Overview of Progress in Neutrino Scattering Measurements

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NuInt07, Fermilab, May 30 – June 3 2007
Scope and Cautionary Remarks

Scope

Review progress in neutrino scattering measurements since NuInt01. Focus on:

- $0.1 < E_\nu \text{ (GeV)} < 10$ neutrino energy range
- Neutrino rather than charged lepton (B. Bradford's talk, this session) or pion/proton scattering data
- Recent data rather than recent development on neutrino scattering modeling (C. Andreopoulos' talk, this session)

Cautionary Remarks

- many of the results that will be shown are still preliminary and may change (starting from NuInt07!) in the future. Those are marked with $\text{P}$ throughout the talk
- direct comparisons between experiments are sometimes difficult. Tried to be explicit about assumptions used
Outline

- Neutrino experiments reporting recent progress
- Quasi-elastic scattering
- Resonant Pion Production
- Coherent Pion Production
- From resonance to DIS region
- Nuclear effects
- Future

Source: NEUT, NuInt05
Neutrino Experiments Reporting Recent Progress

- **K2K near**:
  - *1KT* (Cherenkov detector, water target, $\sim 10^5$ interactions)
  - *SciFi* (segmented tracker, water, $\sim 10^4$ interactions)
  - *SciBar* (segmented tracker, carbon, $\sim 10^4$ interactions)
- **MiniBooNE** (Cherenkov, mineral oil, $\sim 10^6$ interactions)
- **NOMAD** (spectrometer/calorimeter, carbon, $\sim 10^6$ interactions)
- **MINOS** near (magnetized tracking calorimeter, iron, $\sim 10^6$ interactions)
- **Lar50** (Lar TPC, Ar, $\sim 10^4$ interactions)
- Reanalyses of *BNL-7ft + GGM* data (bubble chambers, deuterium and propane/freon, $\sim 10^3$ interactions)

See Session 3 talks for details on most of these
Quasi-Elastic Scattering

- Llewellyn Smith formalism:

\[
\frac{d\sigma}{dQ^2} = \frac{m_N^2 G_F^2 |V_{ud}|^2}{8\pi(\hbar c)^4 E_{\nu}^2} \left[ A(Q^2) \pm B(Q^2) \frac{(s-u)}{m_N^2} + \frac{C(Q^2)(s-u)^2}{m_N^4} \right]
\]

- \((s-u) \sim 4m_N E_{\nu} Q^2\)
- + for neutrinos, - for antineutrinos
- A,B,C depend on two vector \((f_1, f_2)\) and one axial vector \((g_1)\) form factors
- \(Q^2\) dependence of axial vector form factor assumed to have dipole form:

\[
g_1(Q^2) \approx \frac{1.25}{(1+Q^2/m_A^2)^2}, \quad m_A: \text{axial mass}
\]

- Vector form factors: few % deviations from dipole form from electron scattering data (\(\rightarrow B. Bradford, this session\)), causing few % differences in CCQE cross section and axial mass extraction in recent analyses
K2K-SciFi MA Result

- Fit shape of $Q^2$ distribution in 1 track and 2 track QE-enriched CC samples
- Include 2 track nonQE-enriched CC sample to constrain background normalization
- Fit $Q^2$ in separate $E_v$ bins to constrain flux predictions
- Fit only $Q^2 > 0.2$ GeV$^2$ region to avoid large uncertainties due to nuclear effects
- Total sample ~ 7,000 events

Axial mass result: $M_A = (1.20 \pm 0.12)$ GeV

Source: PRD 74, 052002 (2006)
Preliminary MiniBooNE CCQE

- Preliminary axial mass result: \( M_A = (1.22 \pm 0.10) \text{ GeV} \)

Since then, analysis has been updated

- CCQE selection: contained CC events with single decay electron tag, correlated in space with muon track endpoint. 200,000 events with \(~74\%\) estimated CCQE purity

- Fit shape of \( Q^2 \) distribution, to measure both:
  - Axial mass
  - Parameter controlling strength of Pauli suppression in relativistic Fermi gas model

- Achieve good data/MC agreement in CCQE kinematic distributions after tuning these two parameters in MC

(Source: J. Conrad, B. Louis, FNAL Seminar, April 2007)
NOMAD CCQE Cross Section

- Select CCQE events in $3 < E_\nu < 100$ GeV range by requiring:
  - Two tracks, one identified as $\mu^-$, other consistent with proton
  - Invariant hadronic mass: $W < 1.76$ GeV$^2$
  - CCQE-like rather than background-like (RES, DIS) events, based on 3D likelihood
  - $\sim 8,000$ events, with $\sim 71\%$ estimated purity

- Normalization via DIS sample in $40 < E_\nu < 200$ GeV, whose cross section is taken as $\sigma / E_\nu = 0.677 \cdot 10^{-38}$ cm$^2$ / GeV

- Preliminary CCQE cross section: $\sigma(\nu_\mu n \to \mu^- p) = (0.72 \pm 0.01) \cdot 10^{-38}$ cm$^2$

- Error quoted is statistical-only

- Systematic uncertainty evaluation underway, expected to be dominated by nuclear effects

- Measured cross section is $\sim 20\%$ smaller than the world average of previous bubble chamber experiments

(Sources: R. Petti, NuInt05; V. Lyubushkin and B. Popov, Phys. Atomic Nucl. 69, 1876 (2006))
Recent CCQE models now typically use non-dipole vector form factors from electron scattering data, affecting at few % level MA extraction.

Given current accuracy, dipole approximation for axial FF seems OK.

MA values from recent $Q^2$ shape analyses (K2K-SciFi, prelim. MiniBooNE) are consistent with each other, but higher than historical world average.

Prelim. NOMAD CCQE cross section, using different method (DIS normalization), seems to suggest much lower MA values. Need to wait for full systematic error evaluation.

-> experimental biases, or MA parameter is not “universal”? 

Look forward to new NuInt07 CCQE and NC elastic results (Session 5):

- F. Sanchez, “K2K QE Results from SciBar”
- T. Katori, “Charged-Current Interaction Measurements in MiniBooNE”
- C. Cox, “MiniBooNE NC-E Interactions”
Resonance Production

- Single pion production via excitation, and subsequent decay, of resonances of hadronic masses $1.08 < W \text{ (GeV)} < 1.4-2.0$

- 14 final states overall (6 CC, 8 NC):

| CC                  | NC              |
|---------------------|-----------------|
| $\nu_\mu p \to \mu^- \Delta^{++}$ | $\nu_\mu p \to \nu_\mu \Delta^+$ |
| $\Delta^{++} \to p\pi^+$          | $\Delta^+ \to p\pi^0, \Delta^+ \to n\pi^+$  |
| $\nu_\mu n \to \mu^- \Delta^+$   | $\nu_\mu n \to \nu_\mu \Delta^0$ |
| $\Delta^+ \to p\pi^0, \Delta^+ \to n\pi^+$ | $\Delta^0 \to n\pi^0, \Delta^0 \to p\pi^-$  |
| $\bar{\nu}_\mu p \to \mu^+ \Delta^0$ | $\bar{\nu}_\mu p \to \bar{\nu}_\mu \Delta^+$ |
| $\Delta^0 \to n\pi^0, \Delta^0 \to p\pi^-$ | $\Delta^+ \to p\pi^0, \Delta^0 \to n\pi^+$  |
| $\bar{\nu}_\mu n \to \mu^+ \Delta^-$ | $\bar{\nu}_\mu n \to \bar{\nu}_\mu \Delta^0$ |
| $\Delta^- \to n\pi^-$          | $\Delta^0 \to n\pi^0, \Delta^0 \to p\pi^-$  |

- Rein and Sehgal formalism. Resonance production and decay matrix elements computed according to FKR model and resonance decay experimental input

- Transition form factor appearing in production amplitude:

$$G_A(Q^2) \approx (1 + Q^2 / (4m_N^2))^{1/2-n} \frac{1}{(1+Q^2/m_A^2)^2} , \quad m_A : \text{single pion axial mass}$$
Reanalyses of Bubble-Chamber Data

\[ \sigma(\mu^- p \pi^+)/\sigma_{QE}(M_A = 1.07) \]

- BNL-7ft $\nu_\mu p \rightarrow \mu^- p \pi^+$ data ($\sim 3,000$ evts.)
- Good agreement found with R-S model
  (Source: K. Furuno, NuInt02)
- ANL data also reanalyzed and compared to R-S

- Reanalysis of GGM $\nu_\mu p \rightarrow \nu_\mu p\pi^0$ data ($\sim 200$ evts.) to extract absolute xsec
  (Source: E. Hawker, NuInt02)
- Good agreement found with R-S
- First absolute xsec measurement of NC $\pi^0$ production at low energies

NC Single Pion Production

\[ \sigma(\nu_\mu p \rightarrow \nu_\mu p\pi^0) \times 10^{-38} \text{ cm}^2 \]

- GGM, Kreitz, Nuc. Phys. B135, 45 (1978), C$_3$H$_8$ + CF$_3$Br with nuclear corrections
- NUANCE total (free nucleon)
- NEUGEN (free nucleon)
K2K-1KT NC $\pi^0$ Production

- Two e-like rings, 85-215 MeV invariant mass, $\sim$2,500 events with $\sim$71% purity
- Fully corrected $\pi^0$ momentum distribution, normalized to fully contained sample, shows reasonable agreement with predictions
- NC $\pi^0$ production cross section normalized to CC one:
  
  \[ \sigma(\text{NC } \pi^0)/\sigma(\text{CC}) = (0.064 \pm 0.001 \pm 0.007) \text{ at } E_v \sim 1.5 \text{ GeV} \]

(Source: Phys. Lett. B619, 255 (2005))
MiniBooNE NC Pi0 Production

- Preliminary resonant NC $\pi^0$ production cross section:
  \[
  \sigma(\nu_\mu N \rightarrow \nu_\mu N\pi^0) = (1.28 \pm 0.11 \pm 0.43) \times 10^{-38} \text{ cm}^2/\text{CH}_2
  \]
  at $E_\nu \sim 1.3$ GeV and flux extracted via CCQE sample

(Source: J. Raaf, U. of Cincinnati Ph.D. thesis, 2005)

- Analysis updates since then on reconstruction, optical model, selection
- No decay electrons, $e/\mu$ and $e/\pi^0$ likelihood ratios favor $e$ and $\pi^0$ hypotheses, respectively, $80 < m_{\gamma\gamma} < 200$ MeV
- $\sim 20,000$ events with $>90\%$ purity
- Default Monte Carlo underpredicts $\pi^0$ production rate at low $\pi^0$ momenta, but overall not bad

(Source: J. Conrad, B. Louis, FNAL Seminar, April 2007)
MiniBooNE CC Pi+ Production

- Select $\nu_\mu N \rightarrow \mu^- N\pi^+$ events by requiring two decay electrons from $\mu^- \rightarrow e^-$ and $\pi^+ \rightarrow \mu^- \rightarrow e^-$ decays. ~44,000 events ($3.3 \cdot 10^{20}$ pot), ~85% purity

- Neutrino energy from muon kinematics, assuming $m(\Delta) = 1.23$ GeV resonance

- Normalize corrected $CC\pi^+$ rate to CCQE one, to extract cross section ratio

- Get $CC\pi^+$ cross section by multiplying by NUANCE CCQE cross section prediction ($M_A = 1.03$ GeV). ~25% lower than predictions, but comparable uncertainties

(Source: M. Wascko, NuInt05)
Resonance Production Progress Since NuInt01

- A lot more data, clear example being NC $\pi^0$ production shown here, for which we had no absolute xsec measurement before NuInt01
- Three recent results, reasonably consistent with each other:
  - reanalysis of GGM data (black, red)
  - $\sigma$(NC $\pi^0$)/$\sigma$(CC) from K2K-1KT, multiplied here by NEUT CC xsec prediction (blue)
  - preliminary MiniBooNE resonant NC $\pi^0$ xsec, with flux extraction via CCQE sample assuming MA=1.03 GeV (green)
- High statistics samples allow us to test in detail for the first time pion production kinematics. Our current modeling seems OK at the ~20% level
- Look forward to new NuInt07 resonant pion production results (Session 6):
  - J. Link, “Neutral Current $\pi^0$ Production at MiniBooNE”
  - B. Fleming, “Charged Current $\pi^+$ Production at MiniBooNE”
  - L. Whitehead, “Charged Current $\pi^+$ Production at K2K”
  - C. Mariani, “Neutral Pion Production Cross Sections at K2K”
Coherent Pion Production

- Neutrino interacts coherently with nucleons bound in the nucleus, producing a pion.
- Cross section expected to be smaller (up to ~20% for $E_\nu \sim 1$ GeV) than resonant pion production, but with distinct signature:
  - forward-scattered pion
  - no nuclear break-up
- Both CC and NC modes possible: $\nu_\mu A \rightarrow \mu^- A \pi^+$, $\nu_\mu A \rightarrow \nu_\mu A \pi^0$
- Neutrino and antineutrino coherent cross sections expected to be similar.
- Theoretical models vary, but share general ideas:
  - Built on the basis of Adler's theorem, relating neutrino-nucleus cross section to pion-nucleus one, at $Q^2 = 0$
  - Extrapolation to $Q^2 \neq 0$ via propagator term governed by coherent axial mass, $M_A \sim 1-1.35$ GeV.
K2K-SciBar CC Coherent Pi+ Production

- Select CC coherent pion candidates with ~47% expected purity by requiring:
  - CC interaction with 2 tracks, one muon and one $\pi^+$-like track
  - low vertex activity
  - low momentum transfer: $Q^2 < 0.1 \text{ GeV}^2$

- Use control samples to tune momentum scale, nQE/QE ratio, strength of nuclear effects

- 113 events selected, consistent with background-only

- Upper limit (90% CL) on CC coherent pion cross section normalized to CC inclusive:
  $$\sigma(\text{CC coh } \pi)/\sigma(\text{CC}) < 0.60 \cdot 10^{-2}$$
  at $E_\nu \sim 1.3 \text{ GeV}$

(Source: Phys. Rev.Lett. 95, 252301 (2005))
MiniBooNE NC Coherent Pi0 Production

- Select ~30,000 events by requiring no decay electrons, e/μ and e/π⁰ likelihood ratios favor e and π⁰ hypotheses, respectively, m_{γγ} > 50 MeV
- Perform 2D fit in m_{γγ} and E_{π} (1-cos(θ_π)) variables to extract coherent, resonant, background fractions in the sample
- Monte Carlo fit templates reweighted according to π⁰ momentum distribution measured in NC π⁰ rate analysis discussed earlier
- Coherent fraction: \( \frac{N(\text{coh} \, \pi^0)}{(N(\text{coh} \, \pi^0) + N(\text{res} \, \pi^0))} = (18.0 \pm 1.2 \pm 1.0)\% \) at \( E_\nu \sim 1.1 \) GeV

(Source: J. Link, NuFact06)
Summary of Coherent Pion Production Since NuInt01

- Two new low-E results, including first CC result
- Plot shows both NC and CC coherent cross sections normalized to NC and carbon, assuming $\sigma(A) = A^{2/3} \sigma(N)$ and $\sigma(CC) = \sigma(NC)/2$
- Aachen (A~27) nu/nubar NC data (black)
- GGM (A~30) nu/nubar NC data (red)
- K2K-SciBar nu CC data (blue)
- MiniBooNE nu NC data from prelim. resonant xsec measurement (2005) and prelim. coherent fraction measurement (2006) (green)

- Tension between MiniBooNE observation and K2K-SciBar upper limit?
- More experimental input necessary to guide theory: many models on the market, yielding very different predictions
- Look forward to new NuInt07 coherent pion production results (Session 6 and poster):
  - J. Link, “Neutral Current $\pi^0$ Production at MiniBooNE”
  - V. Nguyen, “Angular Dependence of $\pi^0$ Production in the MB Antineutrino Data”
From Resonance Region to Deep Inelastic Scattering

- DIS: dominant process for $E > 3$ GeV. Allows to probe nucleon structure

\[ \mu^- (\mu^+) \]

- Measure $E_\mu, \theta_\mu, E_H$

- Momentum transfer: $Q^2 = 4E_\mu E_H \sin^2(\theta / 2)$

- Bjorken scaling variable: $x = Q^2 / (2ME_H)$

- Inelasticity: $y = (E_H - M) / E_\nu$

- Hadronic mass: $W^2 = M^2 + 2ME_H - Q^2$

- Differential neutrino cross sections $d^2\sigma/(dx dy)$ can be expressed in terms of structure functions $F_2(x, Q^2)$, $xF_3(x, Q^2)$, and $R_L(x, Q^2)$

- Smooth transition from resonance production to DIS regime via Bodek-Yang duality model, tuned to data in low-$Q^2$ overlap region

- Neutrino generators simulate low multiplicity hadronic final states up to some $W \sim 1.4-2$ GeV with resonance formalism, turn to DIS formalism for higher $W$
MINOS Near DIS Distributions

- Large data sample of DIS ($W > 2$ GeV) and transition region ($1.4 < W < 2$ GeV) events

- Require $E_H = \nu < 1$ GeV, and extract flux for $E_\nu > 5$ GeV
- From flux and event distributions, get $d^2\sigma/(dx dy)$ for neutrinos and antineutrinos
  - $\rightarrow$ extract $F_2$ and $xF_3$ in neutrino-iron scattering
NOMAD/NuTeV Differential Cross-Sections

- Measure the CC differential cross section in $\nu$-C interactions for $6 < E_\nu < 300$ GeV, by requiring:
  - $\mu$-ID, $E_\mu > 2.5$ GeV
  - $E_H > 3$ GeV
  - $Q^2 > 1$ GeV$^2$
- Absolute xsec normalization from world average in $40 < E_\nu < 200$ GeV
- Measurement in $(E_\nu, x, y)$ bins, values corrected for bin centering
- First measurement of inelastic CC cross section on a carbon target and large $Q^2$ ($\sim 13$ GeV$^2$) 
  (Source: R. Petti, NuInt05)
- At higher energies: recent NuTeV precision structure functions measurements, with neutrinos and antineutrinos on Fe 
  (Source: M. Tzanov, NuFact06)
Summary of Transition Region Progress Since NuInt01

MINOS and NOMAD: able to cover regions of phase space (high x, low/medium $Q^2$) for structure functions measurements that are complementary to charged lepton scattering and beyond past neutrino scattering experiments. Relevant for relatively low energy neutrino beams.

(Source: D. Naples, APS-DPF 2006)

• Look forward to new NuInt07 transition region/DIS results (Sessions 6 and 8):
  • C. Mariani, “Neutral Pion Production Cross Sections at K2K”
  • D. Naples, “NuTeV Structure Function Measurements”

(Source: R. Petti, NuInt05)
• Fermi motion and binding energy of target nucleons
  -> changes interaction kinematics

• Pauli suppression of the phase space available to final state nucleons
  -> causes $Q^2$-dependent suppression of the cross-sections

• Final state interactions (FSI) inside the nucleus, such as proton re-scattering or pion absorption
  -> can change composition and kinematics of the hadronic part of the final state

• Effect of Fermi motion and Pauli suppression generally simulated according to simple zero-temperature relativistic Fermi gas model for the target neutrons and protons, Various choices for FSI treatment, tuned on $\pi/p$ data

• Depending on energy thresholds and nuclei, understanding nuclear de-excitation via gamma ray emission may also be needed
Nuclear De-excitation in K2K-1KT

• ~40% of neutrino interactions off a nucleon in oxygen accompanied by ~6 MeV gamma ray emission from nuclear de-excitation

• Allows to study $\nu_{\mu} N \rightarrow \nu_{\mu} N$ scattering (NCEL) in water Cerenkov detector

• Select ~3,000 gamma candidate events by requiring low PMT hit multiplicity, containment, single Cherenkov track hit topology.Estimated NCEL purity: ~58%

• 6 MeV peak clearly seen with neutrinos

• After correcting for multi-interactions per spill:
  $N(\text{data})/N(\text{MC}) = 1.23 \pm 0.04 \pm 0.06$
  (detector systematics only)

• MC prediction is normalized with respect to CC inclusive measurement

(Source: J. Kameda, NuInt05)
MiniBooNE+K2K Low-Q^2 Interactions

- Low-Q^2 interactions: mostly affected by nuclear effects, e.g. Pauli suppression
- Early analyses of various low-Q^2 samples at both MiniBooNE and K2K showed a deficit with respect to predictions for Q^2 < 0.2 GeV^2
- Experiments have followed distinct approaches to tune low-Q^2 predictions
  - **MiniBooNE**: introduce extra degree of freedom in relativistic Fermi gas model to control strength of Pauli suppression
    -> nuclear physics explanation
  - **K2K**: most (if not all) of the discrepancy goes away by assuming no coherent pion production
    -> neutrino interaction explanation

(Source: J. Conrad, B. Louis, FNAL Seminar, 2007) (Source: Phys. Rev.Lett. 95, 252301 (2005))
Nuclear Effects in LAr50

- Expose 50 lt. LAr TPC to CERN multi-GeV wide-band beam, using NOMAD as muon spectrometer

- Select “golden” CCQE sample of 86 events with ~80% estimated purity

- Missing transverse momentum sensitive to Fermi motion, proton re-scattering and pion absorption inside the nucleus

- Clear evidence seen for nuclear effects beyond Fermi motion and Pauli suppression

(Source: Phys. Rev. D74, 112001 (2006))
Nuclear Effects Progress Since NuInt01

- Experiments got not only better at correcting for nuclear effects, but also at trying to **quantitatively** evaluate associated uncertainties. Mostly new since NuInt01. Some examples below on nuclear effects uncertainties in recent analyses:

| Experiment     | Quantity                  | Status      | Approx. uncertainty from Fermi gas model | Approx. uncertainty from nuclear FSI |
|----------------|----------------------------|-------------|----------------------------------------|-------------------------------------|
| K2K-SciFi      | CCQE $M_A (Q^2 > 0.2 \text{ GeV}^2)$ | published   | -                                      | ±3%                                 |
| K2K-SciFi      | CCQE $M_A (Q^2 > 0)$        | published   | ±5%                                    | ±3%                                 |
| K2K-1KT        | $\sigma (\text{NC}\pi^0) / \sigma (\text{CC})$ | published   | -                                      | ±2%                                 |
| MiniBooNE      | $\sigma (\text{NC}\pi^0)$  | preliminary | ±15%                                   | ±15%                                |
| MiniBooNE      | $\sigma (\text{CC}\pi^+) / \sigma (\text{CCQE})$ | preliminary | ±5%                                    | ±5%                                 |
| K2K-SciBar     | $\sigma (\text{CC coh } \pi) / \sigma (\text{CC})$ | published   | -                                      | ±0.2% (abs.)                        |
| MiniBooNE      | $\sigma (\text{NC coh } \pi) / \sigma (\text{NC}\pi^0)$ | preliminary | $< \pm 8\%$                           | $< \pm 3\%$                        |

- Tendency to be conservative, also to cover possible model deficiencies (e.g. relativistic Fermi gas model)

- Look forward to new NuInt07 nuclear effects results with neutrinos (Sessions 5,9):
  - T. Katori, “Charged-Current Interaction Measurements in MiniBooNE”
  - A. Curioni, “Neutrino Interactions in LArTPCs”
Summary

Review progress in neutrino scattering measurements since NuInt01:

- Several new cross section results, spanning all relevant channels (CCQE, RES, COH, DIS), and including study of nuclear effects with neutrinos
- Samples of higher statistics allow for more detailed differential cross sections as well
- Large error bars may be deceiving, but tend to represent more accurately current systematic uncertainties affecting the measurements, with respect to what was done in the past
- Nevertheless, recent results not always consistent with each other and with past ones, pointing to either non-understood experimental biases, or deficiencies in the models used to analyze the data. Need to solve this to get to the precision era in few-GeV neutrino-nucleus scattering

The future is bright:

- NuSNS, SciBooNE, T2K Near, MINERvA, MINOS Near, NovA Near,... (Session 3)
- Synergies established with nuclear physics, charged lepton DIS and theory communities