Hadron and Nuclear Physics for Oscillation Experiments

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Introduction

- **ν** cross sections are **crucial** to achieve the **precision goals** of oscillation experiments

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

- **Need for theory?**
  - Measurements are not (cannot be) comprehensive
  - the same (semi)-inclusive cross section can correspond to **different exclusive final states**, depending on the reaction mechanism
  - measurements (partially) rely on **simulations ≈ theory** to determine efficiency, acceptance, …
  - \(E_{\nu}\) is not known: reconstructed using kinematics and/or calorimetry
  - \(\sigma(\nu_{\mu})\) to \(\sigma(\nu_{e})\) extrapolations
  - **Neutrino** c.s. mismodeling could lead to **unacceptably large** systematic uncertainties or biased measurements

F. Sanchez @ NuPhys2015
Nucleon axial form factor

- Fundamental **nucleon** property
- Main source of uncertainty for **QE scattering** on nucleons:
  
  **CCQE** : \( \nu(k) + n(p) \rightarrow l^-(k') + p(p') \)
  \( \bar{\nu}(k) + p(p) \rightarrow l^+(k') + n(p') \)

  **NCE** : \( \nu(k) + N(p) \rightarrow \nu(k') + N(p') \)
  \( \bar{\nu}(k) + N(p) \rightarrow \bar{\nu}(k') + N(p') \)

  \( q = k - k' = p' - p \)

- Largest contribution at **T2K, MicroBooNE**
- Used for kinematic **\( E_\nu \)** reconstruction:

\[
E_\nu^{QE} = \frac{2m_nE_\mu - m^2_\mu - m^2_n + m^2_p}{2(m_n - E_\mu + p_\mu \cos \theta_\mu)}
\]

- Input in models of non-resonant inelastic reactions (**meson production**) and **two-nucleon currents**
Nucleon axial form factor

- What is known:
  - $F_A(0) = g_A \leftarrow \beta$ decay
  - $F_A(\infty) \sim Q^{-4} \leftarrow \text{QCD}$

- Main source of information: bubble chamber (ANL, BNL, FNAL) data

- Dipole ansatz: Bodek et al., EPJC 53 (2008)
  \[
  F_A(Q^2) = g_A \left( 1 + \frac{Q^2}{M_A^2} \right)^{-2} \quad \langle r_A^2 \rangle = \frac{12}{M_A^2}
  \]

- $z$-expansion: Meyer et al., PRD 93 (2016)

- Neural networks + Bayesian statistics: LAR, Graczyk, Saúl-Sala, PRC 99 (2019)

- All methods obtain similar $F_A(Q^2)$…
Nucleon axial form factor

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

  $$\langle r_A^2 \rangle = 0.453(12) \text{ fm}^2$$

- $z$-expansion: Meyer et al., PRD 93 (2016)
  
  $$\langle r_A^2 \rangle = 0.46(22) \text{ fm}^2$$

- Neural networks + Bayesian statistics: LAR, Graczyk, Saúl-Sala, PRC 99 (2019)
  
  $$\langle r_A^2 \rangle = 0.471(15) \text{ fm}^2 \leftarrow \text{ANL only so far}$$

- All methods obtain similar $F(Q^2)$…

- …but with different errors
QE scattering on the nucleon

- **z-expansion** Meyer et al., PRD 93 (2016)

- At $E_\nu \sim 1$ GeV, $\sigma(\text{CCQE})$ has $\approx 10\%$ error

- More precise information about $F_A$ is needed
  - Direct or indirect CCQE measurement on n/p
  - Lattice QCD
- $g_A$ : lower than exp. values have been recurrently obtained

- Recent progress:
  - improved algorithms for a careful treatment of excited states
  - low pion masses

Constantinou, PoS CD15 (2015) 009
**Recent progress:**

- Alexandrou et al., PRD 96 (2017)
- Capitani et al., arXiv:1705.06186
- Gupta et al., PRD 96 (2017)

**Baryon ChPT analysis:** Yao, LAR, Vicente Vacas, PRD 96 (2017)

- $O(p^3)$, $Q^2 < 0.36 \text{ GeV}^2$, $130 \text{ MeV} < M_\pi < 473 \text{ MeV}$, explicit $\Delta(1232)$

- $g_A = 1.237(74)$, $<r_A^2> = 0.263(38) \text{ fm}^2$
Recent progress:

- Alexandrou et al., PRD 96 (2017)
- Capitani et al., arXiv:1705.06186
- Gupta et al., PRD 96 (2017)

More recent progress:

- **A percent-level determination of the nucleon axial coupling from QCD**
  - Chang et al., Nature 558 (2018)

- **Nucleon form factors at low $Q^2$ at the physical point**
  - Shintani et al., PRD 99 (2019)
1π production on the nucleon

\[ \nu_l \ N \rightarrow l \ \pi \ N' \]

- **CC:**
  \[
  \nu_\mu \ p \rightarrow \mu^- \ p \ \pi^+ , \quad \bar{\nu}_\mu \ p \rightarrow \mu^+ \ p \ \pi^- \\
  \nu_\mu \ n \rightarrow \mu^- \ p \ \pi^0 , \quad \bar{\nu}_\mu \ p \rightarrow \mu^+ \ n \ \pi^0 \\
  \nu_\mu \ n \rightarrow \mu^- \ n \ \pi^+ , \quad \bar{\nu}_\mu \ n \rightarrow \mu^+ \ n \ \pi^- 
  \]

- **source of CCQE-like events (in nuclei)**

- **needs to be subtracted for a good \( E_\nu \) reconstruction**

- **NC:**
  \[
  \nu_\mu \ p \rightarrow \nu_\mu \ p \ \pi^0 , \quad \bar{\nu}_\mu \ p \rightarrow \bar{\nu}_\mu \ p \ \pi^0 \\
  \nu_\mu \ p \rightarrow \nu_\mu \ n \ \pi^+ , \quad \bar{\nu}_\mu \ n \rightarrow \bar{\nu}_\mu \ n \ \pi^0 \\
  \nu_\mu \ n \rightarrow \nu_\mu \ n \ \pi^0 , \quad \bar{\nu}_\mu \ n \rightarrow \bar{\nu}_\mu \ n \ \pi^0 \\
  \nu_\mu \ n \rightarrow \nu_\mu \ p \ \pi^-, \quad \bar{\nu}_\mu \ n \rightarrow \bar{\nu}_\mu \ p \ \pi^-
  \]

- **e-like background to \( \nu_\mu \rightarrow \nu_e \) (T2K, NOvA)**
$\nu_l \, N \rightarrow l \, \pi \, N'$

- From Chiral symmetry:

Weak pion production in ChPT

- First comprehensive study in ChPT
- Yao, LAR, Hiller, Vicente Vacas, PRD 98 (2018);
  Yao, LAR, Vicente Vacas, PLB 794 (2019)
- EOMS, explicit $\Delta(1232)$, $O(p^3)$ in the $\delta$-counting: $\delta = m_\Delta - m_N \sim O(p^{1/2})$

  - \[ \begin{align*}
  \text{(a)} & \quad \text{(b)} & \quad \text{(c)} & \quad \text{(d)} \\
  \text{(e)} & \quad \text{(f)} & \quad \text{(g)} & \quad \text{(h)} \\
  \text{(i)} & \quad \text{(j)} & \quad \text{(k)} & \quad \text{(l)}
  \end{align*} \]

- **LECs**: 22 in total
  - 7 unknown (not very relevant)
  - 4 can be extracted from pion electroproduction
  - Information about remaining 3 could be obtained from new close-to-threshold measurements of $\nu$-induced $\pi$ production on protons

- Valid only close to threshold
- Benchmark for phenomenological models
$1\pi$ production on the nucleon

- Pheno models rely on (non-$\nu$) data as input and/or validation
- Vector current can be constrained with $\gamma N \rightarrow N \pi$, $e N \rightarrow e' N \pi$

- e.g. Dynamical Coupled Channel (DCC) Model Nakamura et al., PRD92 (2015)
1π production on the nucleon

- Pheno models rely on (non-ν) data as input and/or validation
- Vector current can be constrained with $\gamma N \rightarrow N \pi$, $e N \rightarrow e' N \pi$
- Axial current at $q^2 \rightarrow 0$ can be constrained with $\pi N \rightarrow N \pi$ (PCAC)

\[
\left. \frac{d\sigma_{CC\pi}}{dE_l d\Omega_l} \right|_{q^2=0} = \frac{G_F^2 V_{ud}^2}{2\pi^2} \frac{2f^2_{\pi}}{\pi} \frac{E^2_{l}}{E_{\nu} - E_l} \sigma_{\pi N}
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\]

- Very limited information about the **axial current** at $q^2 \neq 0$

- Some on $N-\Delta(1232)$ from ANL and BNL data on

  $\nu_\mu \ d \rightarrow \mu^- \pi^+ \ p \ n$

\[
C_5^A = C_5^A(0) \left(1 + \frac{Q^2}{M_{A\Delta}^2}\right)^{-2}
\]

  $M_{A\Delta} = 0.95 \pm 0.06 \text{ GeV}$

  LAR, Hernandez, Nieves, Vicente Vacas, PRD93(2016)

  Hernandez, Nieves, PRD 95 (2017)

- **Little** (no) sensitivity to heavier baryon resonances

- Lattice QCD
Inelastic form factors & LQCD

- N-Δ axial form factors in LQCD

Alexandrou et al., PRD83 (2011)

"The Δ is hard enough..."  C. Morningstar @ NSTAR 2019
1π production on the nucleon

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- Very limited information about the axial current at \( q^2 \neq 0 \)
  - Some on \( N-\Delta(1232) \) from ANL and BNL data on \( \nu_\mu d \rightarrow \mu^- \pi^+ p n \)
  - Little (no) sensitivity to heavier baryon resonances
  - Lattice QCD
  - Direct or indirect CC1π measurement on n/p

- There are hints (T. Sato @ ECT* 2019) that a \( q^2 \) dependence similar to the one exhibited by vector form factors might be more realistic
Neutrino interactions on nuclei

- Multiscale (even at a given $E_{\nu}$), multi-nucleon problem

- Shell structure, collective excitations, QE peak, …

- Initial state description: non-relativistic

- Final state interactions: (relativistic) NN, $\pi N$, …

**B. Frois, NPA 434 (1985)**
QE scattering

Initial nucleon:

- **Local Fermi Gas**
  - Fermi motion: \( p_F(r) = \left[ \frac{3}{2} \pi^2 \rho(r) \right]^{1/3} \)

- *(Relativistic)* mean field potential
  - Schrödinger/Dirac eq. \( \Rightarrow \) **bound-state** wave functions

- **Spectral function**
  
  \[ A(p) = \mp \frac{1}{\pi} \frac{\text{Im} \Sigma(p)}{[p^2 - M^2 - \text{Re} \Sigma(p)]^2 + [\text{Im} \Sigma(p)]^2} \]

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

- \( \text{Im} \Sigma \leftrightarrow \text{NN} \) interactions \( \Rightarrow \) **short-range** correlations
QE scattering

Final nucleon:

- Local Fermi Gas
  - Pauli blocking: $p_F(r) = \left[ \frac{3}{2} \pi^2 \rho(r) \right]^{1/3}$
- Plain waves
- Distorted waves
  - Schrödinger/Dirac eq. ⇒ continuum wave functions
  - Relativistic mean field for both initial and final nucleons ⇒ realistic scaling function

R. Gonzalez et al., PRC 94 (2014)
QE scattering

Final nucleon:

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- Distorted waves
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  - Approximate spectral functions
    - Improves the description of $(e,e')$ at low-momentum transfers
      Ankowski et al., PRD 91 (2015)
QE scattering

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Exclusive final states:
- QM: Distorted waves with complex optical potentials: 1N knockout
- Semi-classical:
  - Cascade: straightline trajectories + NN elastic and inelastic collisions
  - Transport (GiBUU): trajectories in a (x,p) dep. potential + NN collisions
$1\pi$ production on nuclei

- **GiBUU** Leitner, LAR, Mosel, PRC 73 (2006)
  - Effects of FSI on pion kinetic energy spectra
  - Strong absorption in $\Delta$ region
  - Side-feeding from dominant $\pi^+$ into $\pi^0$ channel
  - Secondary pions through FSI of initial QE protons

\[ v_\mu + ^{56}\text{Fe} \rightarrow \mu^- \pi X \quad E_\nu = 1 \text{ GeV} \]
\[ \pi \] production on \(^{12}\)C

**Comparison to MiniBooNE:**
Lalakulich, Mosel, PRC87 (2013)
\( \text{CC}_{\pi^0} \) data: Aguilar-Arevalo, PRD83 (2011)

**Comparison to T2K:**
Mosel, Gallmeister, PRC99 (2019)
\( \text{CC}_{\pi^\pm} \) data: R. Castillo, PhD Thesis (2015)
In spite of flux difference, *MiniBooNE* and *MINERvA* data probe the same dynamics and should be strongly correlated [Sobczyk, Zmuda, PRC 91 (2015)].
Two-nucleon currents

- MiniBooNE data for “CCQE” 2D cross section:
  - can be explained with a Relativistic Fermi Gas model and $M_A \approx 1.35 \text{ GeV}$
  - in disagreement with $M_A \approx 1 \text{ GeV}$ from bubble chamber data
  - but consistent with $F_A$ from the z-expansion

Aguilar-Arevalo et al., PRD81 (2010)
Two-nucleon currents

- **2-nucleon EW currents** exist (are allowed by symmetries)

- Sizable contribution can be inferred from $A(e,e')X$

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**References**

- Megias et al., PRD 94 (2016)
- Gallsmeiter et al., PRD 94 (2016)
Two-nucleon currents

- 2-nucleon EW currents exist (are allowed by symmetries)

- together with better QE nuclear models can explain MiniBooNE data with $M_A \approx 1$ GeV

Martini et al.  
Nieves et al.
Two-nucleon currents

- Large implications for oscillation measurements
- Bias in (kinematic) $E_\nu$ reconstruction

$$E_{\nu}^{QE} = \frac{2m_n E_\mu - m_\mu^2 - m_n^2 + m_p^2}{2(m_n - E_\mu + p_\mu \cos \theta_\mu)}$$

Martini et al., PRD 87 (2013)
Systematic errors are expensive: theory can help…

“(...) the impact of pion and nucleon production through higher-energy inelastic interactions could play a key role. For instance, particles produced in nuclear interactions below detection threshold, or neutrons escaping detection, can lead to a large amount of missing energy. These effects are difficult to quantify as they rely on the predictions of a given nuclear model. Unless they are kept under control, they will generate a bias in the determination of neutrino energy towards lower energies, which in turn would translate into a wrong determination of the value of $\delta_{CP}$.”

R. Acciarri et al., arXiv:1512.06148