

Lattice QCD and Neutrino-Nucleus Scattering

USQCD Whitepaper [arXiv:1904.09931](https://arxiv.org/abs/1904.09931)

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Lattice QCD and Nuclear Physics

- Neutrino energy reconstruction therefore nuclear models.
- Lattice QCD can inform the models several ways:
 - nucleon-level amplitudes (*cf.*, [Rajan's talk](#));
 - nuclear properties informing chiral EFT in nuclear models—or further "data" to constrain;
 - nuclear properties *ab initio* (*i.e.*, directly from \mathcal{L}_{QCD})—
 - ${}^6\text{Li}$ before long! ${}^{12}\text{C}$ before retirement!?! ${}^{40}\text{Ca}$ before death?!?

Lattice QCD and Energy Transfer

- Elastic form factors (*cf.*, [Rajan's talk](#)).
- Inelastic form factors (pretending, e.g., Δ is stable in QCD).
- Amplitudes $NJ \rightarrow N\pi$ (include information equivalent to interference):
 - much harder—the non-trivial info is encoded in volume dependence.
- Hadron tensor for $N+n\pi$... shallow inelastic scattering region.
- Parton distribution functions for deep inelastic region.
 - (last two have a tricky "inverse problem" to get Laplace, Fourier, or Mellin transform from matrix elements on a discrete set.)

Snapshot of Nucleon Form Factors

Sea quarks	Valence quarks	N_{ens}	a (fm)	M_π (MeV)	Collaboration	Ref.	USQCD
2 Wilson-clover	same as sea	11	0.06–0.08	150–490	RQCD	[10]	
2 TM clover	same as sea	1	0.09	130	ETM	[8]	
2 Wilson-clover	same as sea	11	0.05–0.08	190–470	Mainz (CLS)	[7]	
2+1 overlap	same as sea	4	0.11	290–540	JLQCD	[5]	
2+1 domain wall [11]	overlap	3	0.08–0.15	170–340	χ QCD	[3]	✓
2+1 Wilson-clover	same as sea	1	0.085	146, 135	PACS	[1]	
2+1 Wilson-clover	same as sea	11	0.05–0.09	200–350	Mainz (CLS)	[2]	
2+1+1 HISQ [12]	Wilson-clover	8	0.06–0.12	135–210	PNDME	[6]	✓
2+1+1 HISQ [12]	domain wall	16	0.09–0.15	130–400	CalLat	[4]	✓
2+1+1 TM clover	same as sea	3	0.09–0.15	140	ETM	[12]	✓
2+1+1 HISQ	same as sea	3	0.09–0.15	135	Fermilab/MILC	[9]	✓

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Snapshot of Hadron Tensor

The elastic case

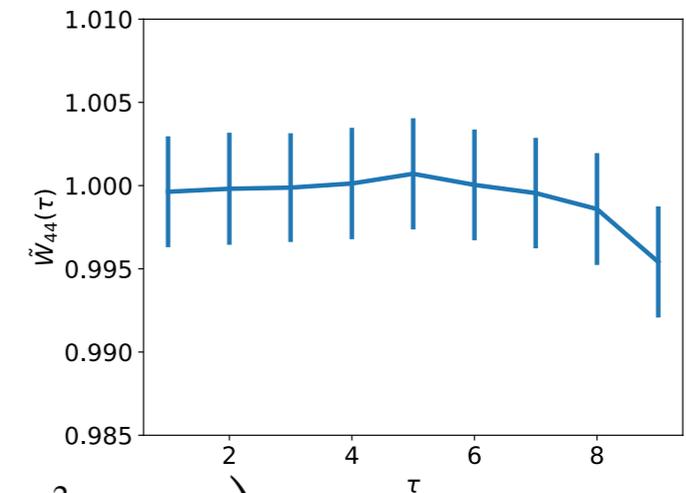
normalized vector current $J_4 = \bar{\psi}\gamma_4\psi$

$$\begin{aligned} \tilde{W}_{44}(\mathbf{p} = 0, \mathbf{q} = 0, \tau) &\stackrel{\tau \rightarrow \infty}{=} |\langle N | J_4 | N \rangle|^2 e^{-(M_p - M_p)\tau} \\ &= F_1^2(q^2 = 0) = g_V^2 = 1 \end{aligned}$$

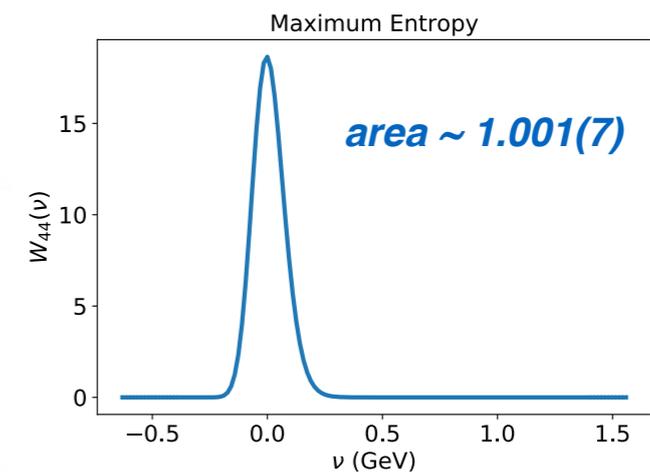
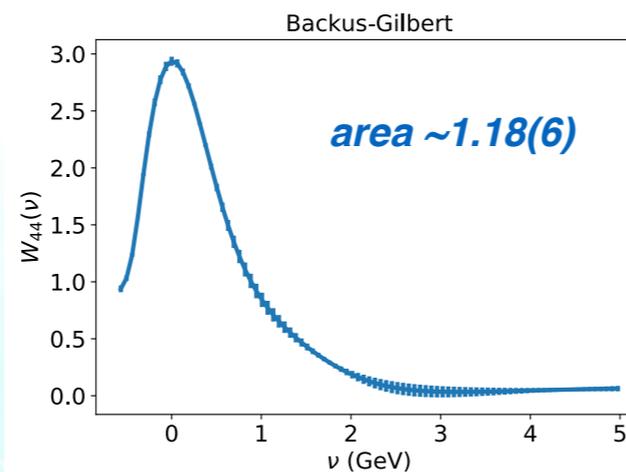


inverse $\tilde{W}_{\mu\nu}(\mathbf{p}, \mathbf{q}, \tau) = \int d\nu W_{\mu\nu}(\mathbf{p}, \mathbf{q}, \nu) e^{-\nu\tau}$

$$\begin{aligned} W_{44}(q^2, \nu) &= \delta(q^2 + 2m_N\nu) \frac{2m_N}{1 - q^2/4m_N^2} \left(G_E^2(q^2) - \frac{q^2}{4M_N^2} G_M^2(q^2) \right) \\ &\stackrel{q^2=0}{=} \delta\nu G_E^2(q^2 = 0) = \delta\nu g_V^2 = \delta\nu \quad \text{delta function at zero} \end{aligned}$$



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note, different x scale

