Hadronic Physics and Higher Twist in PVDIS

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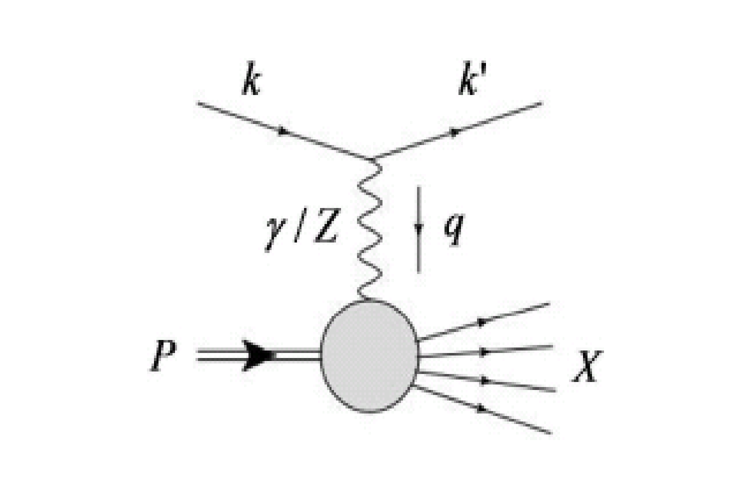
PAVI 14: From Parity Violation to Hadronic Structure

Outline:

1. Brief review on e-D PVDIS and higher-twist correction
2. Some background on nuclear spin problem
3. Study of OAM effect on Twist-4 matrix element
4. Summary

1. Brief review on e-D PVDIS and higher-twist correction



Polarized e, unpolarized D

For γ-Z interference term:

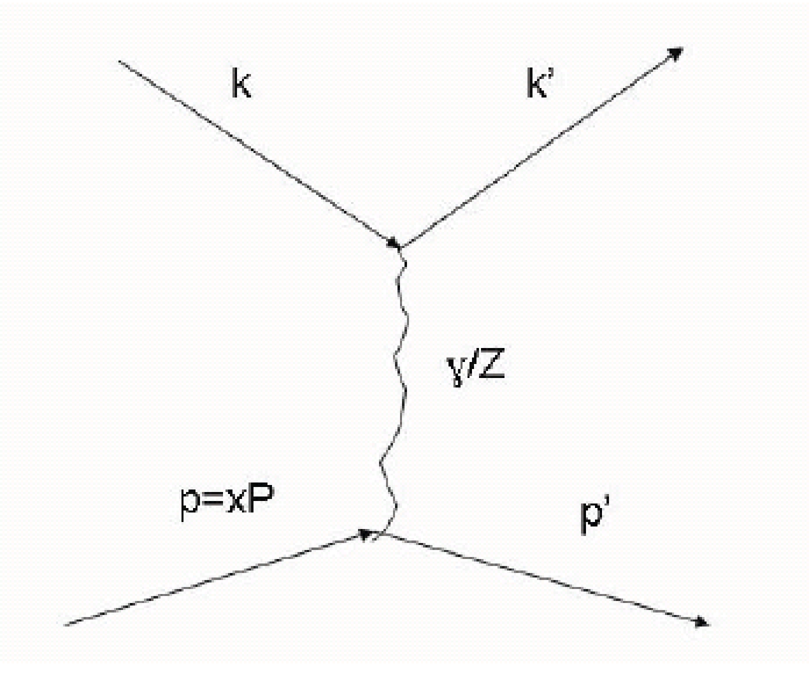
$$d\sigma \sim L^{\mu\nu} W_{\mu\nu}^{\gamma Z}$$

$$L^{\mu\nu} \sim \bar{u}_{s'}(k')\gamma^{\mu} u_s(k) \bar{u}_s(k)\gamma^{\nu}(g_V^e + g_A^e \gamma_5) u_{s'}(k')$$

$$W_{\mu\nu}^{\gamma Z} = (-g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2})\frac{F_1^{\gamma Z}}{M_D} + (P_\mu - \frac{P \cdot q}{q^2} q_\mu)(P_\nu - \frac{P \cdot q}{q^2} q_\nu)\frac{F_2^{\gamma Z}}{M_D P \cdot q} + \frac{i\varepsilon_{\mu\nu\alpha\beta} P^\alpha q^\beta}{2 M_D P \cdot q} F_3^{\gamma Z}$$

Cahn-Gilman formula for Left-Right Asymmetry

R. N. Cahn and F. J. Gilman, Phys. Rev. D17, (1978) 1313



$$y = \frac{E - E'}{E}$$ (fraction of electron energy loss)

$$A_{RL} = \frac{d\sigma_R - d\sigma_L}{d\sigma_R + d\sigma_L}$$

$$\text{Parton model}: d\sigma = \sum_i f_i(x) d\sigma_i$$

After lengthy math, one obtain:

$$A_{RL} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha \sum_i q_i^2 f_i(x)} \sum_i q_i f_i(x) \left(g_A^e g_V^i + g_V^e g_A^i \frac{1-(1-y)^2}{1+(1-y)^2} \right)$$

Assumptions:

1. Ignore sea quarks.
2. Isospin is a good symmetry.

$$\text{Deuteron being isosinglet} \Rightarrow f_u(x) = f_d(x)$$

The PDF-dependence drops out!

Cahn-Gilman formula for Left-Right Asymmetry

$$A_{RL} = \frac{d\sigma_R - d\sigma_L}{d\sigma_R + d\sigma_L} = -\frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\frac{9}{10}\{\tilde{a}_1 + \tilde{a}_2 \frac{1-(1-y)^2}{1+(1-y)^2}\}$$

$$\tilde{a}_{1,0} = (1 - \frac{20}{9}\sin^2\theta_W)$$

$$\tilde{a}_{2,0} = (1 - 4\sin^2\theta_W)$$

For SM at leading-twist

- The LT-result is PDF-independent
- First e-D PVDIS experiment by Yale-SLAC collaboration measured the weak mixing angle
- The Jefferson Lab 12-GeV upgrade enables for the measurement of A_{RL} with 0.5% precision over $0.3 < x_B < 0.7$, providing sensitive probes (or constrains) on many BSM scenarios.

$$\tilde{a}_i = \tilde{a}_{i,0}(1 + R_i)$$

R_i measures the contribution from SM and BSM physics.
SM contributions include:

Radiative Correction
Charge Symmetry Violation (CSV)
Target Mass Correction (TMC)
Sea Quark Effect
Higher Twist (HT)

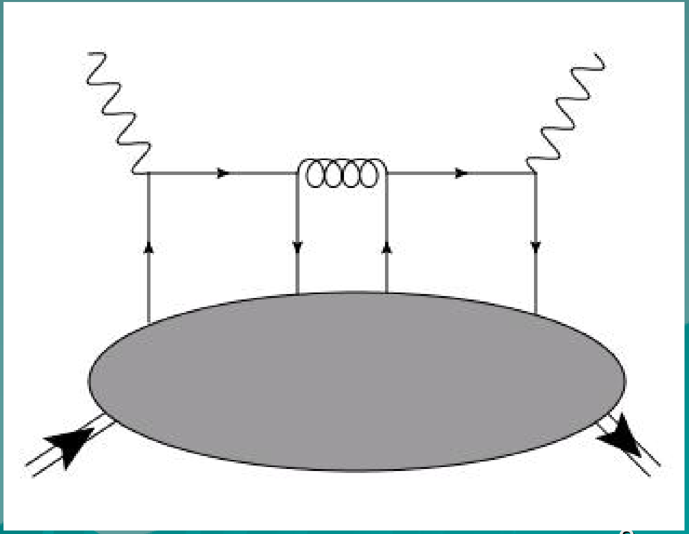
We have to first understand the SM corrections, before it can be used effectively to probe New Physics

Higher Twist correction: Corrections to naïve parton picture which scale as: $(Q^2)^{-(\tau-2)/2}$ τ : "Twist" by including the interactions between partons.

Bjorken-Wolfenstein's observation: In e-D PVDIS, assuming isospin symmetry and neglecting sea quarks, the only twist-4 correction term to $\tilde{a}_1$ is proportional to the following hadronic matrix element

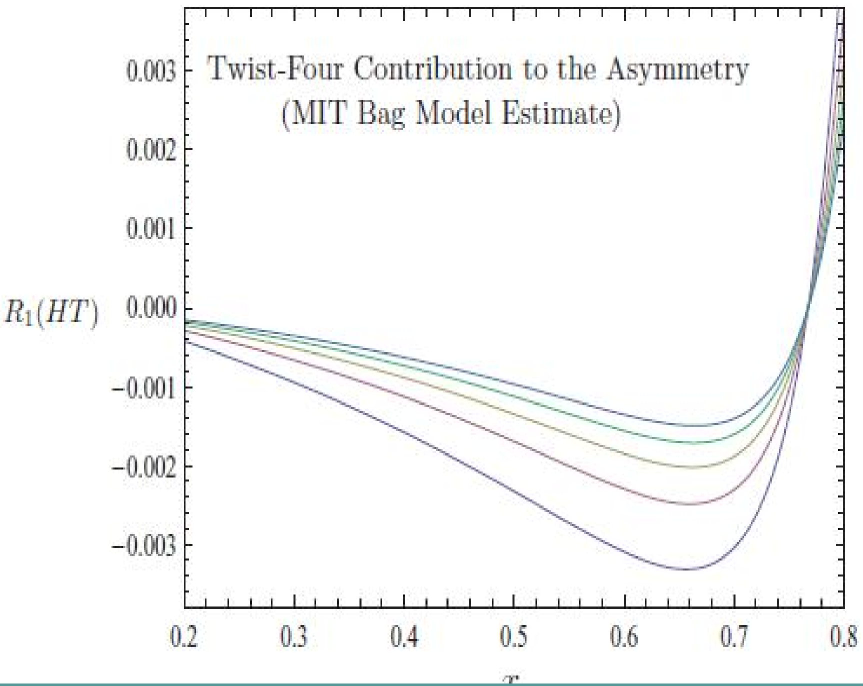
$$< D|\bar{u}(x)\gamma^{\mu}u(x)\bar{d}(0)\gamma^{\nu}d(0)+u\leftrightarrow d|D>$$

J.D Bjorken, PRD 18, 3239 (1978);
L. Wolfenstein, Nucl. Phys. B 146 477 (1978)

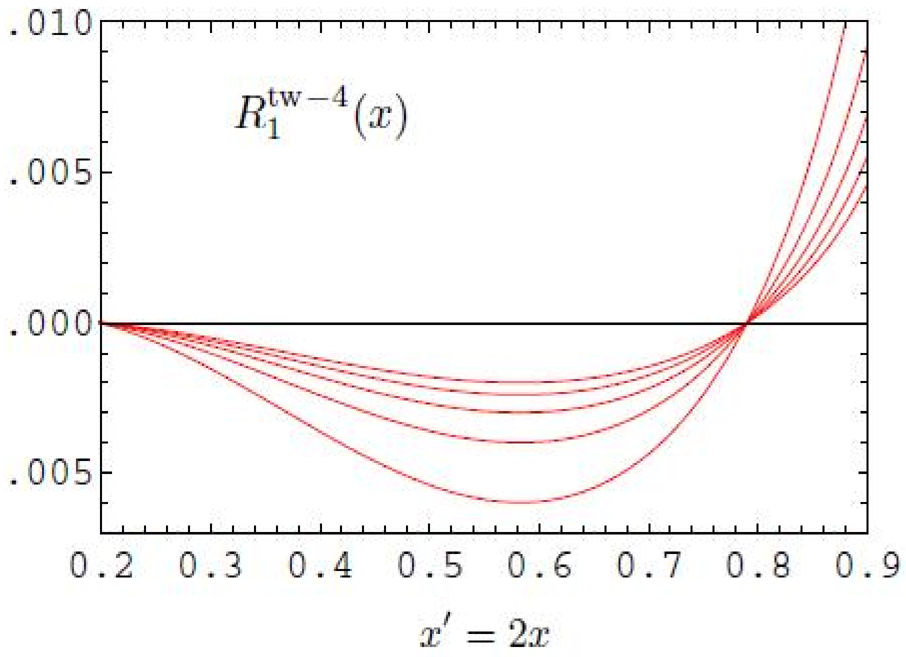


Previous works on twist-4 contribution to R1

$$4\mathrm{GeV}^2 \le Q^2 \le 12\mathrm{GeV}^2$$



x



Bag model

S. Mantry et al, PRC 82, 065205 (2010)

Isotropic light cone wavefunction

A.V. Belitsky et al, PRD 84, 014010 (2011)

2. Some background on nuclear spin problem

The EMC experiment: DIS between longitudinally polarized muon and proton.

European Muon Collaboration, J. Ashman, et al., Nucl. Phys. B 328 (1989) 1.

$$d\sigma = \frac{1}{J}\frac{d^3k'}{2E'(2\pi)^3}\sum_X\prod_{i=1}^{n_X}\int\frac{d^3p_i}{(2\pi)^3 2E_i}\frac{(4\pi\alpha)^2}{Q^4}l^{\mu\nu}W_{\mu\nu}(2\pi)^4\delta^4(P+q-\sum_{i=1}^{n_X}pi)$$

The hadronic tensor can be written as:

$$\begin{aligned}
W^{\mu\nu} &= W^{\{\mu\nu\}} + W^{[\mu\nu]} \\
W^{\{\mu\nu\}} &= (-g^{\mu\nu} + \frac{q^\mu q^\nu}{q^2})F_1 + \frac{1}{P\cdot q}(P^\mu - \frac{P\cdot q}{q^2}q^\mu)(P^\nu - \frac{P\cdot q}{q^2}q^\nu)F_2 \\
W^{[\mu\nu]} &= -i\epsilon^{\mu\nu\lambda\sigma}q_\lambda(\frac{S_\sigma}{P\cdot q}(g_1+g_2) - \frac{q\cdot SP_\sigma}{(P\cdot q)^2}g_2)
\end{aligned}$$

Theoretical prediction, assuming all proton spin is entirely built up of quark spin, and neglect strange quark contribution:

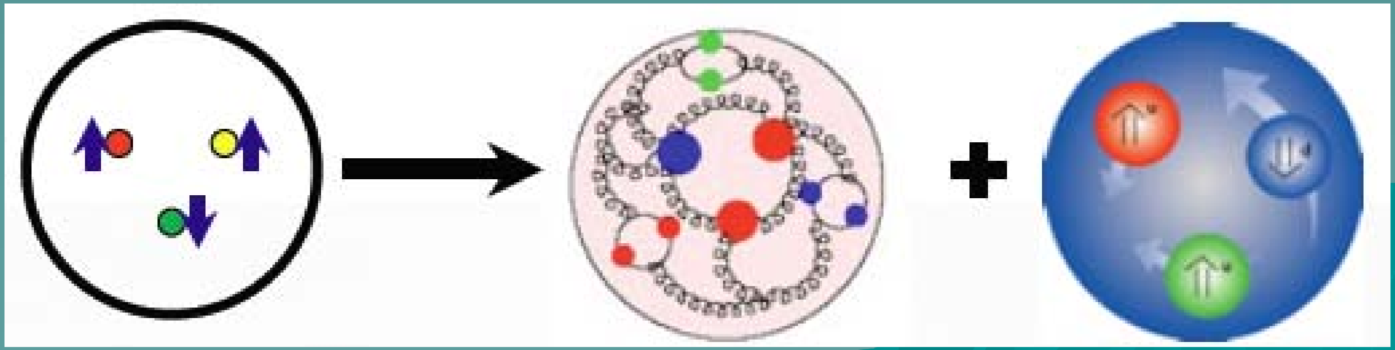
$$\int_0^1 dx g_1^p(x) \quad = \quad 0.189 \pm 0.005$$

J. Ellis and R.L. Jaffe, Phys. Rev. D9 (1974) 1444.

Experimental result:

$$\int_0^1 g_1^p(x) = 0.126 \pm 0.010 \pm 0.015$$

The nucleon spin cannot be made up entirely from the valence quark spin!



- A key question then to explain the source of nucleon spin in terms of QCD DOF.
- Further complication arises as different choices of decomposition of the nucleon spin (e.g. what should be called quark and gluon OAM), are gauge-dependent

R. L. Jaffe and A. Manohar, Nucl. Phys. B337, 509 and X. Ji, Phys. Rev. Lett. 78, 610.

$$\frac{1}{2} = \frac{1}{2}\sum_q \Delta q + \sum_q \mathcal{L}_q^z + \frac{1}{2}\Delta G + \mathcal{L}_g^z$$

- Under light-cone gauge, non-zero quark OAM are responsible for certain DIS observables, e.g Sivers and Boer-Mulders function

Sivers function:

$$f_{1T}^{\perp}(x, \boldsymbol{k}_{\perp}^2) = -i(k^x + ik^y)\frac{M}{2\boldsymbol{k}_{\perp}^2}\int\frac{d\xi^- d^2\boldsymbol{\xi}_{\perp}}{(2\pi)^3} \times e^{-i(\xi^- k^+ - \boldsymbol{\xi}_{\perp}\cdot\boldsymbol{k}_{\perp})} \times \langle P\uparrow|\bar{\psi}(\xi^-, \boldsymbol{\xi}_{\perp})\mathcal{L}_{\xi}^{\dagger}\gamma^+\mathcal{L}_0\psi(0)|P\downarrow\rangle$$

Boer-Mulders function:

$$h_1^{\perp}(x, \boldsymbol{k}_{\perp}^2) = \epsilon^{ij}k_{\perp}^j\frac{M}{2\boldsymbol{k}_{\perp}^2}\int\frac{d\xi^- d^2\boldsymbol{\xi}_{\perp}}{(2\pi)^3}e^{-i(\xi^- k^+ - \boldsymbol{\xi}_{\perp}\cdot\boldsymbol{k}_{\perp})}\frac{1}{2} \times\sum_{\Lambda}\langle P\Lambda|\bar{\psi}(\xi^-, \boldsymbol{\xi}_{\perp})\mathcal{L}_{\xi}^{\dagger}i\sigma^{i+}\gamma_5\mathcal{L}_0\psi(0)|P\Lambda\rangle$$

B. Pasquini and F. Yuan, PRD 81, 114013

They appear in Semi-Inclusive Deep Inelastic Scattering (SIDIS) with transversely-polarized targets.

- It will be interesting to ask, how the inclusion of parton angular momentum (besides quark helicity) would affect other DIS observables which have been previously studied
- Another question will be: how to interpret any study of parton AM in a gauge-invariant way, and as insensitive as possible to a particular choice of AM decomposition.
- As we will see later, detailed analysis of the affect of parton AM on different DIS observables provides a way to disentangle different components of parton AM and study each of them individually

3. Study of OAM effect on Twist-4 Matrix Element

CYS and Michael J. Ramsey-Musolf, PRC 88, 015202

- Model used: OAM-dependent light-cone wavefunction, including only three valence quarks
- Nucleon wavefunction with definite helicity can be decomposed into states of definite L_z of the valence quarks (under light-cone gauge)

$$|P,\uparrow> = |h=\frac{1}{2}, l_z=0> + |h=-\frac{1}{2}, l_z=1>$$

$$+|h=\frac{3}{2}, l_z=-1> + |h=-\frac{3}{2}, l_z=2>$$

- Finite-OAM wavefunction can be obtained from a constituent quark model (e.g. B. Pasquini et al, PRD 78, 034025)
- From nucleon to deuteron: Incoherent Impulse approximation assumed

An explicit example:

$$|h=\frac{1}{2},l_z=0>=\int d[X_3](\psi^{(1)}(1,2,3)+i\varepsilon^{\alpha\beta}k_{1\alpha}k_{2\beta}\psi^{(2)}(1,2,3))\times$$

$$\frac{\varepsilon^{ijk}}{\sqrt{6}}u^{+}_{i\uparrow}(1)\{u^{+}_{j\downarrow}(2)d^{+}_{k\uparrow}(3)-d^{+}_{j\downarrow}(2)u^{+}_{k\uparrow}(3)\}|0>$$

Only **diagonal** components, i.e. <h|…|h> (same h for initial and final states) will contribute.

Main result after performing numerical integration:

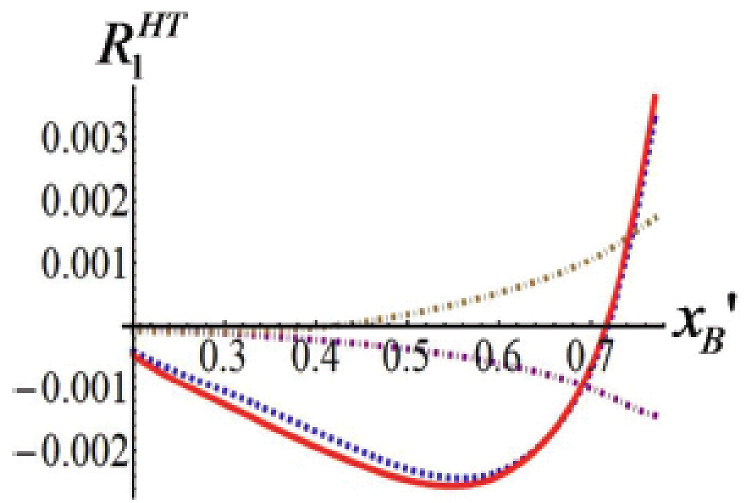
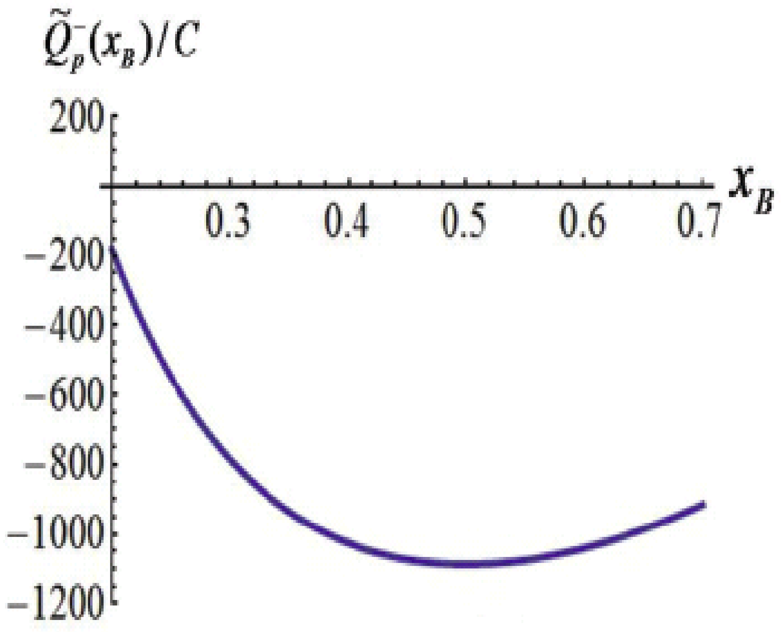
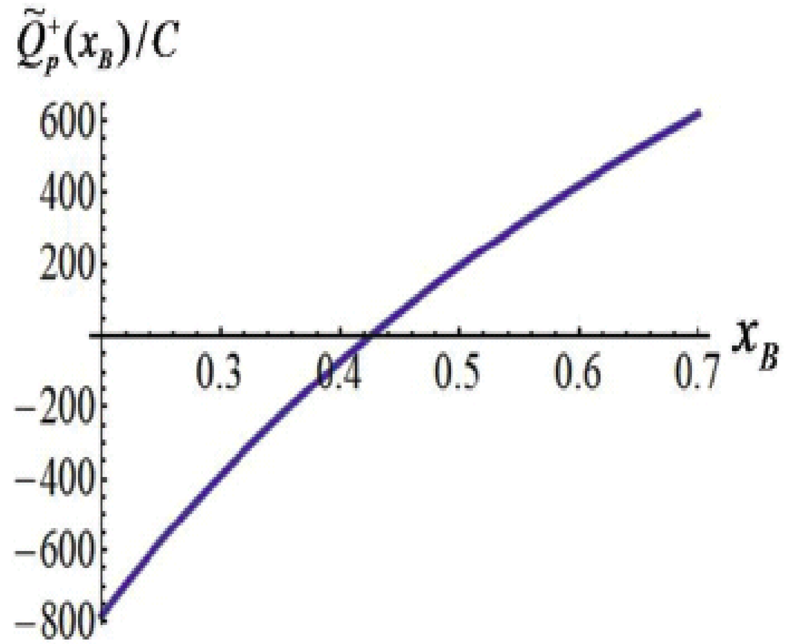


FIG. 3. (Color online) The twist-four correction to R_1 at $Q^2 = 4\ \text{GeV}^2$. The blue dashed curve shows the $l_z = 0$ contribution; purple dot-dashed curve shows the $l_z = 1$ contribution; brown dot-dashed curve shows the $l_z = -1$ contribution; the red solid curve is the sum of all. $l_z = 2$ contribution is negligible and therefore not included.

- Peaked at $0.5 < x_B < 0.6$
- Curve shape similar to previous works, with slightly different magnitude reflecting current degree of theoretical uncertainty
- Non-intuitive observation: partial cancelation between $L_z = \pm l$ contribution at $x_B > 0.4$, leaving $L_z = 0$ piece dominant.

- This cancelation is rather model-independent!





$$L_z = 1 \qquad\qquad L_z = -1$$

- Observed cancelation not shared by other hadronic matrix elements, e.g. Quark Distribution Function:

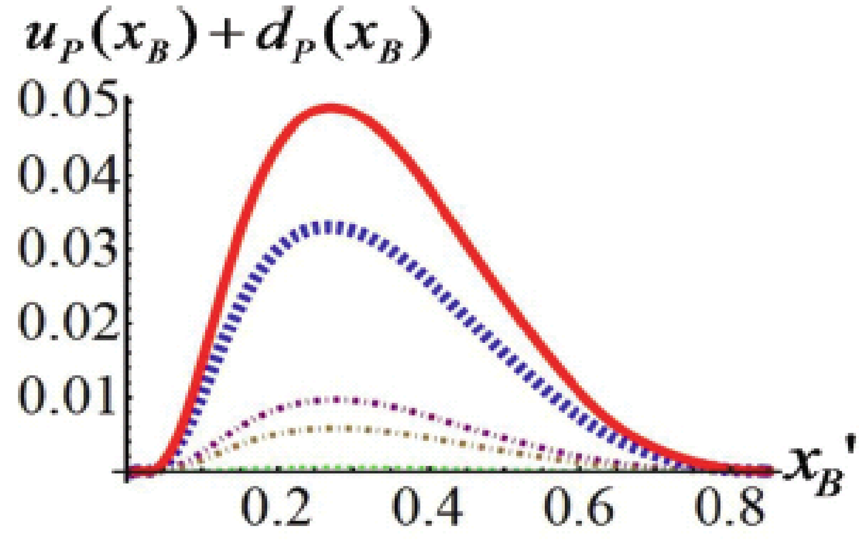


FIG. 4. (Color online) The unnormalized QDF of spin-up proton, split into contributions from different l_z components. Blue thick-dashed curve shows contribution from $l_z = 0$ component; purple dot-dashed curve shows contribution from $l_z = 1$ component; brown dot-dashed curve shows contribution from $l_z = -1$ component; green thin-dashed curve shows contribution from $l_z = 2$ component; red solid curve is the sum of all contributions.

- Twist-4 correction to e-D PVDIS provides a clean probe to the L_z=0 piece of quark OAM!

- Gauge-independent Interpretation: twist-4 correction to eD-PVDIS is essentially transparent to the parton AM dynamics that generates Sivers and Boer-Mulders function in SIDIS.
- Detailed study of different DIS observables helps disentangling effects of different parton AM components.

TABLE II. The dependence on different quark light-cone OAM components of various distribution functions.

Distribution functions	Dominant contribution(s)	Subdominant contribution(s)
Quark distribution functions	$(0\otimes 0)$, $(1\otimes 1)$	$(2\otimes 2)$
PVDIS twist-four correction	$(0\otimes 0)$	$(1\otimes 1)$, $(2\otimes 2)$
Sivers function	$(0\otimes 1)$	$(1\otimes 2)$
Boer-Mulders function	$(0\otimes 1)$, $(1\otimes 2)$	–

$$\left(a\otimes b\right):\left\langle |L_z|=b\right| \;\ldots.\; \left| |L_z|=a\right\rangle$$

4. Summary

1. e-D PVDIS probes not only BSM physics, but also novel features of hadron and nuclear structure.
2. Effect of twist-4 matrix element on $\tilde{a}_1$ certainly comes in when $Q^2 < 2GeV^2$ at region $x_B \sim 0.5-0.7$
3. Far outside this region, the SM corrections that enter JLab e-D PVDIS result will not include twist-4, unless the existing models are completely wrong.
4. The study of higher twist comes with a bonus of helping us in understanding the role of parton angular momentum in nucleon structure.

Backup Slides

Bjorken-Wolfenstein's argument

- The operator of our interest is a product between EM-current and weak neutral current
- The deuteron is an isosinglet
- We can decompose both currents into isovector (V) and isoscalar (S).
- Since deuteron is isosinglet, so <SV>=<VS>=0.
- For leading twist, <SS>=<VV>. The difference <SS>-<VV> is just the twist-four matrix element we showed before.
- Assumptions we made here: isospin symmetry, and that the contributions from sea quarks are negligible.

J.D Bjorken, PRD 18, 3239 (1978);
L. Wolfenstein, Nucl. Phys. B 146 477 (1978)

Brief discussions of other SM effects

- Target Mass Correction (TMC): Correction due to non-zero target mass M. Also scales as $1/Q^2$, but is suppressed because the leading expression does not need the M=0 assumption.
- Sea quark effect: Large only at small x (say x<1/3), so should be distinguishable from HT-effect that peaked at 0.5<x<0.7.
- Charge symmetry violation (CSV):

$$\delta u(x) = u^p(x) - d^n(x)$$

$$\delta d(x) = d^p(x) - u^n(x)$$

A leading-twist effect

$$R_1^{CSV} \sim \frac{\delta u(x) - \delta d(x)}{u(x) + d(x)}$$

Effect estimated using phenomenological parametrizations or non-perturbative calculations

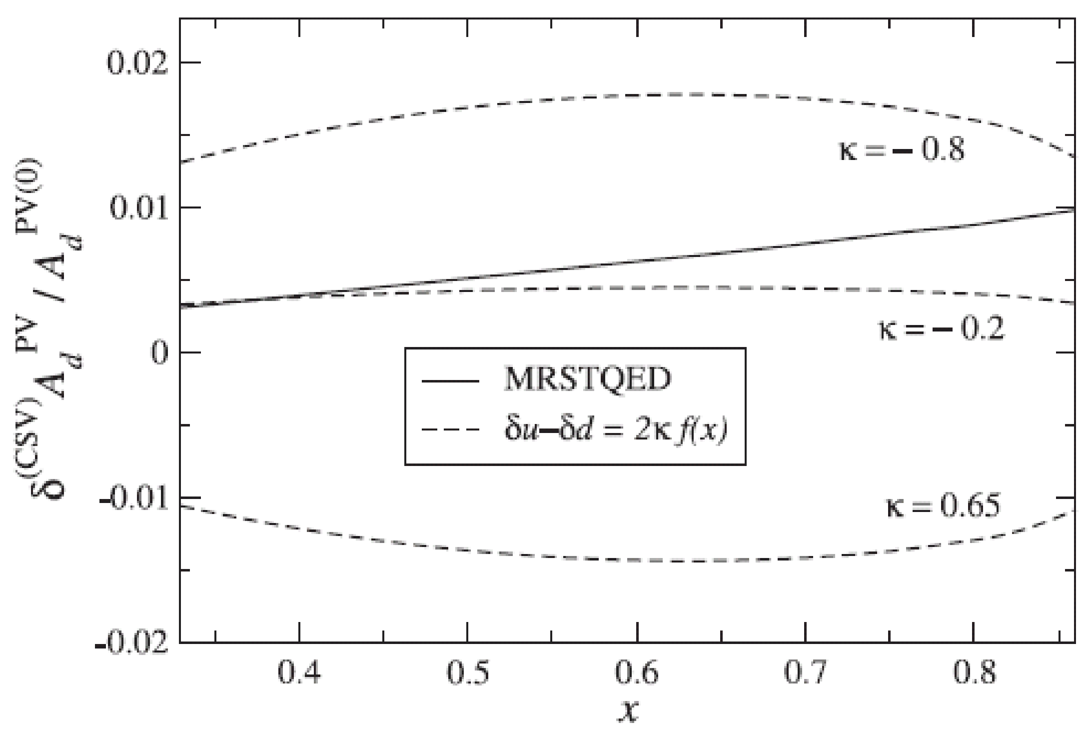


FIG. 8. Relative effects on the deuteron PV asymmetry A_d^{PV} of CSV in PDFs, compared with the charge symmetric asymmetry. The CSV distributions $\delta u - \delta d$ are from the MRSTQED fit [31] (solid curve) and from the parametrization $\delta u - \delta d = 2\kappa f(x)$ (dashed curve, see text), with $\kappa = -0.2$ (best fit), and the two 90% confidence levels, $\kappa = -0.8$ and $\kappa = +0.65$ [30].

T. Hobbs and W. Melnitchouk, Phys. Rev. D77, 114023 (2008)