Single Spin Asymmetry in Heavy Quark Photoproduction (and Decay) as a Test of pQCD

N.Ya.Ivanov

Yerevan Physics Institute, Alikhanian Br.2, 375036 Yerevan, Armenia

We review the properties of the single spin asymmetry (SSA) in heavy quark production by linearly polarized photons and analyze the possibility to measure this SSA in the planned E160/E161 experiments at SLAC.

I. INTRODUCTION

In the framework of perturbative QCD, the basic spin-averaged characteristics of heavy flavor hadro-, photo- and electroproduction are known exactly up to the next-to-leading order (NLO). During the last ten years, these NLO results have been widely used for a phenomenological description of available data (for a review see [1]). At the same time, the key question still remains open: How to test the applicability of QCD at fixed order to the heavy quark production? The problem is twofold. On the one hand, the NLO corrections are large; they increase the leading order (LO) predictions for both charm and bottom production cross sections approximately by a factor of two. For this reason, one could expect that higher-order corrections, as well as nonperturbative contributions, can be essential in these processes, especially for the $c$-quark case. On the other hand, it is very difficult to compare directly, without additional assumptions, pQCD predictions for spin-averaged cross sections with experimental data because of a high sensitivity of the theoretical calculations to standard uncertainties in the input QCD parameters: $m_Q$, the factorization and renormalization scales, $\mu_F$ and $\mu_R$, $\Lambda_{QCD}$ and the parton distribution functions [2,4].

In recent years, the role of higher-order corrections has been extensively investigated in the framework of the soft gluon resummation formalism [4,5,6]. Unfortunately, formally resummed cross sections are ill-defined due to the Landau pole contribution, and numerical predictions for the heavy quark production cross sections can depend significantly on the choice of resummation prescription [7]. Another open question, also closely related to convergence of the perturbative series, is the role of subleading contributions which are not, in principle, under control of the resummation procedure [7,8].

For this reason, it is of special interest to study those observables which are well defined in pQCD. A nontrivial example of such an observable is proposed in [9,10], where the charm and bottom production by linearly polarized photons,
\[ \gamma^+ + N \rightarrow Q + X[\overline{Q}], \quad (1) \]

was considered. In particular, the single spin asymmetry (SSA) parameter, \( A_Q(p_{QT}) \), which measures the parallel-perpendicular asymmetry in the quark azimuthal distribution,

\[
\frac{d^2\sigma_Q}{dp_{QT}d\varphi_Q}(p_{QT}, \varphi_Q) = \frac{1}{2\pi} \frac{d\sigma_Q^{\text{unp}}}{dp_{QT}}(p_{QT}) \left[ 1 + A_Q(p_{QT})P_\gamma \cos 2\varphi_Q \right], \quad (2)
\]

has been calculated. In (2) \( \frac{d\sigma_Q^{\text{unp}}}{dp_{QT}} \) is the unpolarized cross section, \( P_\gamma \) is the degree of linear polarization of the incident photon beam and \( \varphi_Q \) is the angle between the beam polarization direction and the observed quark transverse momentum, \( p_{QT} \). The following remarkable properties of the SSA, \( A_Q(p_{QT}) \), have been observed:

- The azimuthal asymmetry (2) is of leading twist; in a wide kinematical region, it is predicted to be about 0.2 for both charm and bottom quark production.
- At energies sufficiently above the production threshold, the LO predictions for \( A_Q(p_{QT}) \) are insensitive (to within few percent) to uncertainties in the QCD input parameters.
- Nonperturbative corrections to the \( b \)-quark azimuthal asymmetry are negligible. Because of the smallness of the \( c \)-quark mass, the analogous corrections to \( A_c(p_{QT}) \) are larger; they are of the order of 20%.

In Ref. \[10\], radiative corrections to the \( \varphi \)-dependent cross section (2) have been investigated in the soft-gluon approximation. Calculations \[10\] indicate a high perturbative stability of the pQCD predictions for \( A_Q \). In particular,

- At the next-to-leading logarithmic (NLL) level, the NLO and NNLO predictions for \( A_Q \) affect the LO results by less than 1% and 2%, respectively.
- Computations of the higher order contributions (up to the 6th order in \( \alpha_s \)) to the NLL accuracy lead only to a few percent corrections to the Born result for \( A_Q \). This implies that large soft-gluon contributions to the spin-dependent and unpolarized cross sections cancel each other with a good accuracy.

So, contrary to the the production cross sections, the single spin asymmetry in heavy flavor photoproduction is an observable quantitatively well defined in pQCD: it is stable, both parametricaly and perturbatively, and insensitive to nonperturbative corrections. Measurements of this asymmetry would provide an ideal test of the conventional parton model based on pQCD.

\[1\]The well known examples are the shapes of differential cross sections of heavy flavor production which are sufficiently stable under radiative corrections.
Concerning the experimental aspects, the azimuthal asymmetry in charm photoproduction can be measured at SLAC where a coherent bremsstrahlung beam of linearly polarized photons with energies up to 40 GeV will be available soon \[1\]. In the planned E160 and E161 experiments, the charm production will be investigated using the inclusive spectra of the decay lepton:

\[ \gamma^+ N \rightarrow c + X \rightarrow \mu^+ + X. \] (3)

In this paper, we analyze a possibility to measure the SSA in heavy quark photoproduction using the decay lepton spectra. We calculate the SSA in the decay lepton azimuthal distribution:

\[
\frac{d^2\sigma_{\ell}}{dp_{\ell T}d\varphi_{\ell}}(p_{\ell T}, \varphi_{\ell}) = \frac{1}{2\pi} \frac{d\sigma_{\ell}^{\text{unp}}}{dp_{\ell T}}(p_{\ell T}) \left[ 1 + A_{\ell}(p_{\ell T})P_{\gamma} \cos 2\varphi_{\ell} \right],
\] (4)

where \( \varphi_{\ell} \) is the angle between the photon polarization direction and the decay lepton transverse momentum, \( p_{\ell T} \). Our main results can be formulated as follows \[12\]:

- The SSA transferred from the decaying \( c \)-quark to the decay muon is large in the SLAC kinematics; the ratio \( A_{\ell}(p_{\ell T})/A_c(p_T) \) is about 90% for \( p_T > 1 \text{ GeV} \).
- pQCD predictions for \( A_{\ell}(p_{\ell T}) \) are also stable, both perturbatively and parametrically.
- Nonperturbative corrections to \( A_{\ell}(p_{\ell T}) \) due to the gluon transverse motion in the target and the \( c \)-quark fragmentation are small; they are about 10% for \( p_{\ell T} > 1 \text{ GeV} \).
- The SSA \[13\] depends weekly on theoretical uncertainties in the charm semileptonic decays, \( c \rightarrow \ell^+ \nu_{\ell}X_q \) \( (q = d, s) \). In particular,
  - Contrary to the production cross sections, the asymmetry \( A_{\ell}(p_{\ell T}) \) is practically insensitive to the unobserved strange quark mass, \( m_s \), for \( p_{\ell T} > 1 \text{ GeV} \).
  - The bound state effects due to the Fermi motion of the \( c \)-quark inside the \( D \)-meson have only a small impact on \( A_{\ell}(p_{\ell T}) \), in practically the whole region of \( p_{\ell T} \).

So, we conclude that the SSA in the decay lepton azimuthal distribution \[13\] is also well defined in the framework of perturbation theory and can be used as a good test of pQCD applicability to heavy flavor production.

\[2\] For a review see Ref. \[13\].
II. PQCD PREDICTIONS FOR SSA

A. LO Results

At the Born level, the only partonic subprocess which is responsible for the reaction (3) is the heavy quark production in the photon-gluon fusion,

$$\gamma^{\uparrow}(k_{\gamma}) + g(k_g) \rightarrow Q(p_Q) + \overline{Q}(p_{\overline{Q}}) \rightarrow \ell(p_{\ell}) + \nu_{\ell} + q + \overline{q}, \quad (5)$$

with subsequent decay $c \rightarrow \ell^{+}\nu_{\ell}q \ (q = d, s)$ in the charm case and $b \rightarrow \ell^{-}\overline{\nu}_{\ell}q \ (q = u, c)$ in the bottom one. To calculate distributions of final particles appearing in a process of production and subsequent decay, it is useful to adopt the narrow-width approximation,

$$\frac{1}{(p_{Q}^2 - m_{Q}^2)^2 + \Gamma_{Q}^2 m_{Q}^2} \rightarrow \frac{\pi}{\Gamma_{Q} m_{Q}} \delta \left( p_{Q}^2 - m_{Q}^2 \right), \quad (6)$$

with $\Gamma_{Q}$ the total width of the heavy quark. Corrections to this approximation are negligibly small in both charm and bottom cases since they have a relative size $O(\Gamma_{Q}/m_{Q})$.

In the case of the linearly polarized photon, the heavy quark produced in the reaction (5) is unpolarized. For this reason, the single-inclusive cross section for the decay lepton production in (5) is a simple convolution:

$$E_{\ell} \frac{d^3\hat{\sigma}}{d^3p_{\ell}}(\vec{p}_{\ell}) = \frac{1}{\Gamma_{Q}} \int \frac{d^3p_{Q}}{E_{Q}} \frac{d^3\hat{\sigma}_{Q}}{d^3p_{Q}}(\vec{p}_{Q}) \frac{E_{\ell}d^3\Gamma_{sl}}{d^3p_{\ell}}(p_{\ell} \cdot p_{Q}). \quad (7)$$

The leading order predictions for the $\varphi_Q$-dependent cross section of heavy flavor production,

$$\frac{E_{Q}d^3\hat{\sigma}_{Q}}{d^3p_{Q}}(\vec{p}_{Q}) \equiv \frac{2sd^3\hat{\sigma}_{Q}}{du_1dt_1d\varphi_{Q}}(s, t_1, u_1, \varphi_{Q}) = \frac{1}{\pi s} \left[ B_Q (s, t_1, u_1) + \Delta B_Q (s, t_1, u_1) P_{\gamma} \cos 2\varphi_{Q} \right], \quad (8)$$

are given in [9]. Radiative corrections to the cross section (8) was investigated in the soft gluon approximation in Ref. [10].

At the tree level, the invariant width of the semileptonic decay $c \rightarrow \ell^{+}\nu_{\ell}q \ (q = d, s)$ can be written as

$$\frac{E_{\ell}d^3\Gamma_{sl}}{d^3p_{\ell}}(x) \equiv I_{sl}(x) = \frac{G_{F}^2 m_{Q}^3}{(2\pi)^4} |V_{CKM}|^2 x \left( 1 - x - \delta^2 \right)^2 \frac{1}{1 - x} \quad (9)$$

Here $V_{CKM}$ denotes the corresponding element of the Cabbibo-Kobayashi–Maskawa matrix, $G_{F}$ is the Fermi constant, $x = 2(p_{\ell} \cdot p_{Q})/m_{Q}^2$ and $\delta = m_{q}/m_{Q}$.

Let us discuss the hadron level pQCD predictions for the asymmetry in azimuthal distribution of the decay lepton. In this paper, we will consider only the charm photoproduction at the SLAC energy $E_{\gamma} \approx 35$ GeV, $E_{\gamma} = (S - m_{N}^2)/2m_{N}$. Unless otherwise stated, the
CTEQ5M [14] parametrization of the gluon distribution function is used. The default value of the charm quark mass is $m_c = 1.5$ GeV.

Our calculations of the quantities $A_\mu(p_T)$ and $A_c(p_T)$ are given in Fig.1 by solid and dashed lines, respectively. One can see that the asymmetry transferred from the decaying $c$-quark to the decay muon is large in the SLAC kinematics; the ratio $A_\mu(p_T)/A_c(p_T)$ is about 90% for $p_T > 1$ GeV. Note that $p_T \equiv p_QT$ when we consider the heavy quark production and $p_T \equiv p_{\ell T}$ when the quantity $A_\mu(p_{\ell T})$ is discussed.

We have analyzed also the dependence of the SSA in the lepton distribution on the unobserved strange quark mass, $m_s$. Our analysis shows that the LO predictions for $A_\mu(p_T)$ are practically independent of $\delta = m_s/m_c$ at sufficiently large $p_T > 1$ GeV. For more details see Ref. [12].

![Figure 1](image_url)

**FIG. 1.** Comparison of the QCD LO predictions for $A_\mu(p_T)$ and $A_c(p_T)$.

**B. Radiative Corrections**

We have computed both spin-dependent and unpolarized differential distributions (8) of the heavy-quark photoproduction at NLO to the next-to-leading logarithmic accuracy. The NLO corrections to the width of the heavy quark semileptonic decays are known exactly [15,16]. We have found that radiative corrections to the leptonic SSA, $A_\mu(p_T)$, in the reaction (3) are of the order of (1-2)% in the SLAC kinematics.

Two main reasons are responsible for perturbative stability of the quantity $A_\mu(p_T)$. First, radiative corrections to the SSA in heavy quark production are small [14]. Second, the ratio $I_{\text{sl}}^{\text{NLO}}(x)/I_{\text{sl}}^{\text{Born}}(x)$ is a constant practically at all $x$, except for a narrow endpoint region $x \approx 1$ [16]. (Note that $I_{\text{sl}}^{\text{Born}}(x)$ is the LO invariant width of the semileptonic decay $c \to \ell^+ \nu_\ell X_q$ given by (8) while $I_{\text{sl}}^{\text{NLO}}(x)$ is the corresponding NLO one.)
III. NONPERTURBATIVE CONTRIBUTIONS

Let us discuss how the pQCD predictions for single spin asymmetry are affected by nonperturbative contributions due to the intrinsic transverse motion of the gluon and the hadronization of the produced heavy quark. Because of the low $c$-quark mass, these contributions are especially important in the description of the cross section for charmed particle production \[1\]. At the same time, our analysis shows that nonperturbative corrections to the single spin asymmetry are not large.

Hadronization effects in heavy flavor production are usually modeled with the help of the Peterson fragmentation function \[17\],

$$D(y) = \frac{a_\varepsilon}{y \left[1 - 1/y - \varepsilon/(1-y)\right]^2},$$  \hspace{1cm} (10)

where $a_\varepsilon$ is a normalization factor and $\varepsilon_D = 0.06$ in the case of a $D$-meson production.

Our calculations of the asymmetry in a $D$-meson production at LO with and without the Peterson fragmentation effect are presented in Fig.2 by dotted and solid curves, respectively. It is seen that at $p_{DT} \geq 1 \text{ GeV}$ the fragmentation corrections to $A_c(p_T)$ are less than 10%.

Analogous corrections to the asymmetry in the decay lepton azimuthal distribution, $A_\mu(p_T)$, are given in Fig.3. One can see that the effect of the fragmentation function (10) is practically negligible in the whole region of $p_\ell T$.

![Graph showing SSA in a D-meson production](image)

**FIG. 2.** SSA in a $D$-meson production; the QCD LO predictions with and without the inclusion of the $k_T$ smearing and Peterson fragmentation effects.
FIG. 3. SSA, $A_\mu(p_T)$, in the decay lepton distribution; the QCD LO predictions with and without the inclusion of the $k_T$ smearing and Peterson fragmentation effects.

To introduce $k_T$ degrees of freedom, $\vec{k}_g \simeq z\vec{k}_N + \vec{k}_T$, one extends the integral over the parton distribution function to the $k_T$-space,

$$dzg(z, \mu_F) \rightarrow d^2k_Tf(\vec{k}_T)g(z, \mu_F). \quad (11)$$

The transverse momentum distribution, $f(\vec{k}_T)$, is usually taken to be a Gaussian:

$$f(\vec{k}_T) = \frac{e^{-k_T^2/\langle k_T^2 \rangle}}{\pi \langle k_T^2 \rangle}. \quad (12)$$

Values of the $k_T$-kick corrections to the asymmetry in the charm production, $A_c(p_T)$, are shown in Fig.2 by dashed ($\langle k_T^2 \rangle = 0.5$ GeV$^2$) and dash-dotted ($\langle k_T^2 \rangle = 1$ GeV$^2$) curves. One can see that $k_T$-smearing is important only in the region of relatively low $p_T \lesssim m_c$. Note also that the fragmentation and $k_T$-kick effects practically cancel each other in the case of $\langle k_T^2 \rangle = 0.5$ GeV$^2$.

Corresponding calculations for the case of the lepton asymmetry are presented in Fig.3. It is seen that $A_\mu(p_T)$ is affected by $k_T$-corrections systematically smaller than $A_c(p_T)$.

IV. CONCLUSION

In this paper we analyze the possibility to measure the SSA in open charm photoproduction in the E160/E161 experiments at SLAC where a coherent bremsstrahlung beam of linearly polarized photons with energies up to 40 GeV will be available soon. In these experiments, the charm production will be investigated with the help of inclusive spectra of the secondary leptons. The SSA transferred from the decaying $c$-quark to the decay muon is predicted to be large for SLAC kinematics; the ratio $A_\ell(p_T)/A_c(p_T)$ is about 90% at $p_T > 1$ GeV. Our calculations show that the SSA in decay lepton distribution preserves
all remarkable properties of the SSA in heavy flavor production: it is stable, both perturbatively and parametrically, and practically insensitive to nonperturbative contributions due to the gluon transverse motion in the target and the heavy quark fragmentation. We have also found that the QCD predictions for $A_\ell(p_T)$ depend weekly on theoretical uncertainties in the charm semileptonic decays. We conclude that measurements of $A_\ell(p_T)$ in the E160/E161 experiments would provide a good test of pQCD applicability to open charm production.

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