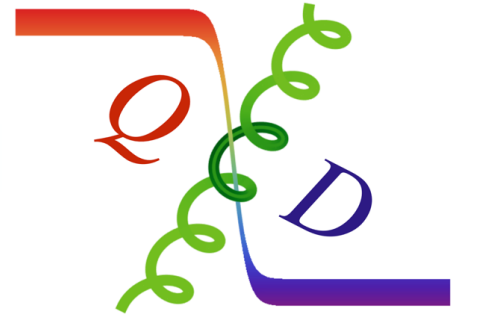




PDF and Neutrino-Nucleon Scattering from Hadronic Tensor

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(χ QCD collaboration)

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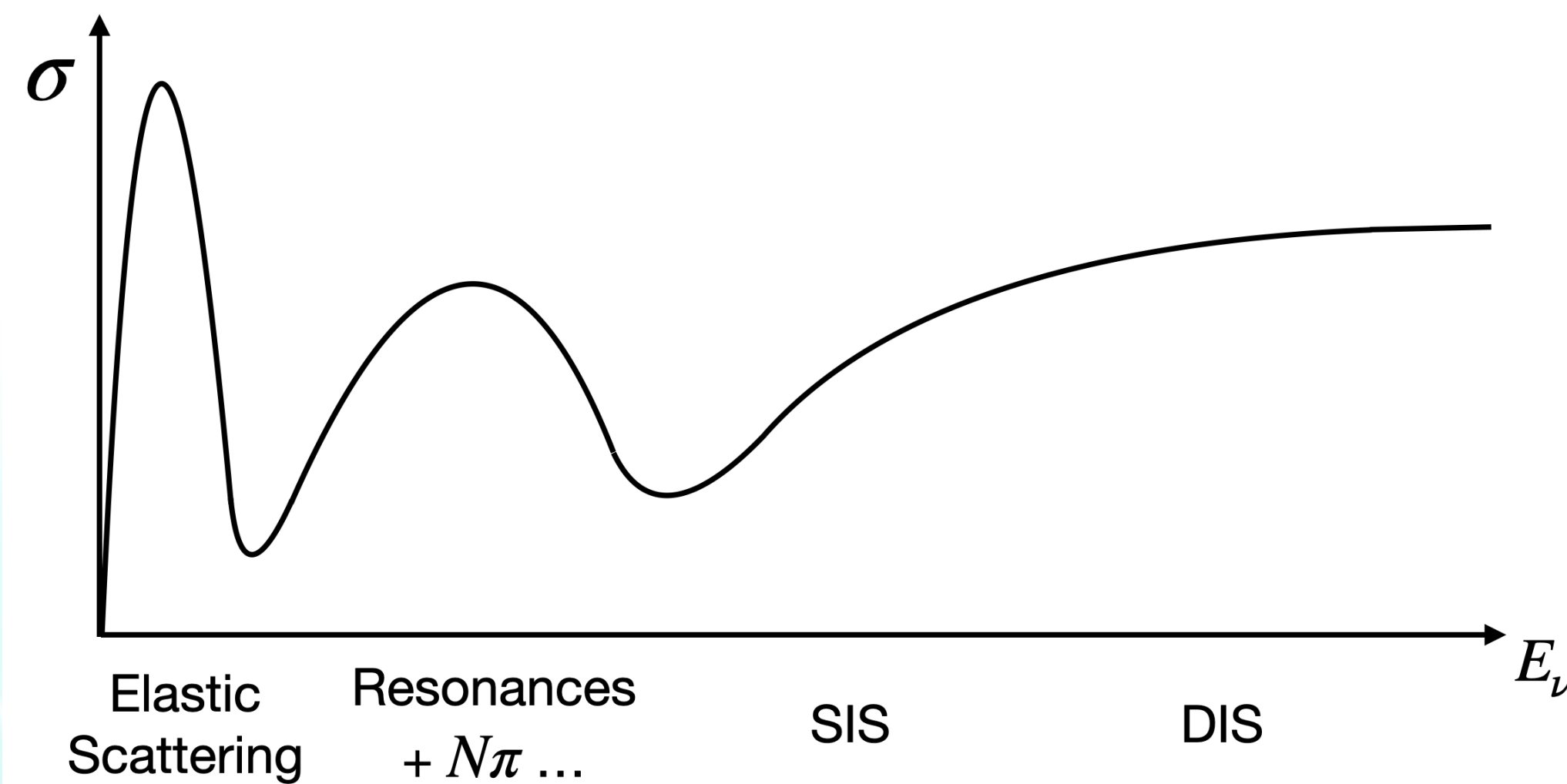
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Hadronic Tensor

$$W_{\mu\nu}(q^2, \nu) = \frac{1}{2} \sum_n \int \prod_{i=1}^n \left[\frac{d^3 \vec{p}_i}{(2\pi)^3 2E_i} \right] \langle N | J_\mu(0) | n \rangle \langle n | J_\nu(0) | N \rangle_{\text{spin ave.}} (2\pi)^3 \delta^4(p_n - p - q)$$

$$W_{\mu\nu}(q^2, \nu) = \frac{1}{\pi} \text{Im } T_{\mu\nu}(q^2, \nu) = \int \frac{d^4 x}{4\pi} e^{iq \cdot x} \langle N | J_\mu(x) J_\nu(0) | N \rangle_{\text{spin ave.}}$$

$$W_{\mu\nu} = \left(-g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2} \right) F_1(x, Q^2) + \frac{\hat{p}_\mu \hat{p}_\nu}{p \cdot q} F_2(x, Q^2)$$



$$W^2 = (q + p)^2 = m_N^2 - Q^2 + 2m_N \nu,$$

$$W^2 > 10 \text{ GeV}^2 \quad Q^2 = 4 \text{ GeV}^2$$

$$\nu > 7 \text{ GeV}$$

Euclidean Hadronic Tensor

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

$$W_{\mu\nu}(\vec{q}, \vec{p}, \nu) = \frac{1}{2m_N i} \int_{c-i\infty}^{c+i\infty} d\tau e^{\nu\tau} \widetilde{W}_{\mu\nu}(\vec{q}, \vec{p}, \tau)$$

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

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

K.-F. Liu, PRD62, 074501 (2000)

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

J. Liang and K.-F. Liu PoS LATTICE2019 (2020) 046

J. Liang et. al., Phys.Rev.D 101 (2020) 11, 114503

◆ **Backus-Gilbert**

G. Backus and F. Gilbert, Geophysical Journal International 16, 169 (1968)

◆ **Maximum Entropy**

E Rietsch et. al., JOURNAL OF GEOPHYSICS, 42:489 (1977)

M. Asakawa et. al., Prog. Part. Nucl. Phys. 46, 459 (2001)

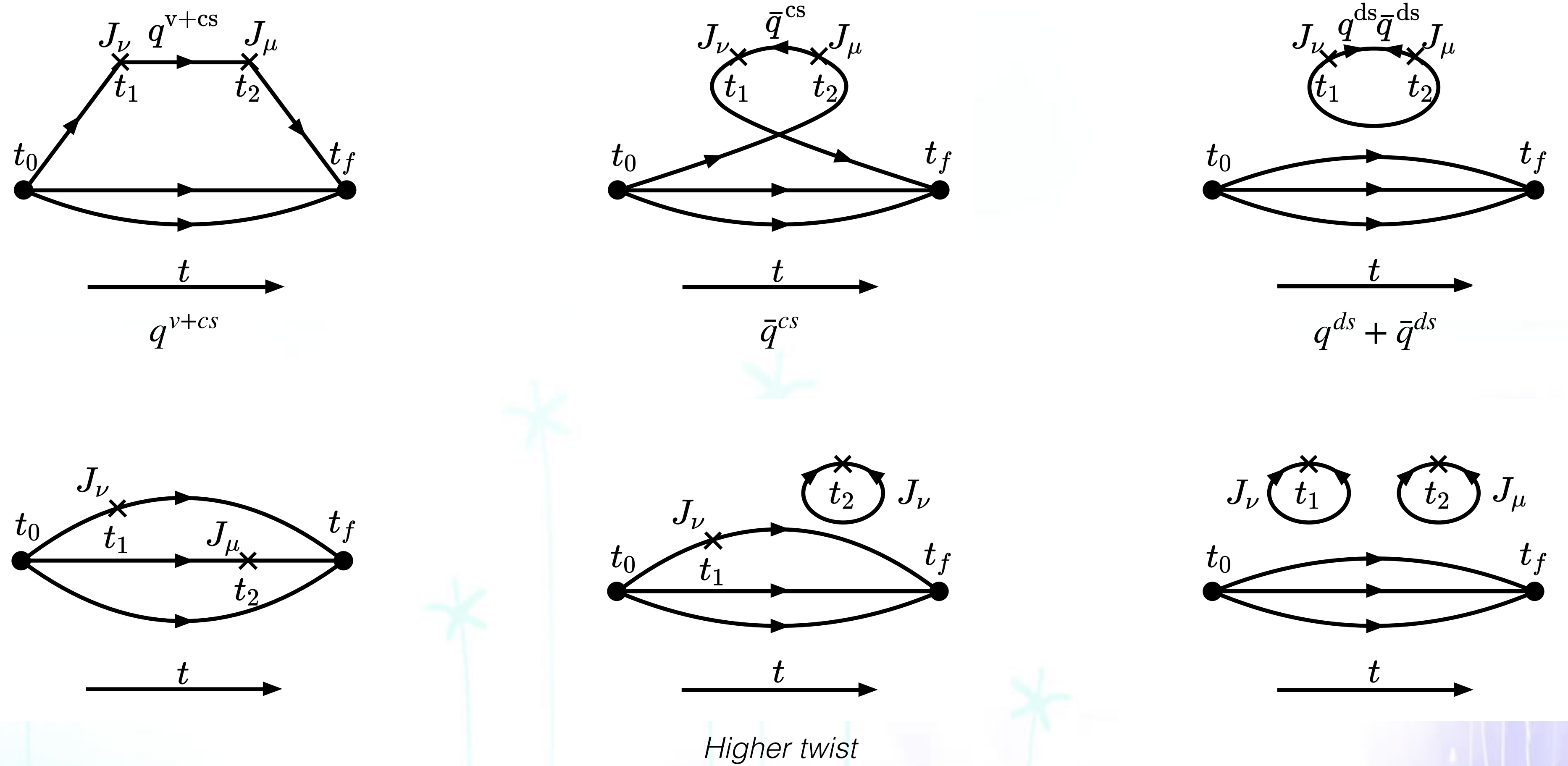
◆ **Bayesian Reconstruction**

Y. Burnier and A. Rothkopf, PRL 111, 182003 (2013)

◆ **Smoothed BR**

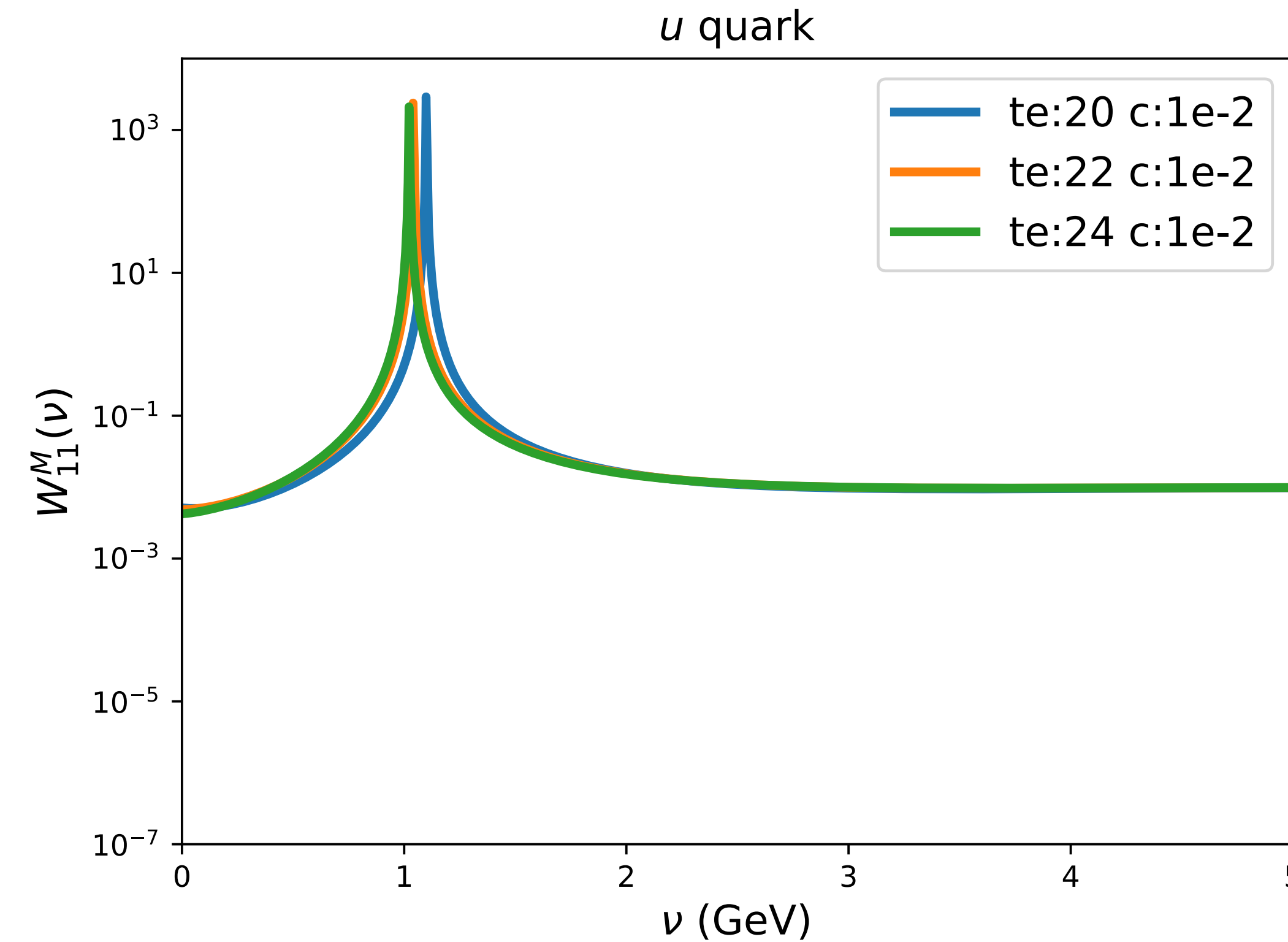
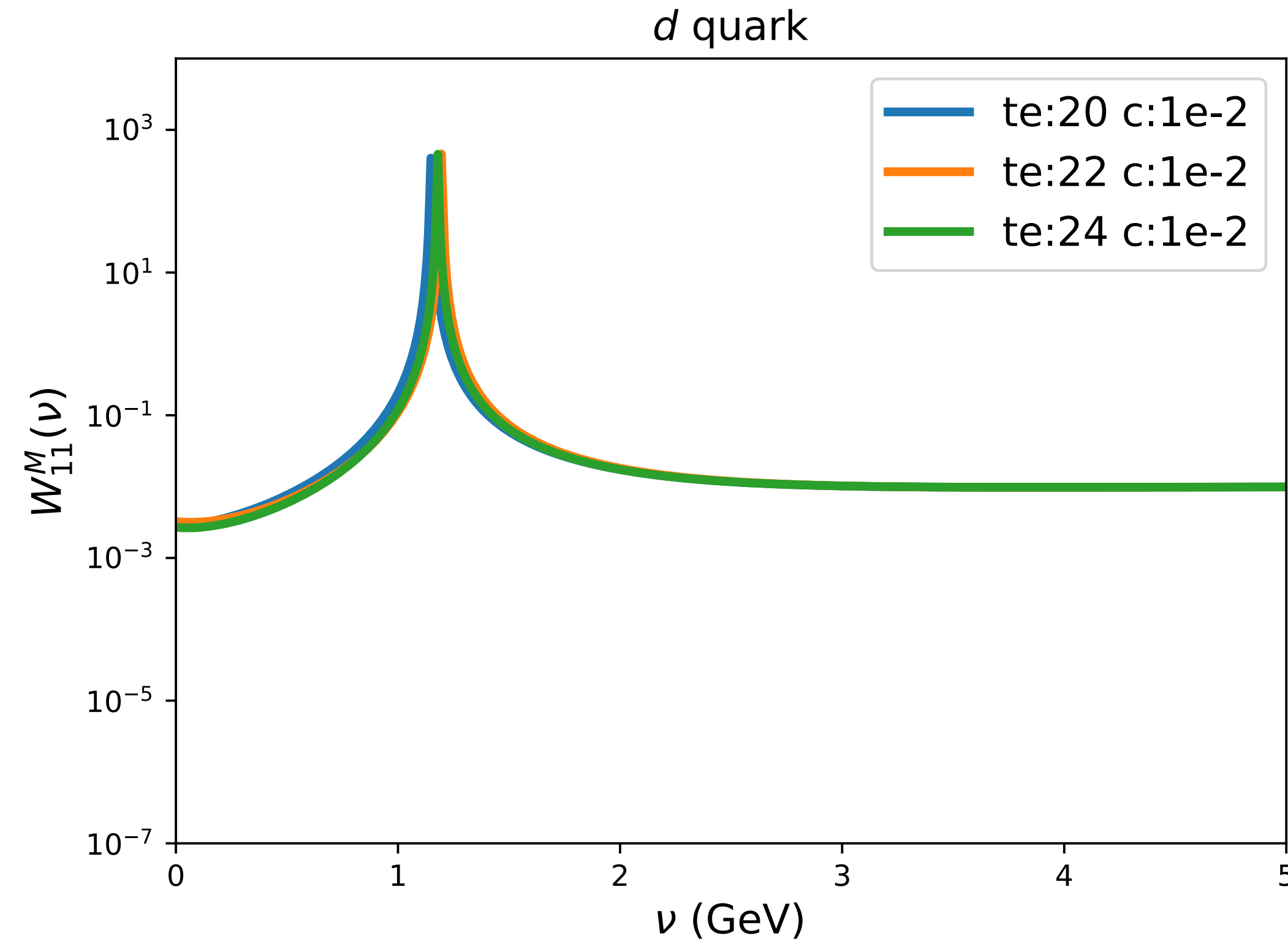
C. S. Fischer et. al., PRD98:014009 (2018)

Contractions



K.F. Liu and S. J. Dong, PRL 72, 1790 (1994)
K.-F. Liu, PRD62, 074501 (2000)
J. Liang et al., PRD (2020) no.3, 034514.

Large Momentum Transfer Case

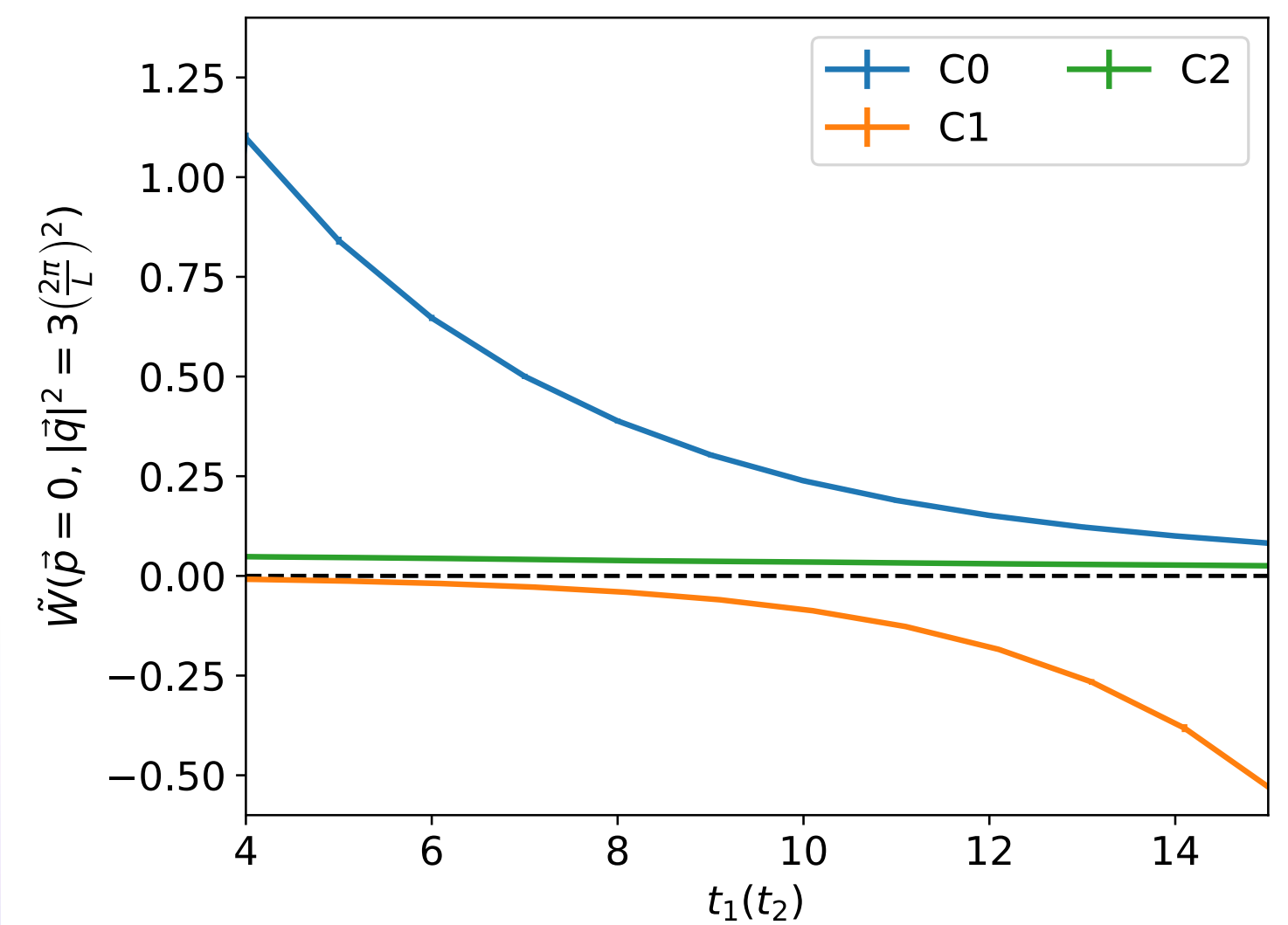
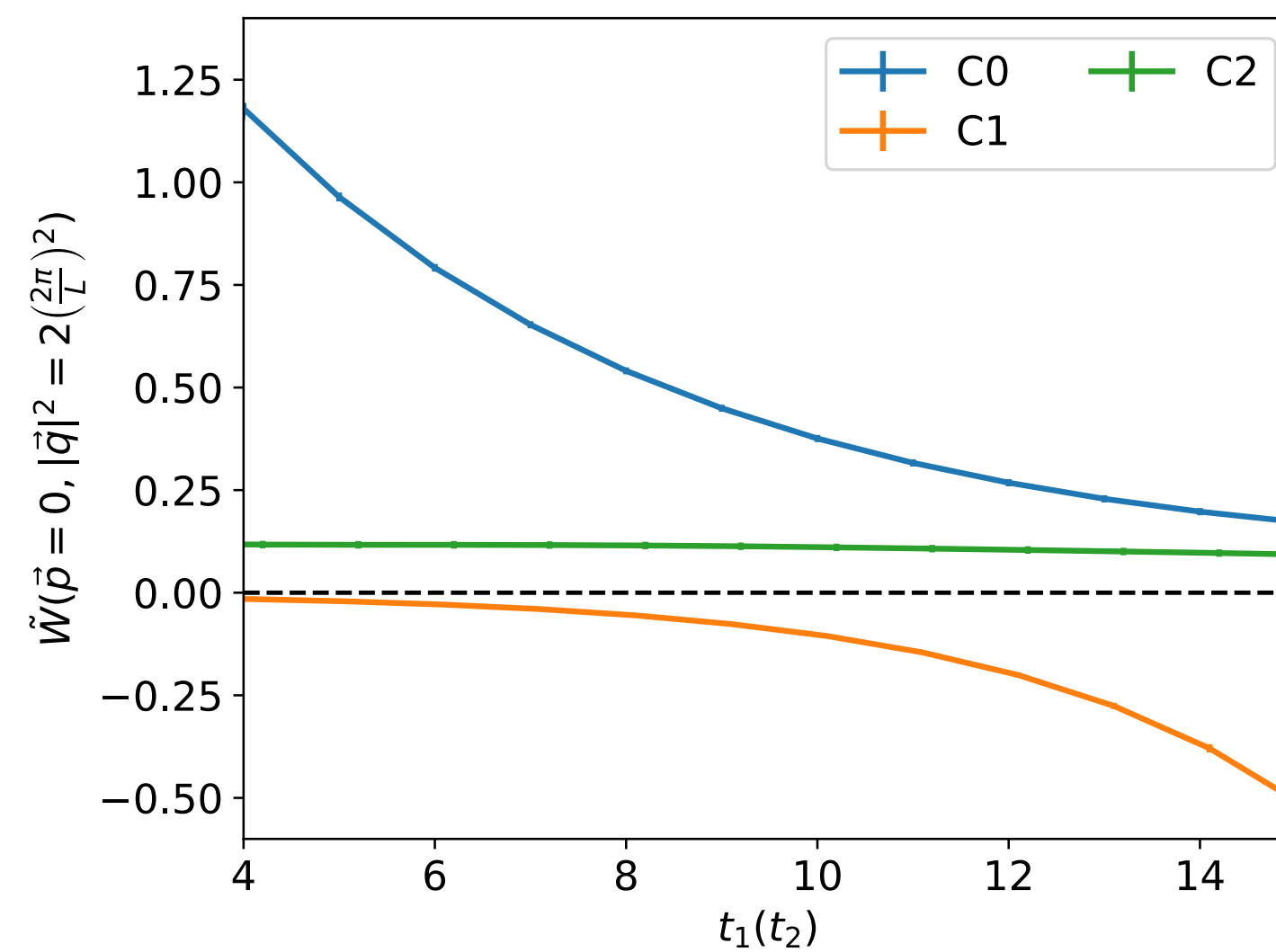
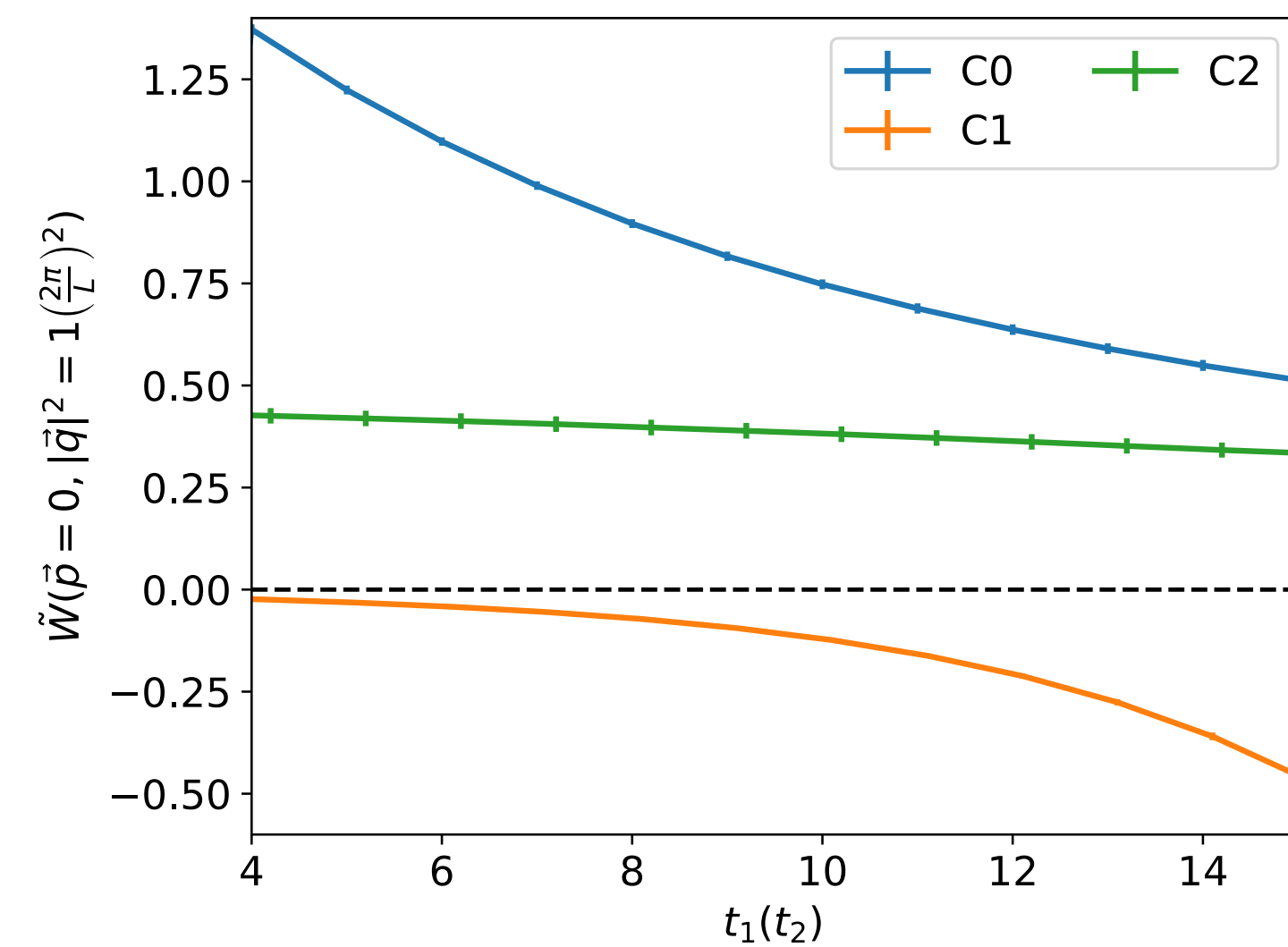
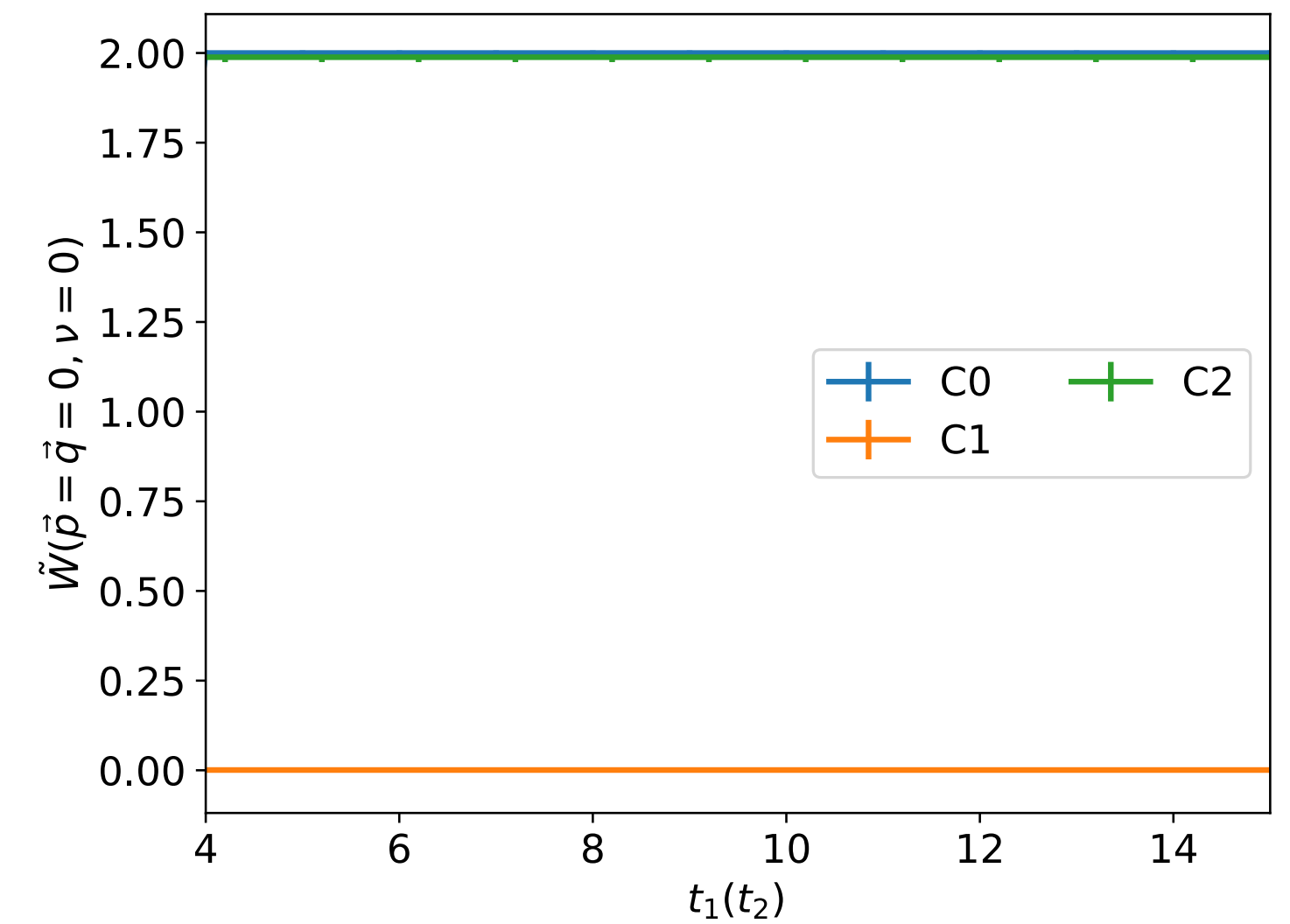
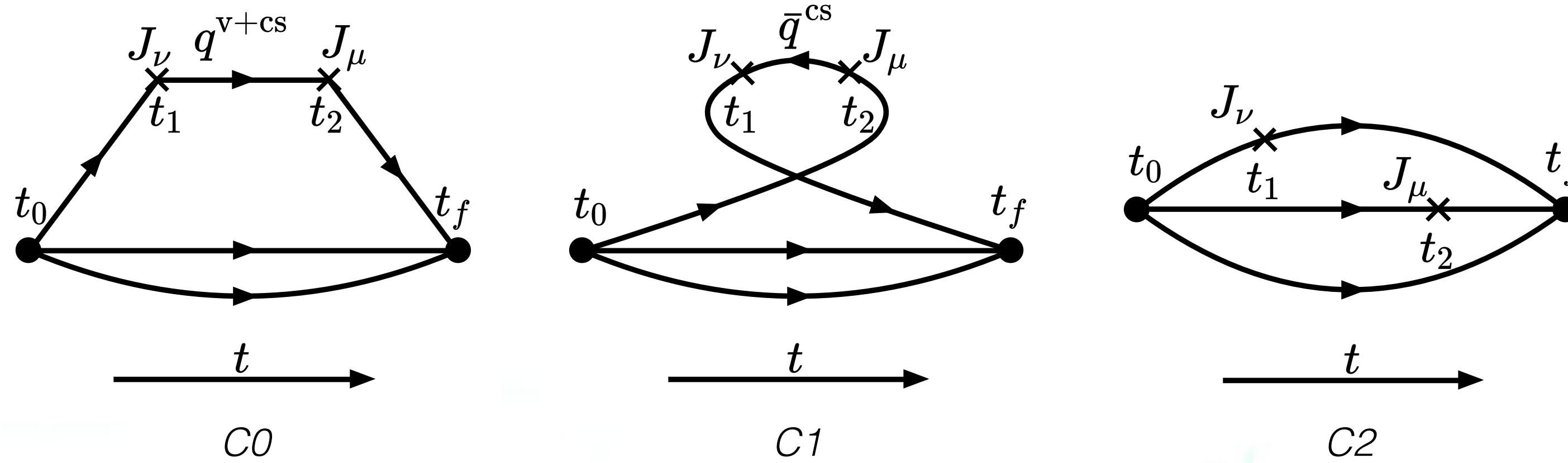


clover anisotropic lattice, $24^3 \times 128$, $a_s \sim 0.12$ fm, $\xi \sim 3.5$, $m_\pi \sim 380$ MeV, $\frac{2\pi}{L} \sim 0.42$ GeV *J. Liang et. al., Phys.Rev.D 101 (2020) 11, 114503*

$\mu = \nu = 1$ and $p_1 = q_1 = 0$ $W_{11}(\nu) = F_1(x, Q^2)$

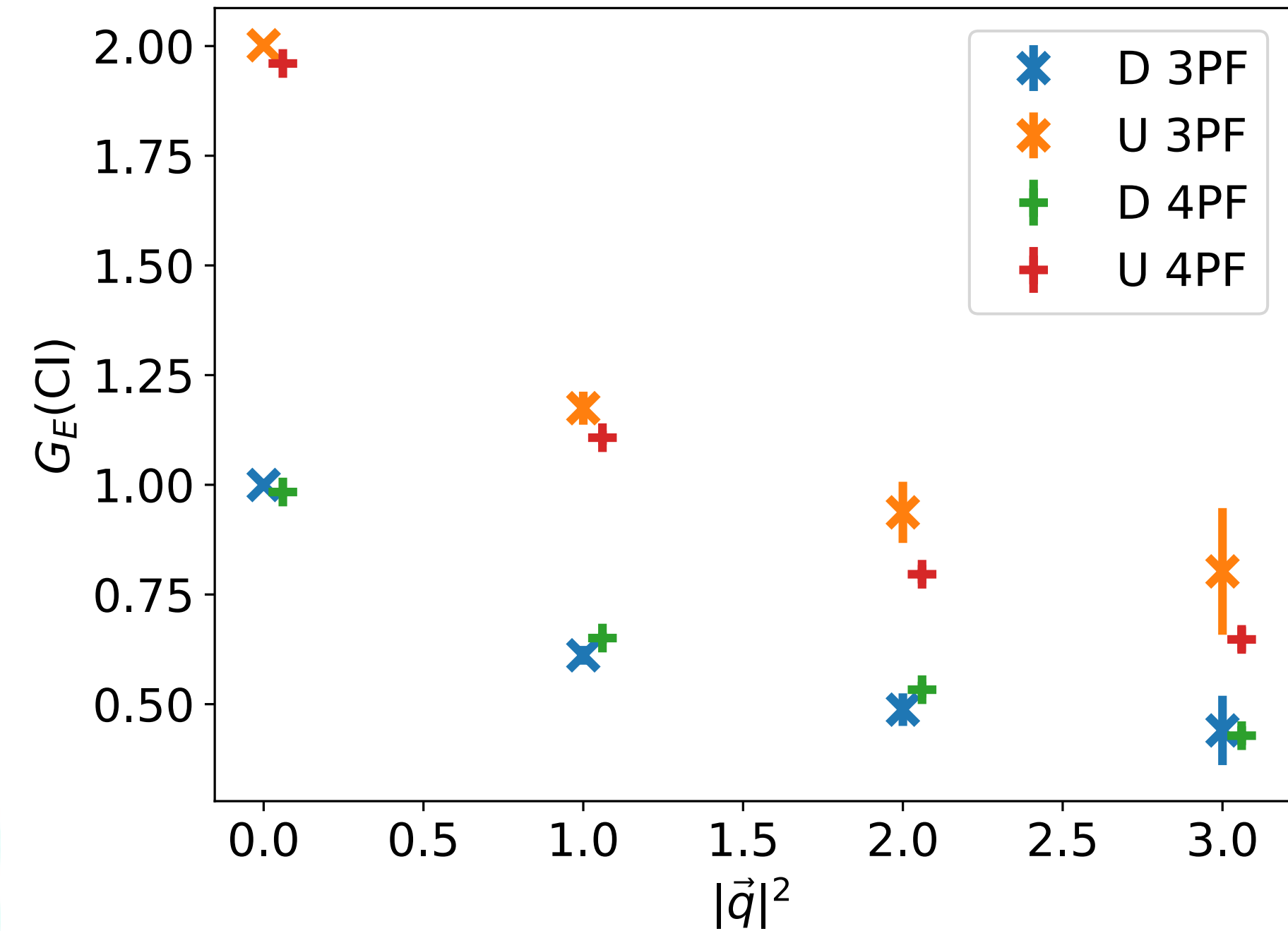
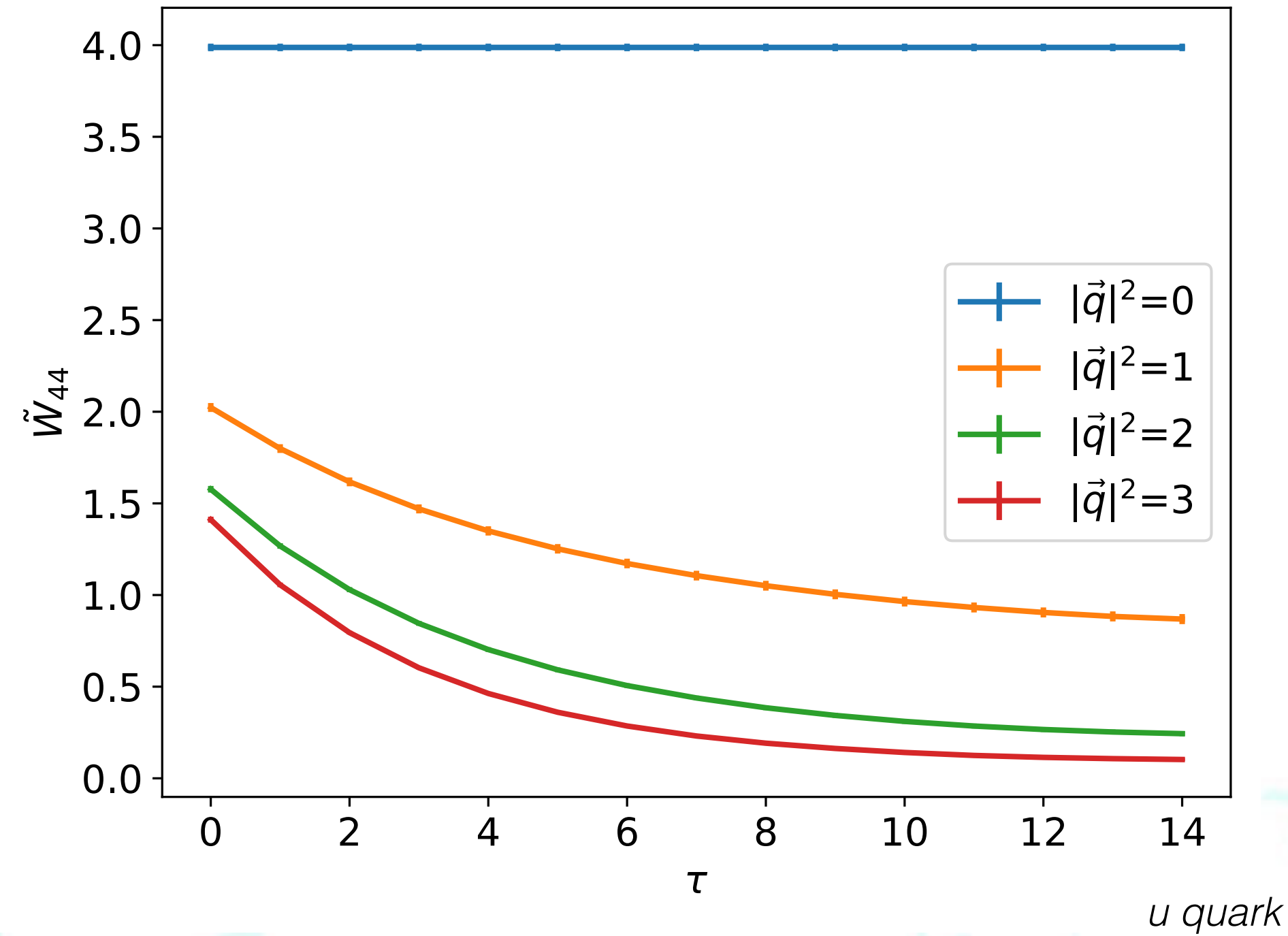
$\boldsymbol{p}$	$\boldsymbol{q}$	E_p	$E_{n=0}$	$ \boldsymbol{q} $	ν	Q^2	x
(0,3,3)	(0,-6,-6)	2.15	2.15	3.57	[2.96, 3.28]	[4, 2]	[0.16, 0.07]

Form Factors



Figures are for u quark

Form Factors



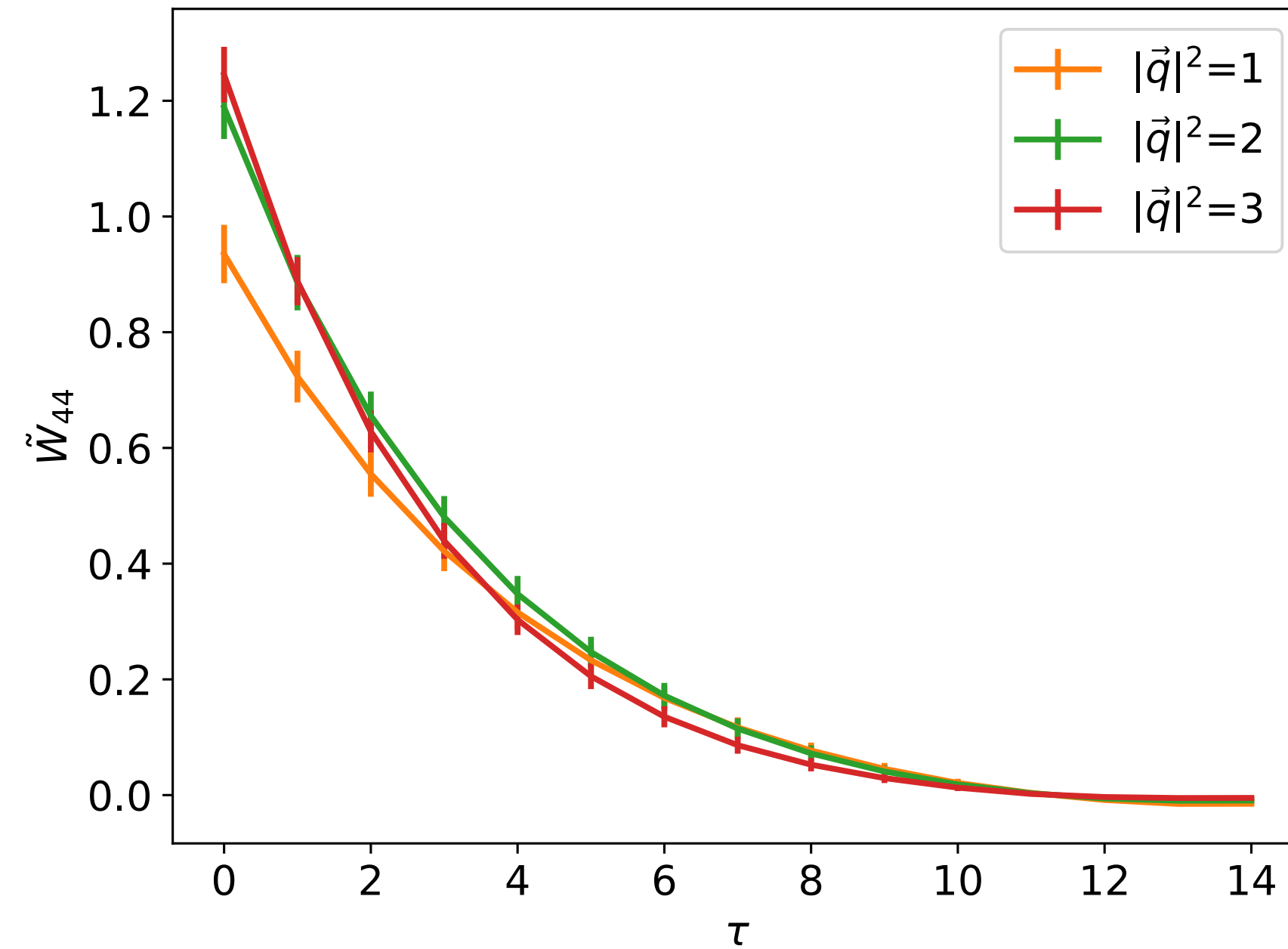
J. Liang and K.-F. Liu PoS LATTICE2019 (2020) 046

$$\widetilde{W}_{44}(\vec{p}, \vec{q}, \tau) = \sum_{\vec{x}_2, \vec{x}_1} e^{-i\vec{q} \cdot (\vec{x}_2 - \vec{x}_1)} \langle p, s | J_4(\vec{x}_2, t_2) J_4(\vec{x}_1, t_1) | p, s \rangle = \sum_n A_n e^{-\nu_n \tau}$$

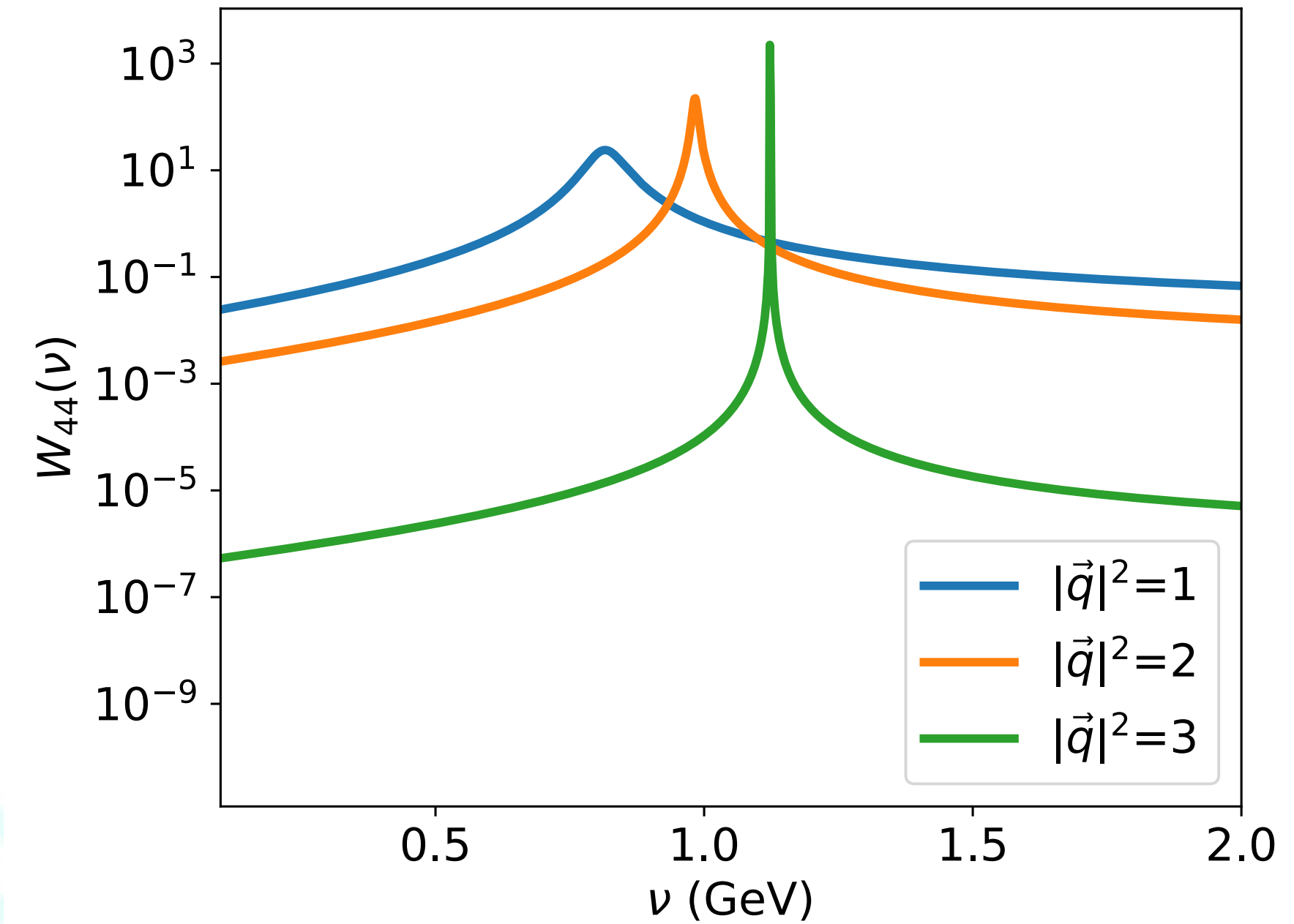
$$A_0 = \langle p, s | J_4(\vec{q}) | n = 0 \rangle \langle n = 0 | J_4(-\vec{q}) | p, s \rangle = G_E^2(Q^2)$$

32IF lattice (a ~ 0.063 fm, pion mass ~ 370 MeV), clover on domain wall, first 4 momentum transfers

Beyond the Elastic Contribution



u quark with elastic contribution subtracted



32IF lattice ($a \sim 0.063$ fm, pion mass ~ 370 MeV), clover on domain wall, first 4 momentum transfers

Summary and Outlook

- ◆ The hadronic tensor can be used to study both the nucleon structure and neutrino-nucleus scattering.
- ◆ We now have good results for the elastic form factors.
- ◆ Finer lattice spacings are essential!
- ◆ We are working on lattices with smaller lattice spacings (~ 0.045 fm) to have better results for the neutrino-nucleon scatterings.
- ◆ To study parton physics, one needs lattices that can accommodate, say, $\nu > 7$ GeV

Thank you!