Nucleon Axial Form Factor from Domain Wall on HISQ

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Outline

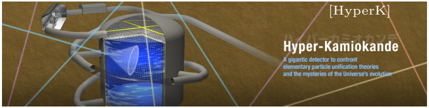
- Neutrino Oscillation
- Quasielastic Scattering
- LQCD Fit Setup
- Fit Stability
- Axial Form Factor
- Future Prospects

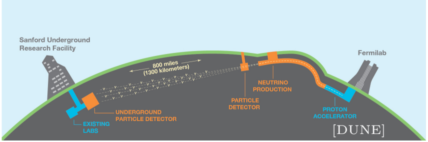
Special thanks: Daniel Xing, Jinchen He

Note: all references in online slides are hyperlinked

Neutrino Oscillation

Neutrino Physics Goals





Flagship long baseline experiments to measure neutrino oscillation

DUNE: USA, HyperK: Japan

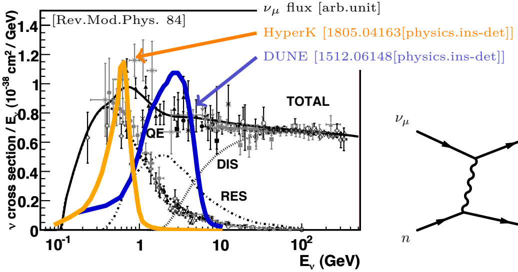
Seek to answer fundamental questions about neutrinos:

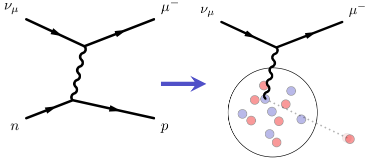
- mass ordering ($\Delta m^2_{32} > 0$?)
- octant ($\sin^2\theta_{23} = 0.5$?)
- CP violation ($\delta_{\rm CP} =$?)
- PMNS unitarity?
- 3 ν flavors?
- precision constraints

Measurements of solar, supernova ν

Data collection starts 2028–2029 $\Longrightarrow$ need support from theory!

Neutrino Oscillation and Quasielastic





Compute *nucleon* amplitudes, ingredients for *nuclear* models

Quasielastic is lowest E_ν, simplest $\Longrightarrow$ most important

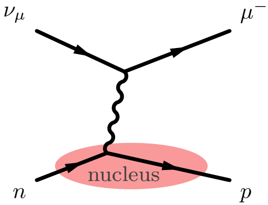
Question:

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

- Hydrogen/Deuterium scattering
- Lattice QCD

Quasielastic Form Factors

Quasielastic (QE) scattering assumes quasi-free nucleon inside nucleus



$$\mathcal{M}_{\text{nucleon}} = \langle \ell | \mathcal{J}^\mu | \nu_\ell \rangle \langle N' | \mathcal{J}_\mu | N \rangle$$

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

- F_1, F_2: constrained by eN scattering
- F_P: subleading in cross section,
  $\propto F_A$ from pion pole dominance constraint

Axial form factor F_A is leading contribution to nucleon cross section uncertainty

Induced pseudoscalar form factor F_P can be determined independently

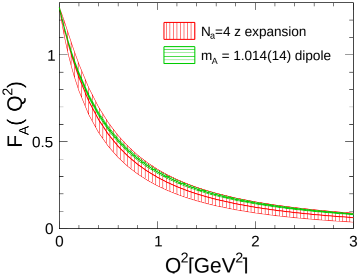
Deuterium Constraints on F_A

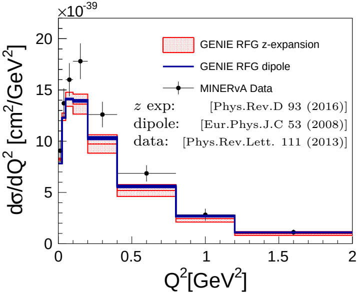
- Outdated bubble chamber experiments:
  - Total $O(10^3)$ ν_μQE events
  - Digitized event distributions only
  - Unknown corrections to data
  - Deficient deuterium correction
- Dipole overconstrained by data
  underestimated uncertainty $\times O(10)$
- Prediction discrepancies could be from nucleon and/or nuclear origins

Coming soon:

MINERνA $\bar{\nu}_\mu p \to \mu^+ n$ dataset
& updated form factor fits

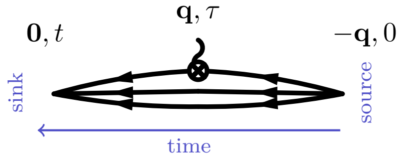
See [Nature 614 (2023)]





Matrix Elements from LQCD

Fit Setup



$$\mathcal{R}_{\mathcal{A}_z}(t,\tau,\mathbf{q}) = \frac{C^{\rm 3pt}_{\mathcal{A}_z}(t,\tau,\mathbf{q})}{\sqrt{C^{\rm 2pt}(t-\tau,\mathbf{0})C^{\rm 2pt}(\tau,\mathbf{q})}} \sqrt{\frac{C^{\rm 2pt}(\tau,\mathbf{0})}{C^{\rm 2pt}(t,\mathbf{0})} \frac{C^{\rm 2pt}(t-\tau,\mathbf{q})}{C^{\rm 2pt}(t,\mathbf{q})}}$$

$$\xrightarrow[t-\tau,\tau\to\infty]{} \frac{1}{\sqrt{2E_{\mathbf{q}}(E_{\mathbf{q}}+M)}} \left[-\frac{q_z^2}{2M} \mathring{F}_P(Q^2) + (E_{\mathbf{q}}+M) \mathring{F}_A(Q^2) \right]$$

$$Q^2 = |\mathbf{q}|^2 - (E_{\mathbf{q}} - M)^2$$

$\mathcal{A}_z$ with $q_z = 0 \implies \mathcal{R}_{\mathcal{A}_z}(t,\tau,\mathbf{q}) \to \sqrt{\frac{E_{\mathbf{q}}+M}{2E_{\mathbf{q}}}} \mathring{g}_A(Q^2)$

$\implies$ No induced pseudoscalar

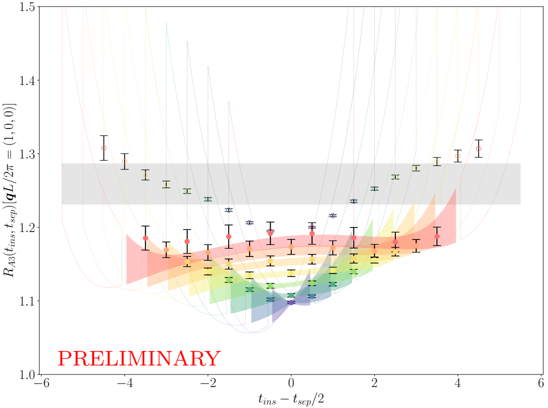
$\implies$ Simplified analysis of $\mathring{F}_A(Q^2) = \mathring{g}_A(Q^2)$

$\implies$ 3-state Bayesian fits to excited states

$\implies$ `a12m130` ensemble only: $a \approx 0.12$ fm, $M_\pi \approx 130$ MeV, $M_\pi L \approx 3.8$

Correlation Function Ratio

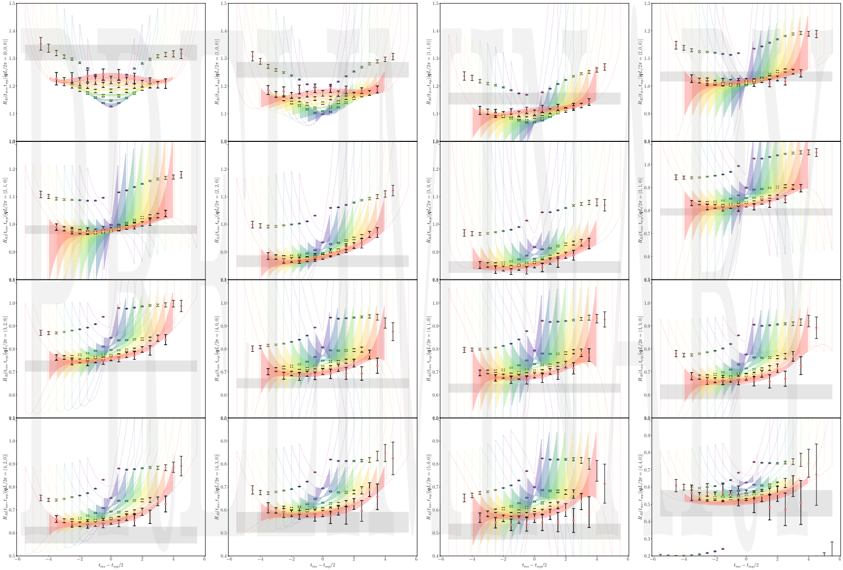
source side ($\boldsymbol{p} \neq 0$)



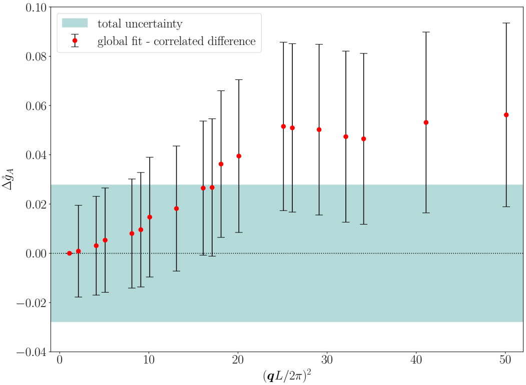
sink side ($\boldsymbol{p} = 0$)

- Horizontal: source-insertion time, centered about midpoint
- Vertical: correlator ratio $\sim$ axial matrix element
- Color: source-sink separation time; $t_{sep}/a \in \{3, \ldots, 12\}$
- Colored bands: fit range
- Gray band: $\mathring{g}_A$ posterior value

$\mathring{g}_A(Q^2)$ Correlators



Stability – Maximum Momentum



Correlated difference with nominal fit

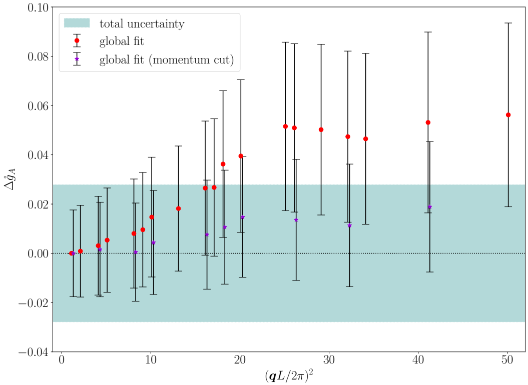
Systematic drift of $\mathring{g}_A$ as more data added to fit

$(\boldsymbol{q}L/2\pi)^2 = 50$ fit: 516 parameters, 1732 timeslices, 1000 samples

> 1200 eigenvalues modified by SVD cut

$\implies$ poorly conditioned covariance matrix?

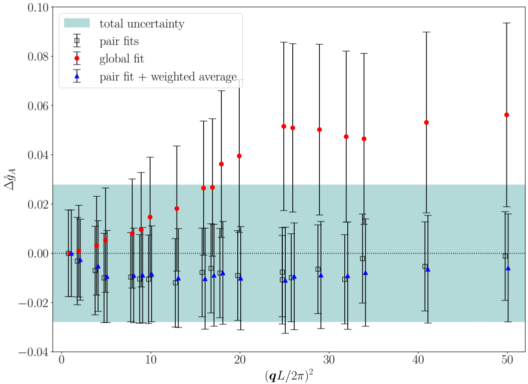
Stability – Maximum Momentum



Remove subset of momenta $\Longrightarrow$ fewer data

Symptoms improve... reduce degrees of freedom further?

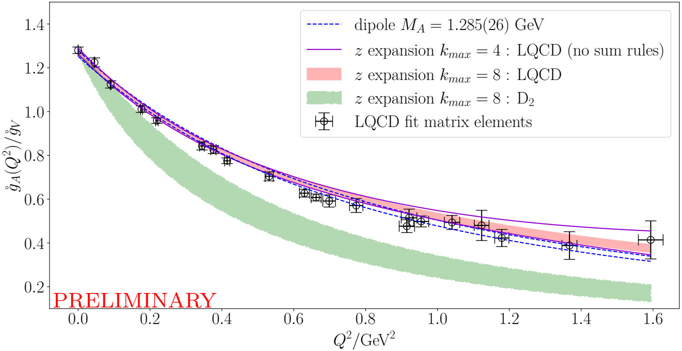
Stability – Maximum Momentum



Fit pairs of momenta ($\boldsymbol{q} = 0$ and one $\boldsymbol{q} \neq 0$)
Final step: drop excited state parameters,
perform weighted average over $\boldsymbol{q} = 0$ parameters,
$\boldsymbol{q} \neq 0$ allowed to float due to correlations but not refit

Pair fit: 60 parameters, 212 timeslices
Averaging fit, $(\boldsymbol{q}L/2\pi)^2 = 50$: 88 parameters

Axial Form Factor Fit



Trend of high-Q^2 enhancement seen in other LQCD results

2–4% LQCD uncertainty vs 10% uncertainty on D_2 result

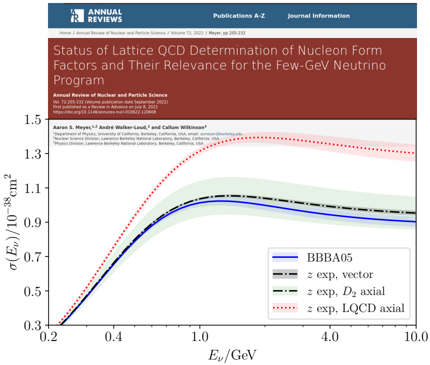
TODO list:

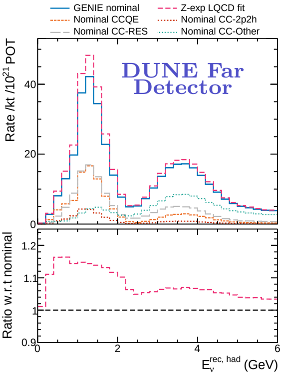
$\boldsymbol{q}L/2\pi = (1, 0, 0)$ matrix element larger than expectation

Deep dive into excited states systematics, prior dependence

More momenta, $q_z \neq 0$, full set of ensembles

Free Nucleon Cross Section

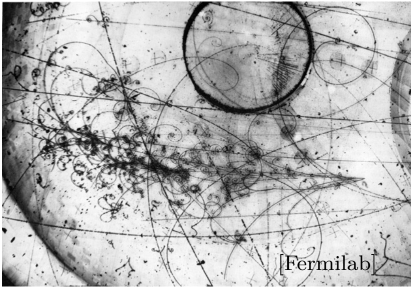




- LQCD prefers 30–40% enhancement of ν_μ CCQE cross section
- recent Monte Carlo tunes require 20% enhancement of QE
  [Phys.Rev.D 105 (2022)] [2206.11050 [hep-ph]]
- QE enhancements produce 10-20% event rate enhancement, E_ν-dependent
- cross section changes at ND ≠ *effective* cross section changes at FD:
  insufficient CCQE model freedom → bias in FD prediction

Concluding Remarks

Outlook



- Nucleon form factor uncertainty significantly underestimated in neutrino cross sections
- LQCD is a proxy for missing experimental data, potential for big impact in neutrino oscillation
- Fits to LQCD data limited by number of samples
  $\implies$ need to work around poorly conditioned covariance
- Excited state contamination is a significant systematics in LQCD

Thank you for your attention!

Backup

Form Factor Parameterizations

Most common in experimental literature: dipole ansatz —

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

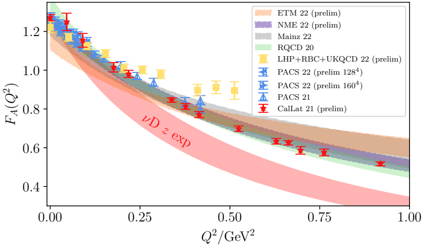
- Overconstrained by both experimental and LQCD data (revisit later)
- Inconsistent with QCD, requirements from unitarity bounds
- Motivated by $Q^2 \to \infty$ limit, data restricted to low Q^2

Model independent alternative: z expansion [Phys.Rev.D 84 (2011)] —

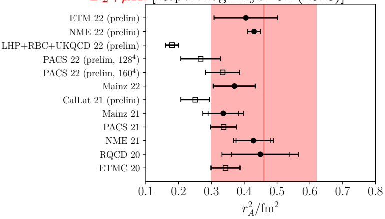
$$F_A(z) = \sum_{k=0}^{\infty} a_k z^k \qquad z(Q^2; t_0, t_{\mathrm{cut}}) = \frac{\sqrt{t_{\mathrm{cut}} + Q^2} - \sqrt{t_{\mathrm{cut}} - t_0}}{\sqrt{t_{\mathrm{cut}} + Q^2} + \sqrt{t_{\mathrm{cut}} - t_0}} \qquad t_{\mathrm{cut}} \leq (3M_\pi)^2$$

- Rapidly converging expansion
- Controlled procedure for introducing new parameters

Axial Radius (r_A^2)



Filled circle: full error budget
Open square: incomplete
$D_2+\mu H$: [Rept.Prog.Phys. 81 (2018)]



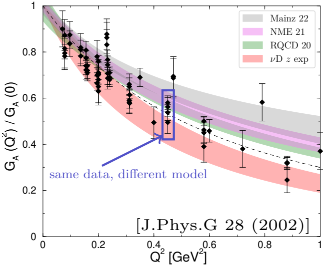
Radius related to slope: $r_A^2 = -\frac{6}{g_A}\frac{dF_A}{dQ^2}\Big|_{Q^2=0}$

Good agreement with r_A^2 from experiment, poor agreement with large Q^2

Fixing radius to agree at large Q^2 would bring radius down to $r_A^2 \sim 0.25$ fm^2

$\Longrightarrow$ Incompatible with dipole ansatz

Electro Pion Production



- Large model uncertainty, not included in world averages
- Valid only in $M_\pi \to 0$, $q \to 0$ limits
- Expansion to $O(M_\pi^2, Q^2)$:
  - restricted Q^2 validity
  - lacks shape freedom in Q^2
- Predates Heavy Baryon χPT, no systematic power counting

Modern experiments do not report $F_A(Q^2) \implies$ averages out of date

Possible argument for comparing to r_A^2 from low Q^2; high Q^2 untrustworthy

Effort needed to update prediction from photo/electro pion production