Introduction

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- significant effort by Sobczyk, Gallagher, Hayato-san organizing and calculating
- experiments make suggestions
- organizers, Nathan Meyer, Tomasz Golan put together comparisons THANKS!!
Basic outline

- Hugh Gallagher organized NUINT04
- SD and Steve Boyd organized theory/generator comparison for NUINT09. Roman Tacik and Jan Sobczyk had big impact getting final results together.
  - Coherent models out of date
  - QE models remarkably together for inclusive, but not for proton (right before MEC became important)
  - Pion production models vary widely
- This time, get ideas from experiments
  - MI NOS, MiniBooNE, T2K, NOvA, LBNE – oscillation, cross section
  - ArgoNEUT, MicroBooNE – Liquid Ar test, cross section
  - MI NERvA – cross section
Categories

- Oscillation backgrounds (NC $\pi^0$)
- QE-like cross section (common oscillation signal)
- Coherent cross section (important osc bkgd)
- FSI issues (strongly affects, ‘masks’ all signals)
- Total Visible Energy (oscillation signal, $E_\nu$ measurement)

*Experimenters are welcome to include their own thoughts*
I. Oscillation backgrounds in $\nu_\mu \rightarrow \nu_\text{e}$.

Primary bkgds: NC $\pi^0$, $\nu_\text{e}$ in beam

T2K PRL 2011

LBNE 2012 simulate ($\bar{\nu}$)

![Graph showing neutrino energy distribution and background sources.](image)
studies

- NOvA A1: EM fraction for NC 2 GeV $\nu_\mu/\bar{\nu}_\mu$ C
  - EM fraction = summed $\gamma$ and $\pi^0$ energy/$\nu$ [$\nu=E_\nu-E_\mu$]
- MINOS B1: $\pi^0$ from NC 5 GeV $\nu_\mu$ Fe
  - $z=E_\pi/\nu_\mu$, i.e. fraction of hadron energy in $\pi^0$'s.
- LBNE C1: total CC xs for 0-10 GeV $\nu_\mu/\bar{\nu}_\mu$ Ar?
  - total and no meson contribution (QE bkgd)

thoughts:
- Good general interest, involves processes not well understood
- $\gamma$'s from decays ok, but $\gamma$'s from nuclear excitations?
- Many sources of $\pi^0$'s – DIS, RES
**NC $\pi^0$ issues**

- T2K 2011 result used empirical estimation of bkgd.
  - build events from atmospheric $\pi^0$ and MC $\pi^{+/-}$. Use regular analysis.
  - normal MC not trusted.
- MINOS used MC simulation.

![Graph showing total NC coherent $\nu_\mu^{12C} \rightarrow ^{12}C \nu_\mu \pi^0$](image1)

![Graph showing $\nu_\mu$ induced NC single $\pi^0$](image2)

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NUINT12 generator comparisons   22 October 2012
II. QE-like background

- Difficult to define QE signal
  - Only detect muon, strong bkgd from pion prod
  - Proton gives clean ID, but has strong FSI which is hard to model
  - Biggest problem seems to be pion abs, satisfies many cuts but gives wrong $E_\nu$ with QE hypothesis.
  - MEC makes it more difficult.
- example shows QE/RES 1 GeV $\nu_\mu$ C simulation. Width of QE peak shows Fermi motion and blue line shows $\pi$ prod events. Where no pion is emitted.
studies

- **MiniBooNE F1**: total CC QE xs w/ and w/o MEC.
  - GENIE has draft version, NEUT has no MEC
- **T2K G1**: mu momentum vs. $\theta$ (2D) plot for 600 MeV $\nu_\mu$ C with and without MEC
- plots below from GENIE (see Teppei Katori’s talk later)
- thoughts:
  - Frontier of theory vs. data – lots of attention needed

![Graphs showing theoretical vs. experimental data](image-url)
III. FSI influences

- examples from NUINT09 study \( [\nu_\mu \text{ Carbon at 1 GeV}] \)
- proton KE from QE (left), \( \pi \) KE from CC1\( \pi \) (right)
- Theorists have little or no FSI, generators have full FSI.
- All curves in right plot except purple have full FSI.
III. FSI influences

- Much of my time has gone to this (GENIE has 2 models)
- One effort has been to model low energy nucleons, best seen in data with neutrons in final state.
studies

- LBNE C2: look at proton multiplicity (all and with KE>50 MeV – common tracking problem) in 2.5 GeV $\nu_\mu$ Ar.
  - No data so far, looking forward to ArgoNEUT this week.

- ArgoNEUT/MiniBooNE D1, E1: proton multiplicity (all and with KE>50 MeV) for 1, 3 GeV $\nu_\mu$ Ar events with no mesons.

thoughts:
- Correct vertex energy changes $E_\nu$ calculation, new access with LAr
- Large variations possible, need validation with neutrinos.
IV. Coherent $\times s$

- SCI BooNE NC Coherent (Phys Rev D 81, 111102(R) (2010))
- measurement depends critically on MC understanding of bkgd and signal.
- efficiency=5.3%, purity=61%

<table>
<thead>
<tr>
<th>Interaction Type</th>
<th># Events</th>
<th>Fraction(%)</th>
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<tbody>
<tr>
<td>CC quasi-elastic</td>
<td>53,363</td>
<td>41.4</td>
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<td>CC single $\pi$ via resonances</td>
<td>29,688</td>
<td>23.1</td>
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<tr>
<td>CC coherent $\pi$</td>
<td>1,771</td>
<td>1.4</td>
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<tr>
<td>CC single meson except $\pi$</td>
<td>839</td>
<td>0.7</td>
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<tr>
<td>CC DIS</td>
<td>6,074</td>
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<tr>
<td>NC elastic</td>
<td>22,521</td>
<td>17.5</td>
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<tr>
<td>NC single $\pi^0$ via resonances</td>
<td>6,939</td>
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<td>NC coherent $\pi^0$</td>
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<tr>
<td>NC single meson except $\pi^0$</td>
<td>4,716</td>
<td>3.7</td>
</tr>
<tr>
<td>NC DIS</td>
<td>1,768</td>
<td>1.4</td>
</tr>
</tbody>
</table>
studies

- MINERvA H3-5: isolated pion energies for 5 GeV $\nu_\mu$ C.
  - $\pi^+$ (CC Coh signal), $\pi^0$ (NC Coh signal), $\pi^-$ (similar to $\pi^+$ in Minerva)
  - sources are RES, DIS in addition to coherent
  - since coherent is few% of RES, cuts are critical
V. Total visible energy (MINOS)

- Add up all pion, photon total energies and nucleon KE.
- Key to MINOS oscillation analysis
- Dominant systematic errors
  - NC background ($\theta$)
  - Relative normalization (N-F) ($\Delta m^2$)
  - Hadronic energy ($\Delta m^2$)
- 1\textsuperscript{st} and 3\textsuperscript{rd} come from MC.

$$E_{\nu} = E_\mu + E_{\text{had.}}$$
V. Total visible energy (MINERνA)

- MINERνA composed of Scin, ECal, and HCal regions.
- Key to $E_\nu$ calculation for higher energies.
- Sensitive to missing energy of neutrals, low $E$ hadrons.

Preliminary systematic errors
Studies

- **MINOS B2**: “$E_{\text{reco}}$” from CC 3 GeV $\nu_\mu$ Fe
  
  \[ E_{\text{reco}} = 1.3 E_{\gamma,\pi^0} + KE_p \text{ (KE}>150 \text{ MeV} \ ? \ KE : 0) + KE_n \text{ (KE}>300 \ ? \ 0.5 \times KE : KE) + E_{\pi^+/-} \ldots \]
  
  Specific to their calorimeter (Fe-scin)

- **ArgoNEUT/MiniBooNE D3, E3**: total visible energy 1, 3 GeV $\nu_\mu$ Ar (no $\nu$, neutrons)
  
  more general

- **MINERvA H17, H18**: distribution of n, p energy as function of $\nu$. for 5 GeV $\nu_\mu$ C.
  
  shows variation in $E_{\text{vis}}$ due to low vs. high energy p,n (FSI)

- **Thoughts:**
  
  - Tricky to interpret because many components.
  - 2D plots have more information
Summary

- Introduction to studies suggested by experiments.
- Many interesting themes
  - oscillation backgrounds
  - QE signal/bkgd (osc signal)
  - FSI effects (low energy nucleons)
  - coherent backgrounds
  - total visible energy (osc signal, common way to calc $E_{\nu}$)

Now, let’s see the results! What to look for:
- Each plot shows a quantity expt sees as important bkgd/syst
- Look for deviations between MC codes
- Look for physics that might cause those deviations.
- If MC’s agree, is that because they all use same model?