Baryon Spectrum in Neutrino-induced Reactions

Luis Alvarez Ruso
Introduction

- **Neutrino** interactions with matter are at the heart of 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, DUNE

- **Goals**: $\nu$ mass hierarchy, CP violation
Introduction

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

- Good understanding and realistic modeling of $\nu$ interactions are **crucial** for
  - $\nu$ detection, flavor identification
  - reduction of **systematic errors**
    - $E_\nu$ reconstruction: using kinematics and/or calorimetry
    - determination of (irreducible) backgrounds

- **Neutrino** cross section mismodeling could lead to **unacceptably large** systematic uncertainties or biased measurements

- Precision of **1-5%** in $\nu$ cross sections might be required
Weak $1\pi$ production

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

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

- **source of CCQE-like events (in nuclei)**
- **needs to be subtracted for a good $E_\nu$ reconstruction**

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

- **e-like background to $\nu_\mu \rightarrow \nu_e$ (MiniBooNE, T2K, NOvA)**
Relevance for oscillation experiments

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- E.g. at MiniBooNE
Relevance for oscillation experiments

- **e-like background to** $\nu_\mu \rightarrow \nu_e$

- E.g. at MiniBooNE

Aguilar-Arevalo et al., PRL102 (2009) 101802

- **NC backgrounds:**
  - $\nu_l N \rightarrow \nu_l \pi^0 N'$
  - $\nu_l N \rightarrow \nu_l \gamma N'$
Weak $1\pi$ production in BChPT

- Yao, LAR, Hiller, Vicente Vacas, PRD 98 (2018);
  Yao, LAR, Vicente Vacas, PLB 794 (2019)

- First comprehensive study in ChPT
- $O(p^3)$ in EOMS regularization scheme
- Explicit $\Delta(1232)$, in the $\delta$-counting: $\delta = m_\Delta - m_N \sim O(p^{1/2})$
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- LECs:
  - 22 in total (CC case)
  - 7 unknown (but not very relevant)
    - 4 of them can be extracted from pion electroproduction
  - information about remaining 3 LEC could be obtained from new close-to-threshold measurements of $\nu$-induced $\pi$ production on protons
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- $O(p^3)$ in EOMS regularization scheme
- Explicit $\Delta(1232)$, in the $\delta$-counting: $\delta = m_\Delta - m_N \sim O(p^{1/2})$

- Valid only close to threshold
- Benchmark for phenomenological models
Pheno Weak $1\pi$ production

- Pheno models rely on (non-$\nu$) data as input and/or validation

- From Chiral symmetry:

\[\begin{array}{c}
\text{W, Z} \\
\text{N} \rightarrow \text{N} \rightarrow \text{N} \rightarrow \text{N} \\
\text{W, Z} \\
\text{N} \rightarrow \text{N} \rightarrow \text{N} \rightarrow \text{N} \\
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\text{W, Z} \\
\text{N} \rightarrow \text{N} \rightarrow \text{N} \rightarrow \text{N} \\
\text{W, Z} \\
\text{N} \rightarrow \text{N} \rightarrow \text{N} \rightarrow \text{N} \\
\end{array}\]

**Pheno Weak $1\pi$ production**

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

  \[
  \begin{align*}
  W, Z & \rightarrow \Delta & \pi \\
  N & \rightarrow \Delta & N
  \end{align*}
  \]

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

  \[
  J^\mu = \overline{\psi}_\mu \left[ \left( \frac{C^V_3}{M} (g^{\beta\mu} q - q^\beta \gamma^\mu) + \frac{C^V_4}{M^2} (g^{\beta\mu} q \cdot p' - q^\beta p'^\mu) + \frac{C^V_5}{M^2} (g^{\beta\mu} q \cdot p - q^\beta p^\mu) \right) \gamma_5 \\
  + \frac{C^A_3}{M} (g^{\beta\mu} q - q^\beta \gamma^\mu) + \frac{C^A_4}{M^2} (g^{\beta\mu} q \cdot p' - q^\beta p'^\mu) + C^A_5 g^{\beta\mu} + \frac{C^A_6}{M^2} q^\beta q^\mu \right] u
  \]

- **Vector form factors $\Leftrightarrow$ Helicity amplitudes**
Pheno Weak $1\pi$ production

- N-Δ transition current

$$J^\mu = \bar{\psi}_\mu \left[ \left( \frac{C^V_3}{M} (g^\beta \mu \sigma - q^\beta \gamma^\mu) + \frac{C^V_4}{M^2} (g^\beta \mu q \cdot p' - q^\beta p'^\mu) + \frac{C^V_5}{M^2} (g^\beta \mu q \cdot p - q^\beta p^\mu) \right) \gamma_5 \\
+ \frac{C^A_3}{M} (g^\beta \mu \sigma - q^\beta \gamma^\mu) + \frac{C^A_4}{M^2} (g^\beta \mu q \cdot p' - q^\beta p'^\mu) + C^A_5 g^\beta \mu + \frac{C^A_6}{M^2} q^\beta q^\mu \right] u$$

- MAID Helicity amplitudes:

Tiator et al., EPJ Special Topics 198 (2011)
Pheno Weak 1π production

- N-Δ transition current

\[ J^\mu = \bar{\psi}_\mu \left[ \left( \frac{C_V^3}{M} (g^\beta \mu \not{q} - q^\beta \gamma^\mu) + \frac{C_V^4}{M^2} (g^\beta \mu q \cdot p' - q^\beta p'^\mu) + \frac{C_V^5}{M^2} (g^\beta \mu q \cdot p - q^\beta p^\mu) \right) \gamma_5 \right. \\
\left. + \frac{C_A^3}{M} (g^\beta \mu \not{q} - q^\beta \gamma^\mu) + \frac{C_A^4}{M^2} (g^\beta \mu q \cdot p' - q^\beta p'^\mu) + C_A^5 g^\beta \mu + \frac{C_A^6}{M^2} q^\beta q^\mu \right] u \]

- Axial form factors

\[ C_A^5(0) = \sqrt{\frac{2}{3}} g_{\Delta N\pi} \leftarrow \text{off diagonal Goldberger-Treiman relation} \]

\[ \mathcal{L}_{\Delta N\pi} = -\frac{g_{\Delta N\pi}}{f_\pi} \bar{\Delta}_\mu (\partial^\mu \pi) \bar{T}_N \]

- Deviations from GTR arise from chiral symmetry breaking

  - expected only at the few % level
Pheno Weak $1\pi$ production

- N-$\Delta$ axial form factors
- $Q^2$ dependence: $C^A_5 = C^A_5(0) \left(1 + \frac{Q^2}{M^2_{A\Delta}}\right)^{-2}$
- From ANL and BNL data on $\nu_\mu d \rightarrow \mu^- \pi^+ p n$
- $M_{A\Delta} = 0.95 \pm 0.06$ GeV
- Unitarization in the leading vector and axial multipoles: phases enforced to fulfill Watson’s theorem LAR, Hernandez, Nieves, Vicente Vacas, PRD 93 (2016)
- Consistent $\Delta$ couplings Hernandez, Nieves, PRD 95 (2017)
Pheno Weak $1\pi$ production

- N-$\Delta$ axial form factors
- $Q^2$ dependence: $C_5^A = C_5^A(0) \left(1 + \frac{Q^2}{M_{A\Delta}^2}\right)^{-2}$

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

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

- ANL and BNL data do not constrain $C_{A3,4}^A$: consistent with zero
- Little (no) sensitivity to heavier baryon resonances
Weak Resonance excitation

- Vector transition form factors can be obtained from partial wave analyses, e.g. MAID
- Goldberger-Treiman relations can be derived for leading axial couplings
- No information about $Q^2$ dependence
- Calculations assume dipole shapes with $M_A = 1$ GeV

Weak Resonance excitation

- Baryon resonances contribute to:
  - the inclusive $\nu_l N \rightarrow l X$ cross section
  - several exclusive channels: $\nu_l N \rightarrow l N' \pi$
    $\nu_l N \rightarrow l N' \gamma$
    $\nu_l N \rightarrow l N' \eta$
    $\nu_l N \rightarrow l \Lambda(\Sigma) K$

- At $E_\nu \sim 1$ GeV (MiniBooNE, MicroBooNE, T2K) $\Delta(1232)$ is dominant
- At $E_\nu > 1$ GeV (MINOS, NOvA, DUNE) $N^*$ become also important
Weak $\eta$ production

- M. Rafi Alam, LAR, M. Sajjad Athar, M. J. Vicente Vacas, in preparation
- $\nu_l N \rightarrow l N' \eta$
- Ingredients: s,u-channel nucleon pole, $N^*(1535)$, $N^*(1650)$
- Consistency with $\gamma(\star)N \rightarrow \eta N$ data
Weak $\eta$ production

- M. Rafi Alam, LAR, M. Sajjad Athar, M. J. Vicente Vacas, in preparation
- $\nu_l N \rightarrow l N' \eta$
- **Ingredients**: s,u-channel nucleon pole, $N^*(1535)$, $N^*(1650)$
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- Ingredients: s,u-channel nucleon pole, $N^*(1535), N^*(1650)$
- Consistency with $\gamma(*)N \rightarrow \eta N$ data
Pheno Weak $1\pi$ production

- **ANL-Osaka Dynamical Coupled Channel (DCC) Model**
  Nakamura et al., PRD92 (2015)
- Resonant ($\Delta, N^*$) + non-resonant amplitudes added coherently
- Unitarization: Lippmann-Schwinger eq.
- Vector current can be constrained with $\gamma^*(N) \rightarrow \pi N, \pi\pi N, \eta N, K\Lambda, K\Sigma$
Pheno Weak $1\pi$ production

- ANL-Osaka Dynamical Coupled Channel (DCC) Model
  Nakamura et al., PRD92 (2015)
  - Resonant ($\Delta, N^*$) + non-resonant amplitudes added coherently
  - Unitarization: Lippmann-Schwinger eq.
  - Axial current at $q^2 \rightarrow 0$ can be constrained with $\pi N \rightarrow \pi N, \pi\pi N, \eta N, K\Lambda, K\Sigma$ (PCAC)

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

- Dipole $q^2$ dependence of the axial current
Pheno Weak $1\pi$ production

- ANL-Osaka Dynamical Coupled Channel (DCC) Model
  Nakamura et al., PRD92 (2015)
  - Resonant ($\Delta, N^*$) + non-resonant amplitudes added coherently
  - Unitarization: Lippmann-Schwinger eq.

![Graphs showing $\sigma$ vs $E_v$ for ANL and BNL measurements]
Pheno Weak meson production

- ANL-Osaka Dynamical Coupled Channel (DCC) Model
  Nakamura et al., PRD92 (2015)
  - Resonant ($\Delta$, $N^*$) + non-resonant amplitudes added coherently
  - Unitarization: Lippmann-Schwinger eq.

\[ \nu_\mu \ p \rightarrow \]
\[ \nu_\mu \ n \rightarrow \]
Weak strangeness production

- $\bar{\nu}_l p \rightarrow l^+ \phi B$  
  Ren, Oset, LAR, Vicente Vacas, PRC91 (2015)

$\phi B = K^- p, \bar{K}^0 n, \pi^0 \Lambda, \pi^0 \Sigma^0, \eta \Lambda, \eta \Sigma^0, \pi^+ \Sigma^-, \pi^- \Sigma^+, K^+ \Xi^-, K^0 \Xi^0$

- $\Delta S = -1$:
  - Cabibbo suppressed but with lower thresholds than $\Delta S = 0$
  - Induced by anti-$\nu$ but not by $\nu$

- $\Sigma \pi$:  
  - $\bar{\nu}_l p \rightarrow l^+ \Sigma^0 \pi^0$
  - $\bar{\nu}_l p \rightarrow l^+ \Sigma^+ \pi^-$
  - $\bar{\nu}_l p \rightarrow l^+ \Sigma^- \pi^+$

- can proceed through the excitation of $\Lambda$ or $\Sigma$ resonances
  - in particular: $\Lambda(1405)$
Weak strangeness production

- $\bar{\nu}_l p \rightarrow l^+ \phi B$  
  Ren, Oset, LAR, Vicente Vacas, PRC91 (2015)

$\phi B = K^- p, \bar{K}^0 n, \pi^0 \Lambda, \pi^0 \Sigma^0, \eta \Lambda, \eta \Sigma^0, \pi^+ \Sigma^-, \pi^- \Sigma^+, K^+ \Xi^-, K^0 \Xi^0$

- SU(3) symmetric chiral Lagrangian
- Physical hadron masses
- Couplings depend on $v_{us}$ and $D, F, f_\pi \leftarrow$ fixed by semileptonic decays
- Global dipole form factor

$$F(q^2) = \left(1 - \frac{q^2}{M_F^2}\right)^{-2} \quad M_F = 1 \pm 0.1 \text{ GeV}$$

- s-wave projection
- Unitarization in coupled channels
Weak strangeness production

- $\bar{\nu}_l p \rightarrow l^+ \phi B$
  - Ren, Oset, LAR, Vicente Vacas, PRC91 (2015)
  - Unitarization in coupled channels

\[
\phi B = K^- p, \bar{K}^0 n, \pi^0 \Lambda, \pi^0 \Sigma^0, \eta \Lambda, \eta \Sigma^0, \pi^+ \Sigma^-, \pi^- \Sigma^+, K^+ \Xi^-, K^0 \Xi^0
\]

- T: Solution of the Bethe-Salpeter eq. in coupled channels
  \[
  T = V + VGT = [1 - VG]^{-1}V
  \]

- V: from leading order chiral Lagrangian
- Cut-off regularization of the loop functions with $q_{\text{max}} = 630$ MeV
- Oset, Ramos, NPA635 (1998)
Weak strangeness production

- $\bar{\nu}_l p \rightarrow l^+ \phi B$
  
  Ren, Oset, LAR, Vicente Vacas, PRC91 (2015)

$\phi B = K^- p, \bar{K}^0 n, \pi^0 \Lambda, \pi^0 \Sigma^0, \eta \Lambda, \eta \Sigma^0, \pi^+ \Sigma^-, \pi^- \Sigma^+, K^+ \Xi^-, K^0 \Xi^0$

- Unitarization in coupled channels

- $\Lambda(1405)$ dynamically generated

- Two poles:
  - $M \approx 1385 \text{ MeV}, \Gamma \approx 150 \text{ MeV}$
  - $M \approx 1420 \text{ MeV}, \Gamma \approx 40 \text{ MeV}$

- $\bar{\nu}_l p \rightarrow l^+ \Lambda(1405)$ vs $\gamma p \rightarrow K^+ \pi \Sigma, e p \rightarrow e' K^+ \Lambda(1405)$
  - no lineshape distortion due to $K^+ \Lambda(1405)$ FSI
  - but Cabibbo suppressed
Weak strangeness production

- $\bar{\nu}_l p \to l^+ \Sigma \pi$
  
  Ren, Oset, LAR, Vicente Vacas, PRC91 (2015)

- Cross sections largely driven by the $\Lambda(1405)$ resonance
- Differences in strength vs the $\pi^0 \Sigma^0$ channel from the $I=1$ amplitude
- Single asymmetric peak with more weight from the 1420 MeV pole
Weak strangeness production

\[ \bar{\nu}_l p \rightarrow l^+ \Sigma \pi \]

Ren, Oset, LAR, Vicente Vacas, PRC91 (2015)

- Single asymmetric peak with more weight from the 1420 MeV pole
- Backwards: ~ Breit-Wigner resonance with \( M \approx 1420 \text{ MeV}, \Gamma \approx 40 \text{ MeV} \)
- Although \( d^2\sigma(\cos\theta = 1) \sim d^2\sigma(\cos\theta = 1)/14 \)
Conclusions and Outlook

- The ongoing $\nu$ oscillation program requires a precise description of weak inelastic processes.
- Theoretical studies rely on experimental information on $\gamma(\star)N, \pi N \rightarrow \pi N, \pi\pi N, \eta N, K\Lambda, K\Sigma$
- Other advanced models $\sim$ ANL-Osaka DCC are needed.
- Experimental information on the $Q^2$ dependence of the inelastic axial current is almost inexistent.
- Precise information at the nucleon level cannot be extracted from $\nu$-nucleus data
Conclusions and Outlook

- The ongoing $\nu$ oscillation program requires a precise description of weak inelastic processes.
- Theoretical studies rely on experimental information on $\gamma(\pi)N$, $\pi N \rightarrow \pi N$, $\pi\pi N$, $\eta N$, $K\Lambda$, $K\Sigma$.
- Other advanced models $\sim$ ANL-Osaka DCC are needed.
- Experimental information on the $Q^2$ dependence of the inelastic axial current is almost inexistent.
- Precise information at the nucleon level cannot be extracted from $\nu$-nucleus data: $\nu_\mu + ^{56}Fe \rightarrow \mu^- \pi X$, $E_{\nu} = 1$ GeV.
Conclusions and Outlook

- The ongoing \( \nu \) oscillation program requires a precise description of weak inelastic processes.
- Theoretical studies rely on experimental information on \( \gamma(\ast)N, \pi N \to \pi N, \pi \pi N, \eta N, K\Lambda, K\Sigma \)
- Other advanced models \( \sim \) ANL-Osaka DCC are needed.
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- LQCD?
Conclusions and Outlook

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- Theoretical studies rely on experimental information on $\gamma(*)N, \pi$.
- Other advanced models (e.g., ANL-Osaka DCC) are needed.
- Experimental information on the $Q^2$ dependence of the inelastic axial current is almost nonexistent.
- Precise information at the nucleon level cannot be extracted from $-n$ucleus data.
- LQCD: "The $\Delta$ is hard enough..." C. Morningstar @ NSTAR 2019
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- Experimental information on the $Q^2$ dependence of the inelastic axial current is almost inexistent.
- Precise information at the nucleon level cannot be extracted from $\nu$-nucleus data.
- LQCD
- New measurements of $\nu$ cross sections on H and D are highly desirable
  - Directly: safety concerns...
  - Indirectly: e.g. subtraction techniques $CH_2 - C$
    Duyang et al., arXiv:1809.08752
- Opportunities for hadronic and BSM (NSI) physics