Fermilab

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The Fermilab Neutrino Platform

Steve Brice

DOE Institutional Review of Fermilab

Thu 12 Feb 2015

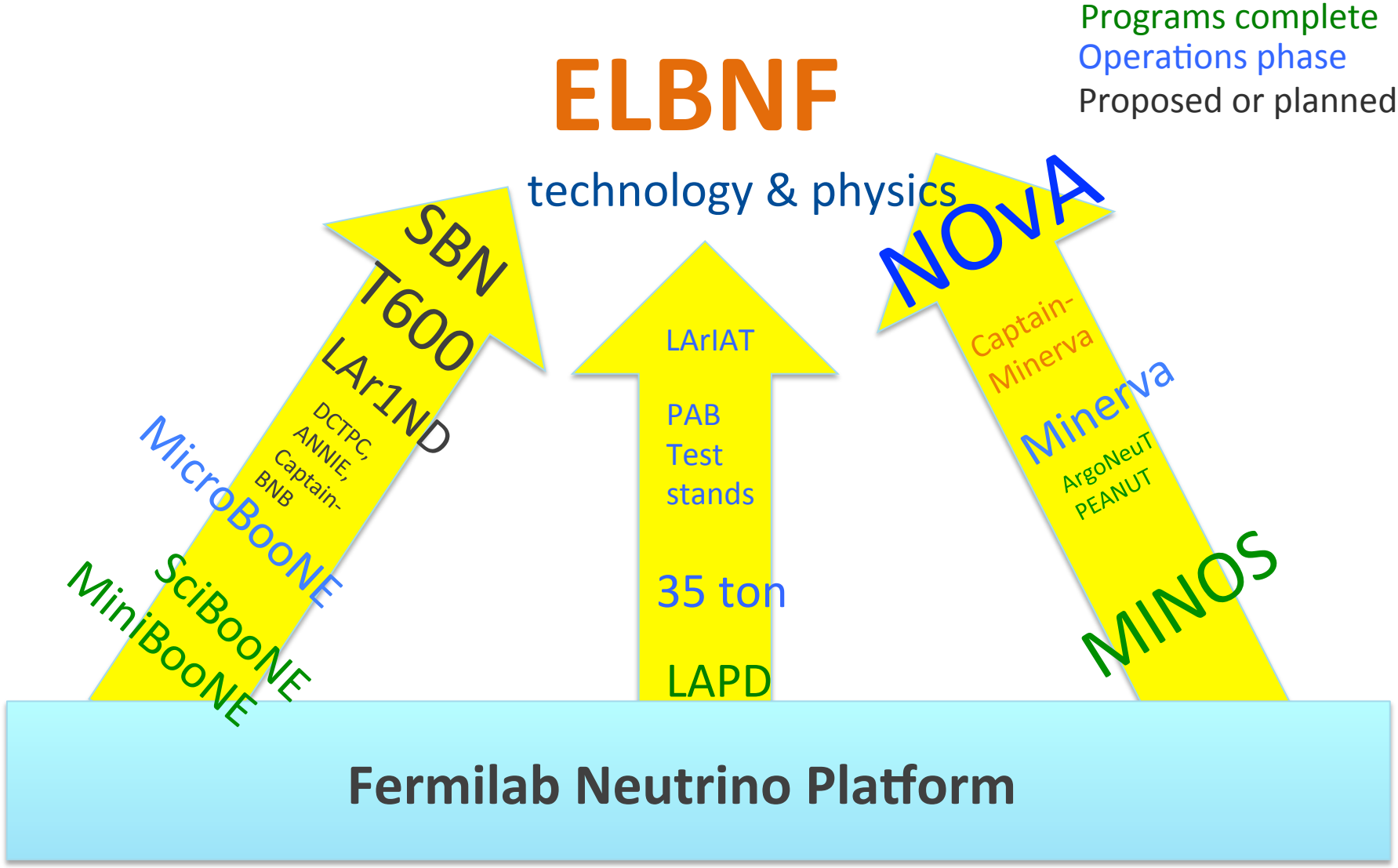
What is the Fermilab Neutrino Platform?

- The suite of Fermilab neutrino activities that are in support of it's experiments, but not experiment specific

- The Neutrino Platform activities …
  - serve the user community and are executed in partnership with it
  - work together coherently to support current and future experiments at all scales
  - span multiple divisions at the lab, but are coordinated by Neutrino Division

- Fermilab has been doing neutrino physics for a long time and the Neutrino Platform is built from that experience

The Fermilab Neutrino Platform



Fermilab Neutrino Platform

Accelerator Division

Neutrino Beams : NuMI, BNB

Charged Particle Test beams

High Power Targets and Horns

Neutrino Division

Detector R&D test stands

Detector Halls : NuMI, SciBooNE, LArTF

Neutrino Beam Group

ND Operations Support

ROC West

Collaboration with Neutrino Theory

Neutrino Physics Center

Scientific Computing Division

GENIE
Geant4

ART
ARTDAQ

LArSOFT

NuTools

Facility Engineering Support Services

Particle Physics Division

Core Computing Division

Technical Division

Fermilab

Outline

- Detector R&D Test Stands
- Detector Operations Group
- Neutrino Div Beam Group
- ROC-West
- Neutrino Theory
- Cross-Section Coordination (NuSTEC and FeNIX)
- Charged Particle Testbeams (LArIAT and MINERvA)
- High Power Target Design
- Computing for Neutrinos

Liquid Argon TPC R&D Facilities

- PAB has become the launch pad of Fermilab's efforts to enable the deployment of a multi-kiloton LArTPC
- Have intentionally established the infrastructure over the last decade to support variety of small scale tests
- Focus on technical topics not previously fully explored
- These smaller tests led to ArgoNeuT, LAPD, LBNE 35t, and MicroBooNE
- Key components include
  - An excellent staff of technicians to support experimenters
  - Dedicated liquid argon distribution system with purification from electronegative contaminants
  - Analyzers to monitor the level of contaminants
  - Condensers to maintain closed systems of liquid argon
  - Common safety system including ODH and ventilation
- Fermilab organizes and hosts workshops dedicated to R&D efforts (LArTPC R&D 2013, 2014; HVNL 2013)

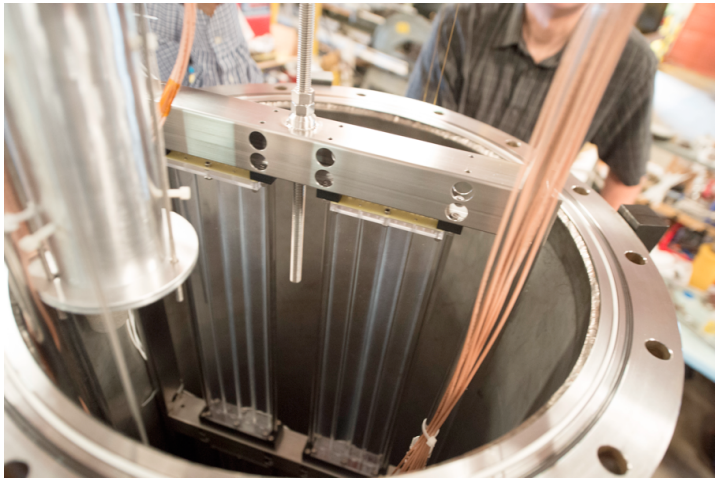
Technicians supporting R&D at PAB

Liquid Argon Purity Demonstrator and LongBo

- LAPD showed that one can achieve several ms long electron drift lifetimes without first evacuating the cryostat
- First use of filters that could be regenerated in situ - now common to all Fermilab LArTPCs
- Achieved > 6 ms lifetime, LBNE requirement is 1.4 ms
- LongBo is first US LArTPC with long (2 m) drift distance
- Installed in LAPD - also tested purification with an actual LArTPC in the volume (> 6 ms achieved)
- LongBo tested cold electronics and high voltage distribution as well, provided timely input for MicroBooNE

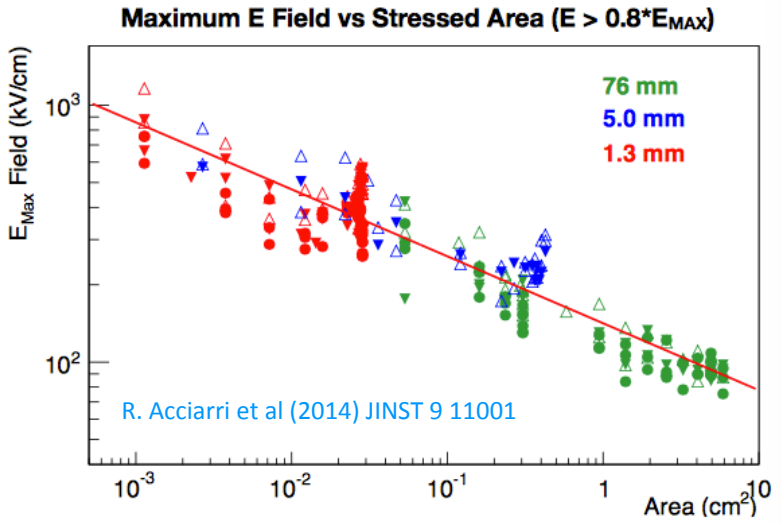
TallBo Facility for Scintillation Light Collection Studies

- TallBo is a 56 cm diameter, 156 cm high cylindrical cryostat
- Dedicated to studying light collection techniques
- Capability to inject contaminants/ dopants into the argon
- Extensively used by Conrad MIT group (MicroBooNE and general R&D) and Mufson Indiana University group (LBNE)
- Other users from LBNE planning studies for 2015 as well



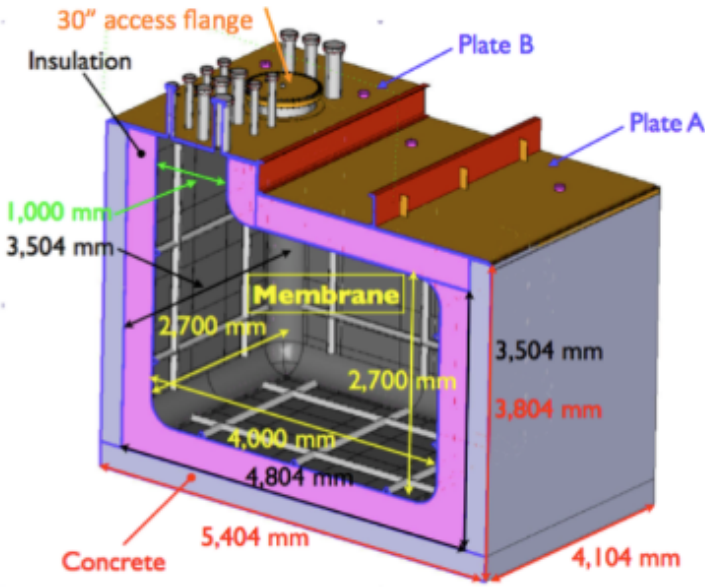
BLANCHE Facility for High Voltage Breakdown Studies

- Funded by LDRD awarded in 2014 to S. Lockwitz
- Goal is to establish guidelines for optimizing high voltage system design for LArTPCs as many experiments are having difficulty achieving stable HV JINST 9 (2014) T08004
- Study dielectric strength of argon as a function of argon purity, stressed area (volume), and light production
- Also testing insulator materials to establish best ones to use for feedthroughs
- After LDRD program is complete, will open facility to other users

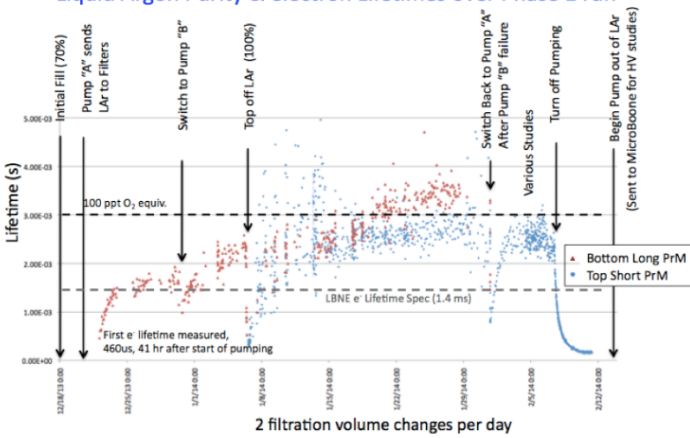


LBNE 35t Prototype Detector

- First test of membrane style cryostat for LArTPCs
- Initial run doubled (3 ms) the minimum electron lifetimes (1.4 ms) needed for LBNE
- Next step is to place mini-APA style TPCs into the cryostat and do a vertical slice test of the detector
- APAs are at Fermilab and are being tested through February 15
- Installation into cryostat planned for March 1, 2015
- Liquid argon filling expected at the end of April



Liquid Argon Purity & electron Lifetimes over Phase 1 run



Next Steps

- Building on the successes of the current program we can meet the needs of the future ELBNF
  - Test enhanced purification with new filter media, necessary for dual phase LArTPCs with 16 m drifts
  - Using dopants, e.g. xenon, has potential to improve scintillation light signal by producing light in range more readily observed by photodetectors
  - SiPMs may be a cost effective photodetector for LArTPCs when coupled to light guides, would like to explore improving readout electronics for them
- When dreaming big, we look to magnetizing LArTPCs
  - Fermilab has the experience with superconducting magnets
  - We have the test beams to study the charge selection and energy reconstruction performance

Neutrino Division Technical Support Department

- Operations and technical support for running experiments and new projects
  - Direct support and coordinate liaison with other lab resources
- Operations group (7 staff)
  - Experienced operations and DAQ staff (earlier collider experience)
  - Current activities: MINOS+, MINERvA, NOvA, MicroBooNE
    - Direct operations support (Experimental Liaison Officers, ROC west)
    - DAQ and electrical infrastructure and software support
  - Future activities – SBN, ELBNF. Already beginning.
- Liquid Argon Engineering group (8 staff)
  - Expertise drawn from across lab
  - Currently supporting next-generation cryostat and cryosystems engineering and drafting at FNAL and liaison with CERN.
  - Expect to expand support as new projects require.

Neutrino Division Beam Group

- **Neutrino Division recently created a Beam Group**
  - A. Marchionni, Ldr.
  - C. James
  - P. Lebrun
  - B. Lundberg
  - Z. Pavlovic
  - D. Jensen, GSR

- The group has a wide range of competencies, from experience in the design, construction and operation of neutrino beamlines, expertise in hadroproduction measurements and neutrino flux predictions, to specific skills in computing and simulation software

- The group will provide support for the experimenters who want to get involved in beam activities, and interface with the AD Targetry Department

Design of new neutrino beamlines and upgrades of existing ones

- **Investigate possible upgrades of the BNB beamline**
- At this time we have a pre-conceptual design for an upgrade to the BNB which involves the addition of a second focusing horn. A team consisting of members of the ND Beam Group and the AD External Beams Group is in place to advance this work to the level of a Conceptual Design, including cost and schedule, by the time of the summer PAC meeting.

- **Participate in the conceptual design and optimization of the LBNF neutrino beamline**
- Working with the ELBNF Collaboration/LBNF project, perform an optimization of the target and horn focusing system to increase the physics reach, and interface with AD Targetry Department to evaluate feasibility and cost of the proposed solutions

Monitoring of the performance of neutrino beamlines

- **Two running beamlines: NuMI and BNB**
- Keep track of running conditions and alignment measurements of beamline components
- Maintain tools to monitor primary proton integrated intensity, targeting precision and stability of running conditions (horn currents, temperatures,…)
- Provide support for neutrino beamline instrumentation (hadron monitor, muon monitors,…) and develop analysis tools

Simulation of neutrino beamlines and prediction of the neutrino fluxes

- **Maintain simulation tools for neutrino beamlines**

- **Precise prediction of neutrino fluxes (BNB, NuMI, LBNF)**
  - Prediction of NuMI fluxes at large off-axis angles (MicroBooNE, SBN)
  - Participation in NuMI-X
  - Make use of existing hadroproduction data
  - Possible participation in future hadroproduction experiment (NA61?)

ROC-West

- The Remote Operations Center (West) is a new control room facility available to any Fermilab experiment.

Neutrino theory

- Fermilab neutrino theory research efforts in Theoretical Physics & Astrophysics Departments cover wide range of topics
  - Two full-time neutrino phenomenologists (Parke + RA Coloma), one active emeritus scientist (Kayser) + several others involved part-time in study of connections between neutrinos and dark matter, cosmology, etc...baseline oscillation experiments

strategies for studying standard ν paradigm

sensitivities of current, proposed experiments

impact of light sterile ν's and non-SM interactions

proposals for future experiments

improved determination of nuclear effects

cosmic neutrinos

Theory visitors

- Andre de Gouvea (Northwestern) spends about one day a week at Fermilab
- Collaborators spend many person-weeks a year here, in particular:
  - Hisakazu Minakata (Sao Paulo)
  - Others include Hiroshi Nunokawa, Renata Zukanovich Funchal, ...
- Invisibles Network (Europe): Silvia Pascoli (Durham) spends between one and two months at the Lab and frequently brings students and RAs. Also member of Fermilab PAC.
- Providing partial support to nuclear theorists
  - Luis Alvarez-Ruso (Valcenia) to interface between nuclear theory and Monte Carlos used in neutrino experiments
  - Joe Carlson (LANL) in Fall (will bring two RAs)
- Neutrino visitors complement expertise of group members.

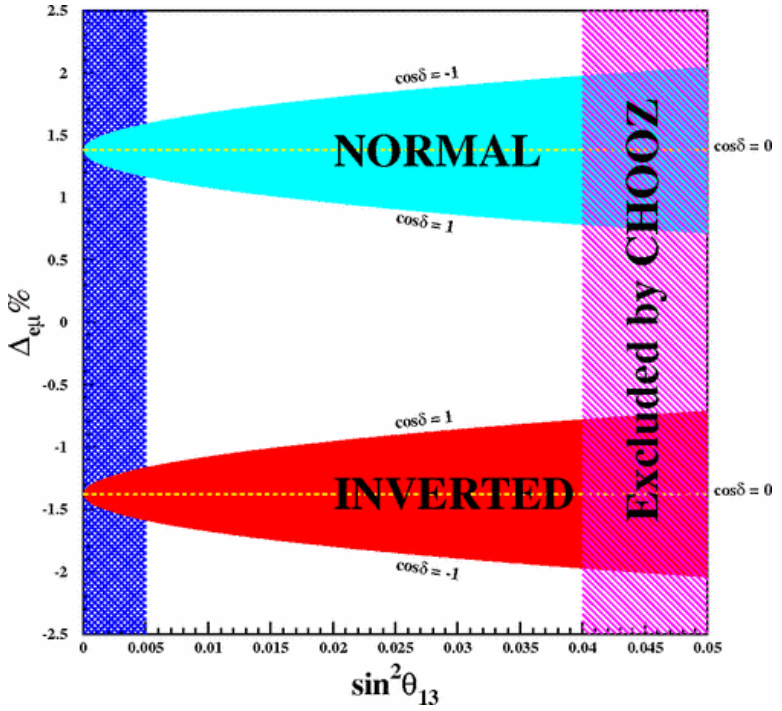
Neutrino phenomenology

- In neutrino disappearance experiments, the effective δm^2 measured at the first oscillation minimum is the flavor average of δm^2_{32} and δm^2_{31} :

MINOS (ν_μ): $\delta m^2_{\mu\mu} = \cos^2\theta_{12}\,\delta m^2_{32} + \sin^2\theta_{12}\,\delta m^2_{31}$

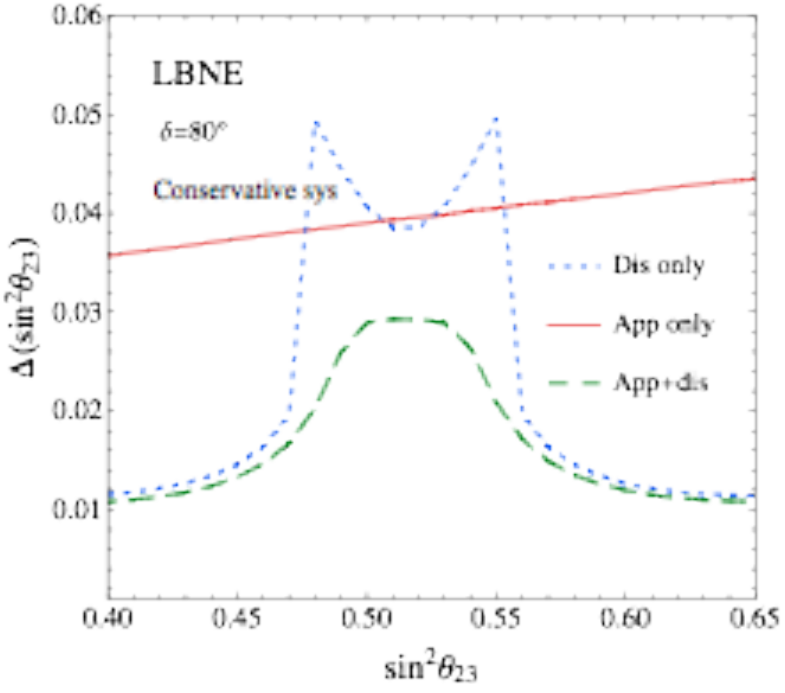
Daya Bay (ν_e): $\delta m^2_{ee} = \sin^2\theta_{12}\,\delta m^2_{32} + \cos^2\theta_{12}\,\delta m^2_{31}$

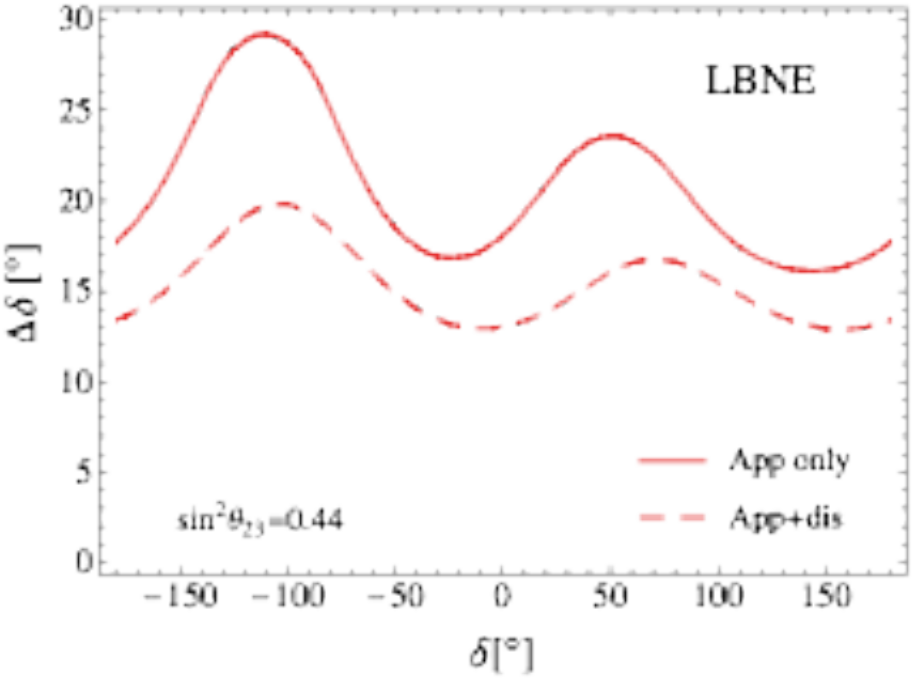
- In principle could be used to determine mass hierarchy with precision measurements of both [Nunokawa, Parke, Zukanovich Funchal, PRD72 (2005) 013009].



Neutrino phenomenology

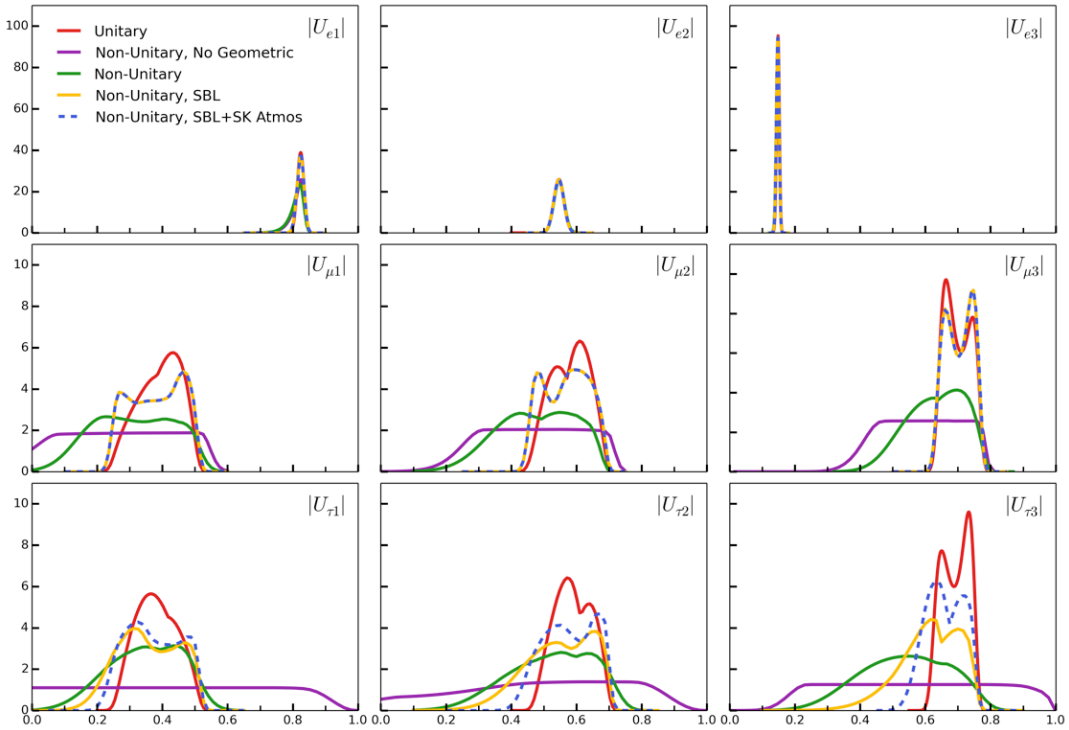
- Interplay between appearance and disappearance channels for precision measurements of θ_{23} and CP-violating parameter δ of long baseline experiments NOvA, ELBNF, HyperK,... [Coloma, Minakata, Parke, arXiv: 1303.6178, 1406.2551]





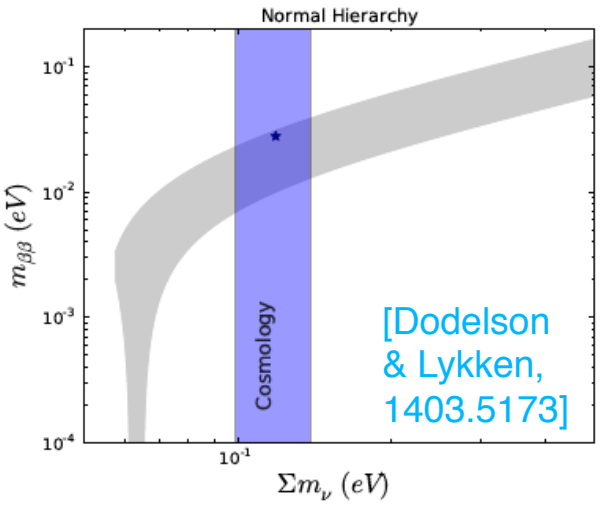
Neutrino phenomenology

- What do we really know about the PMNS matrix, not assuming unitarity?
  - As you relax this assumption the ν_e row doesn't change much, the ν_μ row degrades somewhat and the ν_τ row degrades significantly. [Parke and Ross-Lonergan (Durham, Invisibles Network), in preparation]



(Select) other Fermilab neutrino efforts

- Cosmic constraints on neutrinos
  - Dodelson & Lykken showed that cosmological constraints could provide lower limit on rate for neutrinoless ββ decay and constrain Majorana phase.



- Lattice QCD for neutrino cross sections
  - Kronfeld co-supervising U. Chicago student Aaron Meyer on first-principles calculation of $F_A(q^2)$ merging analyticity constraints with lattice QCD
  - Important input into determination of CCQE X-section
  - Engagement and interest from MINERvA, MicroBooNE, and other experiments
- New-physics searches with neutrinos
  - Fox & Harnik (with Batell) hosted workshop "New approaches in the Search for Dark Matter." Searches for light DM and light mediators with neutrino beams.
  - Dobrescu & Frugiuele showed that NOvA can search for GeV DM [1410.1566].

INT Workshop

- workshop on neutrino-nucleus scattering held at the INT in Seattle Dec 3-13, 2013
  - *>60 theorists and experimentalists, experts in ν and e^- nucleus scattering locked in one room for 2 weeks to hash out this physics*
  - *54 talks, *large blocks of time for discussion*
- pivotal consensus-building workshop
- set a clear direction for future theoretical work and experimental measurements
- follow-up workshop being planned for 2016 (F. Sanchez, Valencia)

arXiv:1412.4294v1 [hep-ex] 13 Dec 2014

Recent advances and open questions in neutrino-induced quasi-elastic scattering and single photon production

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Abstract

The study of neutrino-nucleus interactions has recently seen rapid development with a new generation of accelerator-based neutrino experiments employing medium and heavy nuclear targets for the study of neutrino oscillations. A few unexpected results in the study of quasi-elastic scattering and single photon production have spurred a revisiting of the underlying nuclear physics and connections to electron-nucleus scattering. A thorough understanding and resolution of these issues is essential for future progress in the study of neutrino oscillations.
A recent workshop hosted by the Institute of Nuclear Theory at the University of Washington (INT-13-54W) examined experimental and theoretical developments in neutrino-nucleus interactions and related measurements from electron and pion scattering. We summarize the discussions at the workshop pertaining to the aforementioned issues in quasi-elastic scattering and single photon production, particularly where there was consensus on the highest priority issues to be resolved and the path towards resolving them.

1. Introduction

In this report, we focus on two aspects of neutrino-nucleus scattering that have seen significant developments and were discussed at the "Neutrino-Nucleus Interactions for Current and Next Generation Neutrino Oscillation Experiments" workshop hosted by the Institute for Nuclear Theory in December 3-13, 2013[1].

Email addresses: garvey@lanl.gov (G. T. Garvey), dharris@fnal.gov (D. A. Harris), tanaka@phas.ubc.ca (H. A. Tanaka), rtayloe@indiana.edu (R. Tayloe), gzeller@fnal.gov (G. P. Zeller)

[1]The workshop website with slides presented at the meeting can be found at http://www.int.washington.edu/talks/WorkShops/int_13_54W/

Preprint submitted to Elsevier *December 16, 2014*

workshop summary: G. Garvey (LANL), D. Harris (FNAL), H. Tanaka (TRIUMF), R. Tayloe (Indiana), G. Zeller (FNAL), ***arXiv:1412.4294****, submitted to Phys Reports*

Fermilab

Collaboration with Nuclear Theorists

- Fermilab scientists are actively engaged with nuclear theorists to develop a multi-year program of ab-initio neutrino-nucleus interaction calculations

White paper – Neutrino-Nucleus Interactions Collaboration

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(Dated: October 17, 2014)

This white paper highlights the need for a program of research improving the modeling of neutrino-nucleus scattering for neutrino oscillation experiments and proposes a Neutrino-Nucleus Interactions Collaboration (NNIC) to carry out this work using quantum Monte Carlo (QMC) techniques. The proposed research activity will also

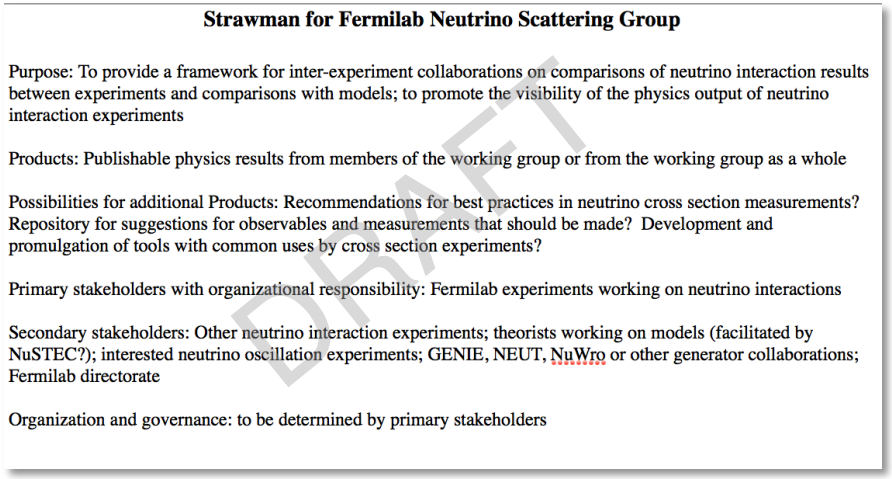
NuSTEC (Neutrino Scattering Theory Experiment Collaboration)

Emphasis on Collaboration between NP Theorists, Event Generator Collaborators and Neutrino Experimentalists

- **Generators**: Coordinate theorist-experimentalist collaborative efforts to improve generator(s).
  - GFMC collaboration: 6 NP Theorists with 4 HEP Neutrino Experimentalists
- **Global Fits**: Combine results from multiple experiments – not only neutrino - to compare with and adjust a theory/model framework.
- **Training**: Organize/Run a a generator and neutrino-nucleus scattering physics theory Training Program
  - Generator School: May 2014 at Liverpool – 25 participants
  - Nuclear Physics Theory Training: Fermilab October 2014 – **85 participants**
  - **Planning for 2015 NuSTEC School underway- Okayama, Nov. 2015**
- **Workshops**: Organize Community-wide Workshops when needed.
  - MEC in Exclusive States – Europe, 2015

FENIX

- **FE**rmilab **N**eutrino **I**nteractions and **XS**s group
- being kick-started by University & Fermilab personnel on MINERvA, MiniBooNE, MicroBooNE, NOvA
- model is LEPWWG
- goal is to combine data sets and provide comparisons of neutrino scattering data coming out of Fermilab (and other) neutrino experiments



Strawman for Fermilab Neutrino Scattering Group

Purpose: To provide a framework for inter-experiment collaborations on comparisons of neutrino interaction results between experiments and comparisons with models; to promote the visibility of the physics output of neutrino interaction experiments

Products: Publishable physics results from members of the working group or from the working group as a whole

Possibilities for additional Products: Recommendations for best practices in neutrino cross section measurements? Repository for suggestions for observables and measurements that should be made? Development and promulgation of tools with common uses by cross section experiments?

Primary stakeholders with organizational responsibility: Fermilab experiments working on neutrino interactions

Secondary stakeholders: Other neutrino interaction experiments; theorists working on models (facilitated by NuSTEC?); interested neutrino oscillation experiments; GENIE, NEUT, NuWro or other generator collaborations; Fermilab directorate

Organization and governance: to be determined by primary stakeholders

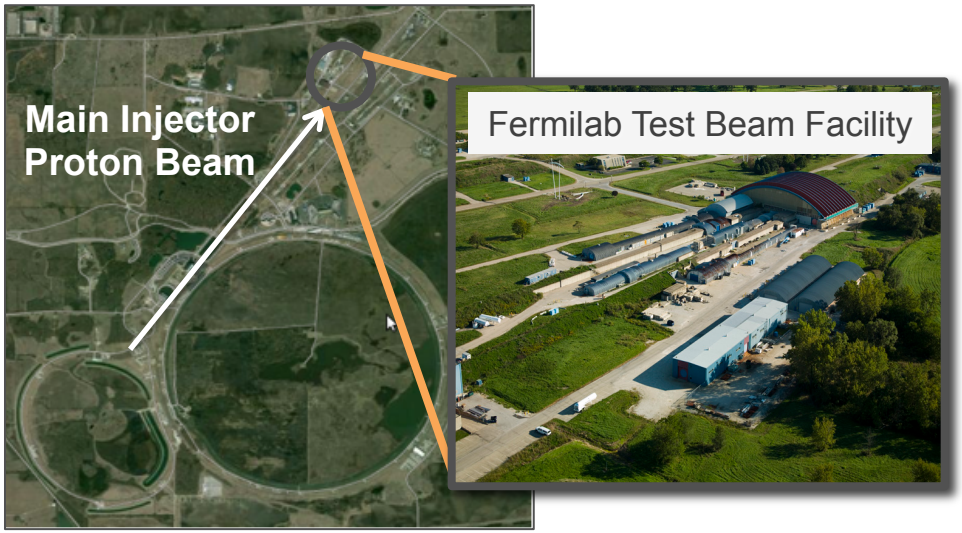
DRAFT

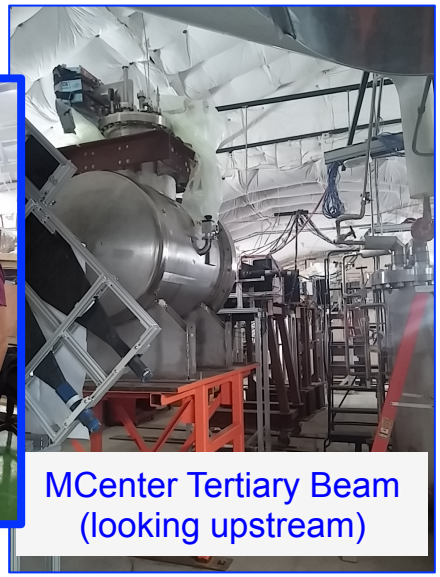
(K. McFarland)

- opportunity to supply input to the PDG and, in general, elevate the s_n measurements coming out of this program

LArIAT (Liquid Argon In A Testbeam)

Repurposed 550-ℓ ArgoNeuT LArTPC detector with modifications for operation in Fermilab Test Beam Facility charged particle tertiary beam (~200 MeV – 2 GeV).





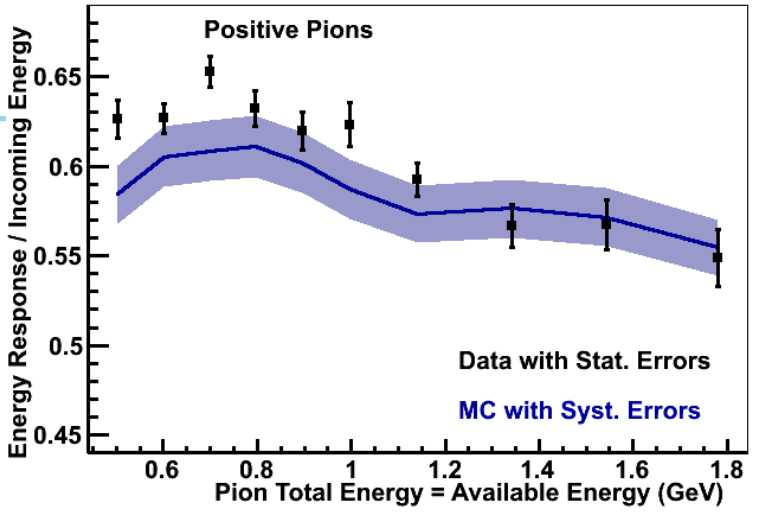
Goals Characterize LArTPC performance in the range of energies relevant to upcoming SBN and LBN experiments for neutrino physics and for proton decay searches.

- Study energy resolution improvement by combining information from scintillation light and ionization charge signals
- Experimentally measure e-γ separation
- Develop criteria for charge sign determination
- Optimize pion and kaon ID capabilities

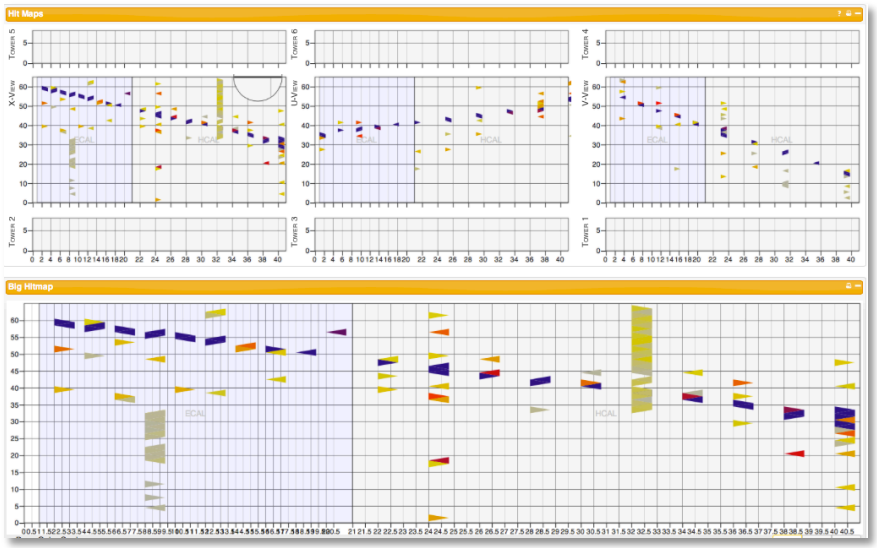
arXiv:1406.5560 [physics.ins-det]

MINERvA ME Testbeam

- what: wire chambers, TOF, veto system and 42 1.2m^2 MINERvA planes readout by 42 multi-anode PMTs
- why: to calibrate the hadronic EM energy scale from 2-6 GeV
- when: commissioning in FTBF now



(example from LE testbeam run)



High Power Targetry at Fermilab

- Located in Accelerator Division
- Central to current/future neutrino programs
- Expertise developed at the lab:
  - NuMI 400kW
  - NuMI / NOvA being upgraded to 700 kW (PIP II)
  - Planning for LBNF includes 1.2MW proton beam
  - …not likely to stop there
- 2014 P5 report:
  - “High power targets… will address *critical* needs…”

Fermilab R & D Program

- Mega-watt class facilities present technical challenges :
  - Radiation damage, heat removal, shock response, radiation protection and remote handling
- Ten-year R&D program addresses these issues :
  - Fermilab hosting fruitful RaDIATE collab.
  - Cooperation with CERN (e.g. HiRadMat)
  - Engineering/Mat. Science with BNL, ORNL etc.
- Fermilab will continue to coordinate activities to enhance and leverage complimentary capabilities

GENIE

- GENIE (Generates Events for Neutrino Interaction Experiments) is an Object-Oriented Neutrino MC Generator supported and developed by an international collaboration of neutrino interaction experts. GENIE is currently used by T2K, MINOS, NOvA, MINERvA, ArgoNeut, MicroBooNE, ELBNF, INO, LAr1-ND and others.
  - Every running and planned neutrino experiment at the lab!
- Fermilab has joined the Executive Board and is driving more thorough physics validation and a more aggressive release schedule.
- We are creating a “developer’s hub” and recently created a user group (along with the Geant4 group) for more active engagement with neutrino experiments at the lab.

Geant4

- Geant4 is a toolkit for the modeling of the passage of particles through matter with applications in HEP as well as nuclear, medical, accelerator, and space physics.
- Fermilab participates in the Geant4 Collaboration in the areas of hadronic physics, CPU performance monitoring and improvement, and maintains a validation database.
- Partnerships with the neutrino community at Fermilab has lead to new efforts within Geant4 (e.g., special programs to study systematic uncertainties of the simulations).
- Neutrino experiments use new Fermilab software tools and infrastructure such as new quick-start toolkits and the above-mentioned validation database, and benefit from the new development efforts such as new physics lists.

art

- Event-processing framework for particle physics experiments, processing data in a variety of contexts, including high-level software filters, online data monitoring, calibration, reconstruction, simulation, and analysis.
- Designed to be used across many experiments.
- Developed and maintained by software engineers who are specialists in the field of particle physics infrastructure software.
- Perhaps the larges user base is within the Intensity Frontier at this time; used by experiments at and outside of Fermilab.
- Significant interaction between users and developers informing framework design.

Artdaq

- Artdaq is a data acquisition toolkit for HEP experiments. It provides core DAQ functionality, and provides a framework for experimenters to build the custom software components that are unique to their experiment. It uses of the art event processing framework for filtering events in software.
- Fermilab is collaborating with experimenters from LArIAT and LBNE 35-ton to develop their DAQ systems using artdaq. Others using artdaq include DarkSide and Mu2e.
- We are adding functionality to the toolkit based on experiment needs, and we are investigating providing a menu of recommended commercial hardware modules for back-end data readout. The goal is to provide off-the-shelf DAQ hardware, firmware, and software to enable experiments to develop their DAQ systems quickly.

LArSoft

- The Liquid Argon Software (LArSoft) project manages simulation and reconstruction algorithms for LAr TPC detectors built on art and ROOT.
- Experiment-specific code for LAr1-ND, MicroBooNE, ELBNF, etc., but also many common core libraries for analysis, reconstruction, event display, event modeling, TPC-specific simulation codes, etc.
- Developed using continuous integration on the Fermilab Central Build Service.
- Some basic stats…
  - 43 releases since January 2014
  - 1200 files, 130k lines of code
  - 50 active contributors, 1800 commit

FIFE

- FabrIc for Frontier Experiments (FIFE) provides collaborative scientific data processing solutions.
- FIFE covers the full range of data processing and storage needs including grid computing on FermiGrid, onboarding users onto the Open Science Grid (OSG), specialized batch submission tools (jobsub), authentication, software delivery to remote worker machines (OASIS/CVMFS), data transfer and delivery (IF Data Handling Client tools, ifdhc, and a File Transfer Service, FTS), file cataloging (Sequential Access via Metadata, SAM), large-scale volatile and long-term storage (dCache), on-demand cloud computing (FermiCloud), Conditions Databases, and Electronic Logbooks.

Summary

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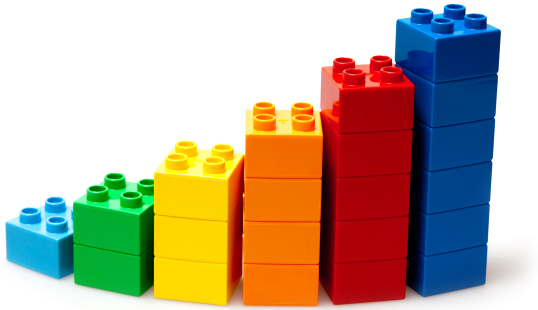
  - serve the user community and are executed in partnership with it
  - work together coherently to support current and future experiments at all scales
  - span multiple divisions at the lab, but are coordinated by Neutrino Division

Backups

The "Platform" is composed of the building blocks upon which we build an experimental program



Small Tests

Small Experiments

Medium Experiments

Large Experiments

Mega (?) Experiments

Fermilab Neutrino Platform

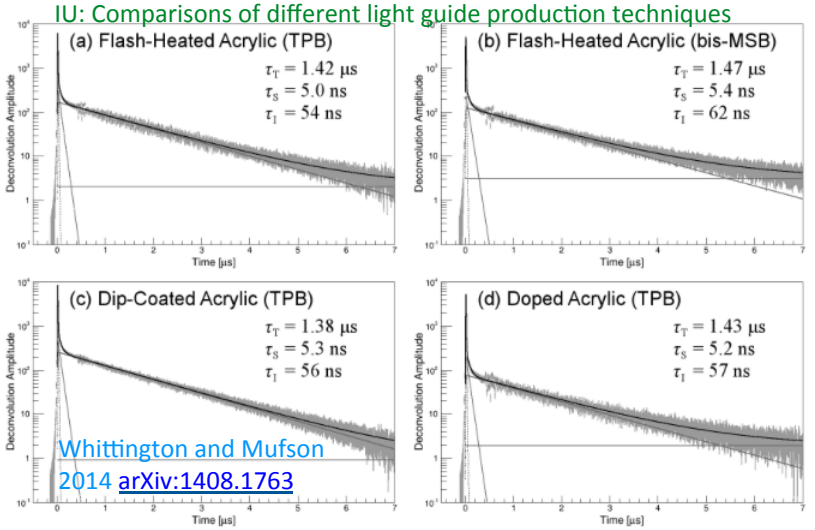
Recent Recommendations and Reviews

- The P5 report's recommendations on detector R&D:
  - **Recommendation 27**: **Focus resources toward directed instrumentation R&D in the near-term for high-priority projects**. As the technical challenges of current high-priority projects are met, restore to the extent possible a balanced mix of short-term and long-term R&D.
  - **Recommendation 28: Strengthen university-national laboratory partnerships in instrumentation R&D through investment in instrumentation at universities.** Encourage graduate programs with a **focus on instrumentation education** at HEP supported universities and laboratories, and fully exploit the unique capabilities and facilities offered at each.

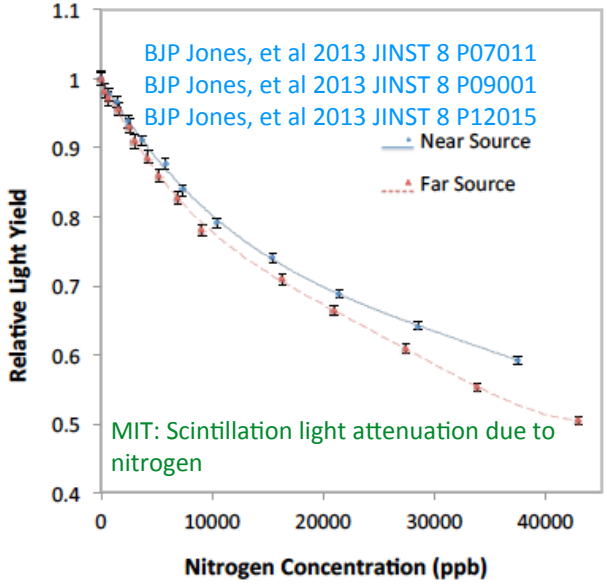
TallBo Facility for Scintillation Light Collection Studies

- TallBo is a 56 cm diameter, 156 cm high cylindrical cryostat
- Dedicated to studying light collection techniques
- Capability to inject contaminants/ dopants into the argon
- Extensively used by Conrad MIT group (MicroBooNE and general R&D) and Mufson Indiana University group (LBNE)
- Other users from LBNE planning studies for 2015 as well

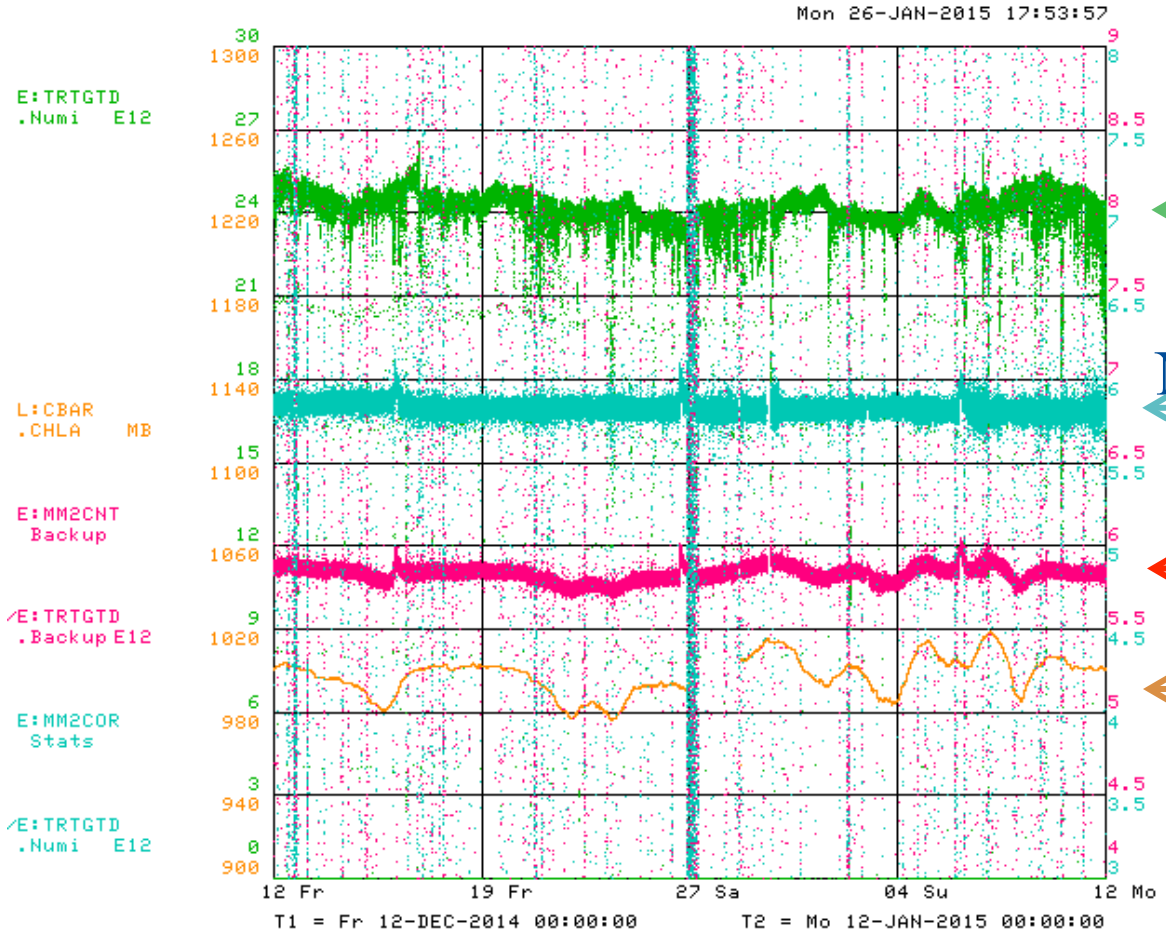
IU: Comparisons of different light guide production techniques



Whittington and Mufson 2014 arXiv:1408.1763



Example: NuMI Muon Monitor #2



Proton intensity

Normalized and corrected Muon Mon. #2 signal

Normalized Muon Mon. #2 signal

Atmospheric pressure

1 month period

ACNET "online" plot. The analysis needs to be extended over many months

LArIAT Collaboration

July 2014 Collaboration Meeting

~70 people from 20 institutions (US, UK, Italy, Japan)

A few of the many contributions:

- Cold electronics (MSU, Boston U, FNAL FWP)
- FPGA-based trigger (W&M)
- TPC refurbishment (Syracuse, Boston U)
- Light collection system (U. Chicago, L'Aquila U, Yale)
- Cherenkov counters (UT Austin, Cincinnati, KEK)
- Online monitoring & controls (LSU)
- DAQ (FNAL)

LArIAT Status

Detector refurbishment complete

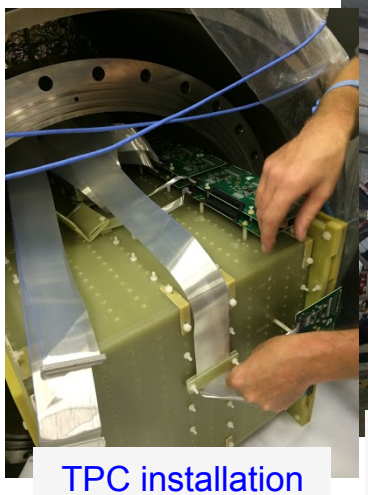
- New TPC wire planes
- New cold electronics readout
- New light collection system

Installed in MCenter

- Tertiary beam components
  target, collimators, magnets
- Beamline detectors
  wire chambers, time-of-flight system
- Auxiliary detectors
  beam halo veto, punch-through veto
- Cryostat with installed TPC
- Simplified cryogenic infrastructure

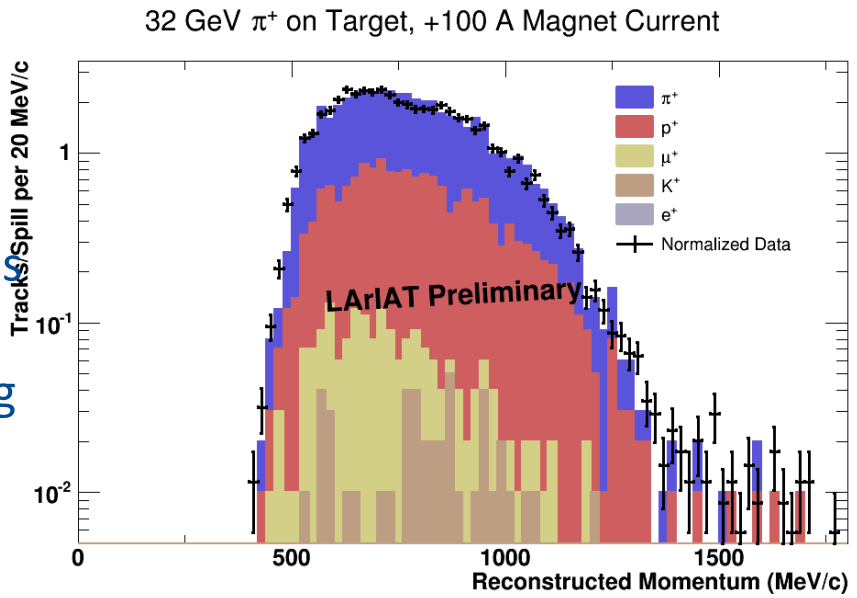
First commissioning steps

- MCenter secondary and tertiary beams commissioned/tuned, Summer 2014
- New LArIAT DAQ commissioned during short engineering run (Sept. 2014)
- Good data/MC agreement!



TPC installation

Tertiary beamline instrumented with wire chambers and TOF



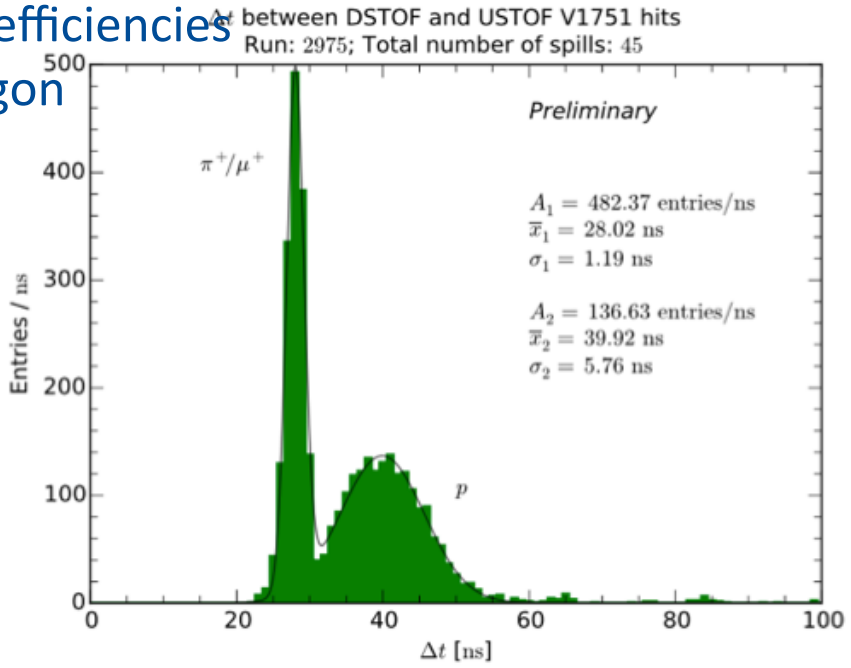
LArIAT Plans

Run 1: Spring 2015

(~3 mos. beam data w/simplified cryogenic system)

Data will be collected for a range of secondary beam energies and tertiary magnet currents (to enhance event rates and tune momentum ranges for particles of interest)

- Use these data to develop improved PID methods using both charge and light collected in the detector
- Study charged particle reconstruction efficiencies
- Investigate hadronic interactions in argon



Shutdown

Install full cryogenic system

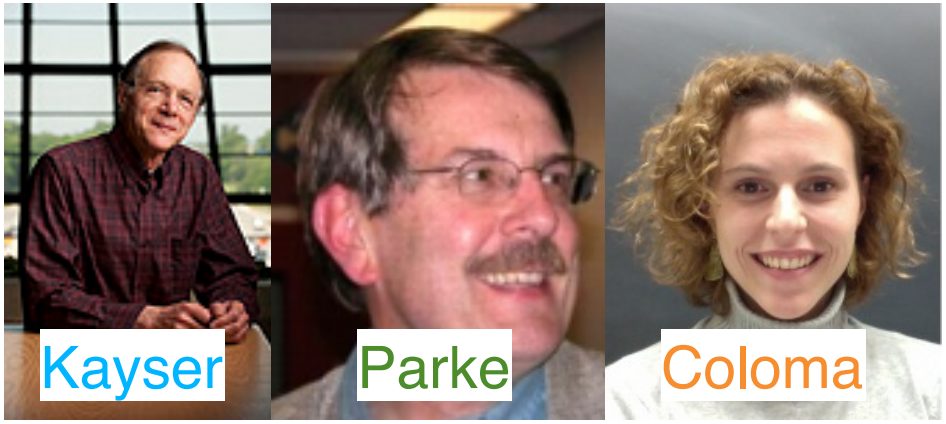
Install Cherenkov counters to tag π vs. μ

Data from engineering run show good separation of protons from π/μ using time-of-flight system, but can't distinguish between π and μ themselves.

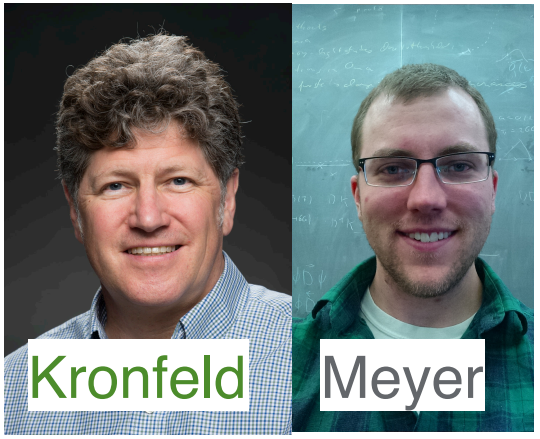
Run 2: ~Fall 2015

Neutrino theory effort (Emeritus, Scientists, RAs, Student)

Phenomenology

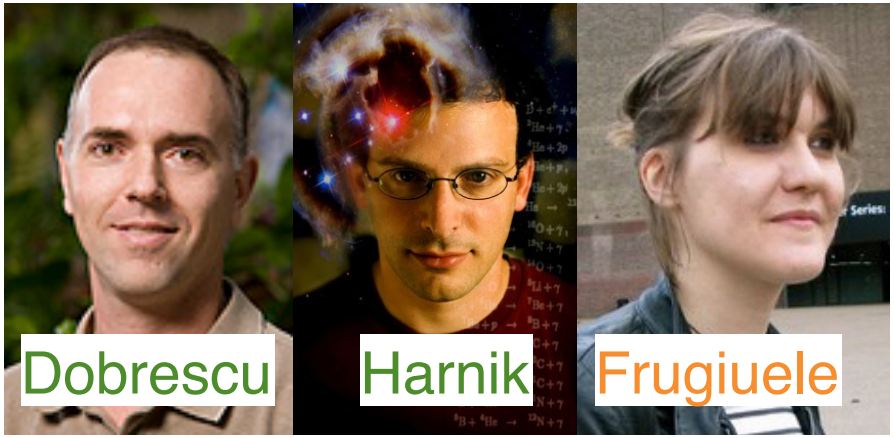


Lattice QCD



Cosmic constraints

DM searches



Intensity Frontier Fellowships

- Build an intellectual hub at Fermilab for IF physics, experimental and theoretical.

- Financial support for 50% time commitment at Fermilab. Terms 6 months to 1 year.

- Strong peer-review by 7 member, majority non-FNAL committee.
  - Committee includes theoretical, non-US, and LHC members.

- Statistics:
  - 24 awards in 4 rounds since 2013
  - 70% neutrino physics
  - 4 IF theorists