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

The Energy Frontier
- Origin of Mass
- Dark Matter
- Unification of Forces
- New Physics Beyond the Standard Model
- Neutrino Physics
- Proton Decay
- Matter/Anti-matter Asymmetry

The Intensity Frontier
- Dark Energy

The Cosmic Frontier

International Collaborations
Experimental Programs at Fermilab

27 countries

17 countries

24 countries

Young-Kee Kim, ICFA Seminar, CERN, October 3, 2011
Intensity Frontier Experiments
International Collaboration

17 countries

Countries Collaborating with Fermilab
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), MINERvA and NOvA
  - 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.
To build upon our existing strengths to establish a world-leading program at the **Intensity Frontier**, enabled by a world-class facility...

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

Technology Development and Fundamental Accelerator Science

...while relying on a strong program of technology development and fundamental accelerator science.
Intensity Frontier Strategy - Experiments

Now                      2013                      2016                       2020’s
MINOS                      MiniBooE                      MINERvA
MINERvA                      SeaQuest                      NOvA
SeaQuest                      NOvA                      NOvA
MicroBooE                      MINERvA                      MINERvA
LBNE
Mu2e
Project X
(LBNE, μ2e, K, nuclear, …)
ν Factory
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:

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

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

\[ \lambda = \frac{1}{n \sigma} \approx 1.5 \times 10^{21} \text{ cm} \approx 1600 \text{ light – years} \]

Experimentalists groaned - need a very intense source of \( \nu \)’s to detect neutrino interactions

At 20 GeV, \[ \frac{\sigma}{E_\nu} \approx 0.6 \times 10^{-38} \text{ cm}^2 \]
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 $\rightarrow$ Carbon target

$pC \rightarrow \pi^{\pm} \text{ and } K^{\pm}$

Magnetic horns focus + or -

$\pi^{+} / K^{+} \rightarrow \mu^{+}\nu_{\mu} \quad \text{or} \quad \pi^{-} / K^{-} \rightarrow \mu^{-}\bar{\nu}_{\mu}$
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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University of Florida
Université de Genève
Universidad de Guanajuato
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University of Rochester
Rutgers University
Tufts University
University of California at Irvine
University of Minnesota at Duluth
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The MINERνA Collaboration

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# Members of the MINERνA Executive Committee
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 MINERvA (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 MINERvA Detector

Charge sharing for improved position resolution and alignment

σ = 2.6 mm

Scintillator - Tracking
Lead - EM calorimetry
Steel - hadronic calorimetry
What does a Neutrino Event “look” like?
Good for identifying electrons

\[ \nu_\mu + \text{Fe} \rightarrow \mu^- + p \]
“Quasi-elastic”

\[ \nu_\mu + \text{C} \rightarrow \mu^- + (p + \pi^0) + \Delta^+ \]
MINER$\nu$A $\nu$ Scattering Physics Program

In red $\rightarrow$ currently studied $\Rightarrow$ Latin American Participation

- *Quasi-elastic
- *Resonance Production - 1pi
- Transition Region – n pi to DIS
- *Coherent Pion Production
- Strange & Charm Particle Production
- * $\sigma_T$ – Inclusive/DIS
  - High-x parton distribution functions
  - Structure Functions and PDFs
- *Nuclear Effects (He, C, H$_2$O, Fe, Pb)
- Generalized Parton Distributions
- *Test Beam Effort
MINERνA Expected Results

- $\sigma_{QE}$ and high $Q^2$ axial form factor of nucleon

Coherent cross-sections vs. energy
(An example simulated analysis using the NEUGEN event generator)
Neutrino Nuclear Effects – results depend on A
Nuclear Parton Distribution Functions - nPDF

Using charged lepton and Using neutrinos

 Already CTEQ/Grenoble/Karlsruhe analysis showing nuclear effects in $\nu - \text{Fe}$ (NuTeV data) quite different than those in $\mu/e - \text{Fe}$

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

<table>
<thead>
<tr>
<th>FAR DETECTOR – 5.4 kt</th>
<th>NEAR DETECTOR – 1 kt</th>
</tr>
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<tbody>
<tr>
<td><img src="image1.png" alt="FAR Detector Image" /></td>
<td><img src="image2.png" alt="NEAR Detector Image" /></td>
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</tbody>
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- Search for non-standard 3x3 mixing behavior
- $\theta_{23}$ and $\Delta m^2_{\text{atm}}$ (the new precision frontier)
- Search for Sterile Neutrinos
- Non-Standard Interactions & Extra Dimensions
- Atmospherics
NuMI Facility / MINOS Experiment at Fermilab

- Near Detector: 980 tons
- Far Detector: 5400 tons

**NuMI: Neutrinos at Main Injector**
- 120 GeV protons
- 1.9 second cycle time
- Single turn extraction (10μs)

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

**Direct measurement of ν vs ¯ν oscillation**
- Magnetized far detector: atm. ν’s.

Det. 1
The MINOS Far Detector

- 8m octagonal steel & scintillator tracking calorimeter
  - Sampling every 2.54 cm
  - 4 cm 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 m²
2-Flavor Oscillation - $\nu_\mu$ 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:

$$U = \begin{pmatrix} \cos \theta & e^{i \delta} \sin \theta \\ -e^{-i \delta} \sin \theta & \cos \theta \end{pmatrix} \quad \text{and} \quad P(\nu_1 \rightarrow \nu_1') = \sin^2 2\theta \sin^2 \left[ 1.27 \Delta m^2 (eV^2) \frac{L(km)}{E(GeV)} \right]$$

with $\Delta m^2 \equiv M_2^2 - M_1^2$

- 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 $P(\nu_\mu \rightarrow \nu_e) \neq \overline{P(\nu_\mu \rightarrow \nu_e)}$.

- The components of U now involve $\theta_{13}, \theta_{23}, \theta_{12}$ and $\delta$ and the probabilities involve $\Delta m_{13}, \Delta m_{23}$ and $\Delta m_{12}$. 

MINOS Best-Fit
7.2 x 10^{20} POT

- Observe 1986 $\nu_\mu$ events in FD expect 2451 with no oscillations

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

- Oscillated/unoscillated
- Controlled by $\sin^2 2\theta$
- Controlled by $\Delta m^2$
- Visible energy (GeV)
- Reconstructed neutrino energy (GeV)

- MINOS sensitivity, $1 \times 10^{30}$ p.o.t.
- Width determined by statistics, beam $\otimes$ detector energy resolution
- Width largely determined by statistics
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 NOvA
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 $L / E \approx 15000$ km/GeV, with a large but not maximal mixing angle, $\theta_{12}$.

- 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, $\theta_{23}$, consistent with being maximal.
Going into NOvA, what have we learned?

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

Fractional Flavor Content varying $\cos \delta$
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 - $\nu_e$ 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 $\nu_e$ charged-current detection

- Primary Physics Goals
  - Confirm $\theta_{13}$
  - Determine Mass Hierarchy
  - Initial look at 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 X₀ 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
NEXT STEP - Fermilab to DUSEL: LBNE Project
Would welcome Latin American Collaborators

1300 km
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 $\delta$ and
  - determining of the mass ordering (sign of $\Delta m_{32}^2$).
- Precision measurements of $\theta_{23}$ and $|\Delta m_{32}^2|$ in the $\nu_\mu$ disappearance channel.
- Search for proton decay, yielding a significant improvement in current limits on the partial lifetime of the proton ($\tau/BR$) in one or more important candidate decay modes, e.g. $p \rightarrow e^+\pi^0$ 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 $\pi^0$ 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

- H- Source
- 3 GeV, 1.0 mA CW Linac
- $\Delta$
- $>2\text{MW} @ 120\text{ GeV}$
- 3 MW @ 3 GeV
- 150 kW @ 8 GeV

Number of Protons

Time
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 \( \mu^- \) decays, look for \( \bar{\nu}_e \) oscillating to \( \bar{\nu}_\mu \) that, when interacting in your detector, yields a \( \mu^+ \) !!

- No need for a fancy electron sensitive detector. Magnetized iron detector will do

- Best configuration with large \( \theta_{13} \)
  - One 100 kt detector at 2000 km
  - \( E_\mu \) 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 MINER\(\nu\)A, MINOS+, NO\(\nu\)A, 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 MINER\(\nu\)A.

- 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.
48 kW

350 kW @ 120 GeV

MINOS at 735 km

MINERvA (Integrated program for Project X and ILC)

SeaQuest

MINOS

Testbeam

MiniBooNE

Intensity Frontier Accelerators (now)
NOvA 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 NOvA 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 NOvA cannot determine the mass ordering by itself. But it can be determined, in principle, by comparing NOvA and T2K.
  - If the neutrino oscillation probability is larger in NOvA 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 $t_0$

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

ICARUS 50L in WANF neutrino beam
Why Off-Axis?

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

$$E_{\nu} = 0.43 \gamma m_{\pi} \frac{1}{1 + \gamma^2 \theta^2}$$

![Graph showing $E_{\nu}$ vs $E_\pi$](image)

![Graph showing $\gamma_{CC events}$ vs $E_\nu$ and $E_\pi$](image)
Making an Antineutrino Beam

Neutrino mode
Horns focus $\pi^+, K^+$

$\nu_\mu$: 91.7%
$\bar{\nu}_\mu$: 7.0%
$\nu_e + \bar{\nu}_e$: 1.3%

Anti-neutrino mode
Horns focus $\pi^-, K^-$

$\bar{\nu}_\mu$: 39.9%
$\nu_\mu$: 58.1%
$\nu_e + \bar{\nu}_e$: 2.0%

Target

Focusing Horns

120 GeV
$p$'s from MI

2 m

15 m

30 m

675 m
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 MiniBooNE 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.
NOvA 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 $\nu$ vs $\bar{\nu}$
Would welcome Latin American Collaborators

- Regardless of interpretation, excess must be understood for $\nu_e$ appearance measurements
- If $\nu$ excess in oscillation region persists, study needed
- For example the T2K experiment - excess would be a background of $\approx 100$ events at $E > 100$ MeV!

- ENTER Liquid Argon TPC detectors for detailed study of neutrino interactions (and oscillations) – currently under construction
  - 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 $6 \times 10^{20}$ POT from on-axis Booster Neutrino Beam
- Collect $8 \times 10^{20}$ 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

R&D

Test stands

0.1 - 10 t

R&D

Physics

LArTPC in a neutrino beam (a la the 50 l in WANF)

0.5 t

ArgoNeuT

R&D

Physics

MicroBooNE

100 - 200 t

R&D

Physics

LAr5

Mass hierarchy, $q_{13}$

R&D

Physics

M x N = 100

DUSEL LAr CP-violation, proton decay

We need to optimize M & N against cost, schedule, and technical feasibility
Fermilab Neutrino Program:
Just Mention - Booster Neutrino Beam

- $4 \times 10^{12}$ 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.