MiniBooNE Analysis of CC$\pi^+$ Events

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Motivation for the Experiment - LSND

State of Oscillation Results

- Simplest model has three neutrino mass eigenstates, but...
- Data indicates 3 mass differences
  - $\Delta m^2_{\text{atm}} \sim 2-3 \times 10^{-3} \text{ eV}^2$
  - $\Delta m^2_{\text{sol}} \sim 7 \times 10^{-5} \text{ eV}^2$
  - $\Delta m^2_{\text{LSND}} \sim 0.1-10 \text{ eV}^2$
MiniBooNE

• Designed to confirm or rule out the LSND oscillation signal by searching for $\nu_\mu \rightarrow \nu_e$ oscillations.
• Measure large samples of low energy $\nu_\mu$ interactions. (200 MeV to ~2 GeV)
• Need to understand these processes for the oscillation analysis.
• Cross sections of interest themselves.
νμ Analyses

CC quasi-elastic

Use to understand νe CCQE cross-section

NC π⁰ production

resonant:
ν + (p/n) → ν + Δ
Δ → (p/n) + π

cohherent:
ν + C → ν + C + π⁰

background to νe appearance

NC elastic

Use to understand lower vertex
CC $1\pi^+$ Production

resonant $\pi^+$ production (dominant)  coherent $\pi^+$ production

- forward emitted $\pi$
- low $Q^2$
CC $1\pi^+$ Production

- K2K: 1st search for coh $\pi^+$ prod at low $E$
- somewhat surprising results …
- see no evidence for coh $\pi^+$ production!

(K2K, hep-ex/0506008)
Event Fractions at MiniBooNE

- 48% CC QE
- 31% CC $\pi^+$
- 8% NC $\pi^0$
- 5% CC $\pi^0$
- 3% NC $\pi^{+/-}$
- 4% multi-$\pi$
- 1% NC elastic

MiniBooNE flux-averaged event compositions
($N_{\text{TANK}} > 200$, $N_{\text{VETO}} < 6$)

5.7x10$^{20}$ protons on target over 700,000 events ...

demonstrate understanding of 79% of events before analyzing $\nu_e$ (<1% of total)
Low Energy $\nu$ Cross Sections

predictions from NUANCE
- MC which MBooNE uses
- open source code
- supported & maintained by D. Casper (UC Irvine)

- standard inputs
  (common ingredients - osc exps)
  - Smith-Moniz Fermi Gas
  - Rein-Sehgal $1\pi$
  - Bodek-Yang DIS
Primary Beam
- 8 GeV protons from Booster
- Into MiniBooNE beamline

Secondary Beam
- Mesons from protons striking Be target
- Focused by magnetic horn

Tertiary Beam
- Neutrinos from meson decay in 50m pipe
- Pass through 500m dirt (and oscillate?) to reach detector
νµ Flux at MiniBooNE Detector

- incident on detector: high purity beam (>99% νµ flavor)

- νµ mainly from π⁺ → µ⁺ νµ

- π production constrained by global π data & E910 ...

- HARP experiment - took data with Be targets for MiniBooNE

MC predicted ν energy spectrum
MiniBooNE Detector

- 800 tons of pure mineral oil
- 6m radius steel sphere
- ~2m earth overburden
- 1520 8" PMTs
  - 1280 in main tank (sphere)
  - 240 in veto region (shell)
  - LSND PMTs/New PMTs
  - DAQ records t,Q
    - “Hits”
MiniBooNE Detector

PMTs collect photons, record t,Q
Reconstruct tracks by fitting time and angular distributions
Triggering

- Beam-1.6 μs spill
- Laser
- Tracker and cubes
- Strobe
- SuperNova
- NuMi
Internal Calibration Sources

- Muon tracker + cubes: provides $\mu$ and Michel $e^-$ of known position and direction in tank, key to understanding $E$ and reconstruction
- Laser flasks (4): used to measure tube charge, timing response
- Neutral Current Elastic sample: provides neutrino sample, protons below Cerenkov threshold == isolate scintillation components, distinguish from fluorescence of detector
Cosmic Muon Calibration
Muon Tracker Data

\[ 400 \text{ MeV} < E_\mu < 500 \text{ MeV} \]

Fit func: \( C \cdot x e^{ \left( \frac{-x^2}{2\sigma^2} \right)} \)

\( \sigma = 4.5^\circ \)
Muon Energy Calibration

Visible energy: electron equivalent energy

Cosmic Muon Energy

Visible Tank Energy (MeV)

Data
Monte Carlo

Cube Range Energy (MeV)
Laser Calibration System

- 4 Flasks distributed about the tank
- Measure tube charge response (needed for energy measurement)
- Fully automated calibration system
- New calibration every 4 days

- Measure tube timing response (needed for event reconstruction)
External Measurements

- Variety of stand-alone tests which characterize separate components of mineral oil
CC $\pi^+$ Production

Why important?

• poses largest background to $\nu_\mu$ QE samples (large $\sigma$ & $\pi^+$ can be absorbed in nucleus)

• useful for understanding $\Delta$ production in CH$_2$ ($\Delta \rightarrow N \gamma$ a background to $\nu_\mu \rightarrow \nu_e$ search)

• possibility for CC $\pi^+$ oscillation search

• useful in understanding our event reconstruction
CC $1\pi^+$ Production

resonant $\pi^+$ production (dominant)

coherent $\pi^+$ production

CC Single Pion Production

CC Coherent Pion Production Cross Section

$\sigma(\nu_\mu + A \rightarrow \mu^- + \pi^+ + A)$
Ratio of $\text{CC}\pi^+/\text{CCQE}$ versus $E$

1. Analyze separate $\text{CC}\pi^+$ and $\text{CCQE}$ data samples.

2. Correct each sample for cut efficiencies, background and energy smearing.

3. Plot ratio versus $E$.

4. Multiply ratio by Nuance $\text{CCQE}$ prediction with $\text{MA}=1.03$ GeV to get $\text{CC}\pi^+$ cross section.
CCQE

- Large cross section.
- One Michel electron.
- Two body kinematics.
- Mostly Cerenkov light from the muon.
- The proton produces some scintillation light.
- Particle identification used to reject other reactions.
# Event Composition CCQE

<table>
<thead>
<tr>
<th>Reaction Type</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCQE</td>
<td>86.0%</td>
</tr>
<tr>
<td>Resonant CC1$\pi^+$</td>
<td>8.9%</td>
</tr>
<tr>
<td>Coherent CC1$\pi^+$</td>
<td>1.4%</td>
</tr>
<tr>
<td>NC 1$\pi^+$</td>
<td>1.7%</td>
</tr>
<tr>
<td>Other</td>
<td>3.5%</td>
</tr>
</tbody>
</table>

- 60,000 events and $3.2\times10^{20}$ POT
MiniBooNE CCQE

**Preliminary**
Monte Carlo error bars from: neutrino $\sigma$, light extinction, & light scattering length uncertainties
MiniBooNE QE Data

\[ \text{E}_v^{\text{QE}} = \frac{2M_pE_\mu - m_\mu^2}{2(M_p - E_\mu + p_\mu \cos \theta_\mu)} \]

- making use of \( E_\mu, \theta_\mu \) ...

- energy distribution that will be used for CC \( \pi^+/\text{QE} \) cross section measurement

- next, numerator (CC \( \pi^+ \)) ...

(J. Monroe)
MiniBooNE CC $\pi^+$ Selection

- very simple selection:
  - events with 2 decay electrons
  - unique, results in 84% purity
CC $\pi^+$ Selection

(1) Three subevents: neutrino event followed by two Michel electrons

(2) Neutrino event in the beam window with $THits > 175$ and $VHits < 6$

(3) Michels: $20 < THits < 200$ and $VHits < 6$

(4) Use single ring fitter to find the muon track.

(5) Fiducial cut at radius of 500 cm
Michel Lifetimes

- Assign Michel closest to the $\mu^-$ endpoint to the $\mu^-$ decay. Correct 80% of the time.

- $\mu^-$ lifetime is 8% less than $\mu^+$ due to $\mu^-$ capture on $^{12}\text{C}$.

\[ \tau = 2070 \pm 16 \text{ ns} \]

\[ \tau = 2242 \pm 17 \text{ ns} \]

(M. Wascko)
\( \pi^+ \) Interactions

(1) Interactions in the nucleus
FSI

(2) Interactions in the Detector. Can use Gcalor or Gfluka in Geant and compare.
# Event Composition

<table>
<thead>
<tr>
<th>Reaction Type</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resonant CC1(\pi^+)</td>
<td>75.8%</td>
</tr>
<tr>
<td>Coherent CC1(\pi^+)</td>
<td>9.2%</td>
</tr>
<tr>
<td>CCQE</td>
<td>4.1%</td>
</tr>
<tr>
<td>Muti-pion</td>
<td>6.1%</td>
</tr>
<tr>
<td>DIS</td>
<td>2.6%</td>
</tr>
<tr>
<td>CC (\pi^0)</td>
<td>1.5%</td>
</tr>
<tr>
<td>Other</td>
<td>0.7%</td>
</tr>
</tbody>
</table>

3.2\(\times10^{20}\) POT and 44,000 events
MiniBooNE CC $\pi^+$ Reconstruction

measure Čerenkov light from muon (to avoid light from $\pi^+$)

see larger deficit in forward $\mu$ (low $Q^2$) than in QE data

(M. Wascko)
MiniBooNE CC $\pi^+$ Data

(M. Wascko)

$$2M_p E_\mu - m_\mu^2 + (m_\Delta^2 - M_p^2)$$

"$E_{v \, QE}$" = ________________

$$2(M_p - E_\mu + p_\mu \cos \Theta_\mu)$$

- use 2 body (QE) kinematics
- assume $\Delta(1232)$ in final state (instead of $p$ in QE case)
- energy distribution that will be used for CC $\pi^+/QE$ cross section measurement
MiniBooNE CC $\pi^+/\text{QE}$ Ratio

- efficiency corrected CC $\pi^+/\text{QE}$ ratio meas on CH$_2$
- eff corrections from MC
- ample statistics → can perform a binned measurement
- current systematics estimate:
  - light propagation in oil: ~20%
  - $\nu$ cross sections: ~15%
  - energy scale: ~10%
  - statistics: ~5%

first measurement of this cross section ratio on a nuclear target at low energy!

(J. Monroe, M. Wascko)
MiniBooNE CC $\pi^+$ Cross Section

- multiplying measured CC $\pi^+/QE$ ratio by QE $\sigma$ prediction ($\sigma_{QE}$ with $M_A=1.03$ GeV, BBA non-dipole vector form factors)
- $\sim$25% lower than prediction, but within errors

(J. Monroe, M. Wascko)  

- MC error band from external $\nu$ data constraints
Plausible Interpretation

• since MiniBooNE 1st meas on nuclear target at these E’s

• at 1st glance, one might think this is pointing to a potential problem with nuclear corrs
Plausible Interpretation

• since MiniBooNE $1^{\text{st}}$ meas on nuclear target at these $E$’s

• at $1^{\text{st}}$ glance, one might think this is pointing to a potential problem with nuclear corrs

• but free nucleon $\sigma$’s disagree!

• MC prediction splits difference

• MiniBooNE results more consistent with ANL than BNL
  - new data helping to decide between 2 disparate $\sigma$ meas
  - once final, type of info that can feed back into open source MC
Conclusions

(1) See significant deficit of events at low Q2 and low angle compared with Nuance prediction.

(2) Measured ratio CC1\(\pi^+\)/CCQE is 20% low compared with Nuance prediction, which was, by construction, the average of previous measurements.

(3) Measured ratio agrees better with ANL.

(4) Preparing new measurements with much improved optical model and reduced systematic errors.