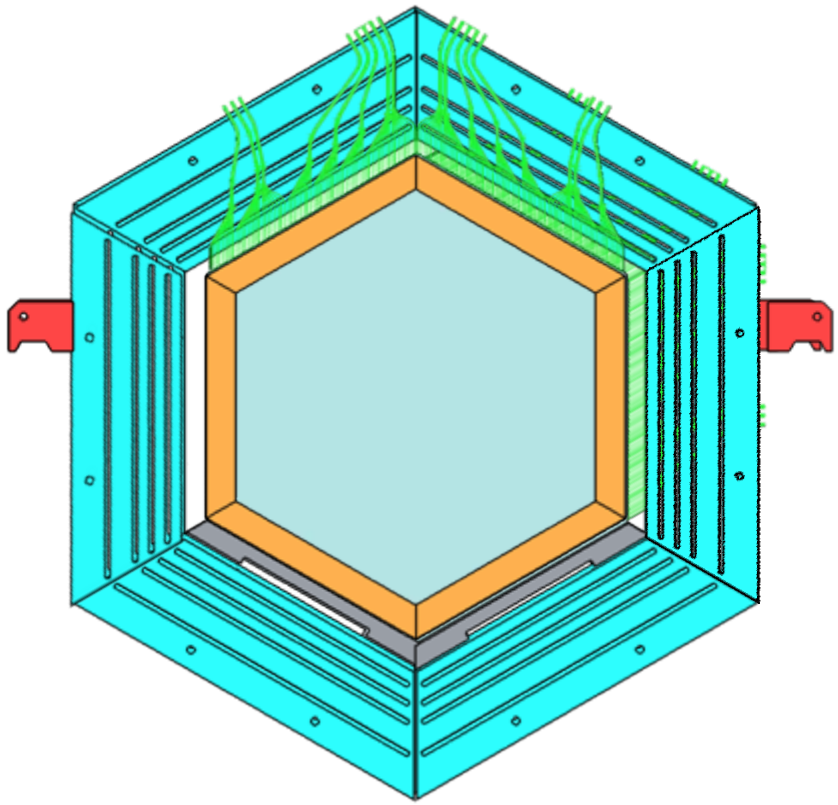
**Lead Sheets for EM calorimetry**

**Inner Detector (ID)**
**Hexagonal X, U, V planes for 3D tracking**

- **A frame with two planes has 304 channels**
  - **256 in inner detector**
  - **48 in outer detector (two per slot)**
- **4¾ M-64 PMTs per module**
  - **OD readout ganged in groups of four planes**

# Parts of MINERvA Modules

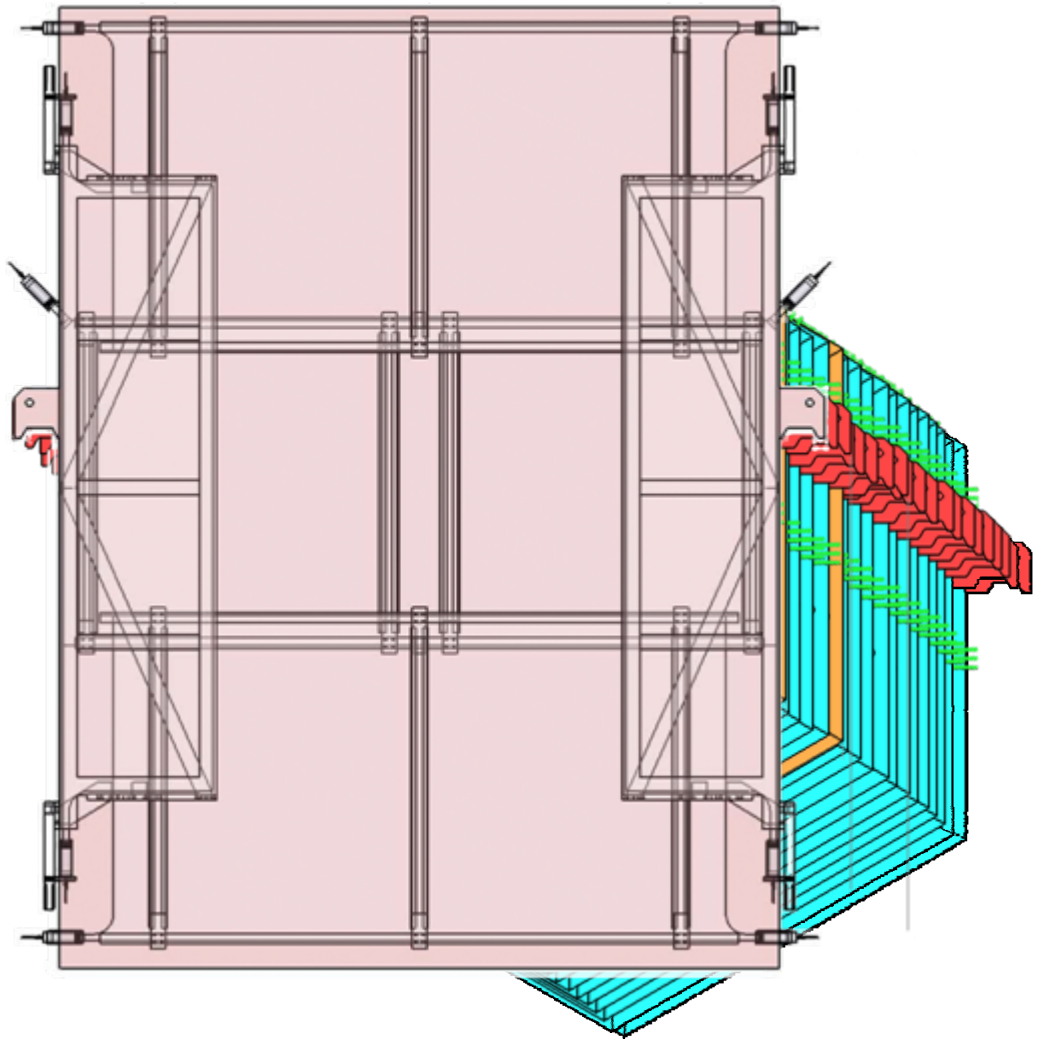
- An Outer Detector Frame is assembled from steel towers
- Frame hooks and support spacers are added



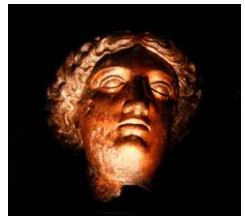
- One or more planes of scintillator is added
  - Pb ring for the side ECAL (not in DS ECALs)
  - complete active target "module"

# Parts of MINERvA Modules (cont'd)

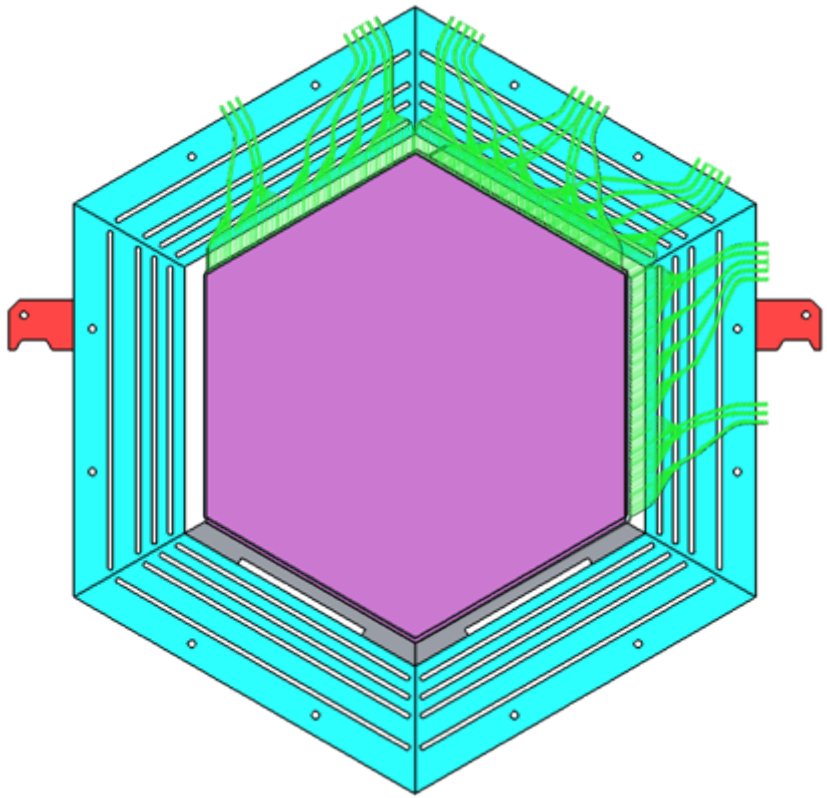
- Modules are stacked up like hanging file folders onto the stand
  - spacing set by flatness of OD steel, fiber clearance
- Nuclear Targets in separate (passive) frames interspersed
- Veto Wall in front of the detector



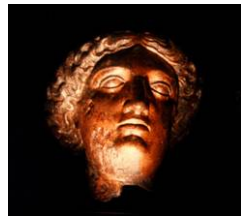
# Parts of MINERvA Modules (cont'd)

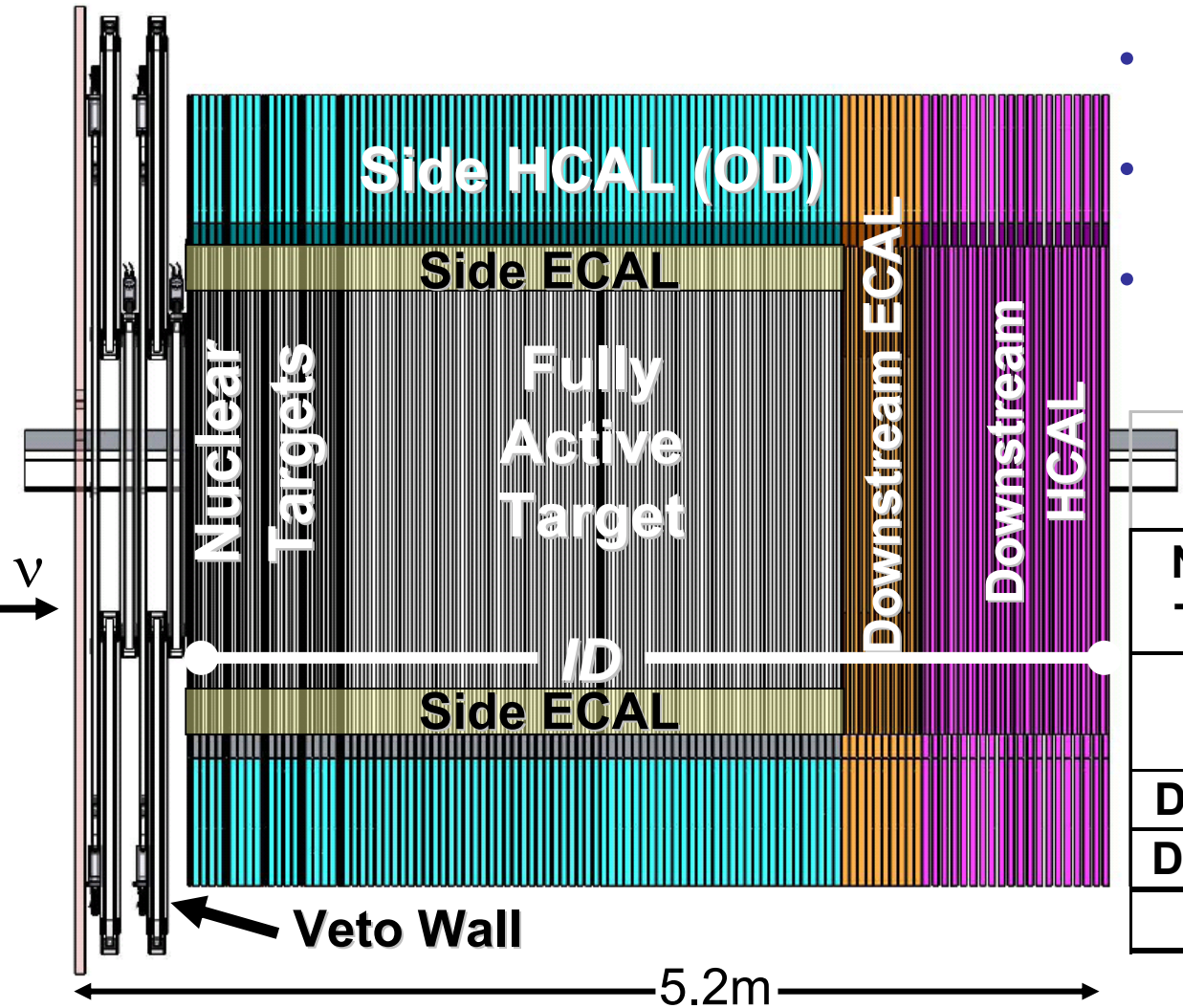


- Calorimeter modules are built by adding absorbers
  - one 1" steel absorber and one scintillator plane in DS HCAL
  - two 5/64" Pb absorbers and two scintillators in DS ECAL



# Complete Detector



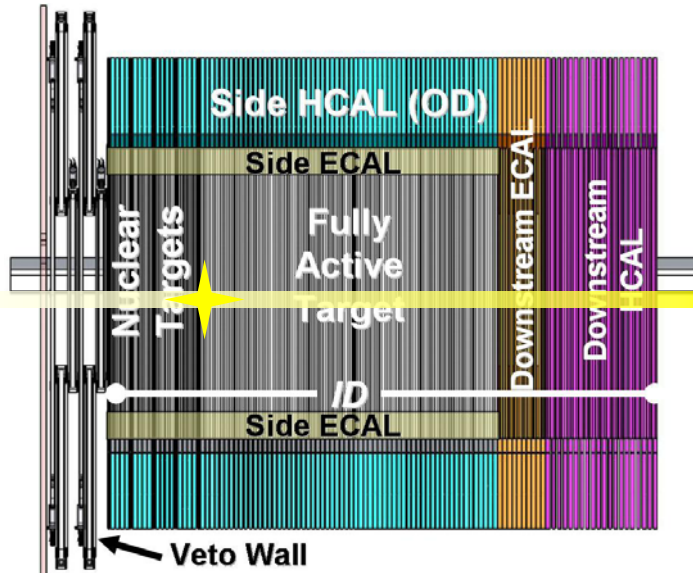


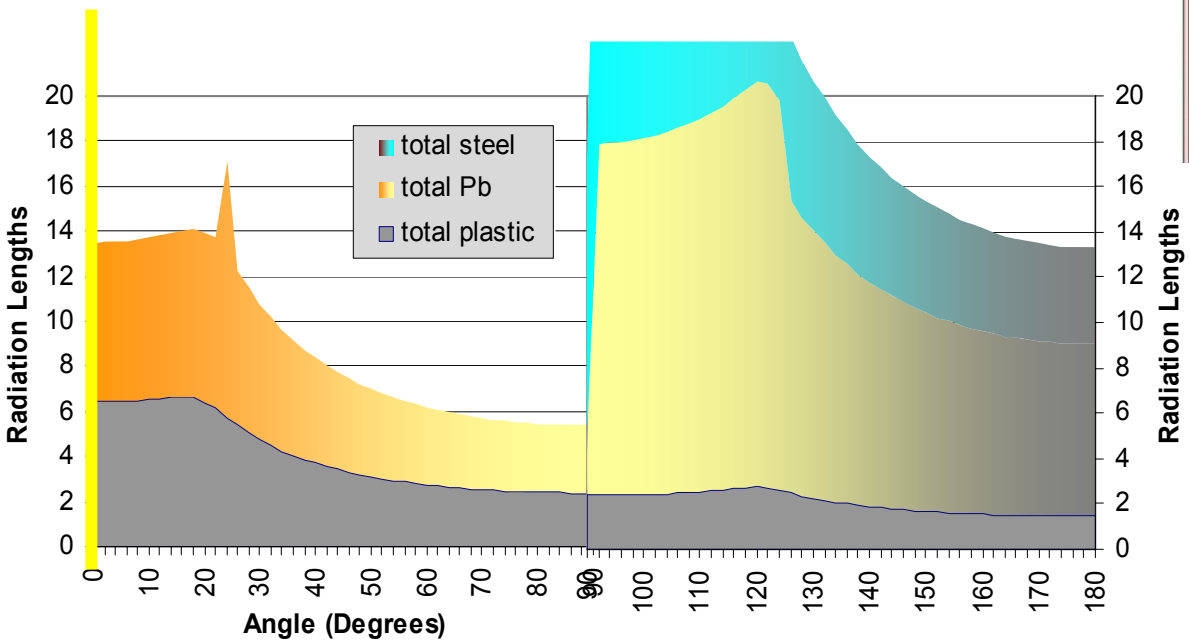

- Thin modules hang like file folders on a stand
- Attached together to form completed detector
- Different absorbers for different detector regions

| | Frames | Scintillator Planes |
|---|---|---|
| Nuclear Targets | 18 | 36 |
| Active Target | 60 | 120 |
| DS ECAL | 10 | 20 |
| DS HCAL | 20 | 20 |
| Totals | 108 | 196 |

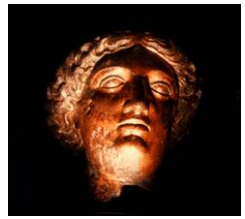
# MINERvA as Calorimeter

- Material in Radiation lengths
  - Relevant for photon and electron analysis
  - Side & DS Pb has 2mm plates

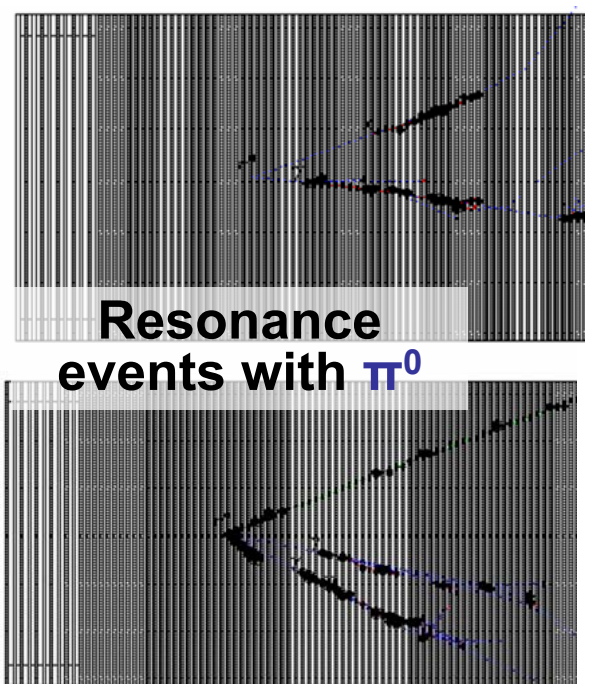


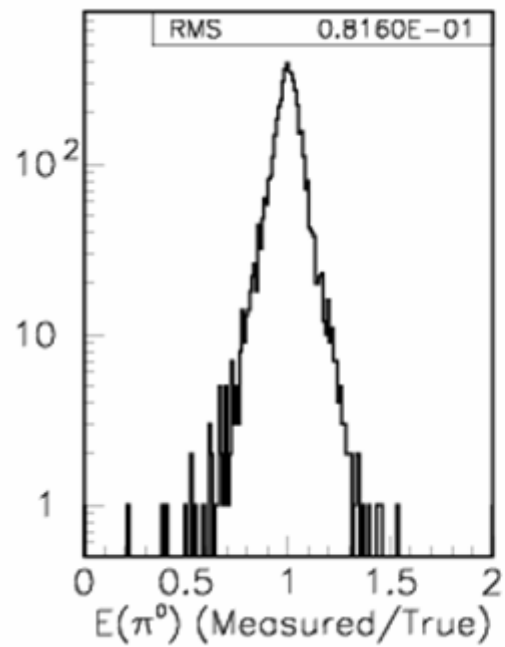



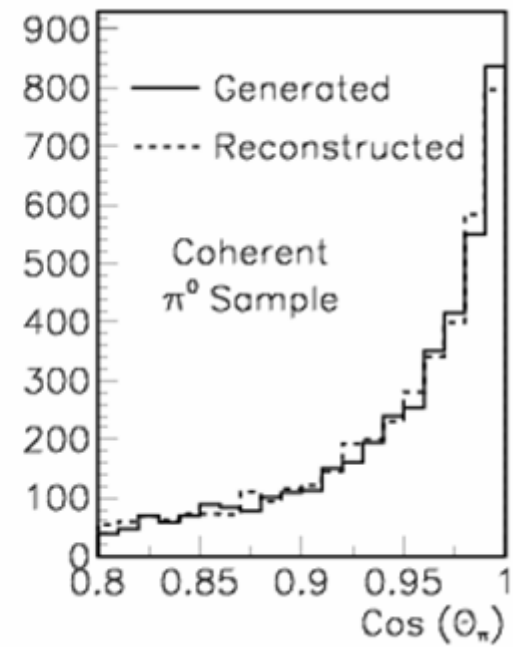
# $\pi^0$ Reconstruction



- photons cleanly identified and tracked
- $\pi^0$ energy res.: $6\%/\sqrt{E}$ (GeV)
- For coherent pion production, $\pi^0$ angular resolution < physics width

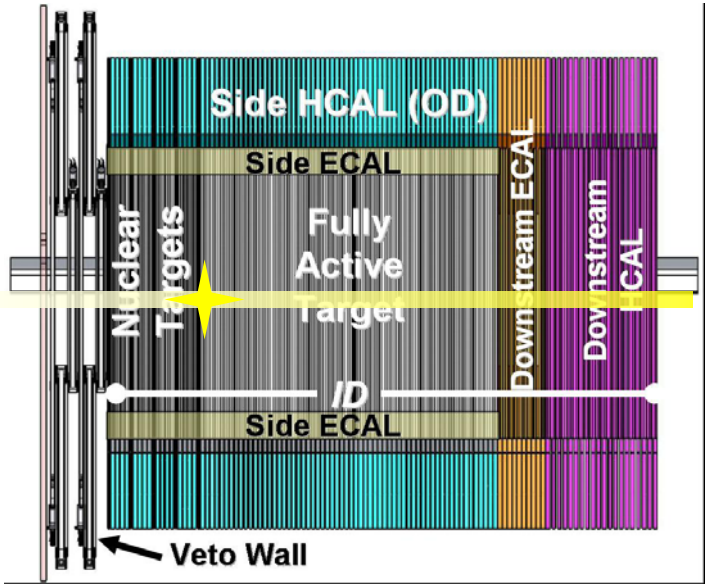


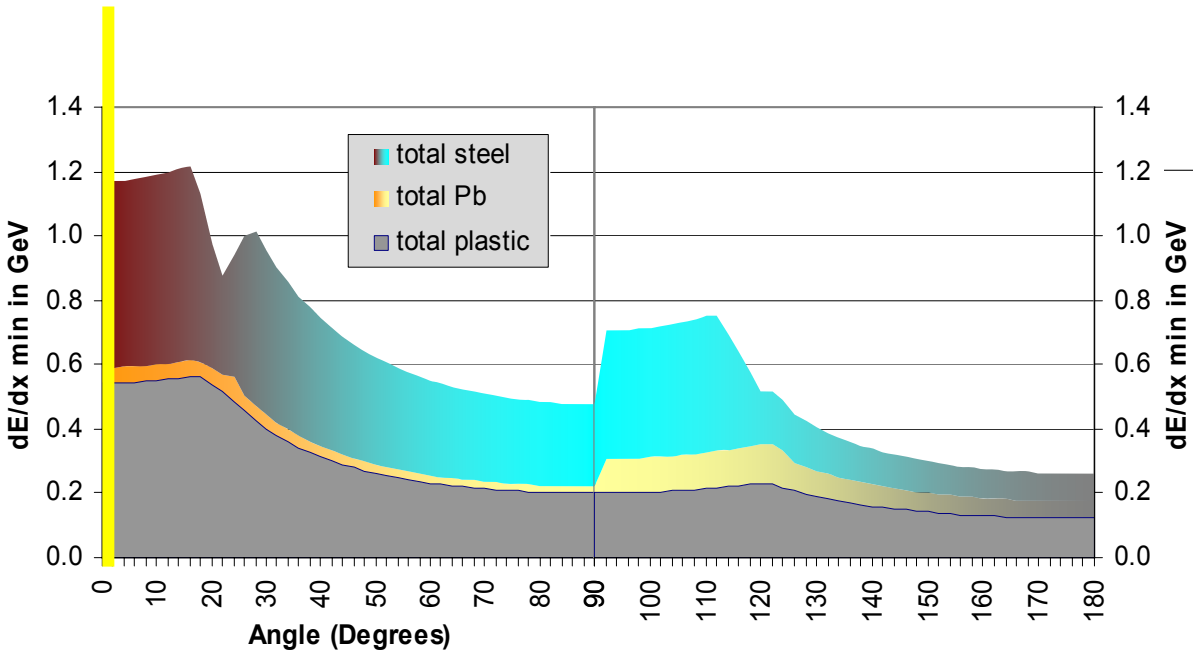



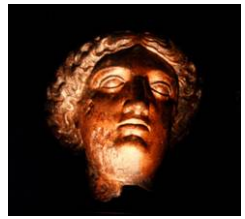
# MINERvA as Range Tracker

- Material Thickness in $(dE/dx)_{min}$
  - Relevant for ranging out low energy particles

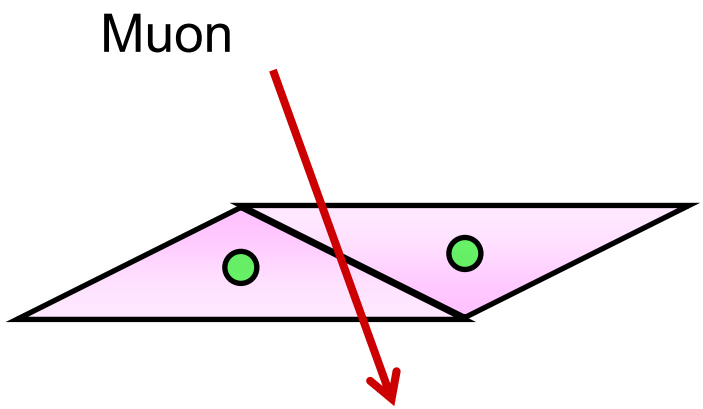


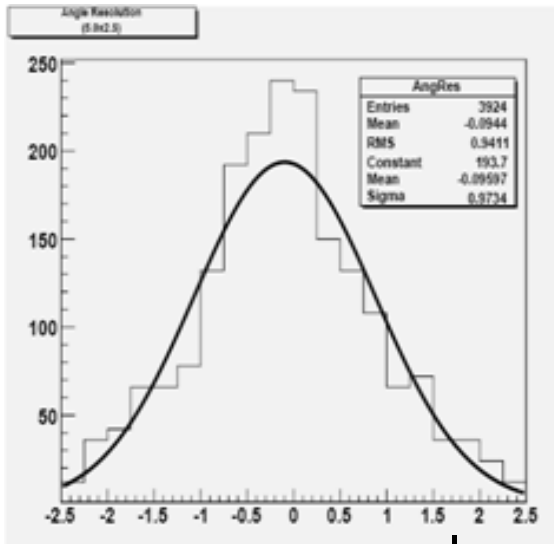



# Muon Angular Resolution

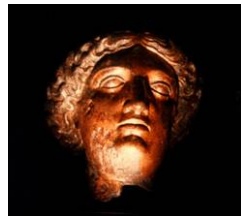


- Charge sharing gives precise coordinate resolution, σ~3mm
- For long tracks (muons), get many space points
  - excellent angular resolution
  - <1° for exiting muon tracks

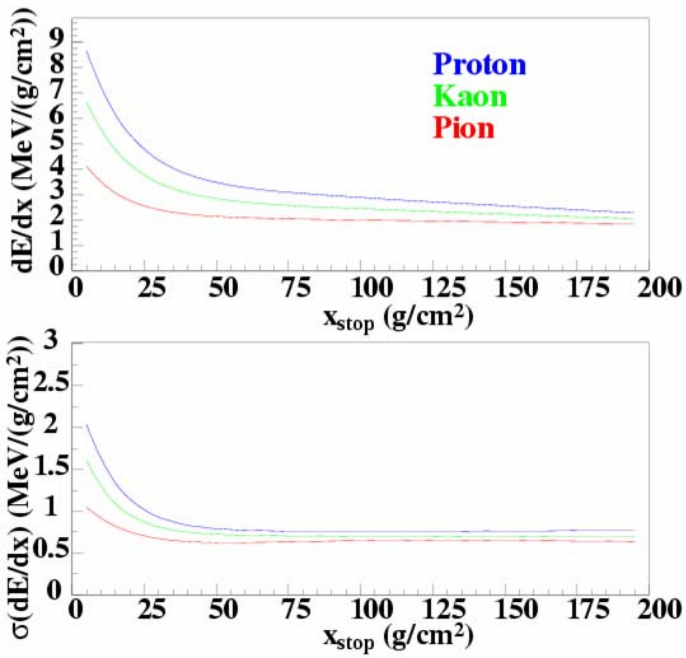


# Particle Identification

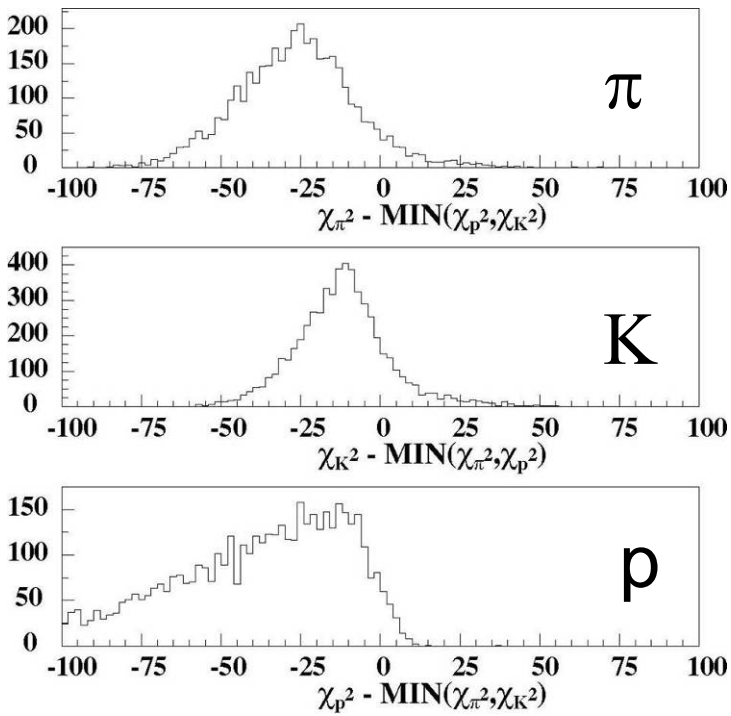


- Particle ID by dE/dx in strips and endpoint activity



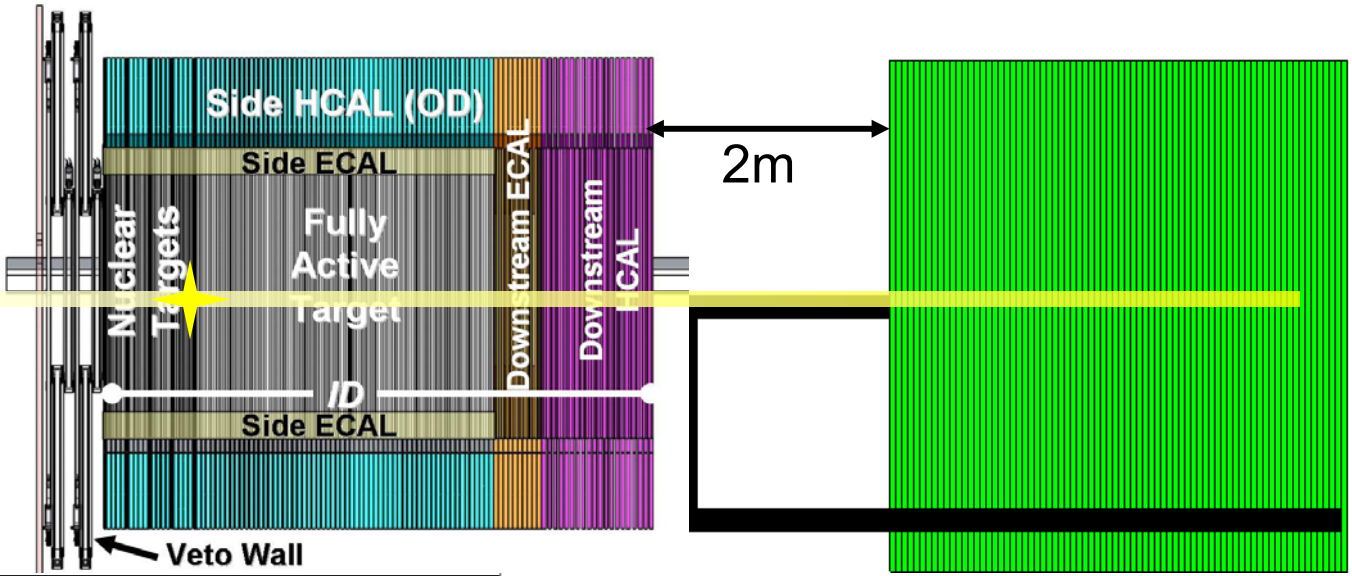

- Many dE/dx samples for good discrimination
  - sensitive to light yield

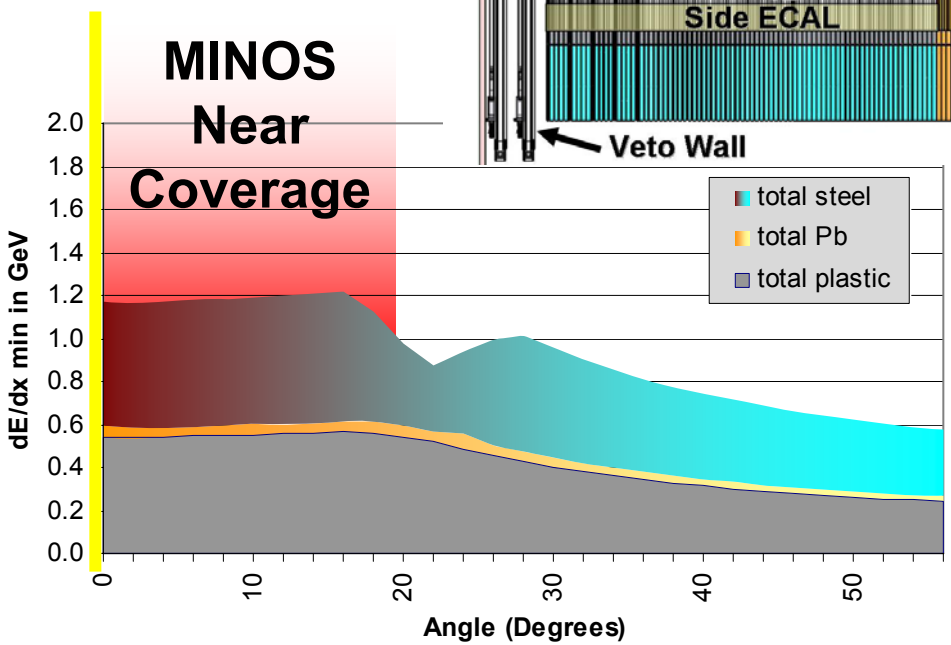
Chi2 differences between right and best wrong hypothesis




R = 1.5 m - p: μ =.45 GeV/c, π = .51, K = .86, P = 1.2
R = .75 m - p: μ =.29 GeV/c, π = .32, K = .62, P = .93

# MINERvA with MINOS Near

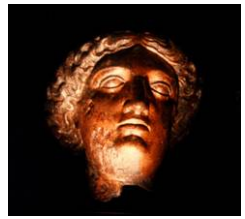



- $(dE/dx)_{min}$ inadequate for μ
  - Rely on MINOS
  - For high momentum, analyze by bend in field, $\delta p/p \sim 12\%$

# progress in detector R&D

# Prototyping

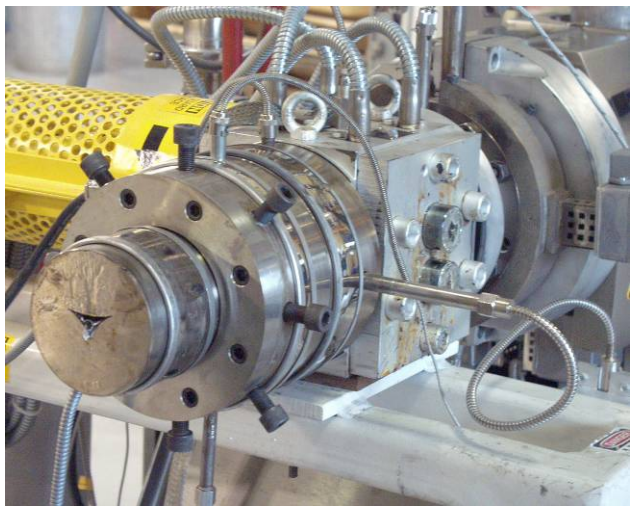


- MINERvA has two foci of prototyping
  - demonstrating basic element performance
    - scintillator/WLS light yield
    - clear fiber cable transmission
    - electronics: noise, charge sensitivity
  - demonstrating construction feasibility
    - extrusion of scintillator
    - prototype PMT box, PMT alignment scheme
    - scale modules of module assembly
    - fiber gluing tests

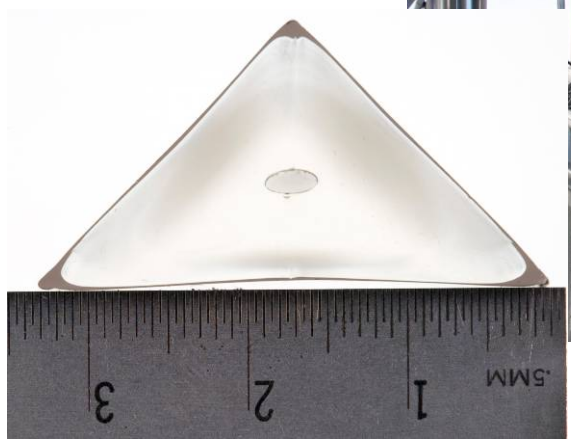
# Scintillator Prototypes

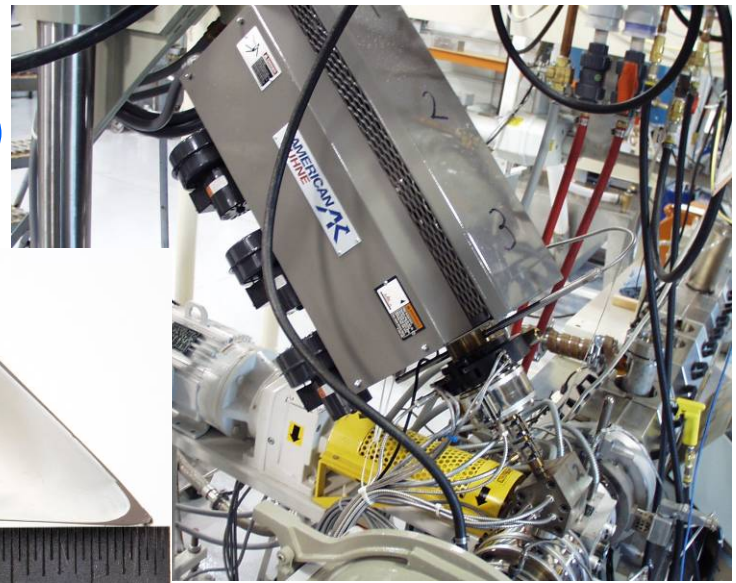
- Focus on producing first ID scintillator triangles
  - Demonstrated feasibility of meeting mechanical specs
  - Provide scintillator for light yield measurements
  - Detailed estimates of labor costs
- Funded by DOE University funds, FNAL FY05 funds

ID Triangle Die
(July ’04-present)

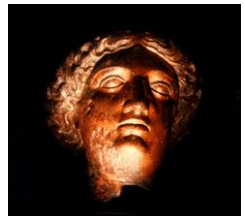


Co-Extruder
(Oct ’05-present)

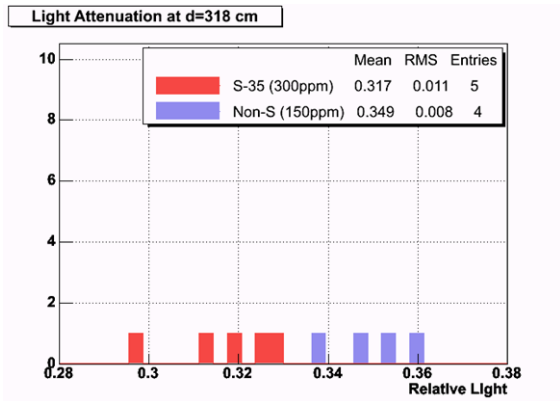


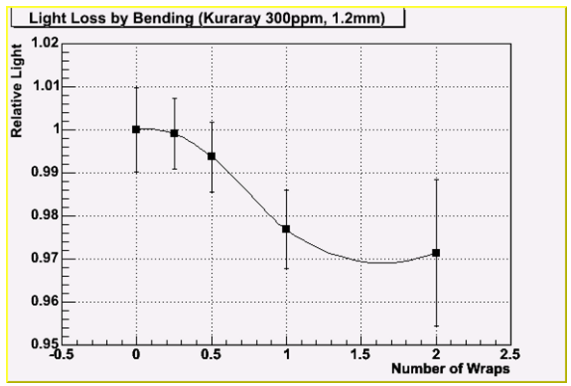


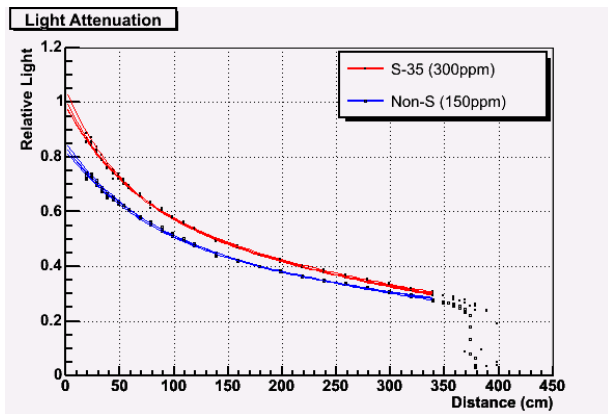
# Fiber Qualification



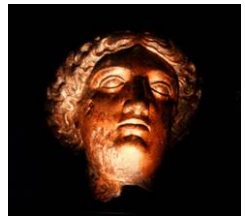
- WLS Fiber testing and qualification
  - attenuation and light yield of WLS fiber for different dopant concentrations
  - fiber flexibility and light loss tests



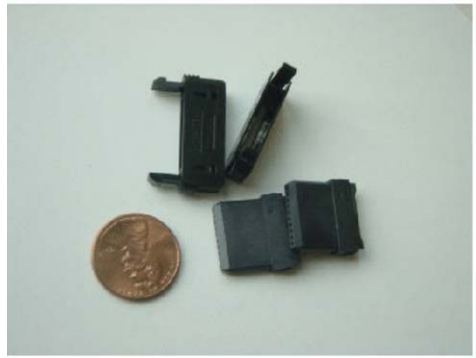


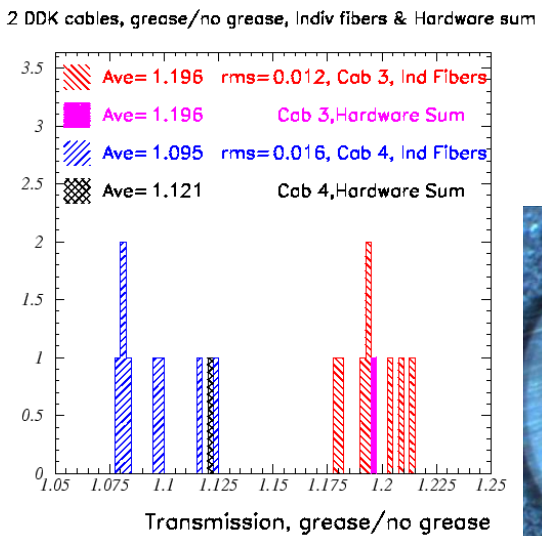



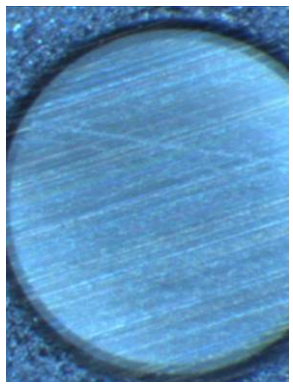
# Prototype Fiber Cables

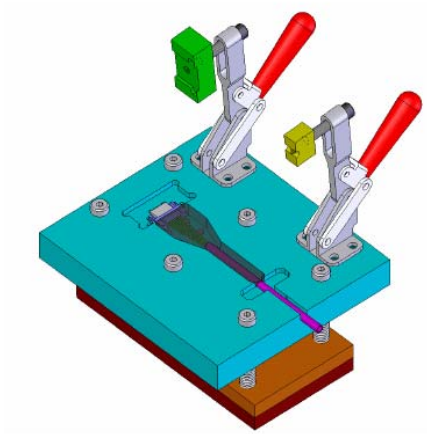


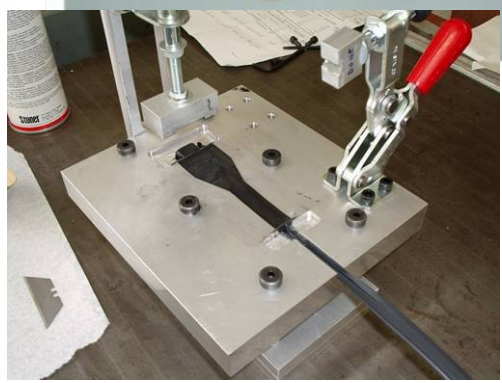
- Here the foci are:
  - engineering and prototyping for production tasks
  - procurement from industry (connectors)
  - transmission measurements



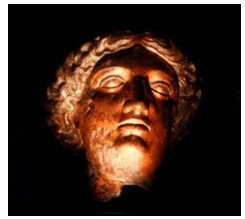


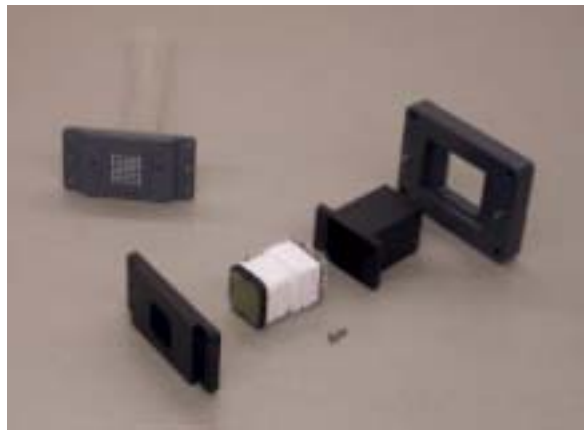


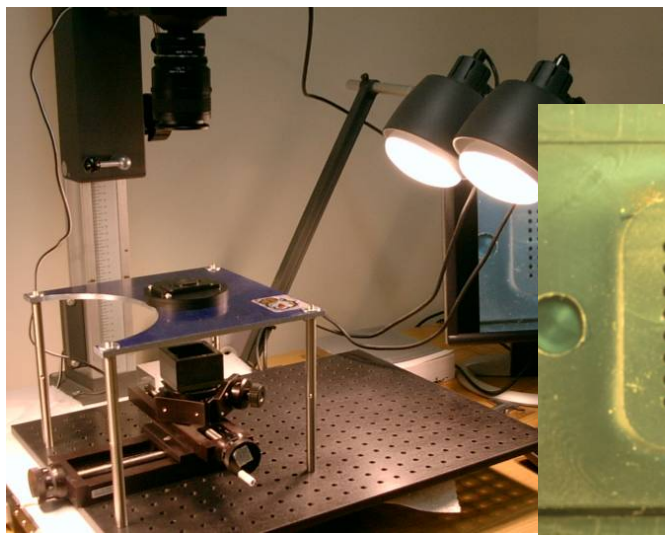


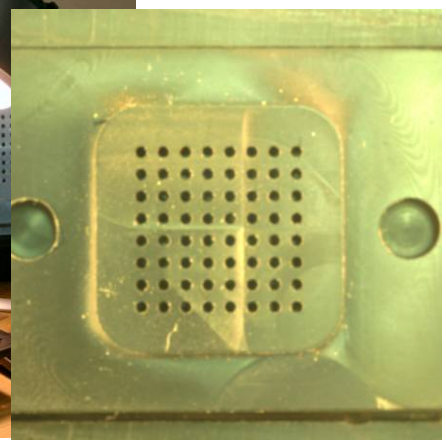
# Prototype PMT Assembly



- Focus on learning steps required to align, test and safely house the photomultipliers
- Interface-heavy tasks (esp. WBS 5) are making use of many other early prototypes
  - fiber cables, PMTs, electronics, etc.

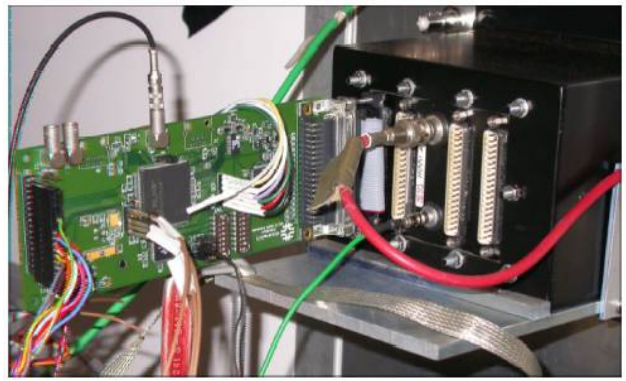


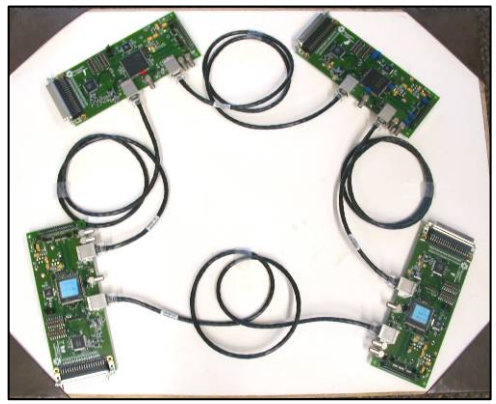




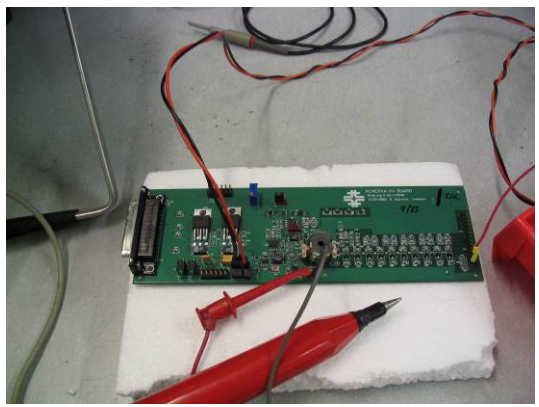
# Electronics Prototypes

- Front End Boards
  - 16-channel prototype, summer 2004 vertical slice
  - LVDS ring/interface and timing jitter successfully tested with four FE prototypes (end 2004)



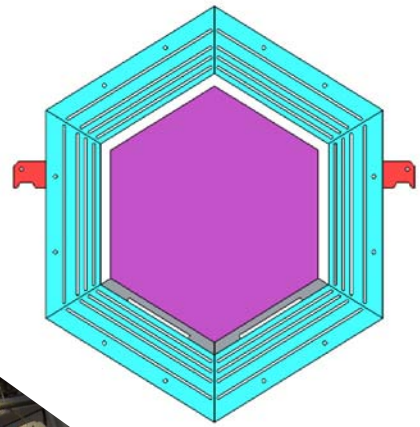


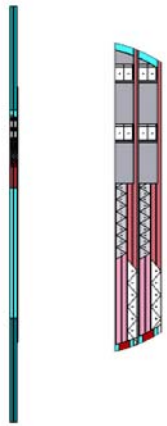
- HV voltage prototype card tested (Oct 2005)

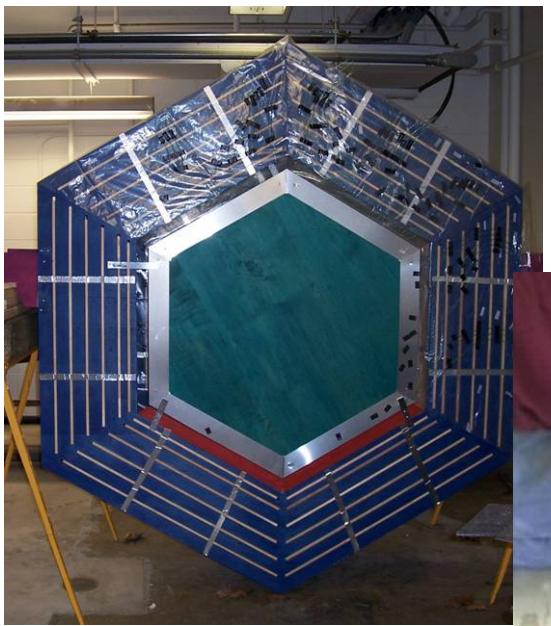


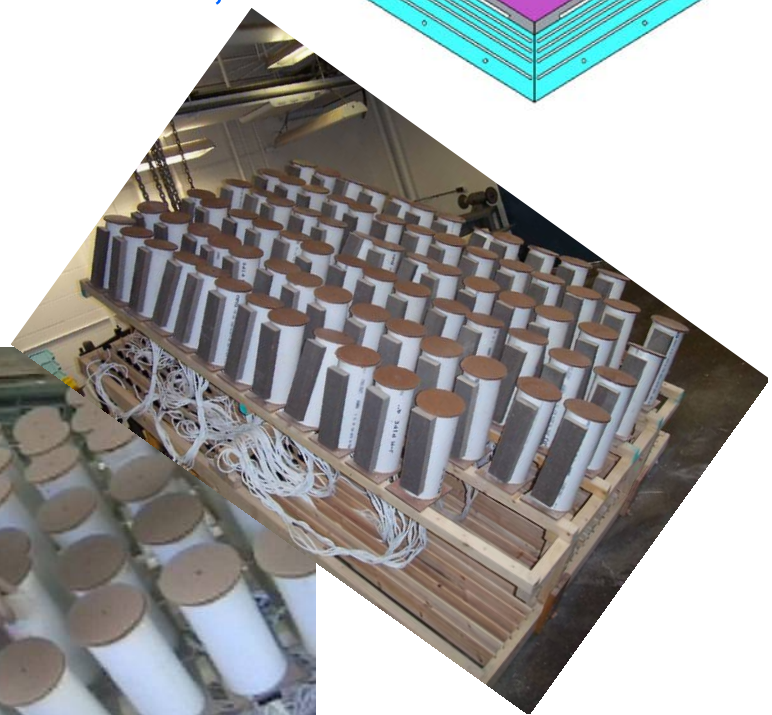
# Mechanical Prototypes

- Mock-ups of critical components for:
  - time-motion studies of assembly
  - determine tooling, fixtures required
  - feasibility evaluation of installation, repair procedures



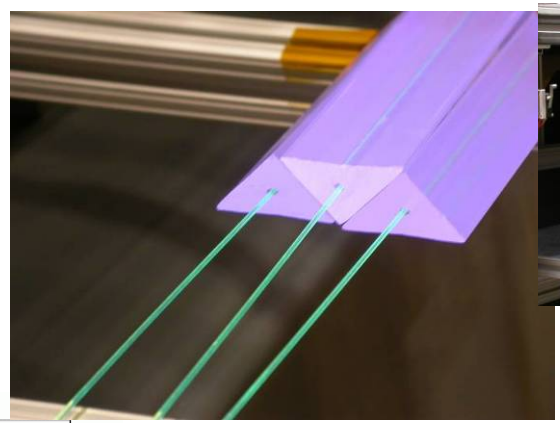


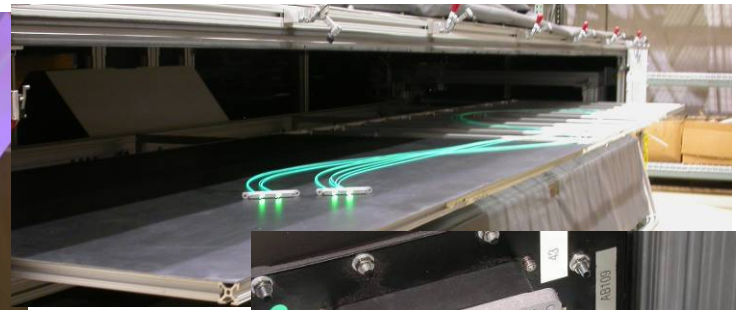


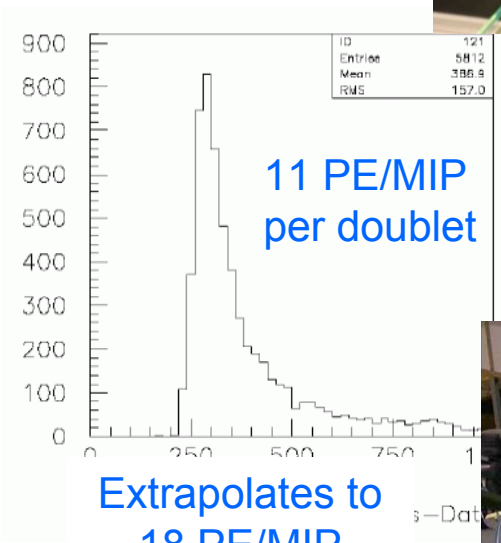


# Vertical Slice Test

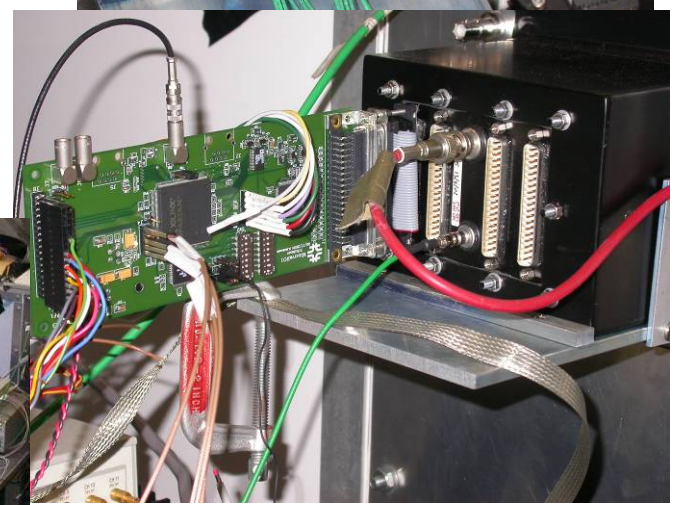
VST1 array, electronics and DAQ



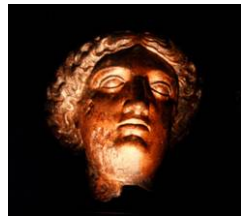





Extrapolates to 18 PE/MIP (5.4 PE/MeV) in final detector



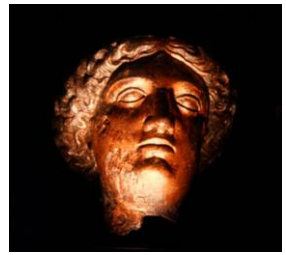
# Continuing VST



- We have tested “more realistic” gating and readout of electronics
  - continues to indicate we can meet timing, noise specifications
- We have used VST setup to project our light yield with different scenarios for scintillator assembly.
- The key test is demonstrating *light yield*, *position* and timing resolution with the final extruded scintillator
  - Have fabricated and installed multi-layer array for cosmic ray tracking. now filled with co-extruded scintillator with glued in fiber
  - Setup is functioning. results soon

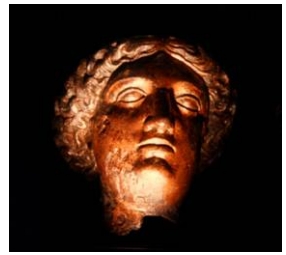
# conclusions

# A Brief History of MINERνA



- December 2002 - Two EOIs for neutrino scattering experiments using the NuMI beam and similar detector concepts presented to the PAC. PAC suggests uniting efforts and preparing proposal.
- December 2003 - MINERνA proposal presented to PAC. PAC requests more quantitative physics studies and details of MINERνA's impact on Fermilab
- April 2004 - Proposal addendum containing additional physics studies and report from the Impact Review Committee presented to PAC. Receive Stage I approval.
- Summer 2004 – Begin R&D Program concentrating on front-end electronics, scintillator extrusions and a "vertical slice test"
- Fall 2004 - Proposal to NP and EPP of NSF and to NP and HEP of DOE to fund bulk of MINERνA.
- January 2005 - First Director's Review of MINERνA
- Spring 2005 – With release of FY06 budget, DOE of budget process crystallizes; decision that MINERνA must be primarily funded through FNAL budget.
- June 2005 – MINERνA project management and structure begin to form
- December 2005 – FNAL Directors' CD1/pre-CD2 readiness review
- February 2006 – Update funding profile without FY07 start to MIE. Begin single module prototype

# MINERvA…

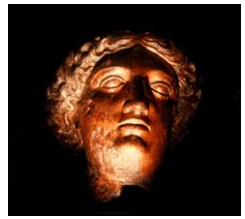


- Opportunity for unique and critical FNAL role in world neutrino efforts in a modest-scale project
  - only possible because of investment in NuMI
  - needed to fully leverage oscillation potential at NuMI
- On track technically to build and use detector
  - R&D and prototyping progressing
- We are doing what projects do…
  … including waiting for approvals and funding

# backup slides

# more on detector

# Mass of MINERvA

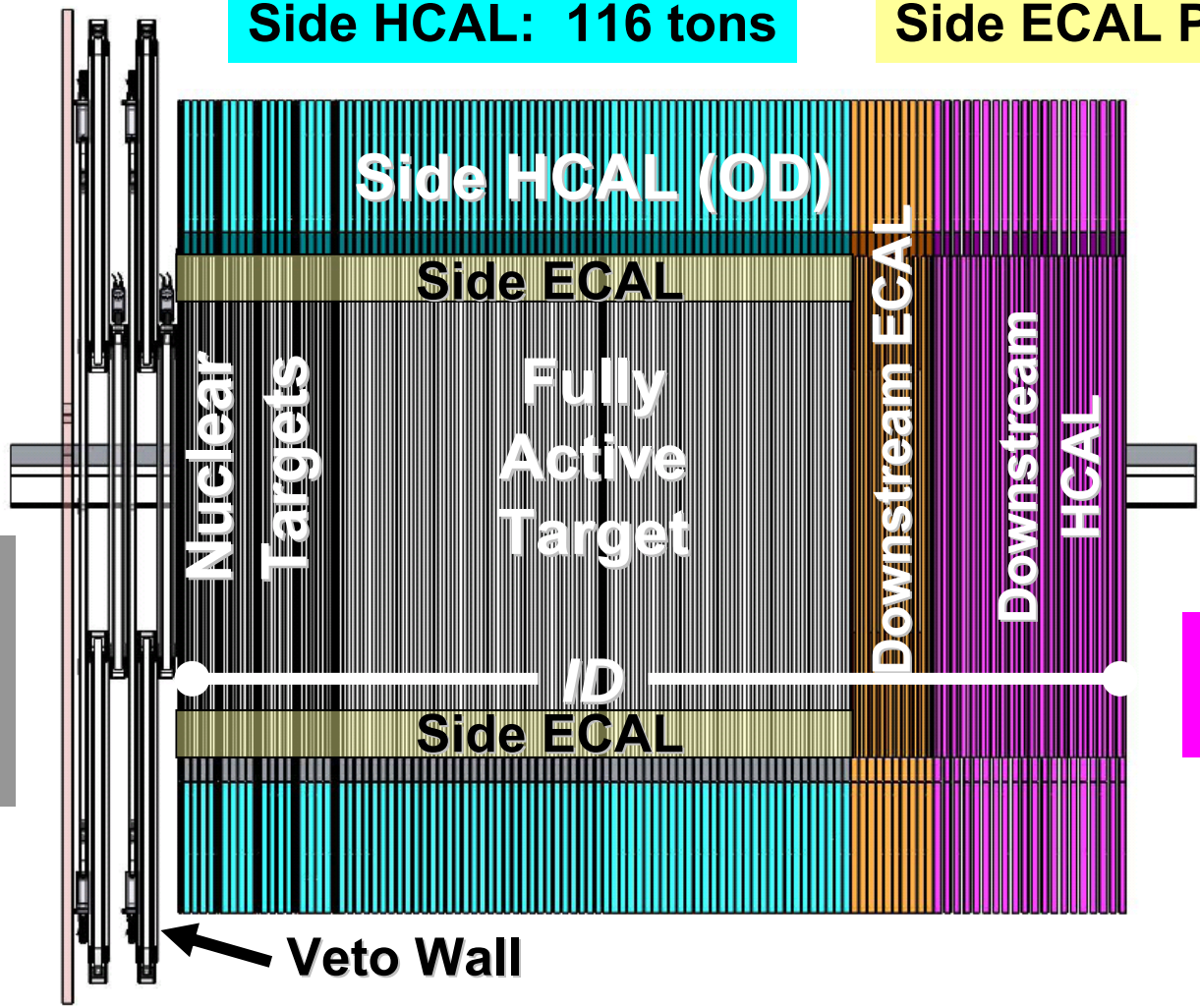


Side HCAL: 116 tons

Side ECAL Pb: 0.6 tons

Fully Active Target: 8.3 tons

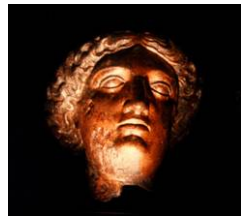
Nuclear Targets: 6.2 tons (40% scint.)



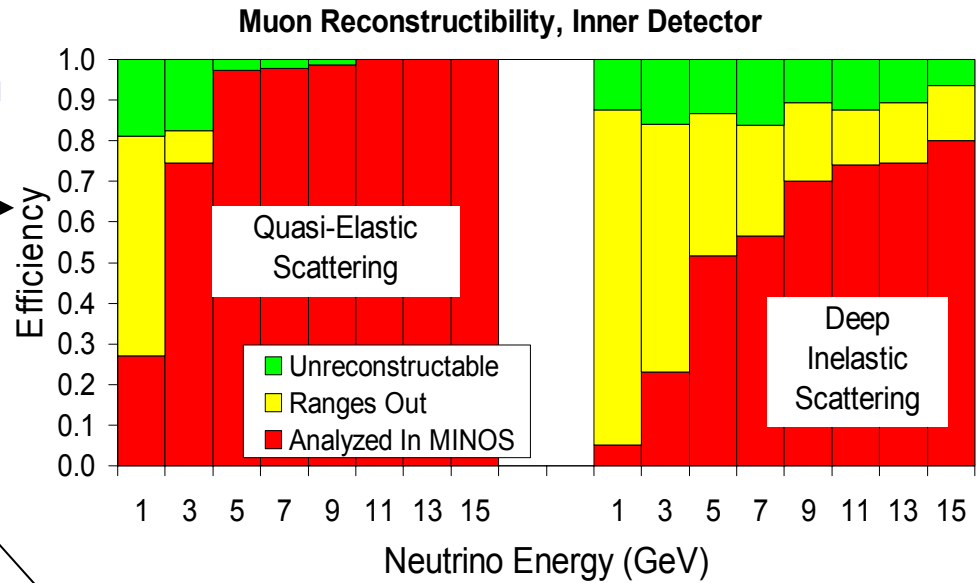

DS ECAL: 15 tons

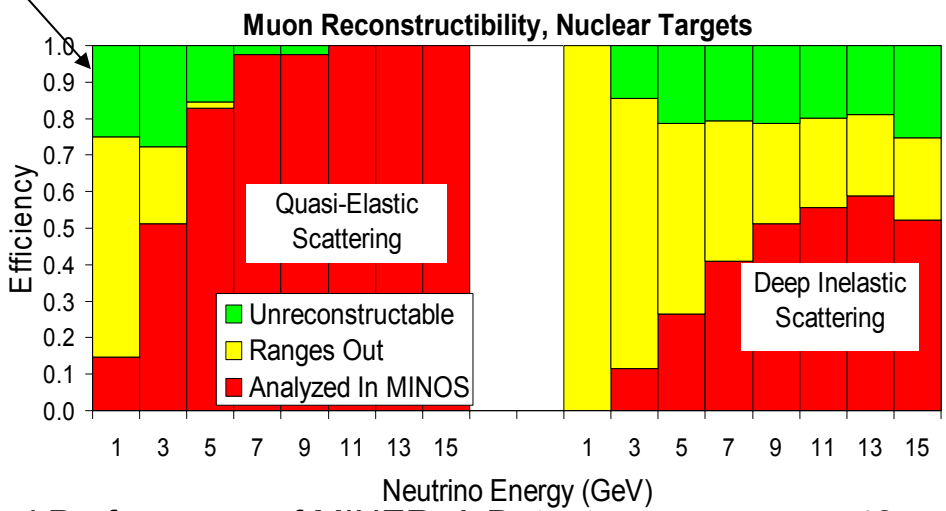
DS HCAL: 30 tons

# Muon Acceptance Study

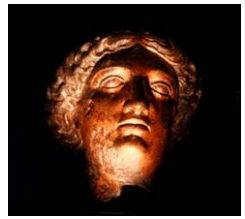


- Fiducial Volume Cuts: radius<75cm
- Look at acceptance for muon
  - Active Target (>50cm from DS ECAL)
  - Nuclear Target Region
- In kinematic extrema of interest:
  - High x DIS: (x>.7)
    - Analyzed in MINOS: >90% active TGT, >80% nucl target
    - Remainder escape the sides
  - High $Q^2$ Quasi-Elastic:
    - Analyzed in MINOS: >99% active TGT, >86% nucl. target

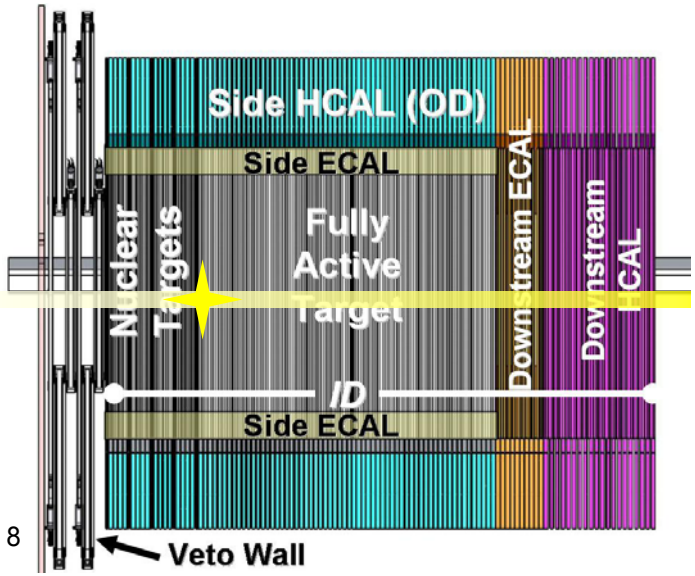


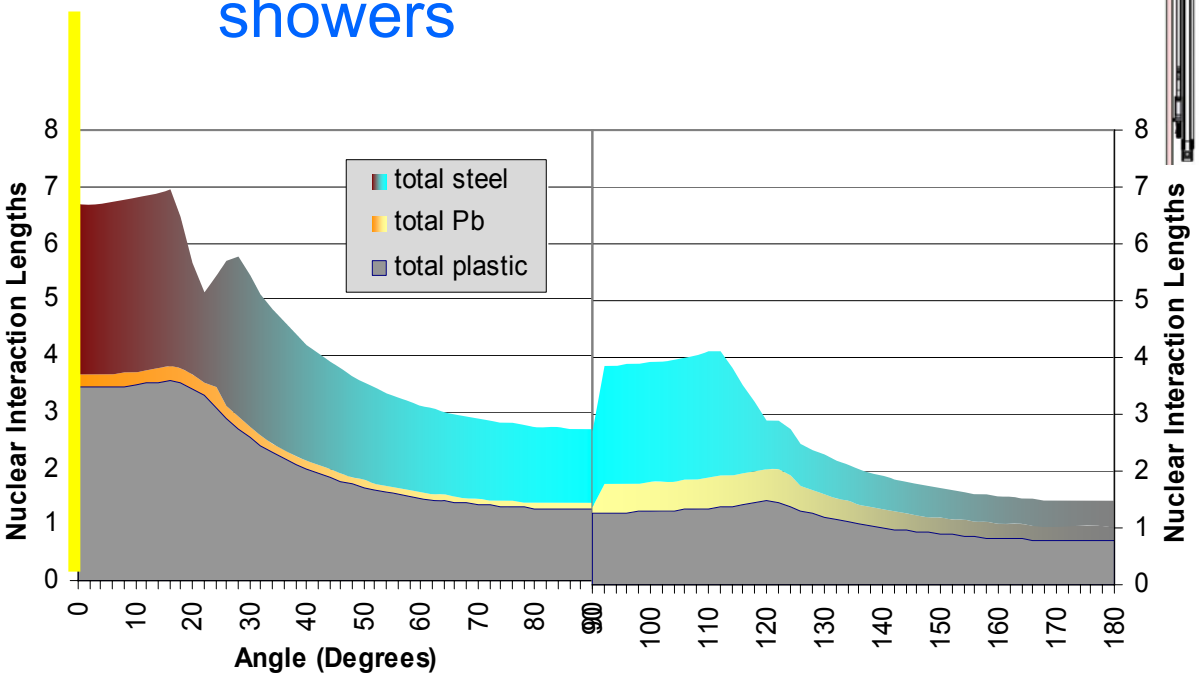



# MINERvA as Calorimeter

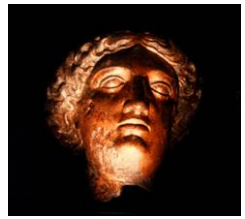


- Material Thickness in Nuclear Interaction Lengths
  - Relevant for containing single hadrons or hadronic showers

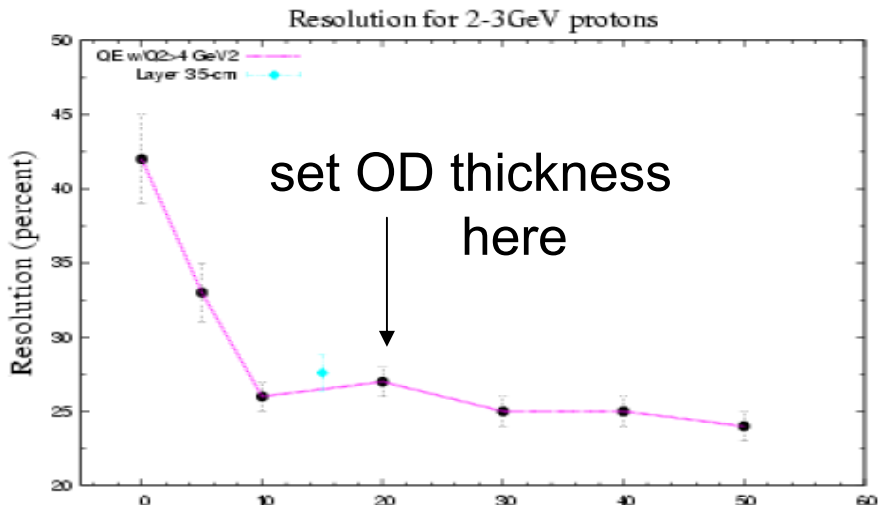


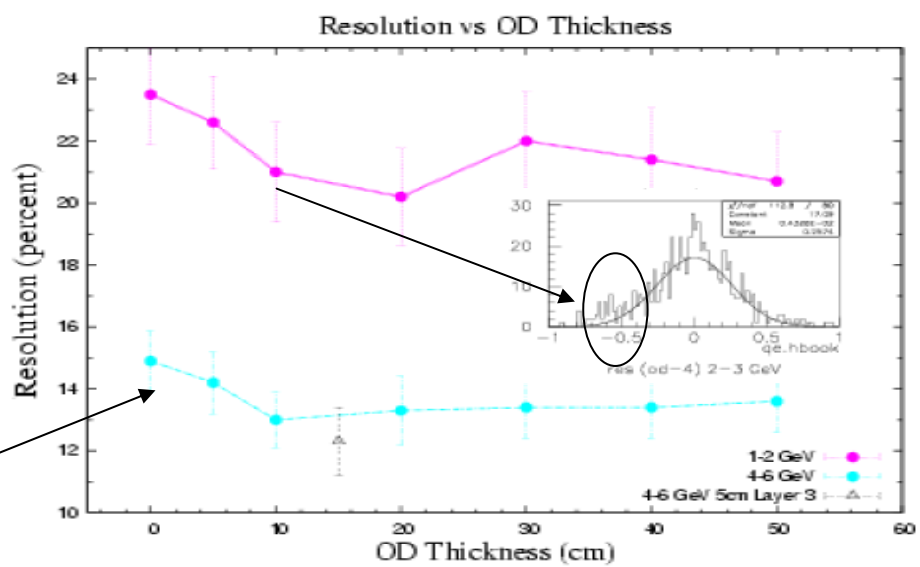
# Hadronic Energy



- Single proton resolution in quasi-elastic events ($p_p$~2.5 GeV)



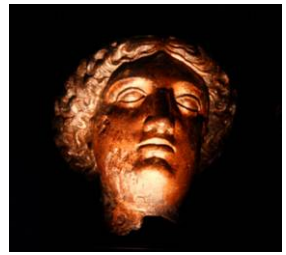

- *Studied dependence of both on calorimeter thickness*
  - *thinned without compromising resolution or adding low-side tail*



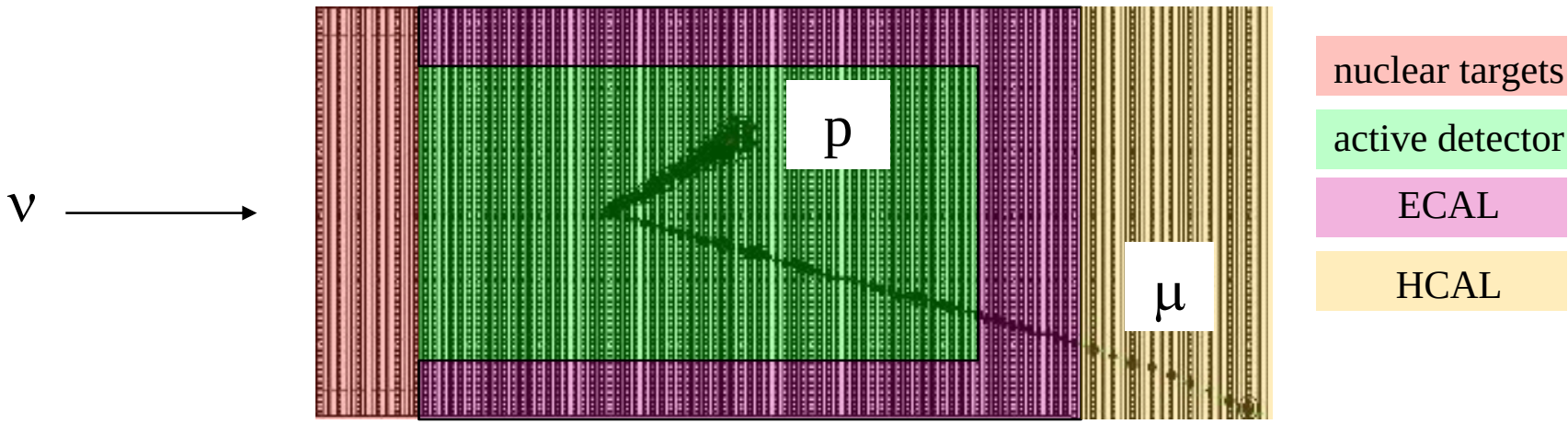

- Shower energy resolution in deep inelastic events (ν~1.5 GeV, 5 GeV)

# sample events

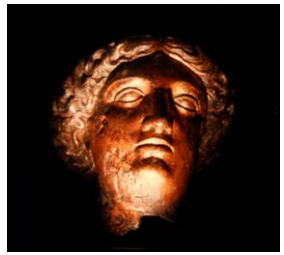
# Illustration: $\nu_\mu n \rightarrow \mu^- p$

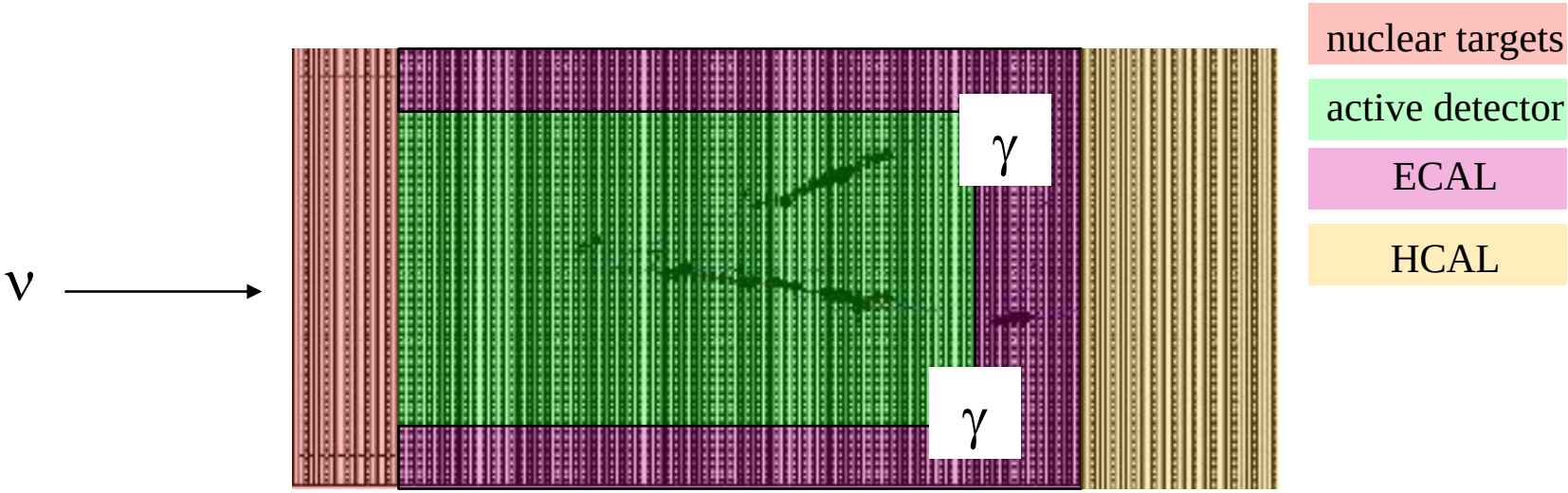


- Reminder: proton tracks from quasi-elastic events are typically short. Want sensitivity to $p_p$~ 300 - 500 MeV
- "Thickness" of track proportional to dE/dx in figure below
- proton and muon tracks are clearly resolved
- precise determination of vertex and measurement of $Q^2$ from tracking



# Illustration: $\nu_\mu p \rightarrow \nu_\mu \pi^0 p$

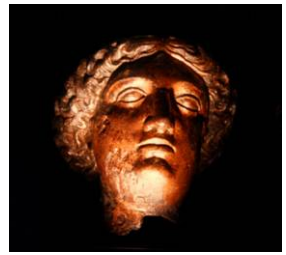





- two photons clearly resolved (tracked). can find vertex.
- some photons shower in ID, some in side ECAL (Pb absorber) region

# more on oscillations

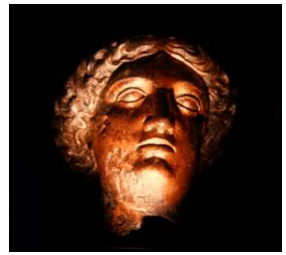
# What about Near Detectors?

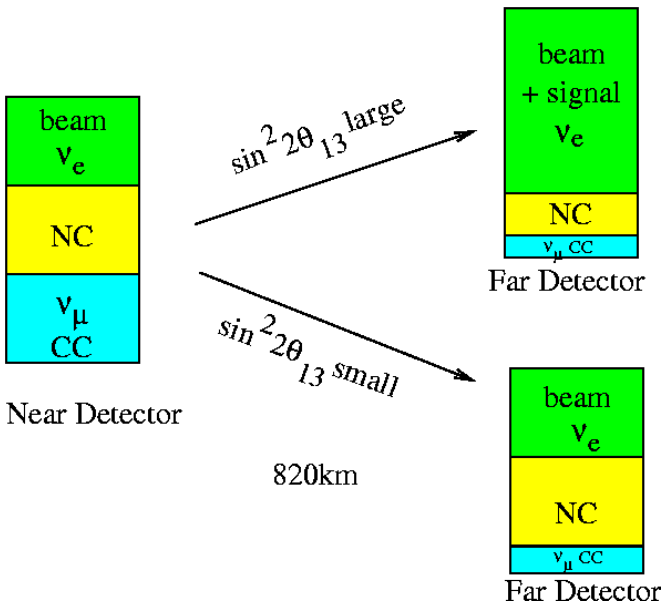


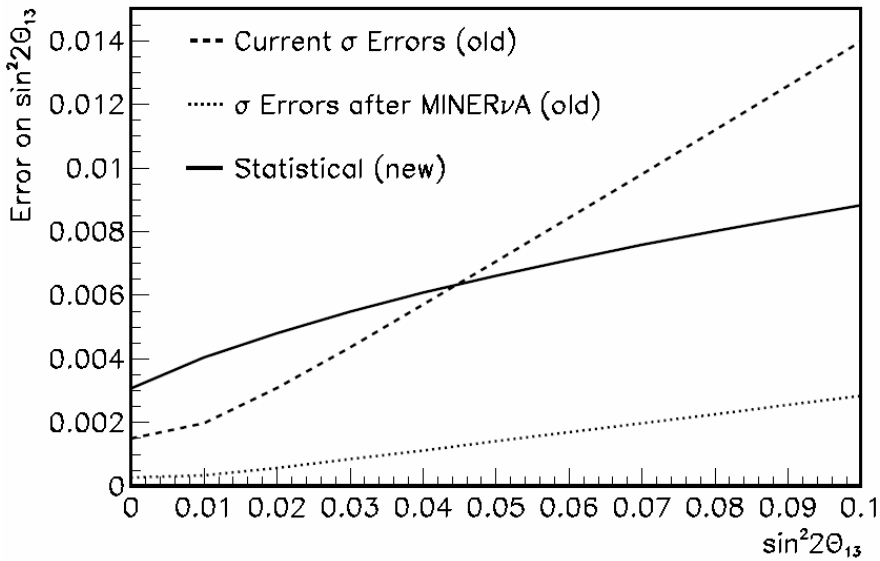
- MINOS Near Detector:
  - Can’t test nuclear effect models with only one nucleus!
- NOvA and T2K Near Detectors:
  - Can’t measure energy dependence with only one energy
  - If near design is same as far, can’t separate backgrounds any better near than far

*MINERvA design solves all three of these problems*

# Old NOvA vs New (TASD) NOvA






**What about the change from old NOvA design to new design?**

Old: FD background was ½ beam $\nu_e$, ½ other

New: FD background is 2/3 beam $\nu_e$, 1/3 other

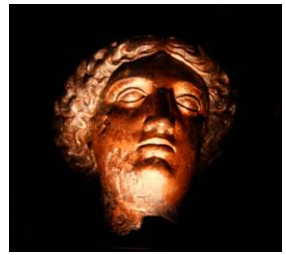
New: Signal has more resonance contributions, more poorly known process

Extrapolating near to far will be easier, but probably by ~30%...

Statistical error is about the same (same FOM)

# more on other physics

# Event Rates



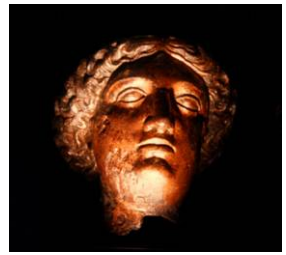
**Fiducial Volume:**
**3 tons CH, ≈ 0.6 t C, ≈ 1 t Fe and ≈ 1 t Pb**
**Expected CC event samples:**
**8.6 M $\nu$ events in CH**
**1.4 M $\nu$ events in C**
**2.9 M $\nu$ events in Fe**
**2.9 M $\nu$ events in Pb**

**Assumes $16.0 \times 10^{20}$ in LE, ME, and sHE NuMI beam configurations over 4 years**

## Main CC Physics Topics (Statistics in CH)

| | |
|---|---|
| • Quasi-elastic | 0.8 M events |
| • Resonance Production | 1.6 M total |
| • Transition: Resonance to DIS | 2 M events |
| • DIS, Structure Funcs. and high-x PDFs | 4.1 M DIS events |
| • Coherent Pion Production | 85 K CC / 37 K NC |
| • Strange and Charm Particle Production | > 230 K fully reconstructed |

# Strange and Charm Production



- MINERvA will focus on exclusive channel strange particle production
  - small sub-sample of fully reconstructed events .
- **Important for background calculations of nucleon decay experiments**
- Measurements of inclusive charm production near threshold to probe charm-quark effective mass
  - siimilar to NOMAD

**Existing Strange Particle Production**

Gargamelle-PS - **15** $\Lambda$ events. FNAL - ≈ 100 events
ZGS -30 events BNL - 8 events
Larger NOMAD **inclusive** sample expected

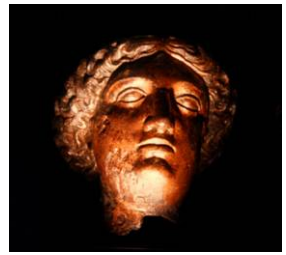
**MINERνA Exclusive States**

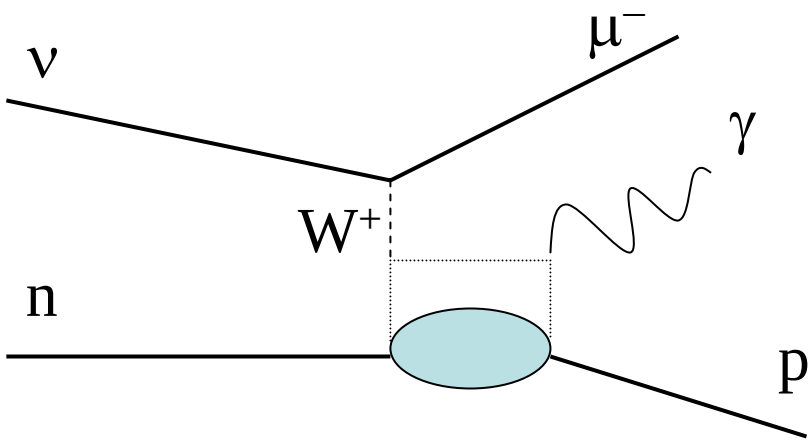
**100x earlier samples**

**3 tons and 4 years**

| | |
|---|---|
| $\Delta S = 0$ | |
| $\mu^- K^+ \Lambda^0$ | 10.5 K |
| $\mu^- \pi^0 K^+ \Lambda^0$ | 9.5 K |
| $\mu^- \pi^+ K^0 \Lambda^0$ | 6.5 K |
| $\mu^- K^- K^+ p$ | 5.0 K |
| $\mu^- K^0 K^+ \pi^0 p$ | 1.5 K |
| $\Delta S = 1$ | |
| $\mu^- K^+ p$ | 16.0 K |
| $\mu^- K^0 p$ | 2.5 K |
| $\mu^- \pi^+ K^{0n}$ | 2.0 K |
| $\Delta S = 0$ - Neutral Current | |
| $\nu K^+ \Lambda^0$ | 3.5 K |
| $\nu K^0 \Lambda^0$ | 1.0 K |
| $\nu K^0 \Lambda^0$ | 3.0 K |

# GPDFs: Weak Deeply Virtual Compton Scattering

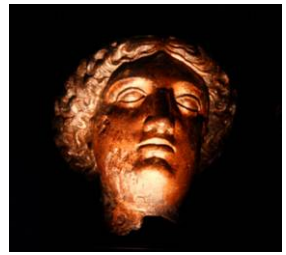





W> 2 GeV, t small, $E_\gamma$ large - Exclusive reaction

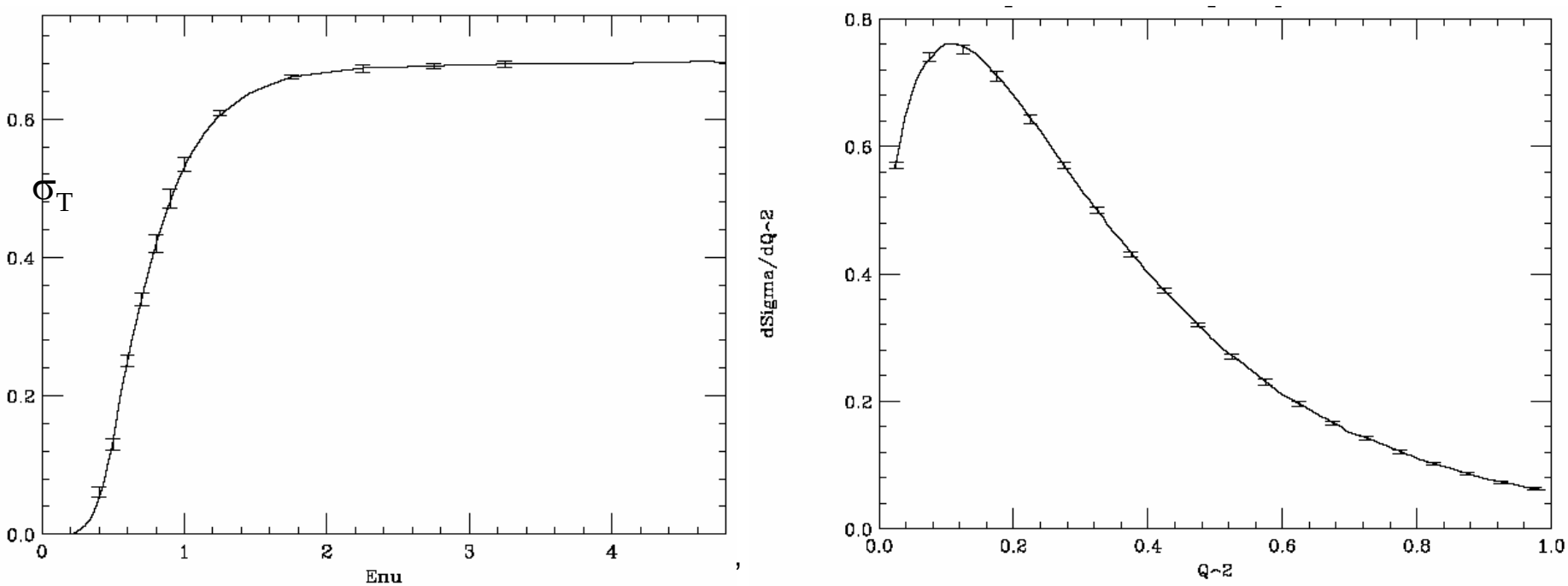
- First measurement of GPDs with neutrinos
- Weak DVCS would allow flavor separation of GPDs
- According to calculation by A. Psaker (ODU), MINERνA would accumulate 10,000 weak DVCS events in a 4-year run

# Resonance Production - Δ

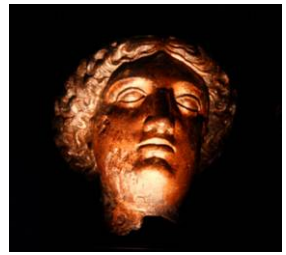


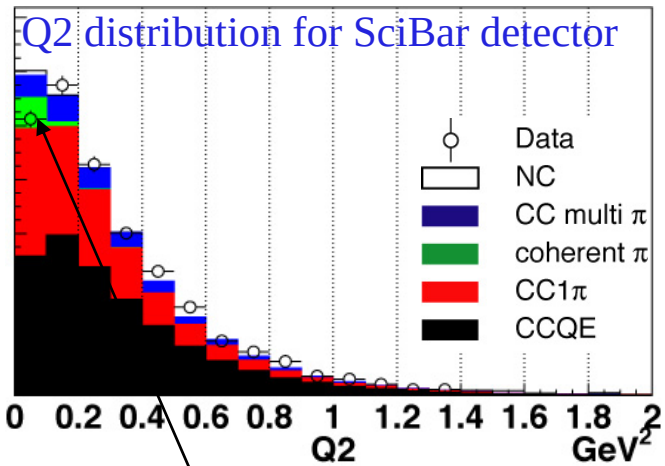
- Resonance Production (e.g. $\nu + N \rightarrow \nu / \mu^- + \Delta$, **1600 K total, 1200K 1π)**
  - Precision measurement of σ and dσ/dQ for individual channels
  - Detailed comparison with dynamic models, comparison of electro- & photo production, the resonance-DIS transition region -- duality
  - Study of nuclear effects and their A-dependence e.g. 1 π <–– > 2 π <––> 3 π final states

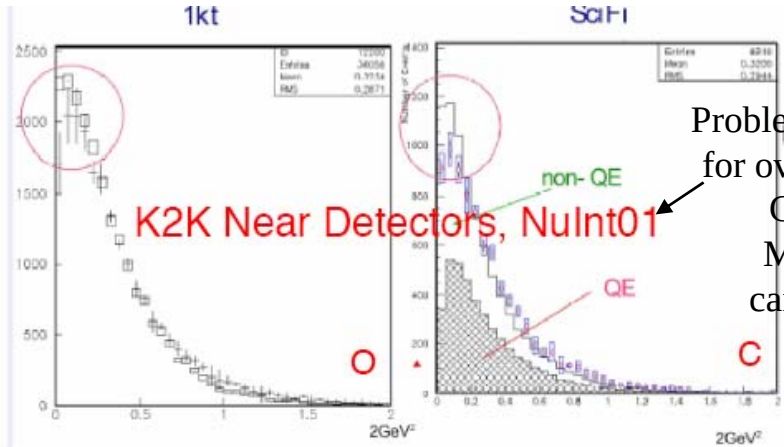
Total Cross-section and $d\sigma/dQ^2$ for the $\Delta^{++}$ **- Errors are statistical only**



# Nuclear Effects

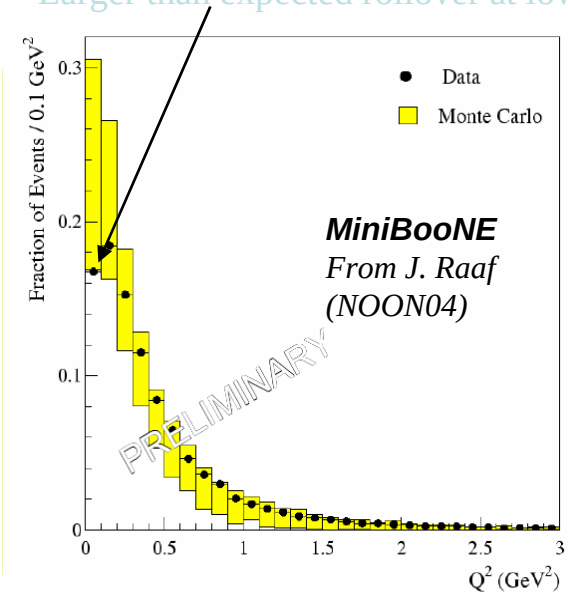





Problem has existed for over four years. Coherent? MINERvA can separate.

Larger than expected rollover at low $Q^2$




All "known" nuclear effects taken into account:
Pauli suppression, Fermi Motion, Final State Interactions

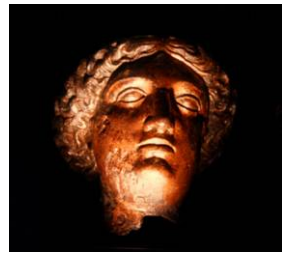
They have **not included** low-ν shadowing that is only allowed with axial-vector (Boris Kopeliovich at NuInt04)

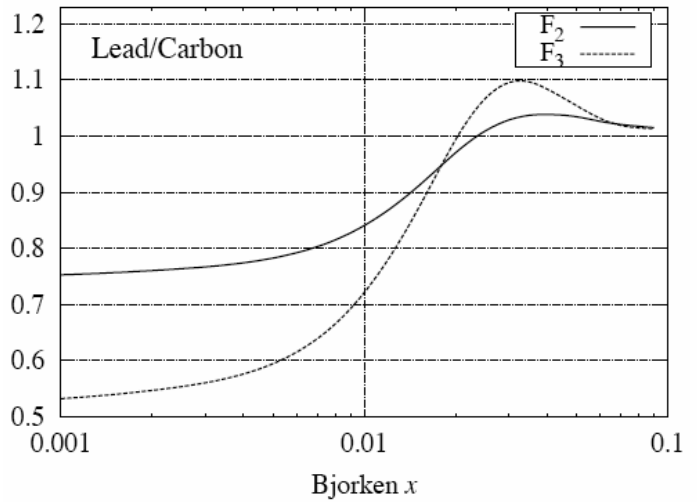
$L_c = 2\nu / (m_\pi^2 + Q^2) \geq R_A$ **(not $m_A^2$)**

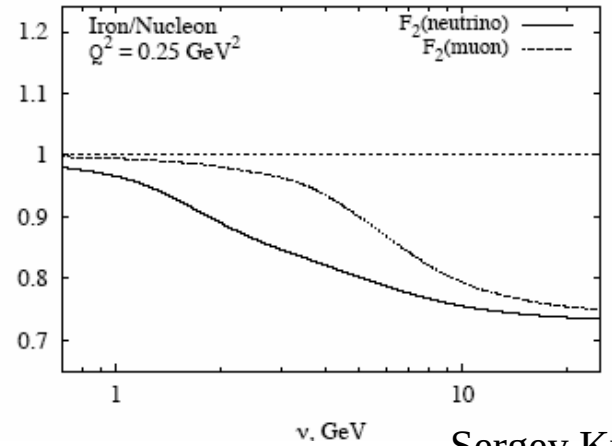
**$L_c$ 100 times shorter with $m_\pi$ allowing low ν-low $Q^2$ shadowing**

ONLY MEASURABLE VIA NEUTRINO - NUCLEUS INTERACTIONS! **MINERνA WILL MEASURE THIS ACROSS A WIDE ν AND $Q^2$ RANGE WITH C : Fe : Pb**

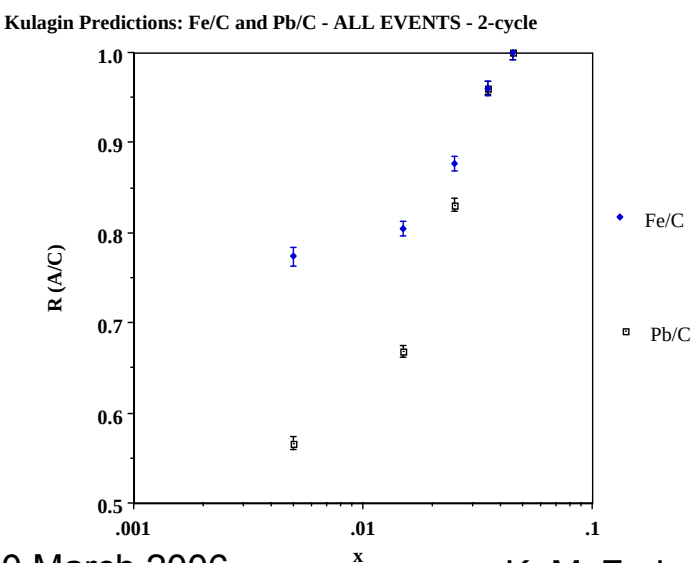
# Difference between $\nu$–A and $\mu$–A nuclear effects in DIS

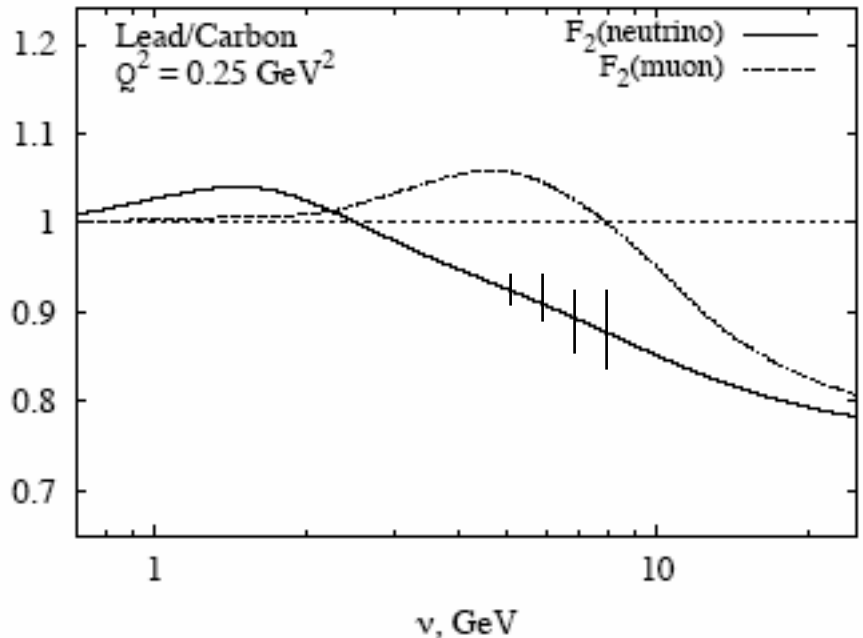





Sergey Kulagin

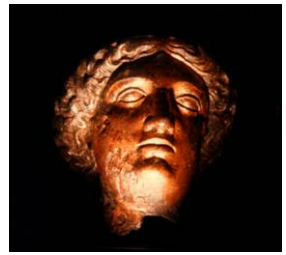


# more on prototyping

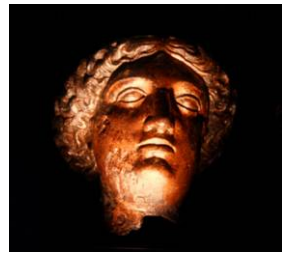
# NuMI beam

# NuMI Beamline

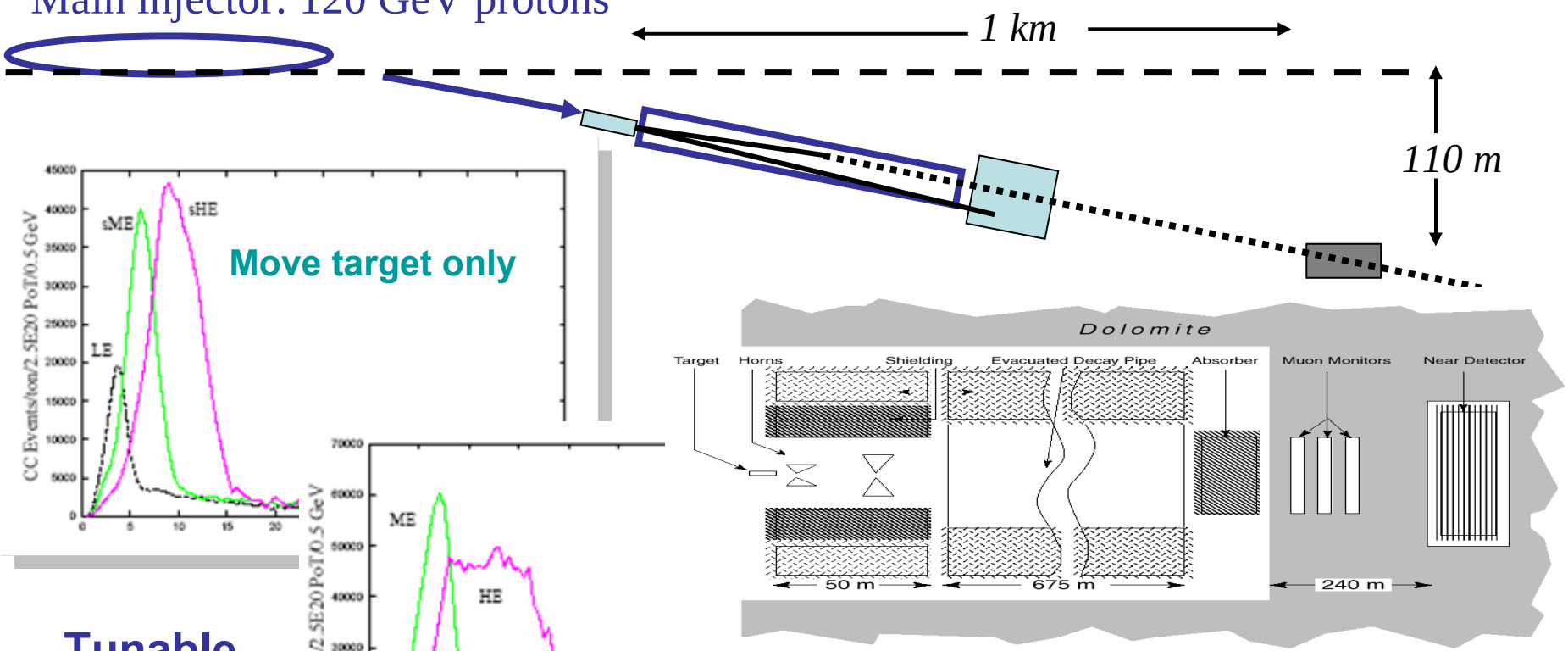


- FNAL has recently commissioned NuMI beamline for MINOS long-baseline experiment
- Why is NuMI an ideal home for a neutrino cross-section experiment?
  - Variable energy, well-understood neutrino flux

# The NuMI Neutrino Beam

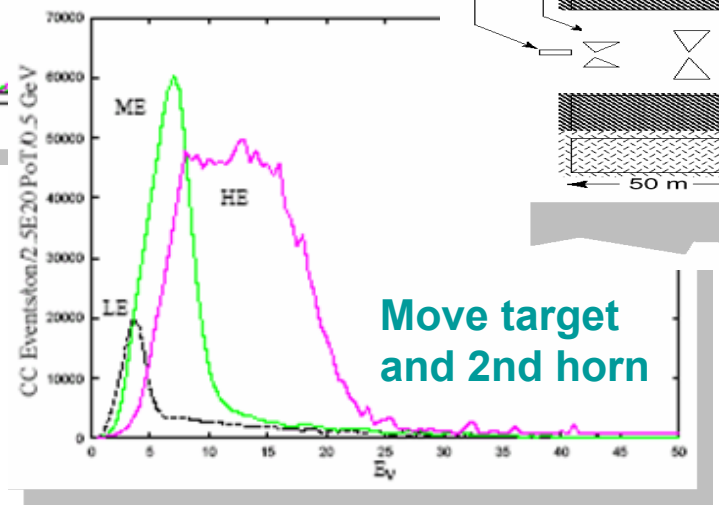


Main injector: 120 GeV protons





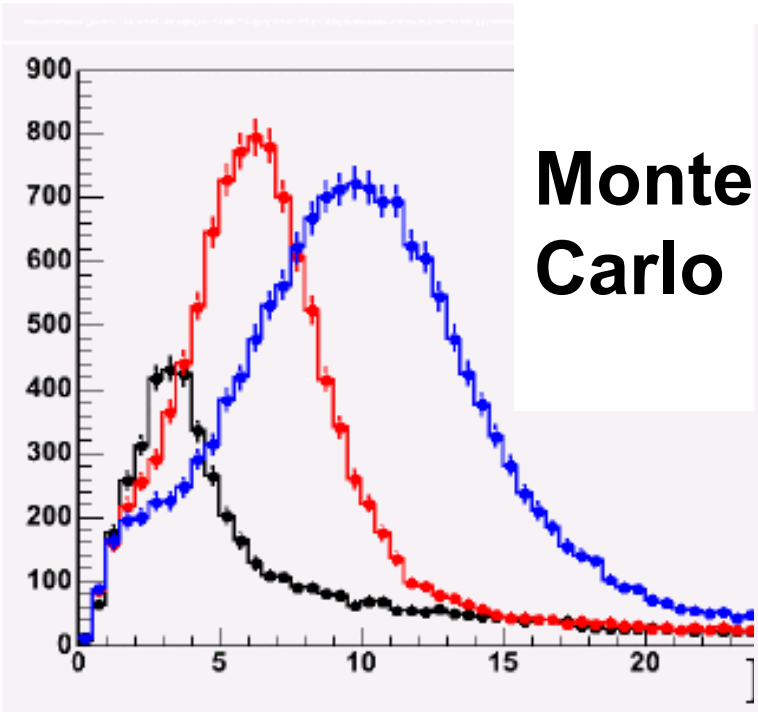




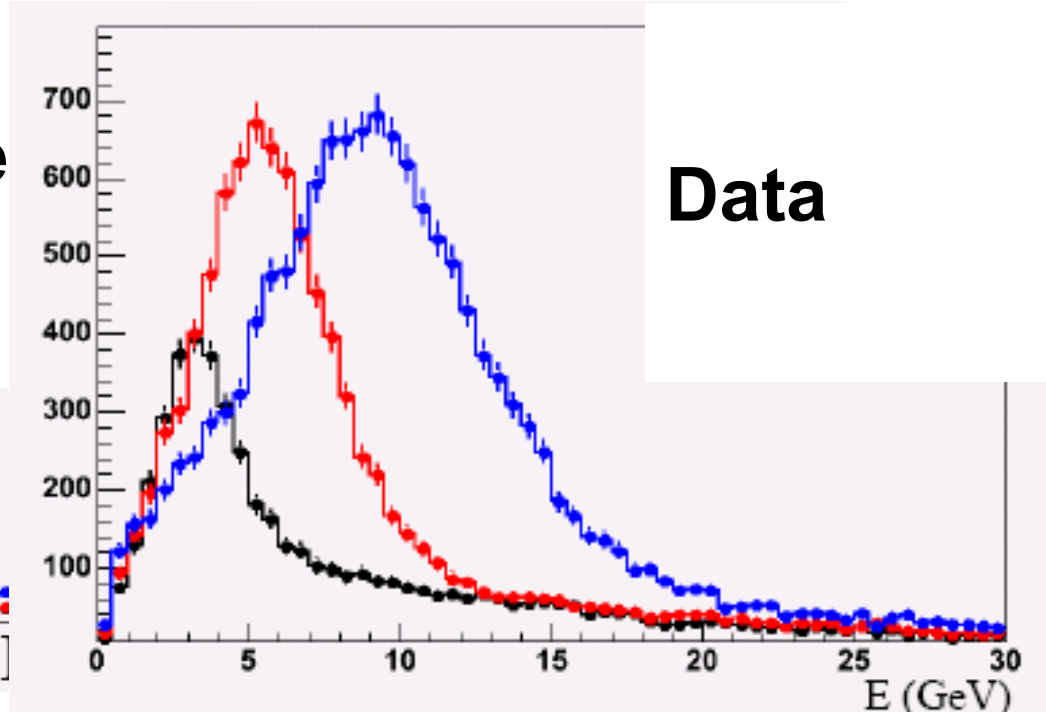

**Tunable beam energy**

**With E-907(MIPP) at Fermilab (measure production from NuMI target) expect to know neutrino flux to ± 4%.**

# NuMI: MINOS ND Events




**Monte Carlo**

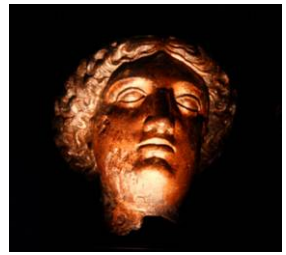



**Data**

**Low Energy**
**Target back 1m**
**Target back 2.5m**

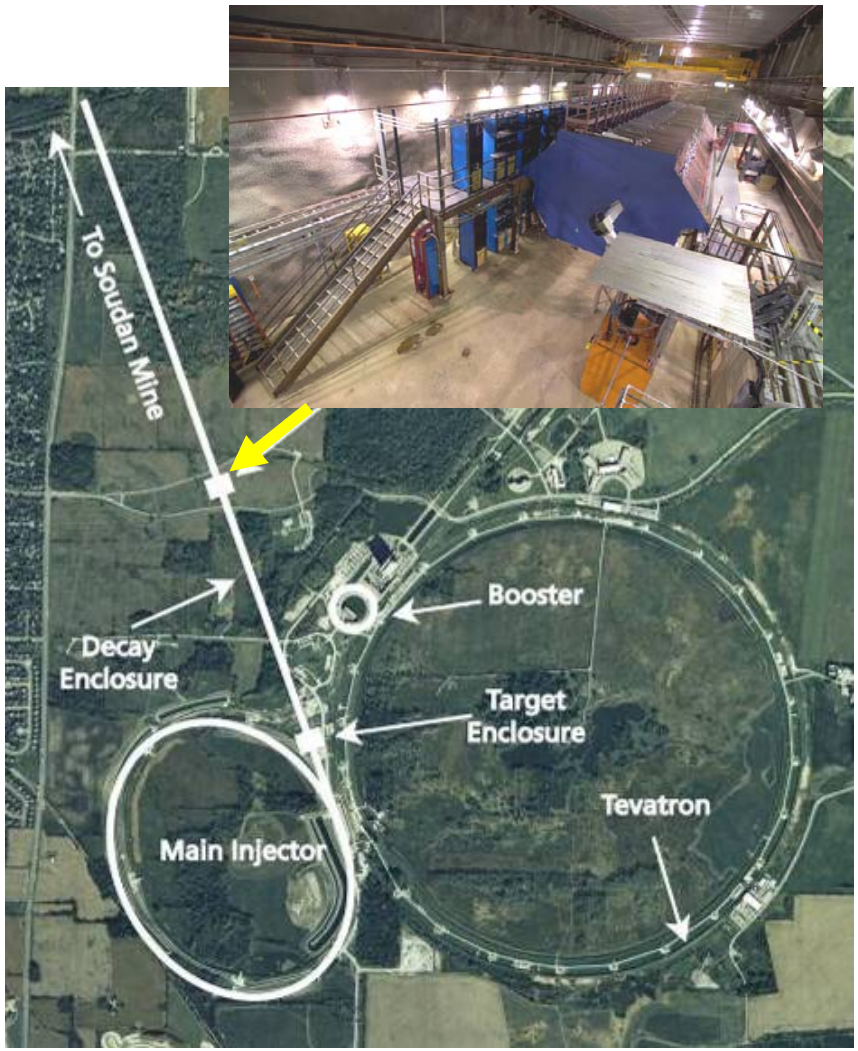
Plots from N.Saoulidou, Fermilab Users Meeting

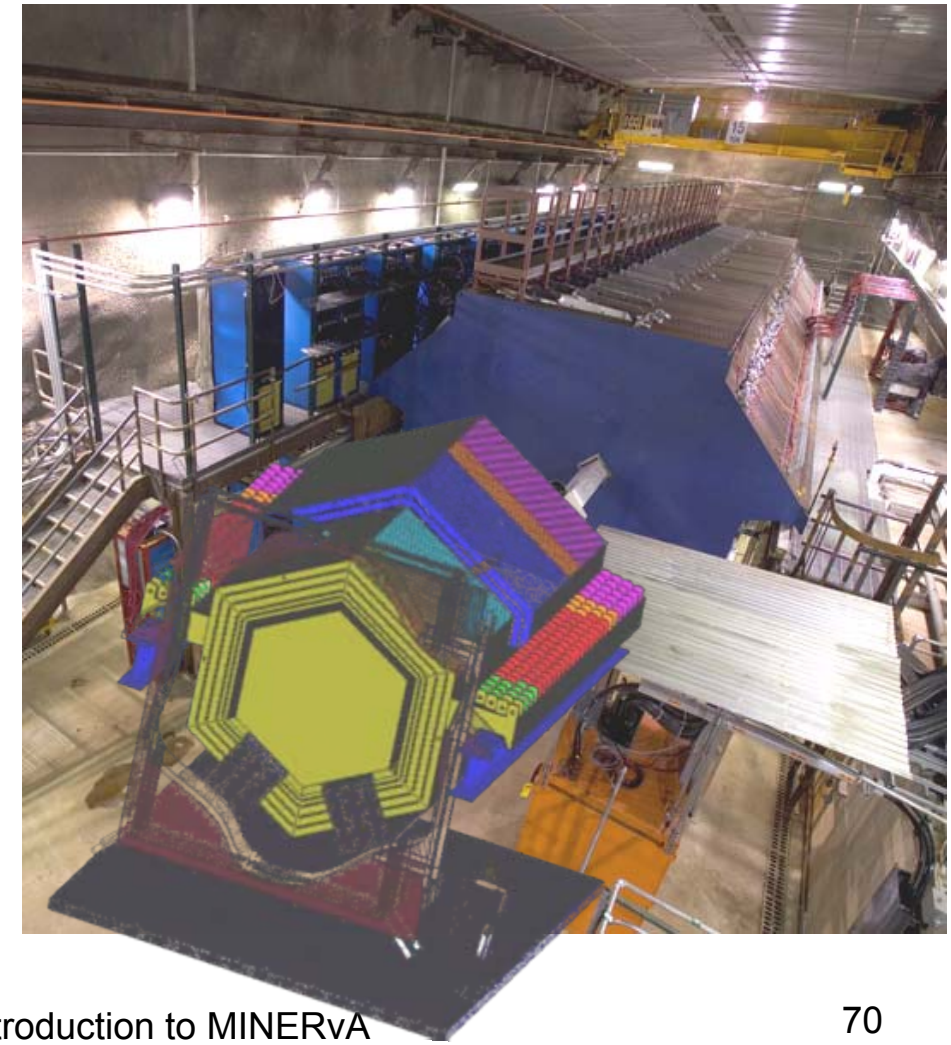
# NuMI Beamline



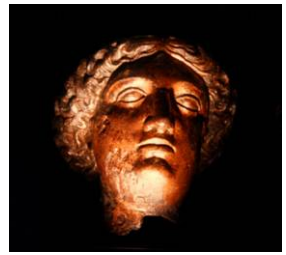
- FNAL has recently commissioned NuMI beamline for MINOS long-baseline experiment
- Why is NuMI an ideal home for a neutrino cross-section experiment?
  - Variable energy, well-understood neutrino flux
  - Spacious on-axis near hall
    - also possible off-axis sites

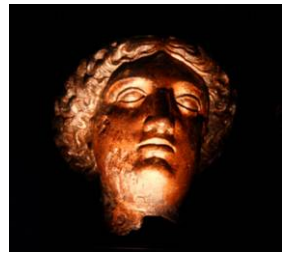
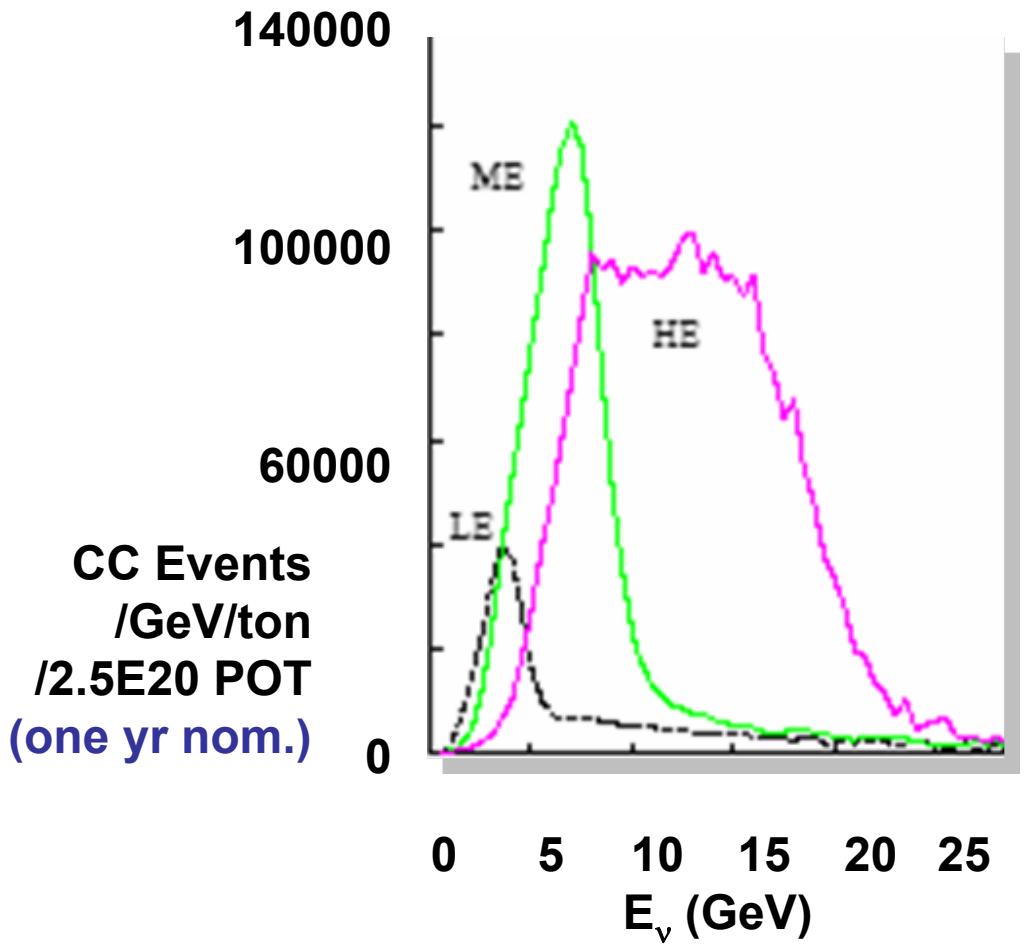
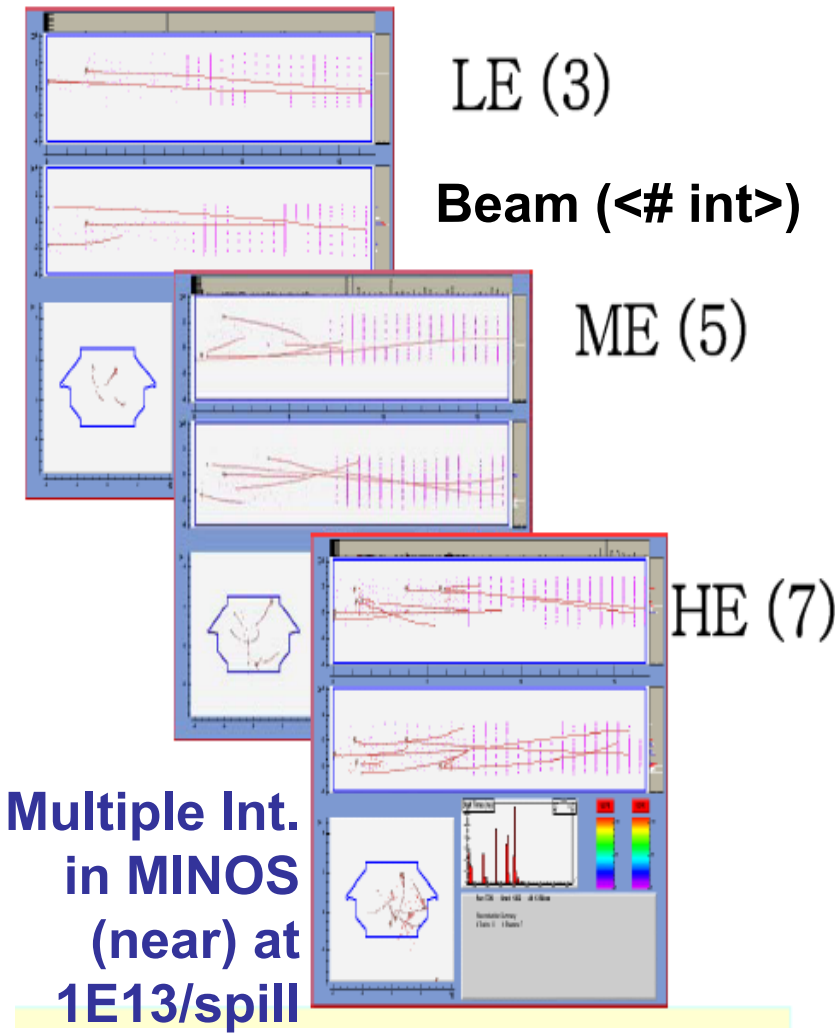
# NuMI Near Hall



# NuMI Beamline



- FNAL has recently commissioned NuMI beamline for MINOS long-baseline experiment
- Why is NuMI an ideal home for a neutrino cross-section experiment?
  - Variable energy, well-understood neutrino flux
  - Spacious on-axis near hall
    - also possible off-axis sites
  - High intensity
    - statistics for low mass detector, capable of reconstructing exclusive final states

# NuMI Beam Intensity (Near)