The Short Baseline Near Detector at Fermilab

Diego Garcia-Gamez for the SBND Collaboration
The University of Manchester
Outline

• SBND Physics Goals
  - Sterile neutrino searches in SBN
  - Neutrino interactions in LAr: cross sections, nuclear effects, …

• SBND Detector
  - Time Projection Chamber
  - Light Detection System

• Time schedule
SBND Physics Goals

Two primary physics goals:

1. Measure the unoscillated fluxes: $\nu_\mu$-CC, $\nu_e$-CC, and NC interactions to enable precise sterile neutrino oscillation searches in combination with the SBN Program far detectors, ICARUS and MicroBooNE.

2. Study neutrino-nucleus interactions on argon with unprecedented precision and detail: inclusive and exclusive cross sections, observation of rare production channels, and careful study of nuclear effects in neutrino-nucleus scattering.

Additional searches include:

3. Detection of supernova $\nu$, dark matter searches (Sub-GeV) …
SBN Sterile Neutrino Oscillation Searches

ν_μ → ν_e appearance sensitivity

SBN sensitivities assume exposures of:
- 6.60×10^{20} protons on target in ICARUS and SBND
- 13.2×10^{20} protons on target in MicroBooNE


Definite test (> 5σ) of the currently allowed oscillation parameter regions
Neutrino Cross Section

✓ $\nu$ experiments use complex nuclei as neutrino target $\rightarrow$ nuclear effects

✓ Intra-nuclear re-scattering and effects of correlation between target nucleons: Significantly alter final state particle topology and kinematics.

High precision measurements of these processes are deemed necessary! $\rightarrow$ SBND is ideal for this purpose

ν $\mu$ CCQE total cross section

MiniBooNE data

Pure quasi-elastic

Including nucleon correlations

Phys Rev C 80:065501
Due to its location near (110 m) the neutrino source and relatively large mass (112 ton active volume) SBND will have the world’s highest statistics in $\nu_\mu$-Ar and $\nu_e$-Ar interactions:

- Measurement of cross sections
- Nuclear effects and their impact on the predicted rates, final states, and kinematics in $\nu$-Ar interactions
- Inform neutrino MC generators and can provide an important discriminator among models
SBND Neutrino Event Rates

\( \nu_\mu CC \), BNB/FHC, \( 6.6 \times 10^{20} \) POT, 112 tonnes active mass

~ 3 years of exposure

<table>
<thead>
<tr>
<th>Hadronic Final State</th>
<th>G17_01b</th>
<th>G17_02a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclusive</td>
<td>5,389,168</td>
<td>5,329,241</td>
</tr>
<tr>
<td>0 ( \pi )</td>
<td><strong>3,814,198</strong></td>
<td><strong>3,744,108</strong></td>
</tr>
<tr>
<td>0 ( \pi + 0p )</td>
<td>27,269</td>
<td>34,696</td>
</tr>
<tr>
<td>0 ( \pi + 1p )</td>
<td>1,629,252</td>
<td>2,235,338</td>
</tr>
<tr>
<td>0 ( \pi + 2p )</td>
<td>1,150,368</td>
<td>637,535</td>
</tr>
<tr>
<td>0 ( \pi + 3p )</td>
<td>413,956</td>
<td>229,239</td>
</tr>
<tr>
<td>0 ( \pi + &gt;3p )</td>
<td>396,212</td>
<td>263,727</td>
</tr>
<tr>
<td>1 ( \pi^+ + X )</td>
<td>942,555</td>
<td>1,021,212</td>
</tr>
<tr>
<td>1 ( \pi^- + X )</td>
<td>38,012</td>
<td>21,242</td>
</tr>
<tr>
<td>1 ( \pi^0 + X )</td>
<td>406,555</td>
<td>370,666</td>
</tr>
<tr>
<td>2 ( \pi + X )</td>
<td>145,336</td>
<td>131,308</td>
</tr>
<tr>
<td>( \geq 3\pi + X )</td>
<td>42,510</td>
<td>40,702</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Physical Process</th>
<th>G17_01b</th>
<th>G17_02a</th>
</tr>
</thead>
<tbody>
<tr>
<td>QE</td>
<td>1,569,073</td>
<td>2,827,928</td>
</tr>
<tr>
<td>MEC</td>
<td>1,398,773</td>
<td>513,453</td>
</tr>
<tr>
<td>RES</td>
<td>1,816,570</td>
<td>1,539,159</td>
</tr>
<tr>
<td>DIS</td>
<td>581,905</td>
<td>441,057</td>
</tr>
<tr>
<td>Coherent</td>
<td>22,846</td>
<td>7642</td>
</tr>
</tbody>
</table>

In enumerating proton multiplicity, we assume their kinetic energy \( \geq 21 \text{ MeV} \)

<table>
<thead>
<tr>
<th>Proton kinetic energy (MeV)</th>
<th>Proton track length (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>( \approx 0.4 )</td>
</tr>
<tr>
<td>50</td>
<td>( \approx 2 )</td>
</tr>
<tr>
<td>100</td>
<td>( \approx 8 )</td>
</tr>
<tr>
<td>200</td>
<td>( \approx 26 )</td>
</tr>
</tbody>
</table>

Also:
- \( \approx 350k \ NC_{\pi^0} \) events
- \( \approx 12k \ \nu_e CC \) events
- \( \approx 1k \) charm (QE) events
- \( \approx 400 \ \nu + e^- \) events

Courtesy of Costas Andreopoulos

G17_01b: Updated empirical model / G17_02a: Theory-driven model
Final State Interactions: $0\pi$

SBND will have 30x higher rate than MicroBooNE $\rightarrow$ ArgoNeuT statistics in ~1 day of beam!!!
The high statistics electron neutrino sample will be hugely beneficial to both SBN and DUNE physics programs

SBND Charge Current Electron Neutrino Expectations (GENIE estimate, rounded)

<table>
<thead>
<tr>
<th></th>
<th>1 Month</th>
<th>3 Years</th>
</tr>
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<tbody>
<tr>
<td>CC $\nu_e$</td>
<td>1 K</td>
<td>37 K</td>
</tr>
</tbody>
</table>

arXiv:1503.01520

Phys. Rev. D 95, 072005

$\nu_e$ CC candidate event
SBND TPC Layout

- Two drift volumes separated by a central cathode plane
- Each drift volume has a 2 m drift distance
- Facing the cathode plane in each drift volume are anode plane assemblies (APAs): 3 planes of sensing wires
- Two sets of field cage modules surround the drift volumes to provide uniform drift field of 500V/cm
SBND is under construction

Cathode frame

APA frame

APA wiring machine

Subframe assembly with single mesh

Laser photo-diode tension device
SBND construction has begun

SBND Detector Hall

Test installation of CRT panels

Timing distributions clearly show the increased activity during the 1.6 μs beam spill of the BNB

- TPC Design and Fabrication ready → 1Q 2018
- TPC Assembly → 4Q 2018
- Detector and Cryogenics Installation → 3Q 2019
- LAr Filling & Commissioning right after
SBND Light Detection System

- SBND is implementing a high LY Light Detection System scheme
- PMTs + Light Guide Bars as detectors
- Possibility of adding WLS covered reflector foils (generic R&D)

Simulations show that it can help determine timing, calorimetry and position resolution → Adding WLS-covered reflector foils improves the overall performance of the system
Summary

- The ND of the Short Baseline Neutrino program at Fermilab is being constructed successfully.

- SBND will play a crucial role in SBN program providing huge data sets of $\nu$-Ar interactions.

- Further develop the LArTPC technology and help build expertise of the global neutrino physics community working toward DUNE.
Back-Up
Short Baseline Neutrino Program at Fermilab

✓ An accelerator-based neutrino beam facility provides a rich oscillation program with a single experiment:
  - both neutrino and antineutrino modes
  - $\nu_\mu \rightarrow \nu_e$ appearance
  - $\nu_\mu$ and $\nu_e$ disappearance
  - CC and NC interactions

→ explore Sterile $\nu$ Oscillations

✓ Detectors that can distinguish electrons from photons to reduce key backgrounds

✓ Multiple detectors at different baselines are key for reducing systematic uncertainties
LArTPC Technology

- Passing charged particles ionize argon
- Electric field drifts electrons meters to wire chamber planes
- Induction/Collection planes image charge, record dE/dx
- Scintillation light in LAr
Multiple Detectors in SBN

\[ N_{ND}^{data}(\nu_\mu) = \Phi_{ND}(\nu_\mu) \times \epsilon_{ND}(\nu_\mu) \times \sigma_{ND}(\nu_\mu) \]

\[ N_{FD}^{expected}(\nu_\mu) = N_{ND}^{data}(\nu_\mu) \times \frac{\Phi_{FD}(\nu_\mu)}{\Phi_{ND}(\nu_\mu)} \times P(\nu_\mu \rightarrow \nu_\mu) \times \frac{\epsilon_{FD}(\nu_\mu)}{\epsilon_{ND}(\nu_\mu)} \times \frac{\sigma_{FD}(\nu_\mu)}{\sigma_{ND}(\nu_\mu)} \]

\( \nu_e \) Cross Section Fractional Uncertainties

Uncertainty on the ratio of MicroBooNE to SBND due to cross section uncertainties

10-15% few %
\[ N_{\text{ND}}^{\text{data}}(\nu_\mu) = \Phi_{\text{ND}}(\nu_\mu) \times \varepsilon_{\text{ND}}(\nu_\mu) \times \sigma_{\text{ND}}(\nu_\mu) \]

\[ N_{\text{FD}}^{\text{expected}}(\nu_\mu) = N_{\text{ND}}^{\text{data}}(\nu_\mu) \times \frac{\Phi_{\text{FD}}(\nu_\mu)}{\Phi_{\text{ND}}(\nu_\mu)} \times \varepsilon_{\text{FD}}(\nu_\mu) \times \varepsilon_{\text{ND}}(\nu_\mu) \times \sigma_{\text{FD}}(\nu_\mu) \times \sigma_{\text{ND}}(\nu_\mu) \]

\[ \nu_e \text{ Cross Section Fractional Uncertainties} \]

\[ \varepsilon_{\nu_e} \text{ cross section correlation matrix} \]

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arXiv:1503.01520

10-15% uncertainty on the ratio of MicroBooNE to LAr1-ND due to cross section uncertainties.

Reconstructed Neutrino Energy [GeV]

Uncertainty [%]
Electron Neutrinos

LAr TPC offers incredible fine tracking along with electron/photon separation

Phys. Rev. D 95, 072005
Neutral Current Backgrounds

Particular importance to neutrino oscillation experiments can be experimentally misidentified as $\nu_e$ CC production.
Final State Interactions

Physical Process

- Quasi-Elastic
- Resonance
- Deep Inelastic

Detector Signature

- $\mu + 0\ p$
- $\mu + p$
- $\mu + 2\ p$
- $\mu + \pi + p$
- $\mu + 2\ p + \pi$
- $\mu + N\pi + N\ p + \ldots$

Courtesy of Corey Adams
Supernova neutrinos

Flavor composition as function of time

Energy spectra integrated over time

Expected signal in 40 kt of liquid argon for the electron-capture supernova at 10 kpc, calculated using SNoWGLoBES

Most challenging/opportunities for scintillation light.

Energy resolution differentiates between models.

Timing differentiates between models.

Depending on how close the SN is, we may be swamped with events?
Supernova neutrinos

- These features happen on timescales of order of ms
- Most light systems under consideration should cope with this

G. Sinev
Sub GeV dark matter searches in SBN detectors

Why are neutrino experiments (e.g. SBN detectors) useful for new particle searches?

- Require lots of protons on target: SBN has a total of $\sim 2 \times 10^{21}$ @ $E_{\text{proton}} = 8 \text{GeV}$
- Detector needs to be close to source (for rate), but far enough away to minimize beam related backgrounds
- Big detector
- Good particle identification
- Good event reconstruction
- Good cosmogenic background rejection, especially below 200 MeV.
Comprehensive Model Configurations

**CMC: “Status Quo”**
- **Nuclear model**: RFG (Bodek-Ritchie)
- **QE**: Llewellyn Smith (CC)
- **Ahrens (NC)**
- **RES/COH π**: Rein-Sehgal
- **DIS**: Bodek-Yang
- **FSI**: hA

**CMC: “Status Quo ++”**
- **“Status Quo”, Plus:**
  - **MEC**: Empirical MEC (Dytman)

**CMC: “Best Empirical”**
- **“Status Quo ++”, With:**
  - **Diffractive π**: Rein
  - **QE hyperon**: Pais
  - **FSI**: Updated hA

**CMC: “Best theory* I”**
- **Nuclear model**: LFG (València)
- **QE**: València (CC)
- **Ahrens (NC)**
- **QE hyperon**: Pais
- **MEC**: València (CC only)
- **RES/COH π**: Berger-Sehgal
- **Diffractive π**: Rein
- **DIS**: Bodek-Yang
- **FSI**: Updated hA

**CMC: “Best Theory* II”**
- **“Best Theory I”, But:**
  - **FSI**: hN

* where “best theory” means “best theory currently available in GENIE” :)

NuInt 2017  J. Wolcott / Tufts
Capabilities of a High LY LDS

Direct light (VUV)
Re-emitted light (Visible)
Total component

Light Yield [phe/MeV]

Drift coordinate location of the events with light

Photo-cathode plane location of the events with light

 ✓ Uniform and enhanced light collection efficiency help triggering and studying low energy events
 ✓ High density array of PMTs allows for the location of the events in the photocathode plane
 ✓ Separating the direct from reflected light can lead to position resolution in drift direction