Deuterium Bubble Chamber Fits

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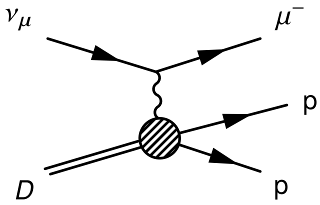
GENIE *z*-Expansion Mini-Workshop

Deuterium Bubble Chamber Interactions



$$\nu_\mu + D \to \mu + p + p \qquad \Longrightarrow \qquad \nu_\mu + n \to \mu + p$$

Interaction of neutrino with neutron in deuterium nucleus

Spectator proton momentum measured
$\Longrightarrow$ consistency check & fix momentum of target neutron

Clean signal compared to other nuclear targets

Deuterium Bubble Chamber Data

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:

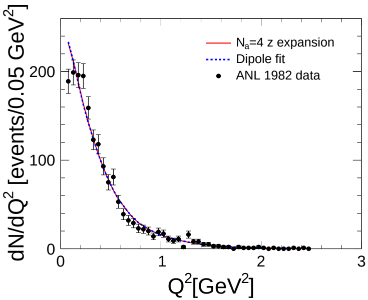
- ANL 1982: 1737 events, 0.5 GeV
- BNL 1981: 1138 events, 1.6 GeV
- FNAL 1983: 362 events, 20 GeV

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

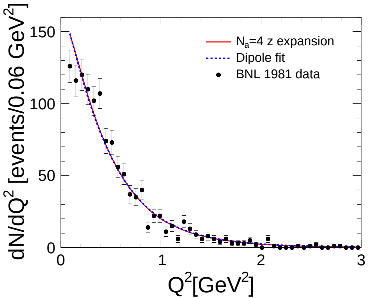


Dipole:

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:

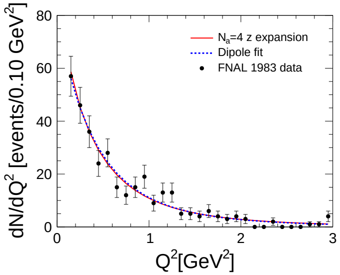
χ^2/N_{bins}	70.9/49
m_A	1.05(4)

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)

Normalization Degeneracy

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



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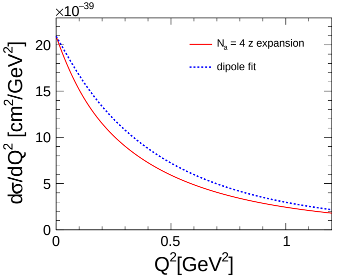


Consequence of self-consistency: cross section prediction

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

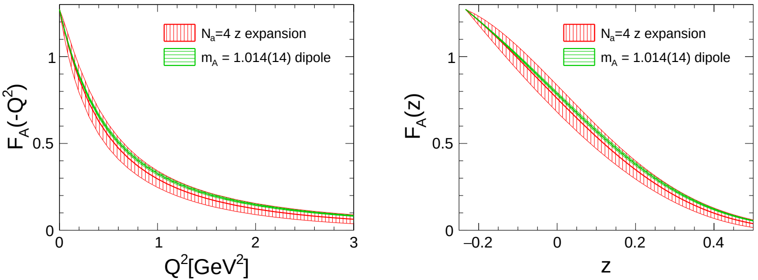
Cut of low-Q^2 data & floating normalization hide cross section differences

Final Fits: Form Factor

Final fits include systematics of acceptance corrections,
deuterium nuclear corrections

z-expansion parameters:

$\{a_1, a_2, a_3, a_4\} = \{2.30(13), -0.6(1.0), -3.8(2.5), 2.3(2.7)\}$

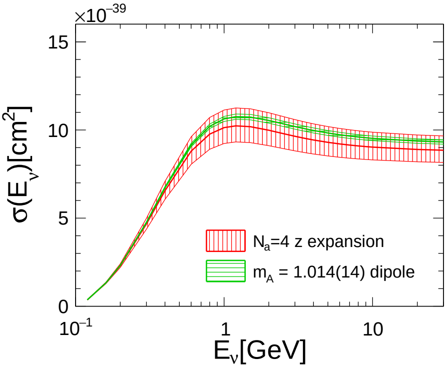


Define axial radius in terms of slope: $$r_A^2 \equiv -\frac{6}{F_A(0)} \frac{dF_A}{dQ^2}\bigg|_{Q^2=0}$$

compare to Bodek *et al.* [Eur. Phys. J. C 53, 349]:

$r_A^2 = 0.46(22)\ \mathrm{fm}^2$ (this work) $\qquad r_A^2 = 0.453(13)\ \mathrm{fm}^2$ (Bodek *et al.*)

Final Fits: ν_μ Cross Section



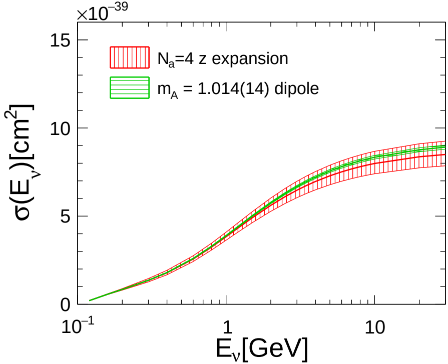
Calculated cross section:

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

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

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

Final Fits: $\overline{\nu}_\mu$ Cross Section



Calculated cross section:

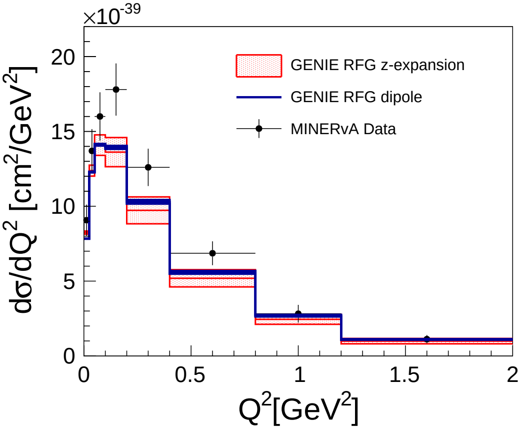
$$\sigma_{\overline{\nu}p\to\mu n}(E_{\overline{\nu}} = 1\ \mathrm{GeV}) = 3.83(23) \times 10^{-39}\mathrm{cm}^2$$

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

$$\sigma_{\overline{\nu}p\to\mu n}(E_{\overline{\nu}} = 1\ \mathrm{GeV}) = 3.890(25) \times 10^{-39}\mathrm{cm}^2$$

z-Expansion in GENIE

z-Expansion versus dipole using GENIE and MINERνA flux

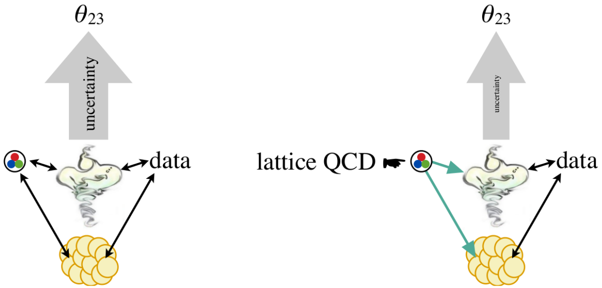


Bubble Chamber Fits Summary

- A fit to the nucleon axial form factor using the z-expansion has been presented
- For fits presented, data only constrains first coefficient with $< 50\%$ error bar
- Use of the dipole severely underestimates the uncertainty on the axial radius and, consequently, the neutrino cross section $\implies$ discrepancy is about an order of magnitude

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!



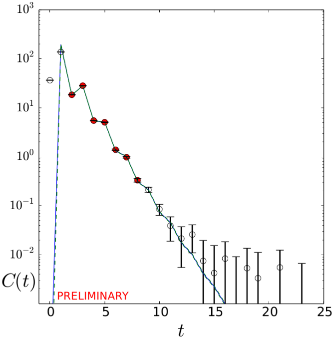
Current Lattice Effort

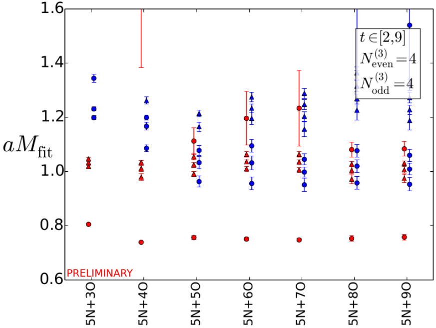
LQCD calculation of form factors underway by MILC/Fermilab Lattice Collaborations

Lattice computation involves several stages, building up to result:

2-point functions = masses, overlap factors

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



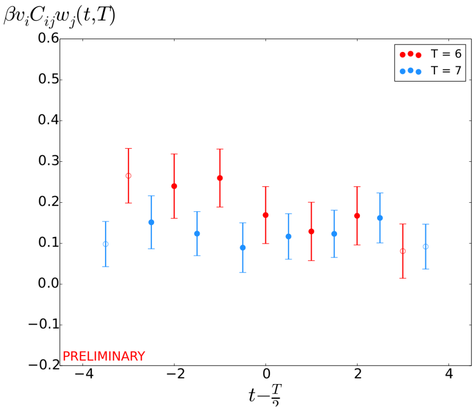


Lattice QCD Axial Form Factor

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



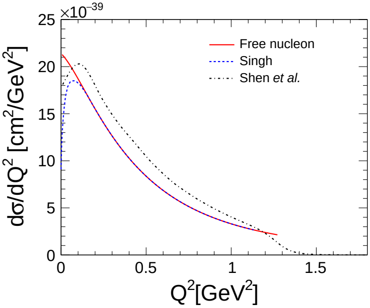
Backup

Deuterium Corrections

Corrections due to deuterium assumed to be E_ν independent

Two corrections tested:

- Singh Nucl. Phys. B 36, 419,
- Shen 1205.4337 [nucl-th]



Fit central values of Shen, Singh are consistent with each other

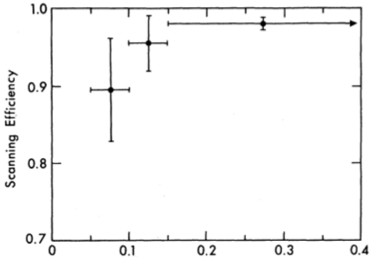
Final fit done with Singh, error bars inflated to give $\chi^2/N_{\text{bins}} \sim 1$

Acceptance Corrections

Acceptance correction included for fixing errors from hand scanning

Q^2 dependent correction, correlated between bins:

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

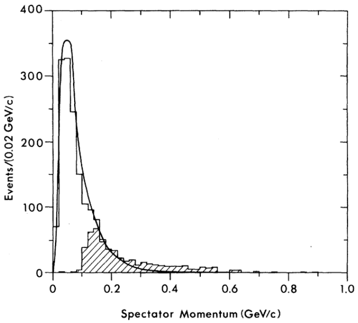


For ANL, BNL, FNAL respectively, $\eta = -1.9, -1.0, +0.01$;

$\Longrightarrow$ minimal improvement in goodness of fit

Spectator Protons

Measurement of spectator protons used as consistency check, fix initial momentum of target neutron



Three-prong events (spectator proton measured) in shaded area

Three-prong used as input with model to predict two-prong events, curve is prediction versus unfilled histogram of two-prong events