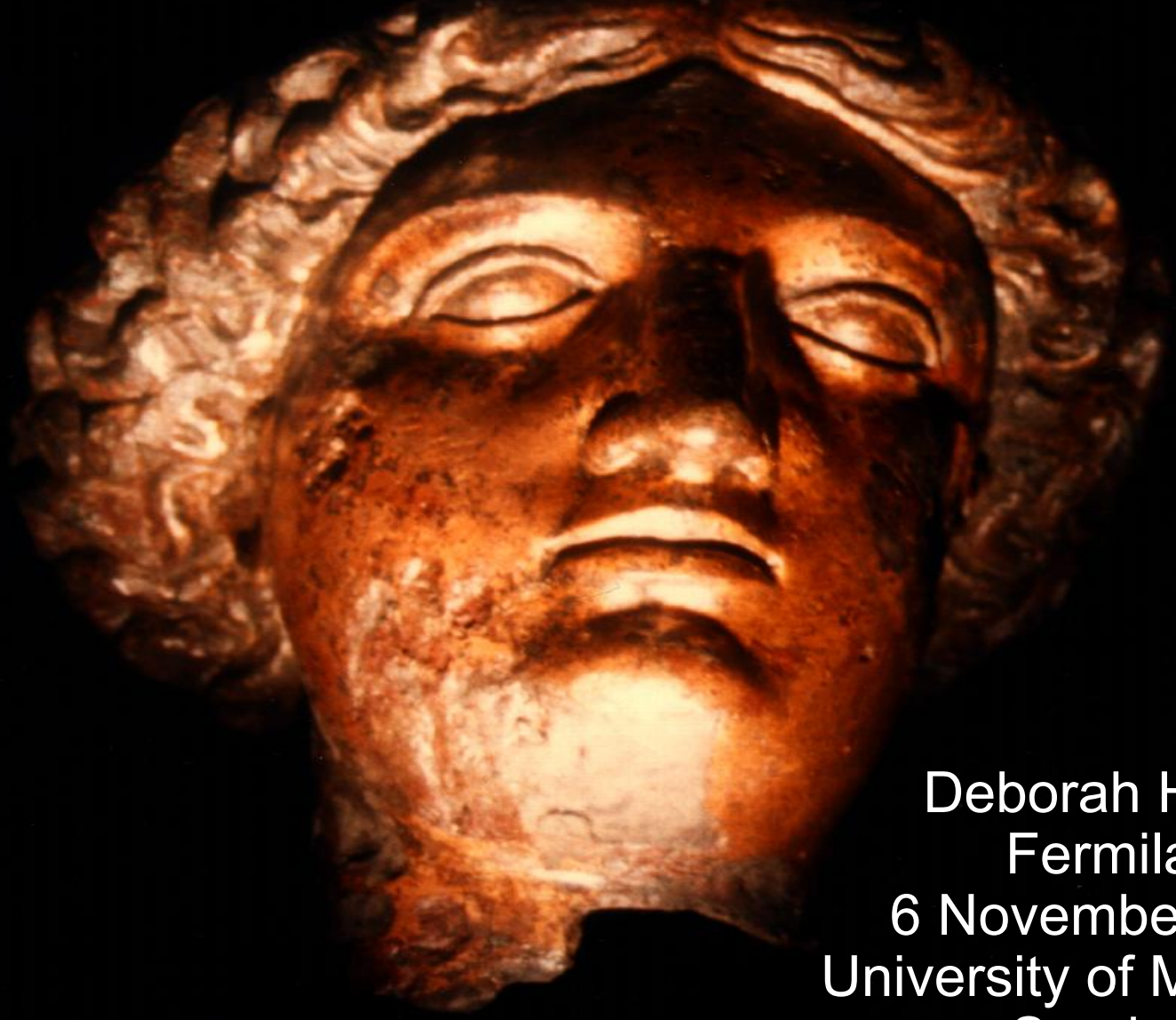
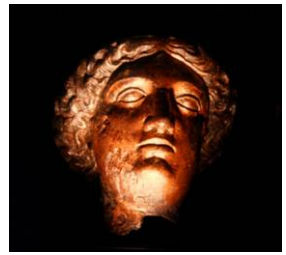
MINERνA



Deborah Harris
Fermilab
6 November 2007
University of Minnesota
Seminar

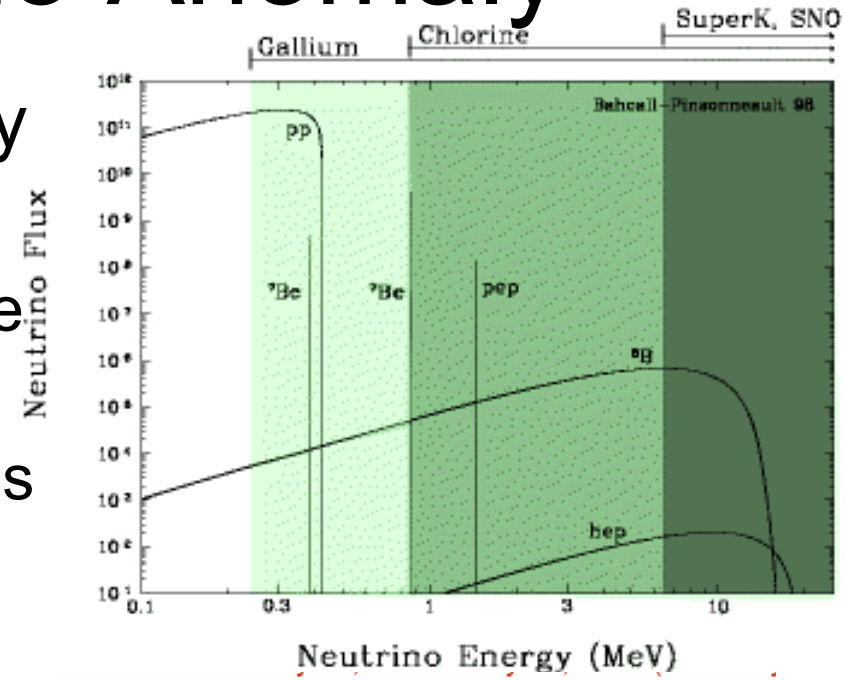
History Repeats itself…

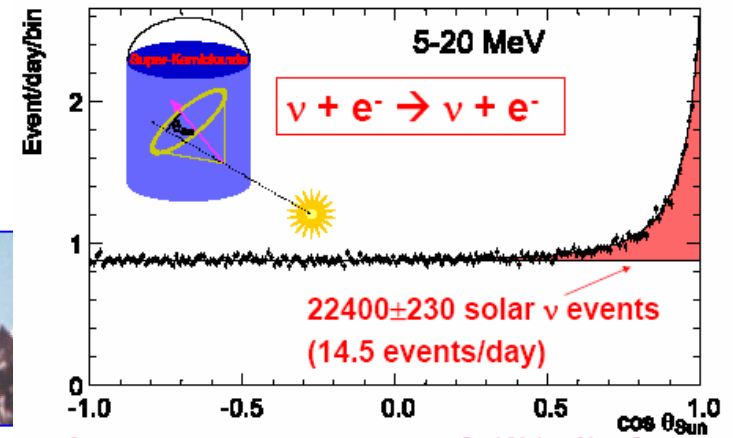


I. From anomaly to “smoking gun” to precision
   I. Solar Neutrinos
   II. Atmospheric Neutrinos
   III. Next steps to understanding neutrino oscillations
II. Current state of knowledge of ν interactions
III. MINERvA
   I. Design
   II. Performance
   III. Status of current Prototyping
   IV. Schedule

Solar Neutrino Anomaly

- There is a glorious history of solar neutrino physics
  - original goals: demonstrate fusion in the sun
  - first evidence of oscillations

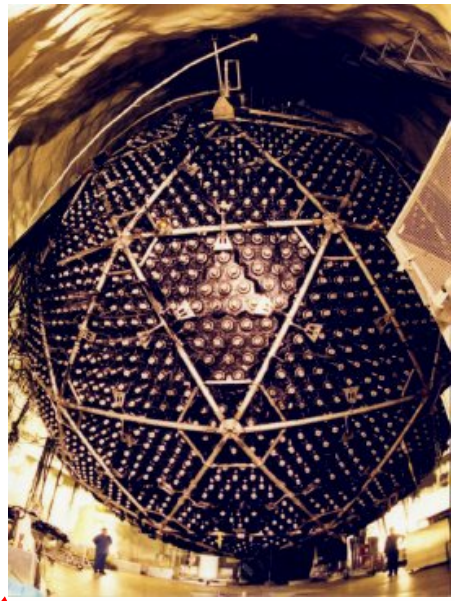


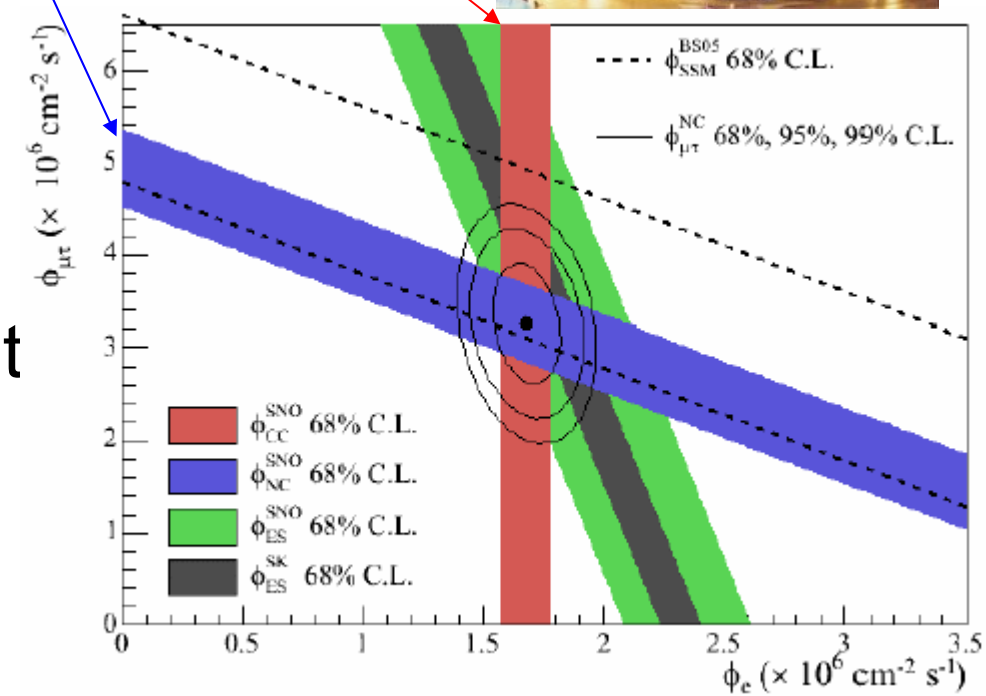


Slide courtesy K.McFarland

Solar Neutrino "Smoking Gun"

- D_2O target uniquely observes:
  - charged-current $\nu_e d \rightarrow ppe^-$
  - neutral-current $\nu_X d \rightarrow \nu_X pn$
- The former is only observed for ν_e (lepton mass)
- The latter for all types
- Solar flux is consistent with models
  - but not all ν_e at earth

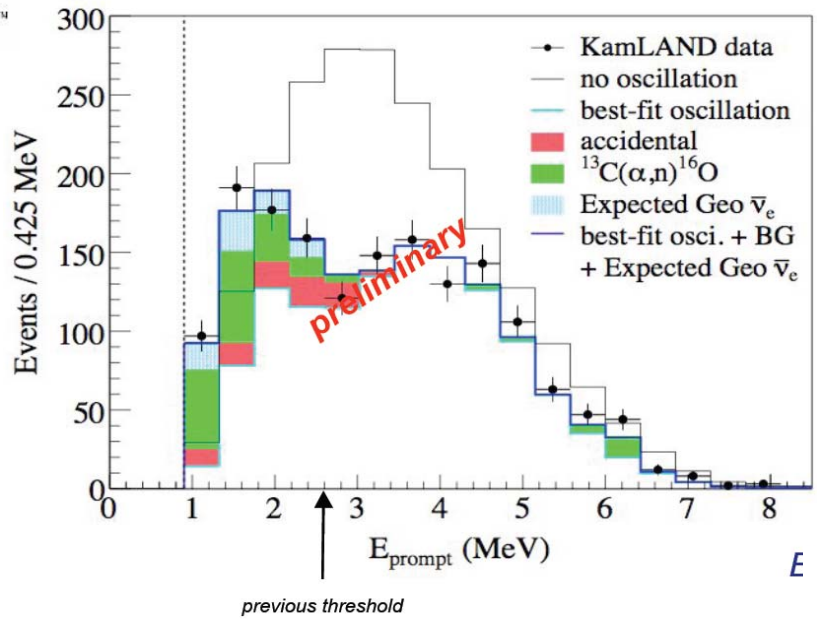




Slide courtesy K.McFarland

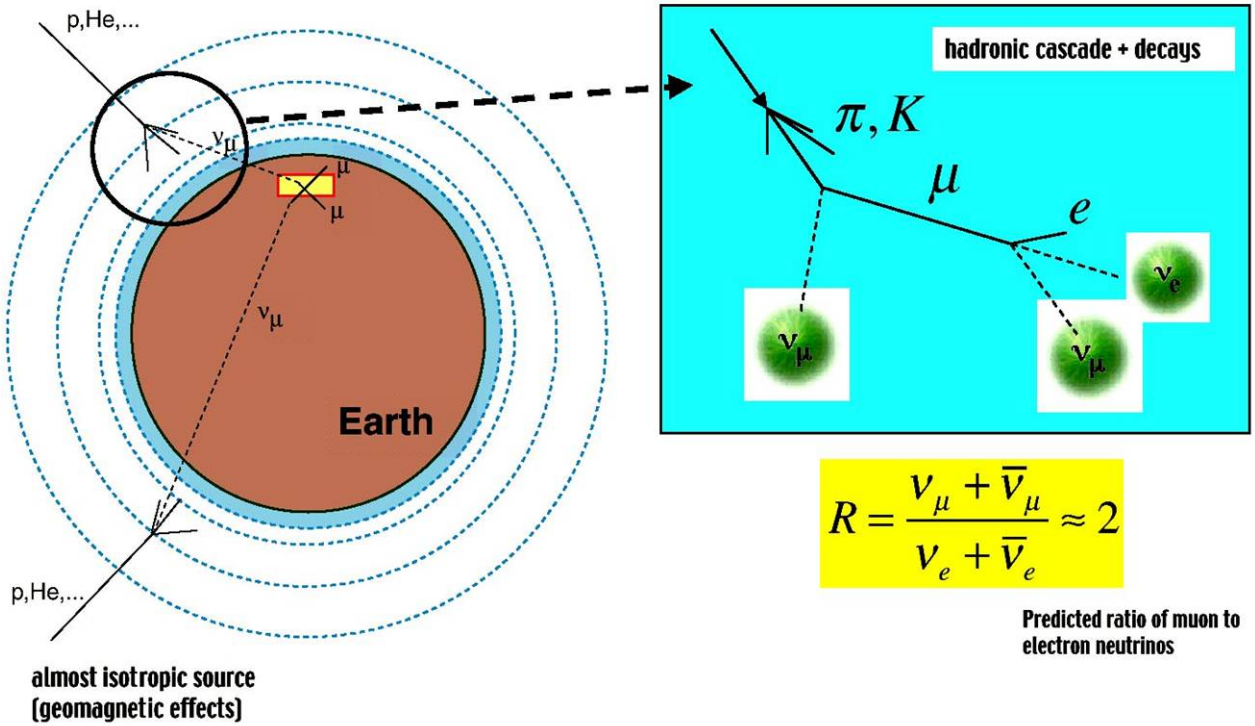
Precision Measurements of solar Neutrino Sector: KAMLAND

- Sources are Japanese reactors
  - *150-200 km* for most of flux.
  - *Rate uncertainty ~4%*
  - *Total uncertainty ~6%*
- 1 kTon scint. detector in old Kamiokande cavern
  - Confirmation of oscillatory nature of disappearance



L. Hsu, FNAL W&C, 10/5/07

Atmospheric Neutrinos



$$R = \frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \approx 2$$

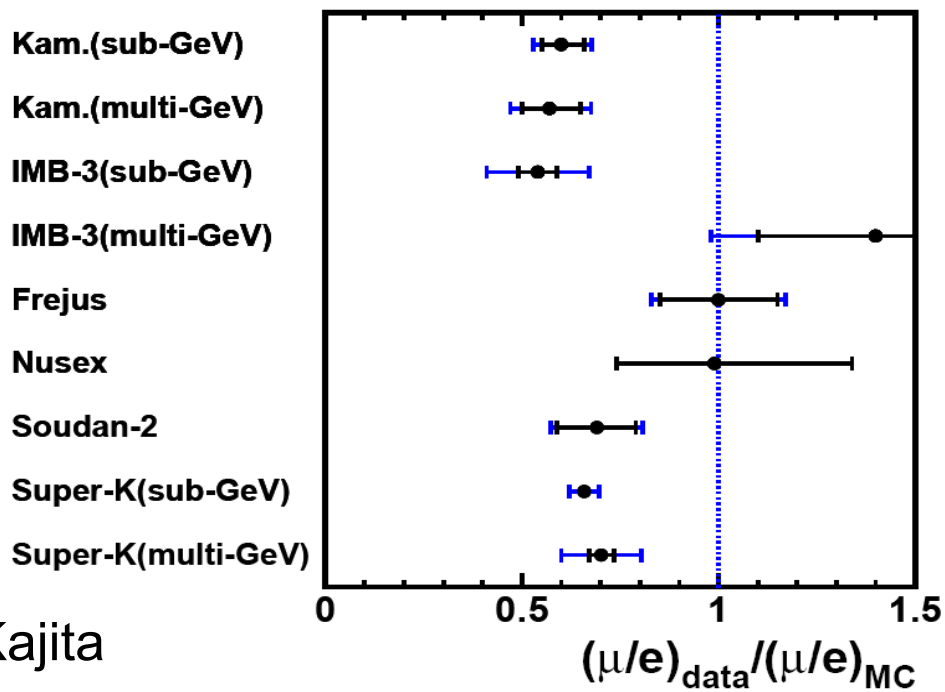
Predicted ratio of muon to electron neutrinos

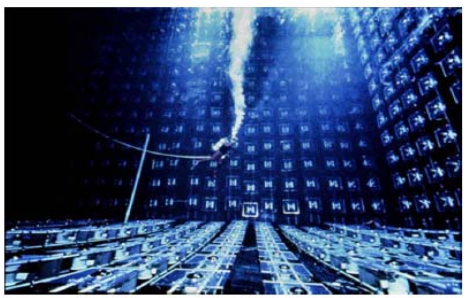
- Neutrino energy: few 100 MeV – few GeV
- Flavor ratio robustly predicted
- Distance in flight: ~20km (down) to 12700 km (up)

Slide courtesy K.McFarland

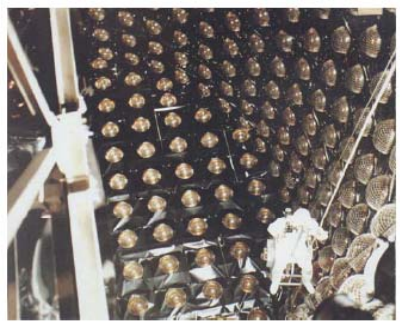
History of Anomalies

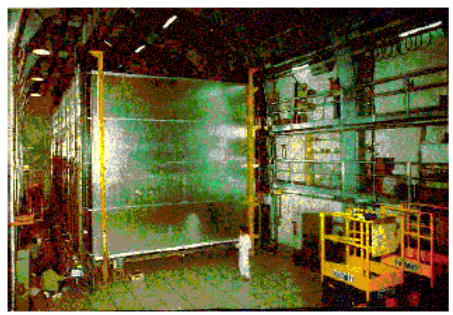
- Atmospheric neutrinos have been seen since 1978
- Deficit of muon-like events compared to electron-like events seen across many decades, many experiments

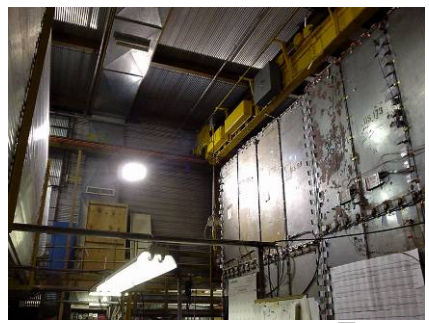




From T.Kajita

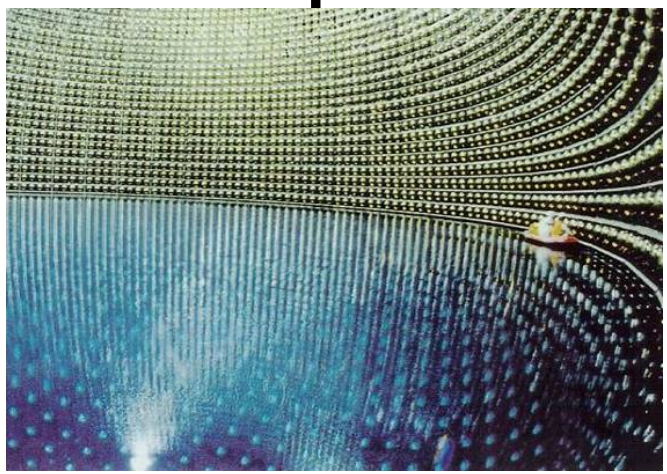


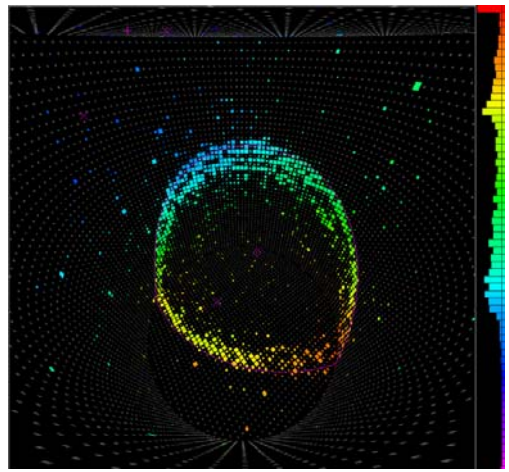


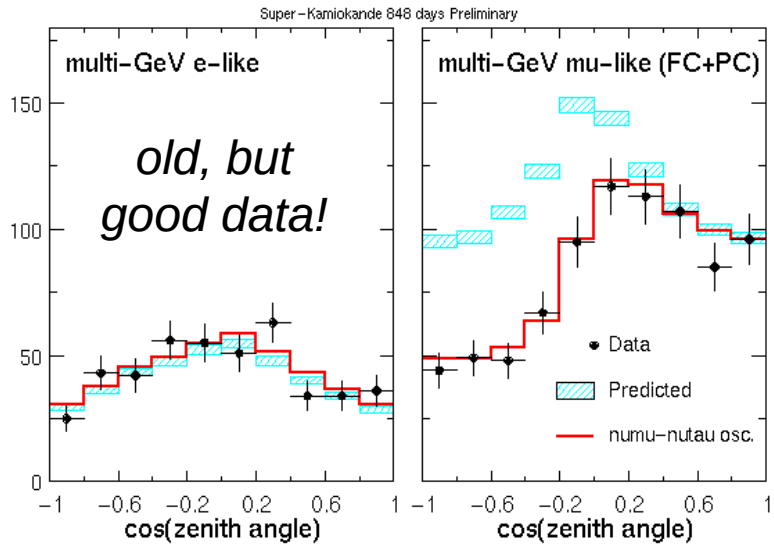


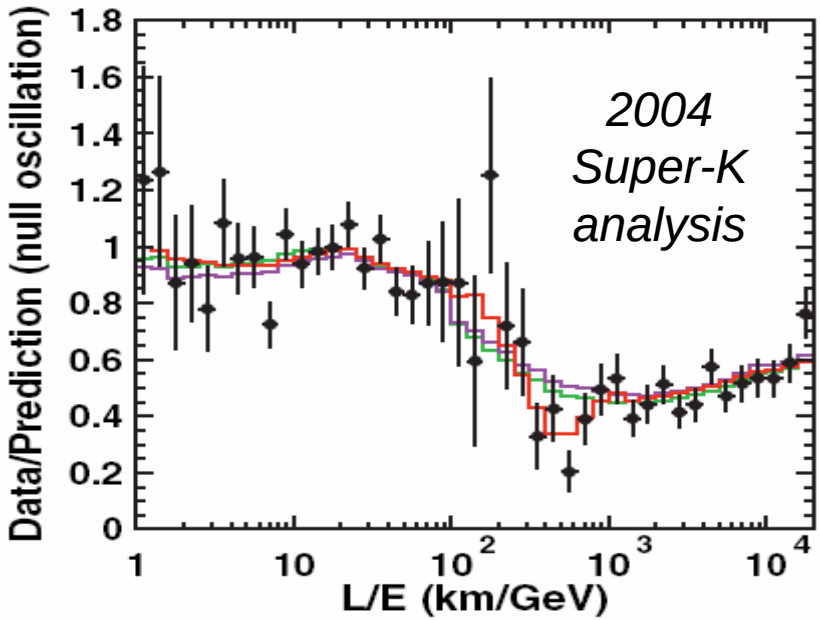
Smoking Gun: Super-Kamiokande

- Super-K detector has excellent e/μ separation



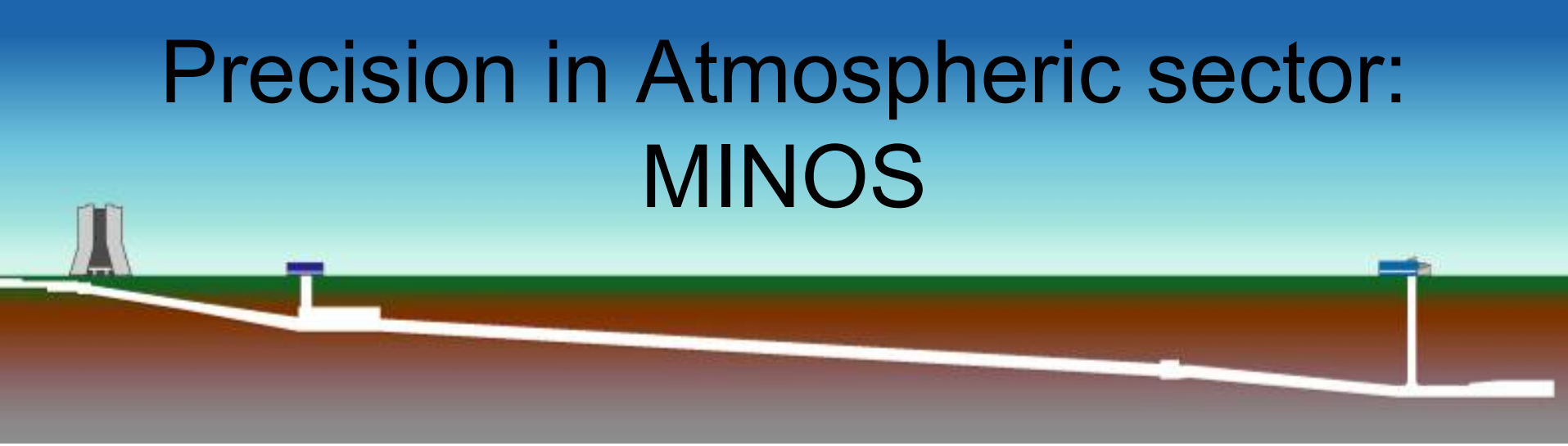




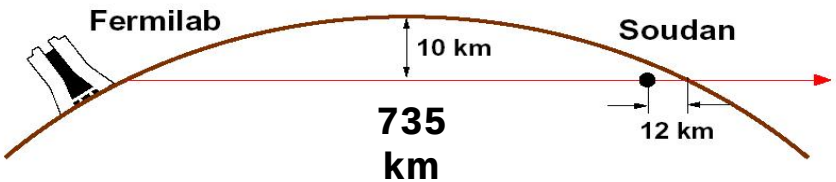


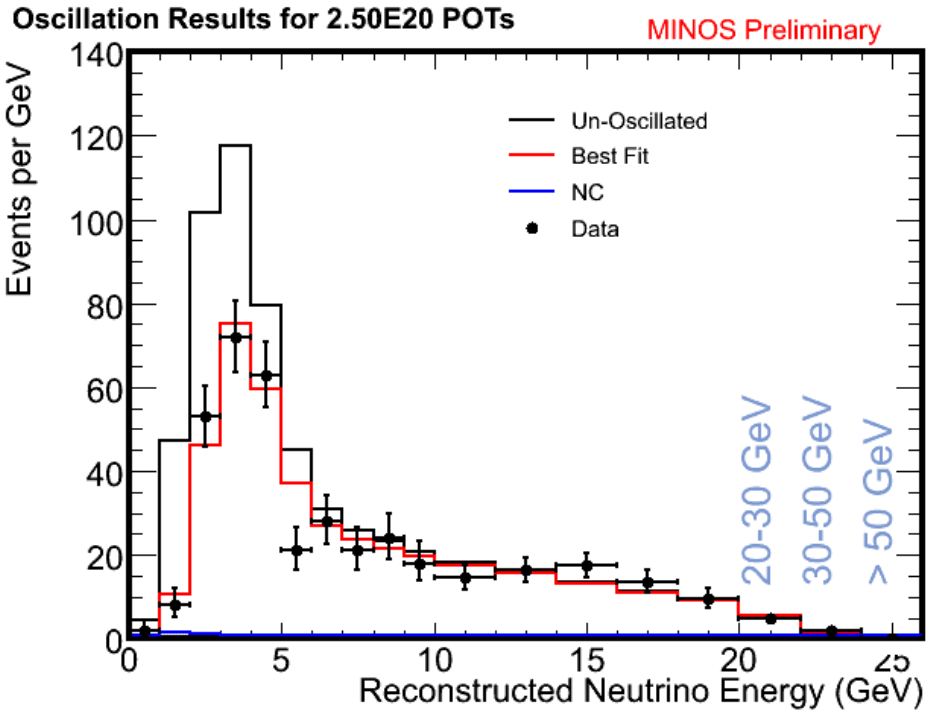
- Up / down difference for μ-like events, not e-like events!

Precision in Atmospheric sector: MINOS



- MINOS Oscillation Experiment: NuMI Beamline at Fermilab produces ν_μ at 100× the intensity ever produced before
- Aims that beam of neutrinos towards Soudan Minnesota
- MINOS results now from from 3 years of running, hopes to triple its statistics in the next 3 years
- Precision on probability measurement: ~5% at peak energy





N.Saoulidou, FNAL W&C

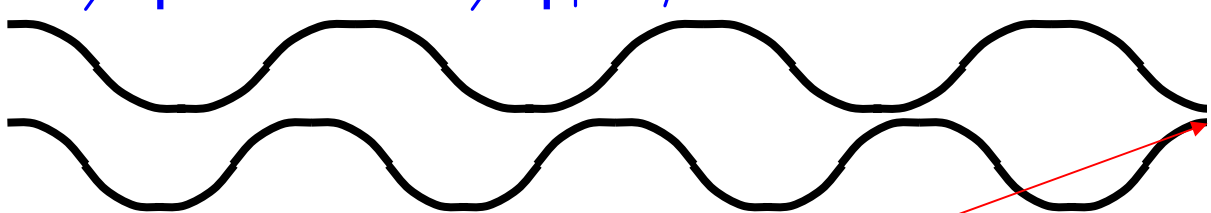
Minimal Oscillation Formalism

- If neutrino mass eigenstates: ν_1, ν_2, ν_3, etc.
- … are not flavor eigenstates: ν_e, ν_μ, ν_τ
- … then one has, e.g.,

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_i \\ \nu_j \end{pmatrix}$$

take only two generations for now!

$$|\nu_\alpha\rangle = \cos \pi/4 \, |\nu_i\rangle + \sin \pi/4 \, |\nu_j\rangle$$



different masses alter time evolution

time →

$$|\nu_\beta\rangle = -\sin \pi/4 \, |\nu_i\rangle + \cos \pi/4 \, |\nu_j\rangle$$

Slide courtesy K.McFarland

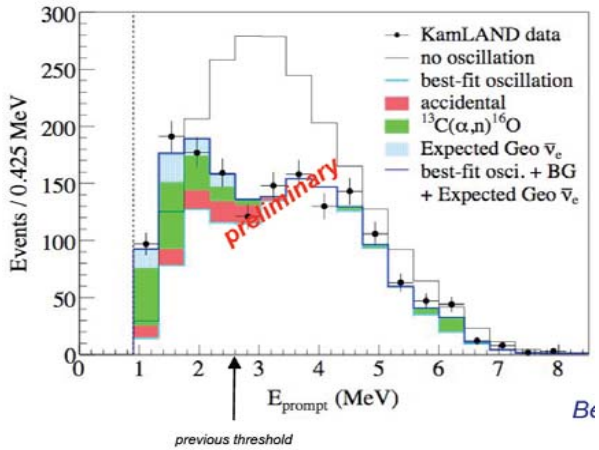
Oscillation Formalism (cont'd)

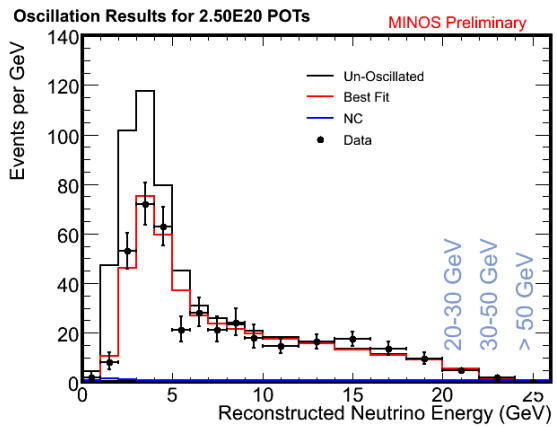
- So, still for two generations…

$$P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta \sin^2\left(\frac{(m_2^2 - m_1^2)L}{4E}\right)$$

appropriate units give the usual numerical factor **1.27 GeV/km-eV²**

- Oscillations require mass differences
- Oscillation parameters are mass-squared differences, Δm^2, and mixing angles, θ.
- But remember the signals:
  - Kamland: 3MeV neutrinos, 180km
  - MINOS: 3000MeV neutrinos, 735km
- There must be more than two mass differences



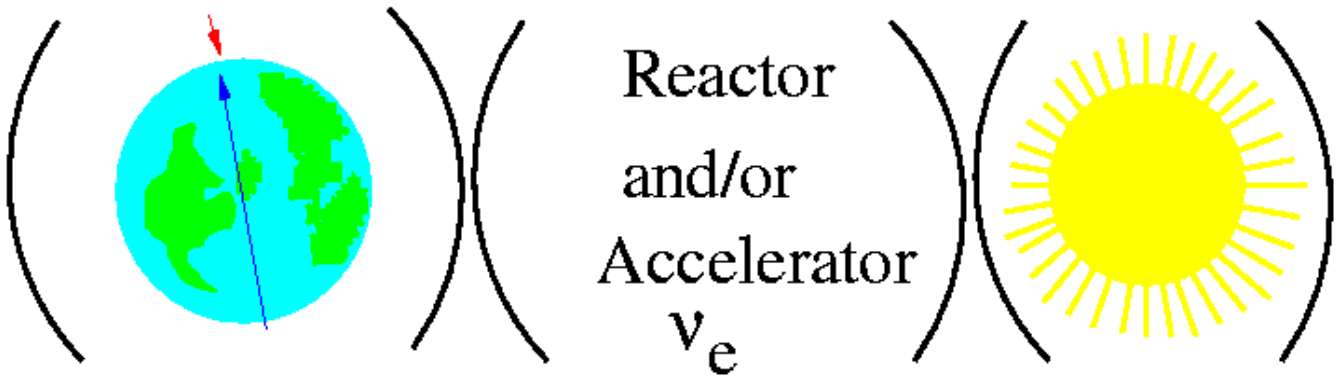


Three Generation Mixing

Lesson Learned from CKM: 3 mixing angles and a phase

Call them $\theta_{12}, \theta_{23}, \theta_{13}, \delta$ if $s_{ij} = \sin\theta_{ij}, c_{ij} = \cos\theta_{ij}$, then

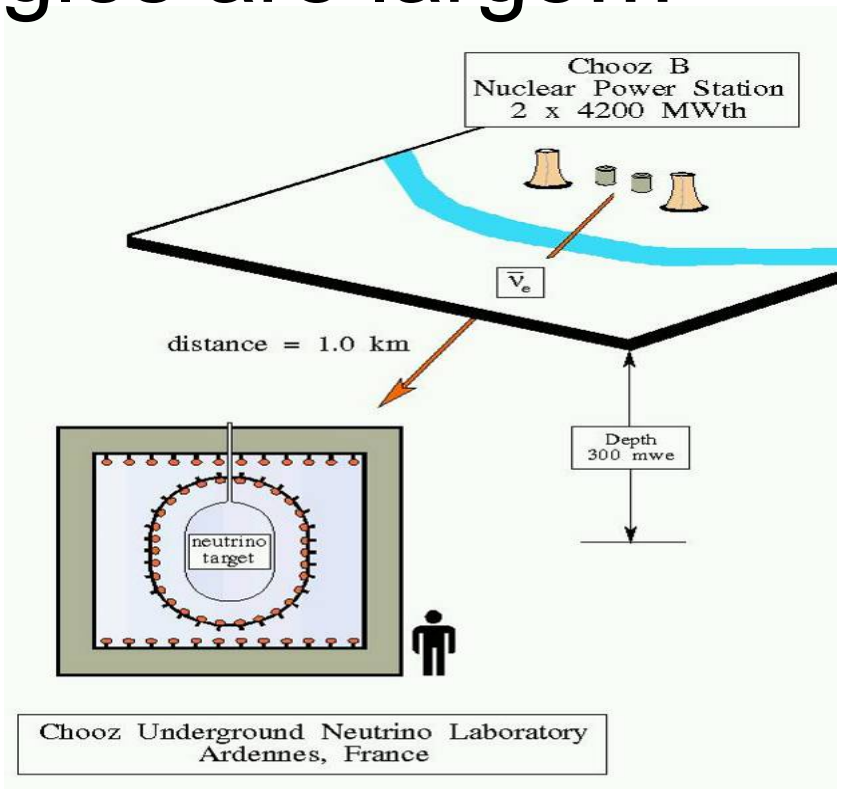
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

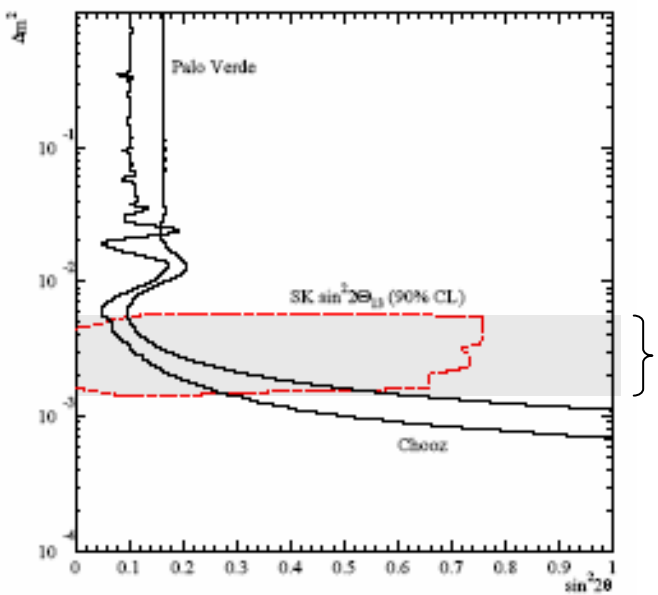
U= 

- Note the new mixing in middle, and the phase, δ

But not all mixing angles are large…

- CHOOZ and Palo Verde expt's looked at anti-ν_e from a reactor
  - compare expected to observed rate, σ~4%





δm^2_{23}

- If electron neutrinos don't disappear, they don't transform to muon neutrinos
  - limits ν_μ->ν_e flavor transitions at and therefore one mixing angle is "small"

Slide courtesy K.McFarland

So what do we know now?

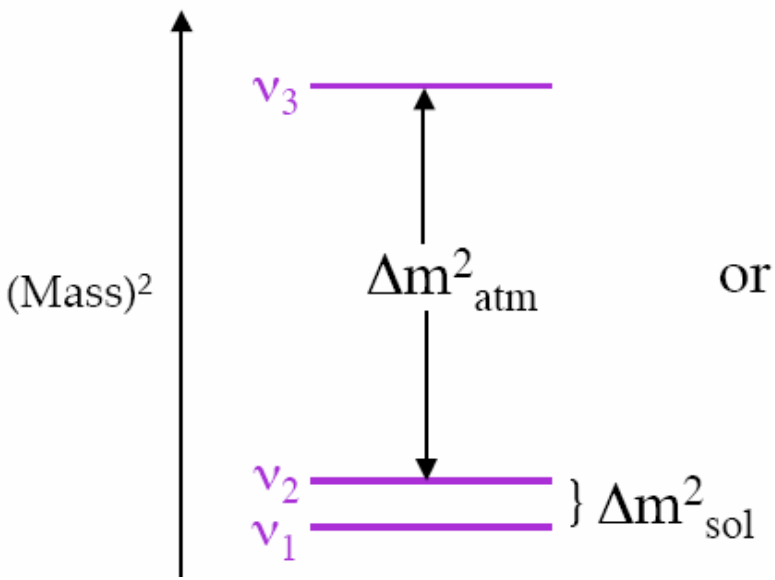
- Mass differences:
  - One is large $2.5\times10^{-3}\text{eV}^2$ (±8%)
  - One is small $8\times10^{-5}\text{eV}^2$ (±2.6%)
  - LSND signal 1-0.1eV^2 ,
    not consistent
    with oscillations
    (thanks to MiniBooNE results)

- Mixing angles:
  - one is around ~45°
  - one is ~35°
  - one is smaller than 9°

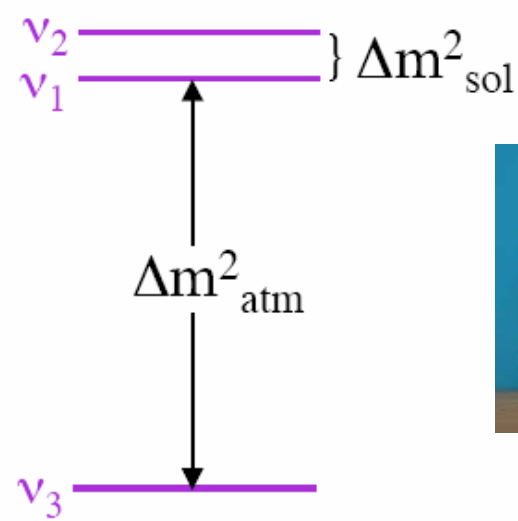
What don't we know yet?

- Do Neutrinos violate CP conservation?
  - We know there's lots of matter in the universe, no antimatter
  - We know quark sector CP violation is very small
- Do neutrino mass states have the same hierarchy as the quark mass states?

figures courtesy B. Kayser



or



$\Delta m_{sol}^2 \rightarrow \delta m_{12}^2 \approx 8\times10^{-5} eV^2$

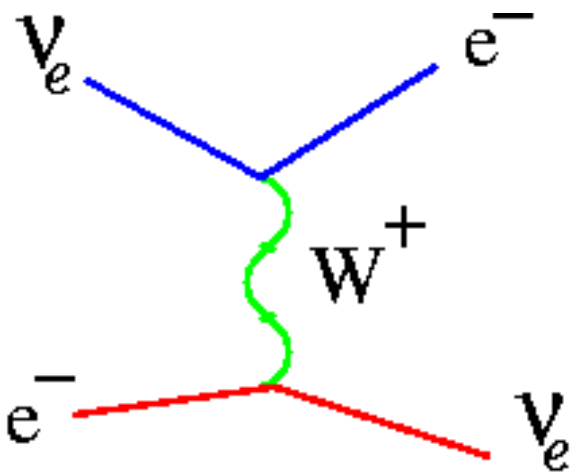
$\Delta m_{atm}^2 \rightarrow \delta m_{23}^2 \approx 2.5\times10^{-3} eV^2$

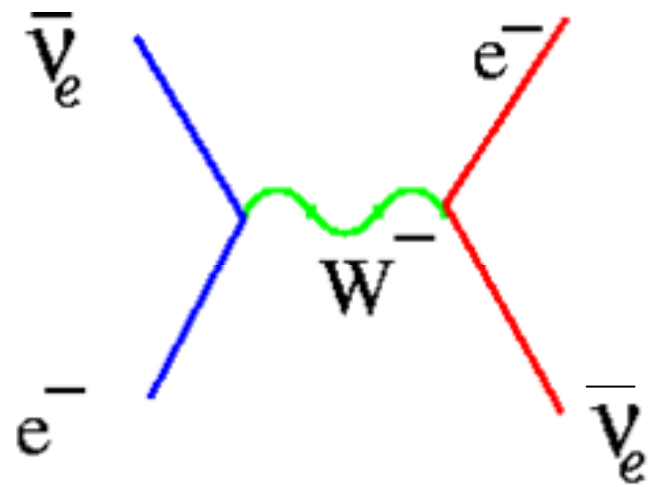
Measuring ν Mass Hierarchy

- Recall the 2-generation formula…

$$P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta \sin^2\left(\frac{(m_2^2 - m_1^2)L}{4E}\right)$$

- Matter changes θ, L for ν_e and $\bar{\nu}_e$'s differently





Wolfenstein, PRD (1978)

$$x = \frac{2\sqrt{2}G_F n_e E_\upsilon}{\Delta m^2}$$

$n =$ e- density

$$\sin^2 2\Theta_M = \frac{\sin^2 2\Theta}{\sin^2 2\Theta + (\pm x - \cos 2\Theta)^2} \qquad L_M = L \times \sqrt{\sin^2 2\Theta + (\pm x - \cos 2\Theta)^2}$$

Next Steps

- First step: need to see if that last mixing angle Θ_{13} is greater than 0
  - Reactor experiment but at 2km, not 180km
  - Electron neutrino appearance in muon neutrino beam at 150km/1GeV
- Next step: compare neutrino and antineutrino oscillation probabilities
- Can history repeat itself again?
  - Anomaly
  - Smoking Gun
  - Precision

Oscillation Probabilities

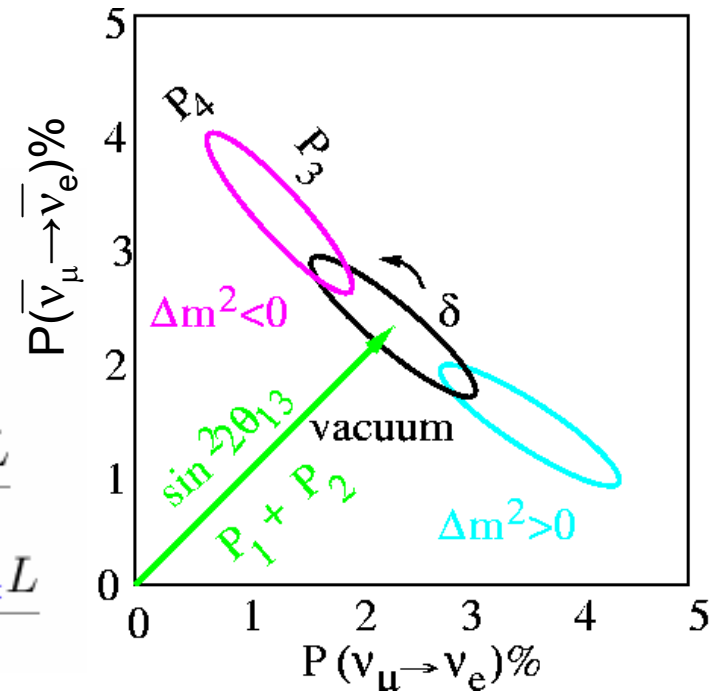
$$P(\nu_\mu \rightarrow \nu_e) = P_1 + P_2 + P_3 + P_4$$

$$P_1 = \sin^2\theta_{23}\sin^2 2\theta_{13}\left(\frac{\Delta_{13}}{B_\pm}\right)^2 \sin^2\frac{B_\pm L}{2}$$

$$P_2 = \cos^2\theta_{23}\sin^2 2\theta_{12}\left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\frac{AL}{2}$$

$$P_3 = J\cos\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\cos\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}$$

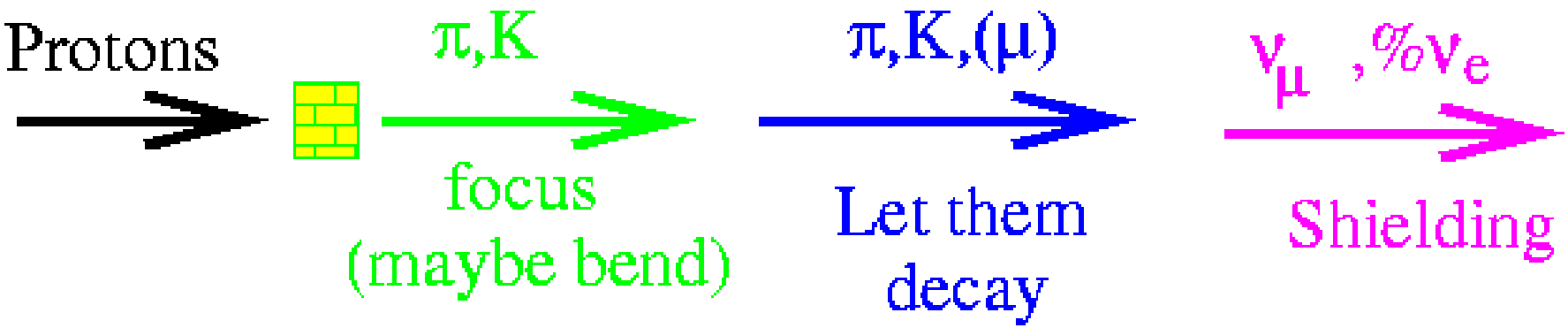
$$P_4 = \mp J\sin\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\sin\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}$$



Minakata & Nunokawa JHEP 2001

- For any one energy and baseline, you don't get the whole story…
- Need two energies, or two baselines, and at least one baseline needs to be long enough to see matter effects

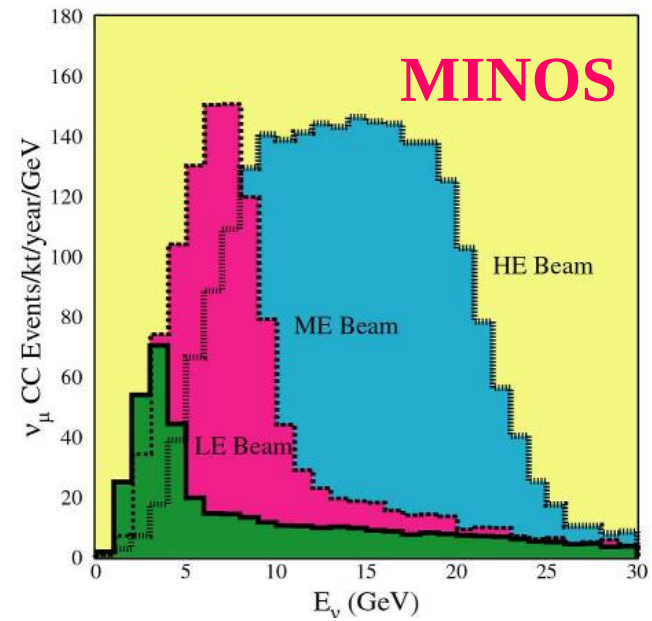
Making Neutrino Beams:

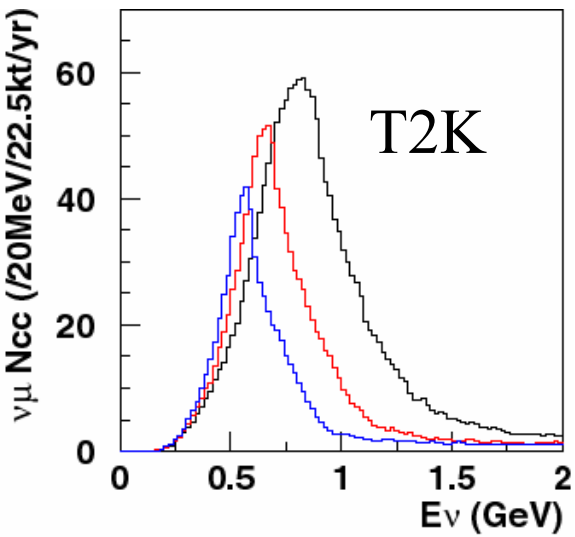


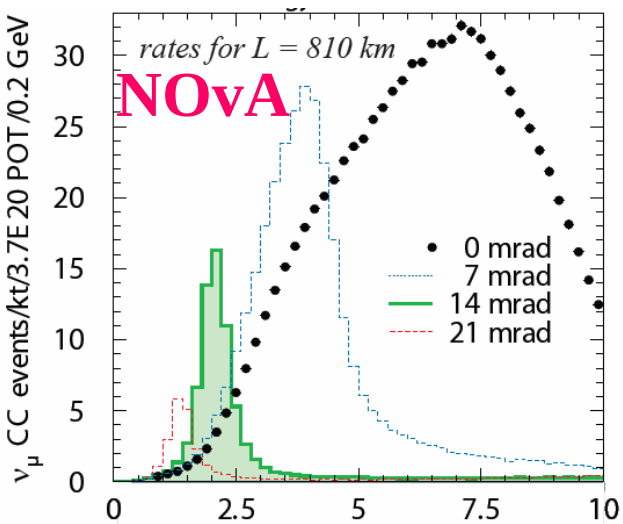
- In principle, it's easy: just make as many pions as you can and make them decay…$\pi \rightarrow \mu\nu_\mu$, $K \rightarrow \mu\nu_\mu$
- In practice, it's never 100% pure, with a broad energy spectrum
  - Mostly ν_μ of broad energy range
  - Per cent level ν_e of even broader range
    - $K \rightarrow \pi\mu e\nu_e$
    - $\mu \rightarrow e\nu_\mu\nu_e$

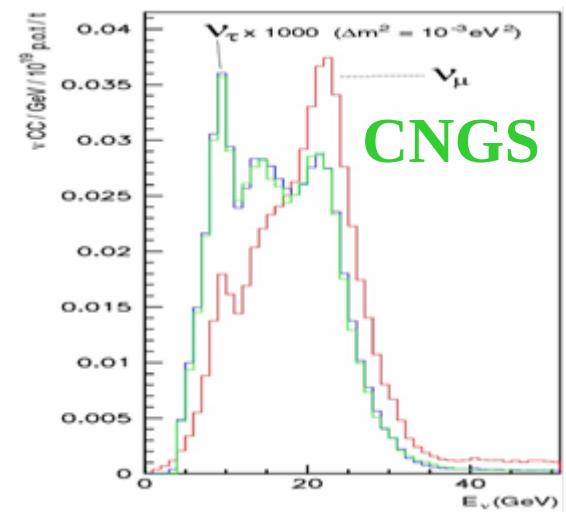
Neutrino Beams for Oscillation Experiments

Exp't	ν_μ Energy (GeV)	ν_e Fraction (%)
K2K	1.4	few
MINOS	2-6	few
OPERA	15-25	few
T2K	0.7	0.4
NOvA	2	0.5









Challenge: Beamlines

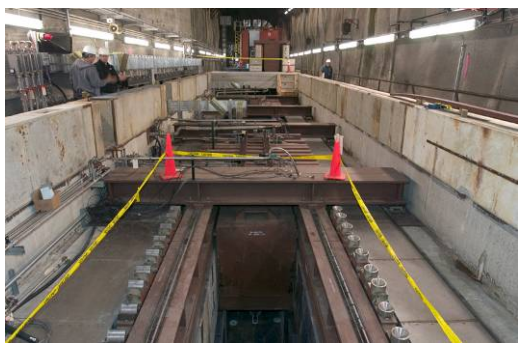
- Handling Many MWatts of proton power and turning it into neutrinos is not trivial!

NuMI tunnel boring machine. 3.5yr civil construction

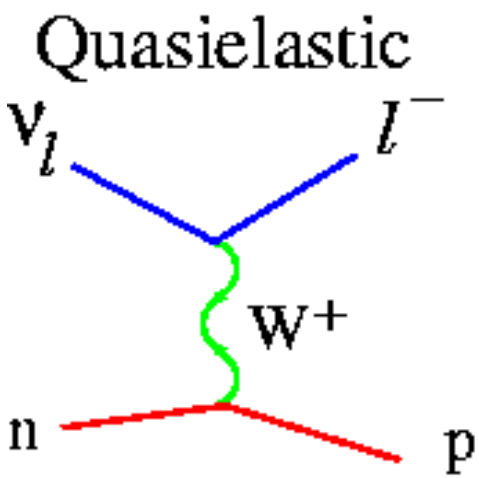
NuMI downstream absorber. Note elaborate cooling. "Cost more than NuTeV beamline…" – R. Bernstein

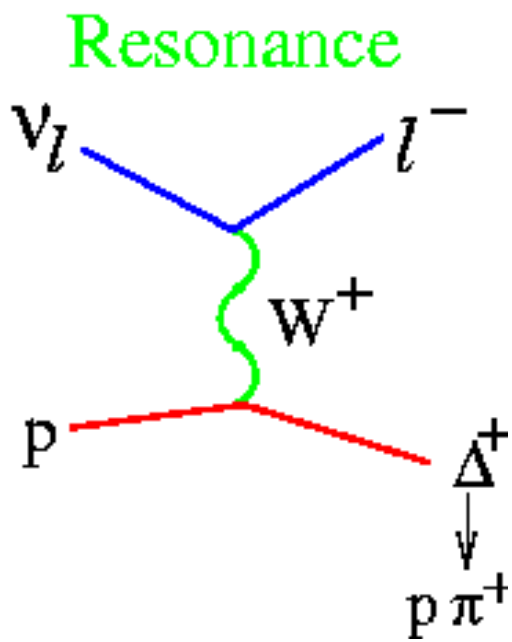
NuMI Horn 2. Note conductors and alignment fixtures

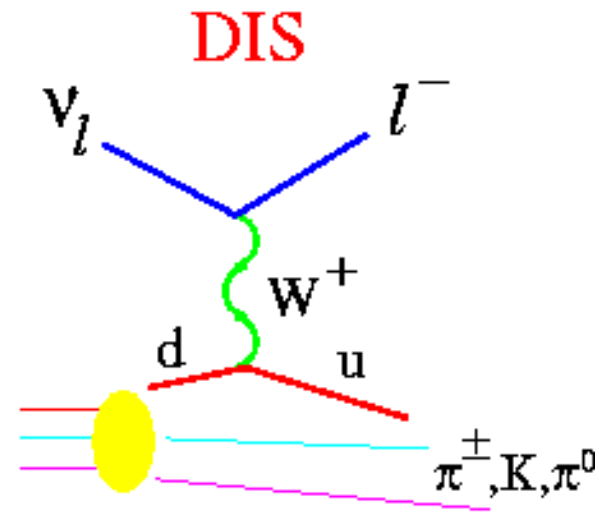
NuMI Target shielding. More mass than far detector!

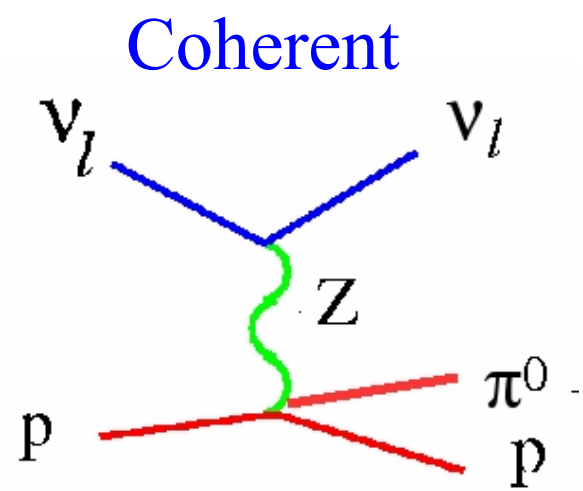


Measuring Neutrino Flavors





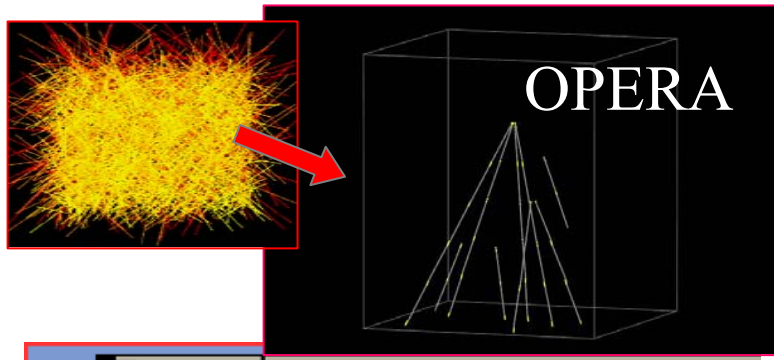


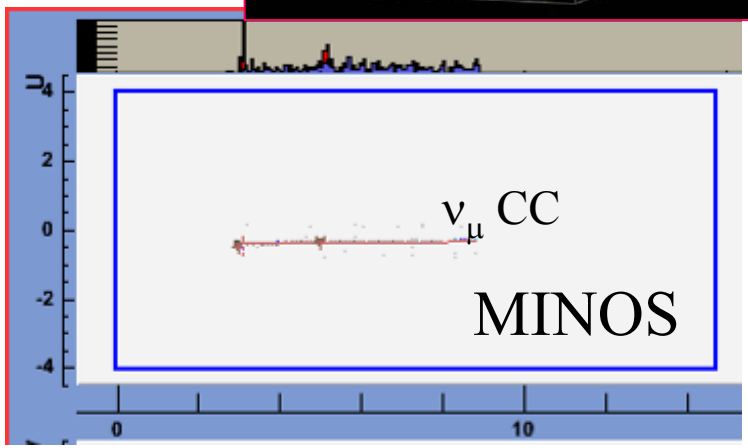


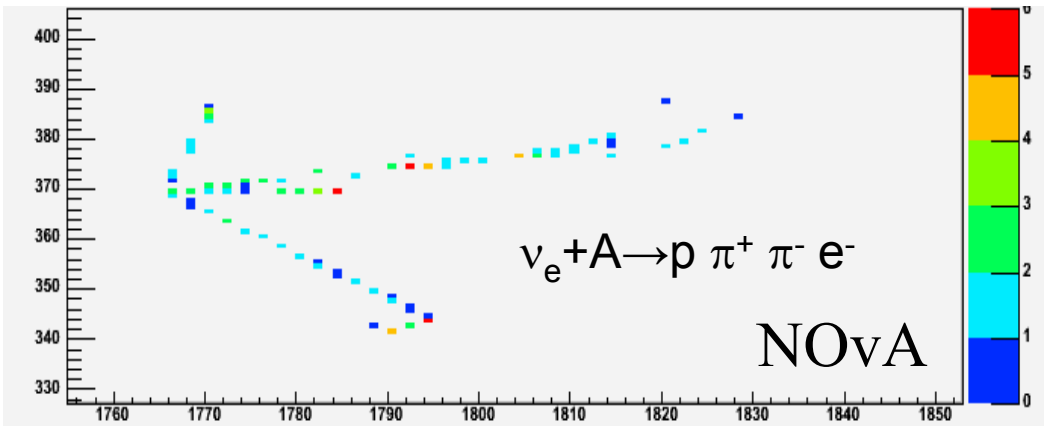
- In principle, it's easy: just need to measure flavor of outgoing lepton
- In practice, it's not so easy:
  - Neutral currents provide π^0's that fake e's
  - Neutral currents provide π^{+-} that fake μ's

What ν events really look like…

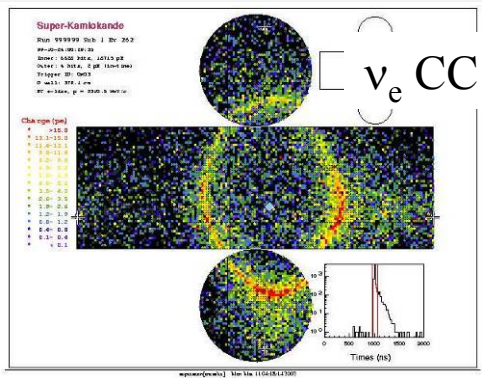
Exp't	ν Energy (GeV)	Detector Technology
K2K	1.4	Water Cerenkov
MINOS	2-6	Steel Scintillator
OPERA	15-25	Emulsion-Lead
T2K	0.7	Water Cerenkov
NOvA	2	Segmented Scintillator







Super-K

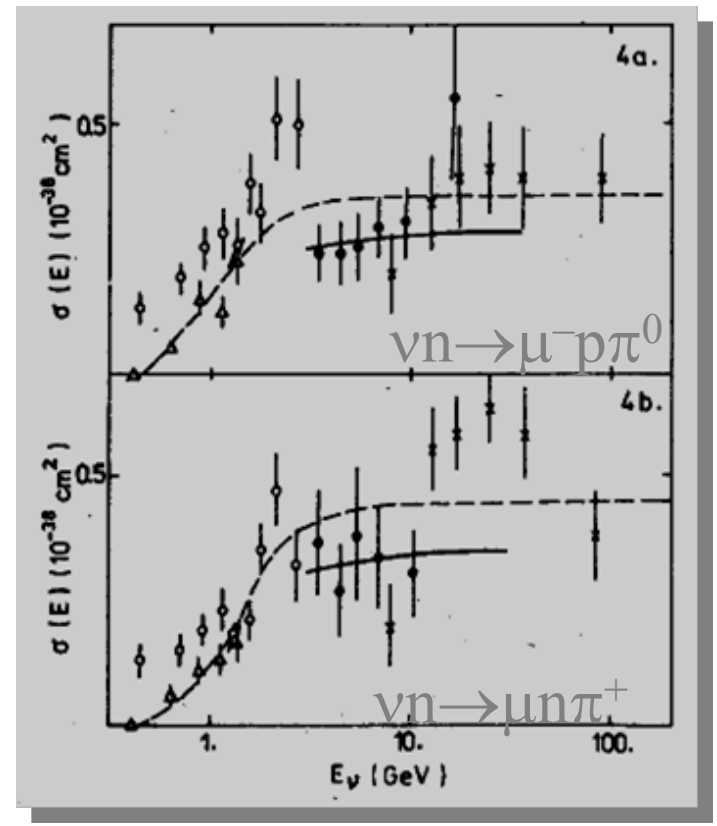


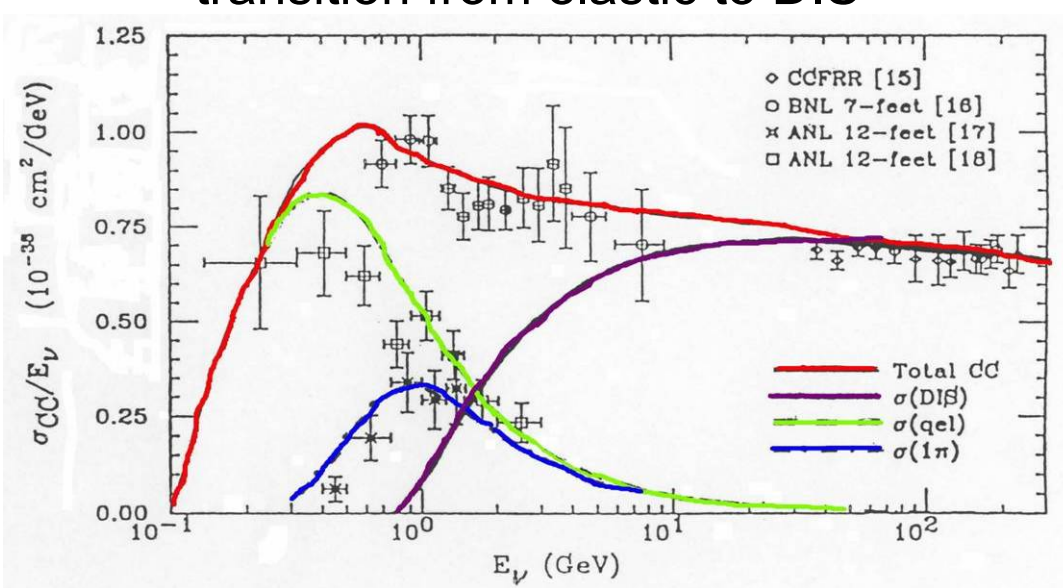
What do we know about Neutrino Interactions

(this is a talk about neutrino interactions…)

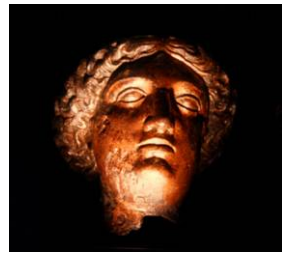
- At 1-few GeV neutrino energy (of interest for osc. expt's)
  - Experimental errors on total cross-sections are large
    - almost no data on A-dependence
  - Understanding of backgrounds needs *differential* cross-sections on target
  - Theoretically, this region is a mess... transition from elastic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

figures courtesy D. Casper, G. Zeller



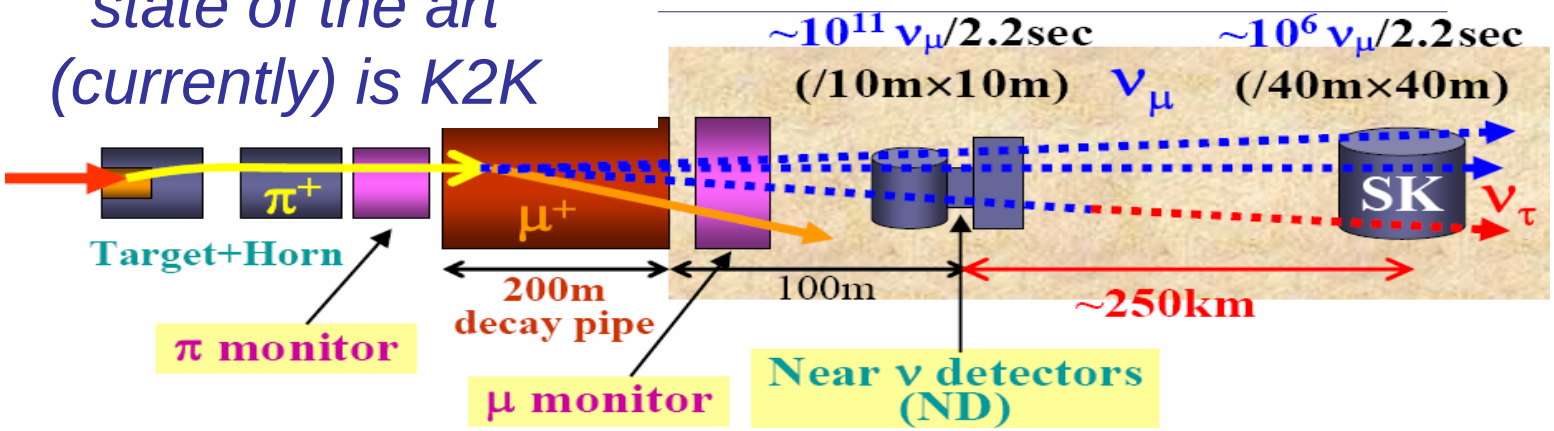


But isn't this simple?



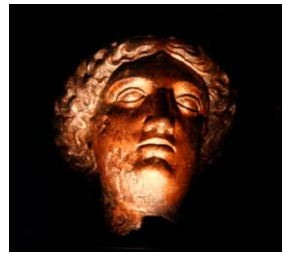
- Neutrino oscillation experiments (nearly) all have near detectors!

state of the art (currently) is K2K

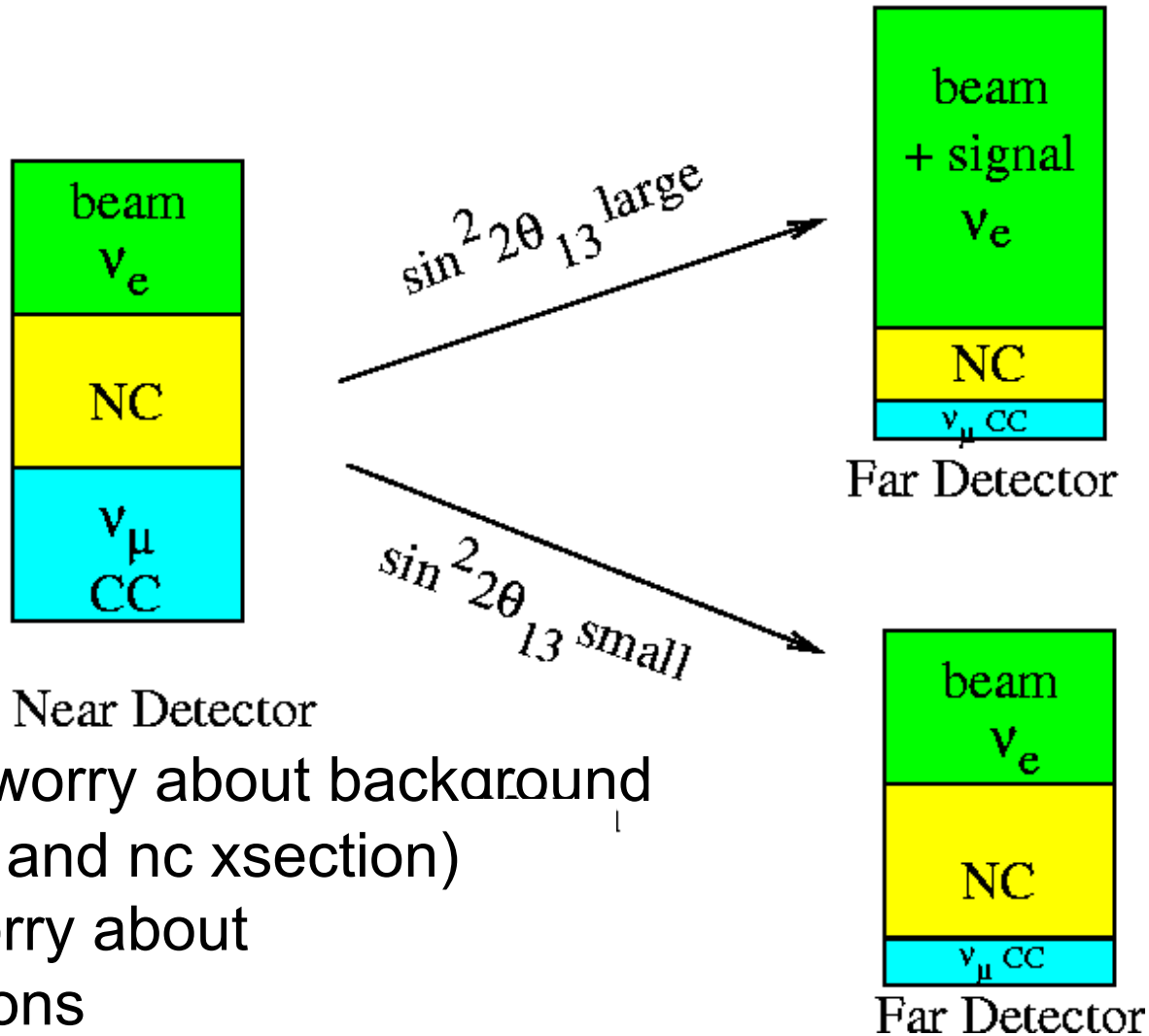


- Shouldn't cross-section uncertainties cancel between near and far detectors?

Toy ν_e Appearance Analysis

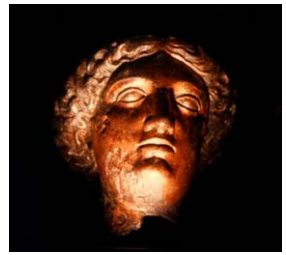


Event Samples
are different
Near to far, so
Uncertainties
In cross sections
Won't cancel



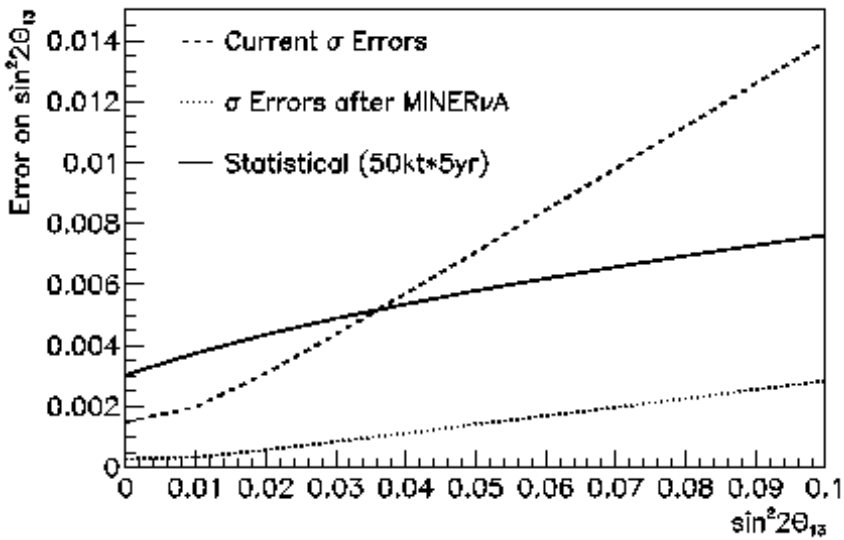
If signal is small, worry about background prediction (ν_e flux and nc xsection)
If signal is big, worry about signal cross sections

How much do cross section errors cancel near to far?



- **Toy analysis**: start with old NOvA detector simulation, which had same ν_e/NC ratio, mostly QE & RES signal events accepted, more ν_μCC/NC accpeted
- Near detector backgrounds have ~3 times higher $\nu_\mu$cc!
- Assume if identical ND, can only measure 1 background number: hard to distinguish between different sources

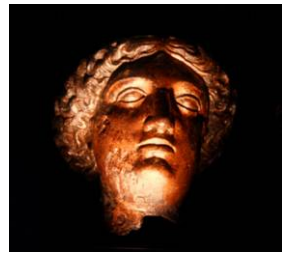
Process	Events	QE	RES	COH	DIS
$\delta\sigma/\sigma$		20%	40%	100%	20%
Signal ν_e $\sin^2 2\theta_{13}$=0.1	175	55%	35%	n/i	10%
NC	15.4	0	50%	20%	30%
ν_μCC	3.6	0	65%	n/i	35%
Beam ν_e	19.1	50%	40%	n/i	10%



For large $\sin^2 2\theta_{13}$, statistical=8%
For small $\sin^2 2\theta_{13}$, statistical=16%

Assume post-MINERνA, σ's known at:
ΔQE = 5%, ΔRES = 5, 10% (CC, NC)
ΔDIS = 5%, ΔCOH_{Fe} = 20%

ν_μ Disappearance: MINOS



CC-like Visible Energy Distributions split by interaction type:

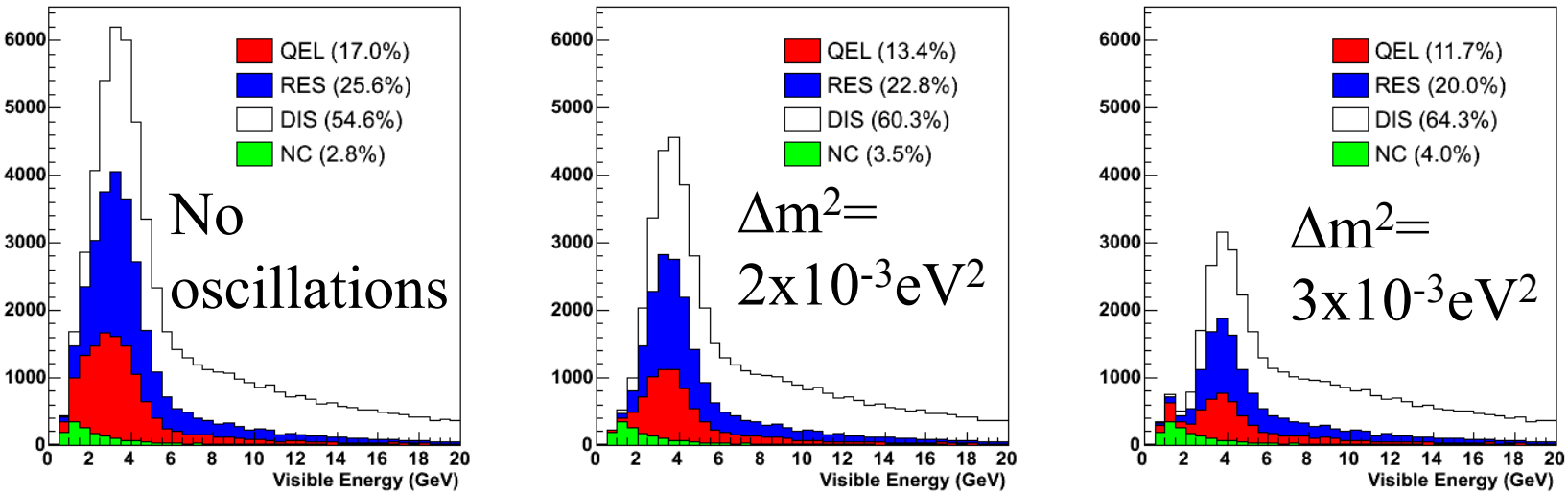
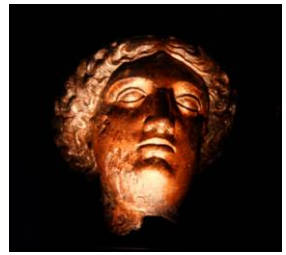
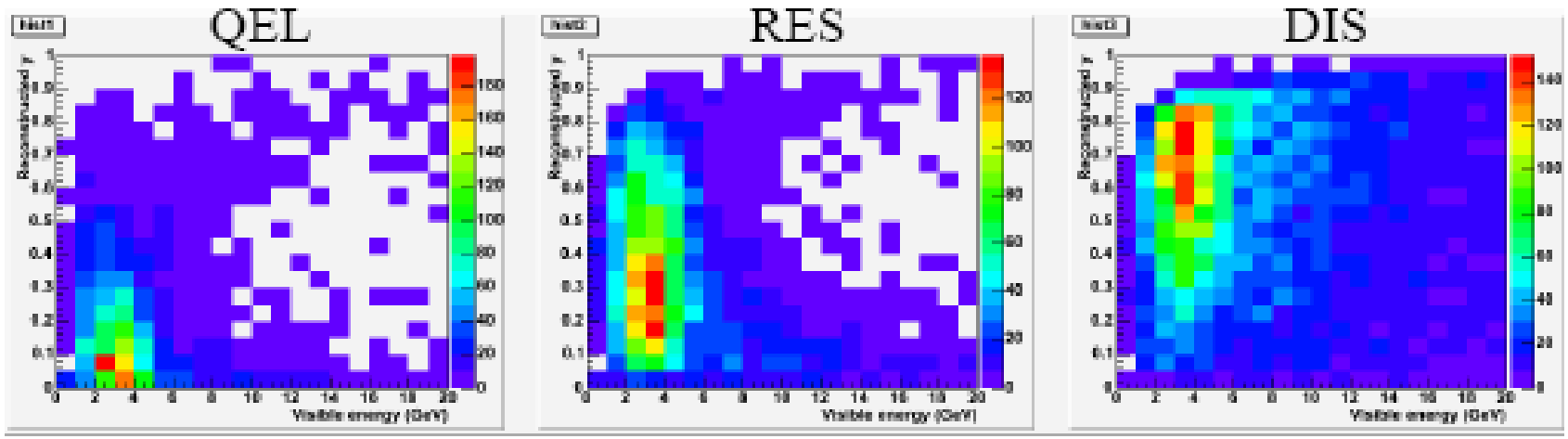


Figure courtesy D. Petyt

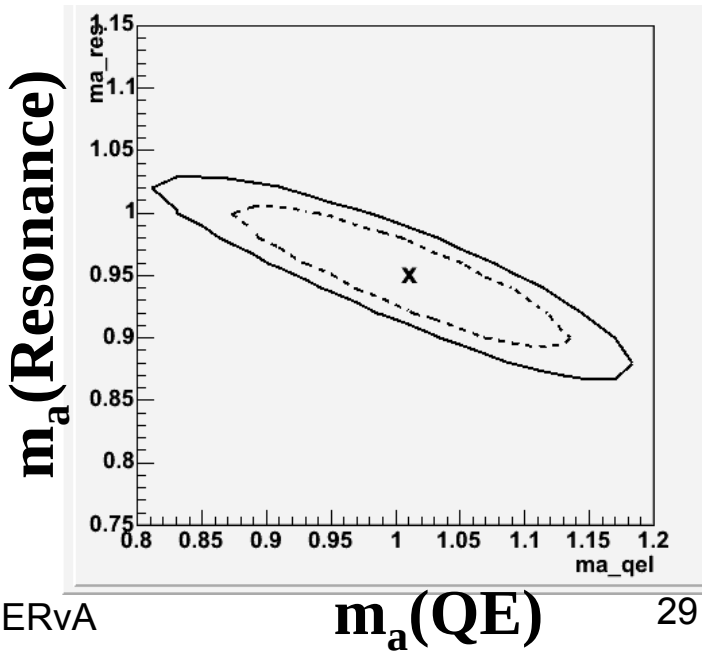
Near Detector has one neutrino energy scale, far detector will have a different scale because of oscillations…need to take cross section uncertainties into effect

ν_μ Disappearance: MINOS, II



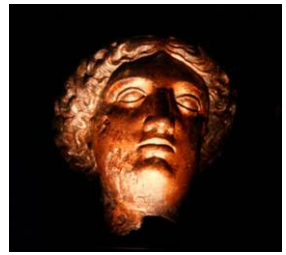


- Fit near detector spectra versus "visible y distribution" to separate different components
- Need to consider all systematic uncertainties simultaneously for total syst. error analysis

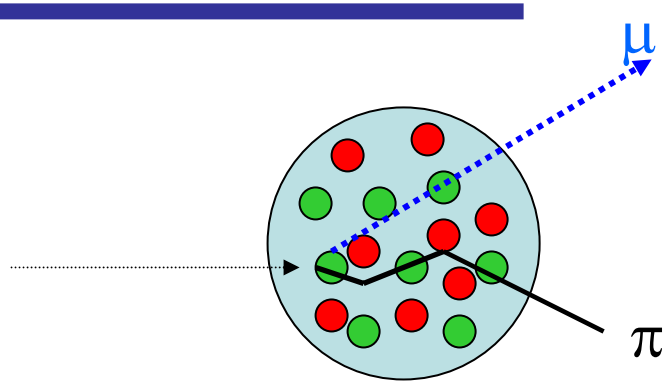


Figures courtesy D.Petyt

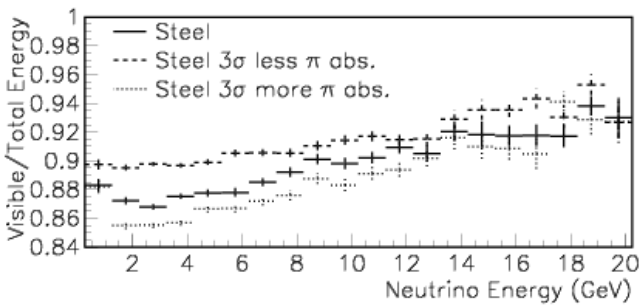
Nuclear effects at MINOS

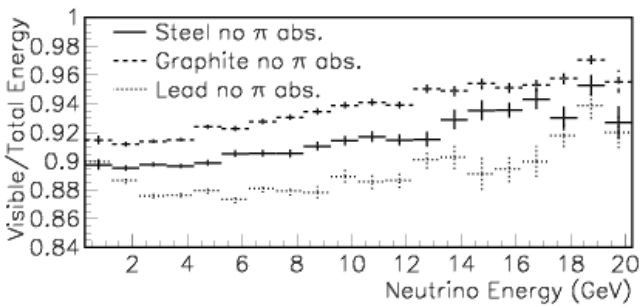


- Visible Energy in Calorimeter is NOT ν energy!
  - π absorption, rescattering
  - final state rest mass

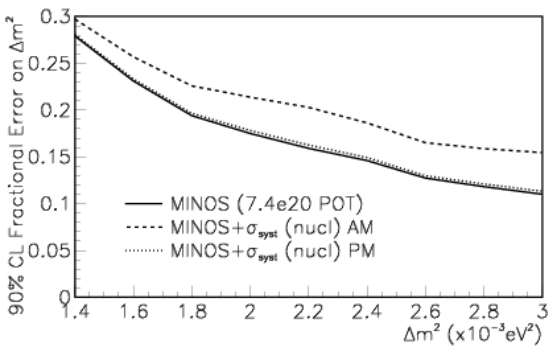


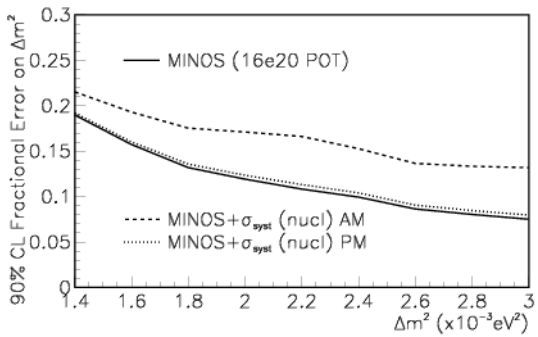
Toy MC analysis:





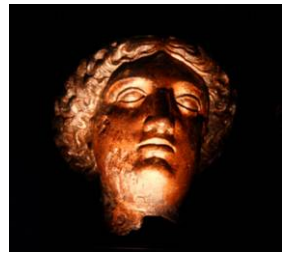
Nuclear Effects Studied in Charged Lepton Scattering, from Deuterium to Lead, at High energies, but nuclear corrections may be different between e/μ and ν scattering





Enter MINERνA…

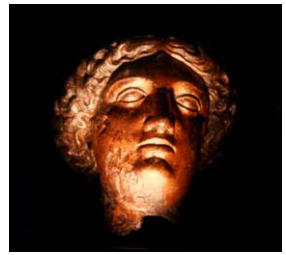
Essence of MINERvA



- MINER*v*A is a compact, fully active neutrino detector designed to study neutrino-nucleus interactions in detail at high statistics
- The detector will be placed in the NuMI beam line upstream of the MINOS Near Detector

- MINERvA's role in the worldwide program:
  - Combination of detector site, intensity and beam energy range of NuMI is unique
  - Detector with several different nuclear targets allows 1st study of neutrino nuclear effects
  - Crucial input to current and future oscillation measurements

The MINERvA Collaboration



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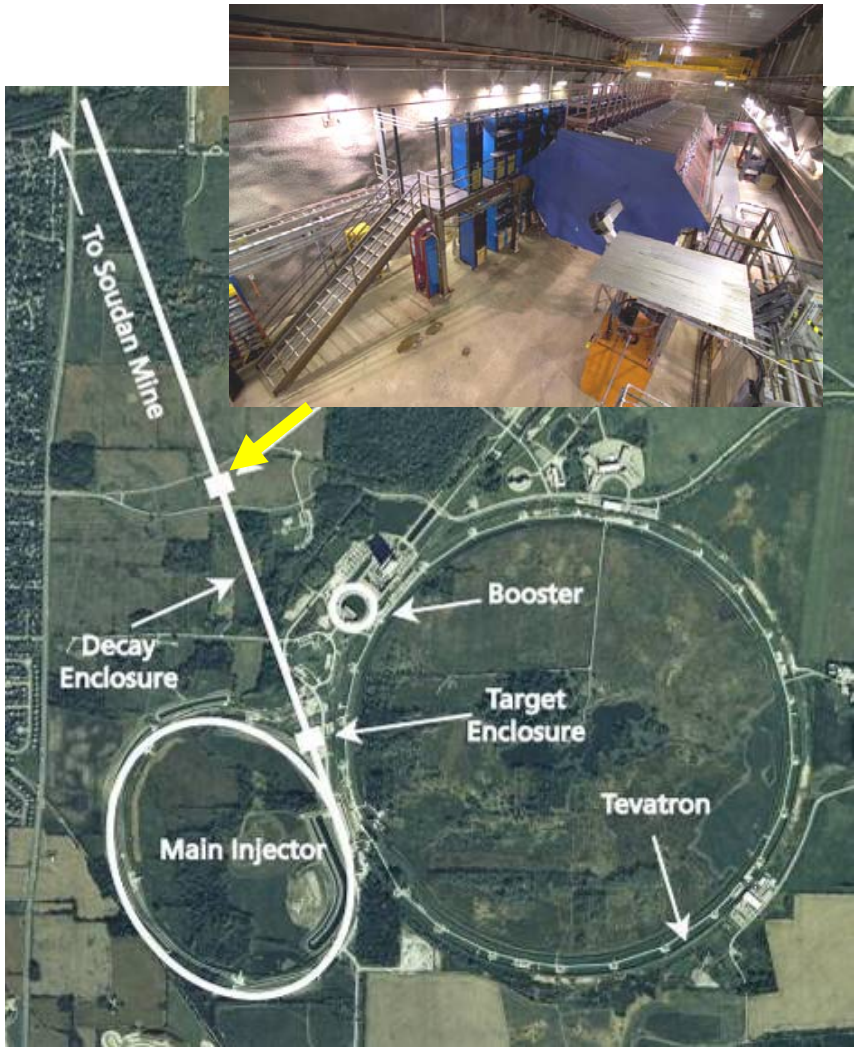
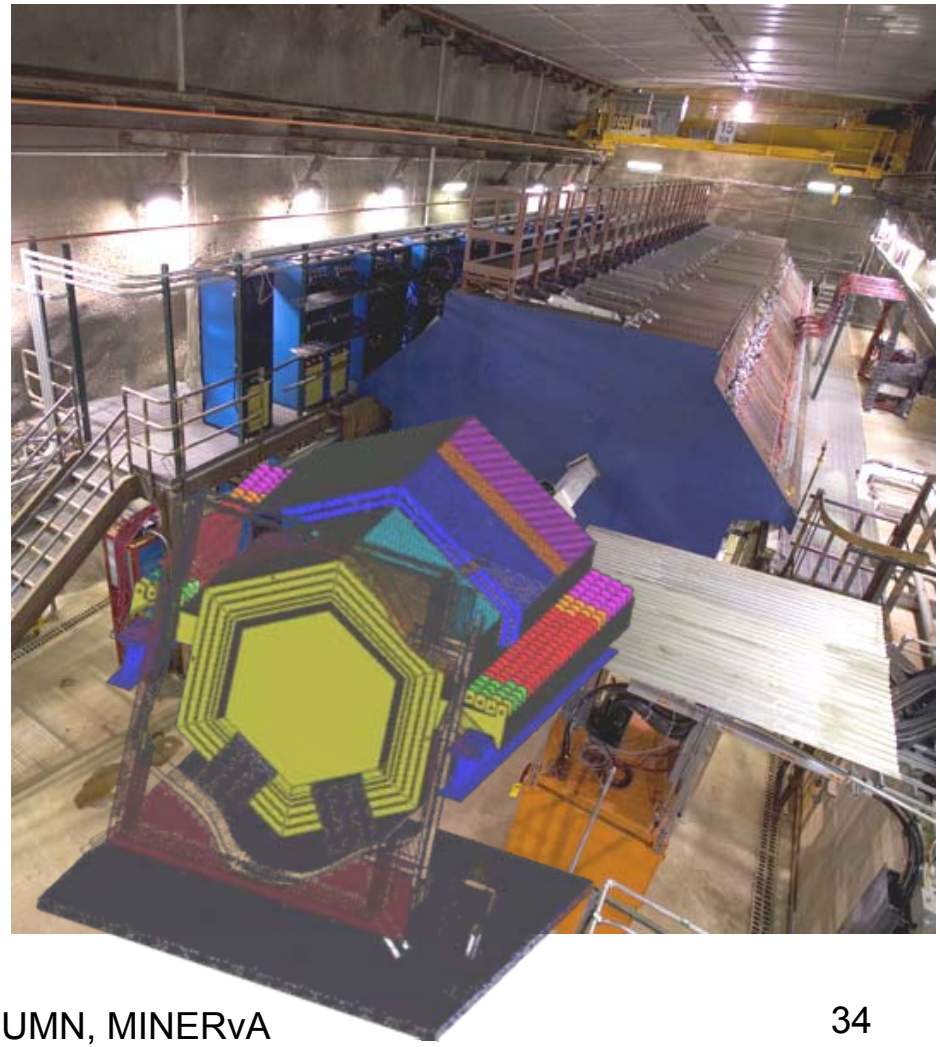
* Co-Spokespersons

\# MINERvA Executive Committee

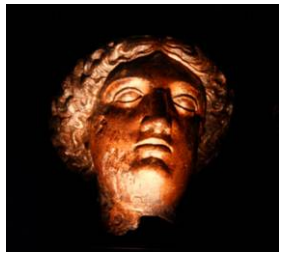
A collaboration of ~80 Particle, Nuclear, and Theoretical physicists from 23 Institutions

NuMI Near Hall

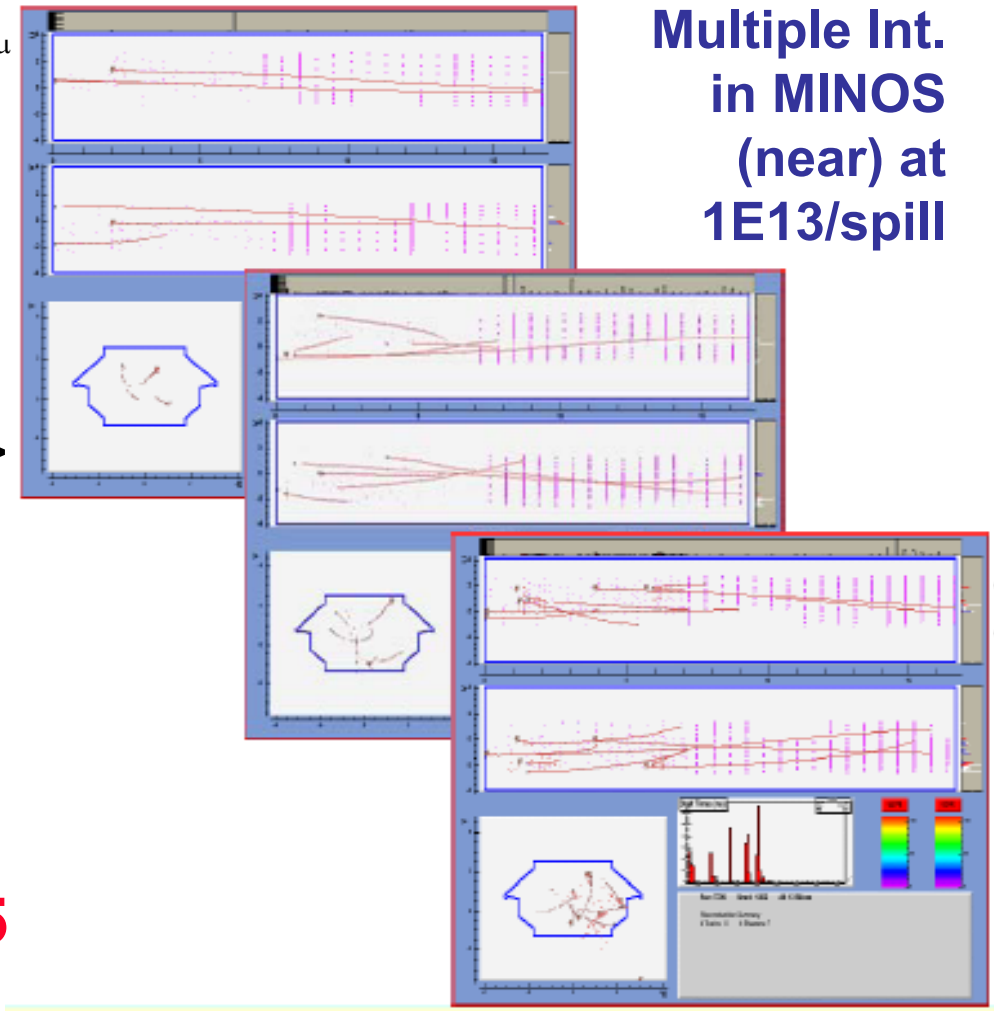




NuMI Beam Intensity (Near)



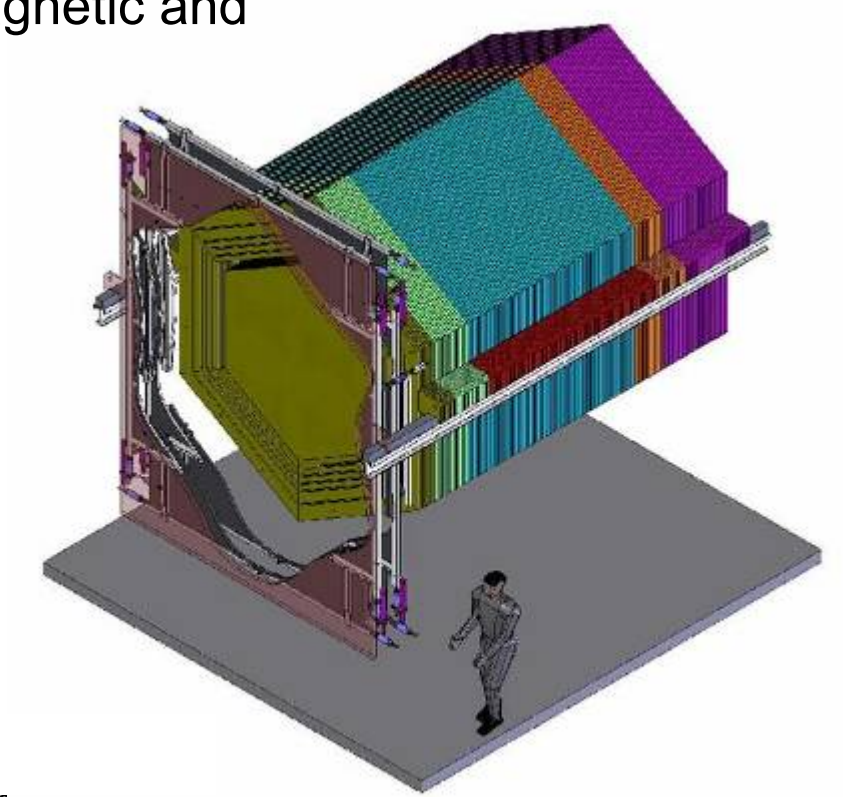
- LE-configuration: **Events-** (E_μ >0.35 GeV) E_{peak} = 3.0 GeV, $<E_\nu>$ = 10.2 GeV, rate = **60 K events/ton - 10^{20} pot**
- ME-configuration: **Events-** E_{peak} = 7.0 GeV, $<E_\nu>$ = 8.0 GeV, rate = **230 K events/ton - 10^{20} pot**
- HE-configuration: **Events-** E_{peak} = 12.0 GeV, $<E_\nu>$ = 14.0 GeV, rate = **525 K events/ton - 10^{20} pot**



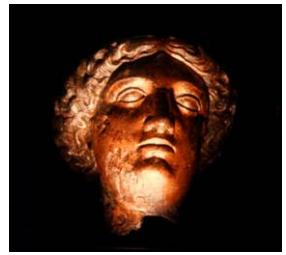
Multiple Int. in MINOS (near) at 1E13/spill

Detector Design

- Active core is segmented solid scintillator
  - Tracking (including low momentum recoil protons)
  - Particle identification by energy deposition (dE/dx)
  - 3 ns (RMS) per hit timing (track direction, identify stopped $K^{\pm}$)
- Core surrounded by electromagnetic and hadronic calorimeters
  - Photon (π^0) & hadron energy measurement
- Upstream region has simultaneous C, Fe, Pb, He targets to study nuclear effects
- MINOS Near Detector as muon catcher

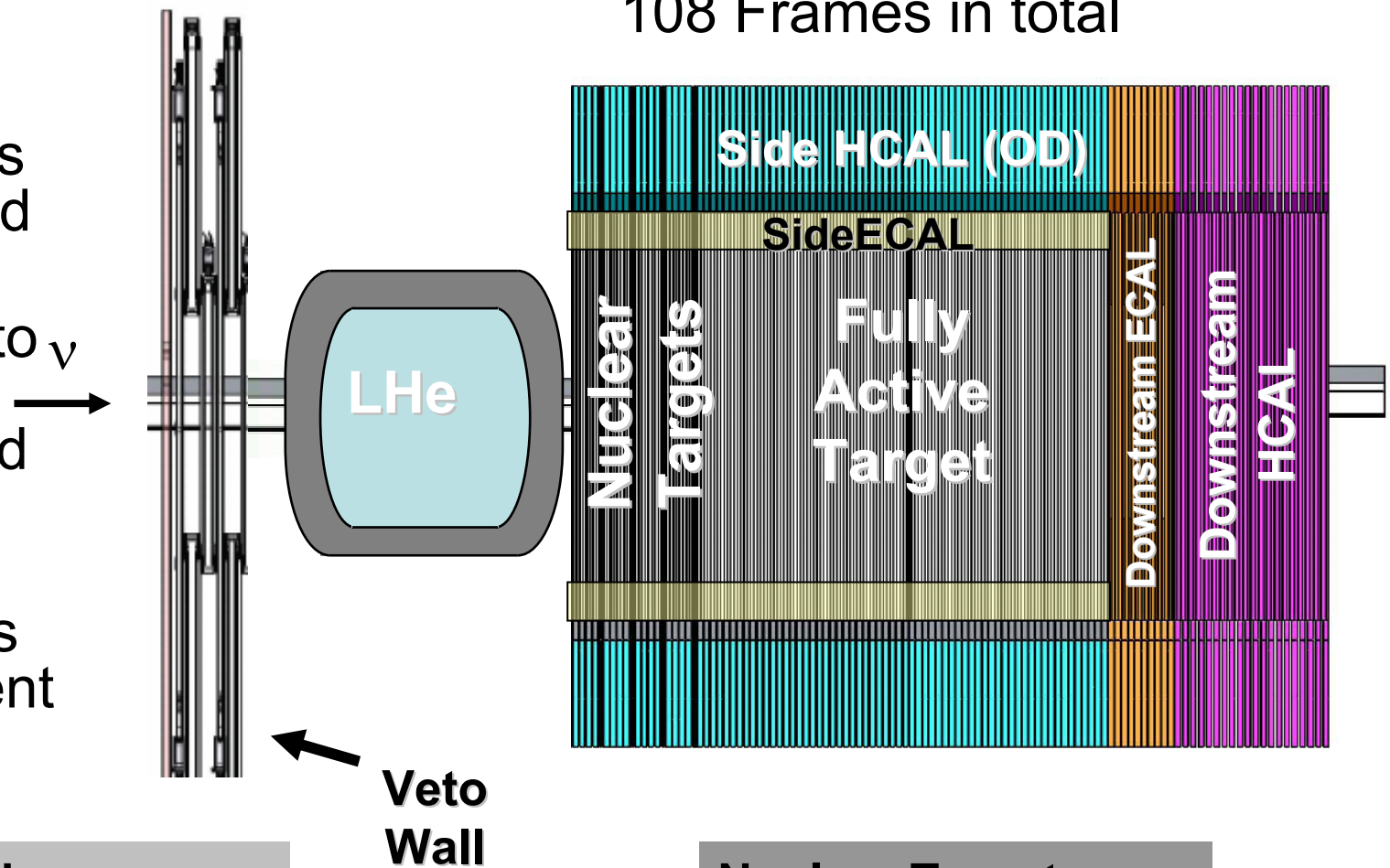


Detector Design, II



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

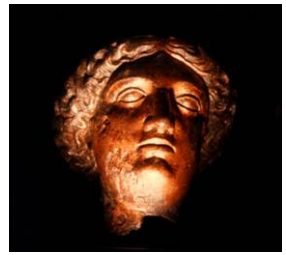
108 Frames in total



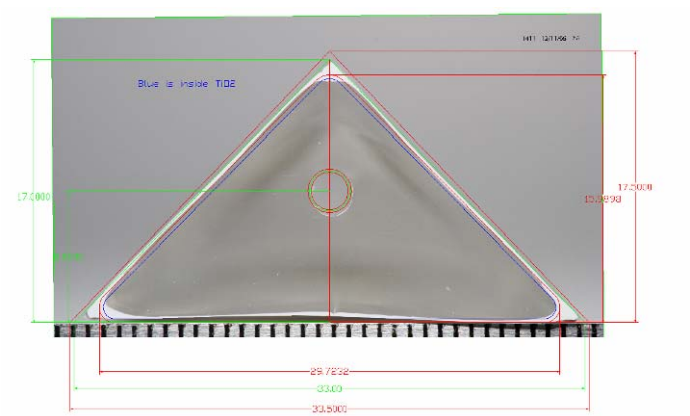
Fully Active Target: 8.3 tons

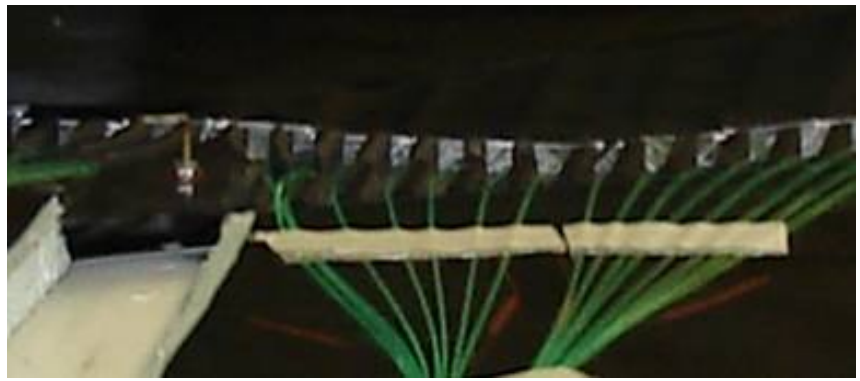
Nuclear Targets: 6.2 tons (40% scint.)

Optical System

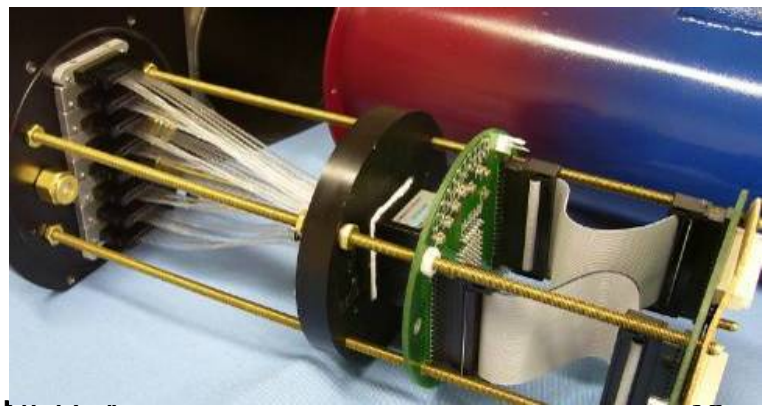


- Blue-emitting extruded plastic scintillator with a hole for a WLS fiber:
- Wavelength Shifting (WLS) fiber glued into scintillator

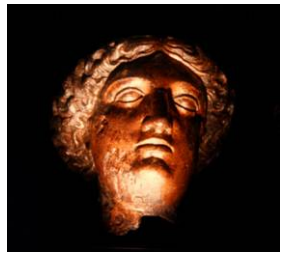




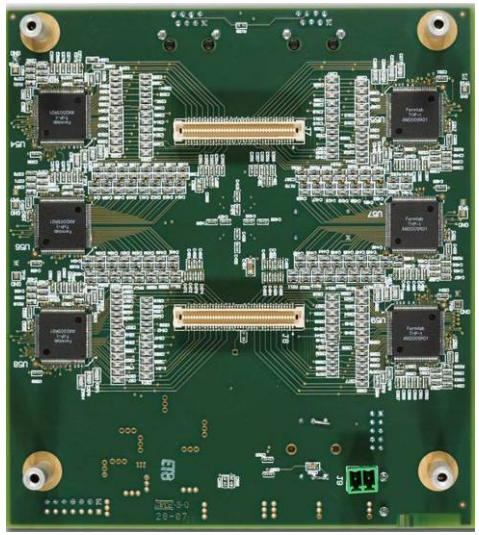
- Clear fiber in light-tight optical cables takes light to PMT box
- "ODU" (Optical Decoder Unit) takes light from optical cable to PMT

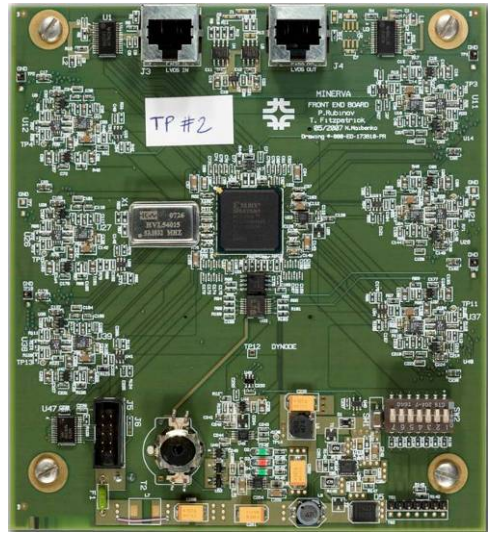


Electronics and DAQ

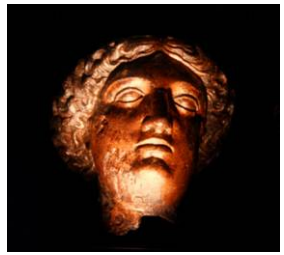


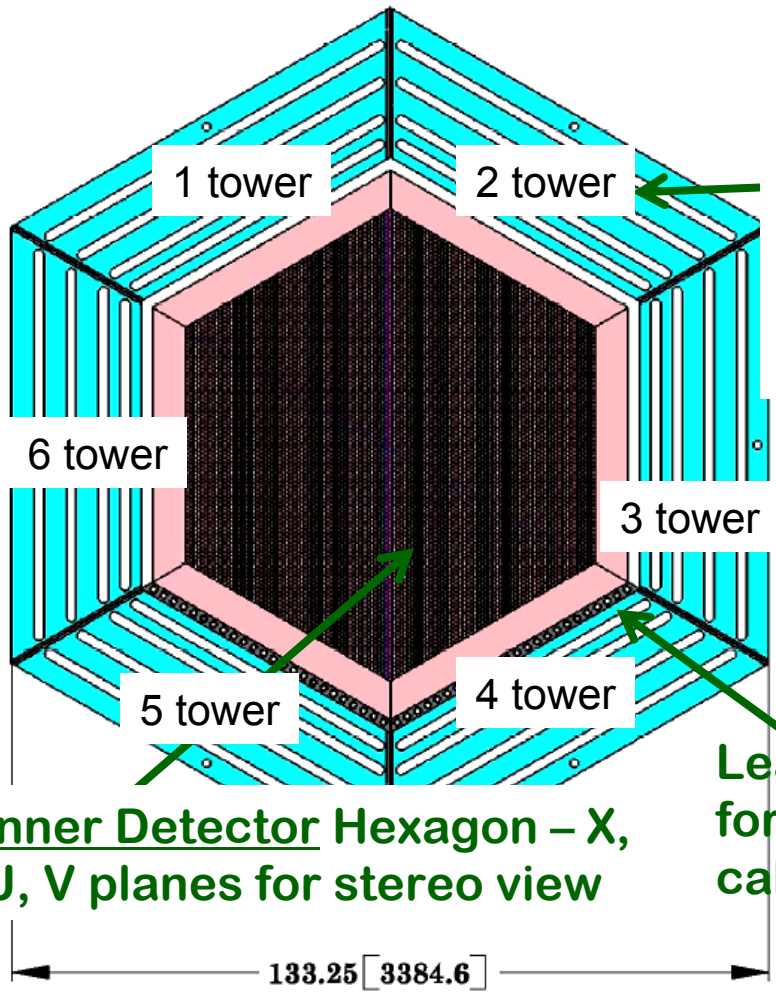
- **Front End Boards**
  - One board per PMT
  - High Voltage (700-800V)
  - Digitization via TriP Chips, take advantage of D0 design work
  - Timing
- **CROC Boards and DAQ**
  - One board per 48 PMT's
  - Front-end/computer interface
  - Distribute trigger and synchronization
  - 3 VME crates & one DAQ computer
- **Power and rack protection**
  - Uses 48V power
  - 7kW needed





MINERvA Detector Planes





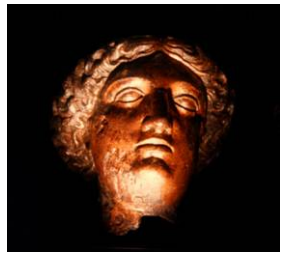
Outer Detector (OD) Layers of iron/scintillator for hadron calorimetry: 6 Towers

Lead Sheets for EM calorimetry

Inner Detector Hexagon – X, U, V planes for stereo view

- **31,000 channels**
  - 80% in inner hexagon
  - 20% in Outer detector
- **500 M-64 PMTs** (64 channels)
- **1 wave length shifting fiber per scintillator**, which transitions to a clear fiber and then to the PMT
- **128 pieces of scintillator per Inner Detector plane**
- **4 or 6 pieces of scintillator per Outer Detector tower, 6 OD detector towers per plane**

Module Prototyping



- Winter/Spring of ’07:
  - Completed construction of full-sized prototype module

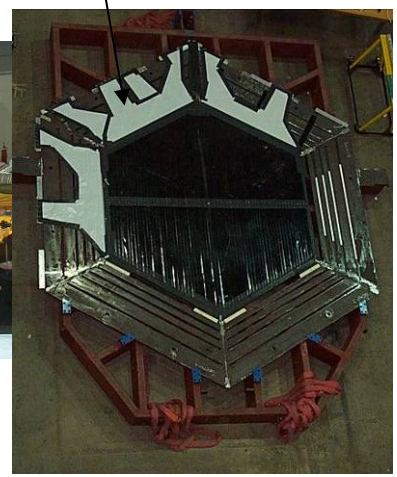
Scintillator from VA

Prototype frame

Prototype detector stand

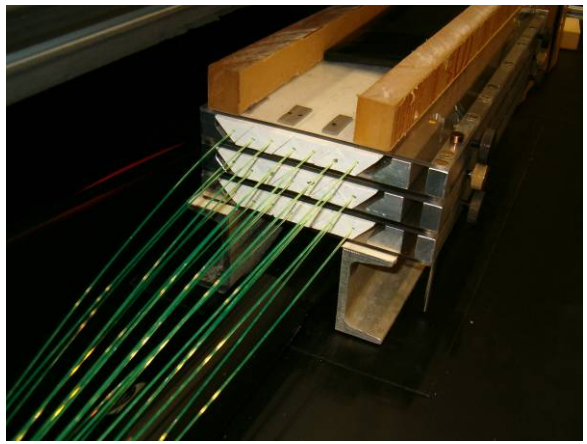
Assembly tech from UofR

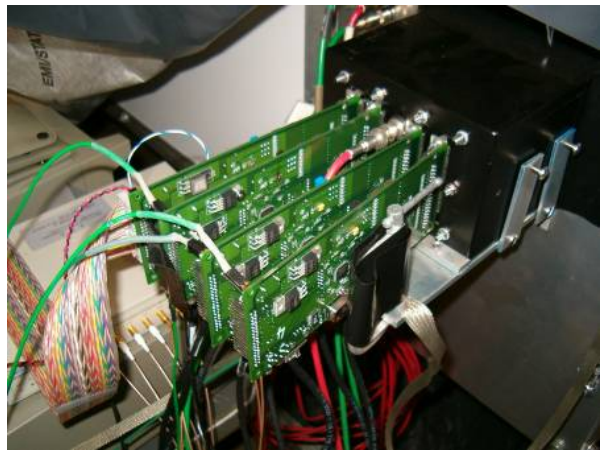
Finished product

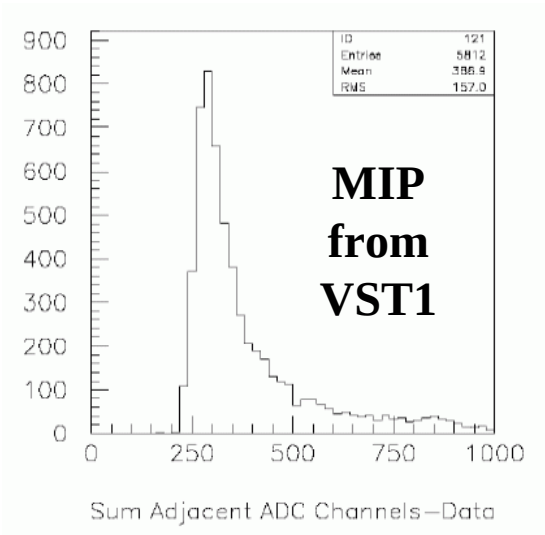


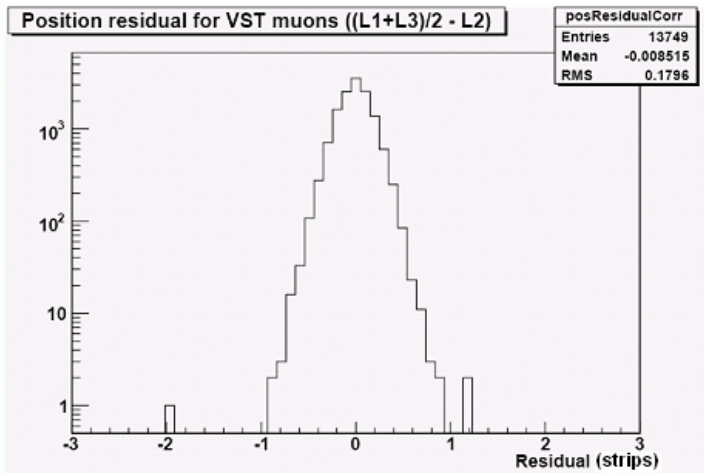
Vertical Slice Test

- Test setup incorporating entire chain of detector
- Verify key parameters:
  - Light yield:
    - **Result: 6.5 pe/MeV**
  - Position resolution:
    - **Result: 2.5 mm**



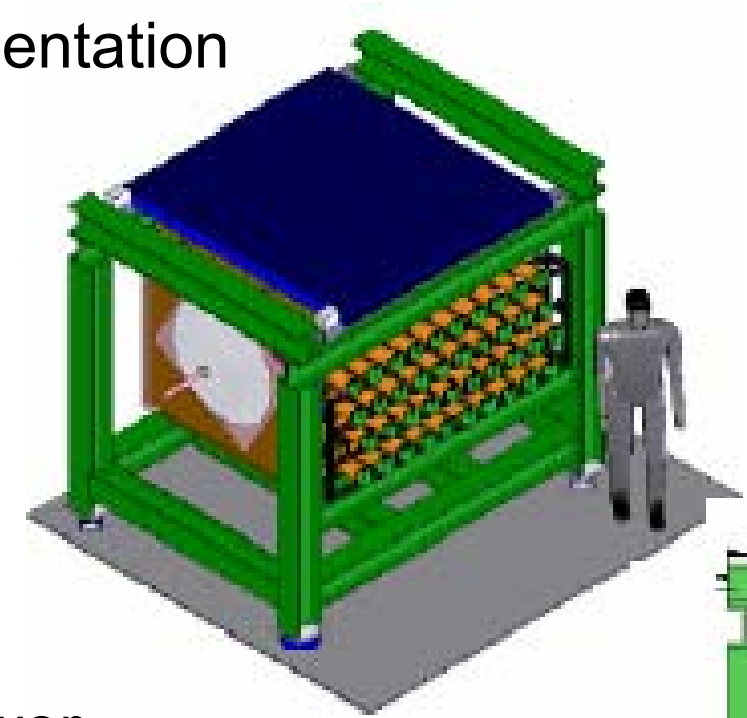


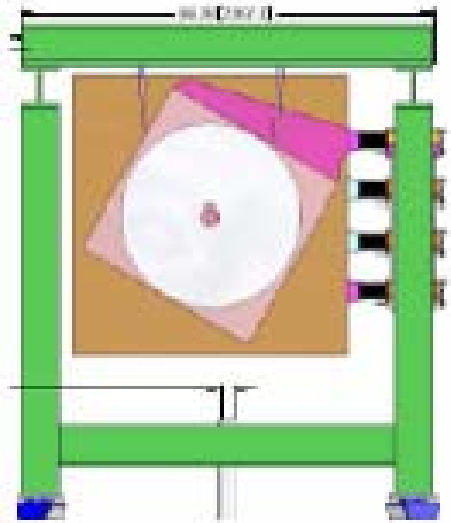




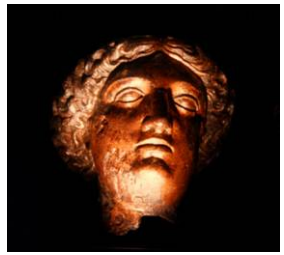
MINERνA Test Beam Detector

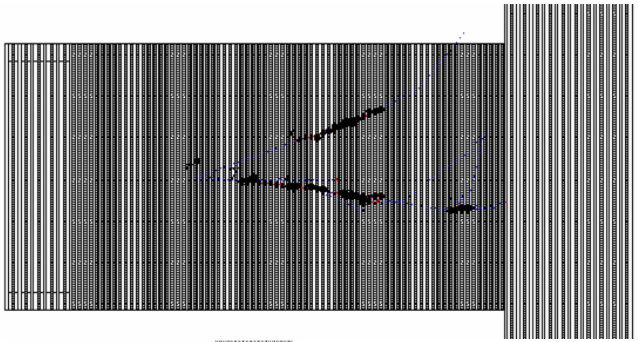
- 40 planes, XUXV orientation as in full MINERvA
- Removable lead and iron absorbers.
- In light-proof box
- Size: ~1.2 x 1.2 m^2
- Includes Fermilab Test Beam Facility upgrade to reach lower π/K/p momenta of order 250 MeV
- **Test Beam run scheduled for fall 2008**

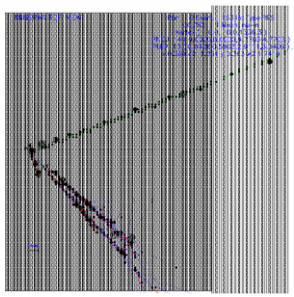




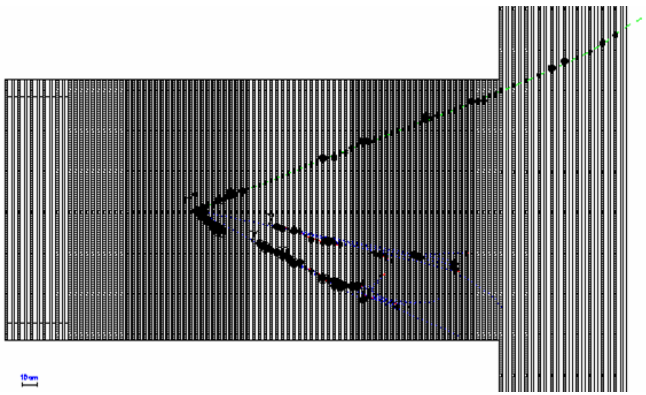
π^0 Reconstruction



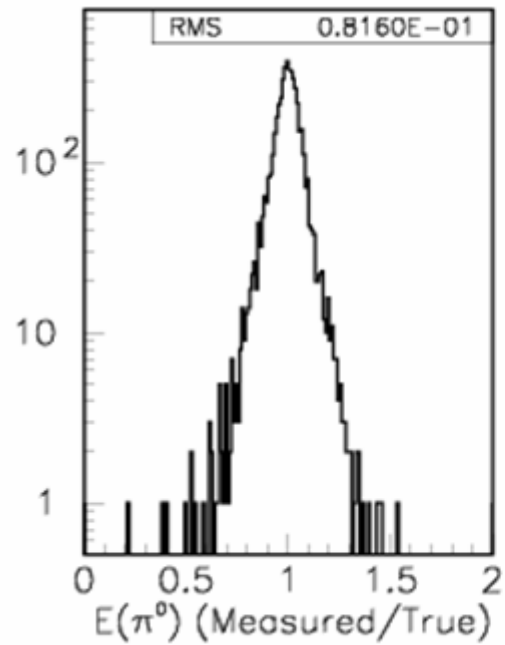


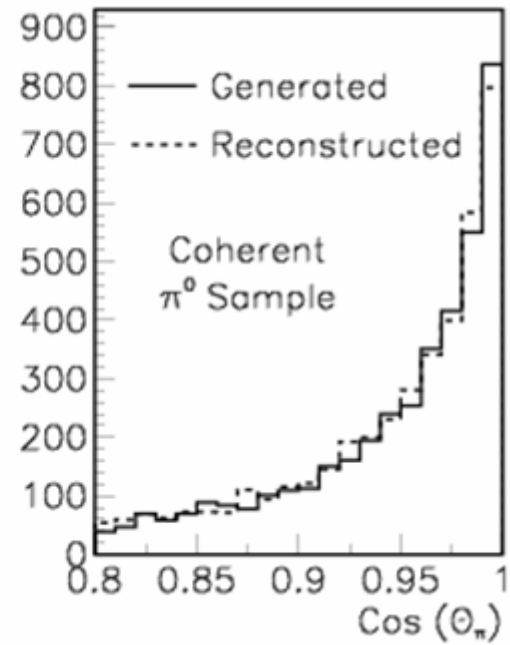


Resonance events with π^0

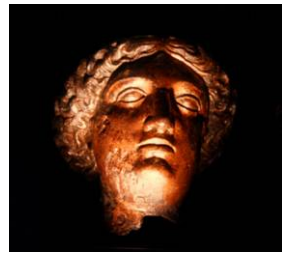


- π^0's cleanly identified
- π^0 energy res.: $6\%/\sqrt{E}$ (GeV)
- For coherent, π^0 angular resolution < physics width

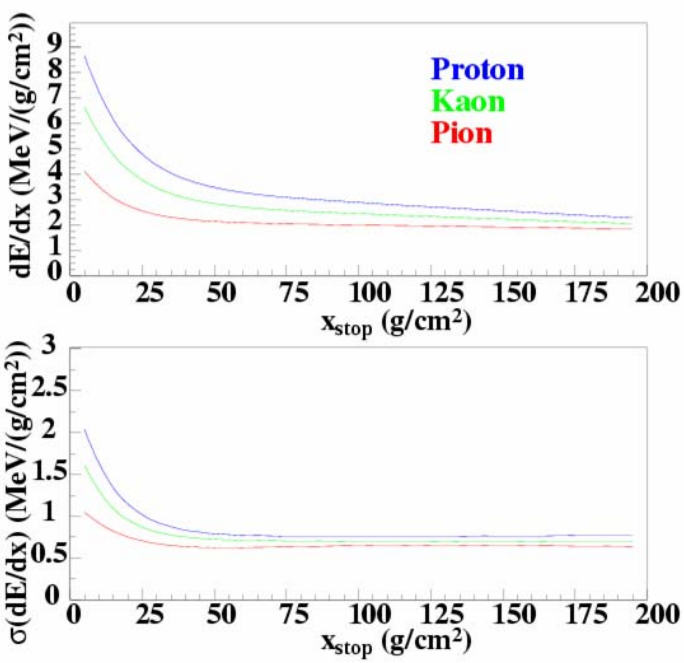




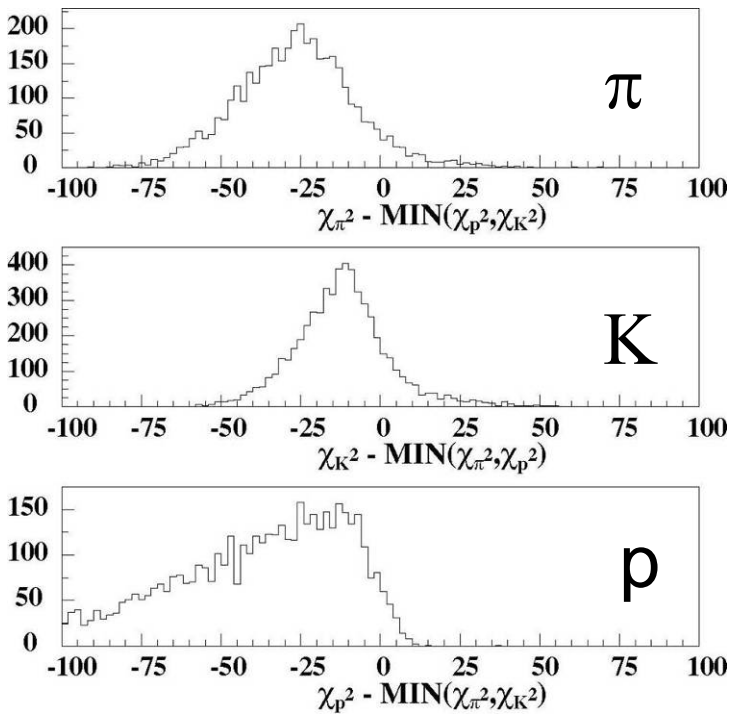
Particle Identification



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



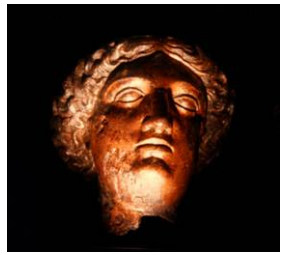
Chi2 differences between right and best wrong hypothesis



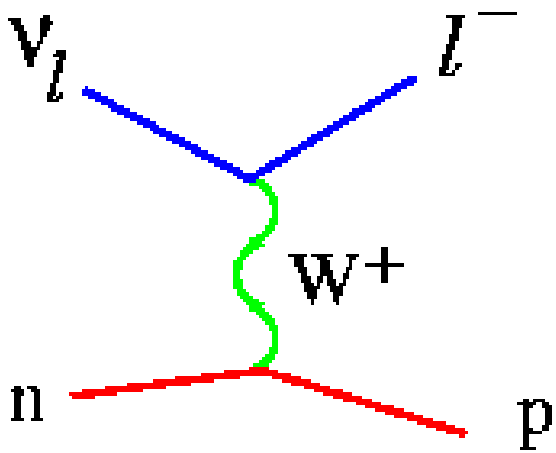
- Many dE/dx samples for good discrimination

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

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



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



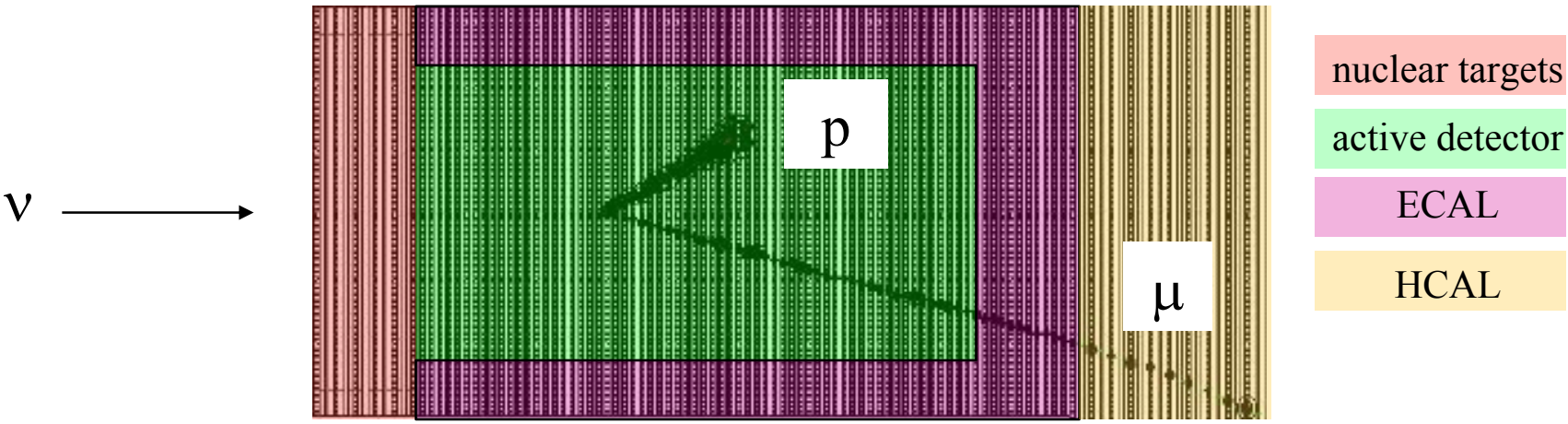
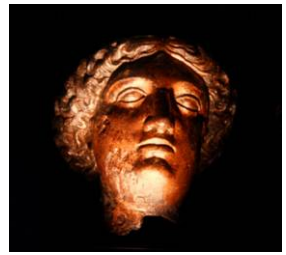
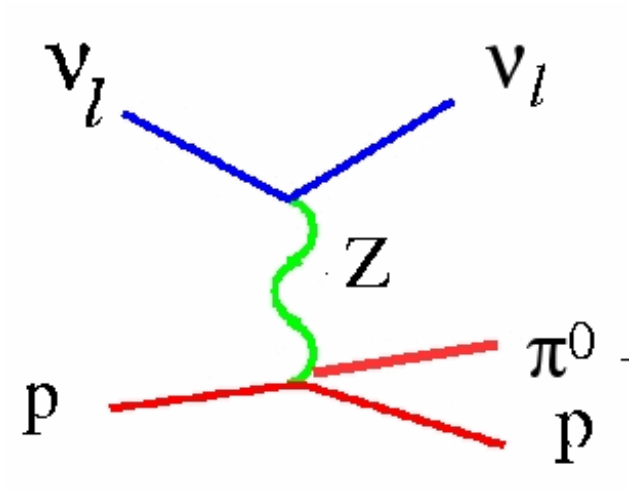
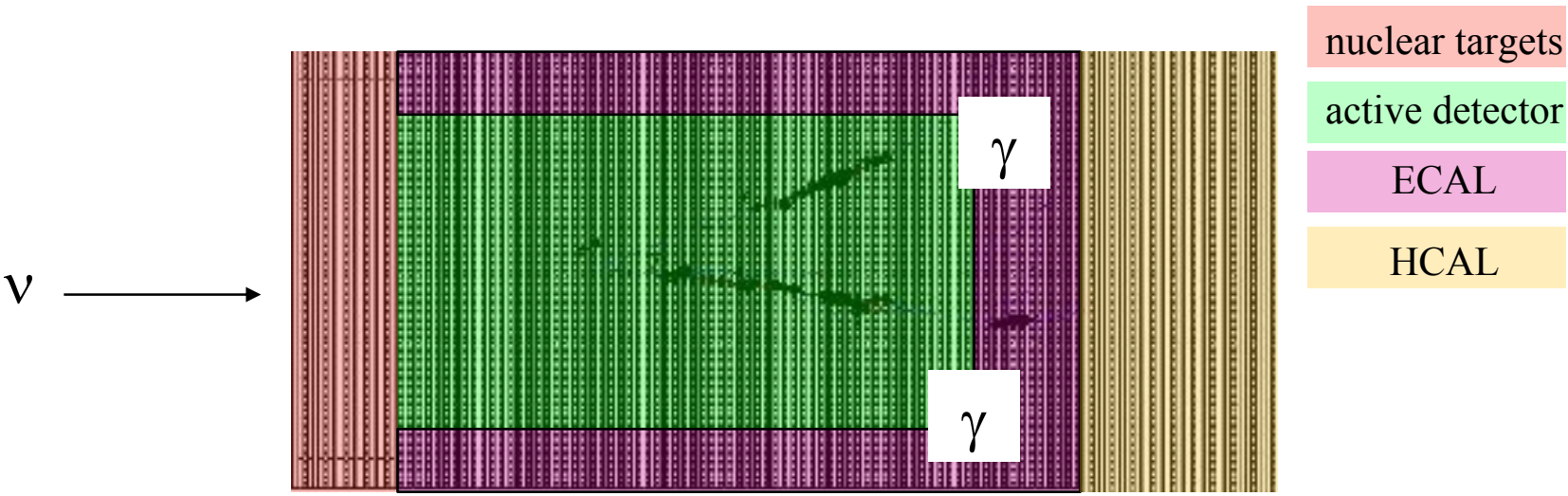


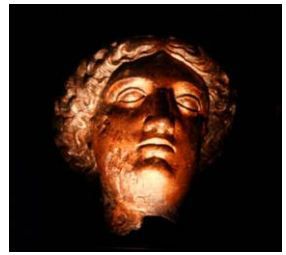
Illustration: $\nu_\mu p \rightarrow \nu_\mu \pi^0 p$



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



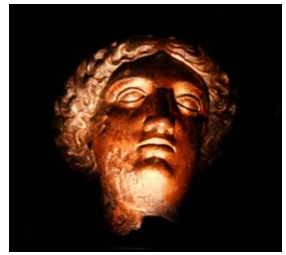




Expected Physics Results

(a sample, see hep-ex/405002)

Event Rates



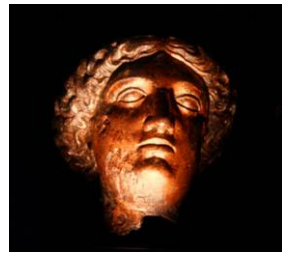
Fiducial Volume:
3 tons CH, ≈ 0.6 t C, ≈ 1 t Fe and ≈ 1 t Pb
Expected CC event samples:
8.6 M ν events in CH
1.4 M ν events in C
2.9 M ν events in Fe
2.9 M ν events in Pb

Assumes 16.0×10^{20} in LE, ME, and sHE NuMI beam configurations over 4 years

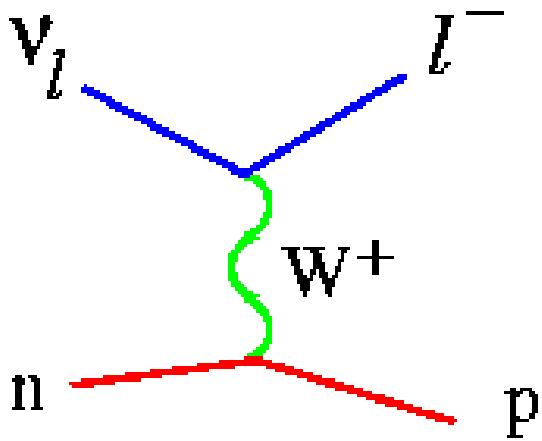
Main CC Physics Topics (Statistics in CH)

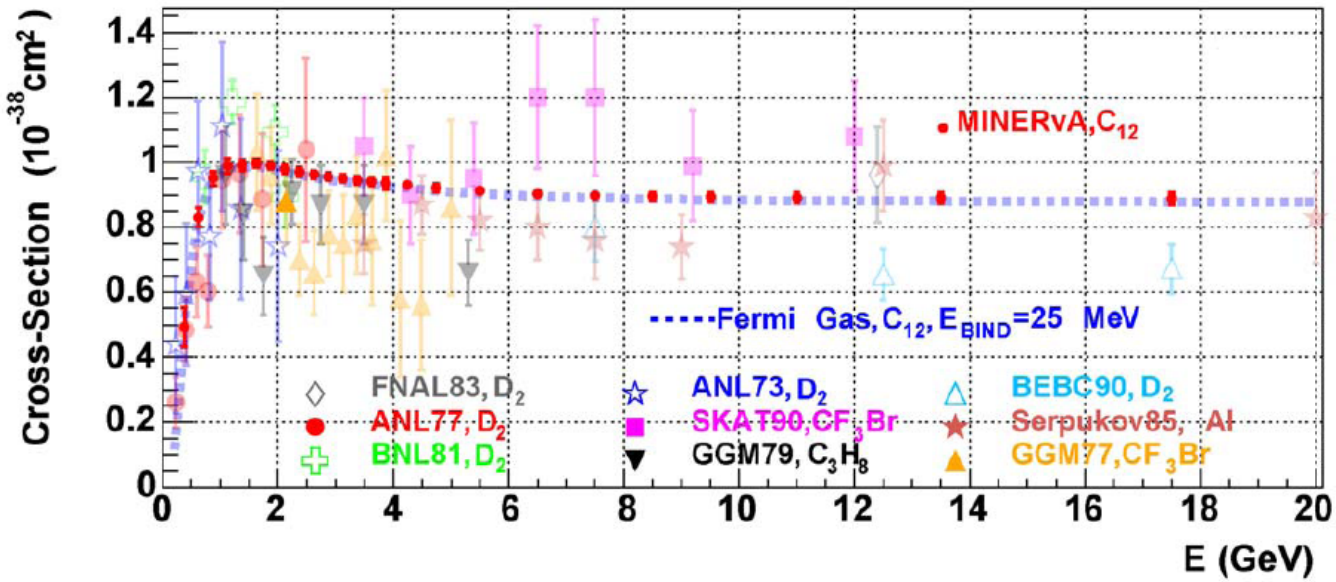
• Quasi-elastic	0.8 M events
• Resonance Production	1.6 M total
• Transition: Resonance to DIS	2 M events
• DIS, Structure Funcs. and high-x PDFs	4.1 M DIS events
• Coherent Pion Production	85 K CC / 37 K NC
• Strange and Charm Particle Production	> 230 K fully reconstructed

Quasi-Elastic Cross Section

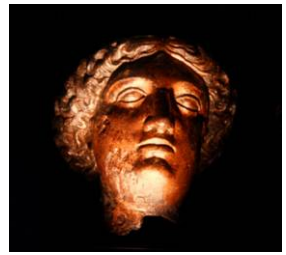


- high efficiency and purity
  - 77% and 74%, respectively
- Precise measurement of $\sigma(E_\nu)$ and $d\sigma/dQ^2$
- Nuclear effects
  - C, Fe, and Pb targets

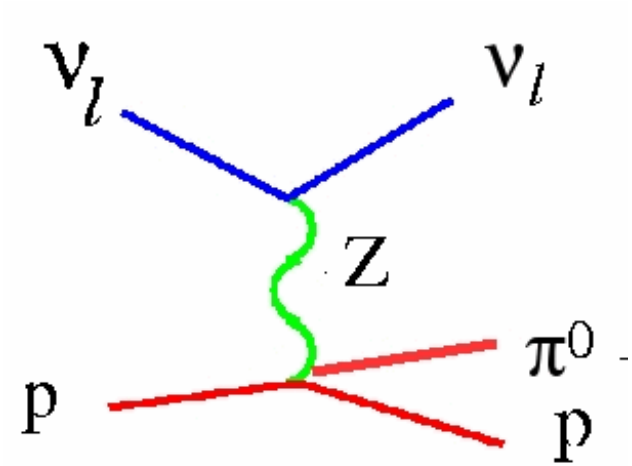




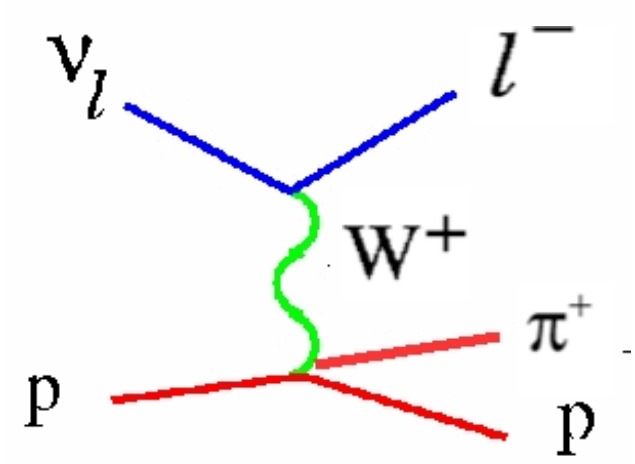
Coherent Pion Production



Neutral Current:



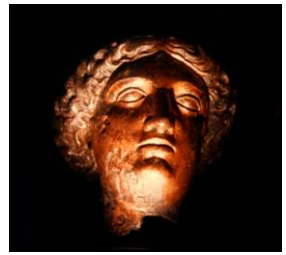
Charged Current:

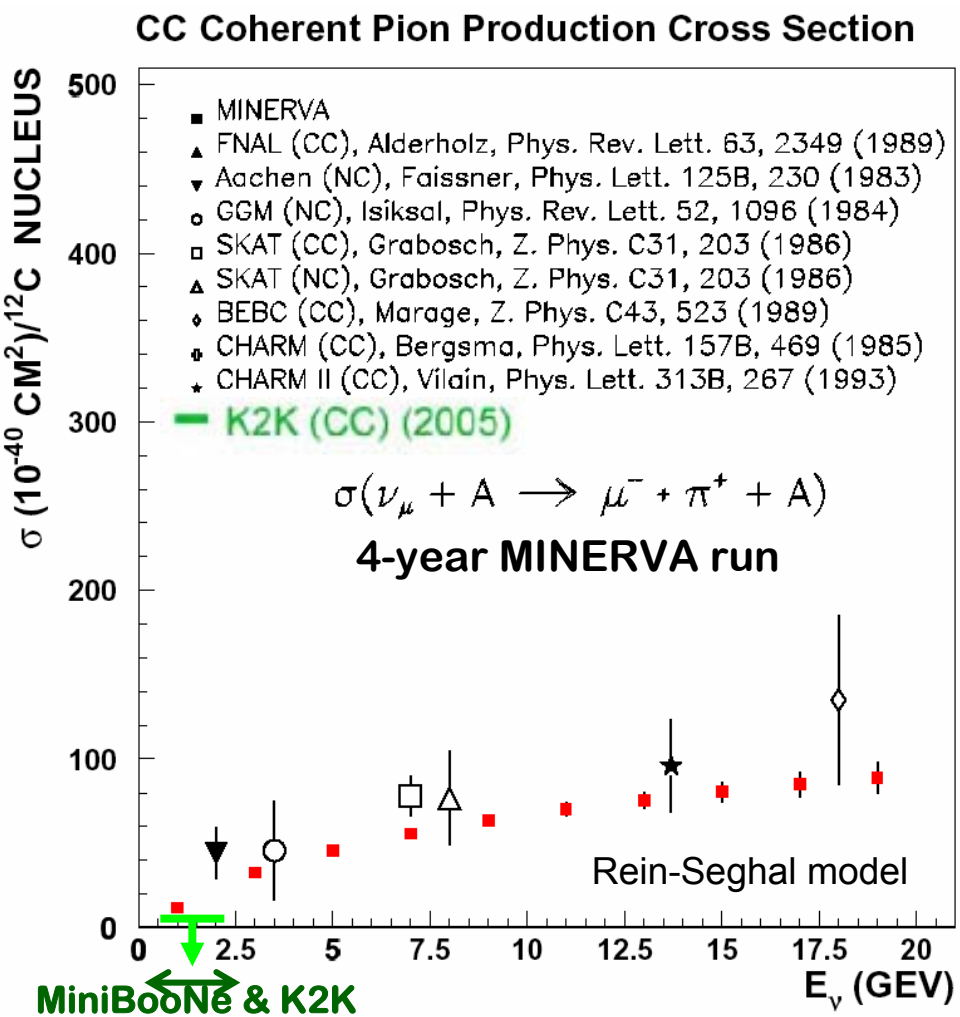


- Measure A-dependence
- Good control of coherent vs. resonance, esp. at high E
  - CC selection criteria reduces signal by factor of three
  - but reduces background by factor of 1000

- 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)

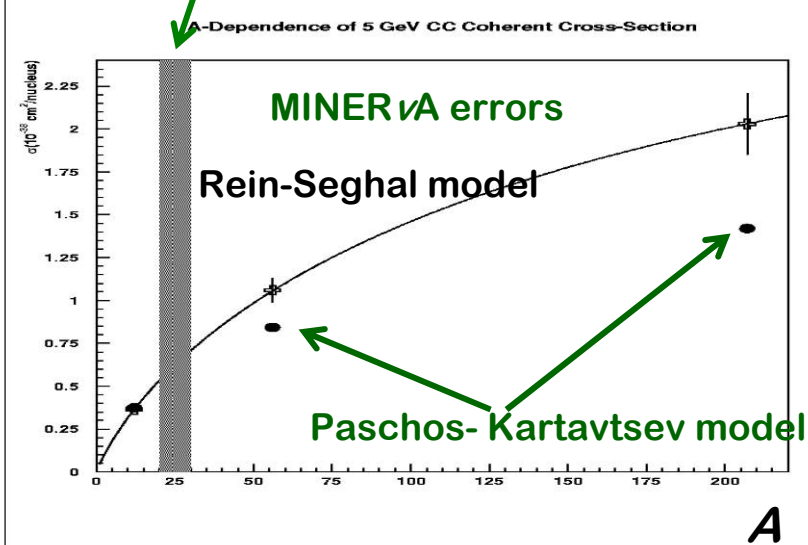
Coherent Pion Measurement





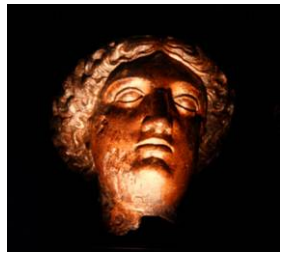
MiniBooNE & K2K measurements

A-range of current measurements before K2K !

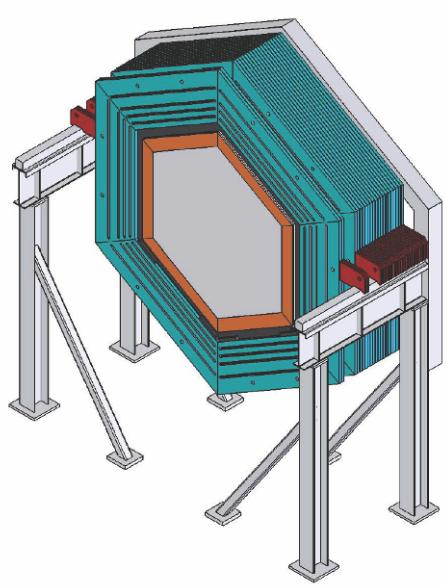


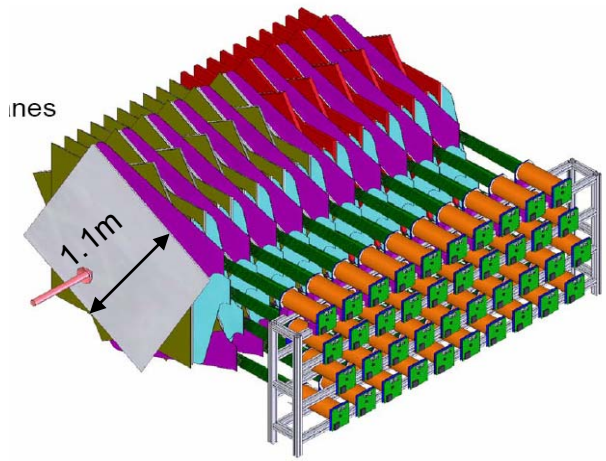
MINERνA's nuclear targets allow the first measurement of the *A*-dependence of σ_{coh} across a wide *A* range

MINERvA Schedule

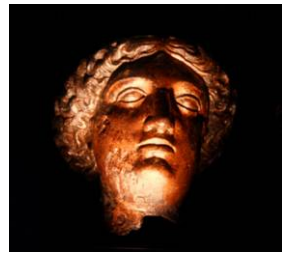


- 2008:
  - Build and test 20-frame prototype above ground
  - Start building full detector (108 frames)
  - Build Test beam detector, run in the fall
- 2009:
  - Finish building full detector
  - Install as early as possible
  - End of 2009: take data with MINOS
- 2010:
  - Low Energy Neutrino Data taking
- 2011 and beyond:
  - Medium Energy Neutrino data with NOvA



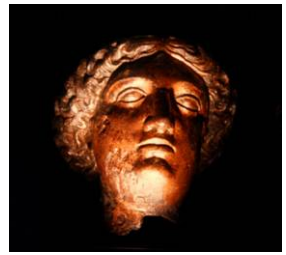


Conclusions

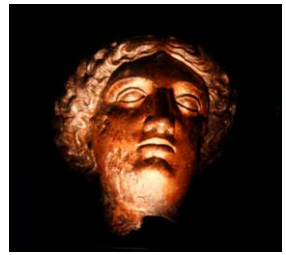


- Neutrino oscillations has a bright future with "superbeam" experiments: T2K, NOvA
  - but experiments need new information on cross-sections, or may be limited by systematics
- MINERvA is poised to measure these cross-sections over a wide range of energies
  - NuMI beamline:
    - tunable 1 – 20 GeV, precisely known neutrino flux
  - The MINERvA detector is optimized to study both inclusive reactions and exclusive final states
- We are building it now!

Backup Slides

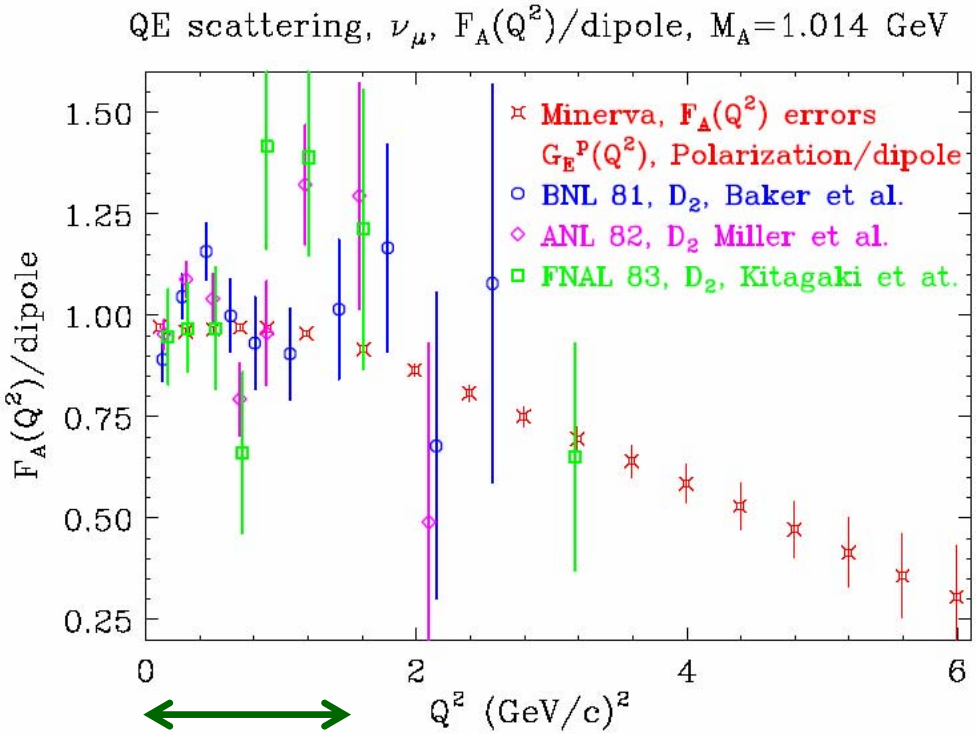


CC QE: Form Factors



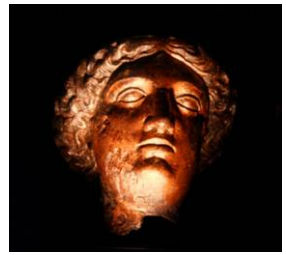
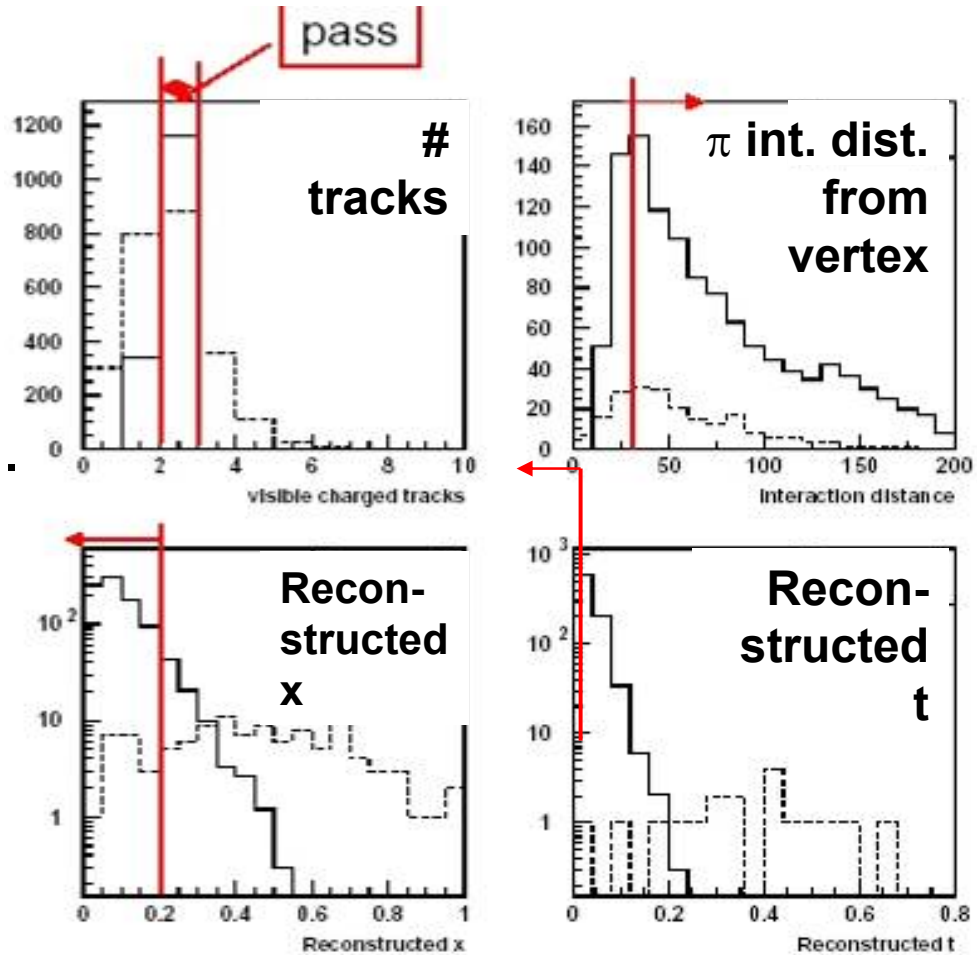
- Vector form factors measured with electrons
- G_E/G_M ratio varies with Q^2 - a surprise from JLab
- Axial form factor poorly known
- Medium effects for F_A measurement unknown
  - Will check with C, Fe, & Pb targets

Projected MINER*ν*A Measurement of Axial FF



Range of MiniBooNE & K2K measurements

Coherent Pion Production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