Uncertainty on Extractions of the Axial Form Factor from Elementary Targets

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INT 23-86W — Theoretical Physics Uncertainties to Empower Neutrino Experiments

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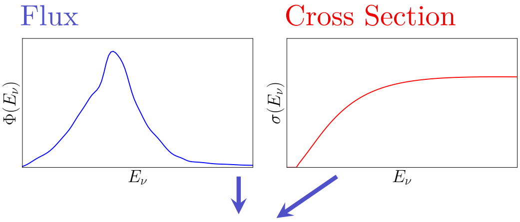
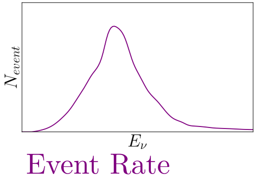
Outline

- Neutrino Cross Sections
- Quasielastic Scattering from Experiment
  - Constraints from Deuterium Scattering
  - Preliminary Hydrogen Scattering
- LQCD Survey of $F_A(Q^2)$
  - Summary of $F_A(Q^2)$ Calculations
  - T2K/DUNE Implications
- Future Prospects

Neutrino Cross Sections

Measuring Oscillation Probability

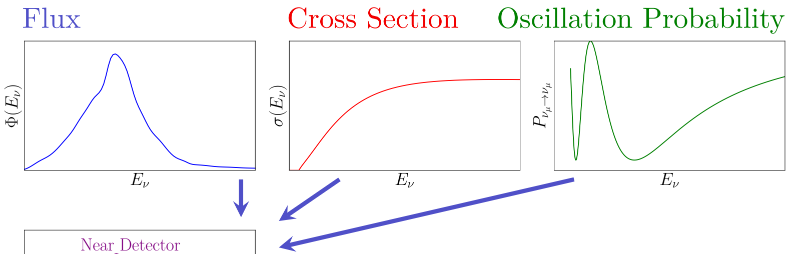


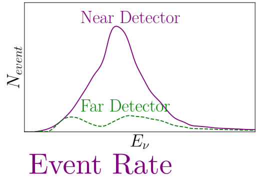


$$N_{\text{event}} = \int_{\text{bin}} dE_\nu \, \Phi(E_\nu)\sigma(E_\nu)$$

Broad flux & distribution of event E_ν

Measuring Oscillation Probability





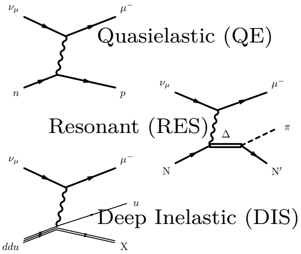
$$N_{\text{event}} = \int_{\text{bin}} dE_\nu \, \Phi(E_\nu)\sigma(E_\nu) \underbrace{\left[\times P(L/E_\nu) \right]}_{\text{far detector only}}$$

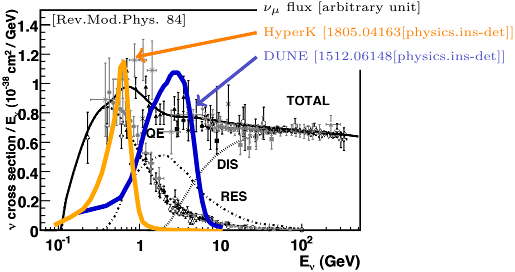
$$\left[P(L/E_\nu) \right]_{\text{bin}} \approx \left[\frac{N_{\text{event}}[\text{FAR}]}{N_{\text{event}}[\text{NEAR}]} \right]_{\text{bin}}$$

Broad flux & distribution of event E_ν

far/near $\Longrightarrow$ oscillation probability, but picture too simplified...

Neutrino Cross Sections





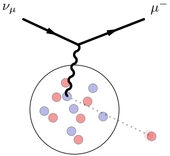
E_ν spans several kinematic regimes

Different interaction channels contributing to event rates

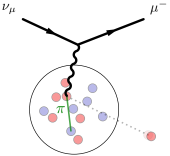
Need precise, theoretically robust cross sections for multiple event topologies

Neutrino Event Topologies

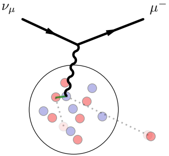
Quasielastic



π production



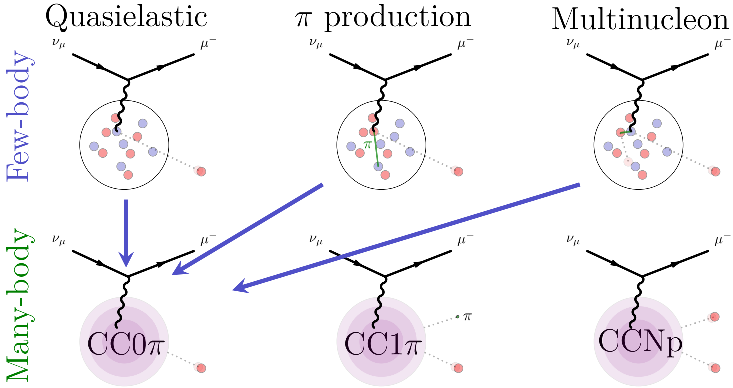
Multinucleon



Reinteractions within nucleus change kinematics

Only particles that escape are detectable

Neutrino Event Topologies



Reinteractions within nucleus change kinematics

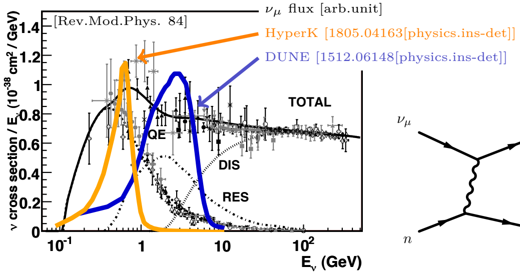
Only particles that escape are detectable

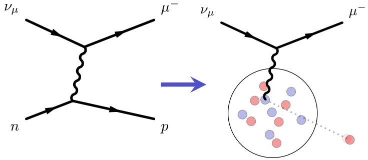
Mismatch between *nucleon* amplitudes & *nuclear* cross sections...

$\implies$ Event-by-event E_ν measurements are not possible

$\implies$ Reconstruct E_ν distributions from measured event rates

Neutrino Oscillation and Quasielastic





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

Quasielastic is lowest E_ν, simplest

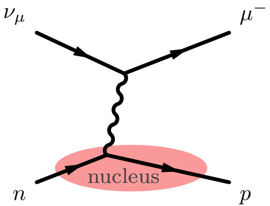
Question:

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

- Hydrogen/Deuterium scattering
- Lattice QCD

QE Experimental Constraints

Quasielastic Form Factors



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

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

Quasi-free nucleon inside nucleus —

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

Leading contribution to nucleon cross section uncertainty is axial form factor F_A

Form Factor Parameterizations

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
- 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)] —

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

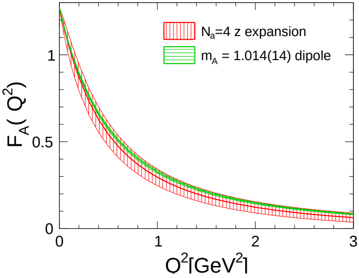
- Rapidly converging expansion
- Controlled procedure for adding parameters

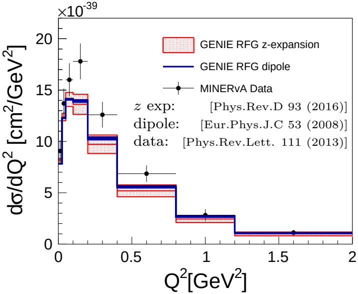
Deuterium Constraints on F_A

- 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:

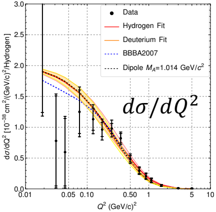
Updated joint fit with
MINERνA $\bar{\nu}_\mu p \to \mu^+ n$ dataset

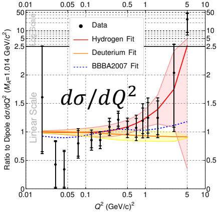


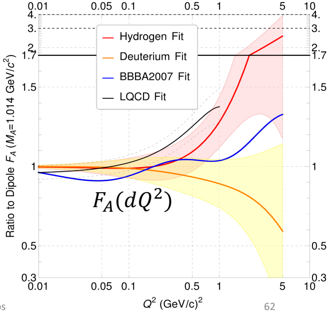


Free Nucleon Axial Form Factor

- We have ~5800 such events on a background of ~12500.
- Shape is not a great fit to a dipole at high Q^2.
- LQCD prediction at high Q^2 is close to this result, but maybe not at moderate Q^2.





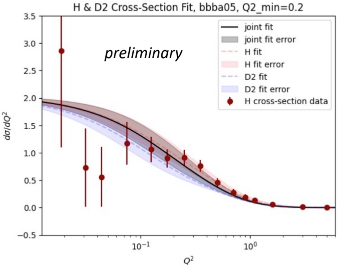


28 September 2023 K. McFarland, Measuring Protons with Neutrinos 62

See also [Nature 614 (2023)]

Compatible with D_2 Data? Mmmmmmaybe?

- We have some progress on joint fits with neutrino-deuterium analysis (*Phys.Rev.D* 93 (2016) 11, 113015), including comprehensive analysis of compatibility.
  - Note that compatibility depends on the choice of vector form factors, since vector-axial vector interference flips sign.
  - We see that compatibility also depends strongly on how low in Q^2 we use the D_2 data, which might suggest low Q^2 nuclear effects?
- With BBBA05 vector form factors and Q^2>0.2 GeV^2, $\delta\chi^2$~5.5, or p-value of ~2%.



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See also [Nature 614 (2023)]

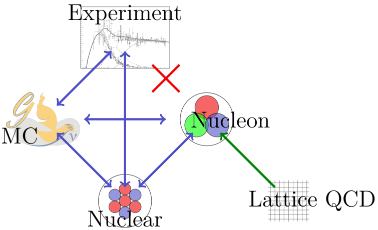
LQCD as Disruptive Technology

How can we improve precision?

Ideal: Modern high stats ν-D_2 scattering bubble chamber experiment

$\Longrightarrow$ LQCD as a complement to experiment

- ✓ No nuclear effects
- ✓ Realistic uncertainty estimates
- ✓ Systematically improvable
- ✓ Computers are (relatively) inexpensive



LQCD Survey and Implications

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Status of Lattice QCD Determination of Nucleon Form Factors and Their Relevance for the Few-GeV Neutrino Program

Annual Review of Nuclear and Particle Science

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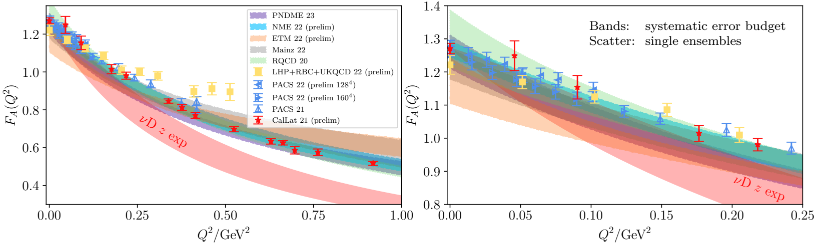
Abstract

Calculations of neutrino–nucleus cross sections begin with the neutrino–nucleon interaction, making the latter critically important to flagship neutrino oscillation experiments despite limited measurements with poor statistics. Alternatively, lattice quantum chromodynamics (LQCD) can be used to determine these interactions from the Standard Model with quantifiable theoretical uncertainties. Recent LQCD results of g_A are in excellent agreement with data, and results for the (quasi-)elastic nucleon form factors with full uncertainty budgets are expected within a few years. We review the status of the field and LQCD results for the nucleon axial form factor, $F_A(Q^2)$, a major source of uncertainty in modeling sub-GeV neutrino–nucleon interactions. Results from different LQCD calculations are consistent but collectively disagree with existing models, with potential implications for current and future neutrino oscillation experiments. We describe a road map to solidify confidence in the LQCD results and discuss future calculations of more complicated processes, which are important to few-GeV neutrino oscillation experiments.

Expected final online publication date for the *Annual Review of Nuclear and Particle Science*, Volume 72 is September 2022. Please see http://www.annualreviews.org/page/journal/pubdates for revised estimates.

Nucleon Axial Form Factor

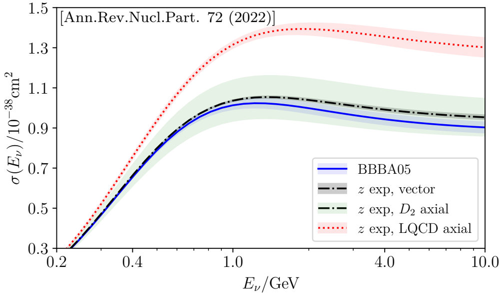


LQCD results maturing:

- Many results, all physical M_π: *independent data & different methods*
- Small systematic effects observed (expectation: largest at $Q^2 \to 0$)
- Nontrivial consistency checks from PCAC

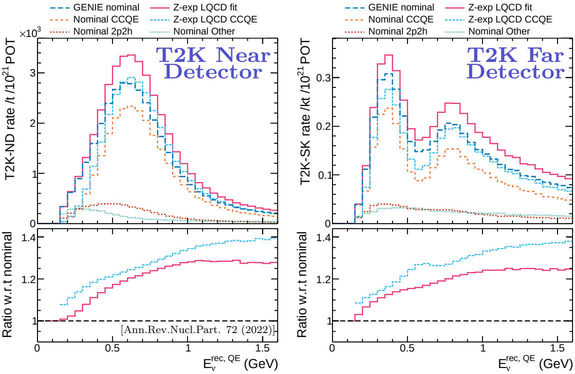
Evidence of slow Q^2 falloff outside of uncertainty from D_2

Free Nucleon Cross Section



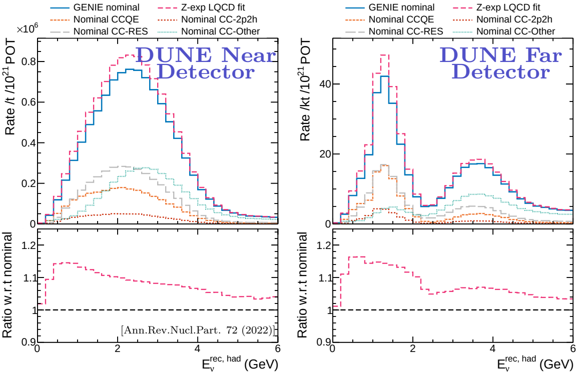
- LQCD prefers 30-40% enhancement of ν_μ CCQE cross section
- recent Monte Carlo tunes require 20% enhancement of QE
  [Phys.Rev.D 105 (2022)] [Phys.Rev.D 106 (2022)]
  similar trend with continuum Schwinger function methods
  [Phys.Rev.D 105 (2022)] [Eur.Phys.J.A 58 (2022)]
- With improved precision, sensitive to vector FF tension (black vs blue)
  [Phys.Rev.D 102 (2020)] vs [Nucl.Phys.B Proc.Suppl. 159 (2006)]

T2K Implications



- Dashed dark blue (GENIE nominal) vs solid magenta (z exp LQCD fit)
- QE enhancements produce 10-20% event rate enhancement, E_ν-dependent
- cross section changes at ND $\neq$ *effective* cross section changes at FD:
  insufficient CCQE model freedom → bias in FD prediction
- Monte Carlo tuning invalidates more sophisticated comparisons

DUNE Implications



- Solid dark blue (GENIE nominal) vs dashed magenta (z exp LQCD fit)
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- cross section changes at ND $\neq$ *effective* cross section changes at FD: insufficient CCQE model freedom $\rightarrow$ bias in FD prediction
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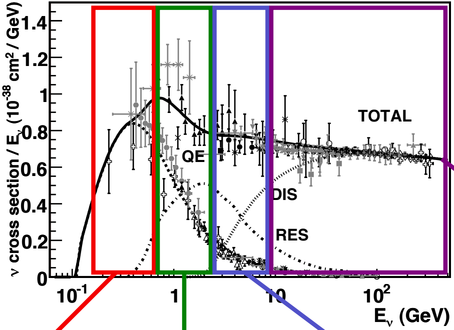
Future Directions

Energy Regimes



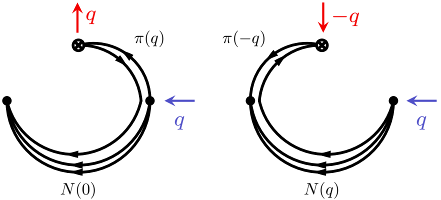
Quasielastic
–Nucleon Form Factors
–Full Error Budgets

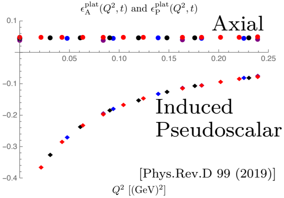
$N \to \Delta, N \to N^*$
–Transition Matrix Elements
–Multiparticle Operators

"Shallow Inelastic Scattering" (SIS)
–Hadronic Tensor
–Four Point Functions

Deep Inelastic Scattering
–Axial quasi/pseudo PDF

LQCD Excited States — χPT and $N\pi$





Contamination in $g_A(Q^2)$ primarily from enhanced $N\pi$,
mostly from induced pseudoscalar

Correlator fits without axial current not sensitive to $N\pi$
[Phys.Rev.C 105 (2022)] [Phys.Rev.D 105 (2022)]

Alternate fit strategies:

- explicit $N\pi$ operators
- include $\mathcal{A}_4$ (strong $N\pi$ coupling)
- Kinematic constraints ($F_P = 0$)

Prediction from χPT: [Phys.Rev.D 99 (2019)]

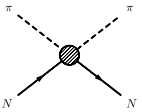
First demonstration of $N\pi$: [Phys.Rev.Lett. 124 (2020)]

χPT-inspired fit methods for fitting form factor data
[Phys.Rev.D 105 (2022)] [JHEP 05 (2020) 126]

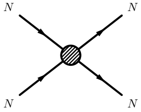
LQCD Target Calculations

(incomplete list!)

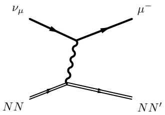
$N\pi$ Scattering



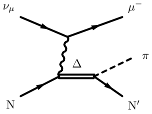
NN Scattering



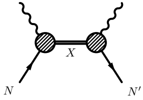
NN Quasielastic



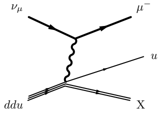
Resonant $N\pi$



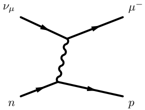
Four-point Inclusive

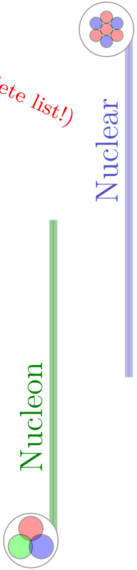


Deep Inelastic

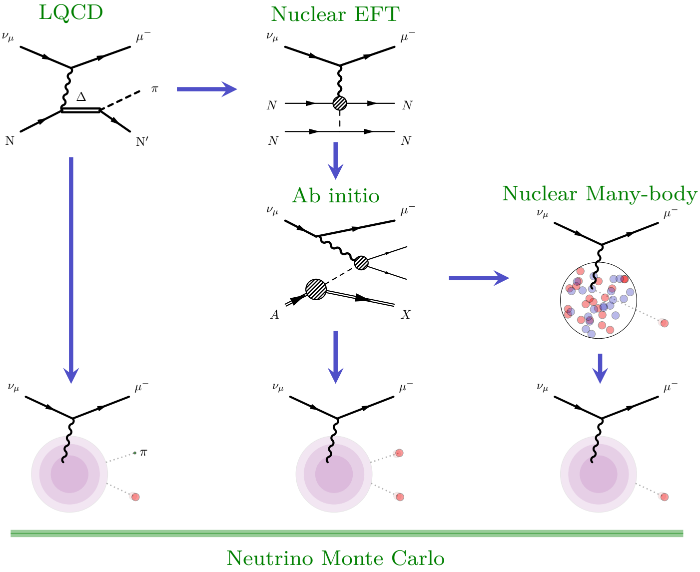


Quasielastic



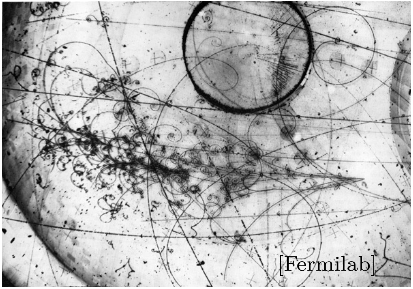


Roadmap To Nuclear



Concluding Remarks

Outlook

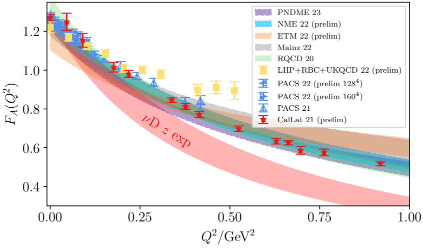


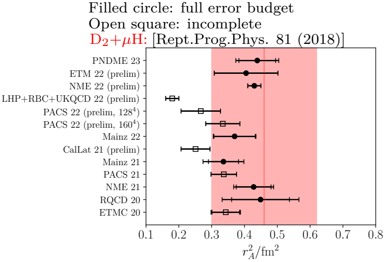
- Nucleon form factor uncertainty significantly underestimated
- Mounting evidence that QE ν cross section underestimated
  $\Longrightarrow$ Attention needed to avoid biased results
- LQCD is a proxy for missing experimental data
- Nucleon-pion effects are the next frontier...
  - Transition form factors
  - Low-energy constants for meson exchange
  - Pion production
- Exciting results upcoming: hydrogen scattering, LQCD

Thank you for your attention!

Backup

Axial Radius (r_A^2)





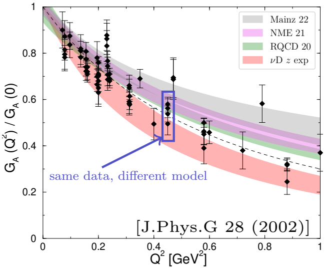
Radius related to slope: $r_A^2 = -\frac{6}{g_A} \frac{dF_A}{dQ^2}\Big|_{Q^2=0}$

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

$\implies$ Incompatible with dipole ansatz

Electro Pion Production



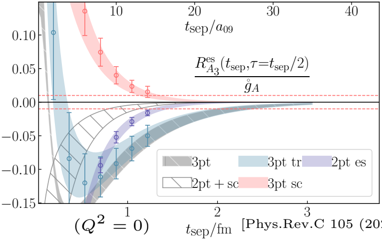
- Large model uncertainty, not included in world averages
- Valid only in $M_\pi \to 0$, $q \to 0$ limits
- Expansion to $O(M_\pi^2, Q^2)$:
  - restricted Q^2 validity
  - lacks shape freedom in Q^2
- Predates Heavy Baryon χPT, no systematic power counting

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

LQCD Excited States — Empirical



$(Q^2 = 0)$ [Phys.Rev.C 105 (2022)]

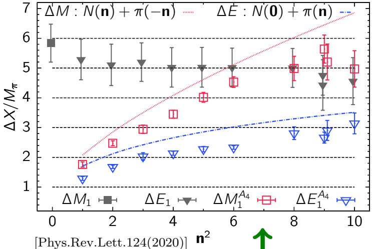
Compare fit to correlator data ratio

Contamination dominated by "transition" states $(0 \to n$, blue)

Typically signal below $\lesssim 1$ fm, contamination $\gtrsim 2$ fm

Excited states present in practically-achievable large time limit

$(Q^2 \geq 0)$



[Phys.Rev.Lett.124(2020)]

NOTE: expect only approx agreement between data/curves

NME collab:

Q^2 contamination from $N \to N\pi$

Dominant contribution agrees with χPT expectation

$N\pi$ is important for $F_A(Q^2)$

LQCD $g_A(Q^2 = 0)$

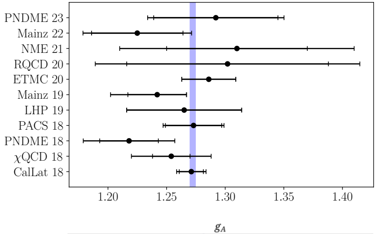
g_A is benchmark for
nucleon matrix elements in LQCD

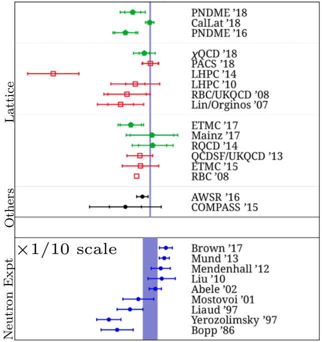
Status circa 2018 summarized by
USQCD white paper
[Eur.Phys.J.A 55 (2019)]

See also: FLAG review
[Eur.Phys.J.C 80 (2020)]

Historically g_A low compared to expt
excited states (+other...)

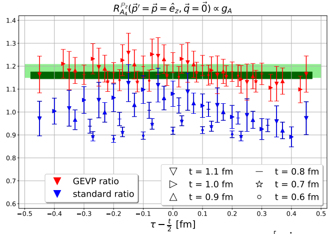
Lots of activity since 2018,
consistent agreement with PDG
full error budgets available

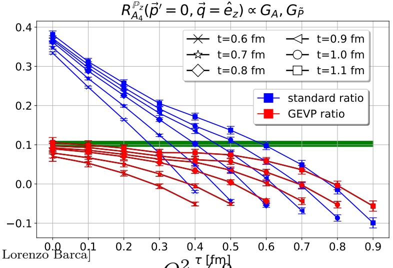




[Eur.Phys.J.A 55 (2019)]

Axial FF - $N\pi$ Interpolating Operators





[priv.comm. Lorenzo Barca]

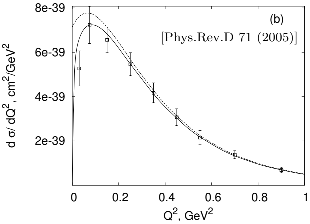
$Q^2 = 0$ $Q^2 \neq 0$

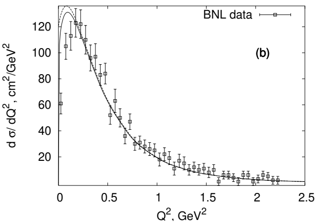
2×2 operator basis, explicit 3- & 5-quark interpolating operators

Significantly flatter ratios, simplified analysis

Will analysis with only 3-quark operators be consistent?

Resonance Production - $N \to \Delta$





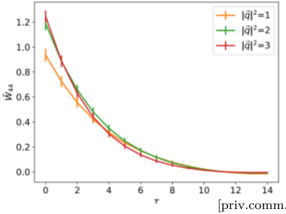
1π cross section known to 30% [Phys.Rev.C 88 (2013)]
DUNE error budget $\lesssim$10% precision [2002.03005 [hep-ex]]

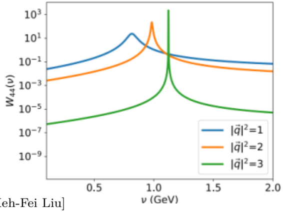
Unconstrained axial form factors in $J^P = 3/2^-$ channels
$\implies$ 100% uncertainties from $V - A$, $A - A$ interference terms

[Phys.Rev.D 74 (2006)]

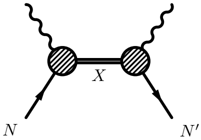
Previous work by ETM: [Phys.Rev.D 83 (2011)] [Phys.Rev.Lett. 98 (2007)]

Resonance Production - $N \to N^*$





[priv.comm. Keh-Fei Liu]

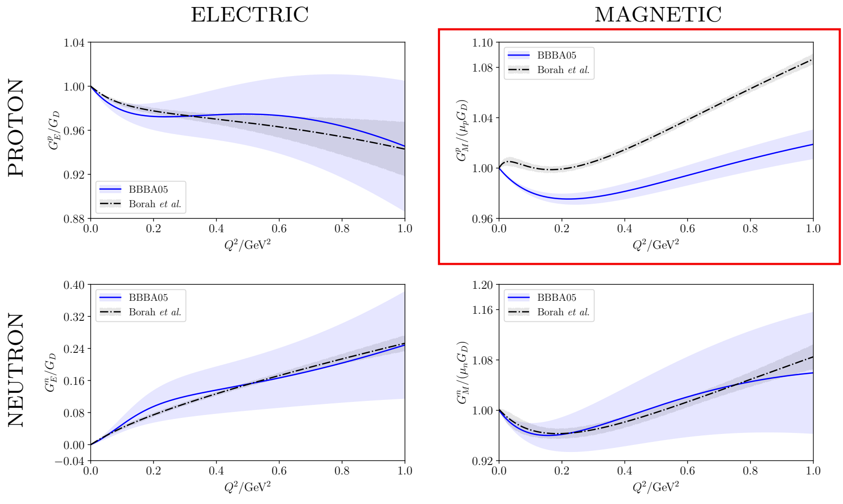


Hadronic tensor methods for addressing SIS (1.4 GeV $\leq W \leq$ 2.0 GeV)
See also: [Phys.Rev.D 101 (2020)]

$\langle \mathcal{O}(0)\mathcal{J}_4(-q)\mathcal{J}_4(q)\bar{\mathcal{O}}(0)\rangle$, $M_\pi \sim 370$ MeV, removed elastic contribution
Large $N\pi$, $N\pi\pi$ contributions

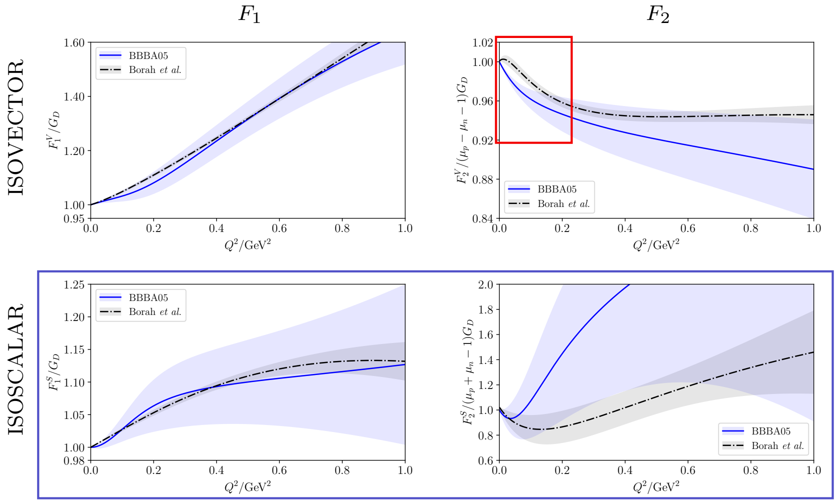
Currently no practical $Q^2 \neq 0$ data in this region [S.Nakamura - NuSTEC S&DIS]

Vector Form Factors - Proton/Neutron



Large tension in proton magnetic form factor

Vector Form Factors - Isospin Symmetric



Uncertain slope of F_2^V

Large uncertainty on isoscalar form factors