Determination of the axial mass in quasielastic antineutrino-nucleon scattering.

Gil Paz

Department of Physics and Astronomy, Wayne State University

Bhubanjyoti Bhattacharya, GP, Anthony J. Tropiano,
PRD **92**, 113011 (2015) [arXiv:1510.05652]

Introduction:
The axial mass of the nucleon

Quasiealstic $\nu - N$ scattering

- Quasiealstic $\nu - N$ scattering: $\nu_\ell + n \to \ell^- + p$
  basic signal for ν oscillation experiment

- At the quark level: $\nu_\ell + d \to \ell^- + u$

- Process "folded" twice

Quark: $\nu_\ell + d \to \ell^- + u$

$\Downarrow$ Form factor

Nucleon $\nu_\ell + n \to \ell^- + p$

$\Downarrow$ Nuclear model

Nucleus: $\nu_\ell + \text{nucleus} \to \ell^- + \ldots$

Quark $\to$ Nucleon

- The interaction

$$\mathcal{L} = \frac{G_F}{\sqrt{2}} V_{ud}^* \, \bar{\ell}\gamma^\alpha(1-\gamma^5)\nu \, \bar{u}\gamma_\alpha(1-\gamma^5)d.$$

- Known current: $\bar{u}\gamma_\alpha(1-\gamma^5)d$

- Parametrize $\langle p(p')|\bar{u}\gamma_\alpha(1-\gamma^5)d|n(p)\rangle$ by form factors:

  F_1, F_2, F_p, F_A, functions of $q^2 = (p'-p)^2$

- Of the form factors, the axial is the least constrained

- What do we know about $F_A(q^2)$?

The Axial Mass

- Consider a small q^2 expansion of $F_A(q^2)$

- $F_A(0) = -1.269$ is known from neutron decay

- Define the axial mass m_A as

$$F_A(q^2) = F_A(0)\left[1 + \frac{2}{m_A^2}q^2 + \ldots\right] \implies m_A \equiv \sqrt{\frac{2F_A(0)}{F_A'(0)}}$$

- Common **model** for F_A: the dipole model

$$F_A = F_A(0)\left[1 - q^2/(m_A^{\mathrm{dipole}})^2\right]^{-2}$$

- One parameter **model** for F_A

  Known to be inadequate for EM form factors

Nucleon $\rightarrow$ Nucleus

- Experiments usually scatter ν off nuclei

  Need a nuclear model: how do nucleons behave in the nucleus

- Popular model: "Relativistic Fermi Gas" (RFG)

  Smith, Moniz, NPB **43**, 605 (1972)

- Model validity and parameters from quasielastic *e*-nuclei scattering

  Moniz, Sick, Whitney, Ficenec, Kephart, Trower, PRL **26**, 445 (1971)

The axial mass problem

- Neutrino scattering:

  $m_A^{\rm dipole} = 1.35 \pm 0.17$ GeV

  MiniBooNE Collaboration

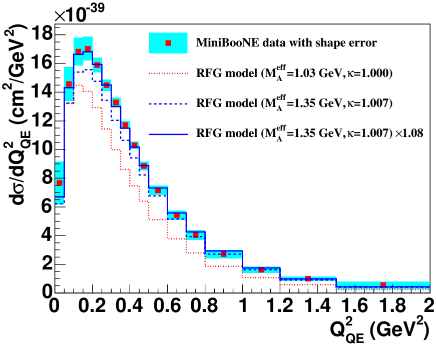
  PRD **81** (2010) 092005

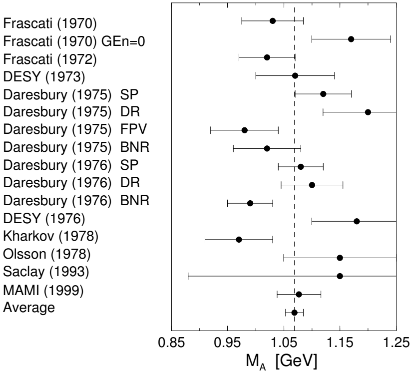
- Pion electro-prodcution:

  $m_A^{\rm dipole} = 1.07 \pm 0.02$ GeV

  Bernard, Elouadrhiri, Meissner

  J. Phys. G 28, R1 (2002)





Both use dipole ansatz for axial form factor

$$F_A = F_A(0)\,[1 - q^2/(m_A^{\rm dipole})^2]^{-2}$$

The axial mass problem

- Axial mass $m_A^{\rm dipole} = 1.35 \pm 0.17$ GeV
  MiniBooNE Collaboration, PRD **81** 092005 (2010)
- Similar result from other recent ν experiments
- K2K SciFi: $m_A^{\rm dipole} = 1.20 \pm 0.12$ GeV
  K2K Collaboration, PRD **74** 052002 (2006)
- K2K SciBar $m_A^{\rm dipole} = 1.144 \pm 0.077({\rm fit})^{+0.078}_{-0.072}({\rm syst})$ GeV
  Espinal, Sanchez, AIP Conf. Proc. **967**, 117 (2007)
- Minos $m_A^{\rm dipole} = 1.19^{+0.09}_{-0.1}({\rm fit})^{+0.12}_{-0.14}({\rm syst})$ GeV
  MINOS Collaboration, AIP Conf. Proc. **1189**, 133 (2009)

- Nomad: $m_A^{\rm dipole} = 1.05 \pm 0.02 \pm 0.06$ GeV
  NOMAD Collaboration, EPJ C **63**, 355 (2009)
- Pion electro-prodcution: $m_A^{\rm dipole} = 1.07 \pm 0.02$ GeV
  Bernard, Elouadrhiri, Meissner, J. Phys. G 28, R1 (2002)
- ν experiments before 1990: $m_A^{\rm dipole} = 1.026 \pm 0.021$ GeV
  Bernard, Elouadrhiri, Meissner, J. Phys. G 28, R1 (2002)
- **What could be the source of the discrepancy?**

Theoretical studies focus on nuclear modeling

- Modify nuclear model

  Butkevich, PRC **82**, 055501 (2010); Benhar, Coletti, Meloni, PRL **105**, 132301 (2010); Juszczak, Sobczyk, Zmuda, PRC **82**, 045502 (2010)

  ...
- Include multi-nucleon emission

  Martini, Ericson, Chanfray, Marteau
  PRC **80**, 065501 (2009), PRC **81**, 045502 (2010);
  Amaro, Barbaro, Caballero, Donnelly, Williamson
  PLB **696**, 151 (2011), PRD **84**, 033004 (2011);
  Nieves, Ruiz Simo, Vicente Vacas
  PRC **83**, 045501 (2011)

  ...
- Modify G_M for bound nucleons but not G_E or F_A

  Bodek, Budd, EPJ C **71**, 1726 (2011)

  ...
- **All** studies use dipole form factor

$$F_A = F_A(0)\,[1 - q^2/(m_A^{\rm dipole})^2]^{-2}$$

What is the axial mass?

- The axial mass is defined as

$$F_A(q^2) = F_A(0)\left[1 + \frac{2}{m_A^2}q^2 + \dots\right] \implies m_A \equiv \sqrt{\frac{2F_A(0)}{F_A'(0)}}$$

- Everyone extracts $m_A^{\rm dipole}$ from

$$F_A = F_A(0)\,[1 - q^2/(m_A^{\rm dipole})^2]^{-2}$$

What is the axial mass?

- The axial mass is defined as

$$F_A(q^2) = F_A(0)\left[1 + \frac{2}{m_A^2}q^2 + \dots\right] \implies m_A \equiv \sqrt{\frac{2F_A(0)}{F_A'(0)}}$$

- Everyone extracts $m_A^{\rm dipole}$ from

$$F_A = F_A(0)\left[1 - q^2/(m_A^{\rm dipole})^2\right]^{-2}$$

- $m_A^{\rm dipole}$ is not m_A!

What is the axial mass?

- The axial mass is defined as

$$F_A(q^2) = F_A(0)\left[1 + \frac{2}{m_A^2} q^2 + \dots\right] \implies m_A \equiv \sqrt{\frac{2F_A(0)}{F_A'(0)}}$$

- Everyone extracts $m_A^{\rm dipole}$ from

$$F_A = F_A(0)\,[1 - q^2/(m_A^{\rm dipole})^2]^{-2}$$

- $m_A^{\rm dipole}$ is not m_A!

- When extractions of $m_A^{\rm dipole}$ disagree is it
- Problem with the dipole model?
- Problem with the nuclear model?
- Real disagreement between experiments?

- Need to extract m_A not $m_A^{\rm dipole}$

Determination of the axial mass in quasielastic neutrino-nucleon scattering

Bhubanjyoti Bhattacharya, Richard J. Hill, GP

PRD **84** 073006 (2011) [arXiv:1108.0423]

z expansion

- Extract m_A using the z expansion:

- Map F_A domain of analyticity onto z-plane unit circle
- Expand F_A in a Taylor series in z: $F_A = \sum_{k=0}^{\infty} a_k \, z(q^2)^k$

- Standard tool in analyzing meson transition form factors

- First applied to baryon form factors to extract proton charge radius
  Richard J. Hill, GP PRD **82** 113005 (2010)

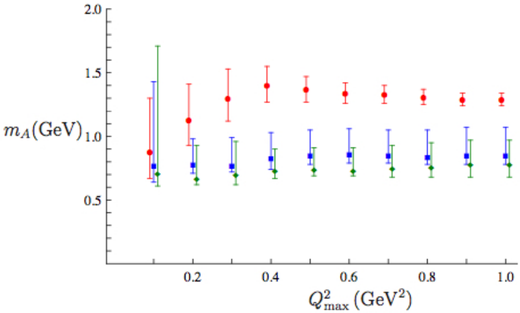
- For the extraction to be independent of the # of parameters
  need to bound $|a_k|$: $|a_k| \leq 5$ and $|a_k| \leq 10$

Goal

- Extract m_A using the z expansion
- Fit to MiniBooNE data for $d\sigma/dE_\mu d\cos\theta_\mu$
  MiniBooNE Collaboration, PRD **81** 092005 (2010)
- Mostly follow MiniBooNE's analysis: use RFG as nuclear model

Neutrino: z expansion

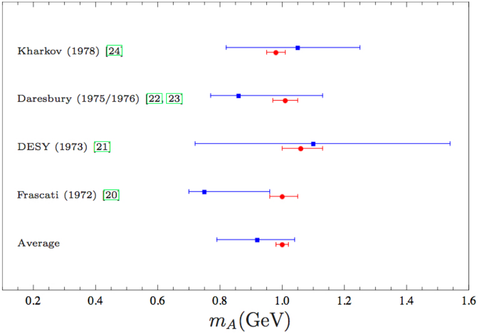
- Our z expansion fit to MiniBooNE data (Assuming RFG):
  Red: dipole, Blue: z, $|a_k| \leq 5$, Green: z, $|a_k| \leq 10$



- Our fit using z expansion: $m_A = 0.85^{+0.22}_{-0.07} \pm 0.09$ GeV
  Our fit using dipole model: $m_A^{\rm dipole} = 1.29 \pm 0.05$ GeV
  MiniBooNE's fit: $m_A^{\rm dipole} = 1.35 \pm 0.17$ GeV

Pion Electro-production: z expansion

- Is there a discrepancy with pion electro-production data?
  Red: dipole, Blue: z, $|a_k| \leq 5$



- Our fit using z expansion: $m_A = 0.92^{+0.12}_{-0.13} \pm 0.08$ GeV
  Our fit using dipole model: $m_A^{\text{dipole}} = 1.00 \pm 0.02$ GeV
  Bernard et. al. fit using dipole model: $m_A^{\text{dipole}} = 1.07 \pm 0.02$ GeV
  Bernard, Elouadrhiri, Meissner, J. Phys. G 28, R1 (2002)

z expansion results

- MiniBooNE (Assuming RFG):

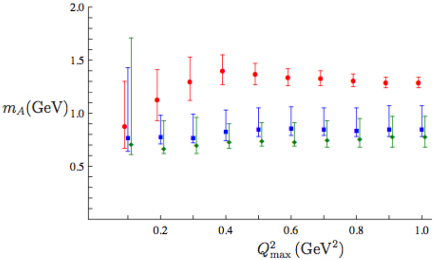
  $m_A = 0.85^{+0.22}_{-0.07} \pm 0.09$ GeV

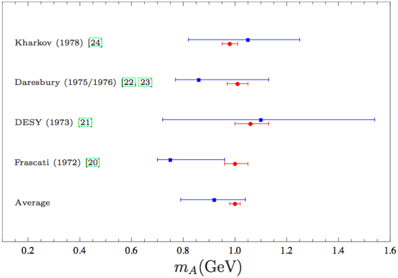
  $m_A^{\text{dipole}} = 1.29 \pm 0.05$ GeV

- Pion electro-prodcution:

  $m_A = 0.92^{+0.12}_{-0.13} \pm 0.08$ GeV

  $m_A^{\text{dipole}} = 1.00 \pm 0.02$ GeV

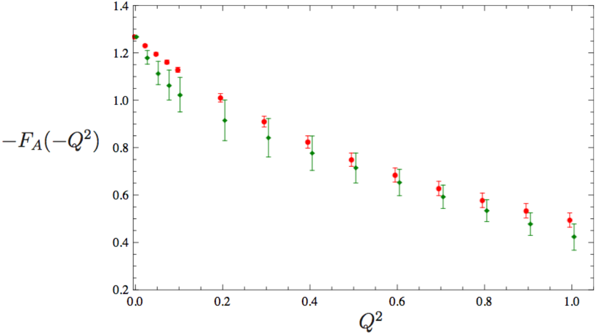




Discrepancy might be an artifact of the use of the dipole form factor...

Going beyond m_A

- We can also extract F_A directly from MiniBooNE data
  Red: dipole, Green: z, $|a_k| \leq 10$



  Error on F_A underestimated in the dipole model

- Can we reproduce this using other neutrino data sets?

Determination of the axial mass in quasielastic antineutrino-nucleon scattering

Bhubanjyoti Bhattacharya, GP, Anthony J. Tropiano

PRD **92**, 113011 (2015) [arXiv:1510.05652]

Quasiealstic $\bar{\nu} - N$ scattering

- More recently apply the z expansion to $\bar{\nu} - N$ scattering
  Bhattacharya, GP, Tropiano,
  PRD **92**, 113011 (2015) [arXiv:1510.05652]

- In particular analyze MiniBooNE's antineutrino data
  MiniBooNE Collaboration, PRD **88**, 032001 (2013)

- Quasiealstic $\nu - N$ scattering: $\nu_\ell + n \to \ell^- + p$
- Quasiealstic $\bar{\nu} - N$ scattering: $\bar{\nu}_\ell + p \to \ell^+ + n$

- For scattering off mineral oil $C_n H_{2n+2}$ ($n \sim 30$):
- $\bar{\nu}$ can scatter off protons in C
- $\bar{\nu}$ can scatter off protons in H

Quasiealstic $\bar{\nu} - N$ scattering

- For scattering off mineral oil C_nH_{2n+2} ($n \sim 30$):

  \- $\bar{\nu}$ can scatter off protons in C

  \- $\bar{\nu}$ can scatter off protons in H

- Cannot tell them apart

$$\frac{d\sigma_{\text{CH2, per nucleon, avg.}}}{dE_\ell d\cos\theta_\ell} = \frac{1}{8.1}\left(6\frac{d\sigma_{\text{C, per nucleon, avg.}}}{dE_\ell d\cos\theta_\ell} + 2.1\frac{d\sigma_{\text{H, avg.}}}{dE_\ell d\cos\theta_\ell}\right)$$

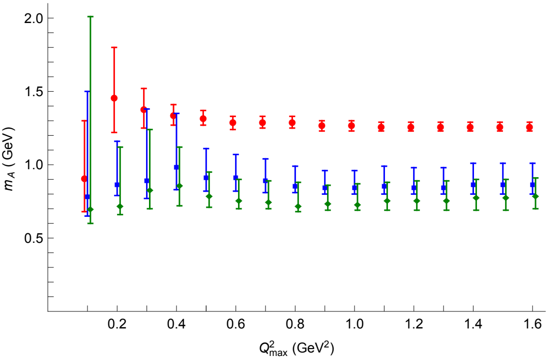
  "avg." = antineutrino flux averaging

- MiniBooNE uses *different* m_A^{dipole} for C and H
  Problematic! the axial mass is a fundamental property of the nucleon
  Might hide nuclear effects in the axial mass

- We use the same F_A for C and H and extract *one* axial mass

Antineutrino: z expansion

- Our z expansion fit to MiniBooNE data (Assuming RFG):
  Red: dipole, Blue: z, $|a_k| \leq 5$, Green: z, $|a_k| \leq 10$

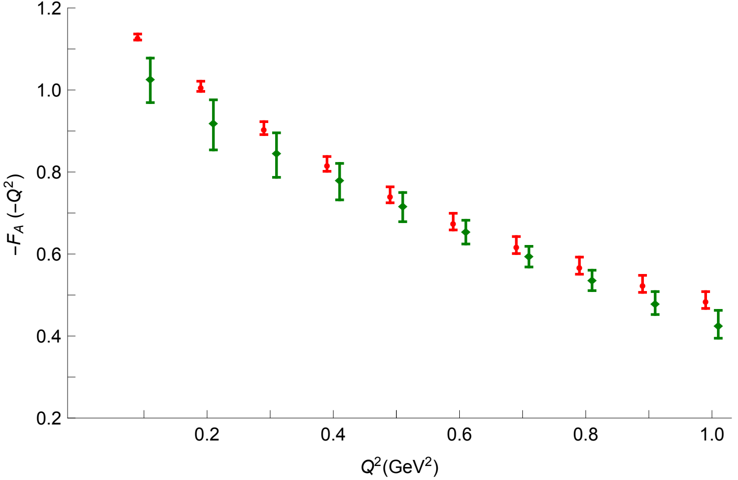


- Our fit using z expansion: $m_A = 0.84^{+0.12}_{-0.04} \pm 0.11$ GeV
  Our fit using dipole model: $m_A^{\text{dipole}} = 1.27^{+0.03}_{-0.04}$ GeV

- Neutrino data z expansion: $m_A = 0.85^{+0.22}_{-0.07} \pm 0.09$ GeV
- Neutrino data dipole model: $m_A^{\text{dipole}} = 1.29 \pm 0.05$ GeV

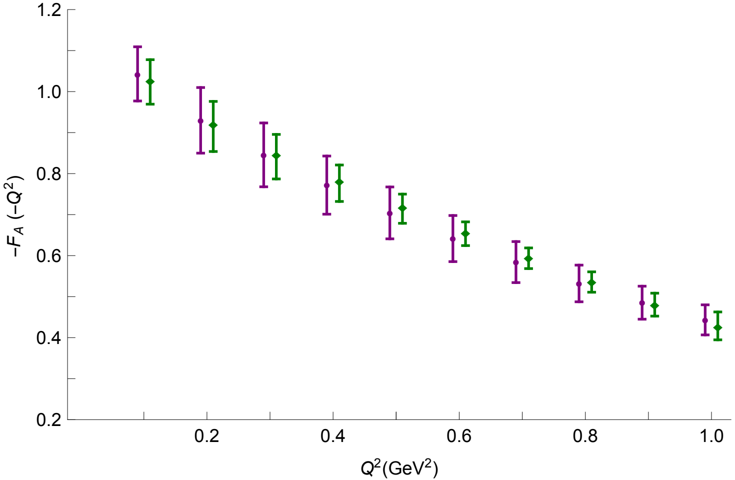
Going beyond m_A

- We can also extract F_A directly from MiniBooNE data
  Red: dipole, Green: z, $|a_k| \leq 10$



Comparing F_A from ν and $\bar{\nu}$ data

- neutrino data (purple circles) and antineutrino data (green diamonds).



z expansion and possible nuclear effects

- ν data using the z expansion: $m_A = 0.85^{+0.22}_{-0.07} \pm 0.09$ GeV

  $\bar{\nu}$ data using the z expansion: $m_A = 0.84^{+0.12}_{-0.04} \pm 0.11$ GeV
- ν data using dipole model: $m_A^{\rm dipole} = 1.29 \pm 0.05$ GeV

  $\bar{\nu}$ data using dipole model: $m_A^{\rm dipole} = 1.27^{+0.03}_{-0.04}$ GeV

z expansion and possible nuclear effects

- ν data using the z expansion: $m_A = 0.85^{+0.22}_{-0.07} \pm 0.09$ GeV
  $\bar{\nu}$ data using the z expansion: $m_A = 0.84^{+0.12}_{-0.04} \pm 0.11$ GeV
- ν data using dipole model: $m_A^{\mathrm{dipole}} = 1.29 \pm 0.05$ GeV
  $\bar{\nu}$ data using dipole model: $m_A^{\mathrm{dipole}} = 1.27^{+0.03}_{-0.04}$ GeV

- The error on m_A not symmetric $\Rightarrow$ fit allows larger m_A
  $\Rightarrow$ increase cross section $\Rightarrow$ problem with nuclear model?

z expansion and possible nuclear effects

- ν data using the z expansion: $m_A = 0.85^{+0.22}_{-0.07} \pm 0.09$ GeV
  $\bar{\nu}$ data using the z expansion: $m_A = 0.84^{+0.12}_{-0.04} \pm 0.11$ GeV
- ν data using dipole model: $m_A^{\text{dipole}} = 1.29 \pm 0.05$ GeV
  $\bar{\nu}$ data using dipole model: $m_A^{\text{dipole}} = 1.27^{+0.03}_{-0.04}$ GeV

- The error on m_A not symmetric $\Rightarrow$ fit allows larger m_A
  $\Rightarrow$ increase cross section $\Rightarrow$ problem with nuclear model?

- Crude qualitative check: multiply $d\sigma_c$ by a constant factor
- factor > 1: error more symmetric
- factor < 1: asymmetry grows
- both cases little change in m_A^{dipole}
- Similar conclusion for ν data

- Hint of a problem with nuclear model?
  Combine z expansion and a non-RFG nuclear model
  Cohen, Hen, GP, Piasetzky, Tockstein *(in progress)*

Deuterium target data

- Even more recently:

  z-expansion extraction from deuterium target data

  Aaron S. Meyer, Minerba Betancourt, Richard Gran, Richard J. Hill
  PRD **93** 113015 (2016)

- They extract $r_A = \sqrt{12}/m_A$ and find $r_A^2 = 0.46(22)\ \text{fm}^2$ or

  $$\boxed{r_A = 0.68^{+0.15}_{-0.19}\ \text{fm}}$$

- Consistent with MiniBooNE neutrino and antineutrino data, e.g.

  $$\boxed{r_A = 0.81^{+0.05}_{-0.10} \pm 0.14\ \text{fm}}$$

  Bhattacharya, GP, Tropiano, PRD **92**, 113011 (2015)

Conclusions

Conclusions

- The future neutrino program requires *precision*
- Need better control of form factors, in particular F_A
- Axial mass problem: different m_A^{dipole} for different experiments
- Using z expansion: *consistent* values for axial mass:

- MiniBooNE ν data using the z expansion: $m_A = 0.85^{+0.22}_{-0.07} \pm 0.09$ GeV
  Bhattacharya, Hill, GP PRD **84** 073006 (2011)
- MiniBooNE $\bar{\nu}$ data using the z expansion: $m_A = 0.84^{+0.12}_{-0.04} \pm 0.11$ GeV
  Bhattacharya, GP, Tropiano PRD **92** 113011 (2015)
- Deuterium target data using the z expansion: $r_A^2 = 0.46(22)$ fm^2
  Meyer, Betancourt, Gran, Hill PRD **93** 113015 (2016)

- Next step: combine z expansion and a non-RFG nuclear model
  Cohen, Hen, GP, Piasetzky, Tockstein *(in progress)*