Intensity Frontier Neutrino Experiments at Fermilab:
Latin American Participation

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CTEQ-Fermilab QCD/Electroweak School

Lima, Peru

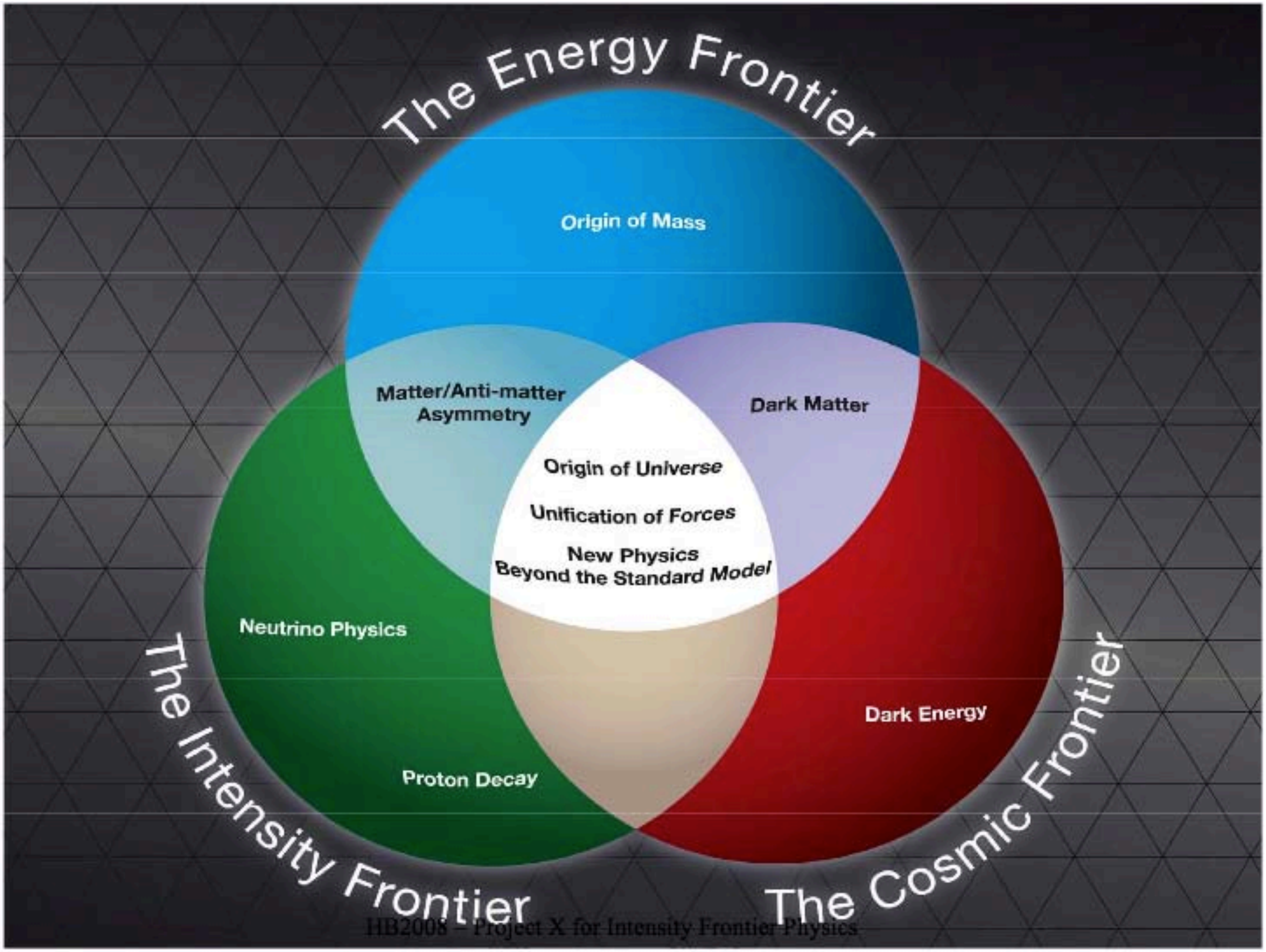
August 2012

The Scene at Fermilab

Goals of this presentation:

1) **Flavor of present/future Intensity Frontier experiments at FNAL**
2) **Outline a model for Latin American collaboration with FNAL Intensity Frontier experiments**

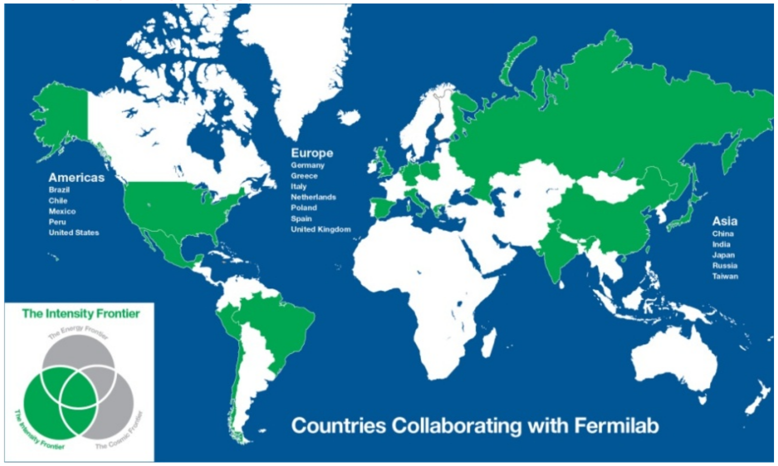
Frontiers at Fermilab



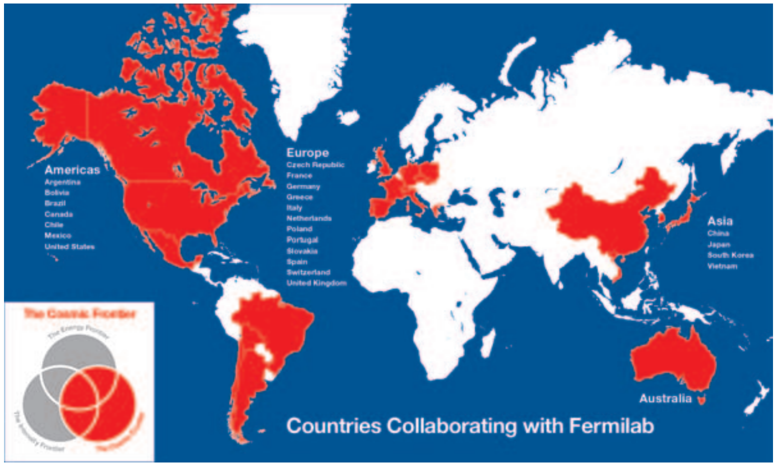
International Collaborations
Experimental Programs at Fermilab

27 countries

17 countries



24 countries



Intensity Frontier Experiments
International Collaboration

Intensity Frontier: FNAL Present and Future Vision

Phased approach with ever-increasing beam intensities and detector capabilities.

- Intensity Frontier – with accelerator turn-on in Spring 2013
  - FNAL actively pursuing a program of neutrino physics with MINOS+, (MiniBooNE), MINERνA and NOνA
  - Add LAr TPC MicroBooNE later in the year/early 2014

- Intensity Frontier – Future Vision
  - The P5 panel recommends an R&D program in the immediate future to design a **multi-megawatt proton** source at Fermilab and a **neutrino beamline to DUSEL** .... R&D on the technologies for a large **multi-purpose neutrino and proton decay detector. This became the LBNE Experiment.**
  - A neutrino program with a **multi-megawatt proton source (Project X)** would be a stepping stone toward a future neutrino source, such as a **neutrino factory** based on a muon storage ring .... This in turn could position the US program to develop a **muon collider as a long-term means to return to the energy frontier in the US.**

Energy and Intensity Frontier Strategy - Accelerators

To build upon our existing strengths to establish a world-leading program at the Intensity Frontier, enabled by a world-class facility

NuMI (120 GeV): 350 kW
Booster (8GeV): 35 kW

→

NuMI (120GeV): 700 kW
Booster (8GeV): 80 kW

→

Project-X:
>2MW @ 120 GeV
3MW @ 3 GeV
150 kW @ 8 GeV

→

Neutrino Factory

…and use this program to provide a cornerstone for an Energy Frontier facility beyond LHC

LHC
Tevatron

→

LHC Upgrades in luminosity and energy

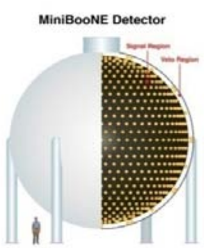
→

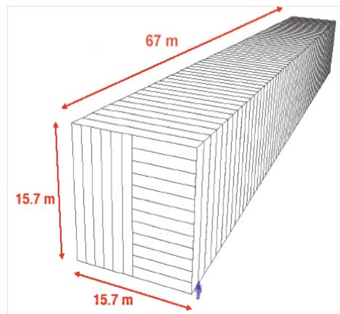
Lepton Colliders

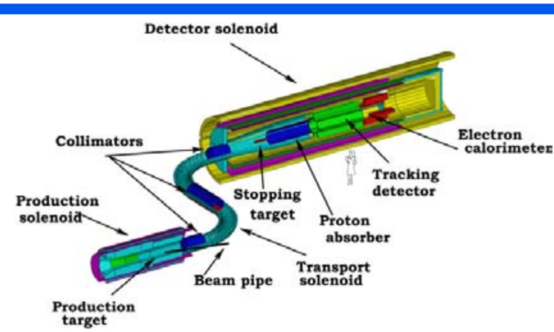
Technology Development and Fundamental Accelerator Science

…while relying on a strong program of technology development and fundamental accelerator science.

Intensity Frontier Strategy - Experiments

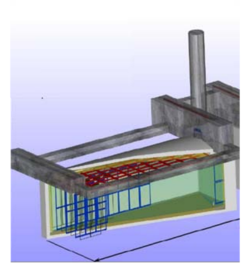


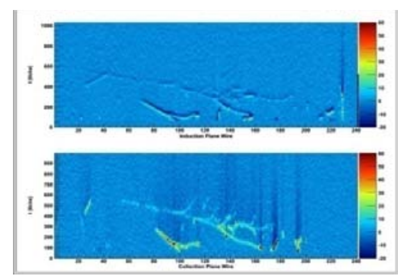




MINOS MiniBooE MINERvA SeaQuest	NOvA MicroBooE MINERvA SeaQuest	NOvA MicroBooE MINERvA LBNE Mu2e	Project X (LBNE, μ2e, K, nuclear, …) ν Factory

Now **2013** **2016** **2020's**





The "Driver" in Designing a Neutrino Experiment

First Calculation of Neutrino Cross Sections using the "Fermi" theory from 1932

Bethe-Peierls (1934): calculation of first cross-section for inverse beta reaction using Fermi's theory for:

$$\bar{\nu}_e + p \rightarrow n + e^+ \quad \text{or} \quad \nu_e + n \rightarrow p + e^-$$

yields:

$$\sigma \approx 10^{-44}\ cm^2 \quad \text{for} \quad E(\bar{\nu}) = 2\ MeV$$

This means that the mean free path of a neutrino in water is:

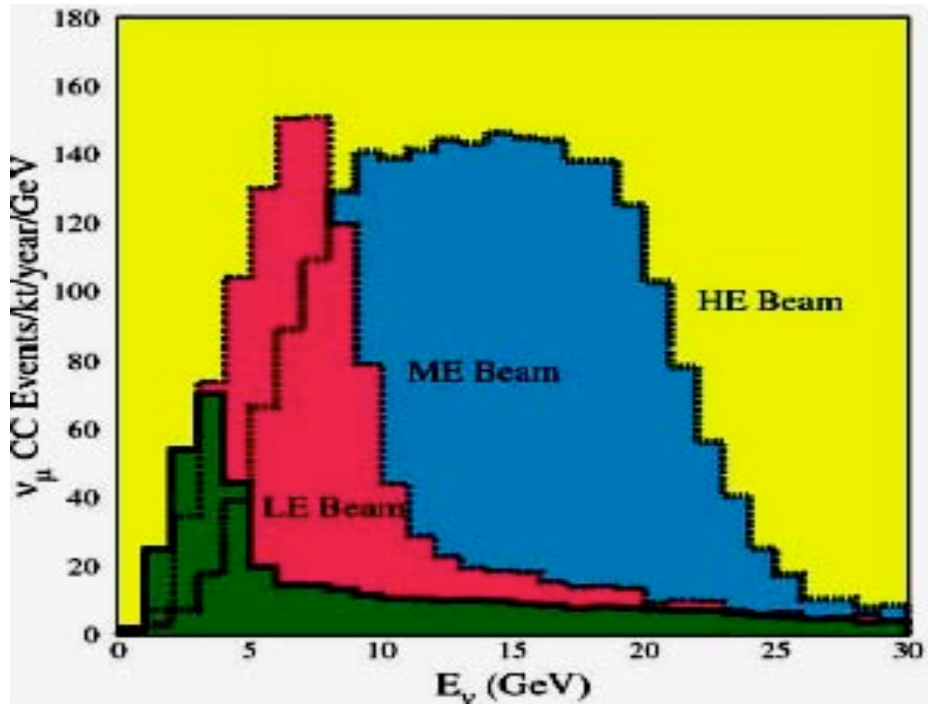
$$\lambda = \frac{1}{n\sigma} \approx 1.5 \times 10^{21}\ cm \approx 1600 \quad light-years$$

Experimentalists groaned - need a very intense source of ν's to detect neutrino interactions

At 20 GeV, **$\sigma / E_\nu \approx 0.6 \times 10^{-38}$ cm^2**

Fermilab Neutrino Program: How to Make a Neutrino Beam
The NuMI (Neutrinos from the Main Injector) Beam

In the Low-energy (LE) configuration delivers ~35x10^{12} protons on target (POT) per spill at ~0.5 Hz, a beam power of 300-350 kW.

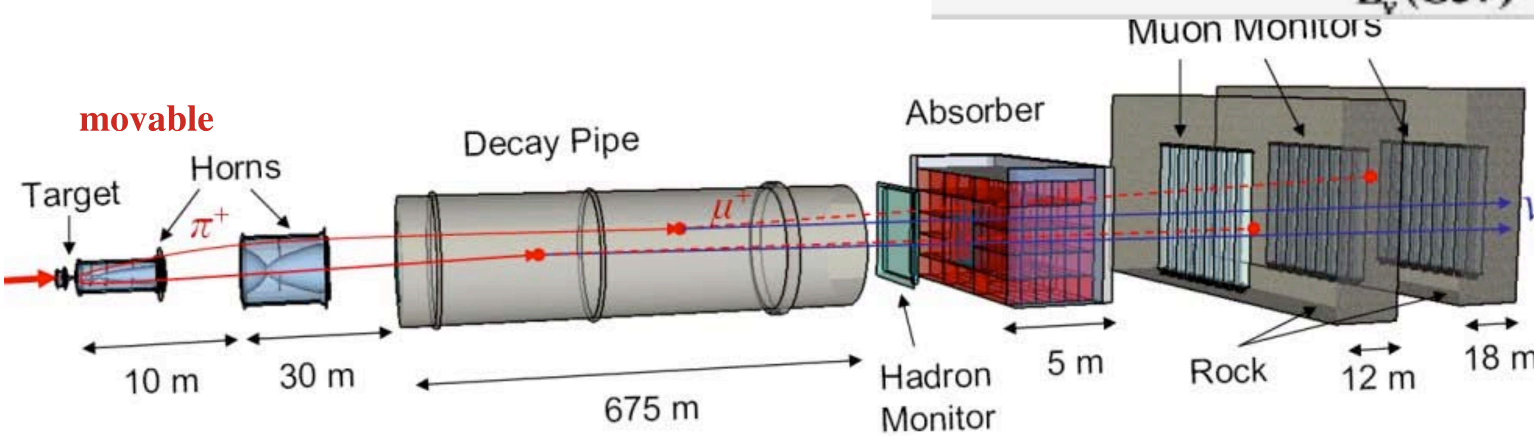


120 GeV proton → Carbon target

pC → $\pi^\pm$ and $K^\pm$

Magnetic horns focus + or -

$\pi^+ / K^+ \rightarrow \mu^+\nu_\mu$ or $\pi^- / K^- \rightarrow \mu^-\bar{\nu}_\mu$

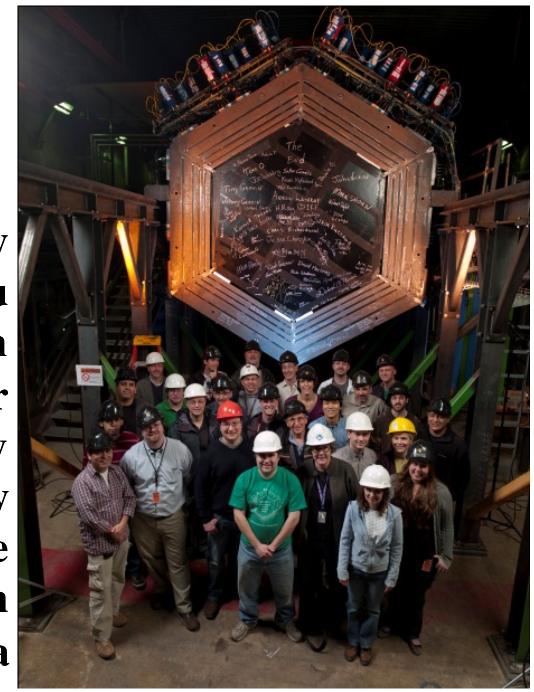


MINERvA

Current & Future: MINERνA

Main INjector ExpeRiment ν -A

- MINERνA: a neutrino scattering experiment at Fermilab in Batavia, IL, USA.
- Collaboration of 80 nuclear and particle physicists.



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Fermilab
University of Florida
Université de Genève
Universidad de Guanajuato
Hampton University
Inst. Nucl. Reas. Moscow
Mass. Col. Lib. Arts
Northwestern University

Otterbein University
Pontificia Universidad Catolica del Peru
University of Pittsburgh
University of Rochester
Rutgers University
Tufts University
University of California at Irvine
University of Minnesota at Duluth
Universidad Nacional de Ingeniería
Universidad Técnica Federico Santa María
William and Mary

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FIVE Latin American Groups

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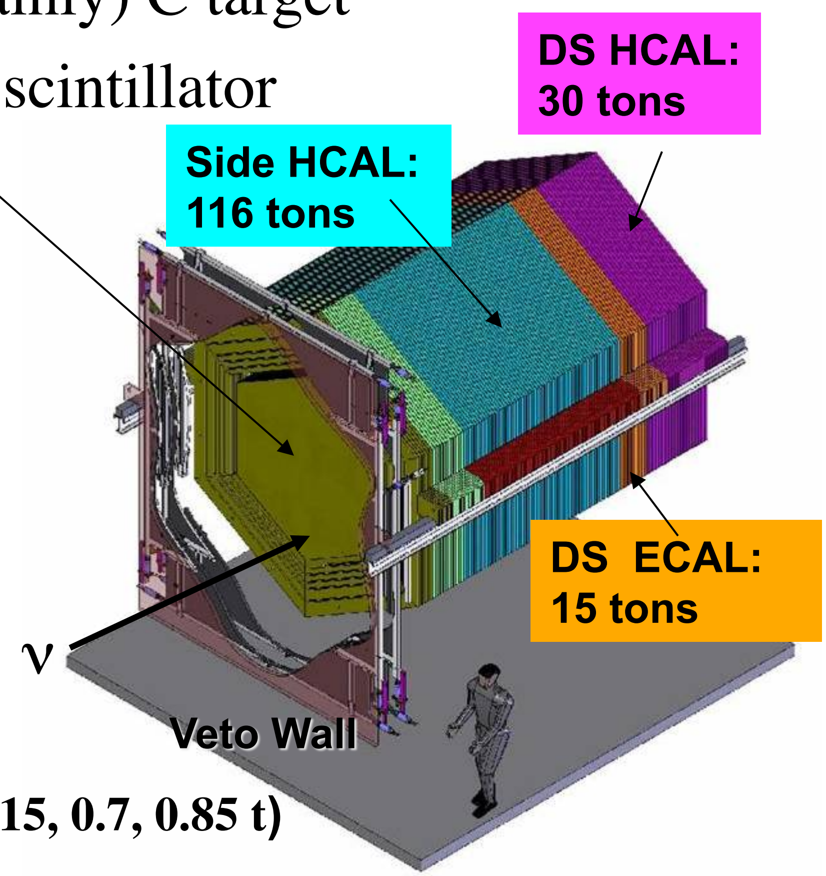
A Basic Neutrino Detector – Heavy Massive Target!
Have to understand how neutrinos interact in a nucleus!

- The MINERνA detector offers high resolution using simple, well-understood technology and a (mainly) C target
- Active core (8.3 t) is segmented solid scintillator
  - Tracking (including low p protons)
  - Particle identification
  - 3 ns (RMS) per hit timing (track direction, stopped *K*±)
- Core surrounded by electromagnetic and hadronic calorimeters
  - Photon (π^0) & hadron energy measurement
- Nuclear Targets: LHe, C, Fe, Pb **(0.2, 0.15, 0.7, 0.85 t)**
- MINOS Near Detector as muon catcher

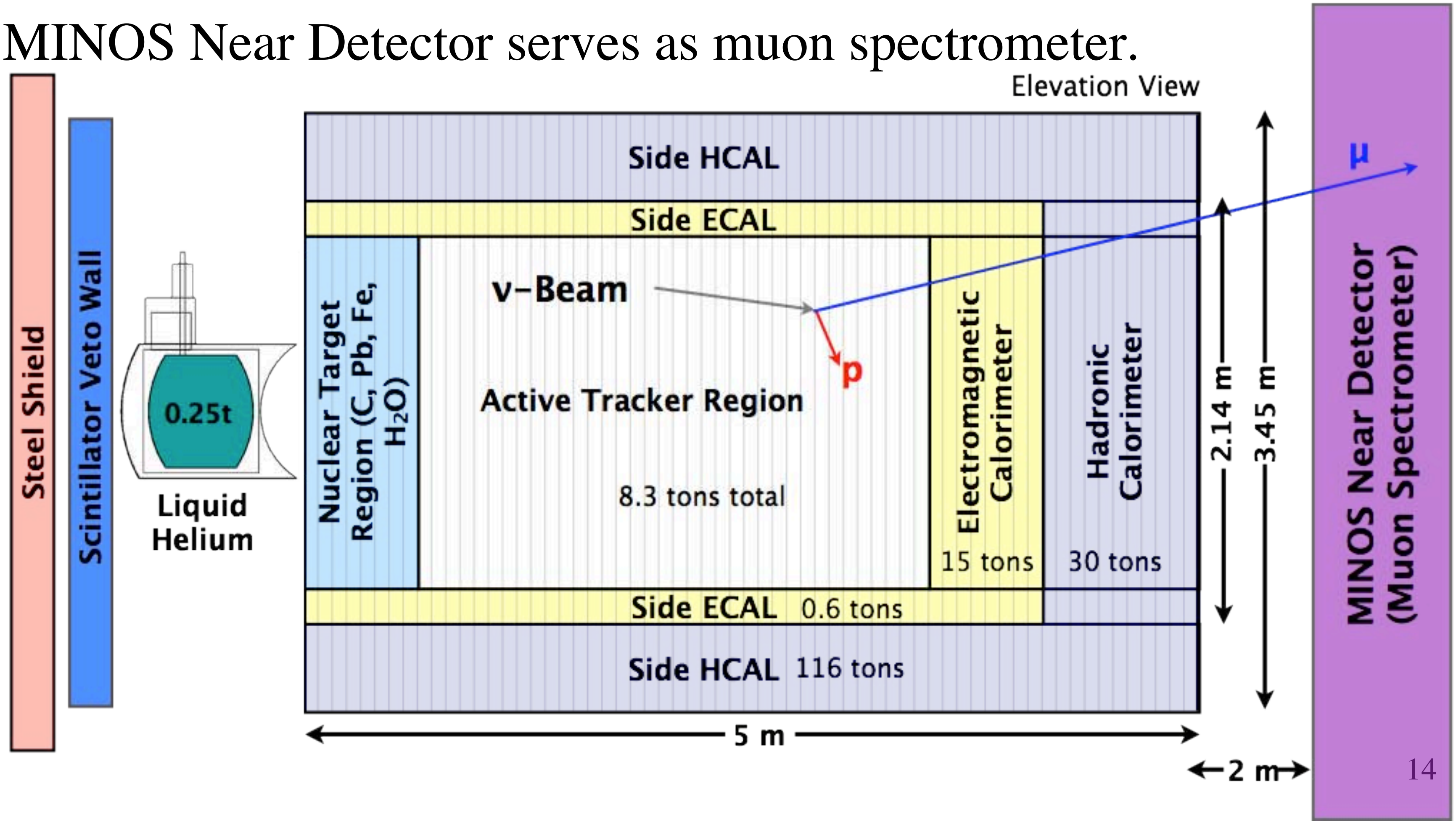


The MINERνA (Near) Detector

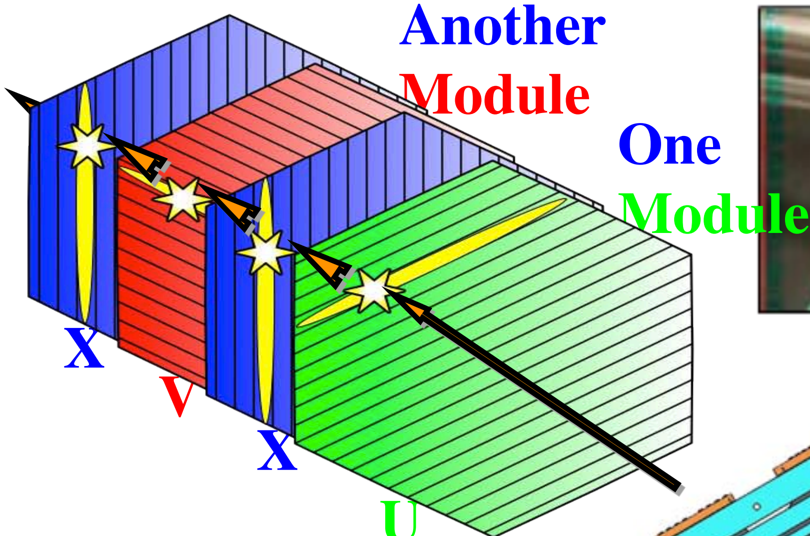
A Detailed Look at Neutrino Interactions in Nuclei

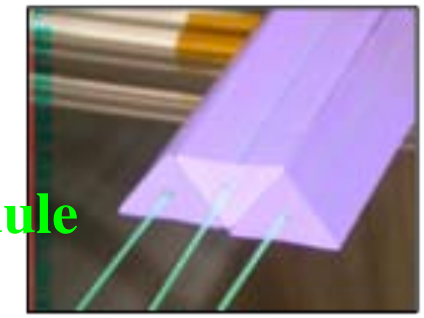
$\nu_\mu + A \rightarrow \mu^- + X$

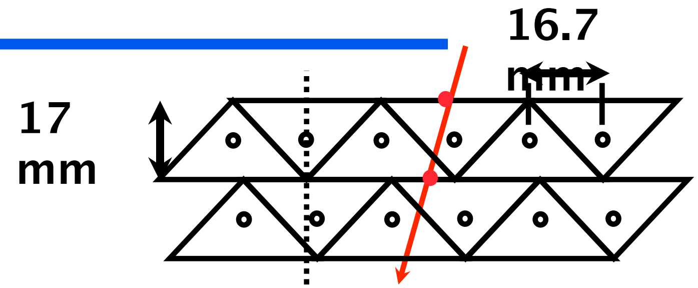
- 120 scintillator modules for tracking and calorimetry (~32k readout channels).
- Cryogenic He and Water targets recently added.
- MINOS Near Detector serves as muon spectrometer.



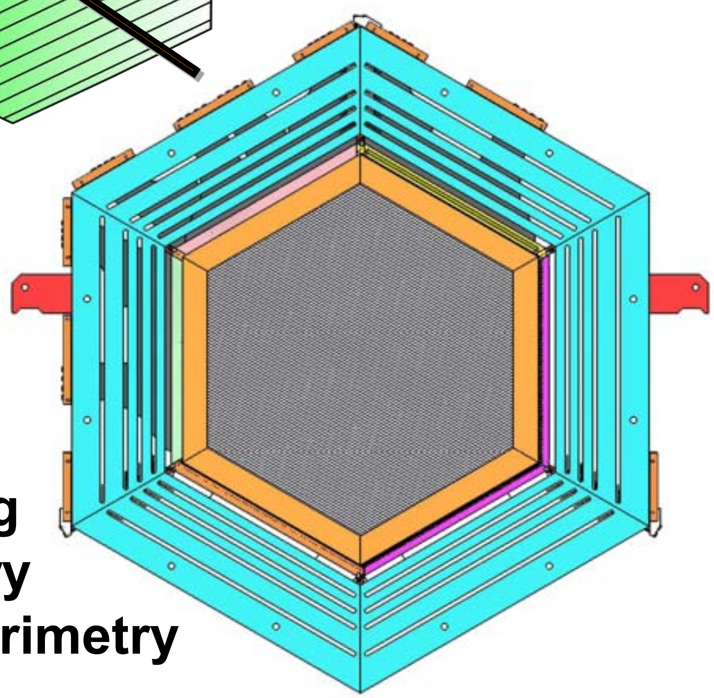
Details of MINERνA Detector

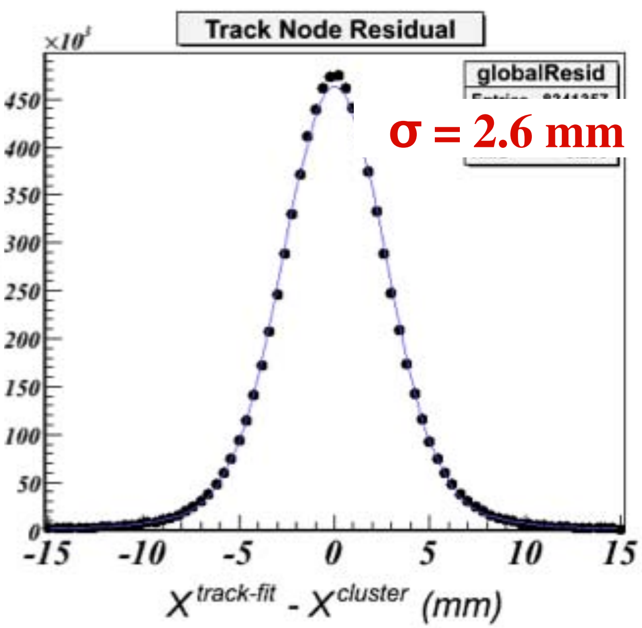






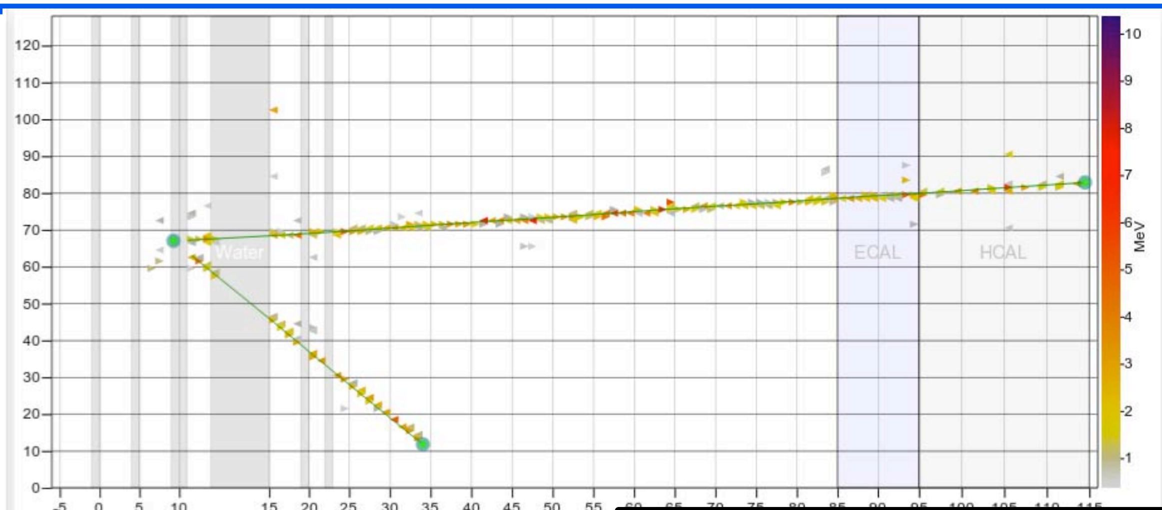
Charge sharing for improved position resolution and alignment





Scintillator - Tracking
Lead - EM calorimetry
Steel - hadronic calorimetry

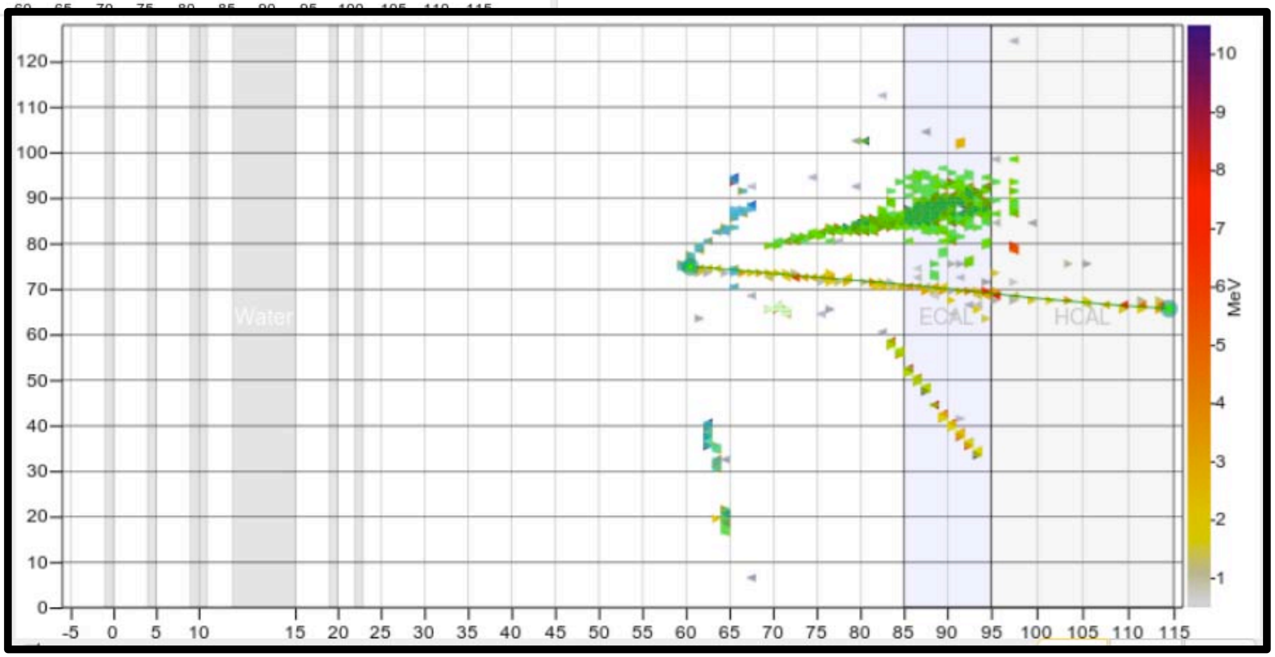
What does a Neutrino Event "look" like?
Good for identifying electrons



$\nu_\mu + Fe \rightarrow \mu^- + p$

"Quasi-elastic"

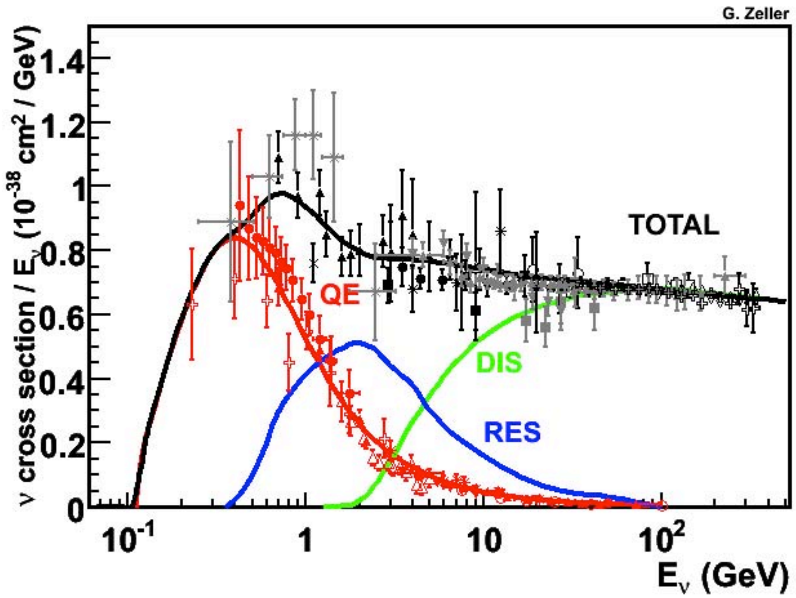
$\nu_\mu + C \rightarrow \mu^- + \underbrace{(p + \pi^0)}_{\Delta^+}$



MINERνA ν Scattering Physics Program

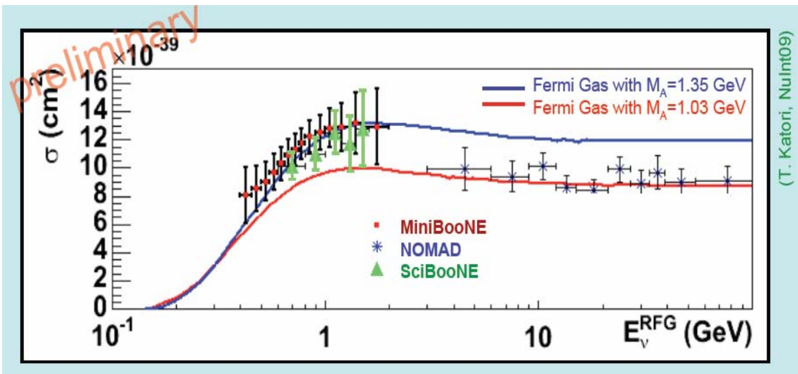
In red → currently studied * → Latin American Participation

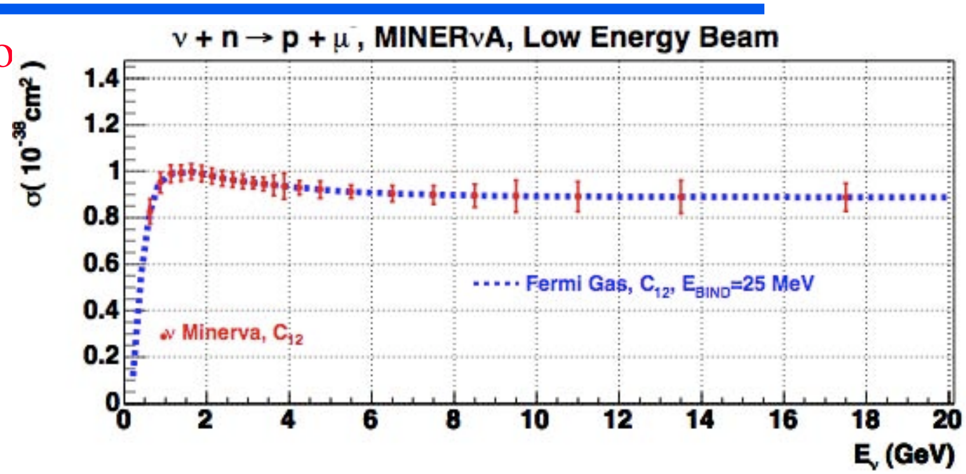
- *Quasi-elastic
- *Resonance Production - 1pi
- Transition Region – n pi to DIS
- *Coherent Pion Production
- Strange & Charm Particle Production
- * σ_T – Inclusive/DIS
  - High-x parton distribution functions
  - Structure Functions and PDFs
- *Nuclear Effects (He, C, H_2O, Fe, Pb)
- Generalized Parton Distributions
- *Test Beam Effort



MINERνA Expected Results

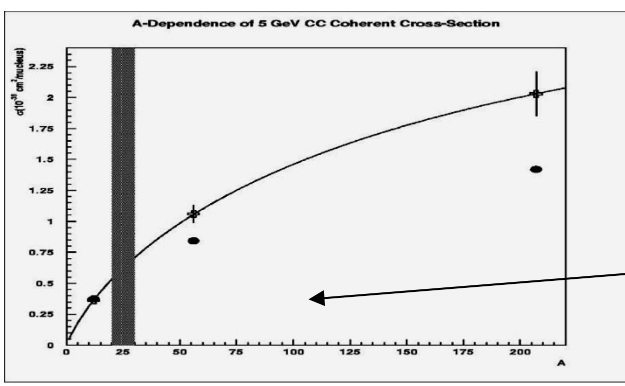
- σ_{QE} and high Q^2 axial form factor of nucleo





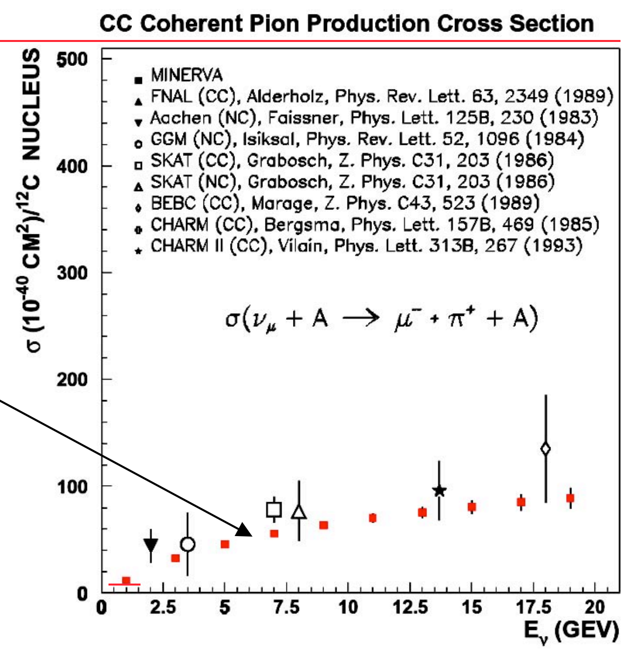
- Coherent cross-sections vs. energy

(**An example simulated analysis using the NEUGEN event generator**)



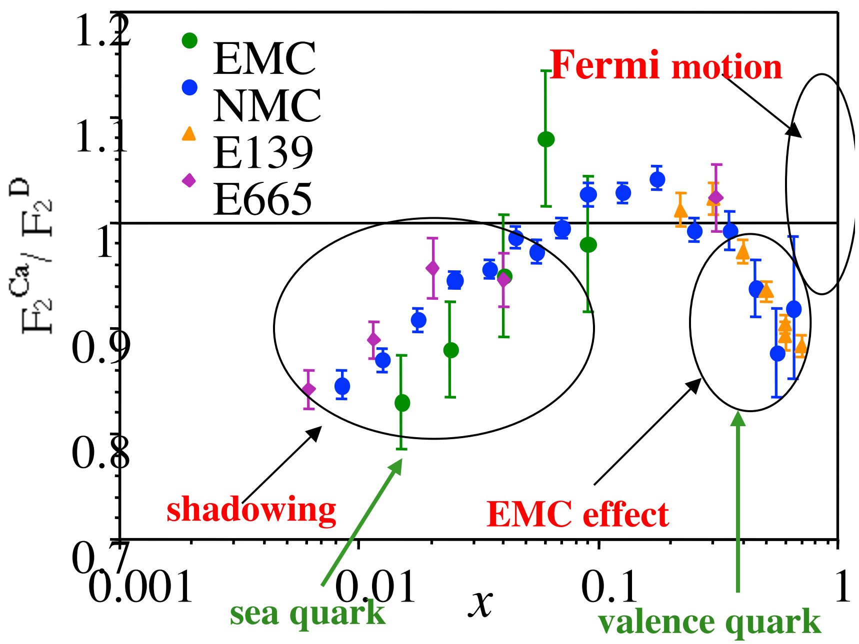
σ vs E_ν

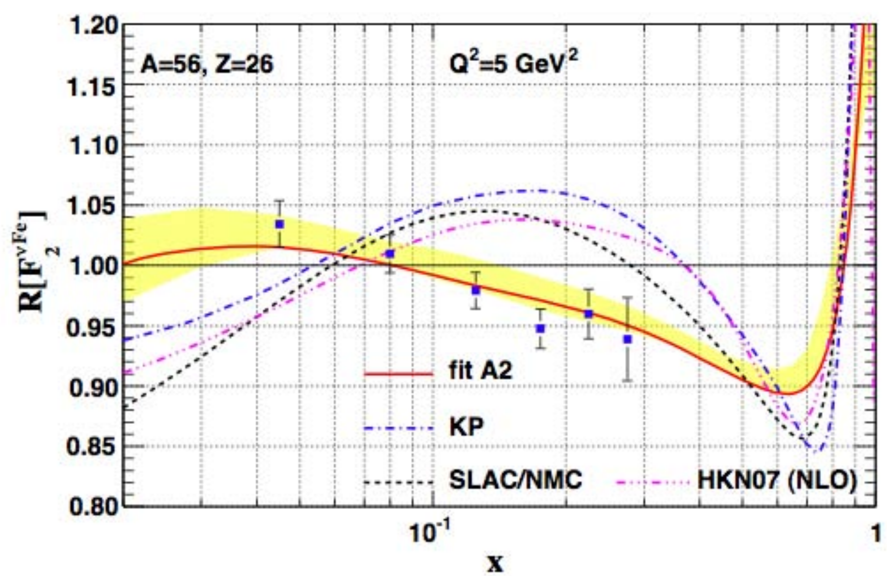
σ vs A



Neutrino Nuclear Effects – results depend on A
Nuclear Parton Distribution Functions - nPDF

Using charged lepton   and   Using neutrinos





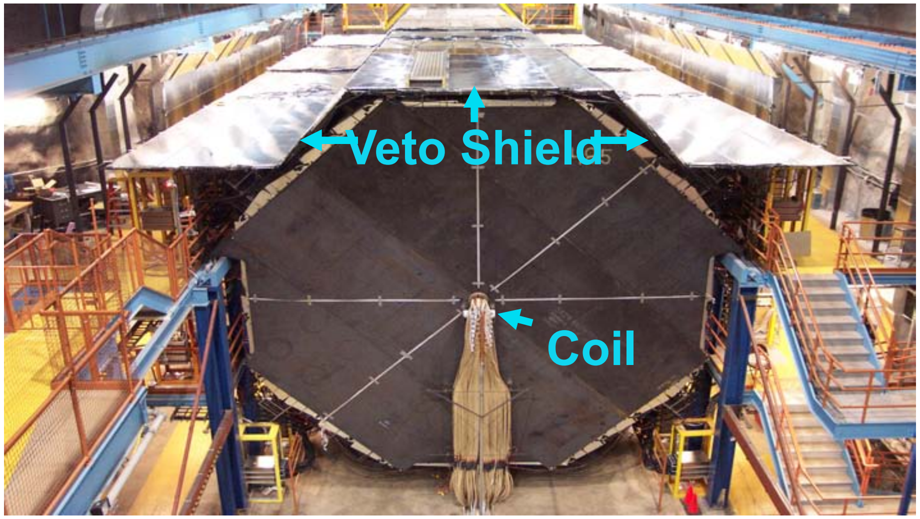
Already CTEQ/Grenoble/Karlsrühe analysis showing nuclear effects in ν − Fe (NuTeV data) quite different than those in μ/e – Fe

PDFs in a nucleon bound in a nucleus are DIFFERENT than PDFs in a free nucleon

Beam-on (2013): The MINOS$^+$ Experiment

Collaborators from Brazil, would welcome others

FAR DETECTOR – 5.4 kt **NEAR DETECTOR – 1 kt**



- Search for non-standard 3x3 mixing behavior
- θ_{23} and Δm^2_{atm} (the new precision frontier)
- Search for Sterile Neutrinos
- Non-Standard Interactions & Extra Dimensions
- Atmospherics

NuMI Facility / MINOS Experiment at Fermilab

- **Precision measurements of:**
  - **Energy distribution of oscillations**
  - **Measurement of oscillation parameters**
  - **Participation of neutrino flavors**

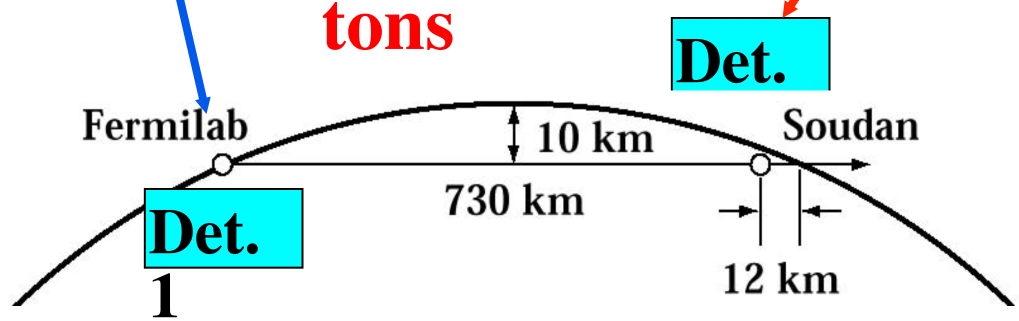
- **Direct measurement of ν vs $\bar{\nu}$ oscillation**
  - **Magnetized far detector: atm. ν's.**

NuMI: Neutrinos at Main Injector

120 GeV protons
1.9 second cycle time
Single turn extraction (10μs)

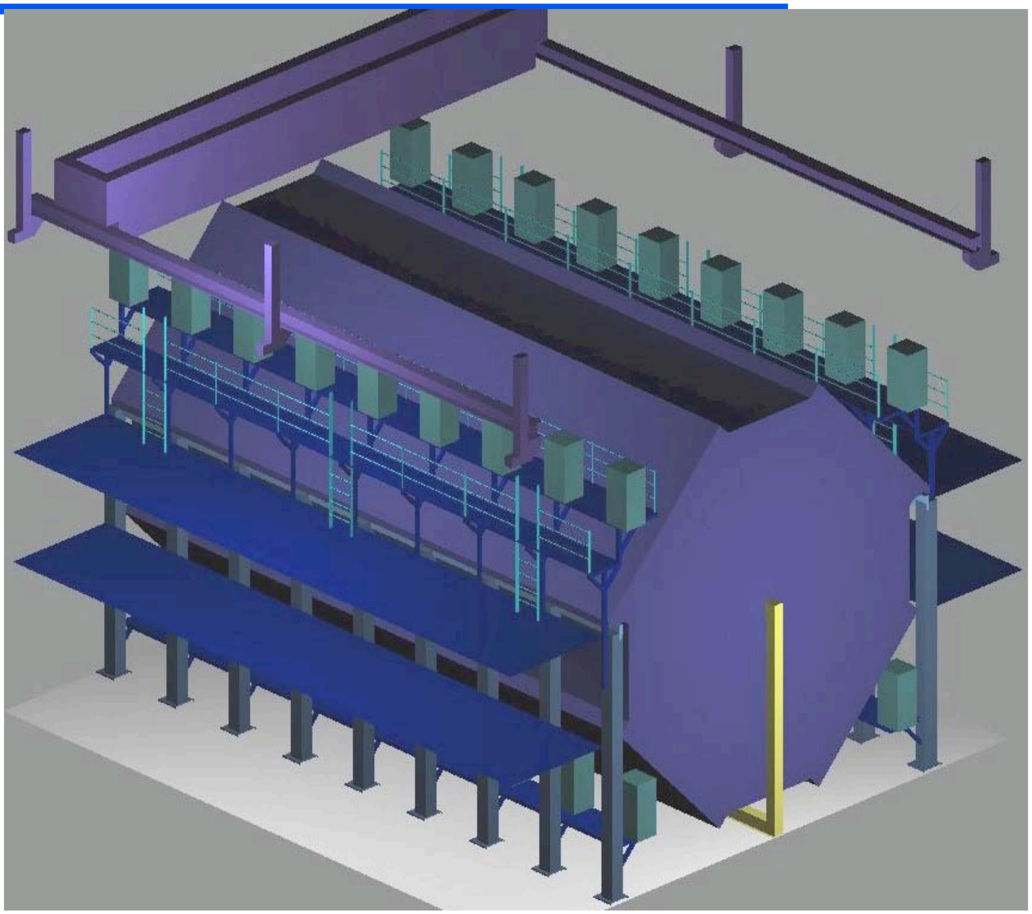
Near Detector: 980 tons

Far Detector: 5400 tons



The MINOS Far Detector

- 8m octagonal steel & scintillator tracking calorimeter
  - Sampling every 2.54 cm
  - 4cm wide strips of scintillator
  - 2 sections, 15m each
  - 5.4 kton total mass
  - 55%/√E for hadrons
  - 23%/√E for electrons
- Magnetized Iron (B~1.5T)
- 484 planes of scintillator
  - 26,000 m^2



2-Flavor Oscillation - ν_μ Disappearance

- **As an example, if there are only two flavors involved in the oscillations then the U matrix takes on the following form and the probability (square of the amplitude) can be expressed as:**

$$U = \begin{pmatrix} \cos\theta & e^{i\delta}\sin\theta \\ -e^{-i\delta}\sin\theta & \cos\theta \end{pmatrix} \quad \text{and}$$

$$P(\nu_1 \to \nu_{1'}) = \boxed{\sin^2 2\theta} \sin^2\left[1.27\Delta m^2 (eV^2)\frac{L(km)}{E(GeV)}\right]$$

$$\text{with} \quad \boxed{\Delta m^2 \equiv M_2^2 - M_1^2}$$

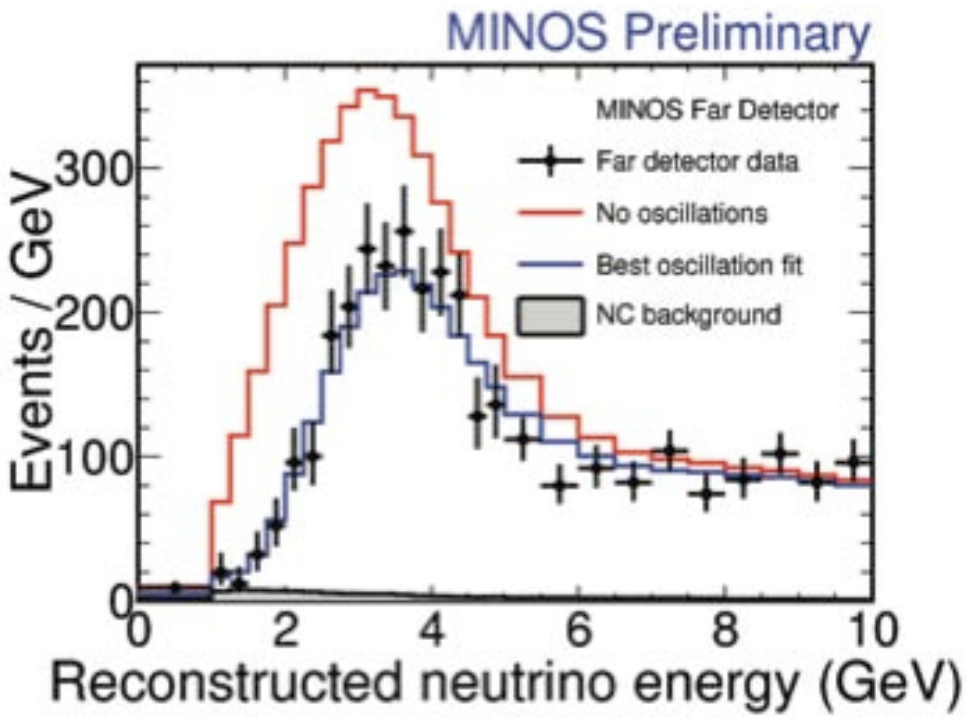
- **Life is more complicated with 3 flavors, but the principle is the same and we get bonus of possible CP violations as in the quark sector $P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$.**

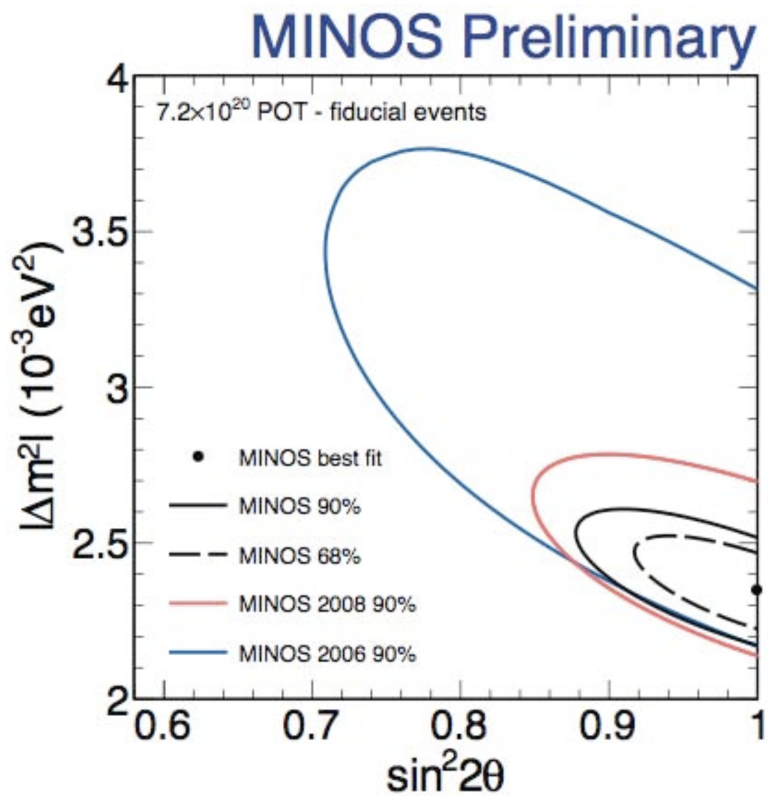
- **The components of U now involve θ_{13}, θ_{23}, θ_{12} and δ and the probabilities involve Δm_{13}, Δm_{23} and Δm_{12}.**

MINOS Best-Fit

7.2 x 10^{20} POT

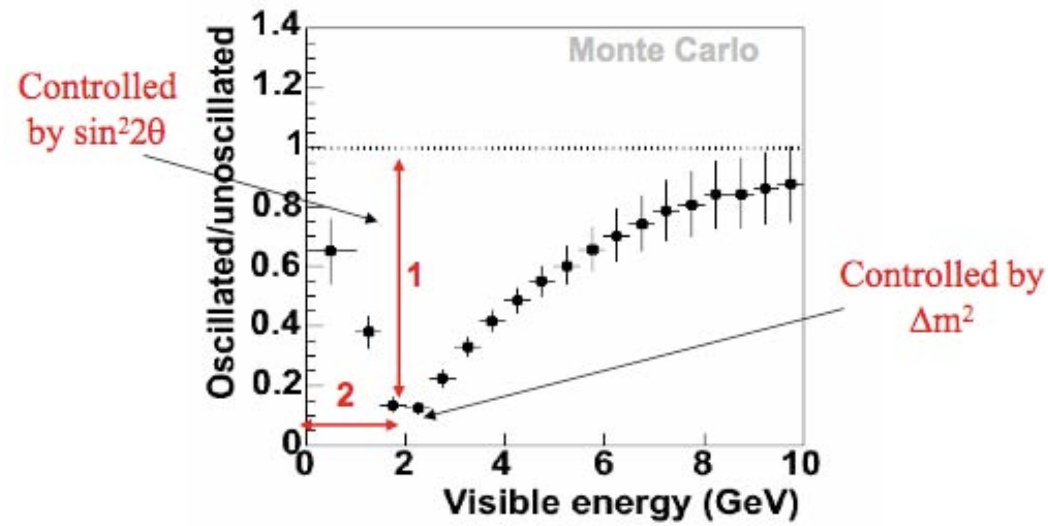
- Observe **1986 ν_μ** events in FD expect **2451** with no oscillations

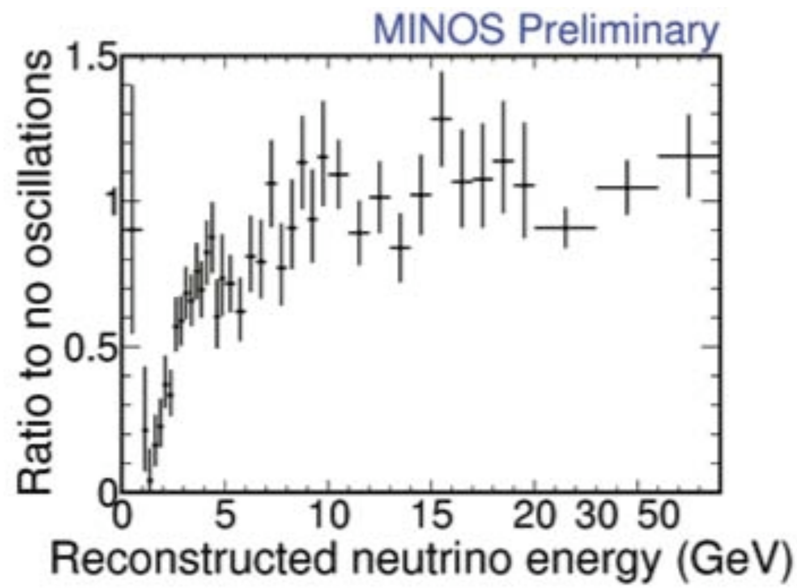


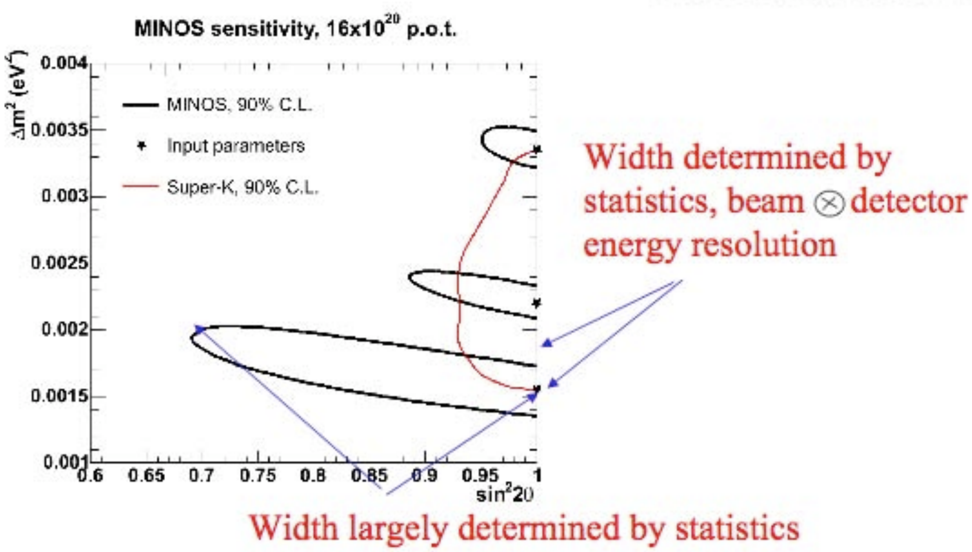


- $\Delta m^2 = 2.35^{+0.11}_{-0.08}$ x 10^{-3} eV^2 (68% CL), $\sin^2(2\theta) > 0.91$ (90% CL)

How to interpret oscillation results

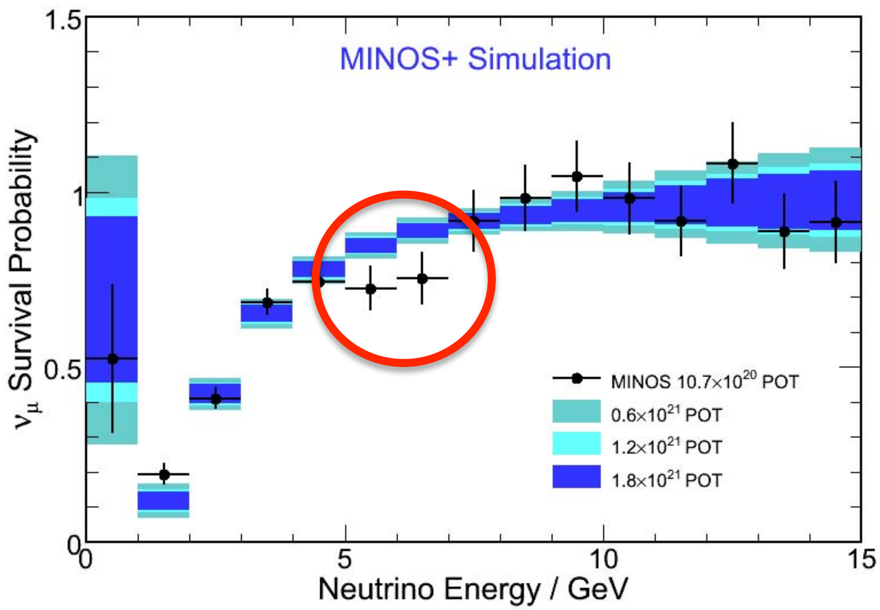


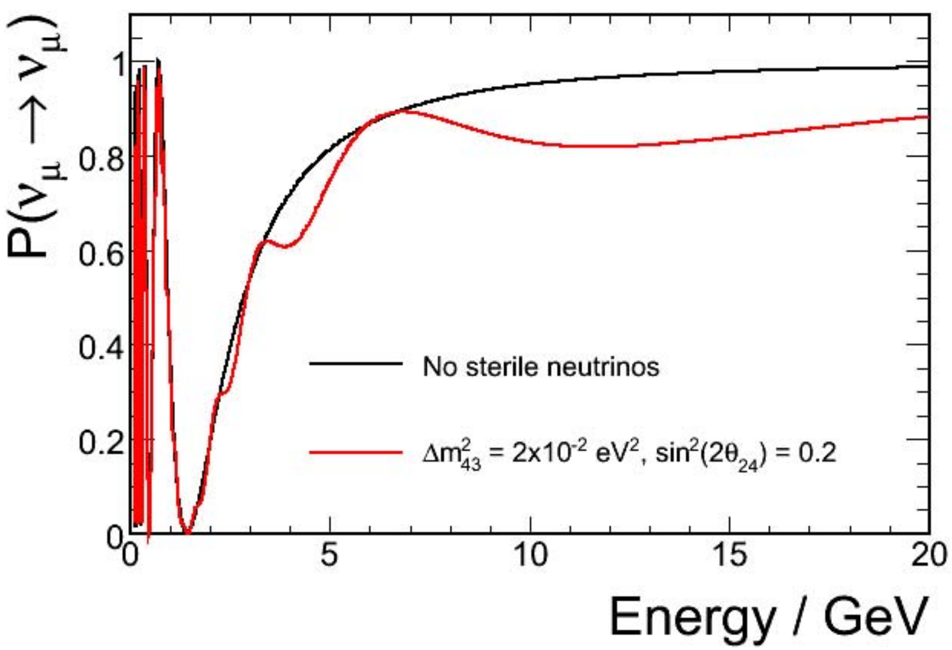




MINOS$^+$: Sterile Neutrinos

- Powerful search for sterile neutrinos
- Odd dip will have to wait for MINOS+ for more study
- Oscillation spectrum pretty insensitive to primary oscillation parameters in this region





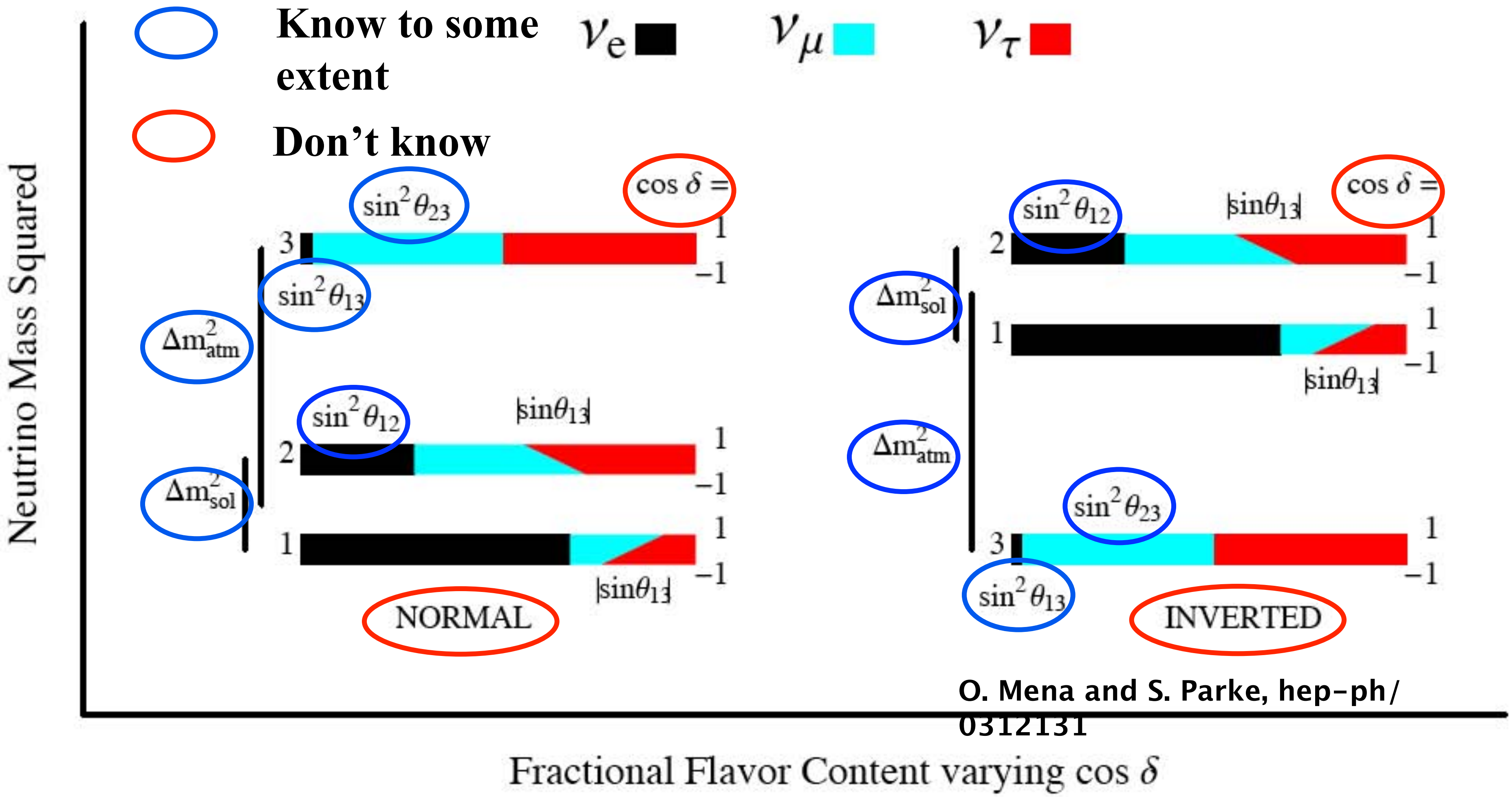
Beam-on 2013
NuMI to NOνA

Going into NOνA, what have we learned?

- From observing neutrinos from the sun and reactors, we have learned that $\nu_e \rightarrow \nu_\mu$ and $\nu_e \rightarrow \nu_\tau$ with $L / E \approx$ 15 000 km/GeV, with a large but not maximal mixing angle, θ_{12}.

- From observing neutrinos produced in the atmosphere by cosmic rays and 1st generation accelerator experiments (K2K and MINOS) we have learned that $\nu_\mu \rightarrow \nu_\tau$ with $L / E \approx 500$ km/GeV, with a mixing angle, θ_{23}, consistent with being maximal

Going into NOνA, what have we learned?



O. Mena and S. Parke, hep-ph/0312131

How important is determining the mass ordering?

- Window on very high energy scales: grand unified theories favor the normal mass ordering, but other approaches favor the inverted ordering.
- If we establish the inverted ordering, then the next generation of neutrinoless double beta decay experiment can decide whether the neutrino is its own antiparticle. However, if the normal ordering is established, a negative result from these experiments will be inconclusive.
- To measure CP violation, we need to resolve the mass ordering, since it contributes an apparent CP violation for which we must correct.

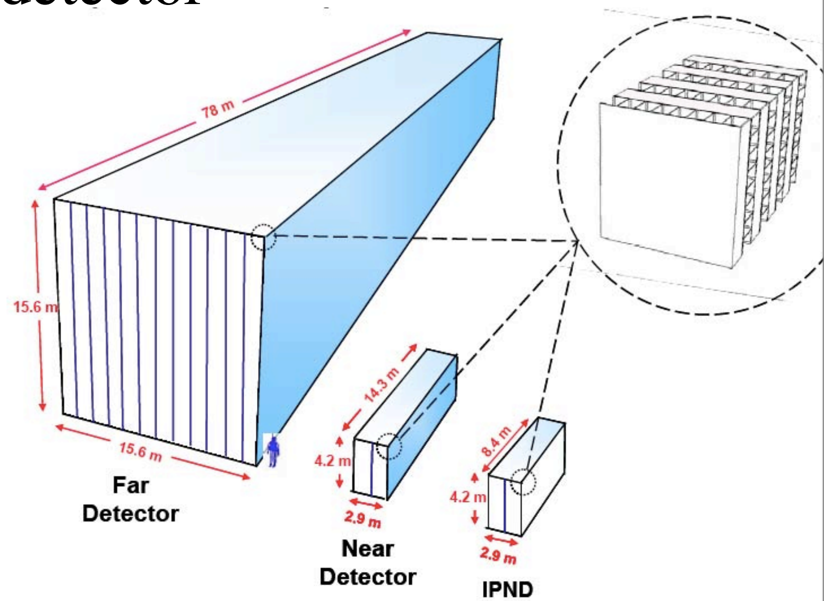
The NOνA Experiment - ν_e appearance

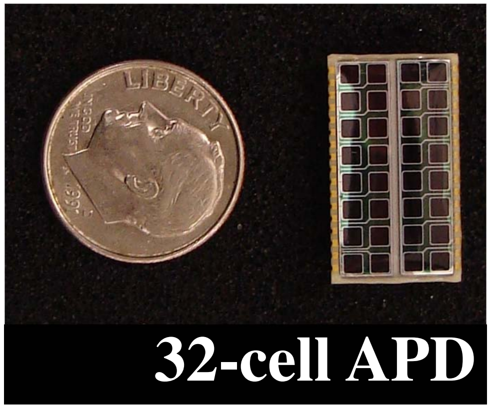
Would Welcome Latin American Collaborators

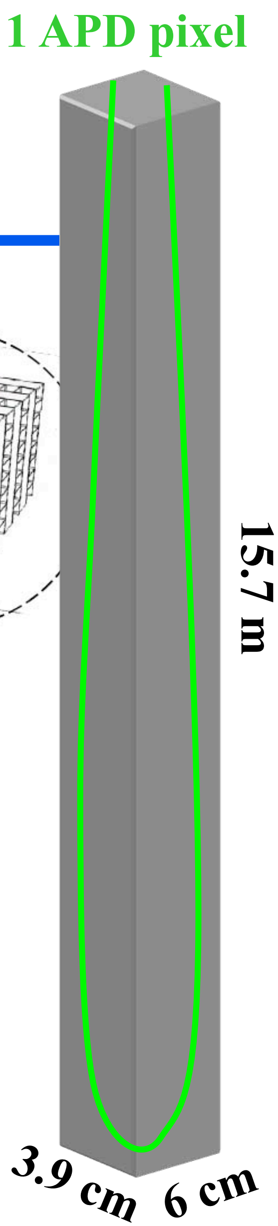
- NOνA is an approved Fermilab $\nu_\mu \rightarrow \nu_e$ appearance experiment currently finishing construction expecting to start Spring 2013
- Unique long baseline
  - Near and Far detectors with a 810 km baseline
  - Located Off the Beam Axis for Background Suppression
  - Use matter effects to determine the neutrino mass hierarchy
- Near and Far Detectors optimized for ν_e charged-current detection
- Primary Physics Goals
  - **Confirm θ_{13}**
  - **Determine Mass Hierarchy**
  - **Initial lookat a CP Violation Measurement.**

NOvA Far Detector

- "Totally Active" scintillator detector
- Liquid scintillator cells
  - 3.9 cm x 6 cm x 15.7m
  - 0.15 X_0 sampling
  - 1654 planes of cells
- Cell walls
  - Extruded rigid PVC
- Readout
  - U-shaped 0.8 mm WLS fiber
  - APDs 85% QE cooled to -15°C
- 14 kT of total mass
  - 15.7m x 15.7m x 67 m







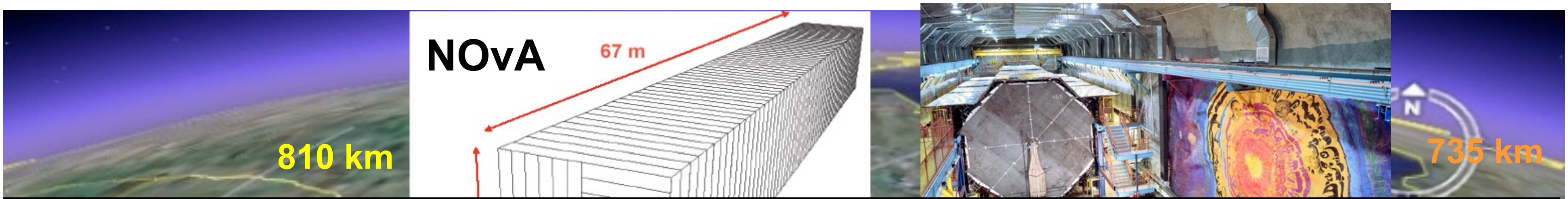
Fermilab Gothic

Reception at Orr

Jim's Ash Trail Store

NEXT STEP - Fermilab to DUSEL: LBNE Project

Would welcome Latin American Collaborators



LBNE Collaboration:

306 members from 58 institutions from India, Italy, Japan, UK, US

Continues to grow!

Matter – Antimatter Asymmetry with Neutrinos

Proton Decay

Supernovae Neutrinos

LBNE Physics Goals

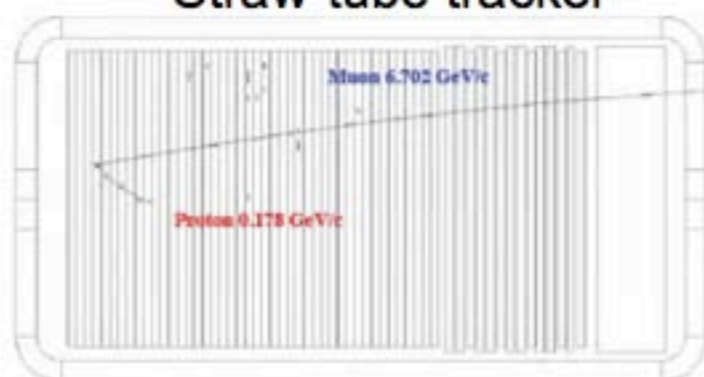
- Search for, and precision measurements of, the parameters that govern $\nu_\mu \rightarrow \nu_e$ oscillations.
  - measurement of the CP violating phase δ and
  - determining of the mass ordering (sign of Δm^2_{32}).
- Precision measurements of θ_{23} and $|\Delta m^2_{32}|$ in the ν_μ disappearance channel.
- Search for proton decay, yielding a significant improvement in current limits on the partial lifetime of the proton (τ/BR) in one or more important candidate decay modes, e.g. $p \rightarrow e^+\pi^\circ$ or $p \rightarrow K^+\nu$.
- Detection and measurement of the neutrino flux from a core collapse supernova within our galaxy, should one occur during the lifetime of LBNE.

LBNE Near Detector Considerations

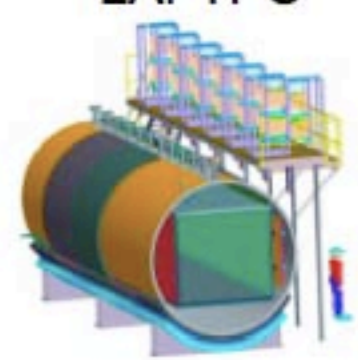
- Neutrino detector to measure un-oscillated beam spectrum and neutrino cross sections needed to make the oscillation measurements.
- Currently concentrating on physics studies to precisely define what is needed.
- Several options under consideration:

Scintillator tracker

Straw-tube tracker

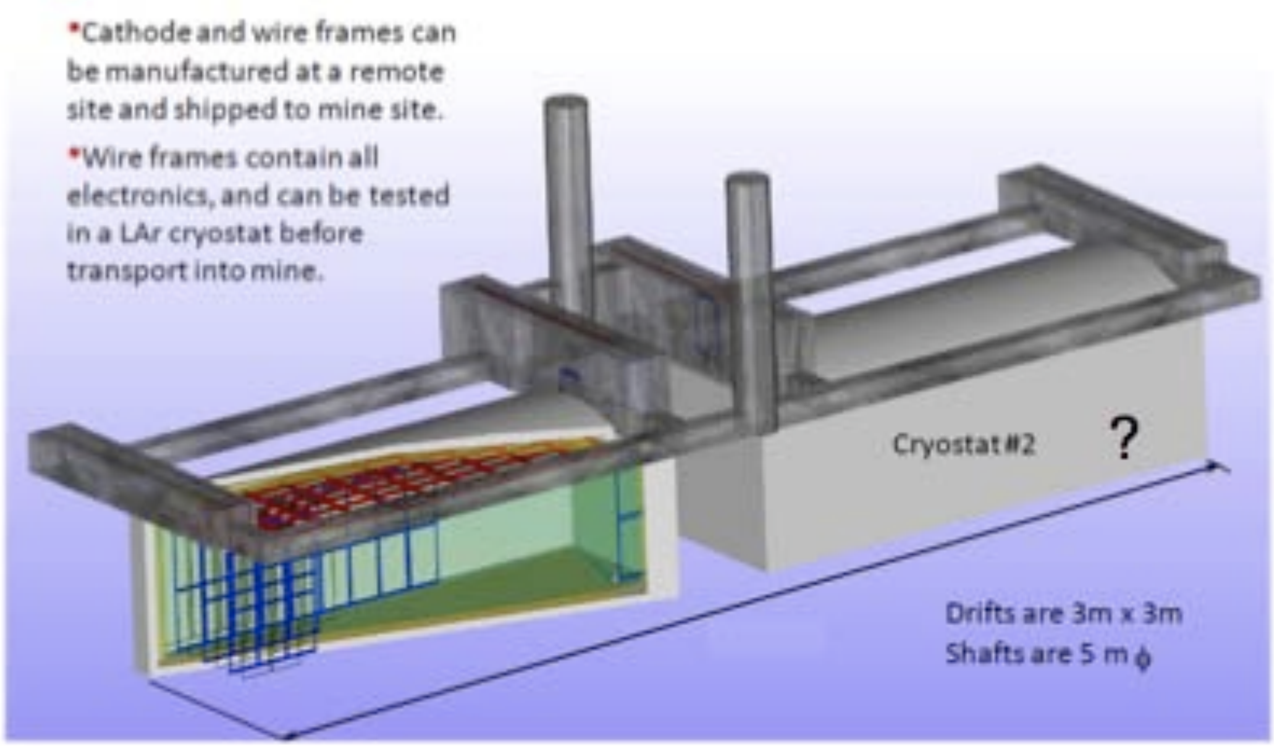


LAr TPC



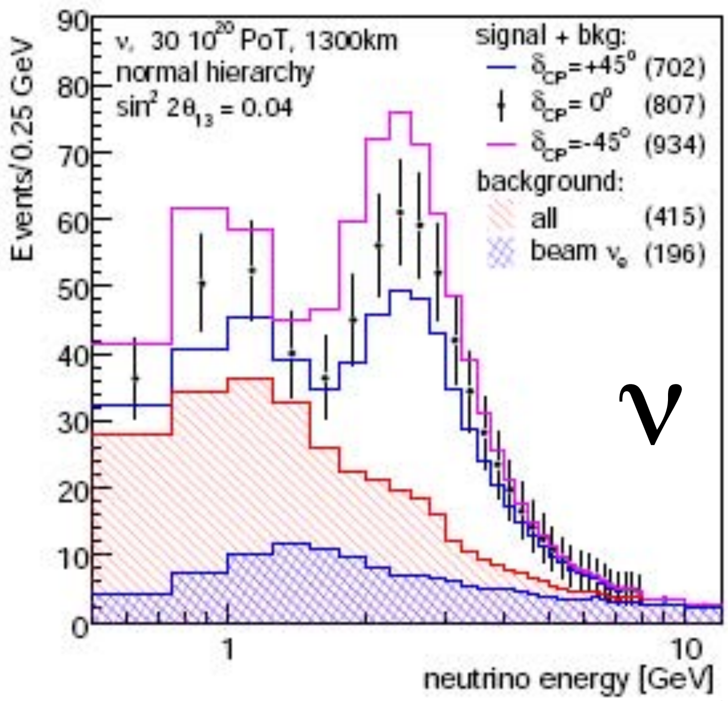
Far Detectors to be placed in DUSEL Facility

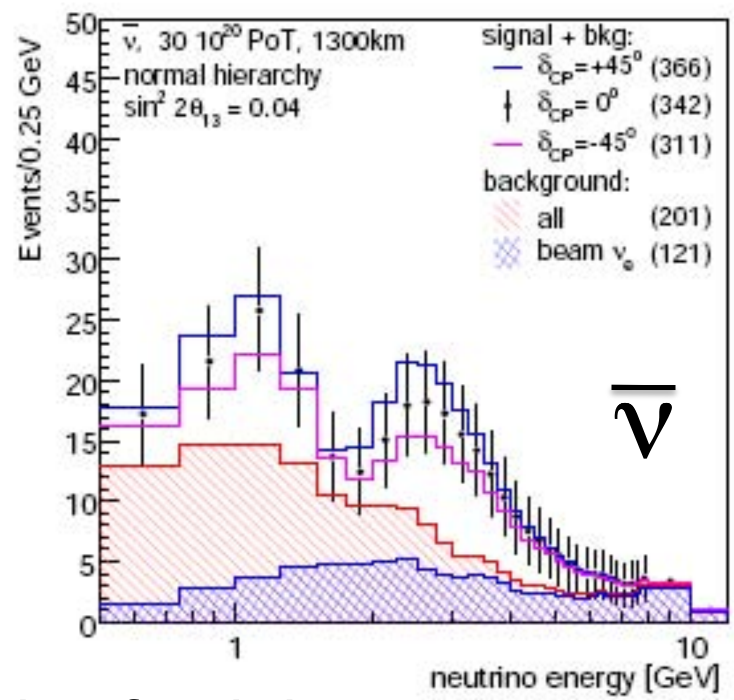
- LAr TPC: Designing ~17 kT fiducial volume modules (~100 kT WC Equivalent) for oscillation physics.
- To be placed closer to the surface (800 foot level)



LBNE uses wideband neutrino beam

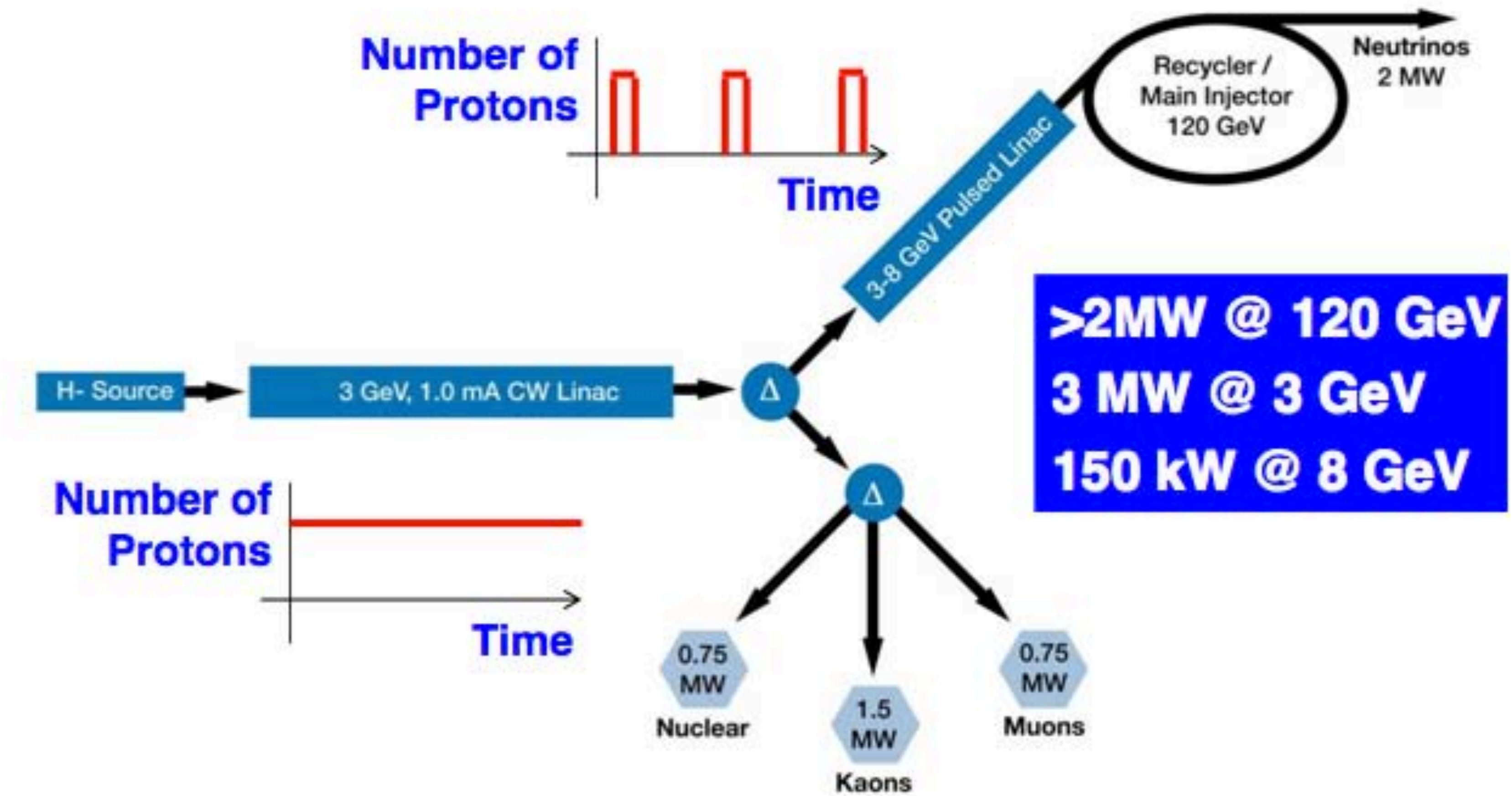
Do we need the capability to study both the 1st and 2nd oscillation maxima in a (wide-band) long baseline experiment in order to break inherent degeneracies between CPv and matter effects





Backgrounds from NC π^0 production feed down
Study above assumes 5% knowledge of background
Basic cross-sections have large uncertainties (30-100%)

Further in the Future Oscillation Experiment(s)
Project X



In the World of High-Power Proton Accelerators Project-X will be Unique

- Highest proton beam power on the planet
- Broadest range of proton beam energies available: 1-120 GeV
- Ability to provide beams to multiple experiments simultaneously
- Ability to tailor the beam properties to the needs of each experiment
- Upgradeable to very high power

Project-X is the ideal machine for intensity-frontier physics

Project X Research Program

Would welcome Latin American Collaborators

- **Long baseline neutrino oscillation experiments:**

  Driven by a high-power proton source with proton energies between 50 and 120 GeV that would produce intense neutrino beams directed toward massive detectors at a distant deep underground laboratory.

- **Kaon, muon, nuclei & neutron precision experiments driven by high intensity proton beams running simultaneously with the neutrino program:**

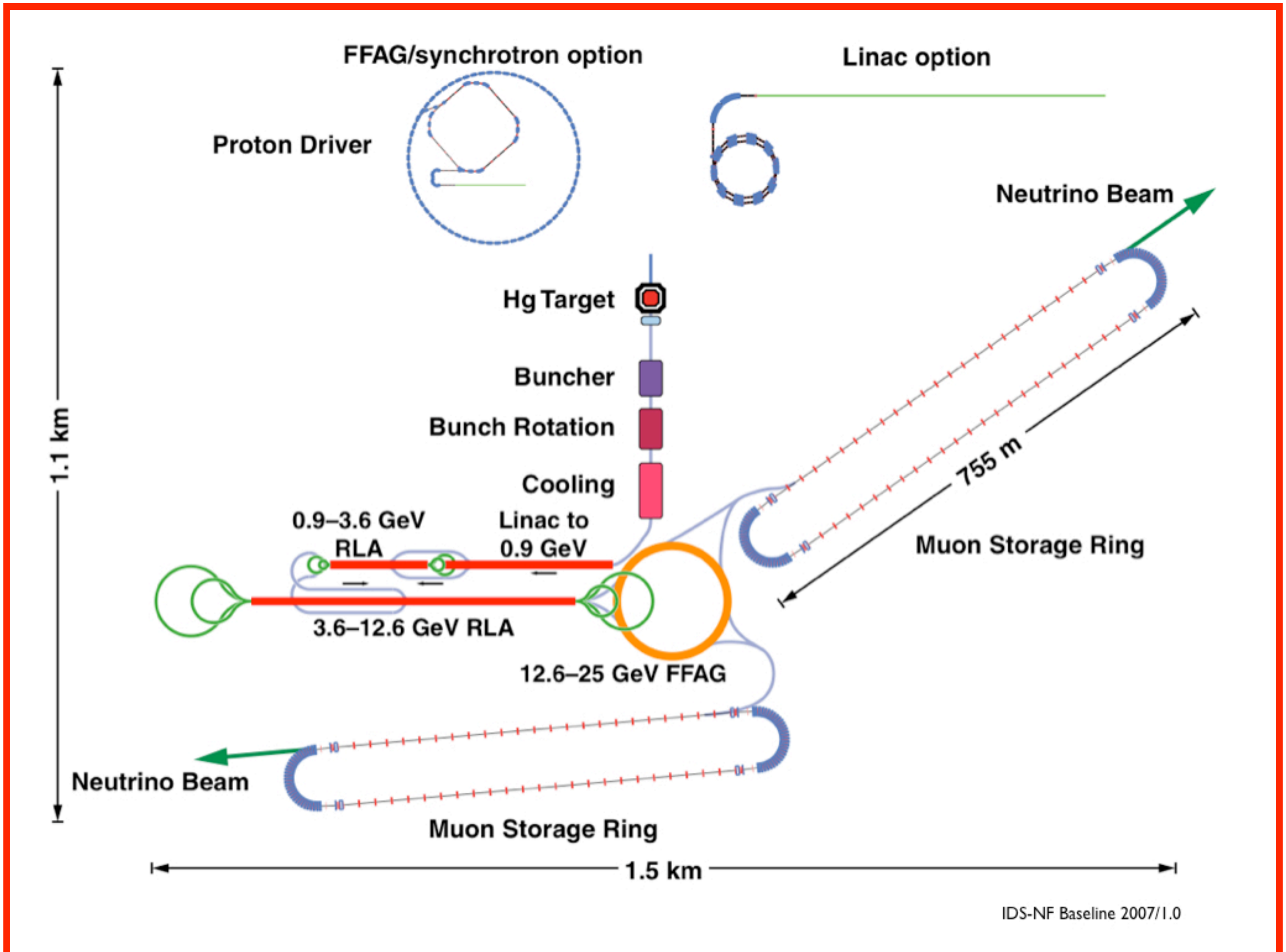
  These could include world leading experiments searching for muon-to-electron conversion, nuclear and neutron electron dipole moments (edms), and world-leading precision measurements of ultra-rare kaon decays.

- **Platform for evolution to a Neutrino Factory and Muon Collider**

The Neutrino Factory

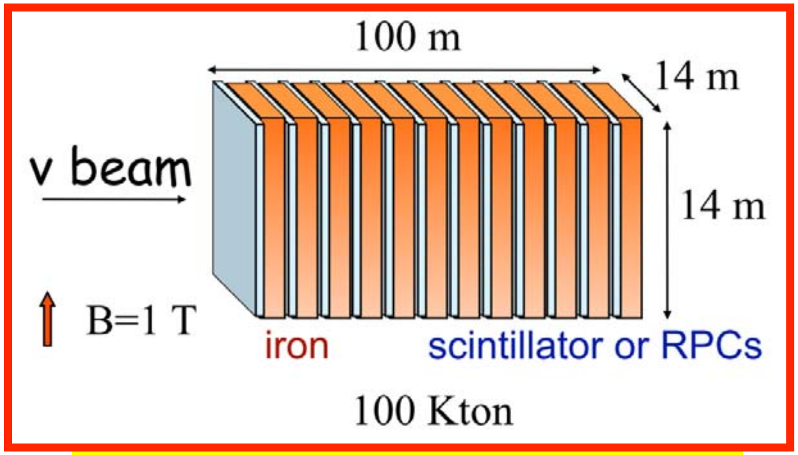
(High intensity circulating muons)

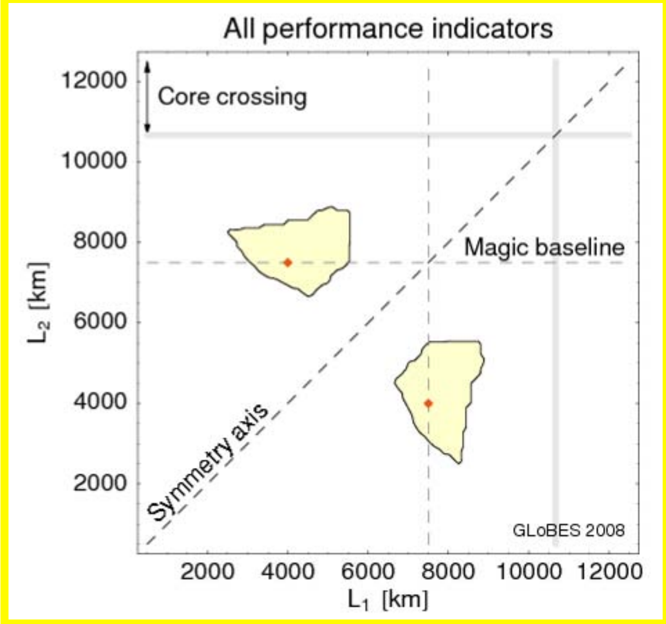
Active collaboration would welcome Latin American collaborators



Muon decay followed by oscillation
$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$

- For circulating μ^- decays, look for $\bar{\nu}_e$ oscillating to $\bar{\nu}_\mu$ that, when interacting in your detector, yields a μ^+ !!
- No need for a fancy electron sensitive detector. Magnetized iron detector will do
- Best configuration with large θ_{13}
  - One100 kt detector at 2000 km
  - E_μ circulating at 10 GeV





LATIN AMERICAN COLLABORATION AT INTENSITY FRONTIER EXPERIMENTS

The MINERνA Model: Latin American collaboration at FNAL

- Students studying for their Masters Degree 22 students
  - Visiting Scientist Invitation
  - J-1 visa Trainee Program: On-site Mentor
  - 1-year residency at Fermilab working on experiment
  - As long as funding permits: Fermilab covers housing costs and adds to perDiem
- Students studying for their Doctorate 9 students
  - Visiting Scientist Invitation and Scholar Visa
  - Multi-year residency at Fermilab working on experiment
  - As long as funding permits: Fermilab covers housing costs
- Post Doctoral Associates 1 so far
  - Visiting Scientist and scholar visa
  - Multi-year residency at Fermilab working on experiment
  - As long as funding permits: Fermilab covers housing costs
- Professors
  - Multiple 2-4 week visits and one 1-year Sabbatical 27 visits 1 Sabbatical
  - As long as funding permits: Fermilab covers housing costs

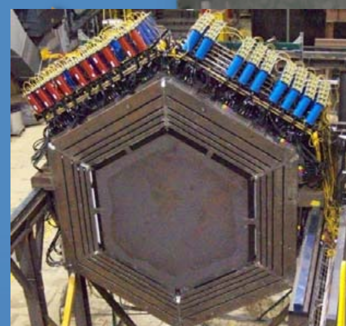
Conclusions

- **Fermilab offers a wide-ranging near-and-further future experimental approach to studying the nature of the neutrino and how it interacts with matter via MINERνA, MINOS+, NOνA, MicroBooNE, (nuSTORM) LBNE and a neutrino factory.**
- **Near-and-further future experiments are still welcoming new groups.**
- **Already a strong Latin American – Brazil, Chile, Mexico and Peru – presence in MINERνA.**
- **All experiments would welcome (additional) collaborators from Latin America**
- **There is at least one working model of how Latin American physicists can collaborate at Fermilab in the Intensity Frontier.**

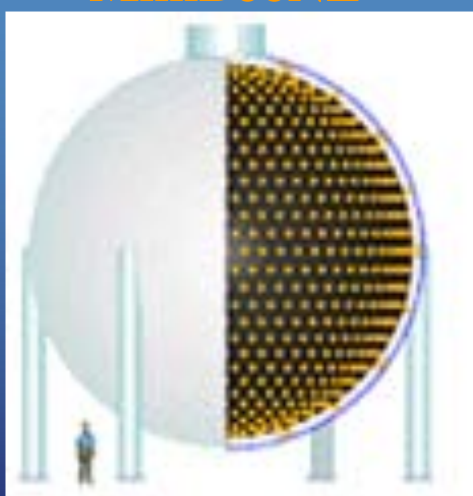
Intensity Frontier Accelerators (now)

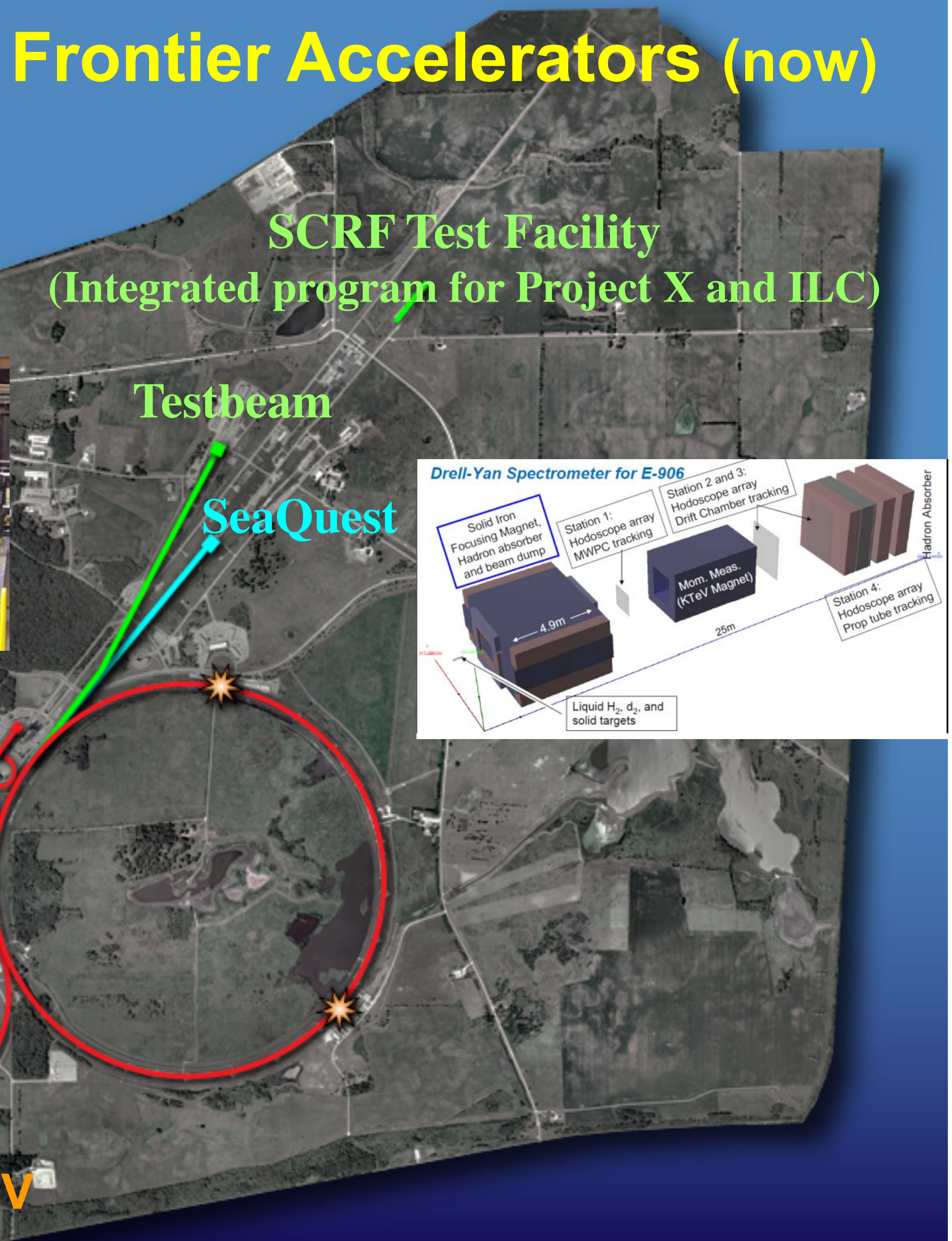
MINOS at 735 km

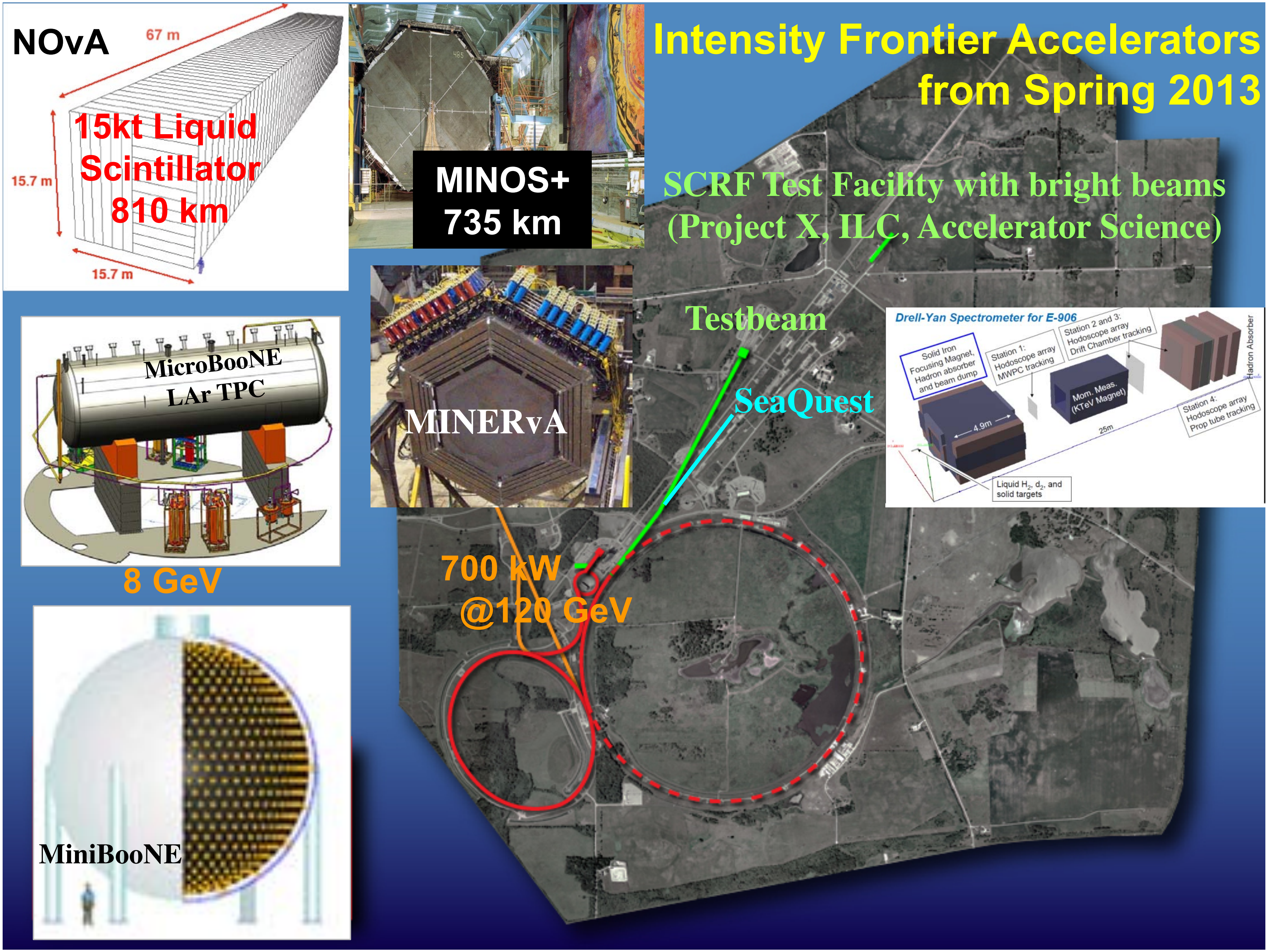
MINERvA



MiniBooNE







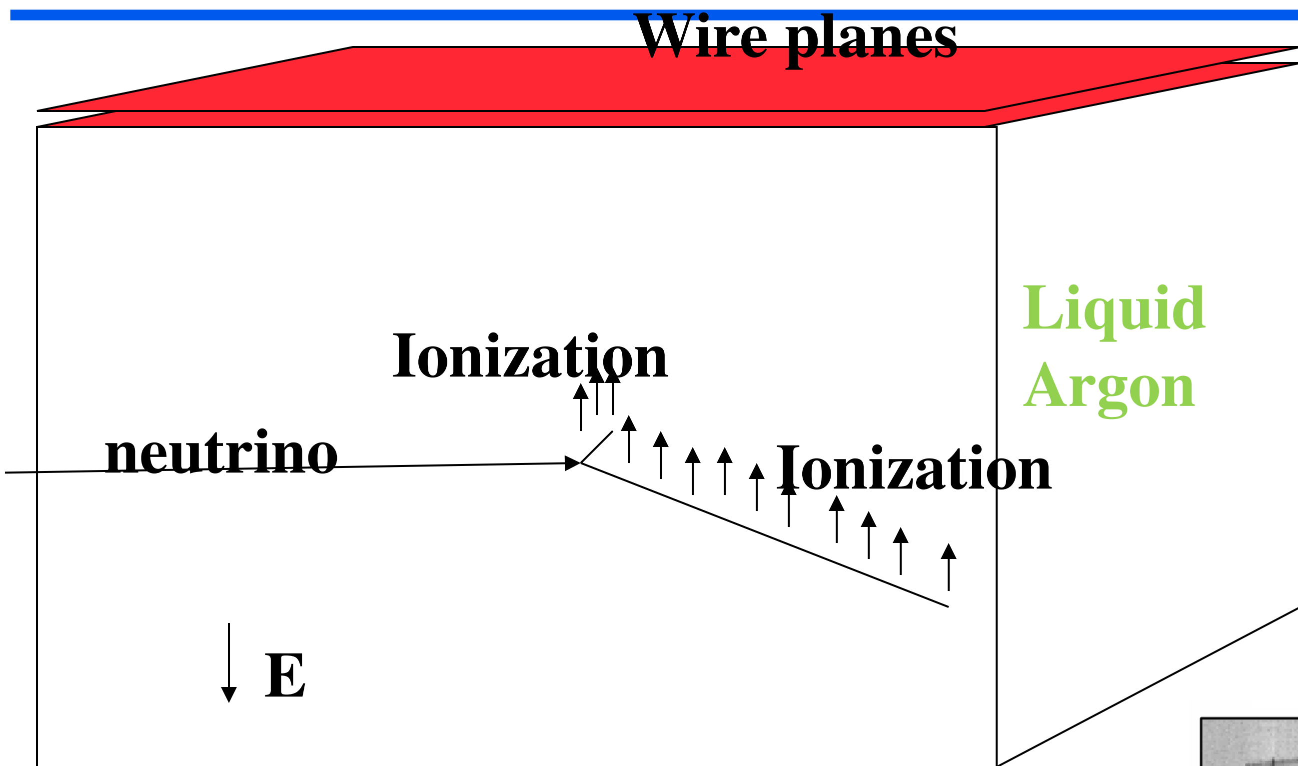
Intensity Frontier Accelerators
from Spring 2013
NOvA
67 m
15.7 m
15.7 m
15kt Liquid
Scintillator
810 km
MINOS+
735 km
MINERvA
MicroBooNE
LAr TPC
8 GeV
MiniBooNE
SCRF Test Facility with bright beams
(Project X, ILC, Accelerator Science)
Testbeam
SeaQuest
700 kW
@120 GeV
Drell-Yan Spectrometer for E-906
Solid Iron Focusing Magnet, Hadron absorber and beam dump
Station 1: Hodoscope array MWPC tracking
Station 2 and 3: Hodoscope array Drift Chamber tracking
Hadron Absorber
Mom. Meas. (KTeV Magnet)
Station 4: Hodoscope array Prop tube tracking
4.9m
25m
Liquid H_2, d_2, and solid targets

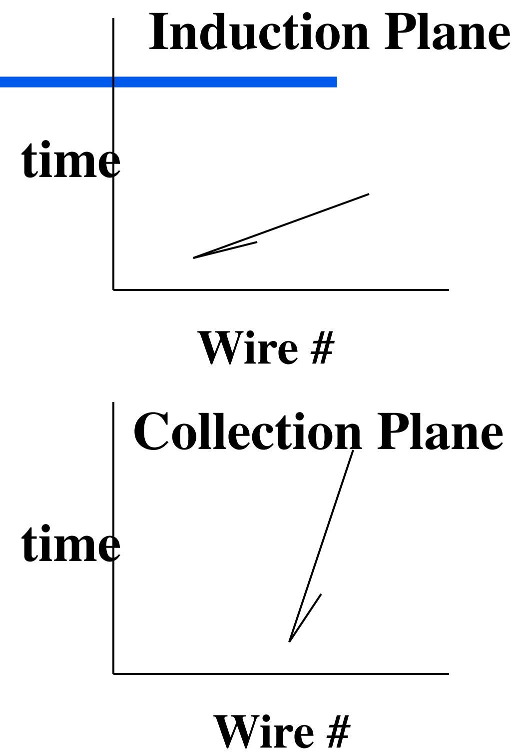
NOνA strategy to measure mass ordering

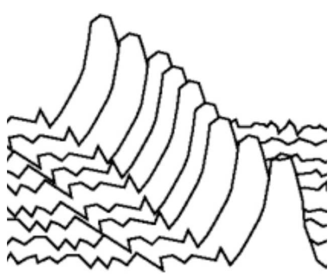
- If the CP-violating term goes in the same direction as the matter effect, then there is no ambiguity and NOνA can determine the mass ordering by itself, given sufficient integrated beam.

- If the CP-violating term goes in the opposite direction as the matter effect, then there is an inherent ambiguity and NOνA cannot determine the mass ordering by itself. But it can be determined, in principle, by comparing NOνA and T2K.
  - If the neutrino oscillation probability is larger in NOνA than in T2K, it is the normal mass ordering; if the opposite, it is the inverted mass ordering.

LAr TPC Technique

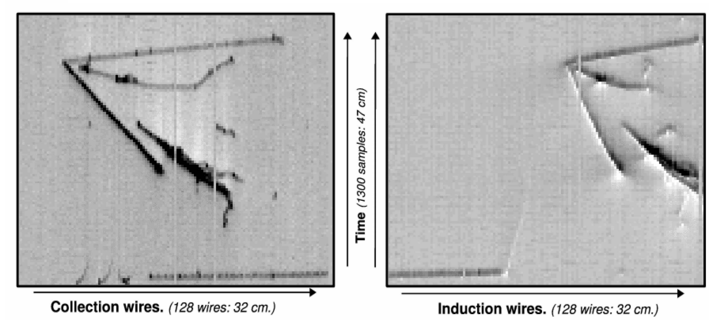






Wire pulses in time give the drift coordinate of the track

Scintillation light can give t_0

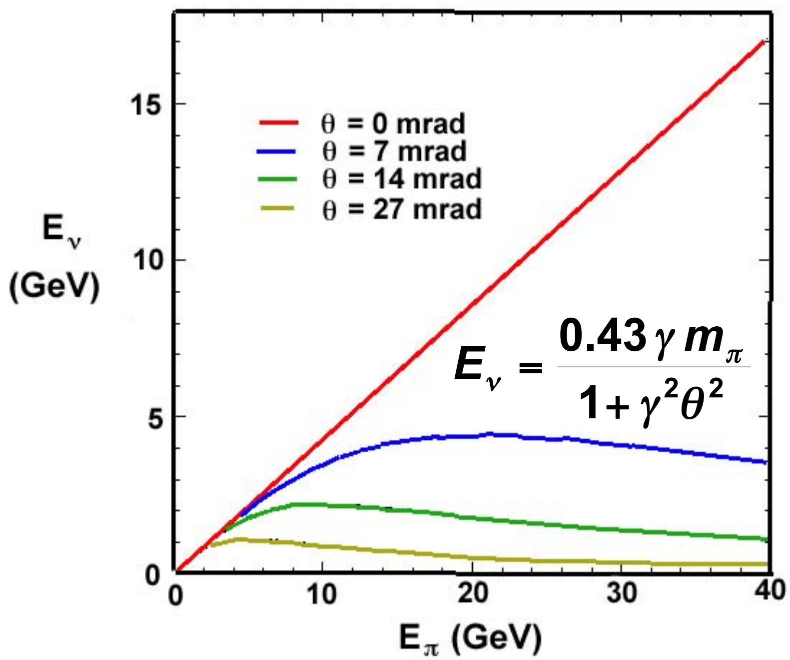


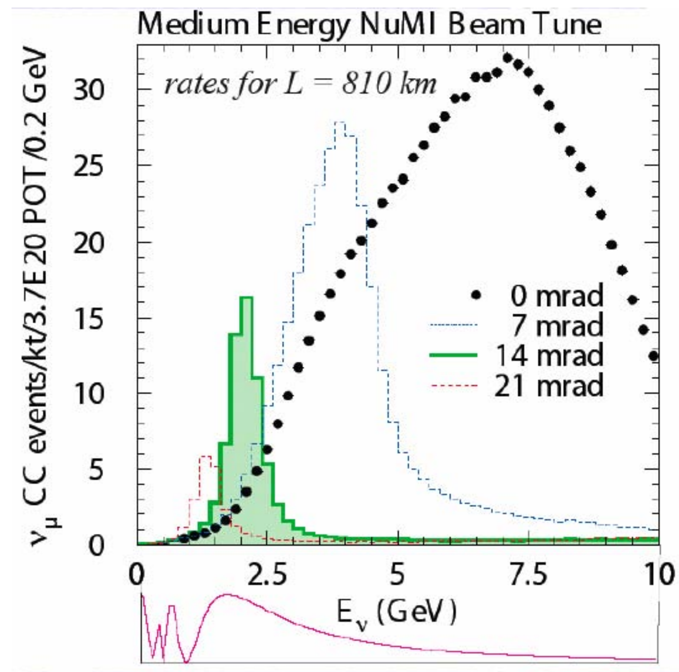
ICARUS 50L in WANF neutrino beam

induction plane + collection plane + time = 3D image of event (w/ calorimetric info)

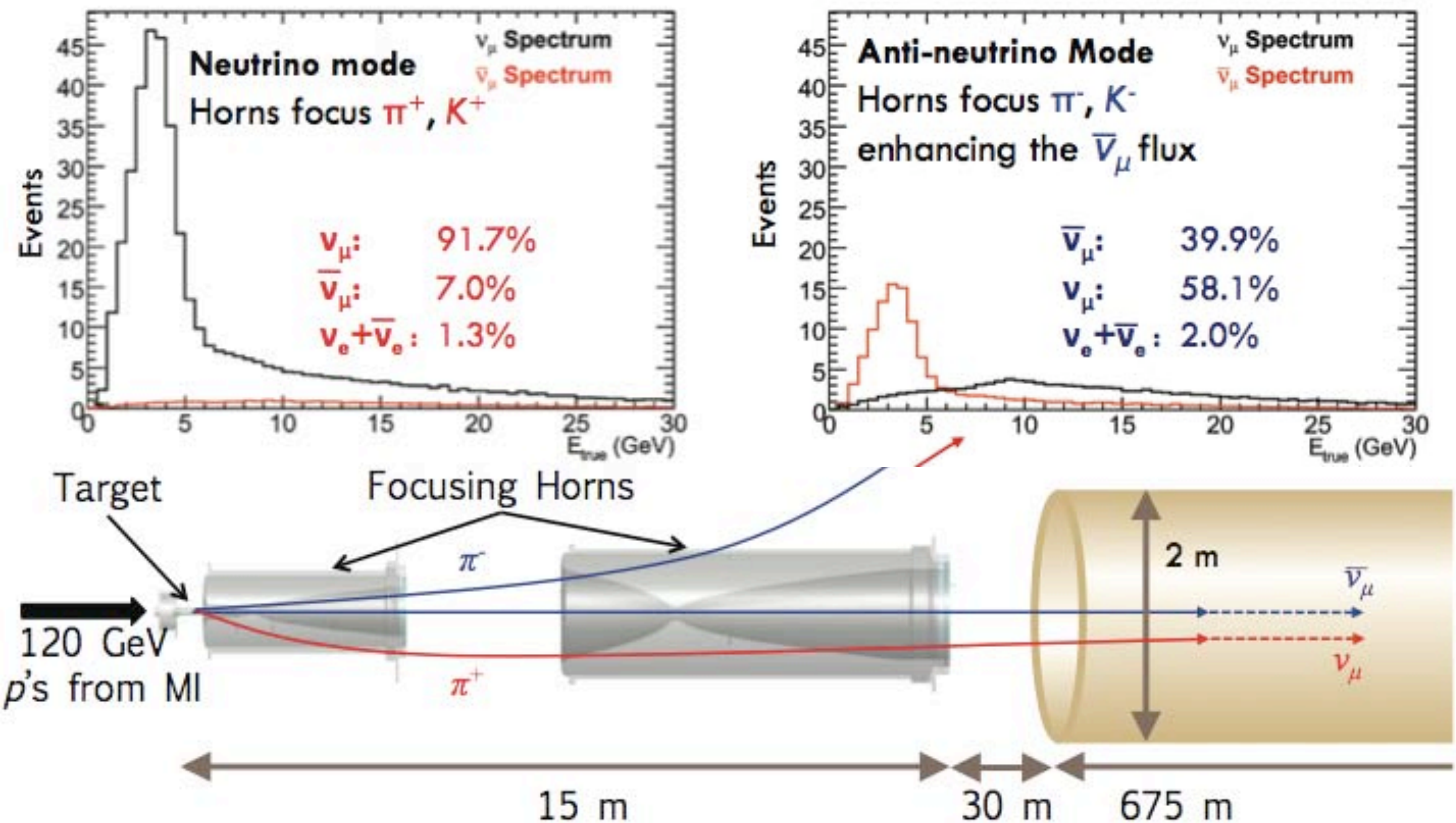
Why Off-Axis?

- Both Phase 2 experiments, NOνA and T2K are sited off the neutrino beam axis. This yields a narrow band beam:
  - More flux and less background (ν_e's from *K* decay and higher-energy NC events)



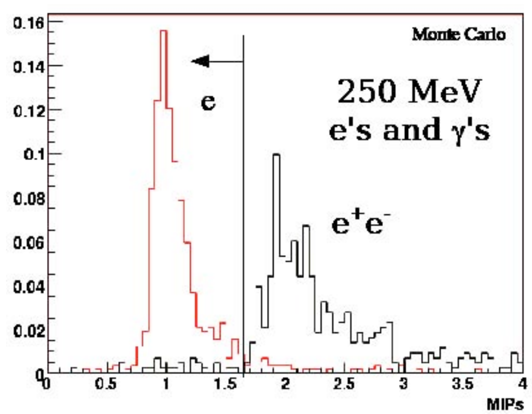


Making an Antineutrino Beam



MicroBooNE: Excellent e/γ separation

- LAr TPC images events and collects charge - do e/γ separation via dE/dx.
- Look at MIP deposition in first 2.4 cm of track before shower starts
  - GEANT4 MC: 90% electron efficiency with 6.5% gamma background
- e/γ separation removes single γ backgrounds



- Electron Neutrino efficiency 2x better than MiniBooNE
- Sensitivity down to 10's of MeV compared to MiniBoNE 200 MeV

Details – details….

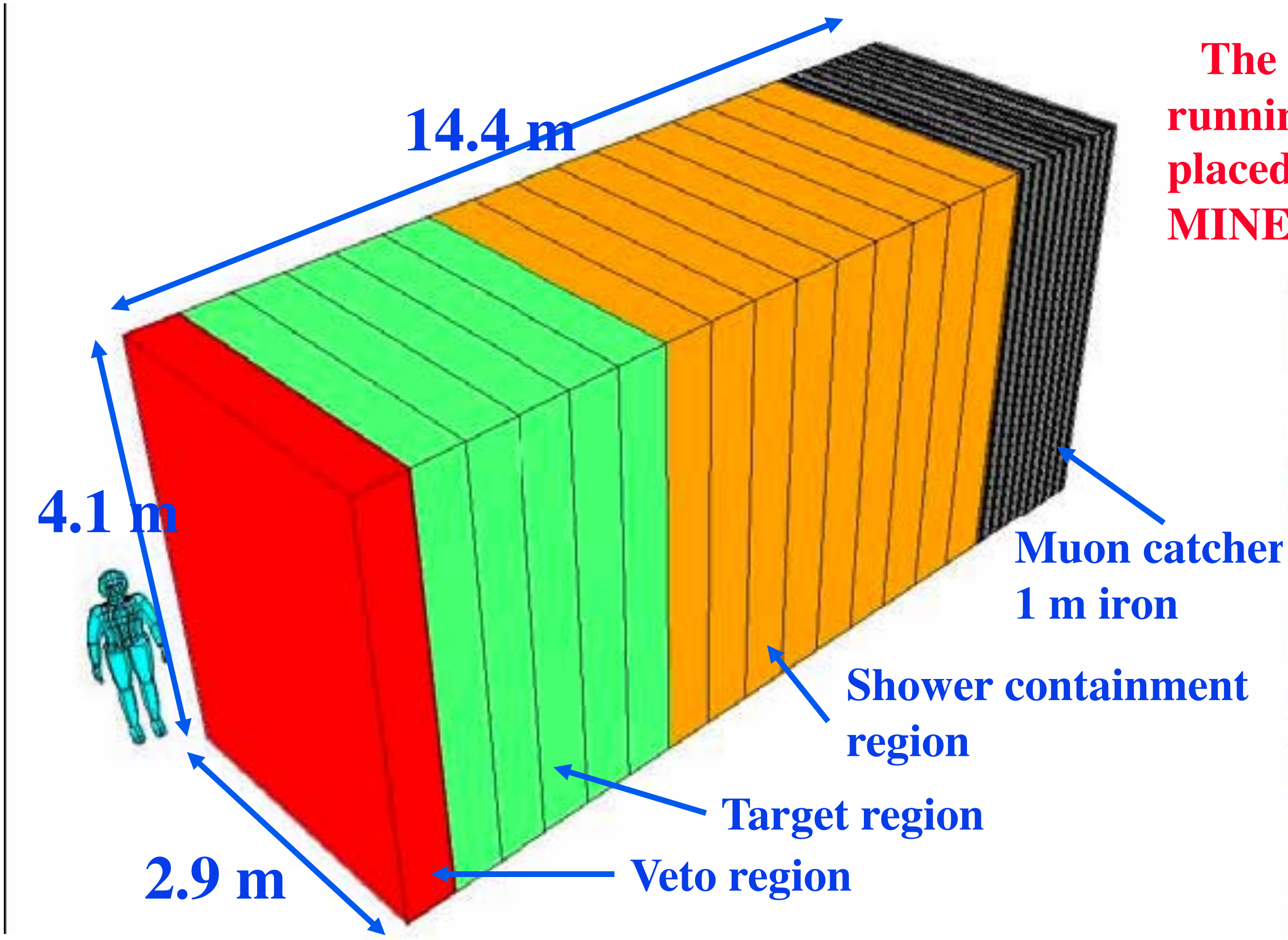
- Freeday: ½ day tour to Pachacamac – Inca ruins just outside of Lima by bus, How many are interested in this tour?

- Nightcap – rough idea of what you want to drink, beer, wine, Pico sours

- Meals at the hotel – many not there last night, would you prefer to eat away from hotel, let us know. Please be back for the nightcap.

NOνA Near Detector

209 T of which 126 T totally active with 23 T fiducial



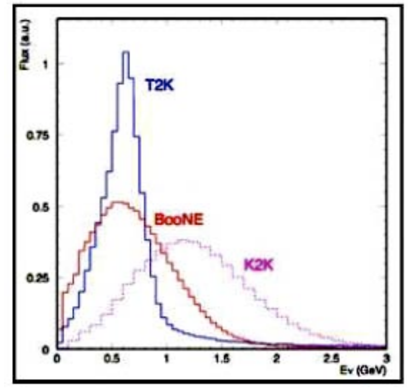
The NOvA Near Detector, now running on the surface, will be placed off-axis in the MINOS / MINERvA access tunnel.

Next year: **MicroBooNE**

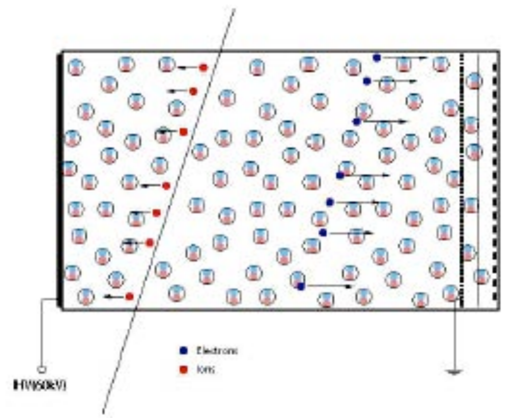
A Closer look at the MiniBooNE Low-E Excess and **ν vs $\bar{\nu}$**

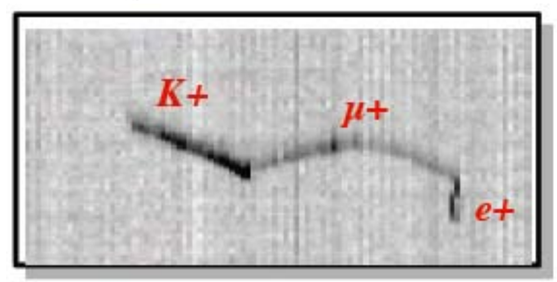
Would welcome Latin American Collaborators

- Regardless of interpretation, excess **must be understood for ν_e appearance measurements**
- **If ν excess in oscillation region persists, study needed**
- For example the T2K experiment - excess would be a background of ≈ 100 events at E > 100 MeV!



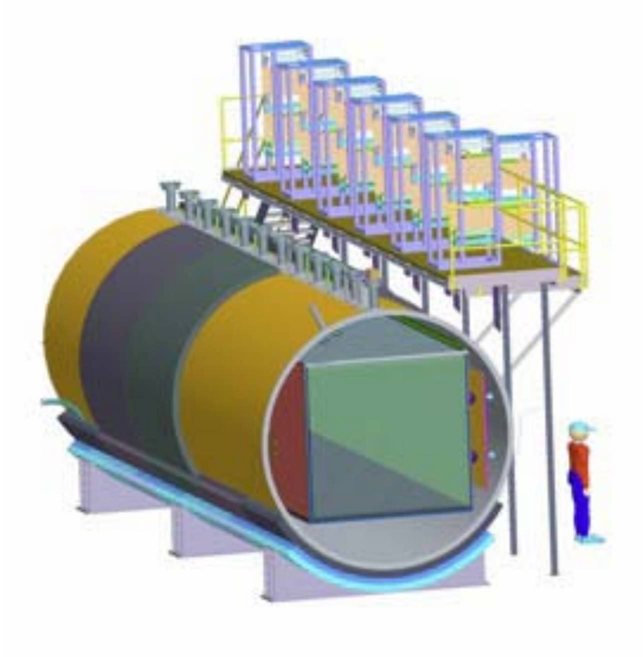
- ENTER Liquid Argon TPC detectors for detailed study of neutrino interactions (and oscillations) – currently under constuction
  - Passing charged particles ionize Argon - 55,000 electrons/cm.
  - Drift ionization electrons over meters of pure LAr to collection planes to image the track.
  - Extensive experience from the European ICARUS effort.



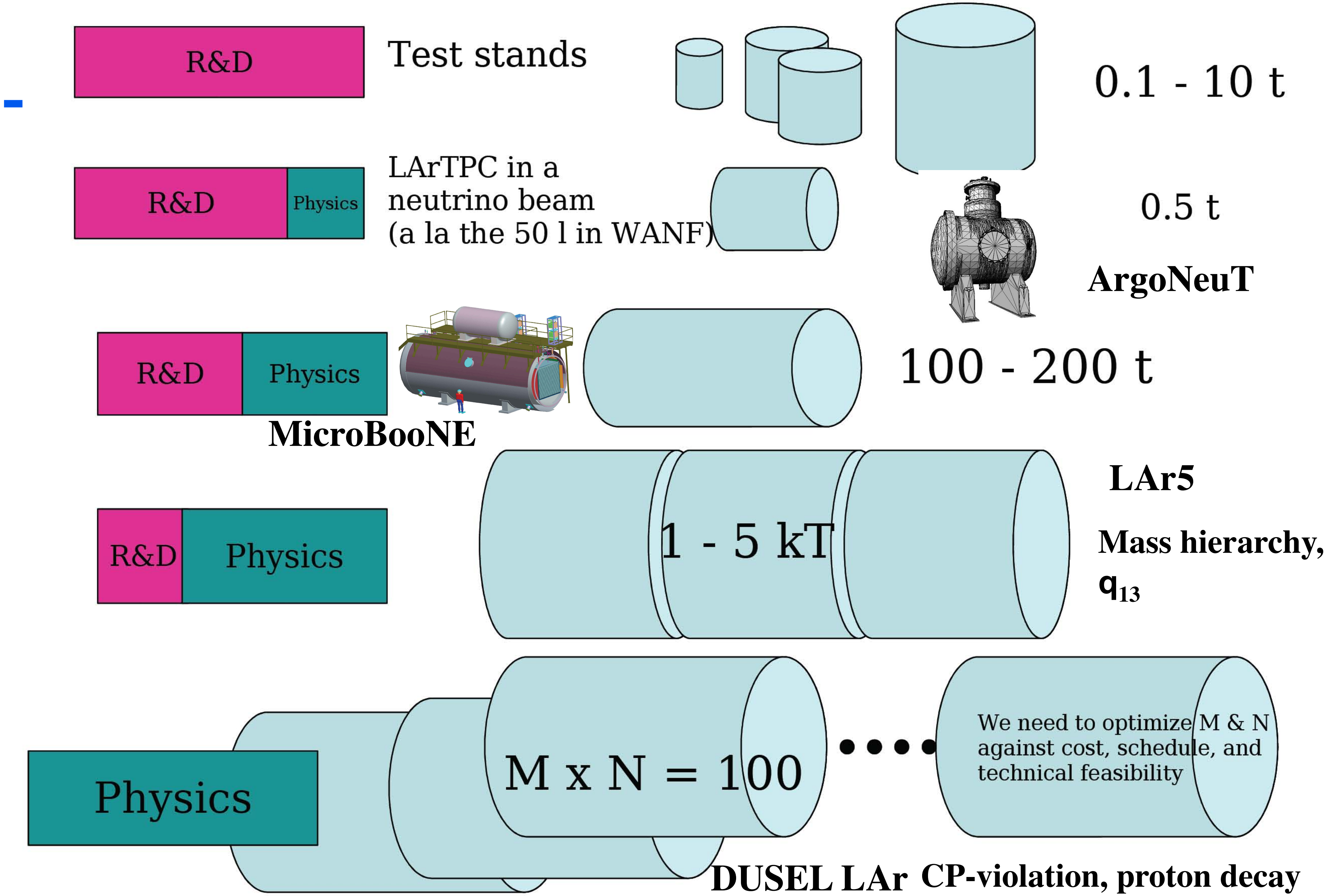


MicroBooNE Liquid Argon TPC

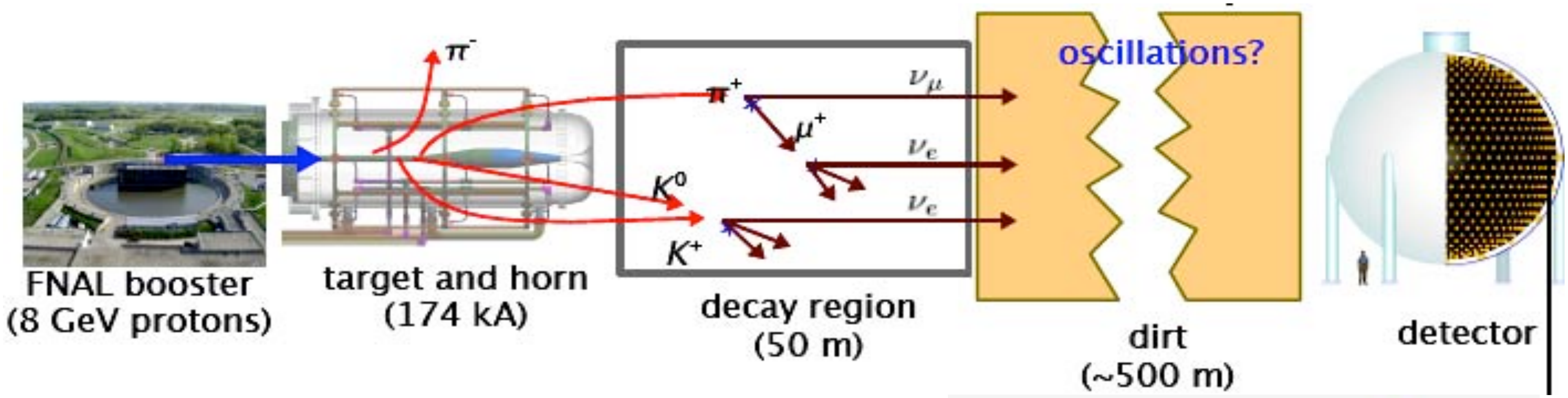
- 70 ton fiducial L Ar TPC detector
- Located in the Booster neutrino beam
- Collect 6×10^{20} POT from on-axis Booster Neutrino Beam
- Collect 8×10^{20} POT from off-axis LE NuMI Beam
- In addition to interesting physics motivation, this is an important step along the way to making LAr TPC a practical detection method for small and LARGE detectors



Evolution of a Liquid Argon Physics Program



Fermilab Neutrino Program: Just Mention - Booster Neutrino Beam



- 4x10^{12} 8 GeV protons hit a Be target at up to 4 Hz.
- Pions focused with a 174 kA pulsed magnetic horn.
- Use HARP hadron production data to predict flux via Geant 4 MC of beamline components.