The MINERνA Neutrino Scattering Experiment at Fermilab

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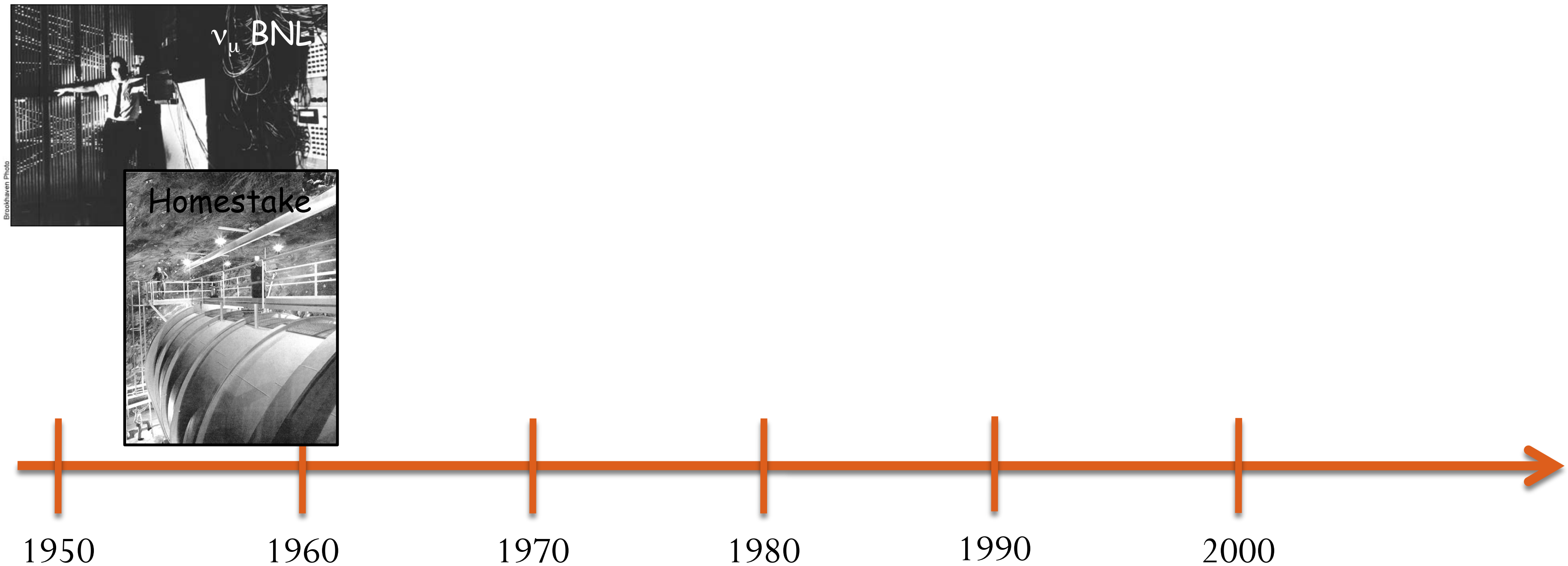
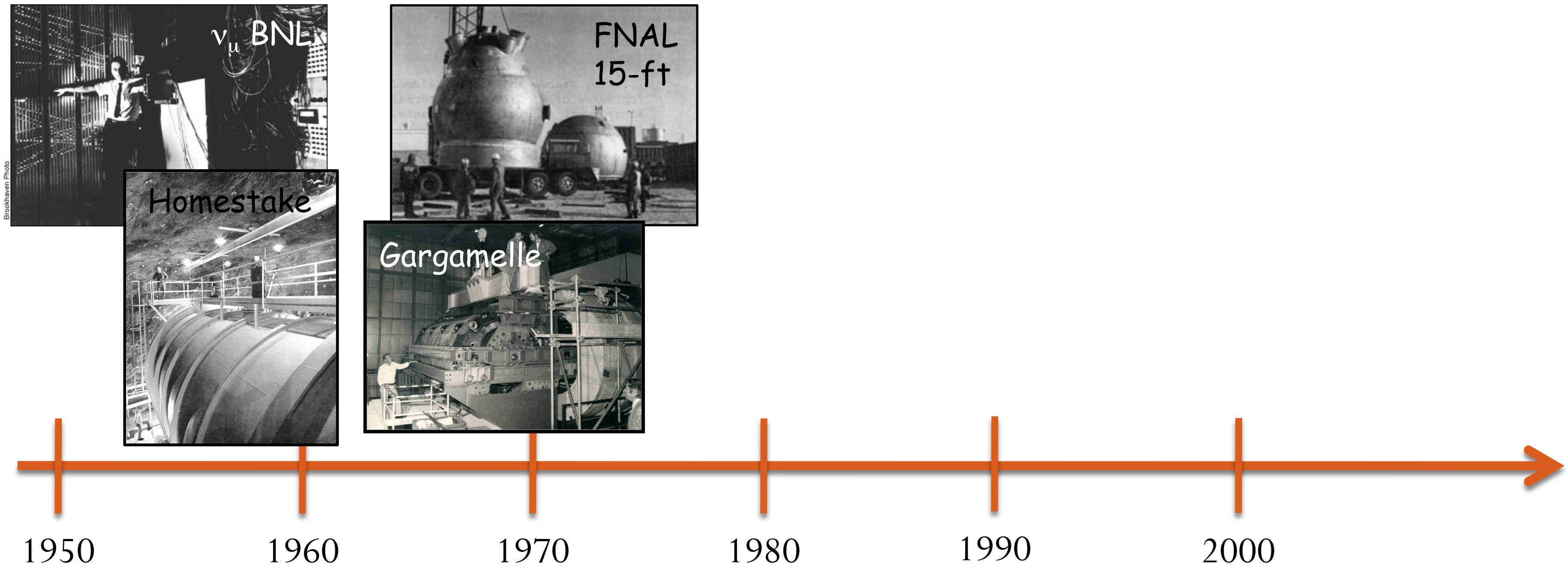
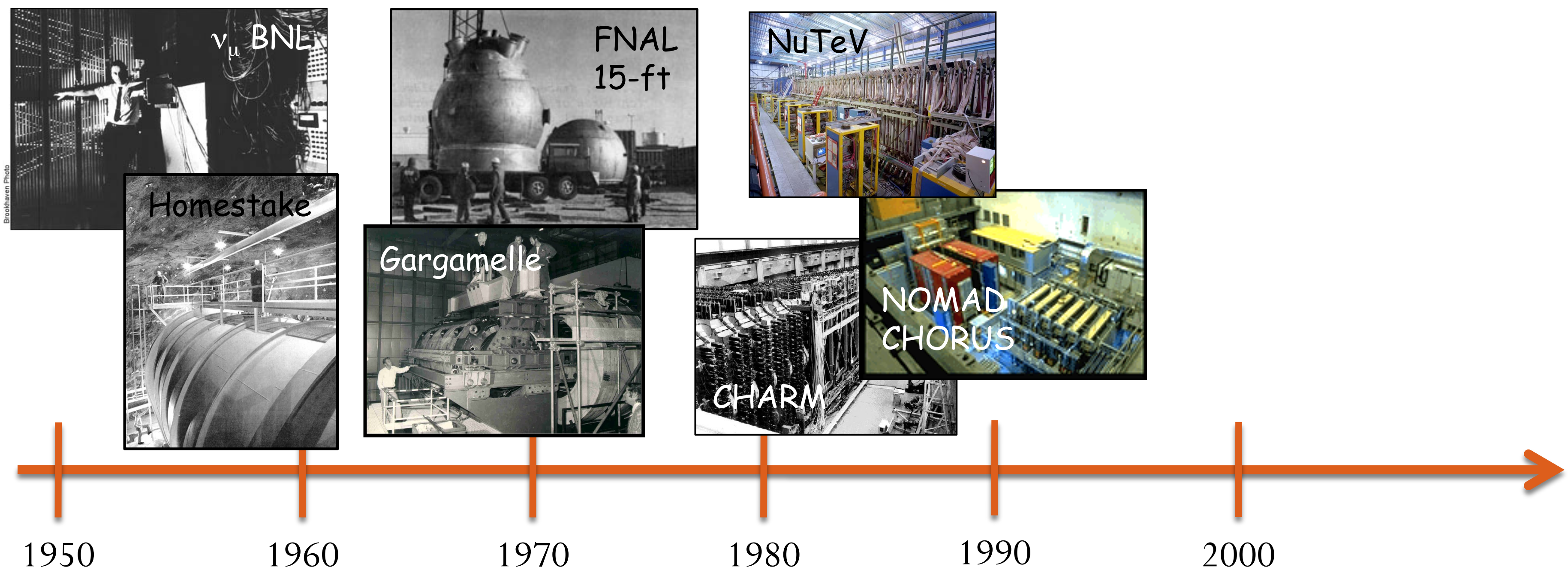
- **Introduction: Current Neutrino Physics Landscape**
  - History of Neutrino Physics in 60 seconds
  - Neutrino Oscillations: Present and Future
  - Neutrino-Nucleus Interactions: Importance for future experiments
- **MINERνA**
  - The MINERνA Experiment
  - MINERνA Status and Prospects
    - Data taking and run plan
    - Data analysis and event reconstruction
    - Looking toward first results
- **Conclusions**



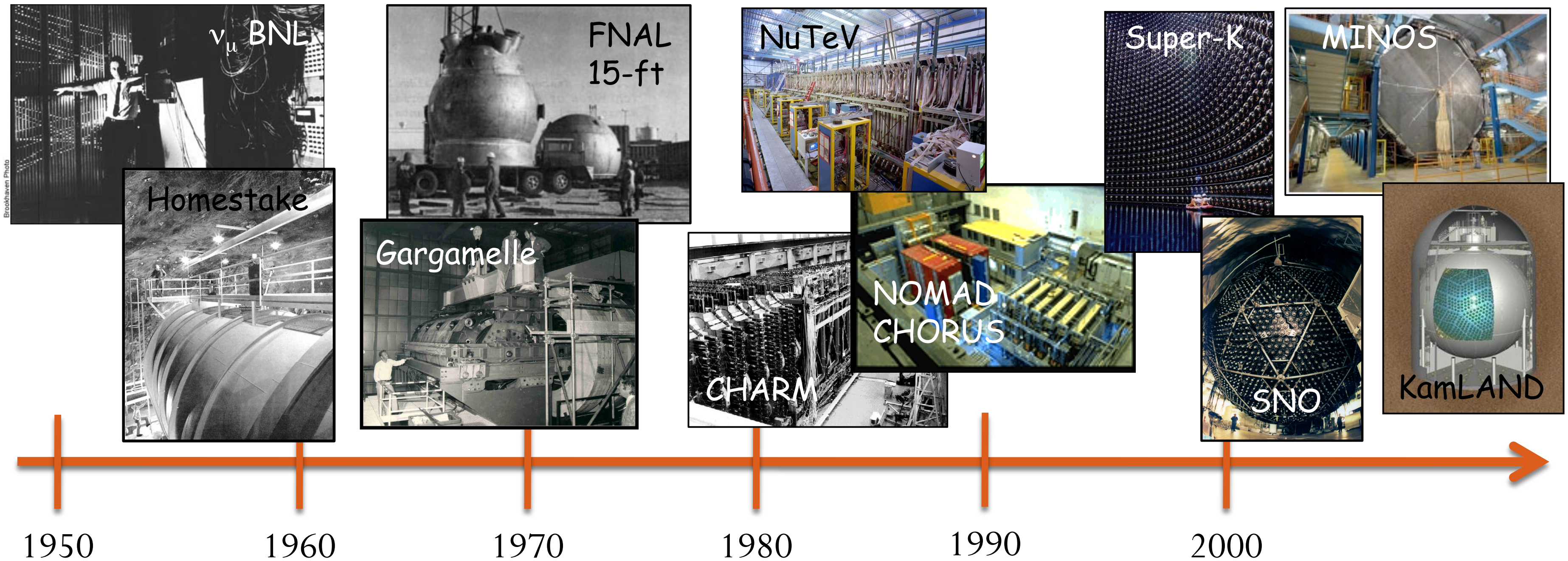
- <u>**Discovery**</u> **in the 50's and 60's**
  - First detection through inverse beta decay of electron neutrinos from a reactor
  - Discovery of muon flavor neutrino and invention of neutrino beam method
  - First detection of solar neutrinos



- **<u>Bubble Chambers</u> in the 70's and 80's**
  - ANL, BNL, FNAL, CERN, IHEP
  - Observation of weak currents
  - First neutrino cross-section measurements; some on low Z targets, deuterium
  - Experiments had small statistics and often poor knowledge of neutrino fluxes



- **<u>Counter Experiments</u> in the 80's and 90's**
  - CDHS, CHARM II, CCFR, NuTeV, NOMAD
  - Higher statistics
  - Neutrino energies generally higher, 100's of GeV
  - Rich physics programs; cross-sections, DIS, structure functions, strange sea, QCD



- **Then we discovered that <u>neutrinos oscillate</u>!**
  - Of course, evidence goes back to Ray Davis' original solar neutrino experiment
  - But it was an entire neutrino industry in the 90's and 00's that started to untangle the parameters
    - Kamiokande, SNO, KamLAND, Super-K, K2K, MINOS, Chooz, many more…
  - Has brought the field back to lower energies, MeV – 10 GeV
  - Focus on intense sources and precision measurements

- ν oscillations first postulated by Pontecorvo in 1957, based on analogy to kaons
- Non-zero mass implies mass eigenstates ≠ flavor eigenstates

flavor states participating in standard weak interactions with charged lepton partners →

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

mixing matrix describing mass state content of flavor states

mass states

- Different ν masses allow for changes in lepton flavor composition as ν propagates:

$$P(\nu_\alpha \to \nu_\beta) = |\langle \nu_\beta | \nu_\alpha(L)\rangle|^2 = \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2[1.27\Delta m^2_{ij} L/E]$$
$$+2\sum_{i>j} \Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2[2.54\Delta m^2_{ij} L/E]$$

- $\mathbf{U_{xy}}$: elements of mixing matrix
- $\Delta m_{ij}^2 = m_i^2 - m_j^2$: mass squared splitting between states
- **L** : the travel path–length of the neutrino
- **E** : the energy of the neutrino

- ν oscillations first postulated by Pontecorvo in 1957, based on analogy to kaons
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Simplified case of direct 2 neutrino oscillations

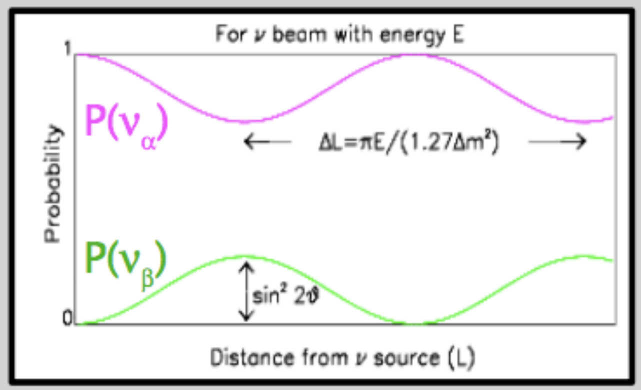
$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos(\theta_{ij}) & \sin(\theta_{ij}) \\ -\sin(\theta_{ij}) & \cos(\theta_{ij}) \end{pmatrix} \begin{pmatrix} \nu_i \\ \nu_j \end{pmatrix}$$

$$\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$$

determines shape of oscillation probability as function of E (or L)

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta_{ij}) \sin^2\left(1.27 \Delta m_{ij}^2 \frac{L}{E}\right)$$

determines amplitude for oscillation ~ probability



- ν oscillations first postulated by Pontecorvo in 1957, based on analogy to kaons
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- **The two neutrino oscillation formula showed up in my undergraduate quantum mechanics textbook:**

> "This is about the simplest nontrivial quantum system conceivable. It is a crude model for neutrino oscillations. . . . . At present this is highly speculative – there is no experimental evidence for neutrino oscillations; however, a very similar phenomenon does occur in the case of neutral K-mesons."
>
> David J. Griffiths – *Introduction to Quantum Mechanics* (Problem 3.58) 1995

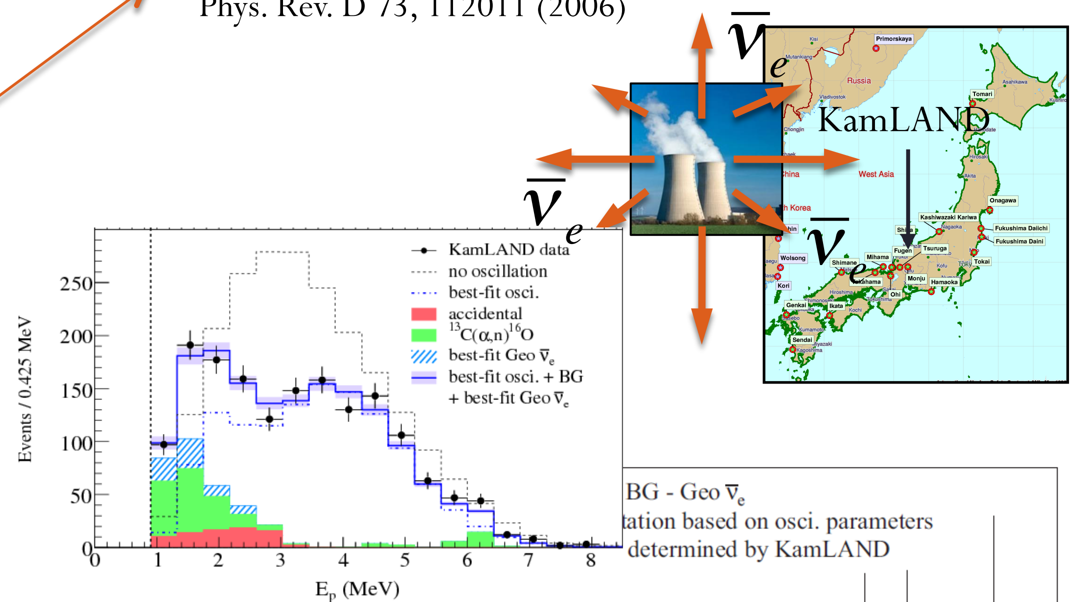
- **Let's see how the evidence has changed in 15 short years…**

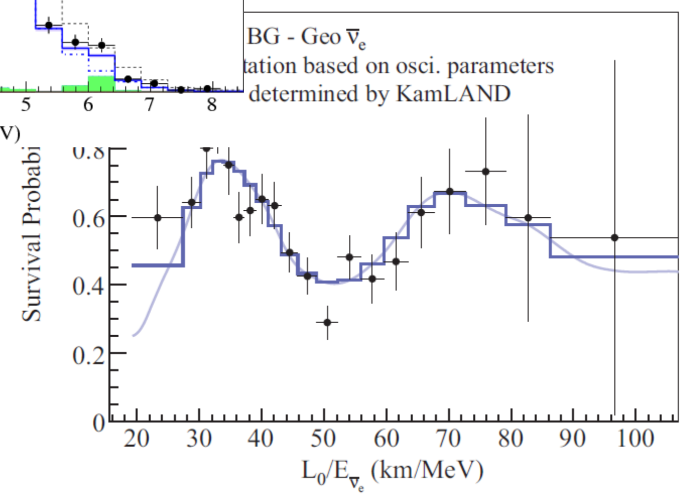
Δm^2_{12}

- First experimental evidence came from electron neutrinos from the sun (Ray Davis at Homestake)
- Confirmation of the oscillation hypothesis came from the **SNO** solar neutrino experiment which could see all neutrino types through NC interactions
- Precision measurements of Δm^2_{12} and θ_{12} came from **KamLAND** in Japan using antineutrinos produced by power reactors

Super-K ν_e seen / ν_e expected: $0.451^{+0.017}_{-0.015}$

Phys. Rev. D 73, 112011 (2006)



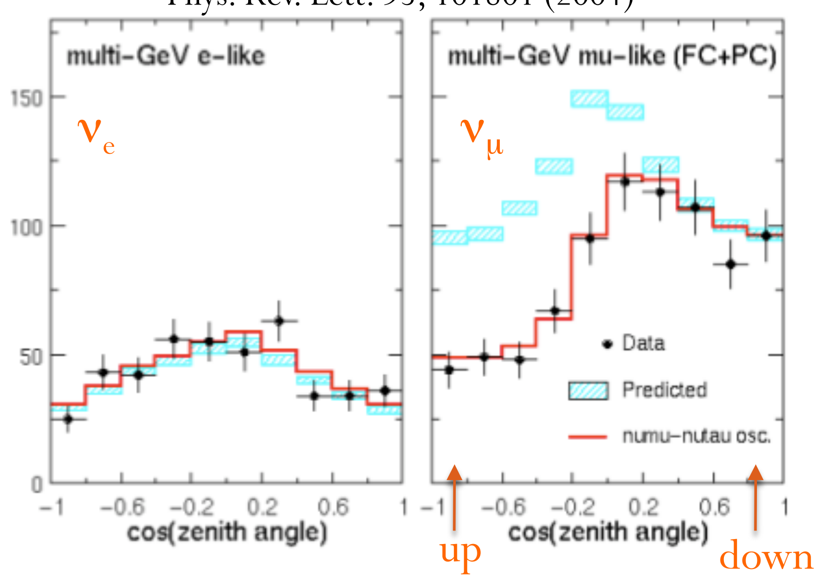


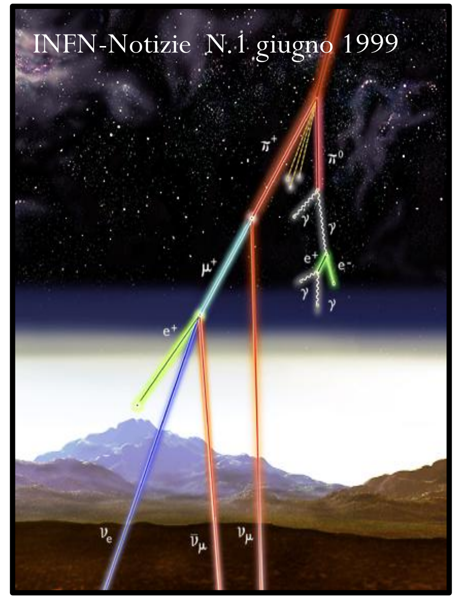
Phys. Rev. Lett. 100, 221803 (2008)

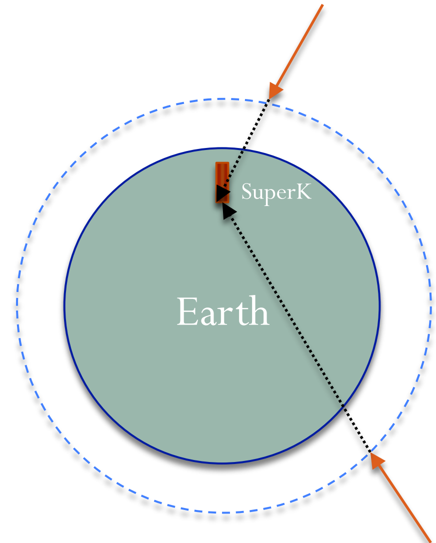
Δm^2_{23}

- First experimental evidence came from neutrinos produced in the atmosphere by cosmic rays
- Again **Super-K** makes a pivotal contribution

Phys. Rev. Lett. 93, 101801 (2004)







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

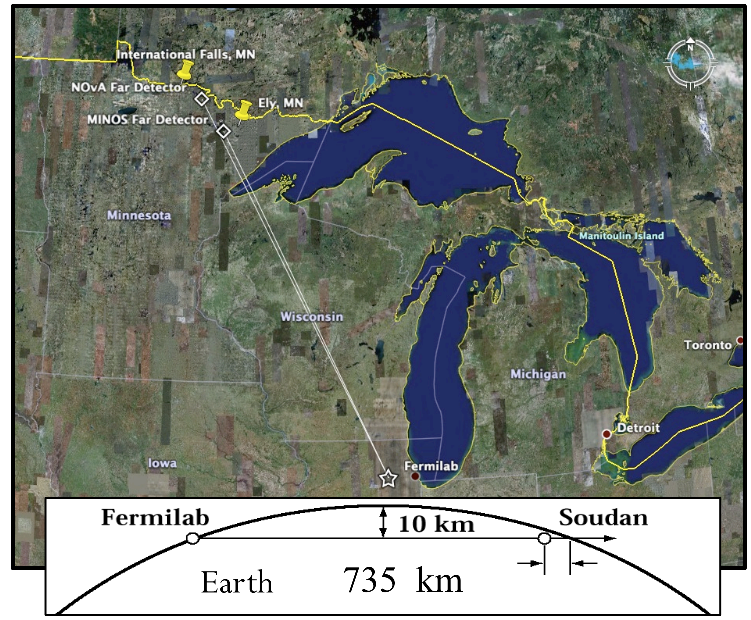
$$\langle E \rangle_{Super-K} \approx 1 - 10\ GeV$$

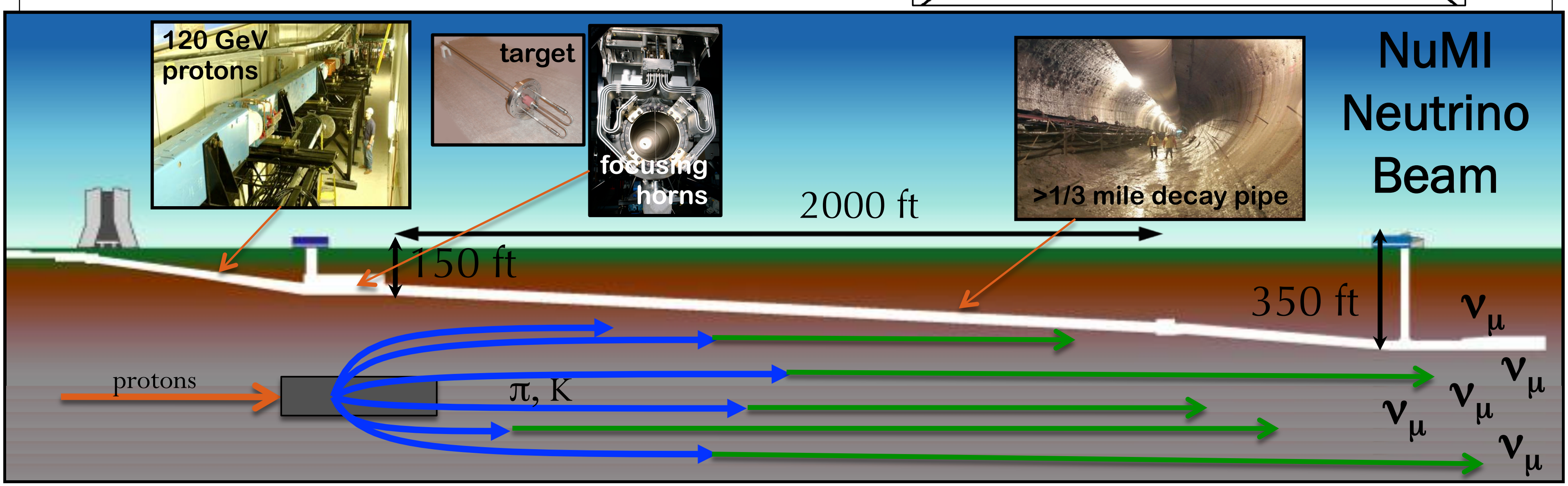
$$\langle L \rangle_{Super-K} \approx 10 - 10^4\ km$$

$$\Delta m^2 \sim 10^{-4} - 1\, eV^2$$

Δm^2_{23}

- First experimental evidence came from neutrinos produced in the atmosphere by cosmic rays
- Most precise measurement of Δm^2_{23} from accelerator-based experiments, **MINOS**.





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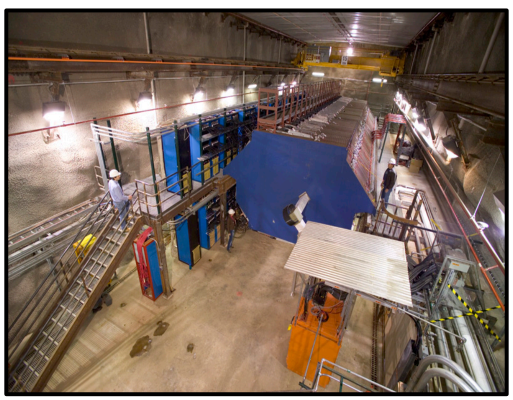
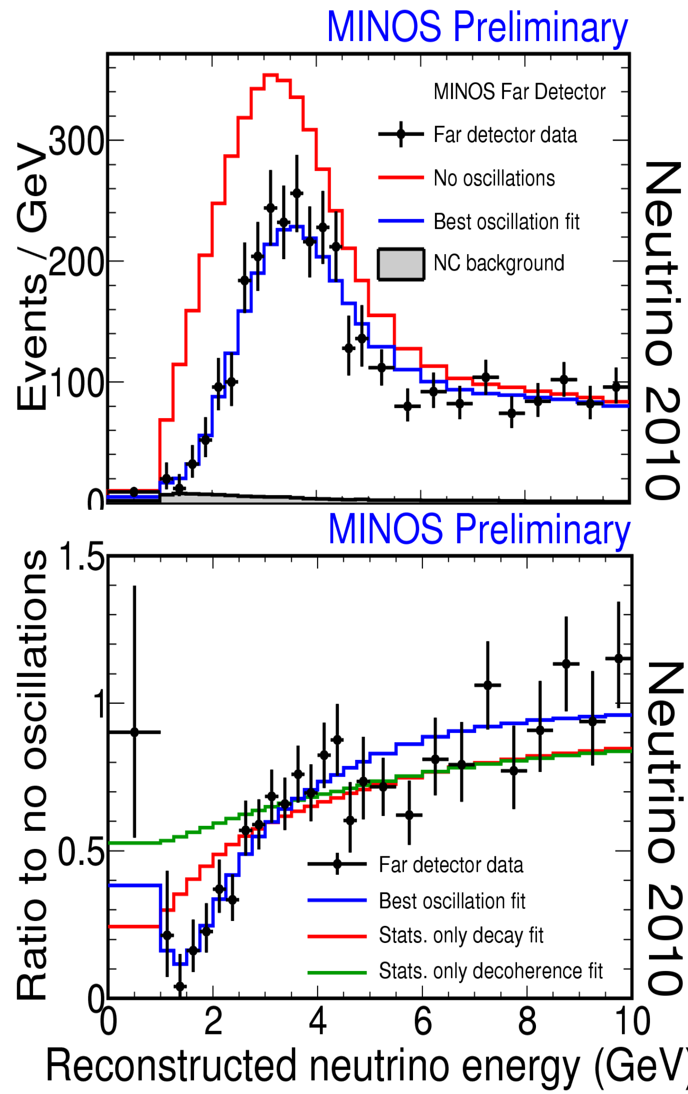

MINOS near detector at Fermilab


MINOS far detector at Soudan, MN



Neutrino Mixing Summary:

- **Atmospheric, accelerator experiments**

$$\Delta m^2_{23} = 2.51 \times 10^{-3} eV^2 \quad (\pm 4.8\%)$$

$$\theta_{23} = 42.3^{\circ}{}^{+5.3}_{-2.8} \quad (+12.5\%)$$

- **Solar, reactor experiments**

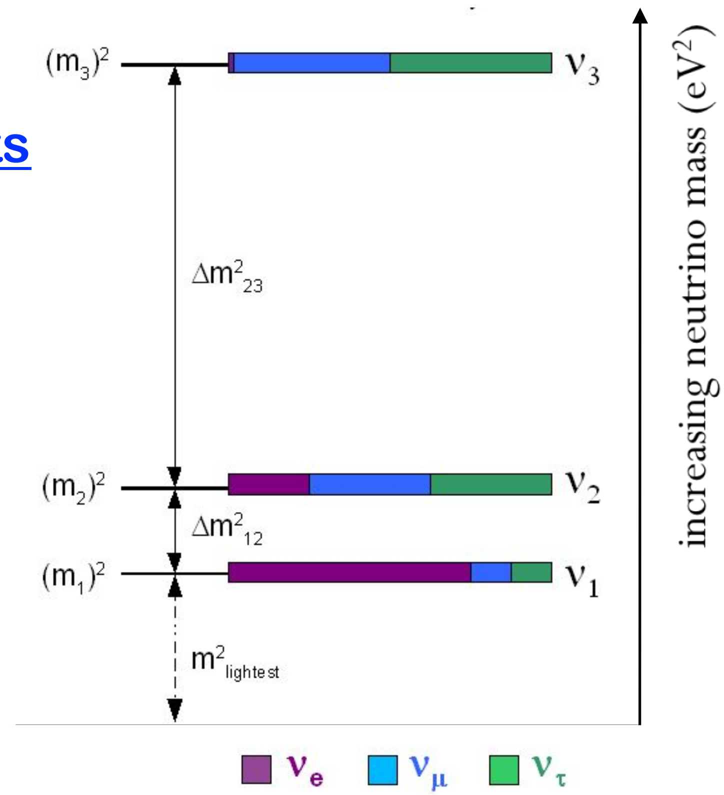
$$\Delta m^2_{12} = 7.59 \times 10^{-5} eV^2 \quad (\pm 2.6\%)$$

$$\theta_{23} = 34.4^{\circ}{}^{+1.0}_{-1.0} \quad (\pm 2.9\%)$$

- **Reactor, accelerator experiments**

$$\theta_{13} < 9.4^{\circ} \quad (1\sigma)$$

* parameter values from global fits to data, hep-ph 1001.4524



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{-i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- <u>**Many Open Questions Remain:**</u>

Why is neutrino mixing so different from quark mixing?

Why is θ_{23} near maximal?

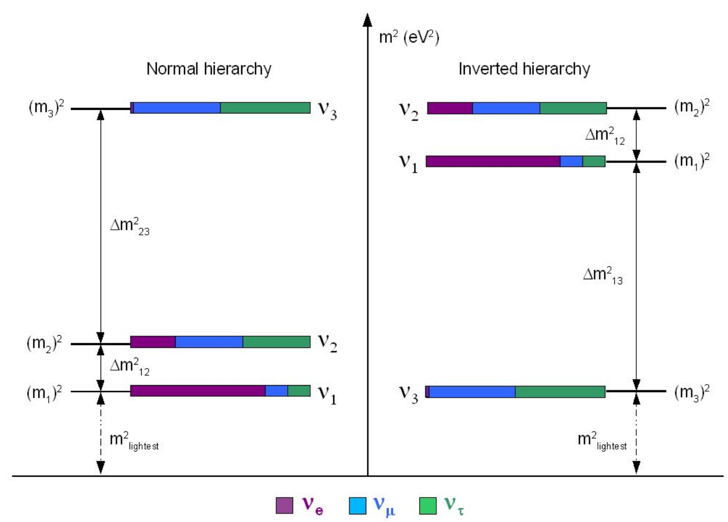
What is θ_{13}? Why is it so small?

Is there CP violation in the neutrino sector?

What is the mass hierarchy?

$$U_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0 \\ 0.2 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$ Quarks

$$U_{MNS} \sim \begin{pmatrix} 0.8 & 0.6 & 0 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$ Neutrinos



Complimentary Experimental Approaches:

- **Short-baseline reactor-based experiments (Double Chooz, Daya Bay)**
  - Unambiguous search for mixing angle θ_{13} through observation of $\overline{\nu}_e$ disappearance

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \cdot \sin^2(1.27 \cdot \Delta m^2_{23} \cdot L/E)$$

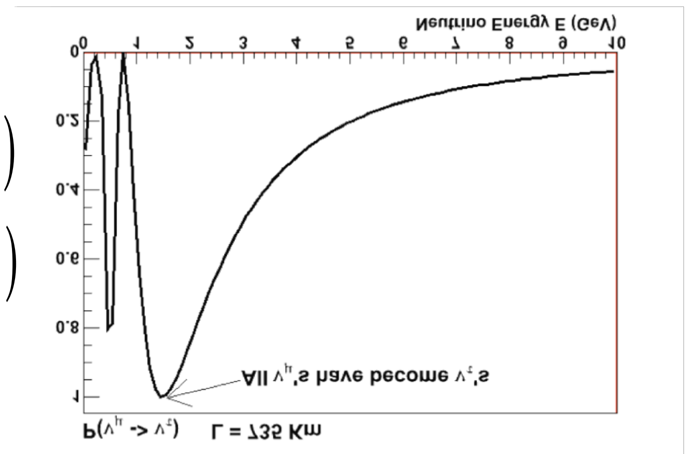
- **Long-baseline accelerator-based experiments (T2K, NOvA, LBNE)**
  - Sensitivity to θ_{13}, θ_{23}, sign(Δm^2_{23}), and ~~CP~~ through observation of ν_μ to ν_e appearance in both neutrinos and antineutrinos

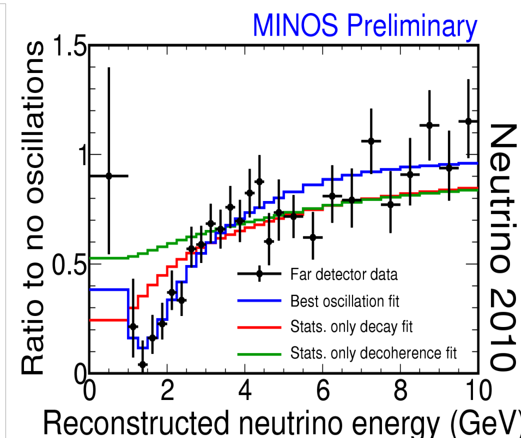
$$P(\nu_\mu \rightarrow \nu_e) \qquad P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$

- **Why the search for θ_{13} and δ^{CP} is a paradigm shift in long-baseline accelerator-based neutrino oscillation experiments**
- K2K and MINOS measured the disappearance of muon neutrinos

$P(\nu_\mu \rightarrow \nu_\tau)$

$P(\nu_\mu \rightarrow \nu_\mu)$





- Transformation to ν_e is a sub-dominant oscillation effect at the Δm^2_{23} scale, so ν_μ disappearance can be analyzed as an **effective two-neutrino system ν_μ to ν_τ**

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - P(\nu_\mu \rightarrow \nu_\tau) = 1 - \sin^2 2\theta_{23} \cdot \sin^2\left(\frac{1.27 \cdot \Delta m^2_{23} \cdot L}{E}\right)$$

- **Why the search for θ_{13} and δ^{CP} is a paradigm shift in long-baseline accelerator-based neutrino oscillation experiments**
- Measuring the conversion to ν_e must be done as a small-scale appearance of ν_e

$$P(\nu_\mu \rightarrow \nu_e) \cong \sin^2 2\theta_{13} T_1 - \alpha \sin 2\theta_{13} T_2 - \alpha \sin 2\theta_{13} T_3 + \alpha^2 T_4$$

$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$$

$$T_1 = \sin^2\theta_{23} \frac{\sin^2[(1-x)\Delta]}{(1-x)^2}$$

$$T_2 = \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \sin\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$

CP Violating

$$T_3 = \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$

CP Conserving

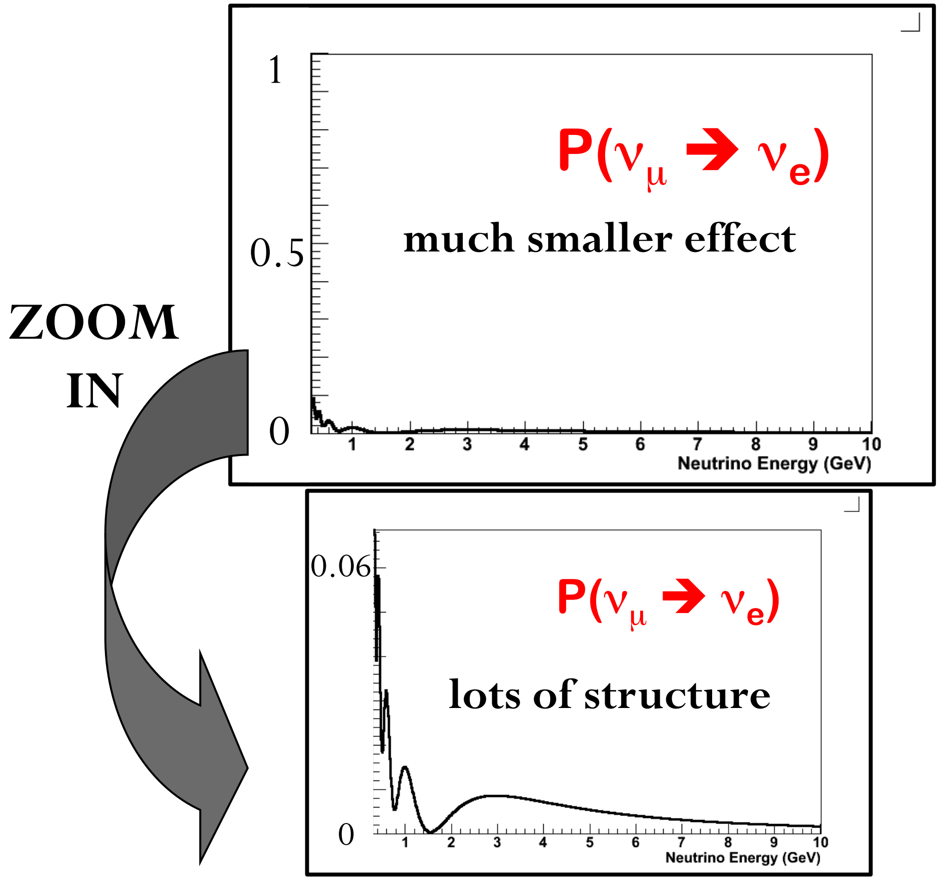
$$T_4 = \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(x\Delta)}{x^2}$$

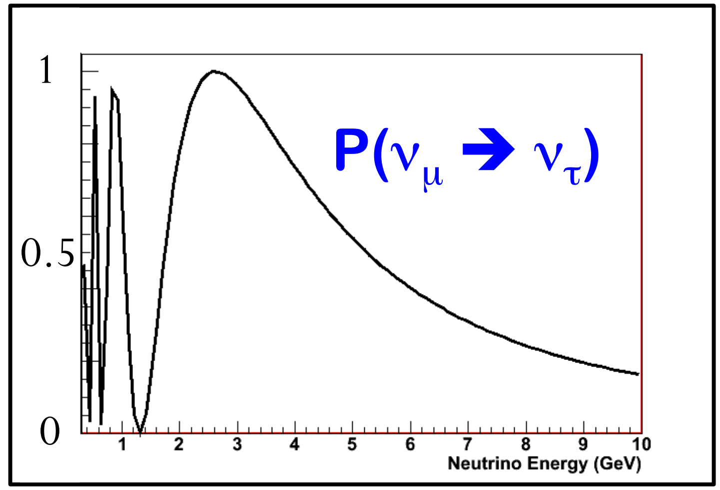
$$\Delta = \frac{\Delta m^2_{31} L}{4E_\nu} \qquad x = \frac{2\sqrt{2} G_F N_e E_\nu}{\Delta m^2_{31}}$$

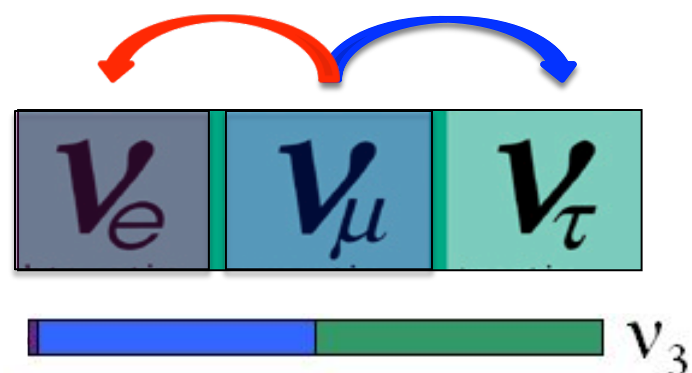
Matter Effects

Rich physics in this next stage!!

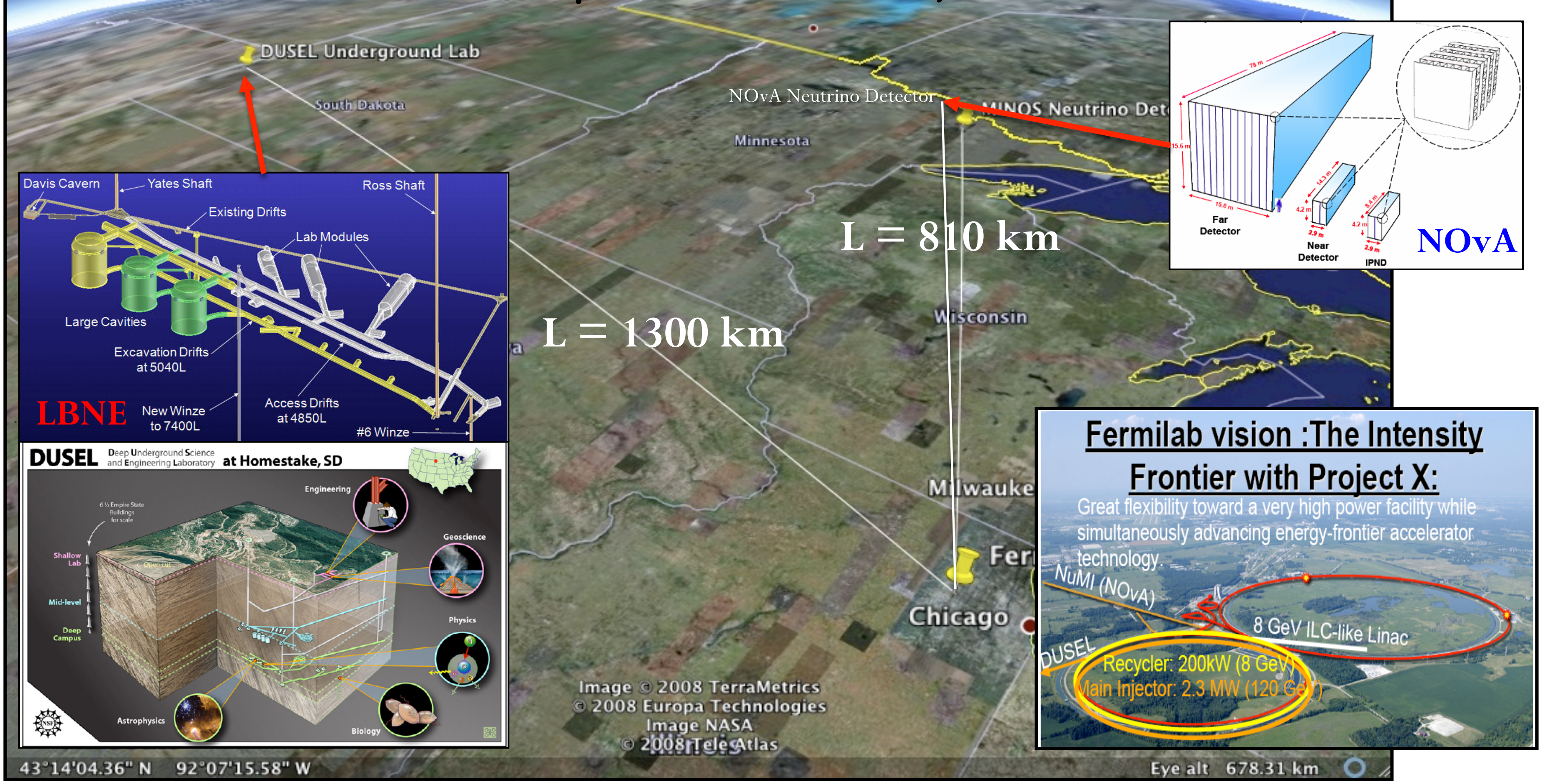
- **Why the search for θ_{13} and δ^{CP} is a paradigm shift in long-baseline accelerator-based neutrino oscillation experiments**



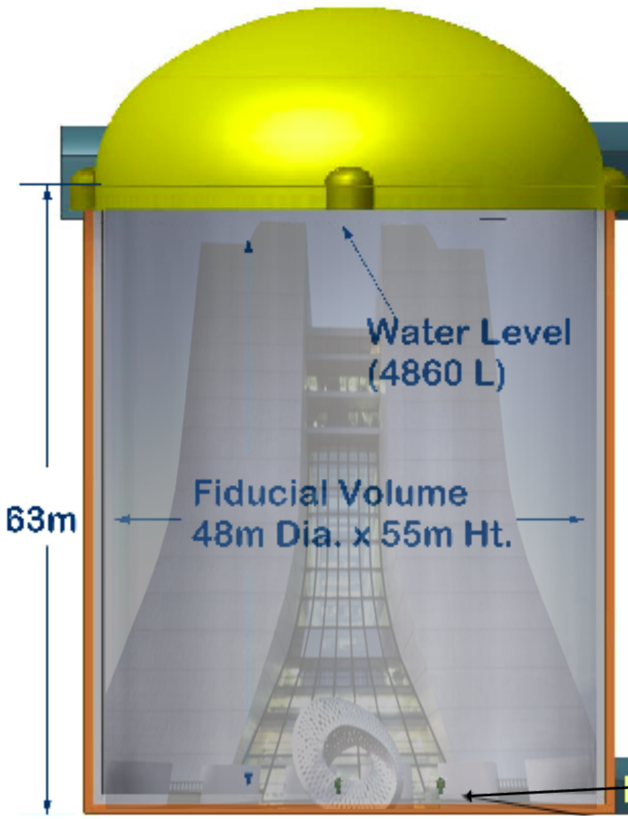




- Next generation US accelerator-based long-baseline (LBL) neutrino oscillation experiments. NOνA, LBNE



- **Long-Baseline Neutrino Experiment (LBNE)**
  - **Neutrino beam from Fermilab to distant, very large neutrino detectors**
  - **Baseline designs involve 100 kton scale water Cherenkov detector(s) AND/OR 17 kton liquid argon TPC neutrino detector(s)**

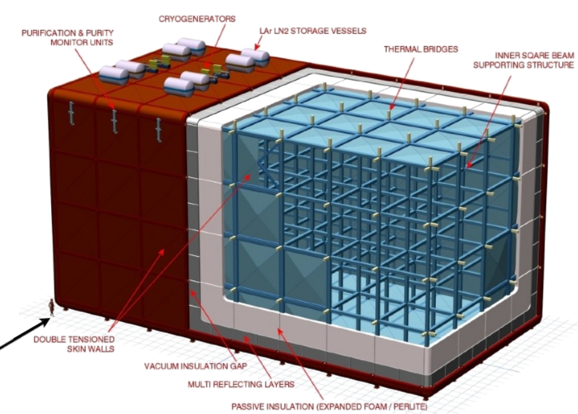


Long Baseline ν Physics
- θ_{13}, Mass Hierarchy, and CP violation
- Osc. parameters precision measurements

Proton Decay

Supernova Burst/Relic neutrinos

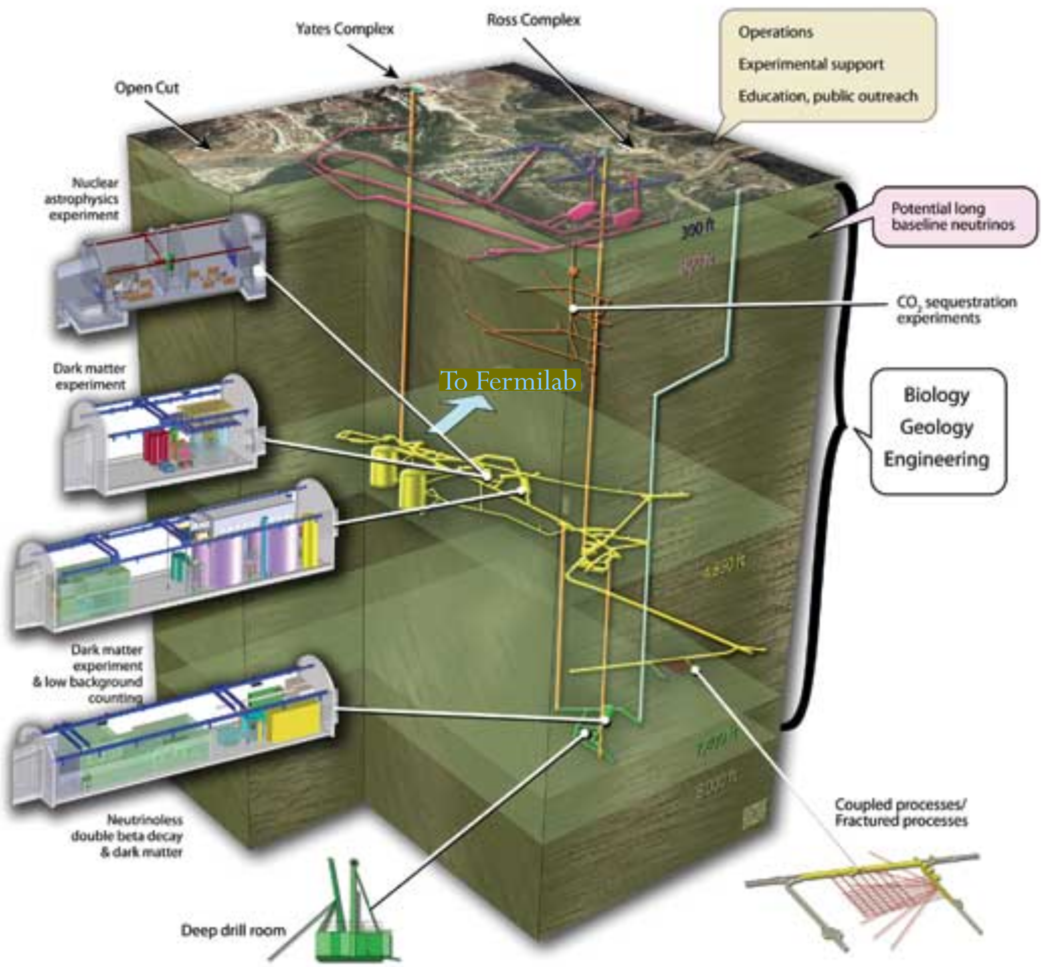
Atmospheric/Solar/UHE neutrinos



neutrino physicists

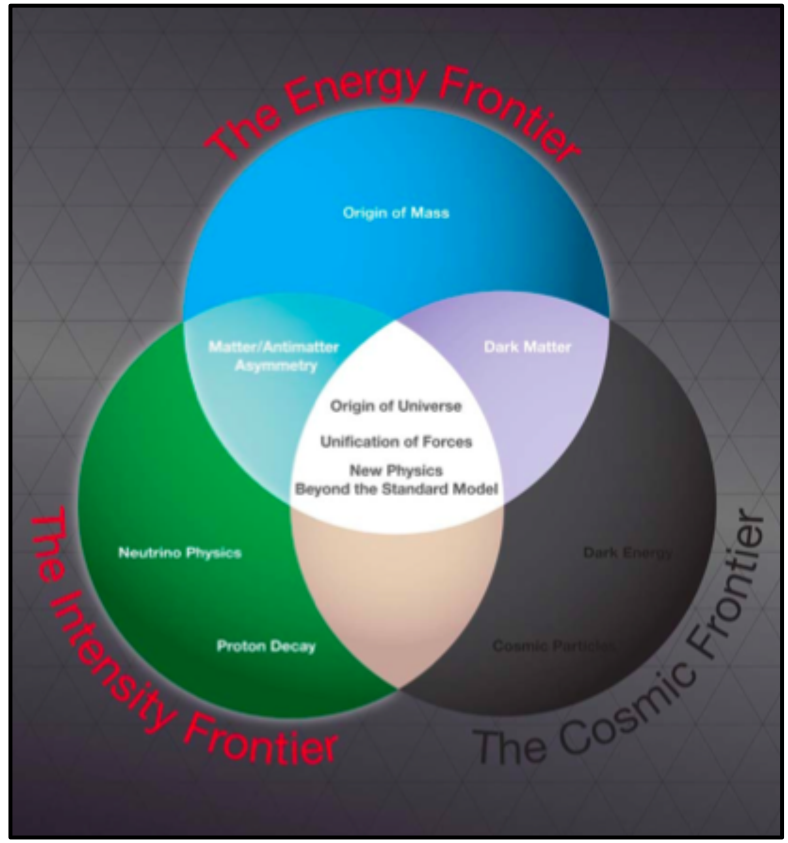
- **Long-Baseline Neutrino Experiment (LBNE)**
- **Deep Underground Science and Engineering Laboratory (DUSEL)**

  - Multi-disciplinary national underground lab (physics, biology, geology, engineering)
  - Homestake gold mine in Lead, South Dakota
  - At 1300 km from Fermilab with large, deep caverns, a perfect site for LBNE detectors



- **Long-Baseline Neutrino Experiment (LBNE)**
- **Deep Underground Science and Engineering Laboratory (DUSEL)**
- **Project X (Project X)**

  - **Fermilab accelerator project which could increase neutrino intensities ~3x while creating the most intense muon, kaon beams for other physics**
  - **Develop to serve as the front end of future facilities: neutrino factory and muon collider**
  - **Could be path to next energy frontier**

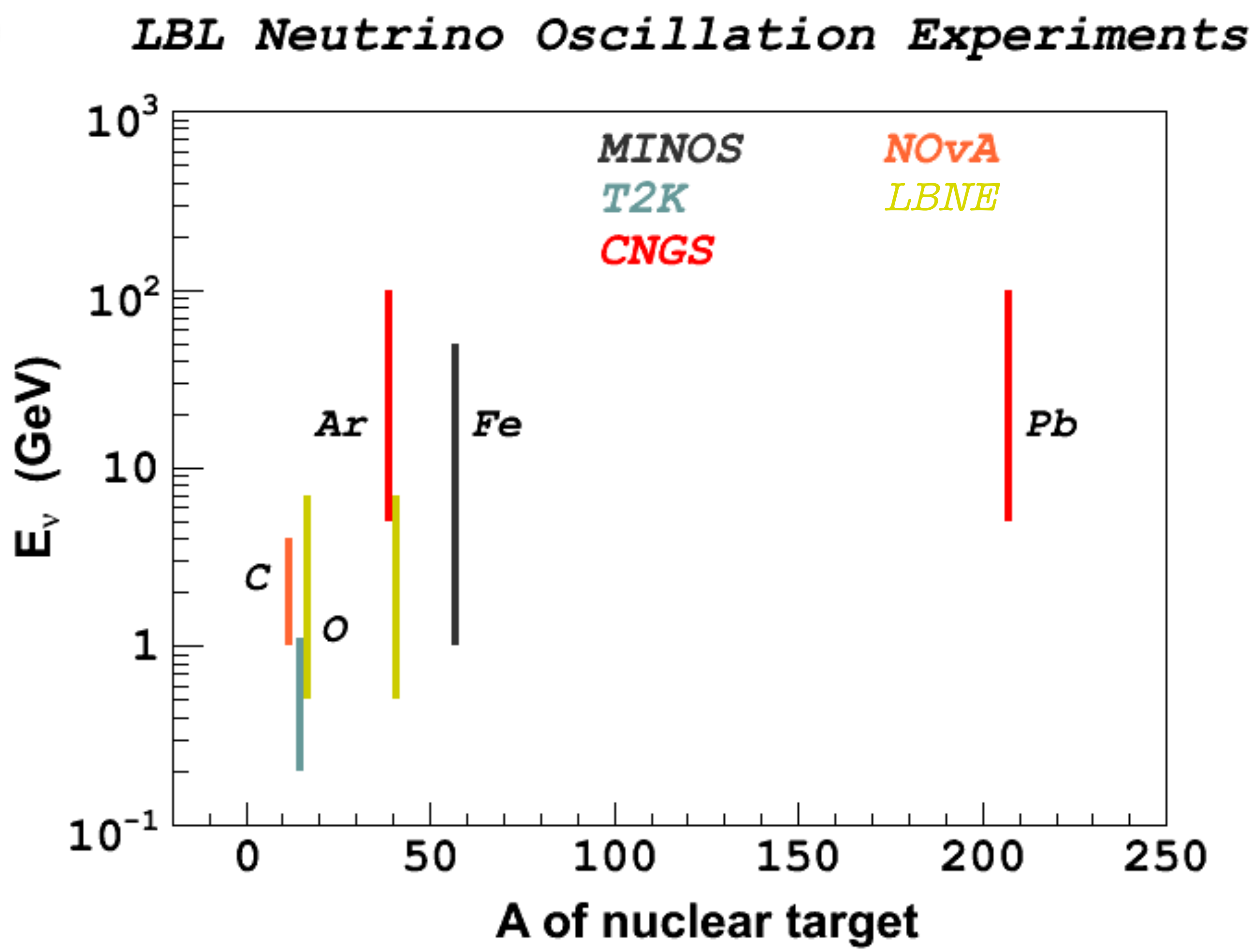


- **Discovery of neutrino oscillations has meant two things for neutrino cross-section physics:**
  - Suddenly we really **care about neutrino cross-sections in the 0.5-10 GeV range** where they are not well measured and the channels are complicated – particularly for new generation of LBL oscillation experiments where statistical errors are approaching systematic errors
  - Suddenly there are **lots of high intensity neutrino beams around the world in the 0.5-10 GeV range** for making these measurements

- **Neutrino energy ranges and detector target materials are crucial aspects of oscillations experiments with regard to neutrino cross-sections:**
  - The need is simple (in principle) – **determine the neutrino flavor and measure its energy**, but…
  - The dominant **interaction channels** change rapidly across the few GeV neutrino energy region
  - Oscillation experiments use **detectors of heavier nuclei** to increase event rates
  - **Nuclear effects** are very complicated and not well known, so the target nucleus has a large impact on how well we can remove backgrounds and understand the kinematics of the final state

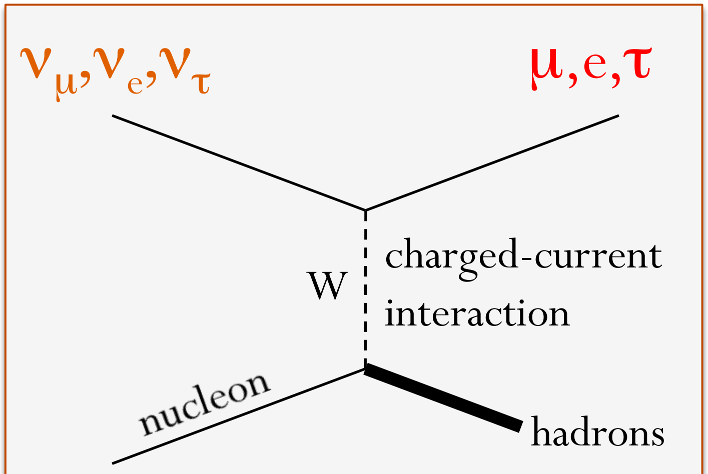
Nuclear targets
Neutrino energies
Interaction channels

- Target Materials:
  - MINOS = Fe
  - CNGS = Pb, Ar
  - T2K = H_2O
  - NOvA = C
  - LBNE = H_2O, Ar

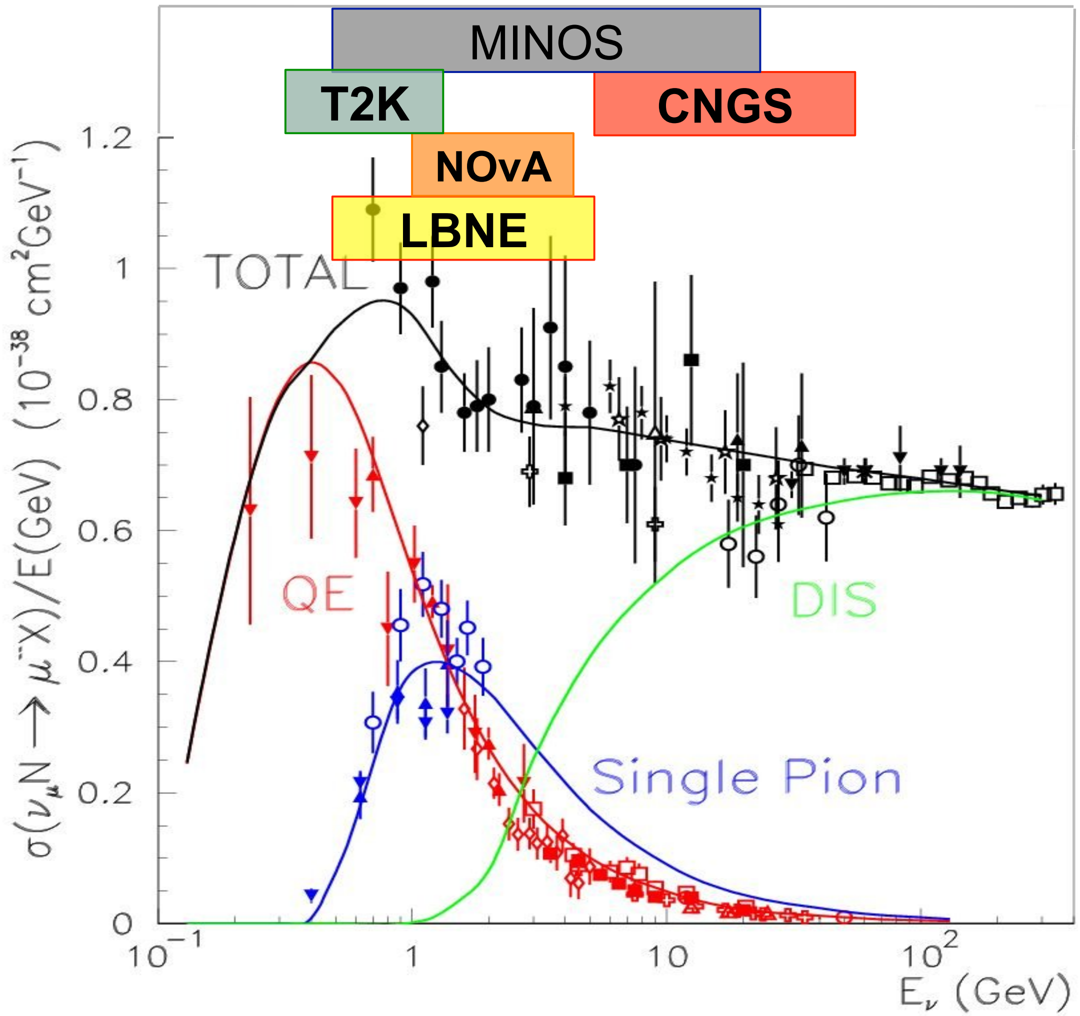


Nuclear targets
Neutrino energies
Interaction channels

- Projection onto the neutrino energy axis tells us which interactions are most important for these experiments



ν_μ charged-current cross-sections



Nuclear targets
Neutrino energies
Interaction channels

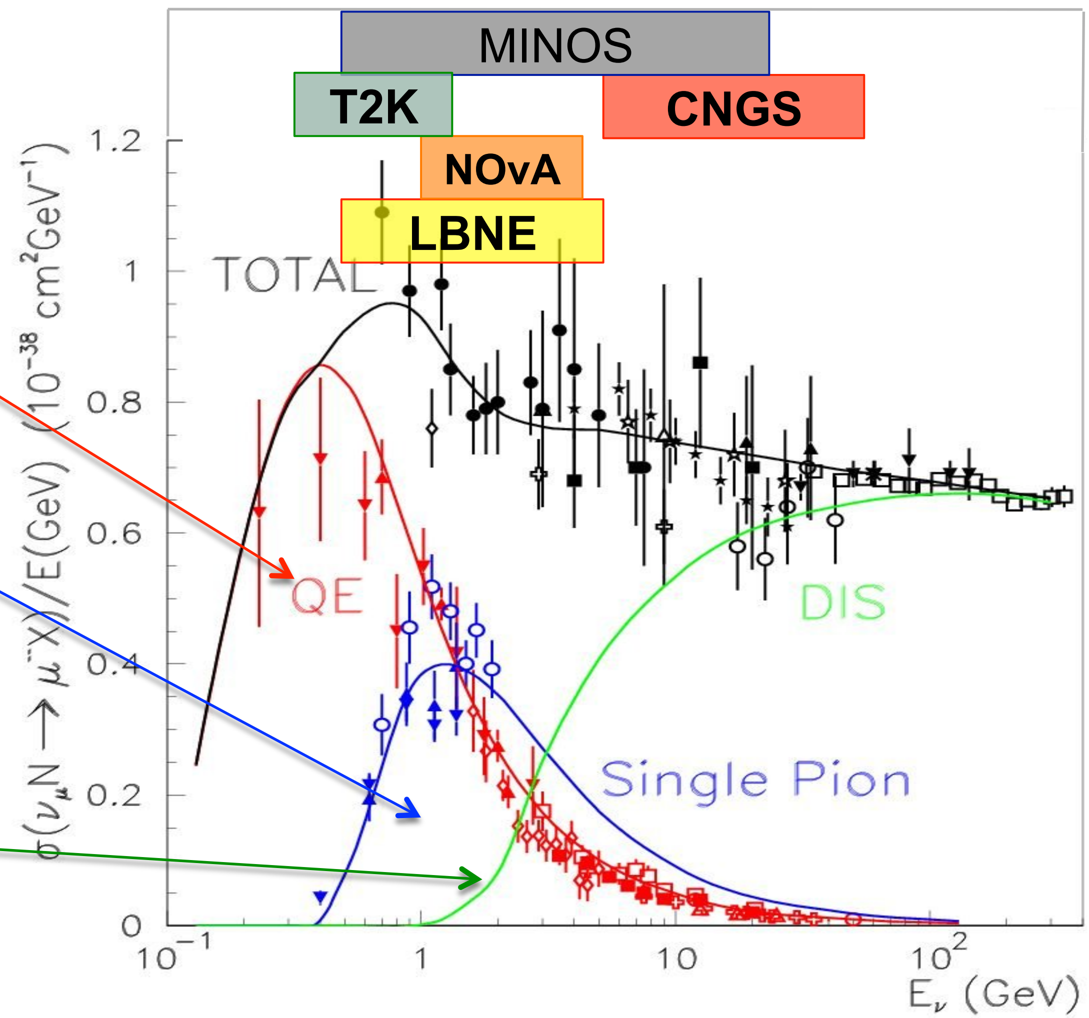
Quasi-Elastic
common signal channel in LBL oscillation experiments

NC π^0 (not shown)
background for ν_e appearance

CC π^+
background for ν_μ CCQE

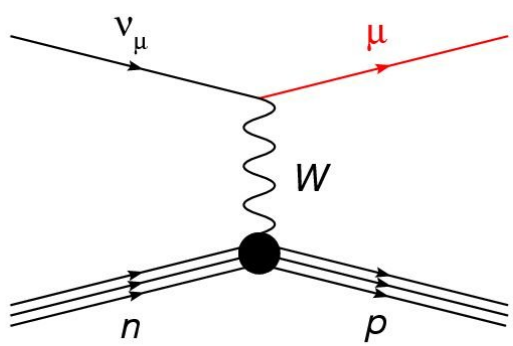
DIS
need to extrapolate into low energy region

ν_μ charged-current cross-sections



Quasi-Elastic

signal channel in LBL oscillation experiments

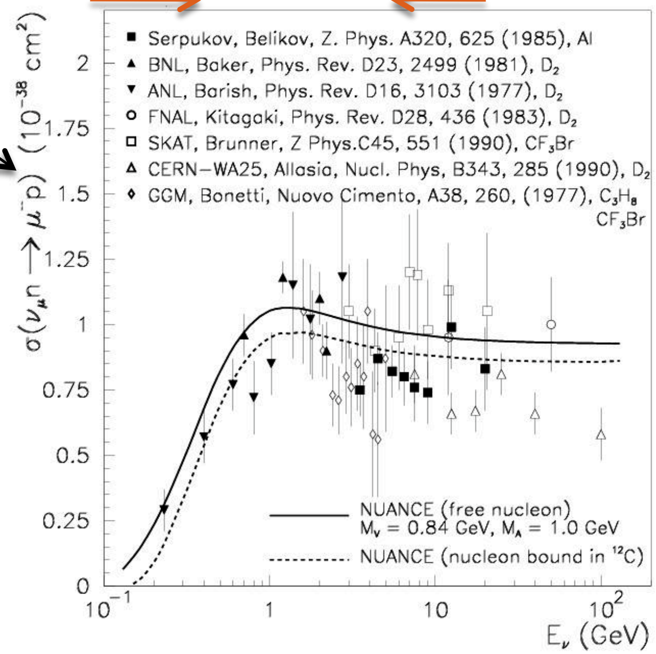


~40% spread across expts

10-20% errors on data sets

relevant for osc expts

no /E(GeV)

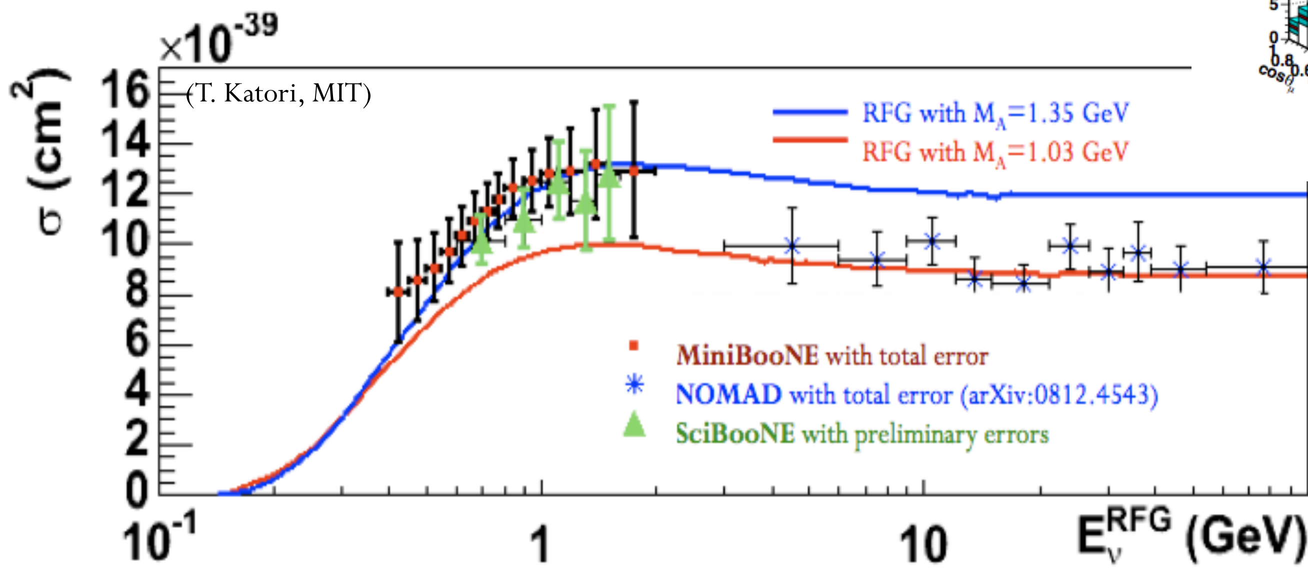


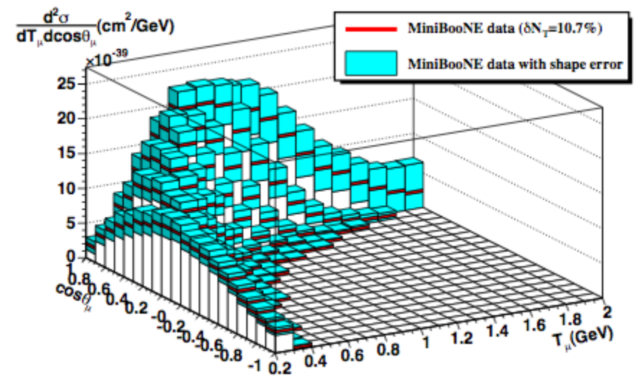
- CCQE is the signal channel for many oscillation experiments
- Clean final state with two identifiable particles (μ,p) or (e,p)
- Muons and electrons simple to separate for ν_μ/ν_e ID
- Final state allows neutrino energy reconstruction with one or both tracks

$$E_\nu^{QE} = \frac{2(m_N - \varepsilon_B) - (\varepsilon_B^2 - 2m_N\varepsilon_B + m_\ell^2 + \Delta M^2)}{m_N + \varepsilon_B - E_\ell + p_\ell \cos(\theta_\ell)}$$

Quasi-Elastic

signal channel in LBL oscillation experiments



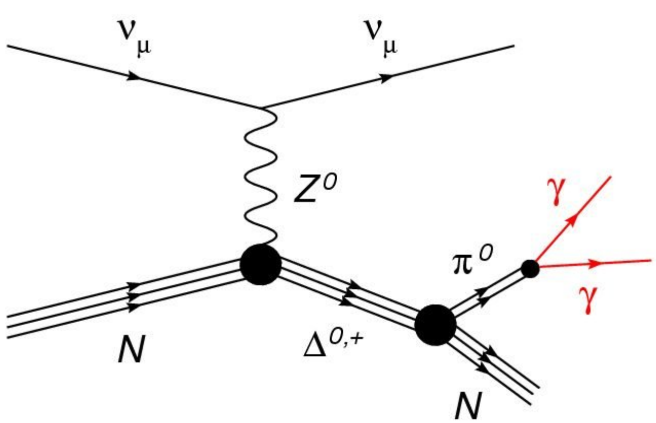


New era of measuring differential cross-sections in neutrino interactions

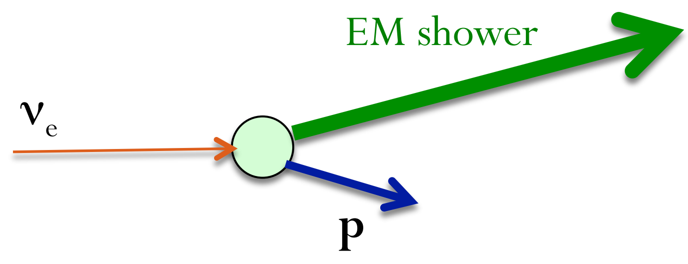
- **Recent MiniBooNE/SciBooNE results in agreement, but tension with higher energy NOMAD results. All three on carbon. Not yet understood.**
- **Leaves one in a dilemma if want to predict how many QE events you expect!**

NC π^0 production

background for ν_e appearance

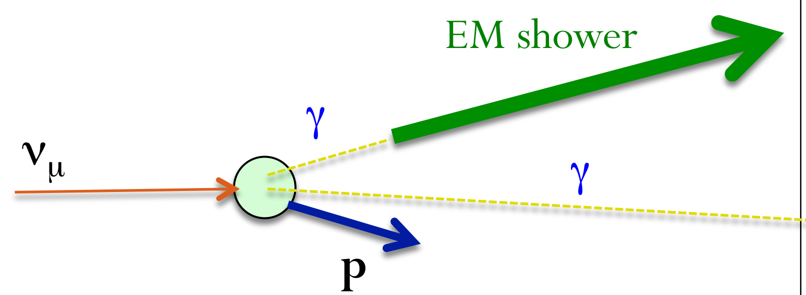


ν_e CCQE



$$\nu_e + n \rightarrow p + e^-$$

ν_μ NC π^0



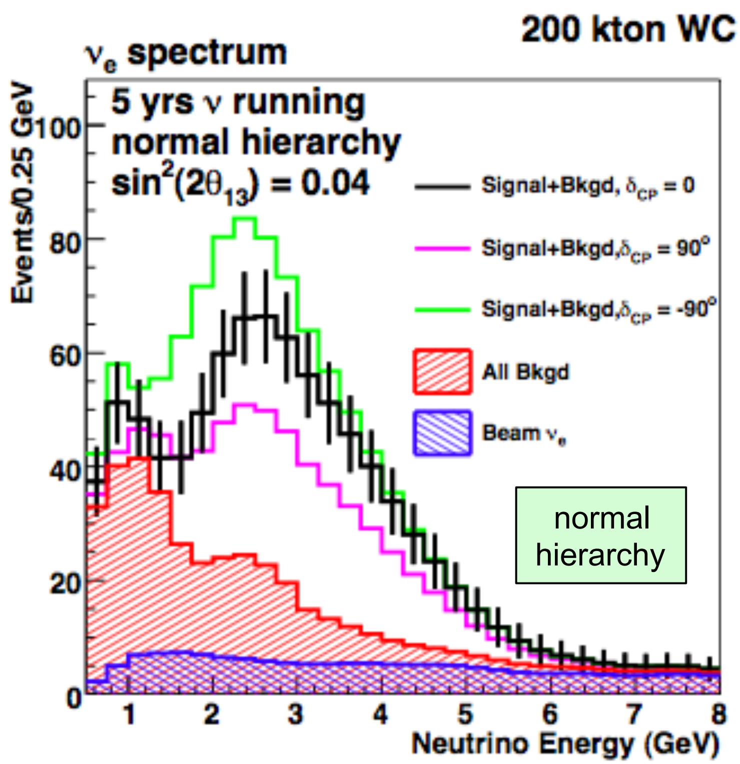
$$\nu_\mu + p \rightarrow p + \pi^0 \rightarrow \gamma + \gamma$$

- **Neutral pions create a bkgd to ν_e CCQE events if one photon is missed in event reconstruction**

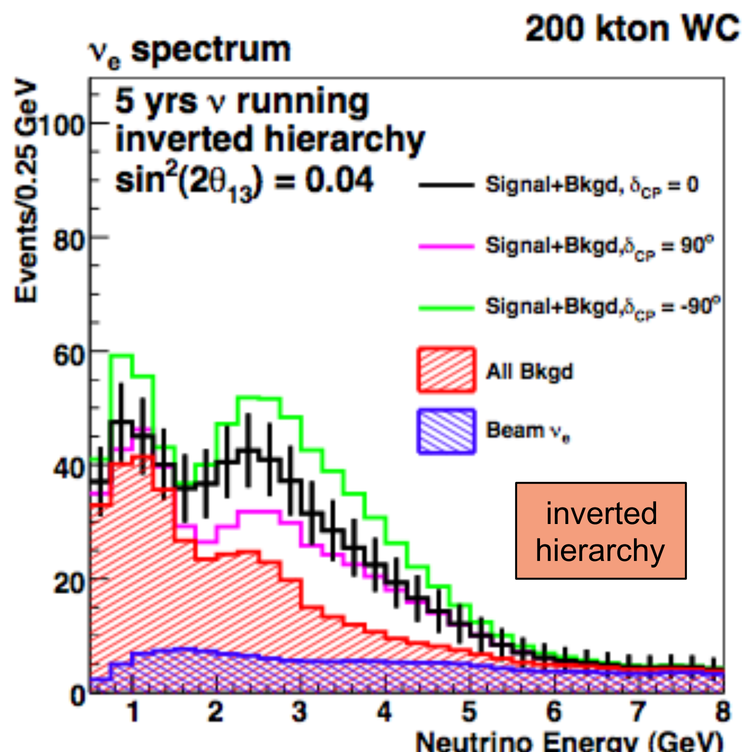
- **Gamma can be lost when it escapes the detector without converting, the 2 gammas overlap, or in asymmetric π^0 decays with one low energy photon**

NC π^0 production
background for
ν_e appearance

- **In ν_e appearance, background is 95% neutral current interactions, mostly π^0's**



LBNE Physics Report (2011)

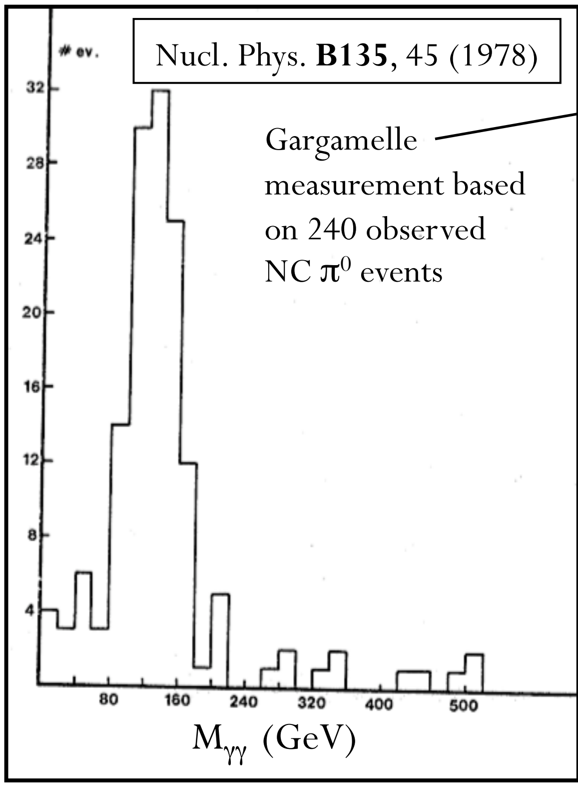


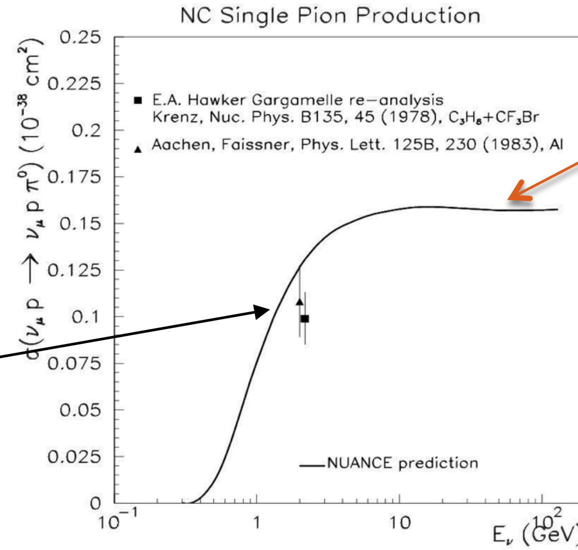
LBNE Physics Report (2011)

NC π^0 production

background for

ν_e appearance

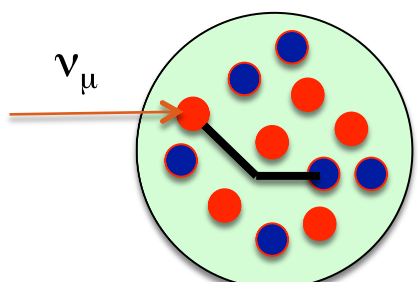




This σ tells you how many π^0 background events should expect to have

Exps typically assign **25-40% uncertainties** to this initial interaction σ

- **Nuclear effects further complicate**



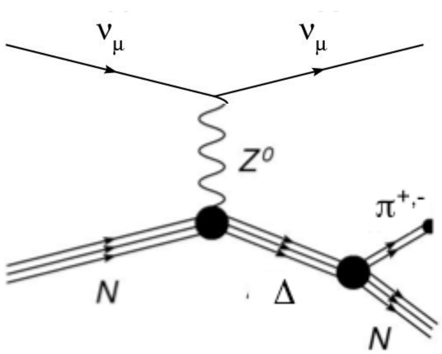
Ex: E_ν = 1 GeV on carbon

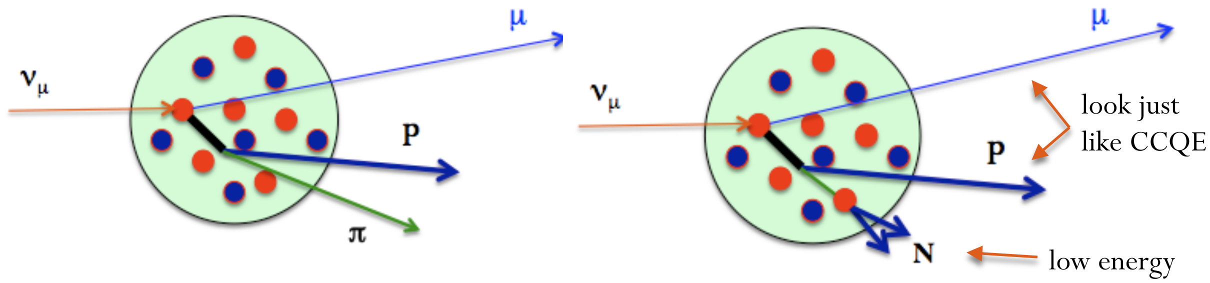
~20% of π^0 get absorbed

~10% charge exchange ($\pi^0 \to \pi^{+,-}$)

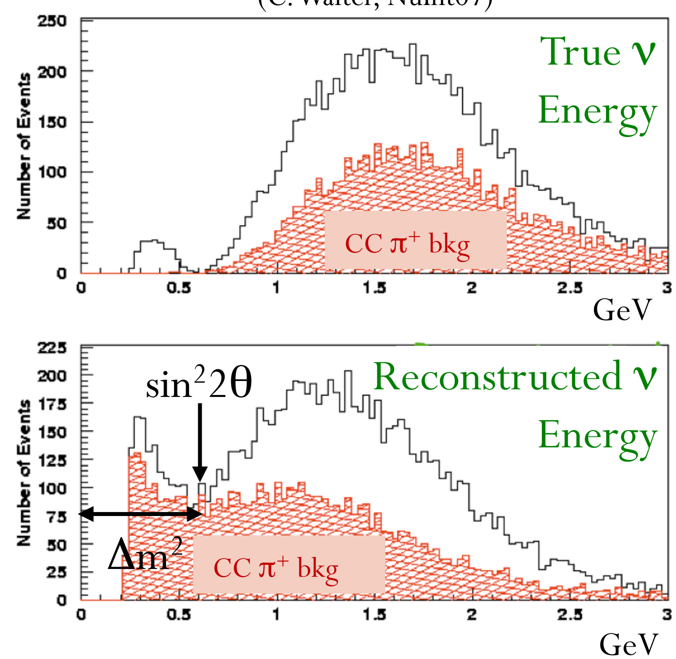
CC π^+ production

background for ν_μ disappearance





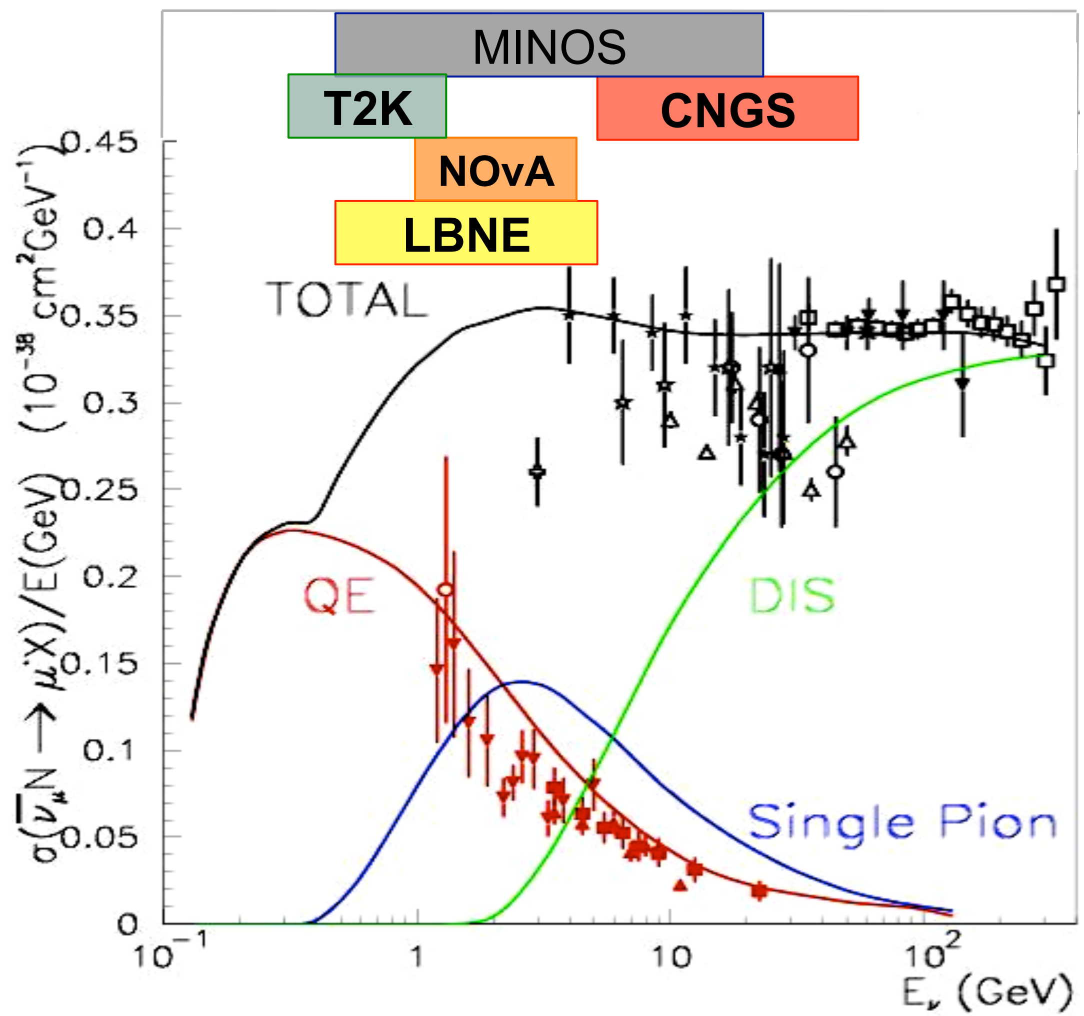
(C. Walter, NuInt07)



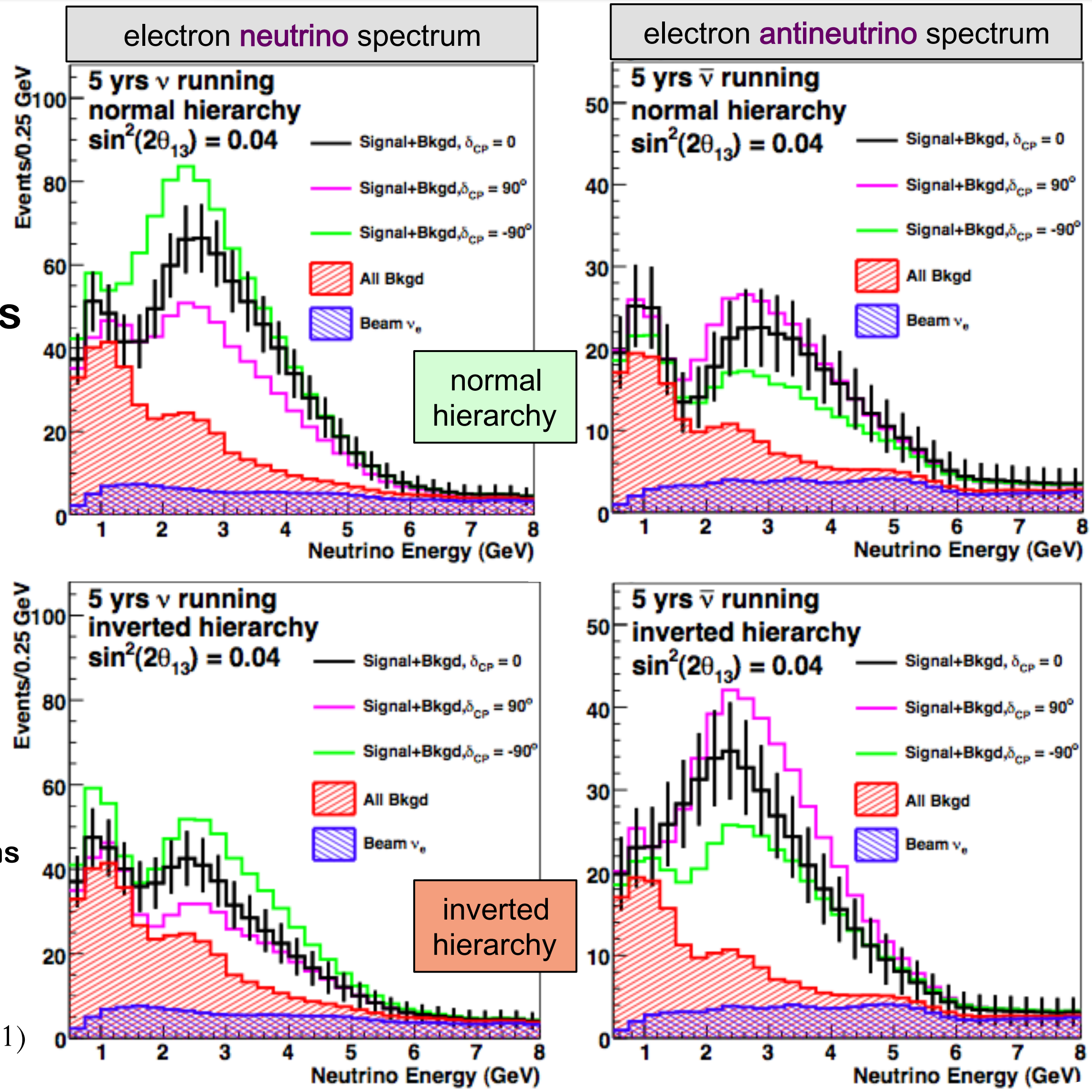
- Pion absorption an irreducible background to CCQE
- Pion re-interaction rate is large (30-40%)
- Pion absorption causes missing energy in the event reconstruction – affects measurement of oscillation parameters, $\sin^2(2\theta_{23})$
- Nuclear effects strike again…

- **Situation is quite a bit worse for antineutrinos!**
- **Nuclear effects can be different from ν interactions and must be measured**
- **Measure ~~CP~~ by comparing $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$**

$\bar{\nu}_\mu$ charged-current cross-sections



- Situation is quite a bit worse for antineutrinos!
- <u>Nuclear effects</u> can be different from ν interactions and must be measured
- Measure ~~CP~~ by comparing $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- Current LBNE sensitivities:
  - Assume 5% normalization error and no shape error on backgrounds
  - Uncertainties are assumed same for neutrino and antineutrino interactions
  - Ongoing work to improve systematic estimates

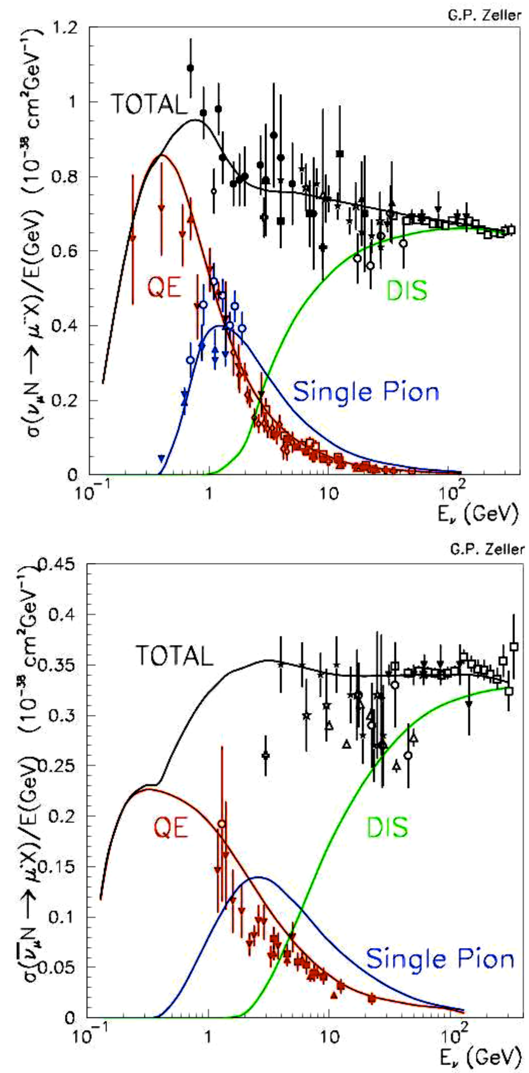


LBNE Physics Report (2011)

- Have a need for improved measurements of both neutrino and antineutrino cross-sections

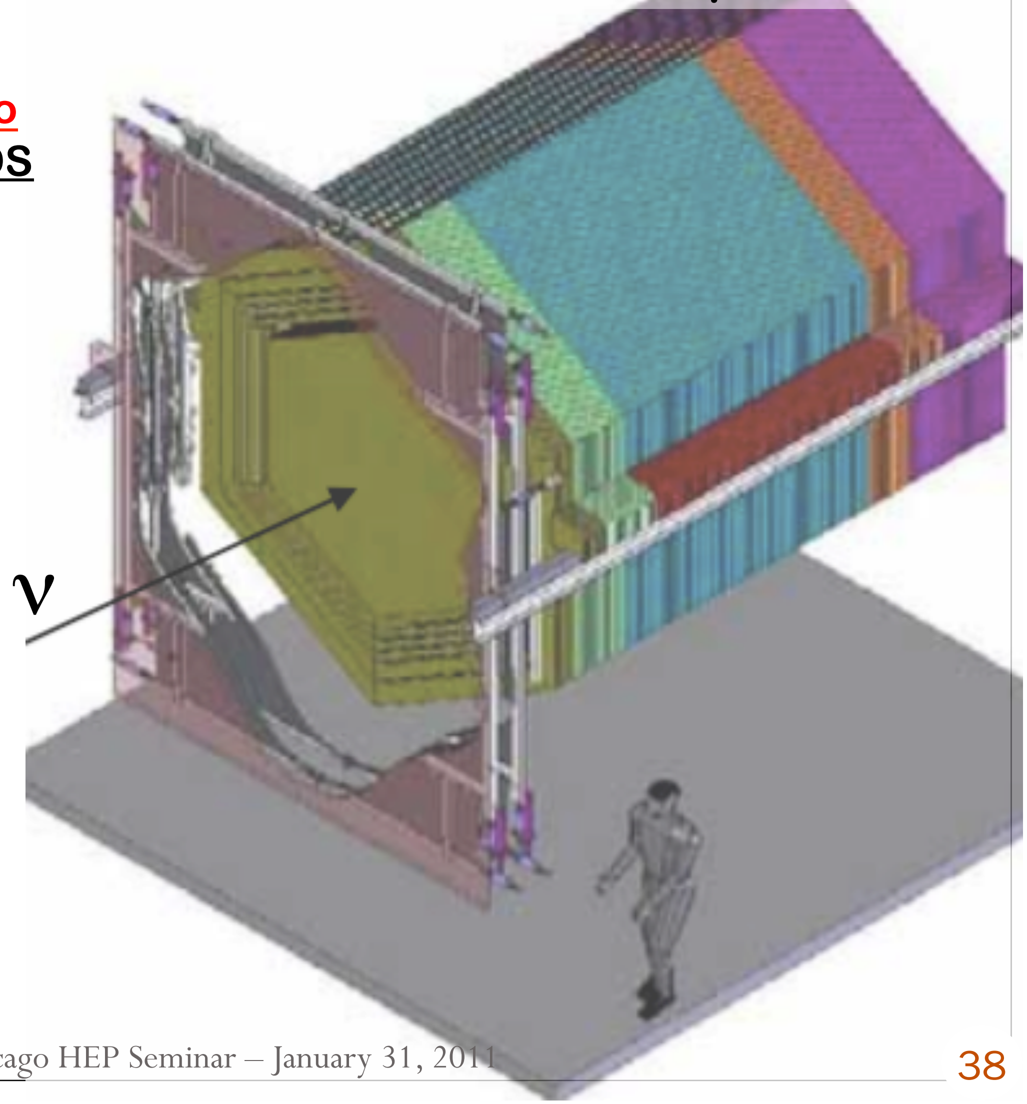
- But just as important is measuring differential cross-sections to map out kinematics of final states – to better predict oscillation signals and backgrounds

- Require improved models of nuclear effects, particularly for nuclei used in neutrino detectors



- **MINERνA is a dedicated neutrino-nucleus cross section experiment**

  - Makes use of the most intense neutrino beam in the world, NuMI, and the MINOS near detector at Fermilab
  - Compact, fully-active detector design
  - Important input to future neutrino oscillation experiments
  - Single detector with multiple nuclear targets allows study of nuclear effects in neutino interactions
  - Neutrino interactions provide a unique probe of the nucleus



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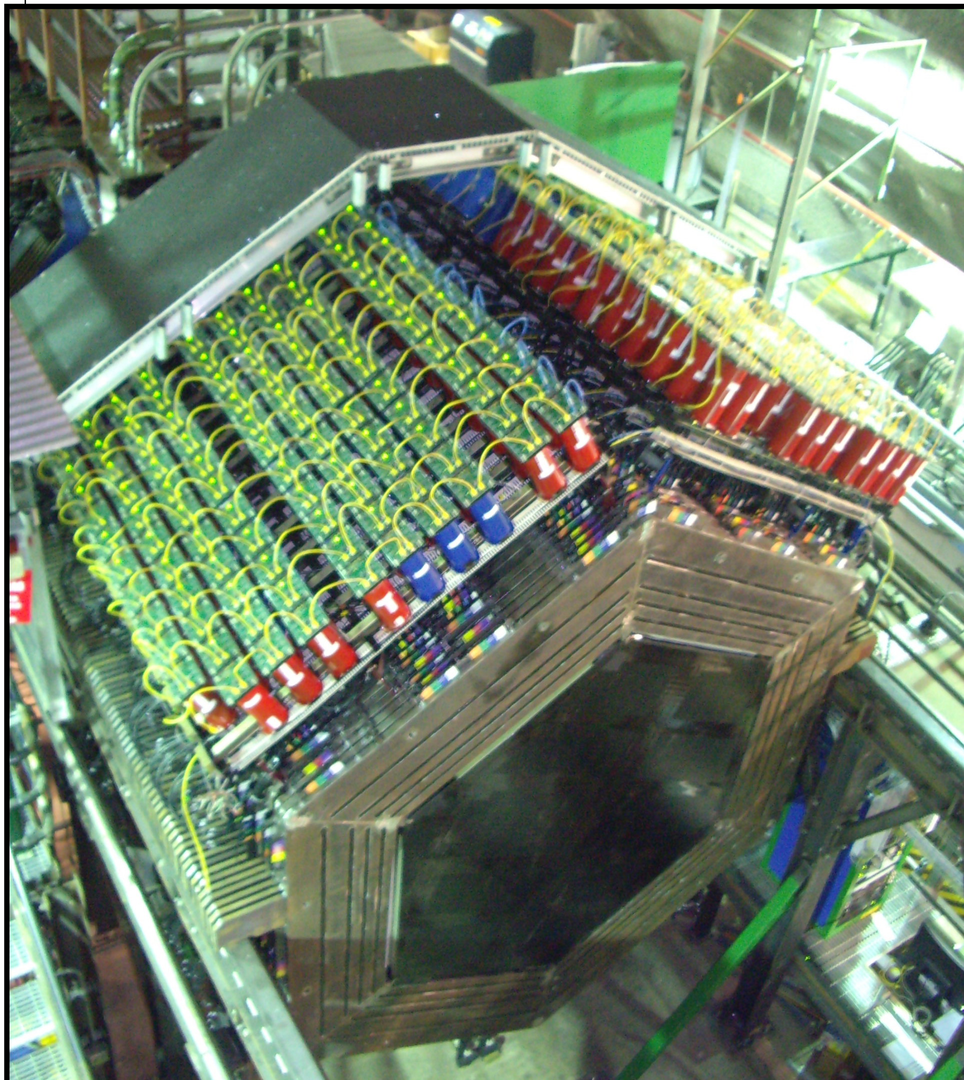
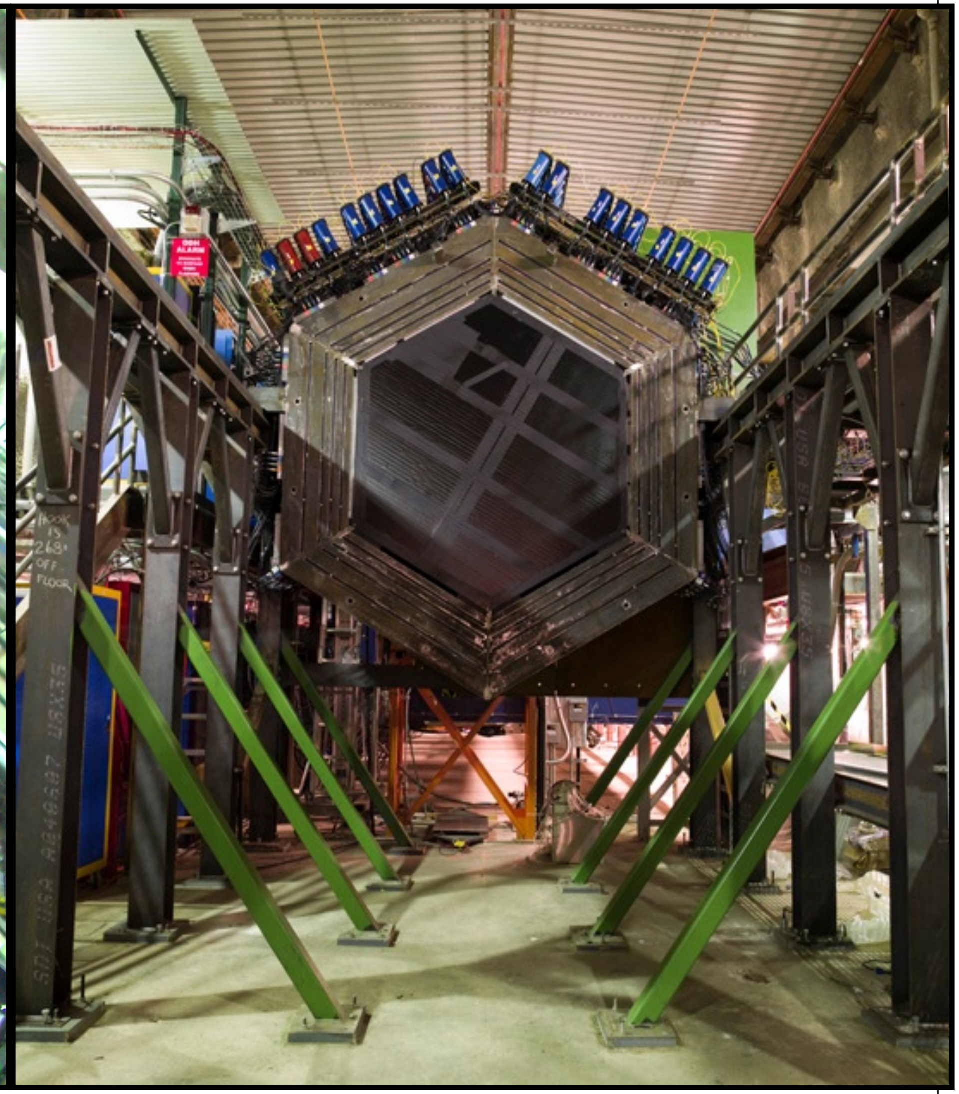
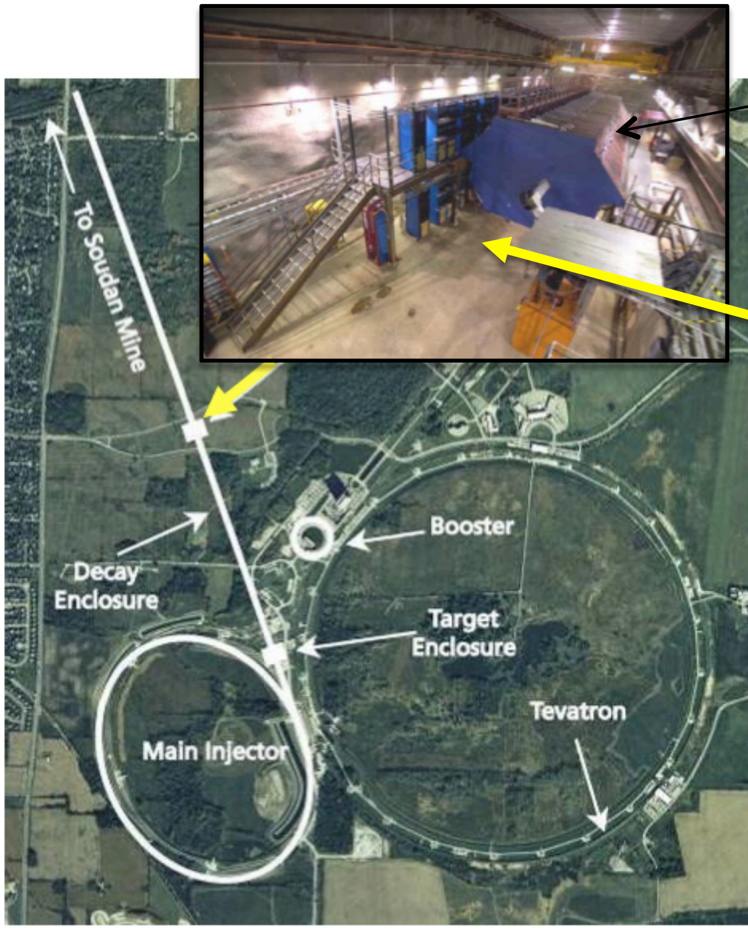
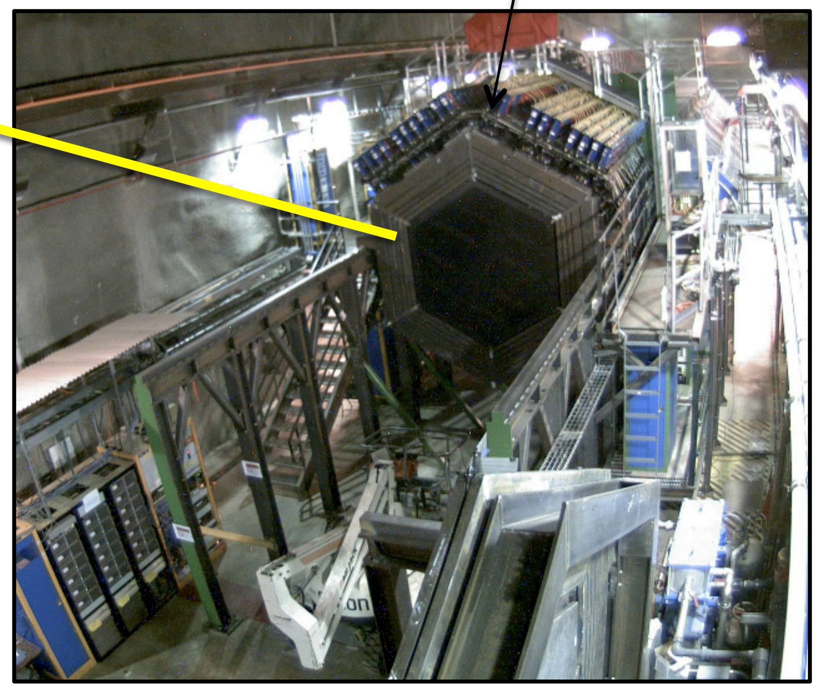


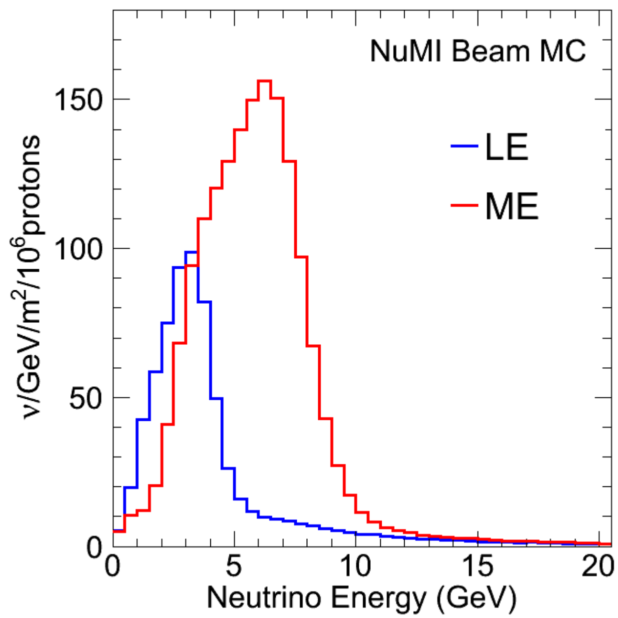


MINERνA makes use of the existing intense NuMI neutrino beam and the MINOS near detector at Fermilab

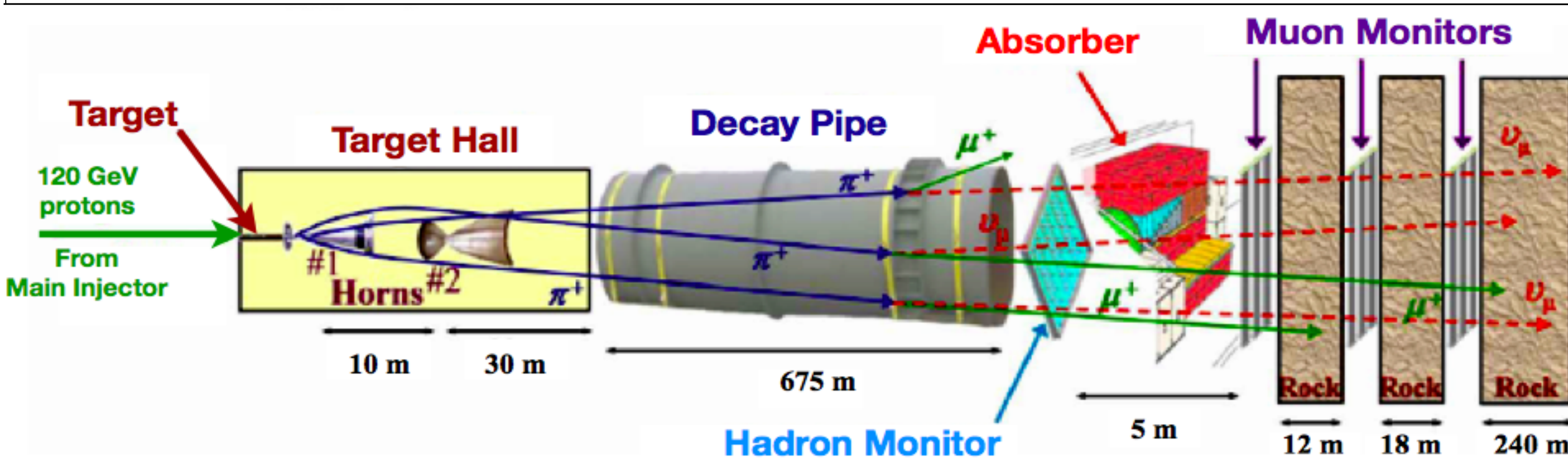


MINOS ND acts as a muon catcher for MINERνA





- Intensity: ~35e12 P.O.T per spill
  - about 1 ν event and a few rock muons in MINERνA per spill
- Spill length/frequency: 10μs / ~0.5 Hz.
- Beam power: 300 – 350 kW
- Mean energy of NuMI ν beam can be tuned by changing longitudinal position of the target relative to the first horn
- Reversing current in focusing horns changes beam from mostly neutrinos to mostly antineutrinos
- Current MINERνA run plan includes exposures of:
  - 4e20 P.O.T. in low-energy (LE) configuration
  - 12e20 P.O.T. in medium-energy (ME) configuration

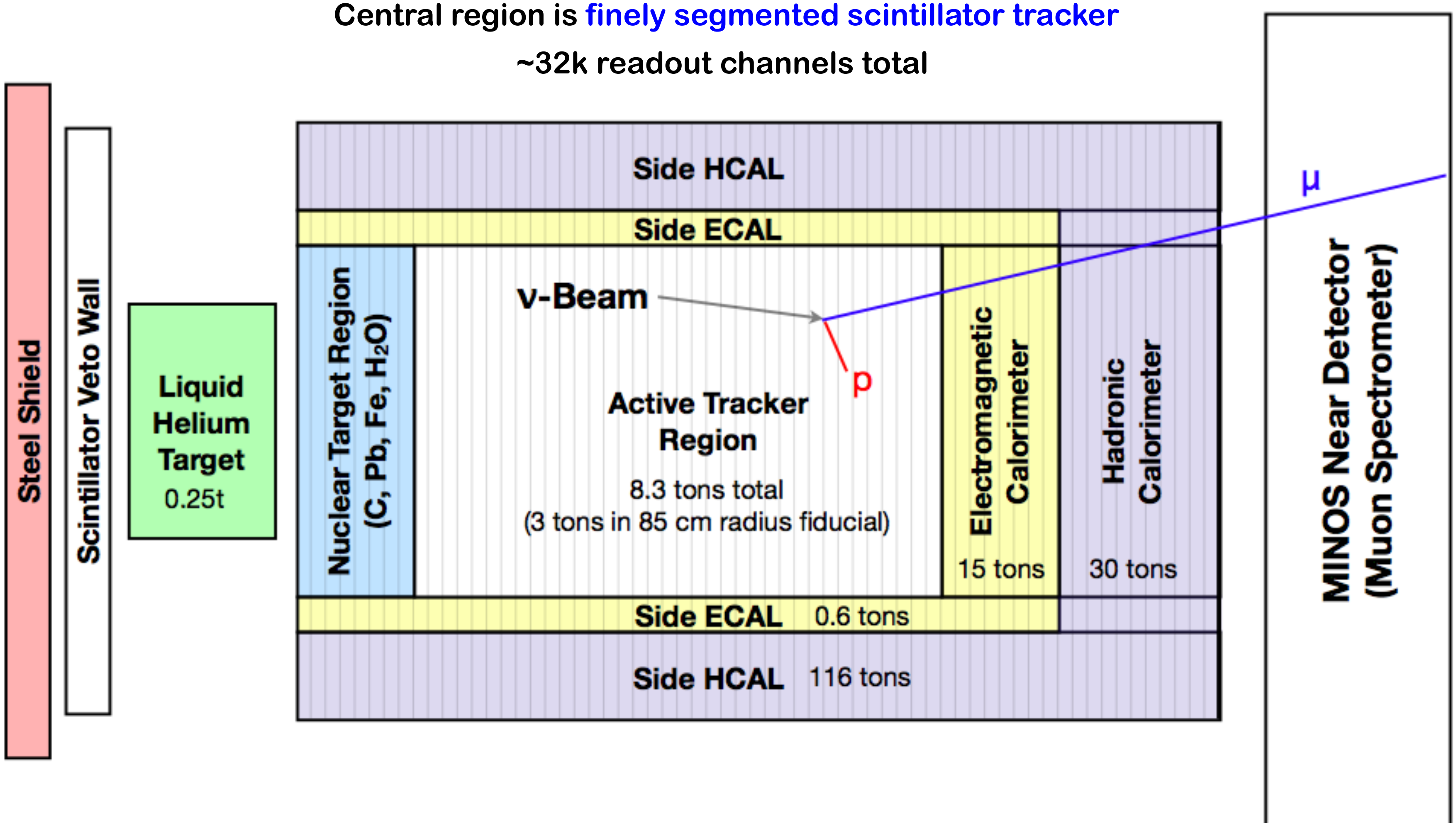


MINERνA detector comprised of 120 "modules" stacked along the beam direction

MINOS near detector acts as muon catcher

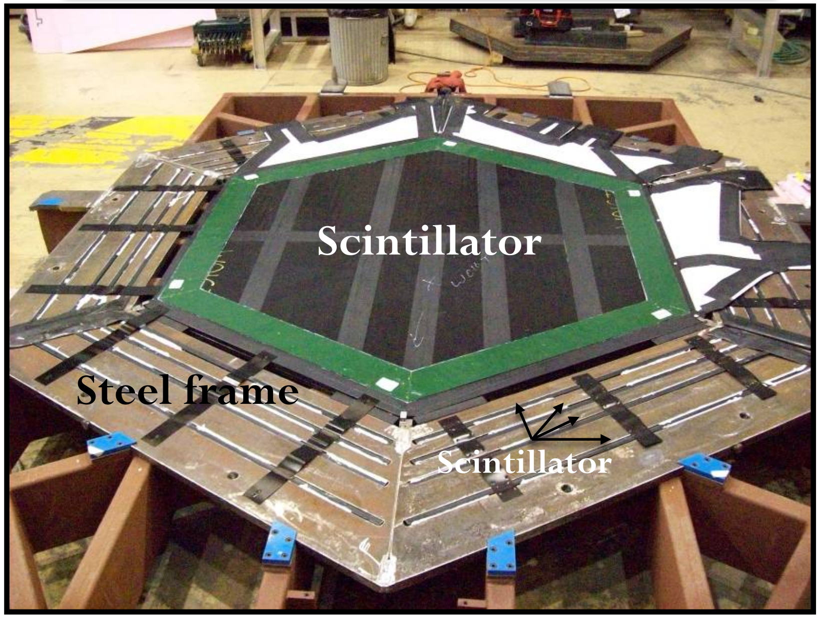
Central region is finely segmented scintillator tracker

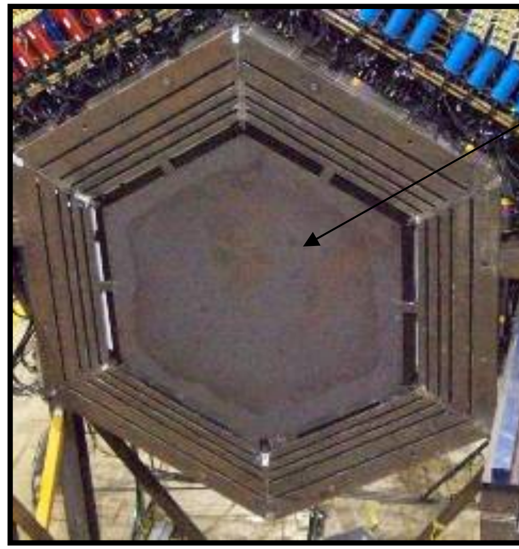
~32k readout channels total



- # 4 basic module types

Tracker modules have two planes of segmented scintillator measuring two different views



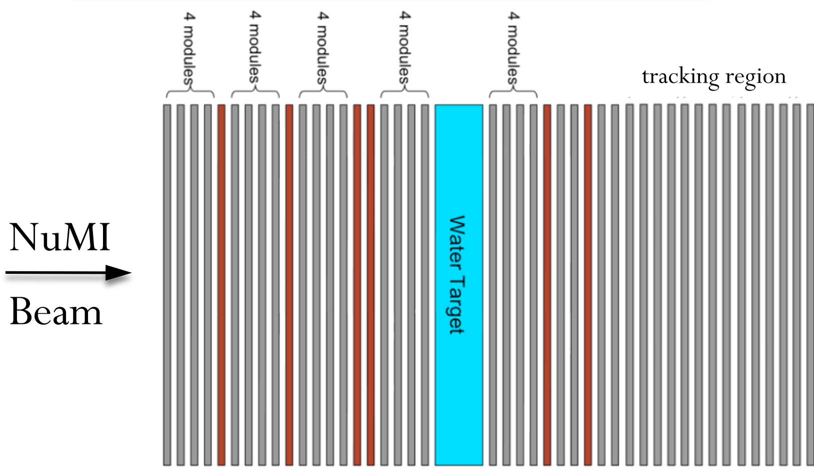


Hadronic Calorimeter (HCAL) modules include 1 inch thick steel absorber and one scintillator plane

Electromagnetic Calorimeter (ECAL) modules incorporate two 2 mm thich lead absorbers with 2 scintillator planes

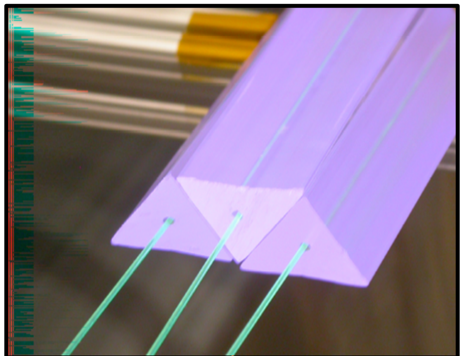
- **4 basic module types**

<u>Nuclear Target modules</u> have no central scintillator. Thin solid sheets welded inside outer steel frame.



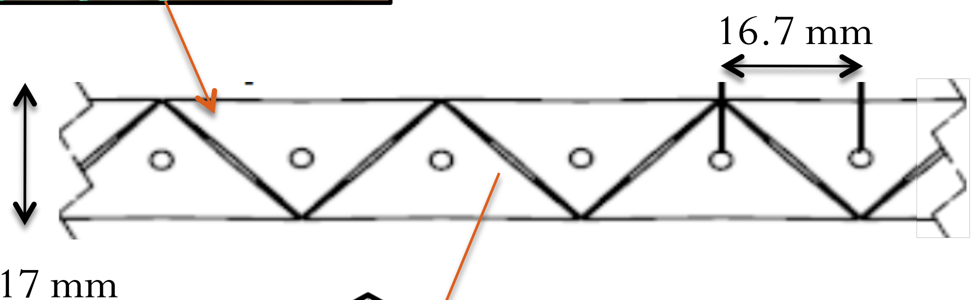
Nuclear Target	Fid .Vol.
CH	3.0t
He	0.2t
C	0.15t
Fe	0.7t
Pb	0.85t

<u>nuclear targets</u> (He, C, Fe, Pb, H_2O, CH)

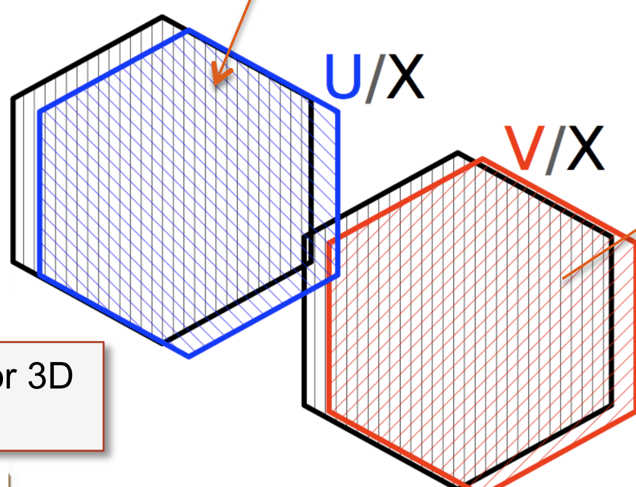


Extruded plastic scintillator & wavelength shifting fibers

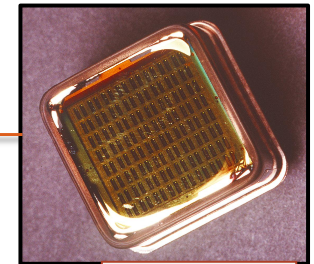
Triangular geometry allows charge sharing for improved position resolution



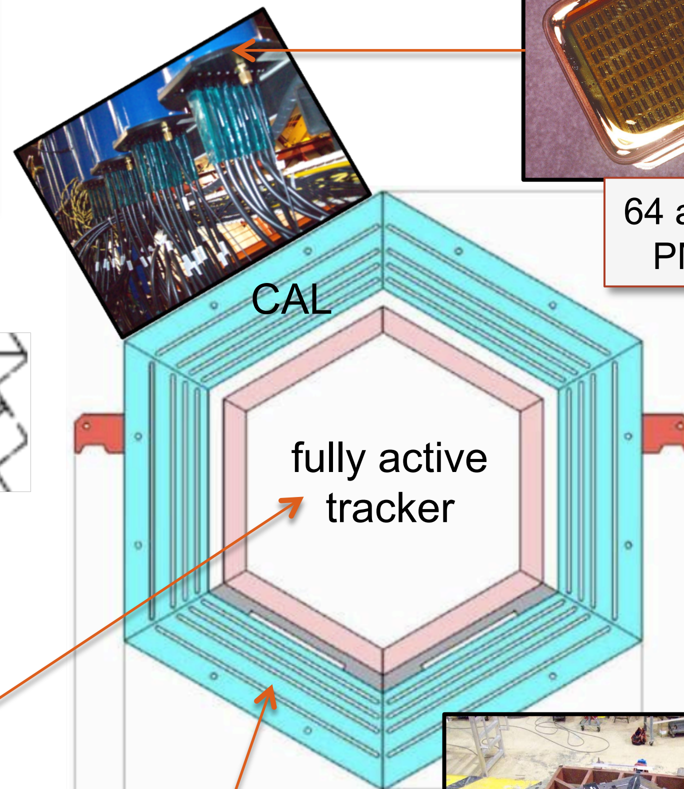
127 strips per plane



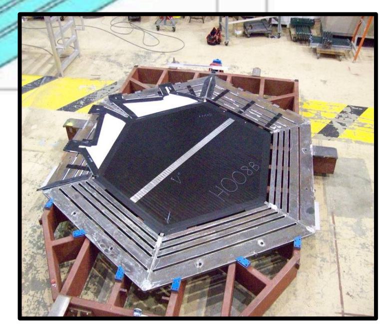
Three views for 3D reconstruction



64 anode PMTs



Iron outer detector instrumented for calorimetry

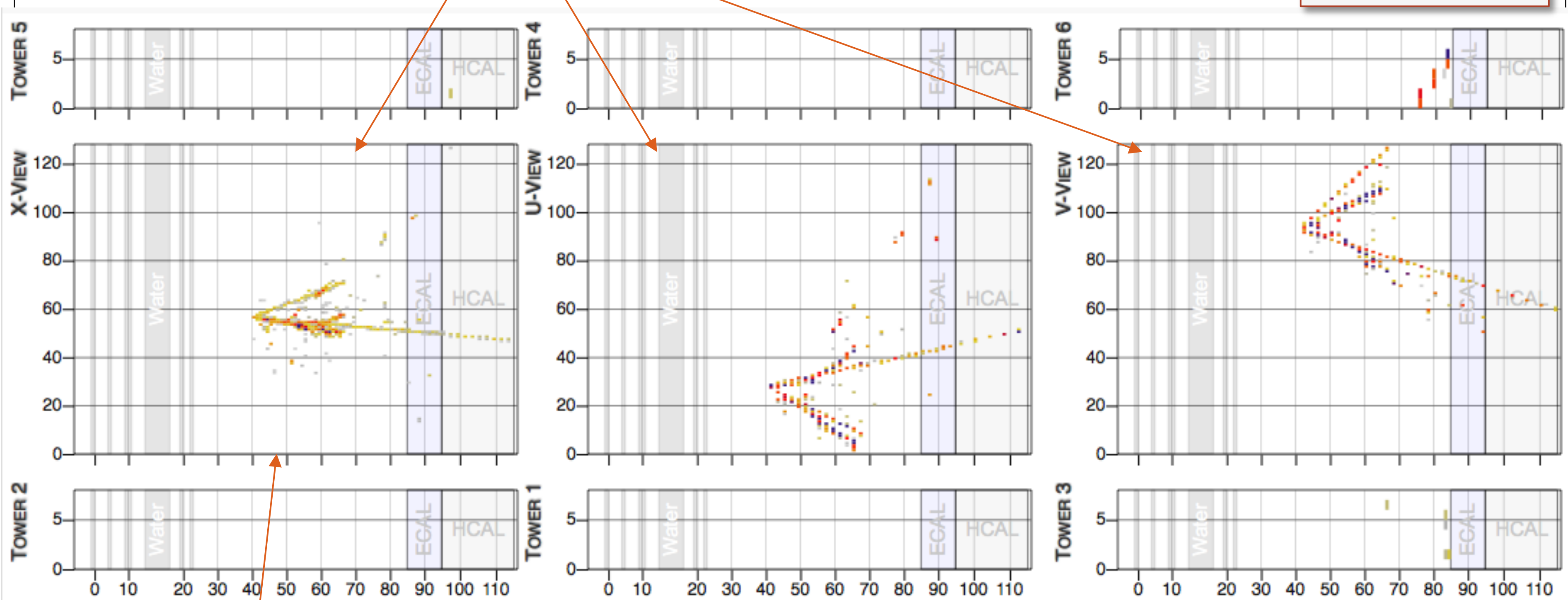


- **So what does an event look like in MINERνA…**

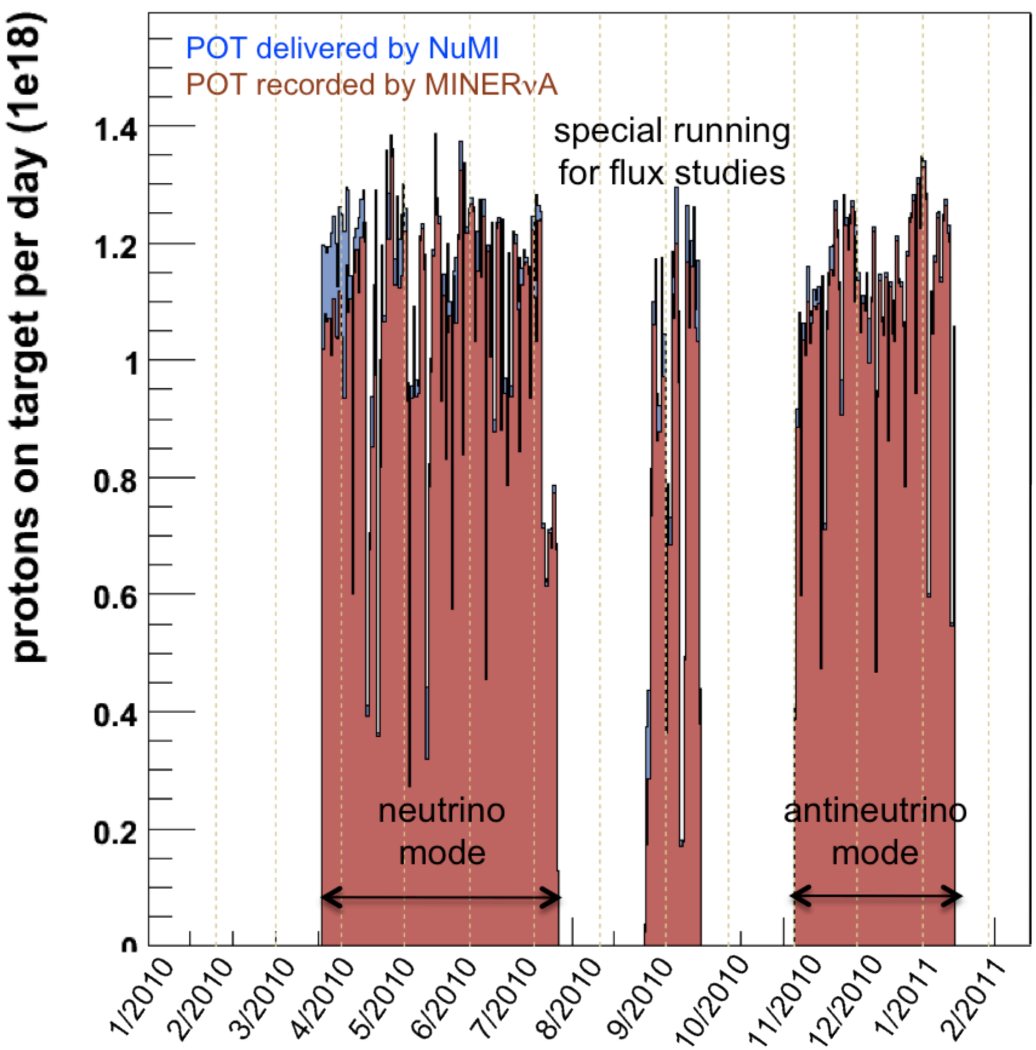
3 stereo views, X—U —V , shown separately

DATA

Particle leaves the inner detector, enters the outer iron calorimeter

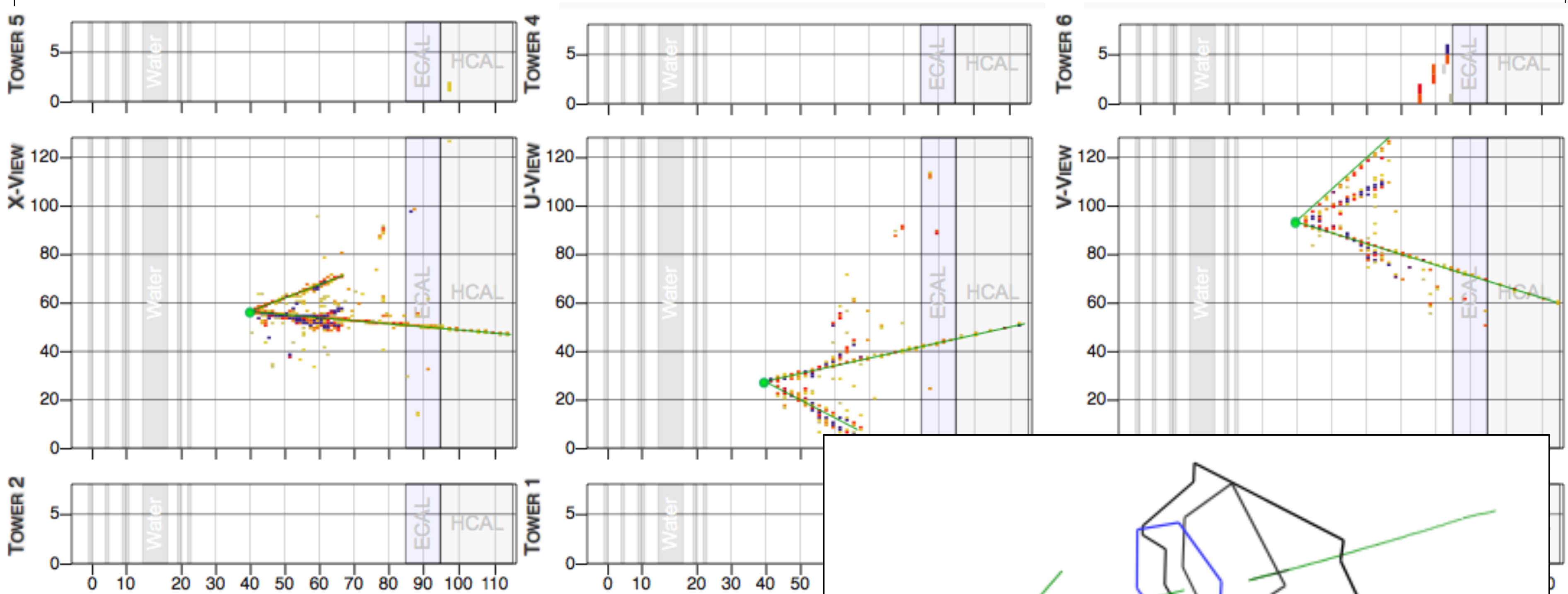


X views twice as dense, UX,VX,UX,VX,…

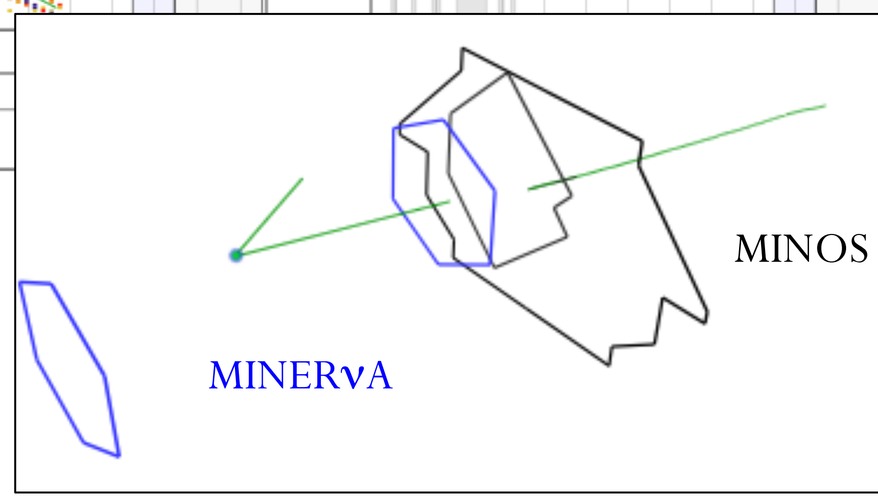


- Detector installation completed in March 2010
- 1.2e20 POT collected in neutrino mode
- 0.93e20 POT collected in antineutrino mode
- Detector live-time > 98%
- Spent the first several months after completing construction improving operations, online monitoring, working on calibrations
- Since then focus has turned to reconstruction, event selection, toward first results

- **Pattern recognition, Track fitting, MINOS track matching**



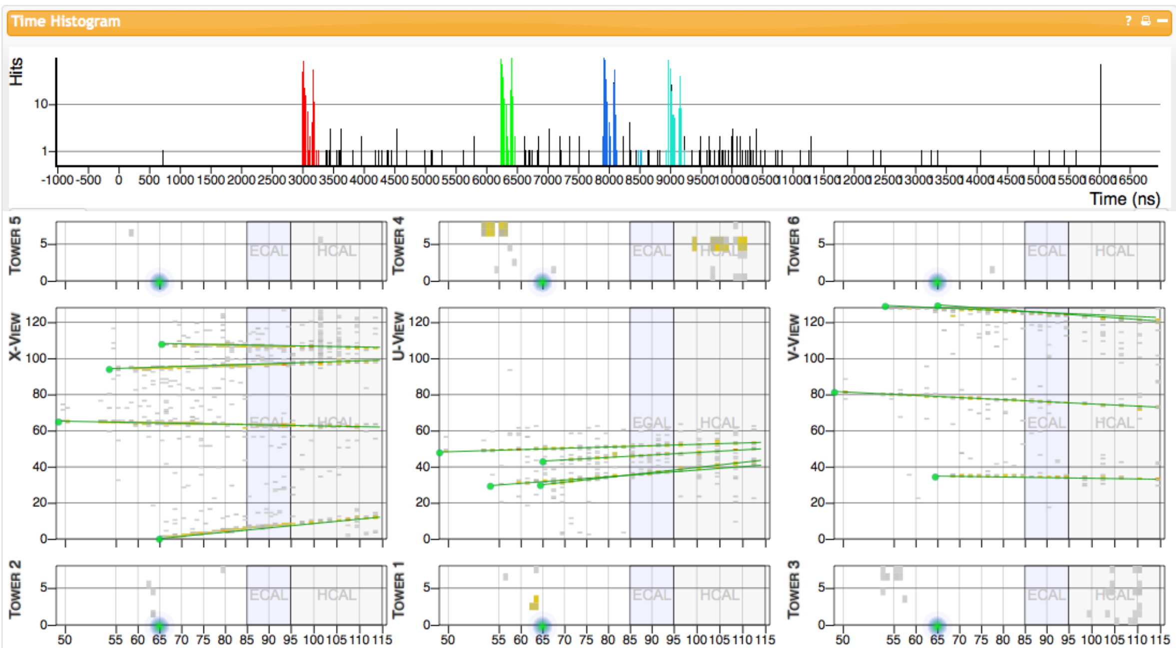
DATA



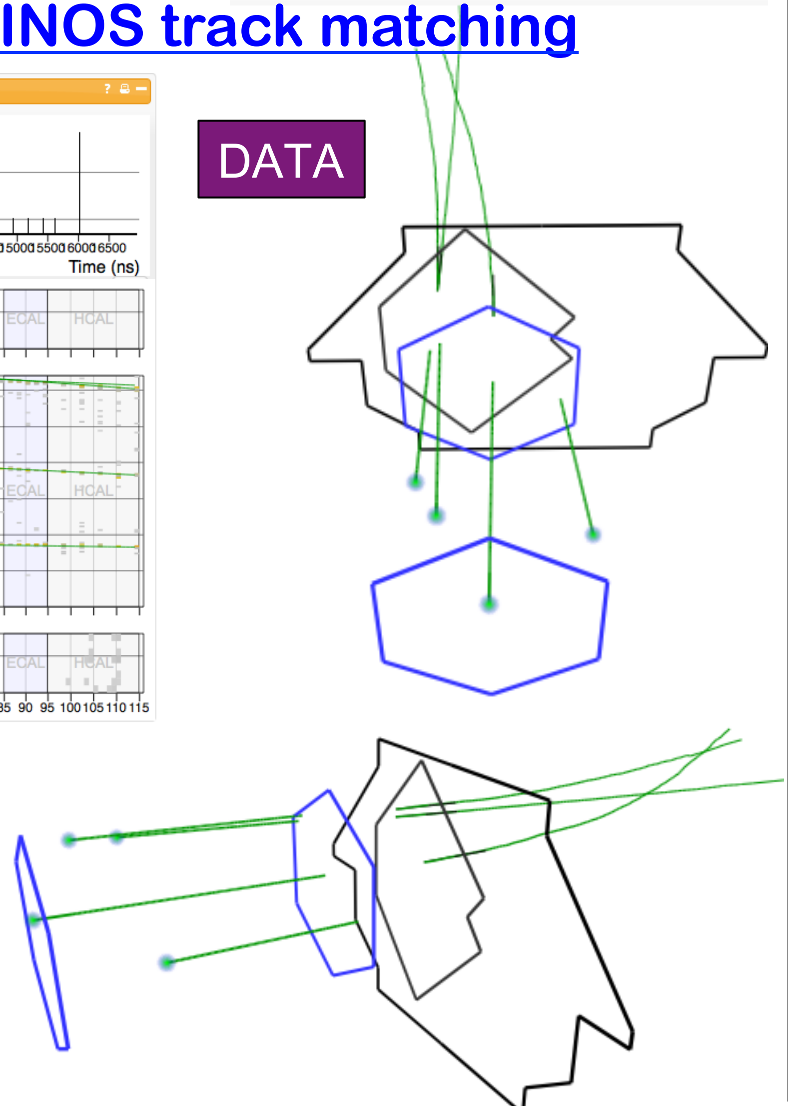
MINOS: p_μ = 6189.4 MeV

MINERνA: p_μ = 7630.8 MeV

• Pattern recognition, Track fitting, MINOS track matching



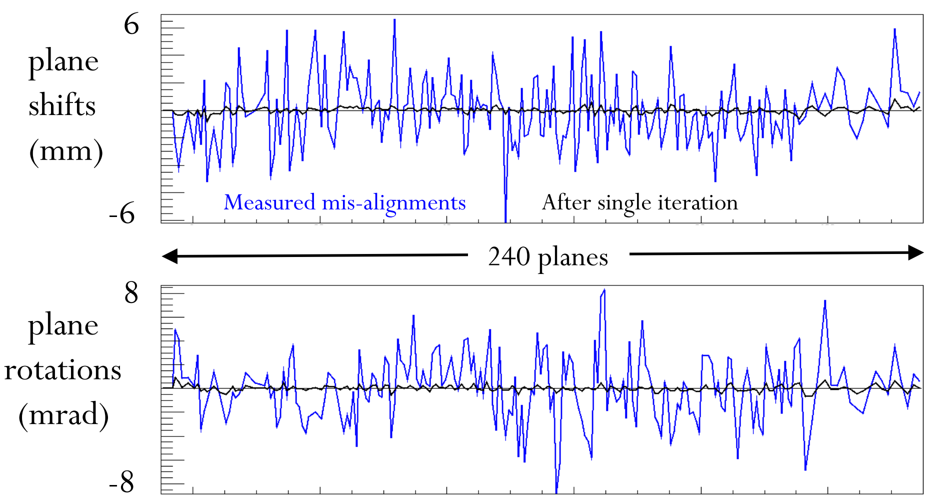
DATA

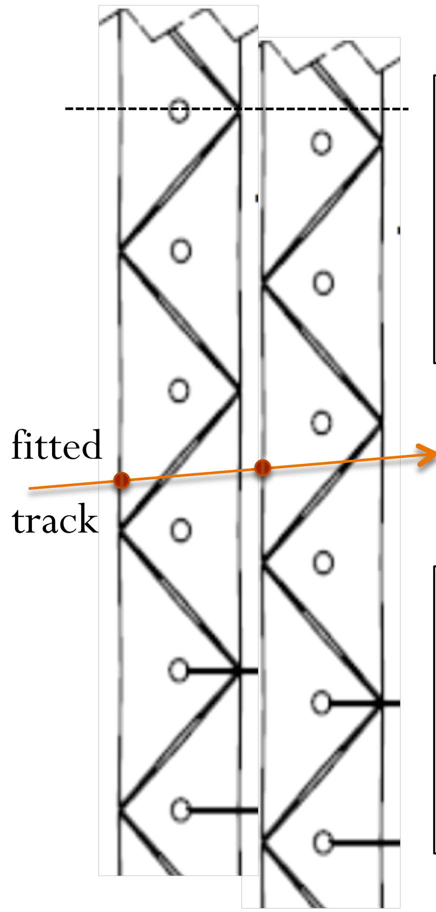


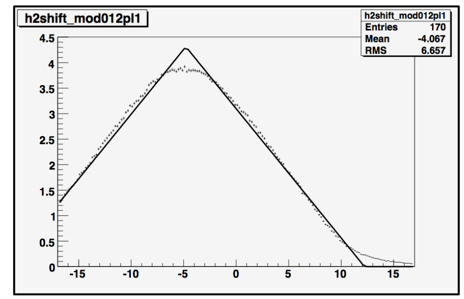
- NuMI Beam is pretty intense
- "Rock Muons" are created in neutrino interactions in the rock surrounding the detector hall
- This display shows 4 rock muons in a single spill
- Separation in time is performed before reconstruction

Rock Muons: calibration, tracking studies, detector alignment

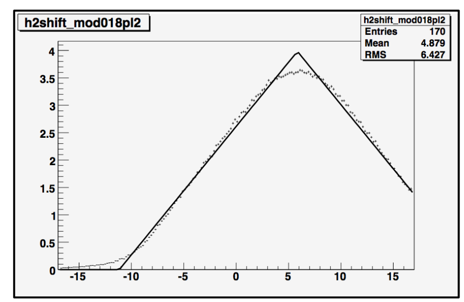
- Rock muons provide a high statistics *in situ* calibration sample of minimum ionizing particles
  - Developing & studying tracking performance
  - Timing calibration of TDCs
  - Detector alignment
  - strip-to-strip energy scale corrections







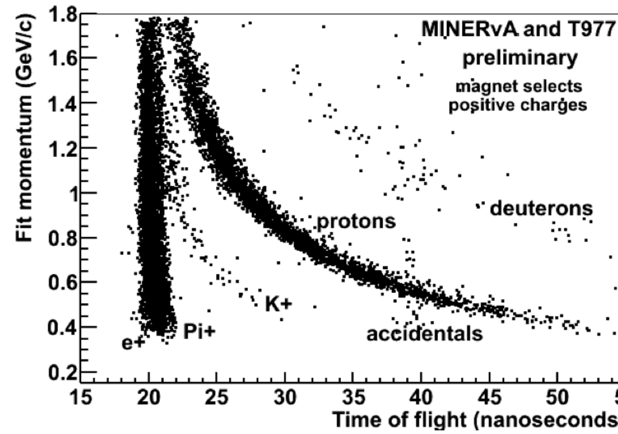
light output/length vs. position along base

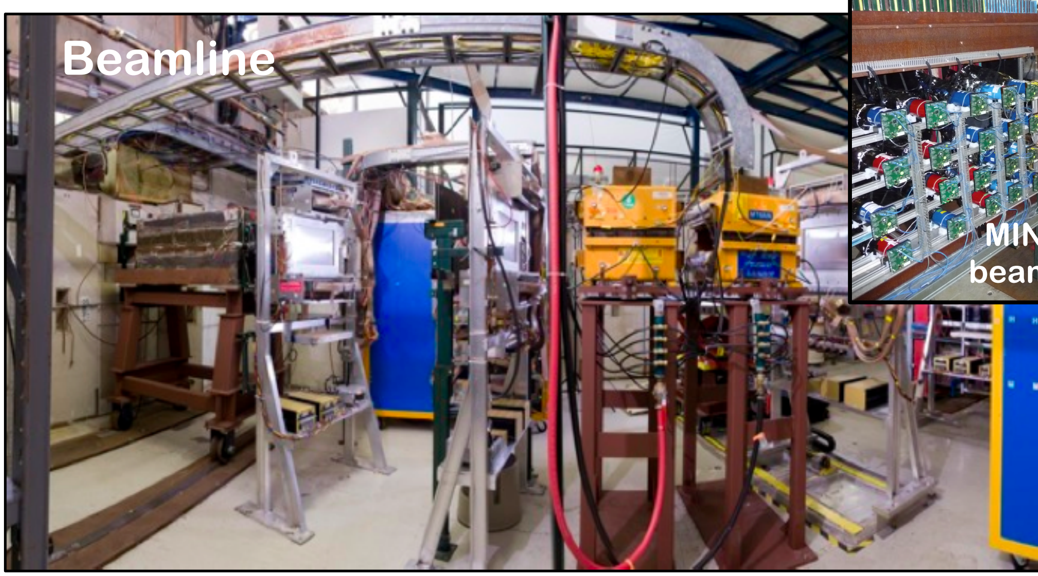


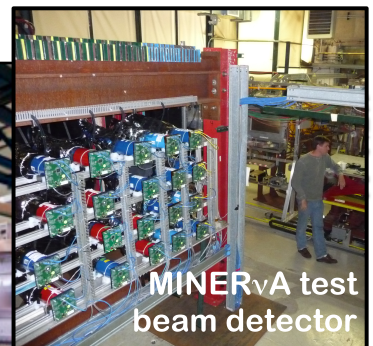
DATA

MINERνA Test Beam Project

- Very important to calibrate the energy response
- 16 GeV pion beam on a copper target produces a tertiary beam between 400-1200 MeV/c
- Four wire chambers, two dipole magnets, and time-of-flight system
- Beamline now a permanent part of the Fermilab facility

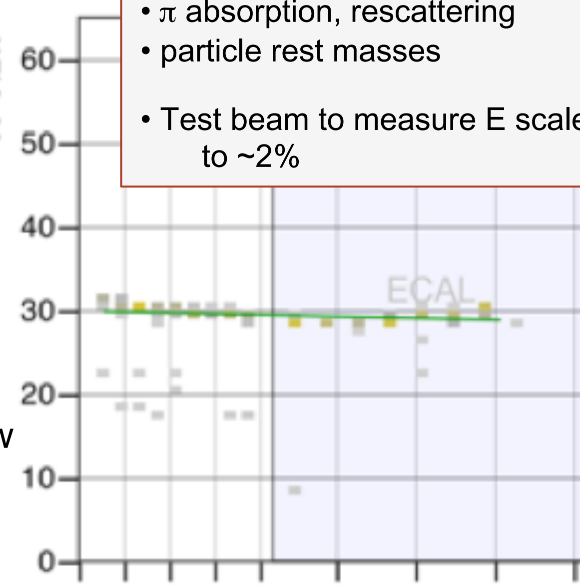






- Visible energy in calorimeter is not particle energy
- π absorption, rescattering
- particle rest masses
- Test beam to measure E scale to ~2%

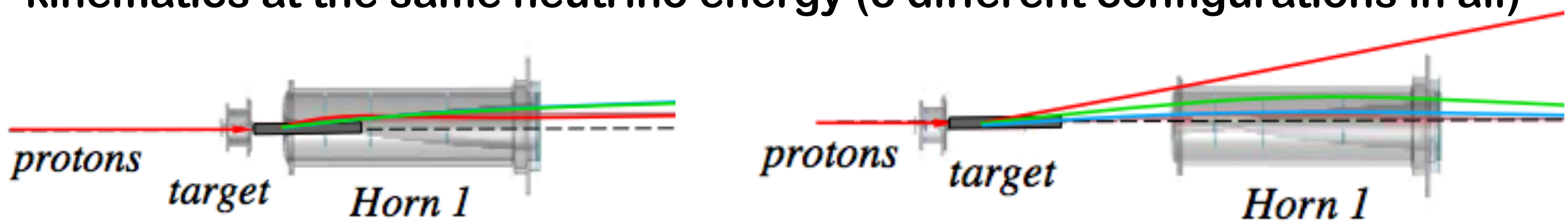
X-view

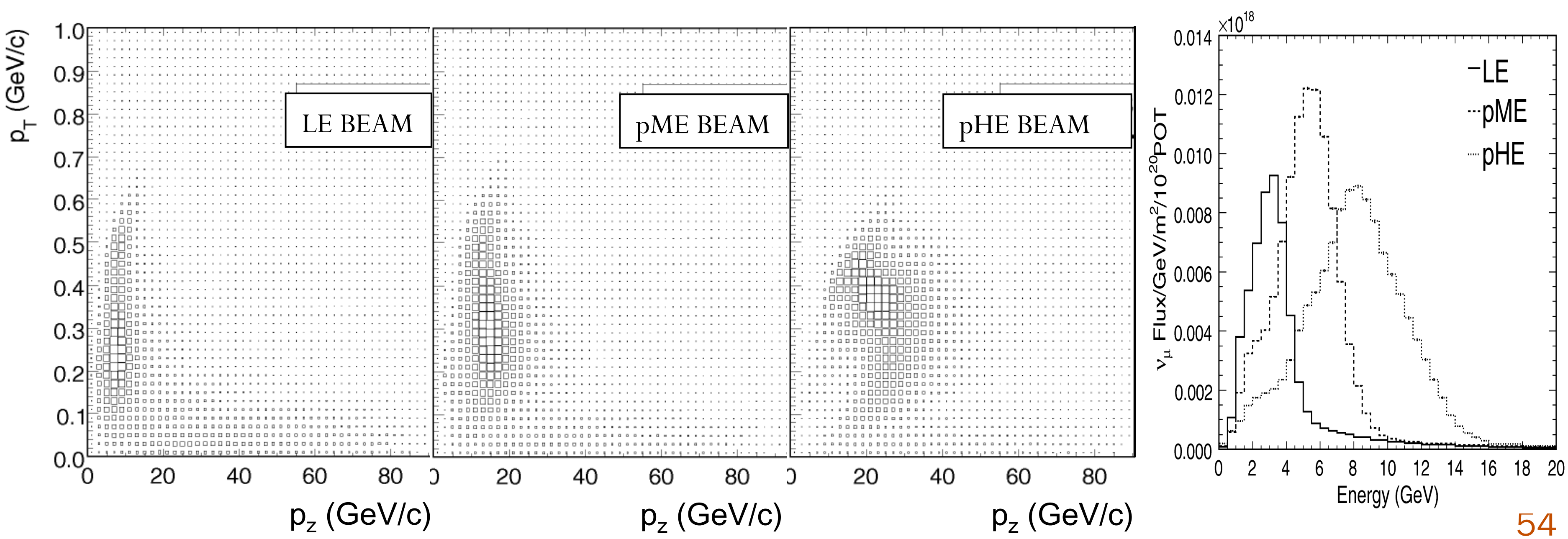


- **Understanding the neutrino flux**
  - Clearly important for any absolute cross-section measurements
  - Traditionally a very difficult problem in neutrino experiments. Past wide band beams limited to ~30% uncertainty in flux calculations. Often relied on knowing neutrino cross-section to measure neutrino flux…
  - Largest uncertainty comes from primary hadron production in the target by incident proton beam
  - MINERνA's goal is 7% in flux shape and 10% in normalization
  - MINERνA will take a multi-faceted approach to reducing flux uncertainties

- **Understanding the neutrino flux**

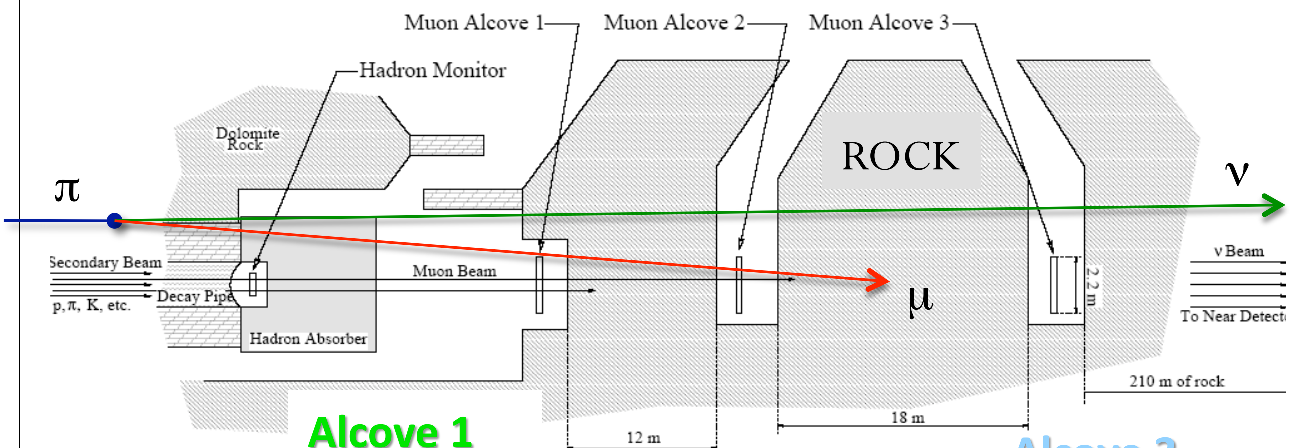
1. **Comparing ν event rates when varying beamline configuration (target z-position and horn current). Each configuration samples different pion kinematics at the same neutrino energy (8 different configurations in all)**





• Understanding the neutrino flux

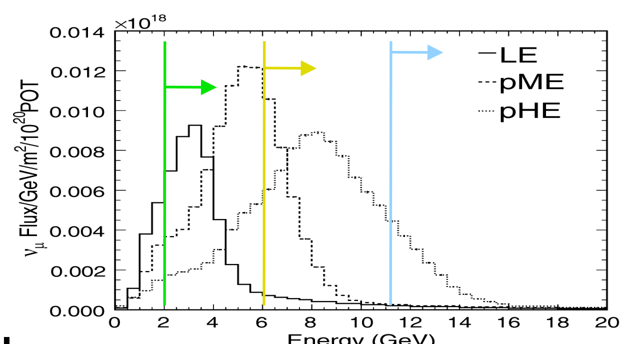
2. In situ measurements using muon monitor system



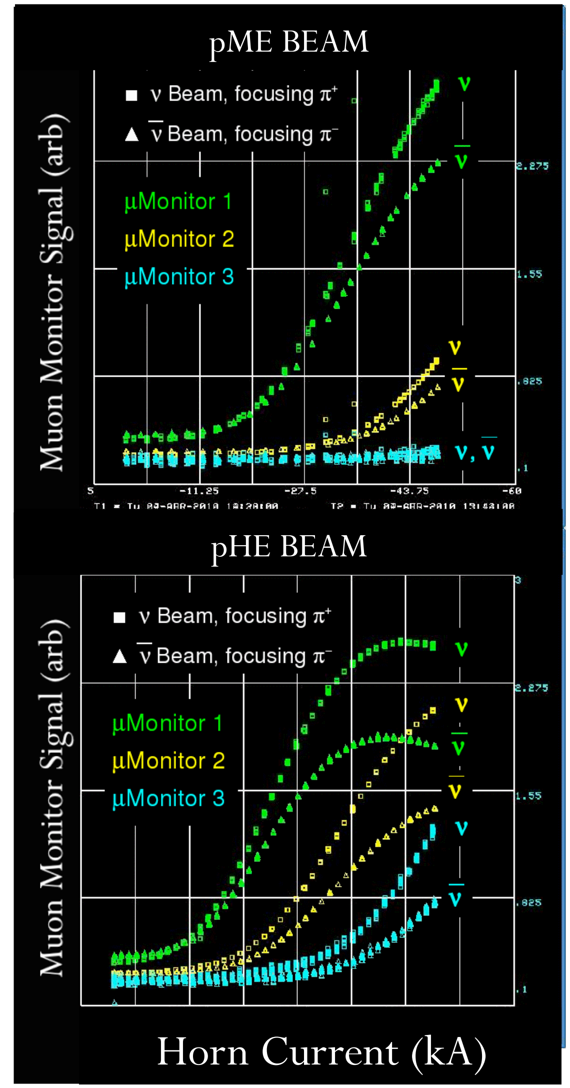
Alcove 1
$E_{\mu,\pi}$ > 4 GeV
E_{ν} > 2 GeV

Alcove 2
$E_{\mu,\pi}$ > 11 GeV
E_{ν} > 6 GeV

Alcove 3
$E_{\mu,\pi}$ > 21 GeV
E_{ν} > 11 GeV



- A large matrix of such data each sampling different hadron phase space
- Global fit to constrain hadron production



- Understanding the neutrino flux

3. Ex situ hadron production data

    - Expected to be less precise than above approaches
    - Use world's data for protons on thick targets (SPY, MIPP, NA49,etc.) for "secondary beam", but requires extrapolations in energy, target thickness and target composition
    - Use world's data to better model "tertiary beam", pion production in other materials in the beamline by lower energy protons and pions
    - The most comprehensive example of this bottom-up approach to neutrino flux prediction is MiniBooNE's flux calculations [Phys. Rev. D79, 072002 (2009)] where a total error of ~9% in the peak is achieved

Looking toward first physics results

- Currently preparing first preliminary results for upcoming neutrino interactions workshop in March in Dehradun, India

- The collaboration has prioritized some analyses for first results:

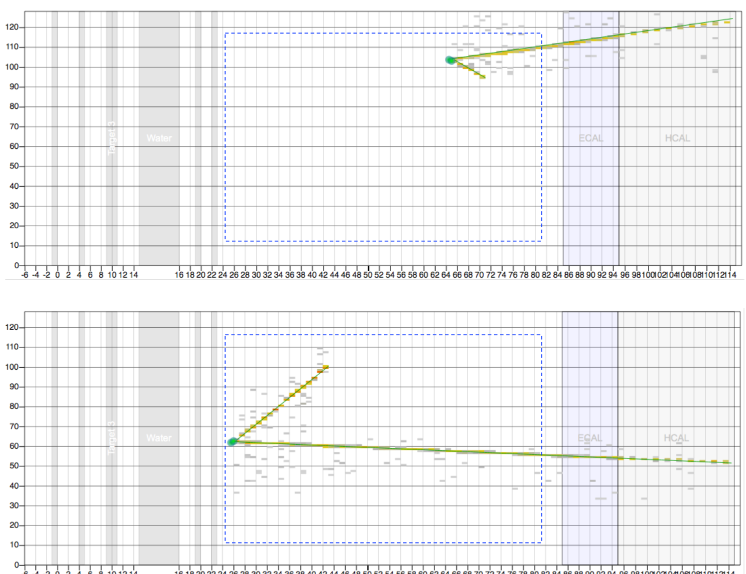
1. CCQE events in scintillator (CH)
   - Low multiplicity final state for straight forward reconstruction
   - Moderate energy, low Q^2 events have decent acceptance into MINOS detector

2. CC events in most downstream nuclear target (Fe, Pb)
   - Nuclear effects important to the community
   - Showcases a unique feature of the MINERνA detector

- [CCQE in scintillator (CH)](#)

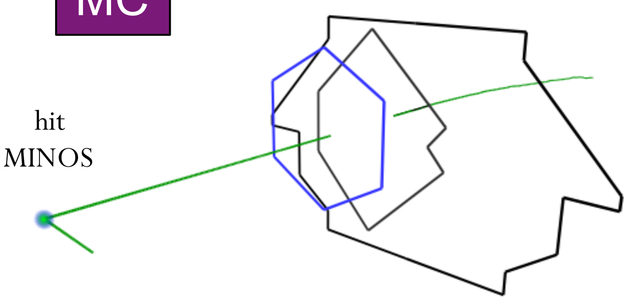
First analysis will do the simplest thing, which is use events where the <u>muon is well reconstructed in MINOS</u>

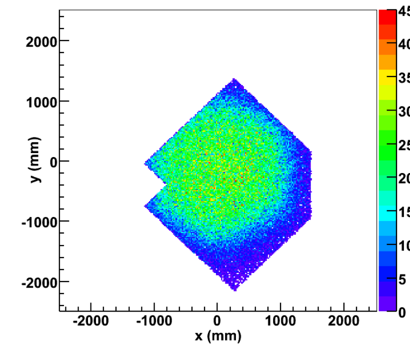
MC

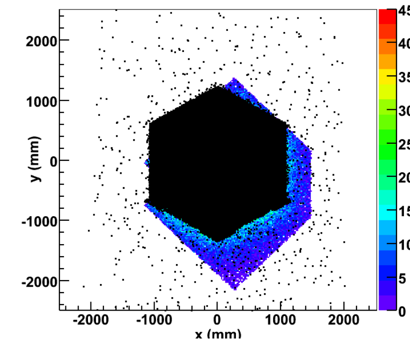


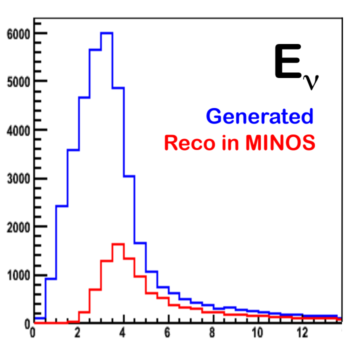
miss MINOS

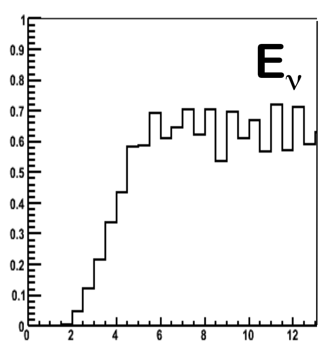
hit MINOS

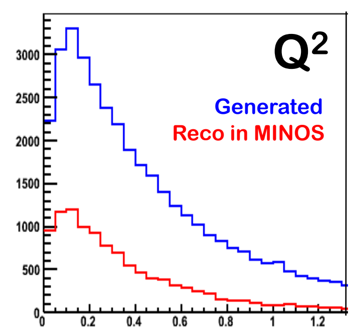


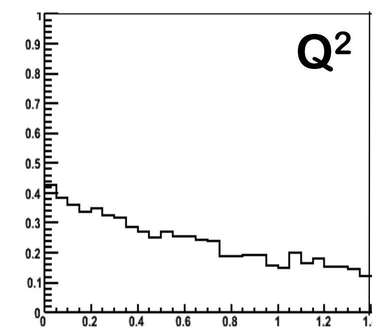






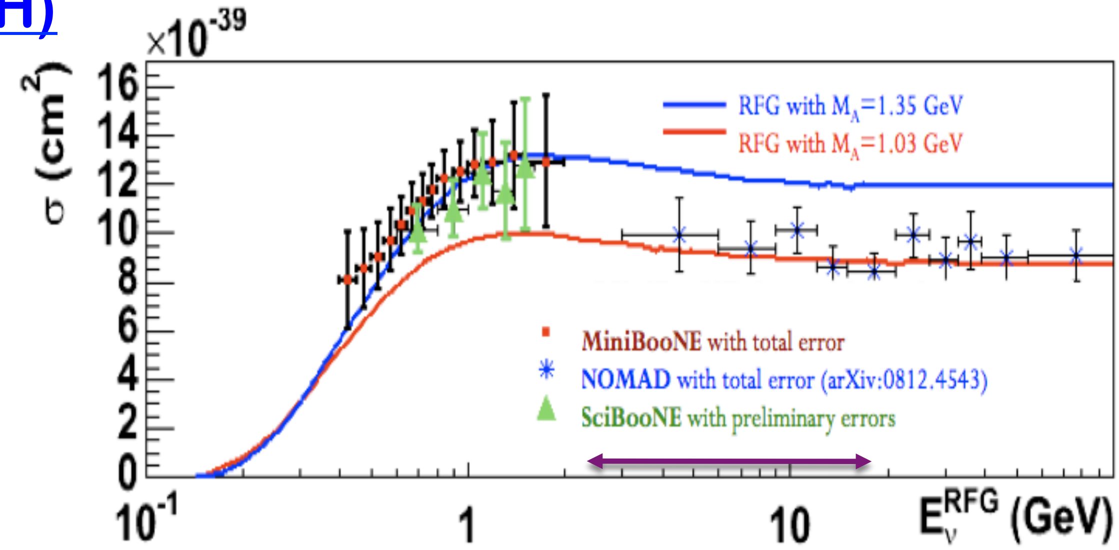


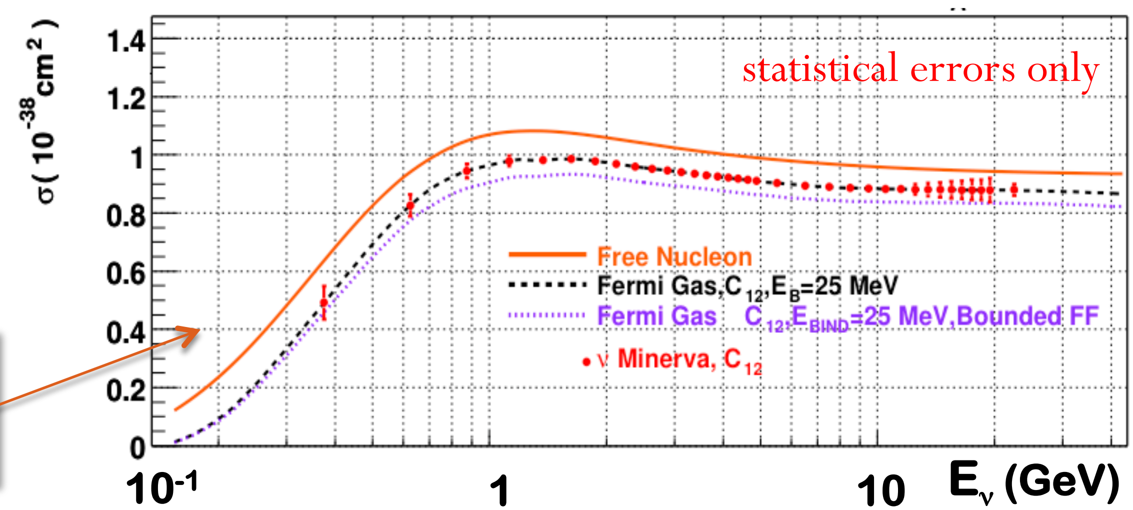




- ## CCQE in scintillator (CH)

- Working toward **data/MC comparisons in ν and $\overline{\nu}$ for NuInt Workshop**
- Initial results will be low statistics and somewhat limited kinematic reach
- Flux uncertainties will be large in first results
- Reach will be extended in future analyses by analyzing "track stubs" in MINOS and muons stopping in MINERνA

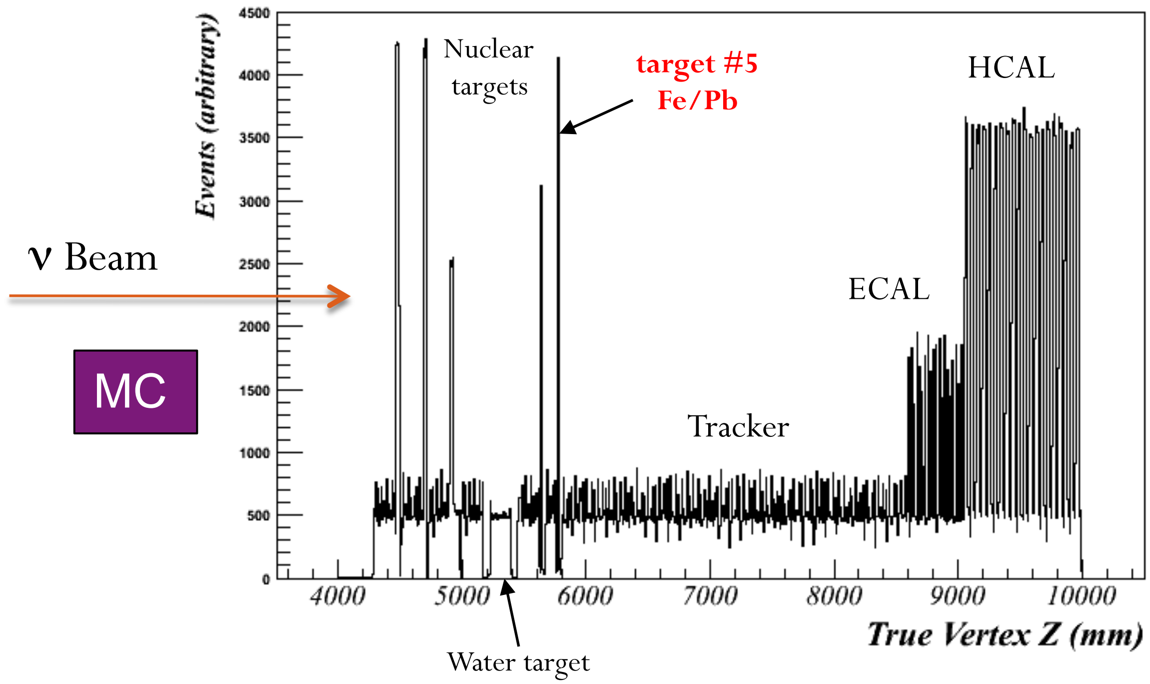




Eventual statistical power of MINERνA CCQE data

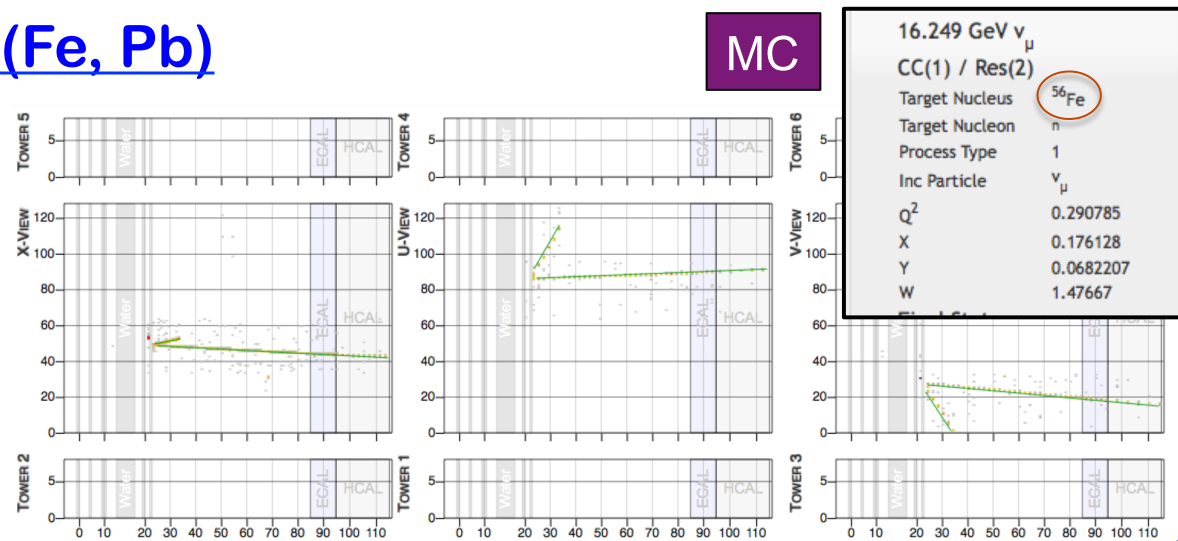
• CC in nuclear target (Fe, Pb)

- Working toward data/MC comparisons in ν and $\overline{\nu}$ for NuInt Workshop
- Restricting analysis to most downstream target simplifies reconstruction and selection:
  - Avoid tracking through dense, passive materials (other targets)
  - Most similar to CC reconstruction and acceptance in scintillator tracker region



CC in nuclear target (Fe, Pb)

MC



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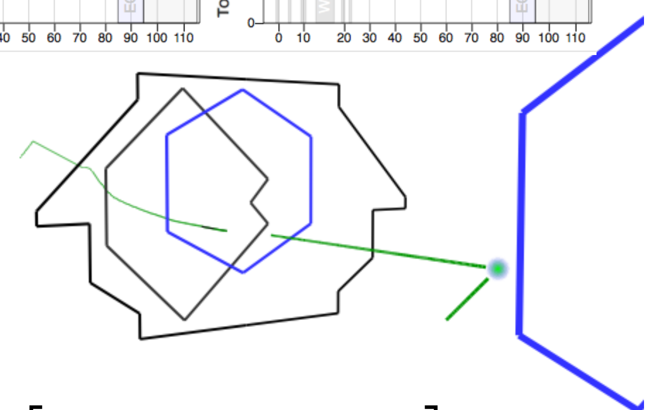


- Looking at ratios removes dependence on flux, while revealing A-dependent nuclear effects in data

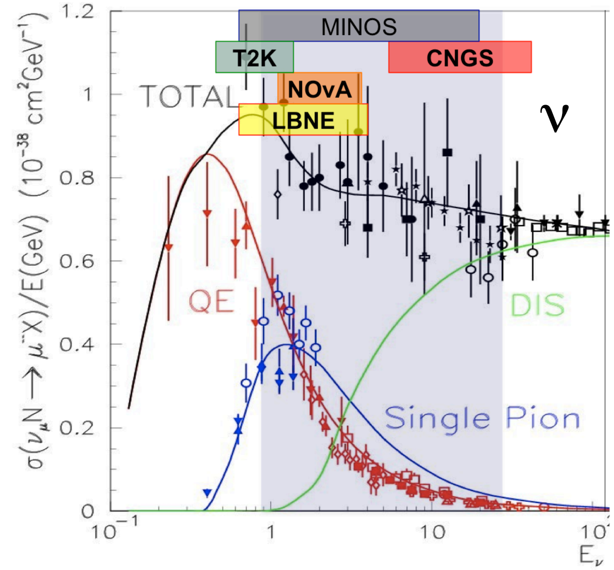
$$\left[\frac{N^{Fe,Pb}(E_\mu,\theta_\mu,\ldots)}{N^{CH}(E_\mu,\theta_\mu,\ldots)}\right]_{MC} \quad vs. \quad \left[\frac{N^{Fe,Pb}(E_\mu,\theta_\mu,\ldots)}{N^{CH}(E_\mu,\theta_\mu,\ldots)}\right]_{DATA}$$

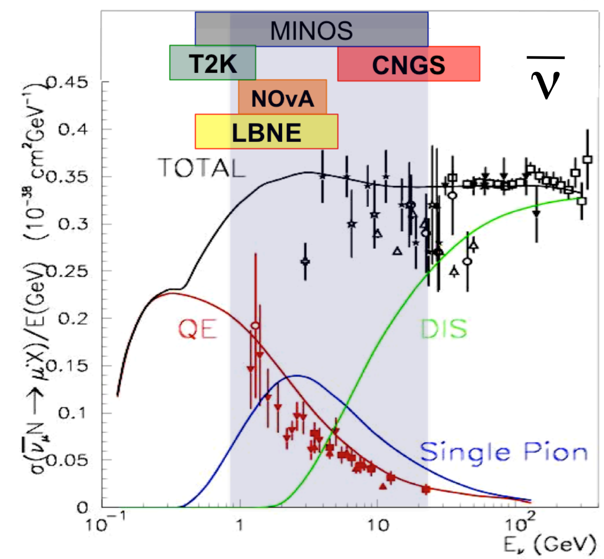
- Today I have focused mostly on lower energy, low multiplicity final state neutrino cross-section measurements to be made by MINERνA (CCQE, single pion, …)
- However, the intense NuMI broad-band neutrino beam and the fine-grained high-resolution MINERνA detector provide an opportunity for a lot of physics beyond cross-sections for oscillations, particularly with the addition of the He target to be installed this year and the higher energy beam running beginning in 2013
  - Deep Inelastic Scattering
  - Parton Distribution Functions of the nucleons
  - Resonant to DIS transition region
  - Charm and strange production

- **4e20 POT low energy beam (3/2010 – 3/2012)**
- **12e20 POT medium energy beam in NOνA era (beginning in 2013)**

Total Events Expected in MINERνA

Coherent pion production	89k CC, 44k NC
Quasi-elastic	0.8 M
Resonance production	1.7 M
Resonance to DIS transition	2.1 M
DIS, structure functions, high-x PDFs	4.3 M
He target	0.6 M
C target	0.4 M
Fe target	2.0 M
Pb target	2.5 M

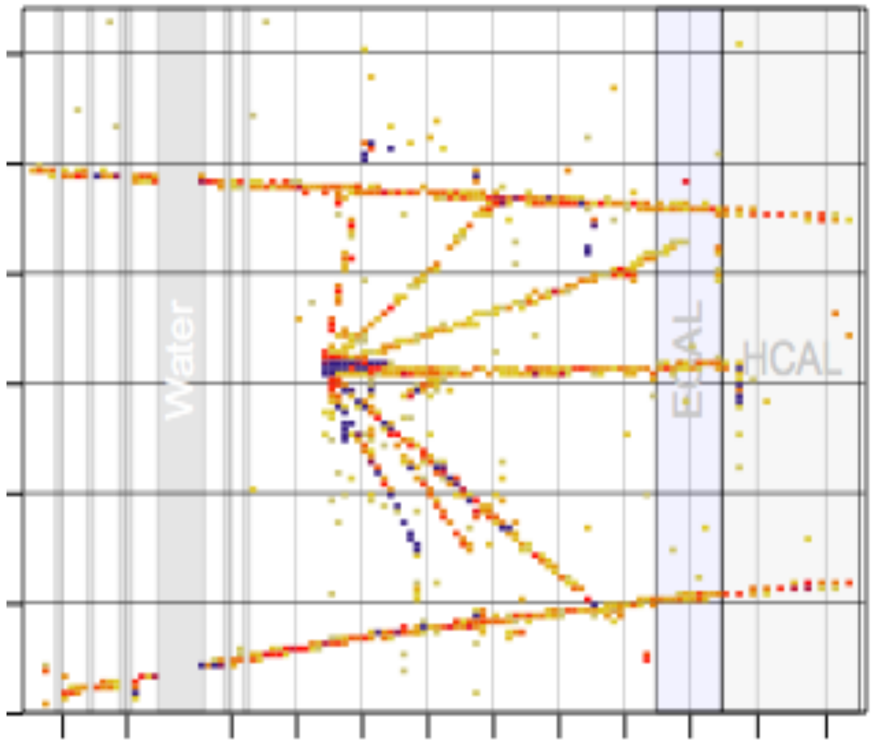




- But low energy cross-sections will be our first results and will have direct impacts for oscillation experiments
  - Absolute cross-sections
  - Differential cross-sections
  - Untangling nuclear effects

- First results from MINERνA should come soon and will be followed by years of new measurements!

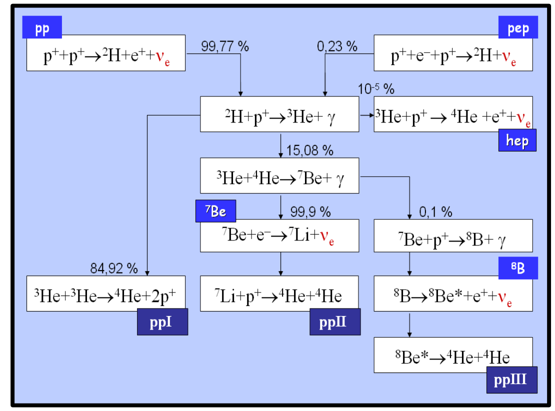
Thank you

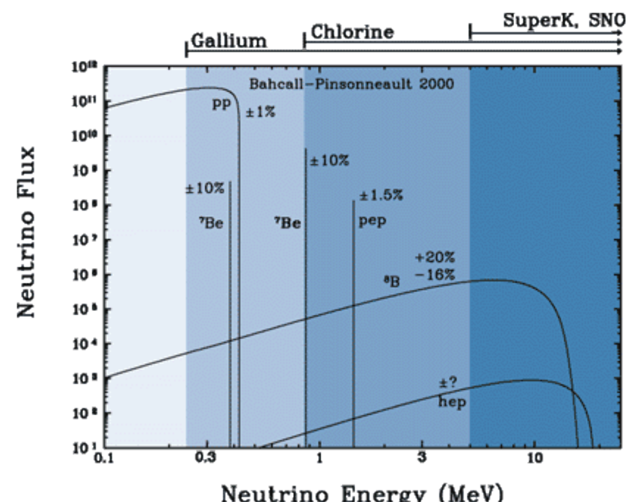


Extras

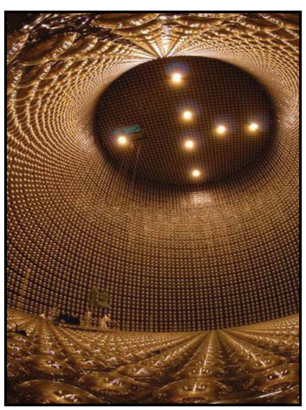
Δm^2_{12}

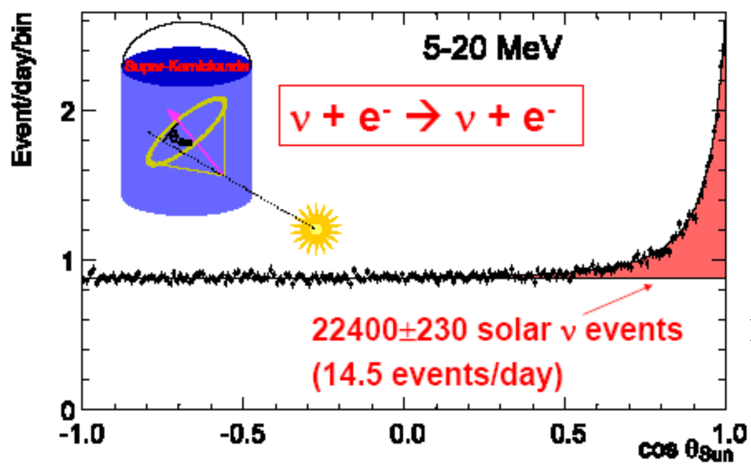
- First experimental evidence came from electron neutrinos from the sun
  - original goal was to demonstrate fusion in the sun, but much fewer than the expected number of ν_e's were detected





Super-K ν_e seen / ν_e expected: $0.451^{+0.017}_{-0.015}$





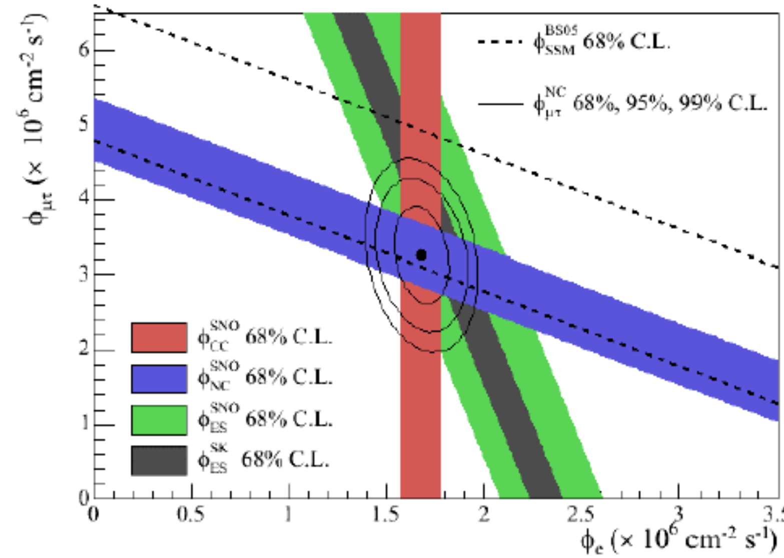
Phys. Rev. D 73, 112011 (2006)

Δm^2_{12}

- First experimental evidence came from electron neutrinos from the sun
- Confirmation of the oscillation hypothesis came from **SNO** which could see all neutrino types

$$\nu_e + d \rightarrow p + p + e^- \quad (CC)$$
$$\nu_x + d \rightarrow p + n + \nu_x \quad (NC)$$
$$\nu_x + e^- \rightarrow \nu_x + e^- \quad (ES)$$

Phys. Rev. C 72, 055502 (2005)



$$\phi_e = 1.76^{+0.05}_{-0.05}(\text{stat.})^{+0.09}_{-0.09}\ (\text{syst.})$$
$$\phi_{\mu\tau} = 3.41^{+0.45}_{-0.45}(\text{stat.})^{+0.48}_{-0.45}\ (\text{syst.})$$

- Total rate matched expectation from solar model, but only 1/3 were electron neutrinos.
  But the sun only makes electron neutrinos!!

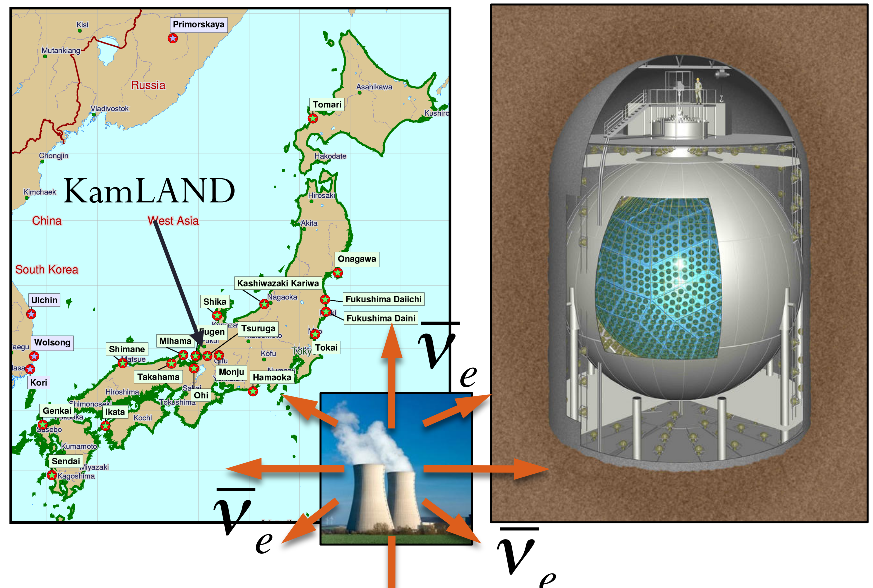
Δm^2_{12}

- First experimental evidence came from electron neutrinos from the sun
- And precision measurements of Δm^2_{12} and θ_{12} came from **KamLAND** in Japan using anti-neutrinos produced by power reactors

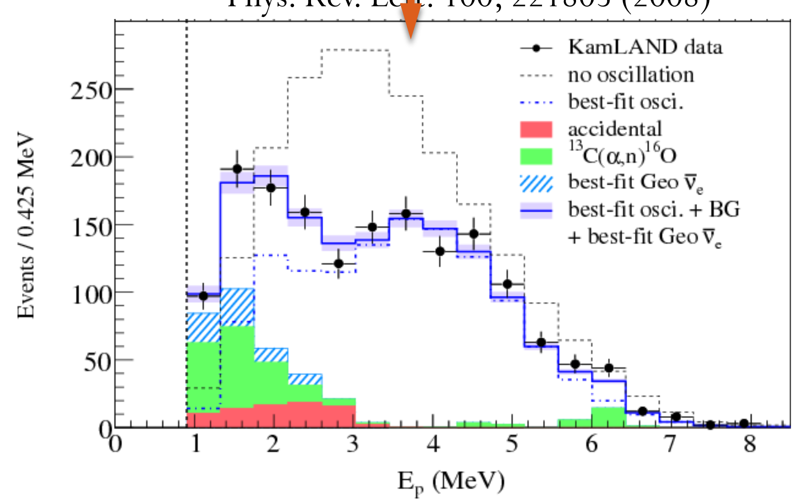
$$\langle E \rangle_{KamLAND} \approx 5\,MeV$$
$$\langle L \rangle_{KamLAND} \approx 180\,km$$

$$for \;\; \sin^2(x) \sim 1$$

$$\Delta m^2 \geq 1 / \left(1.27 * \frac{180\,km}{0.005\,GeV} \right) \sim 10^{-5}\,eV^2$$



Phys. Rev. Lett. 100, 221803 (2008)



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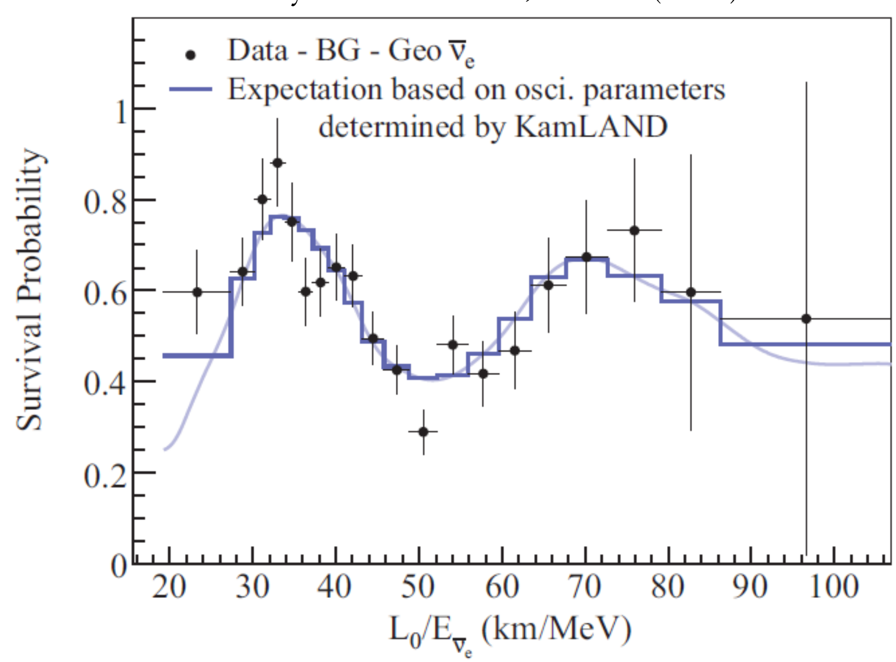
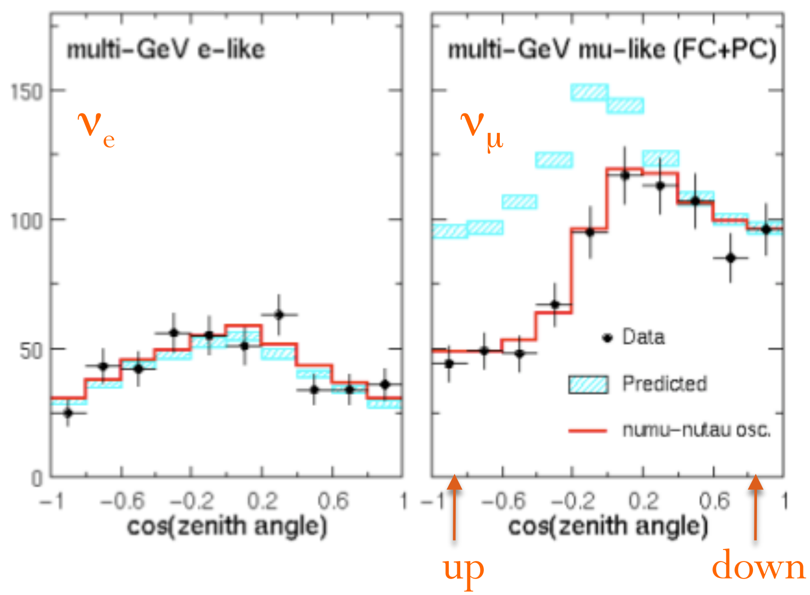
Phys. Rev. Lett. 100, 221803 (2008)

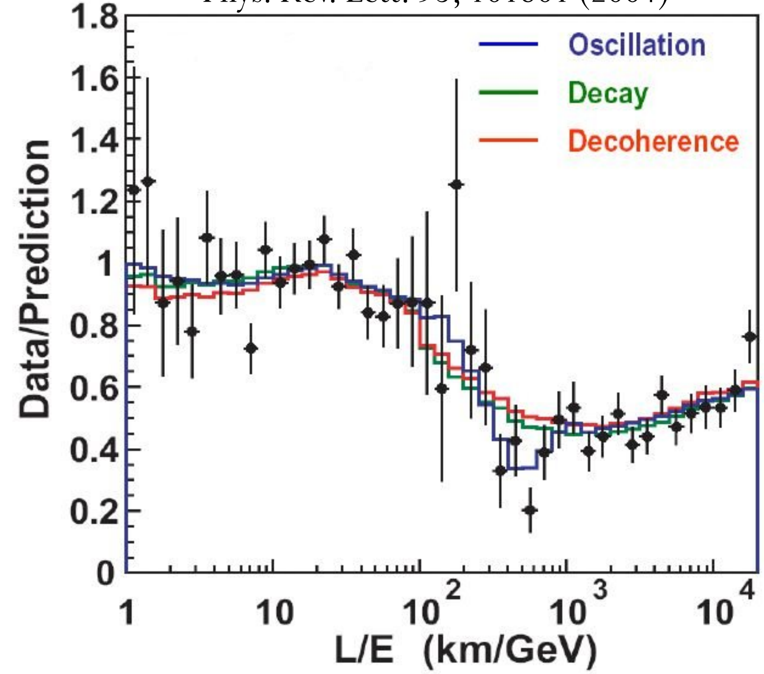


Δm^2_{23}

- First experimental evidence came from neutrinos produced in the atmosphere by cosmic rays
- Again **Super-K** makes a pivotal contribution



Phys. Rev. Lett. 93, 101801 (2004)



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

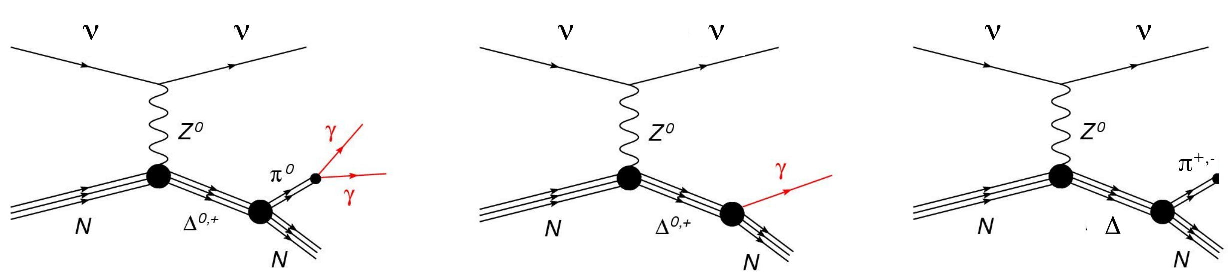
$$\langle E \rangle_{Super-K} \approx 1 - 10\ GeV$$

$$\langle L \rangle_{Super-K} \approx 10 - 10^4\ km$$

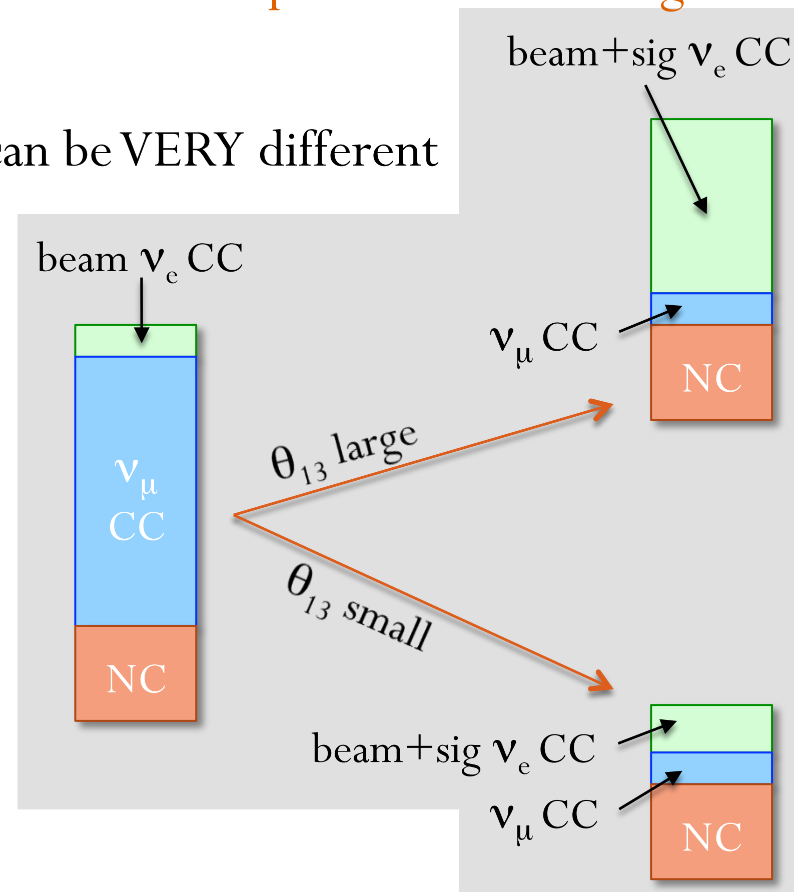
$$\Delta m^2 \sim 10^{-4} - 1\, eV^2$$

- **Why the search for θ_{13} and δ^{CP} is a paradigm shift in long-baseline accelerator-based neutrino oscillation experiments**
- So, one just wants to sample the neutrino flavor content near the beam source and again at a distant detector location

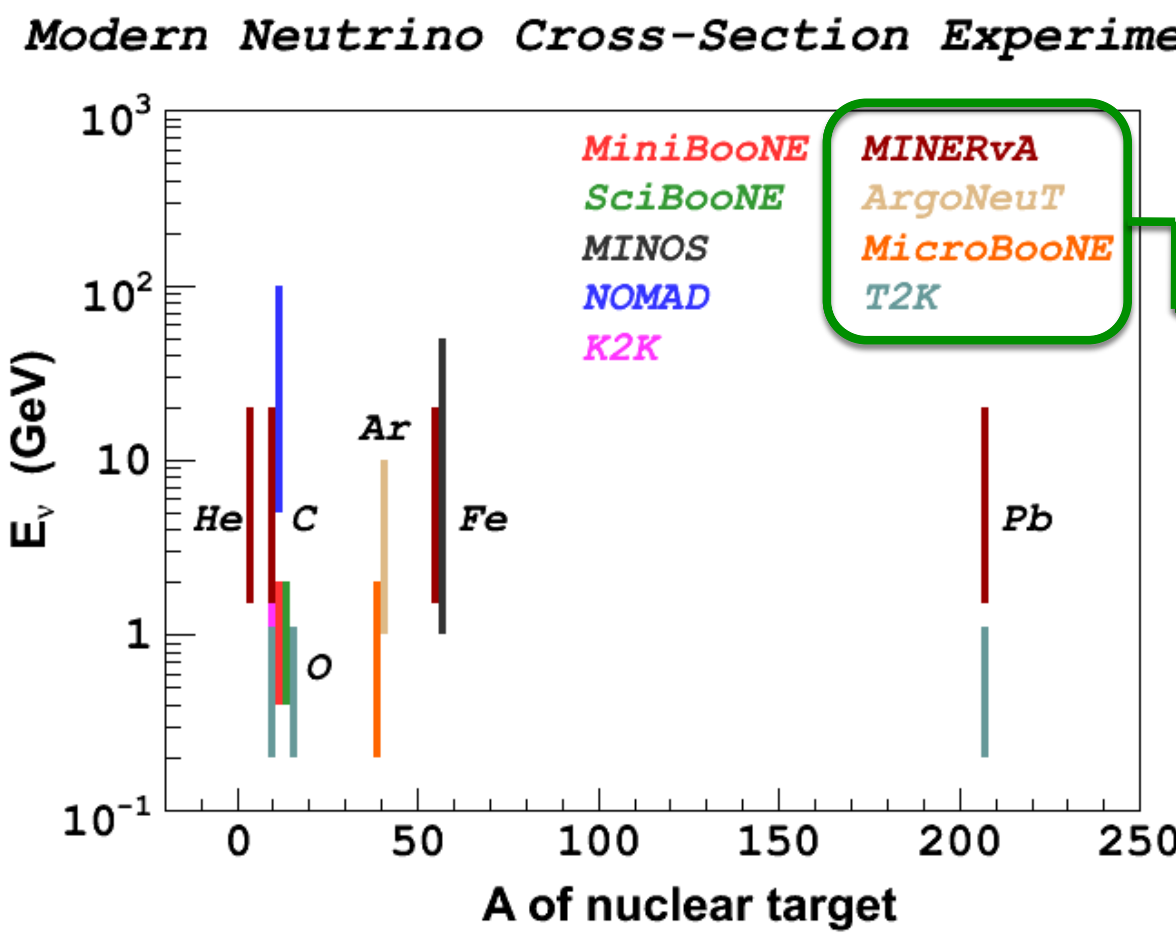
- But, in practice, this is complicated by neutral current backgrounds
  - π^0's/γ's can fake electrons
  - π^{+-}'s can fake muons



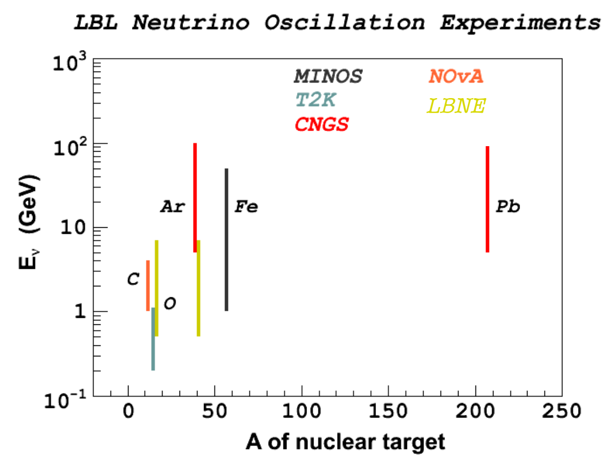
- **Why the search for θ_{13} and δ^{CP} is a paradigm shift in long-baseline accelerator-based neutrino oscillation experiments**
- Can't we just cancel cross-section uncertainties once the experiment is running?
- To date, this has worked extremely effectively
- But fluxes & Detectors at Near/Far locations can be VERY different
  - detector designs are not always identical
  - beam acceptances change the fluxes
  - flux oscillates away or appears between detectors
  - flavor content vs. energy changes dramatically
- Large θ_{13}, need better handle on signal cross-sections (ν_e CCQE, RES, DIS)
- Small θ_{13}, need better handle on background cross-sections (NC π^0)



Nuclear targets
Neutrino energies
Interaction channels

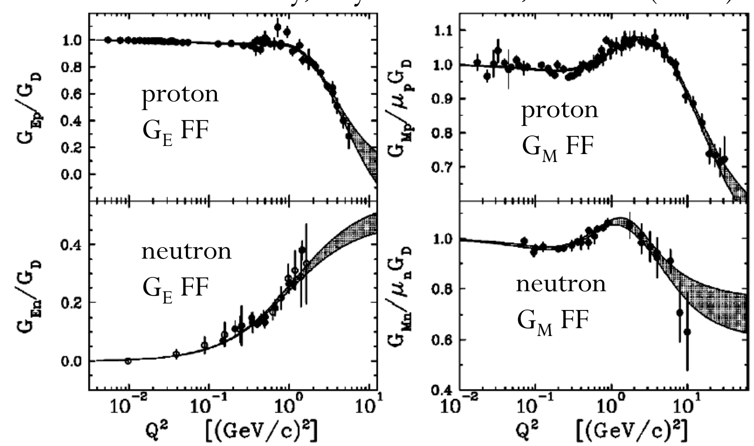


near future neutrino cross-section experiments



- Charged-Current Quasi-Elastic Scattering

Kelly, Phys. Rev. **C70**, 068202 (2004)



- **Vector Form Factors**
  - well known from e^- scattering
  - deviations from dipole form at high Q^2
- **Axial-Vector Form Factor** dominates uncertainty in CCQE cross-section. Assume dipole form:

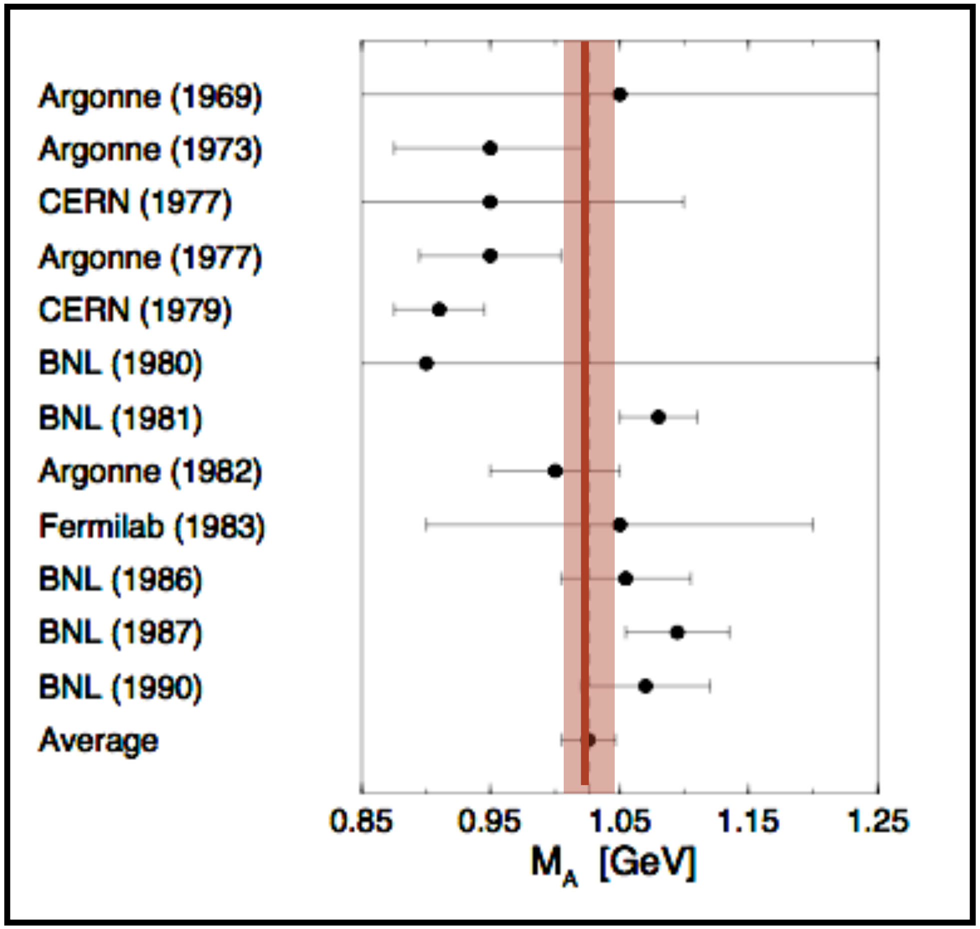
$$F_A(Q^2) = F_A(0)\left(1 + \frac{Q^2}{M_A^2}\right)^{-2}$$

well known from β decay experiments ($Q^2 = 0$) → $F_A(0)$

measured from Q^2 distribution of QE neutrino-nucleon events → M_A

- **Nuclear effects** – simulated with Relativistic Fermi Gas Model “RFG” formalism of Smith and Moniz, NP B43, 605 (1972).

- Charged-Current Quasi-Elastic Scattering



Bernard *et al.*, J. Phys. **G28**, R1 (2002)

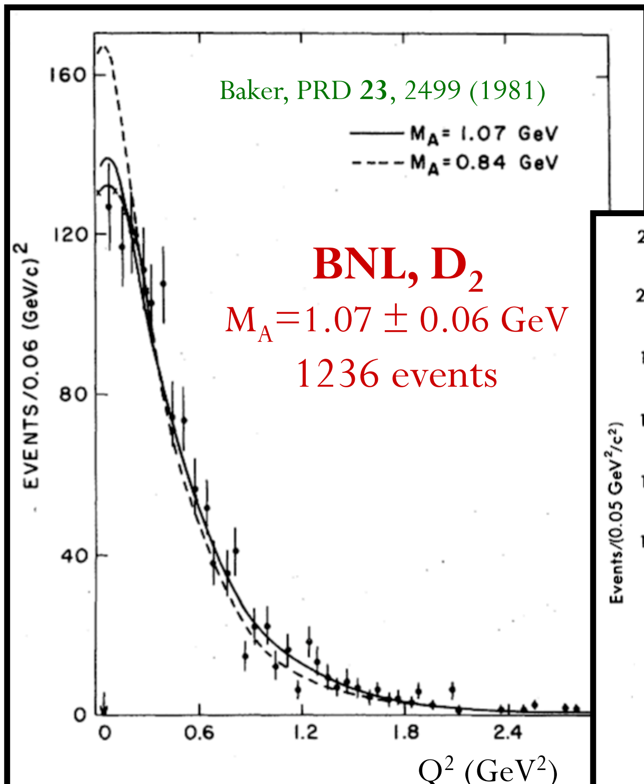
$$F_A(Q^2) = F_A(0)\left(1 + \frac{Q^2}{M_A^2}\right)^{-2}$$

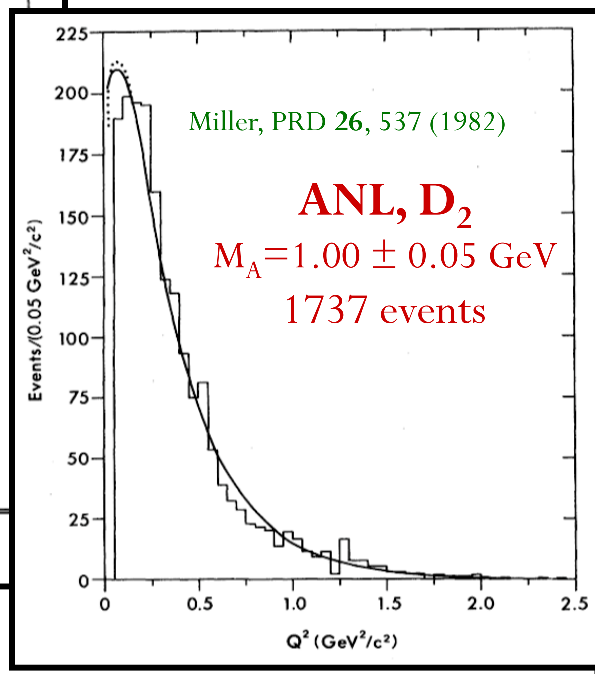
world average: $M_A = 1.03 \pm 0.02$ GeV

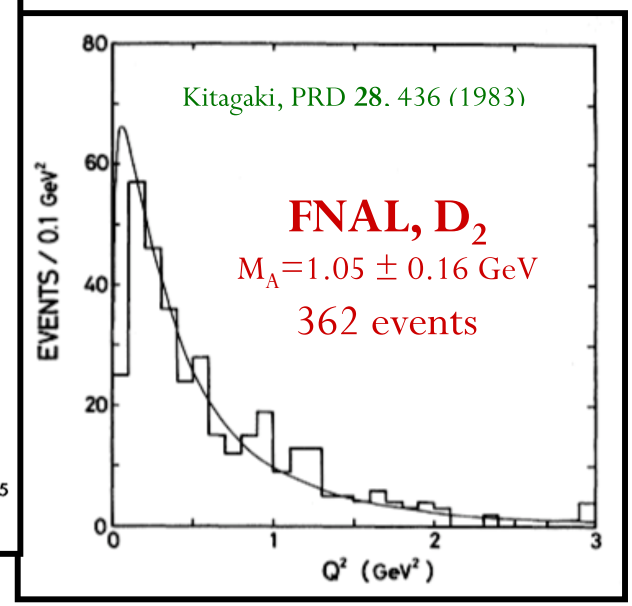
- Was a focus of many early bubble chamber experiments
- Mostly QE data on D_2 (1969-1990)

- Charged-Current Quasi-Elastic Scattering

$$F_A(Q^2) = F_A(0)\left(1 + \frac{Q^2}{M_A^2}\right)^{-2}$$





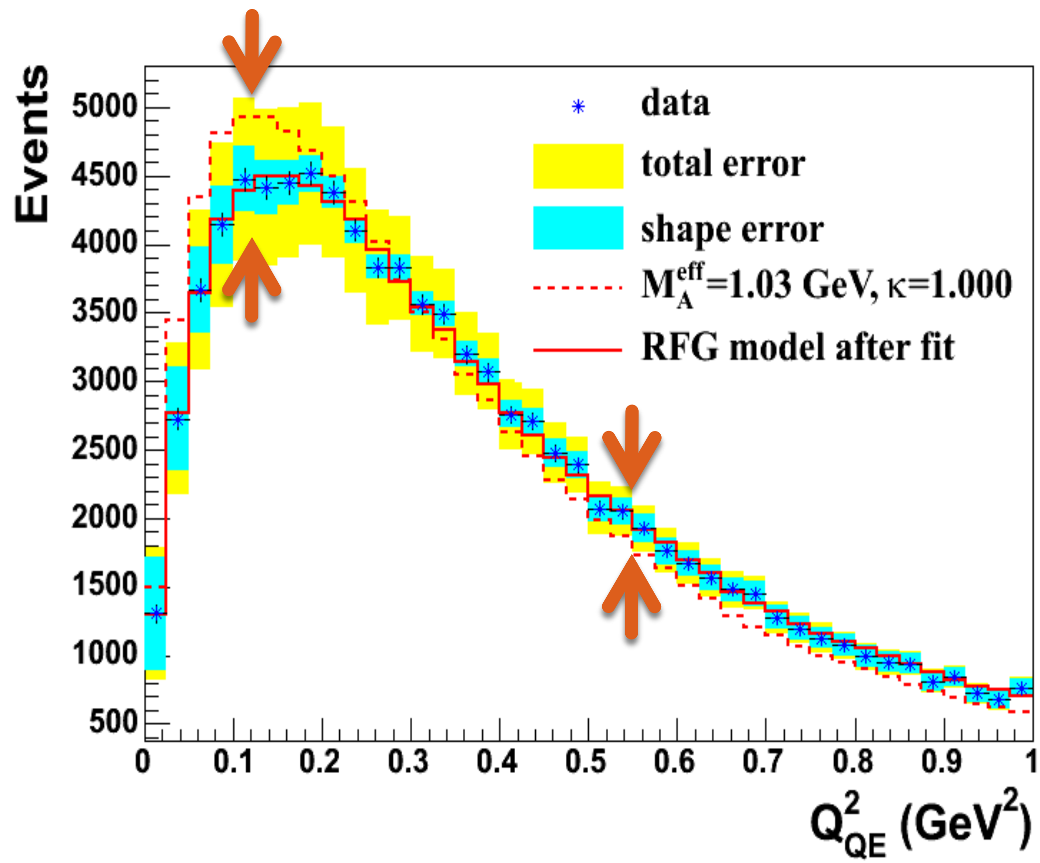


Charged-Current Quasi-Elastic Scattering

- Because of important role of CCQE and M_A, modern experiments have looked to re-measure this parameter
- MiniBooNE data:
  - 146,070 ν_μ QE events on carbon (76% purity)
  - deficit seen at lowest Q^2
  - excess at higher Q^2

$$M_A = 1.35 \pm 0.17\ GeV$$
$$\kappa = 1.007 \pm 0.012$$

scaling parameter to increase Pauli blocking in the mode



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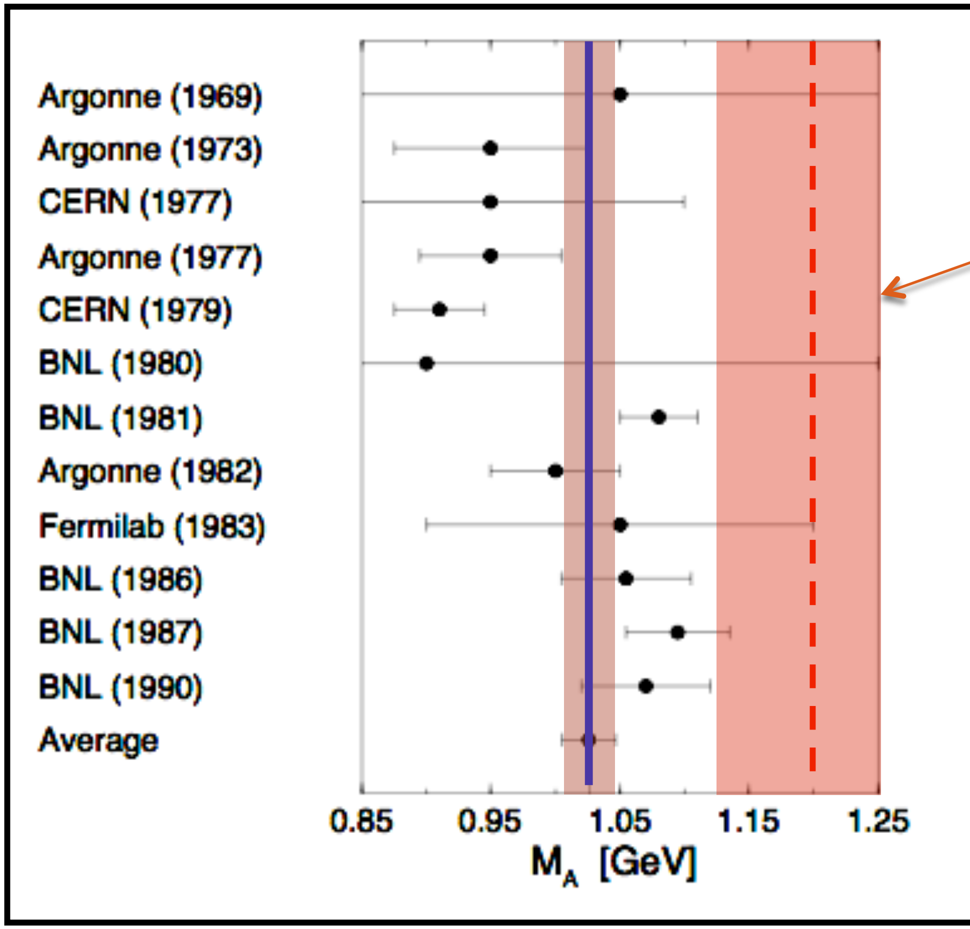
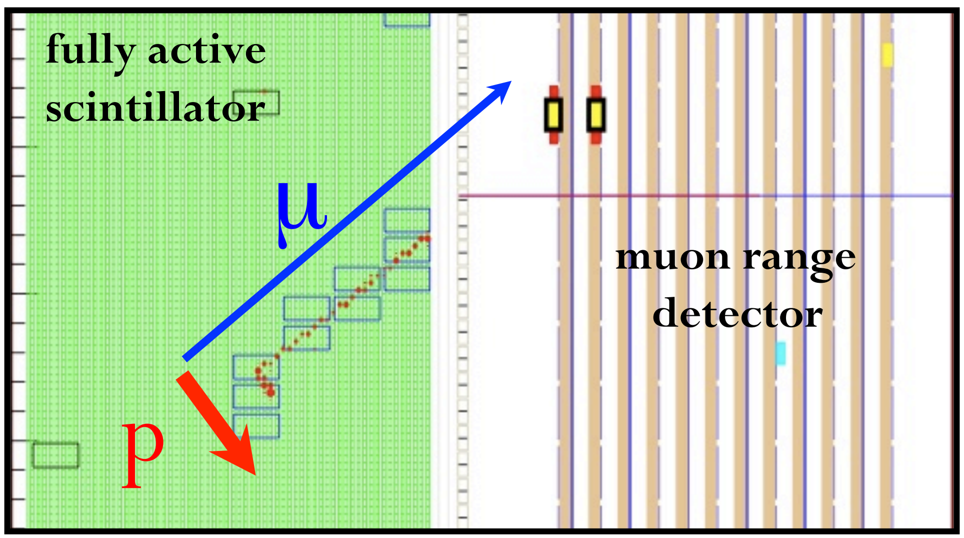


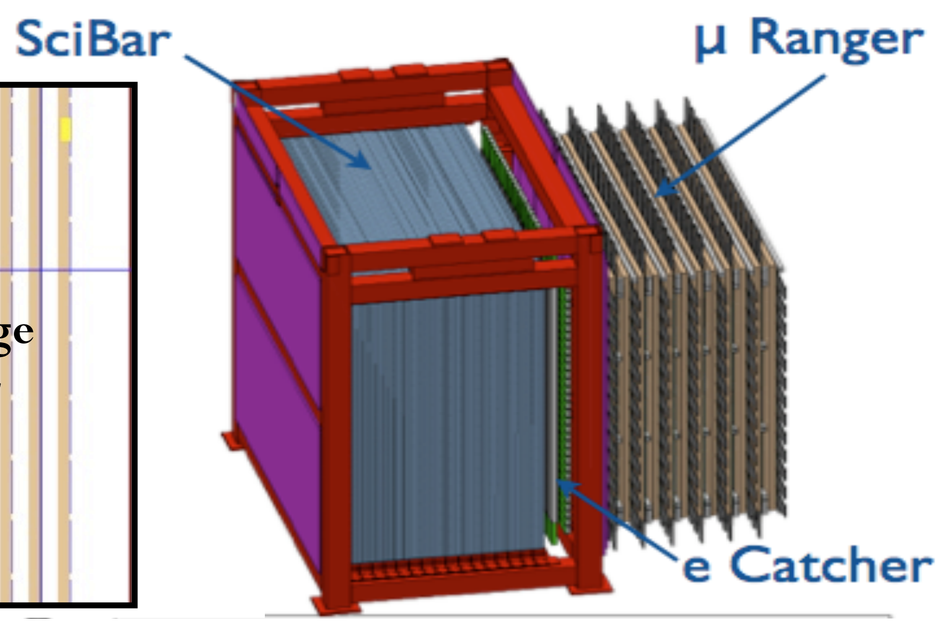
- **K2K SciFi** (^{16}O, Q^2>0.2)
  Phys. Rev. **D74**, 052002 (2006)
  M_A=1.20 ± 0.12 GeV
- **K2K SciBar** (^{12}C, Q^2>0.2)
  AIP Conf. Proc. **967**, 117 (2007)
  M_A=1.14 ± 0.11 GeV
- **MiniBooNE** (^{12}C, Q^2>0.25)
  Phys. Rev. D81, 092005 (2010)
  M_A=1.35 ± 0.17 GeV
- **MINOS** (Fe, Q^2>0.3)
  NuInt09, preliminary
  M_A=1.26 ± 0.17 GeV

- all on nuclear targets
- all use Fermi Gas model
- all see similar Q^2 disagreement

- <u>Charged-Current Quasi-Elastic Scattering</u>

- SciBooNE is a fully active scintillator detector/target
- 2,680 2-track ν_μ QE events on carbon (69% purity)
- have preliminary measurement of $\sigma_{CCQE}(E)$ from $E_\nu = 0.6 – 1.6$ GeV
- active analysis
  - 1track vs 2 track; active contained vs muon range detector
  - differential cross-sections





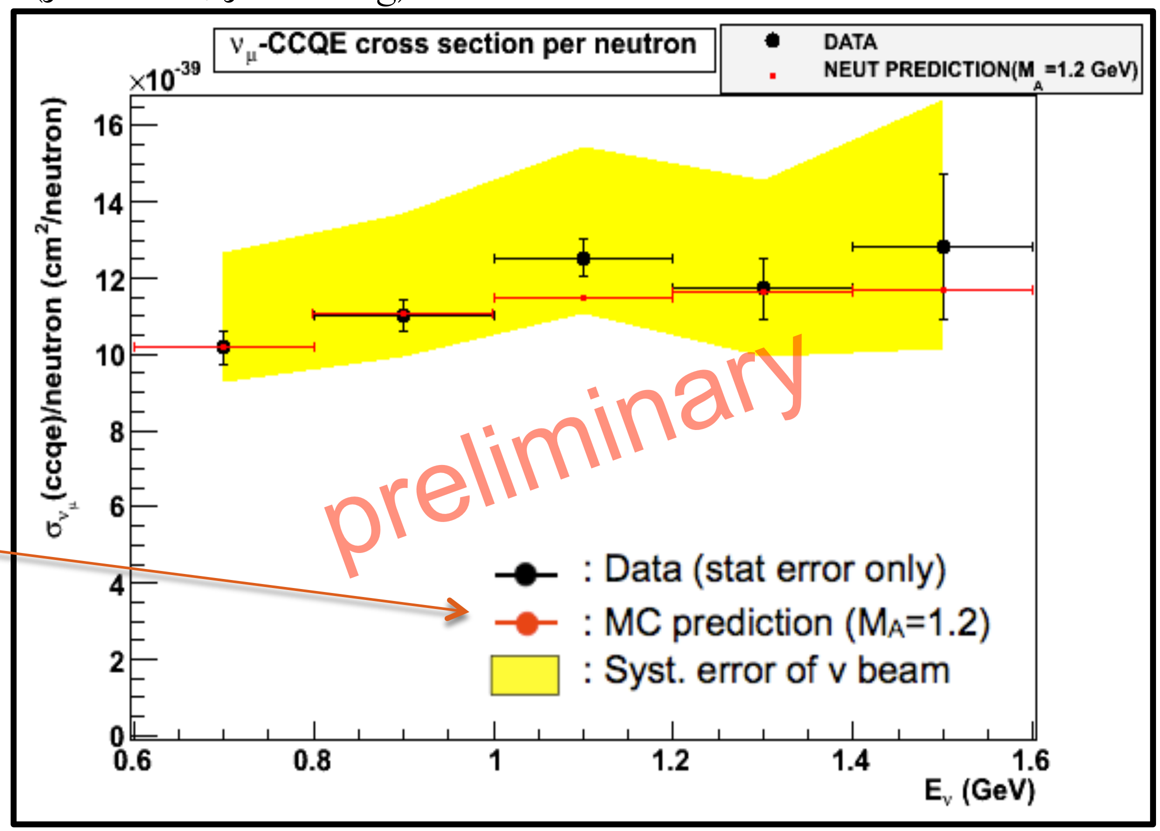
Charged-Current Quasi-Elastic Scattering

- can resolve final state by identifying the proton track as well as the muon

- 2,680 2-track ν_μ QE events (69% purity)

- agrees with model prediction already scaled based on MiniBooNE result (that is, preliminary result consistent with MiniBooNE)

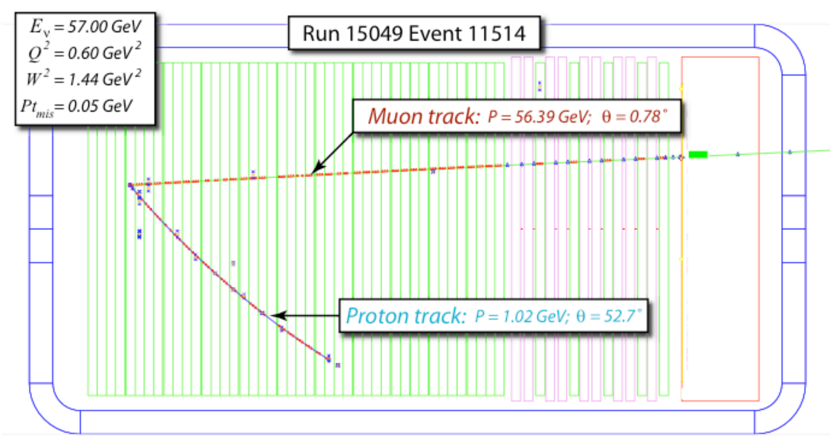
(J. Alcaraz, J. Walding)

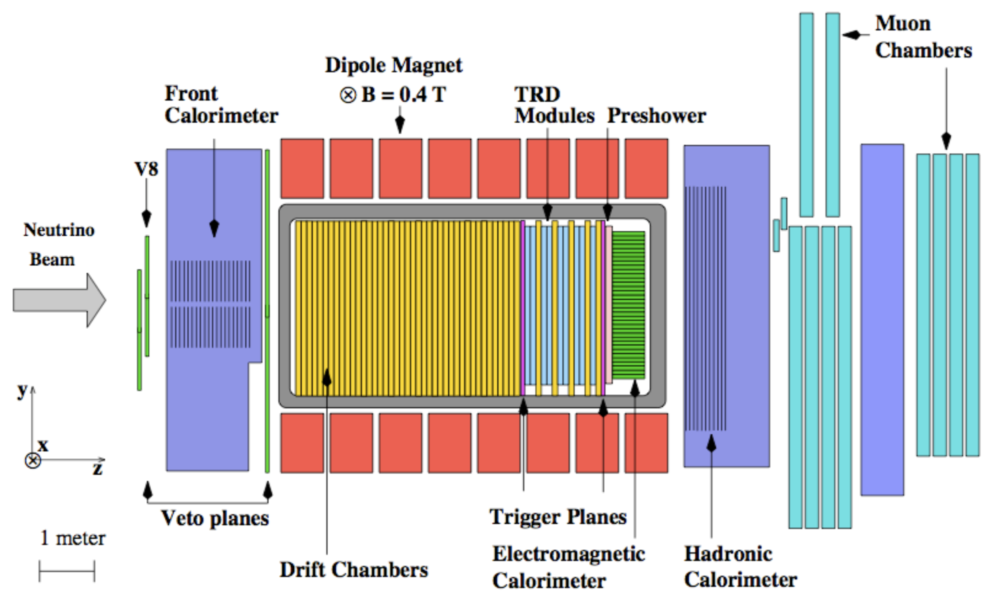


• Charged-Current Quasi-Elastic Scattering

- NOMAD collaboration recently published a quasi-elastic cross-section for neutrinos and antineutrinos
- target nucleus same as BooNEs carbon
- higher energy neutrino flux $E_\nu = 3 - 200$ GeV
- drift chamber tracking detector, high resolution on muon **AND** proton tracks

arXiv:0812.4543v3

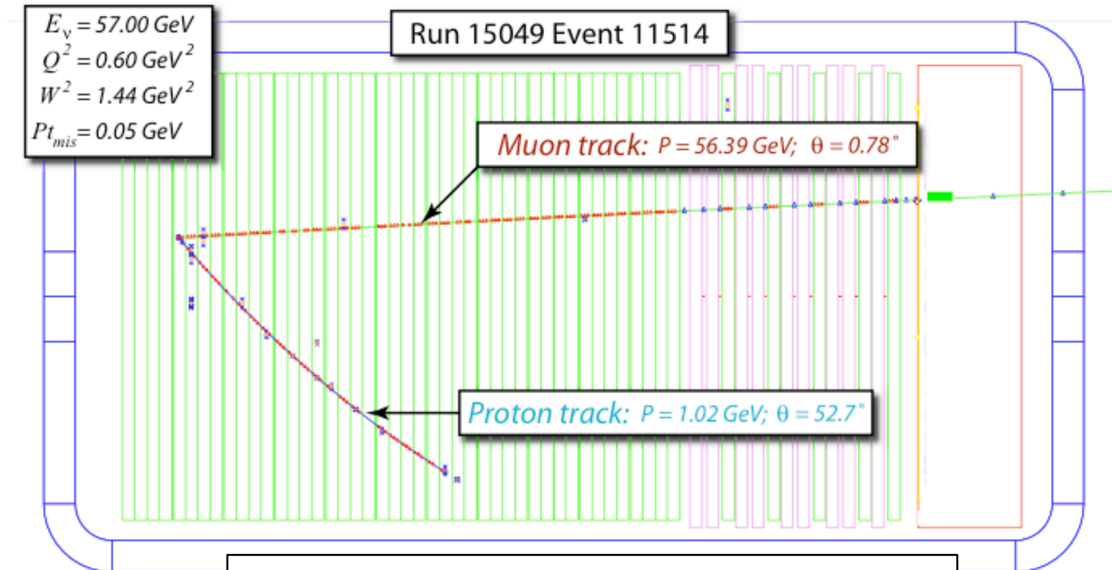


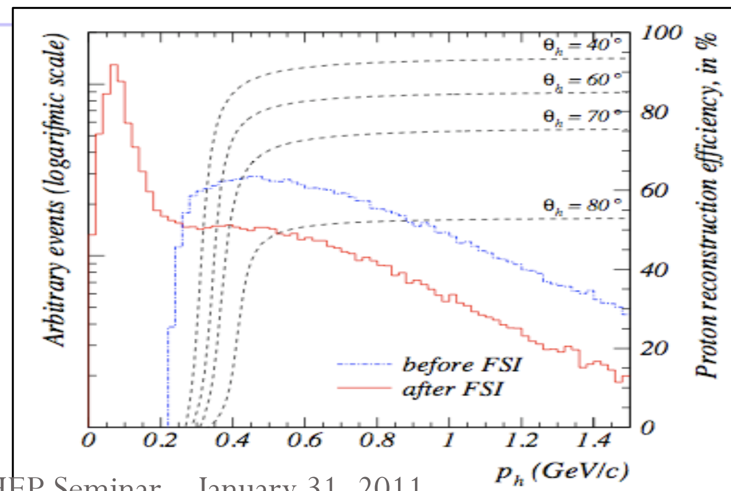


Charged-Current Quasi-Elastic Scattering

• combined 1-track (muon only) and 2-track (muon+proton) samples for measuring CCQE cross-section

• nuclear effects cause migration from 2-track to 1-track, so inclusion of both minimizes systematic from knowing this migration



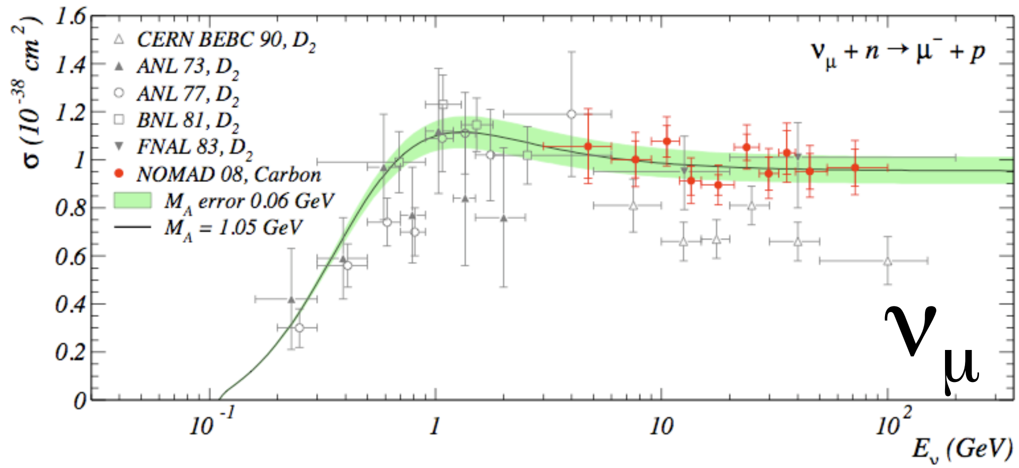


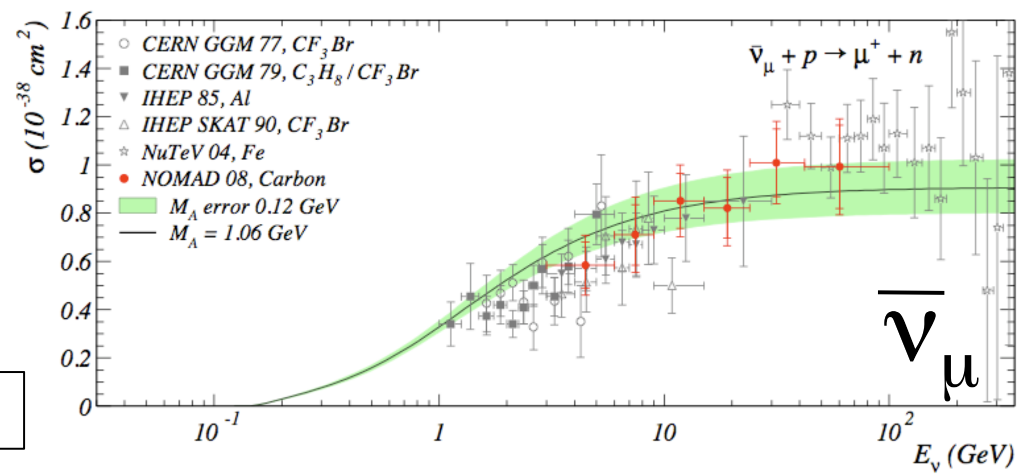
arXiv:0812.4543v3

• Charged-Current Quasi-Elastic Scattering

• can identify μ^+ and μ^- from track bend directions

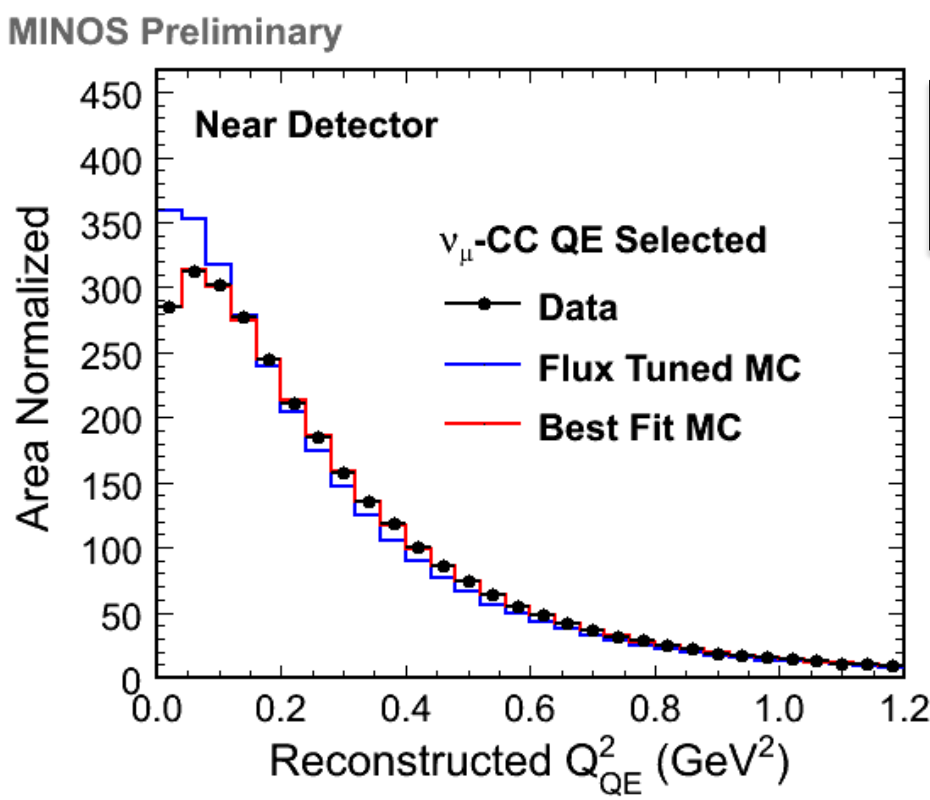
• present both neutrino and antineutrino QE cross-sections above 3 GeV





arXiv:0812.4543v3

- Charged-Current Quasi-Elastic Scattering



MINOS Preliminary

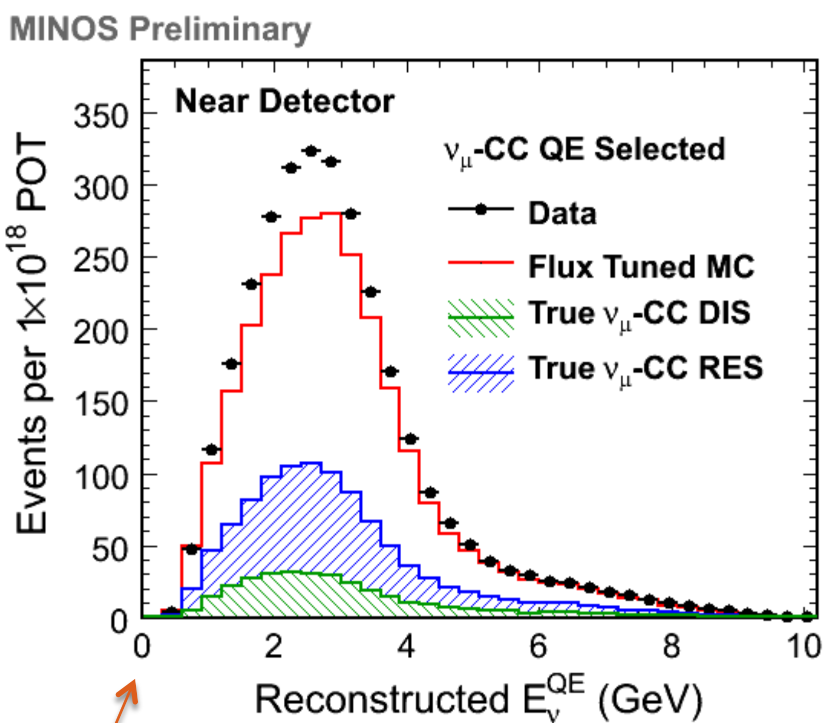
$M_A^{QE} = 1.19\ ^{+0.09}_{-0.10}\,(\text{fit})\ ^{+0.12}_{-0.14}\,(\text{syst})$ GeV

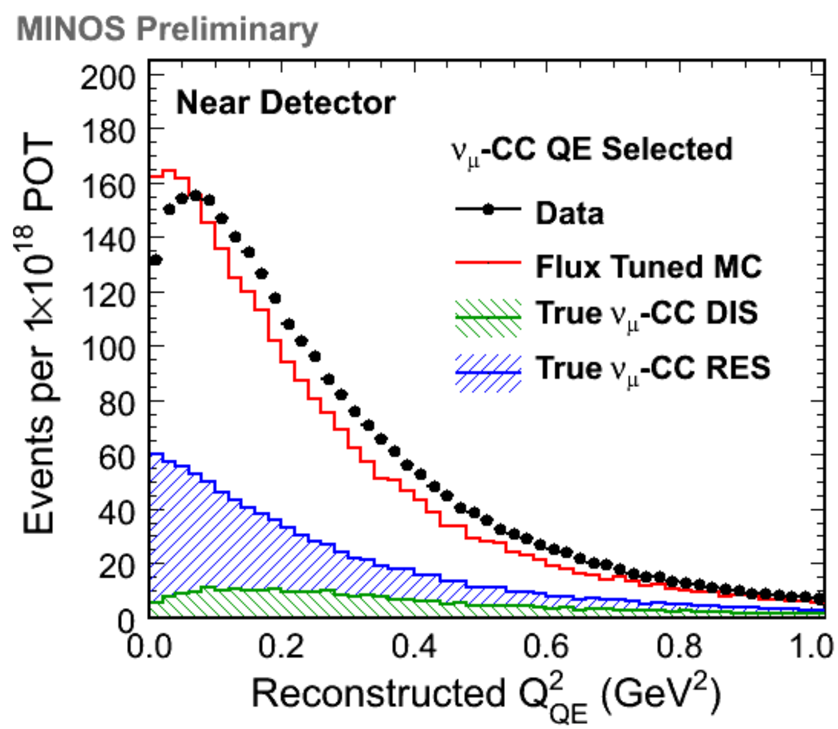
$k^{Fermi} = 1.28 \times k^{Fermi}$

- fit favors a higher value of the axial mass and increases the Fermi momentum by 28% as an effective low Q^2 suppression

- no absolute cross-section values extracted yet – to come

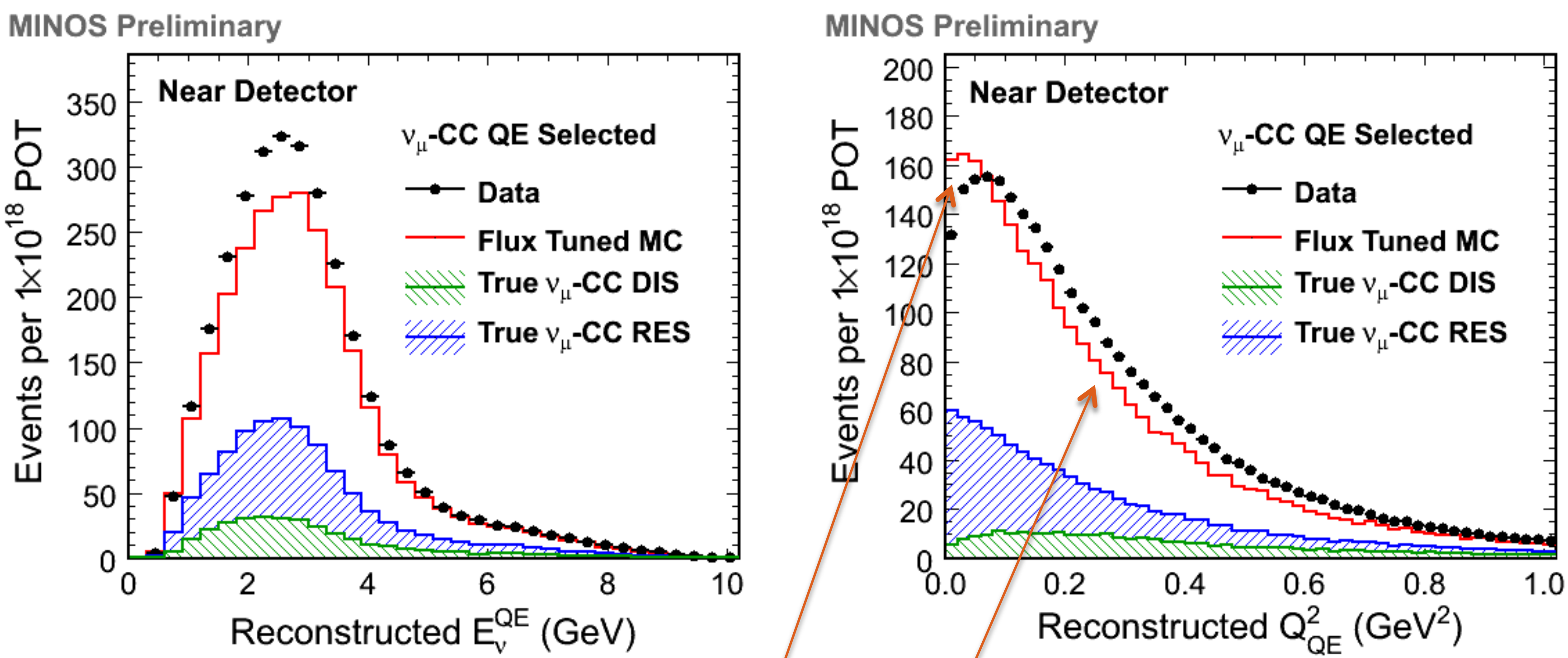
- Charged-Current Quasi-Elastic Scattering





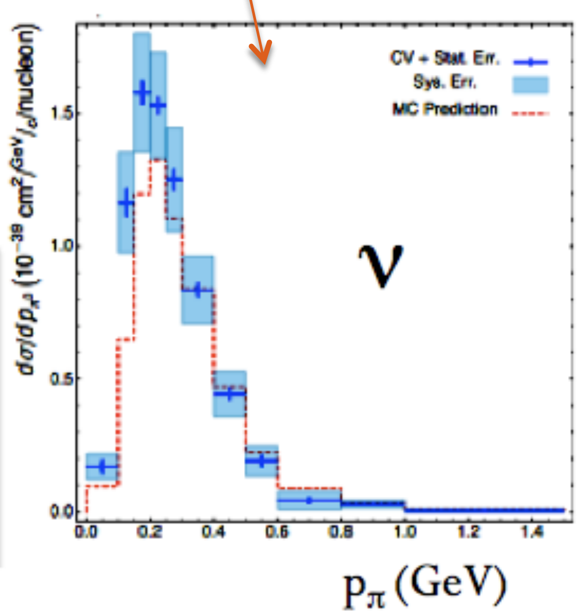
- Similar E_ν excess to those seen in Sci/MiniBooNE data

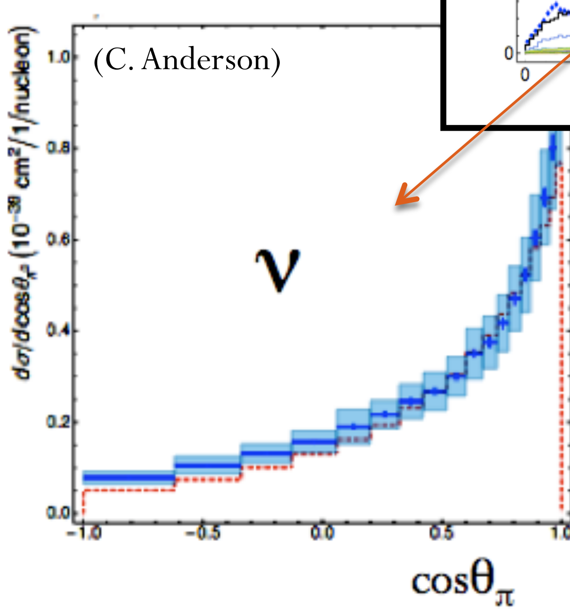
- Charged-Current Quasi-Elastic Scattering

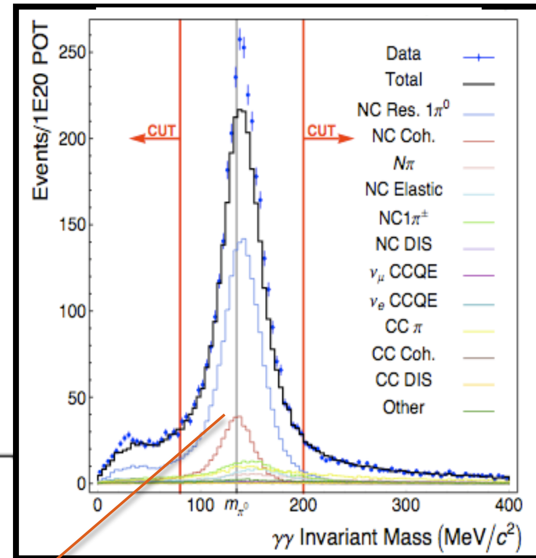


- Similar Q^2 shape disagreements to those seen in MiniBooNE data, but at higher energies and on iron instead of carbon

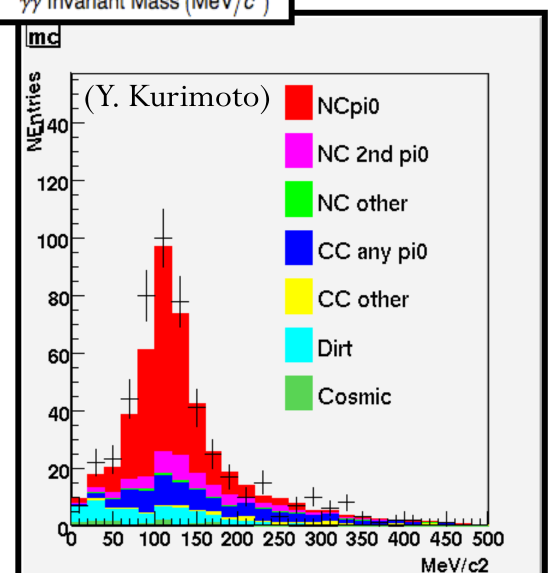
- <u>Single Pion Production</u>
  - Absolute differential cross-sections possible for the first time







(C. Anderson)



- Single Pion Production

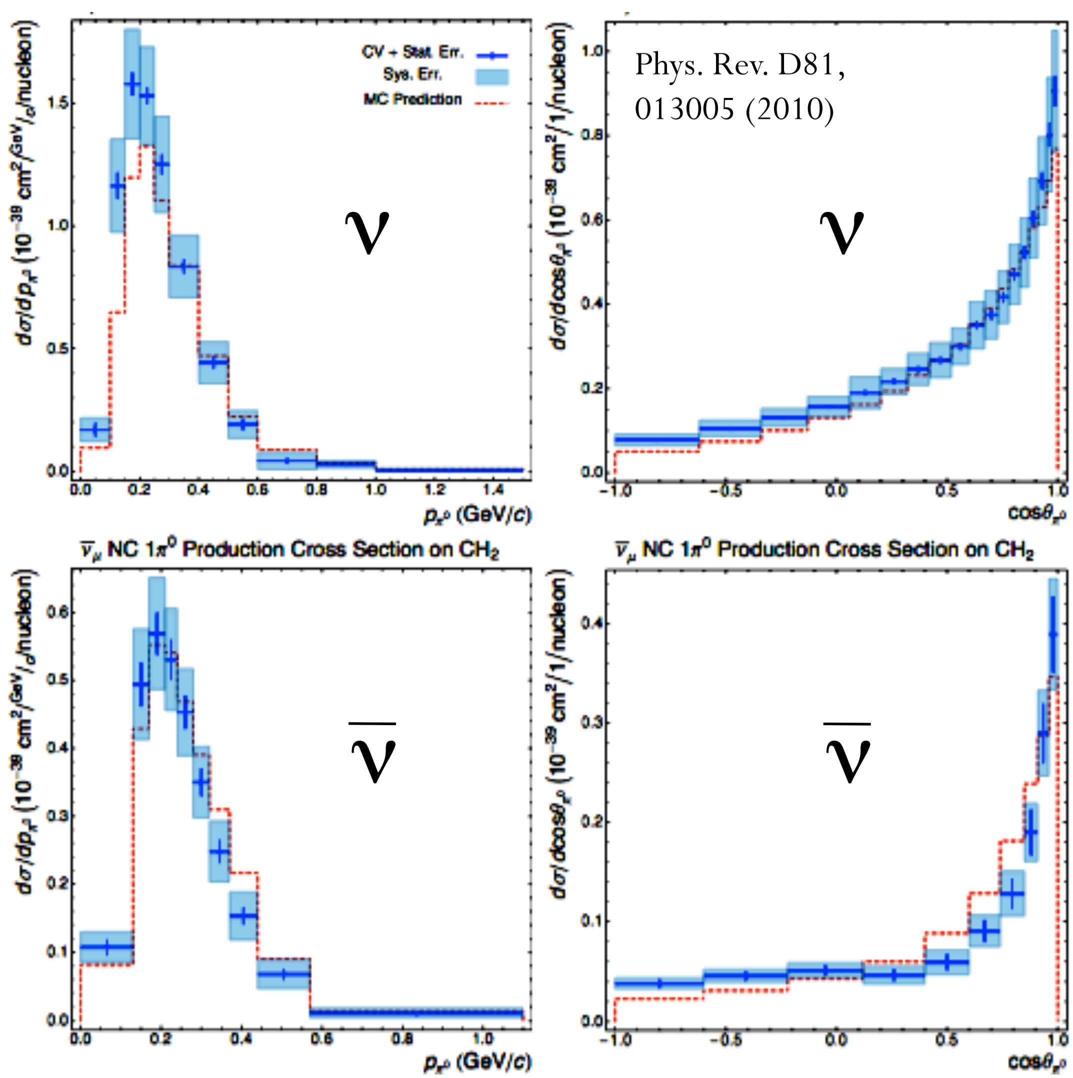
NC π^0 production

- Important new measurements from MiniBooNE including differential cross-sections now available

- On carbon at $<E_\nu> = 0.7$ GeV

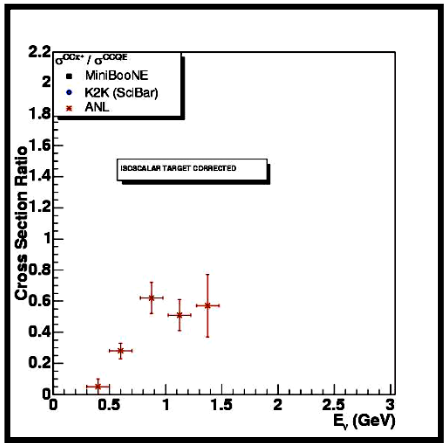
- Did not correct out nuclear effects

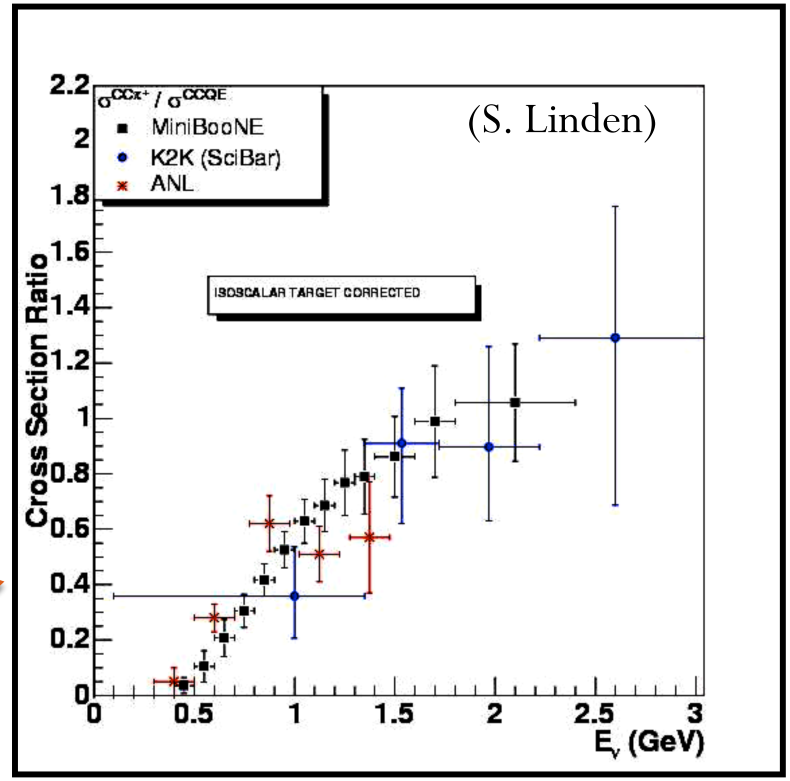
  * total NC π^0 production
  * NC π^0 after π^0 absorption
  * NC $\pi^{+/-} \rightarrow \pi^0$



- Single Pion Production

ANL: Phys. Rev. **D25**, 1161 (1982), deuterium





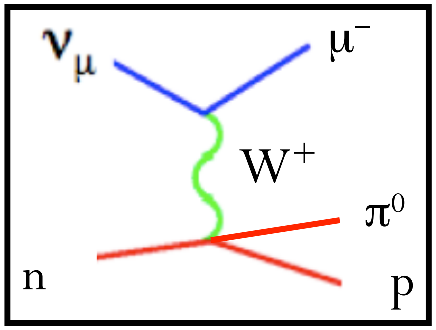
- 26 years between ANL and K2K/MiniBooNE results
- Cross-section ratio to CCQE

K2K: Phys. Rev. **D78**, 032003 (2008)

MiniBooNE: arXiv:0904.3159 [hep-ex]

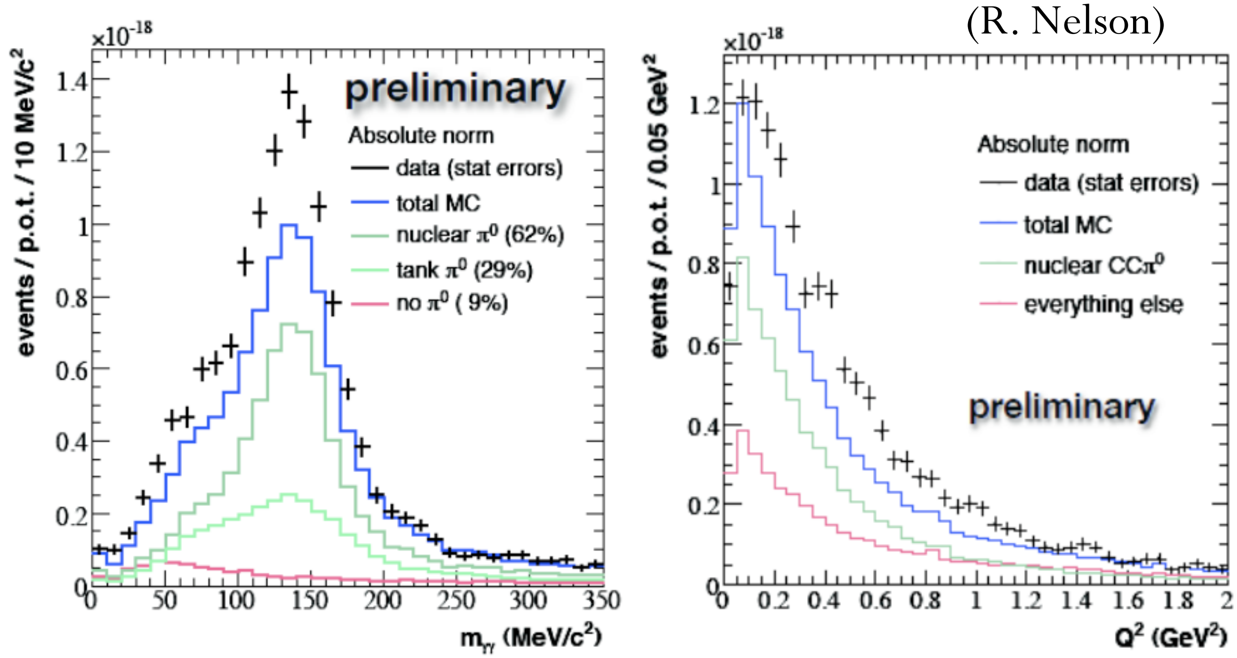
- Single Pion Production

CC π^0 production



- development of 3 Cherenkov ring fitter has made possible the study of CC π^0 production

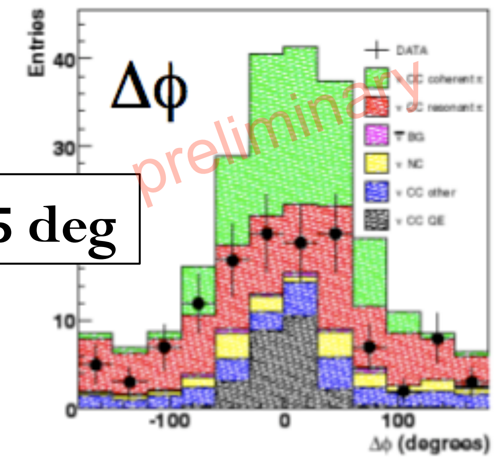
(R. Nelson)



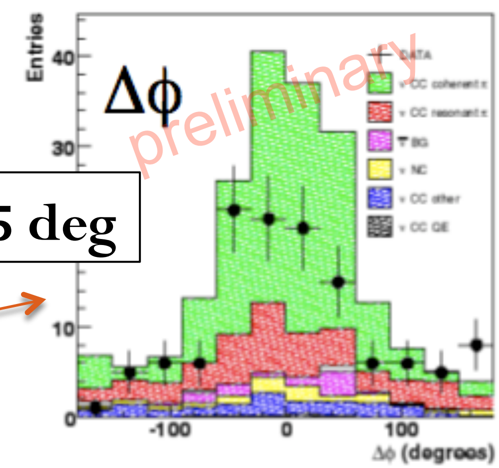
Coherent Single Pion Production (CC/NC)

- Coherent interaction with nucleus leaving it intact, but producing a pion
- very small rate compared to inelastic processes
- many intriguing results recently from K2K, MiniBooNE, SciBooNE
  - K2K first to see no evidence for CC coherent pion production
  - MiniBooNE did see evidence for NC coherent pion production, though below the prediction
  - Active analysis for SciBooNE
    - preliminary evidence for some CC coherent, but pions more forward than model predicts

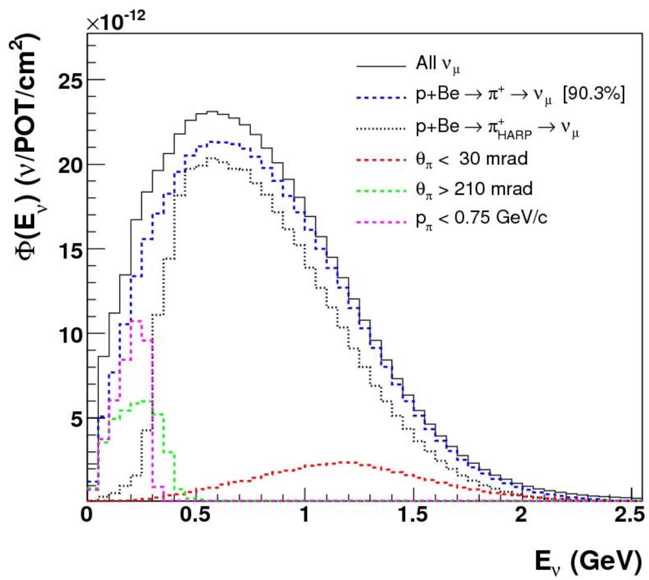
$\theta_\pi > 35$ deg

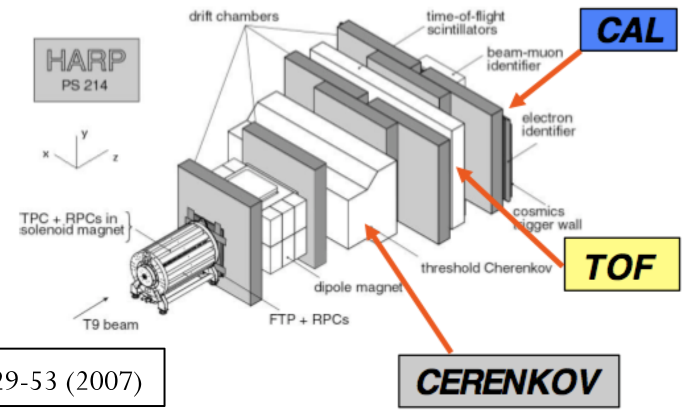


$\theta_\pi < 35$ deg

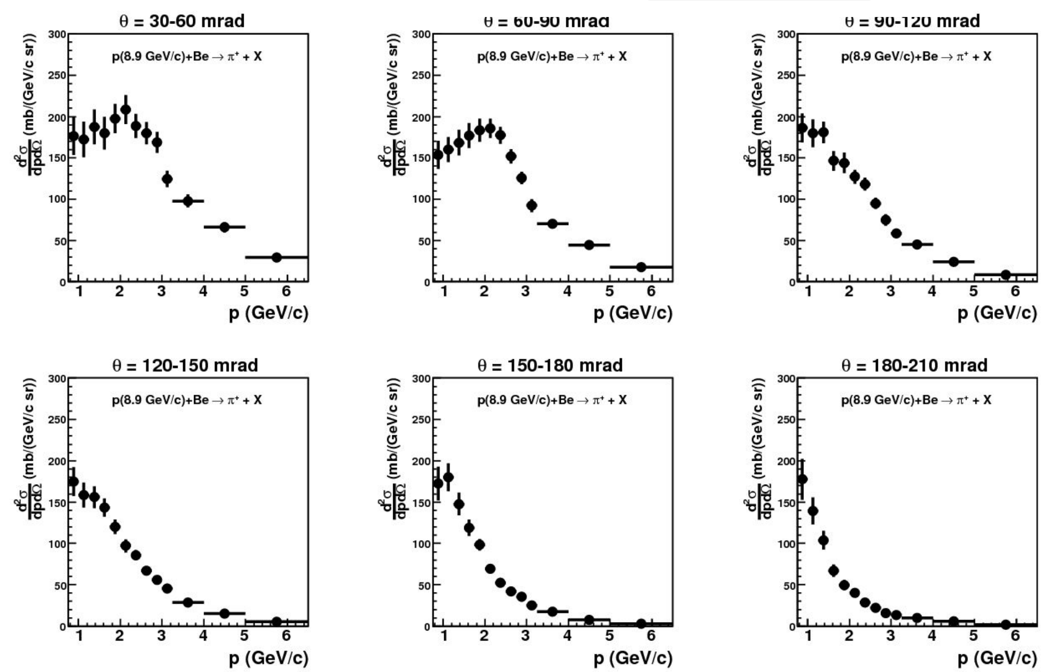


- MiniBooNE and SciBooNE both in Booster Neutrino Beam at Fermilab
  $E_\nu \sim 0.2 - 1.5$ GeV





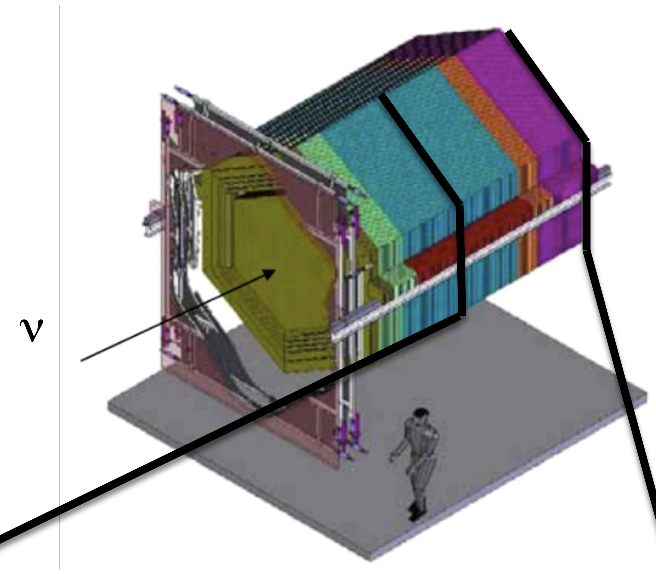
Euro. Phys. J C 52:29-53 (2007)

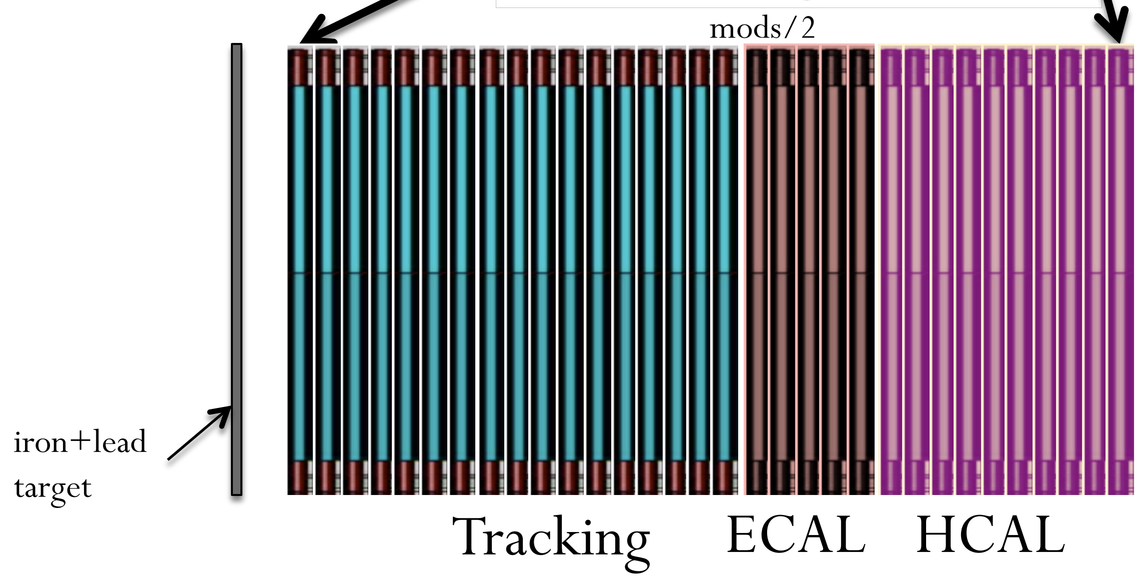


- Absolute normalization of flux using pion production data from the HARP experiment

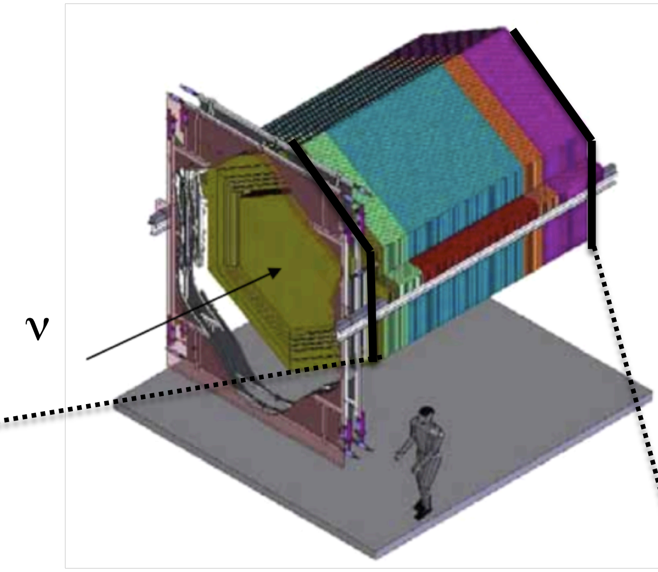
- High statistics CCQE samples show discrepancies with present MC predictions
- We are just now beginning to make real comparisons for other channels between binned data and MC predictions
  - CC π^+/π^0 production
  - NC elastic and NC π^0 production
  - CC/NC coherent interactions off the nucleus as a whole
- Theorists are interested in this problem. Wonderful!
- We must work with them directly or provide data they can use
- **Event rates of exclusive final states off some target nucleus**
  - not corrected back to the nucleon
  - nuclear effects (FSI) are part of this challenging theoretical problem

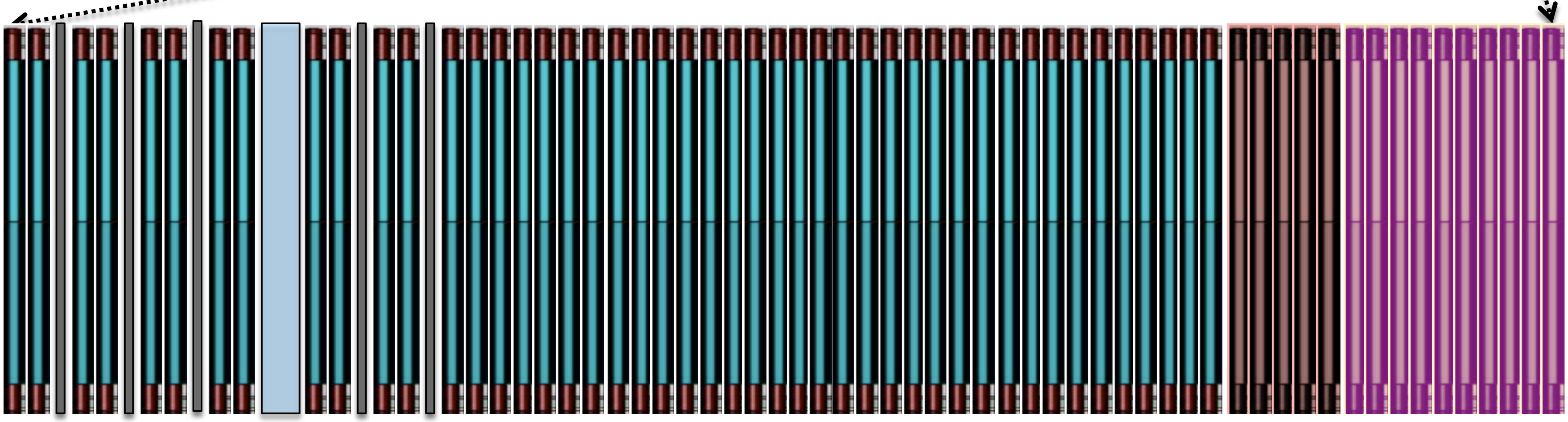
- MINERvA "Frozen" Detector
  - Removed Prototype modules and started installation of final detector during 2009 summer accelerator shutdown
  - Installed **64 modules**
    34 tracking+10 ECAL+20 HCAL
  - Froze detector installation on November 12 to collect NuMI **antineutrino beam data**
  - One nuclear target module (Fe, Pb) included for 2 mo.



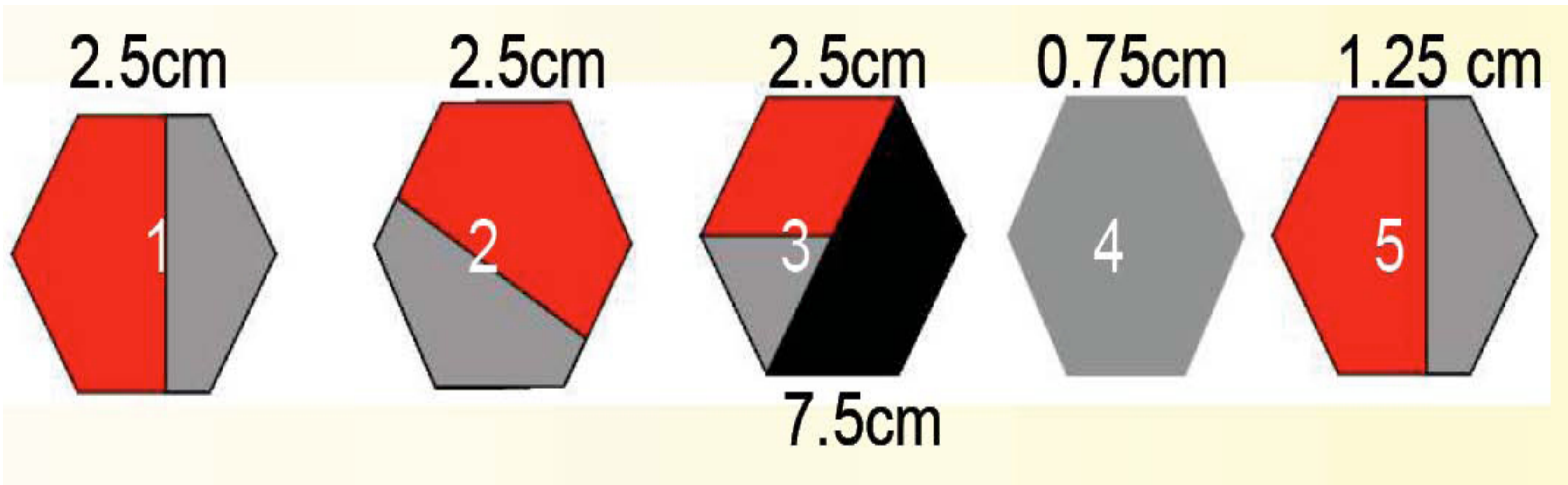


- **MINERνA Installation completed in March, 2010**
- **He/H_2O target to be installed in March, 2011**

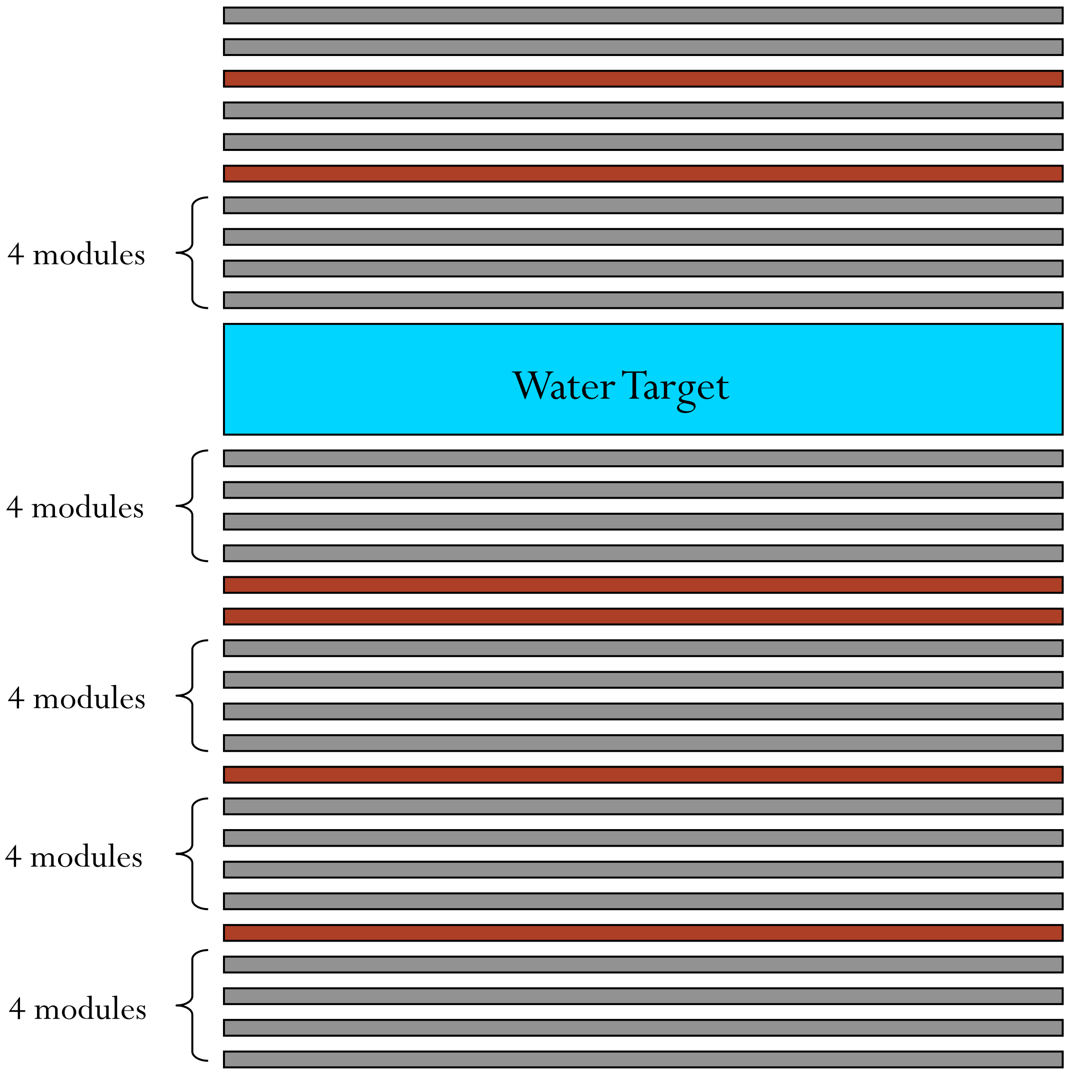


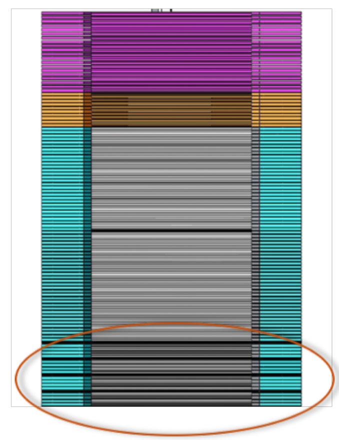


- Red = Iron, Grey = Lead, Black = Carbon



- First two targets: High statistics, compare lead and iron
- Third target: Compare lead, iron, and carbon with same detector geometry
- Last targets: Thin for low energy particle emission studies, high photon detection
- ^{4}He cryogenic target in front of detector


4 modules
Water Target
4 modules
4 modules
4 modules
4 modules



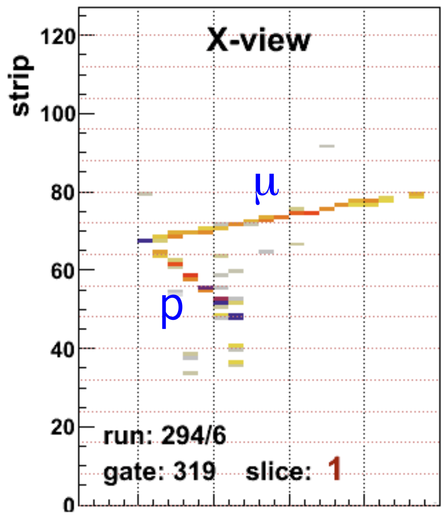
MINERνA Running Schedule

Calendar Year		2010	2011	2012	2013
Tevatron Collider		CDF & DZero	CDF & DZero / OPEN		OPEN
Neutrino Program	B	MiniBooNE	MiniBooNE		OPEN
		OPEN	OPEN / MicroBooNE		MicroBooNE
	MI	MINOS	MINOS		OPEN
		MINERvA	MINERvA		MINERvA
		ArgoNeuT			
			NOvA		NOvA
SY 120	MT	Test Beam	Test Beam		Test Beam
	MC	OPEN	OPEN		OPEN
	NM4	E-906/Drell-Yan	E-906/Drell-Yan		E-906/Drell-Yan

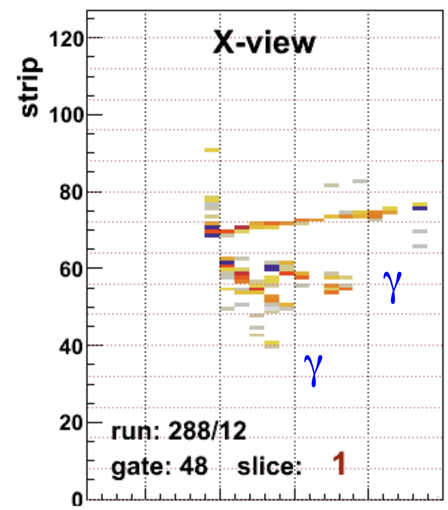
RUN/DATA
STARTUP/COMMISSIONING
INSTALLATION
M&D (SHUTDOWN)

Tracking Prototype Run: 4/09 – 6/09
LE AntiNeutrino Run with Increased Fiducial Mass: 11/09 – 3/10
LE Neutrino Run with Full MINERvA: 3/10 – 3/12
ME Neutrino and AntiNeutrino Runs: Starting Spring 2013

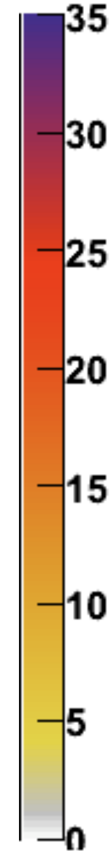
ν_μ CCQE candidate event



ν_μ CC π^0 candidate event

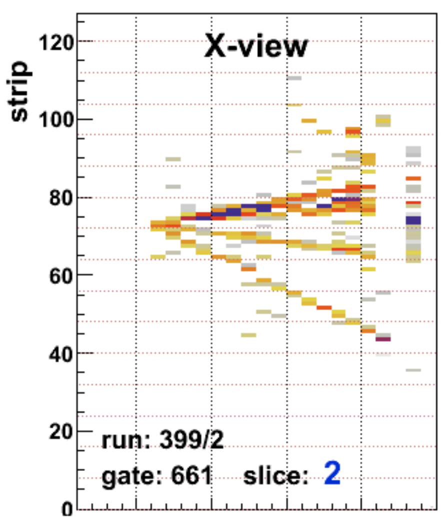


p.e. scale

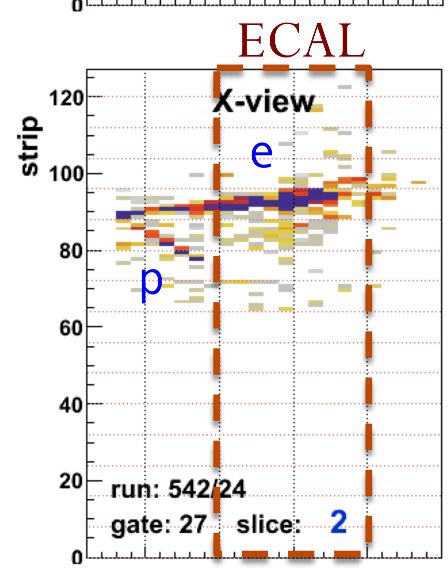


NuMI Beam

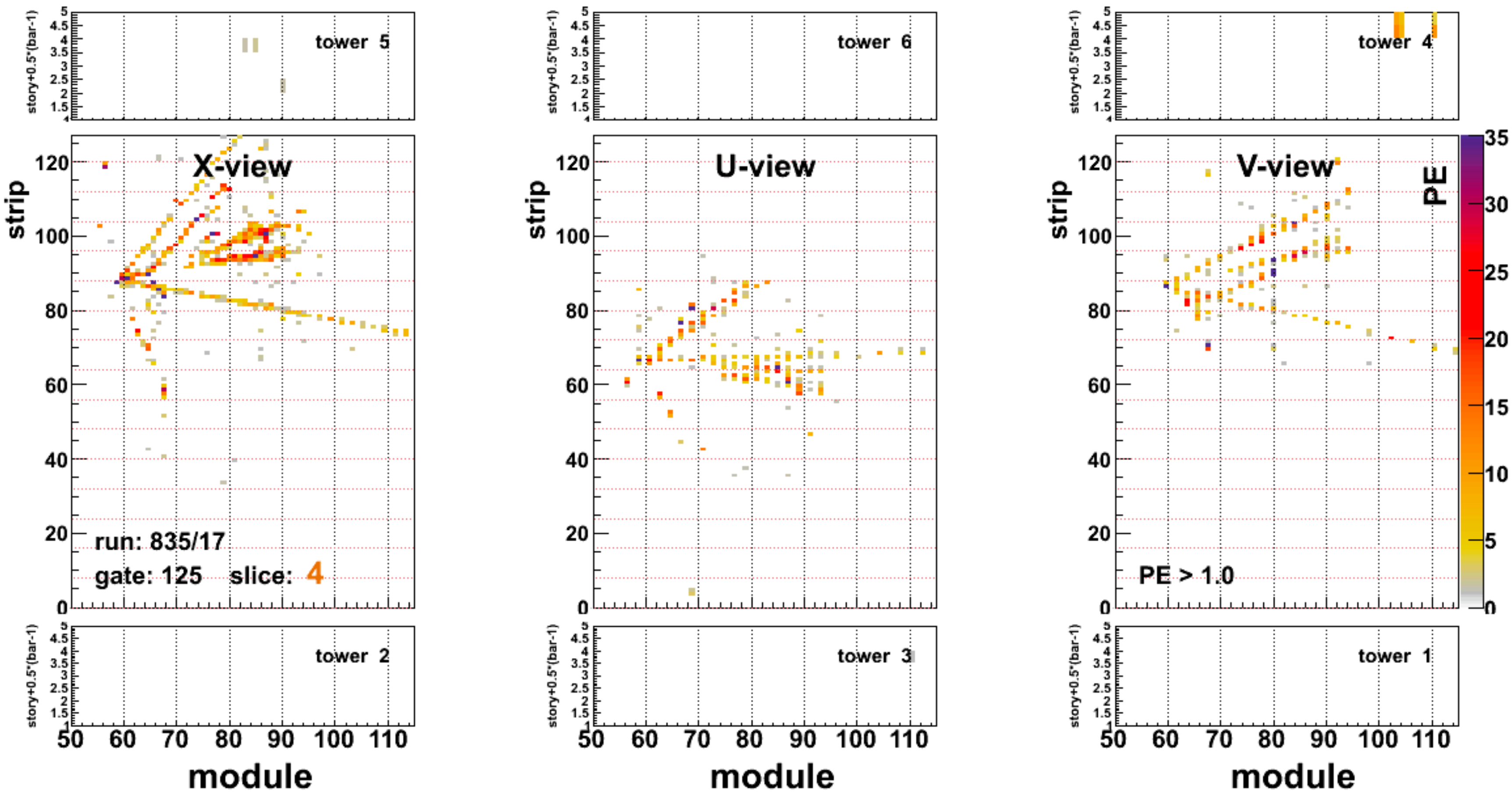
DIS candidate event



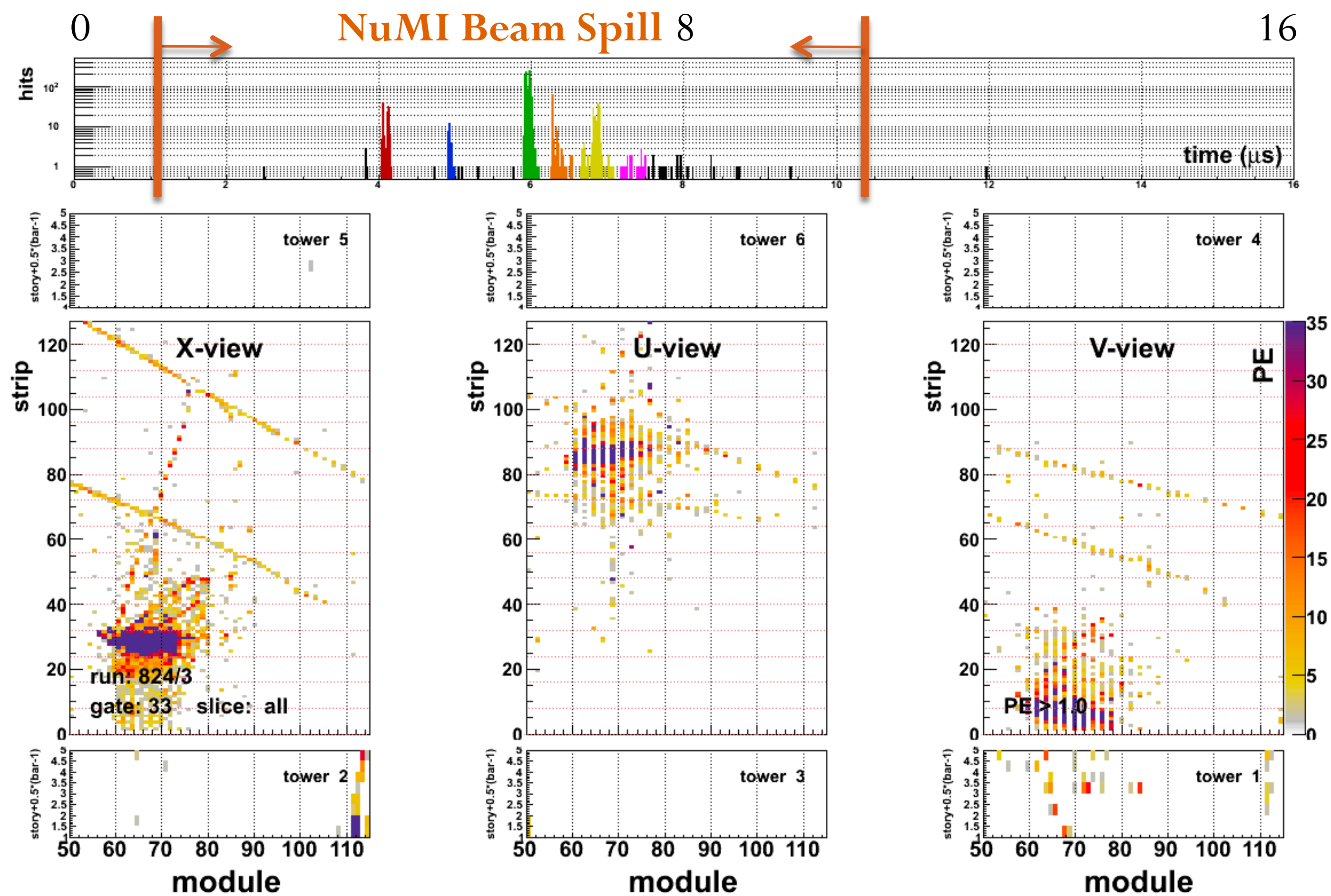
ν_e CCQE candidate event

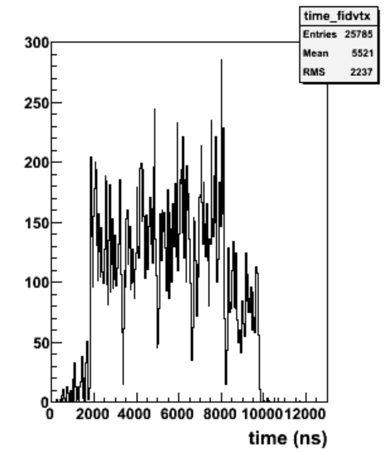


MINOS



Good visibility of tracks in multiple particle final states and secondary interactions.

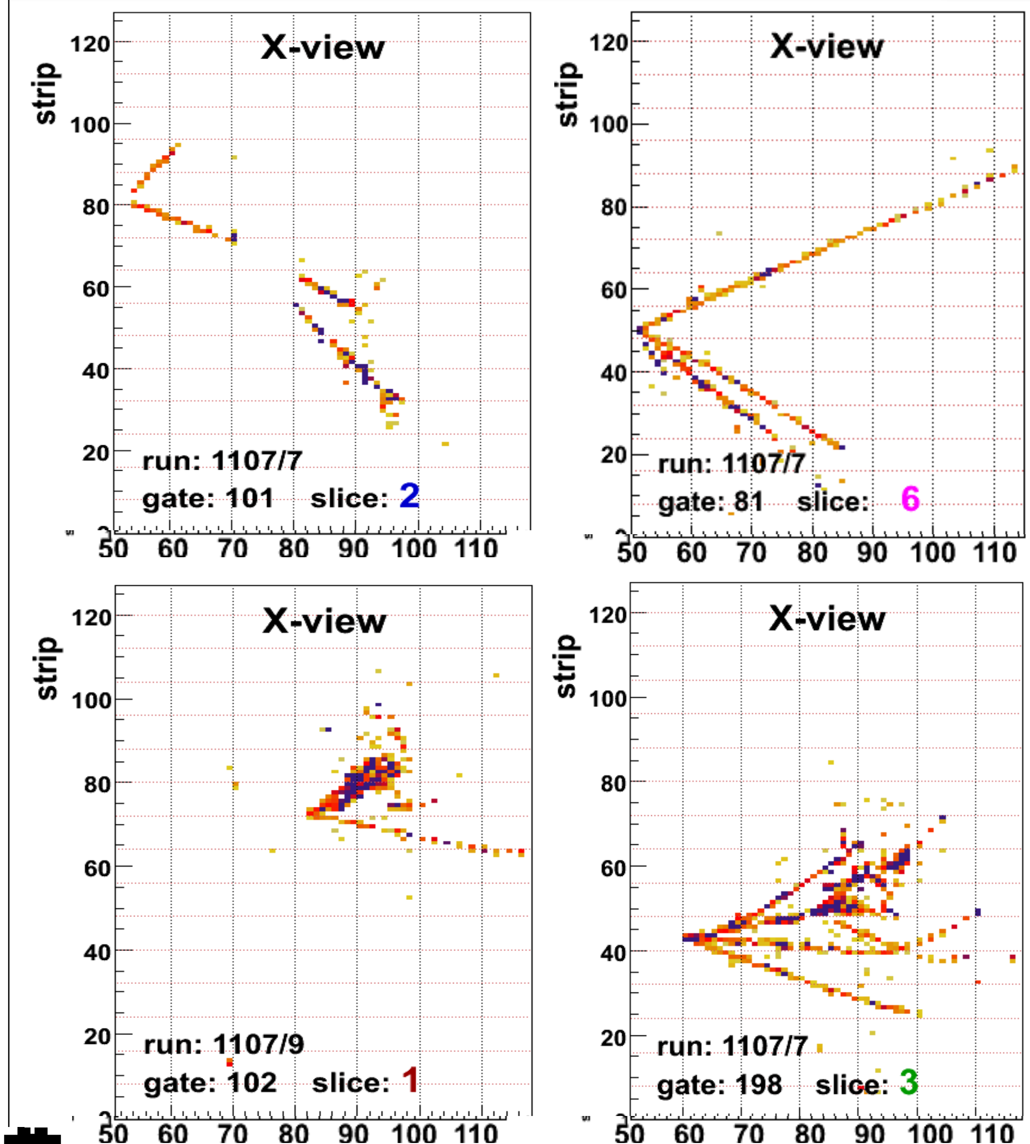




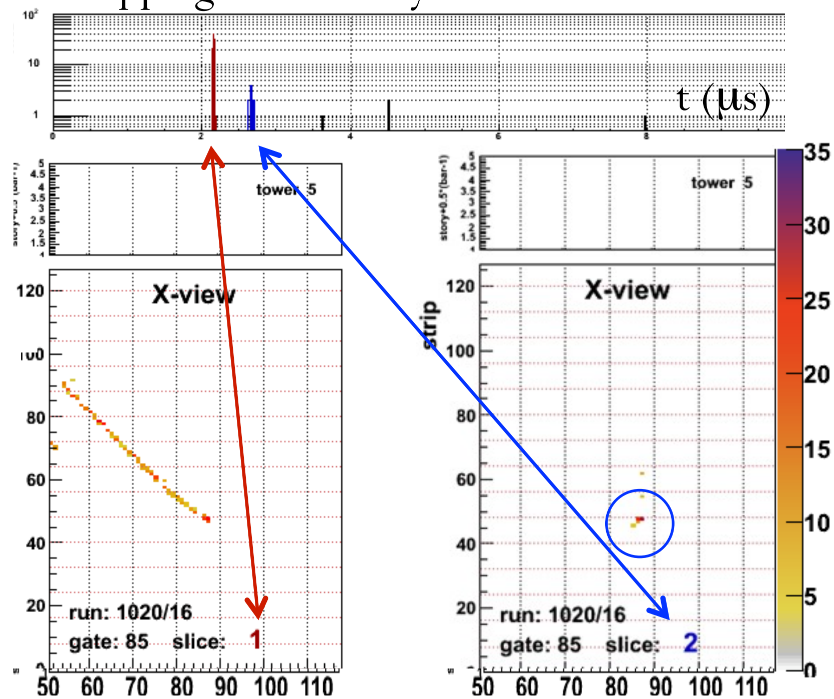
NuMI Beam Spill

10 μs spill structure every 2.2 seconds from the FNAL Main Injector

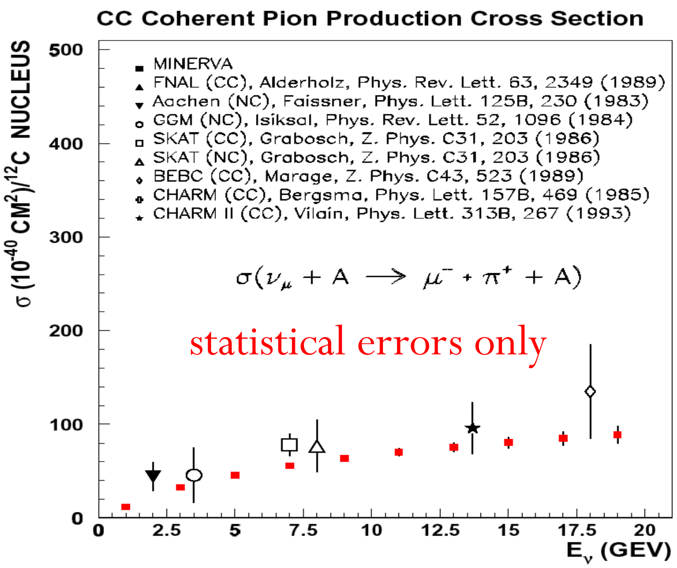
NuMI Beam is very intense. Lots of overlapping activity within a beam spill.

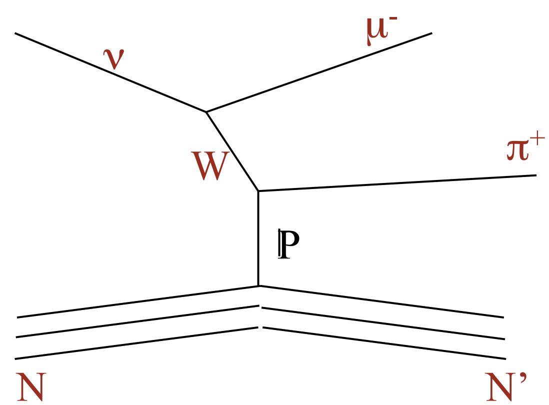


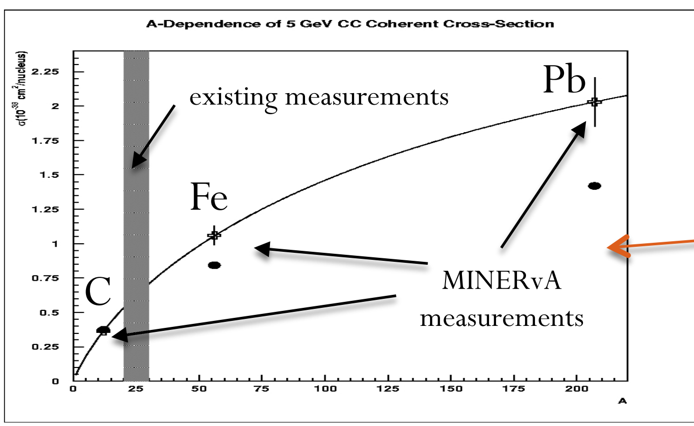
stopping muon decays to Michel electron



- Coherent pion production (CC/NC) off the nucleus







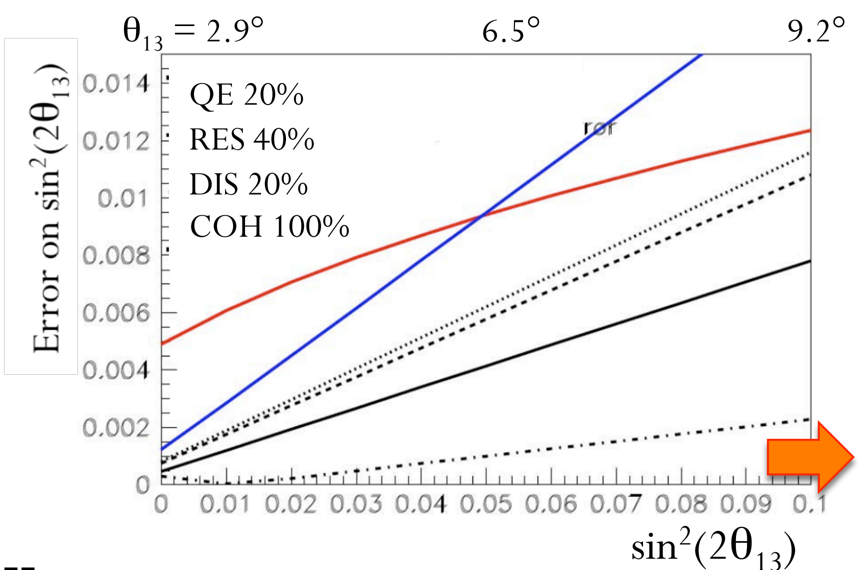
- Scatters off the nucleus as a whole, leaving nucleus in the ground state.
- Comparison with theoretical models
- MINERνA's nuclear targets allow the first measurement of the A-dependence of σ_{coh} across a wide range in a single experiment

- NOvA $\sin^2\theta_{13}$ sensitivity
  - Toy MC study
  - Expected cross-section uncertainties after MINERνA make σ systematic negligible for all values of $\sin^2\theta_{13}$

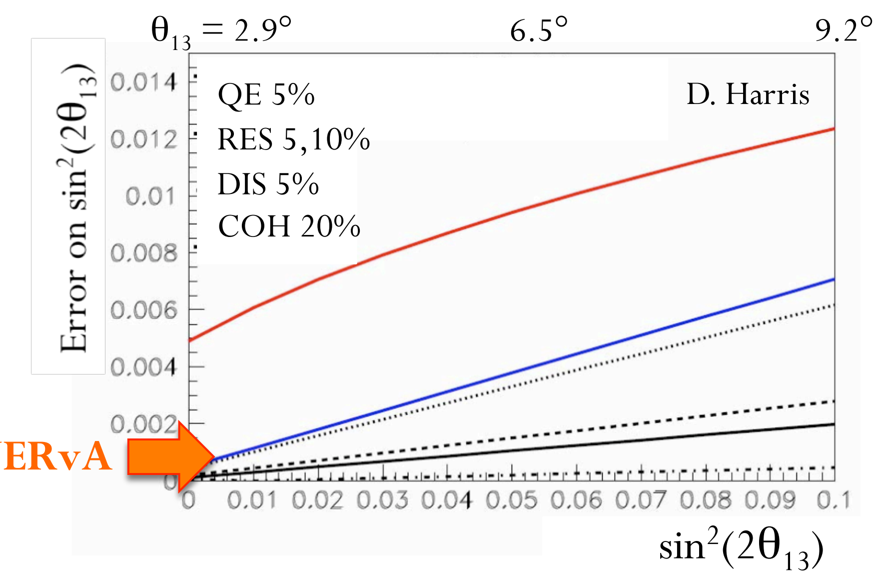
Process	Stats	QE	RES	DIS	COH
Signal ν_e	78 ($\sin^2\theta_{13}$=0.1)	50%	40%	1%	9%
NC	6.6	1%	10%	11%	78%
ν_μ CC	0.7	0%	7%	0%	93%
Beam ν_e	7.2	52%	37%	1%	10%

statistical error on a signal of that size

total systematic error from cross-section uncertainties of the given size

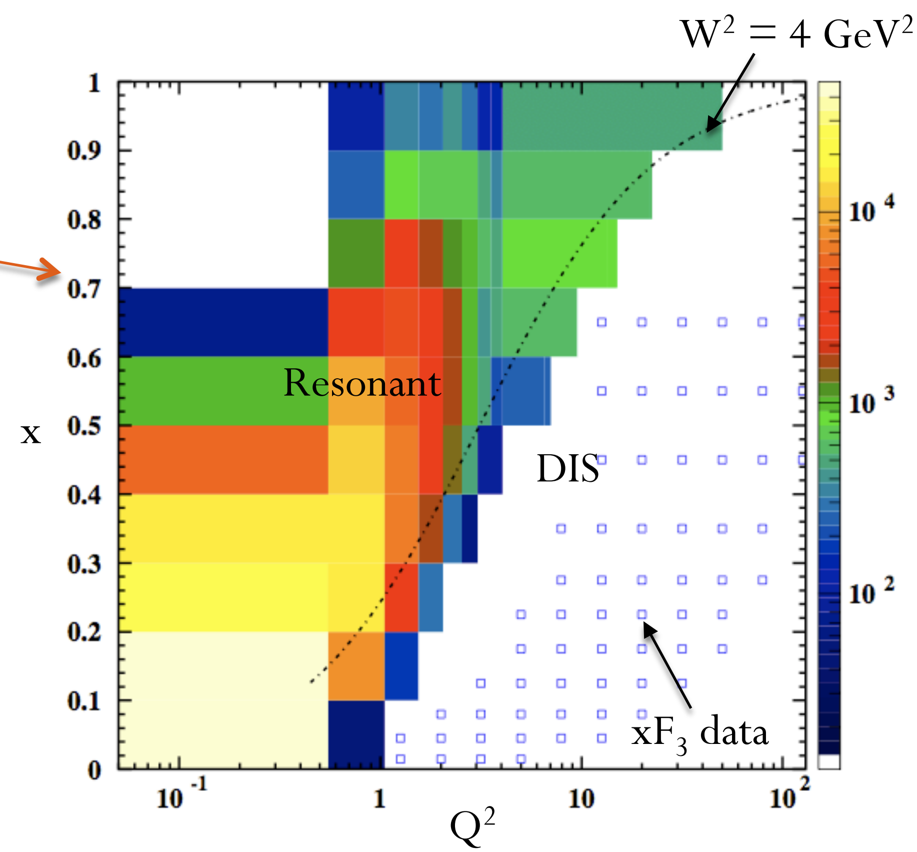


MINERνA



- Deep Inelastic Scattering Physics: PDFs and Nuclear Effects
- The intense NuMI broad-band neutrino beam and the fine-grained high-resolution MINERvA detector provide an opportunity for a lot of physics beyond cross-sections for oscillations

- Expected numbers of events in (x,Q^2) for ~4 years of running in the Resonant → DIS transition region
- Study transition between perturbative and nonperturbative QCD regimes
- High statistics at high x



- Deep Inelastic Scattering Physics: PDFs and Nuclear Effects
- The intense NuMI broad-band neutrino beam and the fine-grained high-resolution MINERvA detector provide an opportunity for a lot of physics beyond cross-sections for oscillations

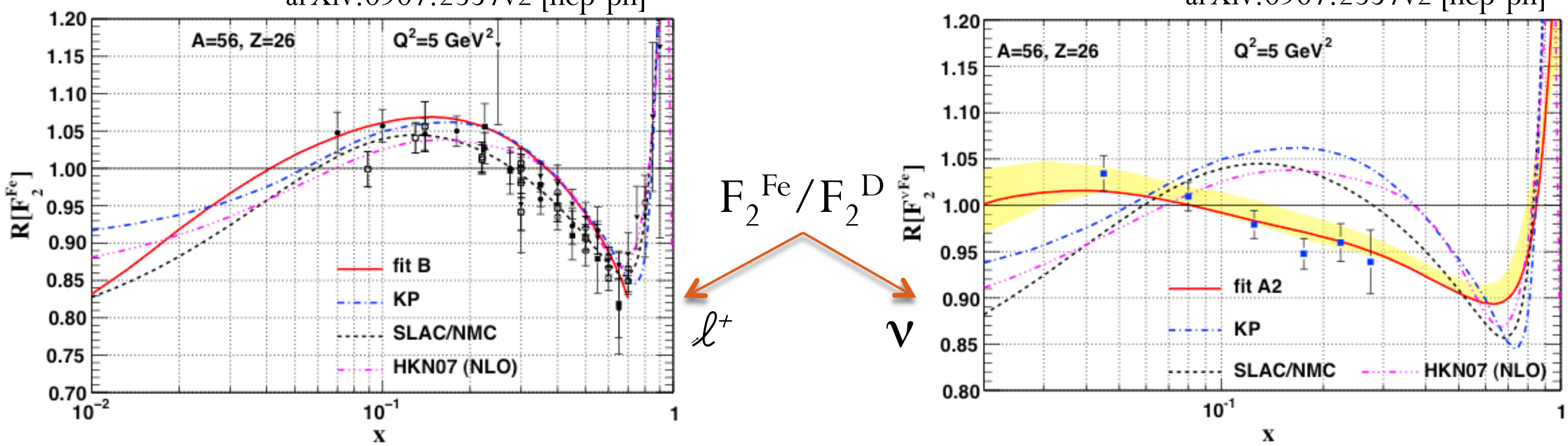
- Neutrino and antineutrino DIS data are **important for measuring fundamental Parton Distribution Functions within nucleons**

- Due to Weak current's unique ability to sample only particular quark flavors:
  - ν interacts with $d, s, \bar{u}, \bar{c}$
  - $\bar{\nu}$ interacts with $u, c, \bar{d}, \bar{s}$

- Ability to use high x data minimizes contributions from gluons and sea quarks, so one can sample d/u directly in $\nu/\bar{\nu}$ ratios

- Deep Inelastic Scattering Physics: PDFs and Nuclear Effects
- The intense NuMI broad-band neutrino beam and the fine-grained high-resolution MINERvA detector provide an opportunity for a lot of physics beyond cross-sections for oscillations
- Inclusion of neutrino **<u>scattering data on heavy nuclei</u>** in QCD measurements is challenged by significant nuclear effects
- Recent studies indicate that nuclear corrections in ℓ^+-A (charged lepton) and ν-A (neutrino) scattering may not be the same

arXiv:0907.2357v2 [hep-ph]   arXiv:0907.2357v2 [hep-ph]



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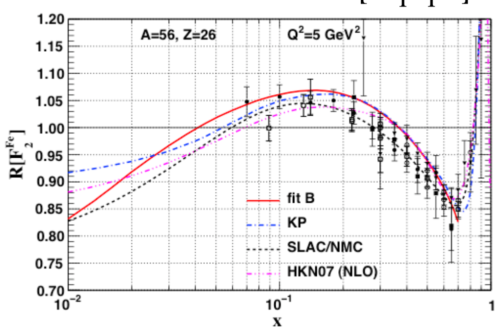
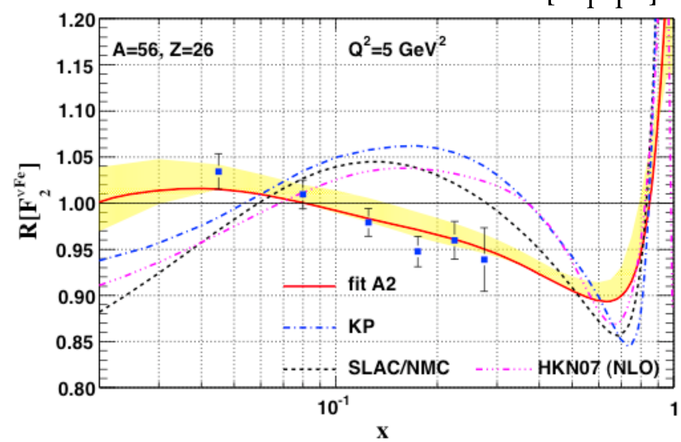


F_2^A/F_2^D : Observable	Experiment	Ref.	# data
D	NMC-97	[31]	275
He/D	SLAC-E139	[18]	18
	NMC-95,re	[32]	16
	Hermes	[33]	92
Li/D	NMC-95	[34]	15
Be/D	SLAC-E139	[18]	17
C/D	EMC-88	[35]	9
	EMC-90	[36]	2
	SLAC-E139	[18]	7
	NMC-95,re	[32]	16
	NMC-95	[34]	15
	FNAL-E665-95	[37]	4
N/D	BCDMS-85	[19]	9
	Hermes	[33]	92
Al/D	SLAC-E049	[38]	18
	SLAC-E139	[18]	17
Ca/D	EMC-90	[36]	2
	SLAC-E139	[18]	7
	NMC-95,re	[32]	15
	FNAL-E665-95	[37]	4
Fe/D	BCDMS-85	[19]	6
	BCDMS-87	[20]	10
	SLAC-E049	[21]	14
	SLAC-E139	[18]	23
	SLAC-E140	[22]	6
Cu/D	EMC-88	[35]	9
	EMC-93(addendum)	[39]	10
	EMC-93(chariot)	[39]	9
Kr/D	Hermes	[33]	84
Ag/D	SLAC-E139	[18]	7
Sn/D	EMC-88	[35]	8
Xe/D	FNAL-E665-92(em cut)	[40]	4
Au/D	SLAC-E139	[18]	18
Pb/D	FNAL-E665-95	[37]	4
Total:			862

- Combined many charged lepton data sets on many different nuclei
- Added **A**-dependent terms to the parameterization to include effects within model

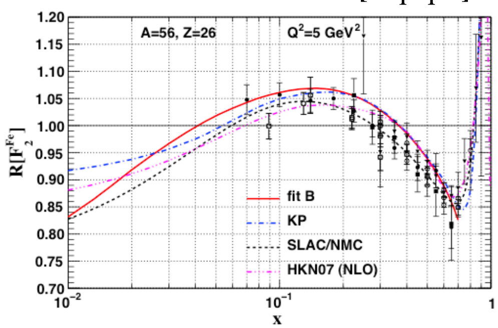
arXiv:0907.2357v2 [hep-ph]



- Only NuTeV iron neutrino data
- Would like to use a similar table of data to properly compare charged and neutral lepton data

Deep Inelastic Scattering Physics: PDFs and Nuclear Effects

arXiv:0907.2357v2 [hep-ph]



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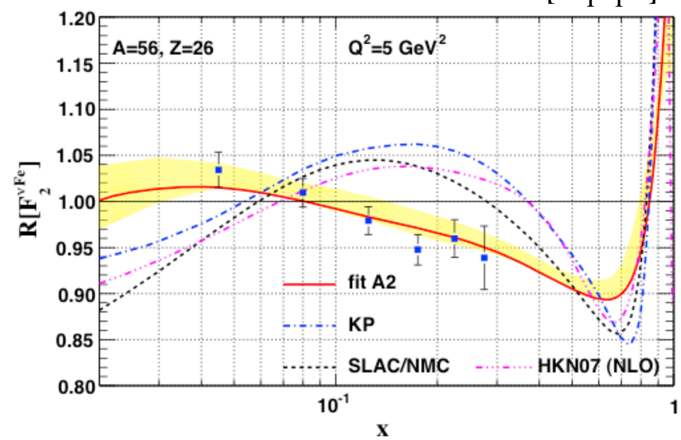
Fe/D	BCDMS-85	[19]	6
	BCDMS-87	[20]	10
	SLAC-E049	[21]	14
	SLAC-E139	[18]	23
	SLAC-E140	[22]	6
Cu/D	EMC-88	[35]	9
	EMC-93(addendum)	[39]	10
	EMC-93(chariot)	[39]	9
Kr/D	Hermes	[33]	84
Ag/D	SLAC-E139	[18]	7
Sn/D	EMC-88	[35]	8
Xe/D	FNAL-E665-92(em cut)	[40]	4
Au/D	SLAC-E139	[18]	18
Pb/D	FNAL-E665-95	[37]	4
Total:			862

arXiv:0907.2357v2 [hep-ph]



- Only NuTeV iron neutrino data
- Would like to use a similar table of data to properly compare charged and neutral lepton data
- MINERvA provides **He, C, Fe, Pb**

- Lots of new interest in neutrino cross-sections in recent years
  - Absolute cross-sections
  - Differential cross-sections
  - Untangling nuclear effects
- Important to get improved measurements
  - Intellectually challenging and interesting
  - Important for the next generation of neutrino oscillation experiments
  - Intense NuMI beam and fine-grained detector opens door to lots of high/low Q^2 and high/low x physics, DIS, PDFs (which I have completely ignored today)
- **The MINERνA experiment at Fermilab will go a long way toward finding many answers starting very soon!**