Higher Twist in Parity-Violating Deep Inelastic Scattering

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Outline

1. e-D PVDIS, asymmetry and HT
2. Nucleon spin puzzle 101 and parton OAM
3. Twist-4 matrix element and its significance in the study of OAM
4. Summary

e-D PVDIS and left-right asymmetry

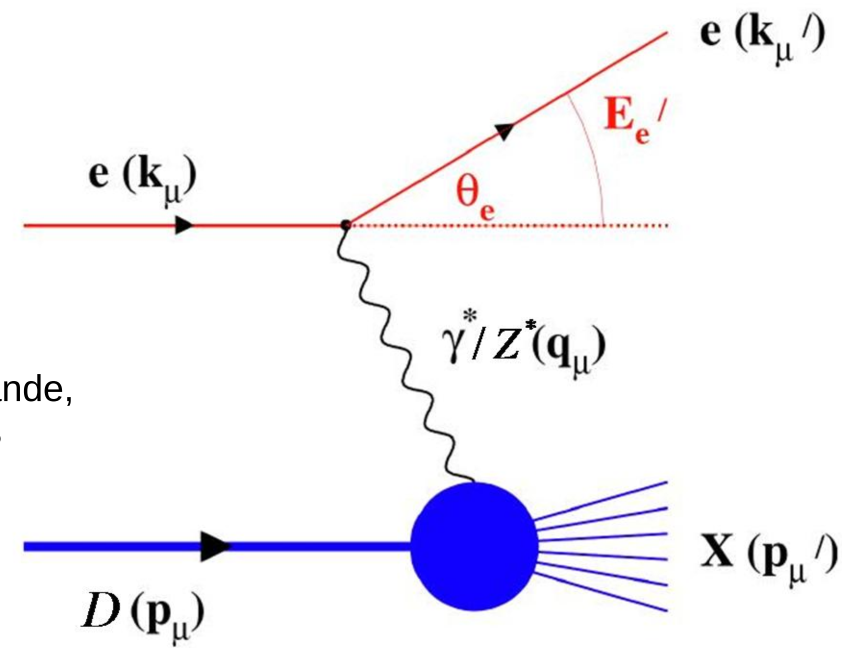


Image: A. Deshpande, NNPSS 2016

Polarized e, unpolarized D

Left-Right Asymmetry:

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

$$\text{Yale-SLAC collaboration (1978)}: \sin^2\theta_W = 0.20 \pm 0.03$$

C. Prescott et al, PLB77, 347 (1978); 85, 524 (1979)

e-D PVDIS and left-right asymmetry

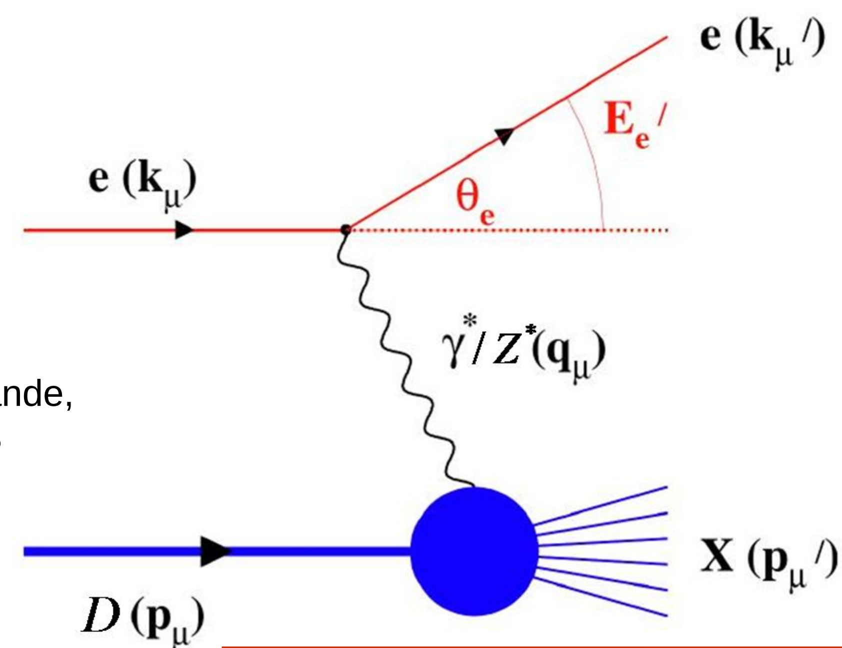


Image: A. Deshpande, NNPSS 2016

$$x_B = \frac{Q^2}{2P\cdot q} \quad \text{(Bjorken-x)}$$

$$y = \frac{E - E'}{E} \quad \text{(fractional energy lost)}$$

γ-Z interference term:

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

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

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

e-D PVDIS and left-right asymmetry

The Cahn-Gilman formula:

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

$$= -\frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\frac{3}{5}\{(\frac{3}{2}-\frac{10}{3}\sin^2\theta_W) + \frac{1-(1-y)^2}{1+(1-y)^2}(\frac{3}{2}-6\sin^2\theta_W)\}$$

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

- Assumptions:
  - Single boson exchange
  - Naïve parton model
  - Ignore sea quarks
  - Good isospin
  - (Implicit) zero target mass & quark mass
- PDF-dependence in the numerator and denominator cancel out (deutron is isosinglet)

e-D PVDIS as probe of new physics

General PV electron-quark interaction Lagrangian:

$$\mathcal{L}_{PV} = \frac{G_F}{\sqrt{2}} \sum_{i=u,d} [C_{1i} \bar{e} \gamma^{\mu} \gamma_5 e \bar{q}_i \gamma_{\mu} q_i + C_{2i} \bar{e} \gamma^{\mu} e \bar{q}_i \gamma_{\mu} \gamma_5 q_i]$$

Map to a general Left-Right Asymmetry:

$$A_{RL} = -\frac{G_F Q^2}{2\sqrt{2}\pi\alpha} \frac{3}{5} \{\tilde{a}_1 + \tilde{a}_2 \frac{1-(1-y)^2}{1+(1-y)^2}\}$$

With all the assumptions before, we have:

$$\tilde{a}_i = -(2C_{iu} - C_{id})$$

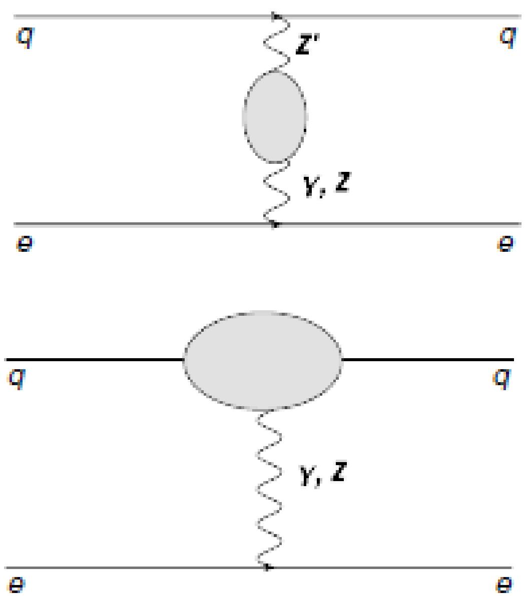
SM tree level: $\tilde{a}_{10} = \frac{3}{2} - \frac{10}{3}\sin^2\theta_W, \ \tilde{a}_{20} = \frac{3}{2} - 6\sin^2\theta_W,$

e-D PVDIS as probe of new physics

A_{RL} provides sensitive probes to BSM scenarios such as leptophobic Z' and SUSY.

M. Gonzalez-Alonso and M. J. Ramsey-Musolf, PRD, 87 (2013) 055013

A. Kurylov, M. J. Ramsey-Musolf and S. Su, PLB 582, (2004) 222



$$\delta C_{2d} \approx \frac{4}{9\pi^2} g'^2 s_W^2 c_W^2 \left(\frac{M_Z}{M_{Z'}}\right)^2 Q'^A_{dd} \times \left[63.24\, Q'^V_{uu} + Q'^V_{dd}\left(-42.66 + \log\frac{M_{Z'}}{M_Z}\right)\right]$$

$$\delta C_{2u} \approx \frac{-8}{9\pi^2} g'^2 s_W^2 c_W^2 \left(\frac{M_Z}{M_{Z'}}\right)^2 Q'^A_{uu} \times \left[Q'^V_{uu}\left(-26.92 + \log\frac{M_{Z'}}{M_Z}\right) + 23.63\, Q'^V_{dd}\right]$$

Leptophobic Z' correction to C_{2q}

e-D PVDIS as probe of new physics

- High-precision measurement of A_{RL} is made possible by the 12 GeV SoLID experiment at JLab (see Seamus's talk)

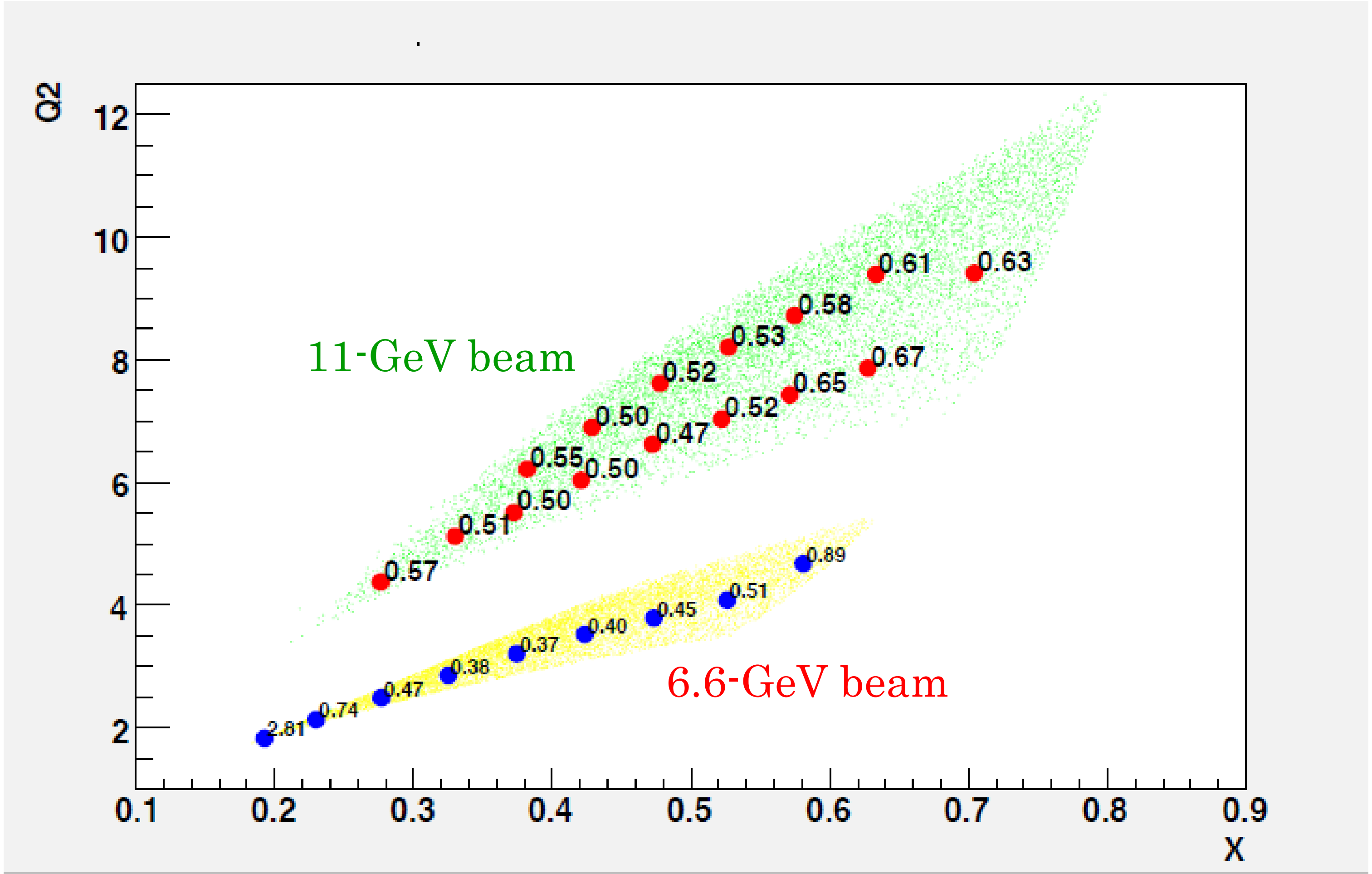


Image: SoLID White-Paper 2014

e-D PVDIS: Higher-Twist Corrections

$$\tilde{a}_i = \tilde{a}_{i0}(1 + R_i)$$

R_i includes the contribution from SM and BSM physics.

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

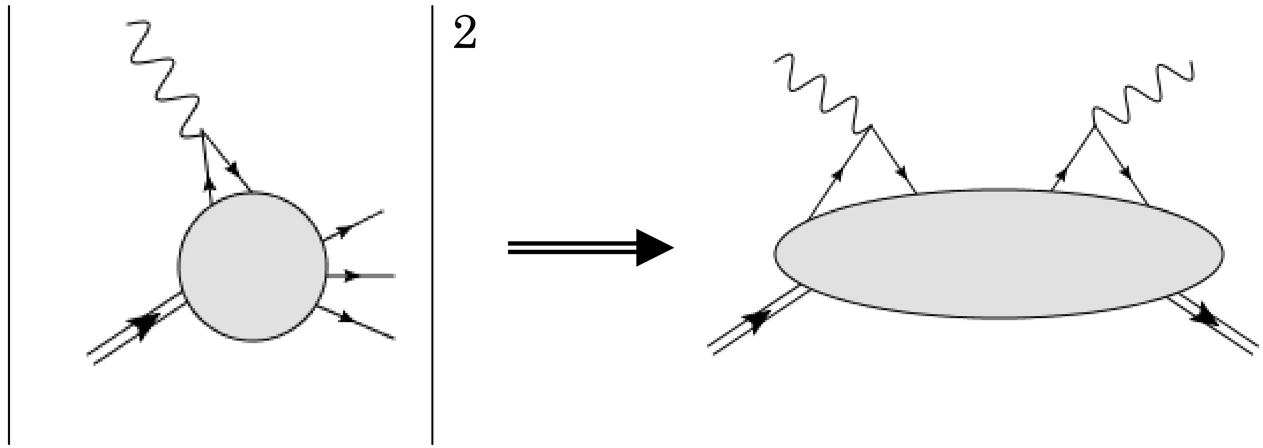
We have to make sure we understand all SM corrections to desired level of precision!

e-D PVDIS: Higher-Twist Corrections

Higher Twist correction: Corrections to naïve parton picture which scale as: $(Q^2)^{-(\tau-2)/2}$ τ :"Twist"

due to interactions between partons.

Structure of full hadronic tensor:

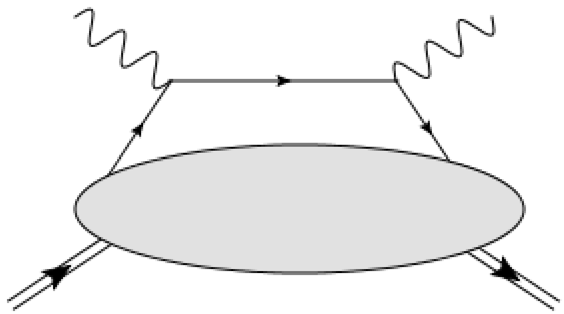


e-D PVDIS: Higher-Twist Corrections

Higher Twist correction: Corrections to naïve parton picture which scale as: $(Q^2)^{-(\tau-2)/2}$ τ : "Twist"

due to interactions between partons.

Leading twist/twist-2 (naïve parton model) structure:

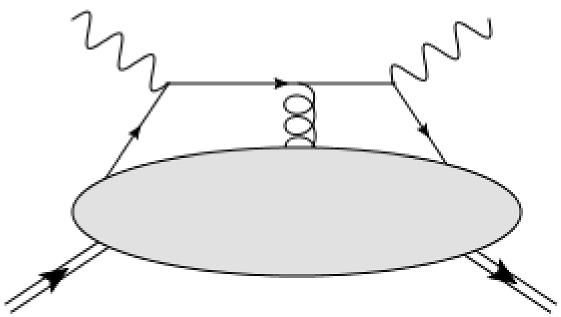


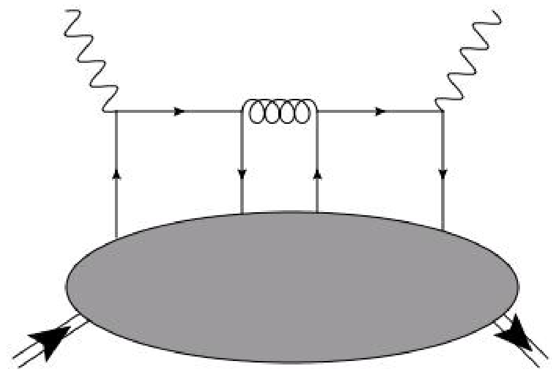
e-D PVDIS: Higher-Twist Corrections

Higher Twist correction: Corrections to naïve parton picture which scale as: $(Q^2)^{-(\tau-2)/2}$ τ :"Twist"

due to interactions between partons.

Examples of higher-twist structures:





e-D PVDIS: Higher-Twist Corrections

Higher Twist correction: Corrections to naïve parton picture which scale as: $(Q^2)^{-(\tau-2)/2}$ τ :"Twist"

due to interactions between partons.

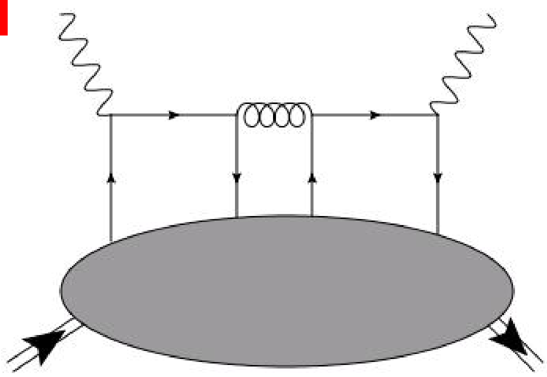
In e-D PVDIS, the **only** twist-4 contribution to R_1 is proportional to the following hadronic matrix element

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

J.D Bjorken, PRD 18, 3239 (1978);
L. Wolfenstein, Nucl. Phys. B 146 477 (1978)
S. Mantry et al, PRC 82, 065205 (2010)

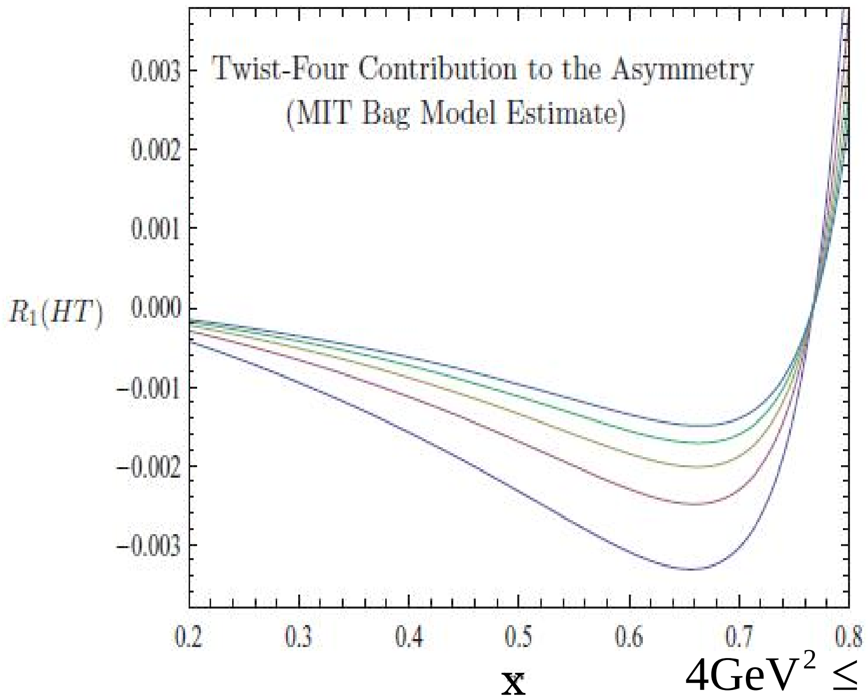
Assumptions:

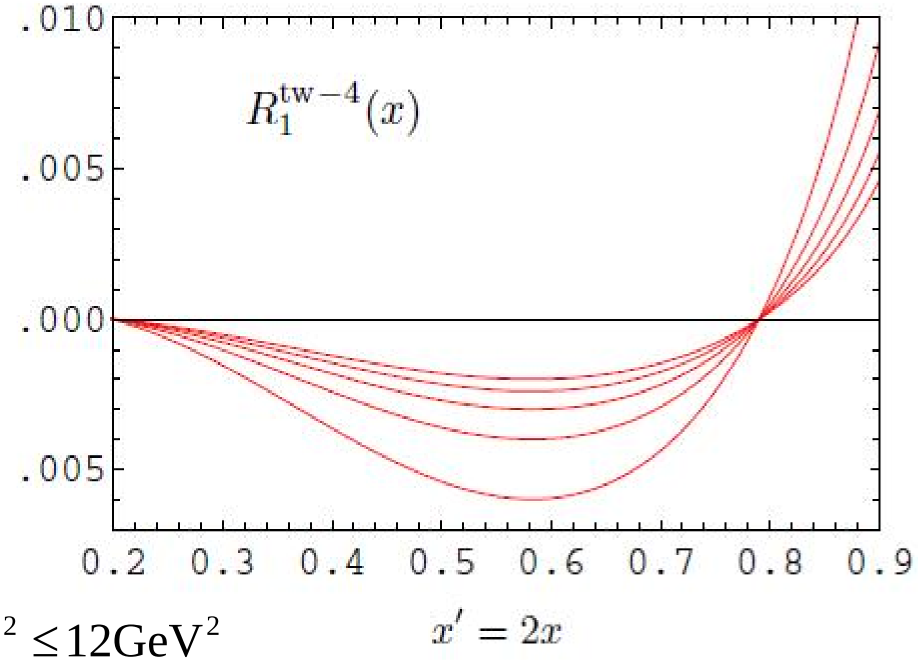
- Isospin symmetry
- neglect sea quark



e-D PVDIS: Higher-Twist Corrections

Previous works on twist-4 contribution to R1





$$4\text{GeV}^2 \leq Q^2 \leq 12\text{GeV}^2$$

Bag model

Isotropic light cone wavefunction

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

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

Nucleon Spin Puzzle 101 and Parton OAM

EMC experiment 1989: DIS between longitudinally polarized muon and proton.

Hadronic tensor:

$$W_{\mu\nu}(P,q) = \frac{1}{4\pi}\int d^4x e^{iq\cdot x}\langle p(P)|[J_\mu(0), J_\nu(0)]|p(P)\rangle$$

$$W_{[\mu\nu]} = -i\varepsilon_{\mu\nu\lambda\sigma}q^\lambda\{\frac{S^\sigma}{P\cdot q}(g_1 + g_2) - \frac{q\cdot SP^\sigma}{(P\cdot q)^2}g_2\}$$

Relation of g_1 to quark helicity:

$$g_1(x) = \frac{1}{2}\sum_i e_i^2 \Delta q_i(x)$$

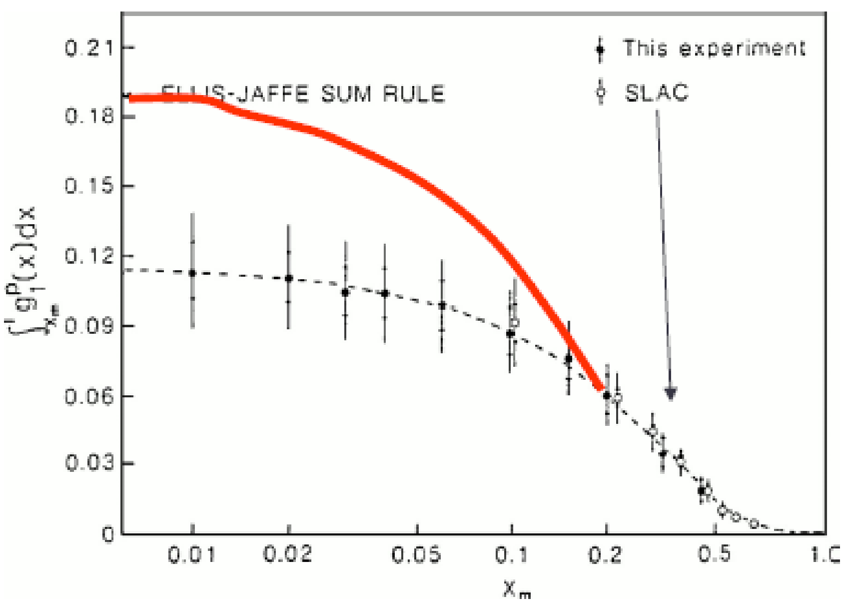
Nucleon Spin Puzzle 101 and Parton OAM

Ellis-Jaffe's Sum Rule: $$\int_0^1 dx g_1^p(x) = 0.189 \pm 0.005$$

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

Assumptions:

- Flavor SU(3) symmetry
- No net sea quark helicity



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

Nucleon Spin Puzzle 101 and Parton OAM

Ellis-Jaffe's Sum Rule: $$\int_0^1 dx g_1^p(x) = 0.189 \pm 0.005$$

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

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_Q + L_G$$

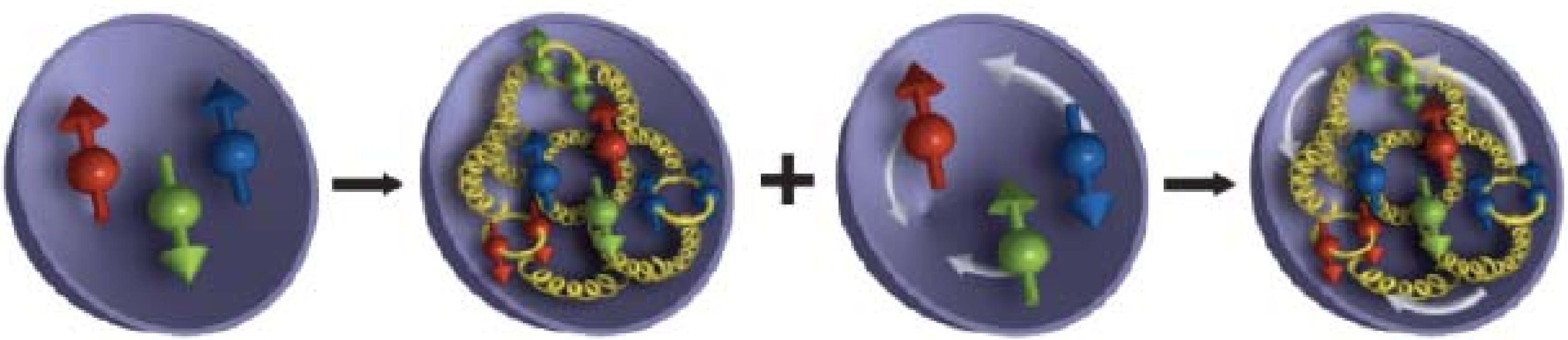
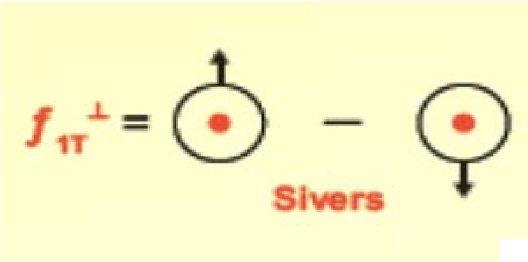


Image: A. Deshpande, NNPSS 2016

Nucleon Spin Puzzle 101 and Parton OAM

Information about parton OAM is partially encoded in the **transverse-momentum-dependent (TMD)** distribution functions

Sivers function



Boer-Mulders function

Image: JW Qiu, NNPSS 2016

Measurable in **Semi-Inclusive Deep Inelastic Scattering (SIDIS)** with unpolarized/ transversely-polarized targets.

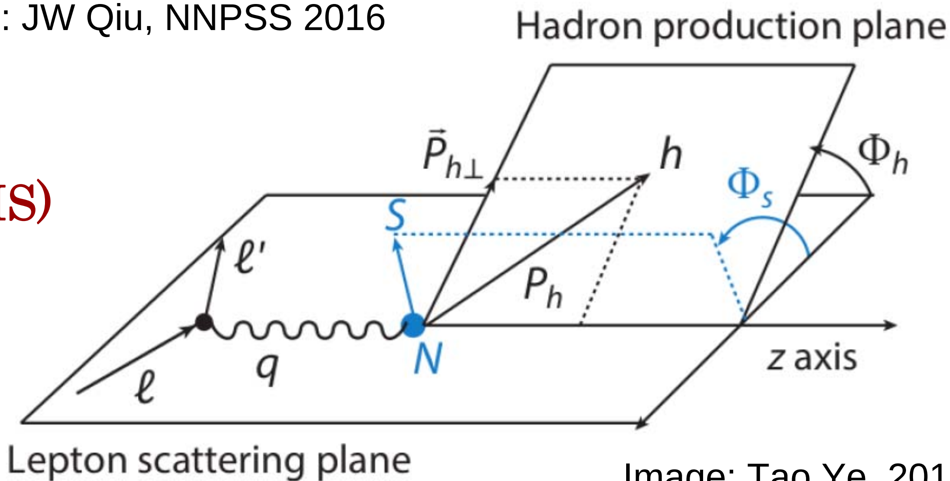


Image: Tao Ye, 2015

Study of OAM Effects in Twist-Four Matrix Elements

CYS and Michael J. Ramsey-Musolf, PRC 88, 015202 (2013)

- **Model**: OAM-dependent light-cone wavefunction, truncated at three-valence-quarks level
- Nucleon wavefunction decomposed into **states of definite L_z** of the valence quarks under light-cone gauge

$$|P,\uparrow\rangle = |h=\frac{1}{2}, l_z = 0\rangle + |h=-\frac{1}{2}, l_z = 1\rangle$$
$$+|h=\frac{3}{2}, l_z = -1\rangle + |h=-\frac{3}{2}, l_z = 2\rangle$$

- Finite-OAM wavefunction can be obtained from a constituent quark model

  B. Pasquini et al, PRD 78, 034025 (2008)

- From nucleon to deuteron: **Incoherent impulse approximation** assumed

Study of OAM Effects in Twist-Four Matrix Elements

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. $< l_z \,|\ldots|\, l_z>$ (same l_z for initial and final states) will contribute.

Study of OAM Effects in Twist-Four Matrix Elements

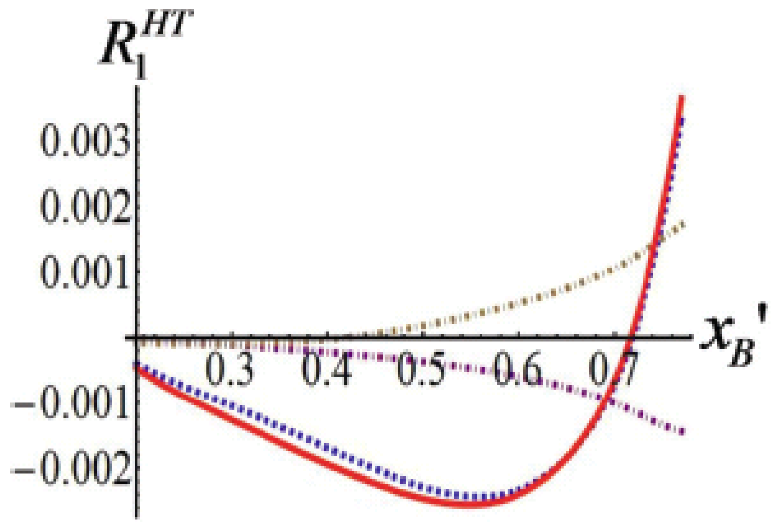
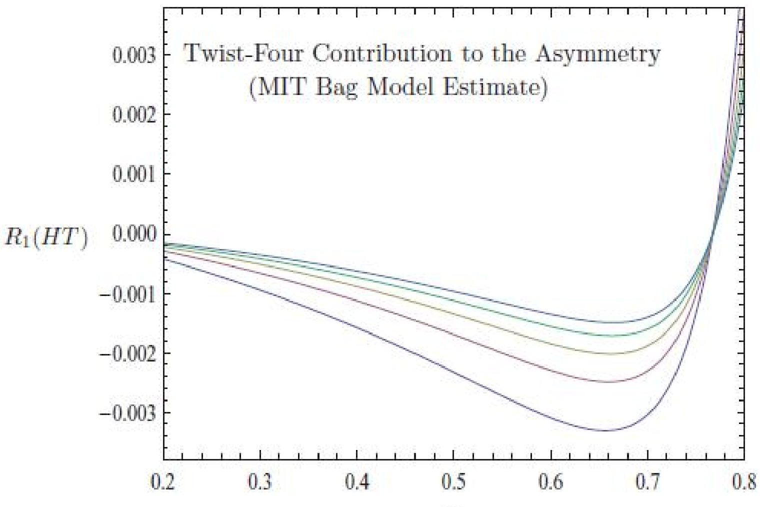
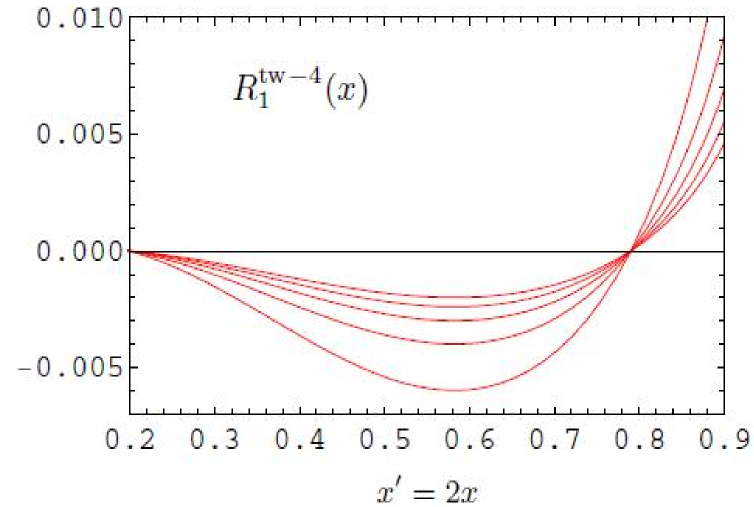


FIG. 3. (Color online) The twist-four correction to R_1 at $Q^2 = 4\ \mathrm{GeV}^2$. The blue dashed curve shows the $l_z = 0$ contribution; purple dot-dashed curve shows the $l_z = 1$ contribution; brown dot-dashed curve shows the $l_z = -1$ contribution; the red solid curve is the sum of all. $l_z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

Study of OAM Effects in Twist-Four Matrix Elements

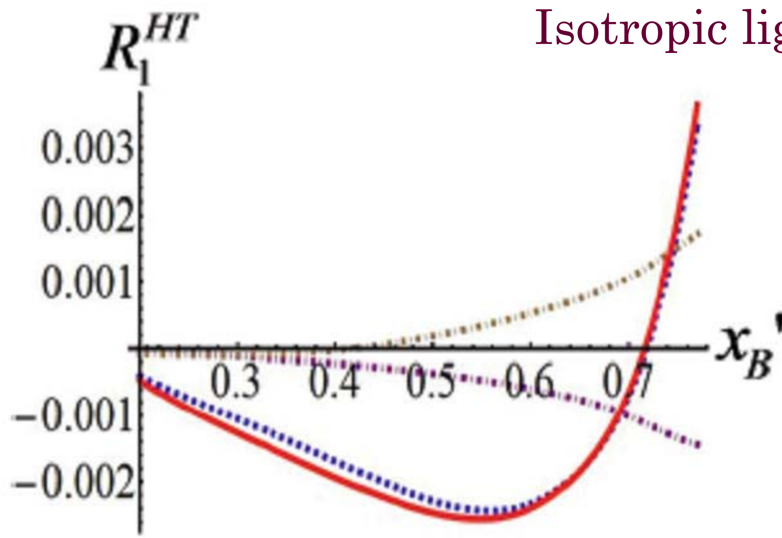


Bag model



Isotropic light cone wavefunction

This work



Region of significance: $Q^2 \leqslant 3\mathrm{GeV}^2$ at $x_B \sim 0.5$-0.7

Study of OAM Effects in Twist-Four Matrix Elements

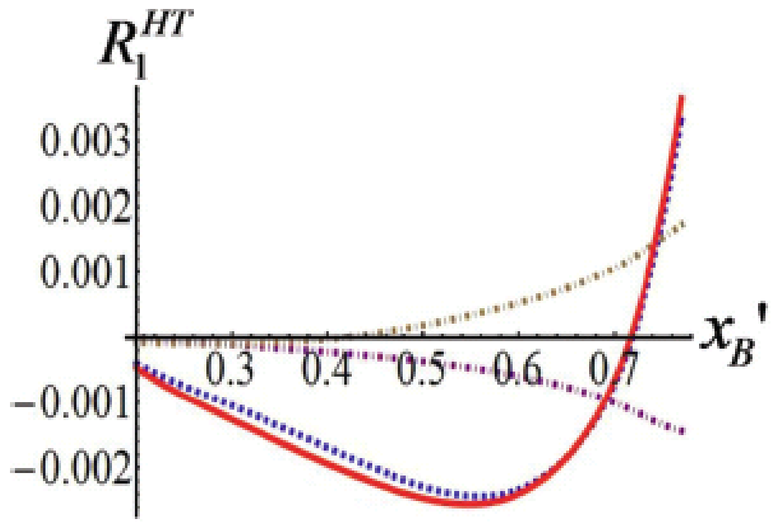
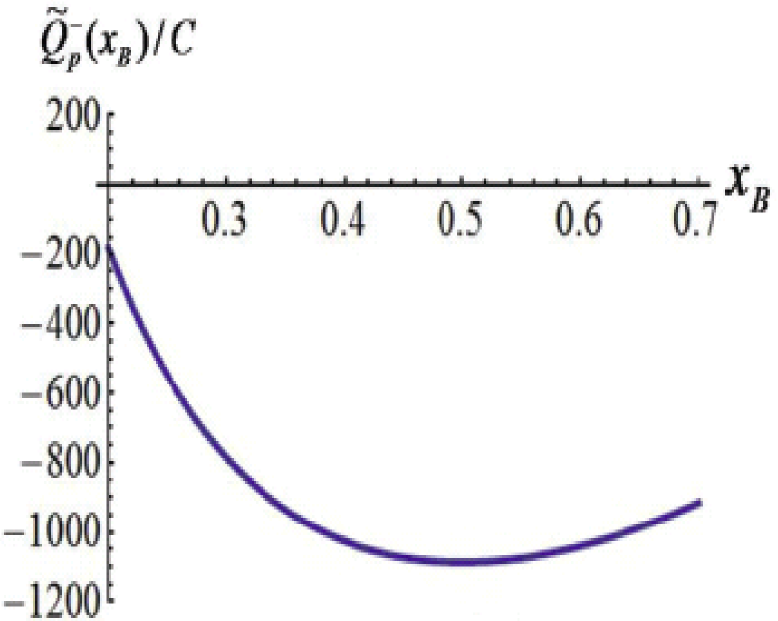


FIG. 3. (Color online) The twist-four correction to R_1 at $Q^2 = 4\ \text{GeV}^2$. The blue dashed curve shows the $l_z = 0$ contribution; purple dot-dashed curve shows the $l_z = 1$ contribution; brown dot-dashed curve shows the $l_z = -1$ contribution; the red solid curve is the sum of all. $l_z =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

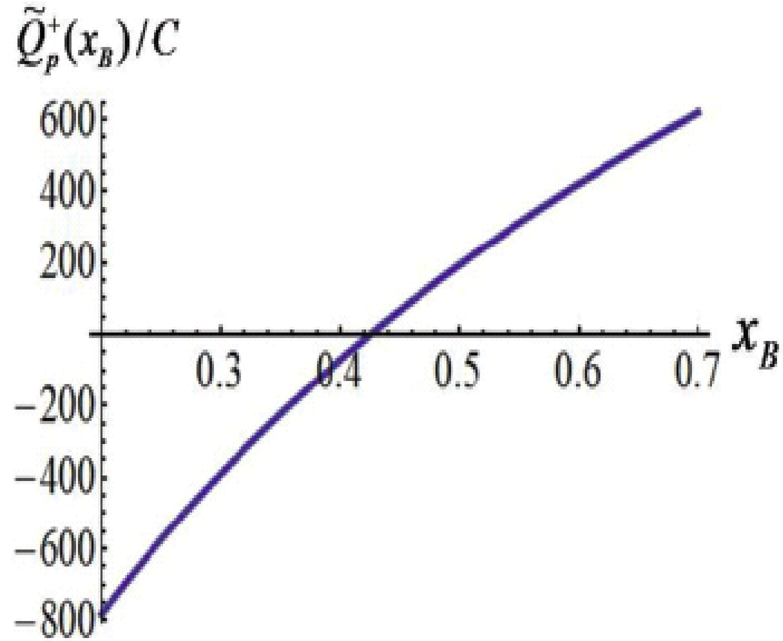
Only one component of quark OAM contributes significantly as the others largely cancel out!

Study of OAM Effects in Twist-Four Matrix Elements

True physics or model artifact?



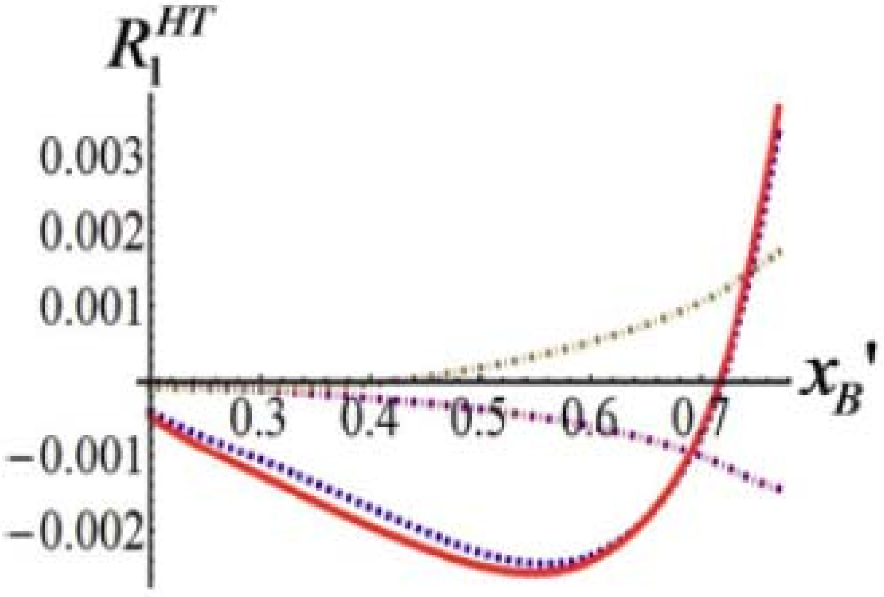
$L_z = 1$



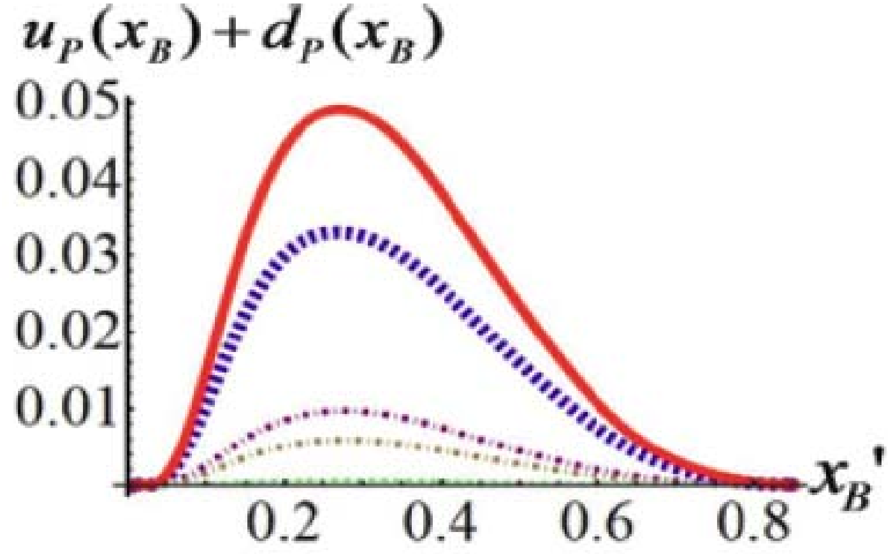
$L_z = -1$

Study of OAM Effects in Twist-Four Matrix Elements

Uniqueness of the cancelation: Contrast with PDF



Twist-4



PDF (arbitrary normalization)

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

Study of OAM Effects in Twist-Four Matrix Elements

- 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	(0×0), $(1\otimes1)$	$(2\otimes2)$
PVDIS twist-four correction	$(0\otimes0)$	$(1\otimes1)$, $(2\otimes2)$
Sivers function	$(0\otimes1)$	$(1\otimes2)$
Boer-Mulders function	$(0\otimes1)$, $(1\otimes2)$	–

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

Summary

1. e-D PVDIS serves as a sensitive probe of both BSM physics and hadron/nuclear structure.
2. Effect of twist-4 matrix element on R_1 is expected to comes in when $Q^2 \leqslant 3 GeV^2$ in region $x_B \sim 0.5$-0.7. Far outside this region, the SM corrections that enter JLab e-D PVDIS result are unlikely to include twist-4
3. The study of higher twist comes with a bonus of helping us to understand the role of parton angular momentum in nucleon structure.

Thank You!

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 (the normal identification that x=momentum fracton only holds in the M→0 limit (or equivalently Q^2→infinity limit). Also scales as $1/Q^2$. Should be distinguishable from HT by looking at the x-dependence.
- 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):

$$\delta u(x) = u^p(x) - d^n(x)$$ A leading-twist effect

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

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

Effect estimated using phenomenological parametrizations or non-perturbative calculations

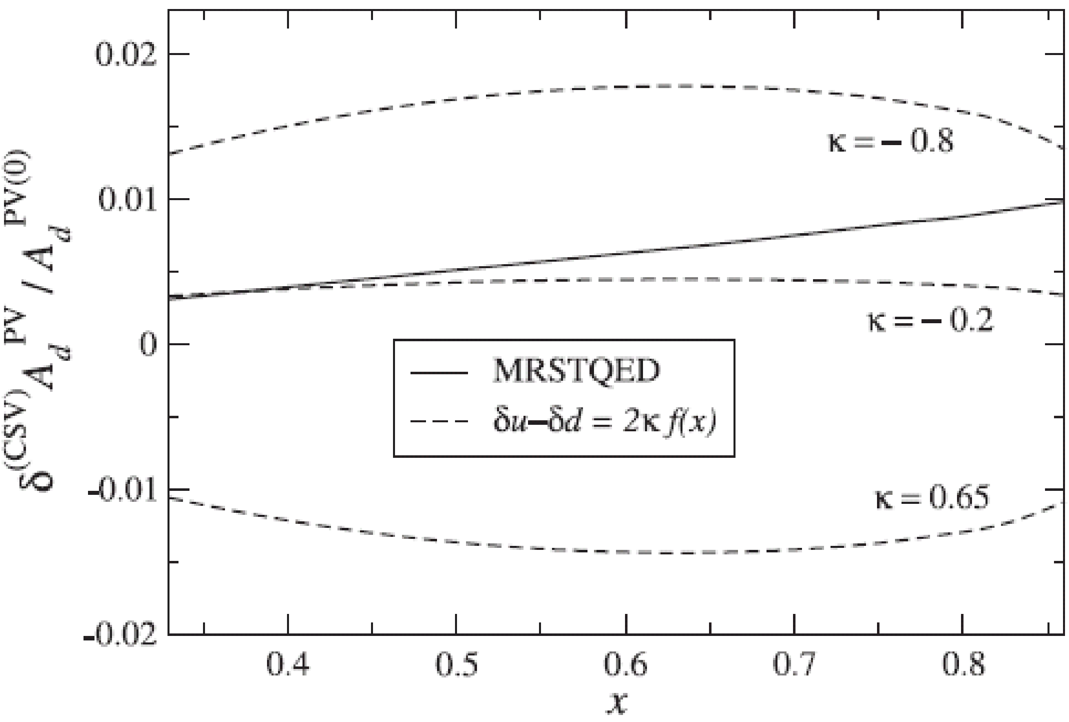


FIG. 8. Relative effects on the deuteron PV asymmetry A_d^{PV} of CSV in PDFs, compared with the charge symmetric asymmetry. The CSV distributions $\delta u - \delta d$ are from the MRSTQED fit [31] (solid curve) and from the parametrization $\delta u - \delta d = 2\kappa f(x)$ (dashed curve, see text),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

Spin-dependent structure function g_1 and the Ellis-Jaffe Sum rule:

$$g_1^p(x) = \frac{1}{4\pi}\int_{-\infty}^{\infty} d(p\cdot y) e^{ixp\cdot y}[\frac{1}{6}S_3^5(p\cdot y) + \frac{1}{6\sqrt{3}}S_8^5(p\cdot y) + \sqrt{\frac{2}{27}}S_0^5(p\cdot y)]$$

Relevant matrix elements:

$$\left\langle p(P)\middle| S_{a\mu}^5(0,0) \middle| p(P)\right\rangle = \left\langle p(P)\middle| \overline{Q}\frac{\lambda_a}{2}\gamma_\mu\gamma_5 Q \middle| p(P)\right\rangle + \ldots$$

- a=3,8: Evaluated based on flavor SU(3) symmetry. Expressed in terms of baryon-meson coupling strengths D and F.
- a=0: ???

Spin-dependent structure function g_1 and the Ellis-Jaffe Sum rule:

$$g_1^p(x) = \frac{1}{4\pi}\int_{-\infty}^{\infty} d(p\cdot y)e^{ixp\cdot y}[\frac{1}{6}S_3^5(p\cdot y) + \frac{1}{6\sqrt{3}}S_8^5(p\cdot y) + \sqrt{\frac{2}{27}}S_0^5(p\cdot y)]$$

Relevant matrix elements:

$$\left\langle p(P)\middle| S_{a\mu}^5(0,0)\middle| p(P)\right\rangle = \left\langle p(P)\middle| \overline{Q}\frac{\lambda_a}{2}\gamma_\mu\gamma_5 Q\middle| p(P)\right\rangle + \ldots$$

- Ellis-Jaffe's assumption: **the net helicity of sea quarks is zero.**
- With this,

$$\left\langle p(P)\middle| S_{0\mu}^5(0,0)\middle| p(P)\right\rangle = \sqrt{2}\left\langle p(P)\middle| S_{0\mu}^5(0,0)\middle| p(P)\right\rangle$$

Ellis-Jaffe sum rule:

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

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

Experimental result:

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