$O(\alpha_s^2)$ corrections to high-q_T polarized gauge boson production at hadron colliders

E. Mirkes [1]
Institut für Theoretische Kernphysik, Universität Karlsruhe, W-7500 Karlsruhe, FRG

J.G. Körner
Institut für Physik, Johannes Gutenberg Universität Mainz, W-6500 Mainz, FRG

and

G.A. Schuler [1]
II. Institut für Theoretische Physik, Universität Hamburg, W-2000 Hamburg, FRG

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We report first results on $O(\alpha_s^2)$ corrections to the parity conserving structure functions that describe high-q_T polarized gauge boson production in hadron collisions. We present some numerical results for polarized W^+ production at the Tevatron $p\bar{p}$ collider. In particular we find that the relation $A_0=A_2$ between the longitudinal and transverse interference structure functions no longer holds true at next-to-leading order (NLO). We calculate the NLO corrections to this relation.

Recently the complete next-to-leading order $O(\alpha_s^2)$ corrections to the production rate of high transverse momentum (q_T) gauge bosons V (V=W, Z, γ^*) at hadron colliders have been completed [1,2]. In this letter we extend the calculation of refs. [1,2] to the polarization of the produced high-q_T gauge bosons to $O(\alpha_s^2)$. The polarization of the gauge boson determines the shape of the spectra of the decay leptons or jets in the laboratory frame which has important implications for the study of the production of new heavy objects as e.g. the top quark. Also the polarization determines the angular distribution of the decay leptons and jets in the gauge boson rest frame which will be an important test of QCD at $O(\alpha_s^2)$. Since the NLO corrections to the rate are sizeable it is important to have available the complete NLO $O(\alpha_s^2)$ corrections to the polarization of high-q_T gauge bosons produced in hadronic collisions. In addition, the inclusion of the $O(\alpha_s^2)$ corrections reduces the renormalization and factorization scale dependence of the $O(\alpha_s)$ results.

$O(\alpha_s)$ contributions to the polarization of high-q_T gauge bosons have been considered in refs. [3–6]. The $O(\alpha_s)$ polarization effects have been found to be sizeable. In this letter we present first results on the $O(\alpha_s^2)$ corrections to the polarization structure functions of high-q_T gauge bosons where we concentrate on the parity-conserving (PC) structure functions.

Consider the $O(\alpha_s)$ differential cross section for gauge boson production followed by the decay into a lepton or quark pair, $p\bar{p}\to V+X\to \ell\bar{\ell}'+X$ (or $q\bar{q}'+X$):

$$\frac{d\sigma(\theta,\phi)+d\sigma(\pi-\theta,\phi+\pi)}{dy\,dq_T^2\,d\cos\theta\,d\phi}=\frac{d\sigma_{U+L}}{dy\,dq_T^2}\frac{3}{8\pi}\times[1+\cos^2\theta+\tfrac{1}{2}A_0(1-3\cos^2\theta)+A_1\sin 2\theta\cos\phi+\tfrac{1}{2}A_2\sin^2\theta\cos 2\phi]\,. \quad (1)$$

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We denote the polar and azimuthal decay angles of the leptons (or jets) in the gauge boson rest frame by θ and ϕ, the transverse momentum and rapidity of the gauge boson by q_T and y, respectively. The unpolarized differential production cross section is denoted by $d\sigma_{U+L}$, whereas A_0, A_1, and A_2 characterize the polarization of the gauge boson. The cross section contribution of the longitudinal polarization is given by A_0, the transverse longitudinal interference by A_1 and the transverse interference by A_2. We have taken the sum of cross sections at (θ, ϕ) and at $(\pi-\theta, \phi+\pi)$ in order to project out the PC hadronic structure functions A_0, A_1 and A_2.

Turning now to the $O(\alpha_s^2)$ corrections we note that the structure functions A_0, A_1 and A_2 obtain contributions from the dispersive part of the hadron tensor $H_{\mu\nu}(O(\alpha_s^2))$. The absorptive parts of $H_{\mu\nu}(O(\alpha_s^2))$ generate two more structure function contributions on the RHS of (1) which are proportional to the angular factors $\sin 2\theta \sin \phi$ and $\sin^2\theta \sin 2\phi$ [7] [#1]. Results on the absorptive $O(\alpha_s^2)$ contributions have already been presented in ref. [7] and will therefore not be discussed any further here. We shall concentrate on the new $O(\alpha_s^2)$ results for A_0, A_1 and A_2.

The following subprocesses (plus their charge conjugate ones) contribute to high-q_T gauge boson (V) production in hadronic collisions up to $O(\alpha_s^2)$:

$$\begin{aligned} H_{\mu\nu}(\text{tree}):\quad & q+\bar{q} \to V+G+G\,, \\ & q+\bar{q} \to V+q+\bar{q}\,, \\ & q+G \to V+q+G\,, \\ & q+q \to V+q+q\,, \\ & G+G \to V+q+\bar{q}\,, \end{aligned} \tag{2}$$

$$\begin{aligned} H_{\mu\nu}(\text{loop}):\quad & q+\bar{q} \to V+G\,, \\ & q+G \to V+q\,. \end{aligned} \tag{3}$$

A numerical study of the $O(\alpha_s^2)$ tree graph contributions (2) with singular regions in phase space excluded has been done in ref. [8]. A complete $O(\alpha_s^2)$ (loop plus tree) *rate* calculation including all the above contributions has become available recently [1,2], after an incomplete $O(\alpha_s^2)$ *rate* calculation involving only the flavour non-singlet contributions had been done already in 1983 [9]. Our aim in this letter is to show the numerical size of the $O(\alpha_s^2)$ corrections to the polarization structure functions A_0, A_1 and A_2.

The corresponding analytical $O(\alpha_s^2)$ expressions for the coefficients A_0, A_1 and A_2 are quite lengthy. The expressions for the dominant subprocesses will therefore be published in a sequel to this letter [10]. The complete set of the analytical results are presented in ref. [11]. Let us mention that the analytical calculation of the $O(\alpha_s^2)$ corrections to the structure functions A_i involves the whole complex machinery of a next-to-leading order parton model calculation. Details of the corresponding treatment of UV, IR and collinear divergencies including a discussion of the mass factorization scheme are given in ref. [10].

To be specific, we shall evaluate the structure functions A_0, A_1 and A_2 for W^+ production at the Tevatron energy $\sqrt{s}=1.8$ TeV where large samples of high-q_T W's are expected in the near future [12]. We work in the Collins–Soper (CS) frame [3] which is defined in the gauge boson rest frame with the event plane as (x, z)-plane. The z-axis in the CS frame bisects the proton and negative antiproton direction and $p_x(\text{proton}) \leqslant 0$ which then defines the polar and azimuthal angles θ and ϕ in (1). A reconstruction of the event kinematics in $W^\pm$ events has a twofold ambiguity in some regions of the phase space. Working in the CS frame [#2] has the unique advantage in that the azimuthal angle ϕ and $\sin\theta$ have the same values in both solutions [7]. The only ambiguity is then the sign of $\cos\theta$, which is similar to the situation in the case of vanishing q_T. The remaining ambiguity will thus only affect the A_1 contribution which is quite small as the following calculation shows.

We work in the $\overline{\text{MS}}$ scheme and use the parton density parametrization set 2 of DFLM [13] with $\Lambda_{QCD}=175$ MeV for five flavours. We identify the scales used in the coupling constant and in the parton distribution function and set them equal to

[#1] The PC dispersive contributions appearing on the RHS of (1) can be projected out to any order by taking the cross section sum: $\sigma(\theta, \phi)+\sigma(\theta, -\phi)+\sigma(\pi-\theta, \pi+\phi)+\sigma(\pi-\theta, \pi-\phi)$.

[#2] The CS frame has been originally introduced to minimize intrinsic transverse momentum effects of the incoming partons. At the scale of the present CERN and Fermilab proton–antiproton colliders, however, the intrinsic transverse momentum effects are no longer so important.

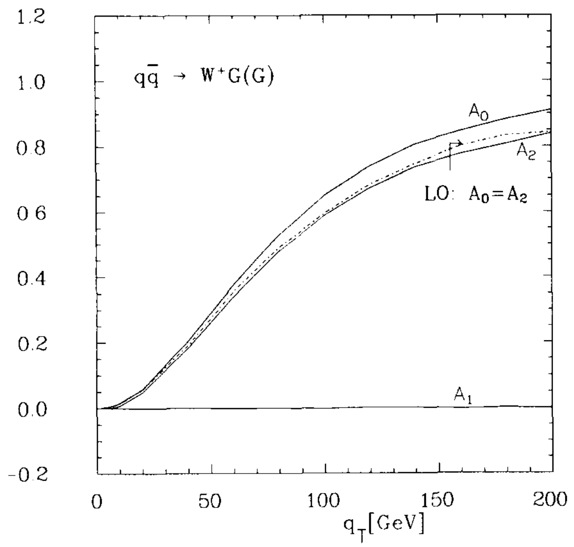

Fig. 1. The angular coefficients A_0, A_1 and A_2 as a function of q_T for $p\bar{p} \to W^+ + X$ at $\sqrt{s}=1.8$ TeV. Shown are the contributions from the $q+\bar{q} \to W^+ + G(+G)$ subprocess. Dashed lines are the corresponding $O(\alpha_s)$ results.

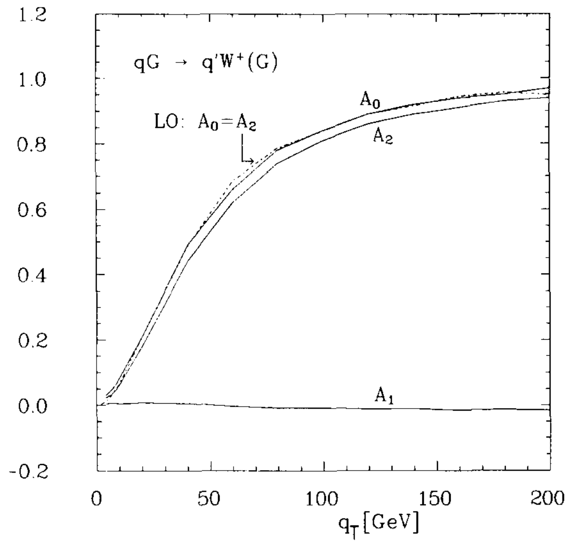

Fig. 2. Same as fig. 1 but for the $q+G \to W^+ + q(+G)$ subprocess.

$\mu^2 = \frac{1}{2}(m_W^2 + q_T^2)$ where m_W is the W mass. The DFLM parametrization was obtained in the DIS scheme but the difference between structure functions evolved in the two schemes at higher scale μ^2 is too small to show up in our plots.

Figs. 1 and 2 show the Born, $O(\alpha_s)$, and the NLO, $O(\alpha_s)+O(\alpha_s^2)$, contribution to the coefficients A_0, A_1 and A_2 for the two subprocesses $q+\bar{q} \to W^+ + G(+G)$ and $q+G \to W^+ + q(+G)$ that are most important at these energies.

We begin by discussing the structure functions A_0 and A_2. As has been emphasized by Tung and collaborators [14] these angular coefficients are simply related by $A_0 = A_2$ (dashed lines) at the Born term level [#3]. A_0 and A_2 are increasing functions of q_T. At high q_T they become very large, about 0.9, and thus are certainly non-negligible. With the inclusion of the NLO corrections (see below) these QCD corrections are reliably calculated for q_T larger than about 20 GeV. If one wants to extend the calculation towards lower values of q_T one has to invoke soft gluon resummation techniques [17] for the singular ($\propto 1/q_T^2$) production cross section $d\sigma_{U+L}$. In figs. 1 and 2 we have plotted the fixed order ratio of the polarized cross sections over the (singular) production cross section. This implies that the structure functions A_i are at least proportional to q_T and thus vanish as $q_T \to 0$.

Turning now to the NLO corrections for A_0 and A_2 we find that the relation $A_0 = A_2$ no longer holds true at $O(\alpha_s^2)$. In the case of the subprocess $q+\bar{q} \to W^+ + G(+G)$ the $O(\alpha_s^2)$ corrections to A_2 are small whereas there are positive corrections of up to 10% to A_0. In contrast, the $O(\alpha_s^2)$ corrections to A_2 are negative for the $q+G \to W^+ + q(+G)$ subprocess by a few percent while the corresponding corrections to A_0 are small. As figs. 1 and 2 show, the deviations from the Born term relation $A_0 = A_2$ can amount to 5–10%. Thus the deviation from $A_0 = A_2$ is larger than that found in the corresponding e^+–e^- case where the deviation from the corresponding relation $\sigma_L = 2\sigma_T$ amounts to only about 1% [16]. Note though that in the latter case there are only loop corrections to this relation whereas in the present case one has tree level contributions also.

Next we discuss the structure function A_1. In LO the structure function A_1 is very small in the CS frame. More precisely, the contribution of the quark initiated process is zero, and the gluon initiated contri-

[#3] The relation $A_0 = A_2$ has recently been used in W decays by UA1 [15] to determine the spin of the gluon. In a scalar gluon theory one finds $A_0 \neq A_2$ [5,16].

bution is small. This happens because the partonic expression for A_1^{qq} is antisymmetric in the partonic Mandelstam variables $\hat{u}$ and $\hat{t}$ but integrated symmetrically in $p\bar{p}$ collisions (we integrate over the full rapidity range). In the case of the qG initiated subprocess the deviation from zero arises from the difference in the up-valence and down-valence distribution functions and thus shows up first at higher values of q_T. For the NLO corrections to A_1 we find that they are too small to be visible in our plots.

In summary, the deviations from the LO $O(\alpha_s)$ expectations for the angular coefficients A_i are less than 10% for Tevatron energies. It is clear that the $O(\alpha_s^2)$ results are more reliable than the $O(\alpha_s)$ results as they depend less on the renormalization and factorization scales. The next step is the investigation of effects of these higher order corrections on the decay particle spectra like the transverse momentum and rapidity distributions of leptonic and hadronic decays of W's and Z's.

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