Fits to ν-CCQE Using Model-Independent Axial Form Factor Parameterization

Ab Initio Approaches

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Motivation

Neutrino physics needs a better understanding of axial form factor:

- Model-dependent shape parameterization introduces systematic uncertainties and underestimates errors
- Nuclear effects entangled with nucleon cross sections
- Measurement of oscillation parameters depends on nuclear models and nucleon-level form factors

Why Do We Still Need Better Theory?

Neutrino physics uses near detector/far detector paradigm, measures number distribution:

$$\frac{N_{\text{CCQE,near}}(E_\nu)}{N_{\text{CCQE,far}}(E_\nu)} = \frac{\phi_{\text{near}}(E_\nu)\,\sigma_{\text{CCQE}}(E_\nu)\,\epsilon_{\text{near}}}{\phi_{\text{far}}(E_\nu)\,\sigma_{\text{CCQE}}(E_\nu)\,\epsilon_{\text{far}}}$$

Problems:

- ϵ depends on near/far detector technology
- σ depends on nuclear models/nuclear target at near/far
- ϕ depends on beam angular distribution
  → near/far detector sample different energy distributions

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More Problems:

- σ is modified by nuclear and radiative corrections
- Effects of corrections removed by studying modification of N with Monte Carlo
- Monte Carlo uses σ as input
- σ calculated by measuring N

Degenerate uncertainties $N \to \mathrm{MC} \to \sigma \to N$

Why Do We Still Need Better Theory?

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Even More Problems:

- Model for σ constructed from single-nucleon cross section
- single-nucleon cross section constrained by assuming a model for σ

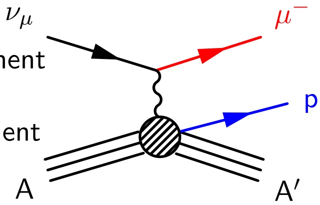
Degenerate uncertainties $\sigma_A \to \sigma_N \to \sigma_A$

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, reference hyperlinks online)

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

Discrepancies in the Axial-Vector Form Factor

Most analyses assume the “Dipole form factor”:

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

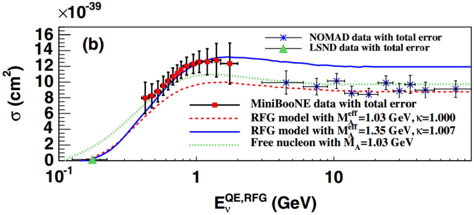
Dipole is an ansatz:

unmotivated in interesting energy range

→ uncontrolled systematics and underestimated uncertainties

Essential to replace ansatz with

model-independent parameterization



MiniBooNE Collab., PHYS REV D 81, 092005 (2010)

z-Expansion

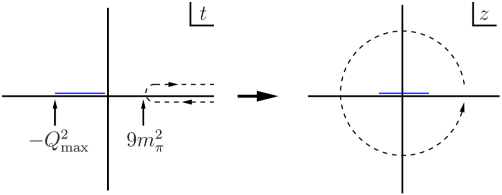
The z-Expansion (Bhattacharya, Hill, Paz arXiv:1108.0423 [hep-ph]) is a conformal mapping which takes the kinematically allowed region ($t \leq 0$) to within $z = \pm 1$

→ For reference, later plots will have $|z_{\max}| = 0.28$

$$t = q^2 = -Q^2 \qquad t_c = 9m_\pi^2$$

$$z(t; t_0, t_c) = \frac{\sqrt{t_c - t} - \sqrt{t_c - t_0}}{\sqrt{t_c - t} + \sqrt{t_c - t_0}}$$

$$F_A(z) = \sum_{n=0}^{\infty} a_n z^n$$



z-Expansion implemented in GENIE, to be released soon [autumn]

Advantages of z-Expansion

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

- Motivated by analyticity arguments
- Provides a prescription for introducing more parameters as data improves
- Allows quantification of systematic errors

From meson (baryon) semileptonic decays, only a few expansion coefficients necessary to accurately represent data

- Coefficient falloff required by perturbative QCD
- For general analysis, see Hill [arXiv:hep-ph/0606023]
- For recent $|V_{ub}|$ determination, see Fermilab/MILC [arXiv:1503.07839]
- For recent $|V_{ub}|/|V_{cb}|$ determination, see LHCb [arXiv:1504.01568]

Evaluation of Fits

Process:

- Fit to increasing $k_{\max}$ until adding new parameters no longer contributes appreciably to error/shape (z^k small)

What to Expect:

- Errors monotonically increase with more parameters
- Higher order coefficients alter fit less than lower order
  - Can cut off at finite $k_{\max}$ with marginal impact to fit
  - Data indicates how many parameters should be used
  - Truncation error is a systematic
- Coefficients $O(1)$, decreasing amplitude as k increases
- Expect shape to fit data, no other requirements on shape

Deuterium Fitting

with Richard Hill, Rik Gran, Minerba Betancourt

Fitting done on deuterium bubble chamber data
(controlled nuclear effects)

Three datasets (reference hyperlinks online):

- 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]

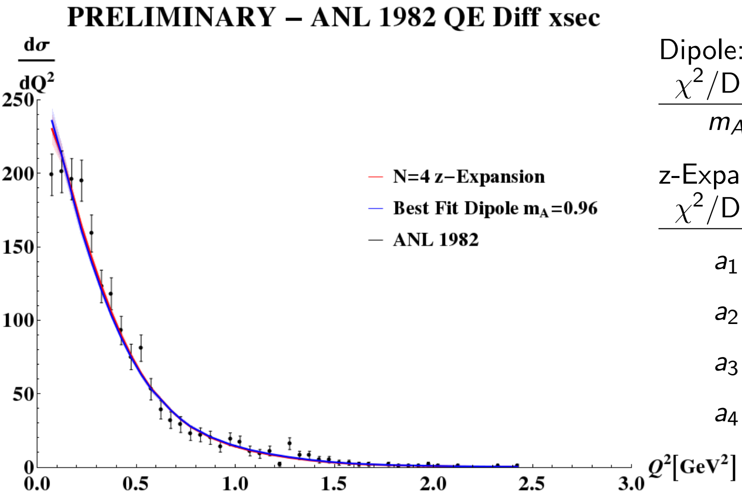
PRELIMINARY shape-only fits to QE differential cross section data

Results propagated to single nucleon QE total cross section

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

Sum rule applied to ensure $F_A \sim 1/Q^4$ as $Q^2 \to \infty$

Deuterium Fitting Results



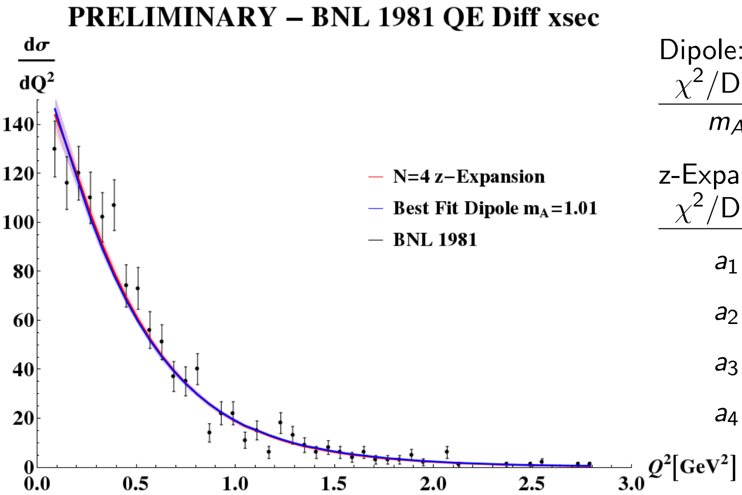
Dipole:

χ^2/DOF	55.3/39
m_A	0.96(5)

z-Expansion:

χ^2/DOF	54.5/36
a_1	$2.43^{+0.13}_{-0.12}$
a_2	$0.66^{+1.09}_{-1.05}$
a_3	$-7.18^{+2.80}_{-2.87}$
a_4	$4.26^{+3.46}_{-3.45}$

Deuterium Fitting Results



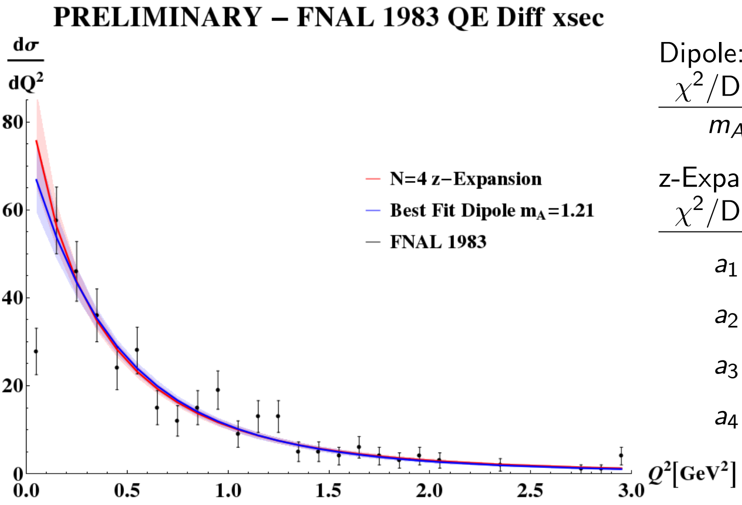
Dipole:

χ^2/DOF	53.3/36
m_A	1.01(5)

z-Expansion:

χ^2/DOF	53.9/33
a_1	$2.30^{+0.12}_{-0.12}$
a_2	$0.88^{+1.22}_{-1.26}$
a_3	$-6.55^{+3.01}_{-3.07}$
a_4	$3.05^{+3.49}_{-3.49}$

Deuterium Fitting Results



Dipole:

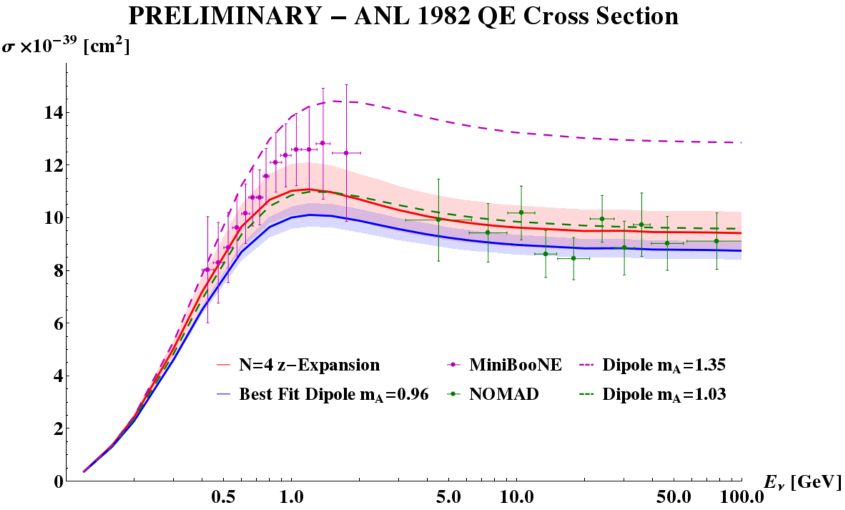
χ^2/DOF	15.9/21
m_A	1.21(12)

z-Expansion:

χ^2/DOF	15.3/18
a_1	$1.95^{+0.16}_{-0.16}$
a_2	$-1.32^{+1.81}_{-1.80}$
a_3	$0.03^{+3.67}_{-3.67}$
a_4	$-0.11^{+3.56}_{-3.56}$

Deuterium Fitting Results

- Quoted NOMAD/MiniBooNE σ are $\frac{1}{6}\sigma_{\text{carbon}}$
- Experiments use different definitions of CCQE
- Dipole guide lines (dashed) are nucleon-level cross section



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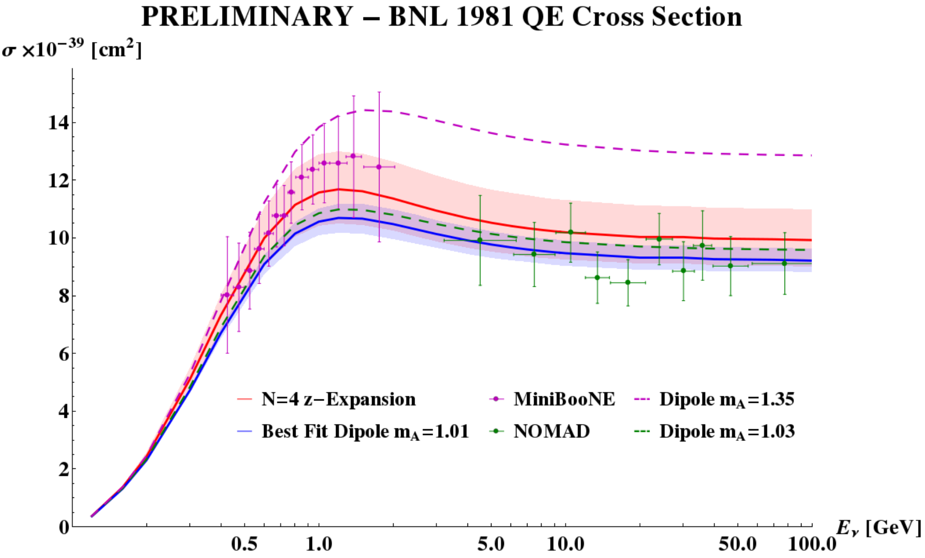

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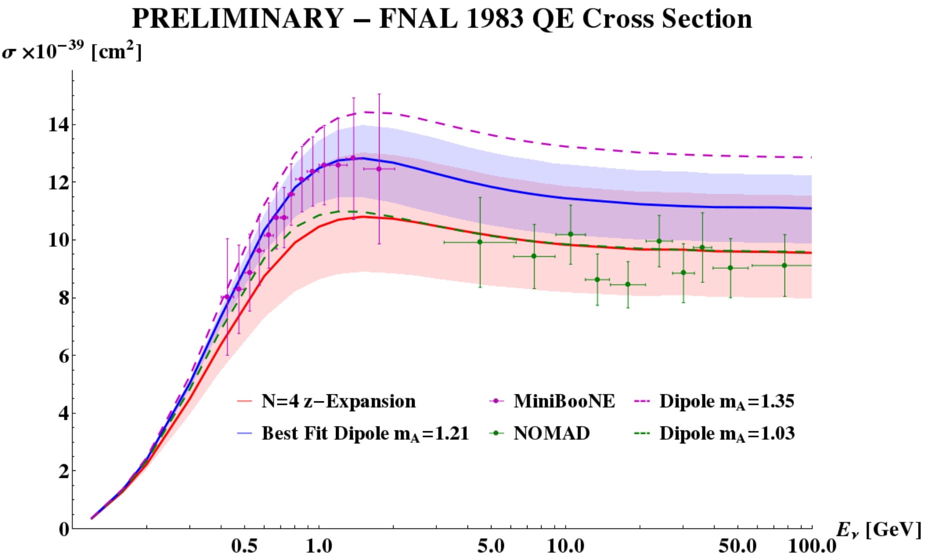

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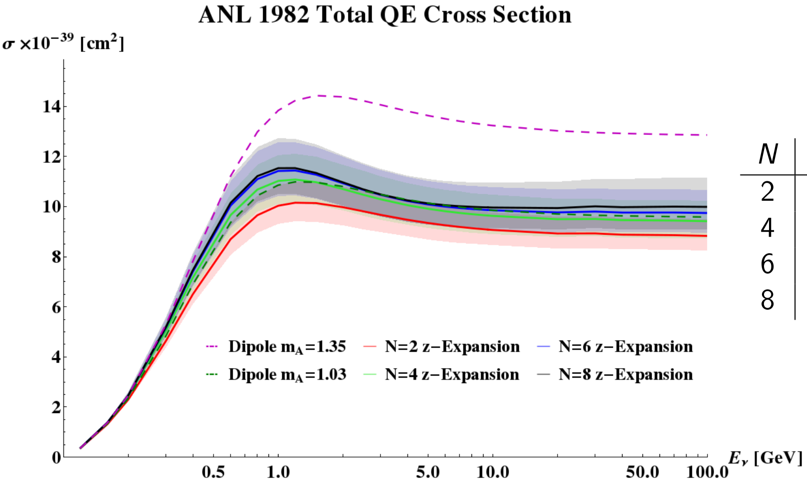
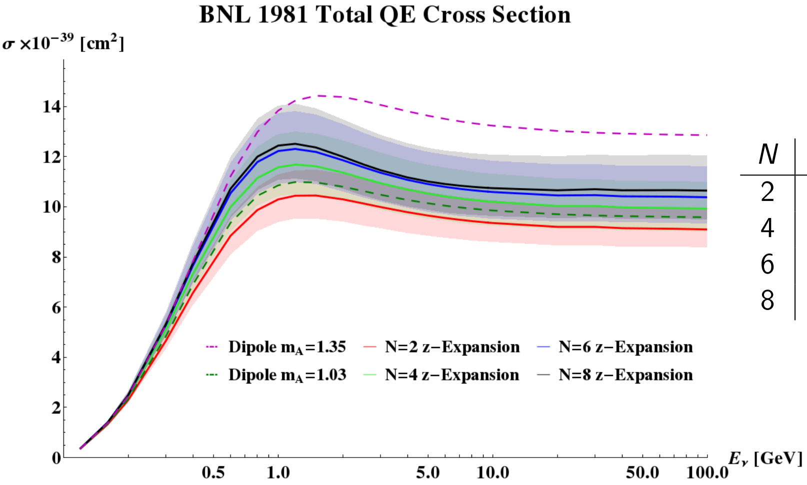


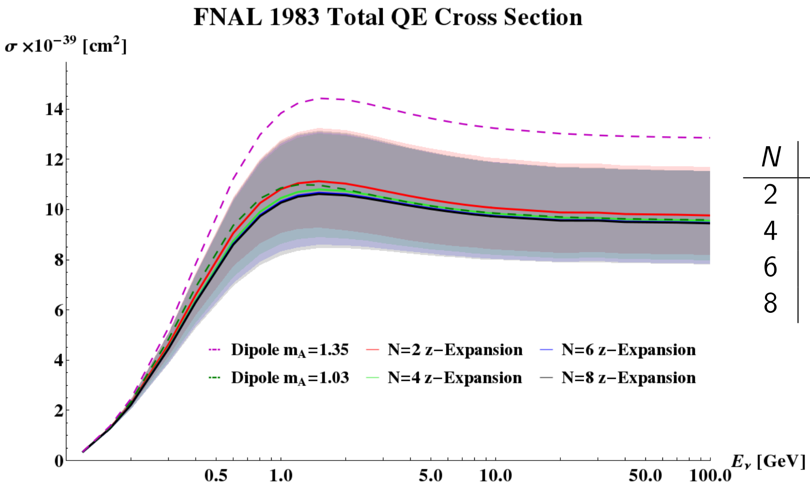
N	χ^2/DOF
2	1.59
4	1.51
6	1.54
8	1.62

Deuterium Fitting Results



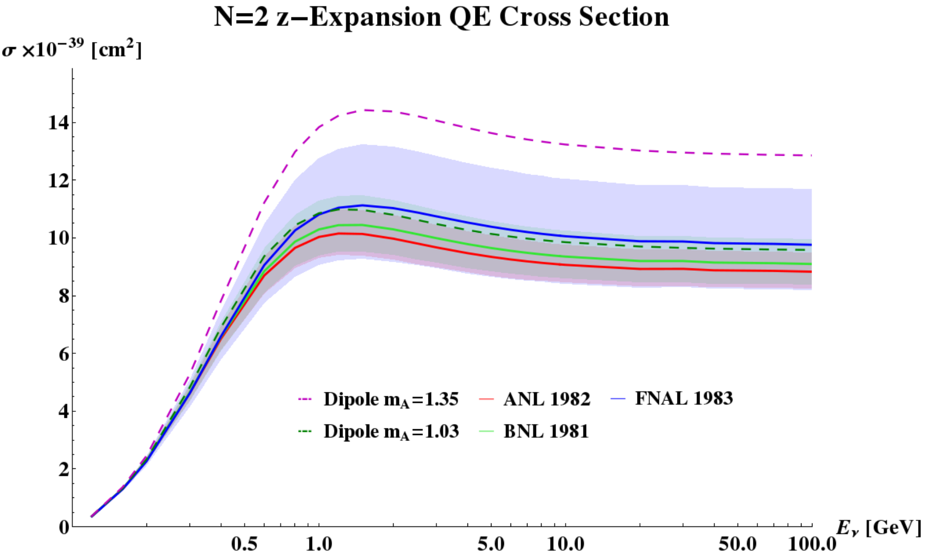
N	χ^2/DOF
2	1.67
4	1.63
6	1.66
8	1.74

Deuterium Fitting Results



N	χ^2/DOF
2	0.78
4	0.85
6	0.95
8	1.09

Deuterium Fitting Results



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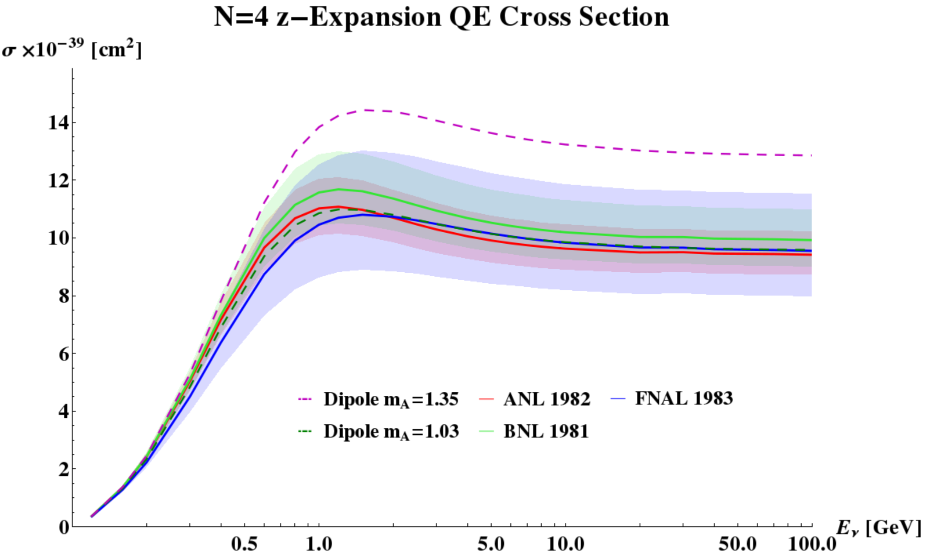

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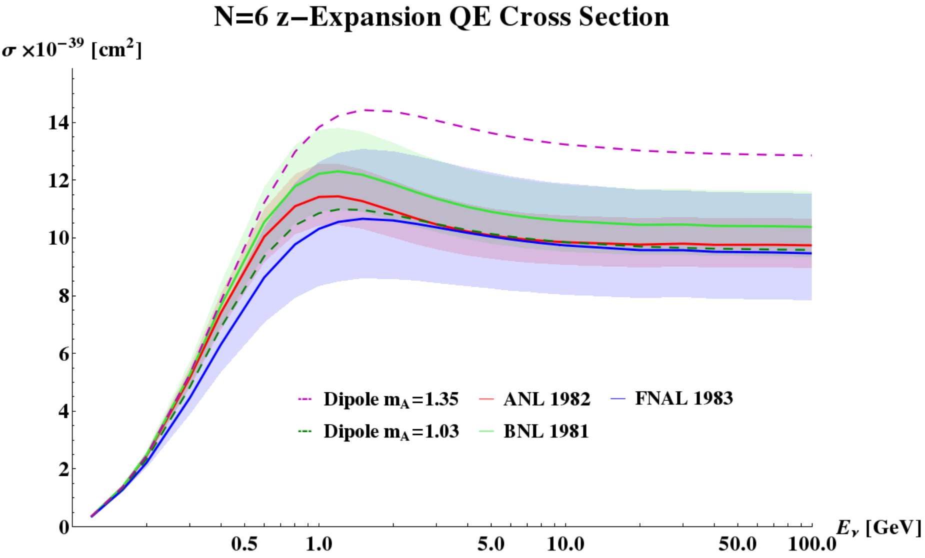
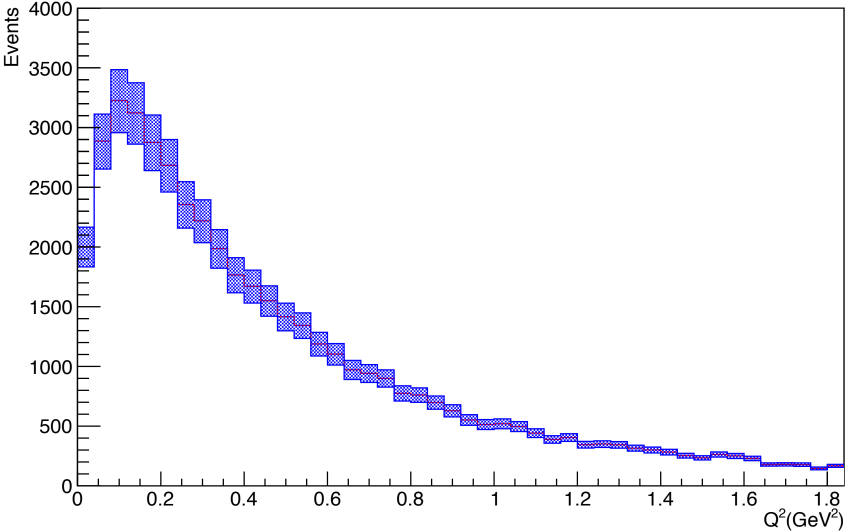


Implications for MINERνA



Fit to BNL N=3
(Figure made by M. Betancourt)

Take Home Messages

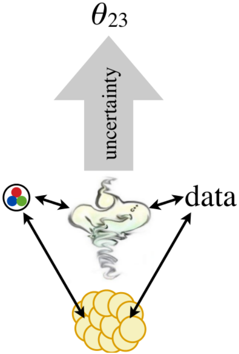
- χ^2/DOF approximately the same for z-expansion and dipole
- FNAL: truncation error negligible for $N \geq 4$
- ANL/BNL: truncation error small by $N = 4$, negligible for $N \geq 6$
- ANL/BNL: Large a_3, deuterium effects?
- Given choice of priors, errors on total cross section larger than dipole by 1.5-2 times
- Total cross sections from z-expansion fits consistent to within 1σ

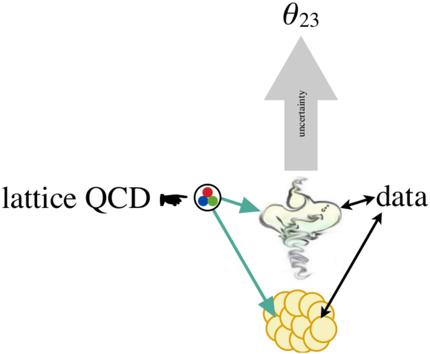
Still to come:

- More detailed deuterium corrections
- Radiative corrections
- Study of effects on MINERνA observables

Lattice QCD in Neutrino Physics

LQCD can play important role in breaking degeneracy





Nucleon-level/Nucleus-level effects entangled
Measurements of observables are model-dependent
LQCD acts as disruptive techology to break the cycle

Lattice F_A Calculation

$g_A = F_A(q^2 = 0)$ is a historically difficult calculation
(world best 10-20% too small)

What makes it hard:

- Baryons(!)
- Finite size effects
- Chiral extrapolation
- Explicit Chiral symmetry breaking - for some formalisms
- Excited state contamination

Lattice F_A Calculation

Will use MILC's 2+1+1 flavor gauge ensembles
What we bring to the table:

- High computation speed → Statistics
- Large lattices → Control finite size effects
- Physical quark masses → Avoid chiral extrapolation
- Exact chiral symmetry → Obtain absolute normalization
- Variational method →
  Mitigate excited state contamination

Outlook

Deuterium Fitting/GENIE:

- Finish fitting/writeup - next few months
- Write correlated reweighting for GENIE
- Coordinate GENIE code release with publication release

Lattice:

- Code testing/development - this/next month
- Production - soon after
- g_A calculation - Spring/Summer 2016
- $F_A(q^2)$ calculation - Fall/Winter 2016

Further (more challenging) lattice QCD calculations:

- $\nu_\ell N \to \nu_\ell N'$
- N-Δ transition currents
- $\nu_\ell N \to \pi \ell N'$
- $\nu_\ell N \to \pi \ell \Sigma$

Conclusions

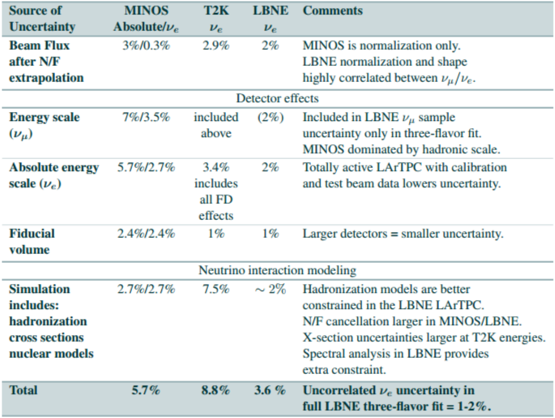
Neutrino physics is subject to
underestimated and model-dependent systematics
→ To reduce systematics from modeling,
need to understand nuclear physics
→ To understand nuclear physics, need to understand
nucleon-level cross sections from an ab initio calculation

- z-Expansion removes model assumptions and permits better understanding of systematic errors
- hydrogen (deuterium) targets have [almost] no nuclear effects
- LQCD offers a way to access nucleon form factors directly

Thanks!

Backup Slide(s)

Error Budgets



Source of Uncertainty	**MINOS Absolute/ν_e**	**T2K ν_e**	**LBNE ν_e**	**Comments**
Beam Flux after N/F extrapolation	3%/0.3%	2.9%	2%	MINOS is normalization only. LBNE normalization and shape highly correlated between ν_μ/ν_e.
Detector effects				
Energy scale (ν_μ)	7%/3.5%	included above	(2%)	Included in LBNE ν_μ sample uncertainty only in three-flavor fit. MINOS dominated by hadronic scale.
Absolute energy scale (ν_e)	5.7%/2.7%	3.4% includes all FD effects	2%	Totally active LArTPC with calibration and test beam data lowers uncertainty.
Fiducial volume	2.4%/2.4%	1%	1%	Larger detectors = smaller uncertainty.
Neutrino interaction modeling				
Simulation includes: **hadronization** **cross sections** **nuclear models**	2.7%/2.7%	7.5%	$\sim 2\%$	Hadronization models are better constrained in the LBNE LArTPC. N/F cancellation larger in MINOS/LBNE. X-section uncertainties larger at T2K energies. Spectral analysis in LBNE provides extra constraint.
Total	**5.7%**	**8.8%**	**3.6 %**	**Uncorrelated ν_e uncertainty in full LBNE three-flavor fit = 1-2%.**

LBNE Experiment