Higher Twist and Parton Angular Momentum in Parity-Violating Deep Inelastic Electron-Deuteron Scattering

Chien Yeah Seng

Amherst Center for Fundamental Interactions

University of Massachussetts Amherst

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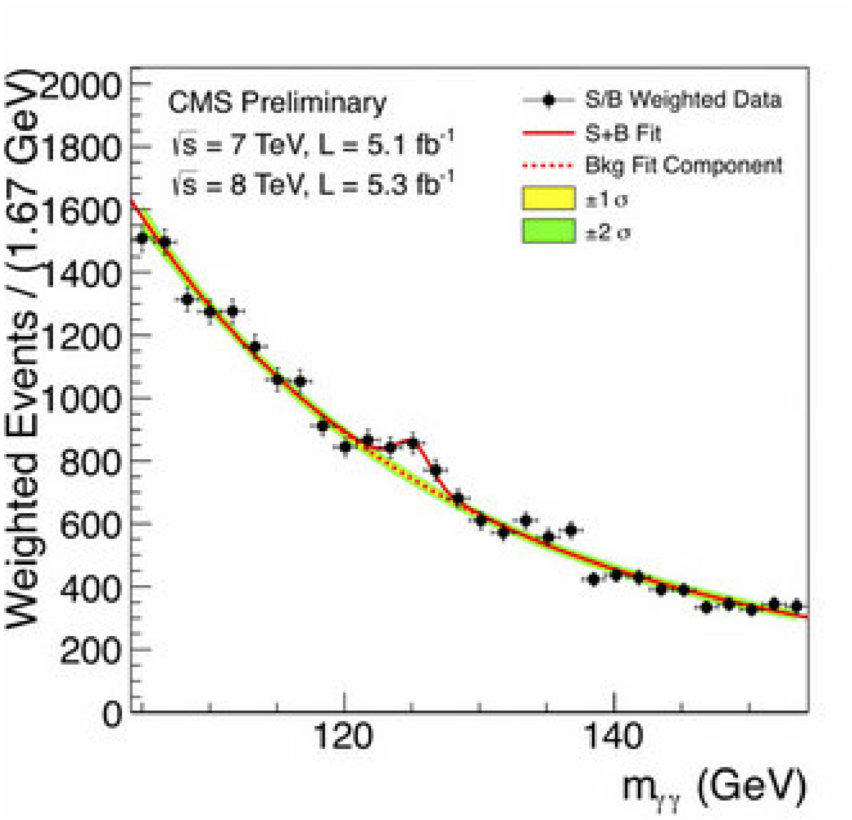
Outline:

1. Brief review on e-D PVDIS and higher-twist correction
2. Brief review on nuclear spin problem
3. Main results of our work
4. Summary

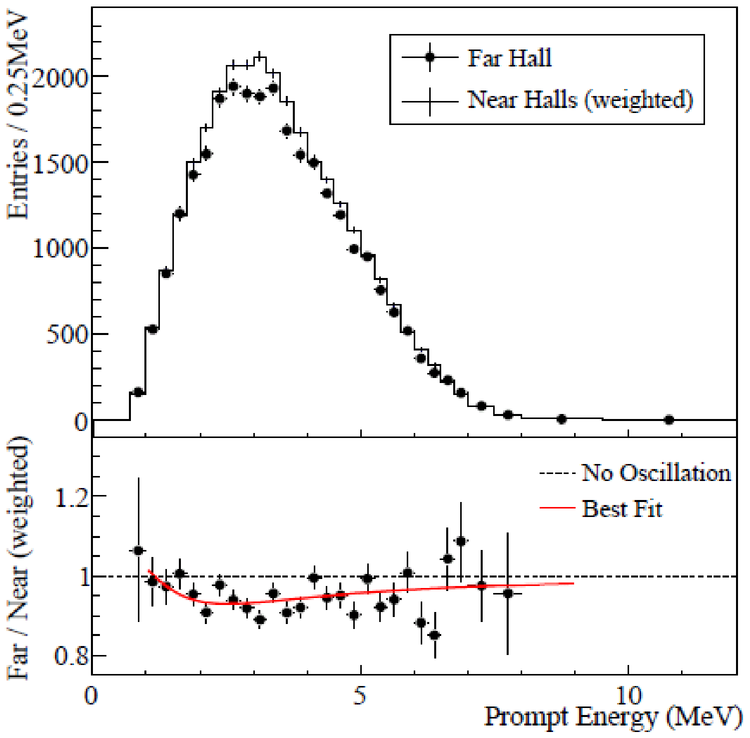
1. Brief review on e-D PVDIS and higher-twist correction

The precision frontier

- Precision frontier as an effective probe of BSM physics, compliment to the energy frontier
- Energy frontier searches for “bumps”, while precision frontier searches for “deviations”

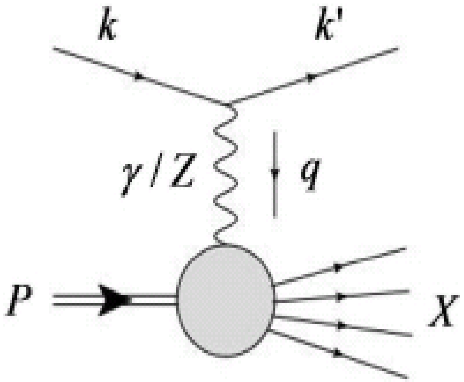


Discovery of higgs at CERN



Daya Bay measurement of ϑ_{13} : hep-ex1210.6327

e-D PVDIS:



Polarized electron, unpolarized target

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

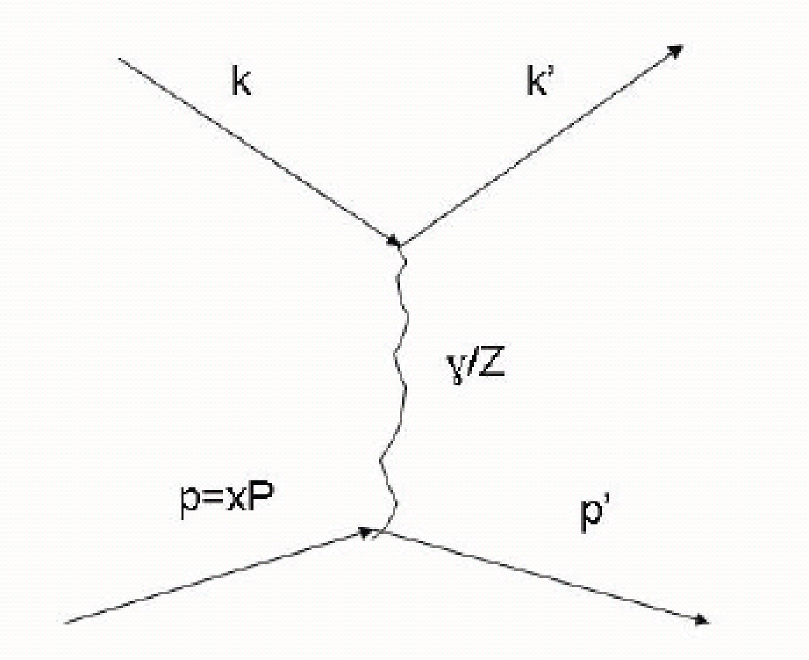
$$L^{\mu\nu} \sim \bar{u}_{s'}(k')\gamma^{\mu}u_{s}(k)\bar{u}_{s}(k)\gamma^{\nu}(g_V^e + g_A^e\gamma_5)u_{s'}(k')$$

$$W^{\gamma Z}_{\mu\nu} = (-g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2})\frac{F_1^{\gamma Z}}{M_D} + (P_\mu - \frac{P\cdot q}{q^2}q_\mu)(P_\nu - \frac{P\cdot q}{q^2}q_\nu)\frac{F_2^{\gamma Z}}{M_D P\cdot q}$$

$$+\frac{i\varepsilon_{\mu\nu\alpha\beta}P^{\alpha}q^{\beta}}{2M_D P\cdot q}F_3^{\gamma Z}$$

Cahn-Gilman formula for Left-Right Asymmetry

$$y = \frac{E - E'}{E}$$ (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 good symmetry.

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

The PDF-dependence drops out!

Cahn-Gilman Formula:

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

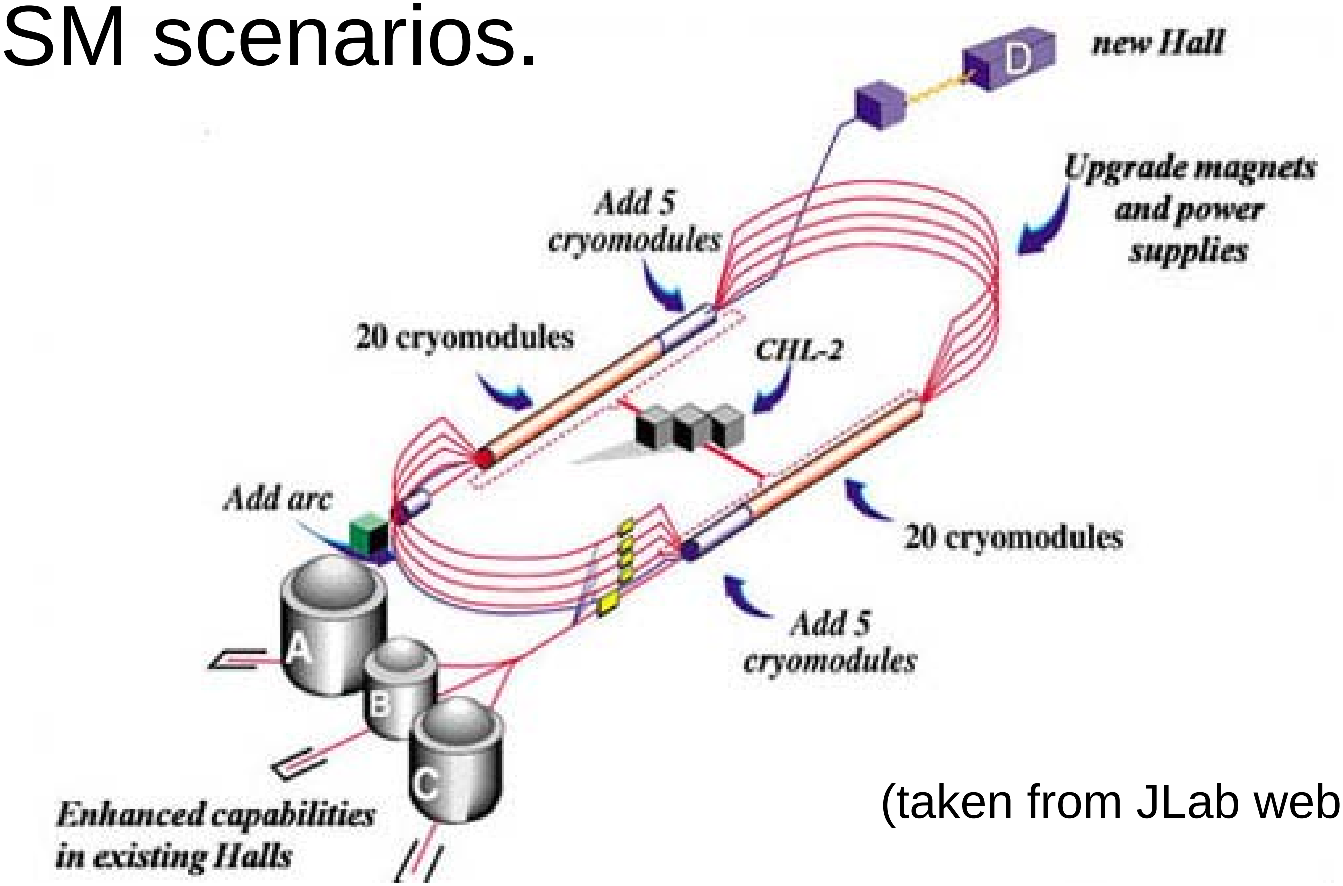
$$\tilde{a}_{1,0}=(1-\frac{20}{9}\sin^2\theta_W)$$

For SM at leading-twist

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

- First PVDIS experiment: Yale-SLAC collaboration (Prescott et. Al), year 1978
- Used to measure 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.



(taken from JLab website)

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

Besides effects of new physics, R_i includes:

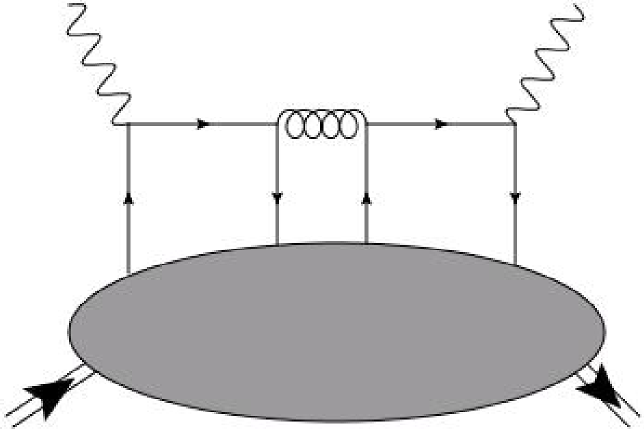
Radiative Correction
Charge Symmetry Violation (CVC) : isospin breaking of PDF
Target Mass Correction : finite hadron and quark masses
Sea Quark Effect
Higher Twist

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.

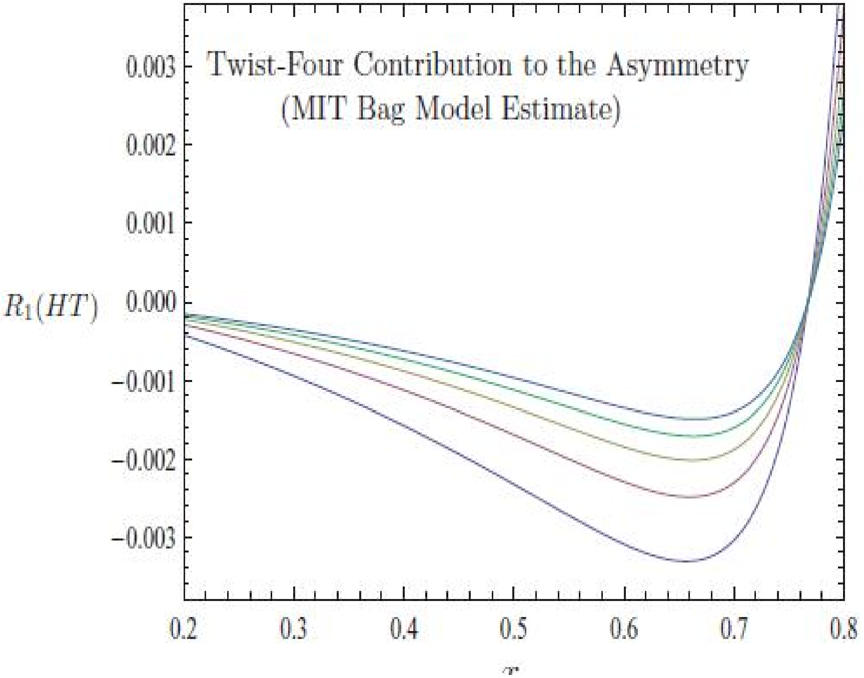
In e-D PVDIS, assuming isospin symmetry and neglecting sea quarks, the only twist-4 correction term to ã$_1$ is proportional to the following hadronic matrix element (first discovered by Bjorken and Wolfenstein):

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

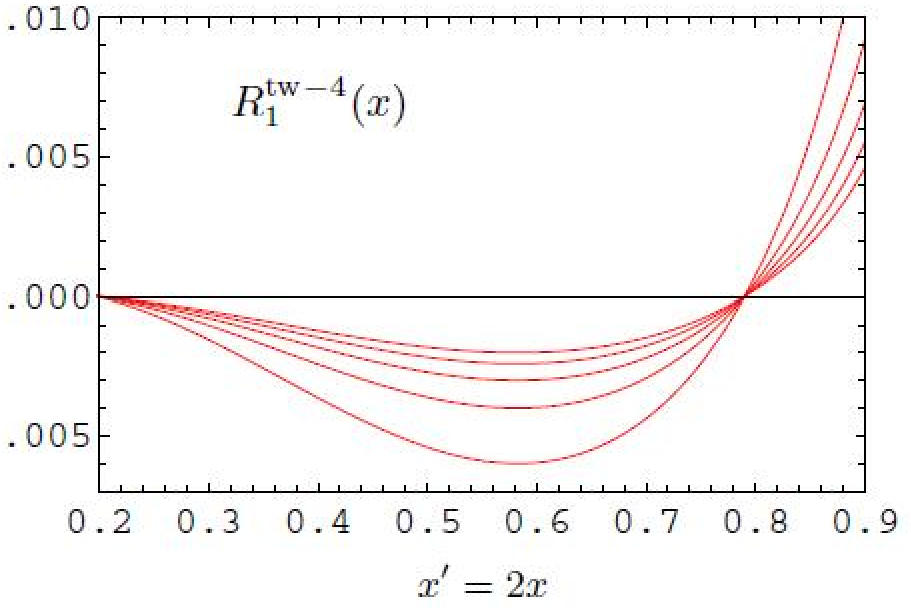


Previous works on twist-4 contribution to R_1

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



x



Bag model

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

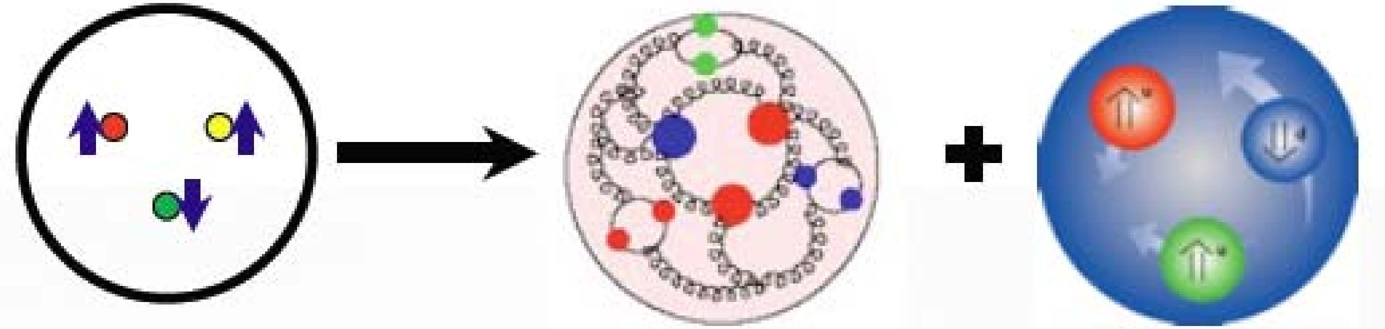
Isotropic light cone wavefunction

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

- Both works give similar R_1 curve shape, but slightly different peak position and size (range from -0.003~-0.005) reflecting the current theoretical uncertainty.
- Both works indicating that the twist-4 contribution to R_1 is right below the reach of the upgraded JLab precision (which measures R_1 at the accuracy of ±0.005)

2. Brief review on nuclear spin problem

- Spin structure of nucleon has been a long-lasting problem since EMC's DIS result with polarized muon beams, which contradicted the Ellis-Jaffe sum rule, implying that the spin of a proton is not built up entirely from the quark spin (the "Spin Crisis")
- A key question is now to explain the source of nucleon spin in terms of QCD DOF.
- Further complication arises as the classification of different components of nucleon spin (e.g. parton helicity and OAM), is gauge-dependent. See e.g. R. L. Jaffe and A. Manohar, Nucl. Phys. B337, 509 and X. Ji, Phys. Rev. Lett. 78, 610.



- 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:

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

(See 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. Main results of our work

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

Caution: “Quark OAM” we mention here is after assuming light-cone gauge

- Model we use: 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

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

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

- 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:

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

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

The functions $\{\psi^{(1)},\ldots,\psi^{(6)}\}$ are obtained from constituent quark model.

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

Our main result after performing numerical integration:

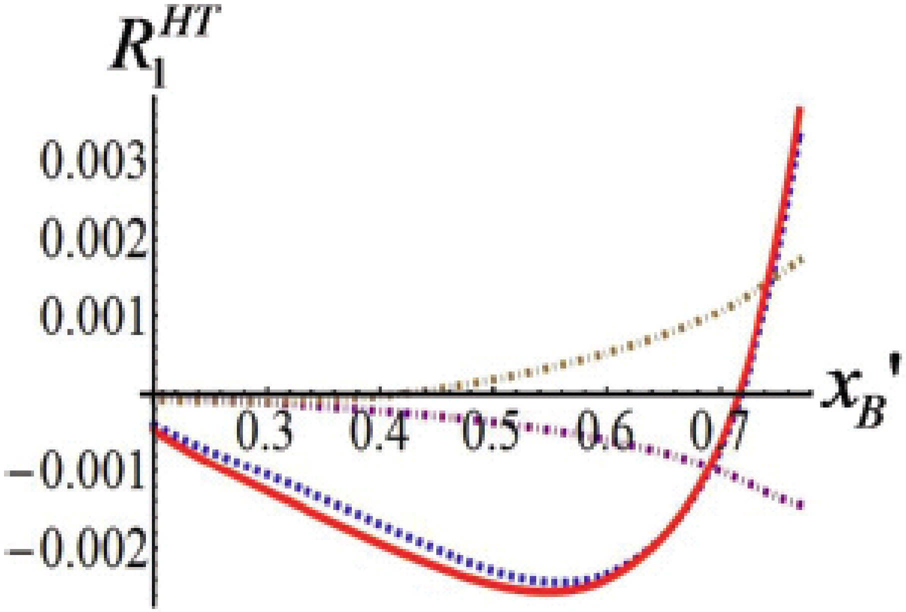
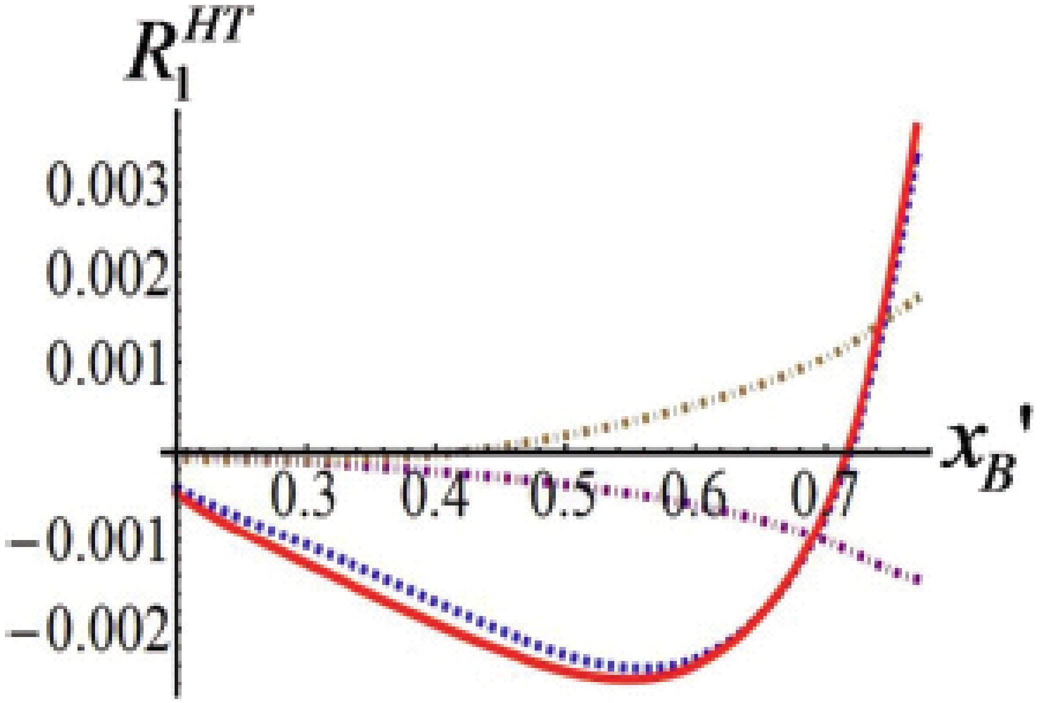
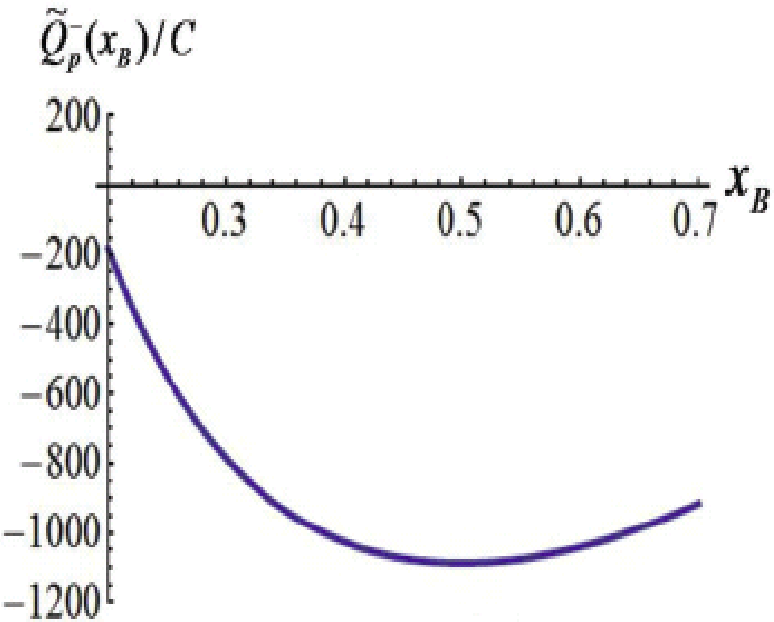


FIG. 3. (Color online) The twist-four correction to R_1 at $Q^2 = 4\ \mathrm{GeV}^2$. The blue dashed curve shows the $l_z = 0$ contribution; purple dot-dashed curve shows the $l_z = 1$ contribution; brown dot-dashed curve shows the $l_z = -1$ contribution; the red solid curve is the sum of all. $l_z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

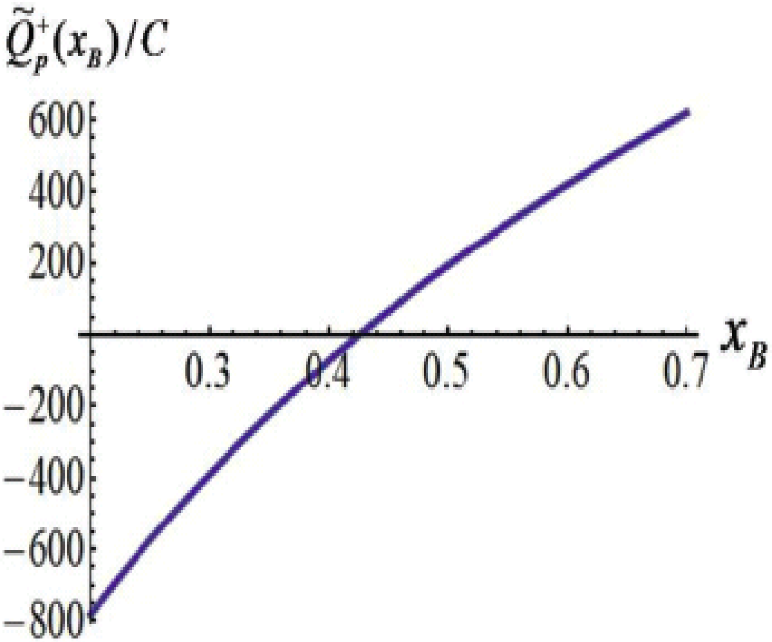
- Similar curve shape with existing results, all suggesting that R_1(HT) is beyond the reach of upgraded JLab accuracy.
- Non-intuitive observation: partial cancelation between $L_z=\pm l$ contribution, leaving $L_z=0$ piece dominant.



- This cancelation is rather model-independent!



$$L_z = 1$$



$$L_z = -1$$

- Similar property not shared by other DIS observables, e.g. Quark Distribution Function:

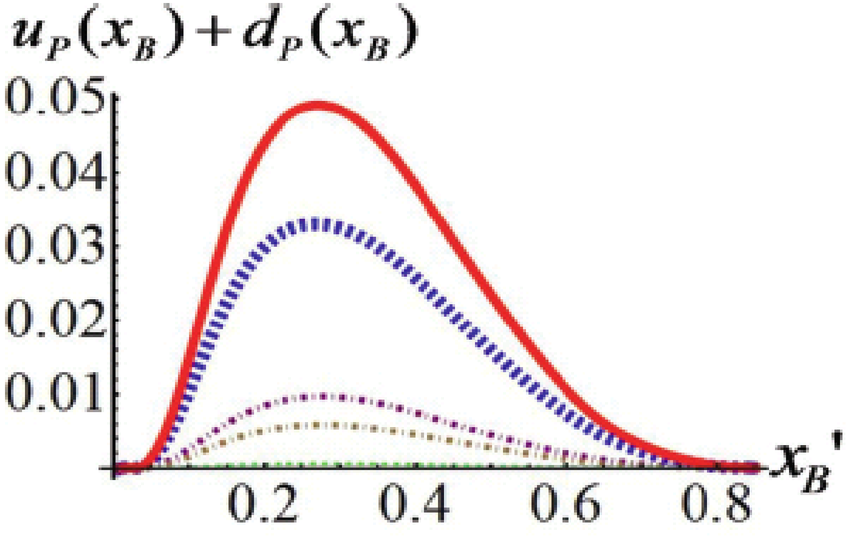


FIG. 4. (Color online) The unnormalized QDF of spin-up proton, split into contributions from different l_z components. Blue thick-dashed curve shows contribution from $l_z = 0$ component; purple dot-dashed curve shows contribution from $l_z = 1$ component; brown dot-dashed curve shows contribution from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

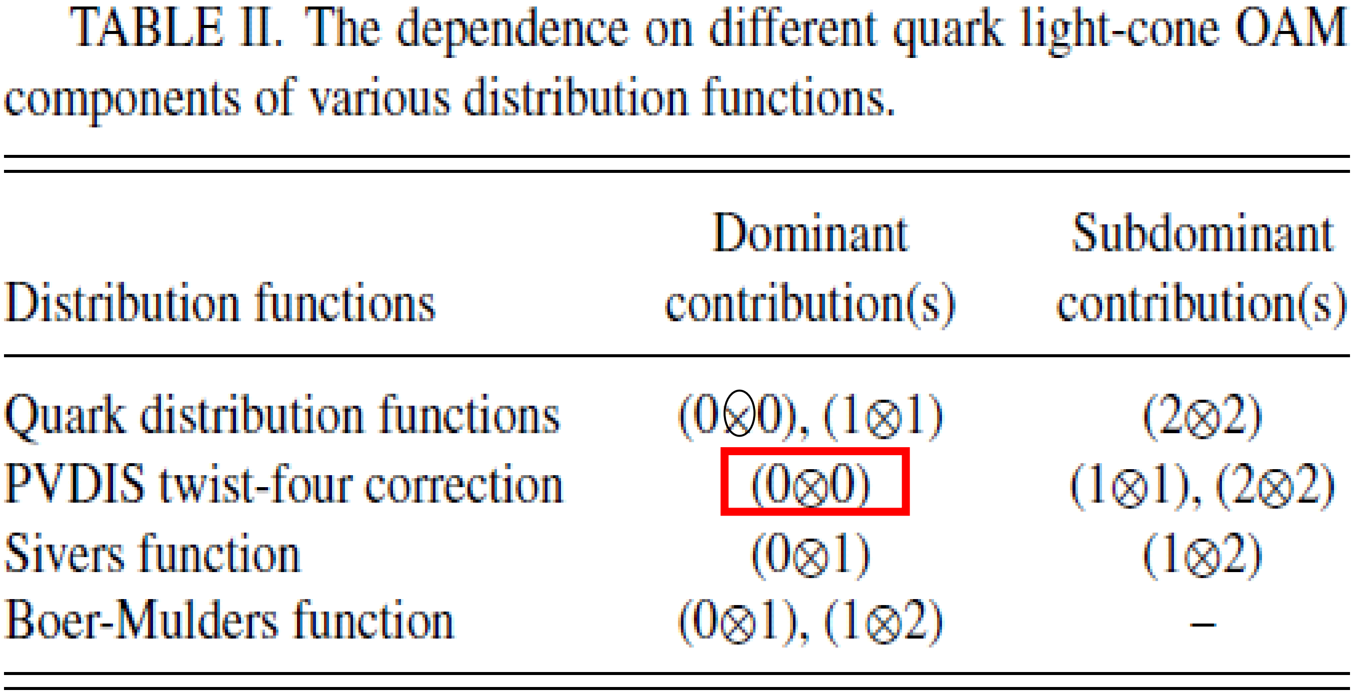


TABLE II. The dependence on different quark light-cone OAM components of various distribution functions.

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

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

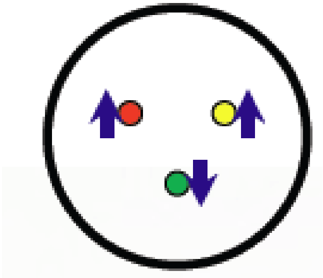
4. Summary

1. e-D PVDIS probes not only BSM physics, but also novel features of hadron and nuclear structure.
2. Various calculations show that the precision needed for the study of twist-four contribution to R_1 is beyond the reach of the 12GeV-upgrade of JLab.
3. Simplification of the interpretation: SM corrections that enter JLab e-D PVDIS result will not include twist-4, unless the existing models are completely wrong.
4. Future effort of increasing experimental precision level is worthwhile, because as shown in our work, it comes with a bonus of helping us in understanding the role of parton angular momentum in nucleon structrure.

Backup Slides

From isotropic to non-isotropic wavefunction

- start from isotropic constituent-quark model



- use Melosh rotation to change “instant-form” wavefunction to “light-front” form:

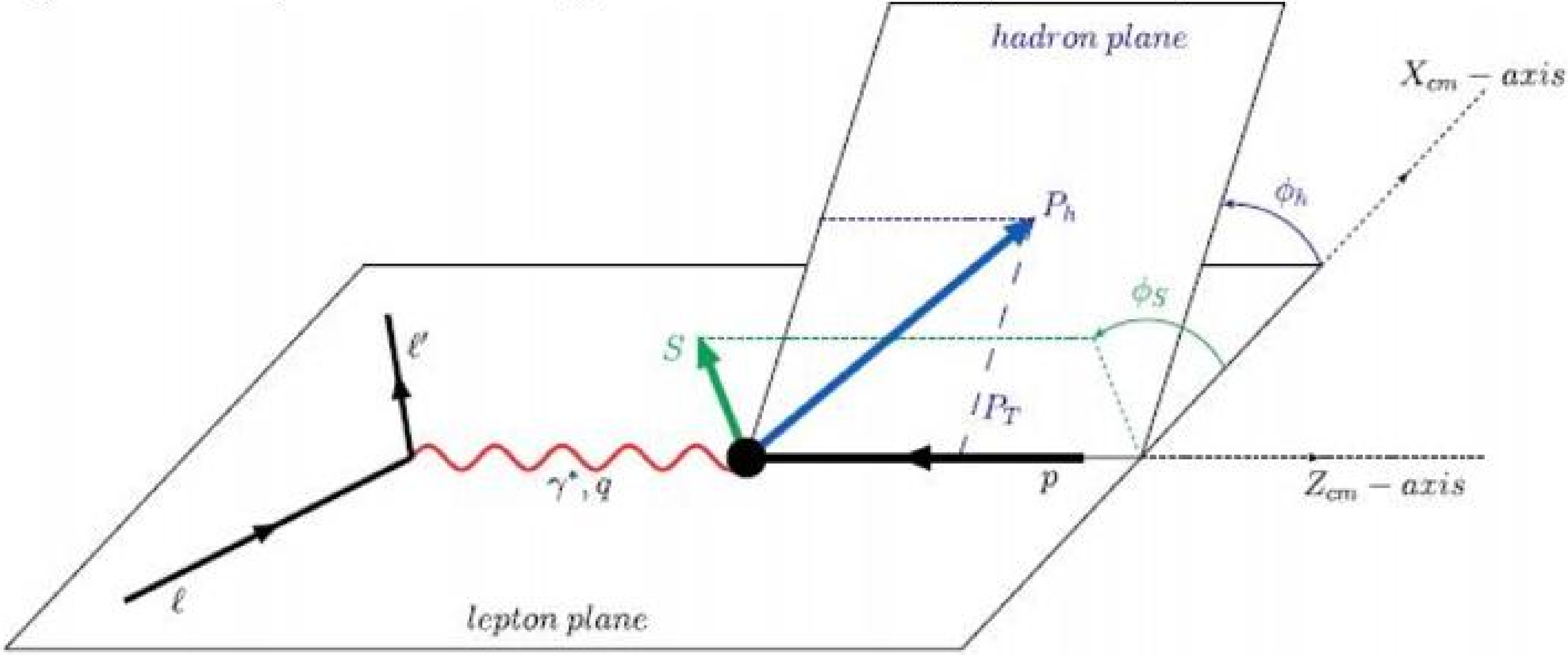
$$|\tilde{\vec{k}}, \lambda, \tau\rangle_{[f]} = \sqrt{2\omega}\,(2\pi)^{3/2} \sum_{\lambda'} D^{1/2}_{\lambda'\lambda}(R_{cf}(\tilde{\vec{k}}))\,|\vec{k}, \lambda', \tau\rangle_{[c]}.$$

$$\tilde{\vec{k}} = (k^{+}, \vec{k}_{\perp}) \qquad \vec{k} = (k_x, k_y, k_z)$$

- non-zero OAM components emerges naturally during the rotation

$$A_{UT}^{\sin(\phi_h-\phi_S)} = 2\frac{\int d\phi_h d\phi_S[d\sigma^{lp^{\uparrow}\to l'hX} - d\sigma^{lp^{\downarrow}\to l'hX}]\sin(\phi_h-\phi_S)}{\int d\phi_h d\phi_S[d\sigma^{lp^{\uparrow}\to l'hX} + d\sigma^{lp^{\downarrow}\to l'hX}]}$$

UT: Unpolarized leptons scattering with Transversely-polarized protons.



M. Anselmino et al, Phys. Rev. D 83, 114019 (2011)

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)