# Expectation for Neutrino-Argon interactions in the Short-Baseline Near Detector (SBND)

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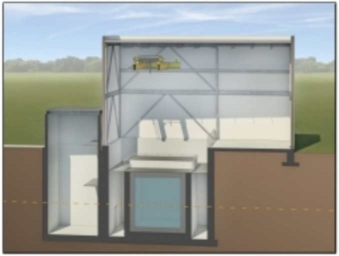
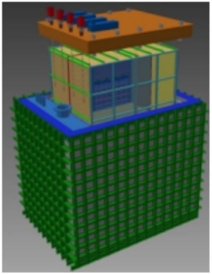
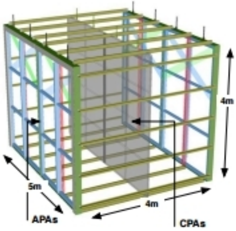
The short-baseline neutrino project (SBN) includes three Liquid Argon Time Projection Chamber detectors (LAr-TPCs) located on-axis in the Booster Neutrino Beam (BNB) at Fermilab

| SBN PROJECT | | | |
|---|---|---|---|
| **Detector** | **Distance** | **LAr Total mass** | **LAr Active mass** |
| **SBND** | **110 m** | **220 ton** | **112 ton** |
| MicroBooNE | 470 m | 170 ton | 89 ton |
| ICARUS-T600 | 600 m | 760 ton | 476 ton |


MINOS
NOvA
600m – Far Detector
ICARUS/T600
MiniBooNE
MicroBooNE
110m - Near Detector
SciBooNE
LAr1-ND
BNB Target



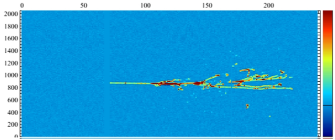


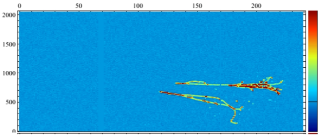



| TPC Parameter | Value |
|---|---|
| Active volume | 5 m x 4 m x 4 m, 112 ton active LAr |
| Number of TPC cells | 2 drift volumes, 2 m drift length each |
| Structure | 2 Anode planes and 1 Cathode plane |
| Maximum drift time | 1.28 $\mu$s |

Measurements that can be performed with SBND:

- SBND will be able to discriminate a single-electron or single-photon in the final state, thing that LSND and MiniBooNE couldn't do. They had anomalies at low energy due to to an electron-like excess events. This is important for oscillation measurement.




(Electron (left) and gammas (right) electromagnetic showers in liquid argon)

- Precise neutrino-nucleus cross-sections measurement, e.g.:
  - $\nu_\mu$ charged-current 0 pion final state event sample will allow the study of nuclear effects in neutrino interactions in argon nuclei.
  - Charged-current event sample will allow $\nu_e$ CC and $\nu_\mu$ CC cross sections measurement. Comparison will test lepton universality.
  - Elastic scattering events $\nu_\mu e \rightarrow \nu_\mu e$ will allow a measurement of $\sin^2\theta_W$.

**Section 1**: Neutrino elastic scattering events selection

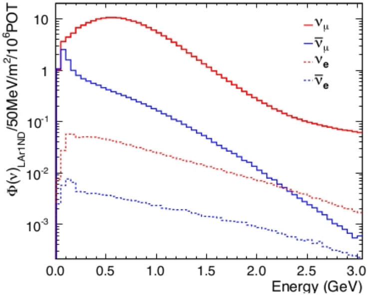
**Section 2**: Neutrino charged-current $0\pi$ expectation

**Section 3**: Neutrino charged-current $1\pi$ expectation

# Section 1: Neutrino elastic scattering events selection

Flux measurement with the highest precision possible for the Booster Neutrino Beam (BNB) through the neutrino elastic scattering interaction because of its well known cross section

$$\Phi = \frac{Events}{\sigma}$$




Booster Neutrino Beam is produced at Fermilab, in neutrino mode its composition is reported in the plot

# Signal

GENIE simulation for SBND active volume
Simulation run: $6.6 \cdot 10^{20}$ POT (3 years)

Uncertainty on flux is one of the highest in neutrino experiments. Short distance allows really high event rate and no oscillation signal, perfect condition for flux measurement.

Process: Elastic scattering

$$\nu_\mu \, e^- \rightarrow \nu_\mu \, e^- \qquad (92.3\%)$$

$$\begin{cases} \nu_e \, e^- \rightarrow \nu_e \, e^- & (4.4\%) \\ \overline{\nu}_\mu \, e^- \rightarrow \overline{\nu}_\mu \, e^- & (2.5\%) \\ \overline{\nu}_e \, e^- \rightarrow \overline{\nu}_e \, e^- & (0.2\%) \end{cases}$$

Irriducible background. Consider all of them as signal and weight the events according to the cross sections

# Elastic scattering cross section

$$\sigma_{\nu_e e \to \nu_e e} = \frac{G_F^2 s}{\pi} \left[ \left( \frac{1}{2} + \xi \right)^2 + \frac{1}{3} \xi^2 \right] = 9.5 \cdot 10^{-49} m^2 (E_\nu / 1 MeV)$$

$$\sigma_{\overline{\nu}_e e \to \overline{\nu}_e e} = \frac{G_F^2 s}{\pi} \left[ \frac{1}{3} \left( \frac{1}{2} + \xi \right)^2 + \xi^2 \right] = 4.0 \cdot 10^{-49} m^2 (E_\nu / 1 MeV)$$

$$\sigma_{\nu_\mu e \to \nu_\mu e} = \frac{G_F^2 s}{\pi} \left[ \left( \frac{1}{2} - \xi \right)^2 + \frac{1}{3} \xi^2 \right] = 1.6 \cdot 10^{-49} m^2 (E_\nu / 1 MeV)$$

$$\sigma_{\overline{\nu}_\mu e \to \overline{\nu}_\mu e} = \frac{G_F^2 s}{\pi} \left[ \frac{1}{3} \left( \frac{1}{2} - \xi \right)^2 + \xi^2 \right] = 1.3 \cdot 10^{-49} m^2 (E_\nu / 1 MeV)$$

$$\xi = sin^2 \theta_W$$

$$s = (P_\nu + P_e)^2 \simeq 2 m_e E_\nu$$

# Background

Events with only an $e^-$ detected in final state

Candidates: Charged channel

$$\nu_e \, \mathrm{N} \rightarrow e^- \; 0p \; 0\pi$$

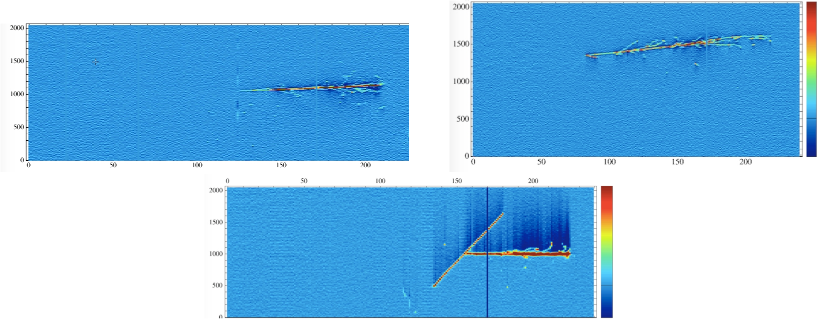
NOTE: Proton with less than 21*MeV* kinetic energy is not reconstructed in detector (ArgoNeuT)

For $6.6 \cdot 10^{20}$ POT:

$$\begin{cases} \text{Elastic scattering: 401 events } (373\ \nu_\mu,\ 18\ \nu_e,\ 10\ \overline{\nu}_\mu) \\ \text{Background: 4534 events} \\ S/B \simeq 0.08 \end{cases}$$

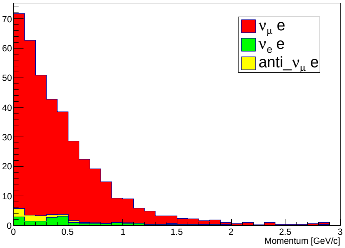
Need a way to select signal from background, kinematic variable selection

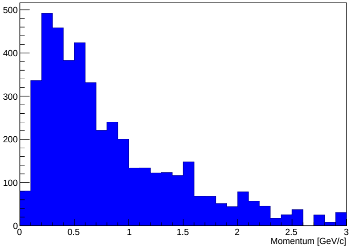
# ArgoNeuT proton discrimination




Background events are due to CC 0p $0\pi$ only because with liquid argon technology it's possible to detect protons at main vertex (clockwise from upper left corner: 0 proton, 1 proton and 2 protons events at vertex)

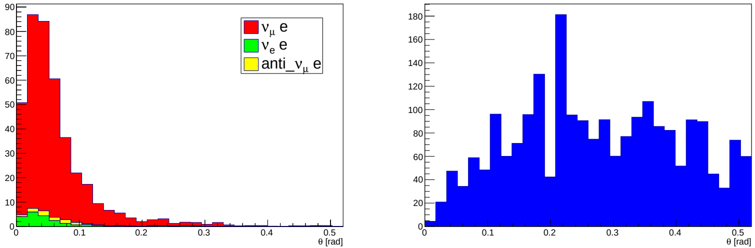
# Kinematic expectation: Momentum distribution




Momentum is not an efficient variable for a cut selection (left: elastic scattering events, right: CC 0p 0$\pi$ events)

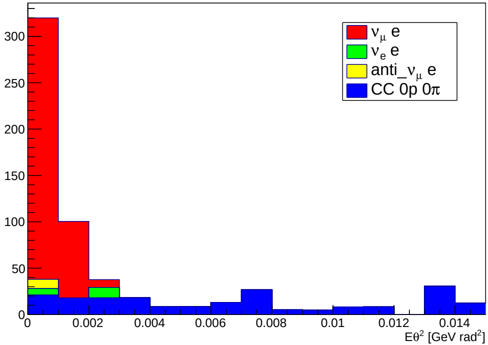
# Kinematic expectation: Angle distribution




Angle alone can't be a reasonable choice even though the separation is more evident (left: elastic scattering events, right: CC 0p $0\pi$ events)

# Cut selection

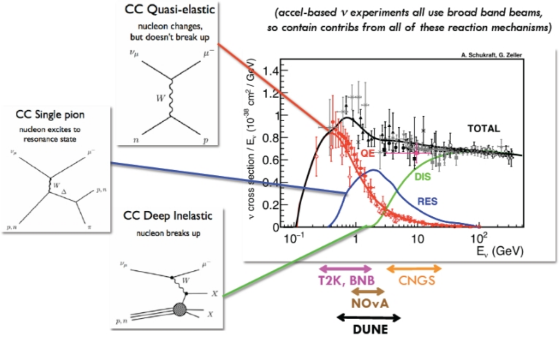
Separation gets evident combining the two: $E \cdot \theta^2$




Possible cut (numbers in brackets includes irreducible background from elastic scattering)

$$\begin{cases} 0.003 \text{ GeV rad}^2\text{: 57(85) background events (S/B = 7.0(4.4))} \\ 0.004 \text{ GeV rad}^2\text{: 75(103) background events (S/B = 5.3(3.6))} \end{cases}$$

# Section 2 and 3: Charged-current events




Neutrino beams are not mono-energetic, multiple processes at a given $E_\nu$

Since $\nu$-experiments use nuclear targets, in the GeV $\nu$-energy range the most important neutrino-nucleus interaction channel is the CC quasi elastic scattering (QE), but nuclear effects play a key role $\rightarrow$ intra-nuclear-scattering

In QE interaction nucleons, $\gamma$ and $\pi$ can be found in final state

# LAr-TPC technology

Full 3D imaging, calorimetric energy reconstruction and particle identification

CC neutrino events can be classified in terms of final state topology based on particle multiplicity

With this type of detector is possible to measure kinematic distributions for all the particles in final state

# Section 2: Neutrino charged-current $0\pi$ expectation

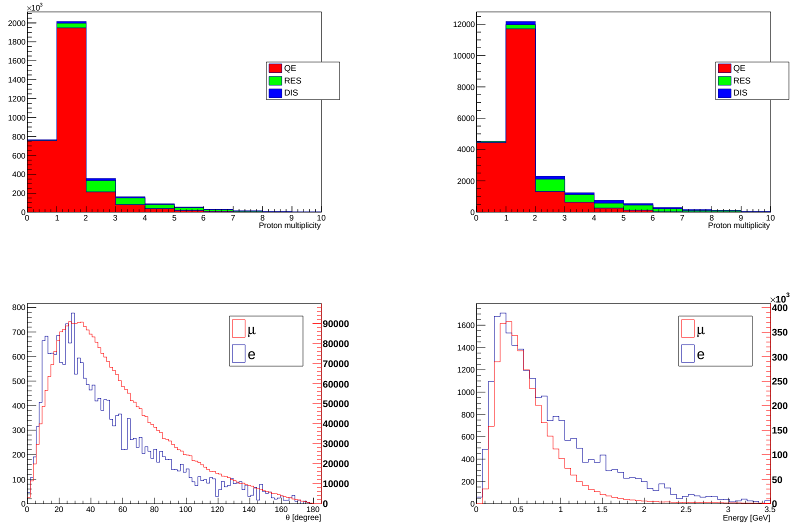
**CC 0 $\pi$ $\nu_\mu$ events**

| Process | N. events | Stat. uncert. (%) |
|---|---|---|
| INCLUSIVE | 3,503,955 | 0.05 |
| QE | 3,064,670 | 0.06 |
| RES | 357,035 | 0.17 |
| DIS | 79,847 | 0.35 |
| 0p | 765,347 | 0.11 |
| 1p | 2,014,640 | 0.07 |
| 2p | 356,401 | 0.17 |
| 3p | 163,532 | 0.25 |
| 4p | 89,408 | 0.33 |
| ≥5p | 114,627 | 0.30 |

**CC 0 $\pi$ $\nu_e$ events**

| Process | N. events | Stat. uncert. (%) |
|---|---|---|
| INCLUSIVE | 22,279 | 0.67 |
| QE | 18,551 | 0.73 |
| RES | 2,694 | 1.93 |
| DIS | 964 | 3.22 |
| 0p | 4,535 | 1.48 |
| 1p | 12,177 | 0.91 |
| 2p | 2,307 | 2.08 |
| 3p | 1,268 | 2.81 |
| 4p | 759 | 3.63 |
| ≥5p | 1,234 | 2.85 |

Estimated events rate using GENIE in SBND active volume for $6.6 \cdot 10^{20}$ POT, a 21 MeV kinetic energy threshold is assumed on protons. No restriction on number of neutrons is made for the table.




Clockwise from upper left corner: proton multiplicity for $\nu_\mu$ CC $0\pi$ events, proton multiplicity for $\nu_e$ CC $0\pi$ events, leptons angle in CC $0\pi$ events, leptons energy in CC $0\pi$ events

# Section 3: Neutrino charged-current $1\pi$ expectation

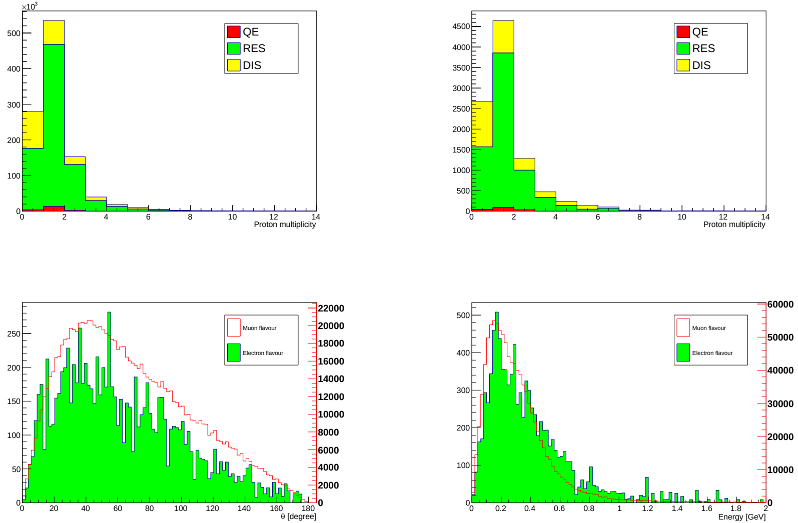
**CC 1 $\pi$ $\nu_\mu$ events**

| Process | N. events | Stat. uncert. (%) |
|---|---|---|
| INCLUSIVE | 1,056,440 | 0.10 |
| QE | 18,785 | 0.73 |
| RES | 809,550 | 0.11 |
| DIS | 218,570 | 0.21 |
| 0p | 279,525 | 0.19 |
| 1p | 537,112 | 0.14 |
| 2p | 155,347 | 0.25 |
| 3p | 41,585 | 0.49 |
| 4p | 19,985 | 0.71 |
| ≥5p | 22,878 | 0.66 |
| **Pion type** | **N. events** | **Stat. uncert. (%)** |
| $\pi^+$ | 1,036,750 | 0.10 |
| $\pi^-$ | 19,691 | 0.71 |

**CC 1 $\pi$ $\nu_e$ events**

| Process | N. events | Stat. uncert. (%) |
|---|---|---|
| INCLUSIVE | 9,775 | 1.01 |
| QE | 164 | 7.81 |
| RES | 6,866 | 1.21 |
| DIS | 2,584 | 1.97 |
| 0p | 2,667 | 1.94 |
| 1p | 4,667 | 1.46 |
| 2p | 1,316 | 2.76 |
| 3p | 505 | 4.45 |
| 4p | 282 | 5.95 |
| ≥5p | 338 | 5.44 |
| **Pion type** | **N. events** | **Stat. uncert. (%)** |
| $\pi^+$ | 9,506 | 1.03 |
| $\pi^-$ | 269 | 6.10 |

Estimated events rate using GENIE in SBND active volume for $6.6 \cdot 10^{20}$ POT, a 21 MeV kinetic energy threshold is assumed on protons. No restriction on number of neutrons is made for the table.




Clockwise from upper left corner: proton multiplicity for $\nu_\mu$ CC $1\pi$ events, proton multiplicity for $\nu_e$ CC $1\pi$ events, $\pi^+$ angle in CC $1\pi$ events, $\pi^+$ energy in CC $0\pi$ events

# Conclusions

Precise neutrino-nucleus cross section measurements are a fundamental prerequisite for every neutrino oscillation experiment, including the future LAr long-baseline neutrino program.

The SBND detectors will collect neutrino samples with high statistics and will make the world's best measurements of $\nu_\mu$-Ar and $\nu_e$-Ar scattering, including rarer processes such as $\nu$-e scattering, strange particle production, multi-nucleon and multi-pion production, and coherent scattering with an argon nucleus.