SBND-PRISM: Sampling Multiple Off-Axis Neutrino Fluxes with the Same Detector

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The Standard Model of Particle Physics

The Standard Model of Particle Physics is one of the most successful theories that humankind ever produced. Despite its success, it is far from being the theory of everything and several outstanding questions remain unanswered.
Open Questions in Particle Physics

- What is Dark Matter?
- Does Supersymmetry Exist?
- Can the Forces Be Unified?
- Why is the Universe Made Wholly of Matter? (CP Violation)
- What is the Nature of the Higgs Boson?
- Why Are There Three Generations of Fermions?
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10^9 + 1 baryons

10^9 anti-baryons
Open Questions in Particle Physics

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Dark Matter: 27 %
Dark Energy: 68 %

5 %

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Neutrinos are the least understood particles in the Standard Model
Neutrinos to Investigate Particles Physics Mysteries

Generations of Matter (Fermions)

<table>
<thead>
<tr>
<th>QUARKS</th>
<th>LEPTONS</th>
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<tbody>
<tr>
<td>d down</td>
<td>Ve electron neutrino</td>
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<tr>
<td>s strange</td>
<td>Vμ muon neutrino</td>
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<tr>
<td>b bottom</td>
<td>Vτ tau neutrino</td>
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<tr>
<td>γ photon</td>
<td>Y</td>
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<td>e electron</td>
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<td>μ charm</td>
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Long Baselines L = 100-1000 km

Eν ~ O(GeV)

Near Detector

Far Detector

Neutrinos are the least understood particles in the Standard Model

Neutrinos oscillate

Implies that neutrinos have mass

This is an extension of the Standard Model

What are the masses of the neutrinos?

What is the ordering of the masses?

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Neutrinos to Investigate Particles Physics Mysteries

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**Neutrinos oscillate**
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What are the masses of the neutrinos?
What is the ordering of the masses?
Several anomalies in the neutrino sector hint for neutrino oscillations at short baselines

How many neutrinos exist?
Are there sterile neutrinos?

Long Baselines $L = 100-1000$ km

Short Baselines $L = 100-1000$ m

E$_{\nu} \sim O(\text{GeV})$

Generations of Matter (Fermions)

Bosons

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**Short Baseline Neutrino Anomalies**

- $\nu_\mu \rightarrow \bar{\nu}_e$
- $\bar{\nu}_e \rightarrow \bar{\nu}_e$
- $\nu_\mu \rightarrow \nu_\mu$

**LSND**

**Reactor Anomaly**

**MiniBooNE**

**Gallium Anomaly**
Short Baseline Neutrino Anomalies

- **LSND**
  - A 3.8 $\sigma$ excess of events over backgrounds was observed, compatible with $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations with $L/E \approx 1$ m/MeV

- **Reactor Anomaly**
  - A 3 $\sigma$ deficit in the detected flux was seen in past reactor experiments when compared to theory calculations

- **Gallium Anomaly**
  - A 3 $\sigma$ deficit in the detected flux was seen in solar neutrino experiments

- **MiniBooNE**
  - No anomaly observed

- **OBSERVED**
  - $\nu_\mu \rightarrow \nu_\mu$
  - $\bar{\nu}_e \rightarrow \bar{\nu}_e$
Short Baseline Neutrino Anomalies

**LSND**
A 3.8 \( \sigma \) excess of events over backgrounds was observed, compatible with \( \bar{\nu}_\mu \rightarrow \bar{\nu}_e \) oscillations with \( L/E \approx 1 \text{ m/MeV} \)

**MiniBooNE**
A 4.5 (2.8) \( \sigma \) excess of events observed with same \( L/E \) as LSND; excess compatible with LSND within a sterile neutrino framework

**Reactor Anomaly**

**Gallium Anomaly**

\[ \bar{\nu}_e \rightarrow \bar{\nu}_e \]

**OBSERVED**
LSND, MiniBooNE

\[ \nu_\mu \rightarrow \nu_\mu \]
Short Baseline Neutrino Anomalies

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**Gallium Anomaly**
OBSERVED

$(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

OBSERVED

$\bar{\nu}_e \rightarrow \bar{\nu}_e$

Reactor anomaly

$\nu_\mu \rightarrow \nu_\mu$
### Short Baseline Neutrino Anomalies

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<th>Anomaly</th>
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<th>Observations/Experiments</th>
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The Short Baseline Neutrino (SBN) program has been designed specifically to address the sterile neutrino interpretation of the experimental anomalies. Three Liquid Argon Time Projection Chamber (LArTPC) detectors located along the Booster Neutrino Beamline (BNB) at Fermilab.

Target

SBND

Argon mass: 112 ton

MicroBooNE

Argon mass: 86.6 ton

ICARUS

Argon mass: 476 ton

(Not to scale)
Booster Neutrino Beam

More on the Booster Neutrino Beam: https://arxiv.org/abs/0806.1449
Neutrino flux at the SBND front face

$\nu_\mu$ (93.6%), $\bar{\nu}_\mu$ (5.9%), $\nu_e + \bar{\nu}_e$ (0.5%)
Neutrino Flux at SBND

Neutrino flux at the SBND front face

$\nu_\mu$ (93.6%), $\bar{\nu}_\mu$ (5.9%), $\nu_e + \bar{\nu}_e$ (0.5%)

$\nu_\mu$ Flux

$\pi^+ \to \nu_\mu + \mu^+$
$K^+ \to \nu_\mu + \mu^+$

Two-body decays

$\nu_e$ Flux

$\mu^+ \to \nu_e + \bar{\nu}_\mu + e^+$
$K^+ \to \nu_e + e^+ + \pi^0$
$K_L^0 \to \nu_e + \pi^- + e^+$

Three-body decays

Different kinematics: two-body vs three-body decay.

The flux of $\nu_e$ has a larger angular spread than that of $\nu_\mu$ (at the same parent energy)
Goals of the SBN Program

Search for eV mass-scale sterile neutrino oscillations

Measure Events:

\[ N_{ND} \propto \phi_{ND} \otimes \sigma \]

\[ \frac{N_{FD}}{N_{ND}} \propto \phi_{FD} \otimes \sigma \otimes P_{osc} \]

Near Detector

Far Detector

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BNB Beamline

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Goals of the SBN Program

**Neutrino-Nucleus Interactions**
- Millions of Interactions per Year
- Precision Physics Studies
- Exclusive Cross-Section Measurements
- Study of Nuclear Effects
- Measure Rare Interaction Channels

**New Physics**
- Light Dark Matter
- Millicharged Particles
- Dark Neutrinos
- Heavy Neutral Leptons
- Neutrino Tridents

**Target**
- **SBND**
  - BNB Beamline
  - Argon mass: 112 ton
  - 110 m

- **MicroBooNE**
  - Argon mass: 86.6 ton
  - 470 m

- **ICARUS**
  - Argon mass: 476 ton
  - 600 m

(Not to scale)
The Short Baseline Near Detector (SBND)

- BNB Beamline
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(Not to scale)
The SBND detector

- Made of two liquid argon time projection chambers.
- 112 ton of liquid argon.
- Dimensions: 4m x 4m x 5m.
- 110 m from the target position.
- SBND is currently being installed.
A Slightly Off-Axis Detector

The SBND detector

The detector is ~74 cm off the beamline
A Slightly Off-Axis Detector

SBND sees neutrinos from several off-axis angles (OAA)

(Off-axis angle is calculated w.r.t. target position)
A Slightly Off-Axis Detector

SBND sees neutrinos from several off-axis angles (OAs)
(Off-axis angle is calculated w.r.t. target position)

The detector can be divided in several off-axis slices:

- $\text{OAA} \in [0.0^\circ, 0.2^\circ)$
- $\text{OAA} \in [0.2^\circ, 0.4^\circ)$
- $\text{OAA} \in [0.4^\circ, 0.6^\circ)$
- $\text{OAA} \in [0.6^\circ, 0.8^\circ)$
- $\text{OAA} \in [0.8^\circ, 1.0^\circ)$
- $\text{OAA} \in [1.0^\circ, 1.2^\circ)$
- $\text{OAA} \in [1.2^\circ, 1.4^\circ)$
- $\text{OAA} \in [1.4^\circ, 1.6^\circ)$
The Off-Axis Angle (OAA)

We can select lower neutrino energies, and a more monochromatic beam, by going off-axis.

Neutrino Energy vs Pion Energy for different decay angles

The plot assumes the pion is perfectly collinear with the beamline (perfect focusing)
Neutrino events are divided based on the off-axis angle (OAA) region they fall in:

- OAA ∈ [0.0°, 0.2°)
- OAA ∈ [0.2°, 0.4°)
- OAA ∈ [0.4°, 0.6°)
- OAA ∈ [0.6°, 0.8°)
- OAA ∈ [0.8°, 1.0°)
- OAA ∈ [1.0°, 1.2°)
- OAA ∈ [1.2°, 1.4°)
- OAA ∈ [1.4°, 1.6°)

The $\nu_\mu$ energy distribution is affected by the off-axis position.

(mean neutrino energy)

Far Off-Axis
On-Axis

(*) nuPRISM https://arxiv.org/abs/1412.3086
Muon neutrino energy spectrum changes with the off-axis angle,
while the electron neutrino one stays almost the same

**Muon-neutrino CC Events**

higher off-axis angle $\rightarrow$ lower mean energy

**Electron-neutrino CC Events**

higher off-axis angle $\rightarrow$ ~same mean energy

High event statistics in all off-axis regions
Moving away from the beam-line axis, the number of $\nu_\mu$ and $\nu_e$ interactions varies differently. While the number of $\nu_e$ events stays almost constant, the number of $\nu_\mu$ events decreases.

**Muon-neutrinos CC Events**
- peak coincident with the on-axis position

**Electron-neutrinos CC Events**
- distribution is almost constant (angular distribution of $\nu_e$ is wider due to three-body decay)
Cosmic Ray Tagger Data

SBND will be surrounded by a cosmic ray tagger to identify cosmic rays.

Part of the SBND cosmic ray tagger system was temporarily installed in the detector hall.

Real data showing muons from muon-neutrino interactions: beam intensity decreases moving away from the beam center.

**CRT Data 2017 - 2018**

**SBND Preliminary**
SBND-PRISM - Physics Opportunities

- Neutrino Oscillations
- SBND-Only Neutrino Oscillations
- Dark Matter Searches
- Study Energy Dependence of Cross-Section
- Interaction Model Constraints
- Muon-to-Electron Neutrino Cross-Section Ratio
- Study Neutrino Energy / Lepton Kinematics Relation
Sterile Neutrino Oscillations with SBND-PRISM

\[ \frac{N_{FD}}{N_{ND}} = \frac{\alpha \phi_{FD} \otimes \sigma \otimes P_{osc}}{\alpha \phi_{ND} \otimes \sigma} \]

Can we make the two fluxes similar?
Sterile Neutrino Oscillations with SBND-PRISM

\[ \frac{N_{FD}}{N_{ND}} = \frac{\alpha \phi_{FD} \otimes \sigma \otimes P_{osc}}{\alpha \phi_{ND} \otimes \sigma} \]

Can we make the two fluxes similar?

Yes!

Fit a linear combination of the ND fluxes to reproduce the FD flux at the ND flux.

Area Normalized

- OAA ∈ [0.0°, 0.2°]
- OAA ∈ [0.2°, 0.4°]
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Can we use SBND-PRISM for SBND-only sterile neutrino searches (without a Far Detector)?

SBND-PRISM potentially allows probing higher values of $\Delta m^2$ for sterile neutrino oscillation searches.
SBND-PRISM: SBND-Only Sterile Neutrino Oscillations

Can we use SBND-PRISM for SBND-only sterile neutrino searches (without a Far Detector)?

SBND-PRISM potentially allows probing higher values of $\Delta m^2$ for sterile neutrino oscillation searches.

Can SBND beat all current limits on APP?

$\Delta m^2 = 10 \text{ eV}^2$, $\sin^2 2\theta_{\mu e} = 0.001$

- $\nu_e$ appearance mode
- very conservative systematics:
  - free norm. + 30% bin-by-bin sys. on bkg

Testing sensitivity with:

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SBND-PRISM: SBND-Only Sterile Neutrino Oscillations

\( \nu_e \) coming from oscillation \( \nu_\mu \rightarrow \nu_e \)

\( \nu_e \) intrinsic from the beam (background)

We run a \( \chi^2 \) test to understand if we are sensitive to these oscillations

\( \chi^2 = 2 \) (w/o PRISM)

(treating SBND as a single detector)

background and signal are compatible

we are not sensitive to oscillations

\( \chi^2 = 13 \) (w/ PRISM)

(treating SBND as made of multiple off-axis sub-detectors)

background and signal are not compatible

we are sensitive to oscillations

\[
\chi^2 = \sum_{j,i} \frac{(N_j - a T_j)^2}{\sigma^2_{bin} N^0_{ij}}
\]
SBND-PRISM: SBND-Only Sterile Neutrino Oscillations

- $\nu_e$ coming from oscillation $\nu_\mu \rightarrow \nu_e$
- $\nu_e$ intrinsic from the beam (background)

The $\nu_\mu$ and $\nu_e$ fluxes behave differently going off-axis, giving rise to different signal-to-background ratios which constrains systematics.

- $X^2 = 13$
  - background and signal are not compatible
  - we are sensitive to oscillations

Can measure oscillations using SBND alone!

- $OAA \in [0.6^\circ, 0.8^\circ]$
- $OAA \in [1.2^\circ, 1.4^\circ]$
- $OAA \in [0.2^\circ, 0.4^\circ]$

Only showing 3 off-axis bins for clarity
Light dark matter (sub-GeV) that is coupled to the Standard Model via a dark photon. The dark photons can be produced by neutral meson decays (pions, etas) in the target, and then decay to the dark matter.

Phys. Rev. D 100 (2019) 9, 095010
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Phys. Rev. D 100 (2019) 9, 095010

The dark matter can then travel to SBND and, through the dark photon, scatter off electrons in the detector.
Dark Matter Searches with SBND-PRISM

**Background**
Neutrino-electron elastic scattering. Neutrinos come from two-body decays of charged (focused) mesons.

**Signal**
Elastic scattering electron events. Dark matter comes from three-body decays of neutral (unfocused) mesons.
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SBND-PRIMS: Neutrinos (background events) decrease with the off axis angle

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Elastic scattering electron events. Dark matter comes from three-body decays of neutral (unfocused) mesons.

Dark matter (signal) events come from unfocused neutral mesons

Example of a neutrino-electron elastic scattering event
Dark Matter Searches with SBND-PRISM

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SBND-PRIMS: Neutrinos (background events) decrease with the off axis angle.

**Signal**

Elastic scattering electron events. Dark matter comes from three-body decays of neutral (unfocused) mesons.

Dark matter (signal) events come from unfocused neutral mesons.

Background events decrease with the off-axis angle!
Conclusions

**SBND-PRISM is a new innovative way to exploit important SBND features**

- Closeness to the neutrino source
- Being slightly off-axis
- Abundance of statistics

**SBND-PRISM largely expands the physics reach of SBND in multiple directions**

- SBN neutrino oscillations
- SBND-only neutrino oscillations
- Dark matter searches
- Neutrino interaction modelling
- …
Thank You!