Effect of Neutrino Interaction Systematics for Future Sterile Neutrino Searches with Accelerator Beams

Corey Adams
Yale University

NuInt 2014
Roadmap

Focusing on **Booster Neutrino Beam**

- **Reduce Photon Background**
- **Reduce flux and cross section uncertainties**
- **Increase Statistics? Multiple Baselines?**
- **Oscillation searches happen here**
Neutrino $\nu_\mu$ $\bar{\nu}_\mu$ $\nu_e$ $\bar{\nu}_e$

Neutrino 93.5% 5.9% 0.5% 0.1%
Anti-Neutrino 83.7% 15.7% 0.4% 0.2%


Intrinsic $\nu_e$ from the beam are the irreducible background in a $\nu_e$ appearance search.
MiniBooNE Detector

\[ \nu_e + n \rightarrow e^- + p \]
Neutral Pion Background

Largest Backgrounds:
\( \pi^0, \text{ single } \gamma \text{ misID} \)

\[
\nu_\mu + N \rightarrow \Delta + \nu_\mu \\
\Delta \rightarrow N + \pi^0 \\
\Delta \rightarrow N + \gamma
\]

(not to mention all the other channels and FSI)

Easy to tag a \( \pi^0 \) as an electron if only one ring is visible (no particle ID for electron vs. photon).

Dominant Background - rate of \( \pi^0 \) production + detector response needs to be well understood.
MiniBooNE $\nu_e$ Appearance

2.8 $\sigma$ excess

Not Hopeless!

High Statistics 2 photon measurement can constrain single photon background.

3.4 $\sigma$ excess

Need to control neutral pions in future $\nu_e$ appearance experiments.

LArTPC

The Liquid Argon Time Projection Chamber

Anode wire planes:

Cathode Plane

$E_{\text{drift}} \sim 500\text{V/cm}$

Read out each wire

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$\nu_e$ experimental Signature - LAr

**Topological** Separation of Electrons, Neutral Pions and Photons

Only Possible with a fine grained detector

Electron Candidate  ArgoNeuT Data

Single Photon  ArgoNeuT Data

Neutral Pion  ArgoNeuT Data

$\sim$5cm gap

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$\nu_e$ experimental Signature - LAr

Calorimetric Separation of Electrons and Photons

Charge per length at the start of the shower ($dE/dX$)

ArgoNeuT Data
Single Photon (small gap)

SIMULATION
A. Szcelc

$\gamma \rightarrow e^- + e^+$

Electrons
Photons

See talk by J. Asaadi - Sat 24 May
New results from A. Szcelc
expected @ Neutrino 2014!

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Energy Reconstruction

\[ E_{\nu}^{QE} = \frac{M E_\mu - m_\mu^2/2}{M - E_\mu + |p_\mu| \cos \theta_\mu} \]

\[ E_{\nu}^{Cal.} = E_{lep} + \sum KE_{vis} + E_{missing} \]

**CCQE Formula**

Visible KE can be constrained by test beam experiments (LArIAT)

\( E_{missing} \) can be constrained, for example, by measuring neutron interactions in LAr (Captain)

What is the multiplicity and spectrum of neutrons produced in neutrino interactions?

**Question for this workshop!**
The MicroBooNE Detector

TPC Assembly began 2012
Cryostat Arrival mid 2013
TPC Insertion Dec. 2013
Endcap Welding mid 2014
Commissioning 2014
Data taking 2014/15 and on!

See Talks By:
O. Palamara (Wed)
S. Gollapinni (Thurs)
MicroBooNE $\nu_e$ Appearance

Primary Background is no longer $\pi^0$

Instead, beam contamination is the dominant background.

MicroBooNE $\nu_e$ Event Rates

Constraints on beam $\nu_e$ are just as important as $\pi^0$ for MicroBooNE.

$\pi^0$ background has high statistics, 2 photon measurement as constraint.

How to constrain the intrinsic event rate?

\[
\begin{align*}
\nu & & \bar{\nu} & & \nu & & \bar{\nu} \\
93.5\% & & 5.9\% & & 0.5\% & & 0.1\%
\end{align*}
\]


LSND Best Fit Amplitude: 0.3%
Intrinsic beam contamination: 0.6%

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The $\nu_\mu$: $\nu_e$ event rate is partially correlated, which can reduce a systematic uncertainty on the intrinsic $\nu_e$ rate with a high statistics measurement of $\nu_\mu$ rate.

\[
\frac{\text{Events} \, \nu_\mu}{\text{Events} \, \nu_e} \propto \frac{\Phi_{\nu_\mu}}{\Phi_{\nu_e}} \left( \frac{\sigma_{\nu_\mu}}{\sigma_{\nu_e}} \right) \quad \text{(Plus detector response!)}
\]
Future Experiments: LAr1-ND

The best way to constrain event rates is with a 2 detector experiment.

Booster Neutrino Beam

MiniBooNE
MicroBooNE (2015)

LAr1 - ND (2018)

See Talk by R. Guenette (Thursday)

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LAr1-ND - Event Rate Predictions

\[ \text{Events}_{ND} \frac{N D}{\mu B} \propto \Phi_{ND} \frac{\sigma_{\nu_e}}{\Phi_{\mu B}} \frac{\epsilon_{ND}}{\sigma_{\nu_e}} \frac{\epsilon_{\mu B}}{\mu B} \]

A near detector allows cancellation of event rate systematics (at least to first order).

The flux prediction extrapolation is not as clean as cross section, but will still be a great improvement to the dead reckoning that MicroBooNE must do.

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If MicroBooNE confirms the MiniBooNE excess as electrons, only with a near detector can we truly confirm an oscillation explanation - with complimentary analysis.

\[ \bar{\nu}_\mu \rightarrow \bar{\nu}_X \rightarrow \bar{\nu}_e \]
\[ \bar{\nu}_\mu \rightarrow \bar{\nu}_X \]
\[ \bar{\nu}_\mu, e \rightarrow \bar{\nu}_X \]
\[ \nu_e \text{ Appearance} \]
\[ \nu_\mu \text{ Disappearance} \]
\[ \text{Neutral Current Disappearance} \]
\( \nu_\mu \) Disappearance

- \( \nu_e \) appearance isn’t the only sterile neutrino signature, \( \nu_\mu \) disappearance is also promising - and complimentary.

- Only possible with ND - cross section and flux uncertainties are too high for one detector alone.

- Primary background is still pion production!

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Charged Pion Background

Charged pions from NC interactions can mimic a muon.

If the pion decays before interacting hadronically, it is indistinguishable from a muon.

Pion interaction cross sections in Liquid Argon are important!

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Conclusions

• Future experiments will mitigate the primary interaction systematic - pion production - through improved detector technology.

• Rate of pion production is important!

• Cross Section uncertainties on argon will play a big role - 2 detector experiments will allow reduction of these systematics.

• Resolving the question of sterile neutrinos with accelerator based experiments is only possible with a near detector.
Backup
$\nu_\mu$ CC Background in the $\nu_e$ Sample?

Need to **not** ID the muon (tag it as a pion? Not see it?) and the event must have a shower.

Used a flat, 0.1% misID rate while we develop better estimates of this background.
Neutral Pions in LAr

ArgoNeuT Data

ArgoNeuT Data
The LSND Result

\[ \bar{\nu}_e + p \rightarrow e^+ + n \]

Sterile Neutrino Sensitivity

A near detector on the Booster Beam Line can extend the reach of MicroBooNE by allowing cancellation of many systematic errors - particularly cross section uncertainties. Also allows high statistics, precision cross section measurements due to high flux.

see talk by R. Guenette