The Nucleon Axial-Vector Form Factor for Precision Neutrino Oscillation Studies

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Motivation

$$\Phi(E_\nu) = \frac{\mathcal{N}(E_\nu)}{\sigma_A(E_\nu)}$$

Oscillation experiments monitor flux by counting interactions assuming cross section, near/far detector do not perfectly cancel

$\implies$ Measurements of neutrino oscillation depend on precise knowledge of neutrino cross section

$$\sigma_A \sim \sigma_{CCQE} \otimes (\text{nucl. models})$$

($\sigma_{CCQE}(E_\nu, Q^2)$ is quadratic function of form factors)

- Large nuclear targets $\implies$ measurements of oscillation parameters depends on nuclear models
- Nuclear effects entangled with nucleon amplitudes $\implies$ factorization is oversimplification
- Model-dependent shape parameterization introduces systematic uncertainties and underestimates errors

Discrepancies in the Axial-Vector Form Factor

σ_{CCQE} dependent on form factors:
$F_{1V}(Q^2)$, $F_{2V}(Q^2)$, $F_A(Q^2)$, $F_P(Q^2)$

Most analyses assume the "Dipole form factor":

$$F_A^{\text{dipole}}(Q^2) = g_A \frac{1}{\left(1 + \frac{Q^2}{m_A^2}\right)^2}$$

Dipole is an ansatz:
unmotivated in interesting Q^2 (4-momentum) region
$\implies$ uncontrolled systematics and underestimated uncertainties

Large variation in m_A over many experiments:
$m_A^{\text{eff}} = 1.35 \pm 0.17$ (MiniBooNE, 1002.2680[hep-ph])
$m_A = 1.026 \pm 0.021$ world avg. QE (Bernard *et. al*, 0107088[hep-ph])

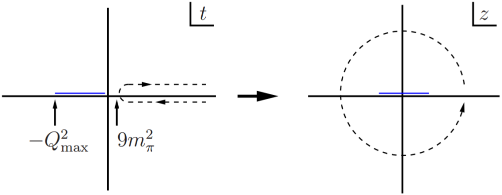
Essential to replace with model-independent parameterization

z-Expansion

The z-Expansion (Bhattacharya, Hill, Paz arXiv:1108.0423 [hep-ph]) is a conformal mapping which takes the kinematically allowed region ($t \leq 0$) to within $z = \pm 1$

$$z(t; t_0, t_c) = \frac{\sqrt{t_c - t} - \sqrt{t_c - t_0}}{\sqrt{t_c - t} + \sqrt{t_c - t_0}} \qquad F_A(z) = \sum_{n=0}^{\infty} a_n z^n$$

$$(t = q^2 = -Q^2 \, , \; t_c = 9m_\pi^2)$$



Advantages of z-Expansion

z-Expansion is a model-independent description of the axial form factor

- Motivated by analyticity arguments
- Only a few coefficients needed to accurately represent form factor
- Provides a prescription for introducing more parameters as data improves
- Allows quantification of systematic errors
- Coefficient falloff required by perturbative QCD

Deuterium Fitting (1603.03048[hep-ph])

with Richard Hill, Rik Gran, Minerba Betancourt

Fits to deuterium bubble chamber data
(relatively small nuclear effects)

Three datasets:

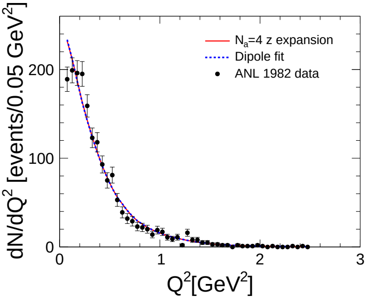
- ANL 1982: 1737 events, 0.5GeV [peak]
- BNL 1981: 1138 events, 1.6 GeV [average]
- FNAL 1983: 362 events, 20 GeV [peak], 27 GeV [average]

Shape-only fits to QE differential cross section data

Gaussian priors used on z-Expansion coefficients:
if (k $\leq$ 5) $\sigma_k = 5$, else $\sigma_k = 25/k$

Sum rules applied to enforce large Q^2 falloff

Deuterium Fits - Differential Cross Section

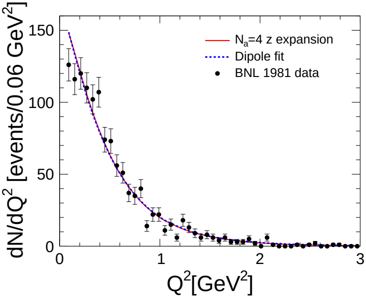


Dipole:

χ^2/N_{bins}	58.6/49
m_A	1.02(5)

z-Expansion:

χ^2/N_{bins}	60.9/49
a_1	2.25(10)
a_2	0.2(0.9)
a_3	−4.9(2.4)
a_4	2.7(2.7)



Dipole:

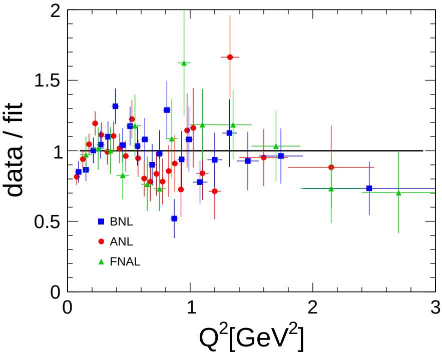
χ^2/N_{bins}	70.9/49
m_A	1.05(4)

z-Expansion:

χ^2/N_{bins}	73.4/49
a_1	2.24(10)
a_2	0.6(1.0)
a_3	−5.4(2.4)
a_4	2.2(2.7)

Residuals

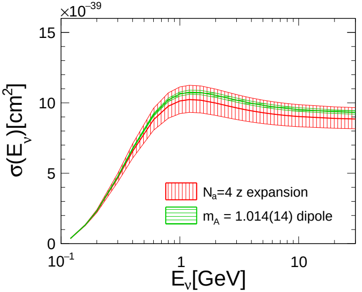
Residuals indicate potentially correlated effect between experiments

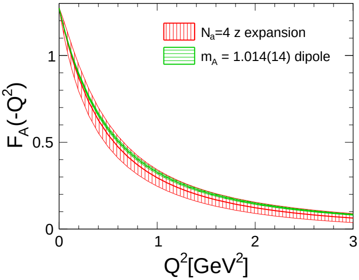


Neither z expansion, nor dipole can properly explain shape of data
$\Longrightarrow$ underestimated systematic effects

Final Fits

Final fits include systematics of acceptance corrections, deuterium nuclear corrections





Calculated observables:

$$r_A^2 = 0.46(22)\,\mathrm{fm}^2\,, \quad \sigma_{\nu n\to\mu p}(E_\nu = 1\,\mathrm{GeV}) = 10.1(0.9)\times 10^{-39}\mathrm{cm}^2$$

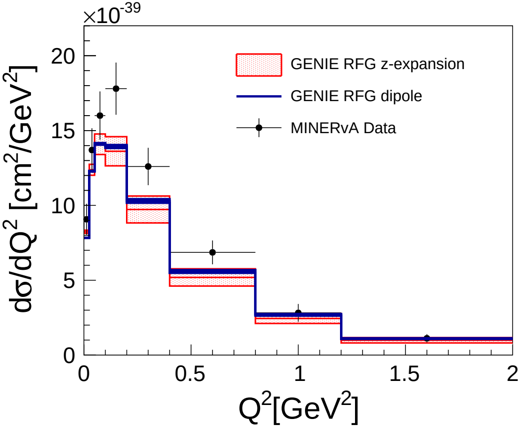
compared with Bodek *et. al* [Eur. Phys. J. C 53, 349]:

$$r_A^2 = 0.453(13)\,\mathrm{fm}^2\,, \quad \sigma_{\nu n\to\mu p}(E_\nu = 1\,\mathrm{GeV}) = 10.63(0.14)\times 10^{-39}\mathrm{cm}^2$$

z Expansion in GENIE

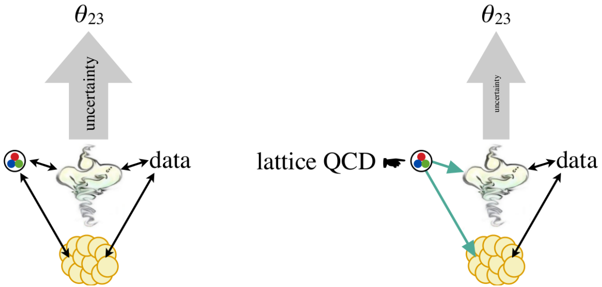
To be officially released in production version 2.12

Currently available in GENIE "trunk" version



Lattice QCD in Neutrino Physics

- LQCD measurements becoming more accurate, precise
  $\implies$ now able to inform neutrino experiment
- LQCD enables clean measurement of form factors (no nuclear corrections, no experiment systematics)
- Offers way of breaking measurement degeneracy between nuclear models, nucleon form factors
- Less explosive than hydrogen!

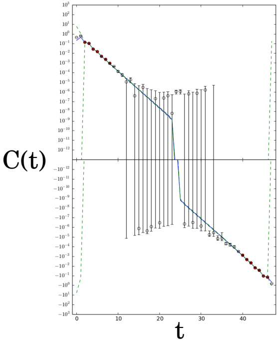


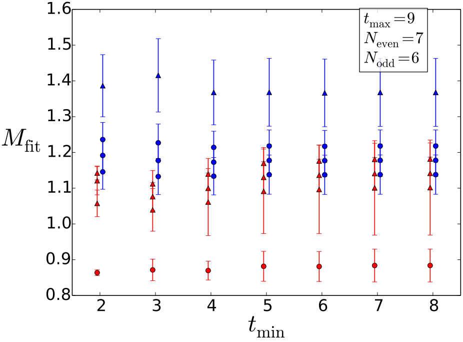
Current Lattice Effort

LQCD calculation of form factors underway by MILC/Fermilab Lattice Collaborations

Lattice computation involves several stages, building up to result:
2-point functions = masses, overlap factors

$$\lim_{t\to\infty} \langle N(0)|N(t)\rangle \sim |a|^2 e^{-m_N t}$$

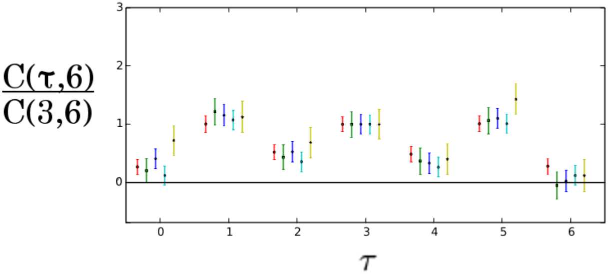




Lattice QCD Axial Form Factor

Use 2-point functions to calculate 3-point functions = form factors

$$\lim_{\tau,t\to\infty} \langle N'(0)|\, A_\mu(x,\tau)\, |N(t)\rangle \sim F_A(Q^2)|a|^2 e^{-m_N\tau} e^{-m_N(t-\tau)} e^{-iq\cdot x}$$



Ratio taken → poor-man's blinding

Conclusions

Neutrino physics is subject to
underestimated and model-dependent systematics
→ To reduce systematics from modeling,
need to understand nuclear physics
→ To understand nuclear physics, need to understand
nucleon-level cross sections from an ab initio calculation

- z-Expansion removes model assumptions and permits better understanding of systematic errors
- hydrogen (deuterium) targets have relatively small nuclear effects
- LQCD offers a way to access nucleon form factors directly

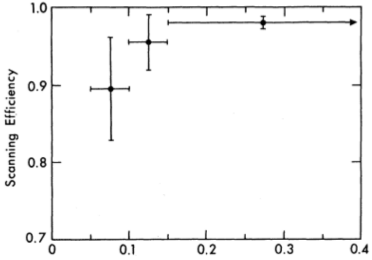
Thanks!

Backup Slide(s)

Acceptance Corrections

Acceptance correction for fixing errors from hand scanning
Q^2 dependent correction, correlated between bins:

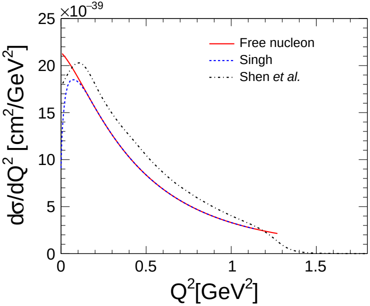
$$\frac{dN}{e(Q^2)} \to \frac{dN}{e(Q^2) + \eta\, de(Q^2)}, \quad \eta = 0 \pm 1$$



For ANL, BNL, FNAL respectively, $\eta = -1.9, -1.0, +0.01$;
minimal improvement of goodness of fit

Deuterium Corrections

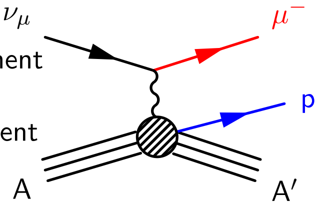
Corrections assumed to be E_ν independent
Two corrections tested:
Singh Nucl. Phys. B 36, 419,
Shen 1205.4337 [nucl-th]



Central values of Shen, Singh are consistent with each other
Final fit done with Singh, inflated error bars

Nuclear Effects

Nuclear effects not well understood
→ Models which are best for one measurement
are worst for another
Need to break F_A/nuclear model entanglement



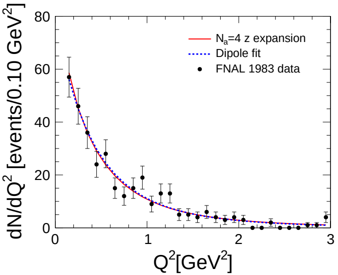
(assumed $m_A = 0.99$ GeV)

NuWro Model (χ^2/DOF)	RFG [GENIE]	RFG+ TEM	assorted others
leptonic(rate)	3.5	2.4	2.8-3.7
leptonic(shape)	4.1	1.7	2.1-3.8
hadronic(rate)	1.7[1.2]	3.9	1.9-3.7
hadronic(shape)	3.3[1.8]	5.8	3.6-4.8

(Minerva collaboration, 1305.2243,1409.4497[hep-ph])

Normalization Degeneracy

Despite similarity of dipole/z expansion, cross sections not the same



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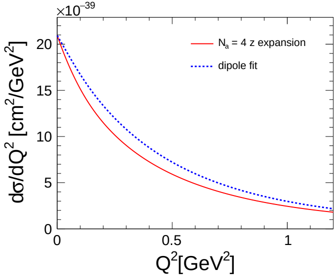

Consequence of self-consistency: cross section prediction

$$\frac{dN}{dE} \propto \frac{1}{\sigma}\frac{d\sigma}{dQ^2}$$

Cross section shape controlled by low-Q^2 data, normalization