Particle Production from MiniBooNE and T2K to MINERvA and LBNE

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Neutrino GiBUU Publications since NUlNT2012

1. “Reaction Mechanisms at MINERvA”
   arXiv:1402.0297 [nucl-th]
   10.1103/PhysRevD.89.093003

2. “Energy reconstruction in the Long-Baseline Neutrino Experiment”
   arXiv:1311.7288 [nucl-th]
   10.1103/PhysRevLett.112.151802

3. “Pion production in the T2K experiment”
   O. Lalakulich and U. Mosel.
   arXiv:1305.3861 [nucl-th]
   10.1103/PhysRevC.88.017601

4. “Pion production in the MiniBooNE experiment”
   O. Lalakulich and U. Mosel.
   arXiv:1210.4717 [nucl-th]
   10.1103/PhysRevC.87.014602

5. “Energy reconstruction in quasielastic scattering in the MiniBooNE and T2K experiments”
   arXiv:1208.3678 [nucl-th]
   10.1103/PhysRevC.86.054606

6. “Neutrino- and antineutrino-induced reactions with nuclei between 1 and 50 GeV”
   arXiv:1205.1061 [nucl-th]
   10.1103/PhysRevC.86.014607

7. “Many-Body Interactions of Neutrinos with Nuclei - Observables”
   arXiv:1203.2935 [nucl-th]
   10.1103/PhysRevC.86.014614
Motivation and Contents

- Determination of neutrino oscillation parameters and axial properties of nucleons and resonances requires knowledge of neutrino energy and momentum transfer.
- Neutrino beams are broad in energy.
- Modern experiments use nuclear targets.
- Nuclear effects affect event characterization, cross section measurements, neutrino energy reconstruction and, consequently, oscillation parameters.
Energy Reconstruction by QE

- In QE scattering on nucleon at rest, only $l + p$, $0 \pi$, is outgoing. Lepton determines neutrino energy:

\[ E_\nu = \frac{2M_N E_\mu - m_\mu^2}{2(M_N - E_\mu + p_\mu \cos \theta_\mu)} \]

- **Trouble:** all presently running exps use nuclear targets
  1. Nucleons are Fermi-moving
  2. Final state interactions may hinder correct event identification

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**GiBUU** : **Theory and Event Generator**

based on a BM solution of Kadanoff-Baym equations

Physics content and details of implementation in:  
**Buss et al, Phys. Rept. 512 (2012) 1- 124**

Code available from gibuu.hepforge.org

Mine of information on theoretical treatment of potentials, collision terms, spectral functions and cross sections, useful for any generator

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Reaction Types

- 2 major reaction types relevant:
  1. QE scattering
    i. true QE (single particle interaction)
    ii. many-particle interactions (RPA + 2p2h + spectral functions)
  2. Pion production
    i. through nucleon resonances
    ii. through DIS

- All reaction types are entangled: final states may look the same
Complication to identify QE, entangled with $\pi$ production
Both must be treated at the same time!
Nuclear Targets (K2K, MiniBooNE, T2K, MINOS, Minerva, ...)

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Neutrino Beams

- Neutrinos do not have fixed energy nor just one reaction mechanism

Have to reconstruct energy from final state of reaction
Different processes are entangled
Neutrino-nucleon cross section

In the region of modern experiments (0.5 – 10 GeV) all 3 mechanisms overlap.
0 Pion Events from GiBUU

From Coloma & Huber: arXiv:1307.1243v1
Pion Production

- Pion production dominated by $P_{33}(1232)$ resonance (not just a heavier nucleon)

$$J_{\Delta}^{\alpha \mu} = \left[ \frac{C_V}{M_N} (g^{\alpha \mu} \not{q} - q^\alpha \gamma^\mu) + \frac{C_V}{M_N^2} (g^{\alpha \mu} q \cdot p' - q^\alpha p'^\mu) + \frac{C_V}{M_N^2} (g^{\alpha \mu} q \cdot p - q^\alpha p^\mu) \right] \gamma_5$$

- $C^V(Q^2)$ from electron data (MAID analysis with CVC)
- $C^A(Q^2)$ from fit to neutrino data (experiments on hydrogen/deuterium), so far only $C^A_5$ determined, for other axial FFs only educated guesses
Pion Production

- Pion production amplitude
  \[n\text{Pion} = \text{resonance contrib} + \text{background (Born-terms)}\]
- Resonance contrib
  - \(V\) determined from e-scattering (MAID)
  - \(A\) from PCAC ansatz
- Background:
  - Up to about \(\Delta\) obtained from effective field theory
  - Beyond \(\Delta\) unknown
  - 2 pi BG totally unknown
Pion Production

Discrepancy between elementary data sets → impossible to determine 3 axial formfactors

New pion data on elementary target desperately needed!

10% error in $C_5^A(0)$

Data:
PRD 25, 1161 (1982), PRD 34, 2554 (1986)
Pion Production

1p-1h-1π X-section:

\[
\frac{d\sigma^{\nu A \rightarrow \nu' X \pi}}{dE} = \int \frac{d^3p}{(2\pi)^3} P(p, E) f_{corr} \, d\sigma^{med} \, P_{PB}(r, p) F_\pi(q_\pi, r)
\]

Hole spectral function

\[
P(p, E) = g \int d^3 r \Theta [p_F(r) - |p|] \Theta(E) \delta \left( E - m^* + \sqrt{p^2 + m^*^2} \right)
\]

Pion fsi (scattering, absorption, charge exchange) handled by transport, includes Δ transport, consistent width description of Delta spectral function, detailed balance
Pion Production

- In-medium self-energy of Delta from Oset et al.
- In-medium self-energy consistent with collision terms in cascade (2 and 3 body coll)
- Calculations include on top of resonance 1-pi decays also 2pi decay channels and semi-inclusive production through DIS
Pions in MiniBooNE

Only BNL input comes close to data

Δ dominant only up to about 0.8 GeV
Pion Spectra in MB

GiBUU results confirmed by Hernandez & Nieves

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Hard to understand: pion data agree with Fermi-motion folded free cross section, but fsi must be there

bands:
uncertainty of axial form factor
Pion Production in T2K

Measurement of pion production between about 0.5 and 0.8 GeV would be a clean probe of $\Delta$ dynamics.

$\Delta$ dominant only up to 0.8 GeV
T2K pion data may help to distinguish between ANL and BNL input
Pion Production in T2K

\[ \Delta \text{ dominant only up to 0.8 GeV} \]

Measurement of \( \pi^+ \) production between about 0.5 and 0.8 GeV would be clean probe of \( \Delta \) dynamics.
Pions at NOvA

Lalakulich et al, PR D86, 014607 (2012)
Pions at MINERvA

1.5 – 10 GeV
no \( W \) cut
\( \Delta \) dominance
because of fsi
Pions at MINERvA

Influence of elementary cross section

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Pions at various experiments

Multi $\pi^+$, target: C for MB, T2K and MINERvA, Ar for LBNE

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FSI increase the cross section!
Semi-inclusive X-sections much larger than exclusive ones
(1 order of magnitude, cf. Athar, Alvarez-Ruso)
Fsi are most important, but different, for pions and kaons
Elementary kaon vertices 'shielded' by secondary production:
\[ \pi + N \rightarrow K + \Lambda \]
Nucleon Knock-out at MINERvA

Extremely strong fsi:
fast initial proton becomes many low-energy nucleons

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Summary

- Pions from resonance decay and DIS are large background contribution to QE
- Pions have to be well under control for QE studies; hindered by uncertainties in elementary X-sections
- Pions up to 800 MeV offer possibility to explore the axial coupling to the Delta
- Kaons are produced enhanced by fsi; makes it very different to isolate elementary kaon prod. X-sections
Comparison with other generators
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What causes all these significant differences??

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