Archeology: Quasielastic Events from Bubble Chambers

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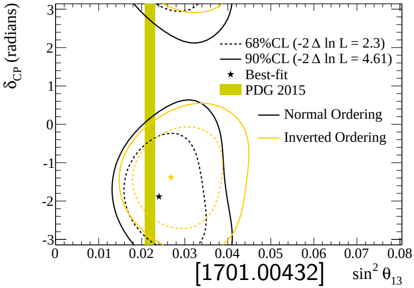
INT 18-2a: Fundamental Physics with Electroweak Probes of Light Nuclei

Outline

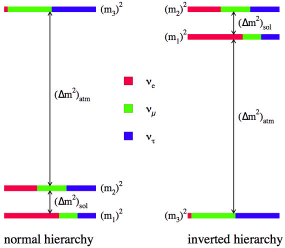
- Introduction
  - Neutrino Experiments
  - QE Scattering
  - Axial Form Factor
- Deuterium Bubble Chamber Data Reanalysis
  - Dipole
  - z Expansion
  - Results and Summary
- Future Prospects
  - Lattice QCD
- Conclusions

Introduction

Neutrino Oscillation Experiment Goals



[1701.00432]



[1307.5487]

Neutrino oscillation experiments are a major focus of upcoming decades

Experiments have several measurement goals:

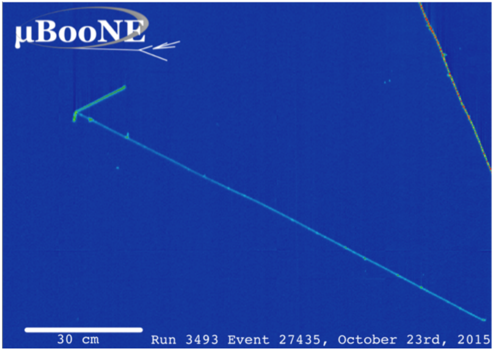
- determine value of δ_{CP}
- determine sign of Δm^2_{31}; i.e. mass hierarchy
- precision determinations of $\Delta m^2_{ij} \equiv m^2_i - m^2_j$ and θ_{ij}

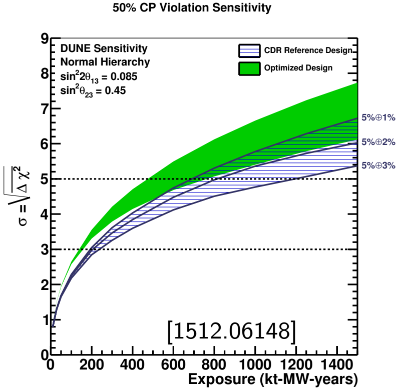
Want to maximize discovery potential for oscillation experiments,
need precise supporting theoretical predictions

Nuclear Targets

Measurements employ large nuclear targets:

- Part of detection material
- Increase cross section to improve event rate





DUNE → Argon, HyperK → H_2O

Nuclear targets are challenging and precision matters

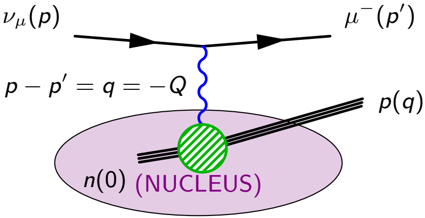
Dissect problem into simple pieces, get robust determinations of simplest

Quasielastic scattering

Quasielastic scattering good starting place understanding neutrino scattering:

ν interacts with single nucleon in nucleus
$\Longrightarrow$ QE is relatively easy measurement,
relatively theoretically clean

QE is primary signal measurement process
for neutrino oscillation experiments



In absence of intranuclear rescattering,
can infer incident neutrino energy from lepton kinematics alone:

$$E_\nu^{QE} = \frac{2(M_n - E_b)E_\ell - ((M_n - E_b)^2 - M_p^2 + m_\ell^2)}{2(M_n - E_b - E_\ell + p_\ell \cos\theta_\ell)}$$

Assumed to be single nucleon interaction, accesses free nucleon amplitudes

$\Longrightarrow$ Use amplitudes from QE as building block for more sophisticated interactions

CCQE Cross section

$$\frac{d\sigma_{CCQE}}{dQ^2}(E_\nu, Q^2) \propto \frac{1}{E_\nu^2}\left(A(Q^2) \mp \left(\frac{s-u}{M_N^2}\right) B(Q^2) + \left(\frac{s-u}{M_N^2}\right)^2 C(Q^2)\right)$$

$$s - u = 4M_N E_\nu - Q^2 - m_\ell^2 \qquad \eta \equiv \frac{Q^2}{4M_N^2}$$

$$\begin{aligned} A(Q^2) = {} & \frac{m_\ell^2 + Q^2}{M_N^2} \times \\ & \left[(1+\eta){F_A}^2 - (1-\eta)(F_1^2 + \eta F_2^2) + 4\eta F_1 F_2 \right. \\ & \left. - \frac{m_\ell^2}{4M_N^2}\left((F_1+F_2)^2 + (F_A + 2F_P)^2 - 4(1+\eta)F_P^2\right)\right] \end{aligned}$$

$$B(Q^2) = 4\eta F_A (F_1 + F_2) \qquad C(Q^2) = \frac{1}{4}\left({F_A}^2 + F_1^2 + \eta F_2^2\right)$$

[1305.7513]

- F_1, F_2 from high-statistics monoenergetic e^- scattering on proton target
- F_P suppressed by lepton mass corrections, constrained by PCAC

$\Longrightarrow$ F_A largest contributor to systematic errors

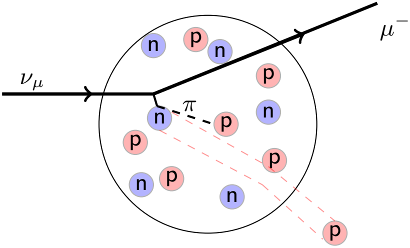
Nuclear Cross Sections

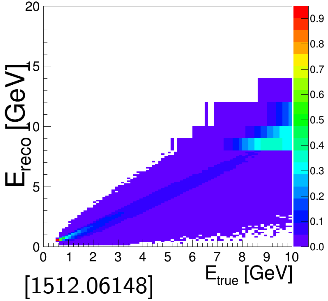
Intranuclear effects can be problematic, even for simple QE:

- Nuclear rescattering can change particle energies
- Topologies can be changed by absorption, emission of other particles

$\Longrightarrow$ Energies cannot be determined on an event-by-event basis
$\Longrightarrow$ Energy spectrum must be reconstructed statistically

Need to go simpler!





Focus

- Large nuclear targets have many interaction channels, want to put simplest on as solid footing as possible
- Quasielastic is simplest interaction channel, probes free nucleon matrix elements
- Separating out quasielastic is nontrivial in large nuclei
- Study QE in smallest nucleus possible

$\Longrightarrow$ Study neutrino QE scattering in Deuterium

Deuterium Bubble Chamber

Dipole Form Factor

Most analyses assume the Dipole axial form factor (Llewellyn-Smith, 1972):

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

[Phys.Rept.3 (1972),261]

Dipole is an ansatz:

- inconsistent with QCD
- unmotivated in interesting energy region

$\Longrightarrow$ uncontrolled systematics and therefore underestimated uncertainties

Large variation in m_A over many experiments
(dubbed the "axial mass problem"):

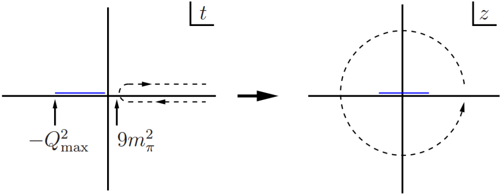
- $m_A = 1.026 \pm 0.021$ (Bernard *et al.*, [arXiv:00107088])
- $m_A^{\text{eff}} = 1.35 \pm 0.17$ (MiniBooNE, [arXiv:1002.2680])

Essential to use model-independent parameterization of F_A instead

z Expansion

The z Expansion [arXiv:1108.0423] is a conformal mapping which takes kinematically allowed region ($t = -Q^2 \leq 0$) to within $|z| < 1$

$$z(t; t_0, t_c) = \frac{\sqrt{t_c - t} - \sqrt{t_c - t_0}}{\sqrt{t_c - t} + \sqrt{t_c - t_0}} \qquad F_A(z) = \sum_{n=0}^{\infty} a_n z^n \qquad t_c = 9m_\pi^2$$



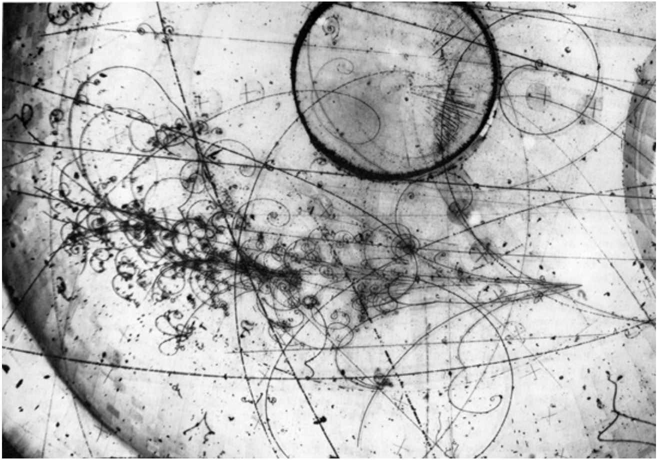
- Model independent: motivated by analyticity arguments from QCD
- Only few parameters needed: unitarity bounds
- Sum rules regulate large-Q^2 behavior

Summary of Existing DBC Experiments

[0812.4543]

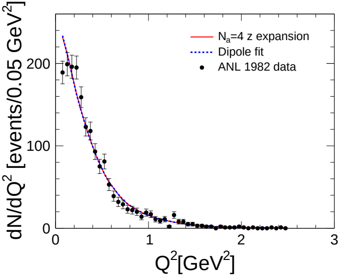
Experiment	Target	Events	Method	M_A, GeV	Ref.
ANL 69	Steel		$d\sigma/dQ^2$	1.05 ± 0.20	[1]
			σ	0.97 ± 0.16	
ANL 73	Deuterium	166	$d\sigma/dQ^2$	0.94 ± 0.18	[2]
			$\sigma \otimes d\sigma/dQ^2$	0.95 ± 0.12	
			σ	$0.75^{+0.13}_{-0.11}$	
ANL 77	Deuterium	~600	$d\sigma/dQ^2$	1.01 ± 0.09	[3]
			$\sigma \otimes d\sigma/dQ^2$	0.95 ± 0.09	
			σ	0.74 ± 0.12	
ANL 82	Deuterium	1737	$d\sigma/dQ^2$	1.05 ± 0.05	[4]
			$\sigma \otimes d\sigma/dQ^2$	1.03 ± 0.05	
BNL 81	Deuterium	1138	$d\sigma/dQ^2$	1.07 ± 0.06	[6]
BNL 90	Deuterium	2538	$d\sigma/dQ^2$	$1.070^{+0.040}_{-0.045}$	[8]
FermiLab 83	Deuterium	362	$d\sigma/dQ^2$	$1.05^{+0.12}_{-0.16}$	[9]
NuTeV 04	Steel	21614	σ	1.11 ± 0.08	[23]
MiniBooNE 07	Mineral oil	193709	$d\sigma/dQ^2$	1.23 ± 0.20	[26]
CERN HLBC 64	Freon	236	$d\sigma/dQ^2$	$1.00^{+0.35}_{-0.20}$	[11]
CERN HLBC 67	Freon	90	$\sigma \otimes d\sigma/dQ^2$	$0.75^{+0.24}_{-0.20}$	[12]
CERN SC 68	Steel	236	$d\sigma/dQ^2$	$0.65^{+0.45}_{-0.40}$	[13]
CERN HLBC 69	Propane	130	$\sigma \otimes d\sigma/dQ^2$	0.70 ± 0.20	[14]
CERN GGM 77	Freon	687	σ	0.88 ± 0.19	
			$d\sigma/dQ^2$	0.96 ± 0.16	[15]
CERN GGM 79	Propane/Freon	556	σ	0.87 ± 0.18	
			$d\sigma/dQ^2$	0.99 ± 0.12	[17]
CERN BEBC 90	Deuterium	552	σ	0.94 ± 0.07	
			$d\sigma/dQ^2$	1.08 ± 0.08	[18]

The Interior of a Bubble Chamber



[Fermilab]

Differential Cross Section [1603.03048 [hep-ph]]

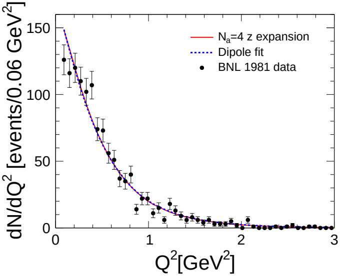


Dipole:

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)



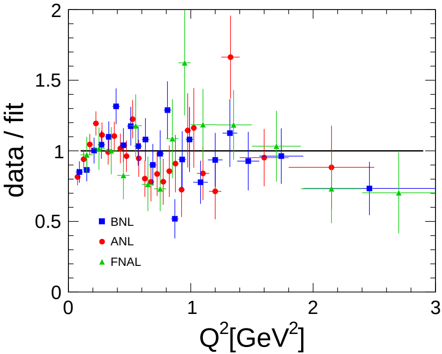
Dipole:

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



Not a perfect description of data $\implies$ possibly correlated systematic effect

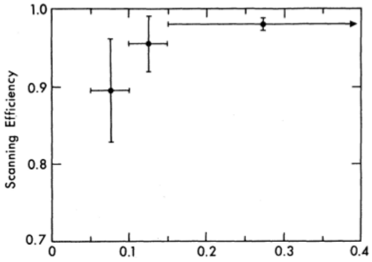
Neither dipole nor z expansion can properly explain shape of data

To account for this in final result, χ^2 errors inflated slightly
$\implies$ 10% of total uncertainty from this inflation

What could explain discrepancy?

- Vector form factor shape? $\implies$ new analysis in Phys.Let.B 777, 8 (2018)
- Deuterium corrections?

Acceptance Corrections



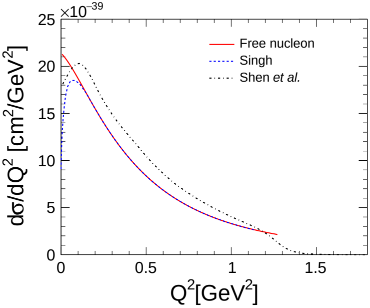
Simplistic model given for acceptance corrections

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

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

All corrections η small; minimal improvement of goodness of fit

Deuterium Corrections



Two corrections tested:

Singh, Nucl. Phys. B 36, 419; Shen *et al.*, 1205.4337 [nucl-th]

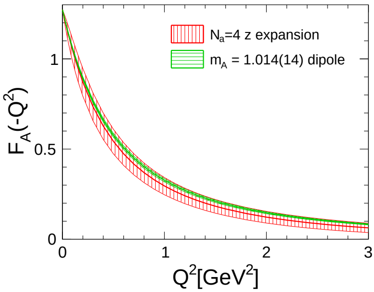
Corrections assumed to be E_ν independent

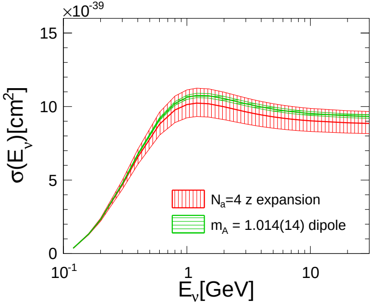
Both corrections have similar trends $\rightarrow$ low Q^2 suppression, mild changes to curvature up to $Q^2 = 1.0\ \mathrm{GeV}^2$

Shen prefers enhancement of Q^2 range

Despite different shapes and magnitude, effect on fits mild

Reanalysis Results Summary [1603.03048 [hep-ph]]





$$\frac{1}{F_A(0)}\frac{dF_A}{dQ^2}\bigg|_{Q^2=0} \equiv -\frac{1}{6} r_A^2$$

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

compared to 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

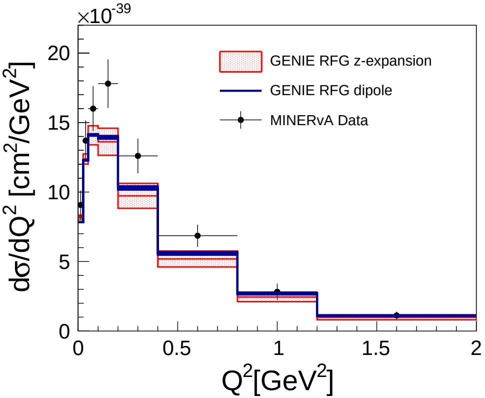
Most theoretically clean data do not constrain form factor precisely

z Expansion in GENIE

z expansion coded into GENIE - may be turned on with configuration switch

Officially released in production version 2.12

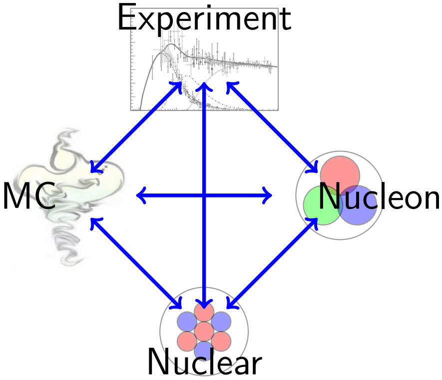
Uncertainties on free-nucleon cross section as large as data-theory discrepancy
$\implies$ need to improve F_A determination to make headway on nuclear effects



See tutorial: https://indico.fnal.gov/event/12824/

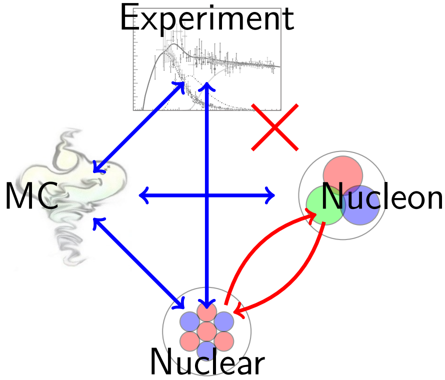
Future Prospects

Lattice QCD as a Tool



The ideal situation: lots of redundancy and checks between elements of analysis

Lattice QCD as a Tool



The ideal situation: lots of redundancy and checks between elements of analysis

In reality: F_A not well determined by experiment
$\implies$ nucleon amplitudes constrained by/used to constrain nuclear models

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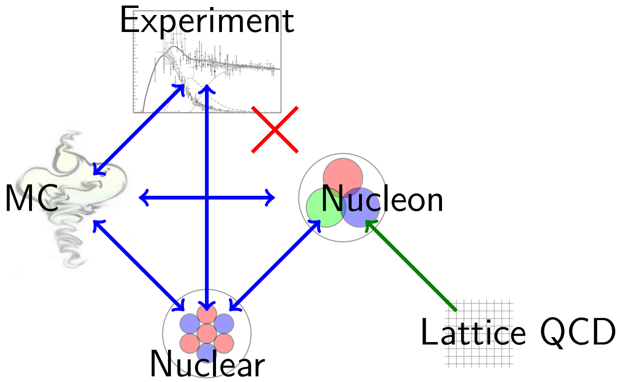


The ideal situation: lots of redundancy and checks between elements of analysis

In reality: F_A not well determined by experiment
$\implies$ nucleon amplitudes constrained by/used to constrain nuclear models

Lattice QCD acts as a disruptive technology to break degeneracy

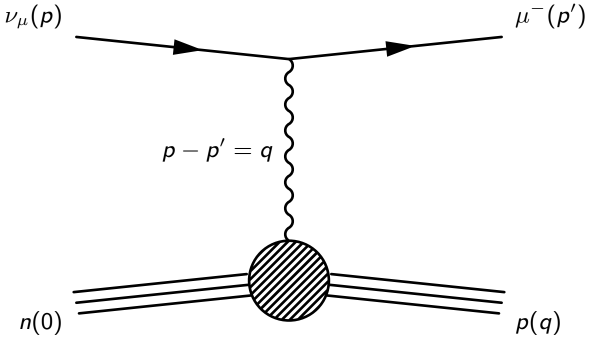
See Phiala's/Andreas's talks for more detail

How Does Lattice Help?

Lattice is well suited to compute matrix elements:

$$\mathcal{M}_{\nu_\mu n \to \mu p}(p, p') = \langle \mu(p') | \left(V_\mu - A_\mu \right) | \nu(p) \rangle \, \langle p(q) | \left(V_\mu - A_\mu \right) | n(0) \rangle$$

Systematically improvable: more computing power $\implies$ more precision



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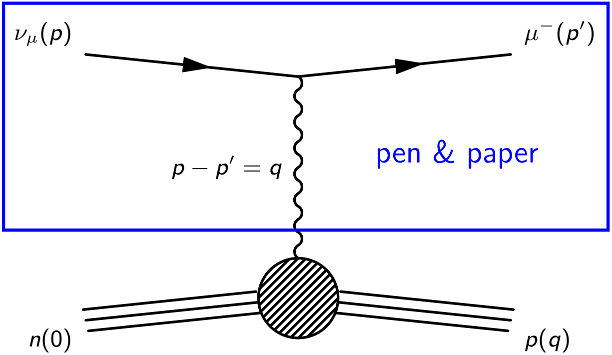

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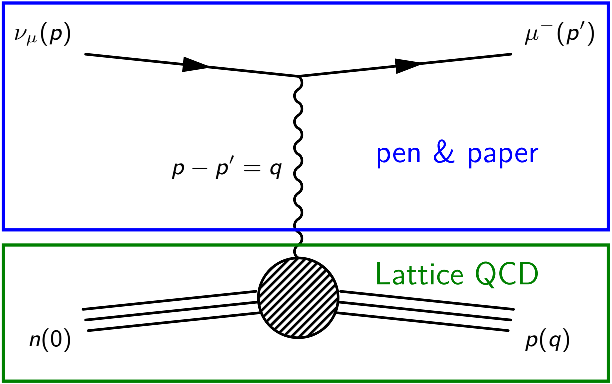

Nucleon axial form factor $G_A(Q^2)$

Previously, [Lin,0802.0863], [Yamazaki,0904.2039], [Bratt,1001.3620], [Bali,1412.7336]

Needed for neutrino oscillation experiments:

Charged current quasielastic (CCQE) neutrino-nucleus interaction must be known to high precision.

Connecting quark - nucleon level: $G_A(Q^2)$ form factor.
nucleon - nucleus level: nuclear model.

Traditionally: information on $G_A(Q^2)$ extracted from expt. using dipole fit:

$$G_A(Q^2) = \frac{g_A}{(1 + \frac{Q^2}{{M_A}^2})^2} \qquad \langle r_A^2 \rangle = \frac{12}{{M_A}^2}$$

World average (pre 1990) from ν scattering $M_A = 1.026(21)$ GeV.

Overconstrained form: different measurements, different M_A.

Lower energy expts: e.g. MiniBooNE: $M_A = 1.35(17)$ GeV
[Aguilar-Arevalo,1002.2680]

Systematics being explored including new analysis of old expt data:
$\langle r_A^2 \rangle = 0.46(22)\ \text{fm}^2 \rightarrow M_A = 1.01(24)$ GeV from z-expansion [Meyer,1603.03048].

Several computations of $F_A(Q^2)$ appeared in response:

LHPC 1703.06703 [hep-lat]
ETMC 1705.03399 [hep-lat]
CLS 1705.06186 [hep-lat]
PNDME 1705.06834,1801.01635,1801.03130 [hep-lat]

Additional g_A computations: (CalLat) 1704.01114,1710.06523
(JLQCD) 1805.10507

Ref.	g_A	$\langle r_A^2 \rangle$ [fm^2]
LHPC	1.208(6)(16)(1)(10)	0.213(6)(13)(3)(0)
ETMC	1.212(33)(22)	0.267(9)(11)
CLS	$1.278(68)(^{+00}_{-87})$	$0.360(36)(^{+80}_{-88})$
PNDME	1.20(3)	0.25(6)
CalLat	1.285(17)	–
JLQCD	1.123(28)(29)(90)	–

Systematics being explored including new analysis of old expt data:
$\langle r_A^2 \rangle = 0.46(22)$ fm^2 $\to$ $M_A = 1.01(24)$ GeV from z-expansion [Meyer,1603.03048].

Conclusions

- Precise determinations of nucleon form factors are an essential part of the long-baseline neutrino oscillation program
- Dipole shape underestimates uncertainties in free-nucleon cross sections
- Need robust determination of nucleon amplitudes with realistic errors to determine impact on future neutrino oscillation experiments
- Updated deuterium experiment would be ideal for reducing uncertainties, but unlikely to happen in near future

- z Expansion parameterization is consistent with QCD and sufficiently general to give realistic uncertainty estimates
- Lattice QCD can access nucleon form factors from first principles in absence of updated deuterium experiment
- Growing interest in neutrino physics in lattice community, can expect many new results in upcoming years

Thanks for listening!

Backup

Calculations of Interest