Symposium on Effective Field Theories and Lattice Gauge Theory

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Effective Field Theory Gauge Lattice

Hadronic matrix elements for Neutrino Cross sections

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IFIC INSTITUT DE FÍSICA CORPUSCULAR

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EXCELENCIA SEVERO OCHOA

Introduction

- Neutrino interactions with matter are at the heart all experiments seeking to unravel its nature.
- Oscillation experiments (with accelerator ν in the few-GeV region): T2K, NOvA, MicroBooNE, Hyper-K, DUNE/LBNF
  - Goals: ν mass hierarchy, CP violation
  - Good understanding of neutrino interactions are important for:
    - ν detection, flavor ID
    - reduction of systematic errors
      - E_ν reconstruction, ν flux calibration
      - determination of (irreducible) backgrounds
  - Precision of 1-5% in ν cross sections might be required

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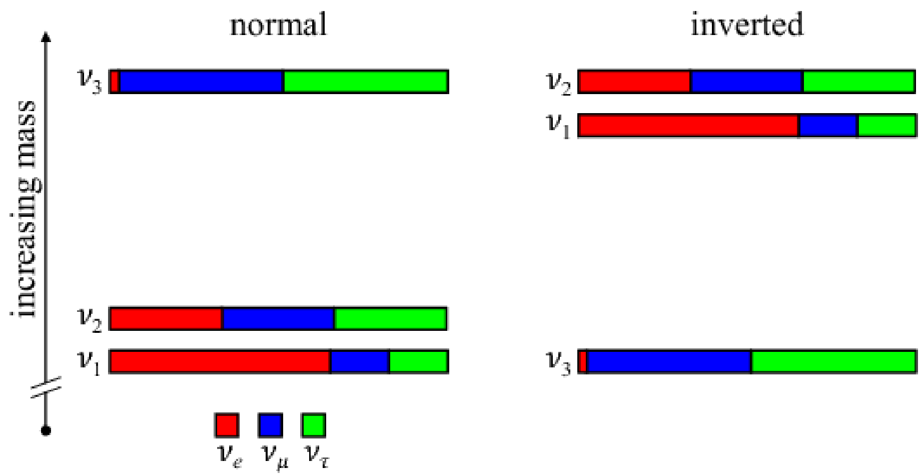

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ν experiments

need you!

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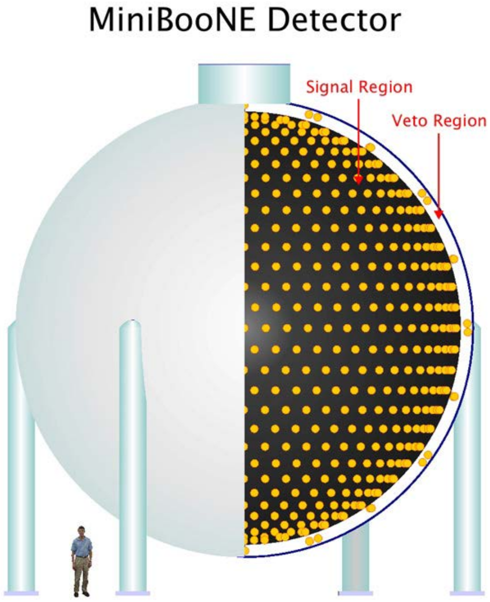
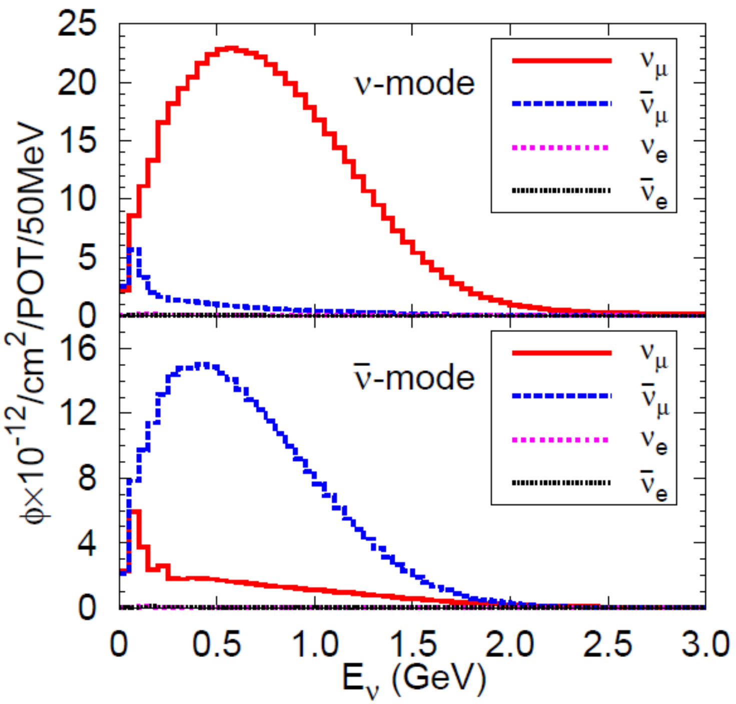
  - E.g. in the MiniBooNE $\nu_\mu \to \nu_e$ search





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- Oscillation experiments (with accelerator ν in the few-GeV region)
  - E.g. in the MiniBooNE $\nu_\mu \to \nu_e$ search
  - Charged current quasielastic scattering (CCQE)
    - ν detection and flavor ID
    - Kinematic E_ν reconstruction

$$\nu_l \, n \to l^- \, p$$
$$\bar{\nu}_l \, p \to l^+ \, n$$

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

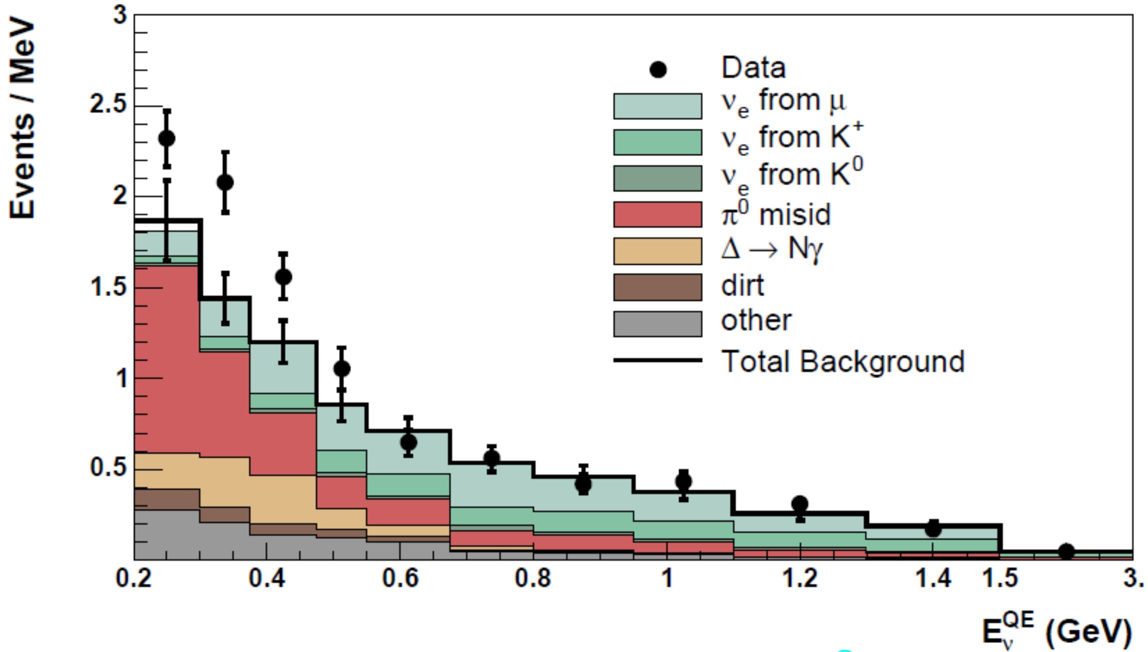
- Needed for oscillation studies:

$$P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta_{23} \, \sin^2 \frac{\Delta m_{23}^2 L}{4E_\nu}$$

Relevance for oscillation experiments

- E.g. in the MiniBooNE $\nu_\mu \to \nu_e$ search
  - Backgrounds

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



  - NC backgrounds: $\nu_l \, N \to \nu_l \, \pi^0 \, N'$

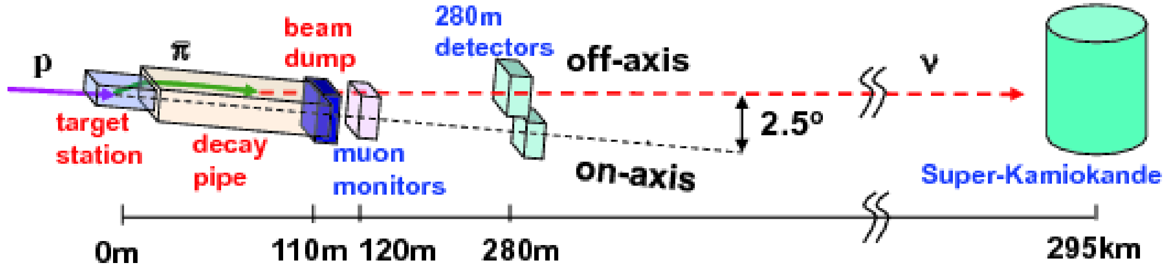
$$\nu_l \, N \to \nu_l \, \gamma \, N'$$

  - Dominated by baryon resonance excitation

Introduction

- Oscillation experiments (with accelerator ν in the few-GeV region)
- Experiments with near & far detectors: T2K, NOvA, MicroBooNE, Hyper-K, DUNE/LBNF

T2K



- Near detectors help to reduce systematic errors:

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

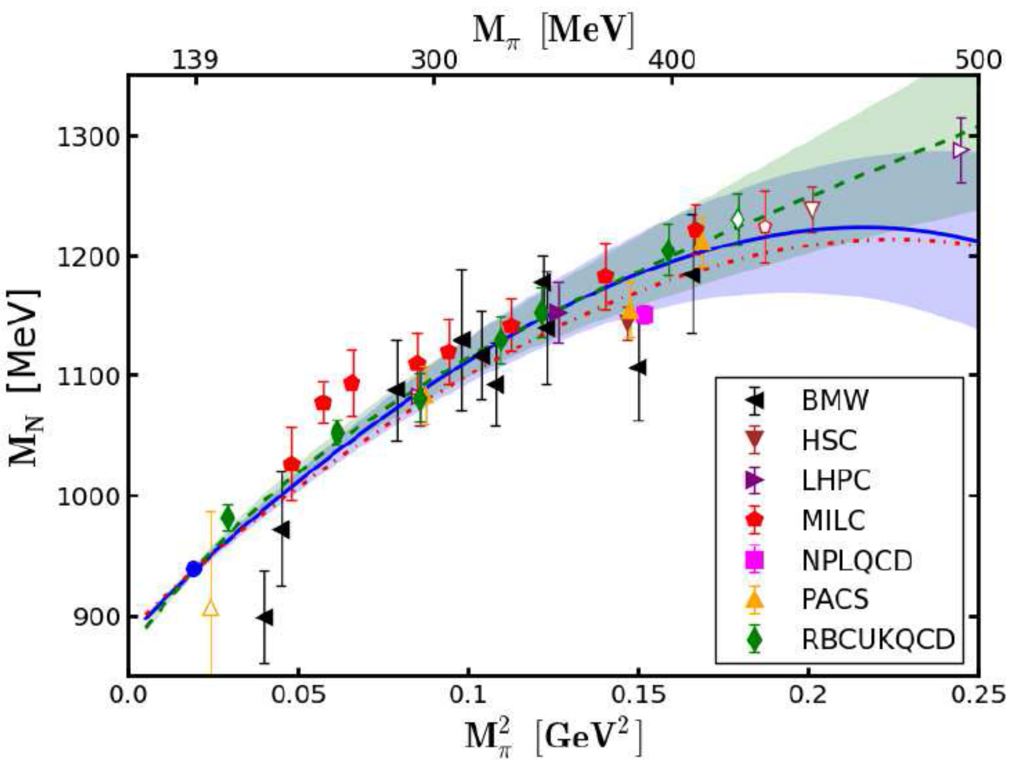
F. Sanchez @ NuPhys2015

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

- exposed to different fluxes with different flavor composition
- different geometry, acceptance and targets

Analogies with direct DM searches

- XENON, LUX, ...
- Spin independent WIMP-Nucleus cross section $\sim \sigma^2_{\pi N}$
- πN sigma term can be extracted using ChPT + lQCD
- With SU(2) p^4 covariant BChPT with $\Delta(1232)$ LAR et al., PRD 88 (2013)



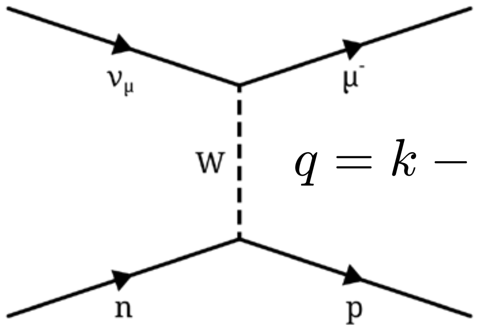
$N_f = 2+1$

Without $\Delta(1232)$: $\sigma_{\pi N}$ =55(3) MeV

With $\Delta(1232)$: $\sigma_{\pi N}$ =44(3) MeV

QE scattering on the nucleon

$$\text{CCQE}: \nu(k) + n(p) \to l^-(k') + p(p')$$
$$\bar{\nu}(k) + p(p) \to l^+(k') + n(p')$$
$$\text{NCE}: \nu(k) + N(p) \to \nu(k') + N(p')$$
$$\bar{\nu}(k) + N(p) \to \bar{\nu}(k') + N(p')$$



$$q = k - k' = p' - p$$

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

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

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

- Vector form factors: $F_{12}^V = F_{12}^p - F_{12}^n$

$$G_E = F_1 + \frac{q^2}{2m_N}F_2 \quad \leftarrow \text{electric}$$

$$G_M = F_1 + F_2 \quad \leftarrow \text{magnetic}$$

QE scattering on the nucleon

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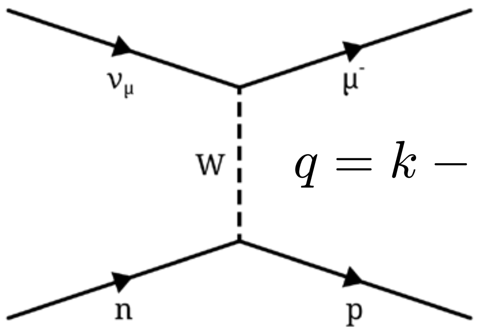

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- Axial form factors:

$$F_A(Q^2) = g_A F(Q^2)\,,\; F_P(Q^2) = \frac{2M^2}{Q^2+m_\pi^2}F_A(Q^2)\,,\; Q^2 = -q^2 > 0$$

$g_A = 1.267 \leftarrow \beta$ decay

PCAC

QE scattering on the nucleon

- Axial form factor: Q^2 dependence
  - CCQE on H and D (BNL, ANL) $\leftarrow$ early 80s

$$F_A(Q^2) = g_A \left(1 + \frac{Q^2}{M_A^2}\right)^{-2} \qquad \langle r_A^2 \rangle = \frac{12}{{M_A}^2}$$

- $M_A = 1.016 \pm 0.026$ GeV   Bodek et al., EPJC 53 (2008)

  - From π electroproduction on p: Bernard et al., PRL69 (1992)

$$6 \left. \frac{dE_{0+}^{(-)}}{dq^2} \right|_{q^2=0} = \langle r_A^2 \rangle + \frac{3}{M}\left(\kappa^{\mathrm{V}} + \frac{1}{2}\right) + \frac{3}{64 f_\pi^2}\left(1 - \frac{12}{\pi^2}\right)$$

- $M_A = 1.014 \pm 0.016$ GeV   Liesenfeld et al., PLB 468 (1999) 20

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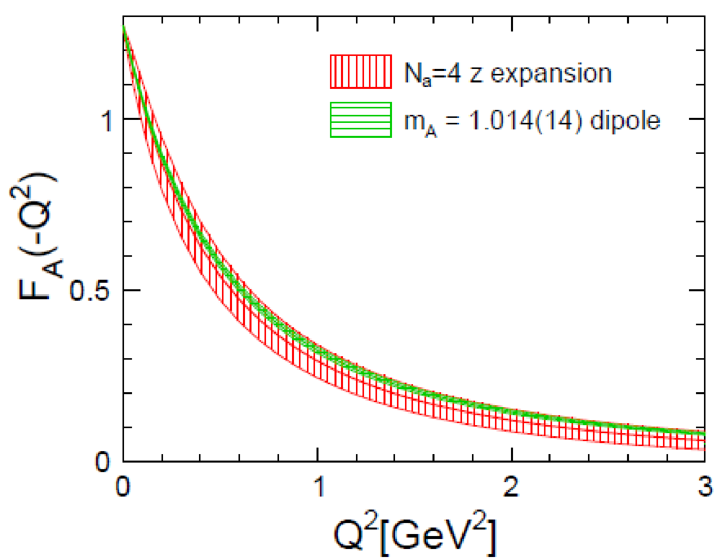
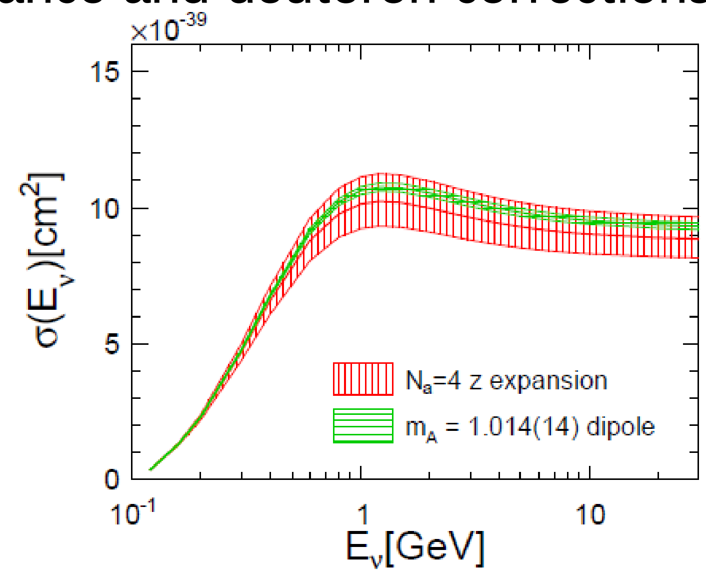
QE scattering on the nucleon

- Dipole ansatz
  - Not theoretically justified
  - Leads to artificially small errors in M_A

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

- z-expansion Meyer et al., arXiv:1603.03048
  - Fit to ANL, BNL, FNAL data
  - Systematic errors: acceptance and deuteron corrections

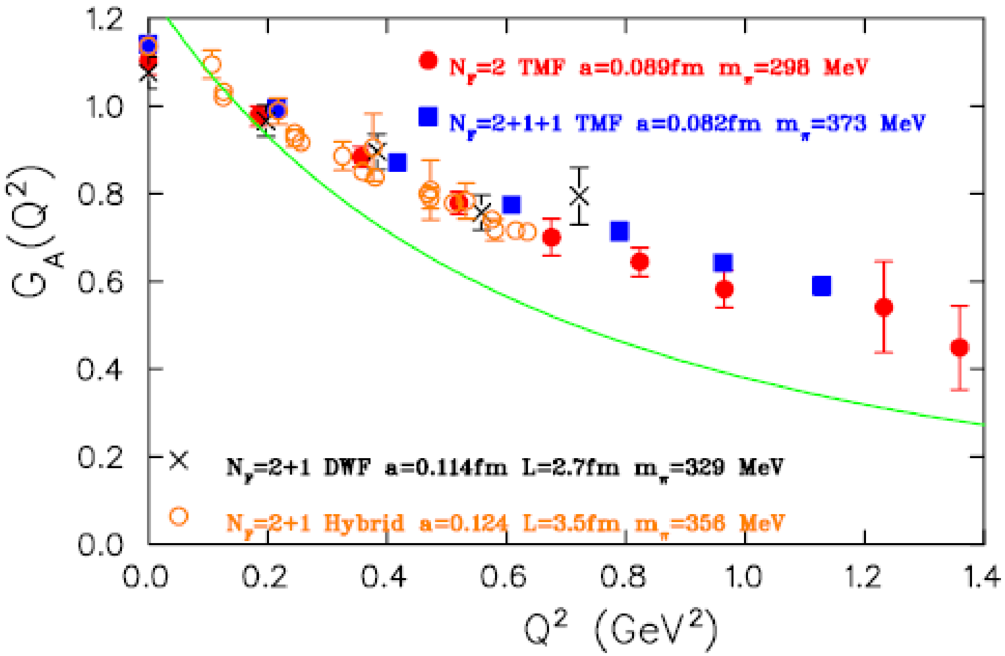




- $\langle r_A^2 \rangle$ = 0.46(22) fm^2 vs 0.453(12) fm^2 Bodek et al., EPJC 53 (2008)

F_A & lQCD

- More precise information about F_A
  - New CCQE measurements on D/H target
  - lQCD

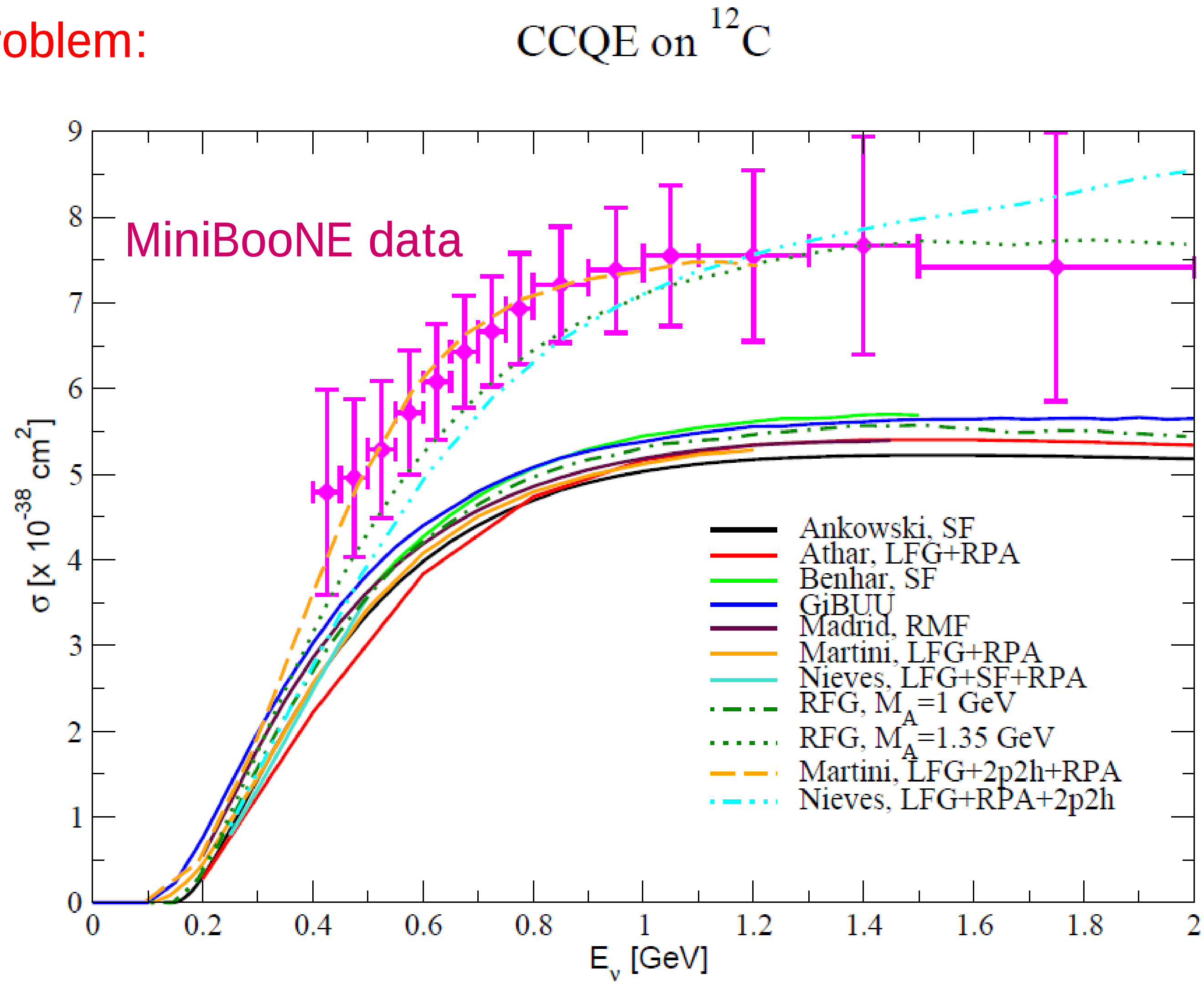


Alexandrou et al., PRD 88 (2013)

  - m_π = 373 MeV $\Rightarrow$ M_A = 1.60(5) GeV $\Leftrightarrow$ $<r_A^2>$ =0.183(6) fm^2
  - Modern data?

CCQE on nuclear targets

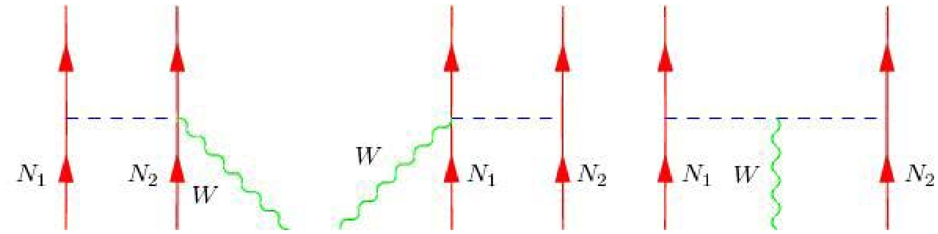
The problem:



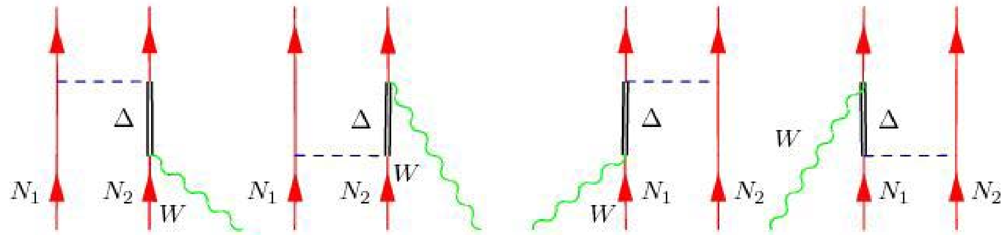
CCQE-like on nuclear targets

The solution:

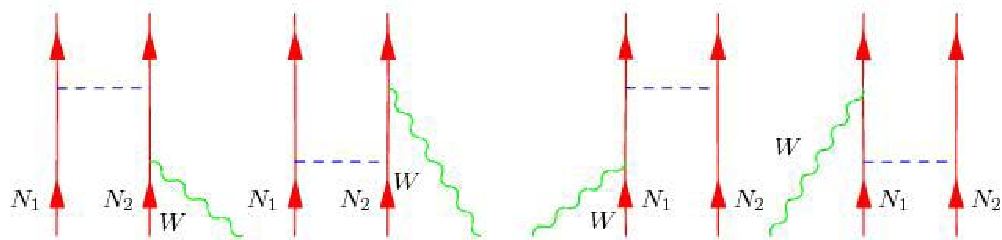
- multinucleon (2p2h) contributions
  - Martini et al., PRC 80 (2009)
  - Nieves et al., PRC 83 (2011)
  - Amaro et al., PLB 696 (2011)
- + RPA (important at low Q^2)



Contact and *pion-in-flight* diagrams



Δ-Meson Exchange Current diagrams



Correlation diagrams

CCQE-like on nuclear targets

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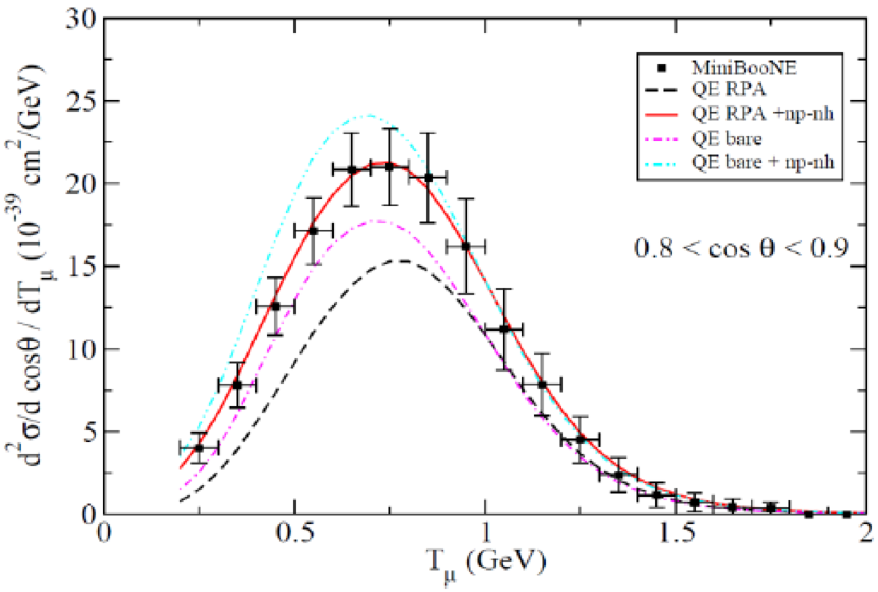
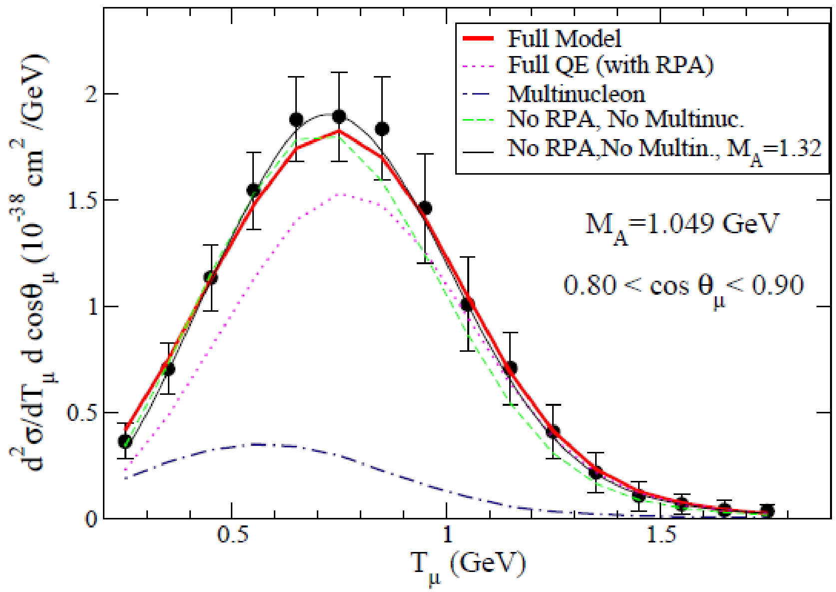
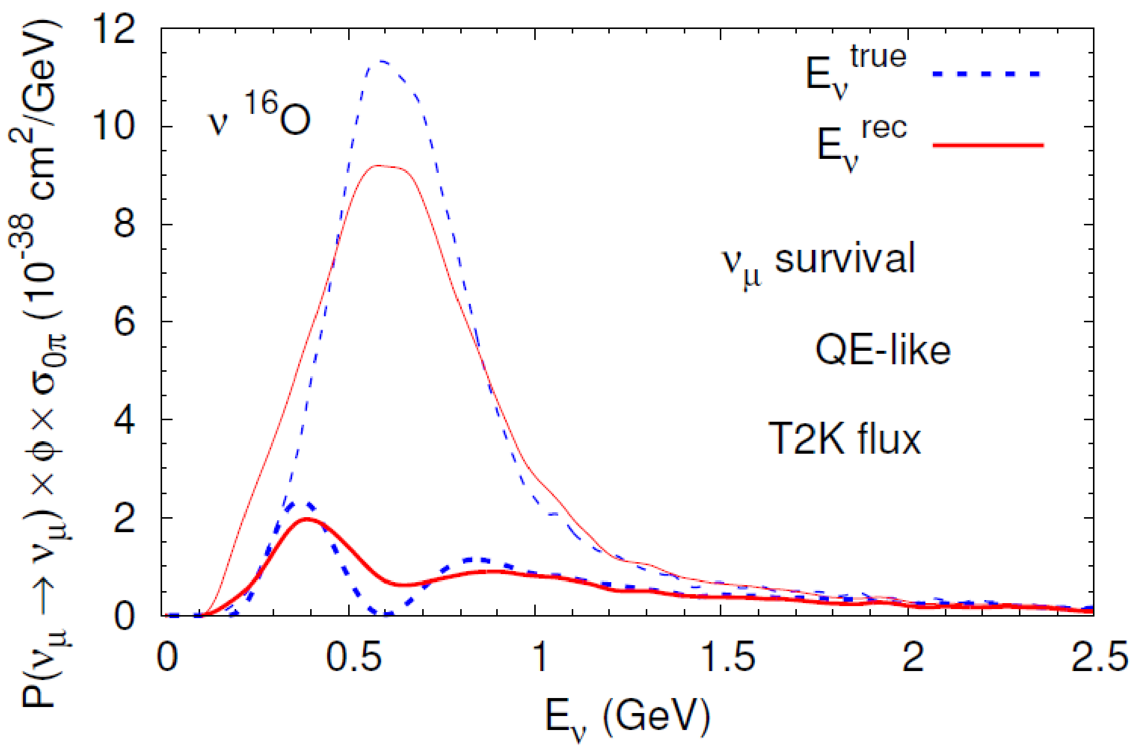
Martini et al.



Nieves et al.



2p2h and E_ν energy reconstruction



- E_ν misreconstruction is bound to have an impact oscillation analyses
  Lalakulich, Mosel, PRC 86 (2012); Coloma, Huber, PRL 111(2013); Jen et al., PRD 90 (2014)
- Bias remains after the ND is taken into account

Ab initio Quantum MC method

- Solution of the quantum many-body problem for nuclear Hamiltonians
  - NN & NNN forces
- Computation of Euclidean (Im time) responses

  = Laplace transforms of Response functions

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\epsilon'\mathrm{d}\Omega}\right)_{\nu/\overline{\nu}} = \frac{G_F^2}{2\pi^2}\,k'\epsilon'\cos^2\frac{\theta}{2}\Bigg[R_{00} + \frac{\omega^2}{q^2}\,R_{zz} - \frac{\omega}{q}R_{0z}$$

$$+\left(\tan^2\frac{\theta}{2} + \frac{Q^2}{2\,q^2}\right)R_{xx} \mp \tan\frac{\theta}{2}\sqrt{\tan^2\frac{\theta}{2} + \frac{Q^2}{q^2}}\,R_{xy}\Bigg]\;,$$

  - 1-body + 2-body (nonrelativistic) currents
  - Cannot describe π production [static Δ(1232)]
- Considerable computational effort: A $\leq$ 12

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  - 1-body + 2-body (nonrelativistic) currents
  - Cannot describe π production [static Δ(1232)]
- Considerable computational effort: A $\leq$ 12
- Significant ($\sim$ 30%) contribution from 2-body current to the transverse/interference NC responses on ^{12}C

  A. Lovato et al., PRL 112 (2014); PRC 91 (2015)

2-nucleon currents in EFT and lQCD

- In Chiral EFT e.g. Barone et al., PRC93 (2016)
  - two-nucleon axial currents: OPE, TPE, CT
  - LO,..., N3LO
  - non-relativistic, no $\Delta(1232)$ intermediate states

- In lQCD:
  - Two-body EM contributions to $n\ p \to d\ \gamma$

    Beane et al., PRL 115 (2015)
  - First step toward the determination of EW two-nucleon interactions

1π production on the nucleon

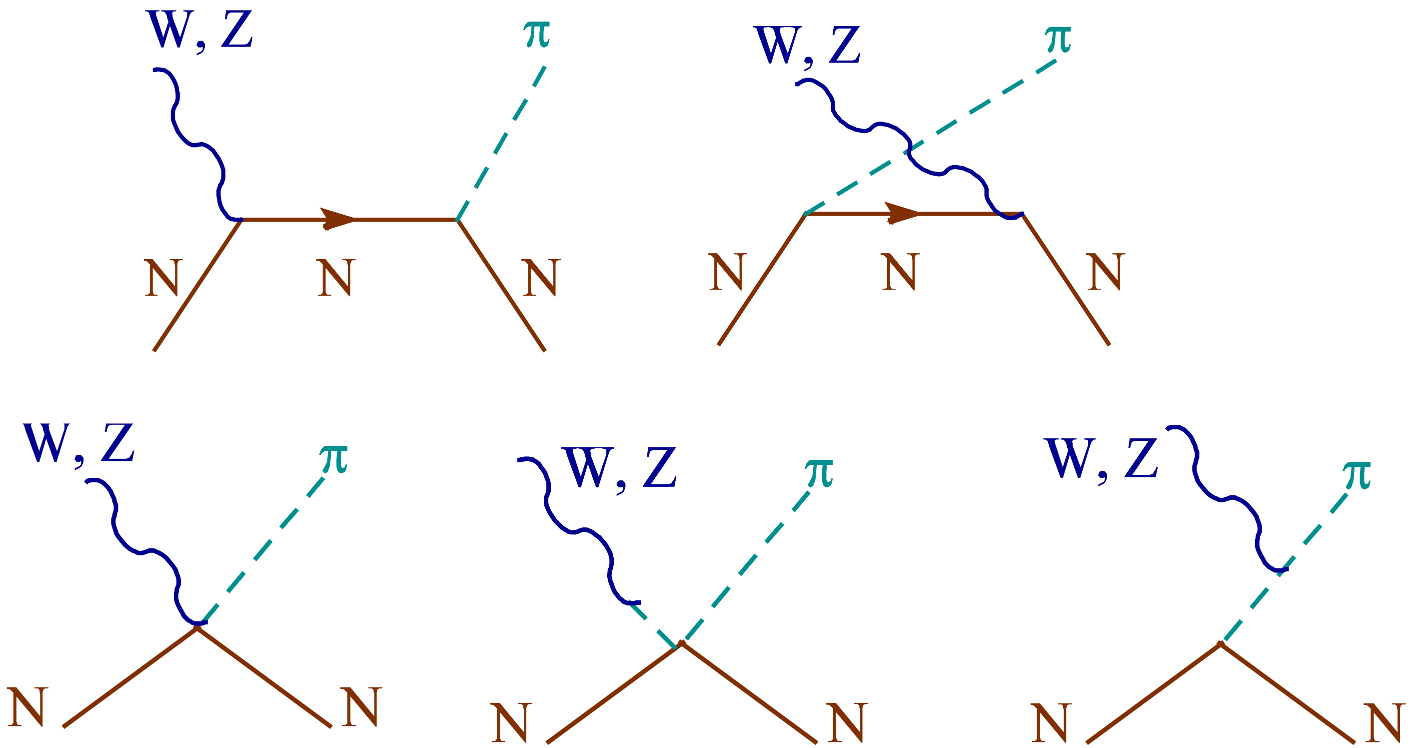
$$\nu_l\, N \to l\, \pi\, N'$$

- CC:
$$\nu_\mu\, p \to \mu^-\, p\, \pi^+, \qquad \overline{\nu}_\mu\, p \to \mu^+\, p\, \pi^-$$
$$\nu_\mu\, n \to \mu^-\, p\, \pi^0, \qquad \overline{\nu}_\mu\, p \to \mu^+\, n\, \pi^0$$
$$\nu_\mu\, n \to \mu^-\, n\, \pi^+, \qquad \overline{\nu}_\mu\, n \to \mu^+\, n\, \pi^-$$
  - source of CCQE-like events (in nuclei)
  - needs to be subtracted for a good E_ν reconstruction
- NC:
$$\nu_\mu\, p \to \nu_\mu\, p\, \pi^0, \qquad \overline{\nu}_\mu\, p \to \overline{\nu}_\mu\, p\, \pi^0$$
$$\nu_\mu\, p \to \nu_\mu\, n\, \pi^+, \qquad \overline{\nu}_\mu\, n \to \overline{\nu}_\mu\, n\, \pi^0$$
$$\nu_\mu\, n \to \nu_\mu\, n\, \pi^0, \qquad \overline{\nu}_\mu\, n \to \overline{\nu}_\mu\, n\, \pi^0$$
$$\nu_\mu\, n \to \nu_\mu\, p\, \pi^-, \qquad \overline{\nu}_\mu\, n \to \overline{\nu}_\mu\, p\, \pi^-$$
  - e-like background to $\nu_\mu \to \nu_e$ (T2K)

1π production on the nucleon

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

- From Chiral symmetry:

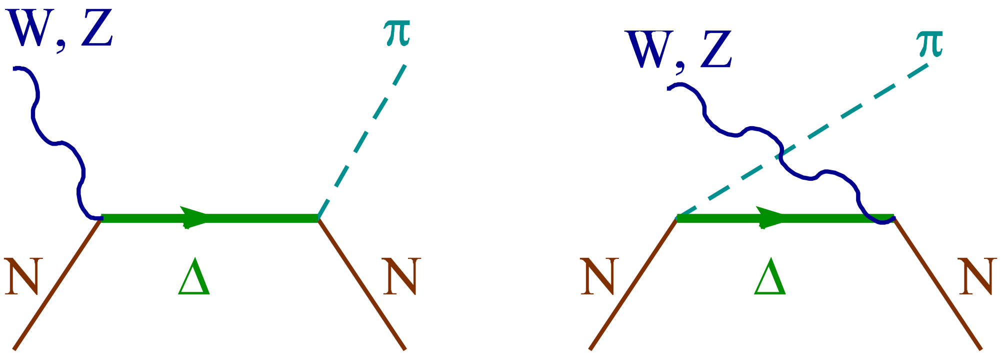


Hernandez et al., Phys.Rev. D76 (2007) 033005

1π production on the nucleon

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

- Δ (1232) excitation:



1π production on the nucleon

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

$$J_\alpha = \bar{u}^\mu(p') \left[\left(\frac{C_3^V}{M_N}(g_{\alpha\mu}\not{q} - q_\alpha\gamma_\mu) + \frac{C_4^V}{M_N^2}(g_{\alpha\mu}q\cdot p' - q_\alpha p'_\mu) + \frac{C_5^V}{M_N^2}(g_{\alpha\mu}q\cdot p - q_\alpha p_\mu) \right)\gamma_5 \right.$$
$$\left. + \frac{C_3^A}{M_N}(g_{\alpha\mu}\not{q} - q_\alpha\gamma_\mu) + \frac{C_4^A}{M_N^2}(g_{\alpha\mu}q\cdot p' - q_\beta p'_\mu) + C_5^A g_{\alpha\mu} + \frac{C_6^A}{M_N^2}q_\alpha q_\mu \right] u(p)$$

C^V_{3-5}, C^A_{3-6} $\leftarrow$ N-Δ transition form factors

- Rarita-Schwinger fields: spin 3/2

$$u_\mu(p, s_\Delta) = \sum_{\lambda, s} \left(1\lambda \frac{1}{2} s \middle| \frac{3}{2} s_\Delta \right) \epsilon_\mu(p,\lambda) u(p,s)$$

- Eq. of motion: $(\not{p} - M_\Delta)\, u_\mu = 0$

- with constrains: $\gamma^\mu u_\mu = p^\mu u_\mu = 0$

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- Helicity amplitudes are extracted from data on π photo- and electro-production in (model dependent) partial-wave analyses

$$A_{1/2} = \sqrt{\frac{2\pi\alpha}{k_R}} \left\langle R, J_z = 1/2 \left| \epsilon_\mu^+ J_{\mathrm{EM}}^\mu \right| N, J_z = -1/2 \right\rangle \zeta$$

$$A_{3/2} = \sqrt{\frac{2\pi\alpha}{k_R}} \left\langle R, J_z = 3/2 \left| \epsilon_\mu^+ J_{\mathrm{EM}}^\mu \right| N, J_z = 1/2 \right\rangle \zeta$$

$$S_{1/2} = -\sqrt{\frac{2\pi\alpha}{k_R}} \frac{|\mathbf{q}|}{\sqrt{Q^2}} \left\langle R, J_z = 1/2 \left| \epsilon_\mu^0 J_{\mathrm{EM}}^\mu \right| N, J_z = 1/2 \right\rangle \zeta$$

Weak Resonance excitation

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

$$J_\alpha = \bar{u}^\mu(p') \left[\left(\frac{C_3^V}{M_N}(g_{\alpha\mu} \not{q} - q_\alpha \gamma_\mu) + \frac{C_4^V}{M_N^2}(g_{\alpha\mu} q \cdot p' - q_\alpha p'_\mu) + \frac{C_5^V}{M_N^2}(g_{\alpha\mu} q \cdot p - q_\alpha p_\mu) \right) \gamma_5 \right.$$
$$\left. + \frac{C_3^A}{M_N}(g_{\alpha\mu} \not{q} - q_\alpha \gamma_\mu) + \frac{C_4^A}{M_N^2}(g_{\alpha\mu} q \cdot p' - q_\beta p'_\mu) + C_5^A g_{\alpha\mu} + \frac{C_6^A}{M_N^2} q_\alpha q_\mu \right] u(p)$$

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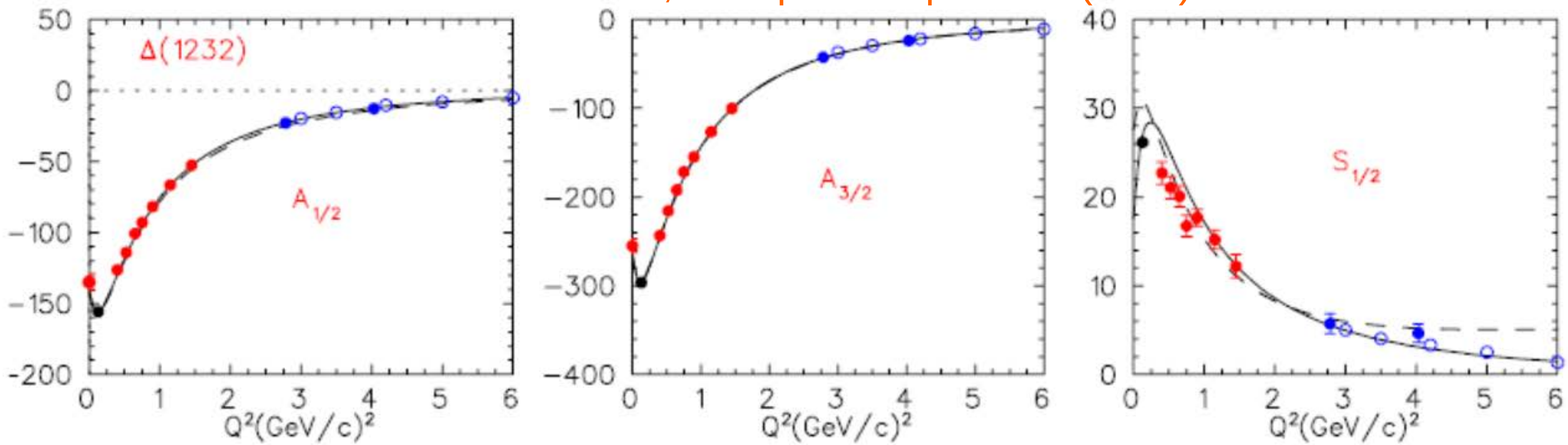
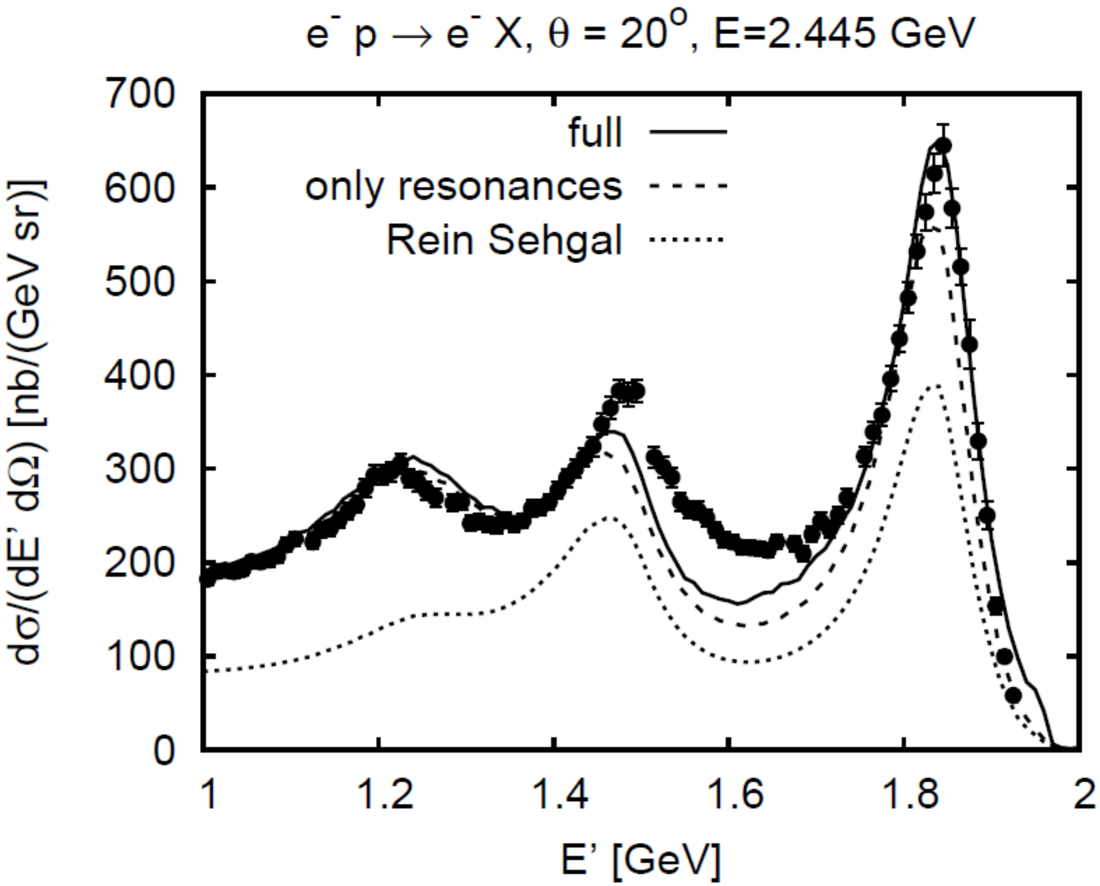
Tiator et al., EPJ Special Topics 198 (2011)



1π production on the nucleon

- Resonance excitation in ν MC generators:

- Rein-Sehgal model: Rein-Sehgal, Ann. Phys. 133 (1981) 79.
- Helicity amplitudes for 18 baryon resonances; relativistic quark model
- Poor description of π electroproduction data on p



Leitner et al., POS NUFACT08

Weak Resonance excitation

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

$$J_\alpha = \bar{u}^\mu(p')\left[\left(\frac{C_3^V}{M_N}(g_{\alpha\mu}\not{q} - q_\alpha\gamma_\mu) + \frac{C_4^V}{M_N^2}(g_{\alpha\mu}q\cdot p' - q_\alpha p'_\mu) + \frac{C_5^V}{M_N^2}(g_{\alpha\mu}q\cdot p - q_\alpha p_\mu)\right)\gamma_5 + \frac{C_3^A}{M_N}(g_{\alpha\mu}\not{q} - q_\alpha\gamma_\mu) + \frac{C_4^A}{M_N^2}(g_{\alpha\mu}q\cdot p' - q_\beta p'_\mu) + C_5^A g_{\alpha\mu} + \frac{C_6^A}{M_N^2}q_\alpha q_\mu\right]u(p)$$

- Axial form factors

$$C_5^A(0) = \sqrt{\frac{2}{3}}\, g_{\Delta N\pi}$$ ← off diagonal Goldberger-Treiman relation

$$\mathcal{L}_{\Delta N\pi} = -\frac{g_{\Delta N\pi}}{f_\pi}\bar{\Delta}_\mu(\partial^\mu\vec{\pi})\vec{T}^\dagger N \qquad g_{\Delta N\pi} \Leftrightarrow \Gamma(N^* \to N\pi)$$

- Deviations from GTR arise from chiral symmetry breaking
- expected only at the few % level

1π production on the nucleon

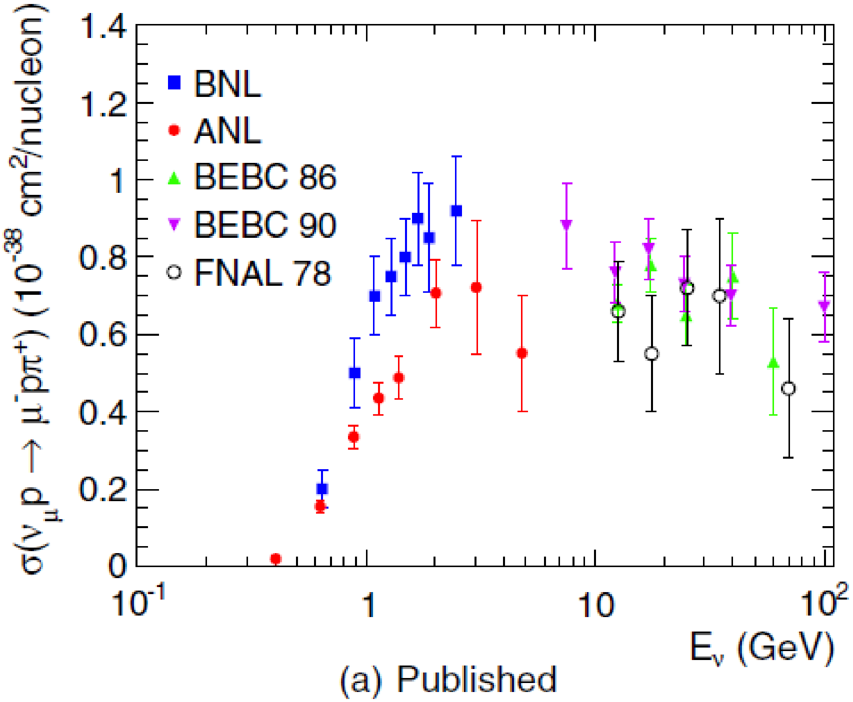
- N-Δ axial form factors: determination of $C^A_5(0)$ and $M_{A\Delta}$
- $$C_5^A = C_5^A(0)\left(1+\frac{Q^2}{M_{A\Delta}^2}\right)^{-2}$$
- From ANL and BNL data on $\nu_\mu\, d \rightarrow \mu^-\, \pi^+\, p\, n$

- Hernandez et al., PRD 81 (2010)
  - Deuteron effects
  - $C^A_5(0)$ =1.00 $\pm$ 0.11, $M_{A\Delta}$ = 0.93 $\pm$ 0.07 GeV
  - 20% reduction vs the GT relation $C_5^A(0) = 1.15 - 1.2$

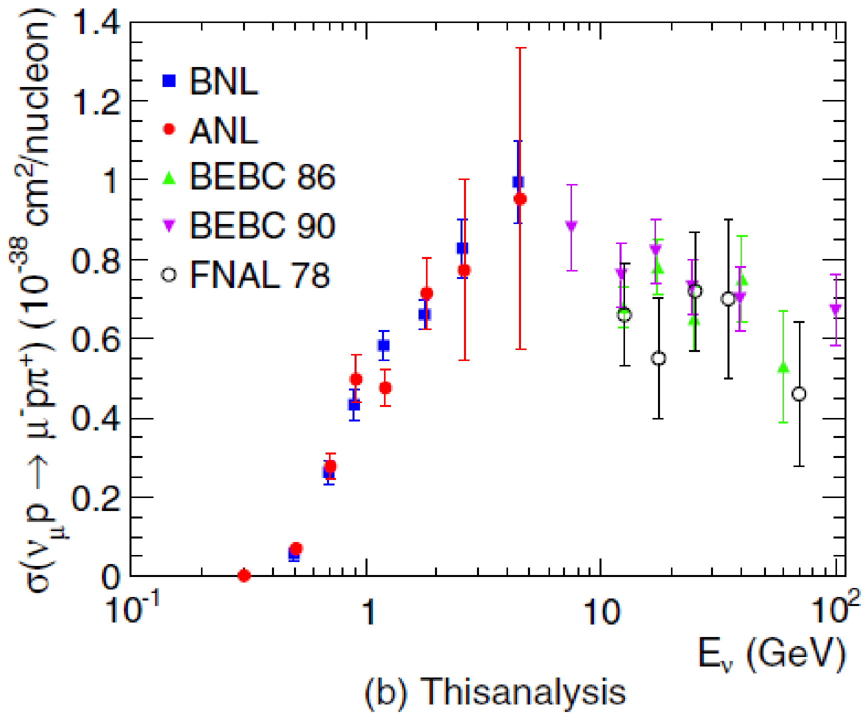
- LAR, Hernandez, Nieves, Vicente Vacas, PRD 93 (2016)
  - Unitarization in the leading vector and axial multipoles
  - Phases enforced to correspond to $\pi N \rightarrow \pi N$ (Watson's theorem)
  - $C^A_5(0)$ =1.12 $\pm$ 0.11, $M_{A\Delta}$ = 0.95 $\pm$ 0.06 GeV
  - Consistent with the off-diagonal GT relation $C_5^A(0) = 1.15 - 1.2$

1π production on nucleons

- Discrepancies between ANL and BNL datasets



(a) Published



(b) Thisanalysis

- Reanalysis by Wilkinson et al., PRD90 (2014)
  - Flux normalization independent ratios: $CC1\pi^+$/ CCQE
  - Good agreement for ratios
  - Better understood CCQE cross section used to obtain the $CC1\pi^+$ one

1π production on nucleons

- Fits to ANL and BNL data
  - $C^A_5(0) = 1.12 \pm 0.11$, $M_{A\Delta} = 0.95 \pm 0.06$ GeV $\leftarrow$ original data (A)
  - $C^A_5(0) = 1.14 \pm 0.07$, $M_{A\Delta} = 0.96 \pm 0.07$ GeV $\leftarrow$ reanalysis (B)
- For $C^A_5(0)$:
  - Relative error: $r_A = 10\ \% \Rightarrow r_B = 6\ \%$

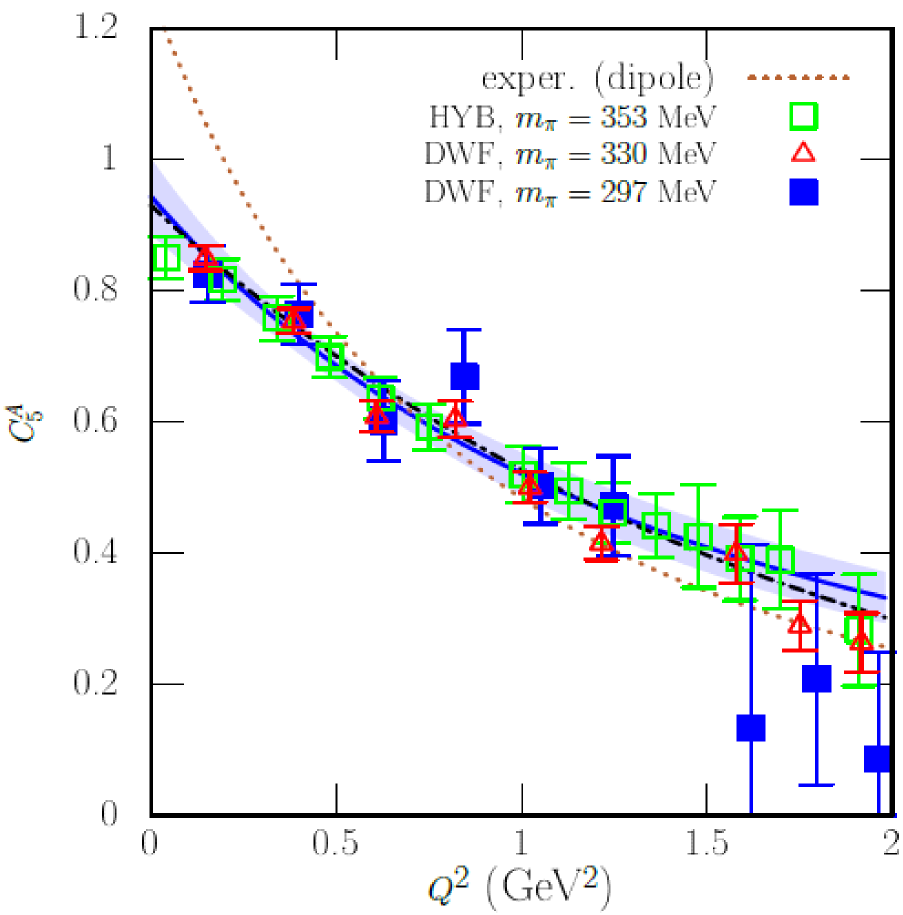
However

  - No improvement in $M_{A\Delta}$ precision
  - ANL and BNL data do not constrain $C^A_{3,4}$: consistent with zero
  - Little (no) sensitivity to heavier baryon resonances

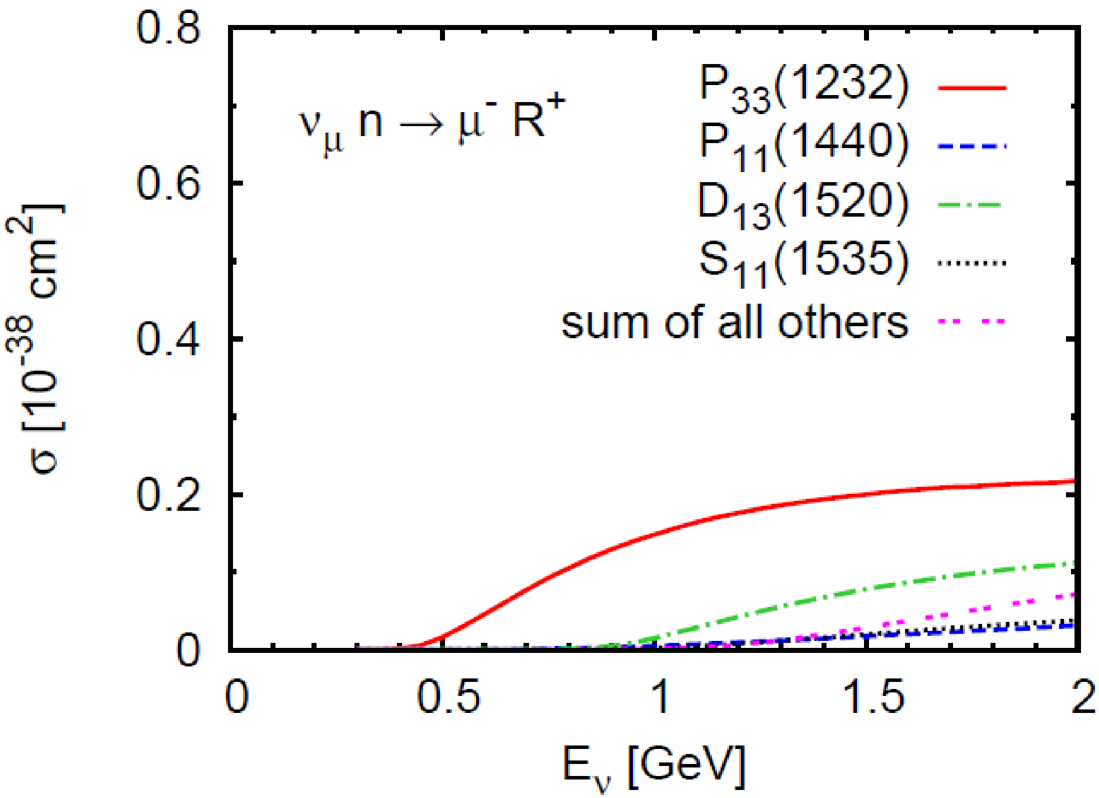
- Modern data: nuclear targets $\leftrightarrow$ in-medium effects, π FSI
- In the absence of new measurements on nucleons...

1π production on nucleons

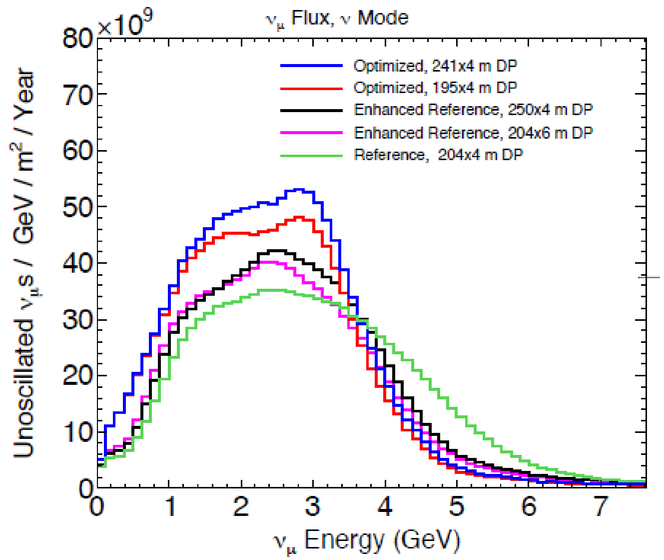
- N-Δ axial form factors in lQCD
- Alexandrou et al., PRD83 (2011)



Inclusive resonance production



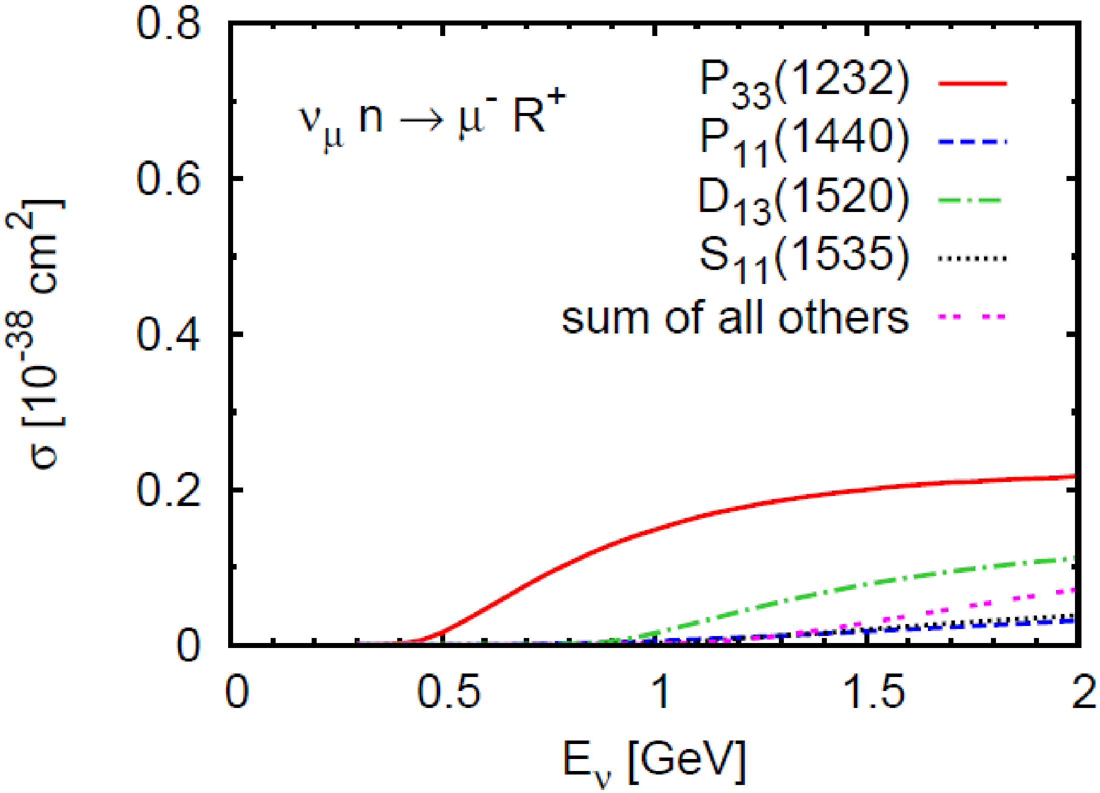
DUNE flux



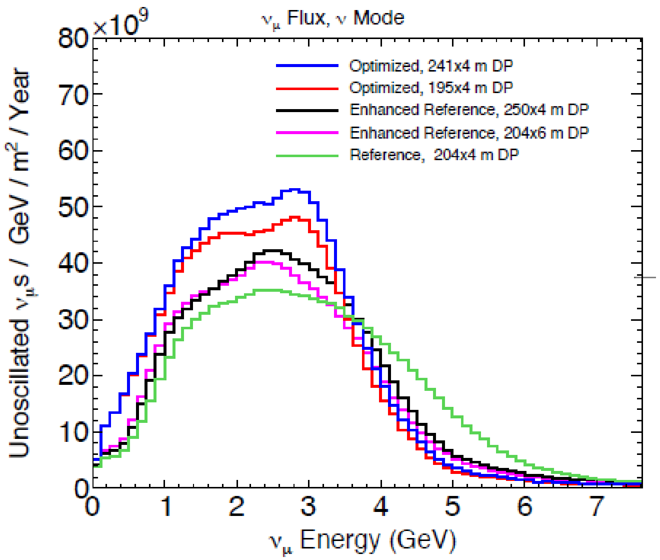
T. Leitner, O. Buss, LAR, U. Mosel, PRC 79 (2009)
T. Leitner, PhD Thesis, 2009

- At E_ν = 2 GeV, CCN*(1520)/CCΔ $\sim$ 0.5, CCN*(1440,1535)/CCΔ $\sim$ 0.22
- N*(1520) is important for $\nu_l\, N \to l\, N'\, \pi$

Inclusive resonance production



DUNE flux

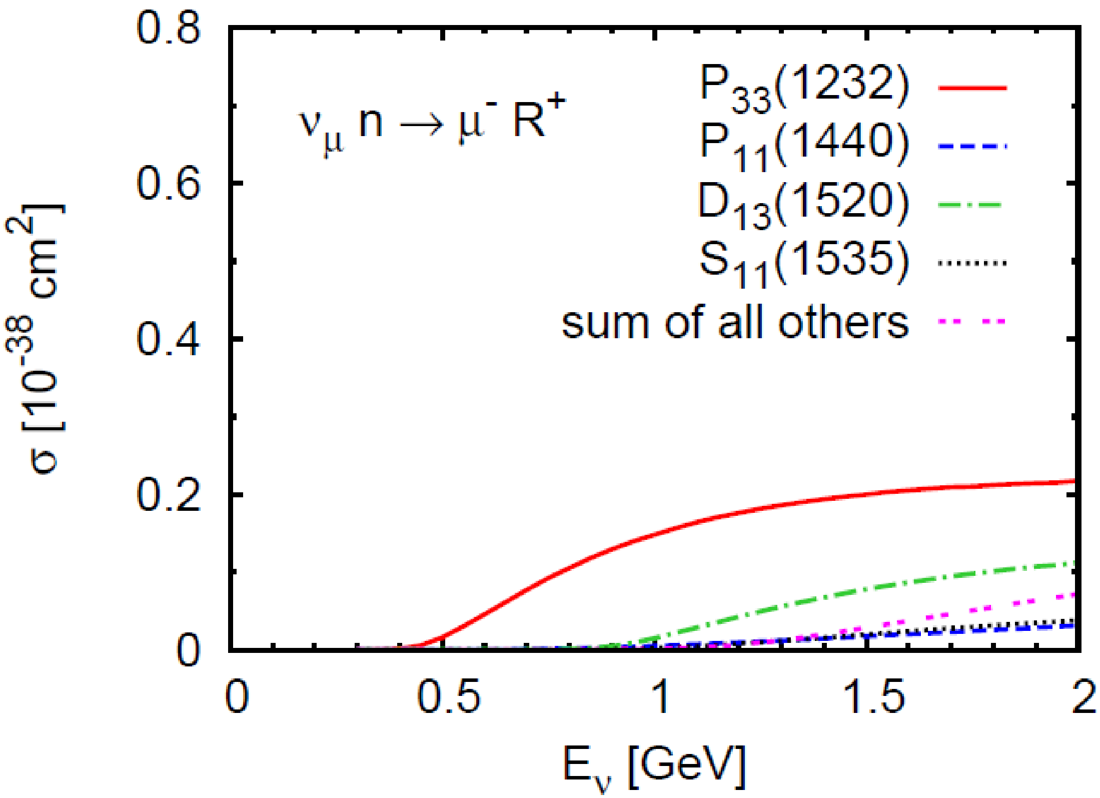


T. Leitner, O. Buss, LAR, U. Mosel, PRC 79 (2009)
T. Leitner, PhD Thesis, 2009

- Baryon resonances contribute to
  - the inclusive $\nu_l N \to l X$
  - several exclusive channels:

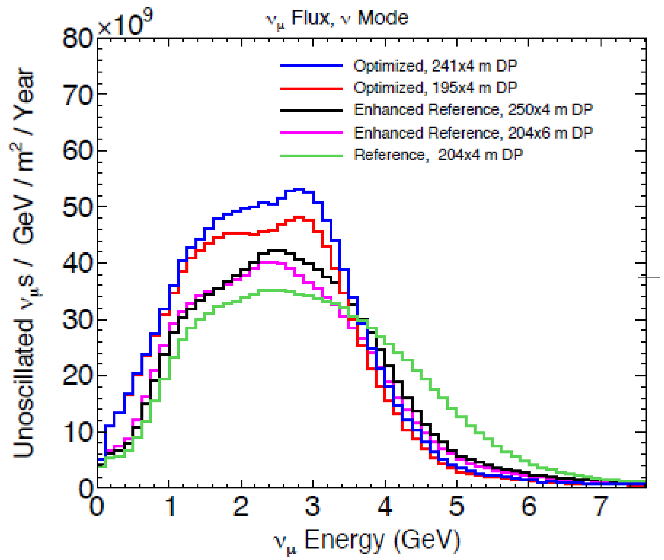
$$\nu_l N \to l N' \gamma$$
$$\nu_l N \to l N' \eta$$
$$\nu_l N \to l \Lambda(\Sigma) \bar{K}$$

Inclusive resonance production



T. Leitner, O. Buss, LAR, U. Mosel, PRC 79 (2009)
T. Leitner, PhD Thesis, 2009

DUNE flux



- Educated guess for the axial sector:

$$F_A(q^2) = F_A(0)\left(1 - \frac{q^2}{{M_A}^2}\right)^{-2}$$

  - GTR for leading $F_A(0)$, M_A = 1 GeV
  - Subleading form factors $\to$ 0

Conclusions

- ν scattering on nucleons and nuclei is relevant for oscillation studies
- Interesting for hadron and nuclear physics
- ν event generators should be improved/corrected/extended using phenomenological models:
  - consistent with symmetries (in particular ChPT close to threshold)
  - consistent with photon, electron, pion scattering data
- Input/benchmarks from ab initio calculations, including lQCD