Neutrino-Nucleon Interactions and Lattice QCD

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(Fermilab Lattice & MILC Collaborations)

Outline

- Motivation from neutrino physics
  - Importance of free-nucleon cross section
  - Where we can contribute
- z expansion
  - Introduction
  - Deuterium bubble chamber analysis
- (Preliminary) Lattice QCD axial form factor computation

Motivation

Oscillation experiments monitor flux by counting interactions assuming a cross section

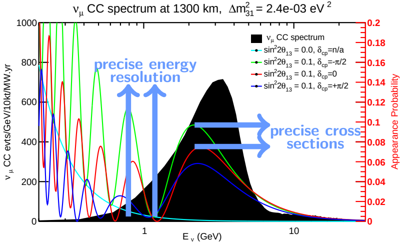
$$\Phi(E_\nu) = \frac{\mathcal{N}(E_\nu)}{\sigma_A(E_\nu)}$$

Ratio of flux at near/far detector cancels some systematics,
but not sufficient for next generation precision measurements

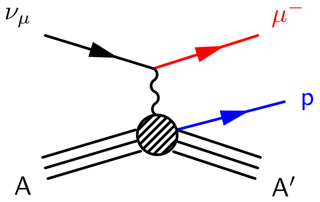
$$\sigma_A \sim \sigma_{CCQE} \otimes (\text{nucl. models})$$

- 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

Cross Sections



(Figure from LBNE, 1307.7335 [hep-ex])



CCQE scattering

- Measurements of neutrino parameters require precise knowledge of cross sections
- $\sigma_{CCQE}(E_\nu, Q^2)$ is quadratic function of form factors: F_{1V}, F_{2V}, F_A, F_P
- Uncertainty on $F_A(Q^2)$ is primary contribution to systematic errors
  - F_{1V}, F_{2V} known from $e - p$ scattering
  - F_P suppressed by lepton mass, approximated by PCAC

Discrepancies in the Axial-Vector Form Factor

Most analyses assume the Dipole axial form factor
(Llewellyn-Smith, 1971):

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

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

Large variation in m_A over many experiments:

- $m_A = 1.026 \pm 0.021$ (Bernard *et al.*, 0107088[hep-ph])
- $m_A^{\text{eff}} = 1.35 \pm 0.17$ (MiniBooNE, 1002.2680[hep-ph])

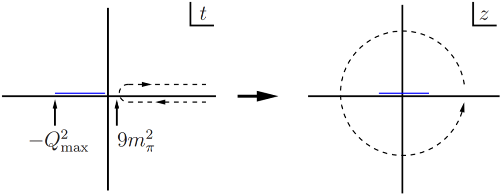
Essential to replace with model-independent parameterization

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 $|z| < 1$

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

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



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

z expansion has been implemented in GENIE, publicly available

Deuterium Fitting

Analysis in Phys. Rev. D 93, 113015 (1603.03048 [hep-ph])
ASM, M. Betancourt, R. Gran, R. Hill

Reanalyzed deuterium bubble chamber data by replacing dipole with z expansion framework

Three datasets:

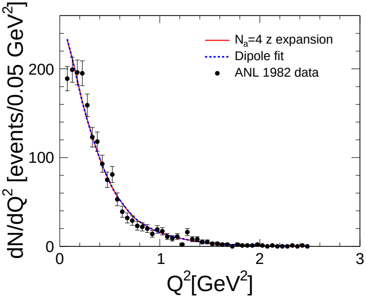
- ANL 1982: 1737 events, 0.5GeV [peak]
- BNL 1981: 1138 events, 1.6 GeV [average]
- FNAL 1983: 362 events, 20 GeV [peak], 27 GeV [average]

Shape-only fits to QE differential cross section data

Gaussian priors used on z expansion coefficients

Sum rules applied to enforce large Q^2 falloff

Deuterium Fits - Differential Cross Section

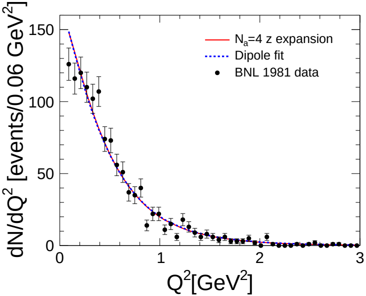


Dipole:

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)



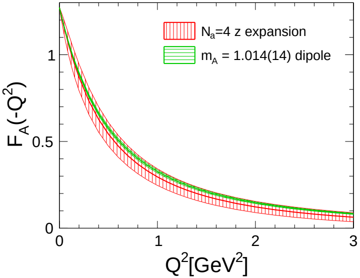
Dipole:

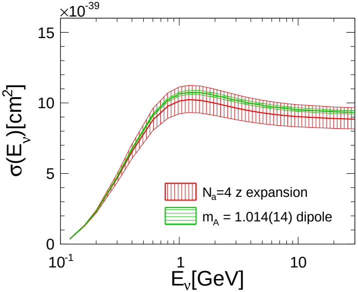
χ^2/N_{bins}	70.9/49
m_A	1.05(4)

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)

Final Fits





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]:

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

Dipole model significantly underestimates error from nucleon form factor

$\implies$ Necessary to use model-independent approach to properly understand systematic uncertainties from nucleon form factors

- z expansion is the appropriate model-independent approach

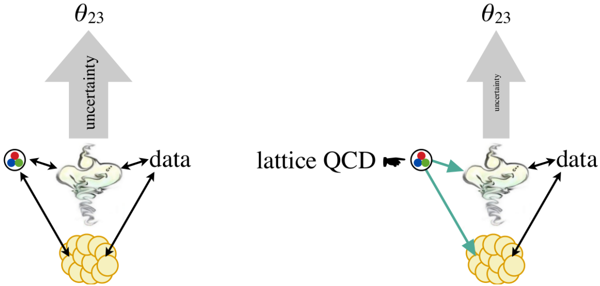
$\implies$ Need another first-principles approach to determine form factor

- Will aid future construction of nuclear models, understanding of nuclear physics
- Lattice QCD provides needed handle

Combination of Lattice QCD and z expansion already very successful in CKM matrix element computations

Lattice QCD in Neutrino Physics

- LQCD measurements becoming more accurate, precise
  $\Longrightarrow$ 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!

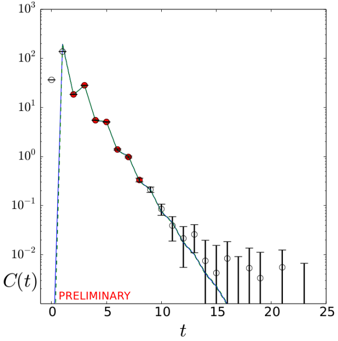


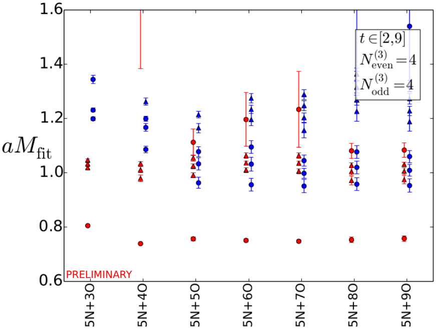
Current Lattice Effort

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

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



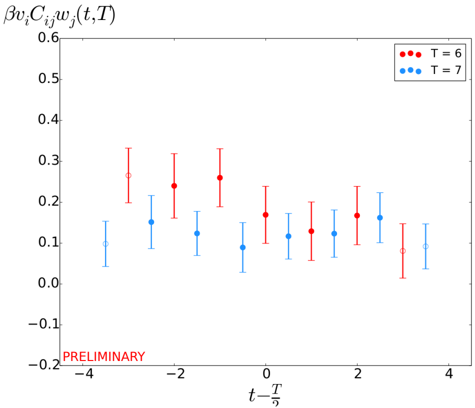


Lattice QCD Axial Form Factor

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

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

Results blinded by constant factor



Conclusions

Neutrino physics is subject to
underestimated and model-dependent systematics
$\rightarrow$ To reduce systematics from modeling,
need to understand nuclear physics
$\rightarrow$ 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
  - z expansion available in GENIE "trunk" version, will be fully supported in v2.12
- hydrogen (deuterium) targets have relatively small nuclear effects
- LQCD offers a way to access nucleon form factors directly

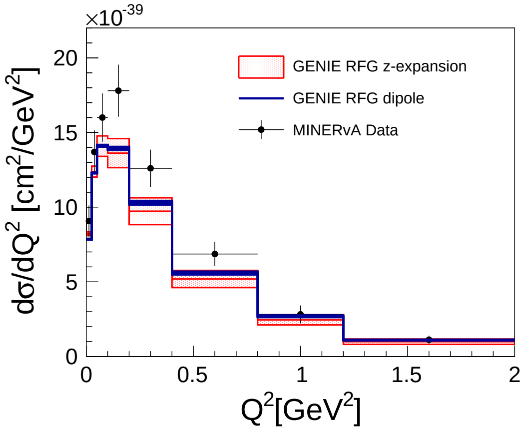
Thanks for listening!

Backup Slide(s)

z Expansion in GENIE

To be officially released in production version 2.12

Currently available in GENIE “trunk” version



3-Point Functions: Normalization of A_μ/Blinding

Calculate form factor:

$$\left.\frac{\langle N|\, Z_A A_\mu \,|N\rangle}{\langle 0|\, Z_A A_\mu \,|\pi^a\rangle}\right|_{q=0} \propto \frac{g_A}{f_\pi}$$

Benefits from statistical cancellation, exact renormalization

Normalize with f_π computed from MILC computation of f_π,
Phys. Rev. D 90, 074509 (1407.3772 [hep-lat])

F_A at nonzero momentum computed as ratio of nuclear matrix elements:

$$\frac{\langle N(0)|\, Z_A A_{\perp\mu}(q) \,|N(q)\rangle}{\langle N(0)|\, Z_A A_\mu(0) \,|N(0)\rangle} \propto \frac{F_A(Q^2)}{g_A}$$

3-Point Functions: Blinding

Value of g_A well-known from neutron beta decay experiments

$\implies$ Blinding implemented as a factor multiplying 3-point function

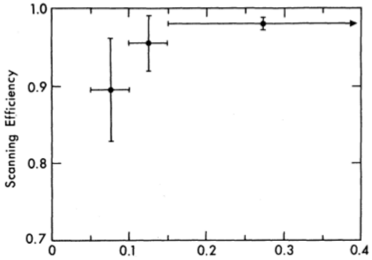
$$\beta \langle N(0)| Z_A A_\mu(q) |N(q)\rangle \sim \beta F_A(Q^2)$$

Blinding known only to few members of collaboration, not to me

Acceptance Corrections

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

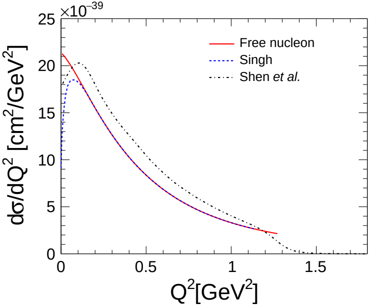
$$\frac{dN}{e(Q^2)} \to \frac{dN}{e(Q^2) + \eta\, de(Q^2)}, \quad \eta = 0 \pm 1$$



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

Deuterium Corrections

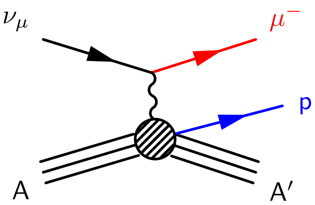
Corrections assumed to be E_ν independent
Two corrections tested:
Singh Nucl. Phys. B 36, 419,
Shen 1205.4337 [nucl-th]



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
$\rightarrow$ Models which are best for one measurement
are worst for another
Need to break F_A/nuclear model entanglement

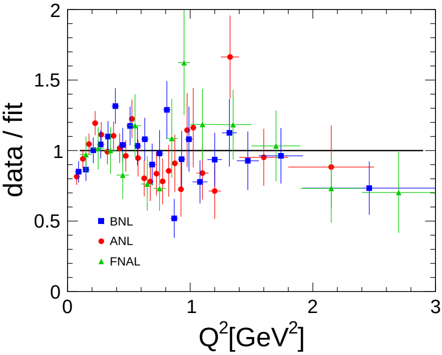


(assumed $m_A = 0.99$ GeV)

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])

Residuals

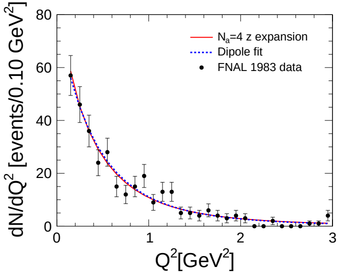


Neither z expansion, nor dipole can properly explain shape of data

Difficult to extract form factor from scattering data,
uncontrolled systematics introduced in process

Normalization Degeneracy

Despite apparent similarity of dipole/z expansion cross sections, form factors quite different



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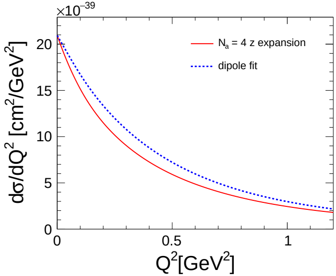

Consequence of self-consistency: cross section prediction

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

Cut of low-Q^2 data & floating normalization hide cross section differences