Overview of (a subset) neutrino experiments: Nu experiments and a new landscape

Bonnie Fleming
Yale University

First results and future prospects with high precision, large LArTPC detectors
From European Strategy Workshop: Big questions

What is the origin of the neutrino masses?

What is the optimal strategy towards a complete set of measurements of neutrino oscillation parameters and towards a precision global fit of the PMNS matrix?

Is the existing experimental program (reactor, SBL) sufficient to confirm or exclude the existence of sterile neutrino states with masses in the eV/c² range?

How to search for heavy neutral leptons with present and future facilities?

Is gravity described by the Einstein theory of general relativity?

How do gravitational waves help to understand Dark Sector of the universe?

What is the proton-proton cross section at ultra-high energies?

How can cosmic neutrino’s help to pin-down their properties oscillations and mass hierarchy?
From European Strategy Workshop: Big questions

What is the origin of the neutrino masses?

What is the optimal strategy towards a complete set of measurements of neutrino oscillation parameters and towards a precision global fit of the PMNS matrix?

Is the existing experimental program (reactor, SBL) sufficient to confirm or exclude the existence of sterile neutrino states with masses in the eV/c² range?

How to search for heavy neutral leptons with present and future facilities?

Is gravity described by the Einstein theory of general relativity?

How do gravitational waves help to understand the Dark Sector of the universe?

What is the proton-proton cross section at ultra-high energies?

How can cosmic neutrino’s help to pin-down their properties oscillations and mass hierarchy?

For both of these, understanding neutrino interactions and measuring cross sections in particular in the 0.5-2 GeV energy range is critical...
Answered one question (neutrino mass) 

→ Created many more….

Now know all the mass differences and mixing angles (their flavor content)  
For the weakly interacting neutrinos
- is CP violated in the neutrino sector?

(do neutrinos oscillate at the same rate as anti-neutrinos?)

- to what extent does the 3ν paradigm describe nature?
Deep Underground Neutrino Experiment (DUNE)

- Look for electron neutrino (anti-neutrino) appearance and muon neutrino disappearance
- Wide band beam – 0.5-10 GeV new neutrino beam at Fermilab
- Baseline of 1300km from Fermilab to Homestake – lots of matter to observe mass hierarchy effects
- Measure CP Violation
From European Strategy Workshop: Big questions

What is the origin of the neutrino masses?

What is the optimal strategy towards a complete set of measurements of neutrino oscillation parameters and towards a precision global fit of the PMNS matrix?

Is the existing experimental program (reactor, SBL) sufficient to confirm or exclude the existence of sterile neutrino states with masses in the eV/c^2 range?

How to search for heavy neutral leptons with present and future facilities?

Is gravity described by the Einstein theory of general relativity?

How do gravitational waves help to understand Dark Sector of the universe?

What is the proton-proton cross section at ultra-high energies?

How can cosmic neutrino’s help to pin-down their properties oscillations and mass hierarchy?
The Reactor Anomaly
At short baselines experiments see fewer neutrinos than expected (red line)

- ???
- Atm. oscillation
- Solar oscillation

Source measurements ...
Electron neutrinos disappearing


The Gallium Anomaly

Accelerator Anomaly

LSND

MiniBooNE

Experiment ran in the 1990s at Los Alamos National Lab

New results at 4.5σ
Signals at SBL are at the 2-4\(\sigma\) level. All pointing in the same direction.

Taken individually, each anomaly is not significant enough to be convincing. But they are all pointing toward the same thing.

Most commonly interpreted as hint for one or more new “sterile” neutrino (oscillates but does not interact weakly) at large \(\Delta m^2_{\text{new}}\) (~1eV\(^2\)) and small mixing.
Short Baseline Results cannot be explained by three neutrinos responsible for long baseline oscillations

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

Need a fourth (or more) “sterile” state

Long baseline experiments
L/E ~10-10,000

Solar experiments

\[ \Delta m^2 \text{(eV}^2\text{)} \]

\[ \sin^2 2\theta \]

\[ m^2 \text{(eV}^2\text{)} \]
Reactor experiments:

Pure $\bar{\nu}_e$ source produced by fissions in $^{235}\text{U}$, $^{238}\text{U}$, $^{239}\text{Pu}$, $^{241}\text{Pu}$

$\bar{\nu}_e$ disappearance baseline $\sim$ m
Fermilab: Three detector Short Baseline Neutrino (SBN) program on the Booster Neutrino Beamline
Muon neutrino beam (same as MiniBooNE) sampled at SBND near detector (no oscillations), far detectors: MicroBooNE, ICARUS

- MicroBooNE: Address the MiniBooNE Low Energy Excess: Is it electrons or photons?
- SBND: Is there a baseline dependent effect?
- ICARUS: With large detector, span all allowed regions in parameter space at 5σ
\( \nu_e \) appearance sensitivity with three detector SBN experiment
Short Baseline
$L/E \sim 1 \text{ km/GeV}$
Hints of new physics
Sterile neutrinos?

Long Baseline
$L/E \sim 1000\text{km/GeV}$
Measuring Mass Hierarchy and Looking for CP Violation

$\nu_\mu \rightarrow \nu_e$ appearance experiments
$E_\nu 1\text{-}10 \text{ GeV}$
Precision detectors:
Liquid Argon TPCs
Along the way: wealth of neutrino interaction measurements important for oscillation physics and for neutrino interaction physics

$\nu_\mu \rightarrow \nu_e$ appearance experiments
$E_\nu$ 1-10 GeV
Precision detectors:
Liquid Argon TPCs
Bubble chamber detectors from 1970’s → fine grained

Moved to massive detectors to gain statistics (compromised precision)

Now moving back to precision detectors but on massive scales → LArTPCS
Liquid Argon Time Projection Chambers

- Passing charged particles ionize Argon
- Electric fields drift electrons meters to wire chamber planes
- Induction/Collection planes image charge, record dE/dx

Light produced at 128nm and shifted to the visible to be collected by PMTs
Detectors have spatial resolution on the order of the wire spacing (several mm) → topology and calorimetry to identify interaction channels
Power of Calorimetry: Identify protons, muons from particle signatures

Color coded: Deposited charge (corresponding to # of ionization electrons)

No charge → A lot of charge

Muon enriched sample

MicroBooNE data

Proton enriched sample

Electron-$\gamma$ separation in LAr

Critical for electron neutrino appearance experiments
Identify the NATURE of the EM signature

Analyzing topology and dE/dx

Topology cut not folded in.

Pixel size: 4mm x 0.3mm

2D views from the two wire planes
Where are we now?

ν-Ar cross section measurements at Fermilab

**MicroBooNE**
- Active mass: 87 tons
- On-axis Booster Neutrino Beam (BNB)
- Operating since 2015
- First cross section measurements 2018

**ArgoNeuT**
- Active mass ~250 kg
- On-axis NuMI beam
- Operated 2009-2010
- Continuing data analysis
νμ Charged-current inclusive channel

The MicroBooNE neutrino energy range is lower than ArgoNeuTs. Different interaction processes dominate the CC inclusive channel!
MicroBooNE CC Inclusive ($\nu_\mu + \text{Ar} \rightarrow \mu + X$)

- 26k events (1.6x10^{20} POT)
- Pioneering use of MCS to include exiting tracks → full kinematic coverage
- First neutrino double differential cross section measurement on argon

arXiv:1905.09694
Published in PRL
MicroBooNE CC Inclusive ($\nu_\mu + \text{Ar} \rightarrow \mu + X$)

- first comparison of event generators to high statistics, 2D neutrino data on argon
- Systematic uncertainties are dominant $\rightarrow$ detector uncertainties $\rightarrow$ expect improvement in future analyses
Charged particle multiplicity in the CC inclusive sample

Counting of observed tracks without particle ID

No efficiency or migration correction

Higher multiplicity bins are dominated by RES and DIS processes.

MicroBooNE observes less high-multiplicity final states relative to low multiplicity states than GENIE
\( \nu_\mu \) CC N protons

Free nucleon

Argon

Short range correlations

Meson Exchange Currents

Final state interactions

Free nucleon scattering yields a single p in the final state.
Proton Multiplicity

- Successfully identify protons
- Multiplicity distribution provides important check of nuclear effects, FSI modeling → of direct relevance to LEE analyses that preferentially select nucleon final states (1p, Np)
- Migration to lower bins due to current high reconstruction threshold

[Graphs and images related to proton multiplicity and data analysis provided]
CC $\pi^0 (\nu_\mu + \text{Ar} \rightarrow \mu + \pi^0)$

- electron and photon reconstruction is key to neutrino oscillation measurements
- MicroBooNE has developed the first fully automated reconstruction tools for EM reconstruction in LAr TPCs
- observe 20% energy resolution with good data/MC agreement
- first measurement of $\nu_\mu$ CC $\pi^0$ cross section on argon
- validates $\pi^0$ production in argon (x2 higher predicted absorption rate than in hydrocarbon)

new paper on $\pi^0$ reconstruction coming soon
\( \nu_e \) from NuMI Beam

- MicroBooNE sits \( 8^0 \) off axis from the NuMI beam
  - NuMI beam is a source of \( \nu_e \)'s in MicroBooNE
  - similar energy as BNB \( \nu_e \)'s
- fully automated \( \nu_e \) selection and reconstruction
- first e/\( \gamma \) separation in MicroBooNE

\( 9/26/19 \)
Additional On-Going Neutrino Analyses

• $\nu_\mu$ NC elastic scattering
• proton identification and reconstruction
• with low proton detection thresholds, we are at the forefront
• MicroBooNE public note #1053

• $\nu_\mu$ NC $\pi^0$ production
• crucial background constraint for $\gamma$ LEE
• MicroBooNE public note #1041
Many New Neutrino Results

- have also studied multiple exclusive modes
- important basis for demonstrating that we understand neutrino interactions on argon for SBN and DUNE

![Diagram](image.png)
Fermilab: Three detector Short Baseline Neutrino (SBN) program on the Booster Neutrino Beamline
SBND and ICARUS under construction → ICARUS filling now!

- SBND near detector → huge statistics for neutrino scattering measurements
  - $1\text{M}$ neutrino interactions per year
  - Set to turn on next year – in final construction stage
DUNE near detector complex still in design stage:

- 1 x $10^{10}$ POT at 120 GeV
- 170,000 CC neutrino interactions (60k NC neutrino interactions) per ton
- ~80 ton LArTPC detector
  - $\rightarrow$ ~$10^5$ neutrino interactions on argon per year
ProtoDUNE single phase commissioned and ran to see test beam before long shutdown!!!
at first glance:

LArTPC data of unprecedented quality

3 GeV - Pion Interaction(s) (and decay)

2 GeV - Electron shower

1 GeV - Pion Interaction (Absorption $\rightarrow$ 2 p)
Summary

- First results on “high” statistics precision measurements from MicroBooNE
- More from MicroBooNE on the way
- Higher statistics precision data coming from SBND and DUNE Near detector
- Many nu cross section measurements on the horizon