SPC Summary on PDF, Hadronic Tensor, EMT FF and Neutrinoless $\beta\beta$ Decay

- Parton Distribution Function [NP, Intensity Frontier]
  - Quasi-PDF, Pseudo-PDF, Lattice Cross Section (LaMET)
  - Neutrino-Nucleon Scattering -- Hadronic Tensor
- Generalized FF – Energy Momentum Tensor
- Neutrinoless Double Beta Decay
- Experimental facilities
  - Present: JLab 12 GeV, LHC
  - Future: EIC, DUNE

TMD Collaboration

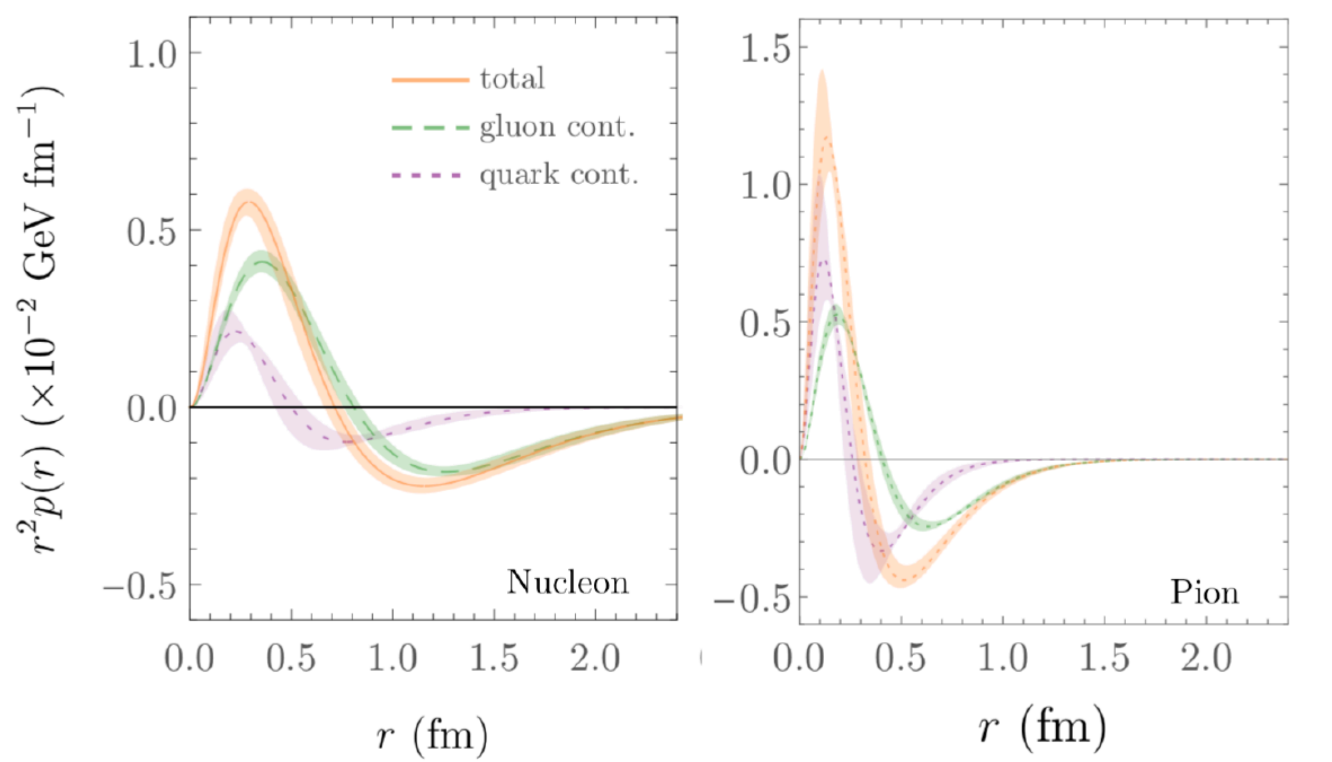
All Hands Meeting

JLab, May 1-2, 2020

Proposals

PI	Title	Status
Constantinou	Quasi-GPDs from Lattice QCD	Continuation
Hackett	Generalized form factors of the proton	New
Karthik	Computing Pion Generalized Parton Distribution on Fine Lattices	Continuation
Liu	Neutrino Nucleon Scattering from Hadronic Tensor	Continuation
Murphy	Nuclear Matrix Elements for Neutrinoless Double Beta Decay from Lattice QCD	Continuation
Richards	Parton Distribution Functions and Amplitudes...	Continuation

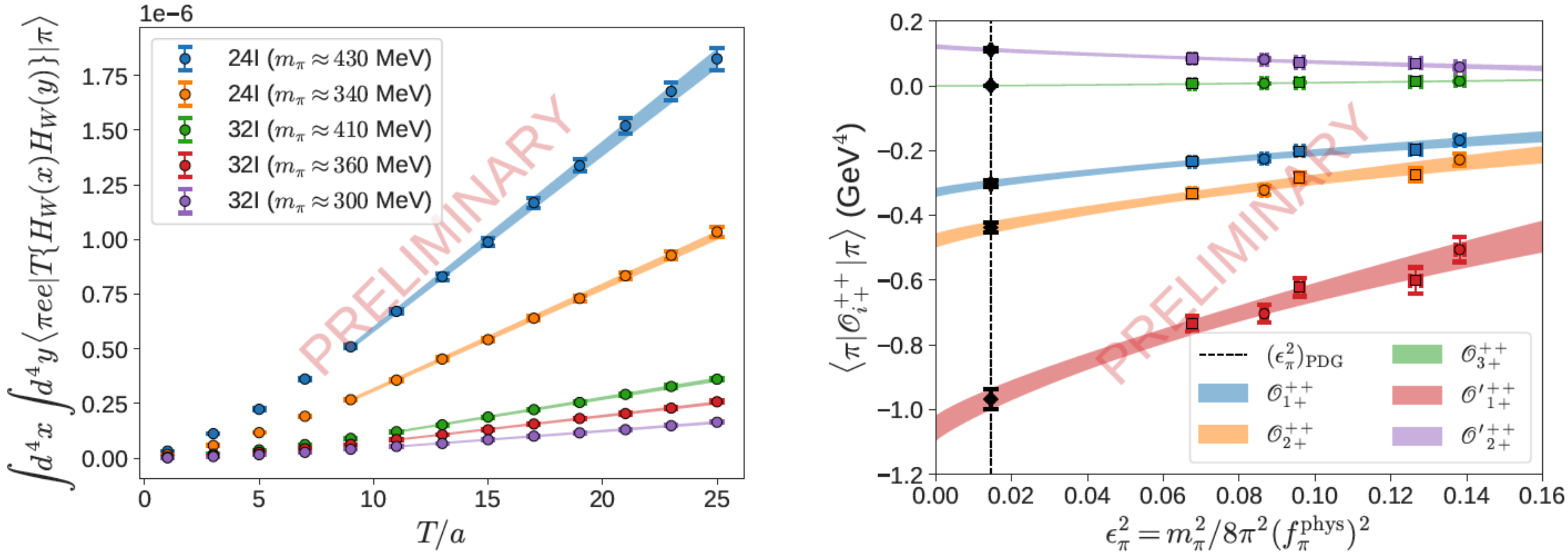
Radial Pressure of Quarks and Glue



(b) Radial pressure distribution of the proton (left), and pion (right), determined from LQCD calculations at an unphysically heavy $m_\pi \sim 450$ MeV.

D. Hackett et al.

$\pi \to \pi ee \Longrightarrow$ nn $\to$ ppee

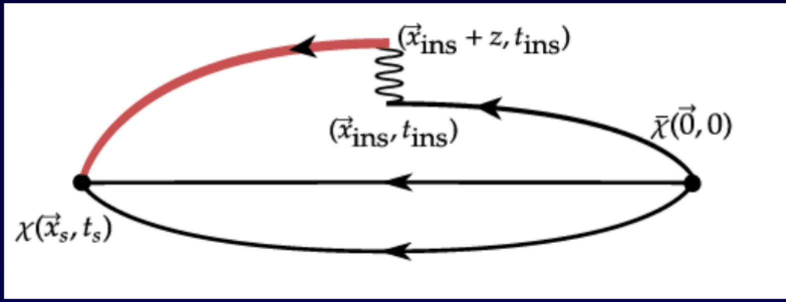


(a) Long-distance (b) Short-distance

Figure 4: Preliminary lattice signals for the integrated four-point correlation function determining the long-distance $\pi \to \pi ee$ amplitude (left), with the exponentially growing contribution from the vacuum intermediate state removed, and a preliminary chiral/continuum/infinite-volume extrapolation of the relevant matrix elements describing the leading-order short-distance contributions to $nn \to ppee$ (right).

D.J. Murphy and W. Detmold (NPLQCD)

Quasi-PDF, Pseudo-PDF, Lattice Cross Section -- Large Momentum Effective Theory (LaMET)



Factorization Theorem

$$\tilde{q}(x, \frac{\mu}{P^z}) = \int_{-1}^{1} C(\frac{x}{y}, \frac{\mu}{|y|P^z}) q(y, \mu)$$

Quasi-PDF and Pseudo-PDF are equivalvent.

T. Izubuchi et al., PRD 98,056004 (2018)

GPD of Nucleon

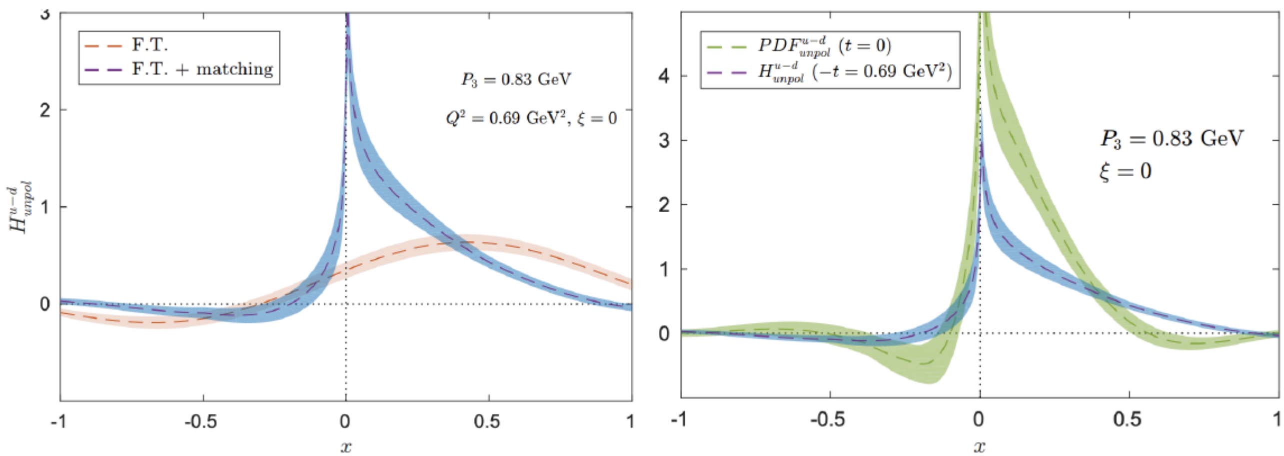
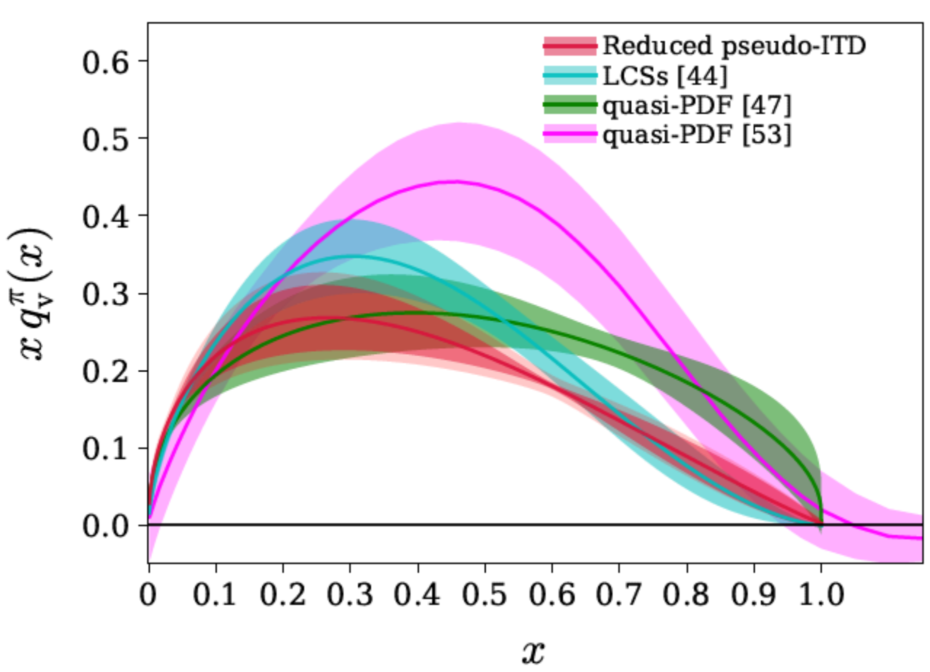
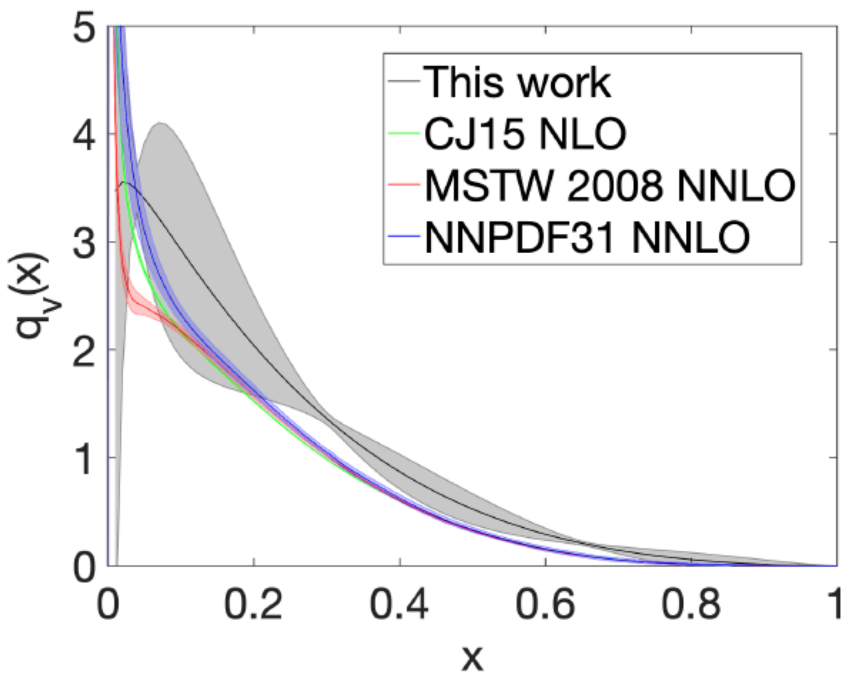


Figure 2: Left: the unpolarized H quasi-GPD and the matched H-GPD. Right: comparison of the unpolarized matched PDF and the H-GPD. The average nucleon boost is 0.83 GeV, for GPD: $\xi = 0$, $Q^2 = 0.69$ GeV^2.

M. Constantinou et al.

Pion and Nucleon PDF

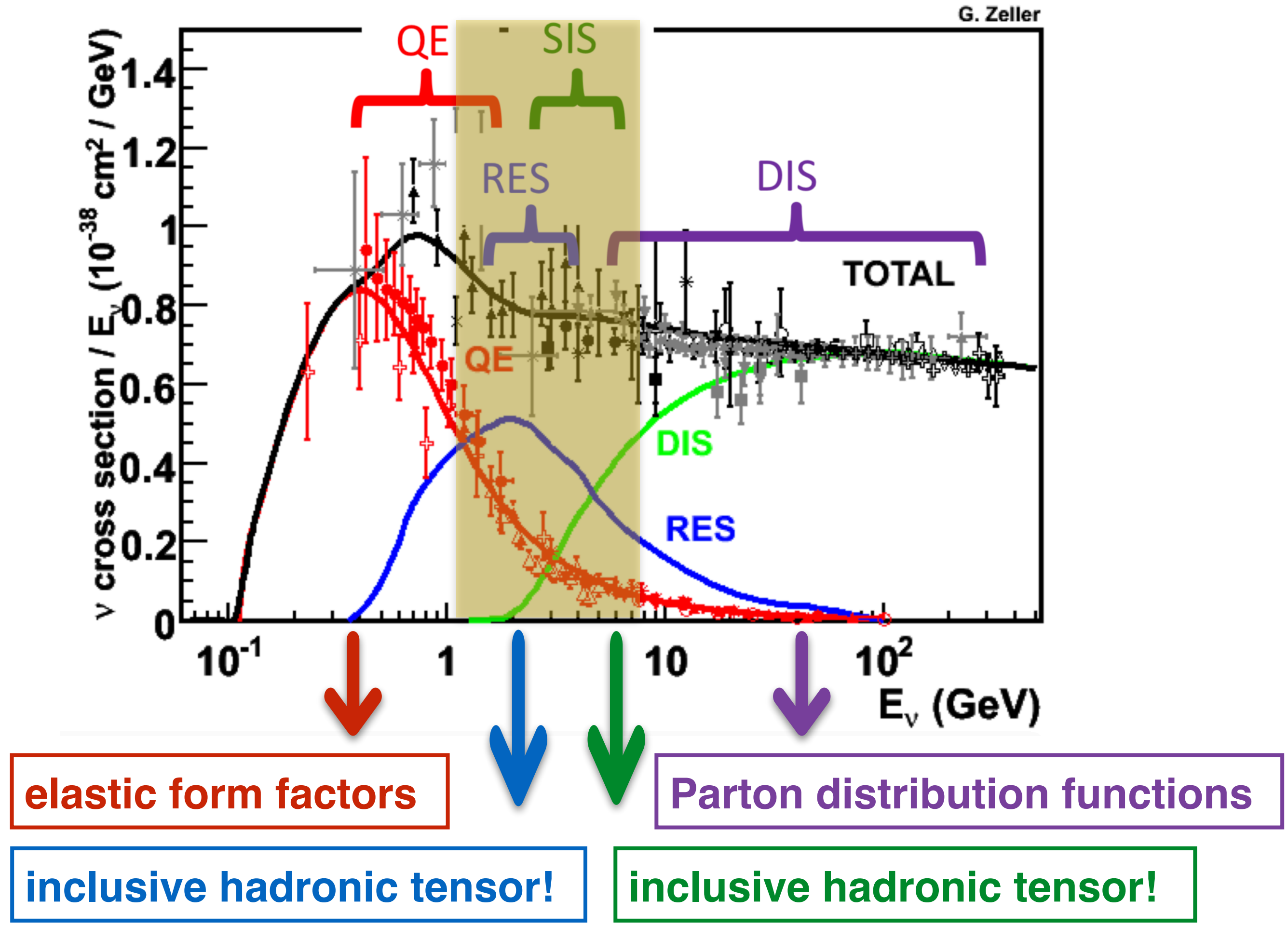




D. Richards et al.

Hadronic tensor and neutrino-nucleus scattering

- New long-baseline neutrino experiments are in preparation: T2K, NOvA, PINGU, ORCA, Hyper-Kamiokande, DUNE...
- Be
  nu
- Ch … e the
  cro



J.A. Formaggio and G.P. Zeller, RMP84, 1307 (2012)

Hadronic tensor on the lattice

four-point function with **3-dimensional Fourier transform**

$$C_4 = \sum_{\vec{x}_f} e^{-i\vec{p}\cdot\vec{x}_f} \sum_{\vec{x}_2 \vec{x}_1} e^{-i\vec{q}\cdot(\vec{x}_2-\vec{x}_1)} \left\langle \chi_N(\vec{x}_f, t_f) J_\mu^\dagger(\vec{x}_2, t_2) J_\nu(\vec{x}_1, t_1) \bar{\chi}_N(\vec{0}, t_0) \right\rangle$$

Euclidean hadronic tensor defined as a function of time difference between the currents

$$\tilde{W}_{\mu\nu}(p, \vec{q}, \tau) = \frac{E_p}{m_N} \frac{\mathrm{Tr}[\Gamma_e C_4]}{\mathrm{Tr}[\Gamma_e C_2]} \rightarrow \sum_{\vec{x}_2 \vec{x}_1} e^{-i\vec{q}\cdot(\vec{x}_2-\vec{x}_1)} \langle p, s \,|\, J_\mu(\vec{x}_2, t_2) J_\nu(\vec{x}_1, t_1) \,|\, p, s \rangle$$

$$= \sum_n A_n e^{-(E_n - E_p)\tau}, \; \tau \equiv t_2 - t_1$$

Solving the **inverse problem** of a Laplace transform to get back to Minkowski space

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

K.F. Liu and S. J. Dong, PRL 72, 1790 (1994)

K.-F. Liu, PRD 62, 074501 (2000)

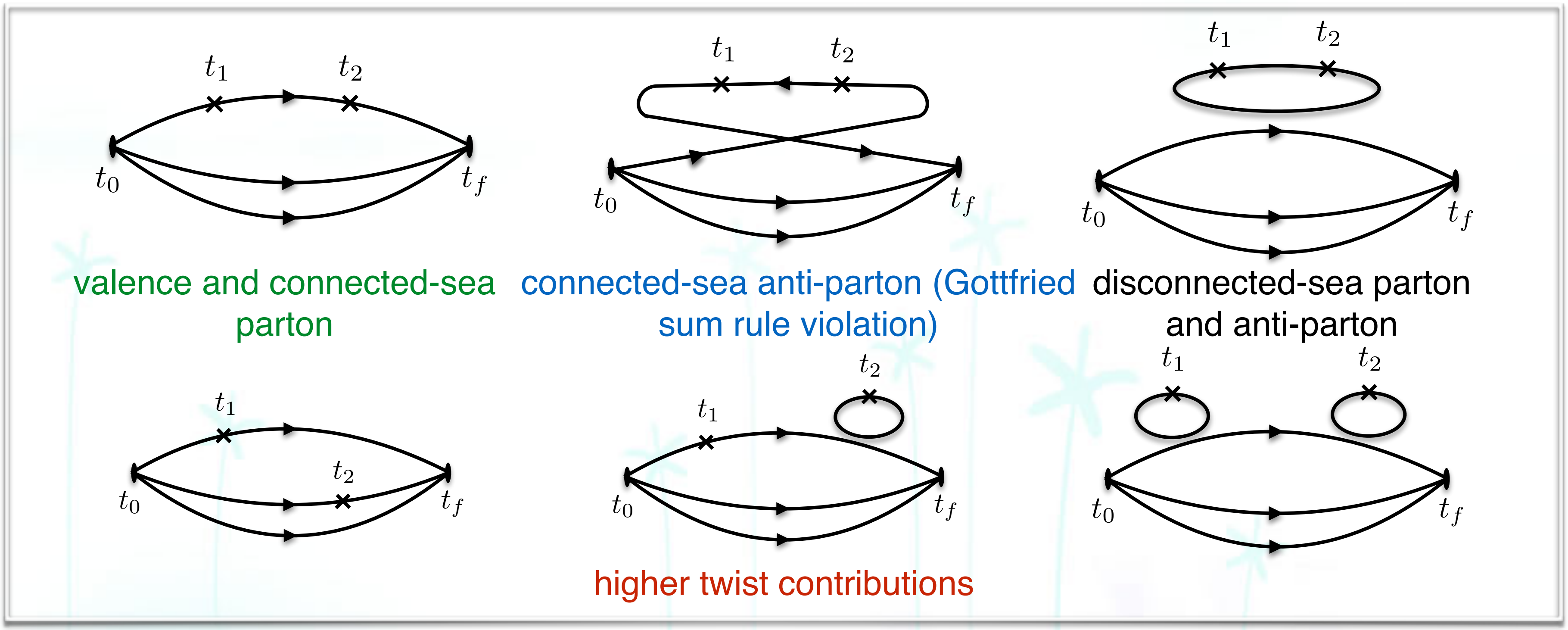
J. Liang et. al., EPJ Web Conf. 175, 14014 (2018)

J. Liang et. al., arXiv:1906.05312

X

Topologically distinct contributions

$$C_4 = \sum_{\vec{x}_f} e^{-i\vec{p}\cdot\vec{x}_f} \sum_{\vec{x}_2\vec{x}_1} e^{-i\vec{q}\cdot(\vec{x}_2-\vec{x}_1)} \left\langle \chi_N(\vec{x}_f, t_f) J_\mu^\dagger(\vec{x}_2, t_2) J_\nu(\vec{x}_1, t_1) \bar{\chi}_N(\vec{0}, t_0) \right\rangle$$



K.F. Liu and S. J. Dong, PRL 72, 1790 (1994)

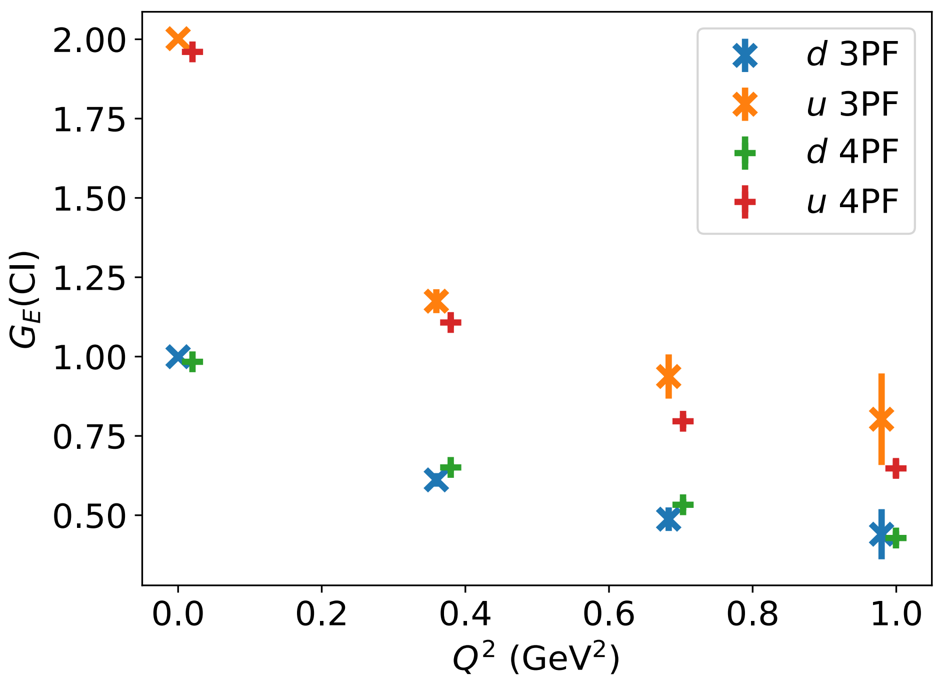
1. More d.o.f.'s in global fittings? Better understand sea partons? (arXiv:1901.07526)

2. How higher twist contributions change with increasing the momentum transfer?

Elastic FFs

$$\tilde{W}_{44}(\vec{p}, \vec{q}, \tau) = \sum_{\vec{x}_2 \vec{x}_1} e^{-i\vec{q}\cdot(\vec{x}_2 - \vec{x}_1)} \langle p, s \,|\, J_\mu(\vec{x}_2, t_2) J_\nu(\vec{x}_1, t_1) \,|\, p, s \rangle = \sum_n A_n e^{-\nu_n \tau}$$

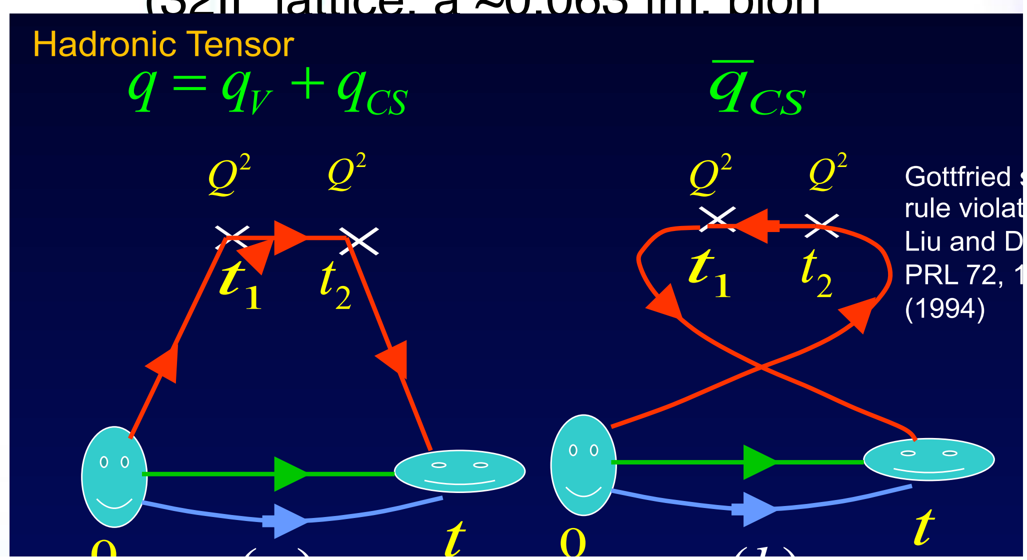
$$A_0 = \langle p, s \,|\, J_4(\vec{q}) \,|\, n = 0 \rangle \langle n = 0 \,|\, J_4(-\vec{q}) \,|\, p, s \rangle = G_E^2(Q^2)$$



J. Liang et al.,1906.05312

FFs extracted from 3-point functions and 4-point functions show consistency.

(32IF lattice, a ~0.063 fm, pion



Summary

- A lot of progress on 4-pt function calculations in the last few years (LaMET, HT, νless $\beta\beta$ decay)
- To reach small x (e.g. < 0.1) in LaMET approach needs large N momentum → small lattice spacing.
- For the HT approach, to reach the DIS region for $Q^2 = 4$ GeV^2, ν needs > 6.5 GeV → small a.
- Examples of lattices with a = 0.03 fm
  - 96^3 x 192, m_π = 270 MeV, m_π L = 3.9
  - 128^3 x256, m_π = 200 MeV, m_π L = 3.9