Contribution of quark-mass-dependent operators to higher twist effects in deep-inelastic scattering

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We look at the contribution of quark-mass-dependent twist-4 operators to the second moments of spin-averaged structure functions and the Bjorken sum rule. Its contribution is non-negligible in the former case due to large Wilson coefficients. We also discuss the values of the twist-4 spin-2 nucleon matrix element within present experimental constraints.

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I. INTRODUCTION

Recent precision spin-averaged lepton-hadron deep inelastic scattering (DIS) data at CERN [1–4] and SLAC [5] provide us with useful information about higher twist effects in spin-averaged structure functions (F_2 and F_L). From these data, we have previously [6] extracted the higher twist effect in the second moments of the structure functions and obtained a model-independent constraint on the nucleon matrix elements of the twist-4 spin-2 operators. These matrix elements provide useful information about correlations between partons inside the nucleon.

In addition, polarized DIS provides crucial information on the spin structure of the nucleon [7–9]. The lowest moment of this spin structure function is related to the nucleon matrix element of the axial vector current. To actually estimate the quark contribution of the proton spin and to understand differences in experimental measurements at different scales, it is necessary to estimate the higher twist effects [10–12].

Higher twist operators appearing in both spin-averaged moments and the Bjorken sum rule have been considered for some time [13–16]. In this work, we study the contribution of twist-4 operators that are proportional to the quark masses. These operators have been neglected so far because of negligible up and down quark masses compared to the hadronic scale. For the Bjorken sum rule, the additional twist-4 operator is $\langle m^2\gamma_5\gamma_\alpha q\rangle$ and indeed negligible. However, for the second moment of spin-averaged structure function, the quark-mass-dependent operator $\langle \bar{q}D_\alpha D_\beta m q\rangle$ contributes with a large Wilson coefficient compared to other twist-4 operators and cannot be neglected.

In Sec. II, we will first discuss the Bjorken sum rule. The relevant operator product expansion (OPE) for the time ordered vector current is derived using the method based on the Fock-Schwinger gauge, which has been used extensively in QCD sum rule calculations [17] and DIS [14,18]. In Sec. III, we will discuss second moments for the spin-averaged structure function and discuss the importance of quark-mass-dependent operators in relation to the recent estimates for the value of total twist-4 effects. We will also discuss the values of twist-4 spin-2 matrix elements within present experimental constraints.

II. BJORKEN SUM RULE

A. OPE

Let us consider the time ordered correlation of the electromagnetic current:

$$T_{\mu\nu}(q) = i\int d^4x e^{iqx}\langle T[j_\mu^{\rm em}(x)j_\nu^{\rm em}]\rangle. \qquad (1)$$

The perturbative part is symmetric in $\mu\nu$ and the lowest antisymmetric part contributing to the Bjorken sum rule is related to the axial-vector current. A simple way to obtain the twist-4 spin-1 contribution, is to make use of the Fock-Schwinger gauge for the external gauge fields. We will follow similar steps given in Ref. [14].

$$T^A_{\mu\nu}(q) = -\int d^4x e^{iqx}[\langle\bar{q}\gamma_\mu S^{(2)}(x,0)\gamma_\nu Q^2 q\rangle + x^\alpha\langle\bar{q}\overleftarrow{D}_\alpha\gamma_\mu S^{(1)}(x,0)\gamma_\nu Q^2 q\rangle + \tfrac{1}{2}x^\alpha x^\beta\langle\bar{q}\overleftarrow{D}_\alpha\overleftarrow{D}_\beta\gamma_\mu S^0(x,0)\gamma_\nu Q^2 q\rangle] - [\mu\leftrightarrow\nu]. \qquad (2)$$

Here, the $S^{(i)}(x,0)$ are quark propagators in external gauge field with i being the sum of the dimensions of external gauge field and quark mass. These are summarized in Appendix A. There are only two independent twist-4 operators contributing to this order:

$$U_\alpha = \bar{q}g\tilde{G}_{\alpha\beta}\gamma_\beta Q^2 q, \qquad L_\alpha = \bar{q}\gamma_\alpha\gamma_5 m^2 Q^2 q, \qquad (3)$$

where, $\tilde{G}_{\alpha\beta} = \frac{1}{2}\epsilon_{\alpha\beta\mu\nu}G_{\mu\nu}$ and conventions for ϵ_{0123} and γ_5 follow that of Muta [19]. Q is the flavor SU(2) charge matrix. To express the second and third term in Eq. (2)

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in terms of these independent operators, we have to extract the spin-1 part of the operators

$$\bar{q}\overleftarrow{D}_\alpha [\gamma_\beta,\gamma_\delta]mq, \quad \bar{q}\overleftarrow{D}_\alpha\overleftarrow{D}_\beta \gamma_5\gamma_\delta q. \tag{4}$$

This can be done [14] by assuming the spin-1 part of the operators to be

$$\mathcal{O}_{\alpha\beta\delta} - \mathcal{O}^{\text{spin 3}}_{\alpha\beta\delta} = g_{\alpha\beta}X_\delta + g_{\beta\delta}Y_\alpha + g_{\alpha\delta}Z_\beta + i\epsilon_{\alpha\beta\delta\sigma}U_\sigma. \tag{5}$$

Taking all traces and using the identities

$$D_\alpha\gamma_\alpha q = -imq,$$

$$\epsilon_{\alpha\beta\mu\nu}D_\mu\gamma_\nu q = -i\gamma_\alpha\gamma_5 D_\beta q + i\gamma_\beta\gamma_5 D_\alpha q - m\gamma_5(\gamma_\alpha\gamma_\beta - g_{\alpha\beta})q. \tag{6}$$

We find

$$\bar{q}\overleftarrow{D}_\alpha [\gamma_\beta,\gamma_\delta]mq = \frac{2}{3}\epsilon_{\alpha\beta\delta\sigma}L_\sigma,$$

$$\bar{q}\overleftarrow{D}_\alpha\overleftarrow{D}_\beta \gamma_5\gamma_\delta q = g_{\alpha\beta}\frac{5}{18}(L-U)_\delta + g_{\alpha\delta}\frac{1}{18}(U-L)_\beta + g_{\beta\delta}\frac{1}{18}(U-L)_\alpha. \tag{7}$$

Using these results, the final answer including the leading order result gives

$$T^A_{\mu\nu}(q) = -\frac{i}{q^2}\epsilon_{\mu\nu\alpha\beta}q_\alpha 2V_\beta - \frac{i}{q^4}\epsilon_{\mu\nu\alpha\beta}q_\alpha(\tfrac{16}{9}U_\beta + \tfrac{20}{9}L_\beta), \tag{8}$$

where the leading operator is

$$V_\beta = \bar{q}\gamma_\beta\gamma_5 Q^2 q. \tag{9}$$

B. Correction to the Bjorken sum rule

The contribution of L_α is easy to estimate. One should note that to a good approximation, $L_\alpha = m^2V_\alpha$, where m^2 is the average quark mass squared. So the contribution of this operator compared to the leading result would just be $\frac{10}{9}\frac{m^2}{Q^2}$. Since m is 5–10 MeV, its contribution is indeed negligible down to very small Q^2.

III. SECOND MOMENTS

A. OPE

To obtain the second moment, we have to consider the OPE to dimension 6 such that the contribution, where one quark is connected, is given by

$$T^c_{\mu\nu}(q) = -\int d^4x e^{iqx}[\langle\bar{q}\gamma_\mu S^{(3)}(x,0)\gamma_\nu Q^2 q\rangle + x^\alpha\langle\bar{q}\overleftarrow{D}_\alpha \gamma_\mu S^{(2)}(x,0)\gamma_\nu Q^2q\rangle + \tfrac{1}{2}x^\alpha x^\beta\langle\bar{q}\overleftarrow{D}_\alpha\overleftarrow{D}_\beta \gamma_\mu S^1(x,0)\gamma_\nu Q^2 q\rangle] + \tfrac{1}{3}x^\alpha x^\beta x^\delta\langle\bar{q}\overleftarrow{D}_\alpha\overleftarrow{D}_\beta\overleftarrow{D}_\delta \gamma_\mu S^0(x,0)\gamma_\nu Q^2 q\rangle] + [\mu\leftrightarrow\nu]. \tag{10}$$

There are four independent twist-4 operators appearing to this order:

$$A_{\alpha\beta} = g\bar{q}[D_\mu, G_{\alpha\mu}]\gamma_\beta Q^2 q = g^2(\bar{q}\gamma_\alpha t^a q)(\bar{q}\gamma_\beta t^a Q^2 q),$$

$$B_{\alpha\beta} = g\bar{q}\{iD_\alpha, \tilde{G}_{\beta\mu}\}\gamma_5\gamma_\mu Q^2 q,$$

$$C_{\alpha\beta} = \bar{q}D_\alpha D_\beta m Q^2 q,$$

$$D_{\alpha\beta} = g\bar{q}[D_\alpha, G_{\mu\beta}]\gamma_\mu Q^2 q. \tag{11}$$

Here, the operators are assumed to be symmetric and traceless with respect to the Lorentz indices. t^a are the generators of SU(3) color matrix normalized to $\mathrm{Tr}(t^a)^2 = \frac{1}{2}$.

The last operator does not contribute to the final answer. Similar steps have to be taken as before to reduce Eq. (10) into the above independent form. Useful identities needed in the intermediate stages are given in Appendix B. The final answer is

$$T^c_{\mu\nu} = \frac{1}{x^2Q^2}[d_{\mu\nu}(\tfrac{5}{8}A + \tfrac{1}{8}B - \tfrac{13}{4}C) + e_{\mu\nu}(\tfrac{1}{4}A - \tfrac{3}{4}B - \tfrac{18}{4}C)]. \tag{12}$$

Here, A, B, C are the spin-independent part of the spin-averaged nucleon matrix elements of the twist-4 spin-2 operators in Eq. (11) such that $\langle A^i_{\alpha\beta}\rangle_N = (p_\alpha p_\beta - \frac{1}{4}M_N^2 g_{\alpha\beta})A^i$ with $A^1 = A, A^2 = B, A^3 = C$. The polarization tensors are defined as $e_{\mu\nu} = g_{\mu\nu} - q_\mu q_\nu/q^2$ and $d_{\mu\nu} = -p_\mu p_\nu q^2/(p\cdot q)^2 + (p_\mu q_\nu + p_\nu q_\mu)/p\cdot q - g_{\mu\nu}$ with $Q^2 = -q^2$ (p_μ is a four-momentum of the nucleon with $p^2 = M_N^2$). There is another contribution to twist-4 part coming from a disconnected four quark operator. This part does not have any additional quark-mass-dependent term, such that the full twist-4 part in lowest order in α_s is

$$T^{\text{twist 4}}_{\mu\nu} = \frac{1}{x^2Q^2}d_{\mu\nu}M_4 + T^c_{\mu\nu}, \tag{13}$$

where M_4 is defined from

$$M_4(p_\alpha p_\beta - \tfrac{1}{4}M_N^2 g_{\alpha\beta}) = \langle(\bar{q}g^2\gamma_\alpha\gamma_5\tau^a q)(\bar{q}g^2\gamma_\beta\gamma_5\tau^a q)\rangle_N. \tag{14}$$

Equation (13) was obtained without the quark-mass-dependent operators in Refs. [14] and [15].

B. Estimate of C

C is related to the second moment of the structure function $e(x)$ [20]. At present, there is no direct experimental way of measuring $e(x)$. To estimate C, we will make the approximation

$$\langle \bar{q} D_\alpha D_\beta Q^2 m q\rangle_N \sim -\frac{4}{9} P^u_\alpha P^u_\alpha \langle m_u \bar{u} u\rangle_N - \frac{1}{9} P^d_\alpha P^d_\alpha \langle m_d \bar{d} d\rangle_N. \tag{15}$$

Here, $P^u(P^d)$ is the average momentum carried by each $u(d)$ quark inside the nucleon, which should be $\frac{1}{6}$ of the nucleon momentum P such that the total momentum carried by three quarks is roughly $\frac{1}{2}P$. Assuming $\langle m_u \bar{u} u\rangle \sim 2\langle m_d \bar{d} d\rangle$ in the proton and using $\Sigma_{\pi N} \sim 45 \pm 10$ MeV [21], we have, in the covariant normalization,

$$\langle m_u \bar{u} u\rangle_N = 2\langle m_u \bar{d} d\rangle_N = 0.06 \quad \text{GeV}^2. \tag{16}$$

This implies

$$\langle \bar{q} D_\alpha D_\beta Q^2 m q\rangle_N \sim (P_\alpha P_\beta - \tfrac{1}{4} M_N^2 g_{\alpha\beta}) \times (-0.0008)\ \text{GeV}^2 \quad \text{proton}. \tag{17}$$

So $C = -0.0008$ GeV^2 for the proton.

C. Experimental data on twist-4 effects in F_2

We have recently extracted the twist-4 effects in the second moment of the structure function F_2 [6]. Assuming

$$F_{2,L}(x,Q^2) = F_{2,L}^{\tau=2}(x,Q^2) + \frac{1}{Q^2} F_{2,L}^{\tau=4}(x,Q^2), \tag{18}$$

where $F_{2,L}^{\tau=2}$ takes into account the target mass correction. We found that, at $Q^2 = 5$ GeV^2,

$$\int_0^1 F_2^{\tau=4}(x) dx = 0.005 \pm 0.004\ \text{GeV}^2 \quad \text{(proton)}$$
$$= \tfrac{1}{2}(M_4 + \tfrac{5}{8}A + \tfrac{1}{8}B - \tfrac{13}{4}C), \tag{19}$$

where the second line shows its relation to the matrix elements including C. The quoted value was obtained from estimates of $F_2^{\tau=4}(x)$ in Ref. [22], which in turn was obtained by fitting the BCDMS and SLAC data on the hydrogen target. We also quoted a value for the neutron which was based on the analysis of the New Muon Collaboration (NMC) for higher twist effect in $F_2^n/F_2^p = 2F_2^d/F_2^p - 1$ [3]. This ratio was obtained from the measurement in the deuteron and proton targets without taking into account any nuclear effects in the deuteron structure function. However, recent analysis showed [23,24] that the nuclear effect is not negligible and accounted for almost all the deviation from the perturbative ratio. So we will not quote the neutron value and hereafter discuss the case of the proton only.

Using the value for C from Eq. (17) and substituting in Eq. (19), we see that the contribution from C accounts for 26% of the experimentally estimated twist-4 effects and cannot be neglected.

D. Experimental data on twist-4 effects in F_L

In Ref. [6], we made similar estimates for the twist-4 effect in the second moment of F_L. This was based on the SLAC data [5] analyzed in Ref. [25]. At $Q^2 = 5$ GeV^2 we found

$$\int_0^1 F_L^{\tau=4} dx = \int_0^1 8\kappa^2 F_2^{LT}(x) dx = 0.035 \pm 0.012\ \text{GeV}^2 \quad \text{(proton)}$$
$$= \tfrac{1}{2}(\tfrac{1}{4}A - \tfrac{3}{8}B - \tfrac{18}{4}C), \tag{20}$$

where the second line shows its relation to matrix elements.

Using the value for C from Eq. (17) and substituting in Eq. (20), we see that in this case, contribution from the quark-mass-dependent operator accounts for only 5%.

E. An estimate of the proton matrix element of M_4, A, and B

Let us now estimate the value of M_4, A, and B for the proton. We will assume $C = -0.0008$ GeV^2. There are only two constraints [Eqs. (19) and (20)] and three parameters to determine. However, there is one positivity constraint ([14]) for the four quark operators. The proof is simple. Suppose the twist-4 four quark operator to be

$$\mathcal{O}_{\mu\nu} = (\bar{q}\Gamma_\mu q)(\bar{q}\Gamma_\nu q) - \frac{1}{4} g_{\mu\nu} (\bar{q}\Gamma_\alpha q)(\bar{q}\Gamma_\alpha q), \tag{21}$$

then, for $\langle \boldsymbol{p} = 0 | \mathcal{O}_{00} | \boldsymbol{p} = 0\rangle$, the matrix element can be written as the sum of full squares:

$$\langle \boldsymbol{p} = 0 | [\tfrac{3}{4}(\bar{q}\Gamma_0 q)^2 + \tfrac{1}{4}(\bar{q}\Gamma_i q)^2] | \boldsymbol{p} = 0\rangle. \tag{22}$$

Hence both M_4 and A should be positive. Since both become four quark operators, we expect them to be similar in magnitude. We will vary M_4 from 0 to $2 \times A$ and solve for A and B. The result is summarized in Table I.

Our analysis suggests the following.

(1) The magnitude of the quark gluon mixed operator

TABLE I. Proton matrix elements of M_4, A, and B.

M_4	A	B
0	0.041	−0.148
$A = 0.017$ GeV^2	0.017	−0.165
$2A = 0.022$ GeV^2	0.011	−0.169

B is relatively large compared to the four quark operators at the 5 GeV^2 scale. The former is in the range of $-(350$–450 MeV$)^2$ and the latter (100–200 MeV)^2, consistent with previous estimates [6].

(2) C is negligible compared to B but not so compared to A. For the transverse moment in Eq. (19), the Wilson coefficient of B is small and its contribution is largely cancelled by that of A. Therefore, the contribution from C, which comes with a large Wilson coefficient, is a sizable part of the estimated twist-4 contribution and cannot be neglected.

IV. CONCLUSION

We have considered the contribution of quark-mass-dependent twist-4 operators to the Bjorken sum rule and momentum sum rule. In the Bjorken sum rule only operators proportional to m^2 appear. This is easily seen because the operator linear in m would be $\bar{q}m\gamma_5 D_\alpha q$ which vanishes when using the equations of motion. So the correction to the leading part is $\frac{m^2}{Q^2}$ and negligible.

However, for the momentum sum rules, $\bar{q}D_\alpha D_\beta mq$ contributes with a large Wilson coefficient and becomes a non-negligible correction to other twist-4 effects.

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APPENDIX A

In this appendix, we summarize the form of quark propagator in external gauge field including mass-dependent terms relevant for the moment calculations. We will group them together according to the dimension of external gauge field plus the dimension of quark mass:

$$S(p) = S(p)^{(0)} + S(p)^{(1)} + S(p)^{(2)} + S(p)^{(3)}, \qquad \text{(A1)}$$

such that

$$\begin{aligned} S(p)^{(0)} &= \frac{1}{p^2} p_\alpha \gamma_\alpha, \\ S(p)^{(1)} &= \frac{1}{p^2} m, \\ S(p)^{(2)} &= -\frac{1}{p^4} p_\alpha \tilde{G}_{\alpha\beta}\, \gamma_\beta \gamma_5 + \frac{1}{p^4} m^2 p_\alpha \gamma_\alpha, \\ S(p)^{(3)} &= \frac{2}{3}\frac{1}{p^6} g[p^2 D_\alpha G_{\alpha\beta}\gamma_\beta - p_\sigma \gamma_\sigma D_\alpha G_{\alpha\beta} p_\beta \\ &\quad - p_\sigma D_\sigma p_\alpha G_{\alpha\beta}\gamma_\beta - 3ip_\sigma D_\sigma p_\alpha \tilde{G}_{\alpha\beta}\, \gamma_\beta\gamma_5] \\ &\quad -\frac{1}{2p^4} mgG_{\alpha\beta}\sigma_{\alpha\beta}. \end{aligned} \qquad \text{(A2)}$$

APPENDIX B

In this appendix, we summarize useful identities that are needed to reduce Eq. (10) into its final form with independent matrix elements. We will only look at the spin-2 part of the operators

$$\begin{aligned} \bar{q}\, \overleftarrow{D}_\alpha \overleftarrow{D}_\beta \overleftarrow{D}_\gamma\, \gamma_\delta q = {}& g_{\alpha\beta}\frac{i}{32}[2D - A - 3B - 2C]_{\gamma\delta} + g_{\alpha\gamma}\frac{i}{32}[4D + 5A - 3B - 2C]_{\beta\delta} \\ & + g_{\alpha\delta}\frac{i}{32}[-2D - A + B + 6C]_{\beta\gamma} + g_{\beta\gamma}\frac{i}{32}[2D - A - 3B - 2C]_{\alpha\delta} \\ & + g_{\beta\delta}\frac{i}{32}[4D + A + B + 6C]_{\alpha\gamma} + g_{\gamma\delta}\frac{i}{32}[-2D - A + B + 6C]_{\beta\alpha}, \end{aligned} \qquad \text{(B1)}$$

where we have neglected the terms proportional to the ϵ tensor,

$$\begin{aligned} \bar{q}\, \overleftarrow{D}_\alpha \overleftarrow{D}_\beta \overleftarrow{D}_\gamma\, \gamma_\delta\gamma_5 q = {}& \epsilon_{\sigma\beta\gamma\delta}\frac{1}{16}[-2B - A - D + 4C]_{\sigma\alpha} + \epsilon_{\alpha\sigma\gamma\delta}\frac{1}{16}[-2A - 2D + 8C]_{\sigma\beta} \\ & + \epsilon_{\alpha\beta\sigma\delta}\frac{1}{16}[-2B - A - D + 4C]_{\gamma\sigma}, \end{aligned} \qquad \text{(B2)}$$

where we have neglected the terms proportional to g. Using Eq. (B2), we can show

$$E \equiv \bar{q}\{iD_\sigma\, \tilde{G}_{\sigma\alpha}\}\gamma_5\gamma_\beta q = [-B - A - D + 4C]_{\alpha\beta}. \qquad \text{(B3)}$$

Other straightforward expansions are

$$\bar{q}i\, \overleftarrow{D}_\alpha \tilde{G}_{\beta\gamma}\, \gamma_5\gamma_\delta q = g_{\alpha\gamma}\frac{1}{16}[3E + B]_{\beta\delta} - g_{\alpha\beta}\frac{1}{16}[3E + B]_{\beta\delta} + g_{\beta\delta}\frac{1}{16}[3B + E]_{\beta\delta} - g_{\gamma\delta}\frac{1}{16}[3B + E]_{\alpha\beta}, \qquad \text{(B4)}$$

and

$$\bar{q}D_\alpha G_{\beta\gamma}\gamma_\delta q = g_{\alpha\beta}\frac{1}{8}[-3A - D]_{\gamma\delta} - g_{\alpha\gamma}\frac{1}{8}[-3A - D]_{\beta\delta} + g_{\beta\delta}\frac{1}{8}[3D + A]_{\beta\delta} - g_{\gamma\delta}\frac{1}{8}[3D + A]_{\alpha\beta}. \qquad \text{(B5)}$$

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