Measurement of $CC\pi^+$ events at MiniBooNE

- $CC\pi^+$ events in MiniBooNE
- Comparisons to model predictions
- First look at neutrino content in anti-neutrino mode using $CC\pi^+$s
Why are $CC\pi^+$ events so interesting?

- Rich channel with resonant and coherent interactions -- lots to learn!
- Largest background to CCQE sample
- Possible signal channel for the oscillation analysis
- Use as cross check to constrain wrong sign flux in anti-neutrino mode

Disagreement in low $Q^2$ seen in MiniBooNE and other experiments
Interest in $\text{CC}\pi^+$:

- Rich channel with resonant and coherent interactions -- lots to learn!
- Largest background to CCQE sample
- Possible signal channel for the oscillation analysis
- Use as cross check to constrain beam flux (anti-neutrino mode)

Disagreement in low $Q^2$ seen in MiniBooNE and other experiments

K2K charged current pion production
CC$_{\pi^+}$ events in MiniBooNE: tagged via outgoing muon and decay products of outgoing $\pi^+$

Two “subevents” from muon and “close” michel

A third “subevent” from “Far” Michel

First subevent consistent with neutrino interaction vertex. Later subevents consistent with michels
Close and Far Michels come from muons with different lifetimes.....

Close michel is from $\mu^-$ (capture 8%)

Far michel is from $\mu^+$

expect usual lifetime

Near Michel Lifetime

Fit Value = $2.13 \pm 0.019 \mu s$

MC Fit Value = $2.12 \pm 0.014 \mu s$

Far Michel Lifetime

Fit Value = $2.23 \pm 0.024 \mu s$

MC Fit Value = $2.23 \pm 0.017 \mu s$
~70,000 events total for 5.8E20 pot
(entire neutrino data set)

67% $\nu_\mu \rightarrow \mu^- p \pi^+$

11% $\nu_\mu n \rightarrow \mu^- n \pi^+$

4.6% $\nu_\mu A \rightarrow \mu^- A \pi^+$

5.7% $\nu_\mu n \rightarrow \mu^- p$

1.6% $\nu_\mu n \rightarrow \mu^- p \pi^0$

2.6% $\nu_\mu N \rightarrow \mu^- X$

83% pure CC$\pi^+$
Modeling CC$\pi^+$ interactions at MiniBooNE:

v3 NUANCE Monte Carlo to generate events (Casper)
- Resonance Model: Rein-Sehgal, Fermi Gas Model, $M_A^{1\pi}=1.1$ GeV, added non-isotropic $\Delta$ decay (Garvey)
- Coherent model: Rein-Sehgal, $M_A^{coh}=1.0$ GeV, constraint from NC$\pi^0$ (MiniBooNE)
- DIS: Bodek-Yang
- FSI: Partnuc model tuned to external $\pi^{-12}$C data

Systematic errors shown on MC include uncertainties on
- Flux
- Cross sections
- Optical model
  (fully correlated error matrix)
Comparing data with Monte Carlo

Muon kinetic energy

data compared with MC

• error bars are statistics plus systematics - fully correlated
• plots are relatively normalized

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Muon angular distribution

- Data compared with MC
- Error bars are statistics plus systematics - fully correlated
- Plots are relatively normalized

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Reconstructed neutrino energy

\[ E_{\nu}^{QE} = \frac{1}{2} \frac{2 M_p E_{\mu} - m_{\mu}^2 + (m_{\Delta}^2 - m_p^2)}{M_p - E_{\mu} + \sqrt{(E_{\mu}^2 - m_{\mu}^2)} \cos \theta_{\mu}} \]

**data** compared with **MC**

- error bars are statistics plus systematics - fully correlated
- plots are relatively normalized
Momentum Transfer, $Q^2$

- Data compared with MC
- Error bars are statistics plus systematics - fully correlated
- Plots are relatively normalized

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Understanding $Q^2$ dis-agreement

\[ \rightarrow \textit{work in progress} \]

- Differing predictions from event generators?
- Nuclear effects missing in nuclear model?
- Outdated vector form factors in R-S?
- Outdated Fermi Gas Model? (need LDA)
- $M_A^{1\pi}$?
- Axial form factors?
- ...
Understanding $Q^2$ dis-agreement

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- ...

MC event generator “owners” prepared special samples using MiniBooNE flux for these comparisons

- NUANCE (Casper)
- NEUGEN (Gallagher)
- NEUT (Hayato)

generator level comparisons for starters......
Look at differences in predictions for $Q^2$ distribution for NUANCE compared to NEUT and NEUGEN.

All generators are R-S based.

NEUGEN: extensive tuning using electron scattering data.

Resonant

Coherent

(generator level comparisons)
Look at differences in predictions for $Q^2$ distribution for NUANCE compared to NEUT and NEUGEN.

Resonant predictions are very similar some differences below $Q^2=0.2$ GeV$^2$
Modeling of nuclear effects not understood?

Compare to Singh model integrated over MiniBooNE flux to get a feel for the effects of using different models....

Suppression due to nuclear effect is ~28%

fairly flat

relatively little suppression at low $Q^2$

(compare 7% to ~35%)
Can different vector form factors make a difference?

Compare NUANCE (R-S) to Lalakulich (Rarita-Schwinger formalism coupled with extensive fitting to electro-production data)

Relatively normalized comparison consistent with each other!
Understanding $Q^2$ dis-agreement

$\rightarrow$ work in progress

- Differing predictions from event generators?
- Nuclear effects missing in nuclear model?
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- Outdated Fermi Gas Model? (need LDA)
- $M_{A}^{1\pi}$?
- Axial form factors?
- ...

So far, no smoking gun -- $\rightarrow$ still investigating.....
\~1000 events so far from $CC\pi^+$ interactions from (Wrong Sign) neutrinos in anti-neutrino mode

larger impurities from anti-nu channels

6.5\% $\nu_\mu n \rightarrow \mu^- p\pi^0$

4.6\% $\nu_\mu N \rightarrow \mu^- X$

5.9\% $\nu_\mu A \rightarrow \mu^- A\pi^+$

6.5\% $\nu_\mu n \rightarrow \mu^- p$

11\% $\nu_\mu n \rightarrow \mu^- n\pi^+$

50\% $\nu_\mu p \rightarrow \mu^- p\pi^+$

good check of WS content in anti-nu mode!
Anti-neutrino mode
CC$\pi^+$ muon energy

- Relatively normalized
- Statistical errors only

Data compared to MC

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Anti-neutrino mode
CC$\pi^+$ muon angle

- Relatively normalized
- Statistical errors only

Data compared to MC

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Anti-neutrino mode
CC$\pi^+$ neutrino energy

\[ E^{\text{QE}}_\nu = \frac{1}{2} \frac{2 M_p E_\mu - m_\mu^2 + (m_\Delta - m_\pi)^2}{M_p - E_\mu + \sqrt{E_\mu^2 - m_\mu^2}} \cos \theta_\mu \]

Data compared to MC
- Relatively normalized
- Statistical errors only

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Anti-neutrino mode

CC$_\pi^+$ Momentum Transfer

Data compared to MC

- Relatively normalized
- Statistical errors only

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Conclusions

• $\text{CC}\pi^+$ sample
  • $\sim 70K$ events in neutrino mode!
  • working to understand $Q^2$ distribution
  • new data from anti-neutrino mode

• Ultimate Goals
  • $\text{CC}\pi^+/\text{CCQE}$ ratio
  • $M_A^{1\pi}$ extraction
  • differential cross section
  • coherent contribution

Exciting time for cross section physics on MiniBooNE!