Measurements of Quasi-Elastic Interactions in the NOMAD Experiment

R. Petti

University of South Carolina, USA

“Neutrino-Nucleus Interactions for Next Generation Neutrino Oscillation Experiments”

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**THE NOMAD DETECTOR**

- **Low-density magnetic spectrometer**
  \[ B = 0.4 \text{ T}, \quad \rho \sim 0.1 \text{ g/cm}^3, \quad X_0 \sim 5 \text{ m} \]

  - high resolution tracking
    \[ \implies \text{mom. resolution } \sim 3.5\% \quad (p<10\text{GeV}/c); \]
  - fine-grained calorimeter
    \[ \implies \sigma(E)/E = 3.2\%/\sqrt{E[\text{GeV}]} \pm 1\%; \]
  - excellent lepton identification
    
    & charge measurement
    \[ \implies \text{can detect } \nu_\mu, \nu_e, \bar{\nu}_\mu, \bar{\nu}_e \text{ CC}. \]

- **Diagram showing the NOMAD detector layout**
  - Neutrino Beam
  - V8
  - Preshower Modules
  - Dipole Magnet
  - TRD
  - Hadronic Calorimeter
  - Drift Chambers
  - Electromagnetic Calorimeter
  - Muon Chambers
  - Veto Planes
  - Trigger Planes
  - Front Calorimeter
**DETERMINATION OF (ANTI)NEUTRINO FLUXES**

- **Detailed calculations developed for** $\nu_\mu \rightarrow \nu_e$ appearance search (LSND at high $\Delta m^2$):
  - FLUKA+GEANT3 description of primary target, beam focusing elements and secondary particle propagation along beam line
  - Constraints on $K/\pi$ vs. $p$ from dedicated SPY/NA56 hadroproduction experiment ($p$ on Be target at 450 GeV)

- **Validation of** $\nu$ and $\bar{\nu}$ fluxes from comparison with different CC spectra in NOMAD:
  - Standard/reversed horn polarity (focusing);
  - Horn / Reflectors switched off

- **Normalization of absolute flux** $\nu_\mu$ flux to world average DIS cross-section $\sigma(E)/E$ in the range $40 \text{ GeV} < E_\nu < 150 \text{ GeV}$ ($\sim 2.1\%$ precision)
  \[ \Rightarrow \text{Need only extrapolation of relative flux below 40 GeV} \]
MONTE CARLO SIMULATION

✧ **Quasi-Elastic (QE) neutrino scattering:**
  - Based upon the Smith-Monitz approach
  - Vector form factors $F_V$ and $F_M$ parameterized following the well-known GKex(05) form
  - Axial form factor with the dipole parameterization $F_A(Q^2) = F_A(0) \left[ 1 + Q^2/M_A^2 \right]^{-2}$

✧ **Single pion production via intermediate resonance state**
  - Based upon the Rein-Sehgal (RS) model
  - Set of 18 baryon resonances with masses below 2 GeV as in RS with parameters updated from PDG

✧ **Deep Inelastic Scattering (DIS)**
  - Primary interaction with modified LEPTO 6.1
  - Hadronization and decays with JETSET 7.4
  - Structure functions re-weighted with LO GRV 98 Bodek-Yang (BY), as well as with full NNLO calculation Alekhin, Kulagin and P. (AKP)

✧ **Benhar-Fantoni parameterization of momentum distribution $n(k)$ in nucleus**

✧ **Final State Interactions (FSI)** modeled with the DPMJET package based on the concept of the formation zone intra-nuclear cascade

✧ **Cross-check signal and background efficiencies with NUANCE and GENIE event generators interfaced with the NOMAD detector simulation and reconstruction**
**SELECTION OF QE EVENTS: 2-TRK SAMPLE**

- **Topologies classified based on # of reconstructed tracks with** \( N_{\text{HITS}} \geq 7 \rightarrow L \sim 18 \text{ cm} 
  - 1 \text{ track sample } (\mu) \rightarrow \text{complementary (control)}
  - 2 \text{ track sample } (\mu + p) \rightarrow \text{golden sample}
  - 3 \text{ track sample etc.}

- **Muon ID and** \( 0 \leq \phi_\mu \leq \pi \)

- **Proton ID with momentum-range relations**

- **Pre-selection cuts:**
  - Angle in transverse plane \( 0.8 \leq \alpha/\pi \leq 1 \)
  - Missing transverse momentum \( P_{\perp}^{\text{miss}} \leq 0.8 \text{ GeV/c} \)
  - Proton angle with beam \( 0.2 \leq \theta_h/\pi \leq 0.5 \)

- **Energy range** \( 3 \leq E_\nu \leq 100 \text{ GeV} \)

- **Kinematic selection with 3D likelihood function:**
  \[ L = [p_{\perp}^{\text{miss}}, \alpha, \theta_h] \]
  with discriminant \( \ln \lambda = \ln L_{\text{QE}}/L_{\text{RES}} \)
  \( \implies \) **Selected 3663 QE candidates in data with** \( \varepsilon_{\text{QE}} = 13\% \) and purity of 74\%.
**SELECTION OF QE EVENTS: 1-TRK SAMPLE**

- Only one reconstructed track with \# of hits $N_{\text{HITS}} \geq 7 \rightarrow L \sim 18 \text{ cm}$
  - Tighter fiducial volume cut than 2-trk sample
  - No reconstructed track segments other than the muon
- **Muon ID and** $0 \leq \phi_\mu \leq 2\pi$
- **Calculate neutrino energy** $E_\nu$ **and missing kinematic variables ($\theta_h$ etc.) assuming QE kinematics with nucleon at rest**
- **Transverse momentum of muon** $P_T^\mu > 0.2 \text{ GeV}/c$
- **Calculated energy (QE) range** $3 \leq E_\nu \leq 100 \text{ GeV}$
- **Muon emission angle** $\theta_\mu/\pi \leq 0.1$
- **Calculated proton angle** $0.35 \leq \theta_h/\pi \leq 0.5$

$\Rightarrow$ **Selected 10358 QE candidates in data with** $\varepsilon_{\text{QE}} = 21\%$ **and purity of 50\%**.
HiResM: A High Resolution Near Detector for the LBNE

R. Petti
University of South Carolina, USA

LBNE Near Detector Workshop
Columbia SC, December 12, 2009

Quasi-elastic \(\mu\) CC candidate in NOMAD

Proton 0.178 GeV/c

Muon 6.702 GeV/c

Proton 0.238 GeV/c

Muon 6.836 GeV/c
Overall $\nu_\mu$ CC QE candidates selected in data 14021 (1-trk + 2-trk) with total QE selection efficiency $\varepsilon_{QE} = 34\%$ and purity of about 50%.

Overall $\bar{\nu}_\mu$ CC QE candidates selected in data 2237 (1-trk) with total QE selection efficiency $\varepsilon_{QE} = 64\%$ and purity of about 38%.

Measurement of total QE cross-sections:
\[
\sigma_{QE}^\nu = [0.92 \pm 0.02(stat.) \pm 0.06(syst.)] \times 10^{-38} cm^2
\]
\[
\sigma_{QE}^{\bar{\nu}} = [0.81 \pm 0.05(stat.) \pm 0.08(syst.)] \times 10^{-38} cm^2
\]

Determination of the effective axial mass $M_A$ from fit to $\sigma(E) \oplus d\sigma/dQ^2$:
\[
M_A(\nu) = [1.06 \pm 0.02(stat.) \pm 0.06(syst.)] GeV
\]
\[
M_A(\bar{\nu}) = [1.06 \pm 0.07(stat.) \pm 0.10(syst.)] GeV
\]
NEW IMPROVED ANALYSIS

✦ A new measurement of QE cross-sections in NOMAD has been completed and is expected to be published next year
  ● Use complete kinematic range \(0 \leq \phi_{\mu} \leq 2\pi\) and larger fiducial volume
  ● More efficient kinematic selection (likelihood function and pre-selection)
  ● Better understanding of reconstruction systematics
  ● Calibration of backgrounds in control regions

\[\Rightarrow \text{Total 2-trk QE candidates selected } \sim 16800\]
with efficiency \(\epsilon_{\text{QE}} = 25\%\) and purity of 57%

\[\Rightarrow \text{Total 1-trk QE candidates selected } \sim 18600\]
with efficiency \(\epsilon_{\text{QE}} = 29\%\) and purity of 57%

\[\Rightarrow \text{High purity samples with tighter kinematic cuts}\]

✦ Measurement of total QE cross-section \(\sigma(E)\):
  \[\sigma_{\text{QE}}^\nu = [0.914 \pm 0.013(\text{stat.}) \pm 0.038(\text{syst.})] \times 10^{-38}\text{cm}^2\text{ avg. 1-trk + 2-trk}\]

✦ Measurement of differential cross-section \(d\sigma/dQ^2\)

✦ Model-independent study of nuclear effects and Final State Interactions (FSI) from comparison of 2-trk and 1-trk samples
Difference between measured 2-trk energy and calculated QE energy with nucleon at rest provides measurement of nuclear effects and FSI.
Comparison between 2-trk and 1-trk cross-sections gives model-independent constraint on FSI.
Good agreement with the $Q^2$ distribution in the 2-trk sample down to low values.
### Characteristics of selected $\nu_\mu$ QE events

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>NOMAD values</th>
</tr>
</thead>
<tbody>
<tr>
<td>QE event selection</td>
<td>2-trk sample: 1 identified muon + 1 identified proton</td>
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<tr>
<td></td>
<td>1-trk sample: 1 identified muon without any other rec. trk</td>
</tr>
<tr>
<td>Nuclear target</td>
<td>64% C, 22% O, 6% N, 5% H, 1.7% Al</td>
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<tr>
<td>Neutrino flux range</td>
<td>$2.5 &lt; E_\nu &lt; 300$ GeV</td>
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<tr>
<td>Sign-selection?</td>
<td>yes</td>
</tr>
<tr>
<td>Muon angular range</td>
<td>$0^0 &lt;</td>
</tr>
<tr>
<td></td>
<td>$0^0 &lt;</td>
</tr>
<tr>
<td>Muon energy range</td>
<td>$E_\mu &gt; 2$ GeV for muon ID</td>
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<tr>
<td>Proton detection threshold</td>
<td>$P \sim 200$ MeV/c</td>
</tr>
<tr>
<td>How is $E_\nu$ determined?</td>
<td>i) Sum of muon $E_\mu$ + proton $E_p$ from $p$ fit in B field (0.4 T)</td>
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<td></td>
<td>ii) Comparison with $E_\nu$ from QE kinematics (from muon only) gives direct</td>
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<td></td>
<td>measurement of nuclear effects</td>
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<td></td>
<td>iii) Comparison of 2-trk vs. 1-trk gives measurement of FSI</td>
</tr>
<tr>
<td>How is $Q^2$ determined?</td>
<td>2-trk sample: $Q^2 = -m_\mu^2 + 2E_\nu (E_\mu-p_\mu\cos\theta_\mu)$</td>
</tr>
<tr>
<td></td>
<td>1-trk sample: $Q^2_{QE}$</td>
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<tr>
<td>Monte Carlo generator</td>
<td>NOMAD generator (LEPTO/JETSET/DPMJET) checked with NUANCE</td>
</tr>
<tr>
<td></td>
<td>(tuned with NOMAD data, resonance Rein-Sehgal)</td>
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<tr>
<td></td>
<td>$d\sigma/dQ^2$, nuclear effects and FSI in C (new analysis)</td>
</tr>
</tbody>
</table>
FUTURE QE MEASUREMENTS WITH LBNE ND

✦ Next generation High-Resolution Near Detector (ND) for LBNE based upon the NOMAD concept:
  ● Low density magnetic spectrometer: \( B = 0.4 \ T, \rho \sim 0.1 \ g/cm^3 \), target \((C_3H_6)_n\)
  ● Straw Tube Tracker with \( \times 12 \) higher granularity than NOMAD
  ● Complete \( 4\pi \) coverage of calorimetry and muon ID

  \[ \implies \text{Improved } p \text{ resolution and reconstruction efficiency } w.r.t. \text{ NOMAD} \]

✦ Expect to collect \( \sim 10(5) \times 10^6 \nu(\bar{\nu}) \) QE events in 5y \( \nu + 5y \bar{\nu} \) data taking with energy range \( 0.5 \leq E_\nu \leq 20 \) GeV

✦ Protons easily identified by the large \( dE/dx \) in tracker & range

✦ New NOMAD QE analysis also used for sensitivity studies in LBNE ND
  \[ \implies \text{Same reconstruction & selection} \]

✦ Use multi-dimensional likelihood functions incorporating the full event kinematics to reject DIS & Res backgrounds
  \[ \implies \text{On average } \varepsilon = 52\% \text{ and } \eta = 82\% \text{ for CC QE at LBNE} \]
  \( \text{(New NOMAD } \varepsilon = 54\%, \eta = 57\%) \)