Measurements of Neutrino Charged Current Interactions at SciBooNE

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Contents

- SciBooNE Experiment
- Neutrino Flux Measurement
- Search of Charged Current Coherent Pion Production
- Summary
Introduction

Neutrino oscillation experiment

\[ \sigma(E) \cdot \Phi_\nu^{\text{near}}(E) \leftrightarrow \sigma(E) \cdot \Phi_\nu^{\text{far}}(E) \]

- Neutrino-nucleus cross-sections at 1 GeV region are not well known
- Energy region for future neutrino experiments (T2K/Noνa)
- MiniBooNE and K2K are revealing surprises.

Need precise measurements in this energy region.

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SciBooNE Experiment

- Fine-grained detector (SciBar) on the Fermilab Booster Neutrino Beamline.
- Cross section measurement for $\sim 1$ GeV neutrino and anti-neutrino
- Essential for future neutrino oscillation measurements (T2K, etc)
- MiniBooNE near detector
SciBooNE Detector

**SciBar**
- scintillator tracking detector
- 14,336 scintillator bars (15 tons)
- Neutrino target
- detect all charged particles
- p/π separation using dE/dx

**Muon Range Detector (MRD)**
- 12 2”-thick steel + scintillator planes
- measure muon momentum with range up to 1.2 GeV/c

**Electron Catcher (EC)**
- spaghetti calorimeter
- 2 planes (11 X₀)
- identify π₀ and νₑ

Newly built at FNAL with materials from past experiments

Used for K2K experiment. Shipped to and re-assembled at FNAL

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SciBooNE Data Taking

- Start beam data taking in June 2007
- Data taking completed on August 18th, 2008
- Total $2.52 \times 10^{20}$ POT for analysis (95% of delivered)
  - Neutrino: $0.99 \times 10^{20}$ POT
  - Anti-neutrino: $1.53 \times 10^{20}$ POT
- Stable data taking

Results from full neutrino data set are presented today

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SciBooNE Analysis

- Neutrino energy spectrum measurements
  - SciBooNE/MiniBooNE joint $\nu_\mu$ disappearance search
  - Beam $\nu_e$ flux measurement for MiniBooNE
- Cross section measurements
  - CC-1 $\pi^+$ production
  - CC-QE scattering
  - CC-1 $\pi^0$ production
  - NC-1 $\pi^0$ production
  - NC elastic scattering
  - Anti-neutrino cross-sections

Covered by this talk

Presented by J. Catala at the poster session

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\( \nu \mu \) Spectrum Measurement

Result of MiniBooNE-only
\( \nu \mu \) disappearance search

(\textit{shape only} analysis)

- MiniBooNE/SciBooNE joint
  \( \nu \mu \) disappearance search

- Share beamline

- Share target material

- **Strong constraint for flux and cross-sections at MiniBooNE**
  \( \text{(Shape + Normalization)} \)

- Feed-back to cross section measurements at SciBooNE

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Event Selection

Use charged current inclusive sample

- Select MIP-like energetic tracks ($P_\mu > 0.25 \text{GeV}$)
- Reject side-escaping muons.
- 3 samples:
  - SciBar-stopped ($P_\mu, \theta_\mu$)
  - MRD-stopped ($P_\mu, \theta_\mu$)
  - MRD-penetrated ($\theta_\mu$)

SciBar stopped
MRD stopped
MRD penetrated

$P_\mu$: Muon momentum reconstructed by its path-length
$\theta_\mu$: Muon angle w.r.t. beam axis

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Extracting $E_\nu$ Spectrum

- Use muon kinematics to extract $E_\nu$ information

$$E_\nu = \frac{m_p^2 - (m_n - V)^2 - m_{\mu}^2 + 2(m_n - V)E_\mu}{2(m_n - V - E_\mu + p_\mu \cos \theta_\mu)}$$

(Assuming CC-quasi-elastic scattering)

- Good coverage of entire kinematic region with these 3 samples.

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Muon Kinematics

SciBar stopped ($P_\mu, \theta_\mu$)

SciBooNE

MC are relatively normalized to data by the number of SciBar-MRD matched event.

MRD stopped ($P_\mu, \theta_\mu$)

MRD penetrated ($\theta_\mu$)

(Unable to reconstruct $P_\mu$ since muons are not stopped in the detectors)

Predict neutrino energy spectrum at SciBooNE by fitting $P_\mu$ and $\theta_\mu$ distribution from each sample

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Spectrum Fit Result

(data-MC)/(stat. error)

Reconstructed $P_\mu$ vs. $\theta$

SB-stop before fit

Reconstructed $P_\mu$ vs. $\theta$

MRD-stop before fit

Reconstructed $\theta$

Data

MC (Before fit)

Entries 67869

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Spectrum Fit Result

\[(\text{data-MC})/(\text{stat. error})\]

**SB-stop before fit**

**SB-stop after fit**

**MRD-stop before fit**

**MRD-stop after fit**

\[\chi^2/\text{ndf:} \]
\[1330/312 \rightarrow 505/312\]

Better data/MC agreement after fitting.

(Plots are relatively normalized)

Working on improving MC prediction.

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Flux Prediction

- Data prefer higher flux around 1 GeV and lower at high-energy region than MC prediction.

- Next:
  - Take detector/cross-section error into account.
  - Tune cross-section model.

[Graph showing flux prediction and ratio to central values]

**Flux comparison with MiniBooNE**

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CC-1 \( \pi^+ \) Measurement

Physics Motivation
- Dominant background process to \( \nu_\mu \) disappearance measurement
- Need precise measurement in the 1 GeV region

CC-resonant \( \pi \) production
- \( \nu + p \rightarrow \mu + p + \pi^+ \)
- \( \nu + n \rightarrow \mu + n + \pi^+ \)

CC-coherent \( \pi \) production
\( \nu + C \rightarrow \mu + C + \pi^+ \)

- Select MRD-stopped and -penetrated event
- Require 2-MIP like tracks
- Require small energy deposit around the vertex
- Require forward pions
- Require non-QE kinematics

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Search for CC Coherent π + Production

Coherent π prediction based on Rein and Sehgal model

No evidence for CC coherent production found.

\( \sigma_{\text{Coh}} / \sigma_{\text{CC}} < 0.67 \times 10^{-2} \) (90% CL) at 1.1 GeV

\( \sigma_{\text{Coh}} / \sigma_{\text{CC}} < 1.36 \times 10^{-2} \) (90% CL) at 2.2 GeV

Paper submitted to PRD.
Hiraide et. al, arXiv:0811.0369
Summary

SciBooNE experiment:
- Precise cross-section measurement at 1 GeV region
- Neutrino flux measurement as a MiniBooNE near detector.
- Successfully completed data taking.
- $\nu_\mu$ spectrum measurement:
  - Established the method for spectrum fitting
- Search for CC coherent $\pi^+$ production
  - No evidence for the signal found
- First official SciBooNE result (submitted to PRD)
- Many results coming soon in the next year!
Thank you

SciBooNE Collaboration

- Universitat Autonoma de Barcelona
- University of Cincinnati
- University of Colorado
- Columbia University
- Fermi National Accelerator Laboratory
- High Energy Accelerator Research Organization (KEK)
- Imperial College London*
- Indiana University
- Institute for Cosmic Ray Research
- Kyoto University*
- Los Alamos National Laboratory
- Louisiana State University
- Purdue University Calumet
- Università degli Studi di Roma and INFN-Roma
- Saint Mary’s University of Minnesota
- Tokyo Institute of Technology
- Universidad de de Valencia

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Backup slides
Booster Neutrino Beamline

- 8 GeV protons sent to target
- Beryllium target: 71cm long 1cm diameter
- Resultant mesons focused with magnetic horn
- Reversible horn polarity
- 50m decay volume
- Mesons decay to $\mu$ & $\nu_\mu$
- Short decay pipe minimises $\mu \rightarrow \nu_e$ decay

SciBooNE located 50m from absorber

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Neutrino Flux

![Graph showing neutrino flux as a function of energy.](image)

Flux (cm$^{-2}$/25MeV/POT)

All, $\nu_\mu$, $\bar{\nu}_\mu$, $\nu_e$, $\bar{\nu}_e$
MuCL cut to remove non-muon tracks

- Remove large portion of NC event
- Reject if proton etc are miss-reconstructed as muon.
- Can be recovered by finding “real” muon

CCQE: Proton is the longest track and identified as muon
Acceptance

![Graphs showing Acceptance vs True E and True Pμ](image)

- Generated in FV
- Total selected
- SciBar stopped
- MRD stopped
- MRD penetrated

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Acceptance in $P_\mu$ vs. $\theta_\mu$

- All generated
- Accepted (sum of 3 samples)

Efficiency (generated/accepted)

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Muon angle, momentum

Reconstructed $\theta$

Reconstructed $P_\mu$

Dirt
NC
CC-multi-pi
CC-1pi
CC-QE

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Enu, Q2

Reconstructed E\nu

Reconstructed Q^2

Reconstructed E\nu

Reconstructed Q^2

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Muon angle, momentum

Reconstructed $\theta$

Reconstructed $P_{\mu}$
Distribution to fit

- Pmu vs. theta-mu

- All bins which has more than 1 MC entry are used for fit

MRD-stop

Reconstructed P_μ vs. θ
data

Reconstructed P_μ vs. θ
MC

(data-MC)/(stat. error)
Distribution to fit

- Same distribution for SciBar stopped
- Just use muon angle for MRD-penetrate sample.

Reconstructed $P_\mu$ vs. $\theta$

**Data**

**MC**

(data-MC)/(stat. error)

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Fitting method

MC template for MRD-stopped

- $E_\nu < 0.5$ GeV
- $0.5 < E_\nu < 0.75$ GeV
- $0.75 < E_\nu < 1.0$ GeV
- $1.0 < E_\nu < 1.25$ GeV
- $1.25 < E_\nu < 1.5$ GeV
- $1.5 < E_\nu < 1.75$ GeV
- $1.75 < E_\nu < 2.0$ GeV
- $2.0 < E_\nu < 2.25$ GeV
- $2.25 < E_\nu < 2.5$ GeV
- $E_\nu > 2.5$ GeV

- Enu: 10bins
- 0.25 - 2.5 GeV, 0.25 GeV step,
- Final bin contain events >2.5GeV
Fitting method

MC template for SciBar-stopped

SciBar-stop and MRD-penetrate samples have less sensitivity to energy distribution.
Mostly normalization for low/high energy part.
$\chi^2$ definition

- **Parameters:** (total 10)
- **Enu scale factor:** 10 bins
- $f_0, f_1, ..., f_9$

Error matrix for each Enu bins (from flux uncertainty only. No other systematics.)

$$\chi^2 = -2 \sum_i N_{bin}(P_\mu, \theta_\mu) \ln \left[ \frac{P(N_i^{\text{data}}; N_i^{\text{MC}})}{P(N_i^{\text{data}}; N_i^{\text{data}})} \right] + \sum_{i,j} V_{ij}^{-1}(f_i - 1) \phi_i^{CV} (f_j - 1) \phi_j^{CV}$$

$$P(N, \mu) = \frac{\mu^N e^{-\mu}}{N!}$$

Poisson log likelihood

$$N(P_\mu, \theta_\mu) = \sum_k f_k n_k(P_\mu, \theta_\mu)$$

MC expectation for each $P_\mu - \theta_\mu$ bins

Contribution from k-th $E_\nu$ bins

MC expected flux (CV)

for each $E_\nu$ bins

$$\phi_k = \sum_{P_\mu, \theta_\mu} n_k(P_\mu, \theta_\mu)$$

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Fitted spectrum

-- MC prediction w/ sys. err.
-- Fit w/ SciBar stopped sample.
-- Fit w/ MRD stopped sample.
-- Fit w/ MRD penetrated sample.
-- Fit w/ all combined sample.

SciBar / MRD
stopped sample are
(roughly) consistent
Plots/Numbers from CC Coherent $\pi^+$ Production Paper
Reconstructed Eν after fitting

SciBar stopped

MRD stopped

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Number of tracks from the vertex (MRD stopped sample)

Vertex activity
Low energy proton is identified as a large energy deposit around the vertex

MuCL of 2nd track for 2 track sample

Vertex activity of \( \mu + \pi \) sample

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Q^2 distributions for fit

(a) 1-track
- DATA
- CC coherent π
- CC resonant π
- Other
- CC QE

(b) μ+p
- DATA
- CC coherent π
- CC resonant π
- Other
- CC QE

(c) μ+π with activity
- DATA
- CC coherent π
- CC resonant π
- Other
- CC QE

(d) μ+π without activity
- DATA
- CC coherent π
- CC resonant π
- Other
- CC QE
**CC coherent $\pi^+$ selection**

**$\Delta \theta_p$**

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**Pion angle**

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**Expected proton track direction assuming CCQE**

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**Observed 2$^{nd}$ track**

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**Muon track**

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Event selection summary

TABLE III: Event selection summary for the MRD stopped charged current coherent pion sample.

<table>
<thead>
<tr>
<th>Event selection</th>
<th>DATA</th>
<th>MC</th>
<th>Coherent $\pi$ Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generated in SciBar fid.vol.</td>
<td>1,939</td>
<td>156,766</td>
<td>100%</td>
</tr>
<tr>
<td>SciBar-MRD matched</td>
<td>30,337</td>
<td>978</td>
<td>29,359</td>
</tr>
<tr>
<td>MRD stopped</td>
<td>21,762</td>
<td>715</td>
<td>20,437</td>
</tr>
<tr>
<td>2 track</td>
<td>5,939</td>
<td>358</td>
<td>6,073</td>
</tr>
<tr>
<td>Particle ID ($\mu + \pi$)</td>
<td>2,255</td>
<td>292</td>
<td>2,336</td>
</tr>
<tr>
<td>Vertex activity cut</td>
<td>887</td>
<td>264</td>
<td>961</td>
</tr>
<tr>
<td>CC-QE rejection</td>
<td>682</td>
<td>241</td>
<td>709</td>
</tr>
<tr>
<td>Pion track direction cut</td>
<td>425</td>
<td>233</td>
<td>451</td>
</tr>
<tr>
<td>Reconstructed $Q^2$ cut</td>
<td>247</td>
<td>201</td>
<td>228</td>
</tr>
</tbody>
</table>

TABLE IV: Event selection summary of MRD penetrated CC coherent pion sample.

<table>
<thead>
<tr>
<th>Event selection</th>
<th>DATA</th>
<th>MC</th>
<th>Coherent $\pi$ Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generated in SciBar fid.vol.</td>
<td>1,939</td>
<td>156,766</td>
<td>100%</td>
</tr>
<tr>
<td>SciBar-MRD matched</td>
<td>30,337</td>
<td>978</td>
<td>29,359</td>
</tr>
<tr>
<td>MRD penetrated</td>
<td>3,712</td>
<td>177</td>
<td>4,375</td>
</tr>
<tr>
<td>2 track</td>
<td>1,029</td>
<td>92</td>
<td>1,304</td>
</tr>
<tr>
<td>Particle ID ($\mu + \pi$)</td>
<td>418</td>
<td>78</td>
<td>474</td>
</tr>
<tr>
<td>Vertex activity cut</td>
<td>167</td>
<td>71</td>
<td>186</td>
</tr>
<tr>
<td>CC-QE rejection</td>
<td>134</td>
<td>67</td>
<td>135</td>
</tr>
<tr>
<td>Pion track direction cut</td>
<td>107</td>
<td>66</td>
<td>109</td>
</tr>
<tr>
<td>Reconstructed $Q^2$ cut</td>
<td>57</td>
<td>60</td>
<td>40</td>
</tr>
</tbody>
</table>
Systematic errors

TABLE V: Summary of the systematic errors in the charged current coherent pion cross section ratio.

<table>
<thead>
<tr>
<th>Source</th>
<th>MRD stopped error ($\times 10^{-2}$)</th>
<th>MRD penetrated error ($\times 10^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector response</td>
<td>+0.10 $\pm$ 0.18</td>
<td>+0.18 $\pm$ 0.18</td>
</tr>
<tr>
<td>Nuclear effect</td>
<td>+0.20 $\pm$ 0.07</td>
<td>+0.19 $\pm$ 0.09</td>
</tr>
<tr>
<td>Neutrino interaction model</td>
<td>+0.17 $\pm$ 0.04</td>
<td>+0.08 $\pm$ 0.04</td>
</tr>
<tr>
<td>Neutrino beam</td>
<td>+0.07 $\pm$ 0.11</td>
<td>+0.27 $\pm$ 0.13</td>
</tr>
<tr>
<td>Event selection</td>
<td>+0.07 $\pm$ 0.14</td>
<td>+0.06 $\pm$ 0.05</td>
</tr>
<tr>
<td>Total</td>
<td>+0.30 $\pm$ 0.27</td>
<td>+0.39 $\pm$ 0.25</td>
</tr>
</tbody>
</table>