Present status of $\nu$ cross sections

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Introduction

- **Neutrino** interactions with **matter** are at the heart many interesting and physical processes: astrophysics, BSM, hadronic & nuclear physics.

- **Oscillation** experiments (with accelerator $\nu$ in the few-GeV region): T2K, NOvA, MicroBooNE, Hyper-K.

- Goals: $\nu$ mass hierarchy, CP violation.

- Good understanding of neutrino interactions are crucial for:
  - $\nu$ detection, flavor identification
  - reduction of systematic errors
    - $E_\nu$ reconstruction, $\nu$ flux calibration
    - determination of (irreducible) backgrounds
      
      e.g. $\nu_l \ N \rightarrow \nu_l \ \pi^0 \ N'$ in $\nu_\mu \rightarrow \nu_e$ searches

      $\nu_l \ N \rightarrow \nu_l \ \gamma \ N'$
Near detectors help to reduce systematic errors:

\[
\frac{N_{\text{events}}^{\text{far}}(E_\nu)}{N_{\text{events}}(E_\nu)} = \frac{\int \sigma(E'_\nu) \Phi(E'_\nu) P(E_\nu|E'_\nu) P_{\text{osc}}(E'_\nu) dE'_\nu}{\int \sigma(E'_\nu) \Phi(E'_\nu) P(E_\nu|E'_\nu) dE'_\nu}
\]

but c.s. uncertainties do not cancel (exactly) in the ratio

- exposed to different fluxes with different flavor composition
- different geometry, acceptance and targets
- Neutrino-nucleus c.s. mismodeling could lead to unacceptably large systematic uncertainties or biased measurements
- Precision of 1-5% in $\nu$ cross sections might be required
Introduction

CC cross sections: world data and NUANCE generator

DUNE flux
$\nu$ QE scattering on the nucleon

**CCQE:** $\nu(k) + n(p) \rightarrow \ell^-(k') + p(p')$

$\bar{\nu}(k) + p(p) \rightarrow \ell^+(k') + n(p')$

**NCE:** $\nu(k) + N(p) \rightarrow \nu(k') + N(p')$

$\bar{\nu}(k) + N(p) \rightarrow \bar{\nu}(k') + N(p')$

$M = G_F \cos \theta_C \frac{\sqrt{2}}{\sqrt{2}} l^\alpha J_\alpha$

where $l^\alpha = \bar{u}(k') \gamma^\alpha (1 - \gamma_5) u(k)$

$$J_\alpha = \bar{u}(p') \left[ \gamma_\alpha F_1^V + \frac{i}{2M} \sigma_{\alpha\beta} q^\beta F_2^V + \gamma_\mu \gamma_5 F_A + \frac{q_\mu}{M} \gamma_5 F_P \right] u(p)$$
QE scattering on the nucleon

- Dipole ansatz:

\[
F_A(Q^2) = g_A \left(1 + \frac{Q^2}{M_A^2}\right)^{-2}
\]

\[\langle r_A^2 \rangle = \frac{12}{M_A^2}\]

- Not theoretically justified
- Leads to artificially small errors in \(M_A\)

- \(z\)-expansion: Meyer et al., PRD 93 (2016) : Fit to ANL, BNL, FNAL data

\[<r_A^2> = 0.46(22) \text{ fm}^2 \text{ vs } 0.453(12) \text{ fm}^2 \text{ Bodek et al., EPJC 53 (2008)}\]
More precise information about $F_A$

Lattice QCD

$M_A = 1.39 \text{ GeV} \iff \langle r_A^2 \rangle = 0.24 \text{ fm}^2$

New CCQE measurements on D/H target

Modern data? heavier targets: CH$_{1,2}$, H$_2$O, $^{40}$Ar, $^{56}$Fe

Gupta et al., arXiv:1705.06834
CCQE on nuclear targets

- Relativistic Global Fermi Gas Smith, Moniz, NPB 43 (1972) 605
  - Impulse Approximation
  - Fermi motion \( f(\vec{r}, \vec{p}) = \Theta(p_F - |\vec{p}|) \)
  - Pauli blocking \( P_{\text{Pauli}} = 1 - \Theta(p_F - |\vec{p}|) \)
  - Average binding energy \( E = \sqrt{\vec{p}^2 + m_N^2} - \epsilon_B \)
  - Explains the main features of the (e,e') inclusive c.s in the QE region
  - Fails in the details (nuclear dynamics needed)
CCQE on nuclear targets

- **Spectral functions**

\[
D(p) = (\phi + M)G(p)
\]

\[
G(p) = \frac{1}{p^0 + E_p - i\epsilon} \left[ \int_{-\infty}^{\mu} \frac{A_h(\omega, \vec{p})}{p^0 - \omega - i\epsilon} d\omega + \int_{\mu}^{\infty} \frac{A_p(\omega, \vec{p})}{p^0 - \omega + i\epsilon} d\omega \right]
\]

\[
A_{p,h}(p) = \mp \frac{1}{\pi} \frac{\text{Im} \Sigma(p)}{[p^2 - M^2 - \text{Re} \Sigma(p)]^2 + [\text{Im} \Sigma(p)]^2}
\]

- \(\text{Im} \Sigma = 0 \Rightarrow \text{mean-field approximation}\)
\[
\frac{1}{\pi} \frac{\text{Im} \rho (\omega, \vec{p})}{\omega + i\epsilon} d\omega
\]

\( ^{12}\text{C} \ (e,e') \ X \)

Ankowski et al., PRD91 (2015)
CCQE on nuclear targets

- Spectral functions

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- \( \text{Im} \Sigma = 0 \Rightarrow \text{mean-field} \) approximation

- Significant improvement in the description of the \((e,e')\) c.s.

- Formalism applicable to inelastic inclusive scattering

- Realistic spectral functions are not available for heavier nuclei (like Ar)
CCQE-like on nuclear targets

- Two-nucleon (2p2h) contributions:
CCQE-like on nuclear targets

MiniBooNE puzzle (2009):

CCQE on $^{12}$C

![Graph showing CCQE data for various models compared to MiniBooNE data.](image-url)
CCQE-like on nuclear targets

- Two-nucleon (2p2h) contributions:
  - Martini et al., PRC 80 (2009)
  - Nieves et al., PRC 83 (2011)
  - Amaro et al., PLB 696 (2011)

- Unsubtracted CCQE-like events alter $E_\nu$ reconstruction, influencing oscillation analyses Lalakulich, Mosel, PRC 86 (2012); Coloma, Huber, PRL 111 (2013)
Weak resonance excitation

- **$\Delta$ (1232) excitation:**

\[
W, Z \quad \pi
\]

- **$N$-$\Delta$ transition current:**

\[
J^\mu = \bar{\psi}_\mu \left[ \left( \frac{C_3^V}{M} (g^\beta q - q^\beta \gamma^\mu) + \frac{C_4^V}{M^2} (g^\beta q \cdot p' - q^\beta p'^\mu) + \frac{C_5^V}{M^2} (g^\beta q \cdot p - q^\beta p^\mu) \right) \gamma_5 + \frac{C_3^A}{M} (g^\beta q - q^\beta \gamma^\mu) + \frac{C_4^A}{M^2} (g^\beta q \cdot p' - q^\beta p'^\mu) + C_5^A g^\beta + \frac{C_6^A}{M^2} q^\beta q^\mu \right] u
\]

- **Vector form factors**

  - extracted from data on $\pi$ photo- and electro-production
Weak resonance excitation

- $\Delta(1232) J^P=3/2^+$

$$J_\alpha = \bar{u}^\mu(p') \left[ \left( \frac{C^V_3}{M_N} (g_{\alpha \mu} q - q_\alpha \gamma_\mu) + \frac{C^V_4}{M^2_N} (g_{\alpha \mu} q \cdot p' - q_\alpha p'_\mu) + \frac{C^V_5}{M^2_N} (g_{\alpha \mu} q \cdot p - q_\alpha p_\mu) \right) \gamma_5 \right.$$ 

$$+ \frac{C^A_3}{M_N} (g_{\alpha \mu} q - q_\alpha \gamma_\mu) + \frac{C^A_4}{M^2_N} (g_{\alpha \mu} q \cdot p' - q_\beta p'_\mu) + C^A_5 g_{\alpha \mu} + \frac{C^A_6}{M^2_N} q_\alpha q_\mu \right] u(p)$$

- **Axial** form factors

- $C^A_5 = C^A_5(0) \left( 1 + \frac{Q^2}{M^2_{A\Delta}} \right)^{-2}$

- $C^A_5(0) = \sqrt{\frac{2}{3}} g_{\Delta N \pi} = 1.15 - 1.20 \quad g_{\Delta N \pi} \Leftrightarrow \Gamma(\Delta \rightarrow N \pi)$

- From **ANL** and **BNL** data on $\nu_\mu \ d \rightarrow \mu^- \ \pi^+ \ p \ n$

  - $M_{A\Delta} = 0.96 \pm 0.07 \ \text{GeV} \quad \text{LAR, Hernandez, Nieves, PRD (2016)}$
  - $C^A_{3,4}$: consistent with zero
  - Little (no) sensitivity to heavier baryon resonances
1π production on the nucleon

$$\nu_l N \rightarrow l \pi N'$$

- From Chiral symmetry:

Weak meson production

- **Strategy:**
  - Resonant + non-resonant amplitudes added coherently
  - Unitarization (in coupled channels)
  - Consistency with $\pi N$ and $\gamma(\ast)N$ reactions

- **E.g.:** Dynamical Coupled Channel (DCC) Model Nakamura et al., PRD92 (2015)
  - Based on a combined analysis of $\pi N$, $\gamma(\ast)N \rightarrow \pi N, \eta N, K\Lambda, K\Sigma$
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1π production on nuclei

- GiBUU Leitner, LAR, Mosel, PRC 73 (2006)
- Effects of FSI on pion kinetic energy spectra
  - strong absorption in Δ region
  - side-feeding from dominant π⁺ into π⁰ channel
  - secondary pions through FSI of initial QE protons

\[ \nu_\mu + ^{56}Fe \rightarrow \mu^- \pi X \quad E_\nu = 1 \text{ GeV} \]
$1\pi$ production on nuclei

- Comparison to MiniBooNE: $CC1\pi^0$ Aguilar-Arevalo, PRD83 (2011)

Hernandez et al., PRD87 (2013)

Lalakulich, Mosel, PRC87 (2013)
$1\pi$ production on nuclei

Comparison to T2K (ND280): $\text{CC}\pi^+$
Abe et al., PRD 95 (2017)

Comparison to MINERvA: $\text{CC}\pi^\pm$
Eberly et al., PRD 92 (2015)

Mosel, Gallmeister, arXiv:1702.04932
Fits are performed to extract PDF

Onset of DIS? Usually $W > 2$ GeV, $Q^2 > 1$ GeV$^2$

At low $W$, $Q^2$ non-trivial interplay of

- Higher Twists
- Nuclear corrections

MINERvA has observed an unexplained discrepancy in the shadowing region

\[ W^{\mu\nu} = W_1 \left( \frac{q^\mu q^\nu}{q^2} - g^{\mu\nu} \right) + \frac{W_2}{M^2} \left( p^\mu - \frac{p \cdot q}{q^2} q^\mu \right) \left( p^\nu - \frac{p \cdot q}{q^2} q^\nu \right) + W_3 i \epsilon^{\mu\nu\alpha\beta} \frac{p_\alpha q_\beta}{2M^2} \]
Instead of Conclusions

NuSTEC: Neutrino Scattering Theory Experiment Collaboration

http://nustec.fnal.gov/