The Axial Form Factor Extracted from Elementary Targets

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on behalf of the **MINERvA collaboration**

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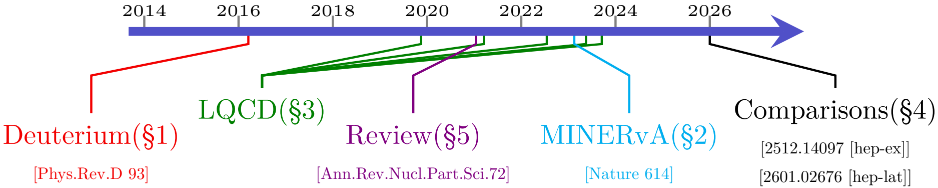
The Nucleon Axial Form Factor Over Time



Developments are overlapping chronologically, not straightforward

Order presented here (in parentheses) is motivated by precision
    Least precise → most precise → implications

Also presents experimental data sources first, then theory
    Deuterium → Hydrogen → LQCD

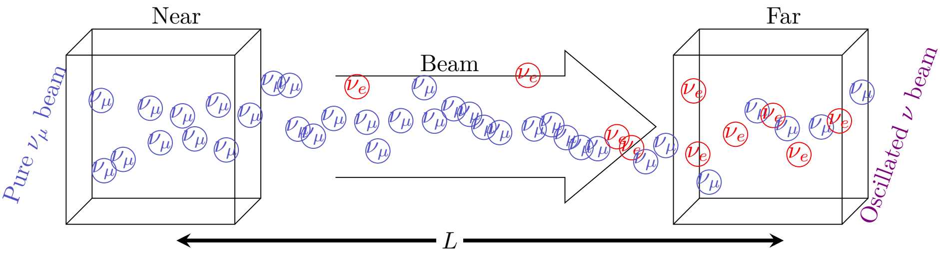
Special Thanks

Many people contributed to my work over the years:

1. Deuterium: Richard Hill, Rik Gran, Minerba Betancourt
2. MINERvA: Tejin Cai, Kevin McFarland, Miriam Moore
3. LQCD: Andreas Kronfeld, André Walker-Loud
4. Averaging: Sara Collins, Rajan Gupta, Lukas Koch,
   Andreas Kronfeld, Sungwoo Park, Sasha Tomalak, Clarence Wret
5. Review: André Walker-Loud, Callum Wilkinson

Introduction

Motivated by accelerator neutrino oscillation experiments



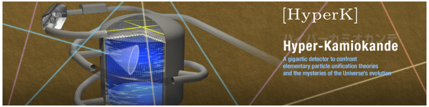
Neutrino oscillation: ν spontaneously change flavor

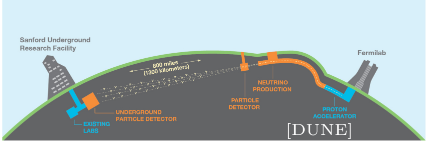
Oscillation parameters not completely known

$\implies$ δ_{CP}, mass hierarchy

Flagship experimental programs upcoming

$\implies$ DUNE, HyperK





Neutrino interactions are hidden within a nuclear target

Small neutrino cross sections

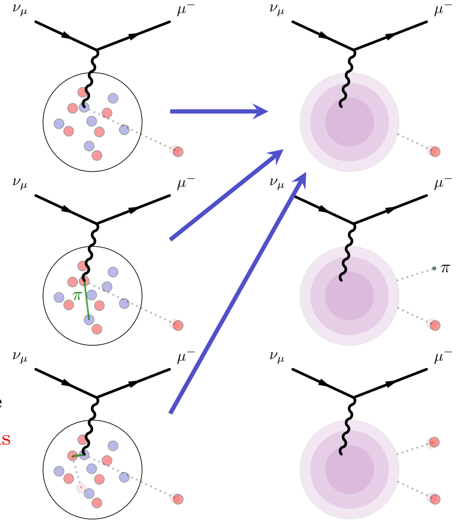
$\Longrightarrow$ large nuclear targets (=detectors)

Nuclear environment complicates measurements:

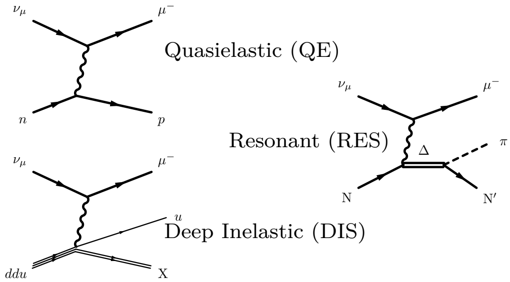
- Many allowed kinematic channels
- Reinteractions within nucleus
- Only final state particles are observable

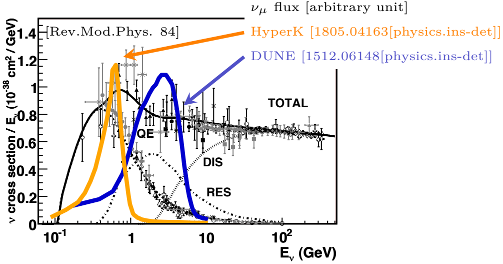
Isolation of quasielastic depends on precise theory knowledge

$\Longrightarrow$ difficult, especially for weak interaction contributions



Using neutrino-nucleon to learn about neutrino-nucleus





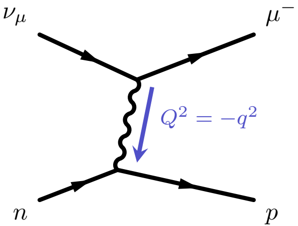
Isolate, quantify, improve quasielastic from neutrino-*nucleon* amplitudes

nucleon inputs → *nuclear* uncertainties

How well do we know free nucleon quasielastic cross section from elementary target sources?

- Deuterium scattering
- Hydrogen scattering
- Lattice QCD

Axial form factor dominates cross section uncertainty



$$\mathcal{M}_{\rm CCQE} \sim \langle \ell | \mathcal{J}^\mu | \nu_\ell \rangle \langle p | \mathcal{J}_\mu | n \rangle \qquad \frac{d\sigma_{CCQE}}{dQ^2} \sim |\mathcal{M}_{\rm CCQE}|^2$$

$$\langle p_k | (\mathcal{V}_\mu - \mathcal{A}_\mu) | n_p \rangle$$
$$= \bar{u}_k^{(p)} \Big[\gamma_\mu F_1(Q^2) + \frac{i}{2M_N} \sigma_{\mu\nu} q^\nu F_2(Q^2) + \gamma_\mu \gamma_5 F_A(Q^2) + \frac{1}{2M_N} q_\mu \gamma_5 F_P(Q^2) \Big] u_p^{(n)}$$

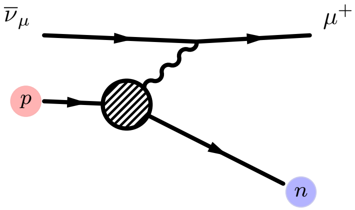
Simplest topology, lowest E_ν – neutrino scatters elastically with nucleon

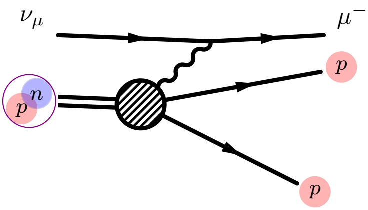
Nucleon response described by *form factors*

- F_1, F_2: vector → constrained by eN scattering
- F_P: “induced pseudoscalar” → subleading, related to other form factors
- F_A: axial form factor

Deuterium Data

Hydrogen vs Deuterium





Hydrogen:

- ✓ Free nucleon
- ✓ Outgoing particles on a plane
- × Antineutrino < neutrino cross section
- × Neutron detection challenging

Deuterium:

- ✓ All particles charged
- ✓ Neutrino > antineutrino cross section
- × Spectator proton not visible at low momentum
- × Nuclear effects (small?)

Historically, hydrogen results were not competitive with deuterium

Promoting the z expansion parameterization

Dipole ansatz —

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

- Overconstrained by both experimental and LQCD data
- Incorrect behavior in limit $Q^2 \to \infty$

z expansion [Phys.Rev.D 84 (2011)] —

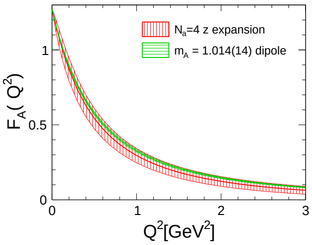
$$F_A(z) = \sum_{k=0}^{\infty} a_k z^k \qquad z(Q^2; t_0, t_{\text{cut}}) = \frac{\sqrt{t_{\text{cut}} + Q^2} - \sqrt{t_{\text{cut}} - t_0}}{\sqrt{t_{\text{cut}} + Q^2} + \sqrt{t_{\text{cut}} - t_0}} \qquad t_{\text{cut}} \leq (3M_\pi)^2$$

- Small parameter expansion
- Sum rule constraints regulate large-Q^2 behavior

Deuterium constraints from dipole historically underestimated

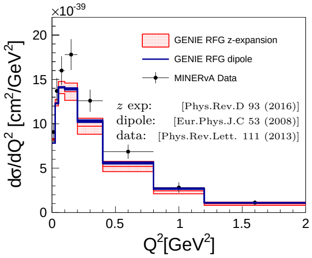
Previous conclusions from [Phys.Rev.D 93 (2016)]

- Fits to digitized distributions from original publications
- Dipole overconstrained by data
  underestimated uncertainty $\times 10$
- Discrepancies in nuclear cross sections could be nucleon and/or nuclear origins



Large systematics at low Q^2

- Deuterium correction
- Efficiency correction

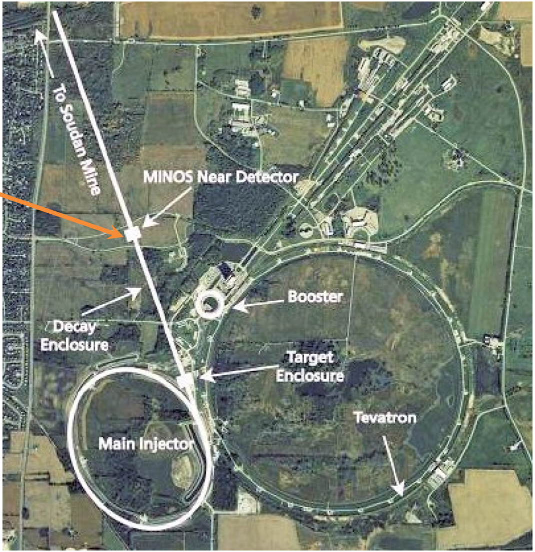


z expansion curve used as a fixed reference throughout presentation

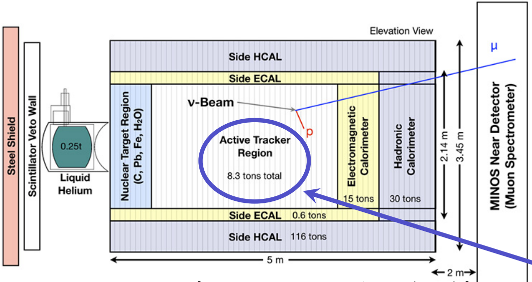
MINERvA Hydrogen Scattering

Fermilab Detector Complex

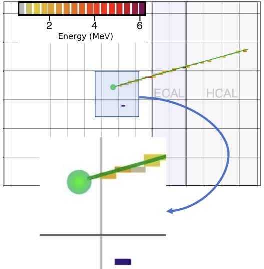
- MINERvA experiment ran from 2009–2019 at Fermilab
- Science goal: measure broad range of neutrino interactions on nuclei
  $\Longrightarrow$ improve neutrino-nucleus modeling
- Still producing scientific results!
- MINERvA just released their open data set for the community to use: https://minerva.fnal.gov/opendata



Hydrogen in the MINERvA Detector



[Nucl.Instrum.Meth.A 743 (2014)]



Scattering interaction $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$
from hydrogen in hydrocarbon scintillator strips

Neutrons detected primarily from protons with ${}^{12}\mathrm{C}(n, np){}^{11}\mathrm{B}$ reaction

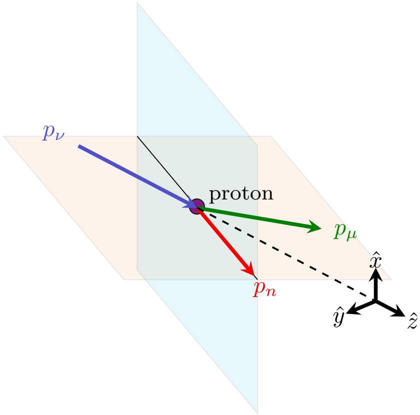
Event selection with $1.5\ \mathrm{GeV} < E_\mu < 20\ \mathrm{GeV}$, $\theta_\mu < 20^\circ$

Selecting Quasielastic Interactions

Reaction $\bar{\nu}_\mu + p \to \mu^+ + n$

Two-body elastic scattering: everything lies in a plane

From μ kinematics, predict n outgoing angle



Selecting Quasielastic Interactions

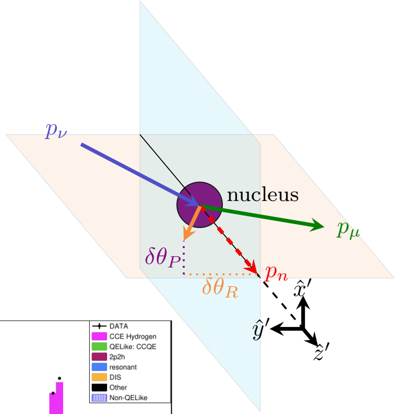
Reaction $\bar{\nu}_\mu + p \to \mu^+ + n$

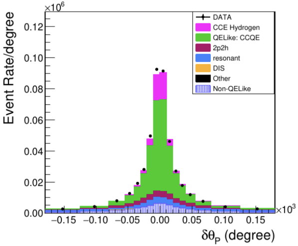
Two-body elastic scattering: everything lies in a plane

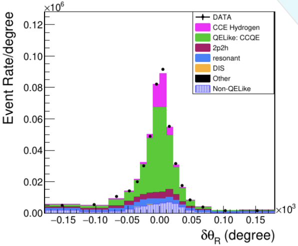
From μ kinematics, predict n outgoing angle

Motion of nucleons in nucleus causes angles to deviate

$\implies$ might lie outside of reaction plane







[Nature 614 (2023)]

Signal & Background

Data constrained backgrounds:

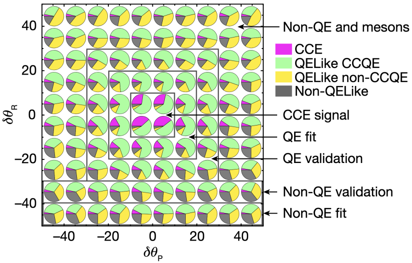
1. Fit to Q^2 for choices of angle deviation
2. Validated against separate region outside of fit & signal
3. Fit used for background of signal region

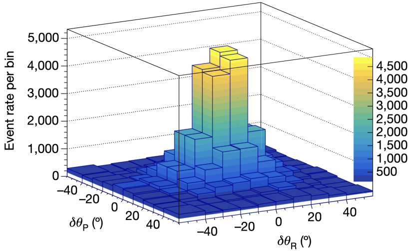
Backgrounds also validated against neutrino scattering mode

(only ν_μ+C$\rightarrow \mu^- + p + X$, no elastic)

Large background subtractions $\implies$ statistics dominated

[Nature 614 (2023)]





Hydrogen & Deuterium Fitting

Updates since Deuterium Fit

Previous datasets:

- ANL, BNL, FNAL $\nu_\mu D \to \mu^- pp$
  deuterium bubble chamber event distributions

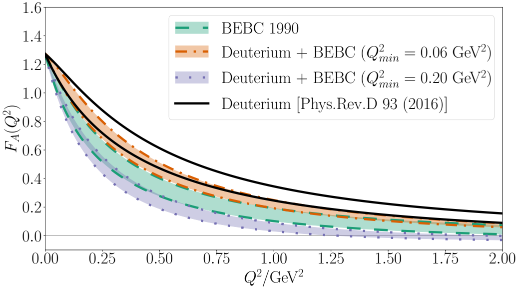
Two additional datasets:

- BEBC 1990 $\nu_\mu D \to \mu^- pp$ [Nucl.Phys.B 343]
- MINERνA 2023 $\bar{\nu}_\mu p \to \mu^+ n$ [Nature 614 (2023)]

Updated vector form factors:

- Use Borah *et al.* z expansion [Phys.Rev.D 102 (2020)]

Deuterium & BEBC are consistent



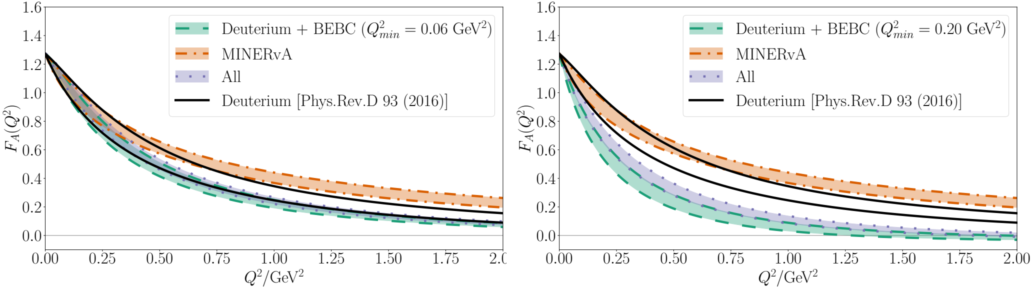
fit	$Q^2_{\rm min} = 0.06$ GeV^2 $\chi^2_{\rm data}$/DoF	$p_{\Delta\chi^2}$	$Q^2_{\rm min} = 0.20$ GeV^2 $\chi^2_{\rm data}$/DoF	$p_{\Delta\chi^2}$
BEBC 1990	6.3/ 9		6.3/ 9	
Deuterium	107.8/104		91.8/ 98	
Deut+BEBC	116.1/111		100.4/105	
$\Delta\chi^2$	1.9/ 1	0.16	2.4/ 1	0.12

$\Delta\chi^2 = \chi^2_{A+B} - \chi^2_A - \chi^2_B \quad \Longrightarrow$ 1 degree of freedom test of compatibility

p values are sensible – different Q^2 cuts pull opposite directions

$\Longrightarrow$ Poorly-described low-Q^2 region, systematics likely still too small

Deuterium & MINERvA not consistent



Apparent improvement to p value at $Q^2_{\text{min}} = 0.06$ GeV^2 only from poorly-described data at low Q^2

Remnant systematic effects in deuterium data?

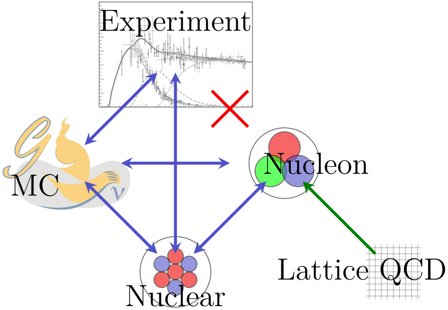
	$Q^2_{\text{min}} = 0.06$ GeV^2		$Q^2_{\text{min}} = 0.20$ GeV^2	
fit	χ^2_{data}/DoF	$p_{\Delta\chi^2}$	χ^2_{data}/DoF	$p_{\Delta\chi^2}$
All Deuterium	116.1/111		100.4/105	
MINERvA	9.1/ 16		9.1/ 16	
All	129.5/125		120.9/119	
$\Delta\chi^2$	4.3/ 1	0.04	11.3/ 1	8×10^{-4}

Lattice QCD

LQCD as an additional source of constraint

LQCD is a complement to experiment

- ✓ First principles calculations of amplitudes
- ✓ No nuclear effects
- ✓ Robust uncertainty quantification
- ✓ Systematically improvable
- ✓ Computers are (relatively) inexpensive



Lattice QCD gives first-principles predictions of QCD

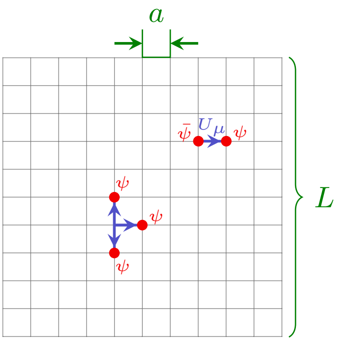
Numerical evaluation of path integral, Euclidean spacetime

Quark, gluon degrees of freedom:

$$\langle \mathcal{O} \rangle = \frac{1}{Z} \int \mathcal{D}\psi \, \mathcal{D}\overline{\psi} \, \mathcal{D}U \; \exp(-S) \, \mathcal{O}_{\psi} \, [U]$$

Parameters: am_{bare}, $\beta = 6/g^2_{\text{bare}}$

Matched to: e.g. $\frac{M_\pi}{M_\Omega}$, $\frac{M_K}{M_\Omega}$, M_Ω

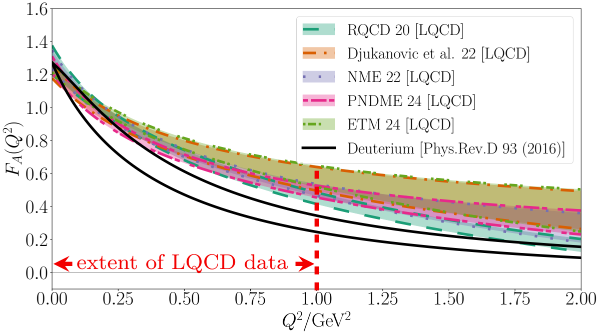


Gluon+$q\bar{q}$ loop contributions *to all orders*

"Complete" error budget has extrapolation guided by:

- Effective Field Theory [a]
- Finite Volume Chiral Perturbation Theory [L, M_π]

LQCD predicts slow falloff with Q^2

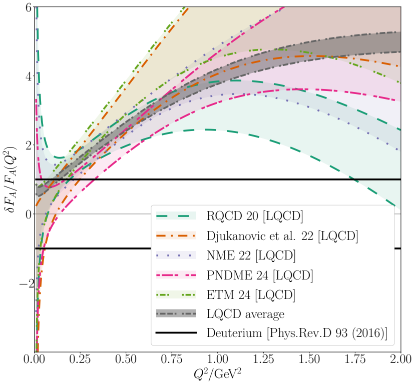


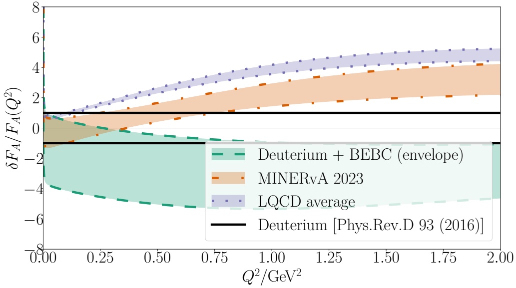
LQCD results maturing:

- Many results, complete error budgets
- Small systematic effects observed (expectation: largest at $Q^2 \to 0$)
- Nontrivial consistency checks (internal and between collaborations)

Fits averaged based on form factor values, derivatives

MINERvA hints at consistency with LQCD average





	ignore unknown		derate	
fit	$\chi^2_{?=0}$/DoF	$p_{\Delta\chi^2}$	$\chi^2_{99\%}$/DoF	$p_{\Delta\chi^2}$
LQCD	7.1/ 8		6.0/ 8	
MINERvA	9.2/16		9.2/16	
MINERvA+LQCD	19.5/22		18.5/22	
$\Delta\chi^2$	3.2/ 1	0.08	3.4/ 1	0.07

LQCD dominates joint fit with MINERvA

Plotted with previous deuterium as reference

99% confidence upper bound allows for consistency

Implications

One-Slide Digression: Axial Radius

Neutrino oscillation cares about cross section integrated over Q^2

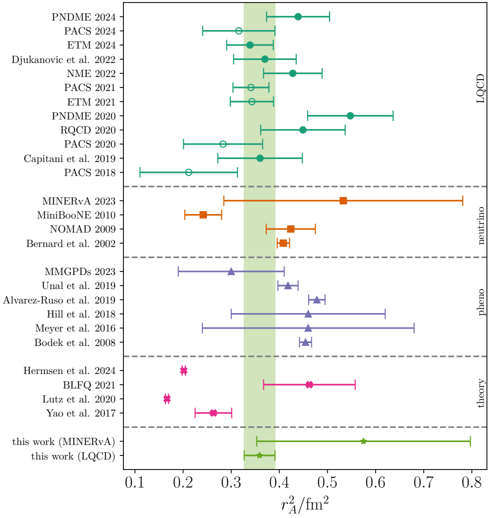
Form factor distilled to single number:

$$r_A^2 = -6 \frac{1}{g_A} \frac{dF_A}{dQ^2}\bigg|_{Q^2=0}$$

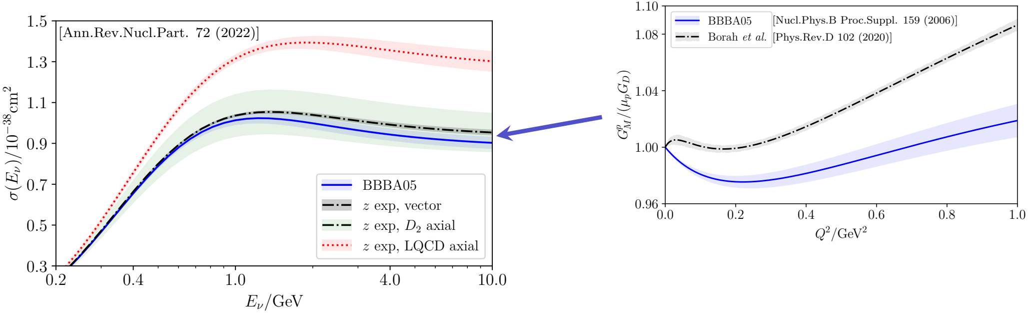
$\implies$ Lossy reduction

$\implies$ Of interest to nuclear applications

Fit	r_A^2/fm^2 $k_{\max}=6$	$k_{\max}=7$	[PRD 93 (2016)]
MINERvA	0.575(222)	0.565(149)	
LQCD	0.369 (30)	0.341 (62)	
Deuterium	0.334(254)	0.434(215)	0.46(22)
MINERvA+LQCD	0.364 (30)	0.408 (55)	



Fits suggest enhanced nucleon quasielastic cross section



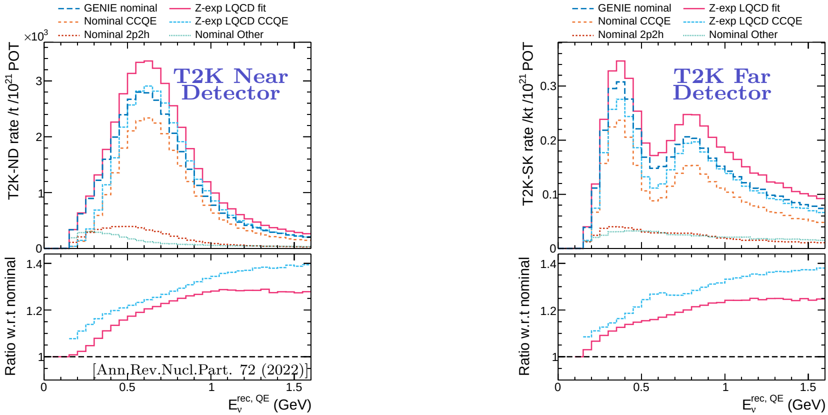
LQCD prefers 30-40% enhancement of ν_μ CCQE cross section

Recent Monte Carlo tunes require 20% enhancement of QE [Phys.Rev.D 105 (2022)] [Phys.Rev.D 106 (2022)]

With improved precision, sensitive to

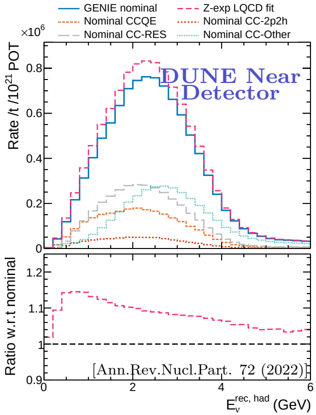
- BBBA vs z expansion vector form factor difference
- isospin-breaking corrections? [Phys.Rev.Lett. 129 (2022)]

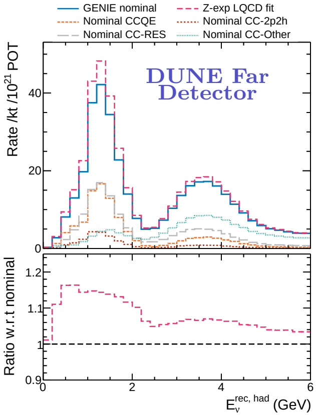
E_ν-dependent neutrino event rates (T2K)



- Dashed dark blue (GENIE nominal) vs solid magenta (z exp LQCD fit)
- QE enhancements produce 10-20% event rate enhancement, E_ν-dependent
- Oversimplification here: nontrivial compensation with other cross sections during Monte Carlo tuning

E_ν-dependent neutrino event rates (DUNE)

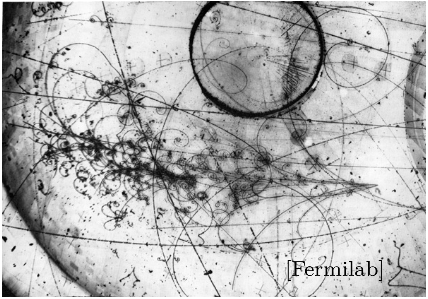




- Solid dark blue (GENIE nominal) vs dashed magenta (z exp LQCD fit)
- QE enhancements produce 10-20% event rate enhancement, E_ν-dependent
- Oversimplification here: nontrivial compensation with other cross sections during Monte Carlo tuning

Concluding Remarks

Outlook



- Nucleon axial form factor uncertainty historically significantly underestimated
- Evidence that QE cross section underestimated,
  $\implies$ beyond deuterium 1σ uncertainty band
- MINERvA approach provides new handle on neutrino-nucleon scattering
- LQCD gives constraints to supplement/enhance experimental data
- Consistency between hydrogen/LQCD; inconsistency with deuterium
- Nontrivial implications of LQCD/MINERvA results for oscillation experiments
- Future measurements needed! LQCD as leading constraint until then

Thank you for your attention!

Backup

LQCD references

Reference	N_{ens}	$N_{\text{ens}}^{\text{phys}}$	quark action	fit method	parameterization
[RQCD 2020]	37	2	clover	χPT-inspired	z^2
[NME 2022]	7	0	clover	Bayesian prior exponential	z^2
[Mainz 2022]	14	1	clover	summation + z expansion	z^2
[PNDME 2023]	13	2	clover (on HISQ)	Bayesian prior exponential	z^2
[ETM 2023]	3	3	twisted mass	Bayesian prior exponential	z^3

Notes:

- $g_A \sim a_0$ is an output for LQCD
  fixed to g_A from experiment in these fits (not in input parameterizations)
- these fits will use sum rules (input parameterizations do not)
- RQCD, NME, Mainz results highly correlated with unknown correlations
  (use covariance derating [Phys.Rev.D 111 (2025)])

Averaging strategy

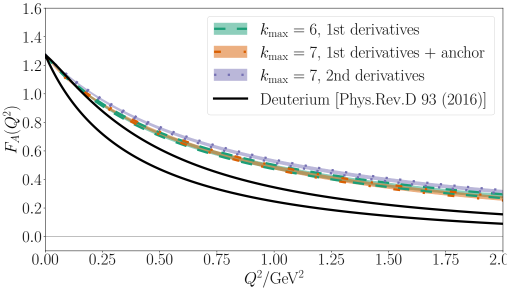
Want same z expansion parameterization used in experiment fitting:

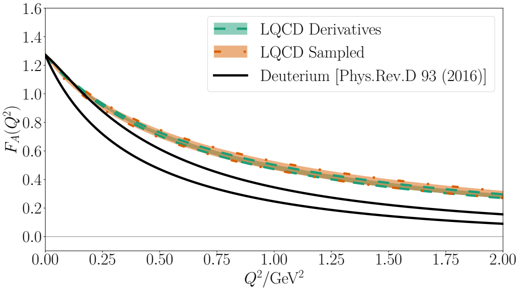
- g_A fixed to exact experimental value $g_A = 1.2754$
- 4 sum rules regulate large-Q^2 behavior
- no priors imposed

Procedure for matching LQCD results with different F_A parameterizations:

1. fit to derivatives $(d/dQ^2)^n F_A(Q^2)$ for $n \in \{0, ..., n_{\max}\}$ with $n_{\max} \leq k_{\max} - 4$
2. derivatives evaluated at $Q^2 = \max\Big[\, |-t_0|,\, 0.05~\mathrm{GeV}^2 \Big]$;
3. test additional anchor point $F_A(Q^2)$ at $Q^2 = 0.75~\mathrm{GeV}^2$

LQCD average insensitive to many variations





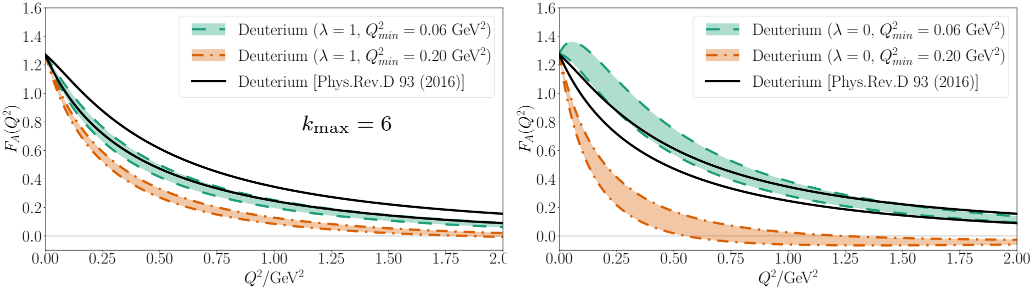
Sampling uses FLAG strategy [2411.04268 [hep-lat]] with Schmelling procedure for unknown correlations

$p_{?=0}$: p value with unknown correlations set to 0

$p_{99\%}$: p value 99% confidence upper bound from derating [Phys.Rev.D 111 (2025)]

fit	$p_{?=0}$	$p_{99\%}$
$\mathbf{k_{max} = 6}$, 1st derivatives (nominal)	0.52	0.65
$k_{\max} = 7$, 1st derivatives (not shown)	0.43	0.55
$k_{\max} = 7$, 1st derivatives + anchor	0.05	0.17
$k_{\max} = 7$, 2nd derivatives	0.32	0.32
$k_{\max} = 6$, sampled	—	—

Degeneracy introduced with old deuterium experiments



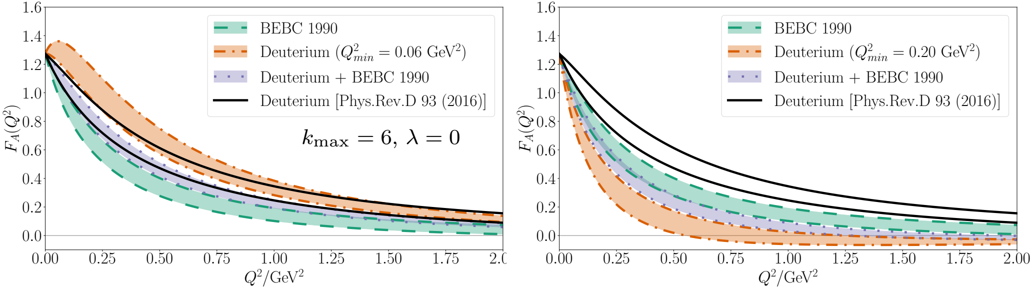
Use χ^2_{data} vs $\chi^2_{\mathrm{penalty}}$ to inform prior width (not assumptions from unitarity)

$$\chi^2_{\mathrm{penalty}} = \lambda \sum_{k=1}^{k_{\max}} \left(a_k / a_0 \sigma_k \right)^2 \quad (\lambda = 1 \text{ in [Phys.Rev.D 93]})$$

Strong dependence on λ, manifests as dependence on Q^2 cuts

Degeneracy between free normalization, axial form factor

Adding BEBC limits variations from degeneracy



Normalization of BEBC restricted to 1 ± 0.1 (flux uncertainty)

Other deuterium pulls BEBC to limit of 1σ uncertainty on normalization